Quantifying and Managing Dynamic Climate Risk

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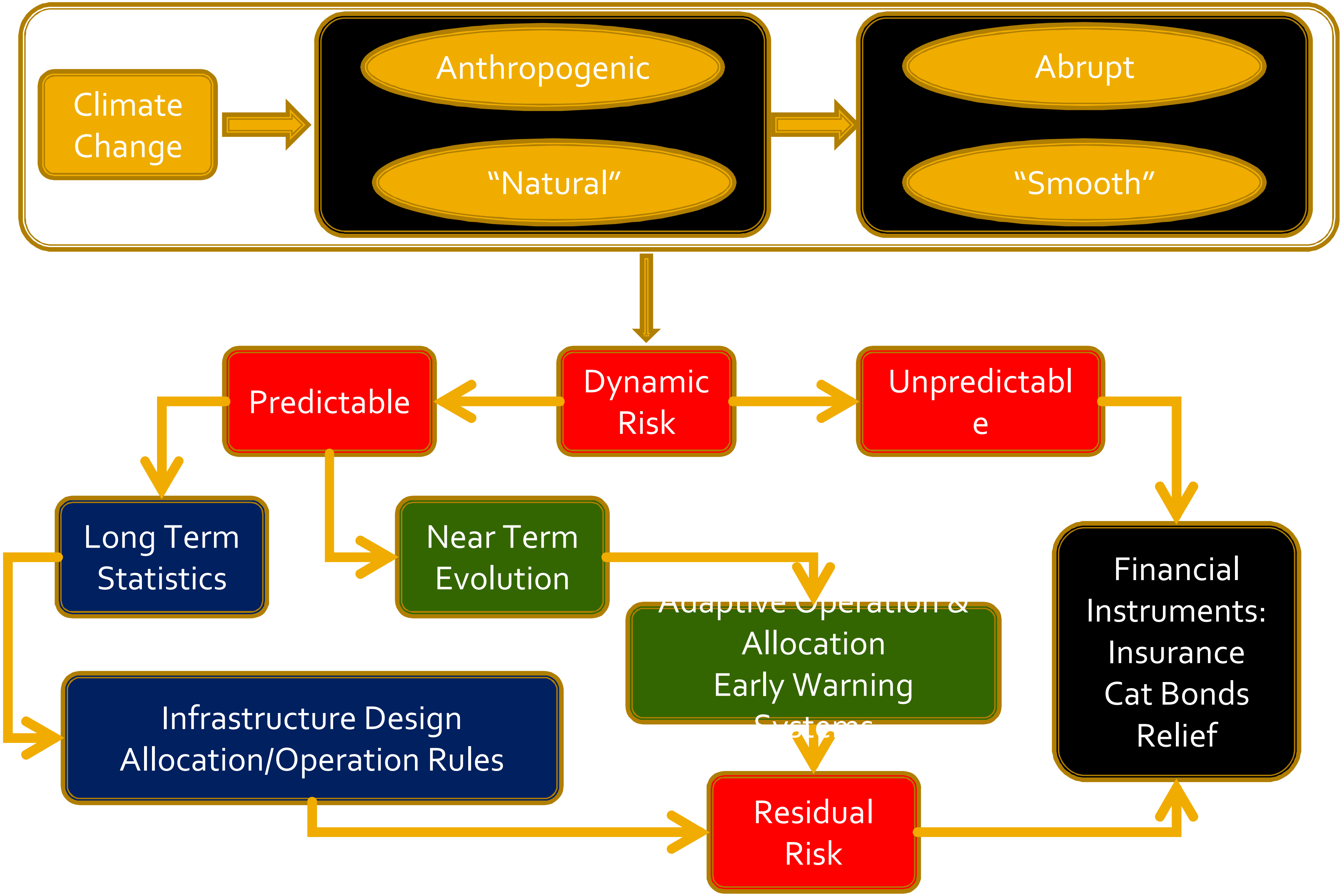
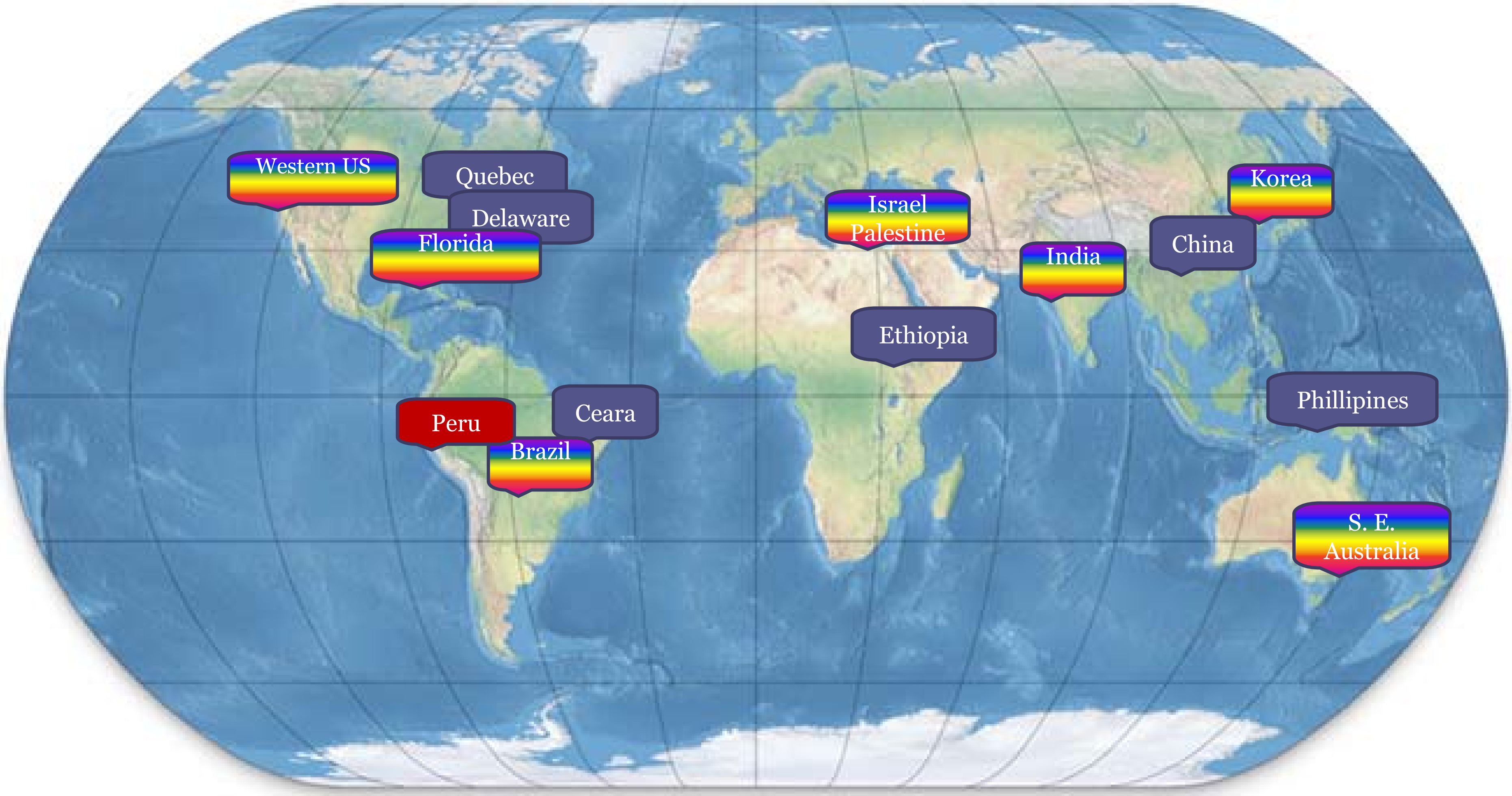
Climate Risk Management

- Mitigation: Reduce net C emissions
  - Important to do now to avert disaster later
- Adaptation: Infrastructure & management to reduce risks & increase resilience to potential changes
  - Hydrologic changes continue to be uncertain (timing+amount)
    - Dynamic range of variations in historical/paleo data quite large relative to most change projections
    - How well do we manage existing climate risk, and how can we improve resilience of the water systems with new climate knowledge?
- Dynamic Risk: Joint probability of a set of outcomes of concern as a function of time
  - model the nonstationarity over time as conditional risk given climate state variables
  - systems for managing the direct and residual risk

Outline


Climate Change
Anthropogenic
"Natural"
Abrupt
"Smooth"
Dynamic Risk
Predictable
Unpredictabl e
Long Term Statistics
Near Term Evolution
Adaptive Operation & Allocation Early Warning Systems
Infrastructure Design Allocation/Operation Rules
Financial Instruments: Insurance Cat Bonds Relief
Residual Risk

Current/Recent Project Activity



Seasonal Forecasting of Rain/Flow including management system

Flood Risk

Comprehensive : Seasonality prediction, Daily weather generation conditional on climate state, Dynamic Flood Risk, Paleoclimate based Simulations, Climate Change Scenarios, Multi-model combination

What Can We Do Today?

- Identify Local & Regional hydroclimate regimes and their manifestation in space and time: Derive from long Global Climate data sets, including retrospective climate model runs
- Monitoring: Identify regime changes and likely attributes of new regime
- Targeted probabilistic forecasts and scenarios of flow, rain and floods at existing gages at multiple time scales and lead times
- Optimally blend multiple models: Verify skill, assess utility and optimally combine multiple information sources to generate more reliable scenarios
- Develop new allocation and operation rules: Responsive to forecast and cognizant of uncertainty

Climate Change and Variability

- Adaptation of hydrologic systems to climate change
  - Can we learn something from the past?
    - ENSO + other low frequency modes
      - Will likely change in the future ……….
  - Can we adapt to persistent changes in the mean/variance exhibited in the paleo record?
    - Is this meaningful for the future when we have a new climate?
    - Relative magnitude of paleo changes relative to recent historical record
    - Storage? Or institutions? Or flexible allocation?

Example 1

- Colorado River Flows
  - How can we translate the tree ring reconstruction of Lees Ferry flows to risk estimates? (frequency, duration and severity of failures of allocation)
  - Can we generate stochastic simulations of flows to characterize how the risk of failure of the water allocation changes in time due to low frequency (inter-annual to century scale) variability?
  - What does this mean for the current allocation and adaptation to climate change?

The Colorado River Compact (1922)

Low flow in the Colorado River Basin spurs water shortage discussion among seven states

2005 Headline

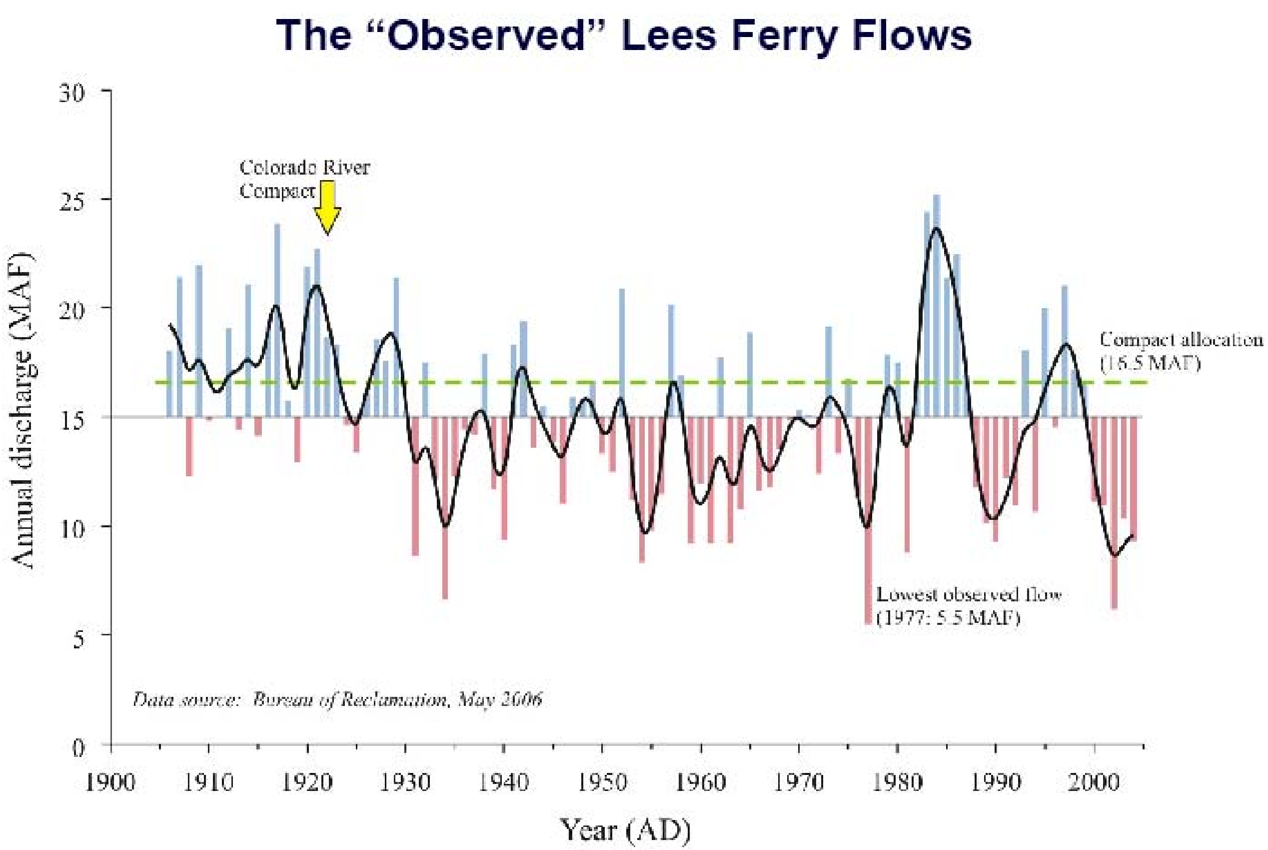
Political Entity	Annual allocation (in acre-feet)
Upper Basin States	7,500,000*
Colorado	3,900,000*
New Mexico	800,000*
Utah	1,700,000*
Wyoming	1,000,000*
Lower Basin States	7,500,000
California	4,400,000
Arizona	2,800,000
Nevada	300,000
Mexico	1,500,000
Total	16,500,000

Lake Mead Could Be Within a Few Years of Going Dry, Study Finds – NY Times Feb 2008

The Colorado River Compact (1922)

Low flow in the Colorado River Basin spurs water shortage discussion among seven states

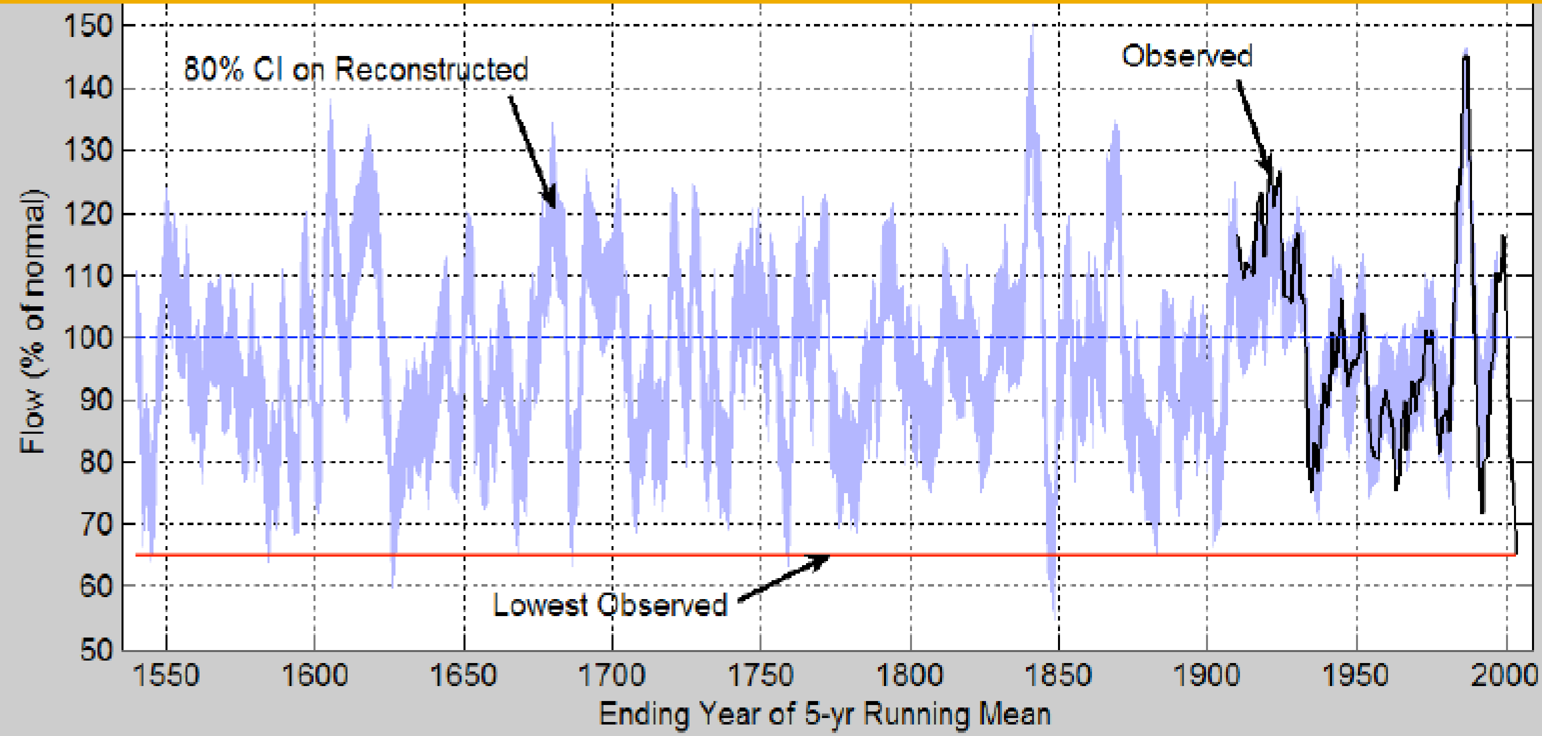
005 Headline



Lake Mead Could Be Within a Few Years of Going Dry, Study Finds – NY Times Feb 2008

Hydrologic/Climatic Variability

How should these long periods of climatic departures be managed?
How adequate are the reservoirs (Storage capacity = 5+ years of mean annual flow?

