Describing the ocean variability as an atmospherically-modulated oceanic "chaos"

T. Penduff
CNRS - IGE

Thanks to
B. Barnier, L. Bessières, J.M. Molines, J.M. Brankart, L. Terray, W.K. Dewar, S. Leroux, G. Sérazin, O. Narinc, F.E. Yan, B.I. Garcia-Gomez, G. Fedele, A. Colella, S. Pierini, S. Cravatte, W. Llovel, A. Hogg, L. Zanna …

OCCIPUT project
OceaniC Chaos – ImPacts, strUcture, predicTability

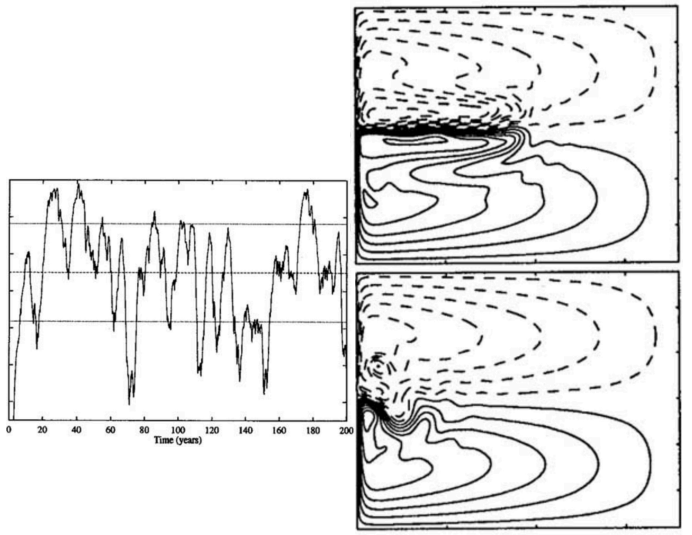
Sea level chaotic variability
(T>2 yr, L>1200 km)
From -5 cm to +5 cm

Idealized models : Low-Freq (LF) Chaotic Intrinsic Variability (CIV)

Constant/seasonal wind forcing : Increased *Re* ➔

Spontaneous emergence of **LF CIV (1-10 year)**

Dijkstra & Ghil 2005; Sushama et al 2007; etc



- **Western boundary current systems**

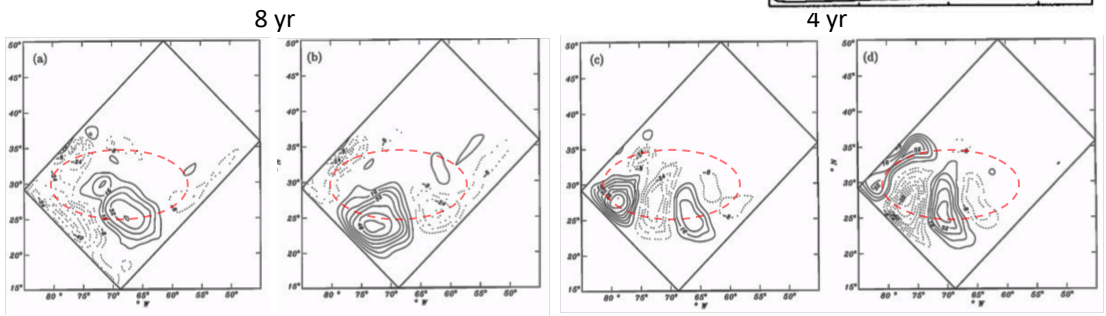
  - Surface jets, DWBC, Recirculation gyres (shape, strength)

    Dewar 2003; Spall 1996; etc

  - Mode waters (low-PV pool volume)

  - Rossby modes

    Hazeleger & Drijfhout 2000; etc

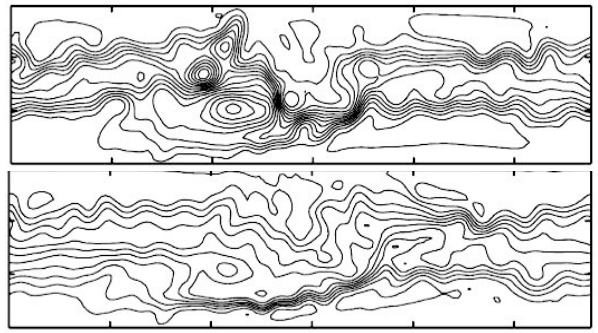


- **ACC** *Current / eddy / topography interactions*

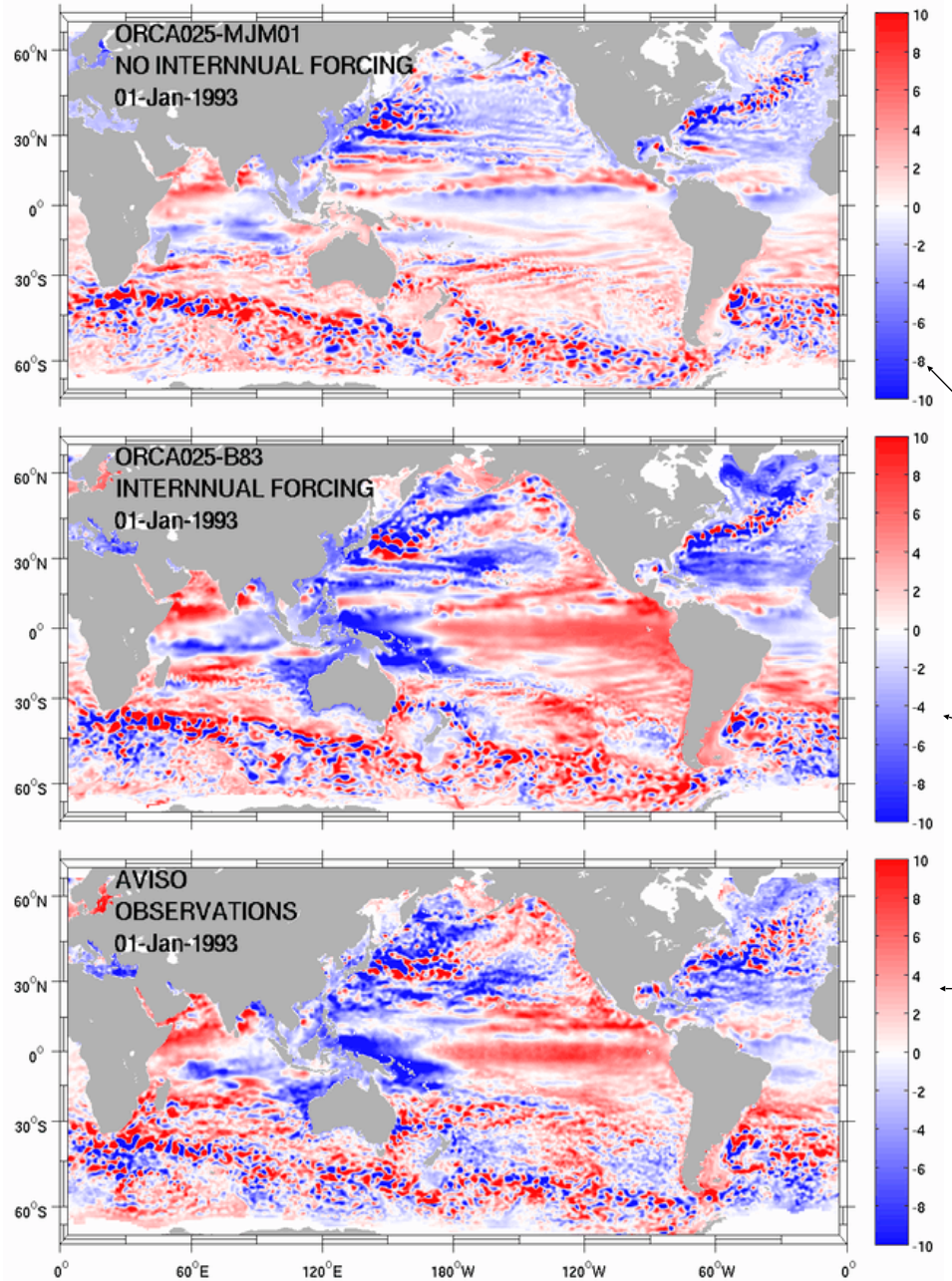
  - path, transport

  - jet jumping & migration

Hogg & Blundell 2006; Thompson & Richards 2011; Chapman & Hogg 2013; etc



Global PE model : Low-Freq (LF) Chaotic Intrinsic Variability (CIV)



Imprints of CIV & atmospheric variability **in a global OGCM?**

Keeping the link with **observations** and **idealized & theoretical** work

Penduff et al (2011)
Gregorio et al (2015)
Serazin et al (2015)

Interannual SLA anomalies (LF CIV) in

NEMO ¼° driven by:

- Seasonal forcing

1) Comparable to idealized models in structures & scales

2) Comparable in amplitude (mid-lat & ACC) to :

