Forced vs chaotic ocean variability [2 < T < 100 yr]: large-scale impacts in the Southern Ocean

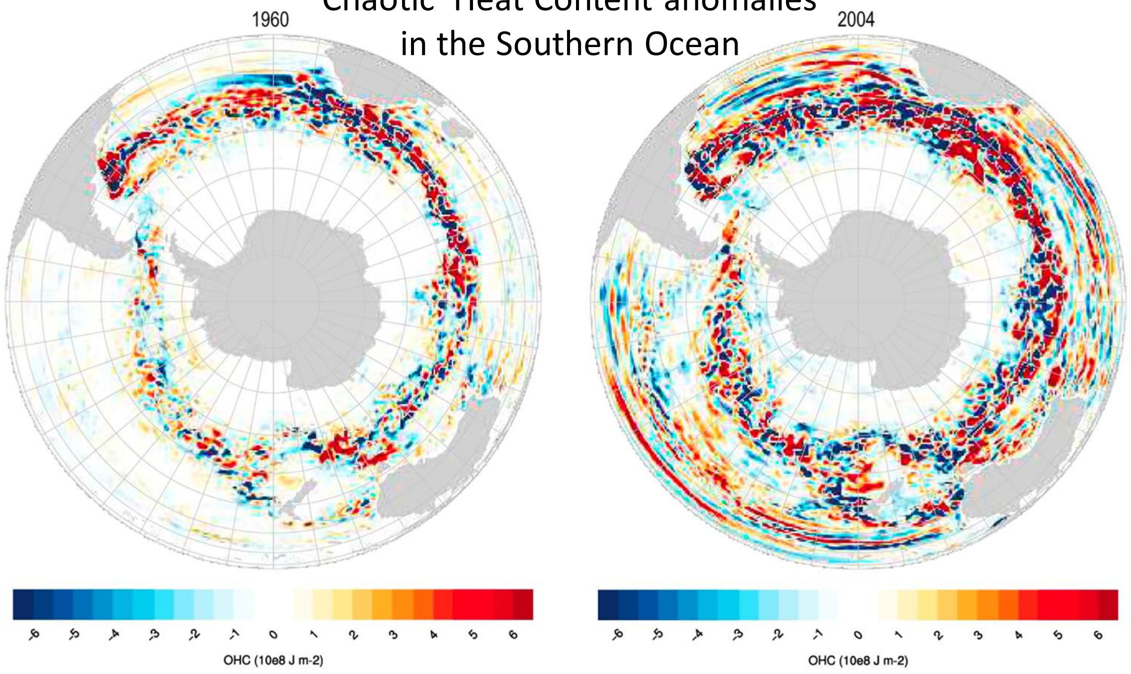
T. Penduff (CNRS-IGE, Grenoble, France)

Thanks to B. Barnier, L. Bessières, J.M. Molines, L. Terray, S. Pierini, G. Fedele, etc
With contributions from S. Leroux, G. Sérazin, F.E. Yan, B.I. Garcia-Gomez, S. Cravatte, W. Llovel, L. Zanna …

Motivation of the IPSODES project:

« Since a substantial fraction [of the Southern Ocean variability] is **known to be intrinsic and therefore basically chaotic**, predictability in this part of the world ocean is particularly poor. »

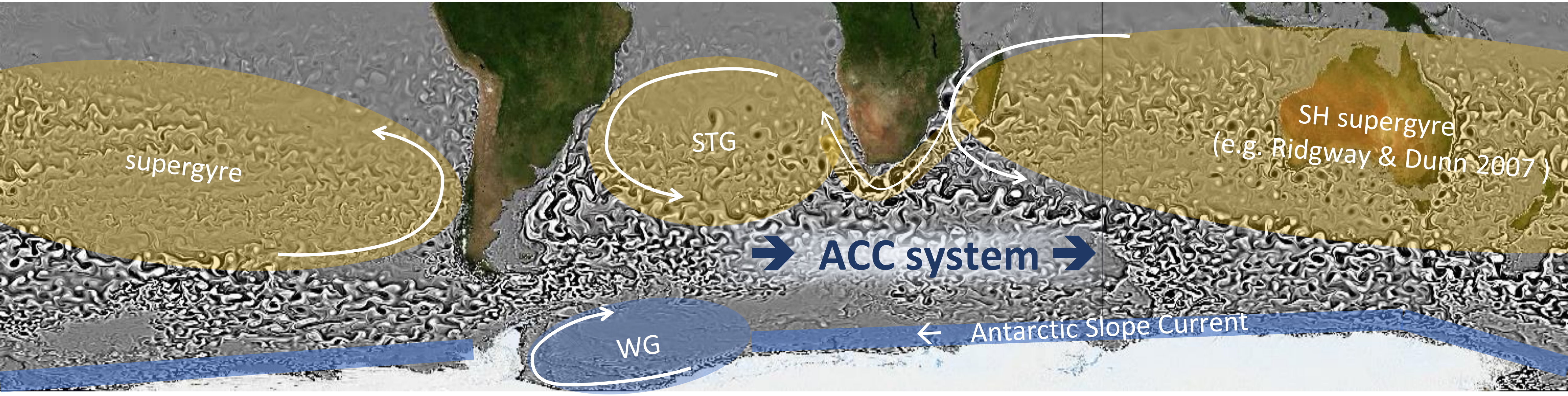
Chaotic Heat Content anomalies in the Southern Ocean



OCCIPUT

Southern Ocean circulation: surface view

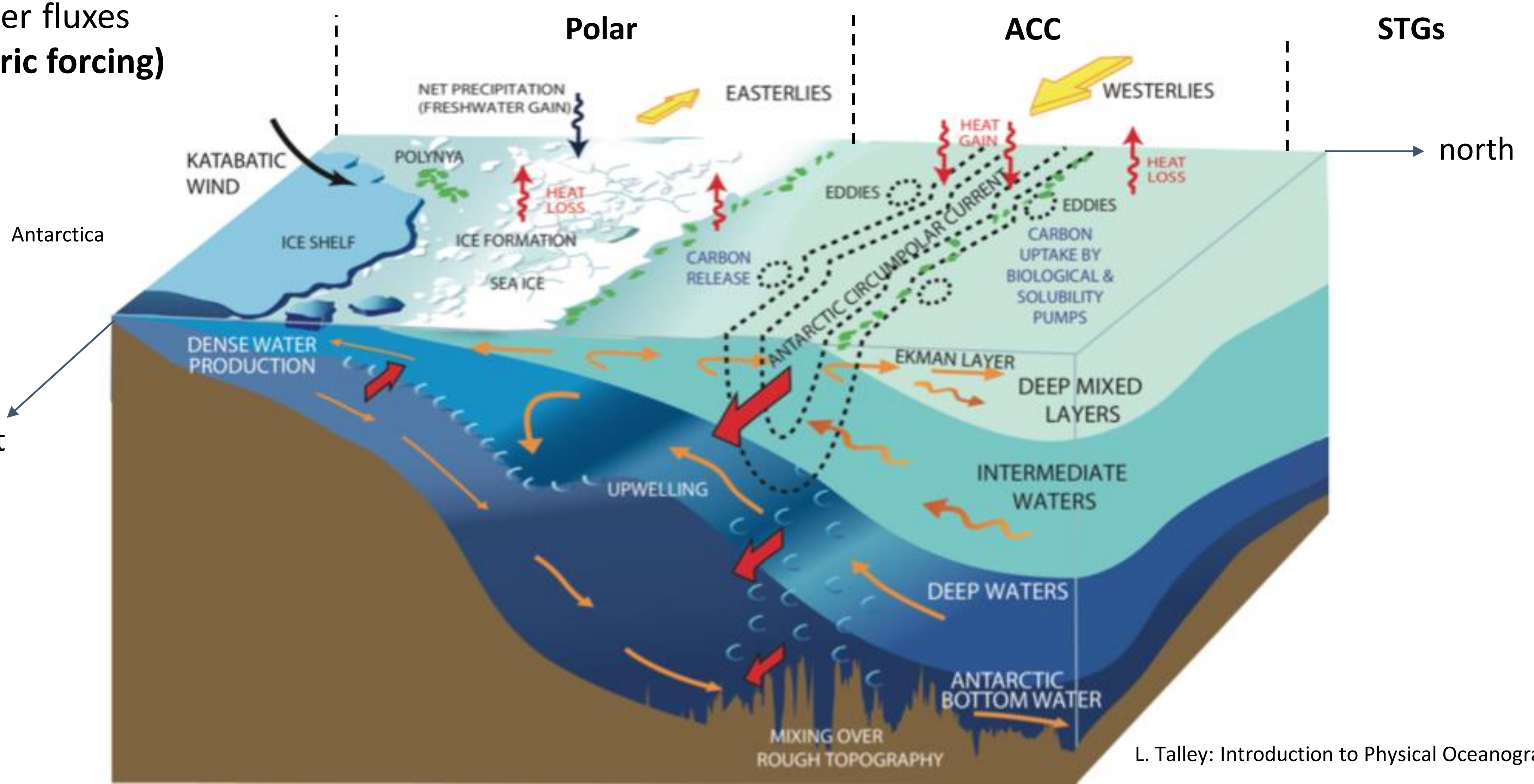
- Sits at the crossroads between the 3 main oceanic basins
- Ubiquitous mesoscale fronts & eddies → many impacts
- Hosts the ACC, strongest (only re-entrant) oceanic current on Earth
- Bounded by STGs (north) & polar regions (south) : 3 distinct dynamics