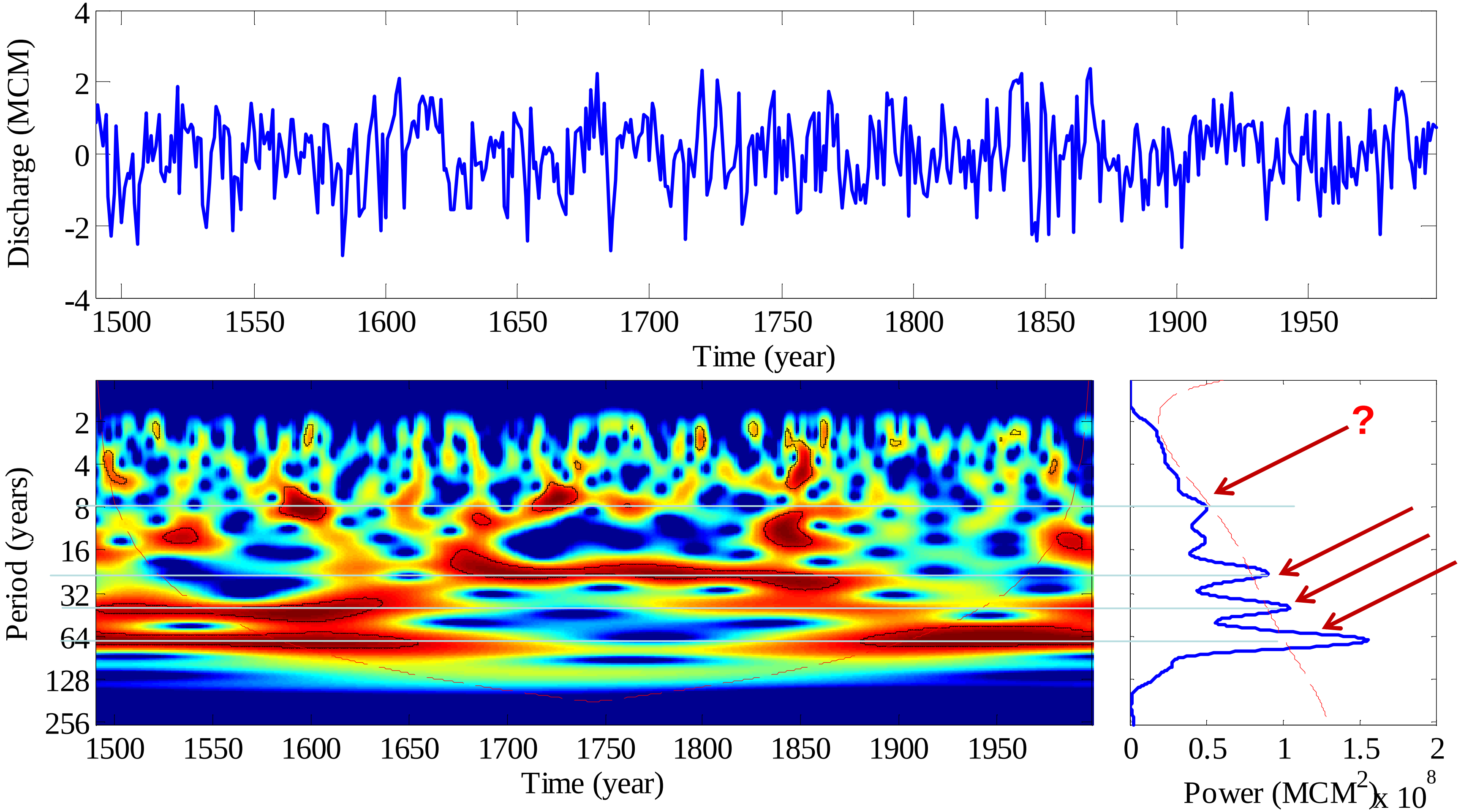


Data analysis courtesy of Dave Meko

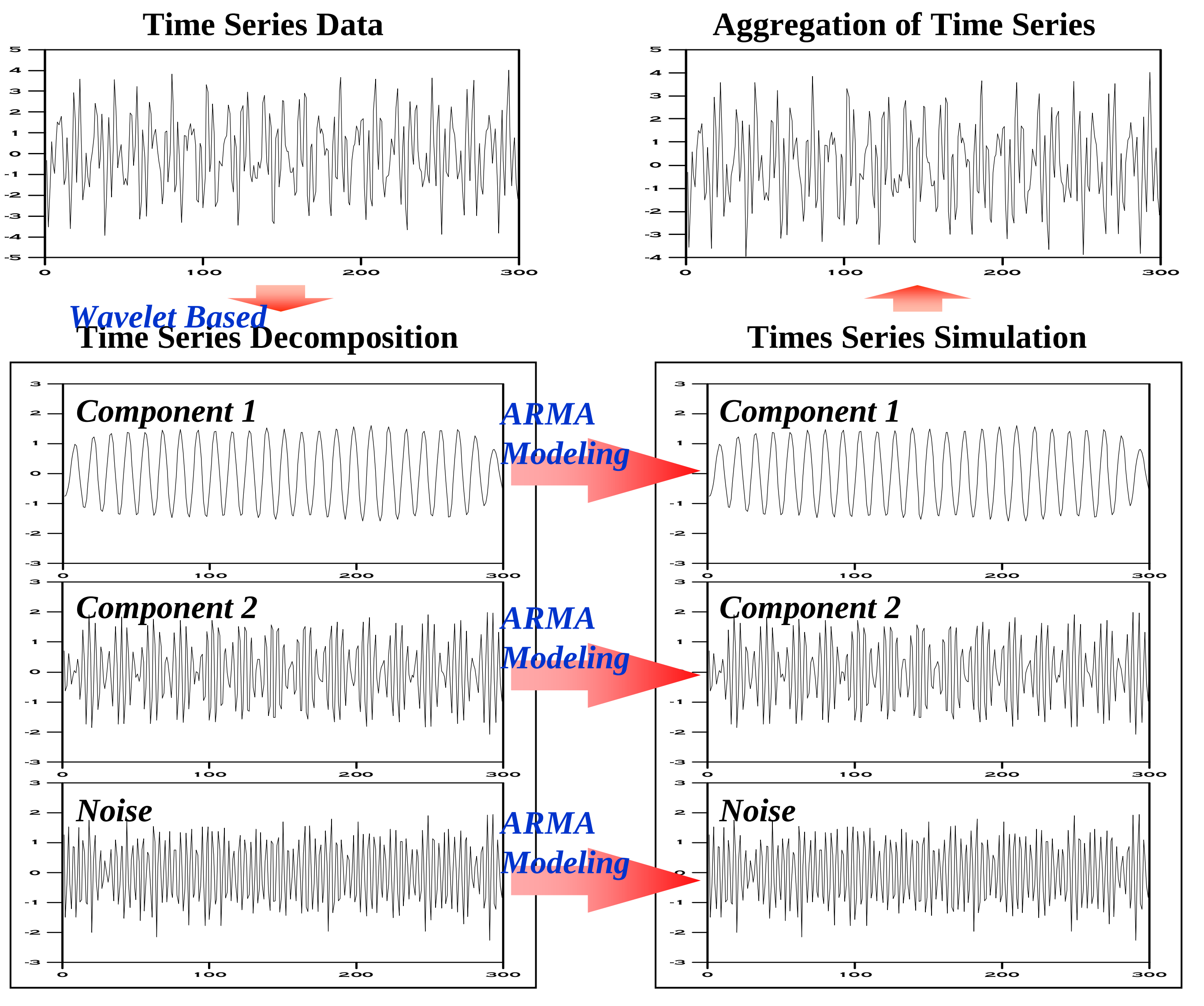
From Eric Kuhn, 2005

1900 to 2004

Lees-B FLOW, reconstruction, wavelet, and global wavelet

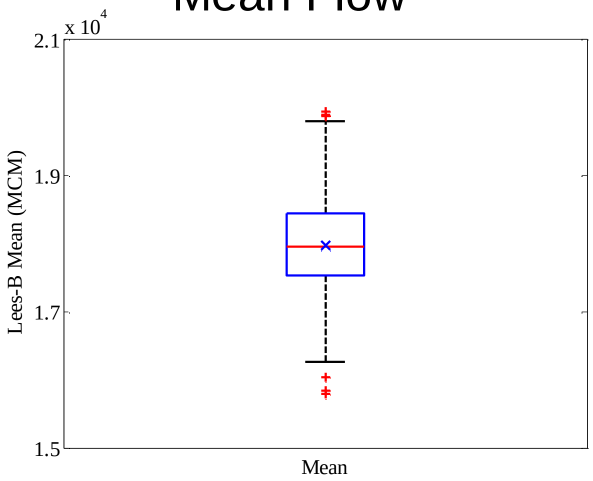


WARM Simulation

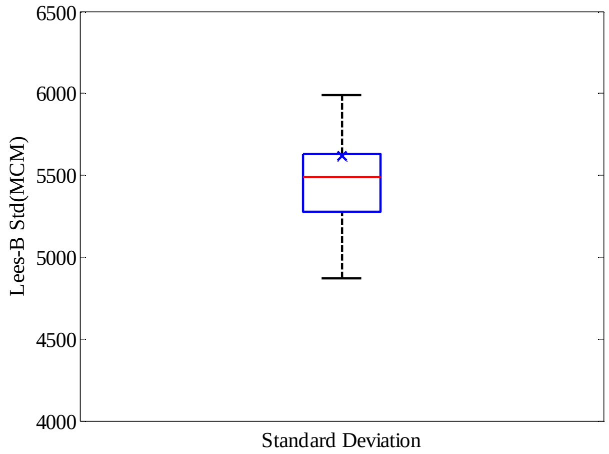


Results; modeling Lees-B

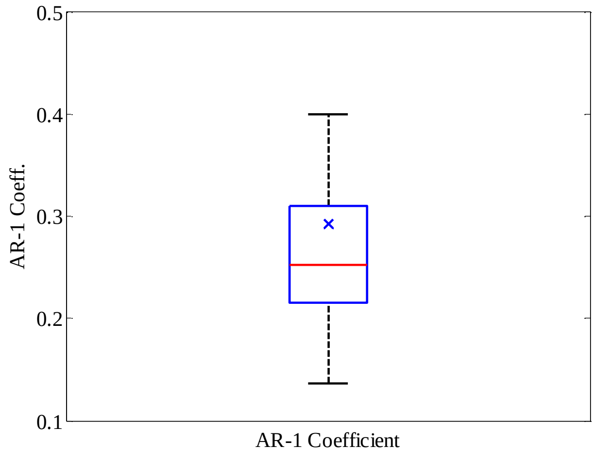
Mean Flow



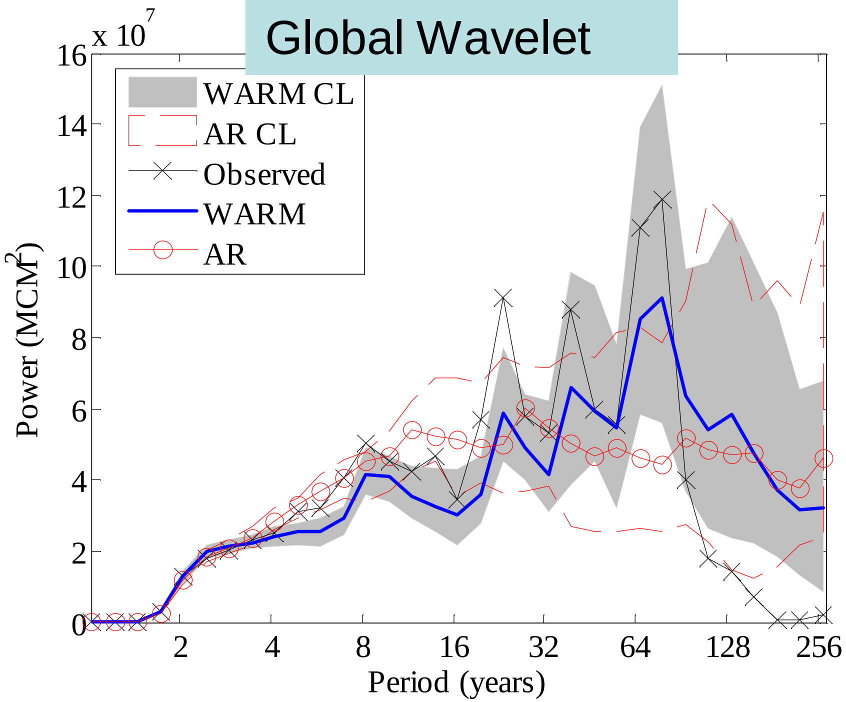
Std Dev of Flow



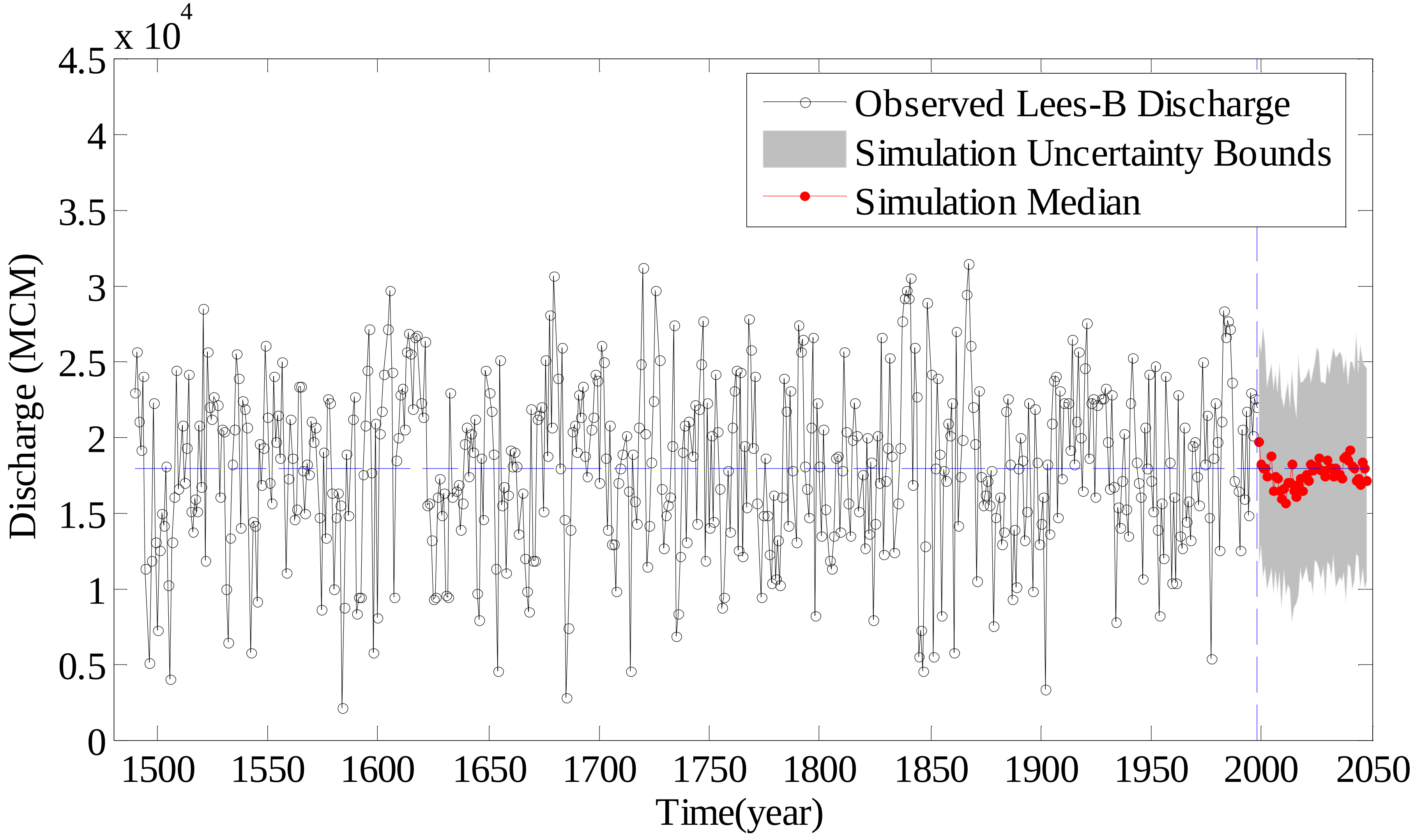
Lag 1 Correlation



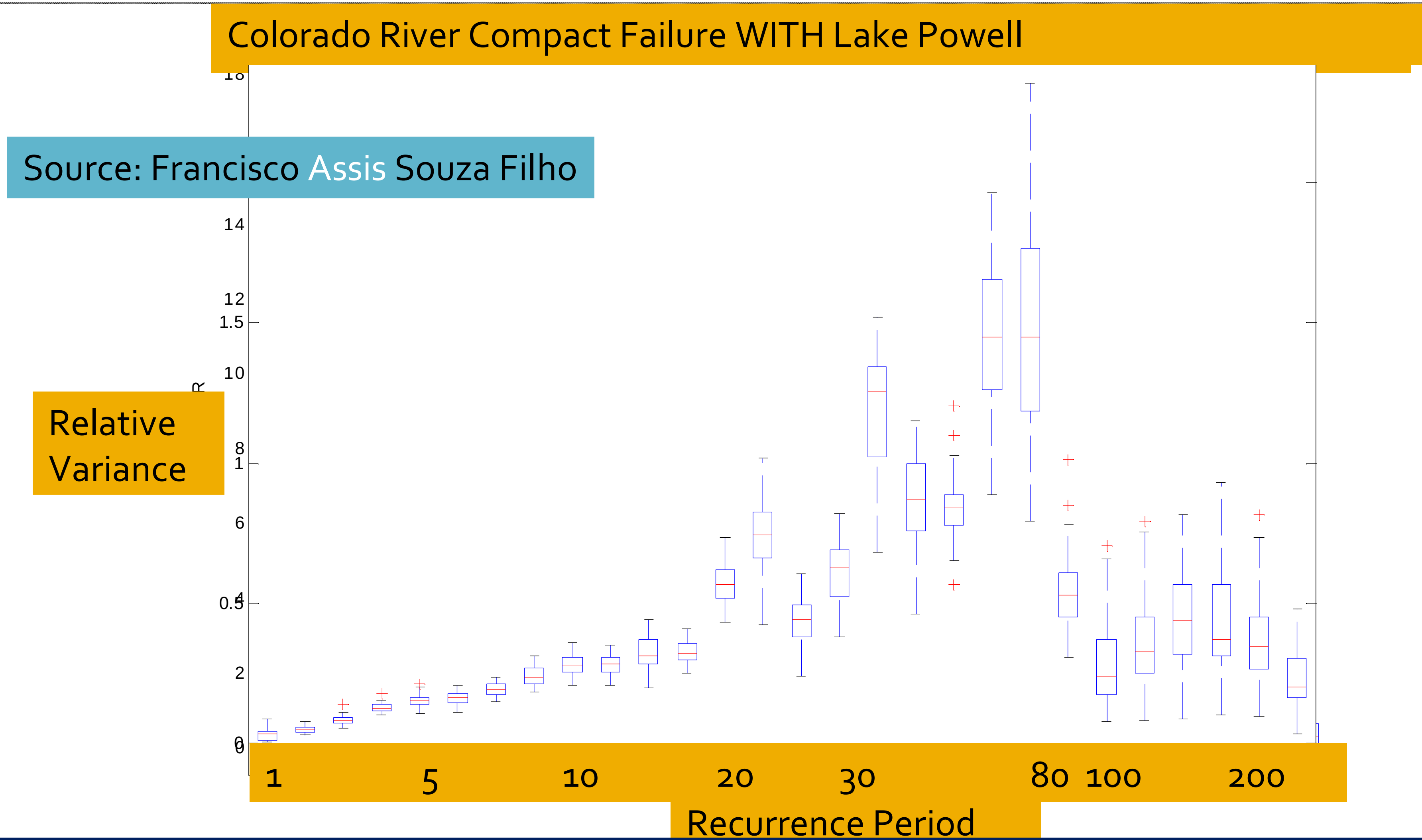
Global Wavelet



Results; simulation



Severity and Frequency of Colorado River Compact Failure (w/ and w/o Lake Powell)



Lessons and questions

- Inability to anticipate and manage persistent climate shifts – e.g., using records that are "short" relative to the scale of climate shifts exposes water managers to the same type of uncertainty as anthropogenic climate change over the next 30 to 50 years
- Storage projects can reduce supply risks, but have limited impact on persistent climatic departures whose time scale > that implied by storage capacity
  - =>One still needs mechanisms to manage the residual risk, even w/o climate change ←→ if we succeed = C.C. adaptation strategy?
- Adaptation using "soft" technologies could be facilitated if we had an ability to anticipate (scenarios or forecasts) the nature of operative climate regimes (Dynamic Risk Management – quantify nonstationarity)
  - How should the compact/reservoir operation be modified if we have a reasonable expectation of x year dry /wet periods?
  - How would such a modification be implemented – how do you identify the regime and the odds of staying in it?
