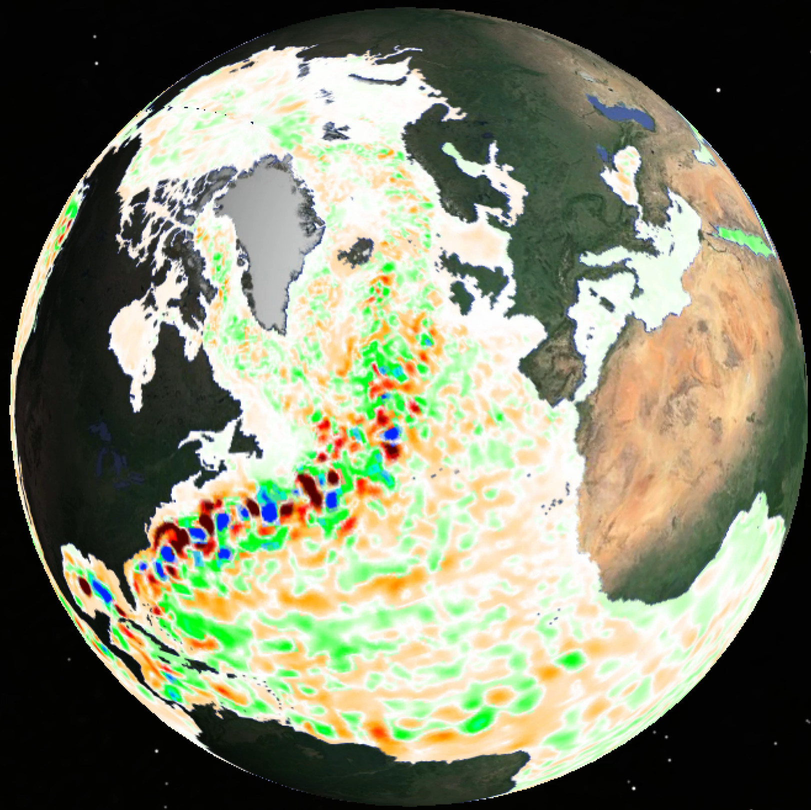
Characterizing the chaotic variability of the global eddying ocean and its atmospheric modulation

sea-level chaotic variability (-20/+20cm)
(seasonally-forced NEMO ¼°simulation)



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S. Grégorio[1], I. Benabicha[1],
B. Barnier[1], J.M. Molines[1]

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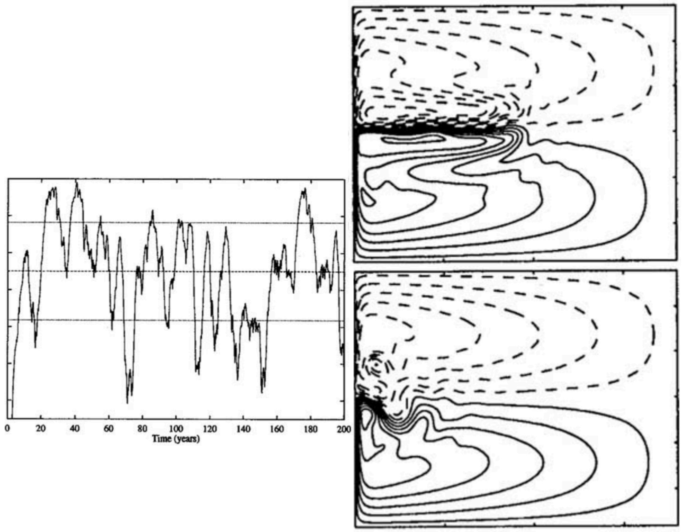
Low-Freq. Chaotic Intrinsic Variability (LFCIV): idealized

Constant/seasonal wind forcing : Increased *Re* ➔

Spontaneous emergence of **LFCIV** **(1-10 year)**

Dijkstra & Ghil 2005; Sushama et al 2007



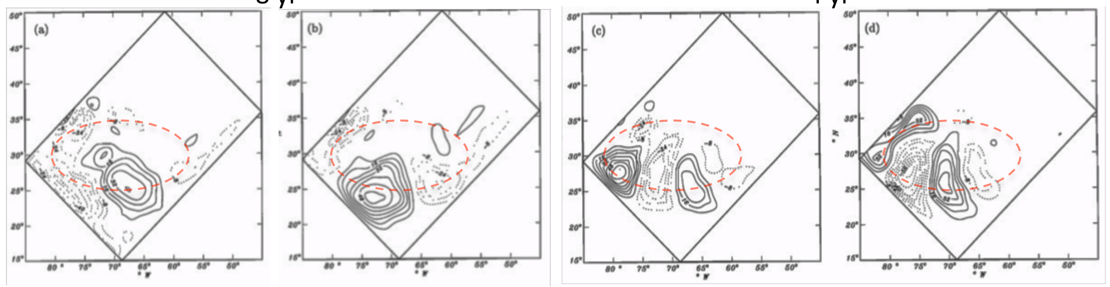
- **Western boundary current systems**
  - Surface jets, DWBC, Recirculation gyres (shape, strength)

    Dewar 2003; Spall 1996; etc
  - Mode waters (low-PV pool volume)
  - Rossby modes

    Hazeleger & Drijfhout 2000

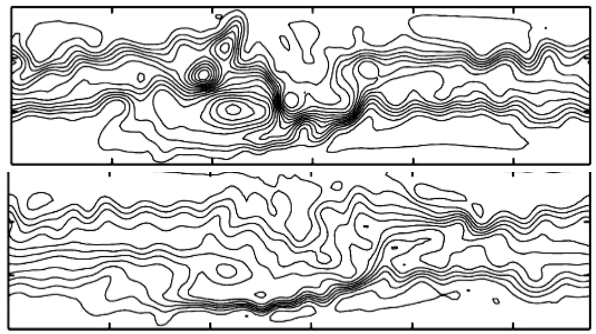
8 yr

4 yr



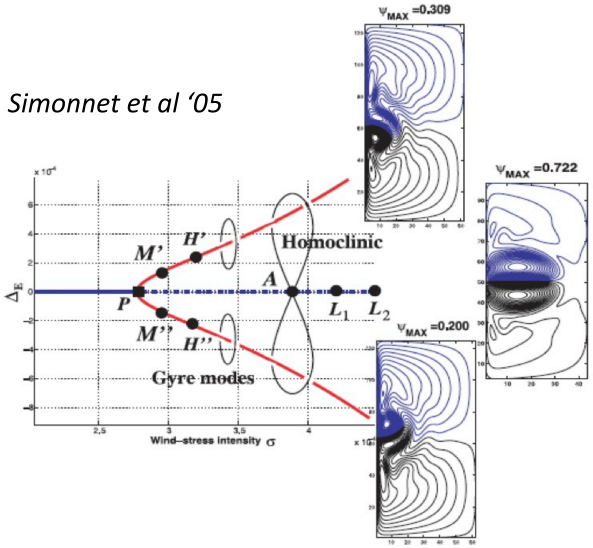
- **ACC** *Current / eddy / topography interactions*
  - path, transport
  - jet jumping & migration

    Hogg & Blundell 2006; Thompson & Richards 2011; etc



LFCIV: 2 main nonlinear paradigms

Simonnet et al '05



Re

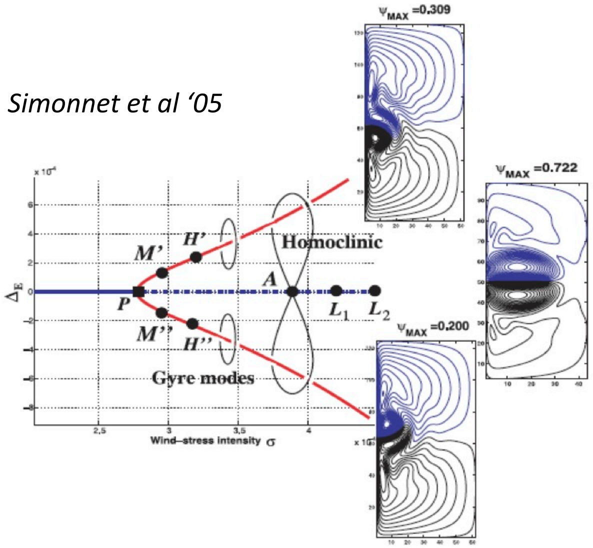
1. **Spontaneous transitions between large-scale equilibria**

   (DST, bifurcation studies, etc : e.g. Dijkstra and Ghil 2005, and ref. therein)

- ✓ **Mean APE field** —*Somehow*→ Low-freq intrinsic variability
- ✓ *Re* number increases → Chaotic transitions
- ✓ **Mesoscale eddies** provide ambiant «noise» but **are not crucial**

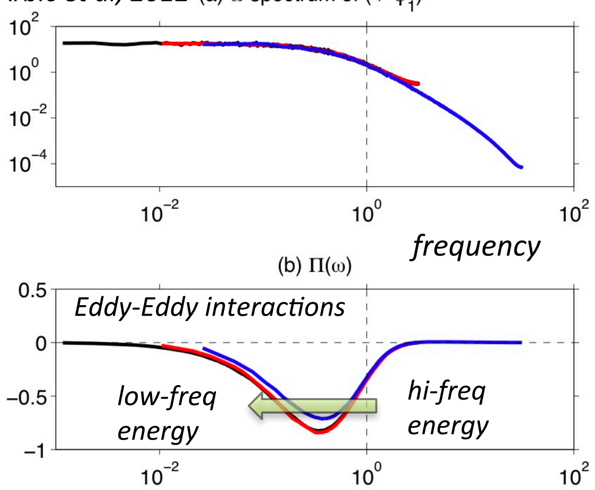
LFCIV: 2 main nonlinear paradigms

Simonnet et al '05



laminar → *mesoscale eddies*

Arbic et al, 2012



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2. **Direct eddy forcing**

   (PV fluxes, inverse cascades : e.g. Berloff et al 2007, Arbic et al 2012, Spall 1996)

   ✓ Mean APE field —***Eddies***→ Low-freq intrinsic variability

   ✓ *Re* number increases ——→ Stronger eddy fluxes

   ✓ **Mesoscale eddies** rectify the flow and **drive LFCIV**

LFCIV: 2 main nonlinear paradigms

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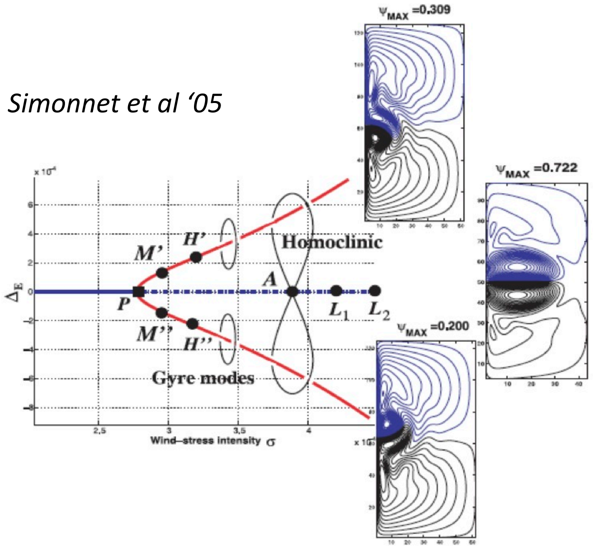
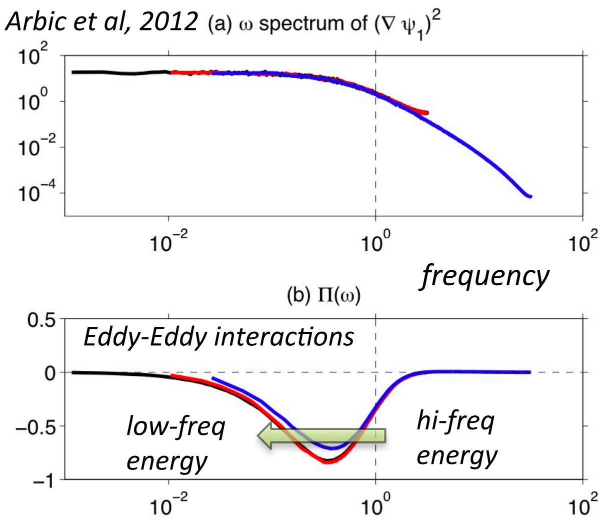