SSH laplacian (relative vorticity)
Global NEMO simulation 1/12°

Southern Ocean circulation: 3D view

Driven by
Momentum, Heat
& Freshwater fluxes
(Atmospheric forcing)



L. Talley: Introduction to Physical Oceanography

Ocean variability [T>1yr]

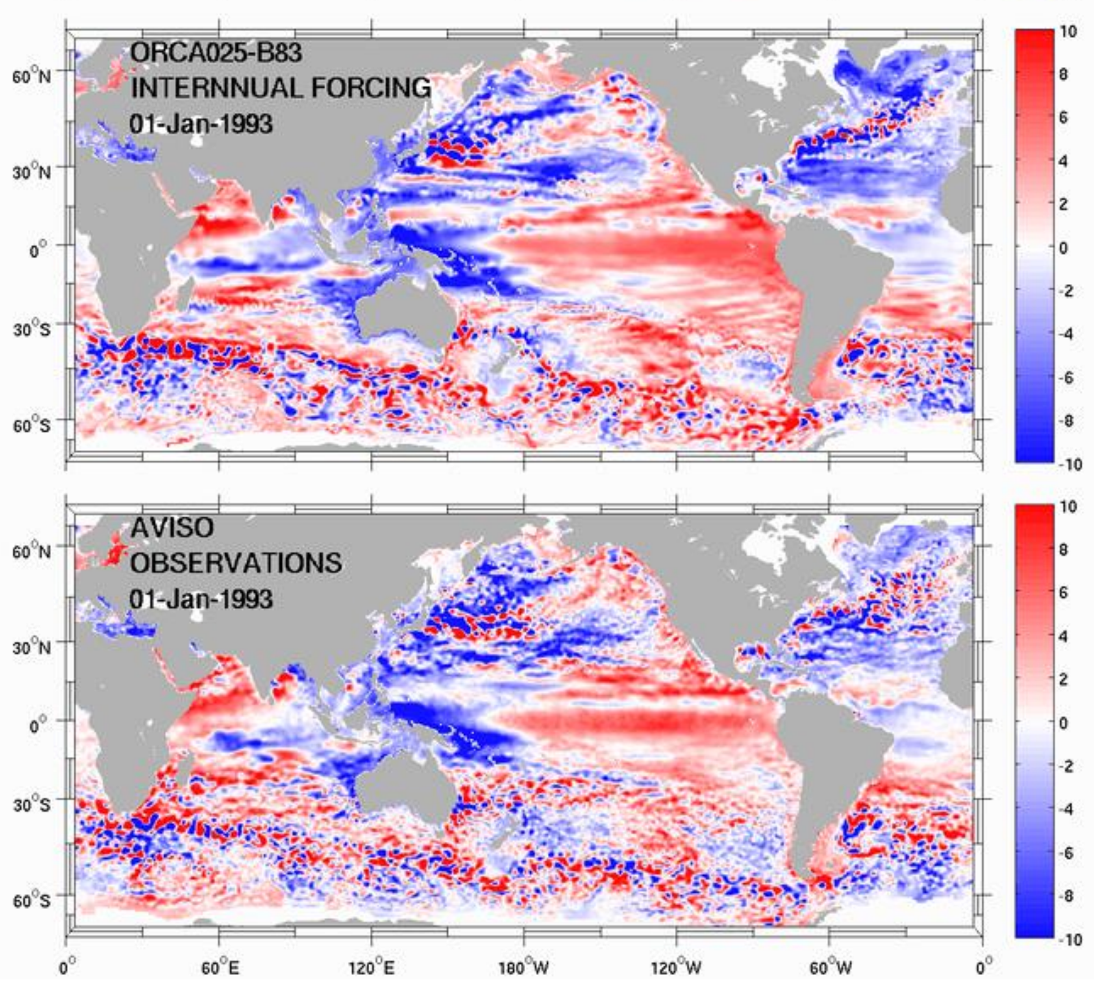
Driven by
Momentum, Heat
& Freshwater fluxes
(Atmospheric variability)

SLA from:

¼° NEMO model with
Realistic atm. Forcing

AVISO altimeter
observations

Penduff et al (2011)



Ocean variability [T>1yr]

Driven by
Momentum, Heat
& Freshwater fluxes
(Atmospheric variability)

… and non-linear
Ocean processes
(Chaotic Intrinsic variability : CIV)

Respective imprints of **atmospheric variability** and **CIV** in the **Southern Ocean** at low-frequency ? Focus on:

→ Climate-relevant variables
→ Large spatial scales
→ 1 yr < T < 100 years

¼° NEMO model with
Seasonal atm. Forcing

SLA from:

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Realistic atm. Forcing

AVISO altimeter
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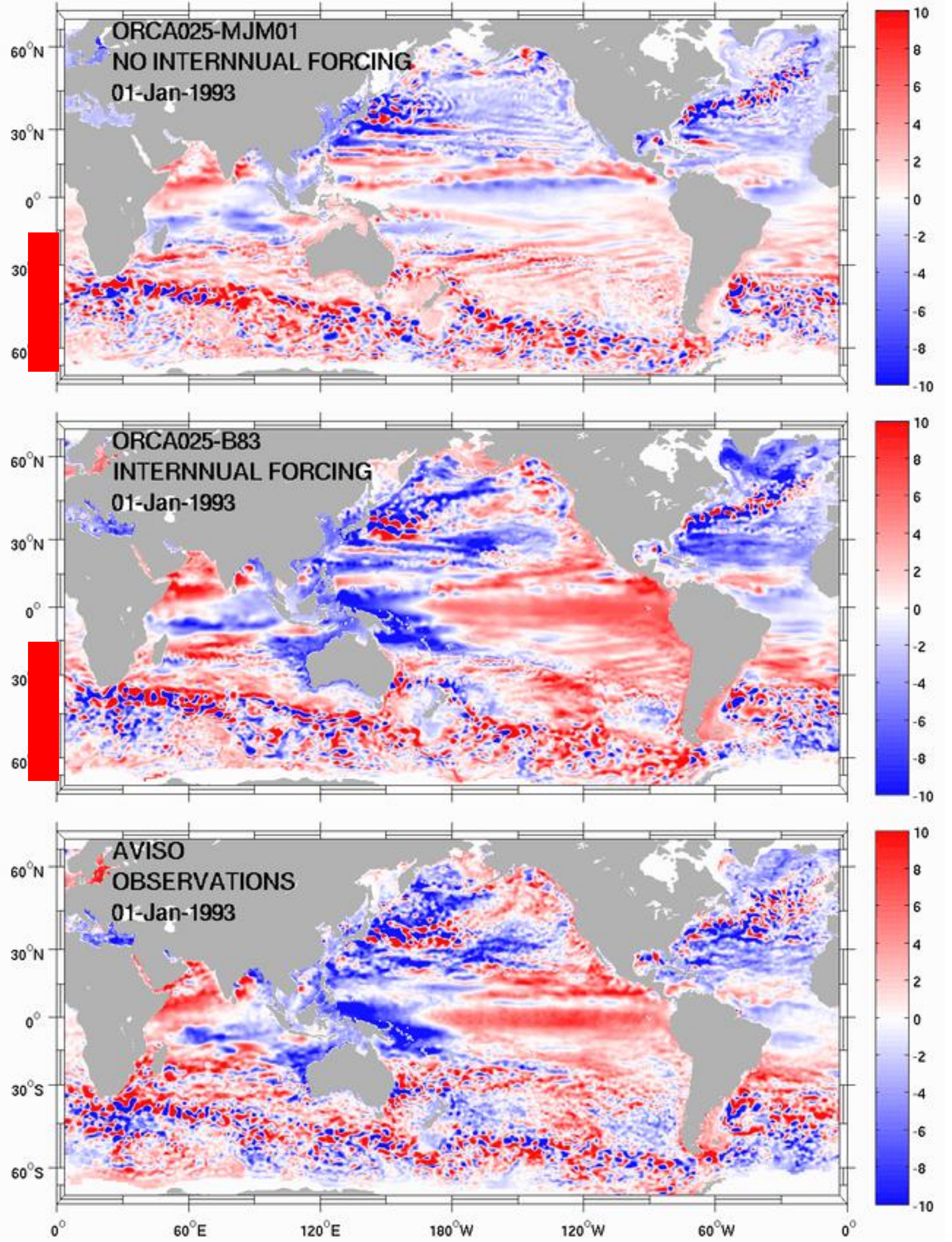
Penduff et al (2011)



Outline

Oceanic imprints of atmospheric variability and CIV

- How do we separate both impacts ?
- Variability at regional scale
  - 2-20 yr ➔ SLA : Dynamical regimes in the S.O ? Imprints on other fields ?
  - 2-100 yr ➔ SLA : CIV vs coupled variability ? Impact on trends ?
- Variability of integrated indices
  - 2-28 yr ➔ Inter-basin heat exchanges ?

    ➔ Remote impacts of S.O. CIV (AMOC, global MHT)

Other results – Perspectives

- Representativeness of simulated/observed data?
- Can we attenuating CIV in observed data ?
- How to avoid separating CIV and forced variability ?

Conclusion

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How to we separate both impacts ?

A) PAIR OF SIMULATIONS (CHAOCEAN)

Global ocean-sea ice NEMO model

Δ = 1/4° and 1/12°

Realistic forcing → Low Pass Filter → **Total variability** : $\sigma_T{}^2$

Seasonal forcing → Low Pass Filter → **Chaotic Intrinsic var :** $\sigma_C{}^2$

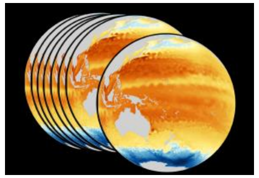
consistent

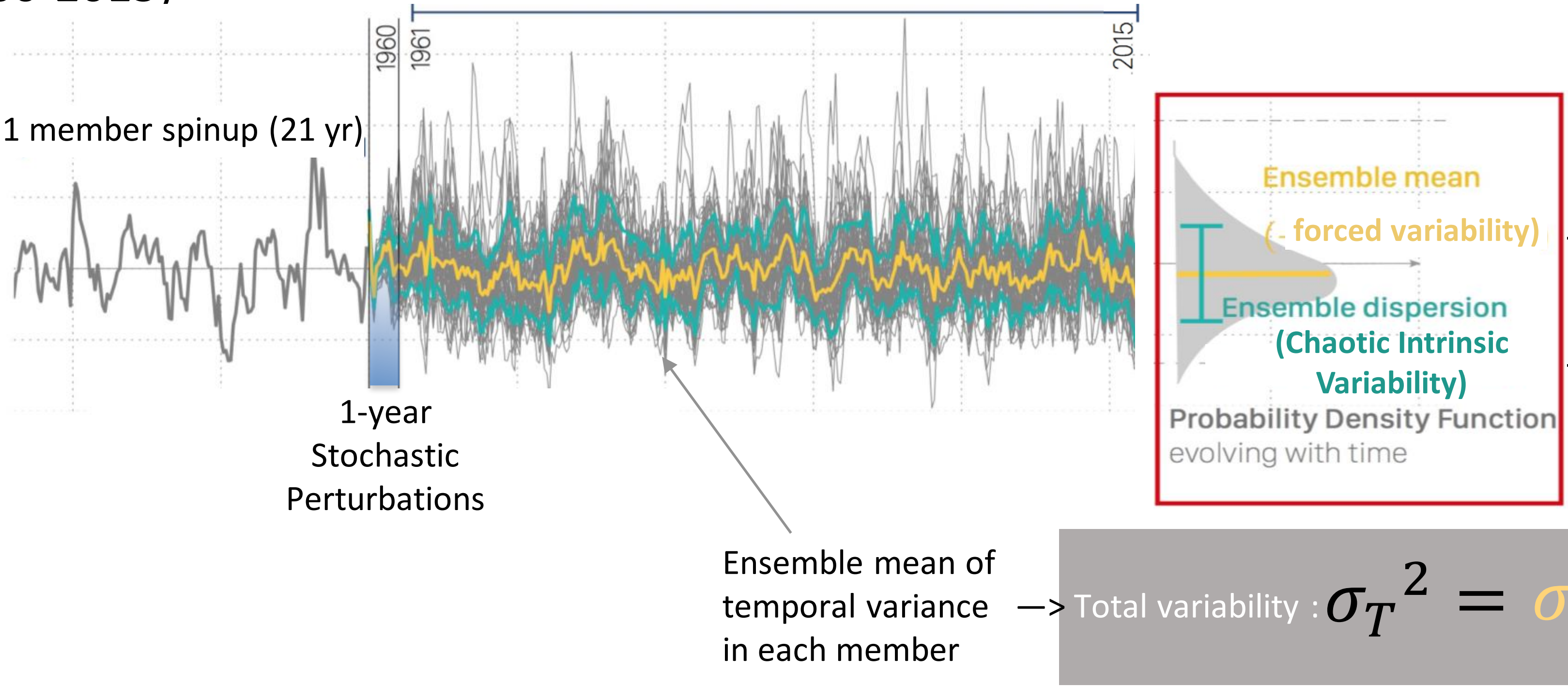
B) ENSEMBLE SIMULATION (OCCIPUT) https://meom-group.github.io/projects/occiput/

Global ocean-sea ice NEMO model. $\Delta = 1/4°$

50 members - **56** years (1960-2015)

Same realistic forcing





0th - order Diagnostics:

Variances

$\sigma_F{}^2$

$\sigma_C{}^2$

Total variability : $\sigma_T{}^2 = \sigma_F{}^2 + \sigma_C{}^2$

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

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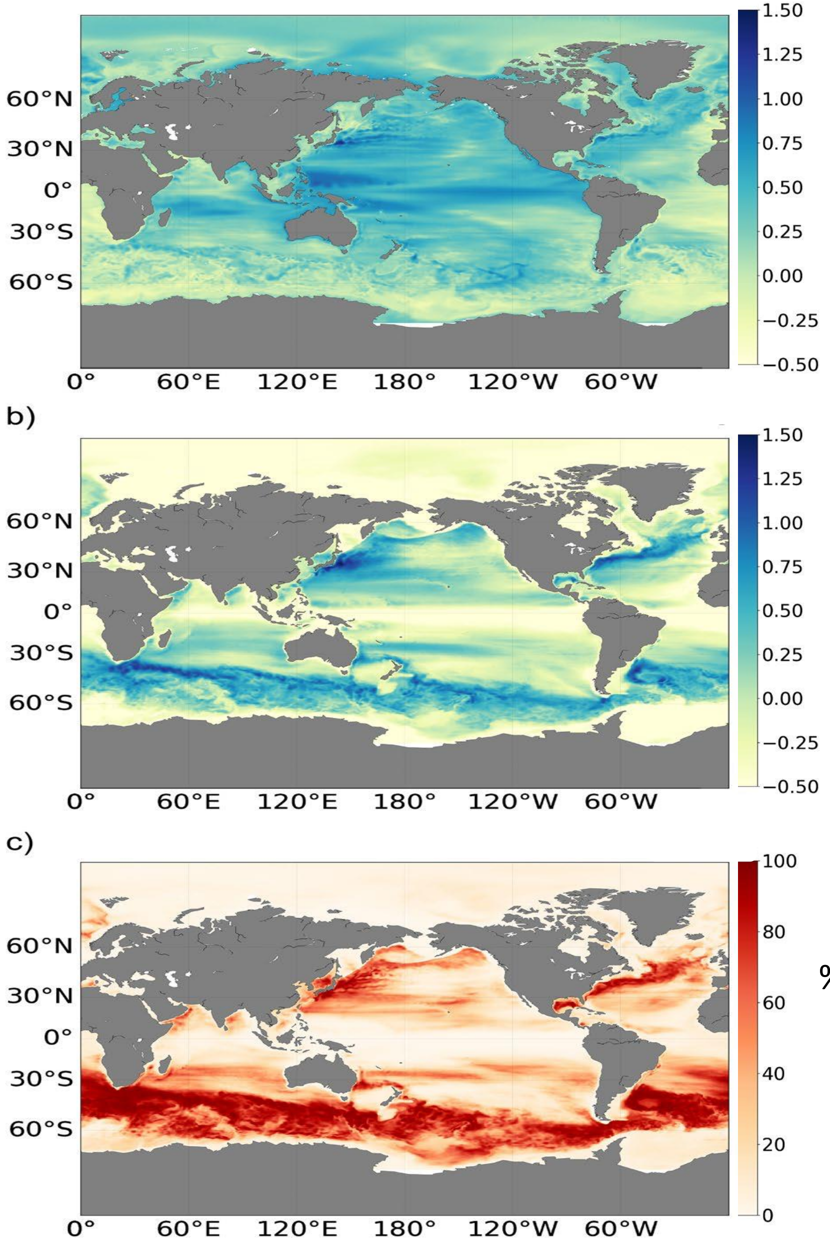
[2 < T < 20 yr] SLA variability

SLA

Forced σ_F



Log_{10}(cm)

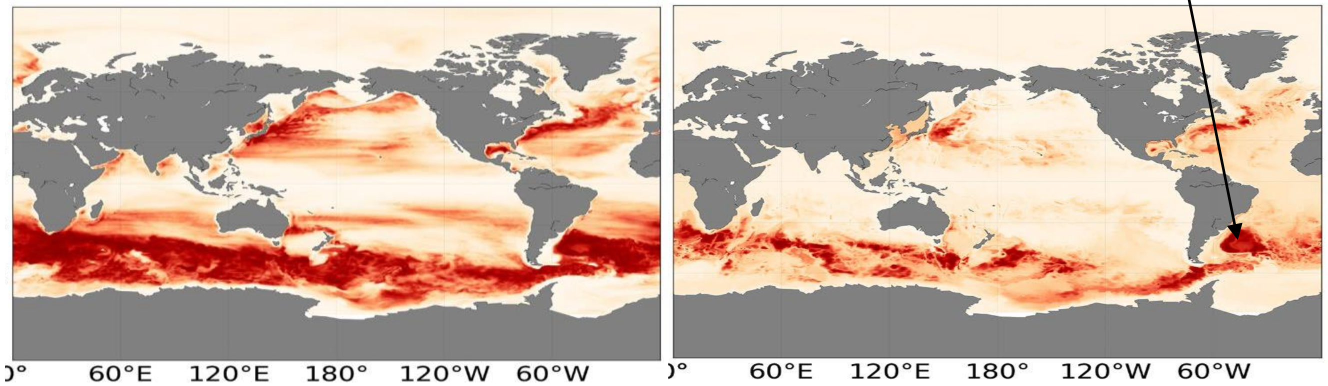
Chaotic σ_C

Log_{10}(cm)

${\sigma_C}^2 / {\sigma_T}^2$ %

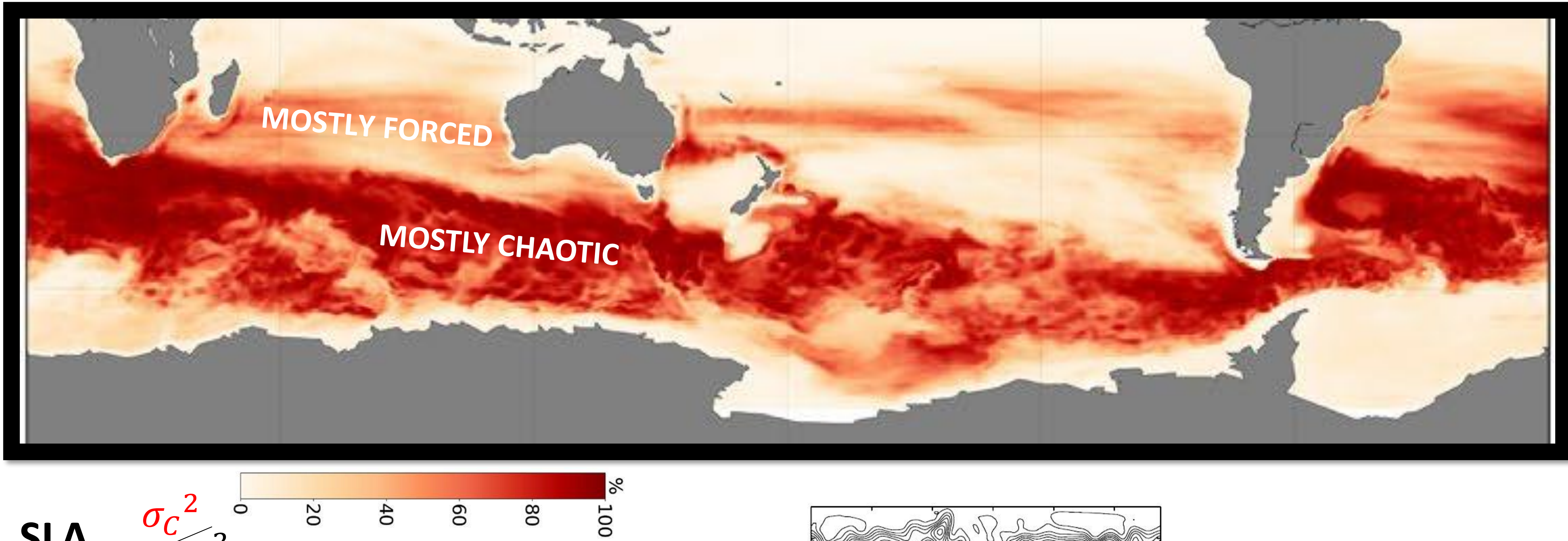
Carret et al (2021)

Steric SLA **Manometric SLA**

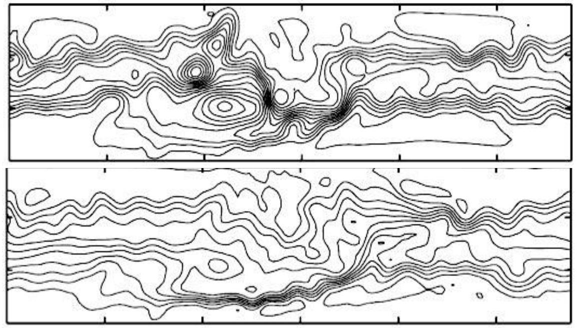


Zapiola gyre LF var.
Bigorre & Dewar 2009,
Venaille et al 2011,
Sgubin et al 2014.