  - How can the impacts of changing the allocation/operation policy be managed?

Example 2

- What can we learn from an idealized model of a storage system (reservoir or aquifer)?
  - Does it matter if the uncertainty is
    - Unstructured (classical AR) or
    - Has structured low frequency components
  - How about human response to climate?
    - Demand decreases slightly in wet spells
    - Demand can increase dramatically in dry spells
  - Ratio of reservoir storage to mean flow or demand and resilience to above factors

A reservoir or aquifer model with input and human behavior responsive to climate

$$\frac{dS}{dt} = I - Q \quad \textit{Conservation of Mass}$$

$$I = LN(\mu,\sigma); CV = \frac{\sigma}{\mu}; \mu = \mu_0 + \sum_j A_j \sin(\omega_j t + \varphi_j) \quad \textit{Recharge or Inflow}$$

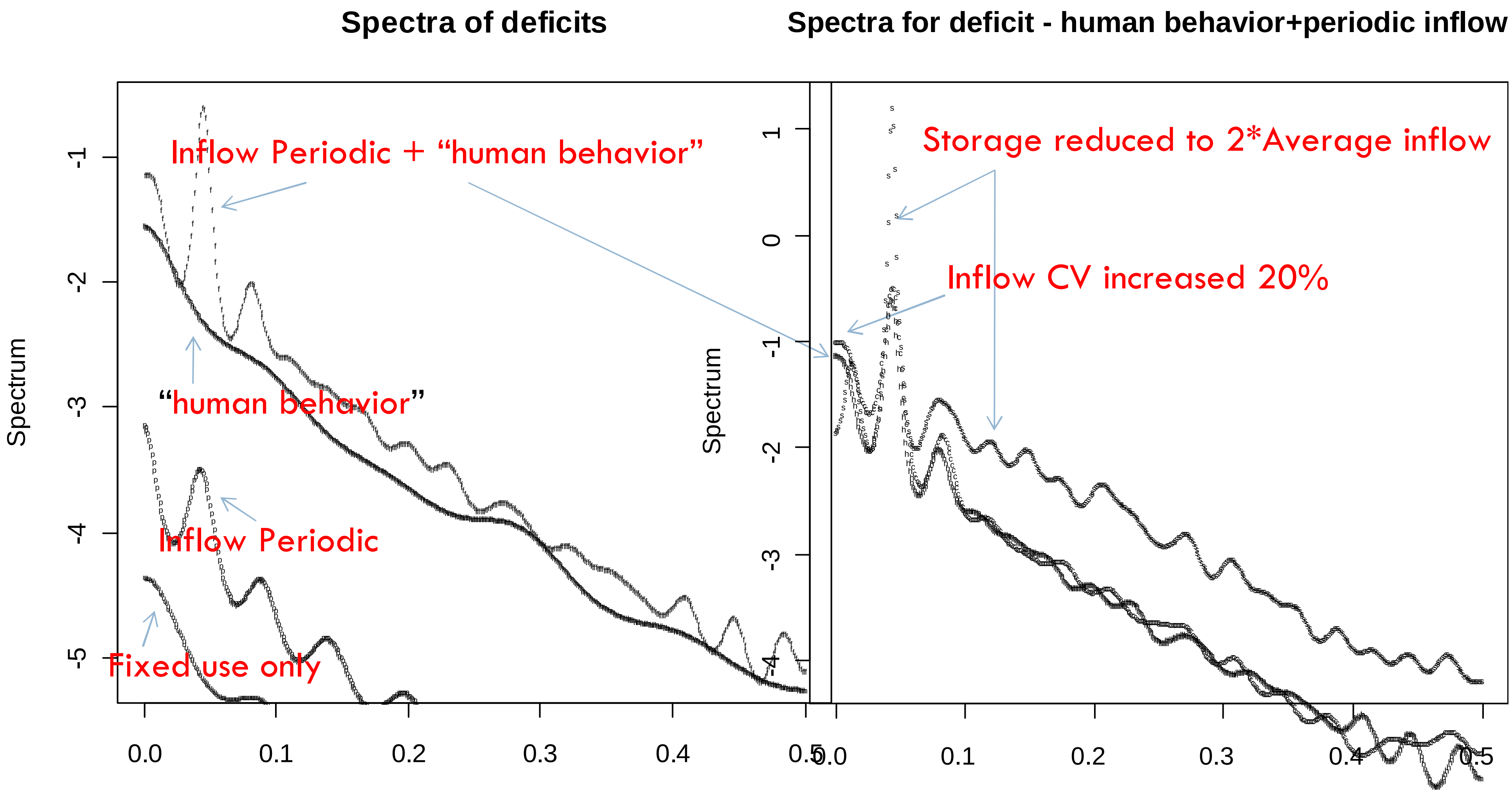
$$Q = f(S), e.g., = \alpha S \text{ "natural discharge" } \textit{Linear Reservoir}$$

$$+ w_0 \left(1 + \delta(I \le I')\beta_1(I' - I) - (1 - \delta(I \le I'))\beta_2(I - I')\right) \textit{ Human use}$$

$$0 \le S \le S_c \quad \textit{Physical limits on Storage}$$

$$Q' = \min(Q, S) \quad \textit{Release is limited to storage}$$

$$d = \max(0, Q - Q') \quad \textit{Deficit or shortage}$$

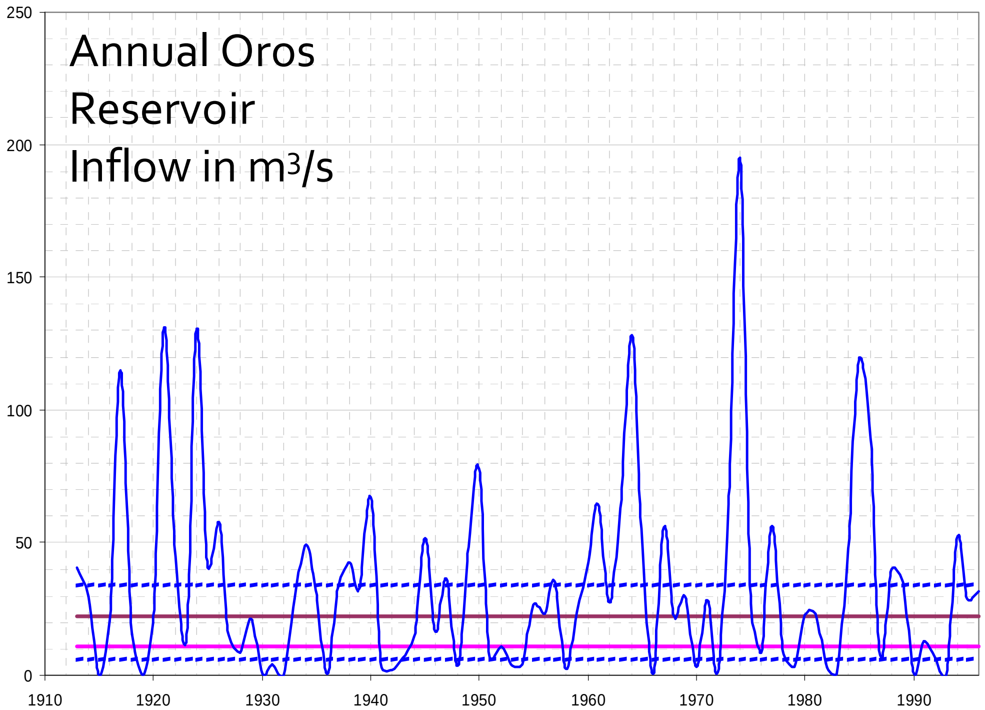


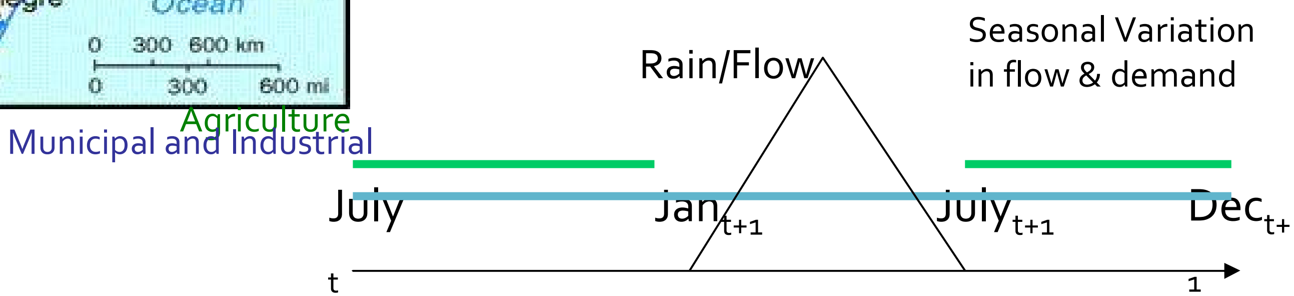
Spectra of deficits
Spectra for deficit - human behavior+periodic inflow
Inflow Periodic + "human behavior"
"human behavior"
Inflow Periodic
Fixed use only
Storage reduced to 2*Average inflow
Inflow CV increased 20%
Spectrum
frequency
-1
-2
-3
-4
-5
1
0
0.0
0.1
0.2
0.3
0.4
0.5