→ *Re*

laminar → mesoscale eddies

Arbic et al, 2012



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LFCIV in a global, realistic, eddying OGCM ?
(imprints, strength, origin, implications)

Outline

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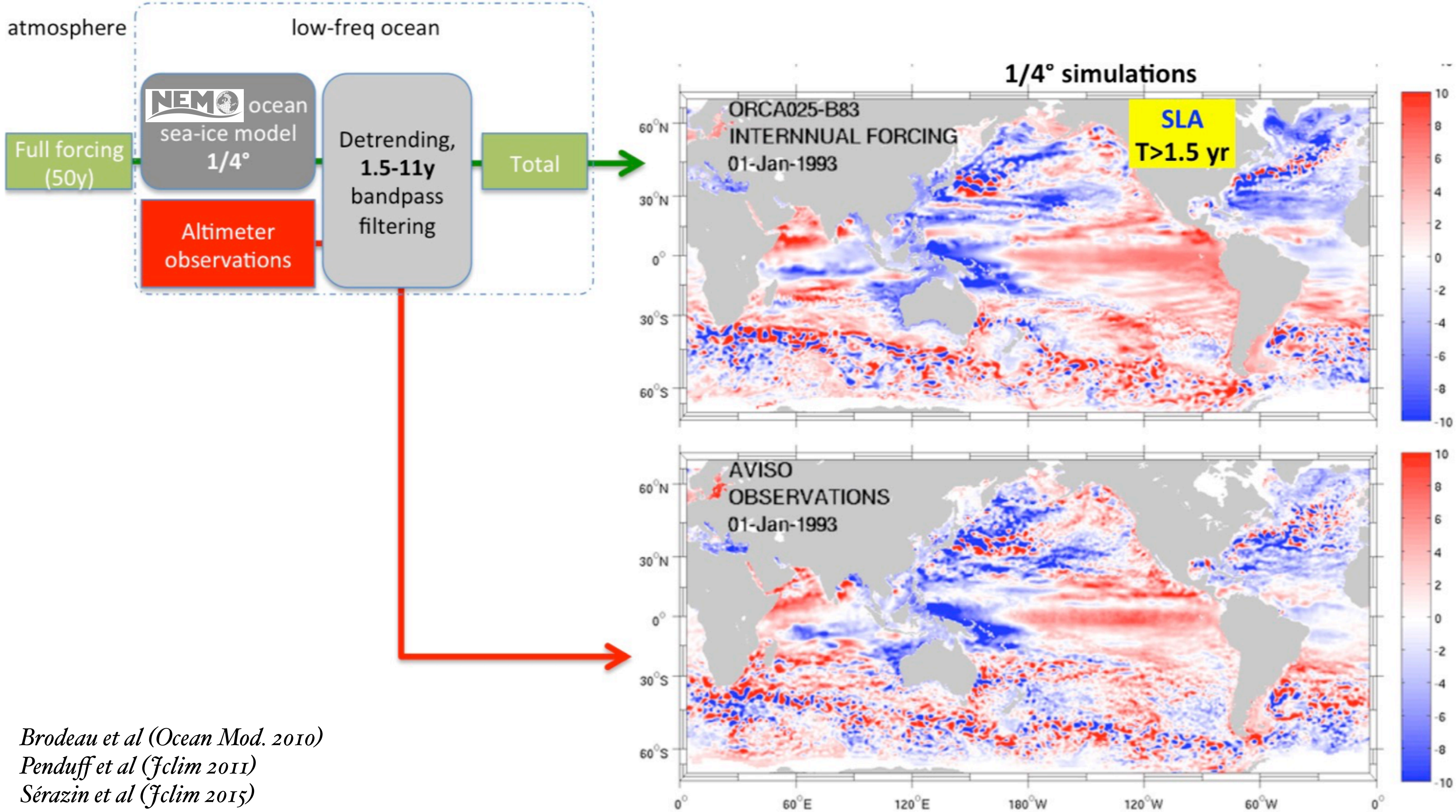
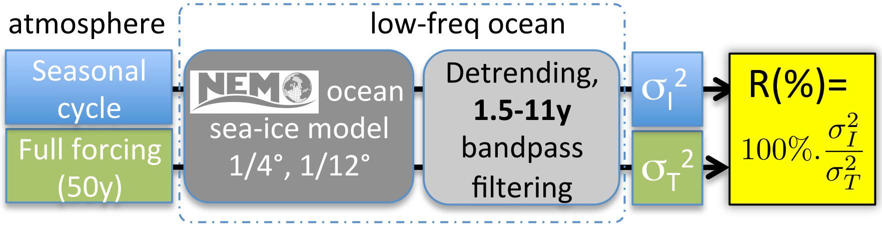
Low-frequency SLA variab.
Experimental strategy

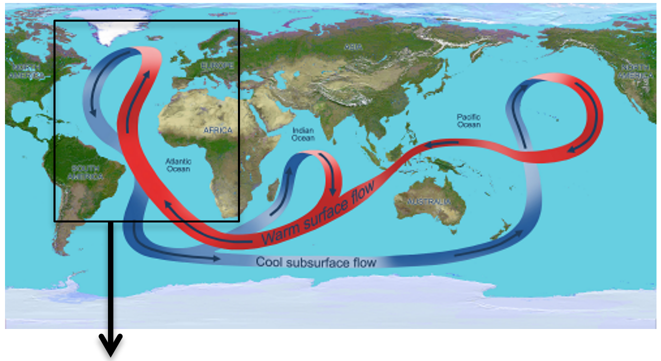
Approach



Brodeau et al (Ocean Mod. 2010)
Penduff et al (Jclim 2011)
Sérazin et al (Jclim 2015)

Chaotic part (%) of the large-scale low-frequency variance

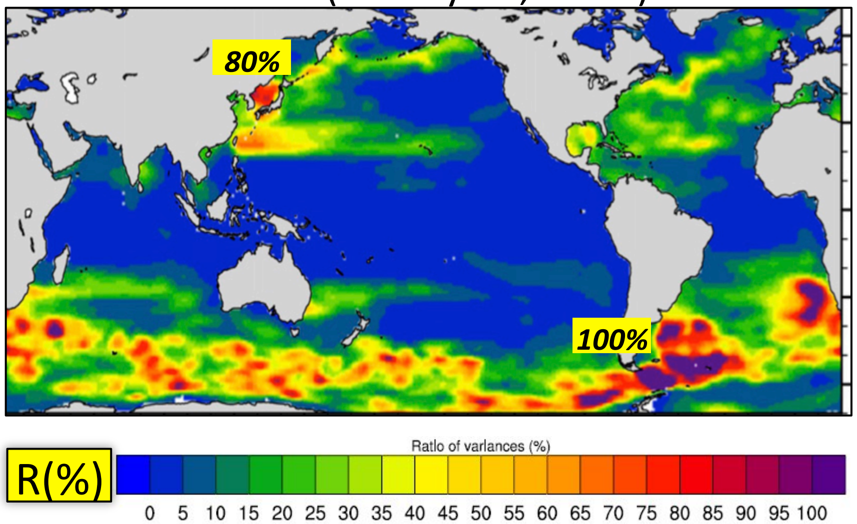


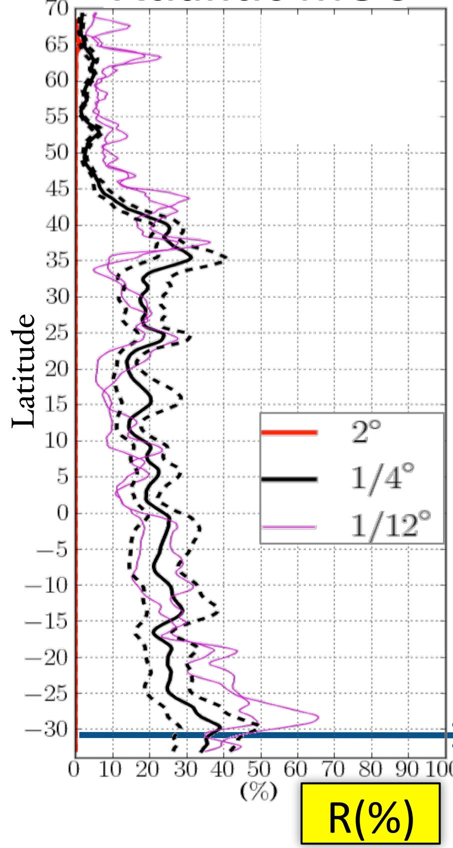


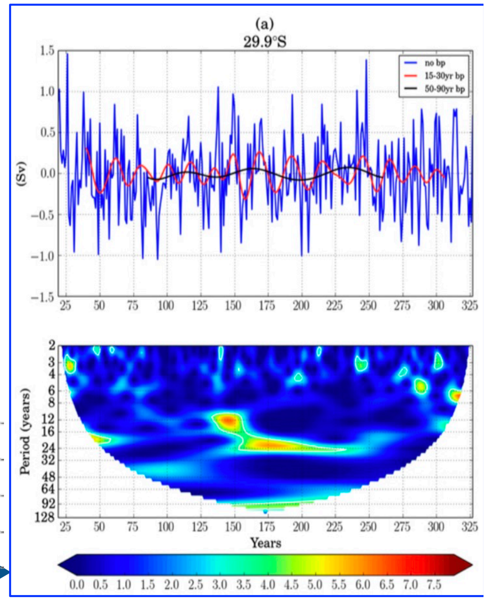
2° simulations : R ~ 0%

Atlantic MOC

SLA (T>1.5 year, L>12°)







Penduff et al (Jclim 2011)
Sérazin et al (Jclim 2015)

Grégorio et al (JPO 2015)