[2 < T < 20 yr]   SLA variability : 2 regimes



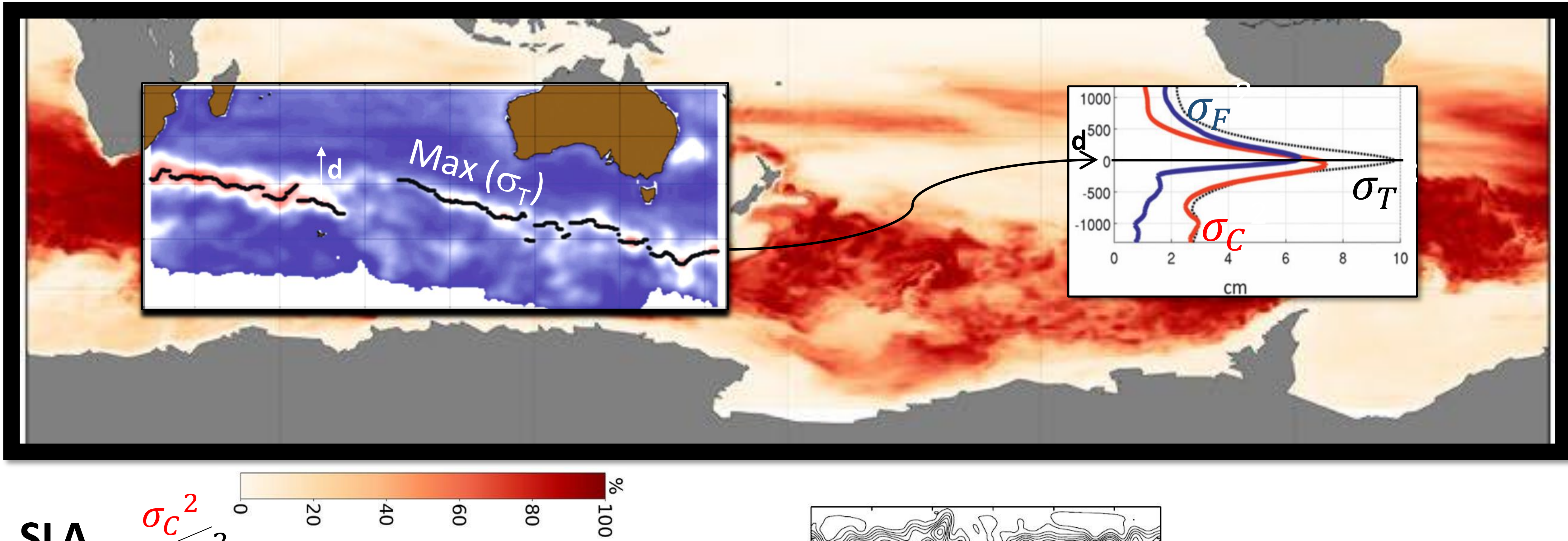
SLA $\sigma_C^{\,2} / \sigma_T^{\,2}$



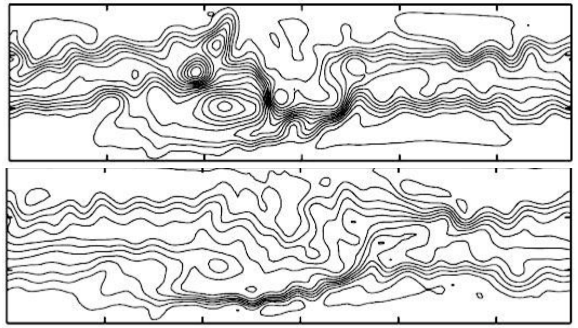
jet jumping & migration
Hogg & Blundell 2006,
Thompson & Richards 2011, etc

Carret et al (2021)

[2 < T < 20 yr]   SLA variability : 2 regimes



SLA σ_C^2 / σ_T^2



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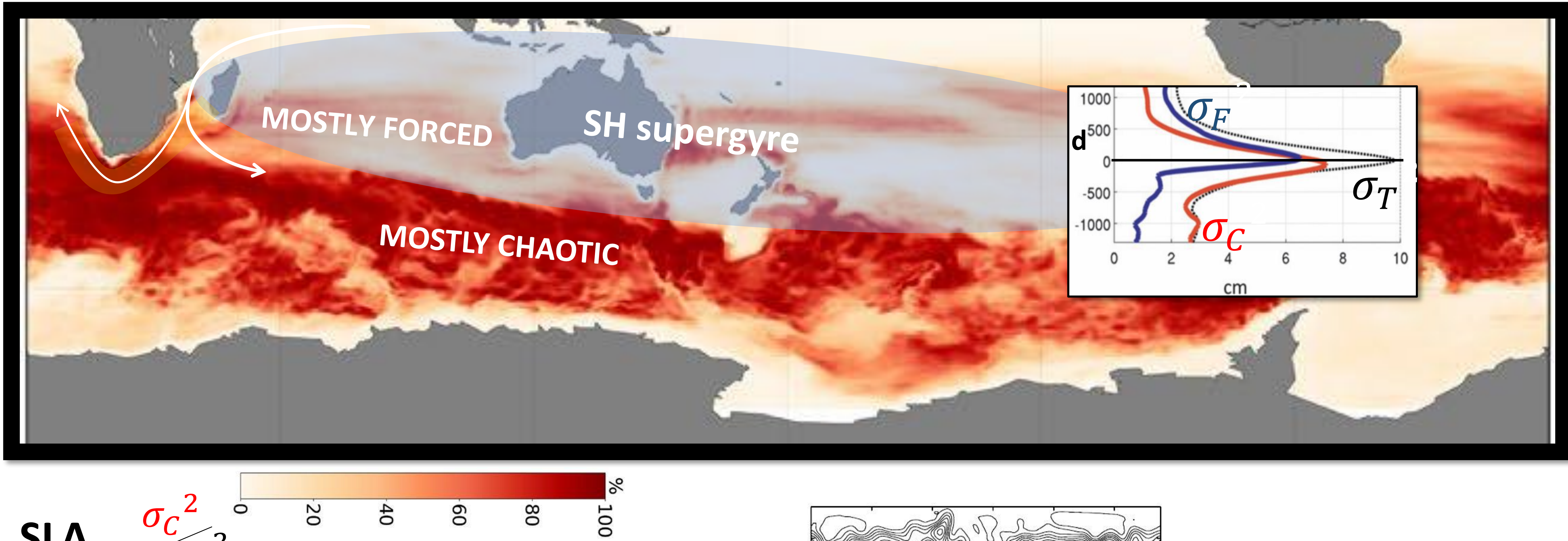
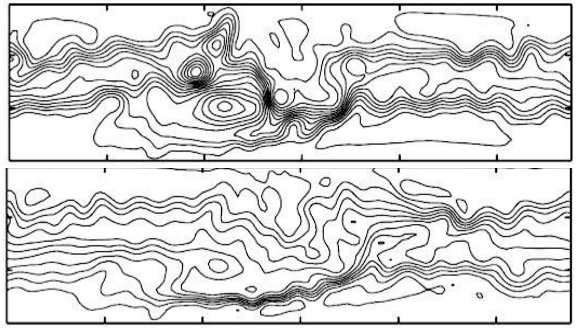


