Fifth Workshop on Understanding Climate Change from Data
The University of Minnesota, Minneapolis, MN, August 4 – 5, 2015

Climate Science to Adaptation:
The "Domain" Legacy of an Expedition

Auroop R. Ganguly

Sustainability & Data Sciences Laboratory (SDS Lab)
Department of Civil and Environmental Engineering
Northeastern University, Boston, MA, USA

08.04.2015

Northeastern

The Physical Science Basis: Our Work on Climate Extremes

Heat Waves & Regional Warming

- Worsening Warming & Heat Waves
  - BAU significantly worse after 2050's
  - Trends in regional warming & heat waves
- Larger Uncertainty & Variability
  - Uncertainties greater than thought
  - Geographic variability significant

Ganguly et al. (2009): PNAS

Extreme Cold Temperatures

- Persisting Cold Spells despite Warming
  - Decreasing frequency of cold snaps
  - Constant or increase in intensity & duration
- Natural variability as regional drivers
  - Global and regional causes
  - Natural climate variability

Kodra et al. (2011): GRL (Nature news)

Kodra & Ganguly (2014): Scientific Reports (Nature)**

Mishra et al. (2015): ERL (urban extremes)**

Precipitation Extremes & IDF Curves

- Trends in Extremes and Design Basis
  - More intense, frequent and duration
  - Non-stationary IDF curves
- Regional Drivers & Uncertainty
  - Larger uncertainty at higher resolutions
  - Indian Monsoon: Higher spatial variability

Khan et al. (2007): WRR

Kao & Ganguly (2011): JGR

Mishra et al. (2014): JGR**

Ghosh et al. (2012): Nature Climate Change**

Wind (Extremes) & Coastal Upwelling

- Historical versus Model Extremes
  - Models need better skills & consensus
  - Ensemble averages occasionally better
- Coastal upwelling under Warming
  - Upwelling intensifies under global warming
  - Differential heating of land-ocean

Kumar et al. (2014): Climate Dynamics**

Wang et al. (2015): Nature**

***** Expedition funded***

The Physical Science Basis: Our Work on Climate Extremes

Heat Waves & Regional Warming

- Worsening Warming & Heat Waves
  - BAU significantly worse after 2050's
  - Trends in regional warming & heat waves
- Larger Uncertainty & Variability
  - Uncertainties greater than thought
  - Geographic variability significant

Ganguly et al. (2009): PNAS

Extreme Cold Temperatures

- Persisting Cold Spells despite Warming
  - Decreasing frequency of cold snaps
  - Constant or increase in intensity & duration
- Natural variability as regional drivers
  - Global and regional causes
  - Natural climate variability

Kodra et al. (2011): GRL (Nature news)

Kodra & Ganguly (2014): Scientific Reports (Nature)**

Mishra et al. (2015): ERL (urban extremes)**

Today we will NOT talk about climate science!
(well, not any more...)

Precipitation Extremes & IDF Curves

- Trends in Extremes and Design Basis
  - More intense, frequent and duration
  - Non-stationary IDF curves
- Regional Drivers & Uncertainty
  - Larger uncertainty at higher resolutions
  - Indian Monsoon: Higher spatial variability

Khan et al. (2007): WRR

Kao & Ganguly (2011): JGR

Mishra et al. (2014): JGR**

Ghosh et al. (2012): Nature Climate Change**

Wind (Extremes) & Coastal Upwelling

- Historical versus Model Extremes
  - Models need better skills & consensus
  - Ensemble averages occasionally better
- Coastal upwelling under Warming
  - Upwelling intensifies under global warming
  - Differential heating of land-ocean

Kumar et al. (2014): Climate Dynamics**

Wang et al. (2015): Nature**

*** Expedition funded*

Impacts & Adaptation: Our work on Water, Ecosystem & Transportation

Water Resources & Global Change

- Climate & Population Change
  - Population larger stress than climate
  - Water stresses larger in specific regions
- Droughts uncertain but extreme
  - Drought trends uncertain in models / data
  - Extreme meteorological droughts growing

Parish et al. (2012): Computers & Geosciences**

The Water-Energy Nexus

- Water stresses on power production
  - Scarcer and warmer water causes stress
  - Climate change leads to regional stress
- Power production under risk
  - Significant risk of exposure to water stress
  - Uncertainty over near term from MICE

Ganguly et al. (2015): IEEE/AIP CiSE**

Ganguli & Ganguly et al. (2015 a; b): WRR (in rev.); JAWRA (in rev.)****

Transportation Infrastructures

- System resilience quantified
  - Robustness to cascading failures
  - Recovery from full or partial loss
- Network science driven
  - Network attributes drive recovery strategy
  - Demonstrated on Indian Railway Networks

Bhatia et al. (2015): PLoS One (in rev.)**

Marine Ecosystems & Food Web

- Keystone and generalist species
  - Robustness depends on the intersection
  - Restoration strategies depends on centrality
- Network science driven
  - Topology may dominate species attributes
  - Global applicability about 60 ecosystems

Bhatia et al. (2015): (in prep.)**

***** Expedition funded***

Impacts & Adaptation: Our work on Water, Ecosystem & Transportation

Water Resources & Global Change

- Climate & Population Change
  - Population larger stress than climate
  - Water stresses larger in specific regions
- Droughts uncertain but extreme
  - Drought trends uncertain in models / data
  - Extreme meteorological droughts growing

Parish et al. (2012): **Computers & Geosciences****

The Water-Energy Nexus

- Water stresses on power production
  - Scarcer and warmer water causes stress
  - Climate change leads to regional stress
- Power production under risk
  - Significant risk of exposure to water stress
  - Uncertainty over near term from MICE

Ganguly et al. (2015): **IEEE/AIP CiSE****

Ganguli & Ganguly et al. (2015 a; b): **WRR (in rev.)**; JAWRA (in rev.)****

Today we will NOT talk about impacts, adaptation and vulnerability

Other than to use two detailed case studies…

Transportation Infrastructures

- System resilience quantified
  - Robustness to cascading failures
  - Recovery from full or partial loss
- Network science driven
  - Network attributes drive recovery strategy
  - Demonstrated on Indian Railway Networks

Bhatia et al. (2015): **PLoS One (in rev.)****

Marine Ecosystems & Food Web

- Keystone and generalist species
  - Robustness depends on the intersection
  - Restoration strategies depends on centrality
- Network science driven
  - Topology may dominate species attributes
  - Global applicability about 60 ecosystems

Bhatia et al. (2015): **(in prep.)****

** ***Expedition funded***

Translating the physical science basis to inform adaptation

Physical Science Basis → **Impacts, Adaptation, & Vulnerability**

Physical Science Basis

- Global Warming: "unequivocal"
  - Human Emissions: "extremely likely" cause
- Credible Climate Projections
  - Resolution: Continental to global
  - Lead Time: 30 years to century and beyond
  - Climate Time Scale: 30 years average

Impacts, Adaptation, & Vulnerability

- Manage unavoidable non-stationarity
  - Changes: mean, variability, extremes
- Crucial Climate Variables
  - Resolution: Local to regional
  - Near-term Planning Horizon: 0 to 30 years
  - Adaptation: Time phased strategy

Climate Risk Management

Critical Infrastructures & Key Resources

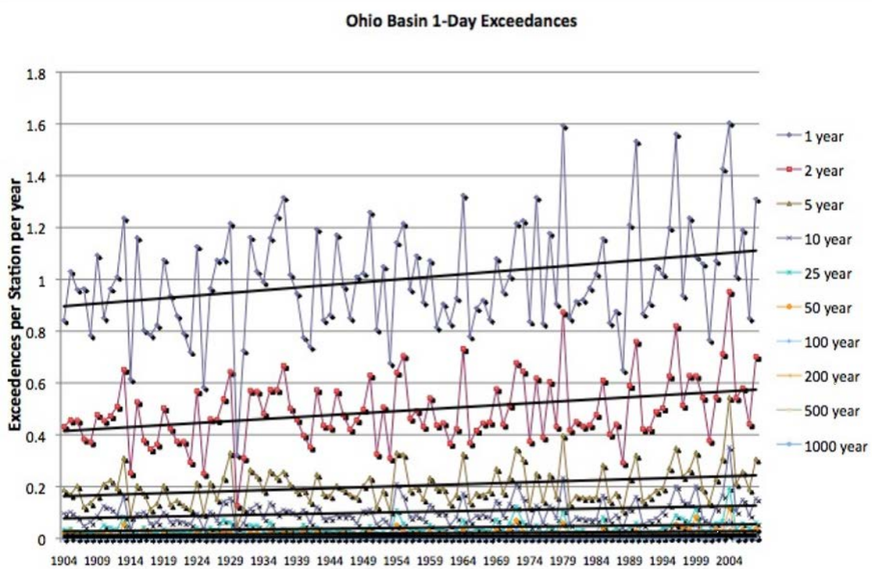
Water-Energy Nexus: Power production

ARPA-E (US DoE), US DoD, NRC, Private Sector

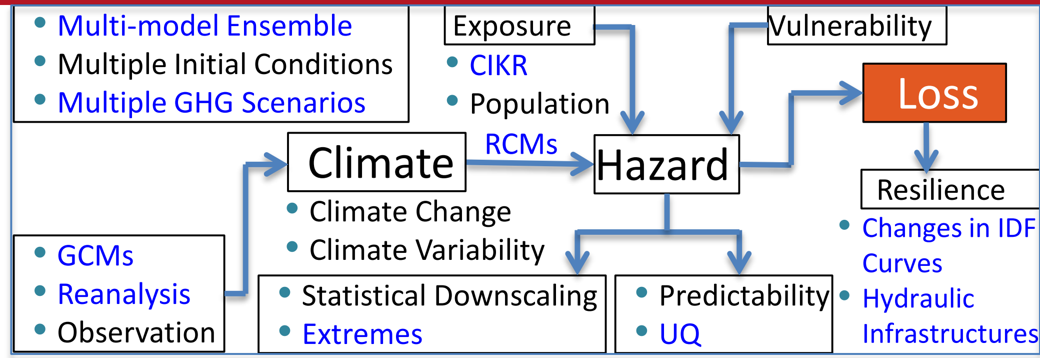
Hazard Preparedness: Coastal infrastructures

