UNIVERSITY OF EXETER

D2262 | EGU2020-11690

Abrupt transitions, wave interactions and precipitation extremes in climate

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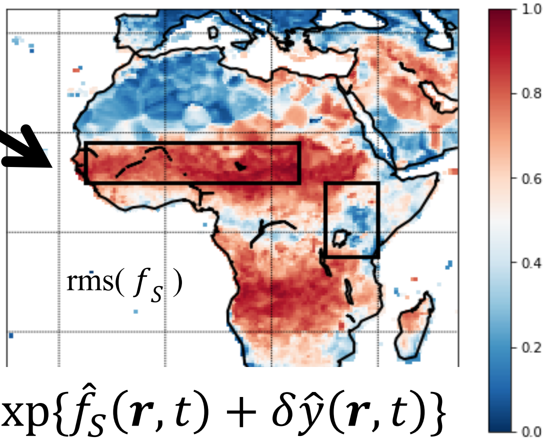
See also: D3930 |EGU2020-11815 **Talking about the physics of climate change, what we know and what extra could we do?** **John Bruun** and Audrey Alejandro

Oscillations, wave transport & stochastic processes impact extreme's and rainfall



ENSO system: (Timmerman *et al.* , 2018) *"warm pool heat advection processes have a key role in determining the long-term memory..".* ENSO eigenmodes: *"operate not far from criticality (zero growth rate) which implies that they can be easily excited by other processes."*

$$\hat{P}(\boldsymbol{r},t) = \exp\{\hat{f}_S(\boldsymbol{r},t) + \delta\hat{y}(\boldsymbol{r},t)\}$$

Rainfall — seasonal — anomaly inc. extremes

Sahel Precipitation: (Nicholson, 2013)

In the Tropical Easterly Jet (TEJ):

"The core speed is anomalously high when annual rainfall is above average in the Sahel, anomalously low during dry years in the region"

What is the nature of the extremes?

(Bruun and Evangelou, 2019) we use universal transport and extreme value theory, with

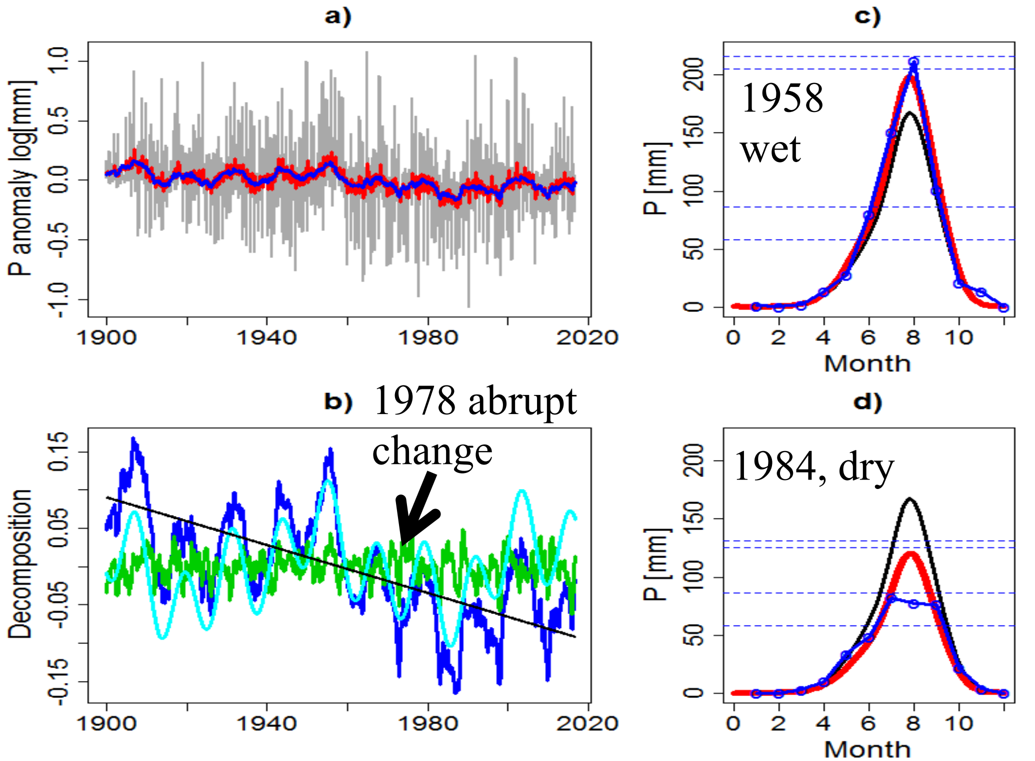
GEV shape parameter $\boldsymbol{\xi}(\kappa)$,

