Enhancing earth system decision making with Dominant Frequency State Analysis

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Decision Making Under Uncertainty: M2D Conference 2018, Isaac Newton Institute, Cambridge

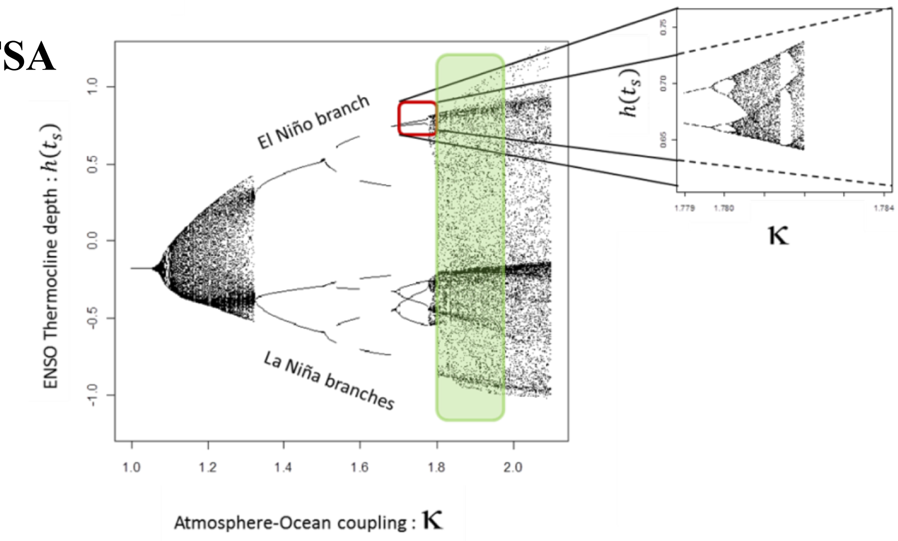
Key themes: Food security, physical processes, reducing uncertainty with both sophistication & simplicity, climate physics, Sahel, universality, extreme value processes, dominant frequency state analysis (DFSA)

Red box: some open discussion, M2D extension, collaboration suggestions….

John: Theoretical Physicist (Lancaster, 1994) and communicator

A. **ENSO dynamics, mesoscale transport, DFSA**

Bruun, *et al.* (2017), Heartbeat of the Southern Oscillation explains ENSO climatic resonances, *J. Geophys. Res. Oceans*, 122, 6746.



B. Universality (Physical, Statistical)
Inc. dynamics, Extreme value theory and cascade risks

C. System identification approaches

D. Global and local social-economic and policy analysis

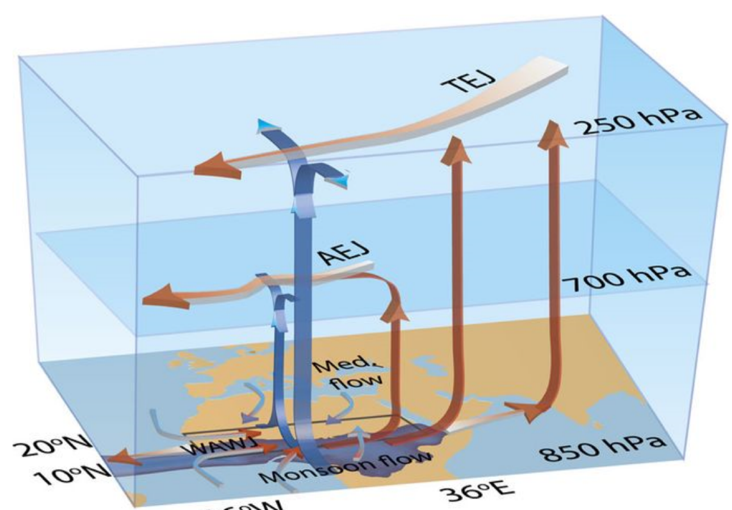
Katy: Physical Geographer (Cambridge, 2010) and communicator

A. Climatic fluid flow dynamics in Southern Ocean

B. Sahel rainfall dynamics and model skill

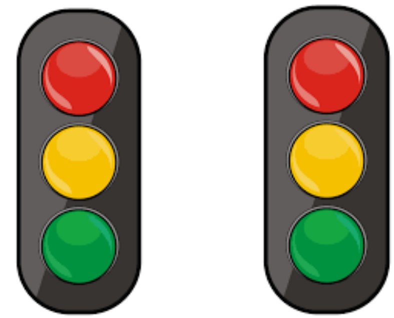
Sheen *et al.* (2017), Skilful prediction of Sahel summer Rainfall on inter-annual and multi-year time scales *Nature Communications*, 8, 14966.

