# Decadal Prediction and Stochastic Simulation of Hydroclimate Over Monsoonal Asia

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## **Motivation**

- Fine spatio-temporal scale estimates of climate over the next 10 to 50 years are needed for long-term planning in water resource and flood management.
- At these scales current GCM climate projections have very large uncertainties.
- What to do?

#### Project Goals

- 1. Develop and test statistical methods of interannual-to-interdecadal simulation & prediction of river flows over monsoonal Asia
- 2. Use multi-centennial tree-ring based reconstructions of stream flow to better identify natural modes of climate variability across monsoonal Asia, and test the candidate prediction schemes retrospectively.
- 3. Merge empirical estimates of climate variability with GCM climate change projections using Monte Carlo simulation to quantify the PDF of the uncertainties
- 4. Test simulations using hydrologic models for two major reservoir systems over Asia:
	- 4.1.Bhakra Beas reservoir in northern India,
	- 4.2.Yangtze River Three Gorges Dam reservoir in China

#### 1. Empirical prediction models



 $\frac{1}{\sqrt{2\pi}}$ 

 $RQUVIQ$ 





1 and the time mean is subtracted.  $1.21$  and the time mean is subtracted. *Parana River flow real-time forecast based on Singular Spectrum Analysis & Linear Prediction*

Robertson et al. (2001, GRL)