- Fully-variable forcing

Altimeter observations

Assessing roles of CIV & atmospheric variability in the ocean

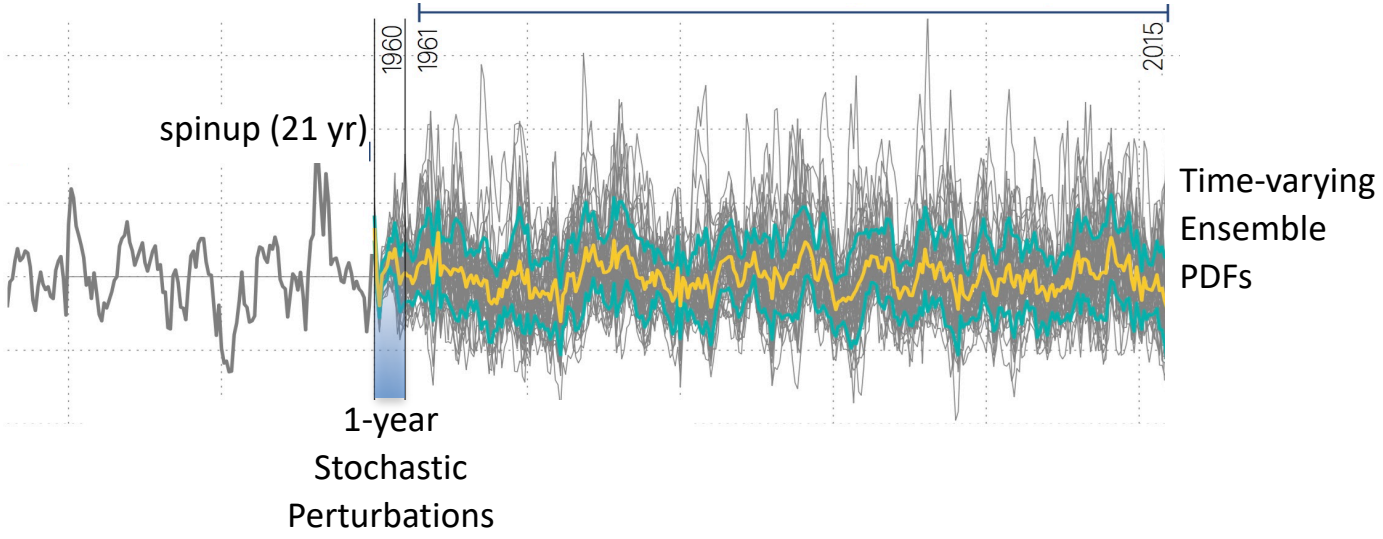
OCCIPUT ENSEMBLE OCEAN SIMULATION https://meom-group.github.io/projects/occiput/

50 members, **same realistic forcing** (~ERA-interim)

Initial perturbations → **56** year integration (1960-2015)

Global ocean-sea ice

NEMO model. Δ = 1/4°



Penduff et al (2014)
Bessières et al (2017)
Leroux et al (2018)

1. Separating CIV and atmospherically-forced variability

OCCIPUT ENSEMBLE OCEAN SIMULATION

https://meom-group.github.io/projects/occiput/

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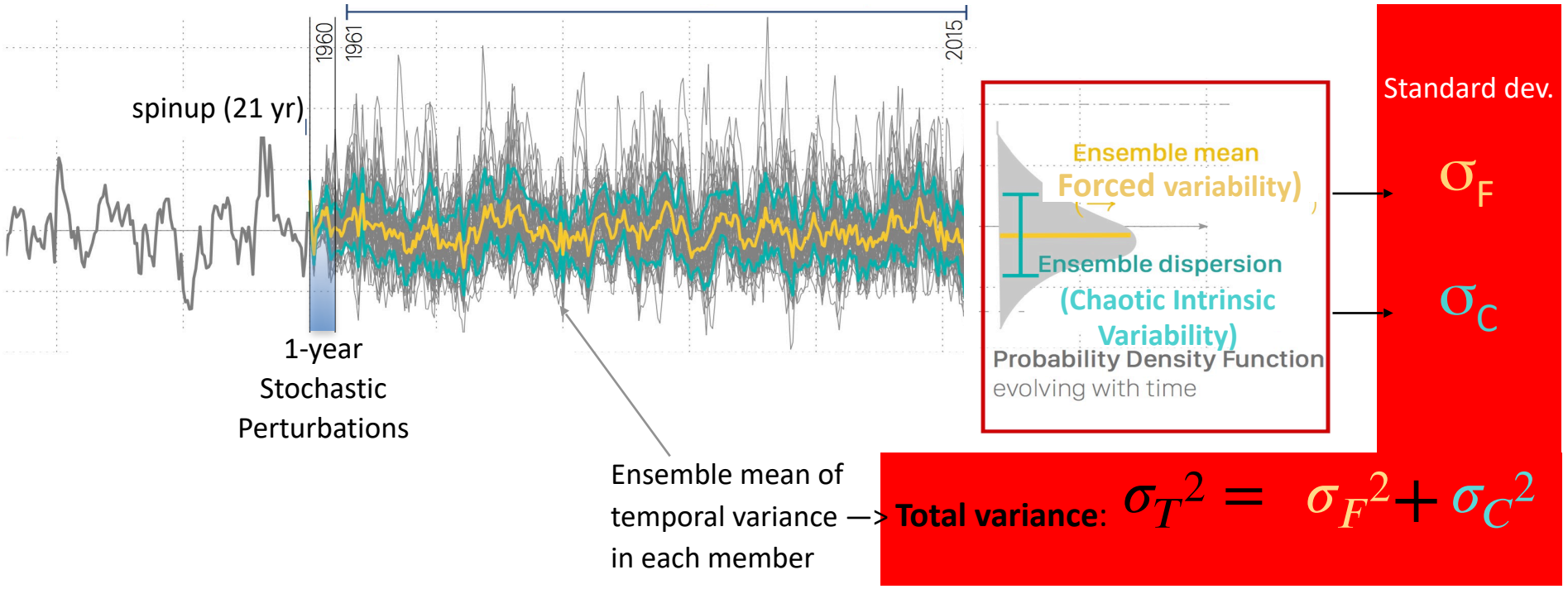


Penduff et al (2014)
Bessières et al (2017)
Leroux et al (2018)

I.
Separating Forced / chaotic variability

$OHC_{0\text{-}700m}$: Forced & Chaotic 2-18 yr variability

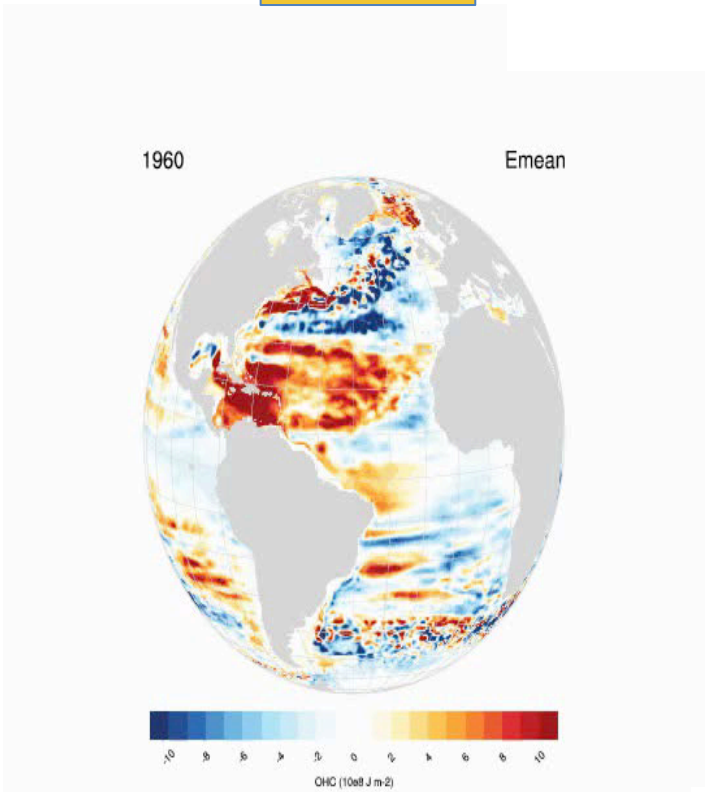
$$OHC = \rho.C_p \int_{-700}^{surf} T(z).dz$$ *yr = 1980,2010 member = 1,50*