Massachusetts Port Authority, NIST, US DoD

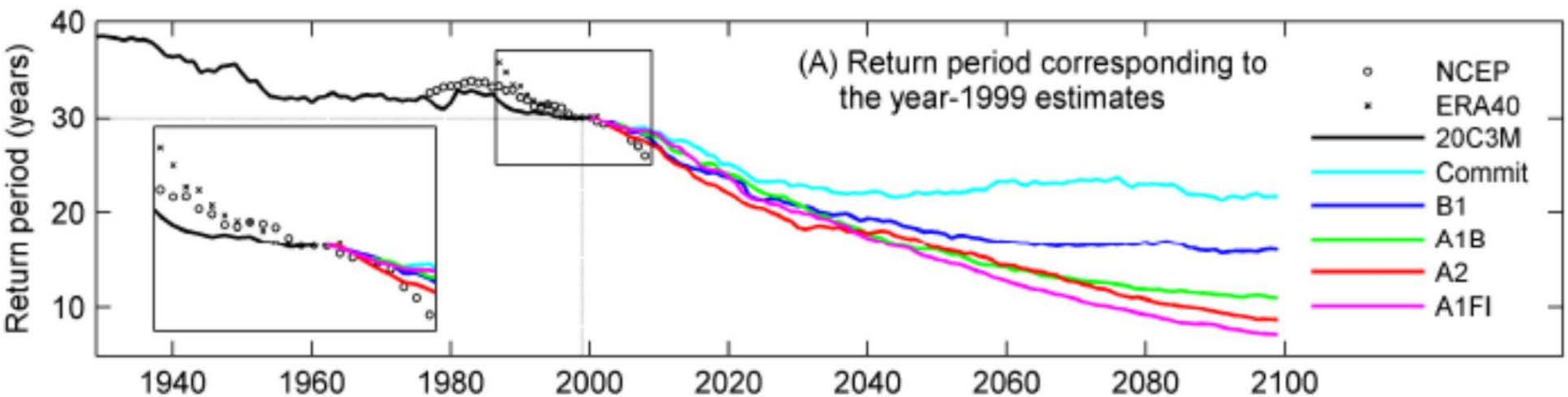
Challenges in Translation: 1. High-Resolution Projections



Source: Geoff Bonnin, National Weather Service

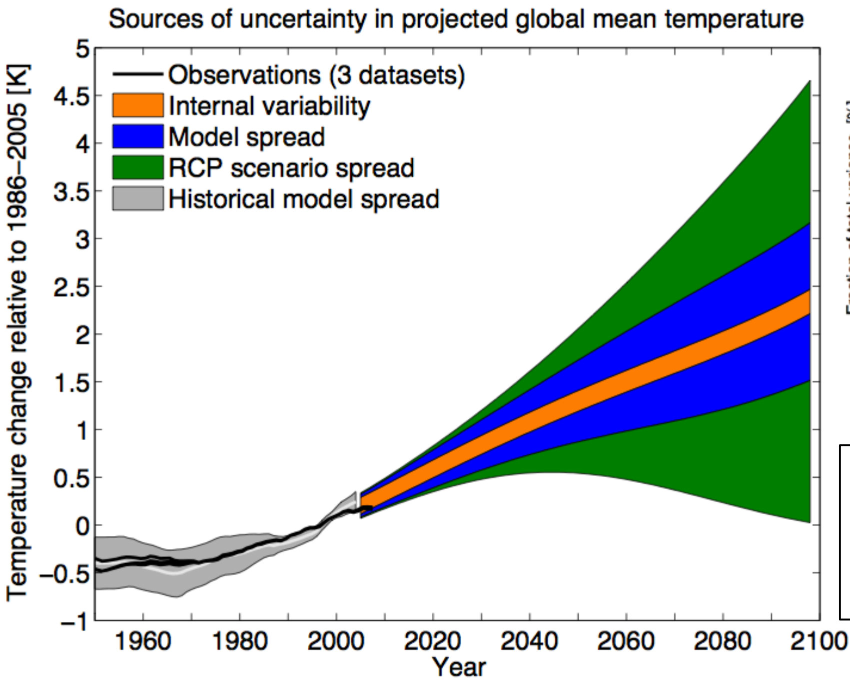


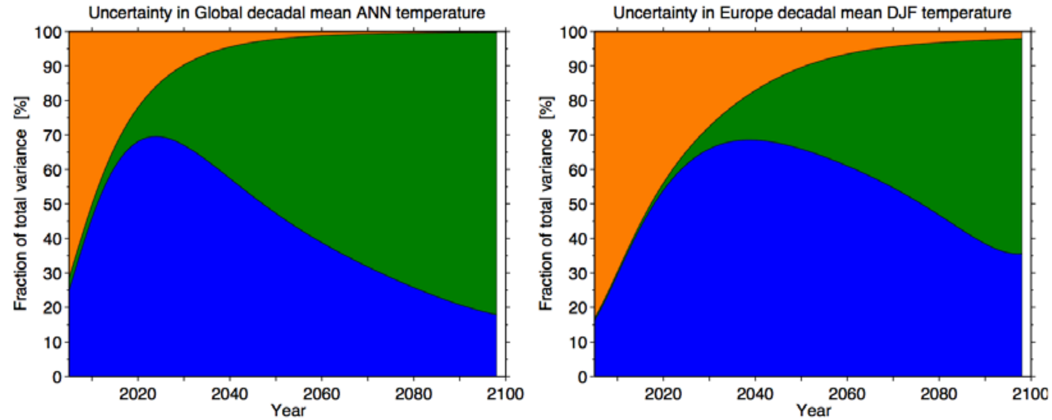
Can we extract non-stationary precipitation extremes IDF signals at scales that matter for infrastructures?



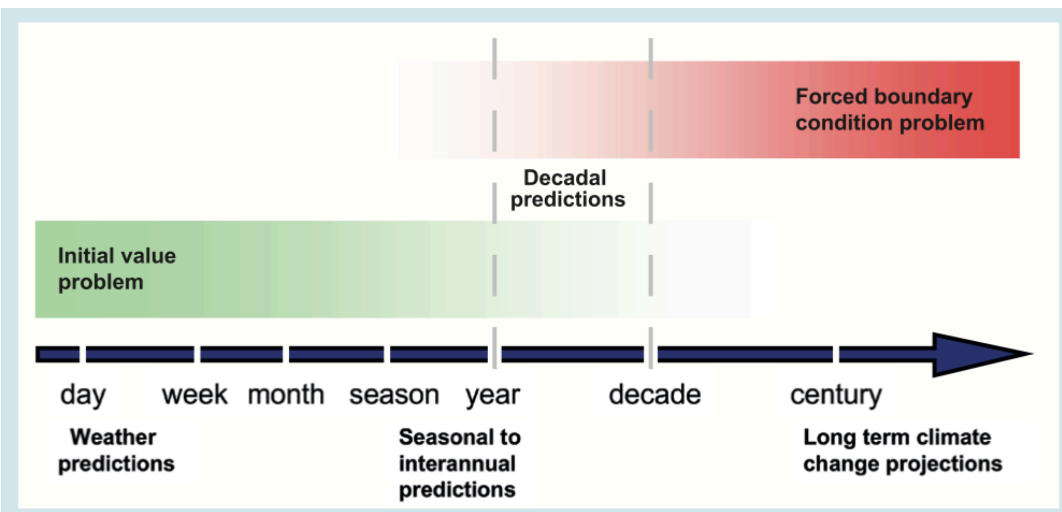
Source: Kao and Ganguly, Journal of Geophysical Research, 2011

Challenges in Translation: 2. Model Spread and Internal Variability





Internal Variability: Sensitivity to initial conditions
Model Spread: Inadequate physics or model parameters
RCP Scenario Spread: Uncertainties in GHG forcings



Internal Variability dominates for ….