Lessons

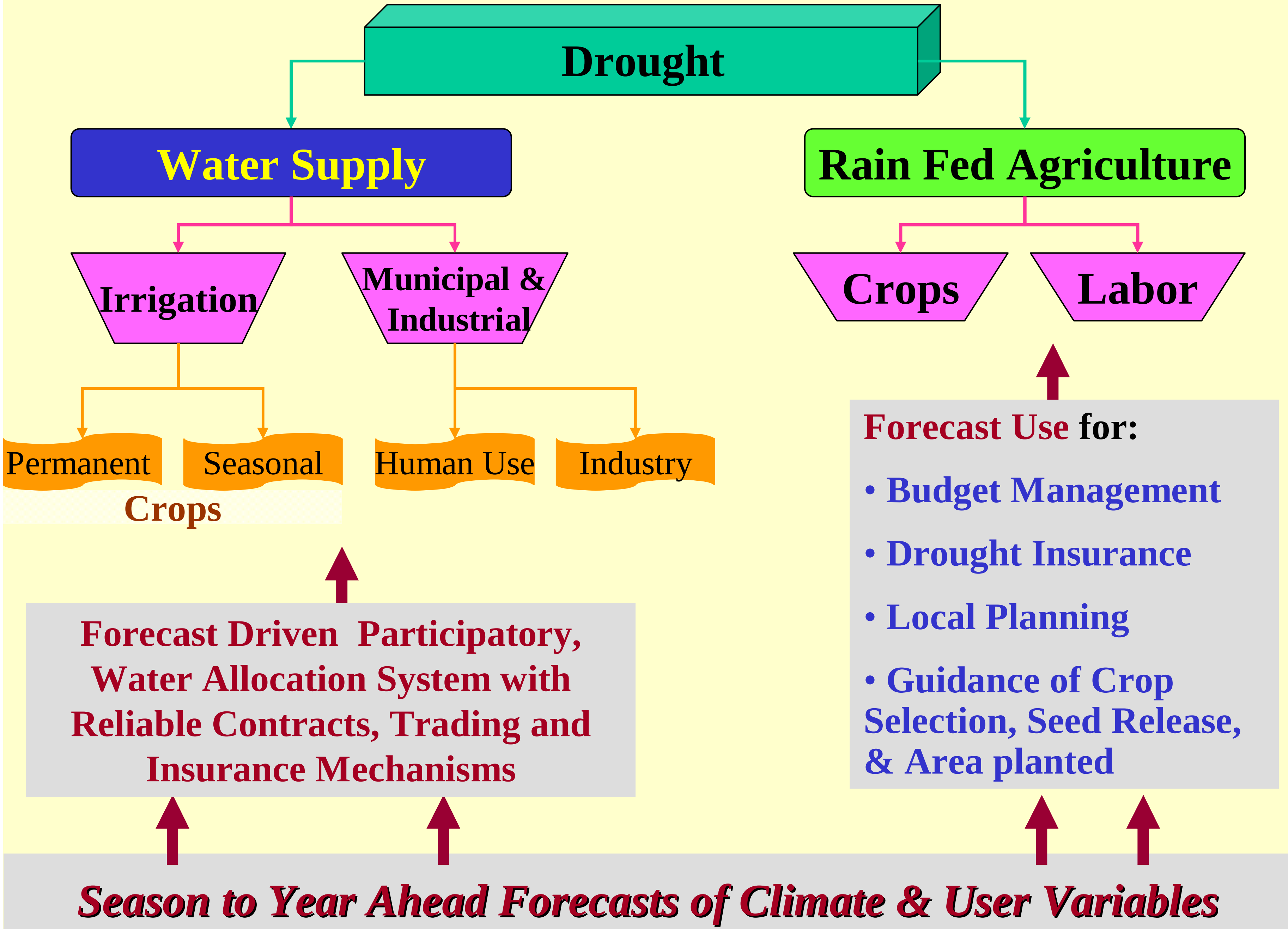
- Having a periodic or low frequency component that has a long duration, but even explains a small % of the variance of the inflow/recharge has a much greater effect on the severity and recurrence of water allocation failures than a corresponding % increase in unstructured uncertainty
- Increasing water demand for water during dry periods has the potential for substantially exacerbating failures – has to be managed ← if the situation can be forecast and appropriate risk management policies exist.
- Increasing storage capacity (larger aquifers) buffers risks better

Example 3: From Interannual Streamflow Forecasts to Dynamic Climate Risk Management Strategies for N. E. Brazil





Personal & Aggregate Impacts of Drought



Month	Action
July	Statistical Forecast Jan-Dec Reservoir Inflows
	Forecast Based Water Allocation via contracts
	Drought Relief Planning
	Sector Contract Sublot Options
	Crop/Labor Sector Guidance
January	**Stat. & Numerical Forecast Jan-Dec Reservoir Inflows**
	Execute Water Contract Options
	Crop/Labor Sector Guidance
	Monitoring of Rainfall/Climate + Dissemination
	Supervised Trading of Water Contracts begins
	Monthly system operation monitoring cycle begins
	No failure likely -> Contract functions
	Restrictions -> Level 1 failure -> Plan in place
	Potential Failure -> Level 2 -> Activate Insurance /Relief Plan
	Identify & allocate surplus water
March	Supervised Trading of Water Contracts closes
	Monthly system operation monitoring cycle continues
	Crop/Labor Sector Guidance continues
	Monitoring of Rainfall/Climate + Dissemination
	Implement Relief Measures as Needed
July	*Repeat Full Cycle*

Decision Time Table

Develop

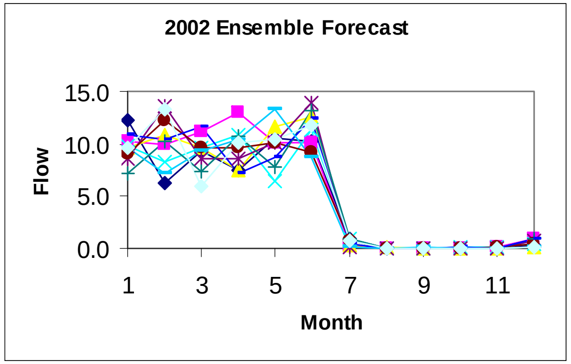
Models to Support Decision of Planners

And of Individuals and Coalitions

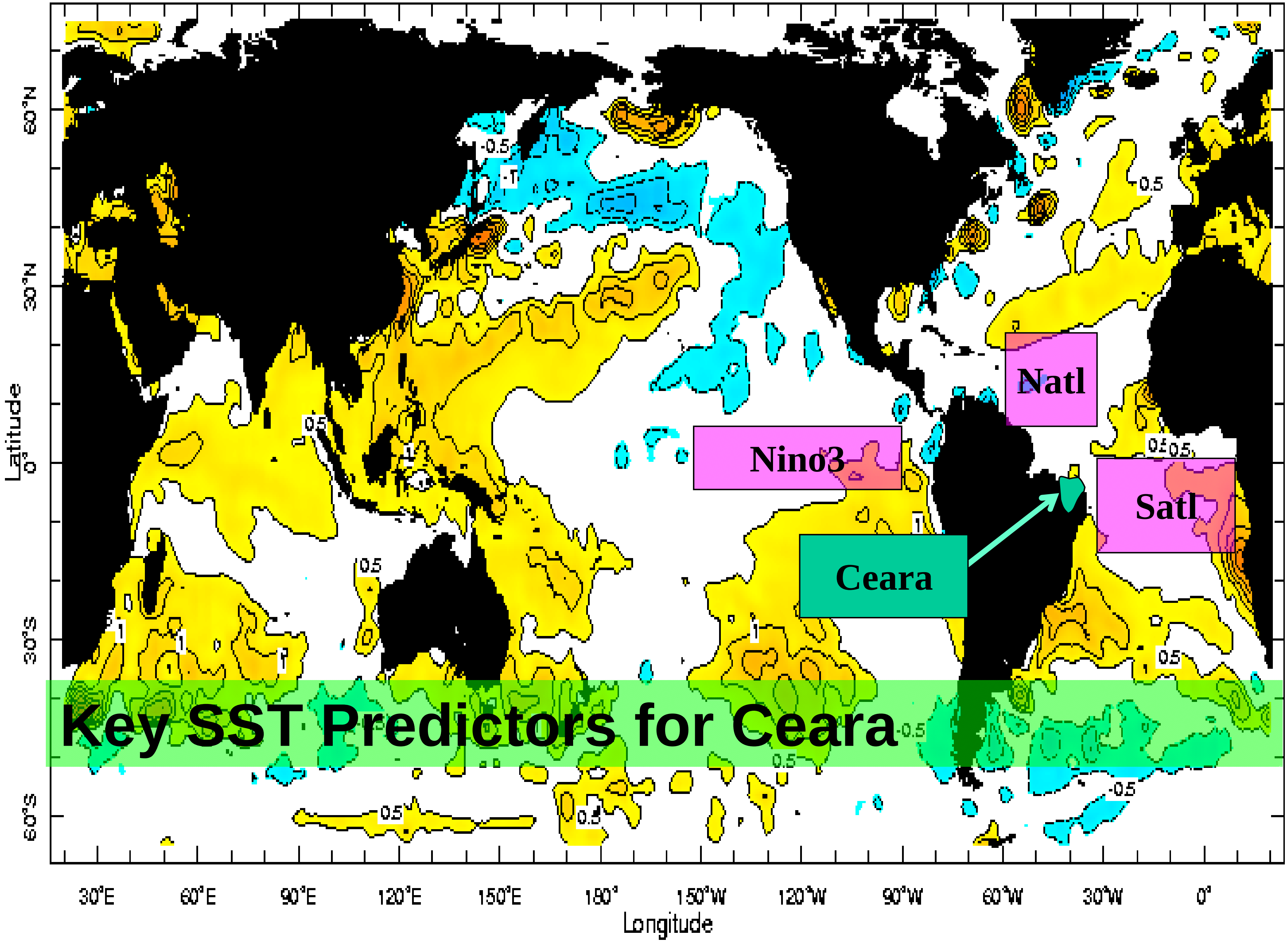
A Forecast Based Integrated Management Approach: 1

• **Start Early: Forecasts from Previous July for Jan-Dec period**

Develop and Update Forecasts of Rain, Flow, Crops & Fiscal Impacts

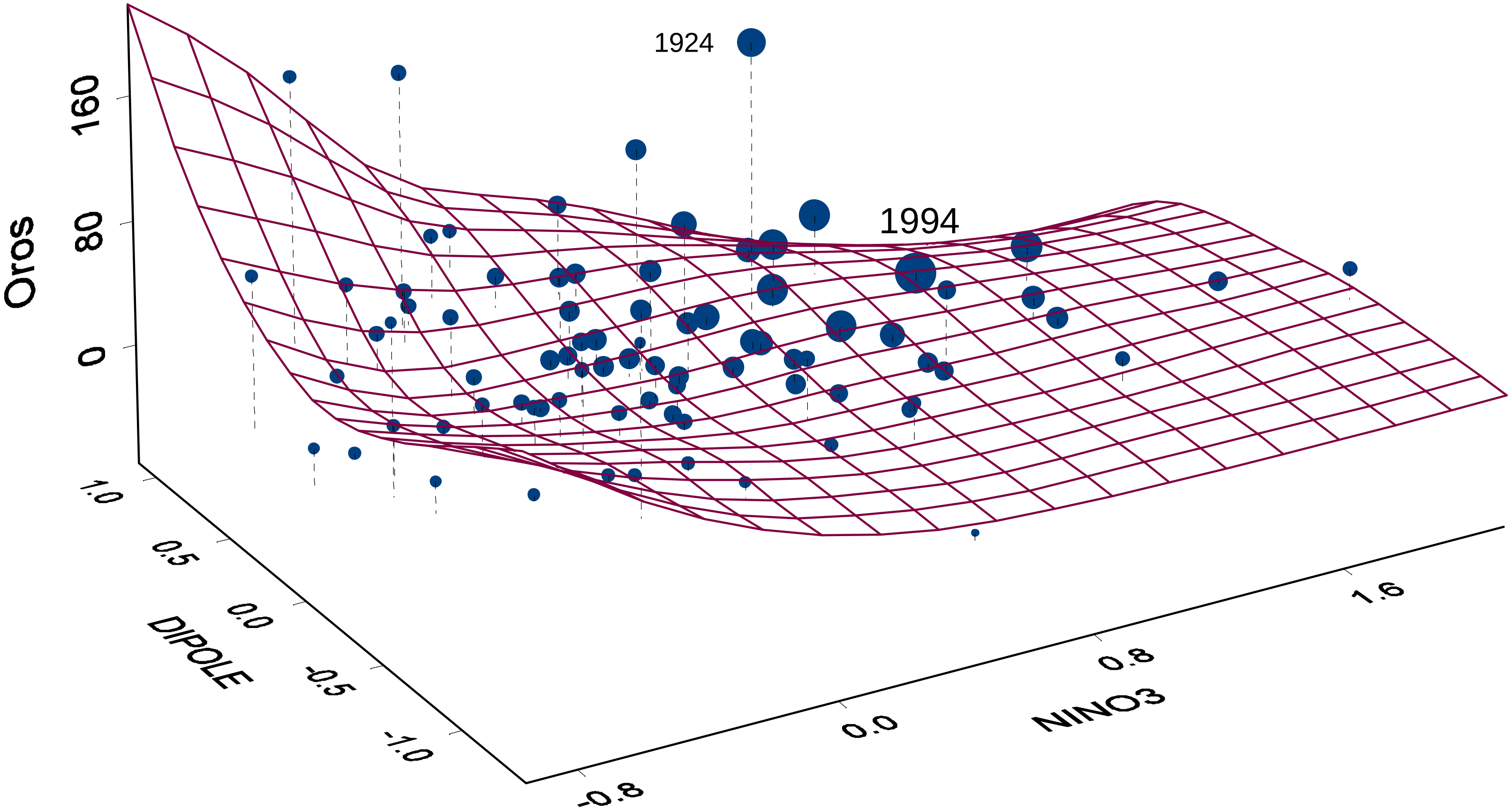


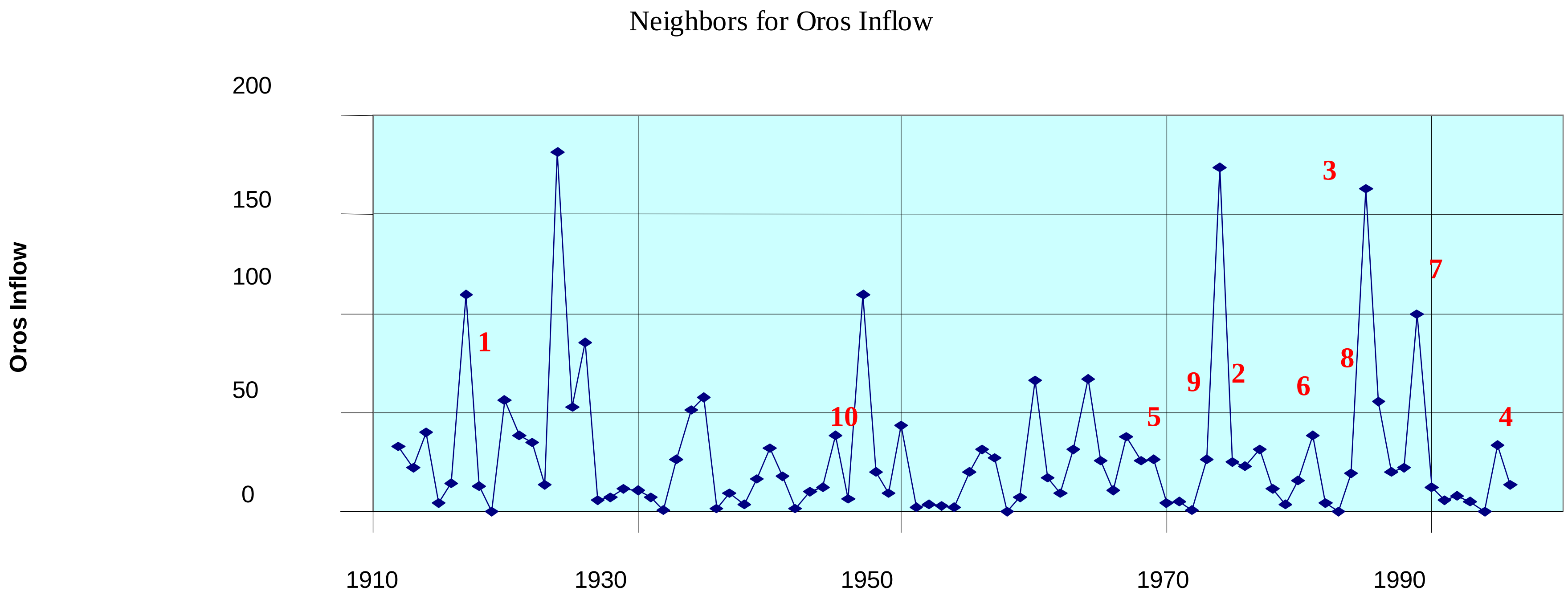
July - Statistical Forecast


Natl
Nino3
Satl
Ceara
Key SST Predictors for Ceara
Latitude
60°N
30°N
0°
30°S
60°S
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
Longitude