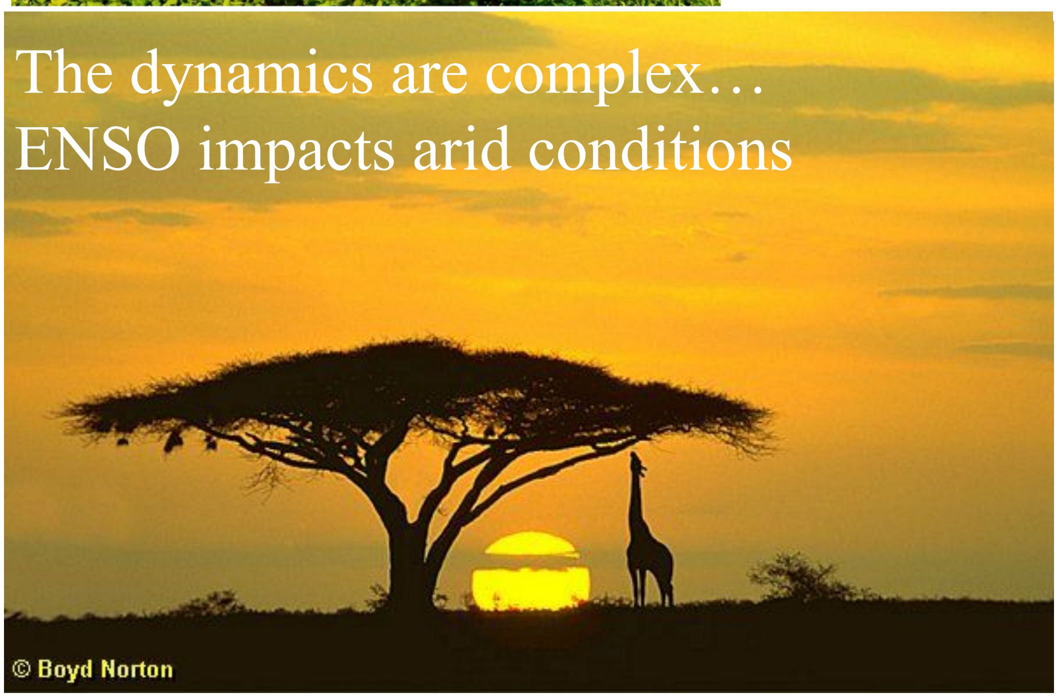
C. Global and regional Aerosol pollution studies



The Sahel rain budget is influenced by planetary scale climatic phenomena

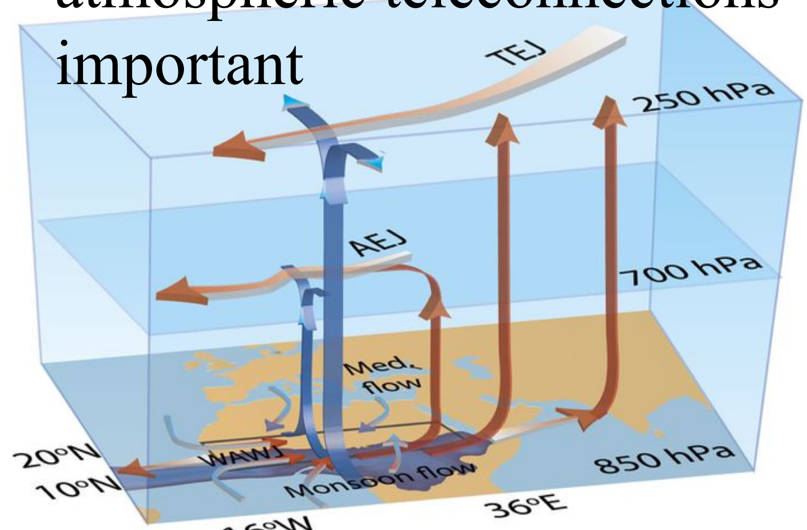
Resilience/food security linked to rain pattern extremes: better understanding enhances our decision making and reduces community risk
Using ‘traffic light’ rain budget risk maps





The dynamics are complex…
ENSO impacts arid conditions

atmospheric teleconnections important



DFSA: motivation non-linear resonance in a periodic dynamic oscillator systems.