- Shorter lead time
- Higher resolution
- Low frequency signals
- Extremes

Source: IPCC AR5 Physical Science Basis and Hawkins & Sutton (2009, 2011)

Under-Preparedness Versus Over-Investment

Source: Rosner et al., 2014 (WRR)

“Non-stationary”

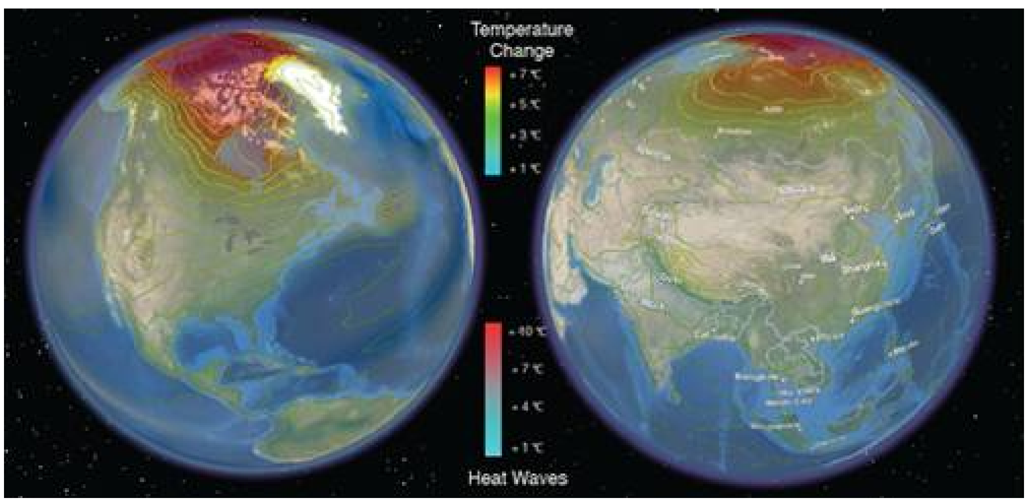
Change in Design Basis?

“Null Hypothesis”

Change is the new normal?

	No Trend in Floods H_o	Trend in Floods H_A
Do Not Adapt	$1 - \alpha$	β Type II Error (under-prepare)
Adapt	α Type I Error (over-invest)	$1 - \beta$ Power

Decision matrix and definitions of type I and type II errors.



Higher trends but larger uncertainty and geographic variability in 21st century temperature and heat waves

Auroop R. Ganguly[a,1], Karsten Steinhaeuser[a,b], David J. Erickson III[c], Marcia Branstetter[c], Esther S. Parish[a], Nagendra Singh[a], John B. Drake[c] and Lawrence Buja[d]

Author Affiliations

Edited by Stephen H. Schneider, Stanford University, Stanford, CA, and approved July 31, 2009 (received for review April 23, 2009)

Source: Ganguly, Steinhaeuser, et al., Proceedings of the National Academy of Sciences, 2009

Impacts & Adaptation: Our work on Water, Ecosystem & Transportation

Water Resources & Global Change

- Climate & Population Change
  - Population larger stress than climate
  - Water stresses larger in specific regions
- Droughts uncertain but extreme
  - Drought trends uncertain in models / data
  - Extreme meteorological droughts growing

Parish et al. (2012): Computers & Geosciences**

The Water-Energy Nexus

- Water stresses on power production
  - Scarcer and warmer water causes stress
  - Climate change leads to regional stress
- Power production under risk
  - Significant risk of exposure to water stress
  - Uncertainty over near term from MICE

Ganguly et al. (2015): IEEE/AIP CiSE**

Ganguli & Ganguly et al. (2015 a; b): WRR (in rev.); JAWRA (in rev.)****

Transportation Infrastructures

- System resilience quantified
  - Robustness to cascading failures
  - Recovery from full or partial loss
- Network science driven
  - Network attributes drive recovery strategy
  - Demonstrated on Indian Railway Networks

Bhatia et al. (2015): PLoS One (in rev.)**

Marine Ecosystems & Food Web

- Keystone and generalist species
  - Robustness depends on the intersection
  - Restoration strategies depends on centrality
- Network science driven
  - Topology may dominate species attributes
  - Global applicability about 60 ecosystems

Bhatia et al. (2015): (in prep.)**

***** Expedition funded***

Impacts & Adaptation: Our work on Water, Ecosystem & Transportation

Water Resources & Global Change

- Climate & Population Change
  - Population larger stress than climate
  - Water stresses larger in specific regions
- Droughts uncertain but extreme
  - Drought trends uncertain in models / data
  - Extreme meteorological droughts growing

Parish et al. (2012): Computers & Geosciences**

The Water-Energy Nexus

- Water stresses on power production
  - Scarcer and warmer water causes stress
  - Climate change leads to regional stress
- Power production under risk
  - Significant risk of exposure to water stress
  - Uncertainty over near term from MICE

Ganguly et al. (2015): IEEE/AIP CiSE**

Ganguli & Ganguly et al. (2015 a; b): WRR (in rev.); JAWRA (in rev.)****

Today we will NOT talk about impacts, adaptation and vulnerability
Other than to use these two case studies...

Transportation Infrastructures

- System resilience quantified
  - Robustness to cascading failures
  - Recovery from full or partial loss
- Network science driven
  - Network attributes drive recovery strategy
  - Demonstrated on Indian Railway Networks

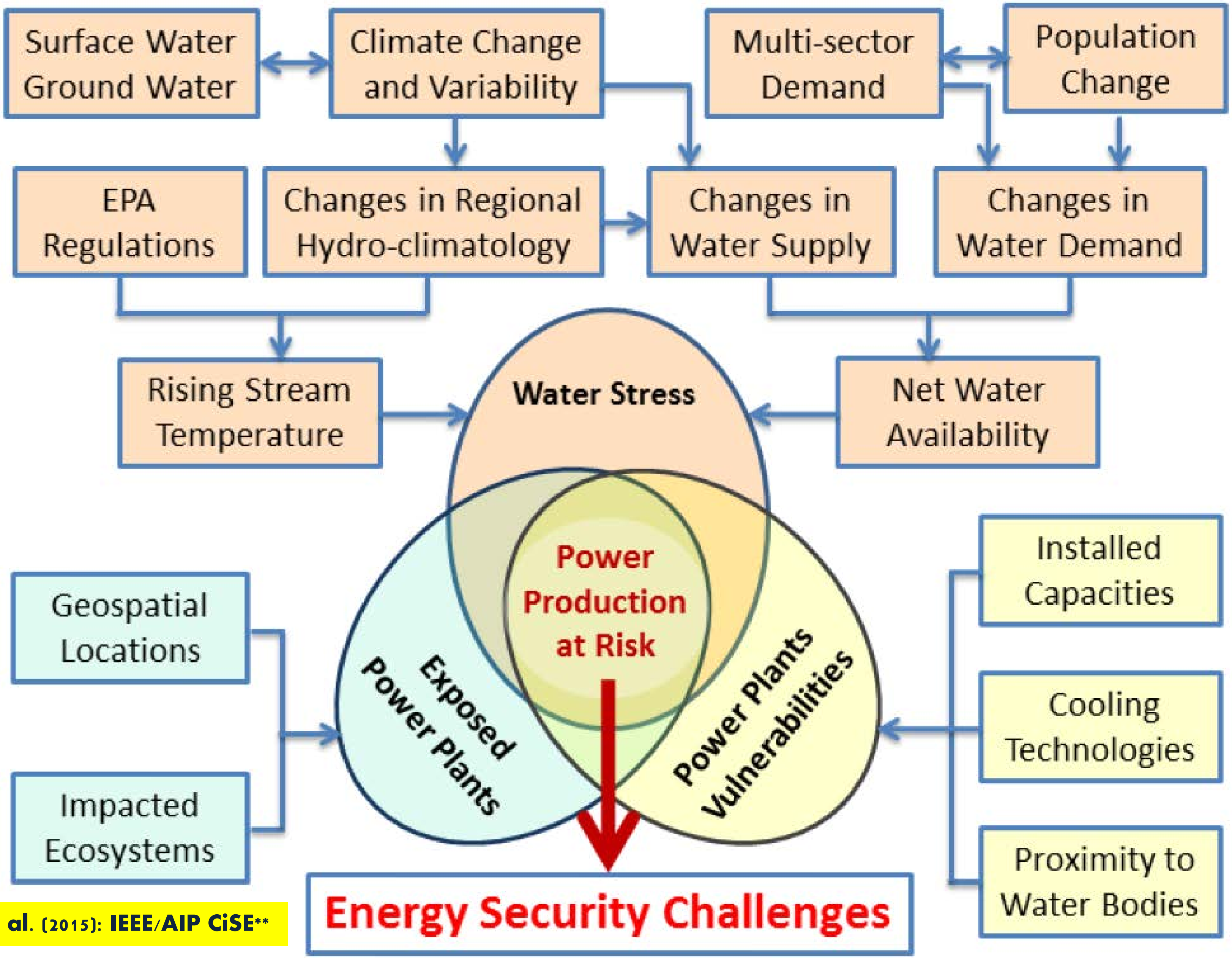
Bhatia et al. (2015): PLoS One (in rev.)**

- Keystone and generalist species
  - Robustness depends on the intersection
  - Restoration strategies depends on centrality
- Network science driven
  - Topology may dominate species attributes
  - Global applicability about 60 ecosystems

Bhatia et al. (2015): (in prep.)**

*** Expedition funded***

Case Study 1: Water Stress on Power Production (DOE/ARPA-E)



Ganguly et al. (2015): IEEE/AIP CiSE**

Case Study 1: Water Stress on Power Production (DOE/ARPA-E)