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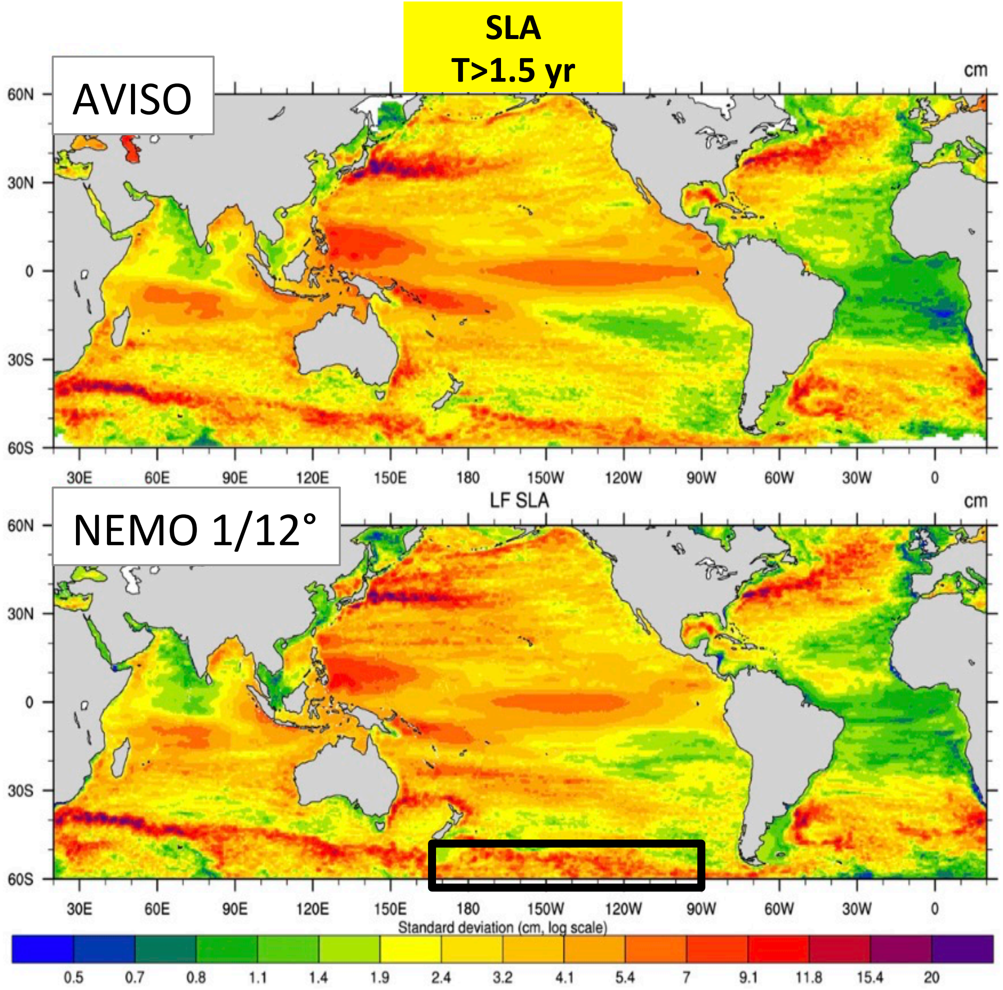
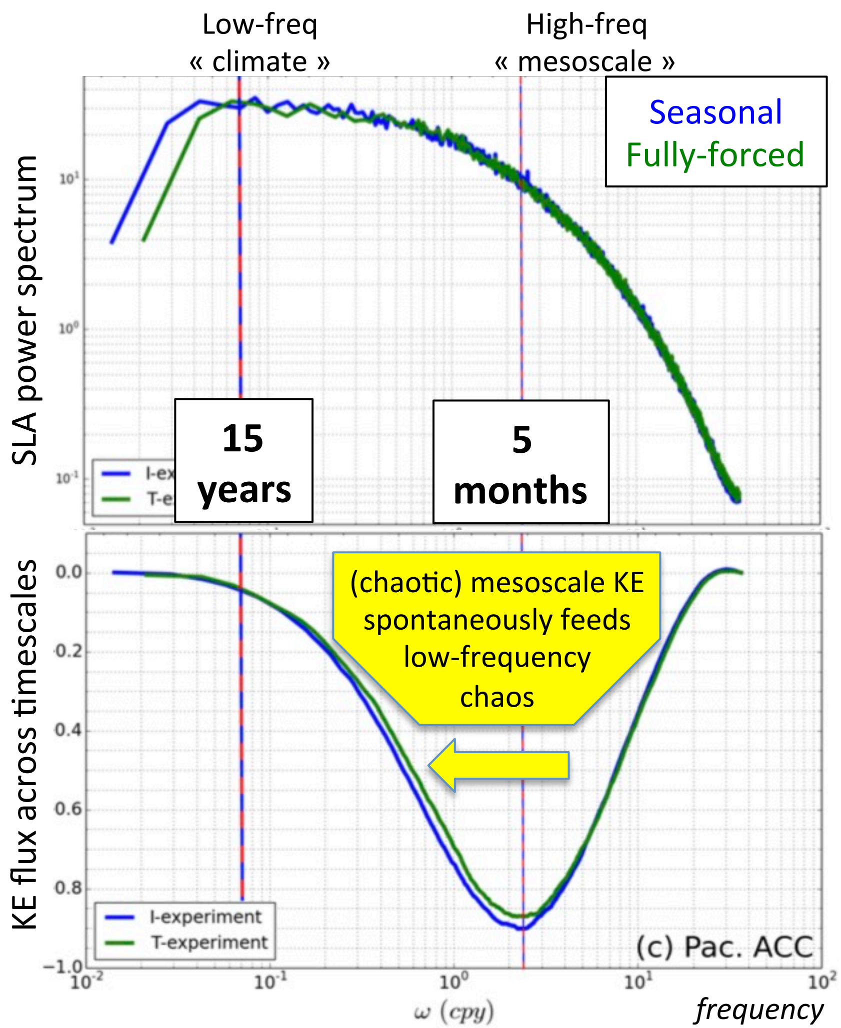
A source of low-freq Chaotic variability : Temporal inverse cascade

$$T_{KE}(k,l,\omega) = Re\{J(\widehat{\psi, \nabla^2\psi}).\hat{\psi}^*\},$$

$$\Pi_{KE}(\omega) = \int_{\omega \le \Omega \le \omega_N} \left(\int_{-k_N}^{k_N} \int_{-l_N}^{l_N} T_{KE}\,(k,l,\Omega) dk dl \right) d\Omega$$

Fully-forced **1/12° simulation** : low-freq SLA std





Arbic et al (JPO 2014)
Sérazin et al (submitted to JPO)

Low-freq Chaotic Intrinsic variability

CHAOCEAN

OCCIPUT
OceaniC Chaos – ImPacts, strUcture, predicTability

LFCIV isolated under seasonal forcing

- Strong
- Broad range of scales
- Multiple imprints on climate indices

LFCIV under full (reanalyzed) forcing

- Ensemble simulation
- Perturbed initial conditions
- Same forcing on all members

LFCIV under full forcing ?

LFCIV ←→ Forced variability ?

Atmospheric constraint
on oceanic state/variability ?

Penduff et al (Clivar Exch. 2014)

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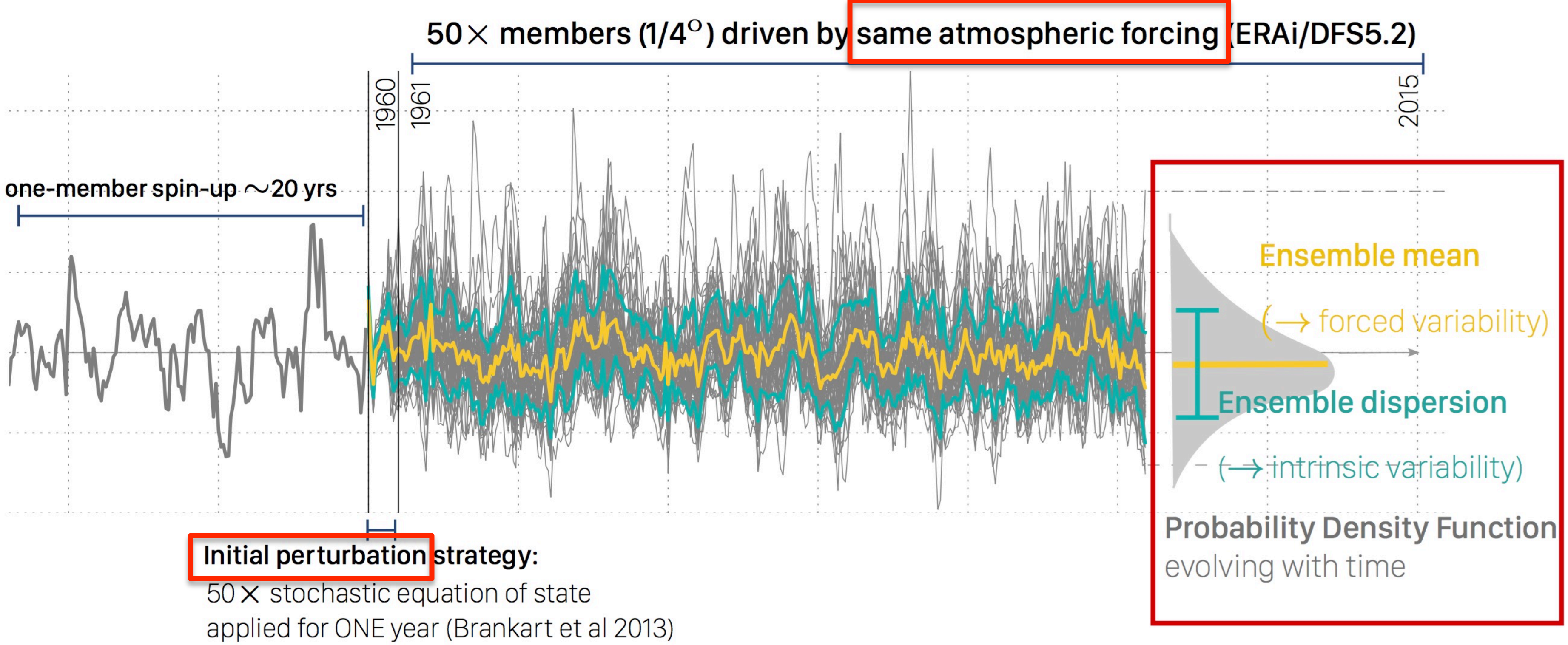
OCCIPUT ensemble simulations

Resources

50-member ¼° ensemble hindcasts :
- Global ocean (56 years)
- North Atlantic (20 years)

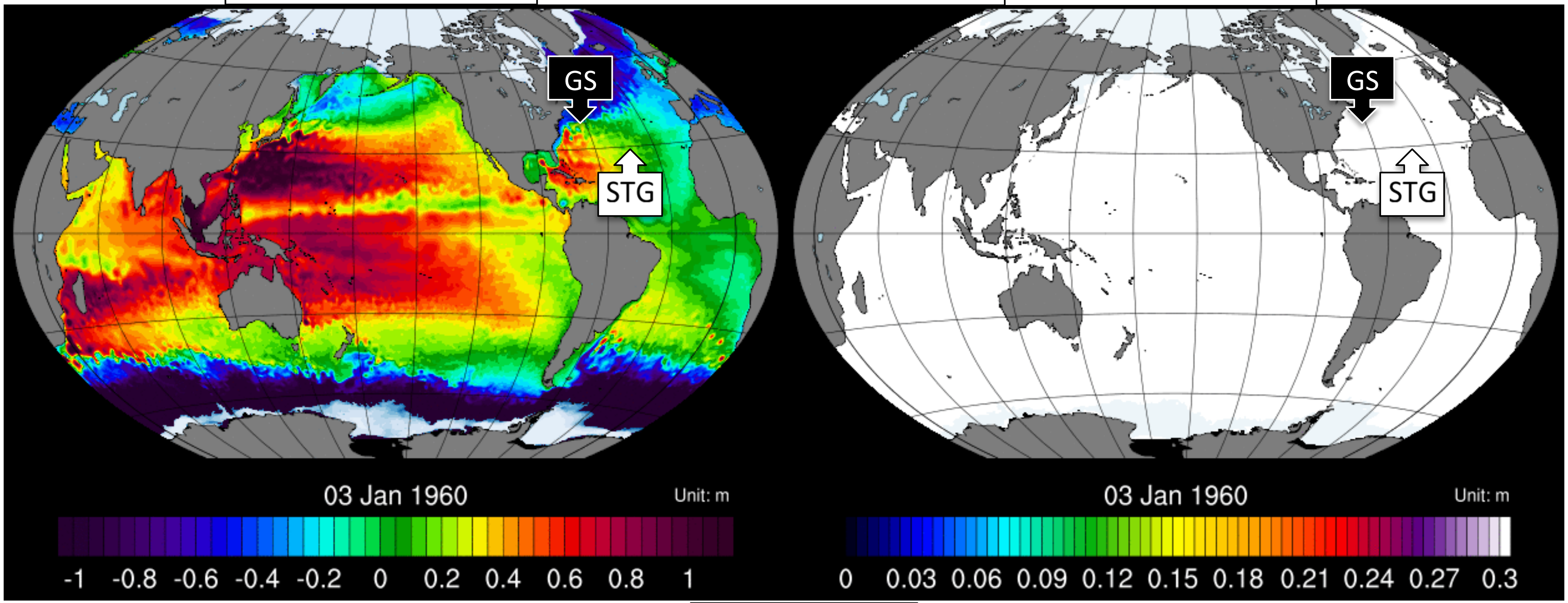


Penduff et al (CLIVAR exch., 2014)
Bessières et al (GMD 2017)