a) Eigenvectors $\boldsymbol{f_1}$, $\boldsymbol{f_2}$ and total combination (scaled red arrow)

b) $\boldsymbol{f_1}$ frequency state

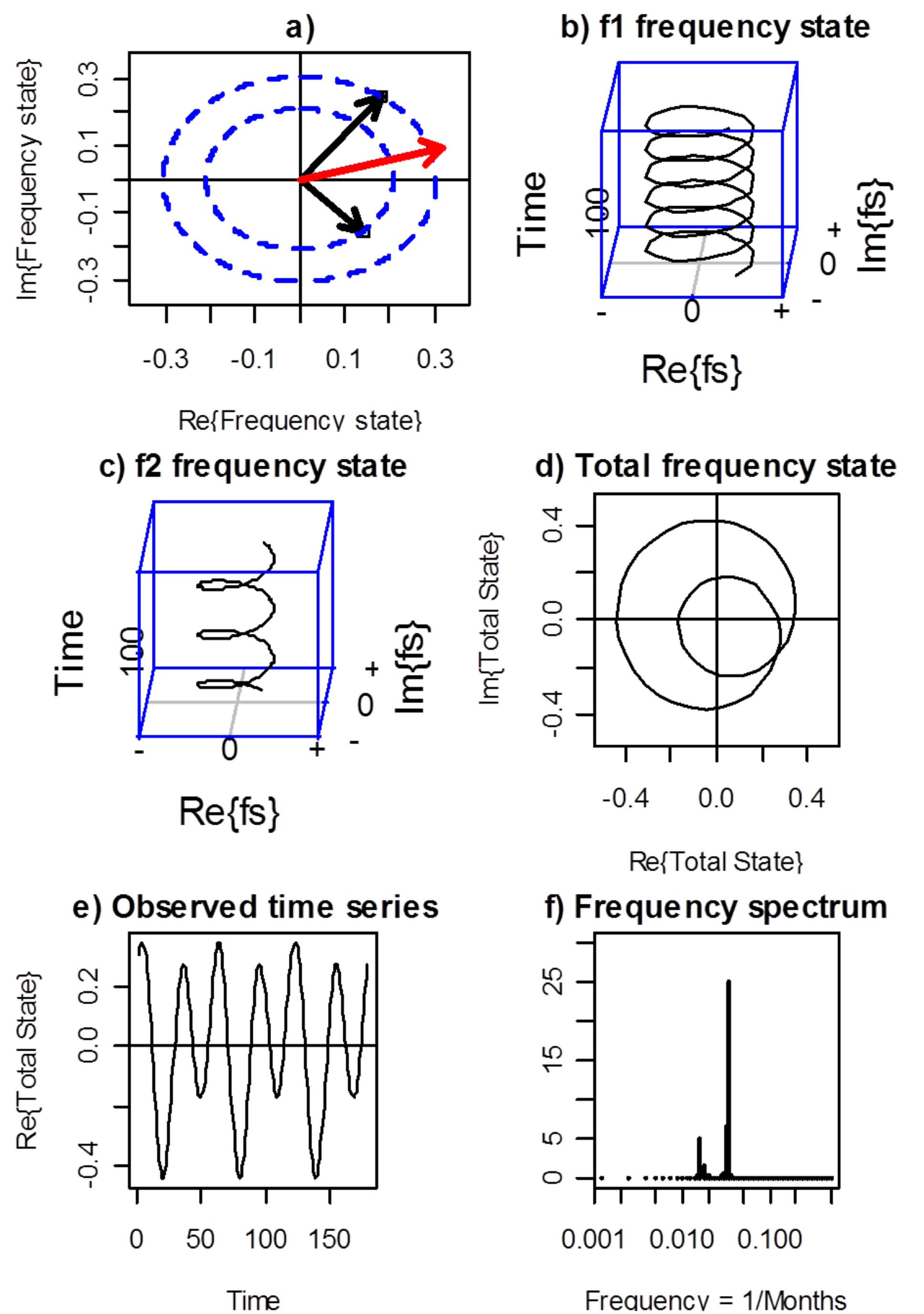
c) $\boldsymbol{f_2}$ frequency state (1/2 'speed')

d) total frequency state (period three orbit)

e) observed time series

f) frequency spectrum of observed time series.