κ: system wave interaction type

to show extreme's abruptly alter with $\kappa \to \kappa$'.

For: $\boldsymbol{\xi} \leq \mathbf{0}$ Thermalization & ergodic wave types

$\boldsymbol{\xi} > \mathbf{0}$ Localization of waves.



Sahel: (GPCC analysis) long term $\hat{f}_{Atlantic}$ & $Trend$ and some ENSO signal (b: green) modulate rain climate $\hat{f}_S$ (c, d: black)

To understand Extreme's large ensembles needed (1000+ , statistical mechanics)

..so we use Random Matrix Theory (RMT) to represent the stochastic GCM's

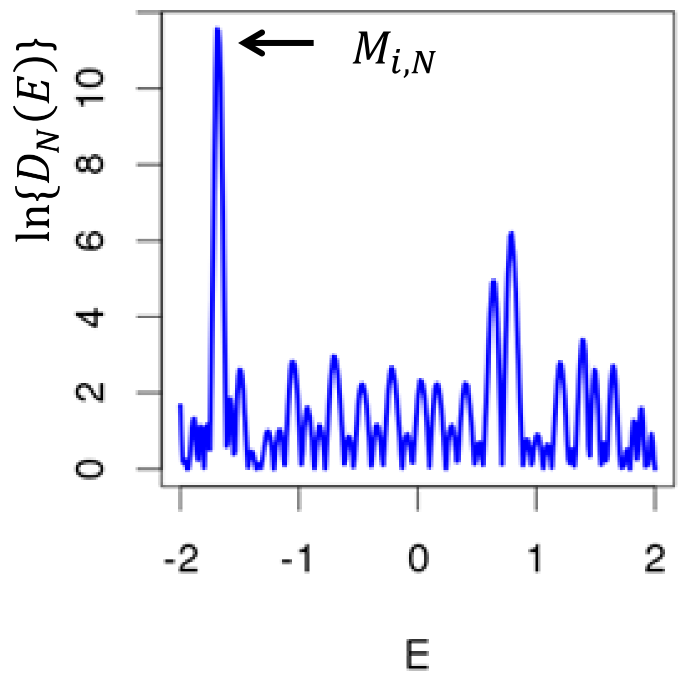
$$\begin{bmatrix} H_o(W) & \Delta \\ -\Delta^* & -H_o^*(W) \end{bmatrix} \underline{\psi} = E\,\underline{\psi}, \quad \Delta = \begin{pmatrix} \Delta_1 & & \\ & \Delta_2 & \\ & & \ddots \end{pmatrix}, \quad \Delta = \begin{pmatrix} 0 & -\Delta_1 & \cdots \\ \Delta_1^* & 0 & -\Delta_2 \\ \vdots & \Delta_2^* & \ddots \end{pmatrix}$$

Energy *E* relationship (Hamiltonian) **Coupling and interaction types including topology**

$H_o(W)$: $N \times N$ Random Matrix, κ: {localized, disordered chaotic, ballistic} wave interactions:

Localization (Anderson, 1958),
Wigner surmise (Wigner, 1955) disorder and universality,
Earth system transport (Delplace *et al*, 2017; Bruun *et al*, 2017),
RMT: (Evangelou and Pichard, 2000; Fyodorov and Simm, 2016).