SLA $\sigma_C{}^2 / \sigma_T{}^2$



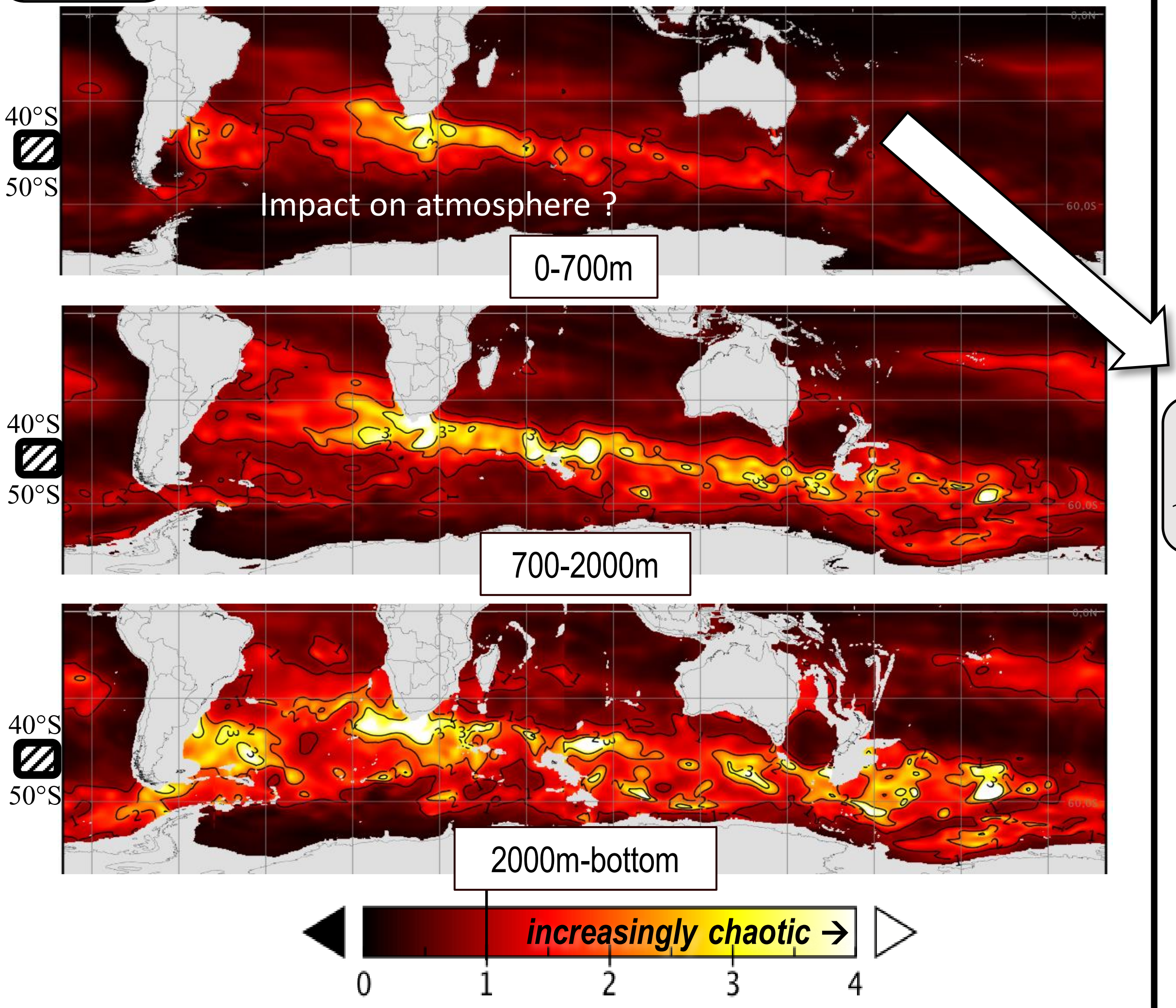
jet jumping & migration

Hogg & Blundell 2006,
Thompson & Richards 2011, etc

Penduff et al (2011)
Carret et al (2021)

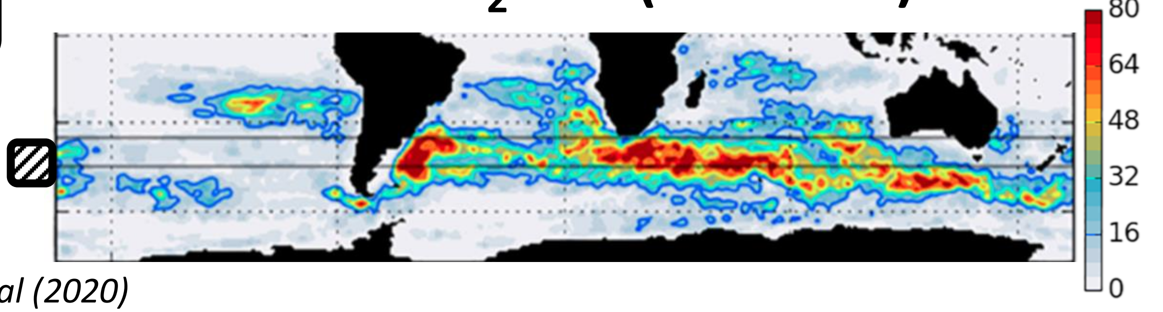
[2 < T < 20 yr] variability : other regional fields

σ_C^2 / σ_F^2 Ocean Heat Content (L>1000km)



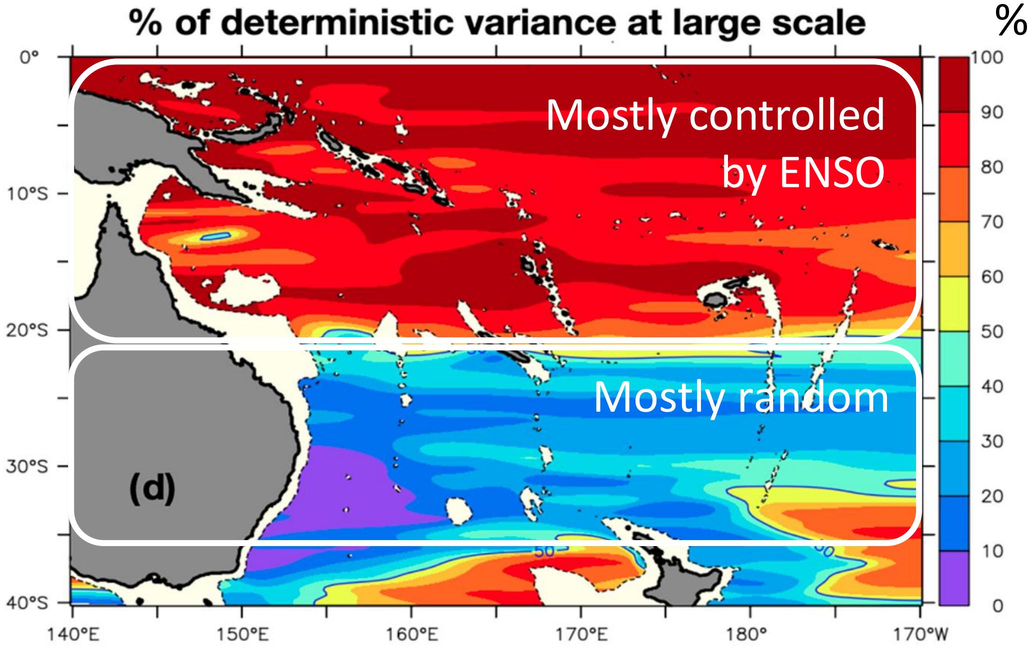
Sérazin et al (GRL 2017)

σ_C^2 / σ_T^2 Air-sea CO_2 flux (L>500km)



Gehlen et al (2020)

σ_F^2 / σ_T^2 Zonal transports (L>500km)



Cravatte et al (2021)