Apply DFSA to determine Earth System modes for any variable. Dynamic characteristics and coloured noise



Example: Identify and estimate non-linear universal properties of non-linear Periodic oscillator

Using the logistic map (period doubling characteristic)

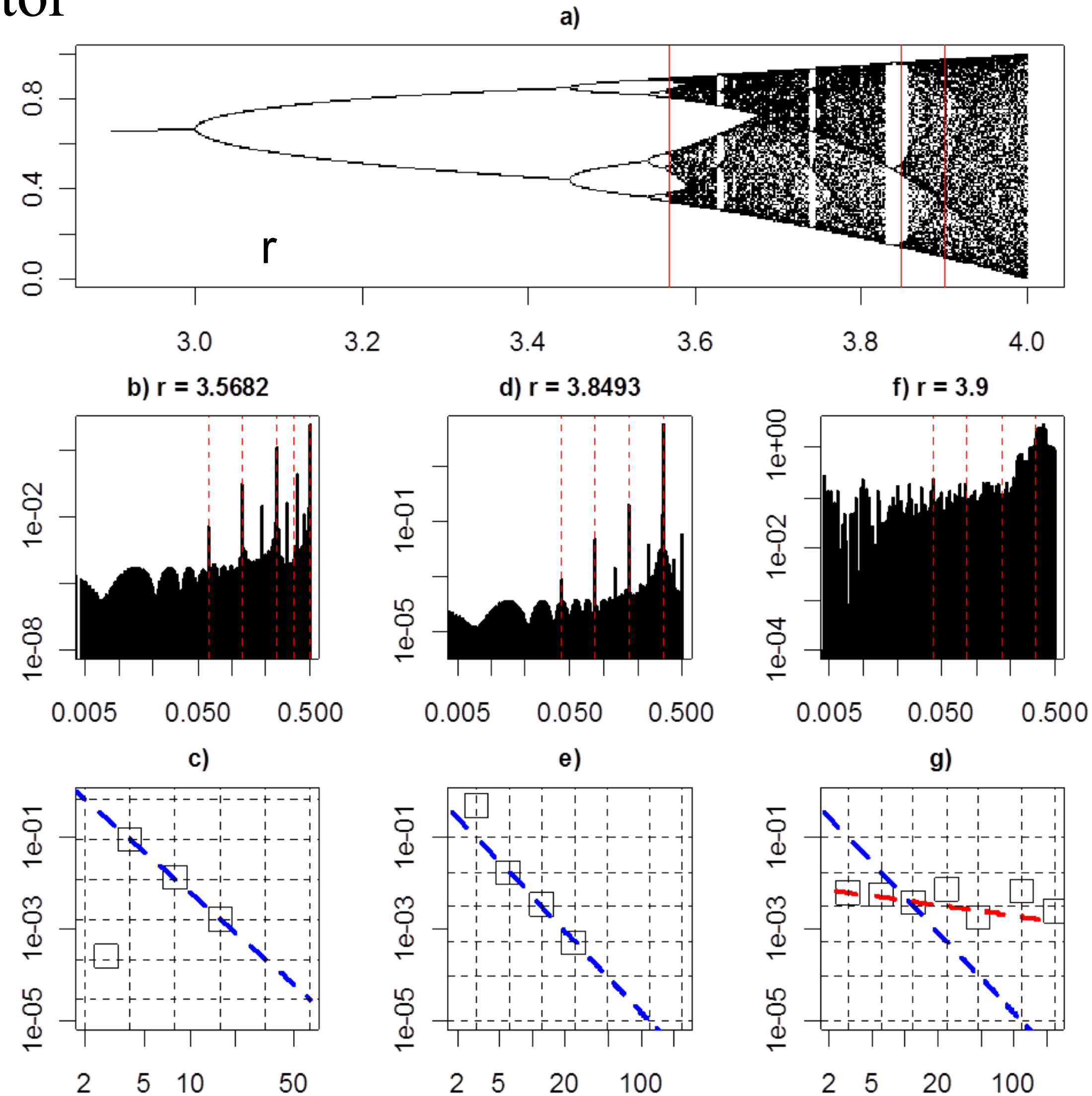
The eigenvalue spectrum has a universal subharmonic decay:

$2n^2$: *8.7dB*

$3n^2$: *7.6dB*

$3n^2 + Intermittency$: *1dB*

(Feigenbaum, 1980; Bruun et al., 1994, 2017)



Dominant Frequency State Analysis (Basic method)

Eigenvalue equation
(a-priori structure on rhs)

$$D\,\{\psi(\boldsymbol{r},t)\} = \lambda\,\psi(\boldsymbol{r},t) \tag{1}$$

Frequency state decomposition

$$\lambda\,\psi(\boldsymbol{r},t) = \sum_{k=1}^{n} \underline{\boldsymbol{f}}_k^s(\boldsymbol{r},t) = \underline{\boldsymbol{f}}^s(\boldsymbol{r},t) \tag{2}$$

$$\underline{\boldsymbol{f}}_k^s(t) = A_k e^{i(\omega_k t + \phi_k)} = A_k\{\cos(\omega_k t + \phi_k) + i\sin(\omega_k t + \phi_k)\} \tag{3}$$