This approach has n (large) ensembles to evaluate N eigenmodes in the extreme limit (Bruun and Evangelou, 2019):



$$D_N(E) = \det(EI - H) = \prod_{j=1}^{N}(E - E_j)$$ **Characteristic polynomial**

$$R_N(E) = |D_N(E)|^2 - 1$$ **Resistance (transport metric)**

$$M_n = \{M_{1,N}, M_{2,N}, \dots, M_{n,N}\}$$ **Ensemble of maxima**

$$Pr\{ (M_n - b_n) / a_n \le z\} \to G(z), \quad n \to \infty$$ **Max-stable renormalisation limit law**

$$G(z) = \exp\left\{-\left[1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\} = GEV(z; \mu, \sigma, \boldsymbol{\xi})$$

Generalised Extreme Value process
shape parameter $\boldsymbol{\xi}$ ≡ extreme type & wave type

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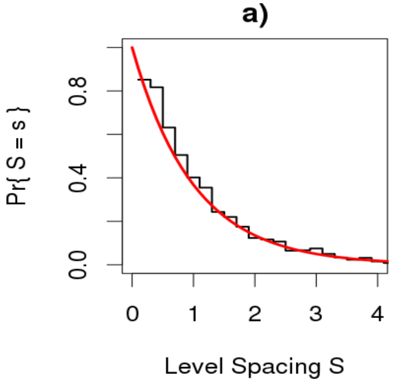
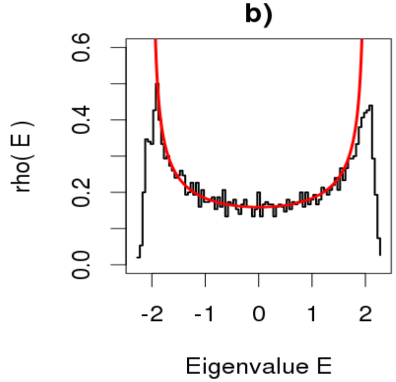
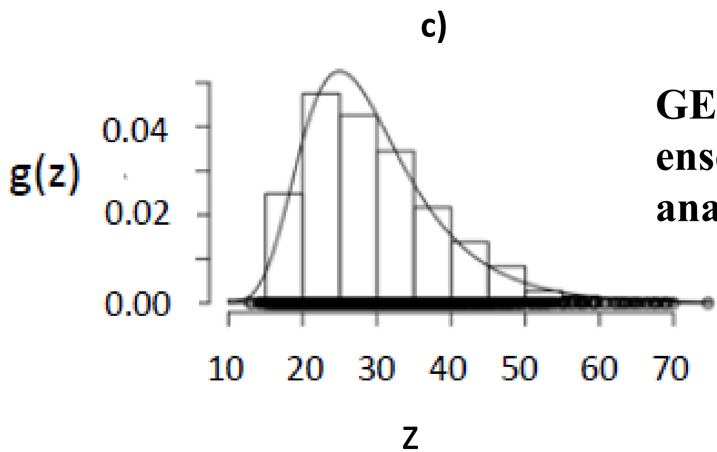
Extreme process state transitions: κ: localized ↔ disordered chaotic