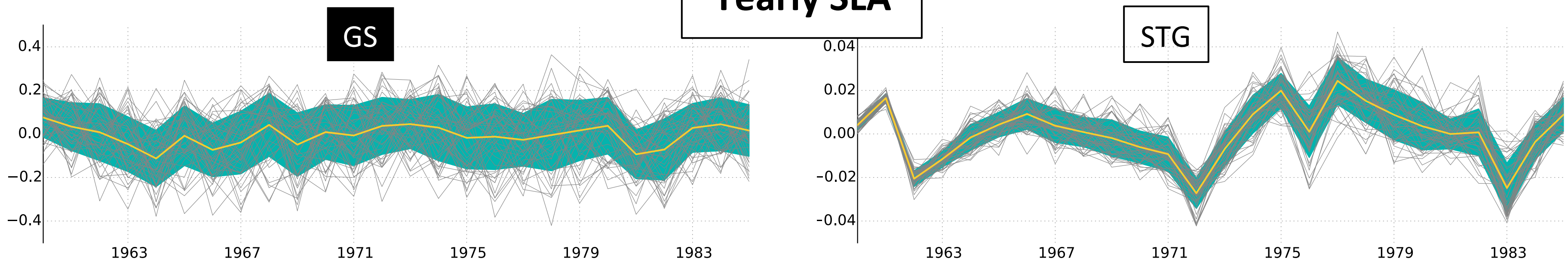
5-day SLA: Forced & Chaotic variability (1960-1965)

Ensemble Mean
FORCED variability

Ensemble STD
CHAOTIC variability



Yearly SLA

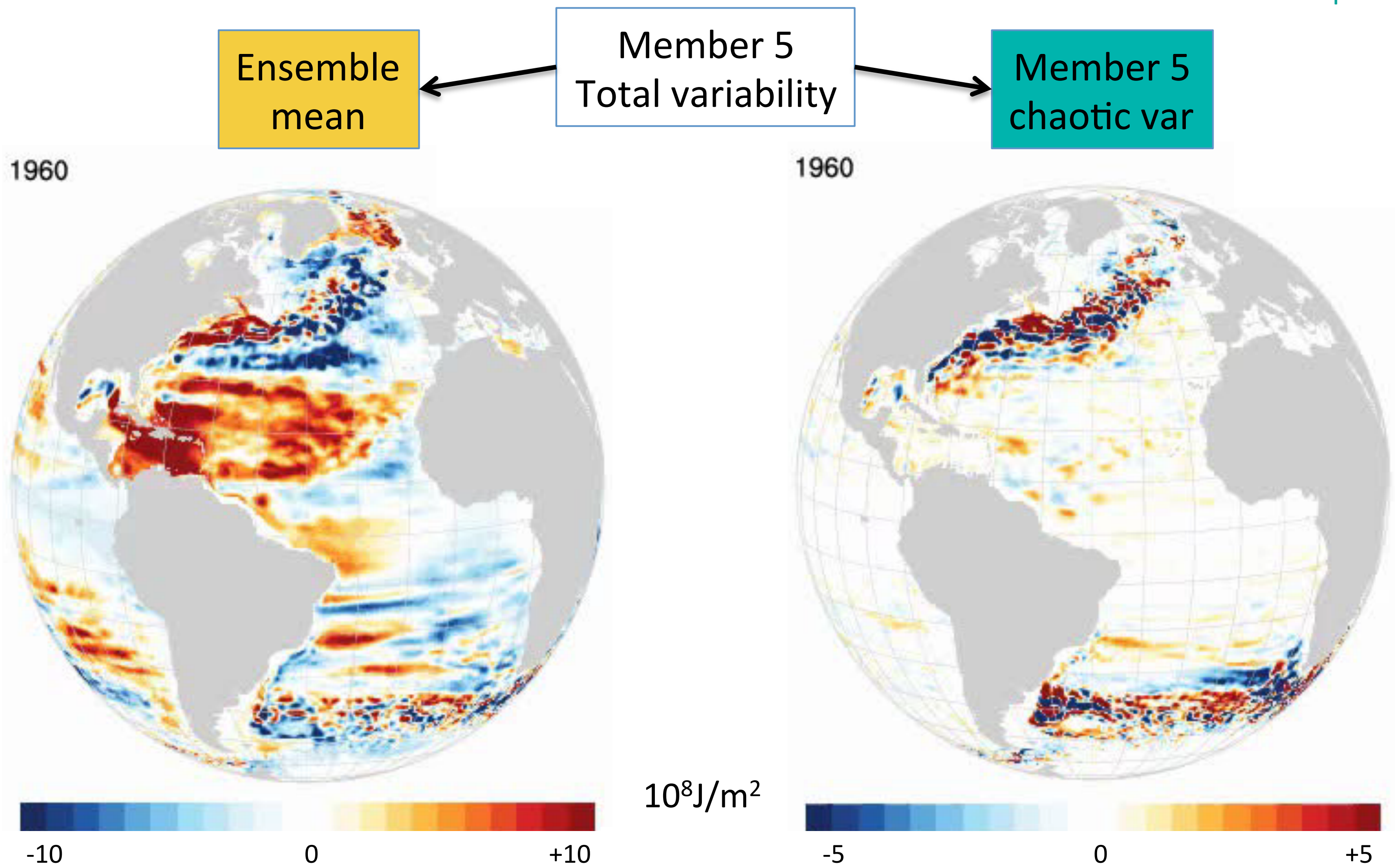


Bessières et al (GMD 2017)

2-15 yr $OHC_{0\text{-}700m}$ Forced & Chaotic variability (1980-2010)

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

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



Sérazin et al (GRL 2017)

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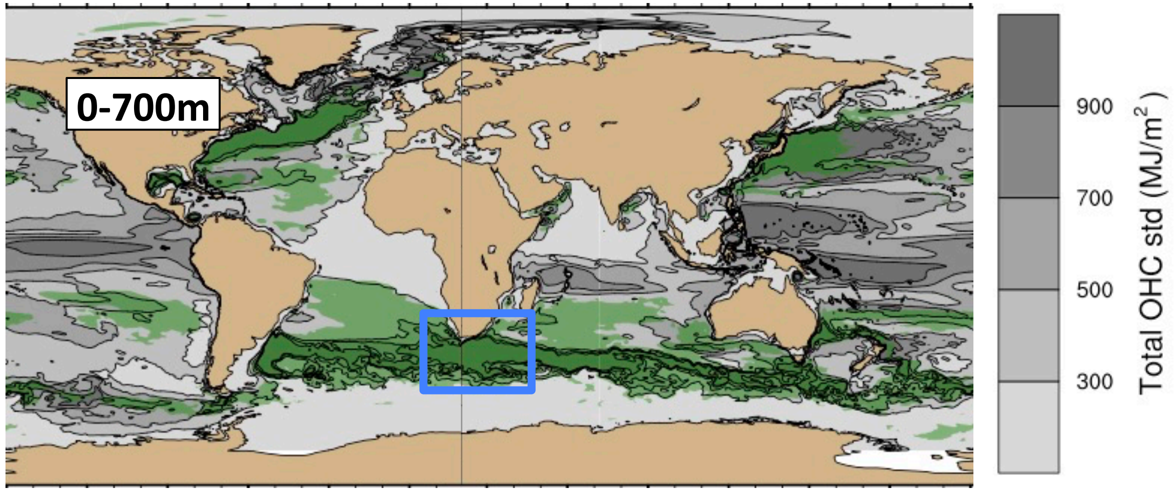
$$OHC = \rho . C_p \int_{-700}^{surf} T(z).dz$$ *yr = 1980,2010 member = 1,50*

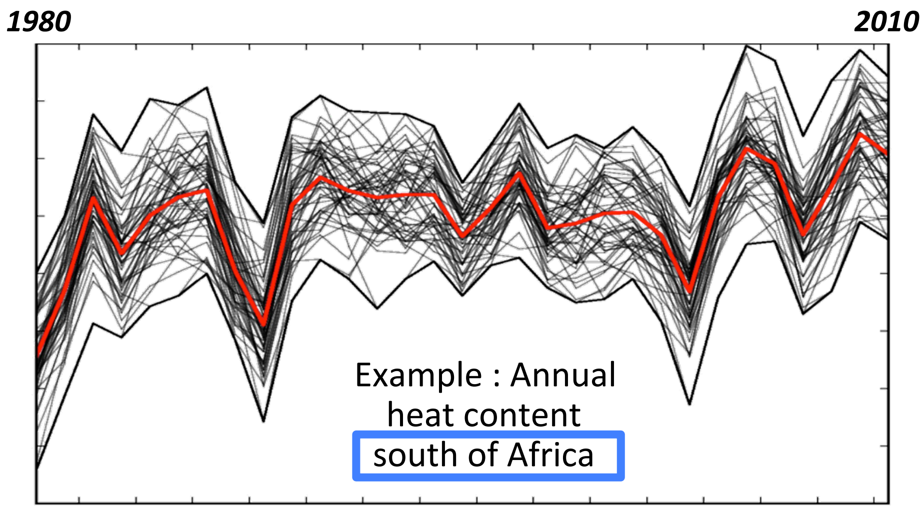
Emean (Tstd) → Total var.

Tstd (Emean) → **Forced var.**

Tmean (Estd) → **Chaotic var.**

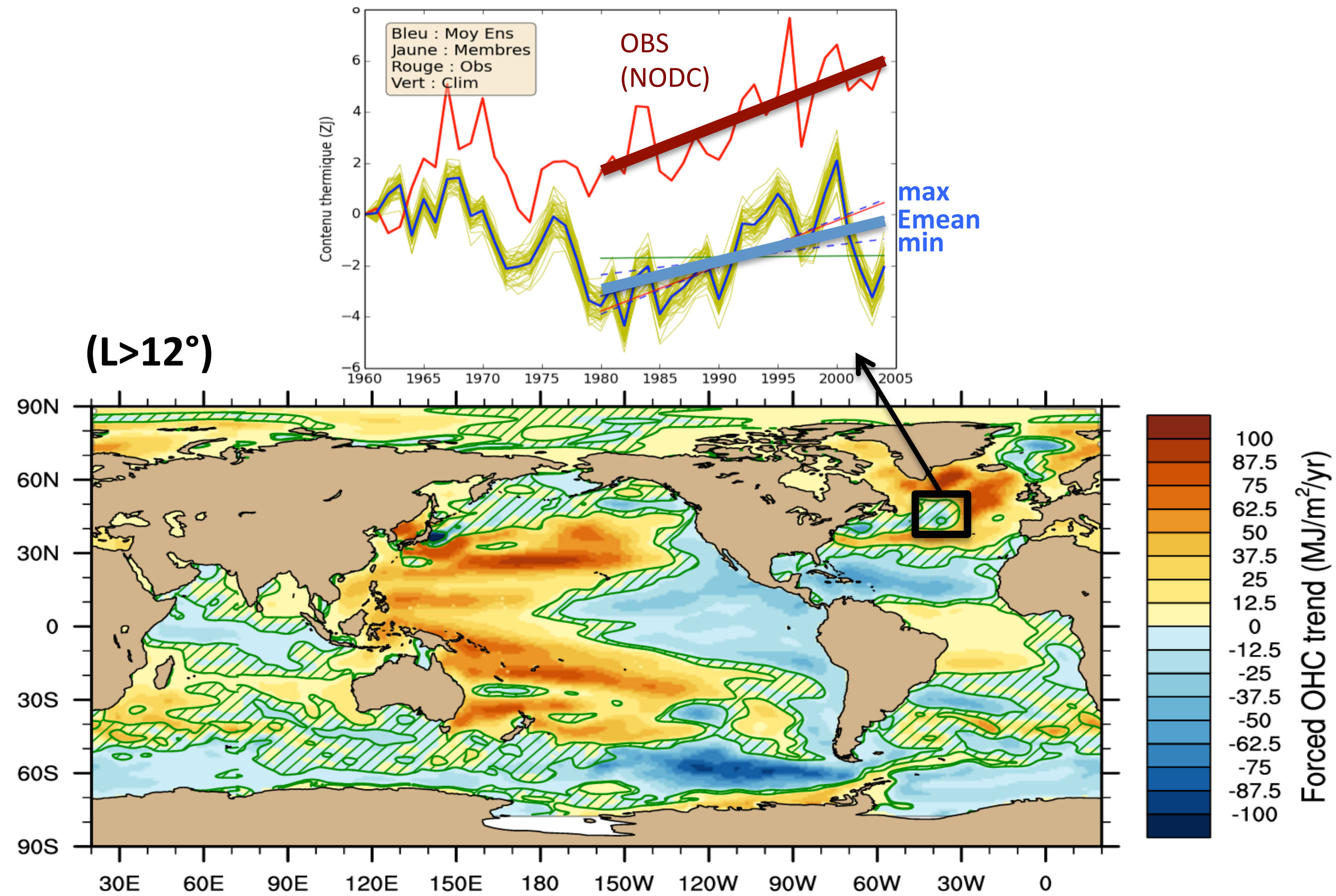
Green: Chaotic exceeds Forced





Sérazin et al (GRL 2017)