Observation of frequency states

$$y(t) = \sum_{k=1}^{n} Re\left\{\underline{\boldsymbol{f}}_k^s(\boldsymbol{r_o},t)\right\} + \alpha I(\boldsymbol{r_o},t) + \eta(\boldsymbol{r_o},t) \tag{4}$$

The $\omega_{process} = \{\omega_1, \omega_2, \dots, \omega_n\}$ are the a-priori identified dominant frequencies at relevant spatial location $\boldsymbol{r} = \boldsymbol{r_o}$, $\alpha I(\boldsymbol{r_o},t)$ are intervention terms and η is a noise process.

Example application to ENSO including thresholds

$$\lambda\,\psi(\boldsymbol{r_o},t) = ENSO(t) : \begin{cases} \boldsymbol{r_o} = tropical\ Pacific \\ \boldsymbol{r_o} = tropical\ and\ extratropical\ Pacific \\ \boldsymbol{r_o} = Pacific\ basin \end{cases} \tag{5}$$

$$ENSO(t) = \sum_{k=1}^{n} f_k^s(t) + \eta(t) \quad for\ A_- < \sum_{k=1}^{n} f_k^s(t) < A_+ \tag{6}$$

with $f^s = Re\left\{\underline{\boldsymbol{f}}^s\right\}$, time t, n distinct frequency states and random noise (and red-noise) $\eta(t)$

Estimation with likelihood $l(\theta)$ inference (no other estimators can asymptotically be more efficient)

$$\nabla_\theta\, \hat{l}\left(\hat{\theta} \mid \text{observed data}\right) = 0 \tag{7}$$

Extending DFSA to resolve spatio-temporal structure

EOF's typically separate the spatial and time components:

$$\lambda\, \psi(\boldsymbol{r}, t) \rightarrow u(\boldsymbol{r}) v(t)$$

With DFSA all the spatial dynamic information is mapped onto the time axis, and an assumption of separation is not required.

Map out the dynamic structure of planetary phenomena $\lambda\, \psi(\boldsymbol{r}, t)$

Use a rapid analysis approach $\lambda\, \psi(r_{ijk}, t)\ \forall\, i, j, k \ \rightarrow v_{ijk}(t)$
Assess heterogeneity through similarity of $v_{ijk}(t)$; $\forall\, i, j, k$ *to give* B_l *sets*.

Sahel downscaling rain budget maps: $Z(\boldsymbol{r}, t)$

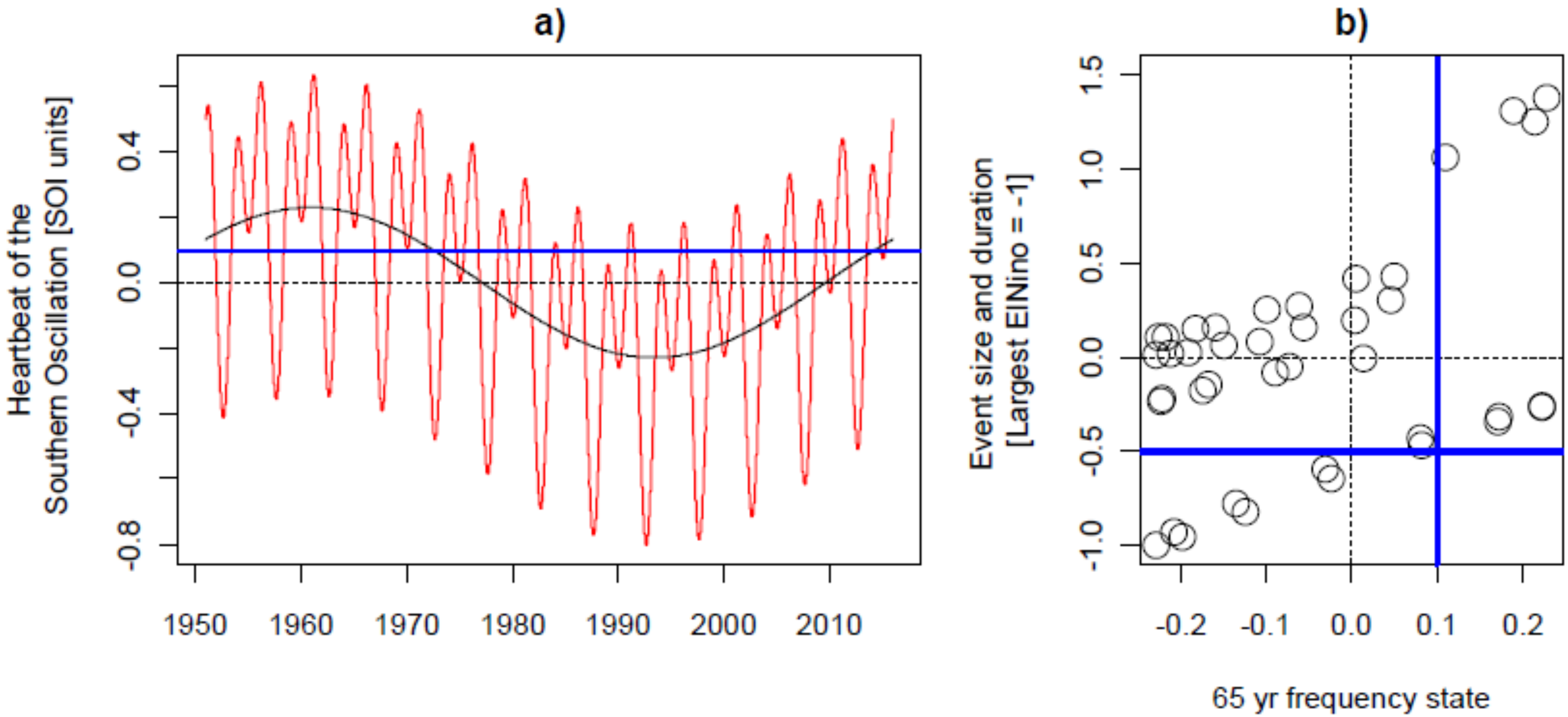
Multiple extensions: Temperature $T(\boldsymbol{r}, t)$, Velocity $v(\boldsymbol{r}, t)$, Biomes $B(\boldsymbol{r}, t)$