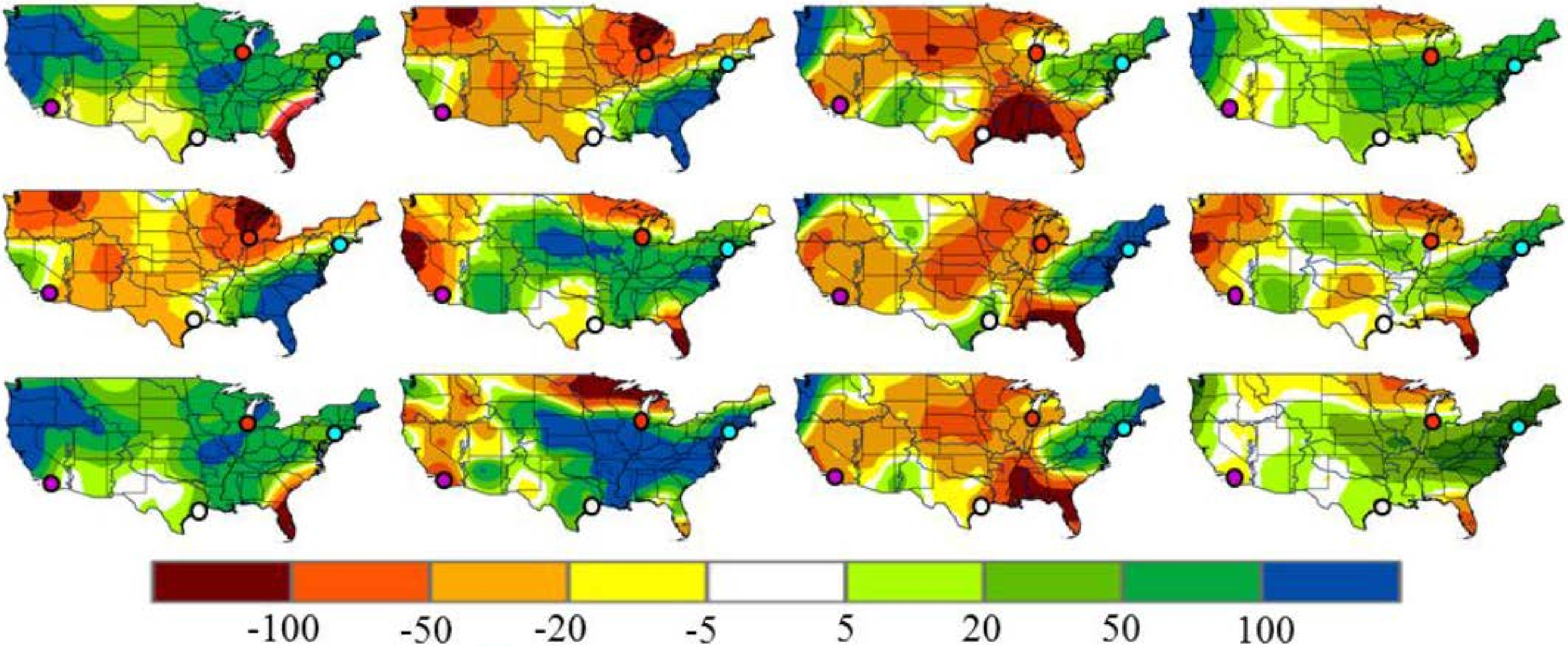


Figure 2. Spatial patterns of changes in freshwater availability (mm/year) in 2030s (2028-2032), relative to 2010s (2008-2012), from an ensemble of three CMIP5 climate models (first three columns from left to right: CCSM4 [U.S.: NCAR/DOE], GISS-E2H [U.S.: NASA], and MIROC5 [Japan: CCSR]) and two initial conditions (top and middle rows) under RCP8.5 emissions scenario over the contiguous United States. The top and middle rows of the fourth column show the three-model ensemble means for the two initial conditions, while the bottom rows of first three columns show the two-member initial condition ensemble means corresponding to the three models. The bottom-right figure shows the overall mean of initial and model ensembles. The four most populous cities - New York, Chicago, Houston, and Los Angeles - are shown in solid colored circle (blue, red, white, and pink, respectively). The boundaries of the river forecast centers and the states within the continental U.S. are shown as solid lines in deep blue and black. A first order estimate of freshwater availability is calculated as the difference between precipitation and evapotranspiration. Darker shades of green followed by blue on right of the scale show wetter conditions while yellow, orange and brown on the left show drier conditions.

Ganguly et al. (2015): IEEE/AIP CiSE**

Case Study 1: Water Stress on Power Production (DOE/ARPA-E)

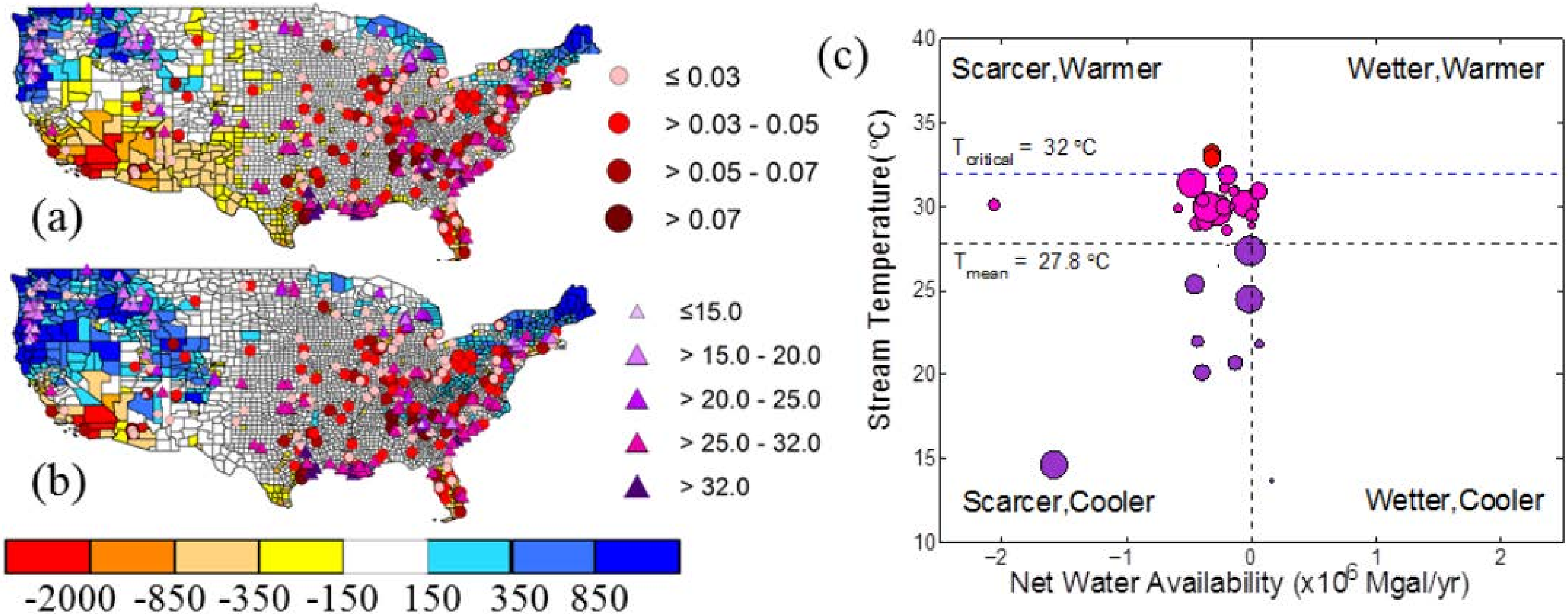


Figure 3. Spatial patterns of net water availability (10^3 Mgal/year) in 2030s (2028-2032) for two plausible future conditions: (a) ensemble minimum and (b) ensemble median. The 6-member ensemble includes two initial conditions and three models. Water consumption of 1700 m^3/year/per person has been used to calculate net water availability[26]. Wet-cooled thermoelectric power plants (with capacity ≥ 0.02 Quad/year) are shown as solid circles where the sizes of the circles represent generation capacities (Quad/year) of the power plants. Projected maximum stream temperatures (°C) in 2030s at USGS streamgage locations are shown as triangles. Stream temperatures are projected using nonlinear regression approaches. Median values of bias corrected air temperature from climate models are used as the predictors. Regions are called "water stressed" when the projected net water availability is below zero and the projected stream temperature is above 32°C[27]. A scatter plot (c) shows U.S. power production at risk owing to projections of decreasing water availability and increasing stream temperature. The sizes of the bubbles represent existing capacities of the power plants, while the colors symbolically represent the power production at risk. The horizontal line at the top shows the allowable temperature threshold for water temperature to be released to water body.

Ganguly et al. (2015): IEEE/AIP CiSE**

Case Study 1: Water Stress on Power Production (DOE/ARPA-E)