Eigenvalue interaction & density



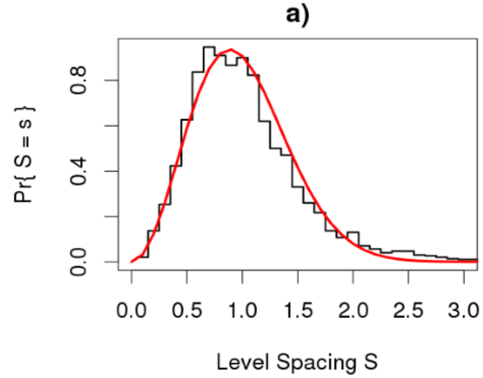


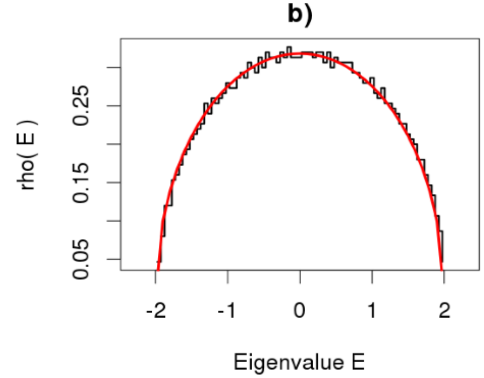


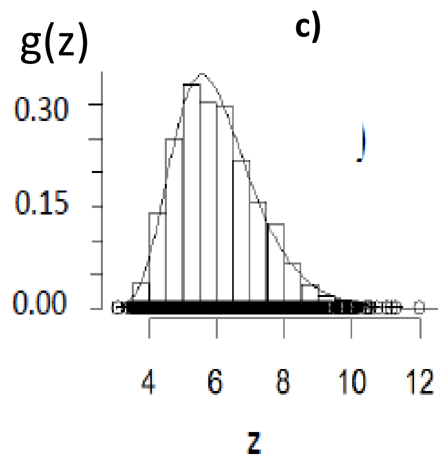
GEV ensemble analysis

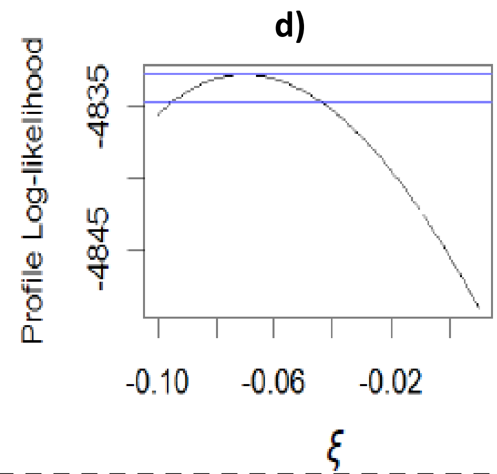
Localized system: high stochastic/disorder no eigenvalue interaction, non-ergodic. Extremes (Fréchet type) $\xi > 0$ a very heavy tailed process

Eigenvalue interaction & density









Disordered chaotic: moderate stochastic/disorder eigenvalue interaction (level repulsion) thermalization, ergodic inc topological/ ballistic waves Extremes: Weibull of Gumbel type: $\xi \leq 0$

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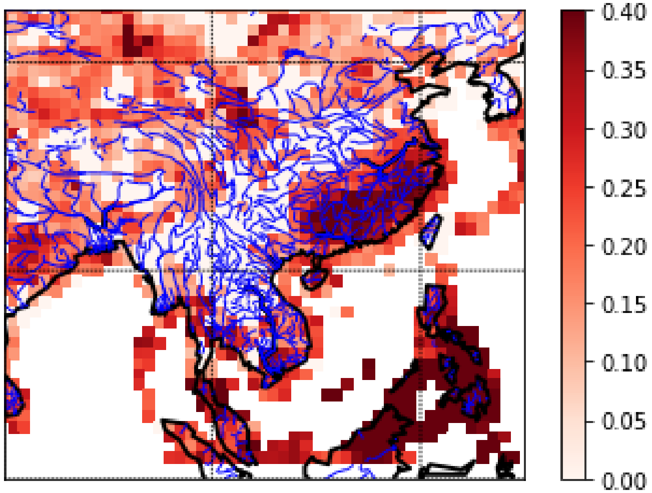
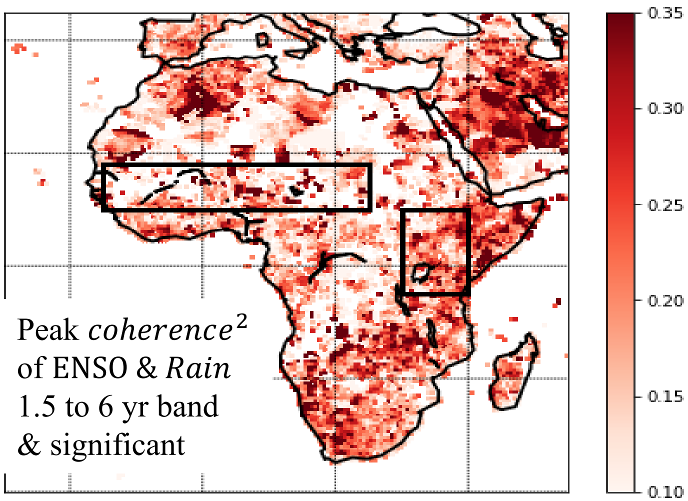
Precipitation extremes (Africa and SE Asia)