Semiparametric k-Nearest Neighbor forecast model

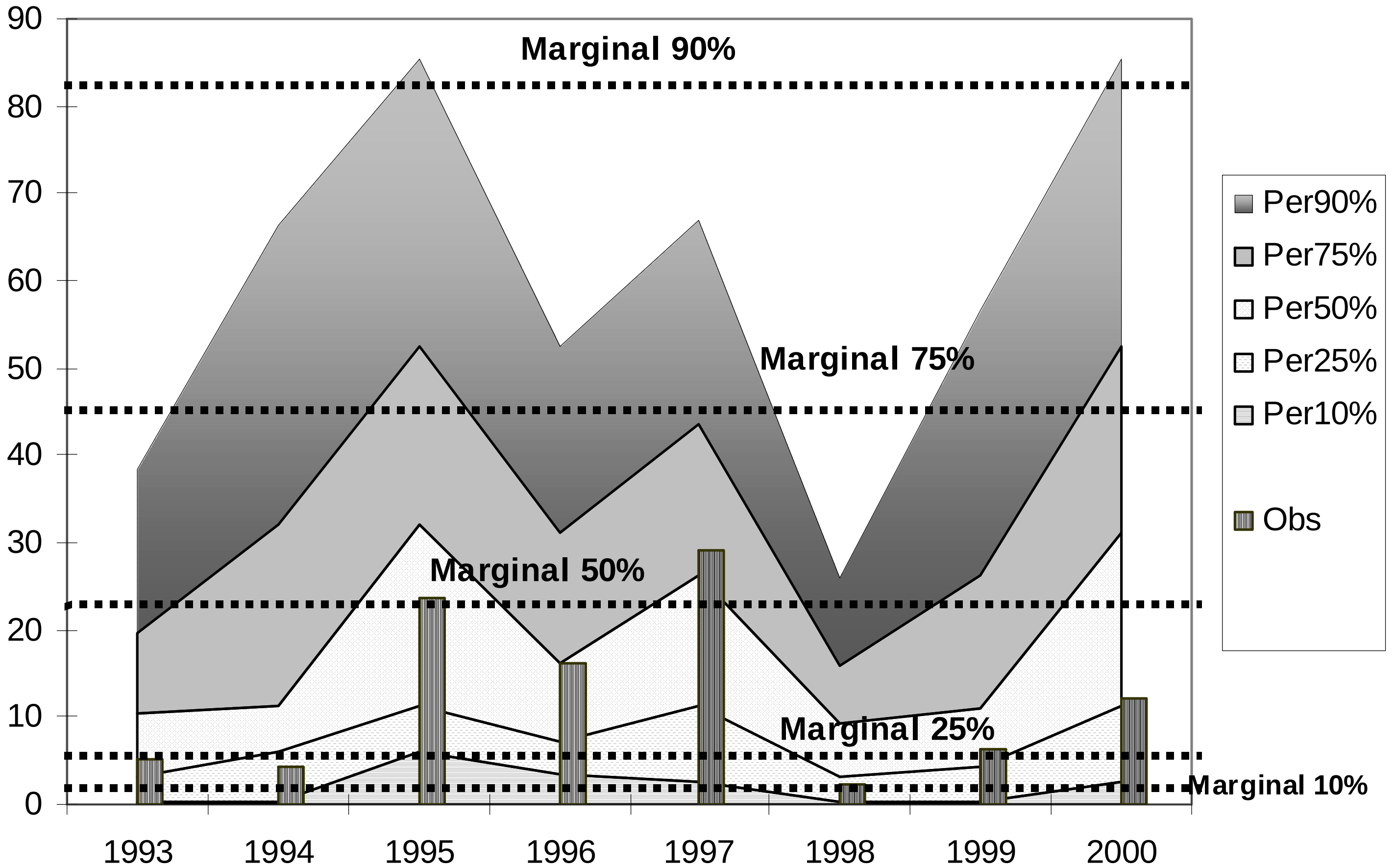
1994 forecast from July –neighbors in historical data (1914-1990)





Index	Year	Weight
1	1921	14%
2	1975	9%
3	1985	6%
4	1996	6%
5	1971	5%
6	1984	5%
7	1989	5%
8	1986	3%
9	1973	3%
10	1949	3%
Sum		59%

Out of Sample Semi-Parametric Model
6 month ahead Forecast performance



Marginal = Flow Percentile based on 78 years of data

Shaded areas= Forecast Percentiles

Oros Annual Flow Forecast from previous July for Jan-June flow

– model fit 1914-1991, Predict 1993-2000 Correlation (Median Forecast w/ Obs)=0.9

A Forecast Based Integrated Management Approach: 2

• **Start Early: Forecasts from Previous July for Jan-Dec period**

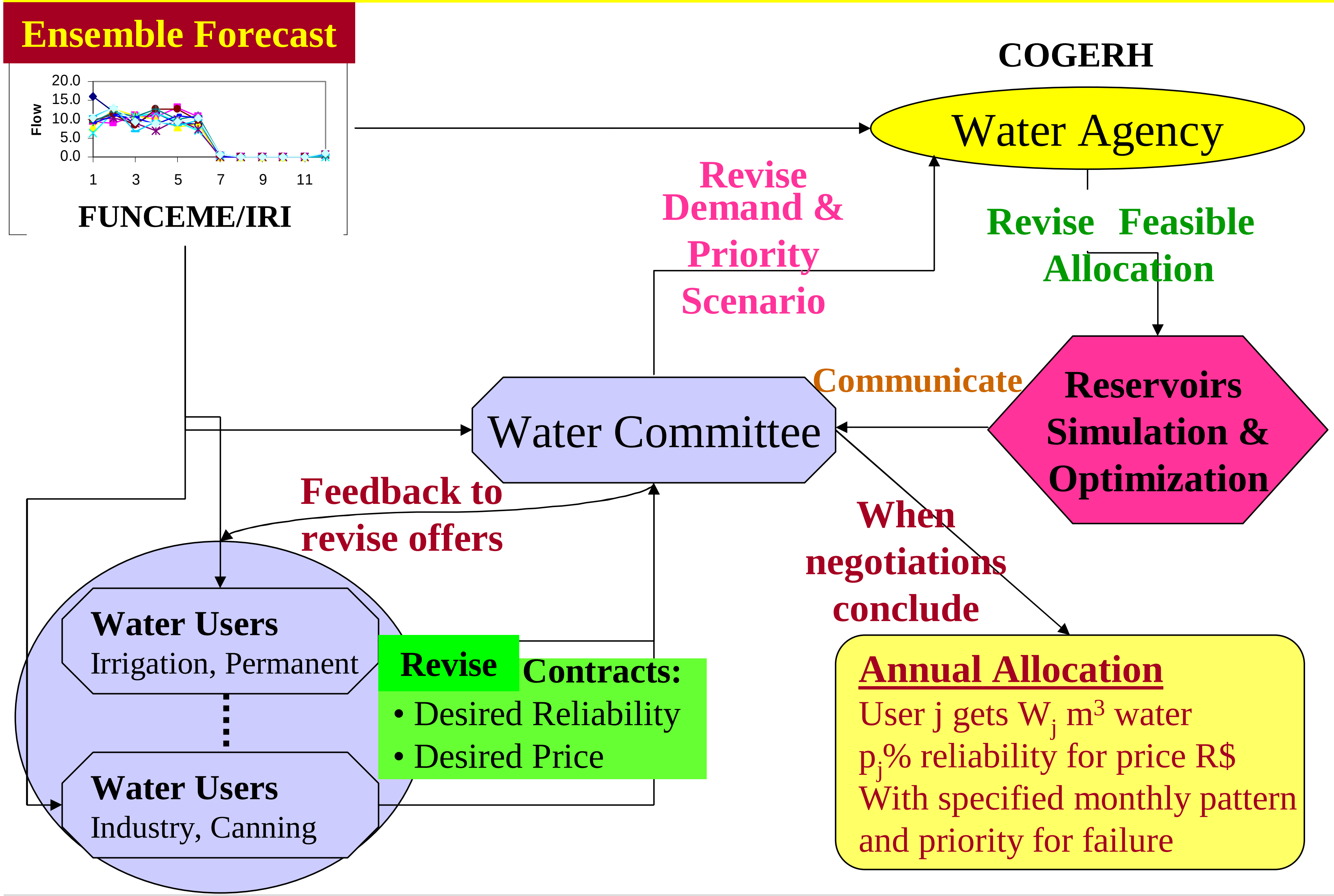
Develop and Update Forecasts of Rain, Flow, Crops & Fiscal Impacts

• **Engage Institutions in Planning Exercises Using Forecasts:**

Water Committees Develop Allocation Rules & Contracts

State & Local Drought Relief & Agricultural Agencies Plan & Budget

Jan-Dec Water Macro-Allocation Plan --- Developed July-Oct



Linking Science to Society

INTERNATIONAL RESEARCH INSTITUTE

Dynamic Water Allocation Model -Formulation

- Water Contracts Specification
- Water Allocation Model for Bulk Sector contracts
  - Simulation – Optimization Approach
  - (a) Objective Function – to maximize release
  - (b) Constraints – to incorporate system specific information.
- Reservoir Inflow Forecasts Ensembles

Water Contracts Specification

- Duration, T (e.g., 1year)
- total volume of water, R_i (e.g., 10,000 m^3) to be delivered over duration, T
- Within period distribution, β_{ti} (e.g., equal for each month),
- Amount, ϕ_i (e.g., R$50,000) to be paid for the water if contract terms are met
- Target reliability, $(1-p_{fi})$ (e.g., 90%)
- **In the event inflows are less than forecast**
  - Restrictions, w_i*, are applied that the supplier can impose as part of the contract
  - Restriction fraction, α_{ij}, signifying the reduced supply under restriction level 'j' (where j = 1, …, n_r with n_r is the total number of restriction levels agreed by the water committee)
- Compensations under restrictions (γ_{ij}) and contract failure (ν_i)

Water Allocation Model

- Modify the Allocation Rule – Maximize the annual value from releases conditioned on the forecast information

$$O = \sum_{i=1}^{n} \phi_i (R_i)$$

  - R_i – Release (Yield) for use 'i'
  - ϕ_i - Unit Use of Water for Delivery
  - N – Number of uses (Contracts)

***Objective Function*:**

Maximize the net value from contracts and surplus water provision $$O = \sum_{i=1}^{n} \phi_i(R_i)$$

Subject to

•$P(W_i \geq W_i^*) \leq p_{fi}$ **- Contract Level Constraint**

This checks that the volume of restrictions is at the desired reliability ($1-p_{fi}$) and is defined through the number of traces for which the restriction volume, W_i exceeds the design restriction volume W_i^*)

•$P(S_T \leq S_{T*}) \leq p_s$ **- End of the Year Storage Constraint**

This checks that the end of contract period (S_T)storage exceeds the reserve target storage (S_{T*}) with the desired probability (p_s). The target storage and the corresponding probability are specified from the system evaluation model and discussions with the committee.

•$P(RL_j) \leq p_{lj}$ – **Restriction Frequency Constraint**

This constraints the maximum number of times a particular restriction level can be enforced

RL_j – Restriction level 'j'; p_{lj} – restriction level enforcement probability

Reservoir Simulation (for each ensemble 'k')

- Inflow Forecast : q_{tk}; t=1…,T; k=1,…,N
- Continuity Equation, t=1,2, …, T

$$S_t = S_{t-1} + q_t - E_t - \sum_{i=1}^{n} R_{ti}$$

- $SD_t = -S_t \mid S_t < 0$ (Account the Deficit)
- $R_{ti}=\beta_{ti}R_i$ (Target Release for each user)
- Evaporation : $E_t = \psi_t \delta_1 ((S_t + S_{t-1})/2)^{\delta_2}$

A Forecast Based Integrated Management Approach: 3

- **Start Early: Forecasts from Previous July for Jan-Dec period**

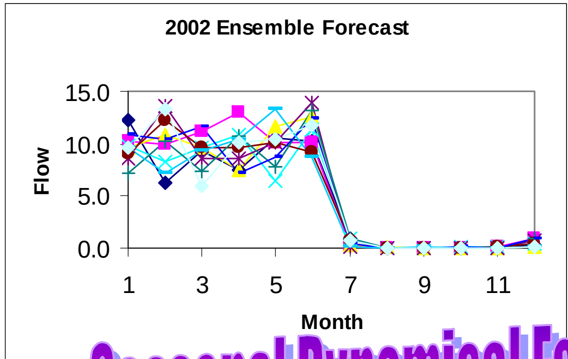
- **Engage Institutions in Planning Exercises Using Forecasts**