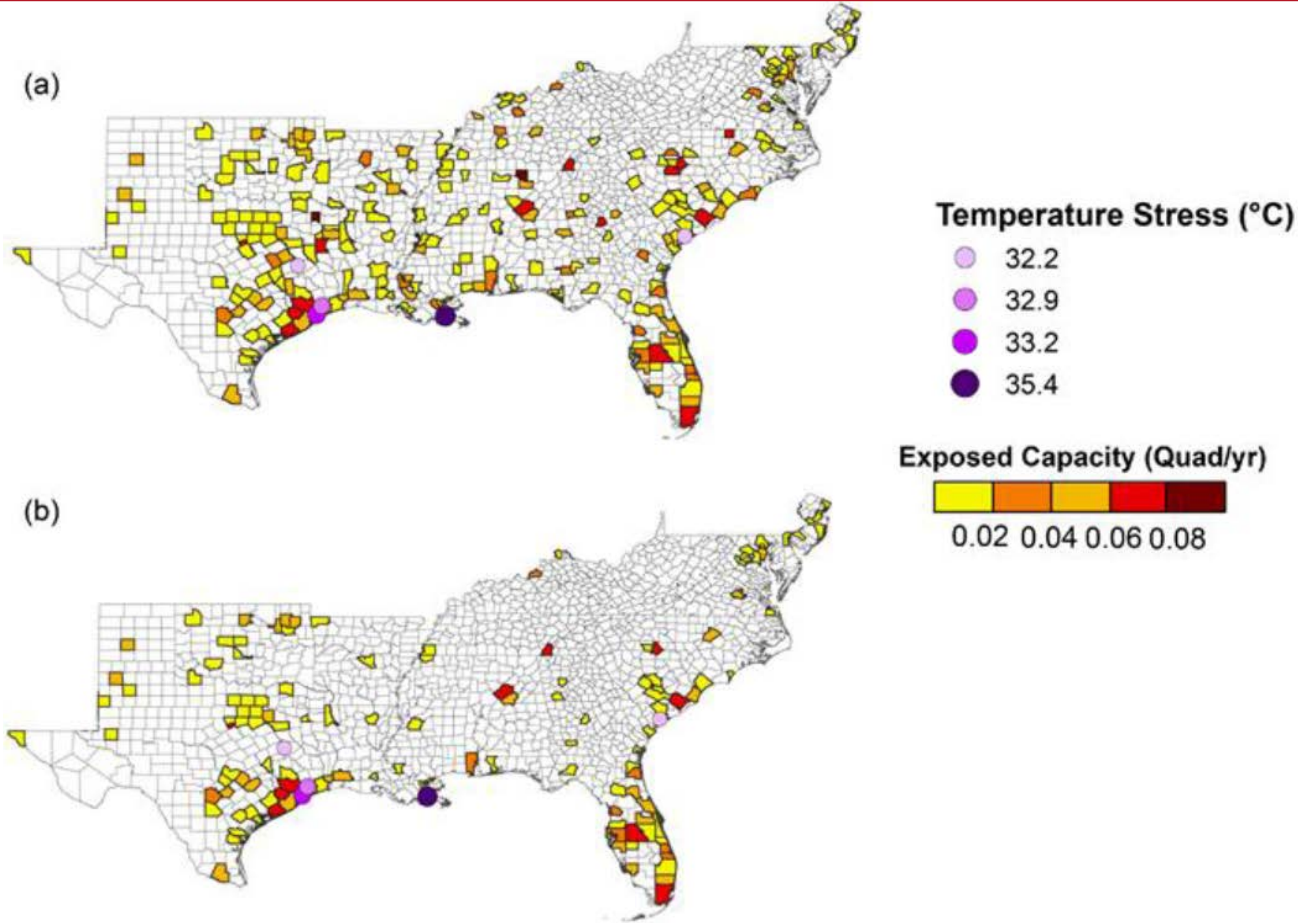
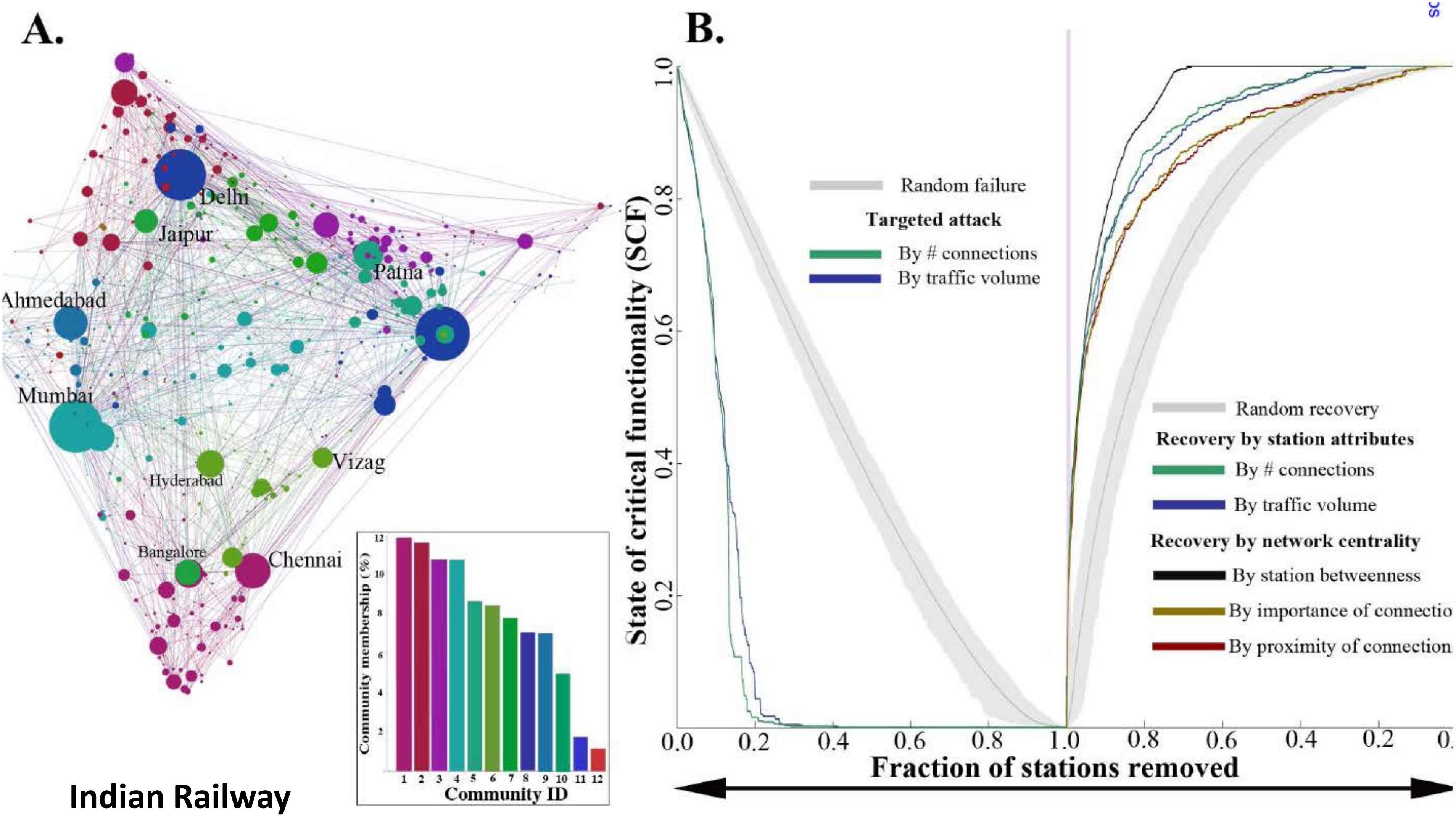


Figure 4. Power production capacity exposed to decrease in water availability and rising stream temperature in Southeastern U.S. (SUS) during 2030s (2028-2032) for two plausible future conditions: (a) ensemble minimum and (b) ensemble median. The SUS includes 13 states from the Mid-Atlantic coast west to Texas. Total power production at risk is calculated by aggregating annual production capacity (capacity ≥ 0.02 Quad/year) of all power plants[3] in the counties, where water availability is negative. The stream gauges where the projected maximum stream temperature (°C) in 2030 exceeds above the EPA specified threshold (32°C) is marked with circles; the shades and size of the circle are proportional to the magnitude of the stream temperature.

Ganguly et al. (2015): IEEE/AIP CiSE**

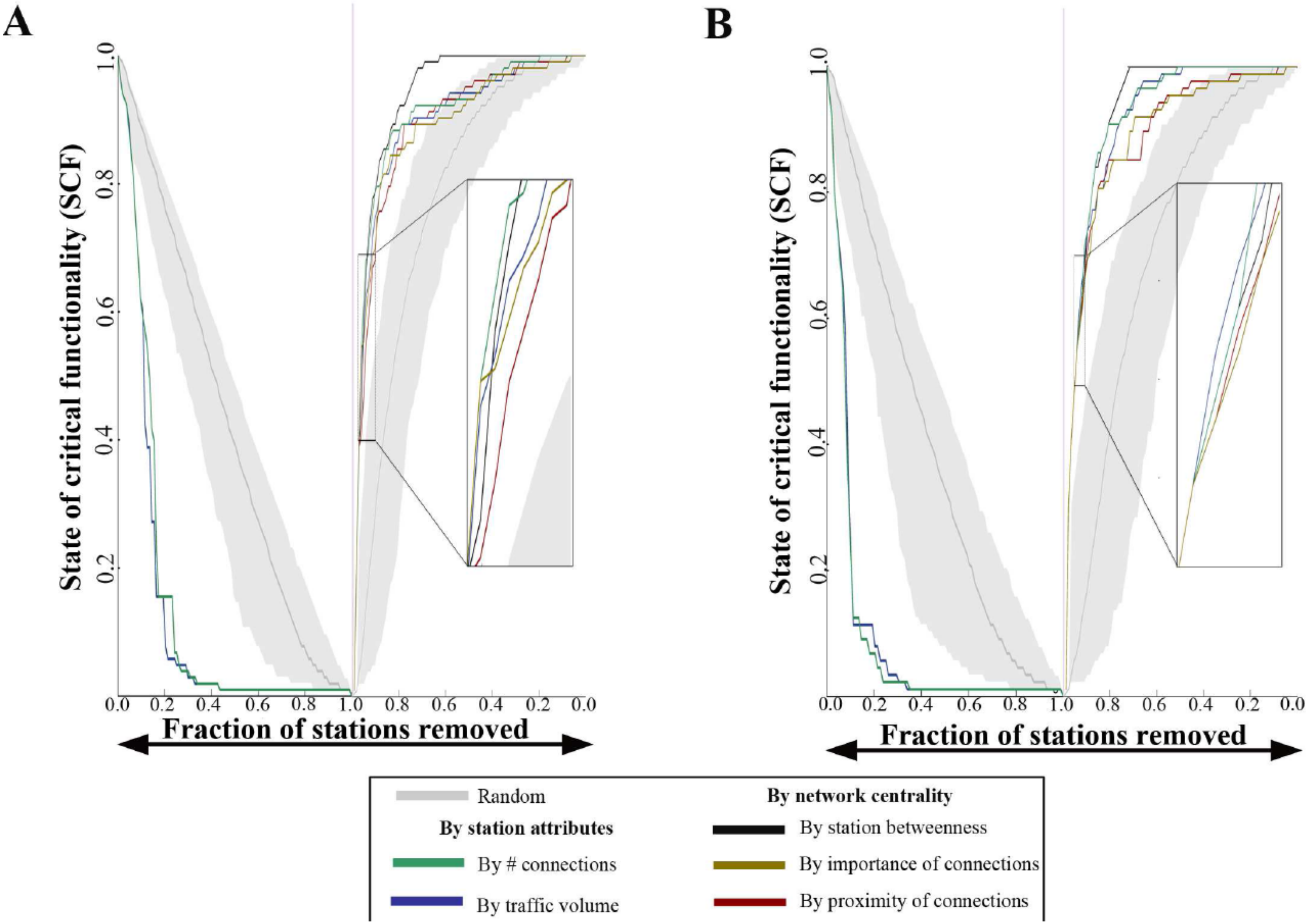
Case Study 2: Critical Infrastructures Resilience (DHS / Massport)