Teleconnection ENSO influence (e.g. co-spectrum ENSO ~ Precipitation) via Tropical wave guide and mode locking properties: ITCZ over Sahel (Sahara heat low, Atlantic convection) and Asia (Tibetan plateau and Maritime Continent effects).

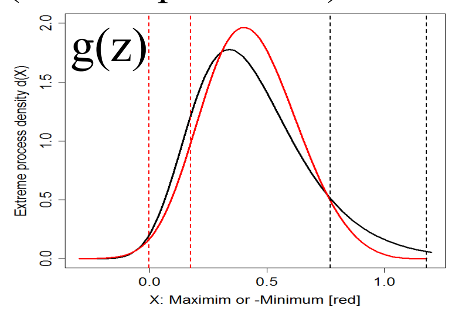




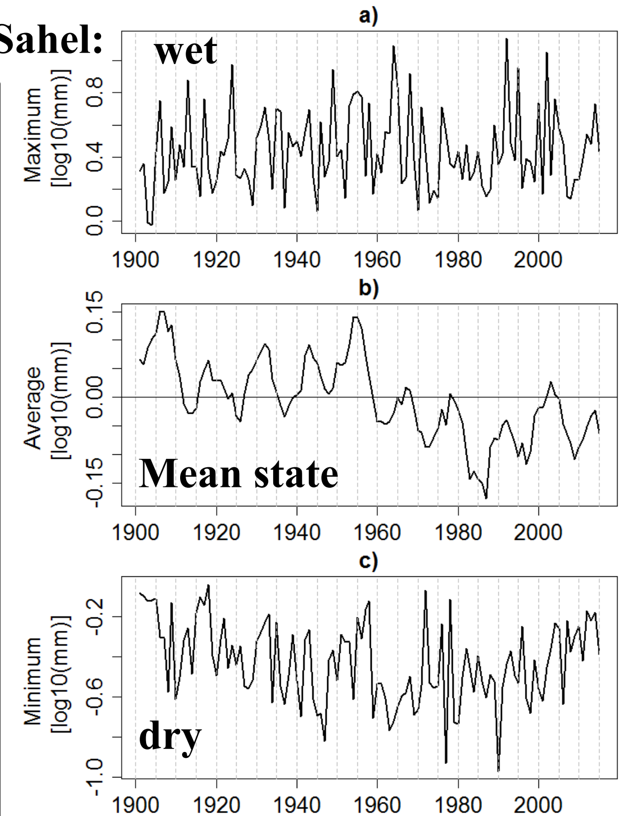
Sahel extremes g(z): wet and dry have GEV shape parameter

$$\boldsymbol{\xi \leq 0}$$

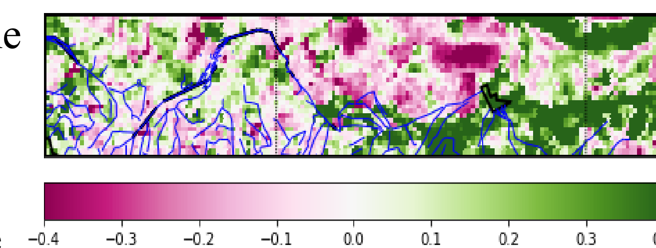
so this implies a Weibull thermalized system (i.e. in equilibrium).