Member 5
Total variability

Forced variability

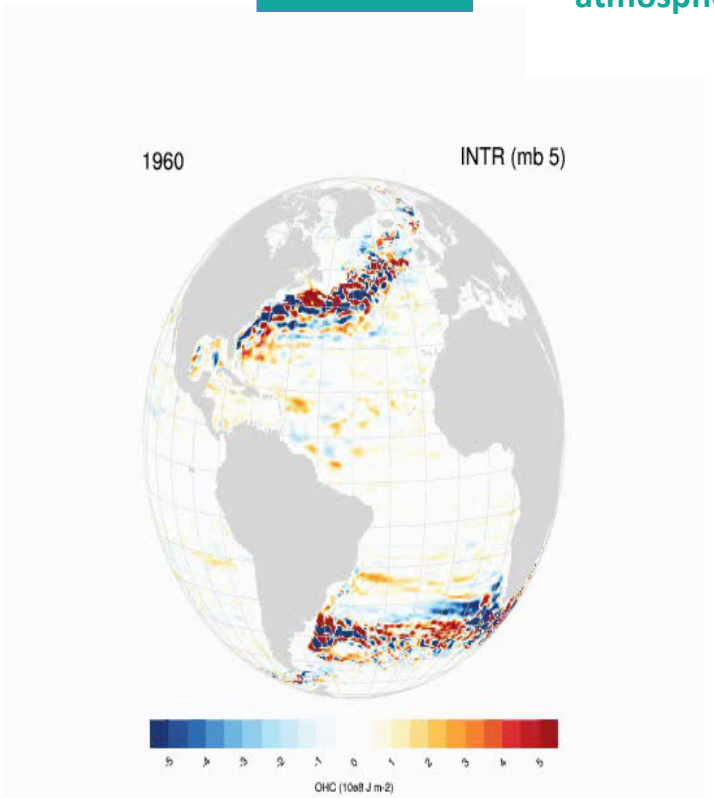
Chaotic variability

Zero in 2° simulations. Large potential impact on atmosphere/climate



-10 0 +10

$10^8 J/m^2$



-5 0 +5

Serazin et al (GRL 2017)

$OHC_{0\text{-}700m}$: Forced & Chaotic 2-18 yr variability

$$OHC = \rho.C_p \int_{-700}^{surf} T(z).dz$$

yr = 1980,2010 member = 1,50

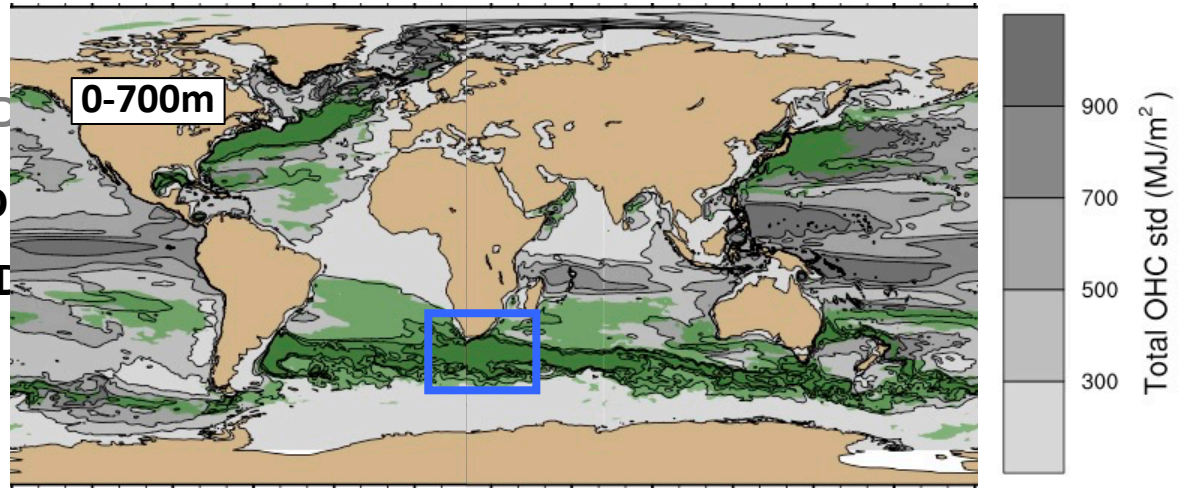
Emean (Tstd) → Total STD

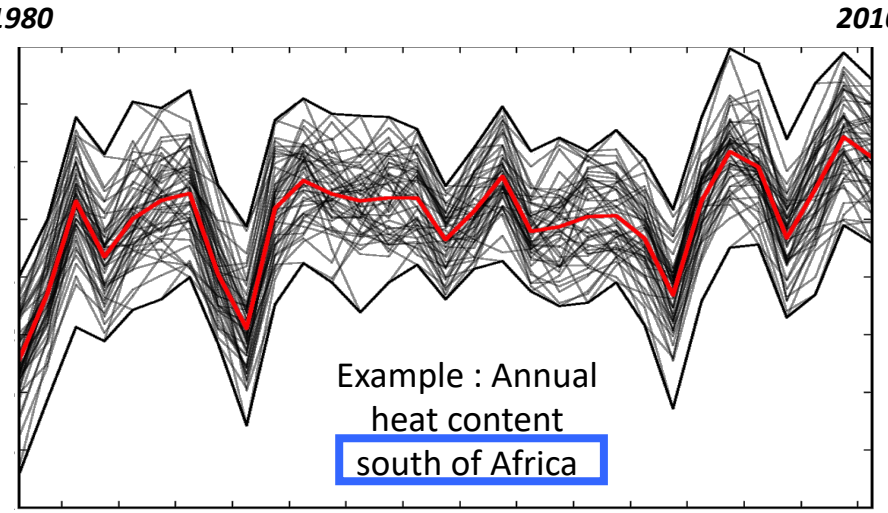
Tstd (Emean) → **Forced STD**

Tmean (Estd) → **Chaotic STD**

Green: Chaotic exceeds Forced

Limited Potential Predictability





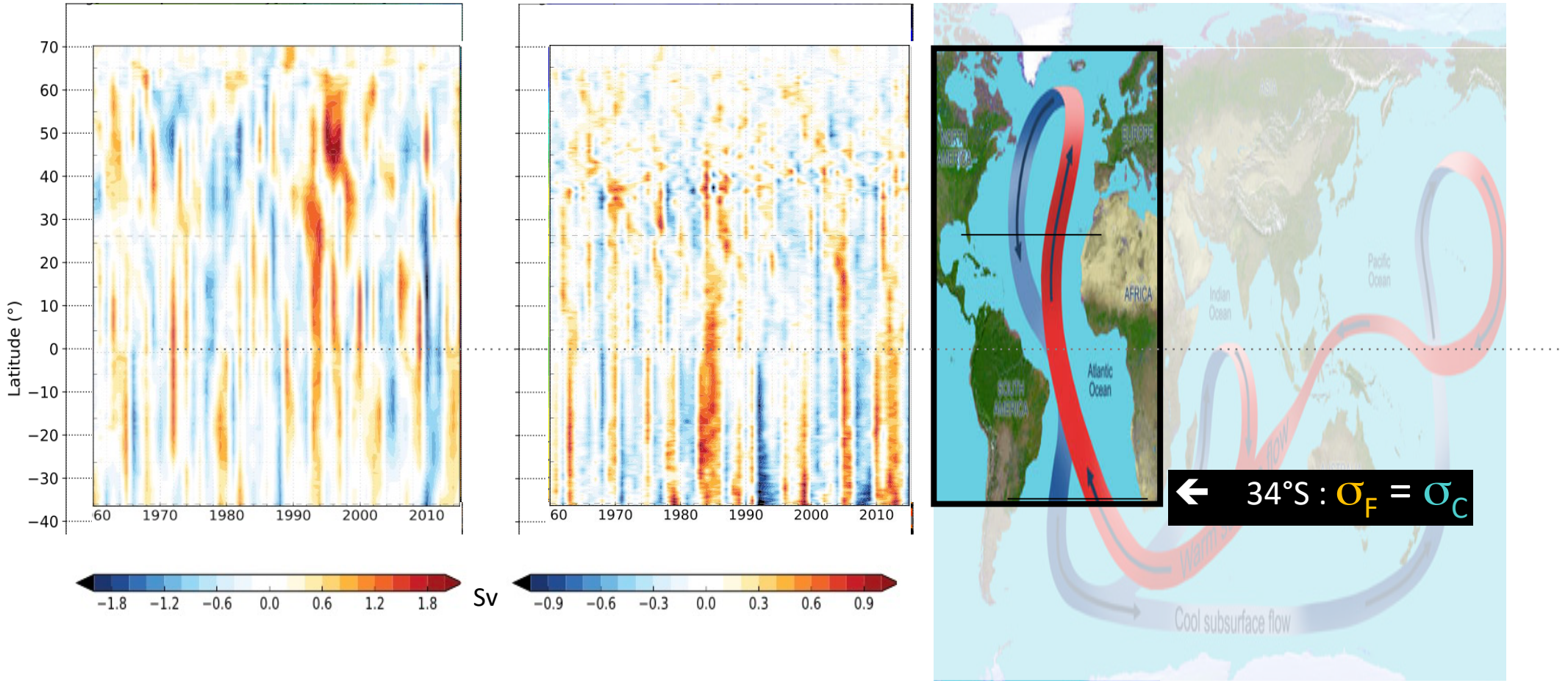
Serazin et al (GRL 2017)