Outcome: Greatly improved climate prediction and resolution from ensembles.

The Heartbeat of the Southern Oscillation

The tropical ENSO attractor with 2.5, 5 and 65 year frequency states:

This attractor structure explains prolonged and contracted ENSO event modulation effects large:small El Niño 2:1 (La Niña 12:1) and the 1970's 'change of state' is a nonlinear threshold effect.

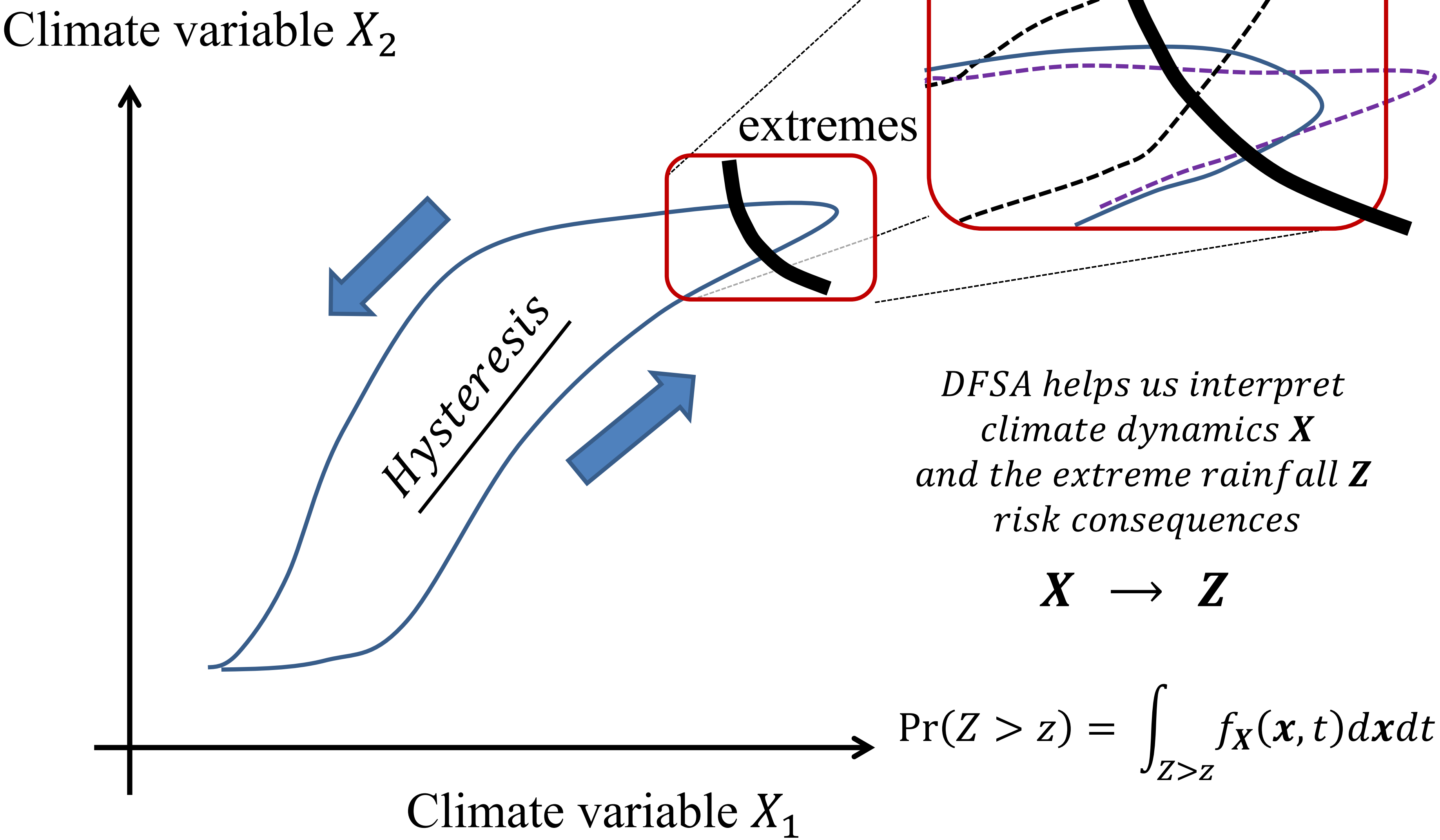


Current conditions indicate the ENSO process is in an unstable warm phase…

The ENSO climate hysteresis may be ‘tearing’