Sahel:



Within Sahel: dry extreme shape ξ_{Min} directionally suggests $\boldsymbol{\xi > 0}$ in West (Lake Chad area): is this evidence of Anthropocene induced localization? TEJ intensity also appears to be a mechanism.



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Wave interaction type influences the occurrence of extremes

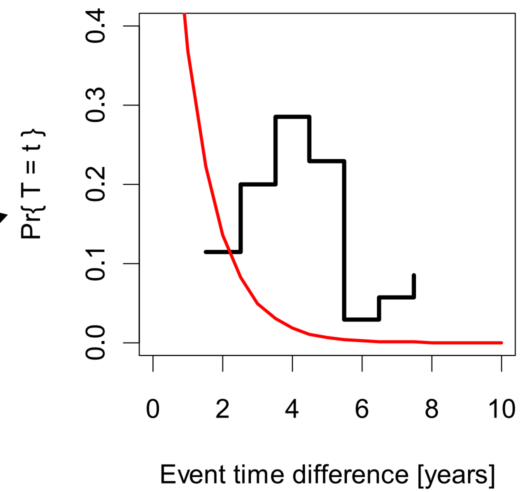
Climate extremes: mostly Weibull type $\boldsymbol{\xi < 0}$, an ergodic equilibrium state (thermalization).

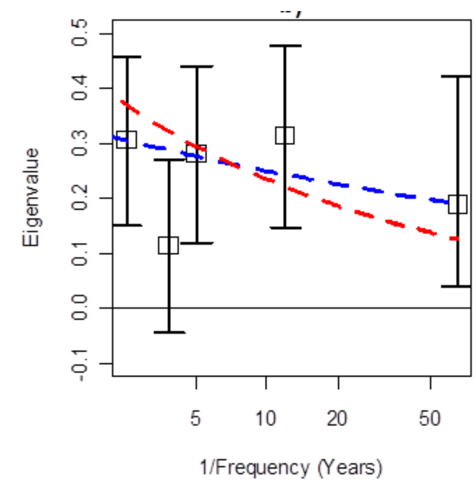
The ENSO periodic map is a Wigner surmise (interacting resonance eigenvalues) so has $\boldsymbol{\xi < 0}$. *Do El-Niño's initiate stochastically ?*

If so time between events δt will be a Poisson process:

$$P(\delta t) \propto \exp(-\delta t)$$

From 35 events (HadISST record) it does not look Poisson! Implies the process is both regular and stochastic and ergodic.





Red line: $3n^2 + I$ periodic map
Blue line: SOI frequency states
(Bruun *et al*., 2017)

Random, stochastic and regular phenomena are intrinsic to Earth transport processes:

wave interaction properties: topological, earth rotation, wave guides and analysis imply mosly $\xi(\kappa) \leq 0$ which corresponds to ergodic phenomena, interacting eigenmodes and thermalization properties (equilibrium).

Could localization wave properties occur in special cases? $\boldsymbol{\xi(\kappa) > 0}$ would indicate this

….are we seeing this in the form of Anthropocene induced aridification for parts of Sahel?

Abrupt transitions (an alteration of extreme process) can be monitored via $\boldsymbol{\xi(\kappa)}$.

References that build this finding

Anderson, P.W. (1958), Absence of diffusion in certain random lattices, *Phys Rev*. **109**, 1492.