Atlantic MOC : yearly hovmoellers

Member 5
Total variability

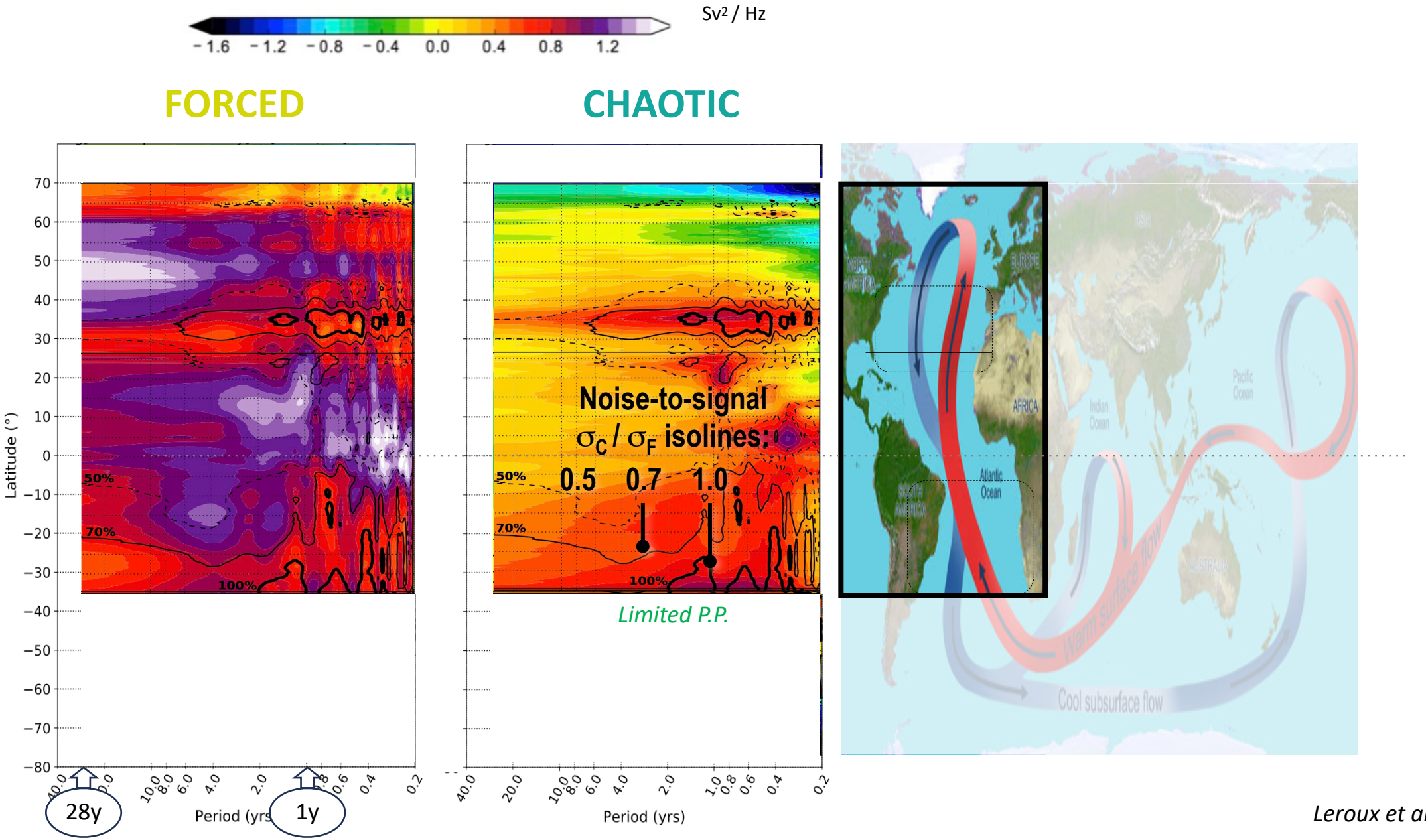
FORCED

CHAOTIC



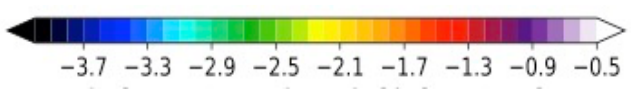
Leroux et al (Jclim 2018)

Atlantic MOC : spectra



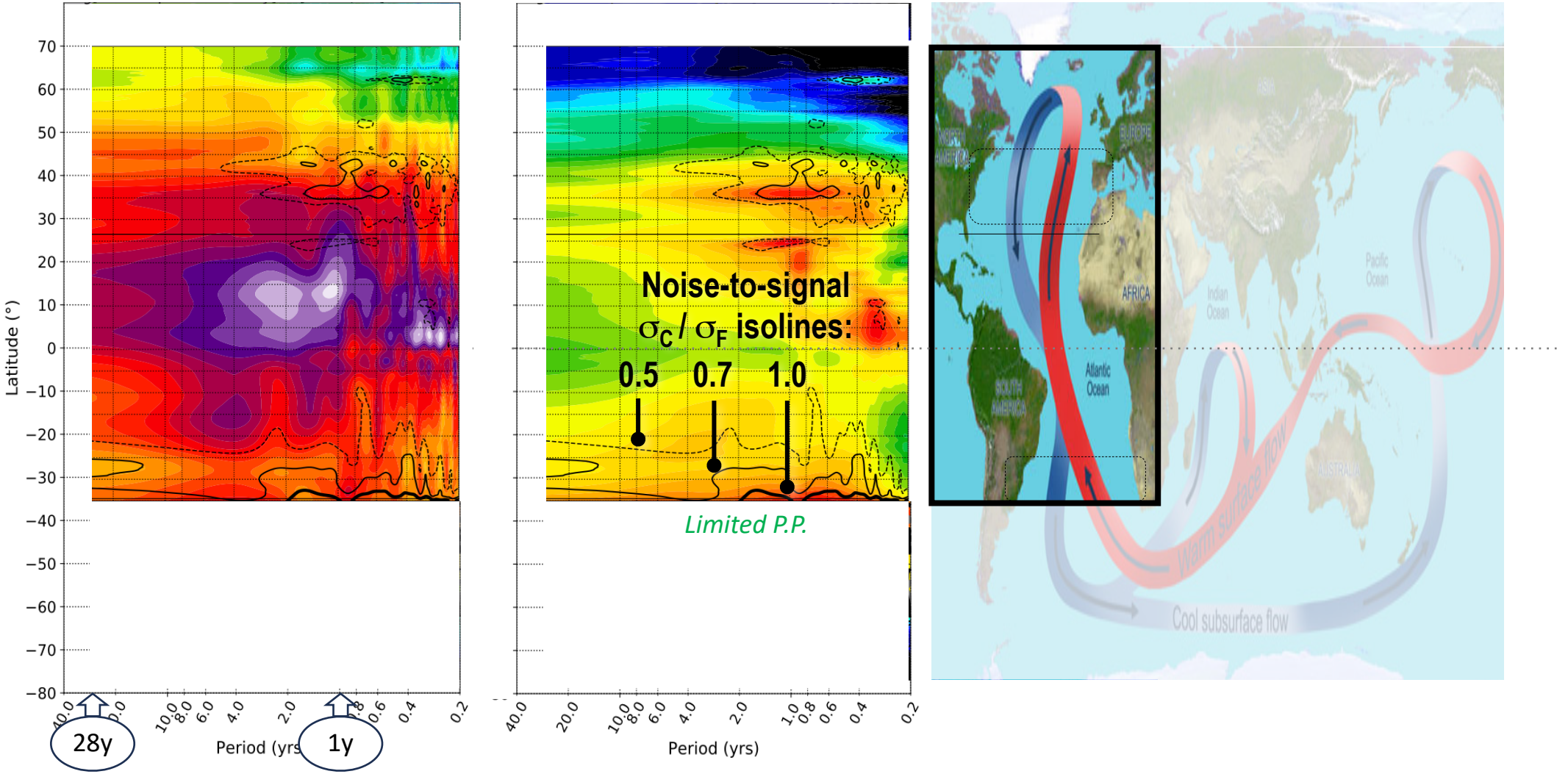
Leroux et al (Jclim 2018)