The extreme range may change: implications for Sahel

Here is a visual explanation of extremes…



*DFSA helps us interpret climate dynamics **X** and the extreme rainfall **Z** risk consequences*

$$\boldsymbol{X} \longrightarrow \boldsymbol{Z}$$

$$\Pr(Z > z) = \int_{Z>z} f_{\boldsymbol{X}}(\boldsymbol{x}, t)\, d\boldsymbol{x}\, dt$$

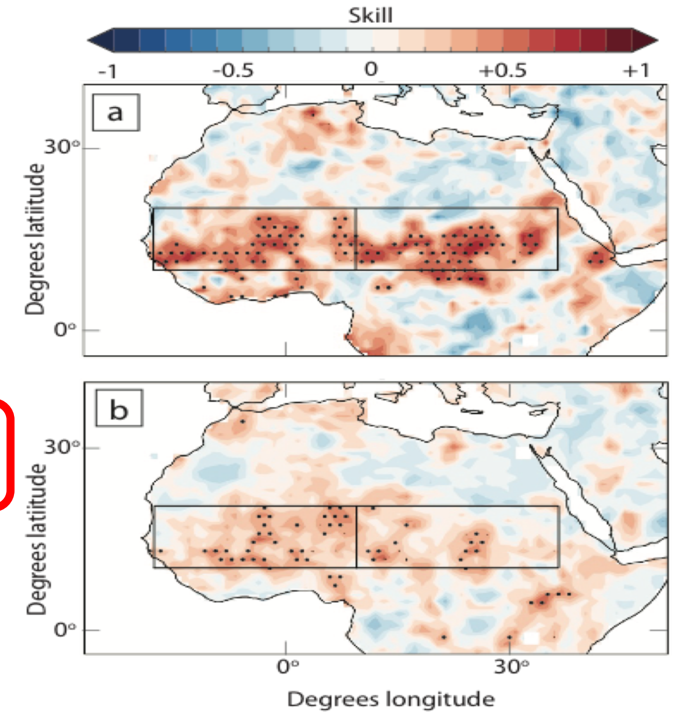
Bruun and Tawn (1998)

Sahel rain budget, downscaling, DFSA and extremes

Sahel downscaling rain budget cyclic plus other decomposition maps:

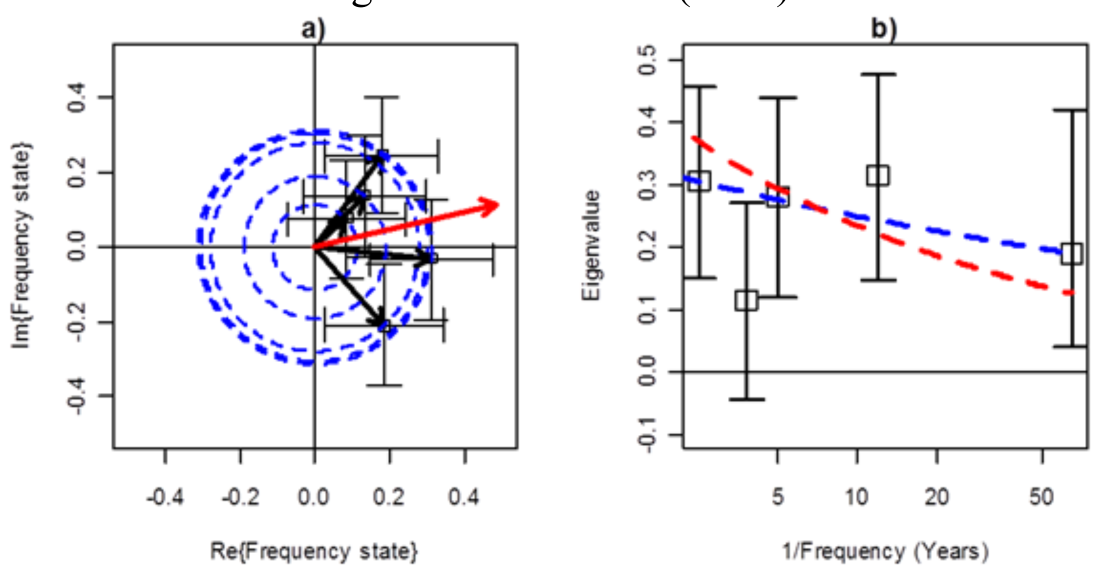
$$Z(\mathbf{r},t) = C_S(\mathbf{r},t) + C_L(\mathbf{r},t) + Trend(\mathbf{r},t) + \eta(\mathbf{r},t)$$

Seasonal *Long term*



Sahel skill assessment (stipples show significant improvement in boxes above). Regional downscaling has shown potential for good predictive skill in these regions. Sheen *et al*. (2017)

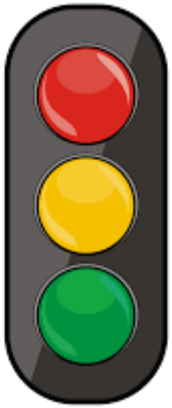
Sahel DFSA
Investigation looks at seasonal, long term and trend decomposition
It is shown here for ENSO
Bruun *et al*., (2017)



Food security and resilience:

Assisting Climate Adaptation with Communities In the African Sahel (ACACIAS) (NERC/DIFD SHEAR proposal (PI: Sheen), prepared with M2D help, waiting result).

‘Traffic light’ risk charts of rain budg



Seasonal, long term modes (DFSA)
1/10 and 1/100 year event extreme
risk level (rainfall and arid).

1954 (wet) vs 1984 (dry) assessed
Spatial DFSA enhances analysis capacity

Food security: In Sahel countries Gross Domestic Product (GDP) is sensitive to agricultural production.

e.g. in Senegal a 20% change in agricultural growth contributes to a 3.5% change in GDP.

A 3.5 bn$ per year is vulnerable to agricultural instability and hence climate volatility in Senegal and Ghana (our focus).

Wider analysis: 30bn$ is at stake in whole Sahel these methods help better understand *resilience* for us all.

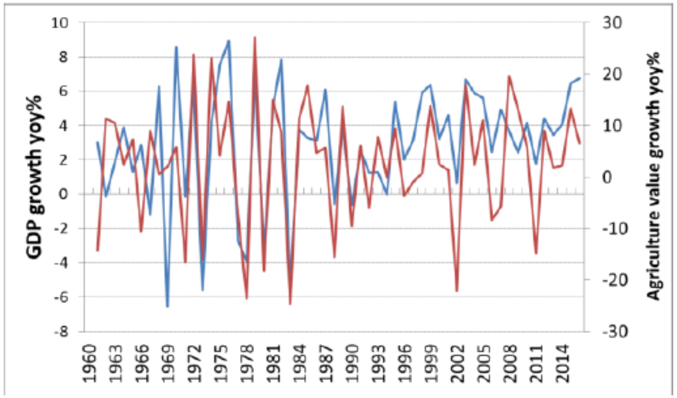


Figure 1: Senegal annual GDP growth (blue) and agricultural growth (red). Note high volatility during 1970-1980s drought period. Variability and correlation are quantified in Table 1. Data from World Bank, 2018.

Summary

Coffee cup science   Fractals

- DFSA enables the accurate investigation of low amplitude and low frequency climatic modes
- It complements and extends current methods
- Multiple applications: ENSO, teleconnection, downscaling, …
- Focus here: Resilience and food security to extreme climate changes
- Improved decision making with sophisticated yet simple models