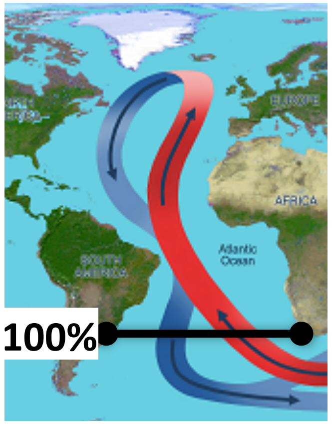
30-year OHC$_{0\text{-}700m}$: Forced vs Chaotic trends (1980-2010)



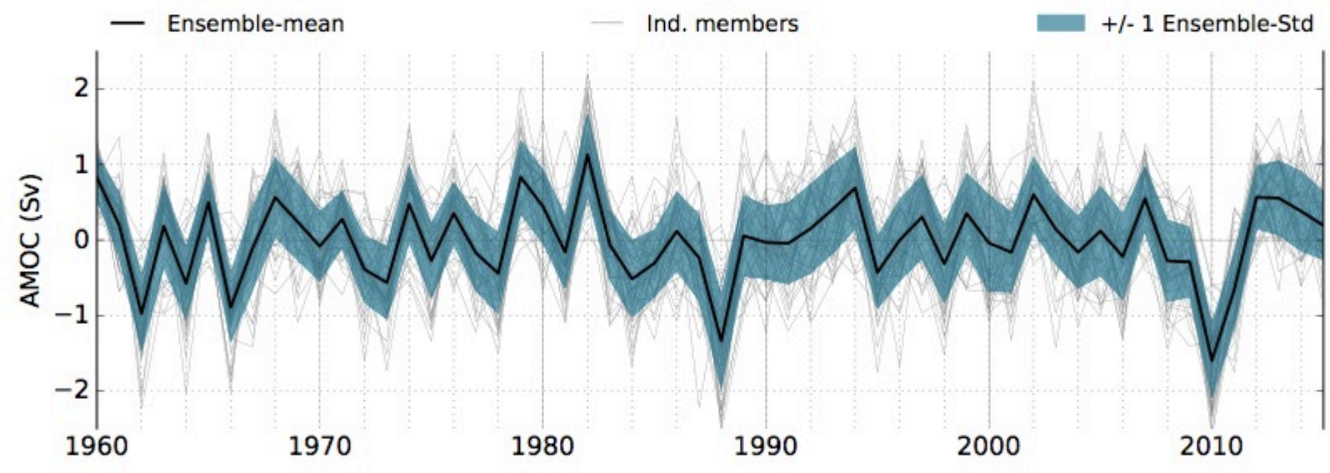
30-year OHC trends exhibit a large ensemble spread. Trends cannot be unambiguously attributed to the atmospheric forcing

Sérazin et al (GRL 2017)

Yearly Atlantic MOC : Forced & Chaotic STDs (1960-2015)

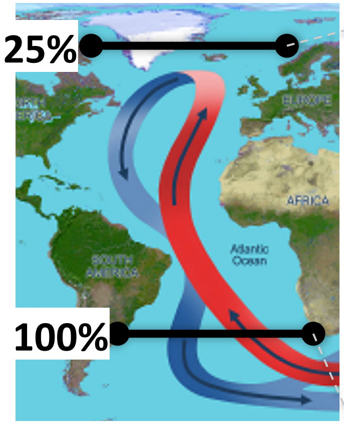


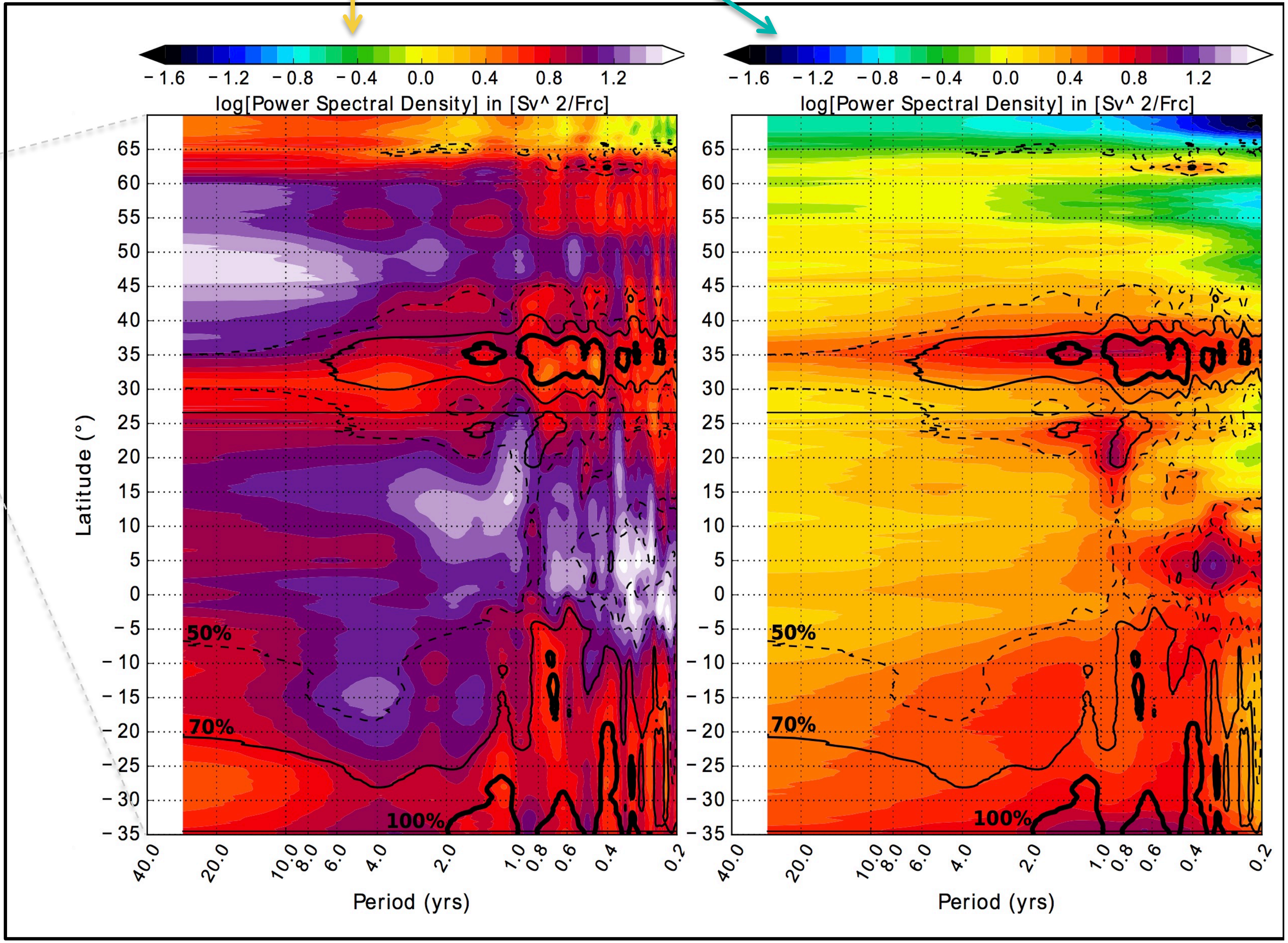
34.5°S



Leroux et al (in rev. J. Clim)

Yearly Atlantic MOC : Forced & Chaotic spectra (1960-2015)

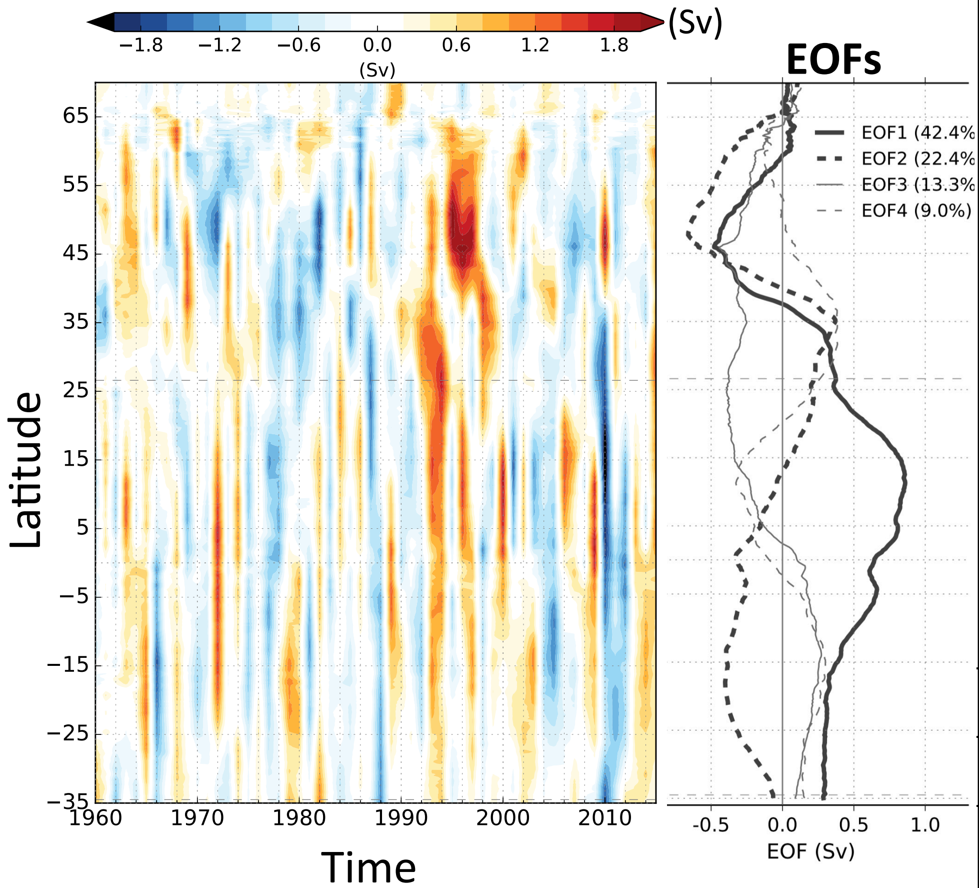




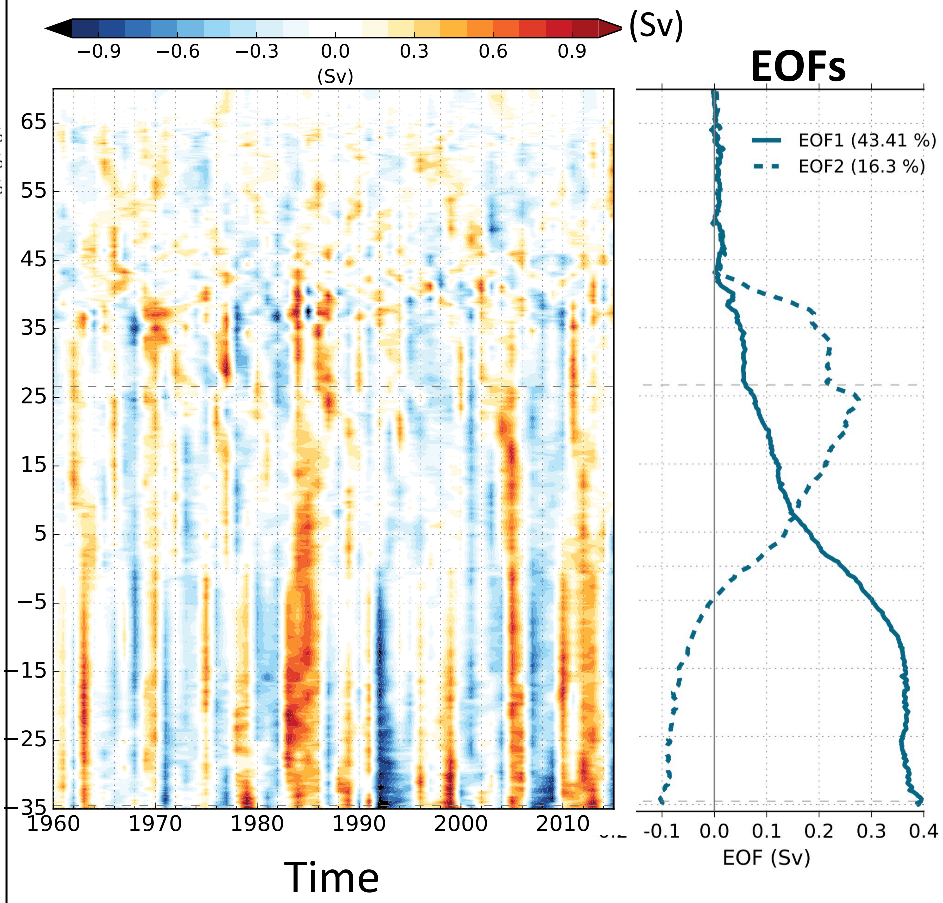
Leroux et al (in rev. J. Clim)