Atlantic MHT : spectra

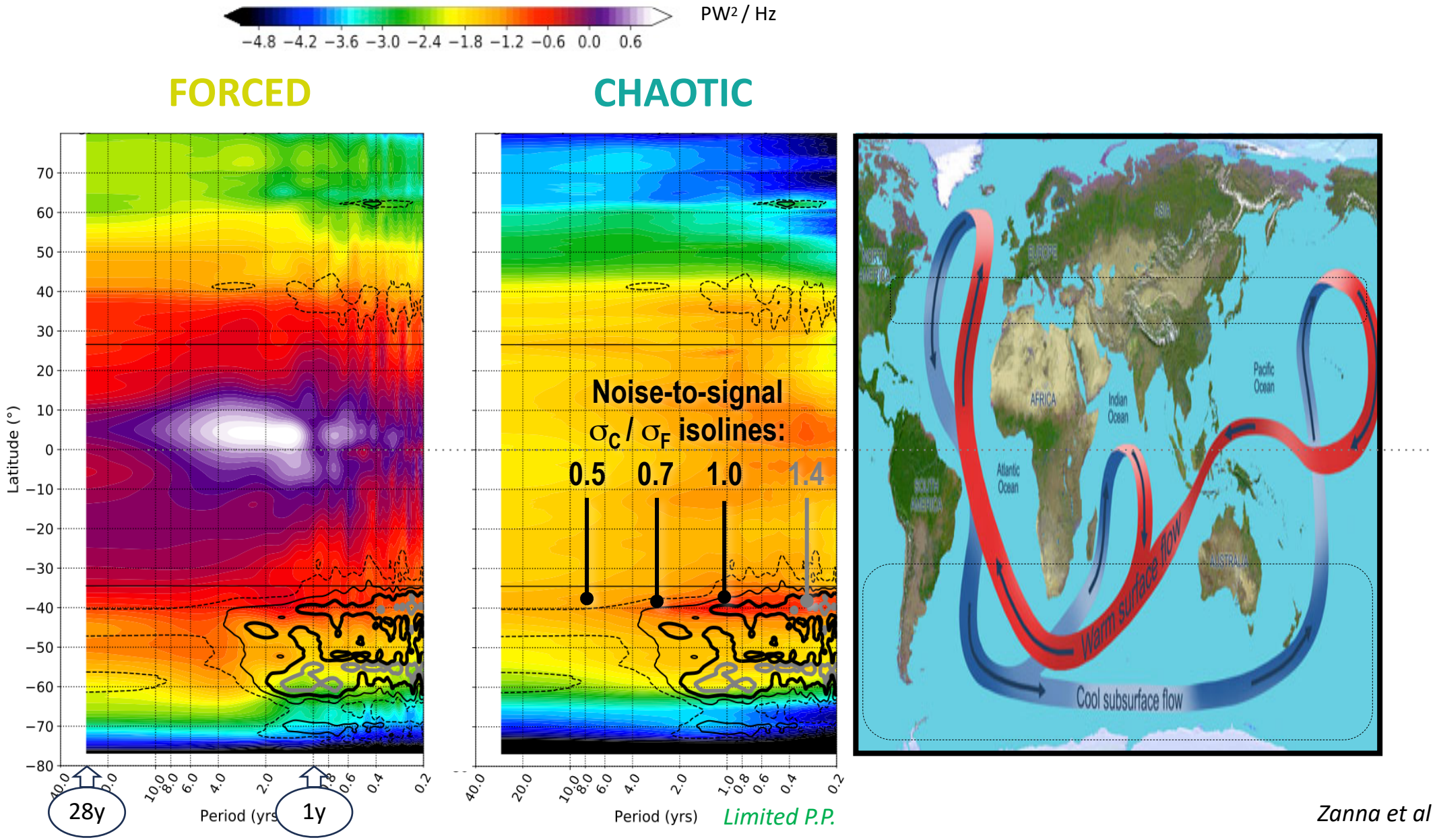


PW² / Hz

FORCED **CHAOTIC**



Global MHT : spectra



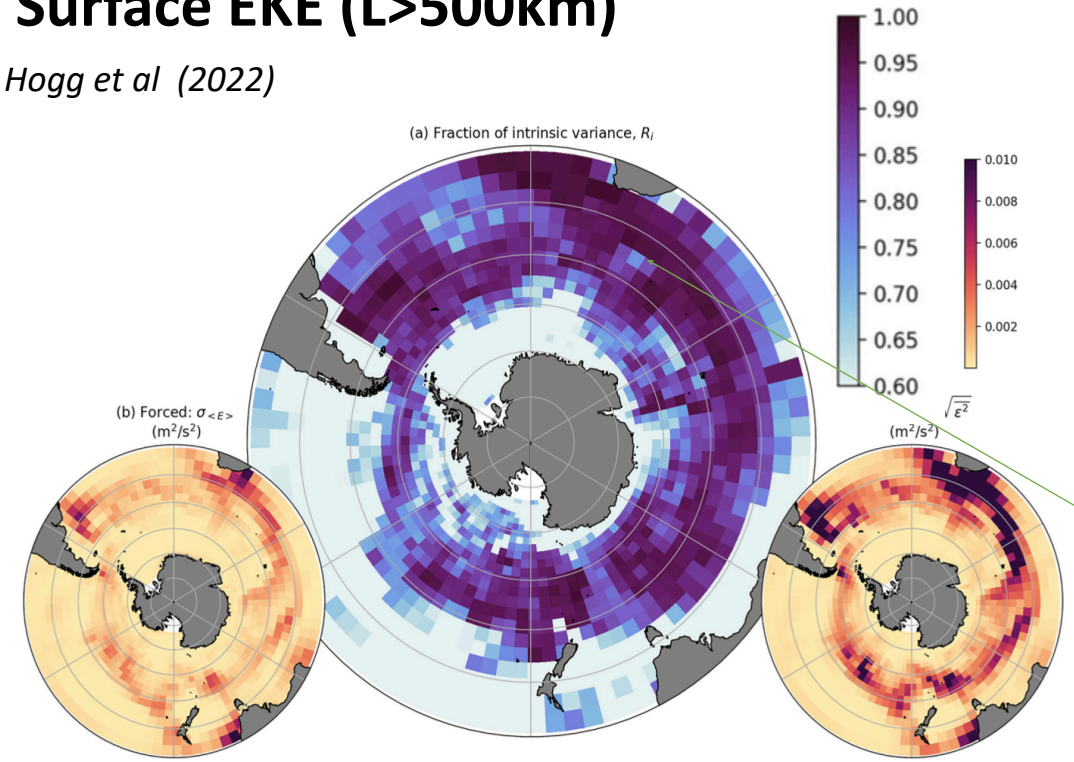
Zanna et al (QJRMS 2018)

Other indices: Forced & Chaotic 2-18 yr variance ratios

$$\frac{\sigma_C^2}{\sigma_T^2}$$

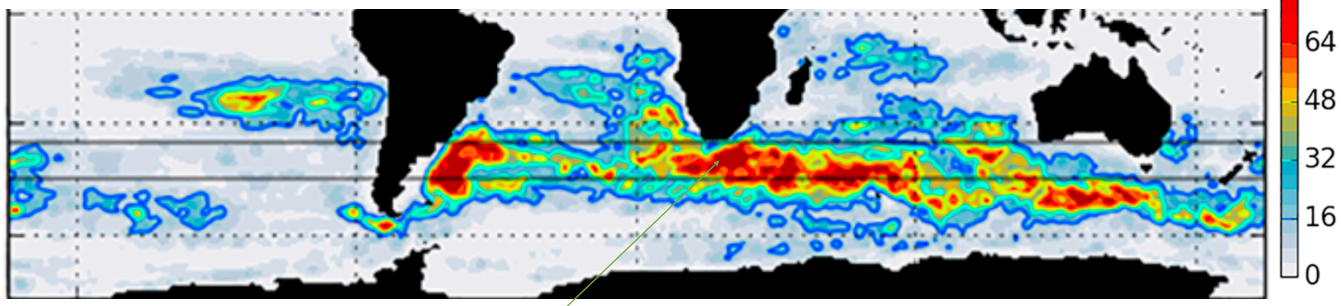
Surface EKE (L>500km)

Hogg et al (2022)



Air-sea CO_2 flux (L>500km)

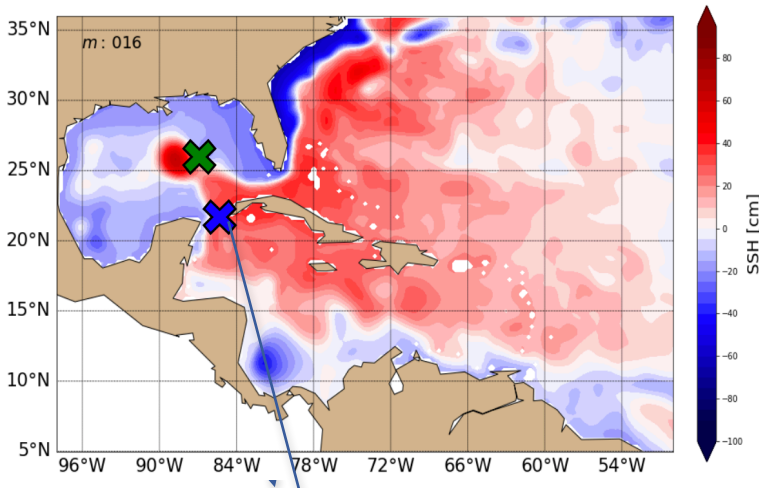
Gehlen et al (2020)



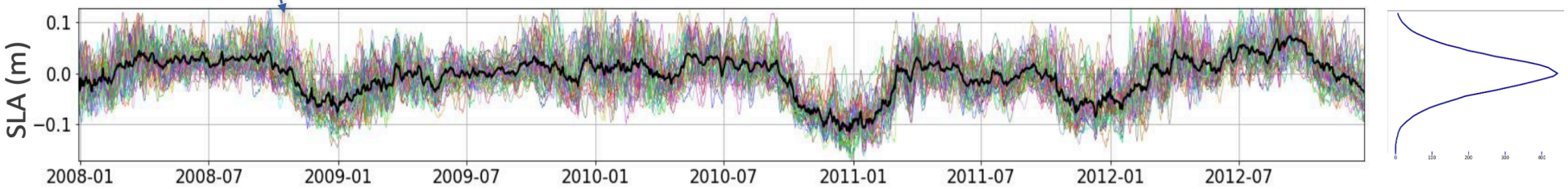
Limited P.P.