- **Update Forecasts routinely during the rainy season and Operate Systems:**

  Dynamical model forecasts of rain amount and dry/wet spells

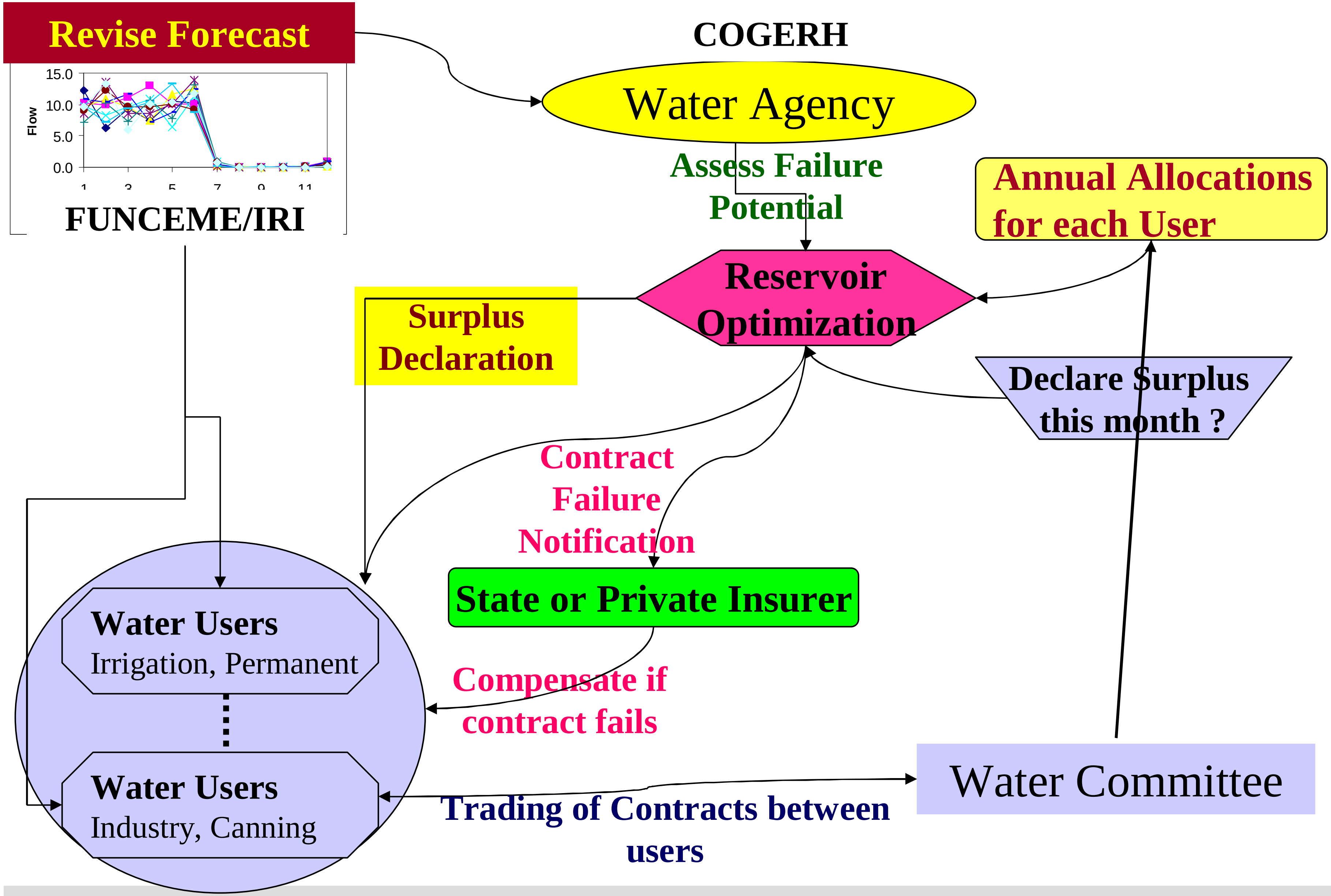
  Water System Operation

  Drought and Agricultural Monitoring



Seasonal Dynamical Forecasts & System Operation

Jan-Dec Water System Operation --- Monthly Forecast Updates



Performance Evaluation

Forecast	$\hat{\mu}_{SF}$	$\hat{\sigma}_{SF}$	$\hat{\mu}_{SP}$	$\hat{\sigma}_{SP}$	$\hat{\mu}_{E}$	$\hat{\sigma}_{E}$	$\hat{\mu}_{R}$	$\hat{\sigma}_{R}$
KNN	**0.04**	**0.03**	**225.2**	**869.0**	**93.2**	**65.8**	**708.6**	**615.1**
Null	**3.1**	**11.8**	**234.7**	**891.4**	**96.6**	**67.2**	**697.6**	**590.8**

μ,σ – Mean and Standard Deviation

SF – Shortfall;   SP – Spill

E – Evaporation; R - Release

Lessons

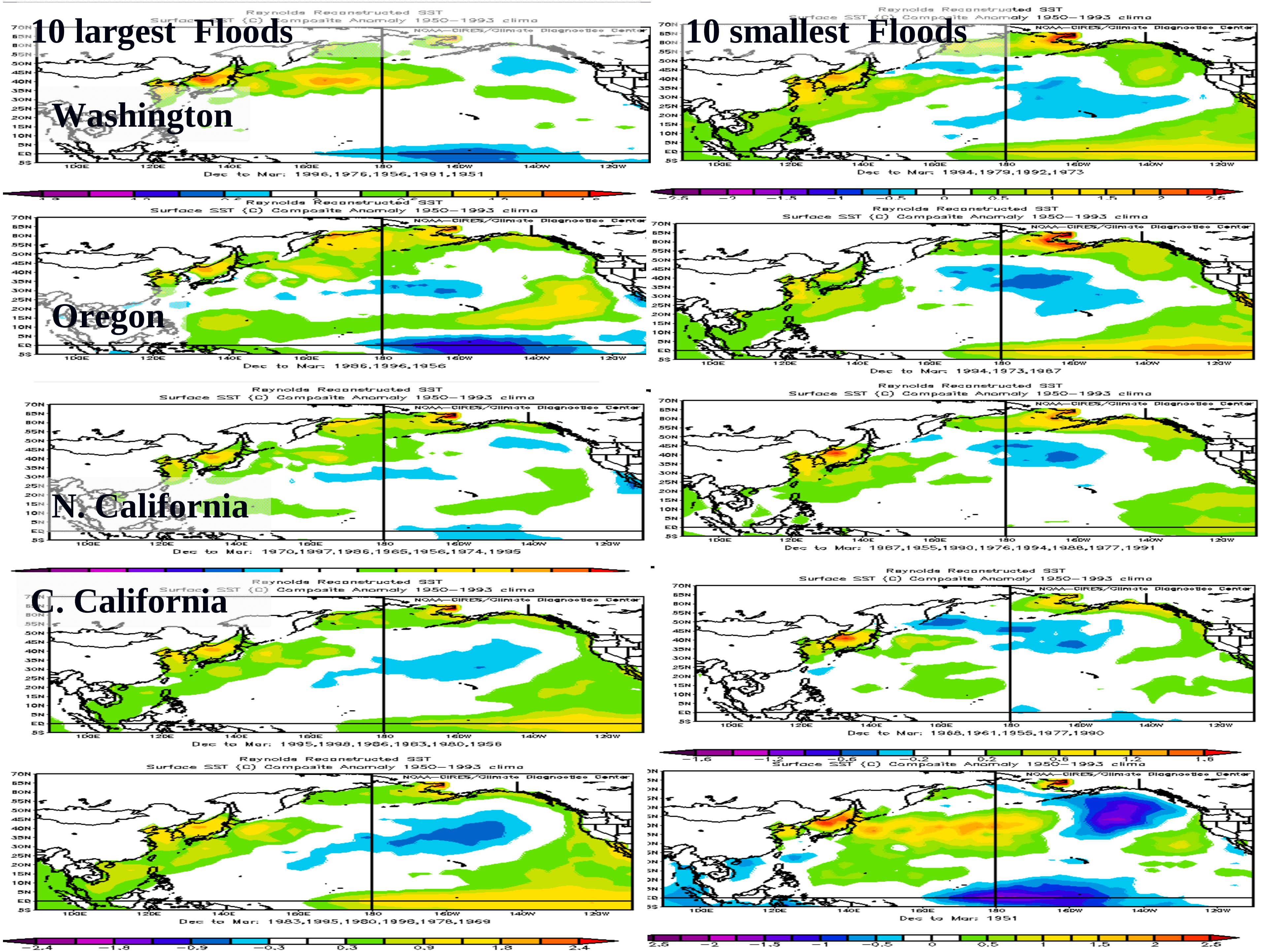
- Having a periodic or low frequency component that has a long duration, but even explains a small % of the variance of the inflow/recharge has a much greater effect on the severity and recurrence of water allocation failures than a corresponding % increase in unstructured uncertainty
- Increasing water demand for water during dry periods has the potential for substantially exacerbating failures – has to be managed ← if the situation can be forecast and appropriate risk management policies exist.
- Increasing storage capacity (larger aquifers) buffers risks better

Example 4: Flood Risk – Season Ahead Prediction

- Are extreme floods predictable using climate precursors?
  - Do SST boundary/initial conditions contain sufficient information to inform us as to the potential for an extreme flood?
  - If yes, then can this be used to simulate changing flood probabilities?

The Beat of Floods in the Western United States: How the Pacific Sets a Hazardous (Shahar Adomi – High School Senior)

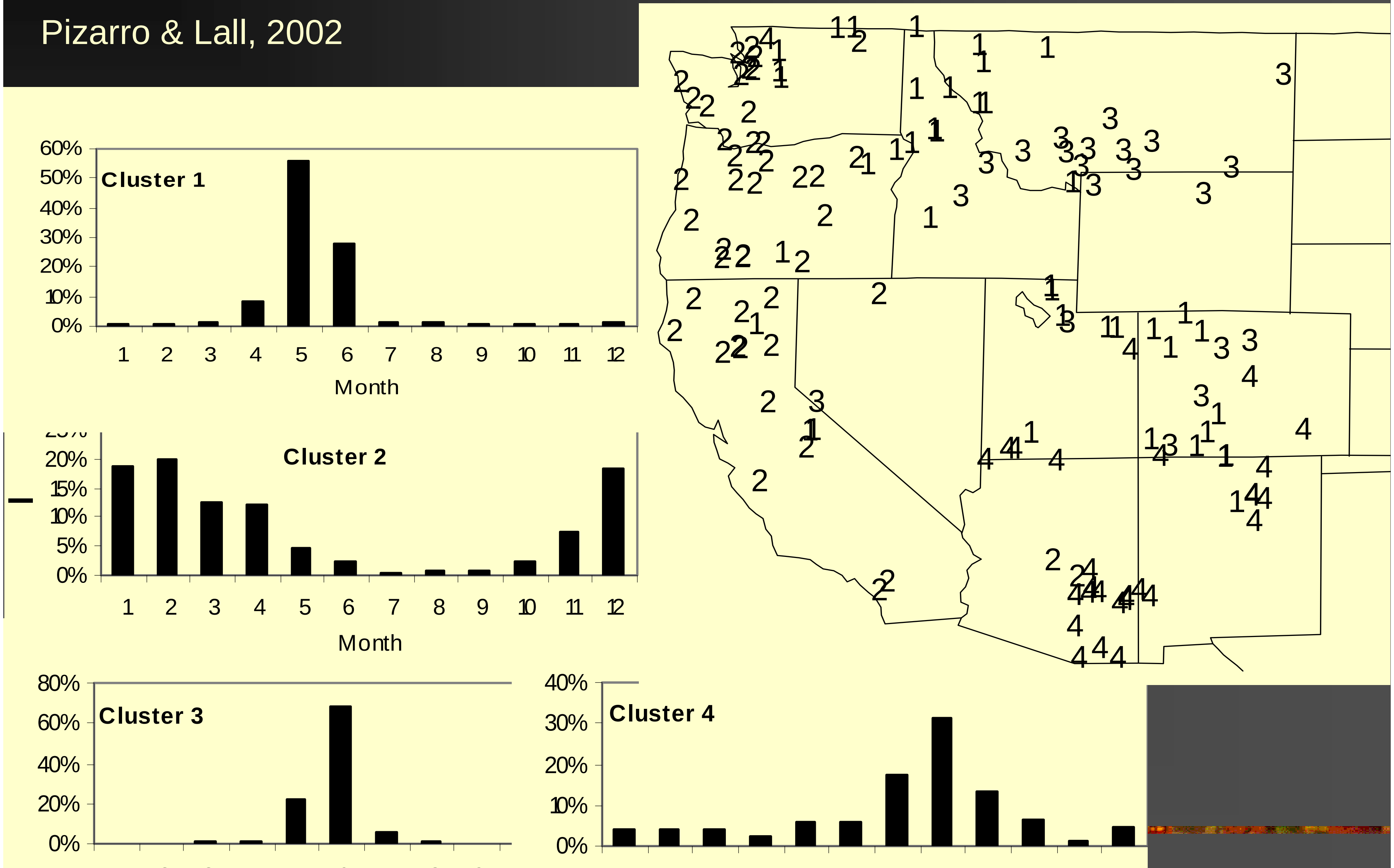
- 50 stations in the coastal Western US, each with 60 or more years of unregulated Ann. Max. Flood data (*Dec-Mar floods)
- Divide into 5 groups of 10 stns each by latitude
- Identify 10 years each with largest /smallest floods for each station
- Identify years in which at least 5 of 10 stations have a flood ranked in the top or bottom 10

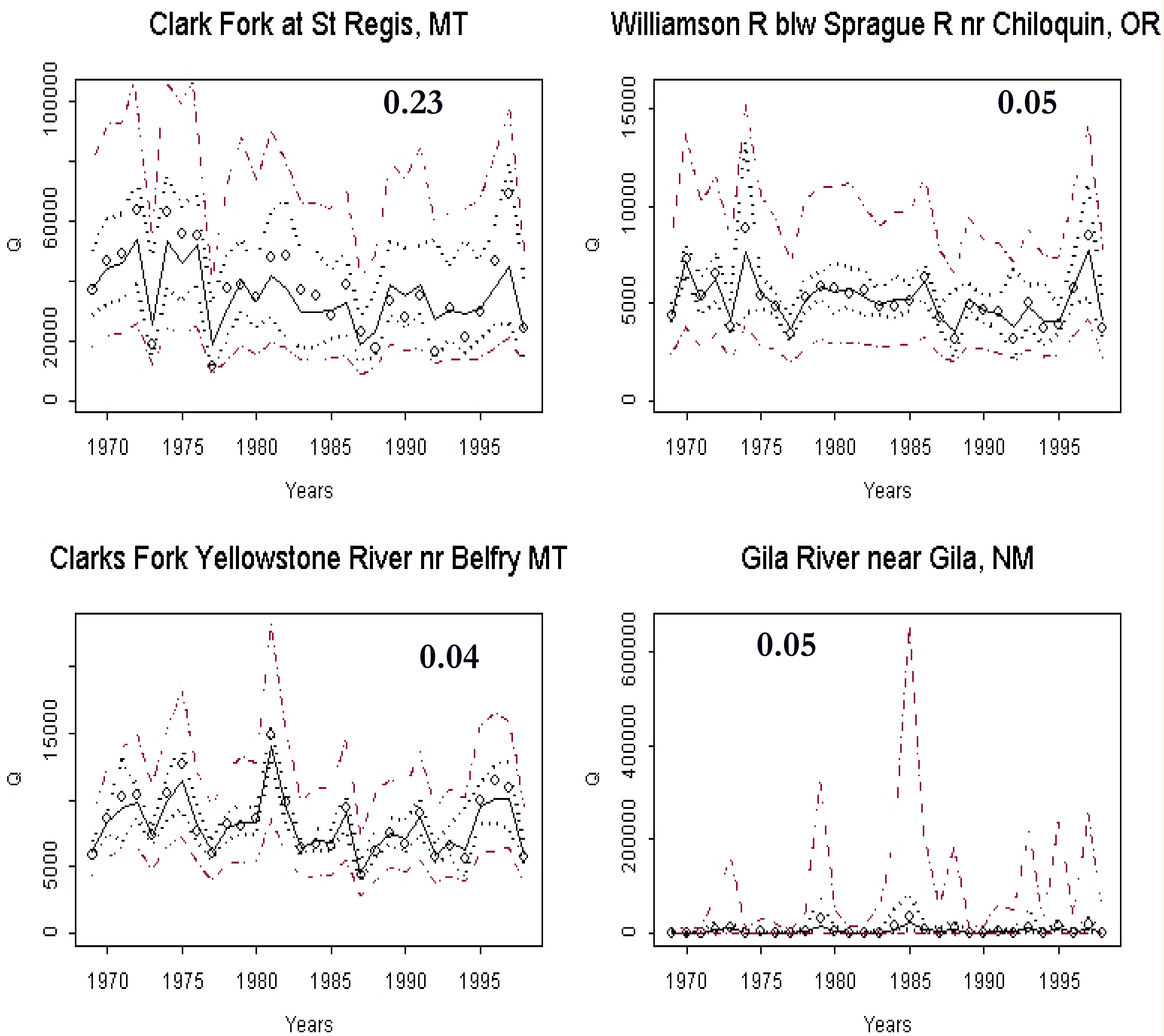


10 largest Floods
10 smallest Floods
Washington
Oregon
N. California
C. California
Reynolds Reconstructed SST
Surface SST (C) Composite Anomaly 1950-1993 clima
NOAA-CIRES/Climate Diagnostics Center
Dec to Mar: 1996,1976,1956,1991,1951
Dec to Mar: 1994,1979,1992,1973
Dec to Mar: 1986,1996,1956
Dec to Mar: 1994,1973,1987
Dec to Mar: 1970,1997,1986,1965,1956,1974,1995
Dec to Mar: 1987,1955,1990,1976,1994,1988,1977,1991
Dec to Mar: 1995,1998,1986,1983,1980,1956
Dec to Mar: 1968,1961,1955,1977,1990
Dec to Mar: 1983,1995,1980,1998,1978,1969
Dec to Mar: 1951