Forced & Intrinsic AMOC interannual variability : latitude-time

Forced AMOC interannual variability



Chaotic AMOC interannual variability (member 1)



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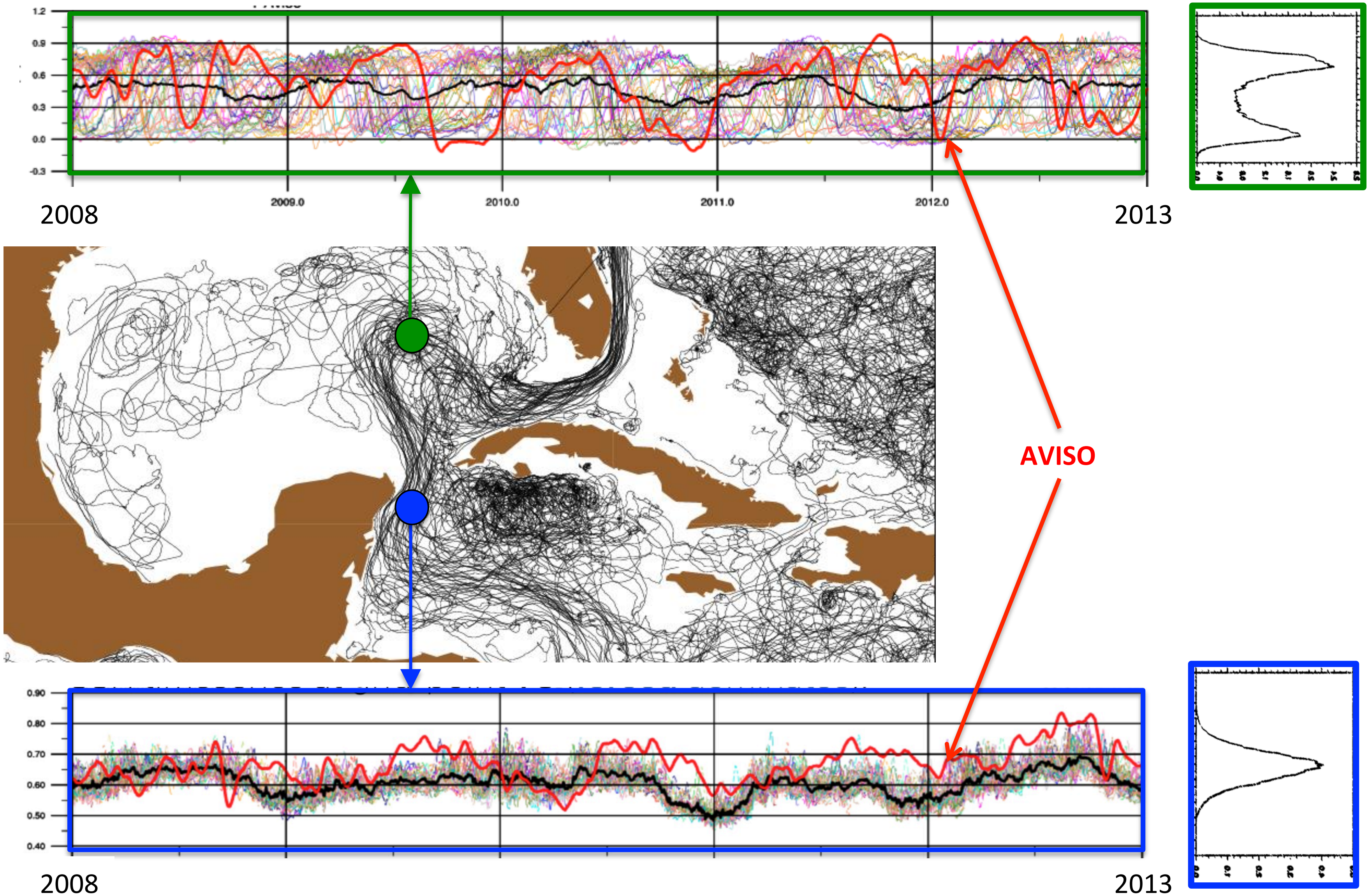
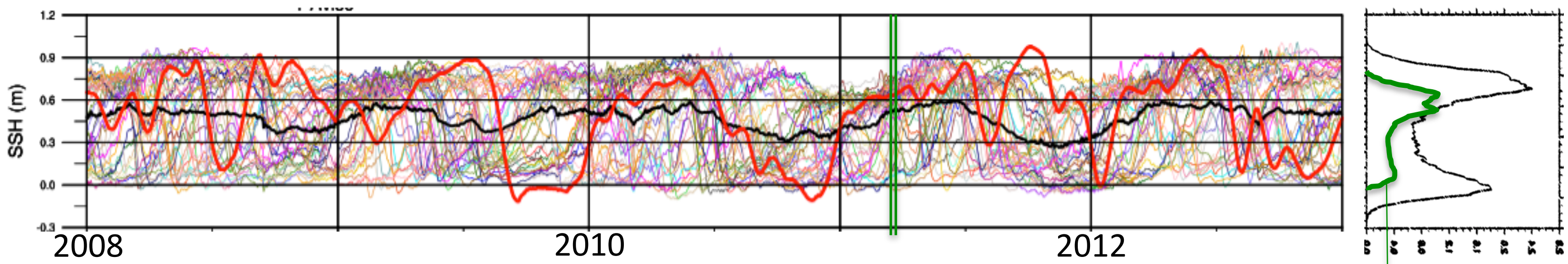
Daily SSH: contrasted dynamical regimes



PV. Huot (M2R 2016)
I Garcia Gomez, PhD thesis

Information theory

Daily SSH: atmospherically-modulated, non-gaussian Chaotic variab.



Daily entropy : $$S(x,y,t) = \sum_{i=1}^{50} -p_i(x,y,t).log_2(p_i(x,y,t))$$

Disorder/chaos	*None*	*Max*
Forcing constraint	*Max*	*None*

- Oceanic chaos increases S
- Atmosphere forces low S values
- Hurricanes force S = 0
- Ocean propagates S

PV. Huot (M2R 2016)
I Garcia Gomez, PhD thesis

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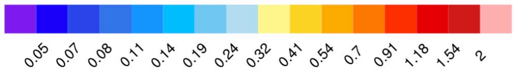
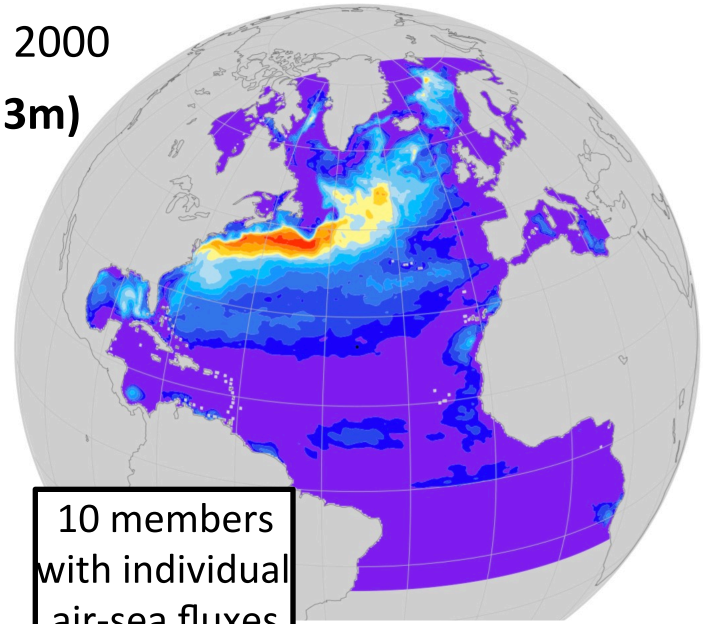
Monthly SST: Turbulent air-sea fluxes and Chaotic variability

10-member NATL025

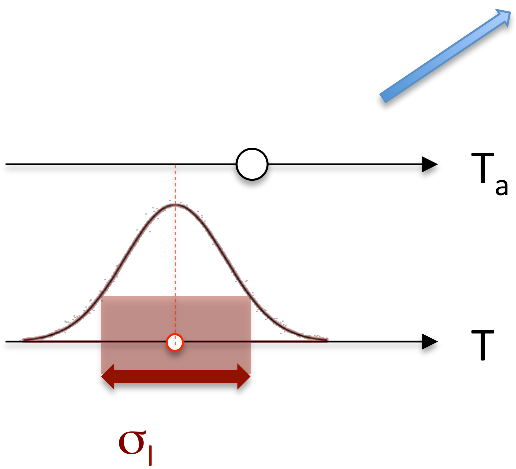


Jan 17th 2000

σ_c(T@3m)



10 members with individual air-sea fluxes



Member i : T change due to turbulent air-sea flux

$$Q_{turb}^{i} = \partial_t T^i = -\lambda(T^i - T_a)$$

T^i is relaxed toward T_a

λ~1/40 days

(Barnier, 1998)

Monthly SST: Turbulent air-sea fluxes and Chaotic variability

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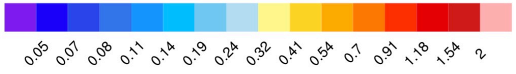

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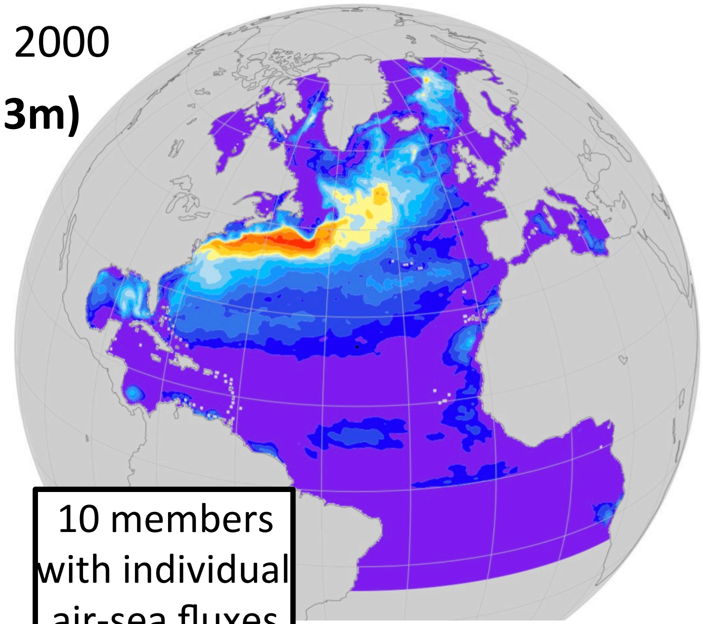