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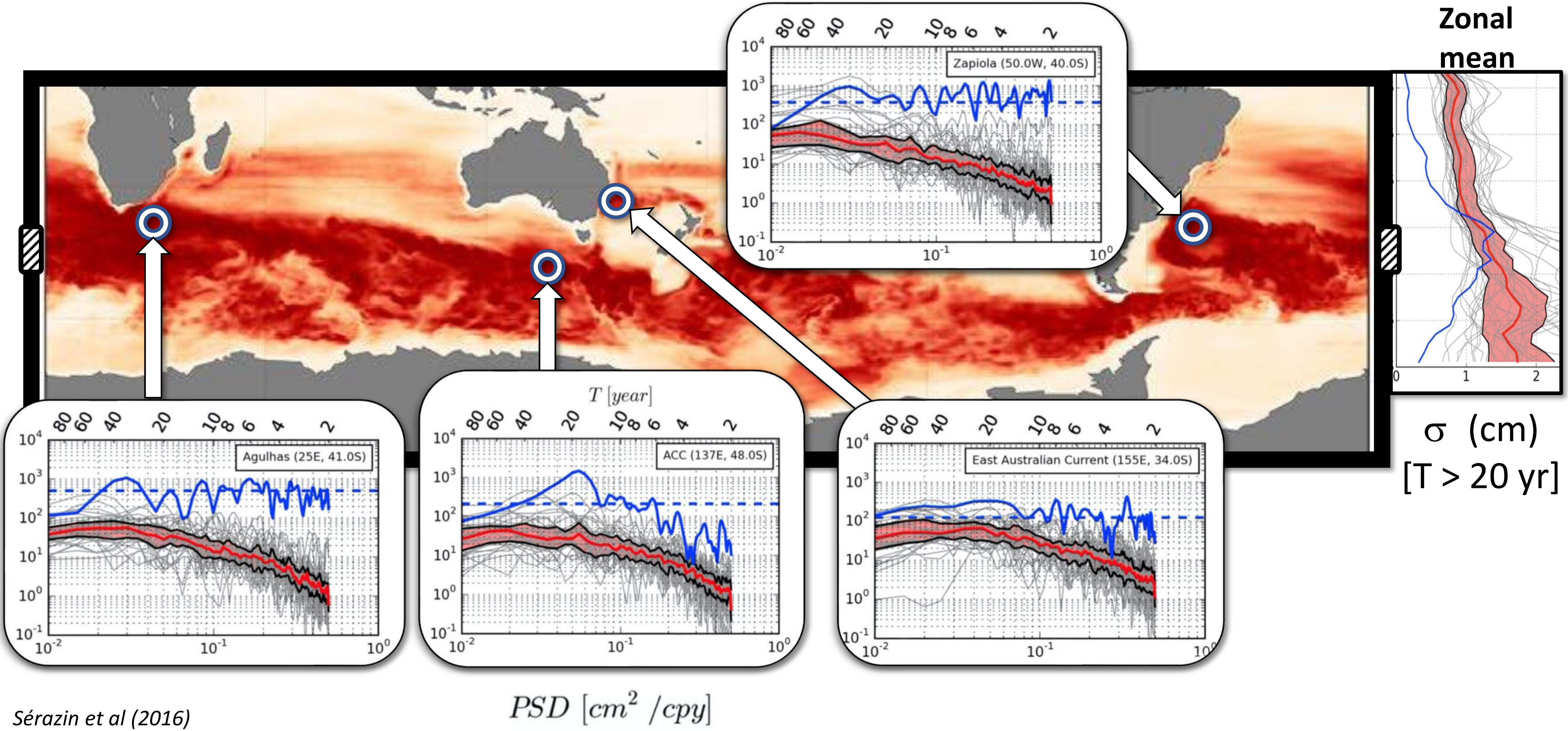
[2 < T < 100 yr] SLA variability : CIV vs coupled var (19 CMIP5 runs)



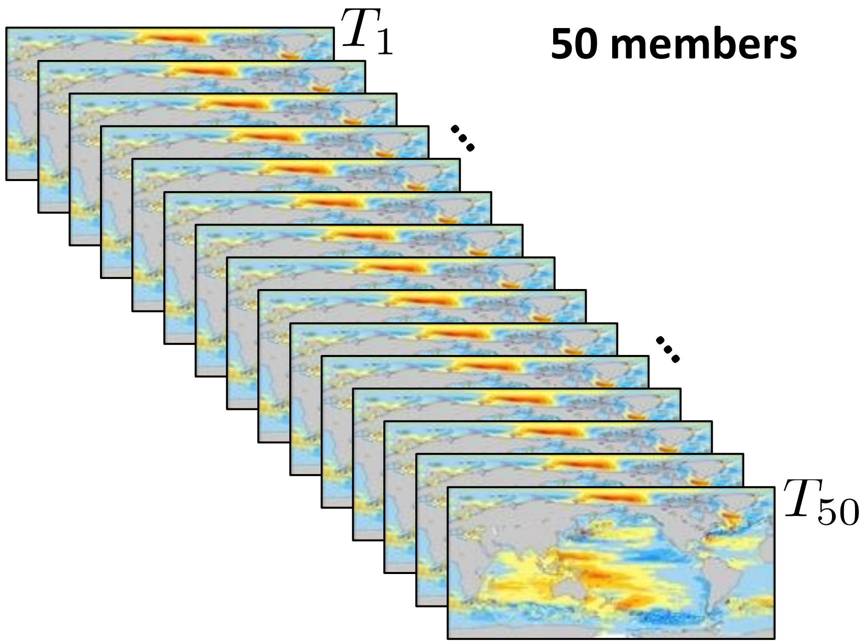
Sérazin et al (2016)

1993-2015 **SLA trends : contamination by CIV ?**

Globally-averaged sea level trend removed

Sea level trends can NOT be surely attributed to the external forcing [natural + anthropogenic] where
(95% confidence)

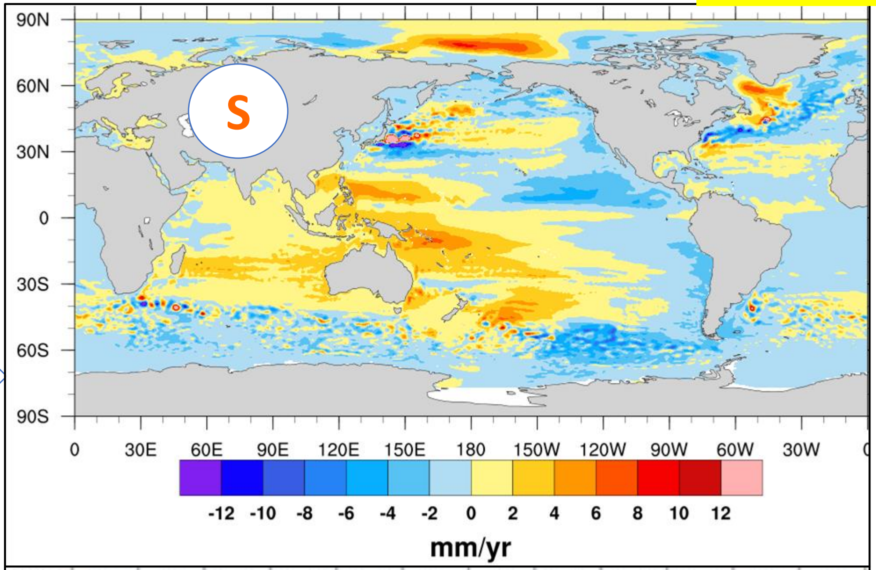
|S/N| < 2

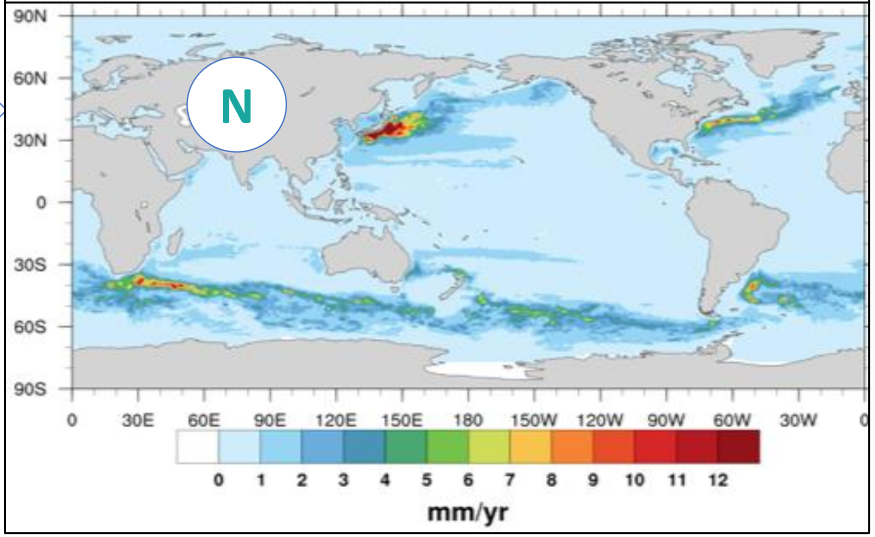


50 members

Ens. mean ➔ **SIGNAL** :
FORCED SLA trends

Ens. std ➔ **NOISE** :
RANDOM SLA trends





Model drift removed
Gaussian ensemble PDFs

Llovel et al (2018)