OK. But **can we separate CIV and forced variability?**

[daily] SSH



Reasonable



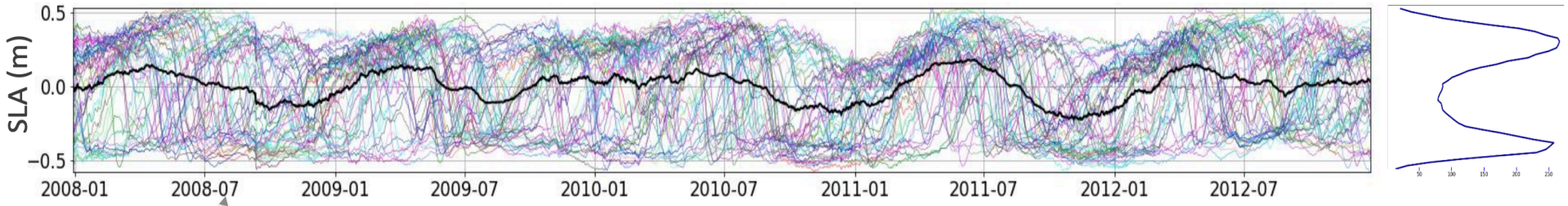
***Gaussian** e-PDFS : E-mean & E-std are sufficient*

➔ ***Variability ~ deterministic signal + gaussian noise***

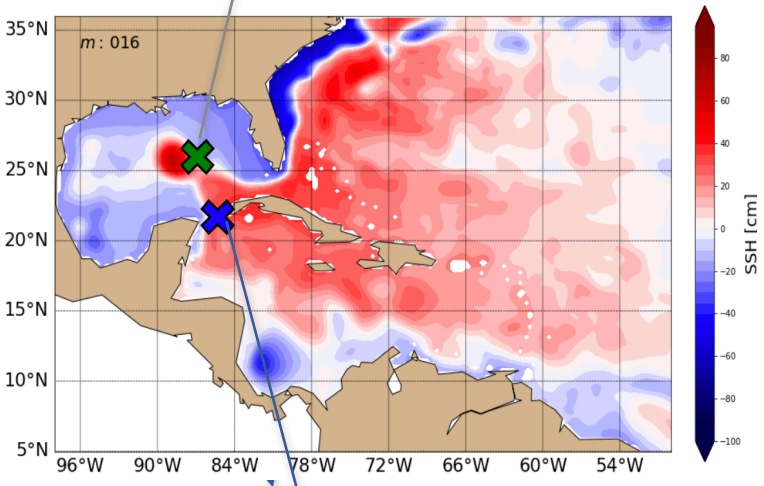
Garcia-Gomez 2020

OK. But **can we separate CIV and forced variability?**

Questionable



[daily] SSH

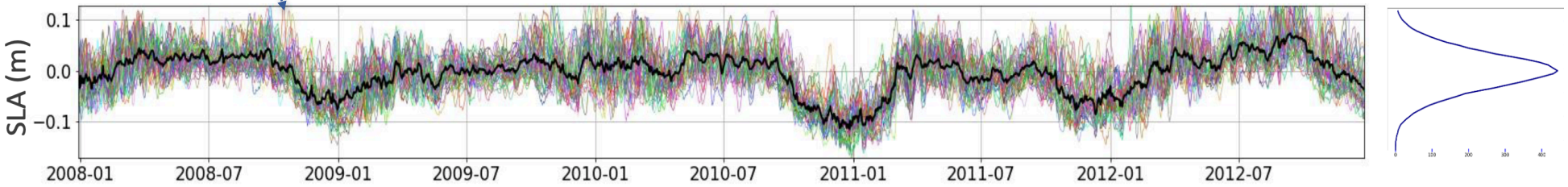


***Non Gaussian** : E-mean & E-std are not sufficient*

➔ ***Non-autonomous Dynamical Systems***

The atmosphere modulates the oceanic « chaos »

Reasonable



***Gaussian** e-PDFS : E-mean & E-std are sufficient*

➔ ***Variability ~ deterministic signal + gaussian noise***

Garcia-Gomez 2020

II.
No Forced / chaotic separation: Non-autonomous DS viewpoint

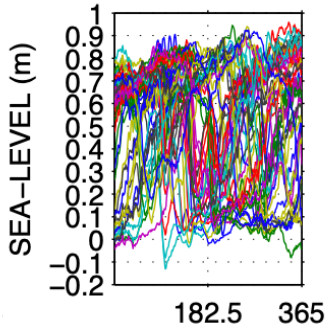
1. Analog **predictability**

Non-autonomous DS
Fully-variable forcing

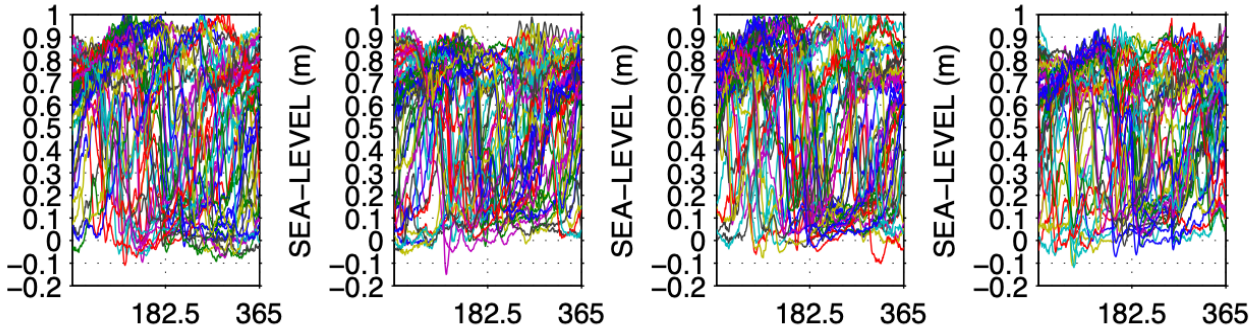
Boer 2000

(attempt)

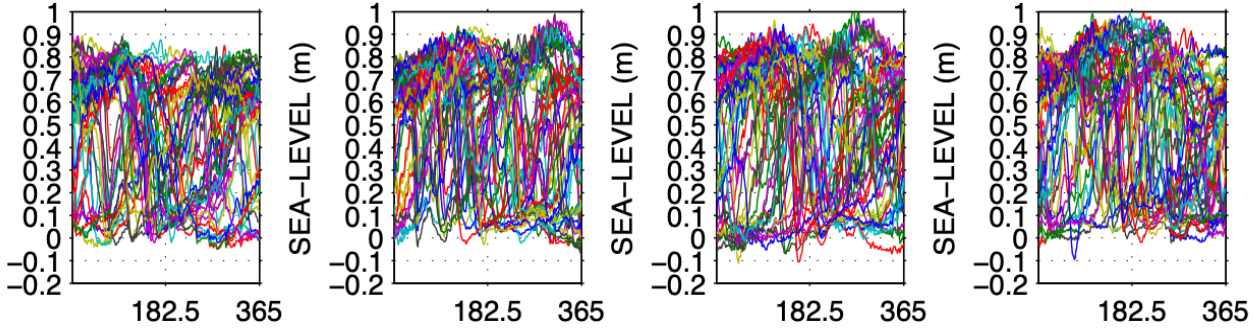
50 members
x 9 years (2004-2012)
= 450 one-year daily
timeseries of sea level η



2004

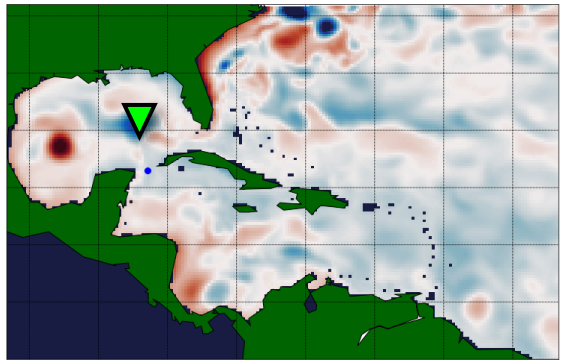


2005 2006 2007 2008



2009 2010 2011 2012

[daily] SSH in the Loop Current



15-day LC predictability?