Bruun, J.T. and Evangelou, S.N. (2019), Anderson localization and extreme values in chaotic climate dynamics, arXiv:1911.03998**.**

Bruun, J.T.*,* Allen, J.I. and Smyth, T.J. (2017)*,* Heartbeat of the Southern Oscillation explains ENSO climatic resonances*, J. Geophys. Res. Oceans,* **122***,* 6746–6772*, doi:*10.1002/2017JC012892.

Bruun, J.T. and Tawn, J. A. (1998), Comparison of approaches for estimating the probability of coastal flooding. *App. Statist*, **47**, 3, 405-423.

Bruun, J.T., Evangelou, S.N. and Lambert, C.J. (1995), Universal level statistics in the presence of Andreev scattering, *J. Phys. Cond. Matter,* **7**, 4033-4050, doi:10.1088/0953-8984/7/21/004.

Delplace, P.; Marston, M. and Venaille, A. (2017), Topological origin of equatorial waves, *Science*, **358**, 1075-1077, 10.1126/science.aan8819.

Evangelou, S.N. and J.-L. Pichard, J.-L. (2000), Critical quantum chaos and the one-dimensional Harper model, *Phys. Rev. Lett.,* **84**, 1643.

Feigenbaum, M.J. (1980), The metric universal properties of period doubling bifurcations and the spectrum for a route to turbulence, *Ann. N.Y. Acad. Sci*., **357**, 330-336.

Fyodorov, Y.V. and Simm, N.J. (2016) On the distribution of the maximum value of the characteristic polynomial of GUE random matrices *Nonlinearity* 29, 2837.

Nicholson, S.E. (2013) The West African Sahel: a review of recent studies on the rainfall regime and its interannual variability. *ISRN Meteorology*, 453521.

Santhanam, M.S. and Patra, P.K. (2001) Statistics of atmospheric correlations, *Phys. Rev E*.,**64** (1), 016102.

Sheen, K. L. *et al*. (2017) Skilful prediction of Sahel summer rainfall on inter-annual and multi-year timescales. *Nat. Com.,* **8**, 14966.

Skákala, J., & Bruun, J.T. (2018), A mechanism for Pacific interdecadal resonances, *J. Geophys. Res. Oceans*, **123**, 6549–6561. https://doi.org/10.1029/2018JC013752.

Suarez, M. and Schopf, P.S. (1988), A delayed action oscillator for ENSO, *J. Atmos. Sci.,* **45**, 3283-3287.

Tong, H. (1990), Non-linear time series, a dynamical system approach, Oxford statistical science series; 6. OUP Inc., New York.

Timmerman, A. *et al*. (2018) El Niño-Southern Oscillation complexity, *Nature,* 559(7715):535-545

Tziperman, E; Stone, L.; Cane, M.A.; and Jarosh, H. (1994), El Niño chaos: overlapping of resonances between the seasonal cycle and the Pacific Ocean-Atmosphere oscillator, *Science*, **264**, 72-74.

Wheeler, M. and G.N. Kiladis, 1999: Convectively Coupled Equatorial Waves: Analysis of Clouds and Temperature in the Wavenumber–Frequency Domain. *J. Atmos. Sci.,* **56**, 374–399

Wigner, E. (1955), Characteristic vectors of bordered matrices with infinite dimensions, *Annals of Mathematics*, **62 (3)**: 548–564. doi:10.2307/1970079.

Williams, P.D. (2012) Climatic impacts of stochastic fluctuations in air–sea fluxes, *GRL*, **39**, L10705.

Wing, A.A. and Emanuel, K.A. (2014); Physical mechanisms controlling self-aggregation of convection in idealized numerical modeling simulations, *J. Adv. Model. Earth. Syst.*, 6, 59– 74.

Young, P.C. (2011), Recursive estimation and time-series analysis, 2nd ed, Springer-Verlag Berlin Heidelberg.

Young, P.C.; McKenna, P. and Bruun, J.T. (2001), Identification of non-linear stochastic systems by state dependent parameter estimation, *Int. J. Control*, **74**, 18, 1837-1857, doi:10.1080/00207170110089824.