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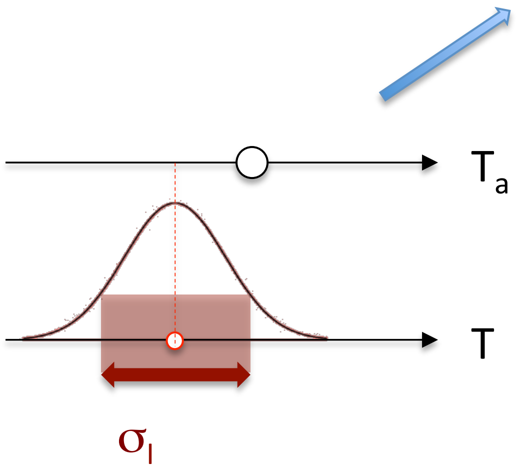

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$$Q_{turb}^{\,i} = \partial_t T^i = -\lambda(T^i - T_a)$$ T^i is relaxed toward T_a

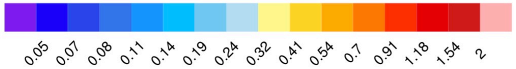
Forced	$\partial_t \langle T \rangle = -\lambda(\langle T \rangle - T_a)$	<T> is relaxed toward T_a
Chaotic	$\partial_t T{*}^i = -\lambda(T{*}^i)$	

$T^i = \langle T \rangle + T{*}^i$

λ~1/40 days
(Barnier, 1998)

Monthly SST: Turbulent air-sea fluxes and Chaotic variability

10-member NATL025



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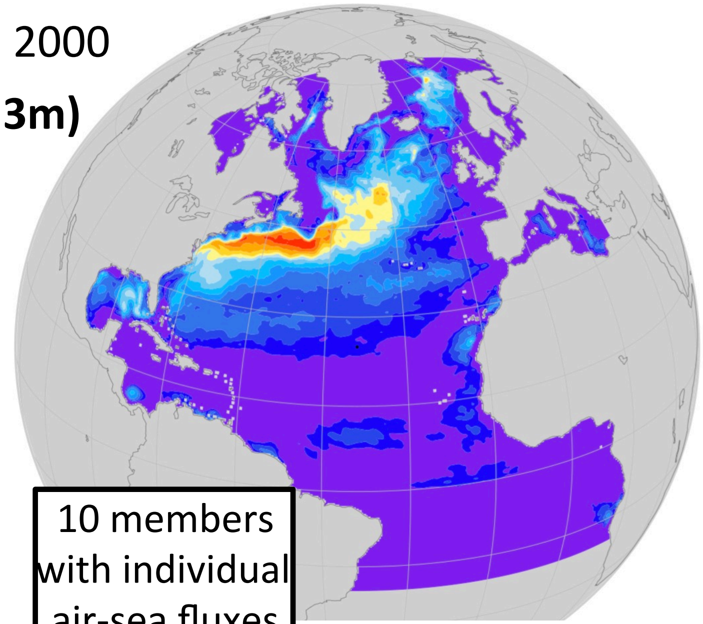

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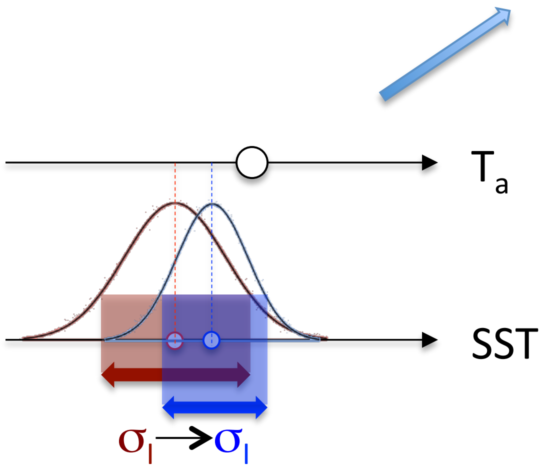

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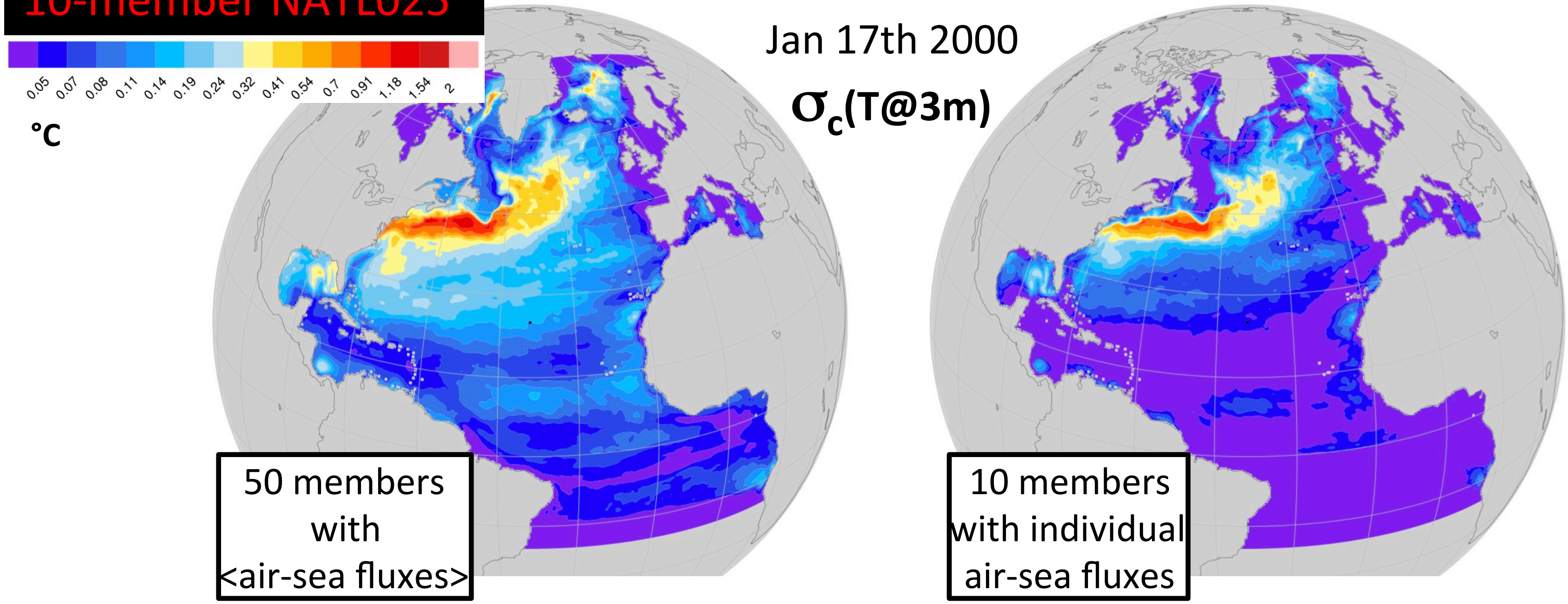
Forced	$\partial_t \langle T \rangle = -\lambda(\langle T \rangle - T_a)$	<T> is relaxed toward T_a
Chaotic	$\partial_t \sigma_I^2 = -\lambda.\sigma_I^2$	**σ_I (chaotic) is damped**

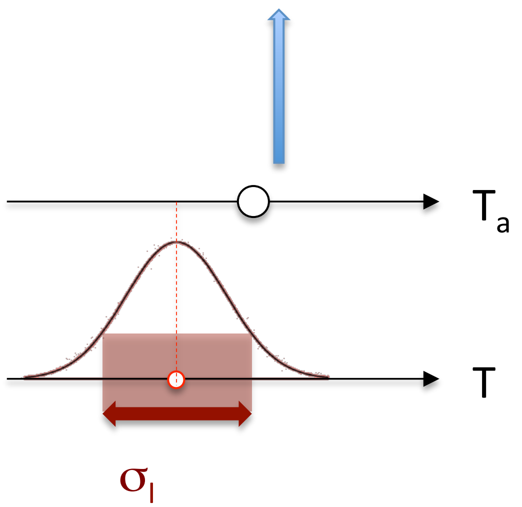
$$T^i = \langle T \rangle + T^{*i}$$

λ~1/40 days
(Barnier, 1998)

Monthly SST: Turbulent air-sea fluxes and Chaotic variability

10-member NATL025





Member i : T change due to <turbulent air-sea flux>

$$\langle Q_{turb}\rangle = \partial_t T^i = -\lambda(\langle T\rangle - T_a)$$ T^i is relaxed toward T_a

Forced $$\partial_t \langle T\rangle = -\lambda(\langle T\rangle - T_a)$$ <T> is relaxed toward T_a

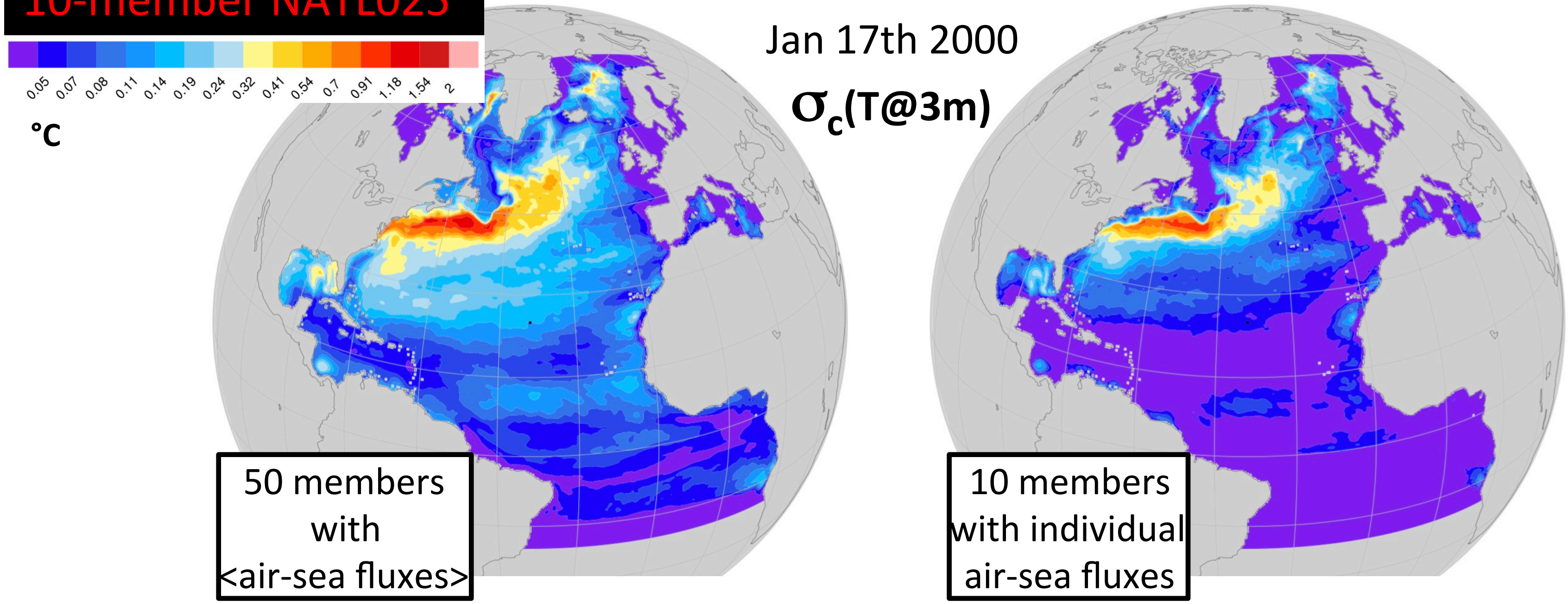
Chaotic $$\partial_t T*^i = 0$$ **σ_I (chaotic) is untouched**