#### Stochastic inverse models (EMR) with past noise forecasting (PNF) is episodes of strong anomalies in the evolution of the Niño-3 tochaetic invorce mor in 2008—much better than the mean EMR method does. While the mondiale during the energies interference in the energies of construction interference in the energies of cons ence between the LFV modes, QQ and QB (2, 26).  $\mathcal{S} = \{ \mathcal{S} \mid \mathcal{S} \text{ is a non-trivial } \mathcal{S} \text$  $\begin{array}{ccc} \n 1 & \sqrt{r} & \mathbf{A} & \mathbf{D} \\
 1 & \mathbf{A} & \mathbf{D}\n \end{array}$ entire equatorial Tropical Pacific and Indian Ocean area, where  $2 \frac{1}{4} \frac{1}{6} \frac{1}{6} \frac{1}{16} \frac{1}{12} \frac{1}{14} \frac{1}{16} \frac{1}{16}$ −0.2 0 0.2 0.4 0.6  $0.8$ 1 Near 2000 2004<br>Pear<br>Niño−3 Prediction skill, 2000–2009: Correlation Lead (month) corr EMR RNF **RNF+reshuffle** E. IN A AMifle 2 4 6 8 10 12 14 16 0.5 1 1.5 Niño−3 Prediction skill, 2000−2009: RMS Error<br>Possible, 2000−2009: RMS Error Lead (month) EMR PNF PNF+reshuffle EMR+reshuffle 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 <sup>−</sup>1.5 −1 −0.5 0  $\Omega$ . 1 1.5 2 Year Niño−3, 14 month prediction, 2000−2009 Data EMR PNF QQ+QB A B C  $-$  Niño-3 prediction skill for  $\sim$ curve) validated at 14-mo lead, compared to the actual data (black), EMR S S N  $\overline{a}$  $\overline{\phantom{0}}$  $\sim$  1  $\blacksquare$  $\sqrt{80}$   $\sqrt{5}$   $\sqrt{2}$  model is model in the  $\sqrt{2}$  model in the  $\sqrt{2}$  model in the  $\sqrt{2}$  $\epsilon$  N  $\mathcal{L}^{\text{max}}_{\text{max}}$ 0.4  $\int_t^l \xi(t) \hat{f}(t) dt$   $0 \leq L - 1.$  $\sim$   $\sim$   $\sim$  E 120° E 120° W 60°  $\sim$   $\sim$  S S N N N N N N PNF Corr 0.2 0.4 0.6  $\overline{\phantom{0}}$  E 120°  $E = \frac{1}{2}$  E 120°  $\blacksquare$  $U \sim -Z$  S S N N N N N N  $\overline{\phantom{a}}$  $\mathbf{L}$  S N N N N N N PNF RMS 5  $W$  0 $^{\circ}$ APPLIED Chekroun et al. (2M1<sup>-</sup> PNAS)  $\mathbf{P}_{\text{C}}$  $\mathcal{L}_{\mathcal{S}}$  method selects snippets snippets snippets  $\mathcal{L}_{\mathcal{S}}$  that allow us to reach the goal set in the preceding section: in preceding section: in preceding  $\mathbf{r}$ z Stochastic, inverse mode illustrates this improvement in predicting the Niño-3 index by  $f_{\alpha}$  is a mean of the mean  $\langle \text{DM}\vert \Gamma \rangle$ **Fi**forecasting (PNF) issued each month to the control of the control of<br>International control of the control  $\mathbf{v}$  using  $\mathbf{x} =$ 114 values of t "  $\sim$  running from October 1998 to  $\sim$  1998 to  $\sim$  1998 to  $\sim$  1998 to  $\sim$  1998 to  $\sim$ episodes of strong anomalies in the evolution of the evolution of the  $\mathcal{L}_{\mathcal{A}}$  $\begin{bmatrix} 1 & 1 & 1 \end{bmatrix}$   $\begin{bmatrix} 1 & 1 &$  $\begin{matrix} \text{PNF} \ \text{OQ+OB} \end{matrix}$  and the substantial better, it is at no time substantial  $\bigwedge$  $\begin{array}{ccc} \begin{array}{ccc} \n\bullet & \bullet & \bullet & \bullet \n\end{array} & \begin{array}{ccc} \n\bullet & \bullet & \bullet & \bullet & \bullet \n\end{array} & \begin{array}{ccc} \n\bullet & \bullet & \bullet & \bullet & \bullet \n\end{array} & \begin{array}{ccc} \n\bullet & \bullet & \bullet & \bullet & \bullet \n\end{array} & \begin{array}{ccc} \n\bullet & \bullet & \bullet & \bullet & \bullet \n\end{array} & \begin{array}{ccc} \n\bullet & \bullet & \bullet & \bullet & \bullet \n\end{array} & \begin{array}{ccc} \n\bullet & \bullet & \bullet & \bullet & \bullet \n\end{array}$  $m_{\rm s}$  of construction details interference interference interference interference  $e^{-0.5}$  $\begin{array}{ccc} \n\hline\n\end{array}$   $\begin{array}{ccc} \n\$ better skill in Niño-3 prediction beyond 6 mo, compared with the standard EMR method of Kondrashov et al. (16). The optimal experimental condition of the optimal experimental o<br>The optimal experimental experimental experimental experimental experimental experimental experimental experim  $\sqrt{1-\lambda}$  and  $\sqrt{1-\lambda}$  starting from different initial states, synchromatic initial states, synchromos (FIVIR) with nast noise at  $\sum_{i=1}^n$ the characteristic decay time τ of the ENSO eigenmode asso- $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} \in \mathbf{B}(\mathbf{x}, \mathbf{x})$  for  $L(\mathbf{x}, \mathbf{r}'_t, \xi_k t)$  of  $\geq L-1$ .  $\mathcal{L} \cup \{\mathcal{N}_k\}$  is a contribution of long-term  $\mathcal{N}_k$  predictability.  $E_{\rm eff} = 10^{14} \, {\rm M_{\odot}}$  shows that  $E_{\rm eff} = 10^{14} \, {\rm M_{\odot}}$  shows that  $E_{\rm eff}$ **entire equatorial Tropical Pacific ACC SST Skill at 14-mo l<mark>ead</mark>**  $\overline{a}$  Prediction skill,  $\overline{a}$ corr 2000 2009. NIND 2000 2009. NIND 20101 Year Niño−3, 14 month prediction, 2000−2009 Data EMR PNF  $\sim$  Q  $\sim$ A B  $\overline{0}$  $60^{\circ}$  E 120 $^{\circ}$  E 180 E  $120^{\degree}$  W  $W$  60 $\degree$  W 0 $\degree$  20° 'S 10° ⁄\$|  $0^{\prime}$  $10^{\degree}$  N 20° N 30° N 40° N 50° N 60° N EMR Corr  $\Omega$ 0.2 0.4 0.6  $\mathbf{0}^{\circ}$  $\mathcal{A}60^\circ$  E  $\gamma$  $\sqrt[7]{120^2E}$  $180^{\frac{1}{2}}$  $\mathbb{E} \rightarrow 120$  W  $\frac{1}{2}$  60 20° S 10° S <u>ْڻ</u> 10° N 20° N 30° N 40° N 50° N 60° N RNF Cŏrr  $\Omega$ 0.2 0.4 0.6  $\mathcal{S}$  $\mathcal{L}$  $\frac{1}{4}$ 0  $\mathcal{T}$  50° N 60° N  $\mathcal{L}(\mathcal{L})$ A B y  $T$ oexploit knowledge of past noise, as we propose to do here, as  $\blacktriangle$ requires first and model  $\blacktriangle$ **the Stochastic inverse**  $\sum_{i=1}^{\infty}$  $\mathbb{R}$  person of  $\mathbb{R}$   $\mathbb{R}$ and 0 < ϵ ≪ 1; the perturbed path of the noise is χ<sup>ϵ</sup> tðω<sup>0</sup>  $\overline{\phantom{a}}$  $\Delta$  $\sum_{\text{Niño}-3, 14 \text{ month prediction, } 2000}$  $n_{\text{1.5}}$  at time space  $\sum_{\text{PNE}}$  bata  $\begin{bmatrix} 1 \\ 0.5 \end{bmatrix}$  $\mathcal{A}$  $\wedge$   $\wedge$  .  $\cup$  $\rho_{\text{max}}$  $\rightarrow$  $-1$  $\sum$  $\frac{1}{2000}$ <br> $\frac{1}{2000}$   $\frac{1}{2001}$  $\frac{1}{2002}$  at the  $\frac{1}{2003}$  and  $\frac{1}{2004}$  and  $\frac{1}{2005}$  and  $\frac{1}{2000}$  $s = 2000$  at time s and  $s = 2000$  and  $s = 2002$  and  $s = 2003$  by the two noise paths  $s = 2000$  by the two noise paths  $s = 2003$  by the two noise paths  $s = 2003$  by the two noise paths  $s = 2003$  by the two noise paths  $s =$  $\blacktriangle$  $\overline{\mathbb{R}}$  $\frac{1}{\sqrt{2}}$  $\frac{1}{\sqrt{1-\frac{1$  $\frac{1}{\sqrt{2}}\sum_{i=1}^{N} \frac{1}{\sqrt{N}}\sum_{i=1}^{N} \frac{1}{\sqrt{N}}$  $\overline{\phantom{a}}$  $\overline{\phantom{a}}$  $\sqrt{\frac{1}{2} \sqrt{\frac{1}{4}} \cdot \frac{1}{6}}$  lead (month) interested in the expected response, and given  $\mathbf{C}$  is the expected response, and given  $\mathbf{C}$  $\frac{1}{\sqrt{2}}$  $\frac{1}{2}$ ðs;uÞ  $\overline{\phantom{a}}$ At this point, we take a brief except of the scope o present paper and note that, by taking and  $\sum_{\text{PNF}}$  and  $\sum_{\text{PNF}}$  and  $\sum_{\text{PNF}}$  $\begin{array}{|c|c|c|c|}\n\hline\n0.5 & \text{EMR}+{\rm reshuffile} \\
\hline\n2 & 4 & 8 & 10\n\end{array}$ tead (month) (20) response theory for smooth, time-dependent perturbations  $\diagdown$ Fðx;tÞ of autonomous systems with chaotic behavior. In that themodolo (EMD) with poot noi EMR (10, 11, 1990) and the stochastic system in the stochastic system in the stochastic system in the stochastic systems of the stochastic systems of the stochastic systems of the stochastic systems of the stochastic syste  $\alpha$  is the compact of  $\alpha$  is the compact of  $\alpha$  or  $\alpha$  or  $\alpha$  is the compact of  $\alpha$  $\mathcal{L} = \mathcal{L} \cup \mathcal{L}$  is the slowest and most energetic modes,  $\mathcal{L} = \mathcal{L} \cup \mathcal{L}$  $\alpha$  and  $\alpha$  is a time-dependent linearity, and L is a time-dependent linear opera-dependent linear opera-dependent linear opera-dependent linear opera-dependent linear opera-dependent linear opera-dependent linear opera top level, l ¼ 0, the linear stochastic equations that relate the aux- $\begin{array}{ccc} \n\cdot & \cdot & \cdot & \cdot & \cdot \n\end{array}$  $t$  and reduce  $t$ t 4 blokking;<br>ro  $\frac{1}{2}$ <sup>t</sup>Þdtþ  $\lambda$  $\Lambda$  and  $\frac{1}{2}$  and  $\$ ble are linear maps and the same lines of the same lines. The same lines is a same lines of the  $\frac{1}{20}$  , so  $\frac{1}{20}$  , so  $\frac{1}{20}$  ,  $\frac{1}{20}$  ,  $\frac{1}{20}$  ,  $\frac{1}{20}$  $\mathcal{L}$  is the Lie  $\mathcal{U}$  of  $\mathcal{U}$ sidual forcing, has a lag-1 vanishing autocorrelation. The stochas- $\begin{array}{c} \n\hline\n\hline\n\end{array}$ <sup>t</sup> are ordered from the one with strongest memory, r 1944<br>| $t_{\rm 20\,s}$  , to the most weakly and the most weakly and the most  $t_{\rm 10}$ out this section, ξ<sup>t</sup> in Eq. 3 is to be understood thus as an approx- $\sum_{i=1}^{n}$  imation over  $\sum_{i=1}^{n}$  interval of definition  $\sum_{i=1}^{n}$  $\frac{1}{\sqrt{2\pi}}$  $\bigvee_{14} \bigvee_{14} \bigvee_{16} \bigvee_{17} \bigvee_{18} \bigvee_{19} \bigvee$  $\mathcal{N}$  have shown that a two-level Email  $\mathcal{N}$ el—i.e., L ¼ 2 in Eq. 3—can simulate key features of the global sea surface temperature (SST) field's LFV and is quite competitive in predicting ENSO events on the seasonal-to-interannual  $\frac{1}{\sqrt{6}}$  and  $\frac{1}{\sqrt{6}}$  and SSTORS OVER STORES OVER SOME ITALIANS OVER SOME INTERVAL ÅR DET STORES OVER SOME ITALIANS OVER SOME ITALIANS O  $\frac{1}{14}$  sensitivity to changes in the model sensitivity to changes in the model sensitivity of  $\frac{1}{2}$  $P_{\text{max}}$  procedures  $\beta$  $\frac{1}{\sqrt{2}}$ Consider now the observable ψðxÞ≔‖x‖, where ‖ · ‖ denotes