Dependance on:

- Initial state
- Initial day

1. Analog **predictability**

Non-autonomous DS
Fully-variable forcing

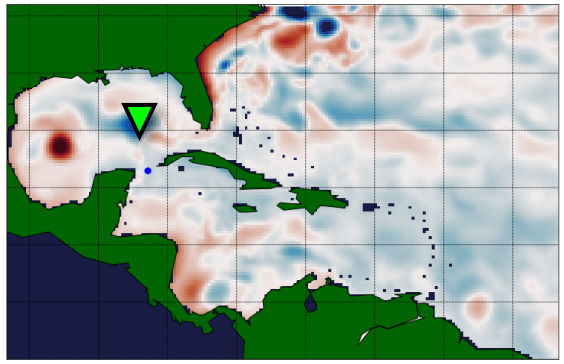
Boer 2000 (attempt)

- 15-day period within each year : d_i … d_i+15
- 50 x 9 = 450 sea level timeseries : $\eta(d_i)$ … $\eta(d_i+15)$
- Sort and bin all time series by initial state $\eta(d_i)$
- 15-day separation factor Δ between initially close members

15-day shift

$$\Delta(d_i, \eta(d_i)) = \left\langle \frac{\delta(d_i + 15)}{\delta(d_i)} \right\rangle_{Pairs}$$

[daily] SSH in the Loop Current



15-day LC predictability?
Dependance on:
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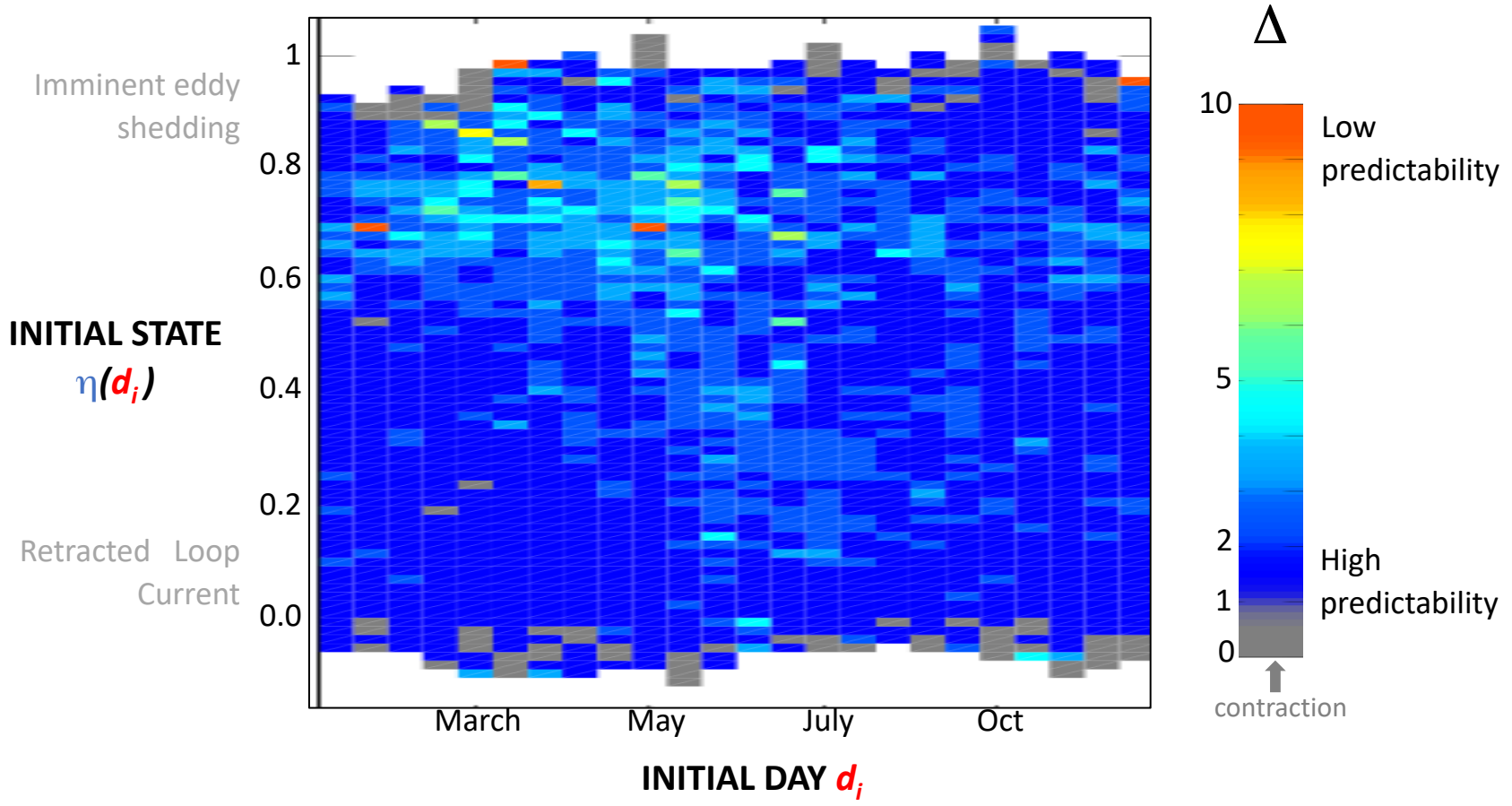
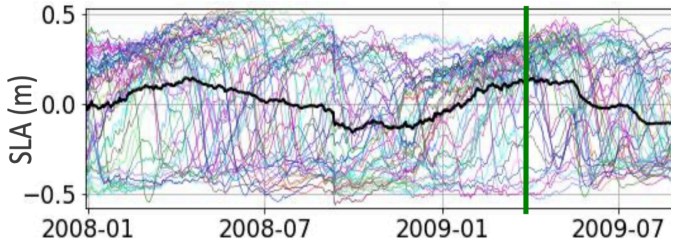
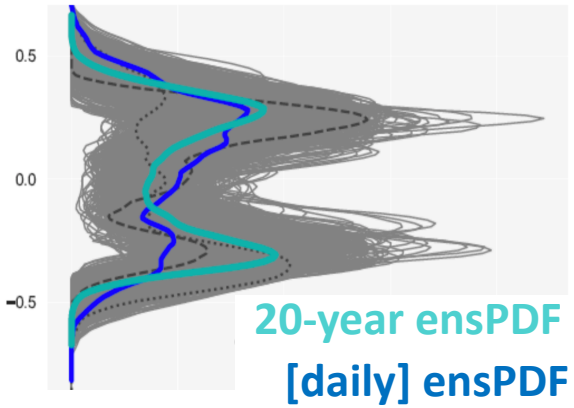


2. Forcing modulates chaotic attractor

Non-autonomous DS
Fully-variable forcing



[daily] SSH in the Loop Current



20-year ensPDF = Q

[daily] ensPDF = P

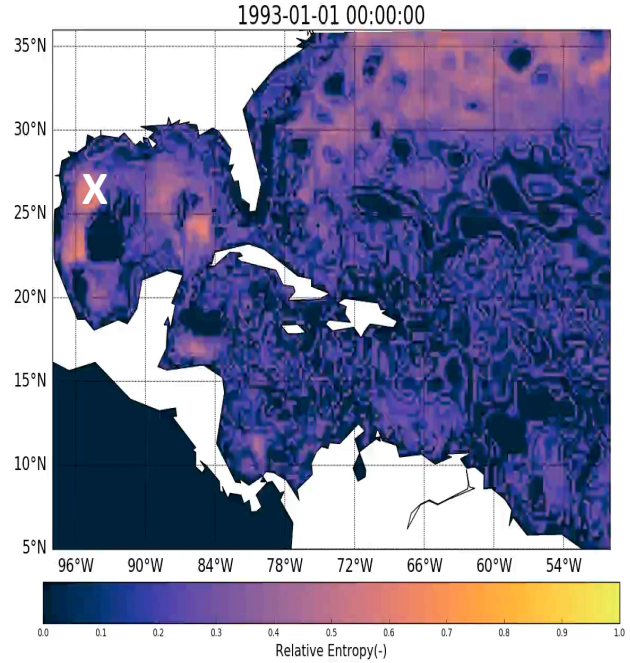
Deciles : N=10

$$E_{ref}(x,y) = -\sum_{i=1}^{N} Q_i.ln(Q_i)$$

$$E_{daily}(x,y,t) = -\sum_{i=1}^{N} P_i.ln(P_i)$$

[daily] $S(x,y,t) = \frac{E_{daily}}{E_{ref}}$

Normalized entropy S : [daily] atmospheric constraint on the oceanic chaos



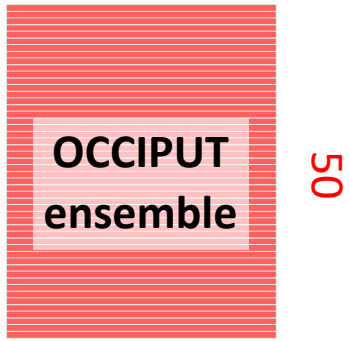
S=0
Strong constaint

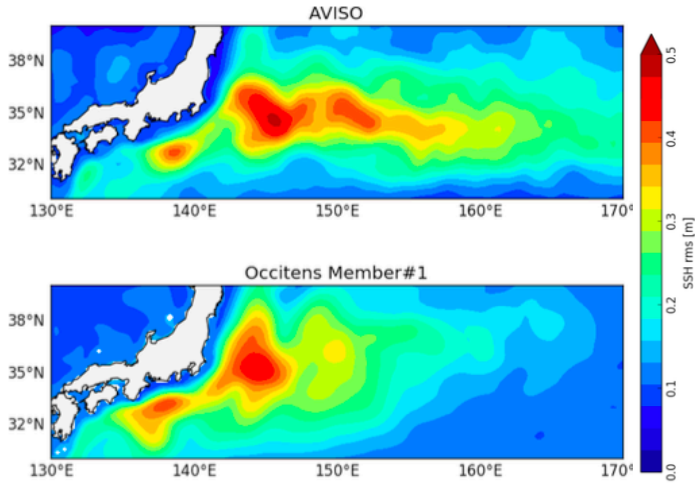
S=1
Weak constraint

Garcia-Gomez 2020

3. Forcing modulates chaotic attractor in phase space

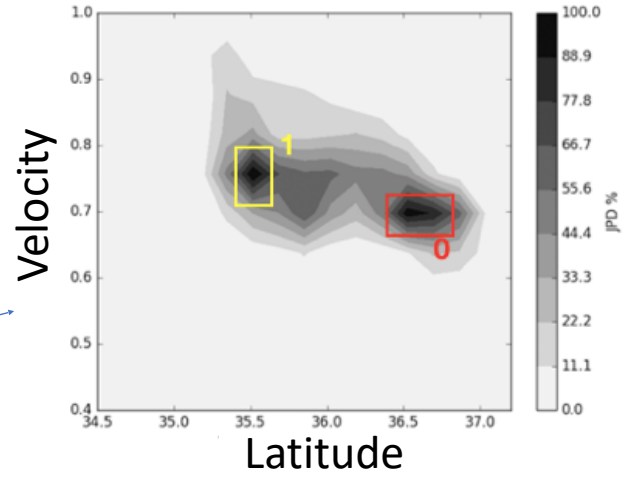
Non-autonomous DS
Fully-variable forcing