Ann. Max. Flood Seasonality in the West

Pizarro & Lall, 2002

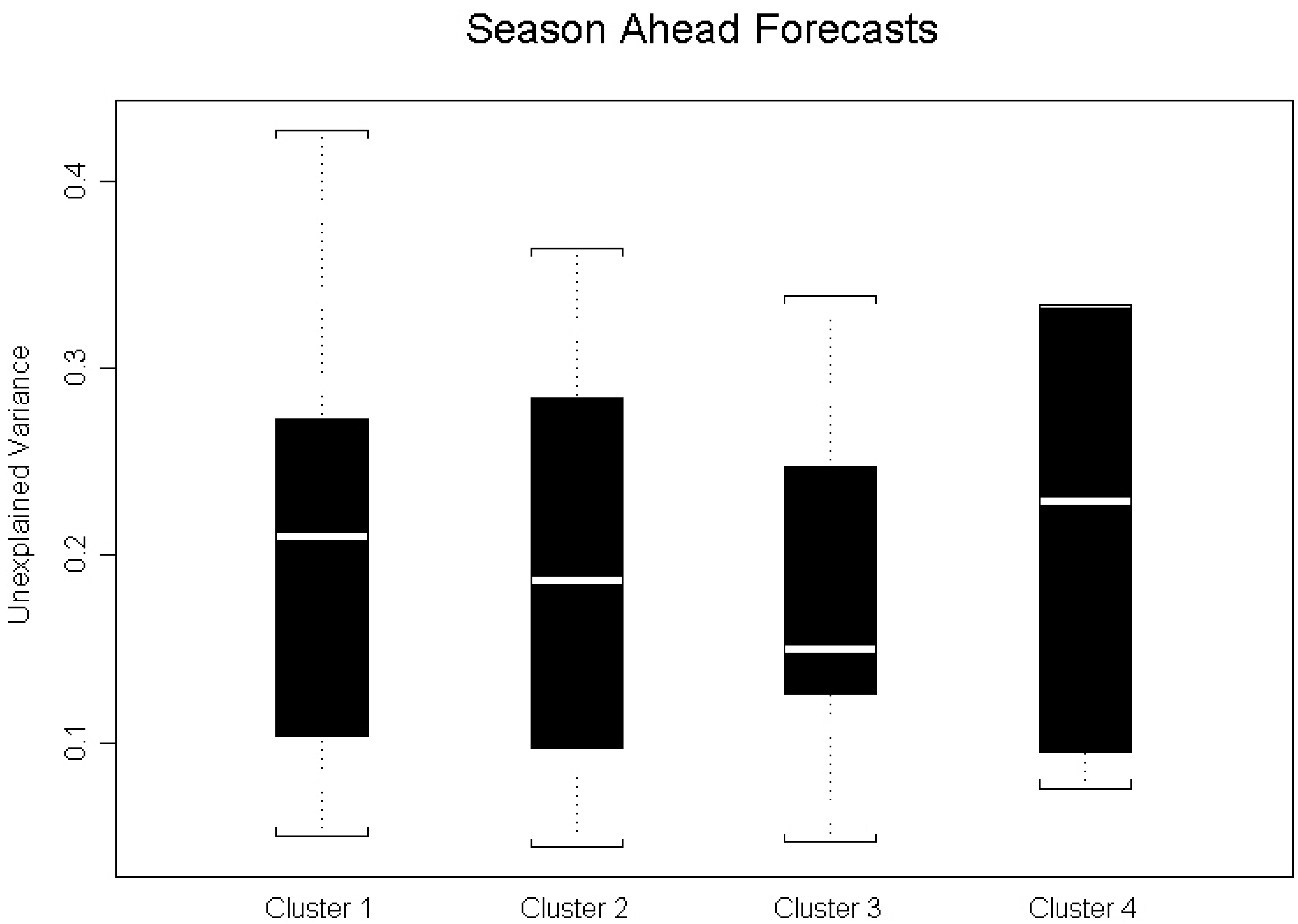




Three-fold cross-validation results for 1 station randomly drawn per cluster. Unexplained variance in box with 5, 25, 50, 75, 95th %tiles Used Nonlinear regression with Bagging of Annual Max Flood at each site on 4 predictors: seasonal mean of NINO3.4, PDO and seasonal trend of NINO3.4 and PDO

Unexplained Variance under sequential blind forecasts- season ahead

Source: Gonzalo Pizarro



Lessons

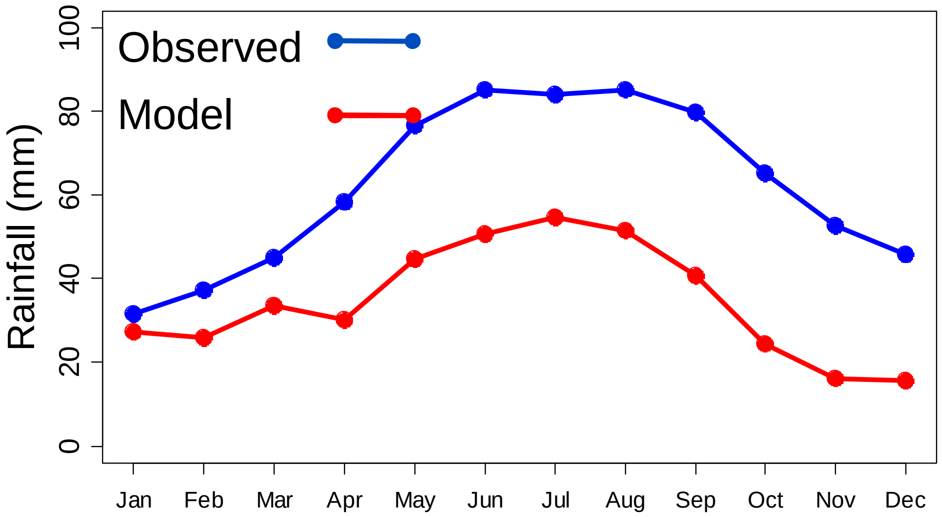
- Flood extremes may represent significant organization and predictability of the climate system → rivers in the sky that start in the tropical oceans
- Interaction of base mechanisms that lead to convection and transport of moisture through the atmosphere with local/regional convection may lead to major floods.
- Given the inability of GCMs to represent these processes, re-analysis and statistical tools are likely to be very informative in building a conceptual flood model.
- Opportunity to inform flood risk management

Summary

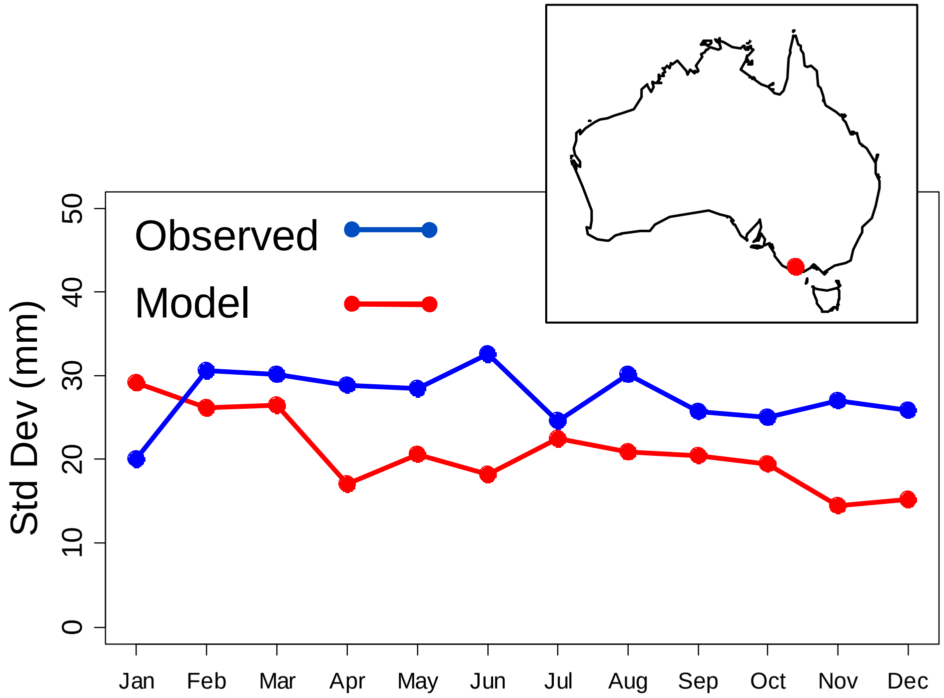
- To quantify dynamic risk, the general framework we work in is to predict a suite of hydrologic statistics at multiple stations using multiple climate predictors.
- The predictors may come from multiple climate models or paleo data or historical data or another statistical model. They are selected based on both physical intuition and statistical measures.
- A Probability network model usually underlies the modeling structure. All model and parameter uncertainty are a) communicated through the modeling chain, and b) estimated simultaneously in a Hierarchical Bayesian Framework. Most models considered are Nonlinear and NonGaussian, and may mix modeling in the time and frequency domain
- Much of our work goes towards designing risk management instruments given that risks/uncertainties can be quantified. Both participatory management and institutional management frameworks are considered.
- Climate change adaptation requires a dynamic risk estimation and management framework. Models need to be probabilistically verified and the full uncertainty has to be considered → management or hypothesis testing

GCM rainfall

- Spatial Scale
- Biases in means (up to 3x) and standard deviations (up to 2x)