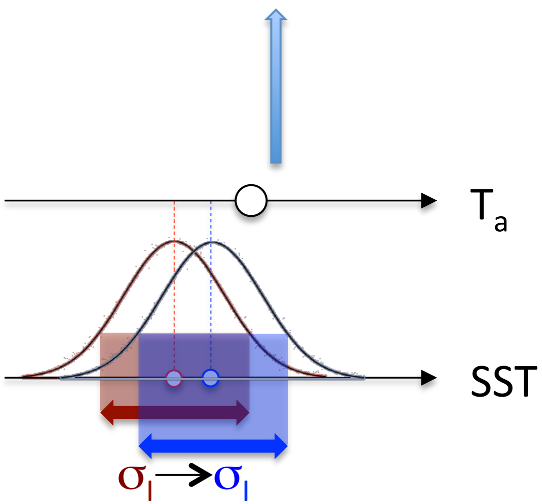
T^i = $<T>$ + T^{*i}

λ~1/40 days
(Barnier, 1998)

Monthly SST: Turbulent air-sea fluxes and Chaotic variability

10-member NATL025





Member i : T change due to <turbulent air-sea flux>

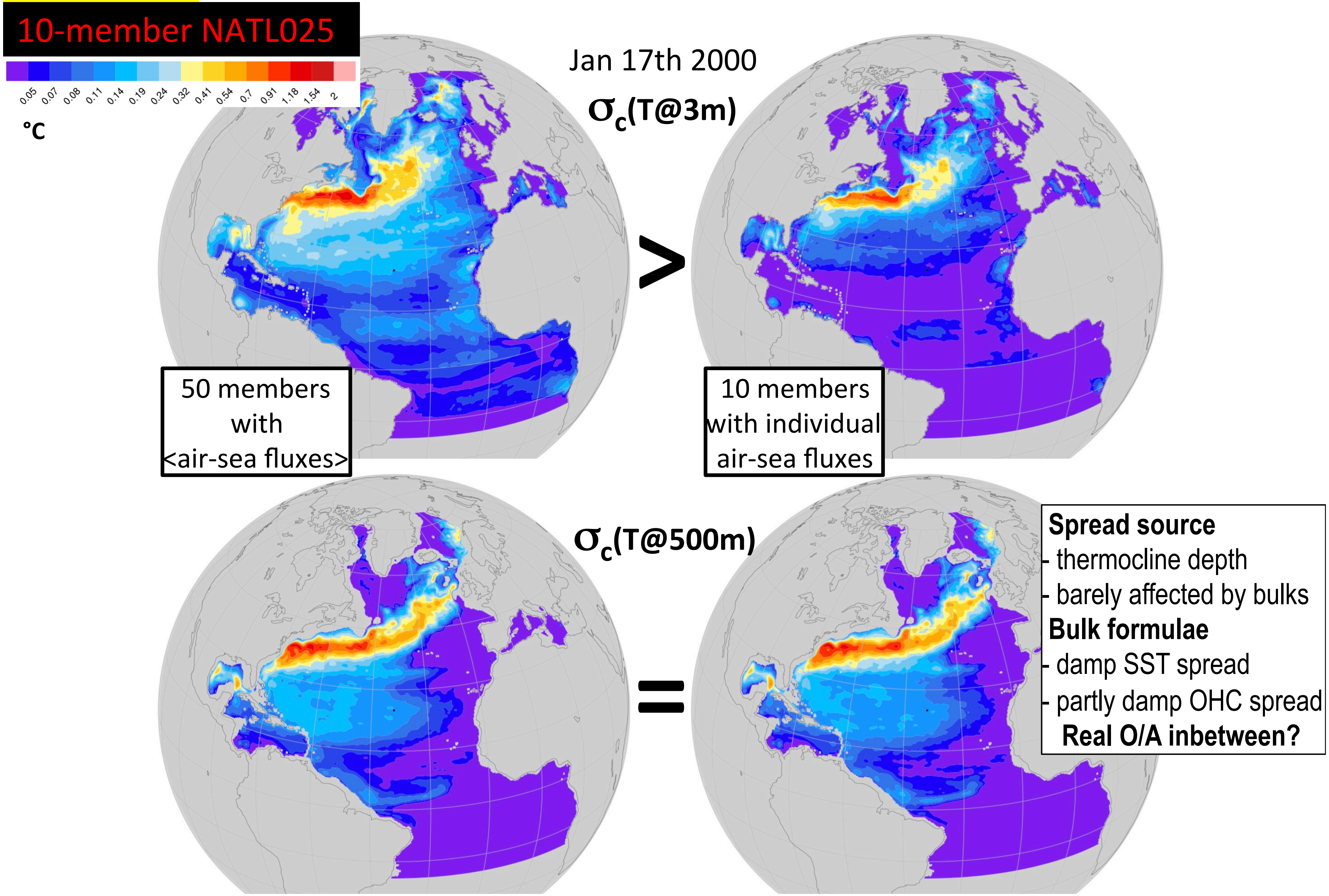
$$\langle Q_{turb} \rangle = \partial_t T^i = -\lambda(\langle T \rangle - T_a)$$ T^i is relaxed toward T_a

Forced	$\partial_t \langle T \rangle = -\lambda(\langle T \rangle - T_a)$	<T> is relaxed toward T_a
Chaotic	$\partial_t \sigma_I^2 = 0$	**σ_I (chaotic) is untouched**

$T^i = \langle T \rangle + T^{*i}$

λ~1/40 days
(Barnier, 1998)

Monthly T : Turbulent air-sea fluxes and Chaotic variability



Outline

Low-Freq Chaotic Intrinsic Variability in the global ocean

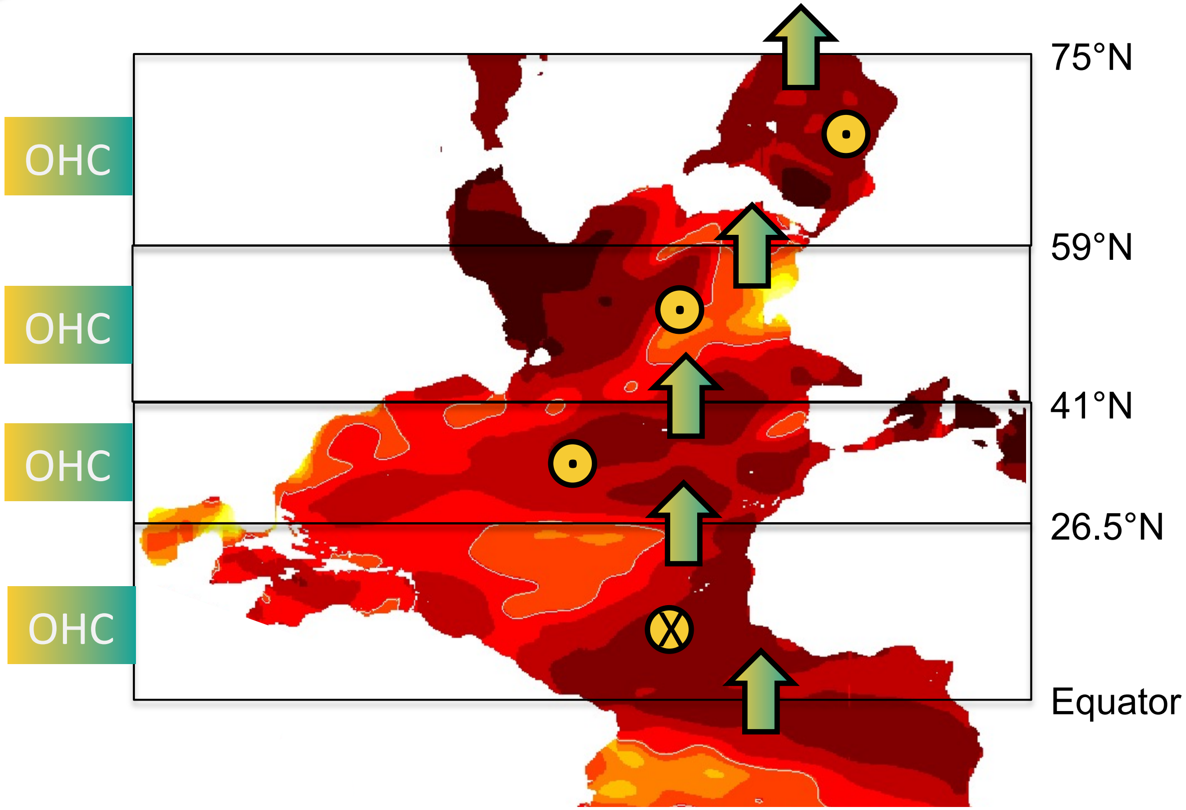
1. LFCIV isolated under seasonal forcing
   - Imprint on observed fields (Sea-level, AMOC)
   - A possible generation mechanism
2. LFCIV modulated by full (reanalyzed) forcing
   - OCCIPUT Ensemble simulations
   - Sea-level, OHC, AMOC
3. New directions and challenges
   - Non-gaussianity, information theory
   - Ocean chaos ←→ atmosphere
   - Multivariate analyses (MHT – OHC – Qnet)
4. Conclusions and perspectives

Forced & Intrinsic multivariate/multiscale variability

Forced

Chaotic

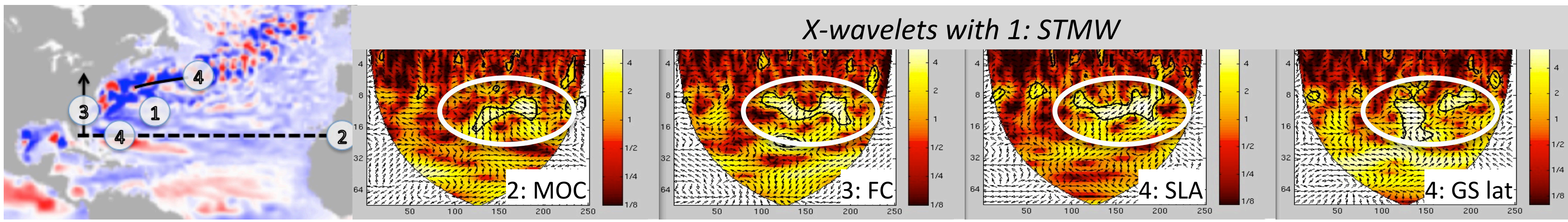
$$\partial_t OHC = Q_{net} + (MHT_{south} - MHT_{north})$$



chaos controls 25% of the OHC LF/LS std

Internship by Imane Benabicha

Internship by Alice Barthel



Outline

Low-Freq Chaotic Intrinsic Variability in the global ocean

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Conclusions & Perspectives

Low-frequency (T > 1 year) ocean variability

- Laminar models (2°) : ~100% Forced → *Deterministic hindcasts OK*
- Eddying models (1/4°, 1/12°) : Atmospherically-modulated chaos (OHC, SST, MOC, SSH, etc)

  Chaotic var. : strong, up to multidecadal/basin scales (MOC, OHC, SST…)

  Poorly-known & complex → *Probabilistic hindcasts required*

Open questions & perspectives

- (multiple) dynamical processes, energetics, etc ? → *GFD studies, idealized simulations*
- Oceanic chaos → D/A of climate variability / change? → *Ensemble synthetic observations*
- Oceanic chaos → air-sea fluxes → atmosphere/climate ? → *Investigations starting*
- Collaborative investigations → *OCCIPUT data subsets*

SLA : Penduff et al (J. Clim 2011)
Scales : Sérazin et al (J. Clim 2015)
MOC, MHT : Grégorio et al (JPO 2015)
OCCIPUT : Penduff et al (Clivar Exch. 2014)
Ensemble NEMO : Bessières et al (GMD 2017)

SLA (D & A) : Sérazin et al (GRL 2016)
OHC : Sérazin et al (GRL 2017)
MOC : Leroux et al (J. Clim in rev)
Temporal inv. casc. : Sérazin et al (JPO subm.)