Kuroshio Velocity: **Vel**(time,member)
Latitude: **Lat**(time,membler)

50-member 36-year
Joint Probab. Distrib.: BIMODAL



Fedele et al 2021

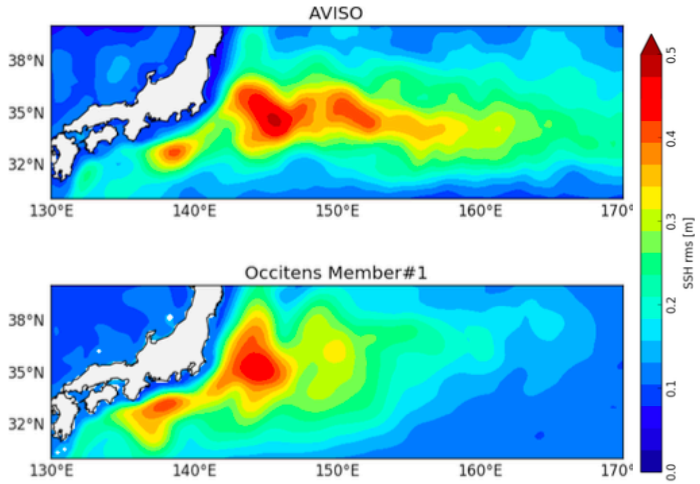
3. Forcing modulates chaotic attractor in phase space

Non-autonomous DS
Fully-variable forcing

OCCIPUT ensemble

50

1980 36 years **2015**



Kuroshio Velocity: **Vel**(time,member)
Latitude: **Lat**(time,membler)

Quasi-autonomous DS
Climatological forcing

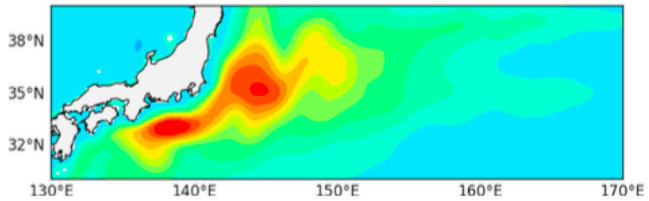
Climatol. pseudo-ensemble

50

36 years

330-year climatological run (same model)

Yr 0 **Yr 330**



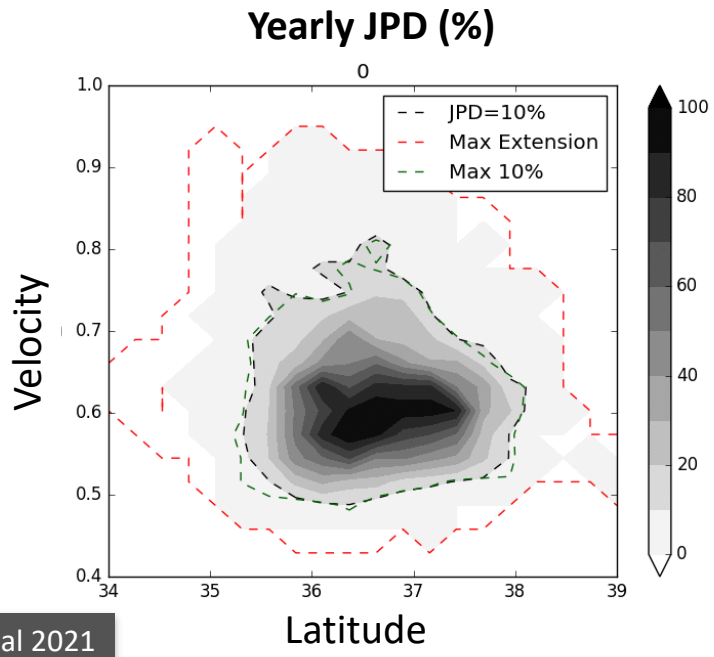
Fedele et al 2021

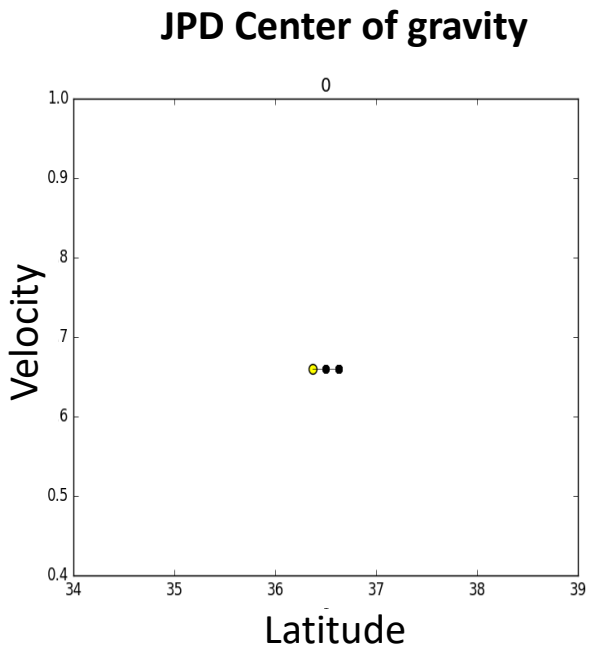
3. Forcing modulates chaotic attractor in phase space

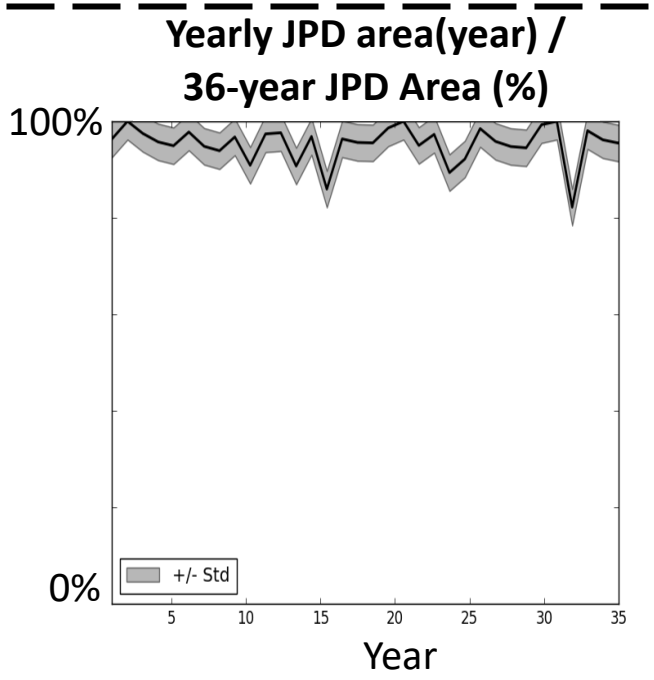
Non-autonomous DS
Fully-variable forcing

Quasi-autonomous DS
Climatological forcing

System's attractor is barely affected by (cyclo) stationary forcing





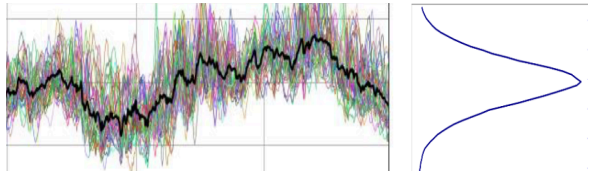


Fedele et al 2021

Conclusion: ocean variability (& predictability)

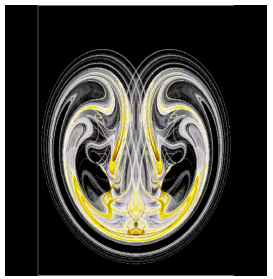
= **Forced variability** + **CIV (in the non linear regime)** → Separation?

- Simple. Classical (e.g. IPCC). OK if gaussian E-PDFs
- **CIV** affects most ocean climate indices (up to basin-scale, up to 100 years)
- **CIV** locally > **forced variability** → reduces potential predictability



= **Atmospherically-modulated CIV**

- **Atmosphere** modulates the **ocean's chaotic attractor**
- Valid if Gaussian or not. More rigorous (DST) → predictability, bifurcations…
- Challenging (OGCM size) but promising (understand dynamics, interpret obs.)



Lorenz Random attractor (Chekroun et al, 2011)

OCCIPUT papers : https://meom-group.github.io/projects/occiput/

OCCIPUT outputs : Thierry.Penduff@cnrs.fr

Absent tomorrow :
glad to chat on Wednesday