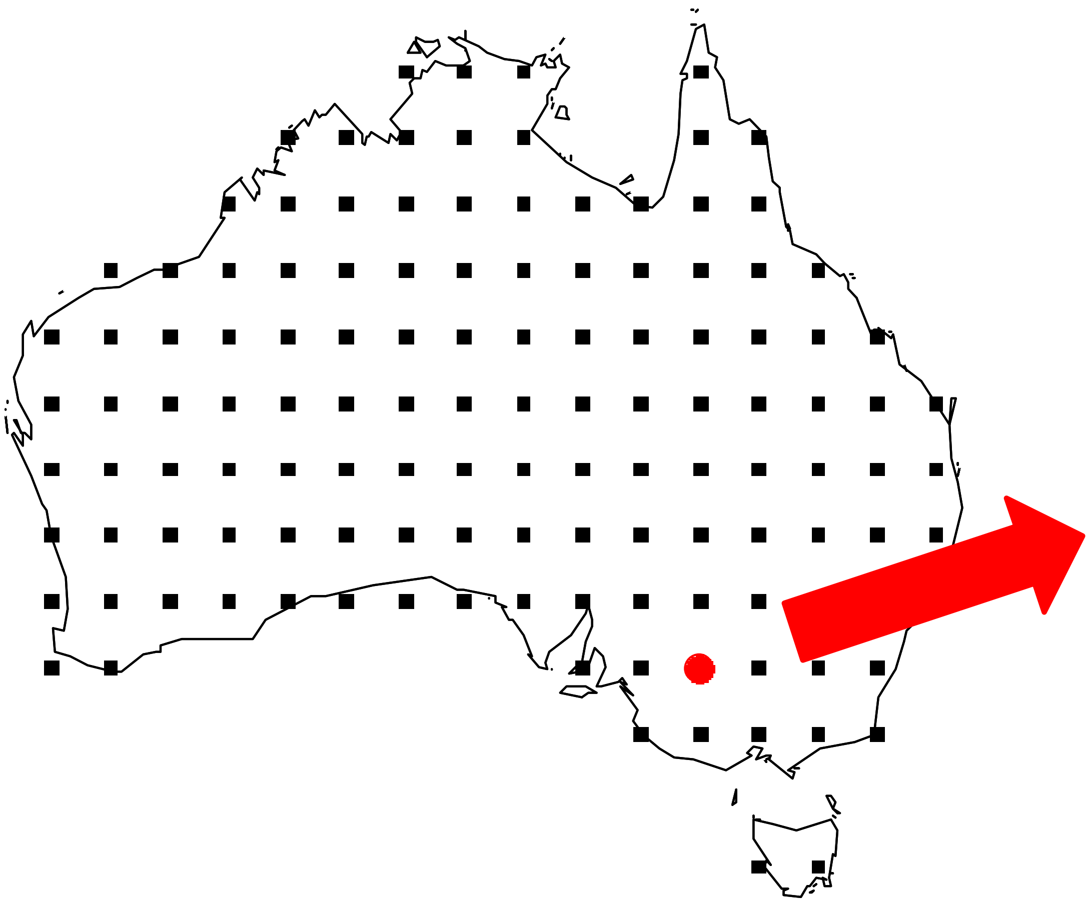
Monthly Rainfall Means

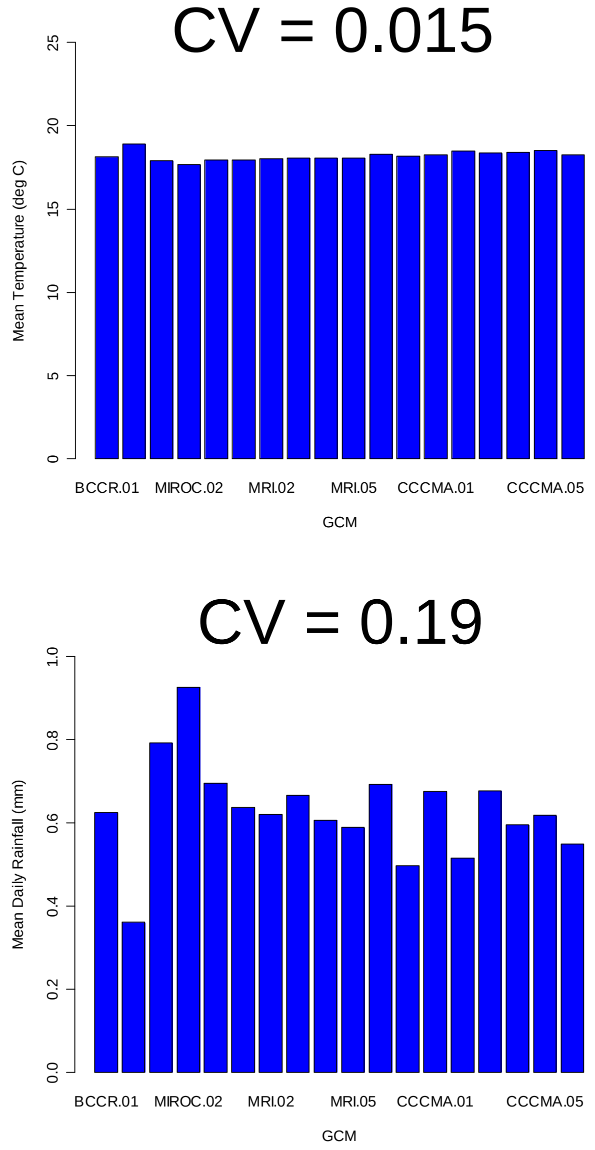


Monthly Rainfall Std Dev

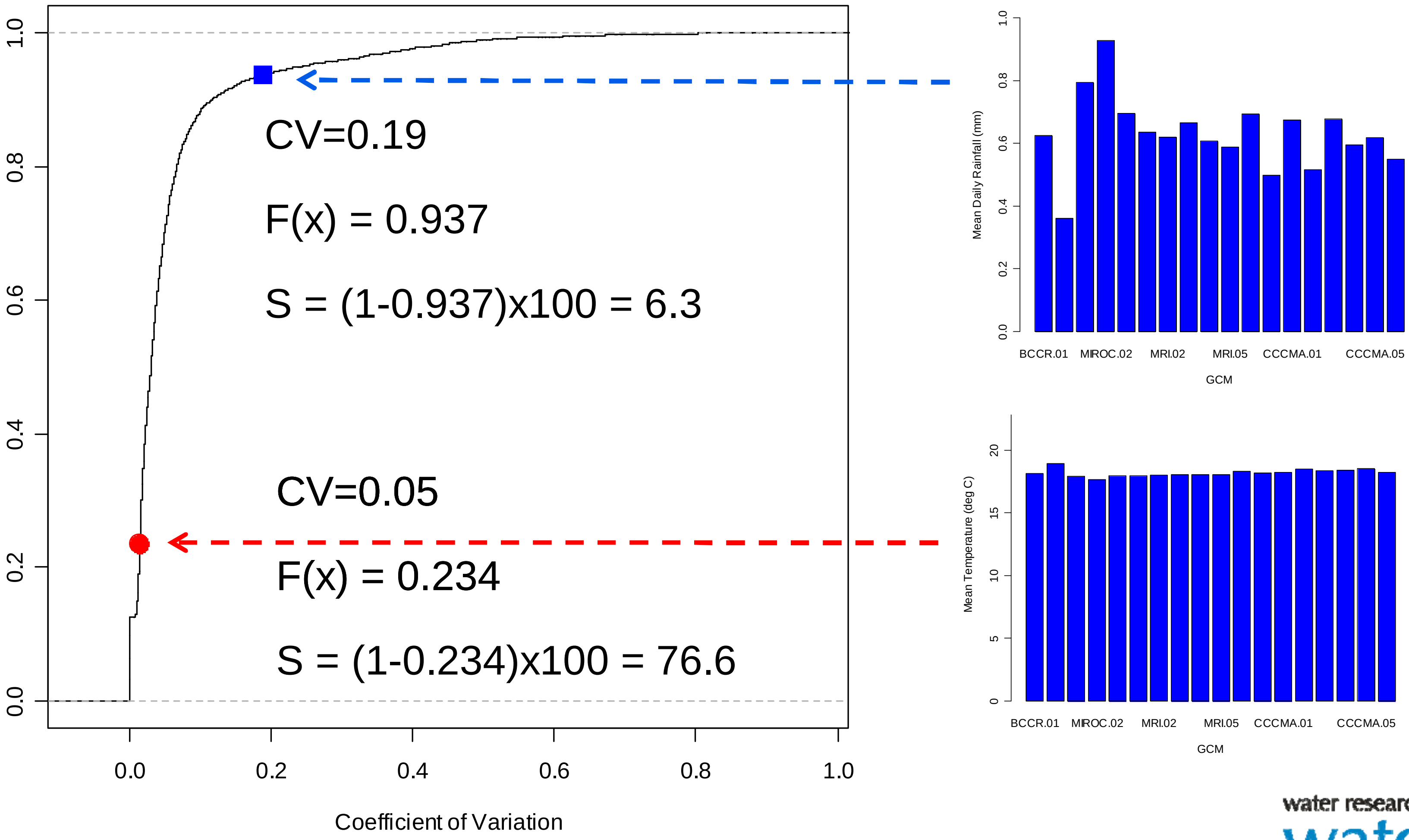
Fiona Johnson and Ashish Sharma

Coefficient of variation across model ensemble members at a cell





Skill Score



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Using the skill score

- Median values of CV across models for all grid cells across Australia used to compare variables

VARIABLE	SRESA2	SRESB1
Temperature	72	82
Wind Speed	42	50
Longwave Rad	24	24
Shortwave Rad	68	69
Specific Humidity	53	51
Precipitation Rate	7	7
Precipitable Water	53	53
Surface Pressure	97	99

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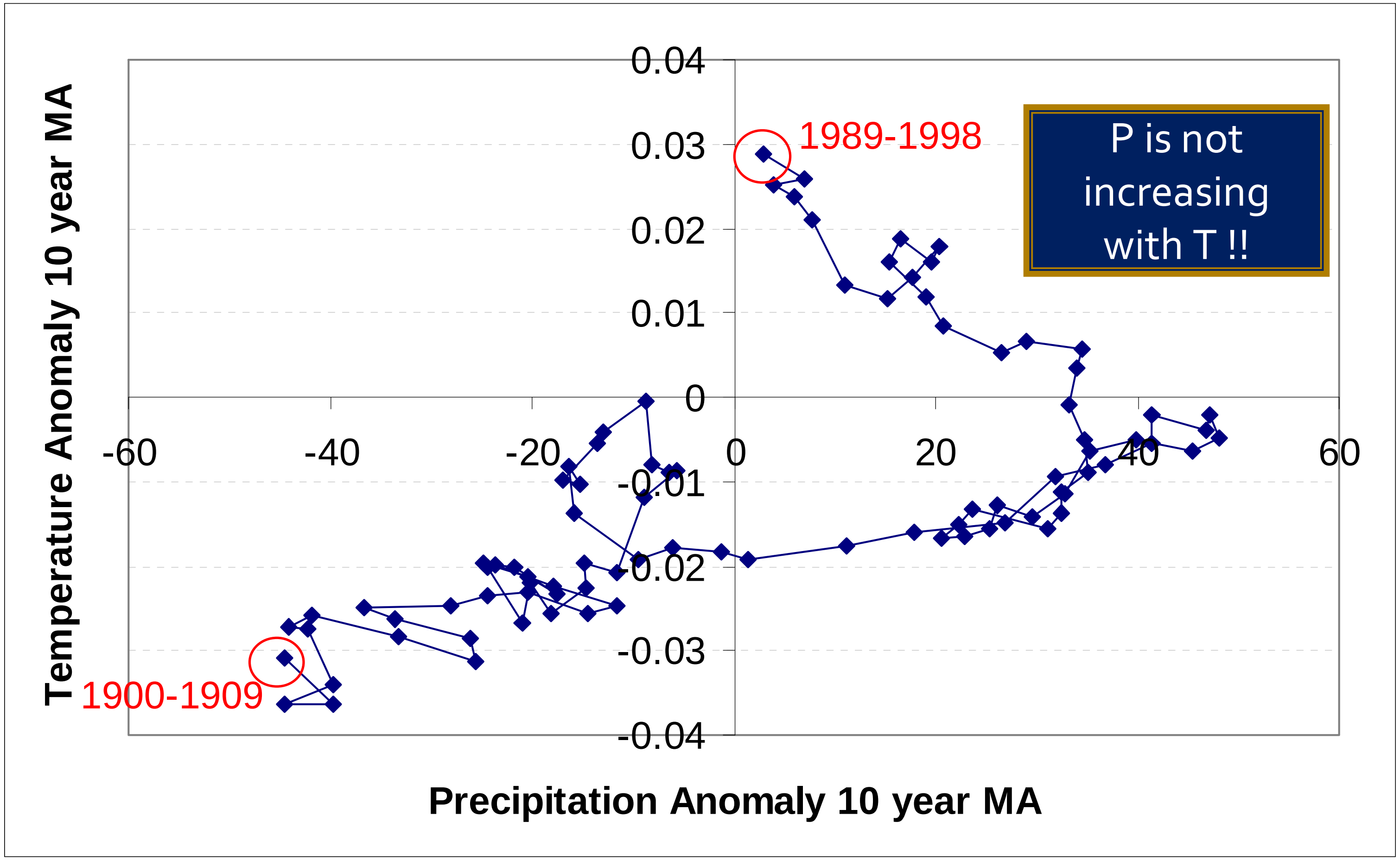
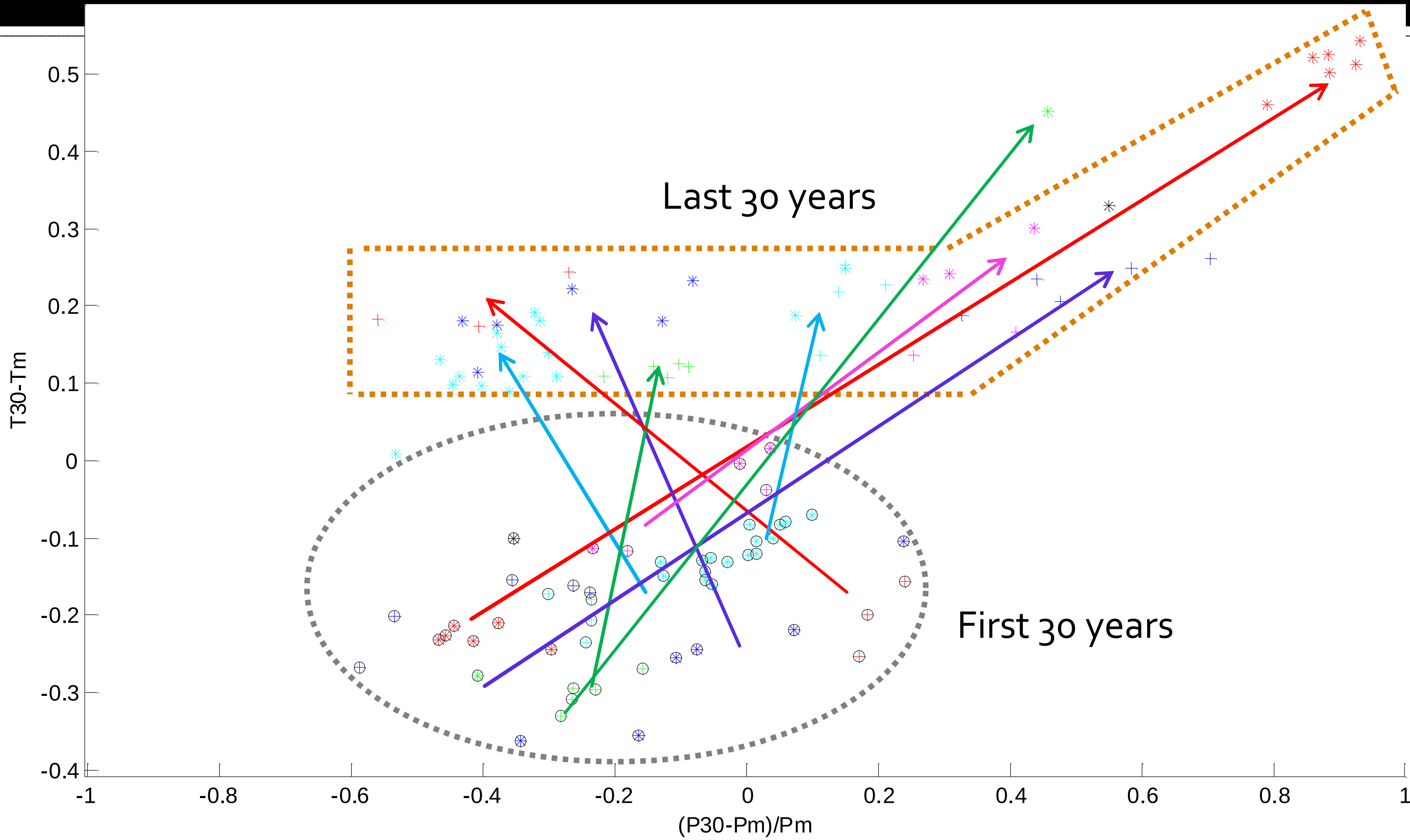
Hulme Jones Gridded Data Phase Plot using only 6oN-6oS



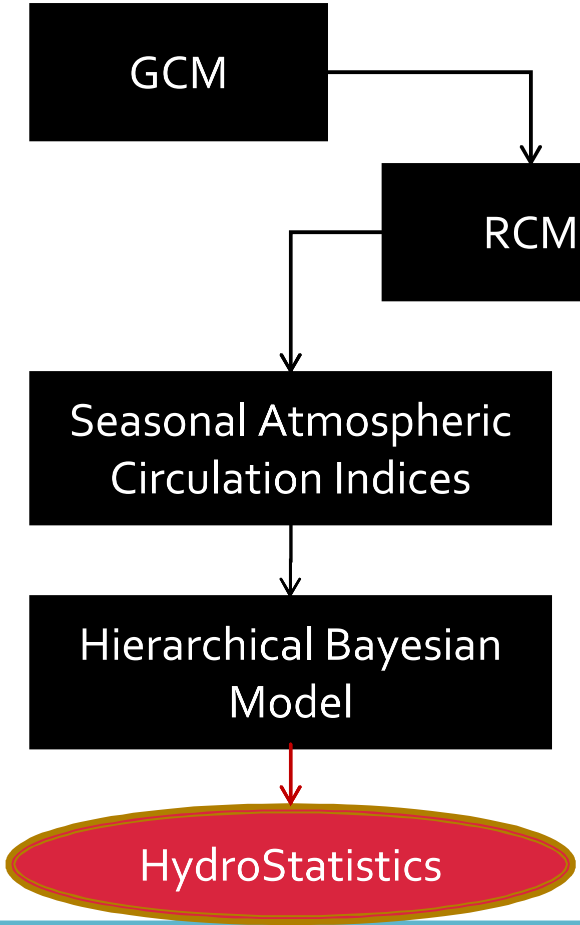
Source: Francisco Assis Souza Filho

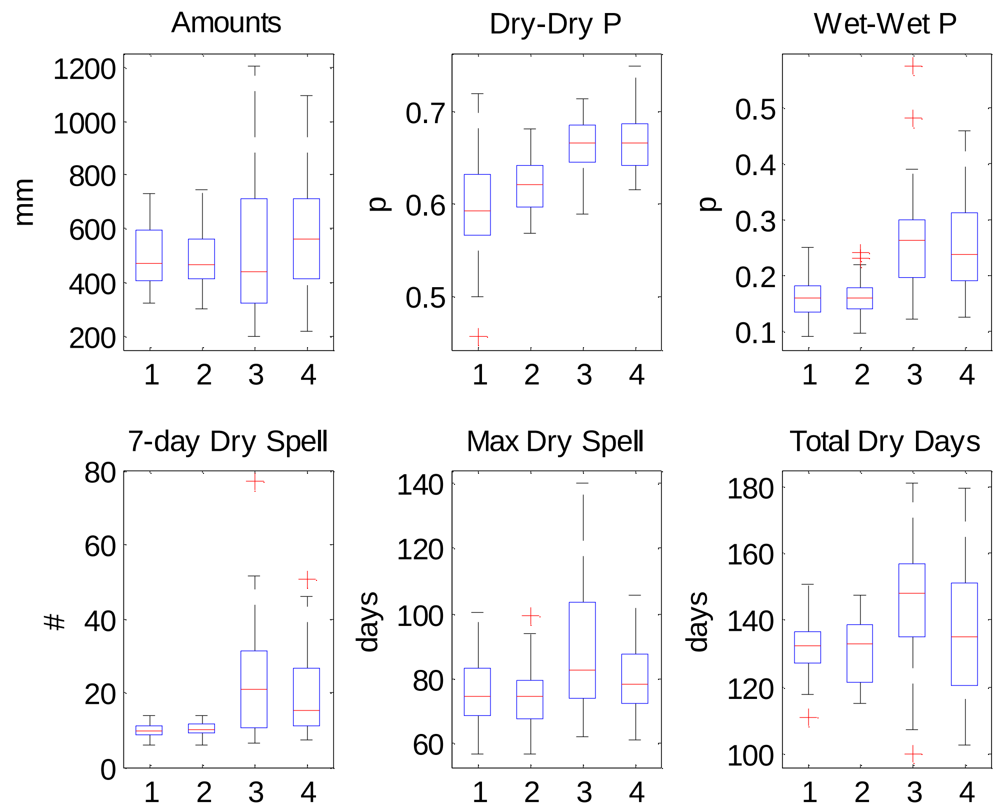
Phase Plot of GCM Global Precip and Temp Anomalies for 1st and last 30 years relative to the grand mean of the 20th century using 46GCMs /ensembles Colors and symbols identify a specific GCM and its ensembles



Source: Francisco Assis Souza Filho

So…can we use the GCM 21st century simulations for something hydrologic and how? (one example pathway)





Source: Abed Khalil and Rana Samuels

Wet season Statistics for 19 stations in **Israel-Palestine** for 1) observations, 2) 1961-90 Model, 3) 2071-2100 A2, 4) 2071-2100 B2 IPCC Scenario