Indian Railway Networks

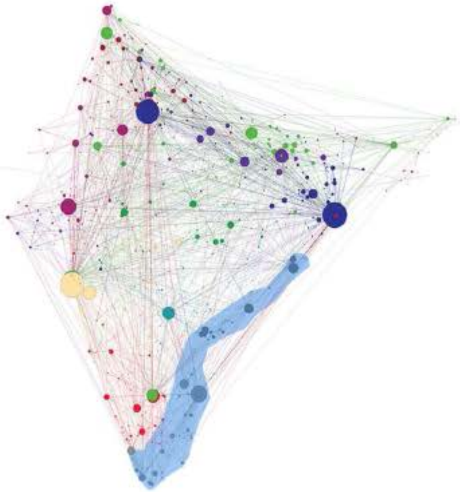
Bhatia et al. (2015): PLoS One (in rev.)**

Case Study 2: Critical Infrastructures Resilience (DHS / Massport)

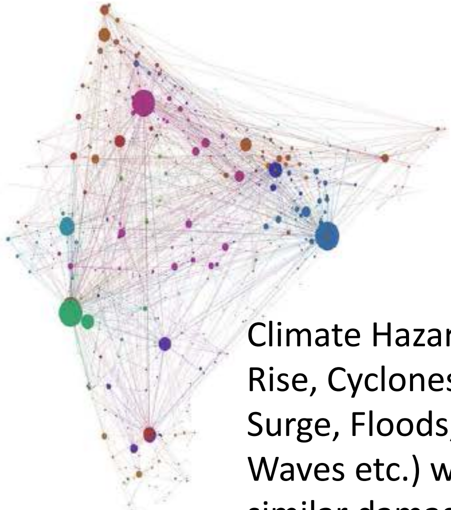


Bhatia et al. (2015): PLoS One (in rev.)**

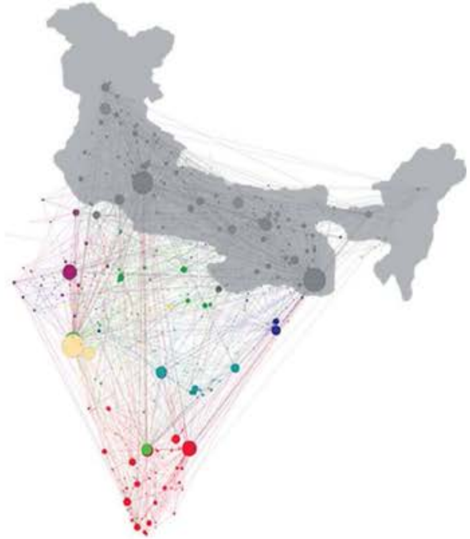
Case Study 2: Critical Infrastructures Resilience (DHS / Massport)



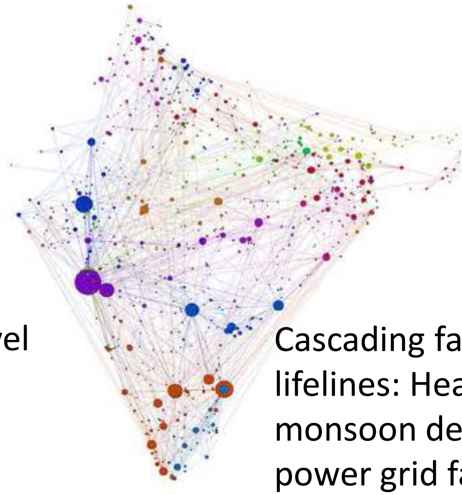
A. **2004 Indian Ocean Tsunami**



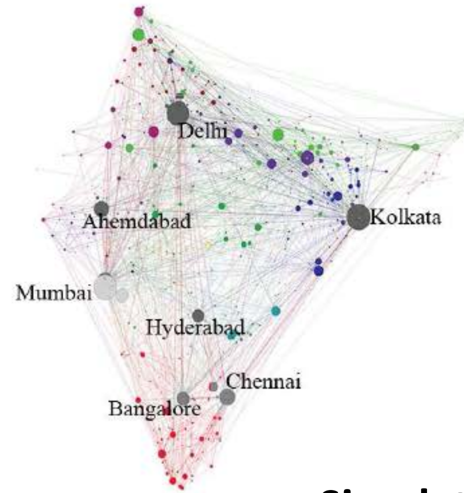
Climate Hazards (Sea Level Rise, Cyclones, Storm Surge, Floods, Heat/Cold Waves etc.) would cause similar damage



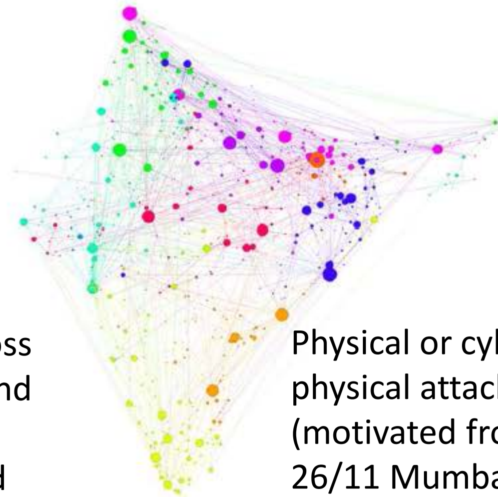
B. **2012 Indian Power Blackout**



Cascading failures across lifelines: Heat waves and monsoon delays cause power grid failures and then railways



C. **Simulated Terror Attack**



Physical or cyber-physical attacks (motivated from 26/11 Mumbai attacks in 2008)

Bhatia et al. (2015): PLoS One (in rev.)**

Towards Solutions: Our Work on "Physics-Guided Data Mining"

High-Resolution Projections

- Statistical Downscaling Methods
  - Multivariate Dependence: MI, Copula
  - Spatiotemporal , High-Dim: Sparsity
- Downscaling of Extremes
  - Characterization & Dependence
  - Covariate Discovery & Predictions

Chatterjee et al. (2012): SDM** **Das et al. (2014a): IEEE TGRS****

Khan et al. (2007): PRE **Das et al. (2014b): NPG****

Khan et al. (2006): GRL **Kuhn et al. (2007): AWR**

Uncertainty in Physics or Models

- Multi-Model Variability
  - Ensemble Averages & Skill-Selected Models
  - Skills vs. Convergence vs. Physics/Correlation
- Physical Relations & Dependence
  - Multivariate Physics & Correlative Relations
  - Multi-scale & Multi-frequency relations

Ganguly et al. (2013): CRC Press**

Kodra et al. (2012): ERL** **Kodra et al. (2014): Dissertation****

Kumar et al. (2014): Climate Dynamics**

Ganguly et al,. (2014): NPG Editorial Perspectives**

Intrinsic System Variability

- Nonlinear Dynamical Systems
  - Information Theoretic Characterizations
  - Detection & Predictability Bounds
- Multi-scale & Time-frequency effects
  - Probabilistic Graphs & Complex Networks
  - Statistical & Signal Processing Methods

Steinhaeuser et al. (2012a;b): Climate Dynamics; SADM****

Khan et al. (2007): PRE **Khan et al. (2005): NPG**

Kodra et al. (2012): ERL (supplement)**

Decision Support & Policy Tools

- Risk & Resilience Assessments
  - Coastal & Urban Infrastructures
  - Power Production & Water Supply
- National Security & War Games
  - Multimodal Supply Chain Security
  - Climate War Games & Negotiations
  - Regulatory Principles with Uncertainty

Rolland et al. (2014): Buffalo Law Review

Ganguly et al. (2009): ACM GIS

**** *Expedition funded***

"Physics-Guided Data Mining": Paradigm shift or marketing jargon?

Ganguly et al,. (2014): NPG Editorial Perspectives**

Bhatia et al. (2015): in prep.**

- **What data mining?**
  - New methods in data science
  - Novel adaptation of data science methods
  - New applications of the state of the art
- **What physics?**
  - Known but not within climate models
  - Why not? Incomplete and/or incompatible
- **What guidance?**
  - Input (e.g., covariate, indicator) selection
  - ML architecture or statistical framework

Note: This is NOT data assimilation: No observations to update state for climate projection time horizons!