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 20° N

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2. Tree-ring based reconstructions of stream flow

## Tree-ring reconstructions of Upper Indus River Discharge



#### Monsoon Asia Drought Atlas (MADA) 1300–2005 Mancoon Acio Drought Atloc (MAADA) consistent with Divugited and (1911 IDI).<br>The coral corals of all also show that low variance also show that low variance is also show that low variance  $1000$  and  $2000$



Cook et al. (2010, Science)

## 3. Monte-Carlo simulation based on low-frequency modes

#### identified as a single index derived as a weighted linear rainfall series is displayed in Fig. 3. This figure shows that IVAN STOCNASTIC SIM ence the rainfall. While it exhibits patterns of correlations Concept of data-driven stochastic simulation

that the strongest correlations are on the two regions with



or may be a subset of those series that are most relevant for

*Schematic representation of generation of daily rainfall scenarios conditional on a scenario of seasonal/ annual climate indices*

## Graphical model structure for stochastic downscaling of rainfall and temperature



# **4. Hydrologic modeling case studies**



DIIAKIA DAIII, IIIUIA

Bhakra Dam, India **Three-Gorges Dam, China** 

#### **Dynamic Risk Management: Multipurpose Reservoir System Operation** guided by Multiscale *Climate Information:* Beas-Sutlej Rivers, India

**Decisions**: 1. Storage (as a f(time) to allocate for monsoon flood volume 2. Irrigation &Hydropower release schedule & canal flows **Challenges:** Prediction of a) spring fill cycle flows and timing, b) monsoon flood flow volume and duration, and c) winter precipitation and melt period dynamics. Marked interannual and decadal variability with superposed glacier melt trend. Approach:



## **Summary**

- Fine spatio-temporal scale estimates of climate over the next 10 to 50 years are needed for long-term planning in water resource and flood management.
- Stochastic simulation in conjunction with reservoir management models provides a pathway to adapt to climate change by building resiliency through testing sensitivity to hydroclimate drivers.
- Empirical stochastic models in conjunction with proxy reconstructions of hydroclimate provide a means to resolve decadal-scale variations and test potential predictabilty