** ***Expedition funded***

“Physics … marketing jargon?

Ganguly et al.. (2014): NPG Editorial Perspectives**

Bhatia et al. (2015): in prep.**

- Consider three examples
  - ❑ Statistical Downscaling
  - ❑ Multi-Model Uncertainty
  - ❑ Internal Variability

** *Expedition funded*

“Physics-Guided Data Mining”: Statistical Downscaling

Next Step: Combine new methods (e.g., Das et al. 2014; 2015) with a new strategy for validation of SD (Salvi et al. 2015)

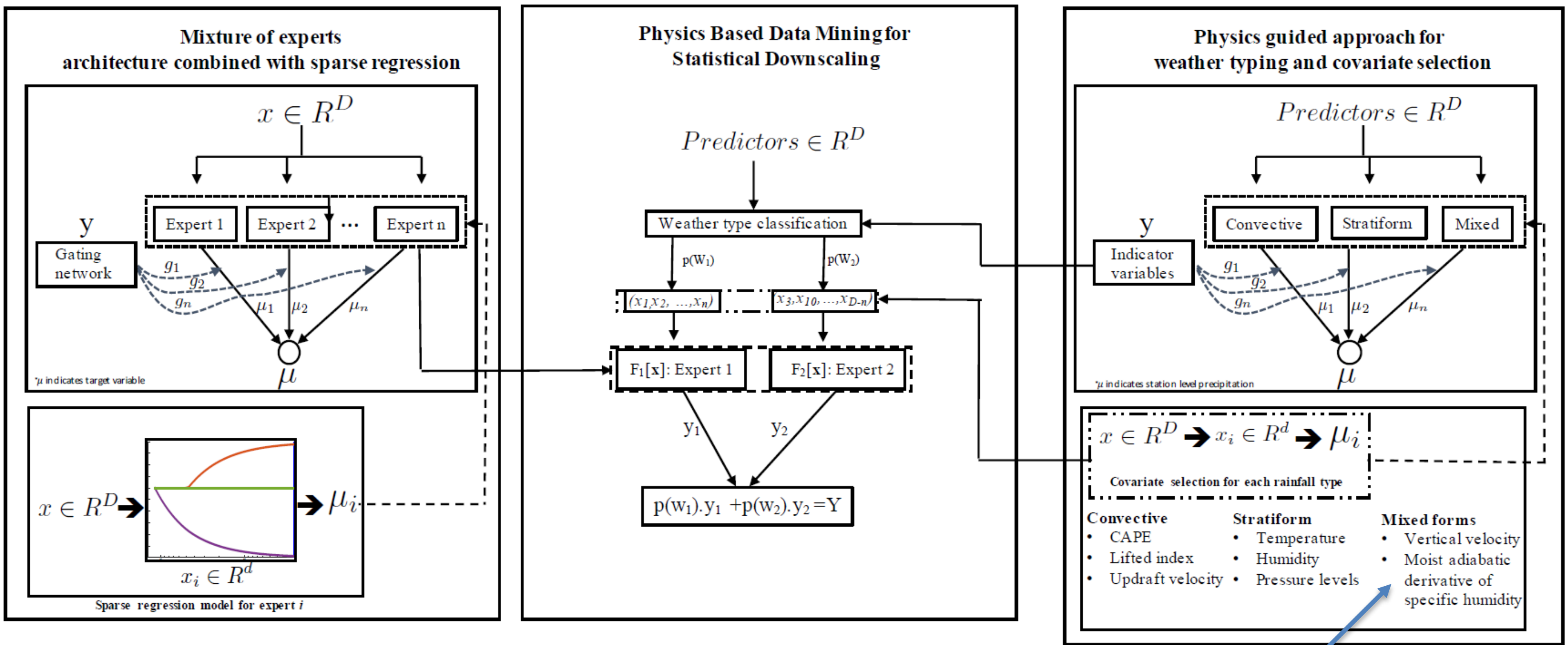
Das et al. (2014a): IEEE TGRS**

Ganguly et al.. (2014): NPG Editorial Perspectives**

Das et al. (2014b): NPG**

Bhatia et al. (2015): in prep.**

Salvi et al. (2015): Climate Dynamics**



Jordan & Jacobs (1994): Hierarchical mixture of experts…
O’Gorman et al. (2009): Precipitation Extremes Scaling…
Tipping (2001): Sparse Bayesian learning…
Etc.

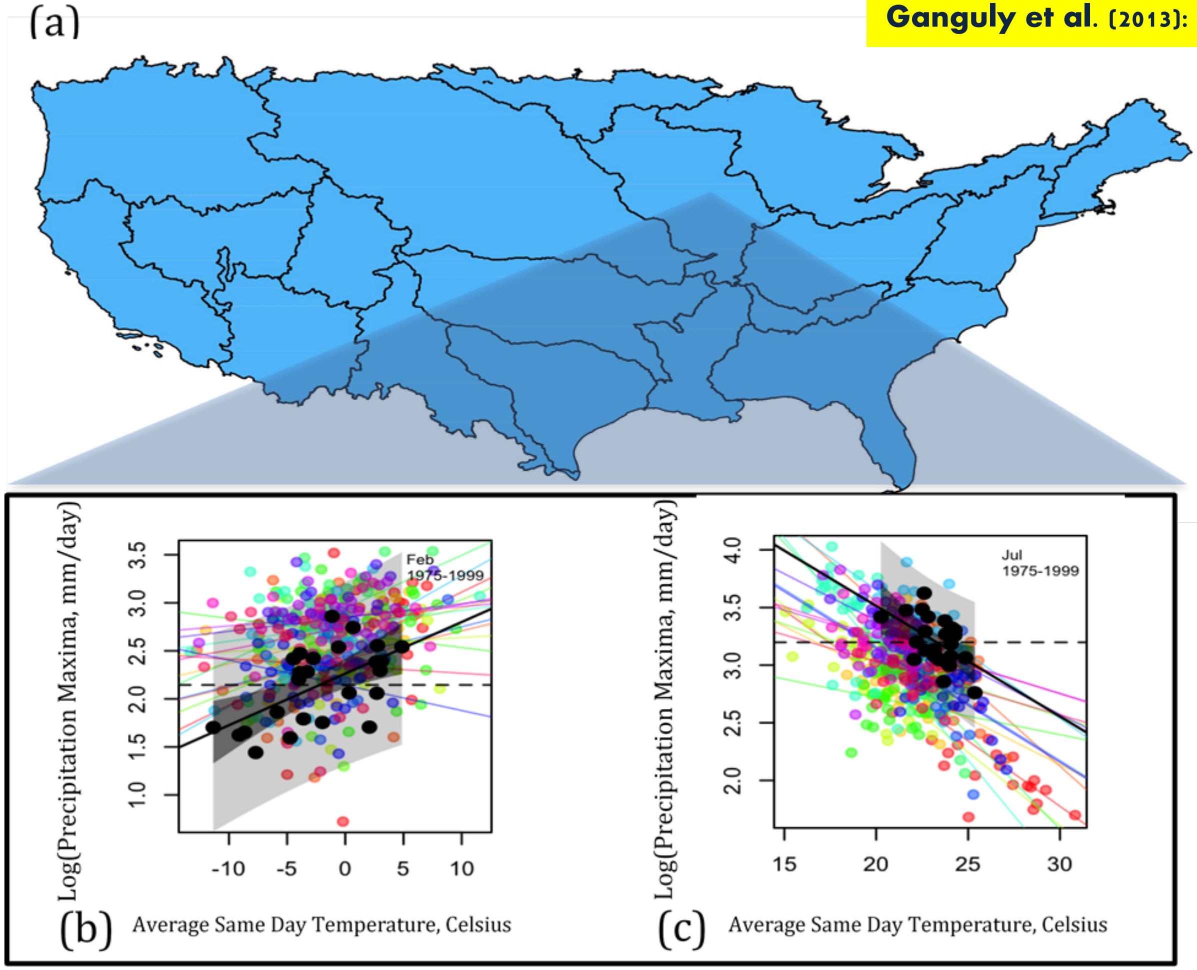
$$P_e \sim -\left\{ \omega_e \frac{dq_s}{dp} |_{\theta^*, T_e} \right\}$$

***** Expedition funded***

“Physics-Guided Data Mining”: Multi-Model Uncertainty

Kodra et al. (2014): Dissertation** **Ganguly et al.. (2014): NPG Editorial Perspectives****

Ganguly et al. (2013): CRC Press** **Bhatia et al. (2015): in prep.****



Augmenting skill and consensus based formalisms with physical and data-driven relations

- Clausius Clapeyron
- CAPE
- Etc.

Smith et al. (2009): JASA…
Etc.

$$E(\lambda_i|\{X_0,\ldots,X_9,Y_1,\ldots,Y_9\}) \approx \frac{a+1}{b+\frac{1}{2}((X_i-\tilde{\mu})^2+\theta(Y_i-\tilde{\nu}-\beta_x(X_i-\tilde{\mu}))^2)}.$$

Skill “weight” Consensus

***** Expedition funded***

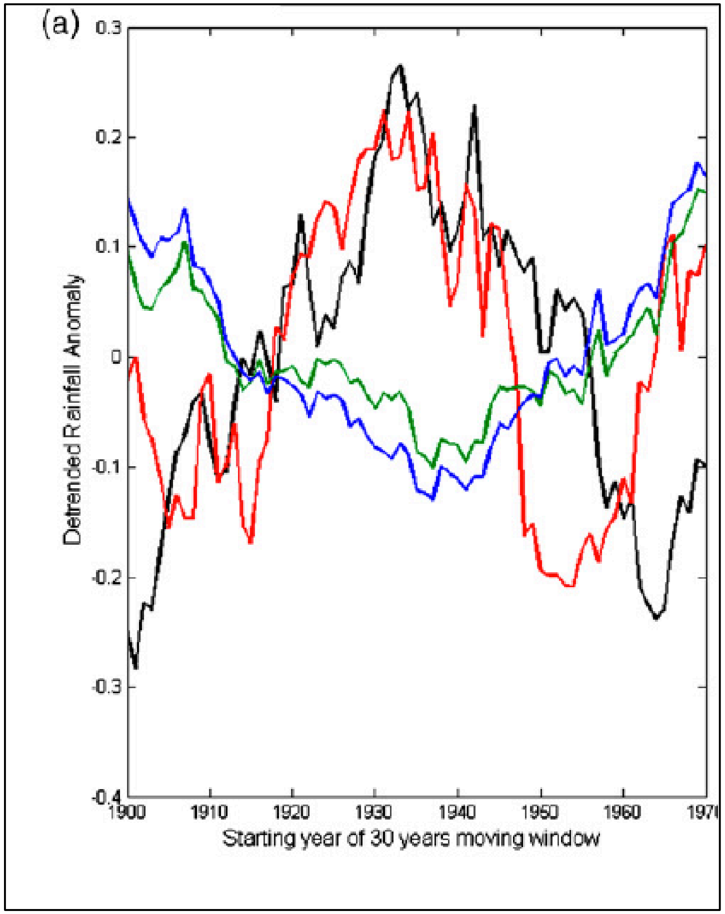
“Physics-Guided Data Mining”: Internal Variability

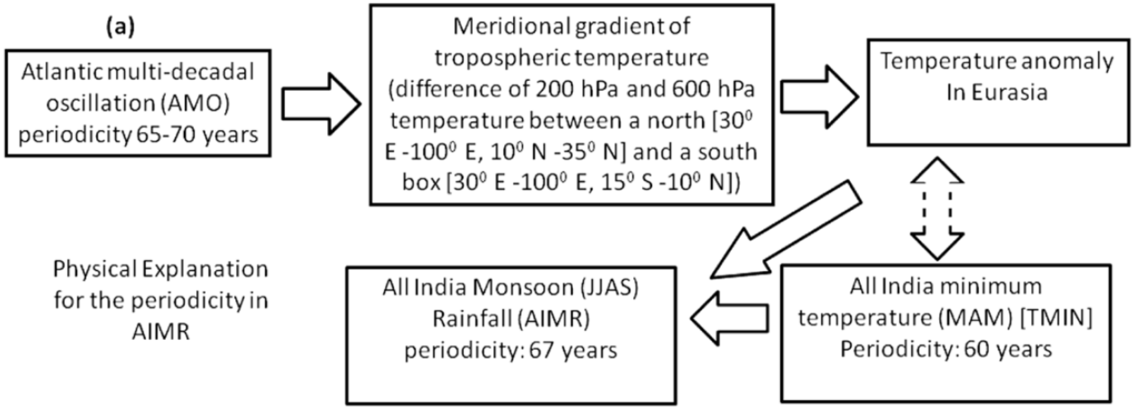
Kodra et al. (2012): ERL**

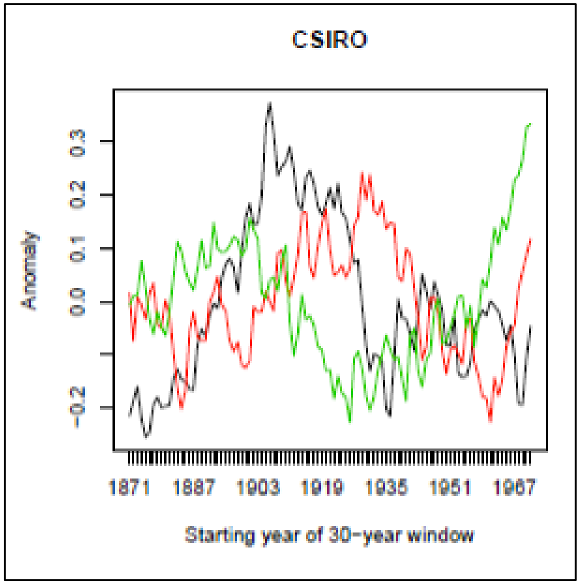
Ganguly et al.. (2014): NPG Editorial Perspectives**

Kumar et al. (2015): in prep.**

Bhatia et al. (2015): in prep.**



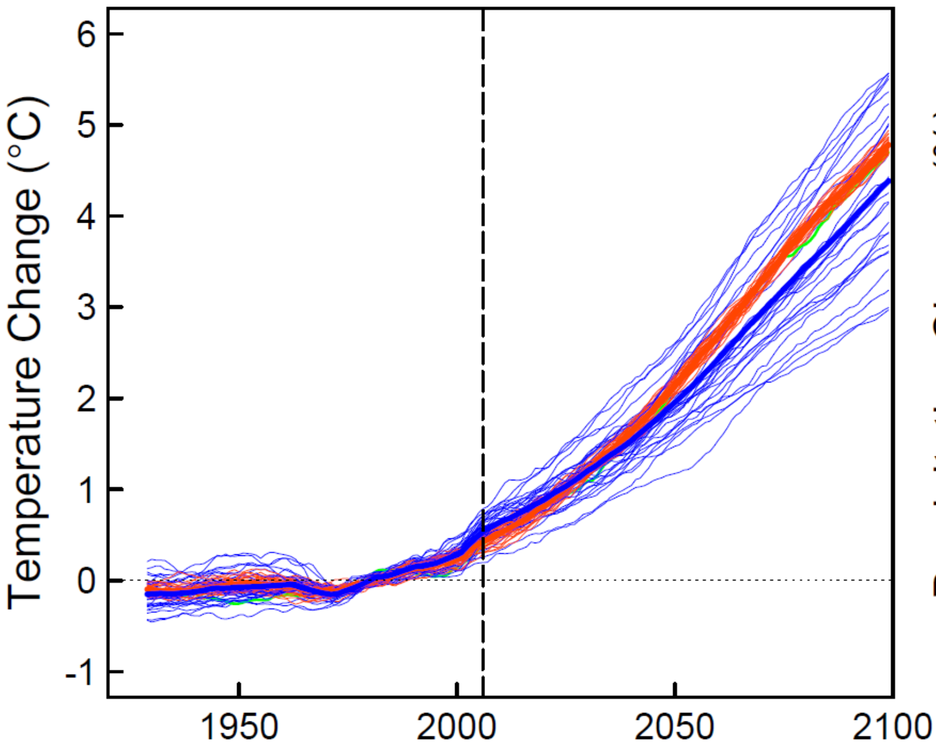


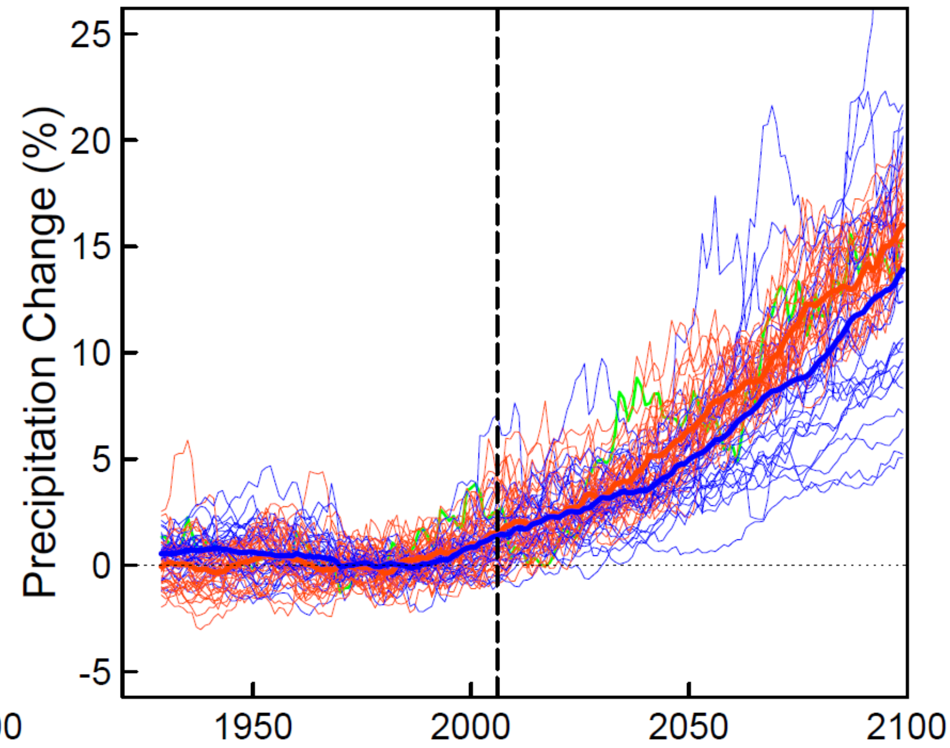


***** Expedition funded***

“Physics-Guided Data Mining”: Paradigm shift or marketing jargon?

Internal Variability in Climate: Does this really matter?





Global JJA
Blue: MME
Red: MICE
Green: Common Model

Kumar et al. (2015): in prep.**

** ***Expedition funded***