1993-2015 **SLA trends : attribution to external forcing ?**

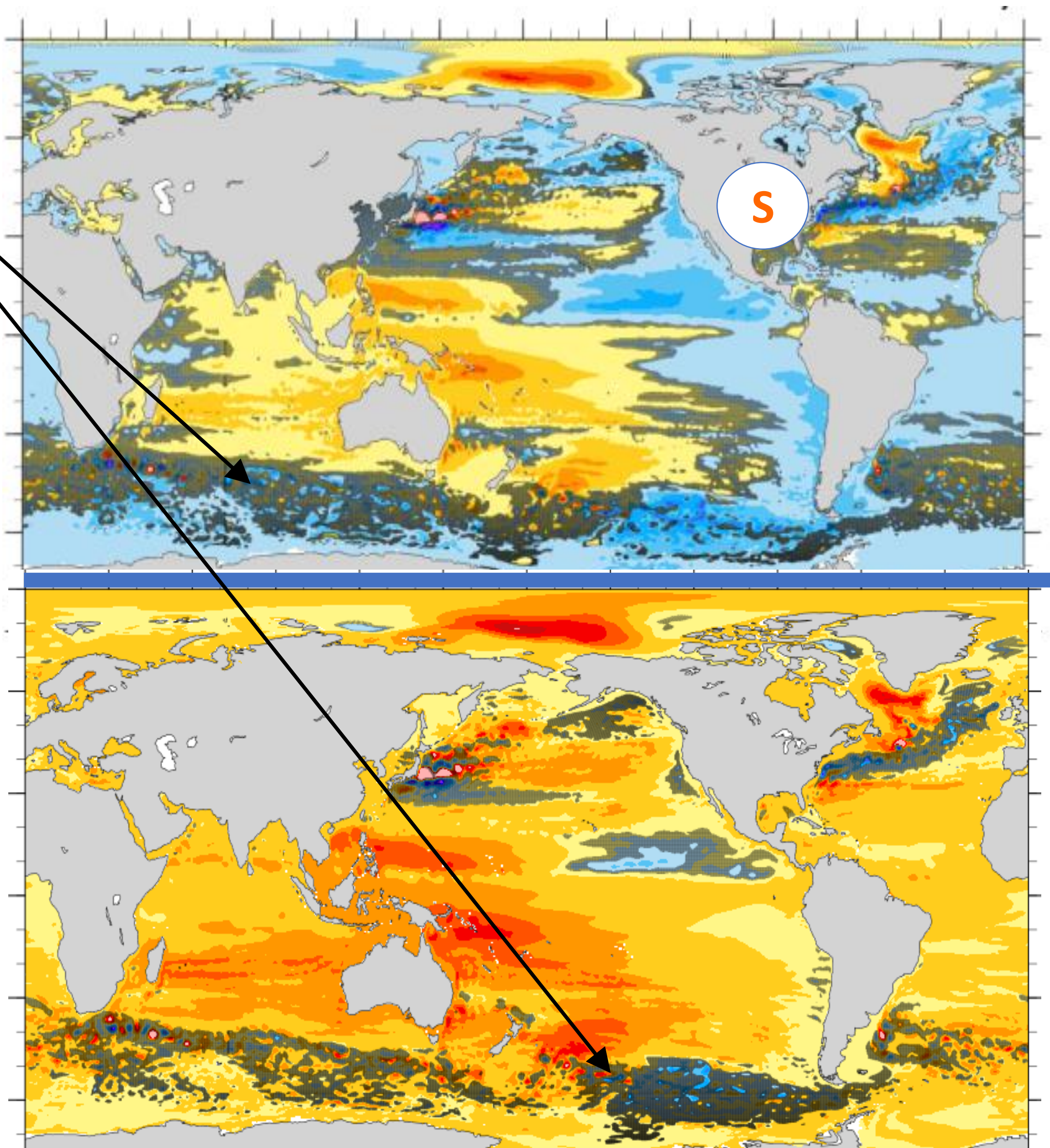
Sea level trends can NOT be surely attributed to the external forcing [natural + anthropogenic] where
(95% confidence)

|S/N| < 2

37.5% of the global ocean area

18% of the coastal ocean area

Globally-averaged sea level trend removed



Globally-averaged Forced sea level trend set to 3.2 mm/year

Llovel et al (2018)
Penduff et al (2019)

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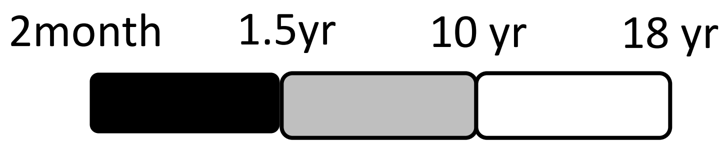
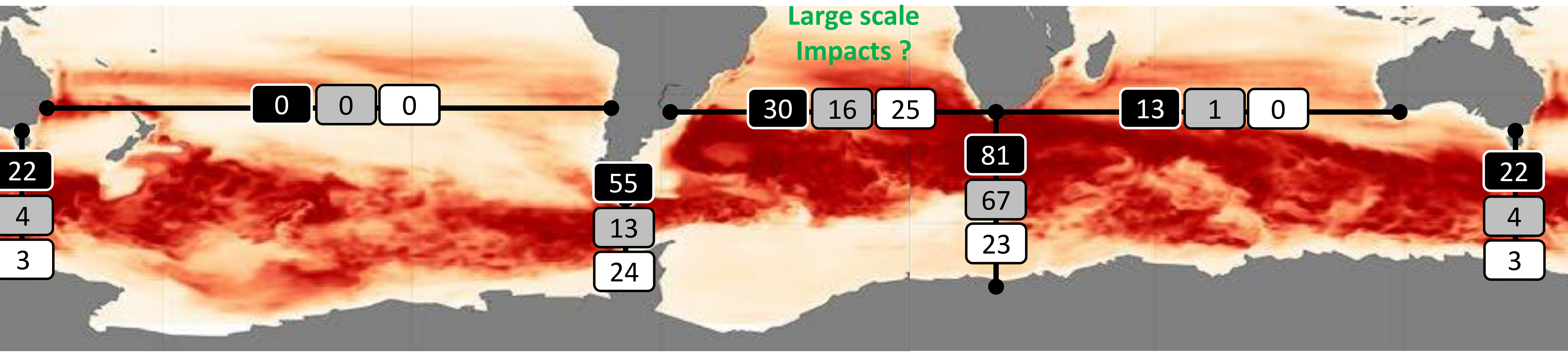
[2 < T < 18 yr] inter-basin heat transport variability

Chaotic part of the heat transport variance : σ_C^2 / σ_T^2 (%)

3 ranges of timescales





Yan (2018)

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Large scale impacts of S.O. intrinsic variability : Atlantic MOC

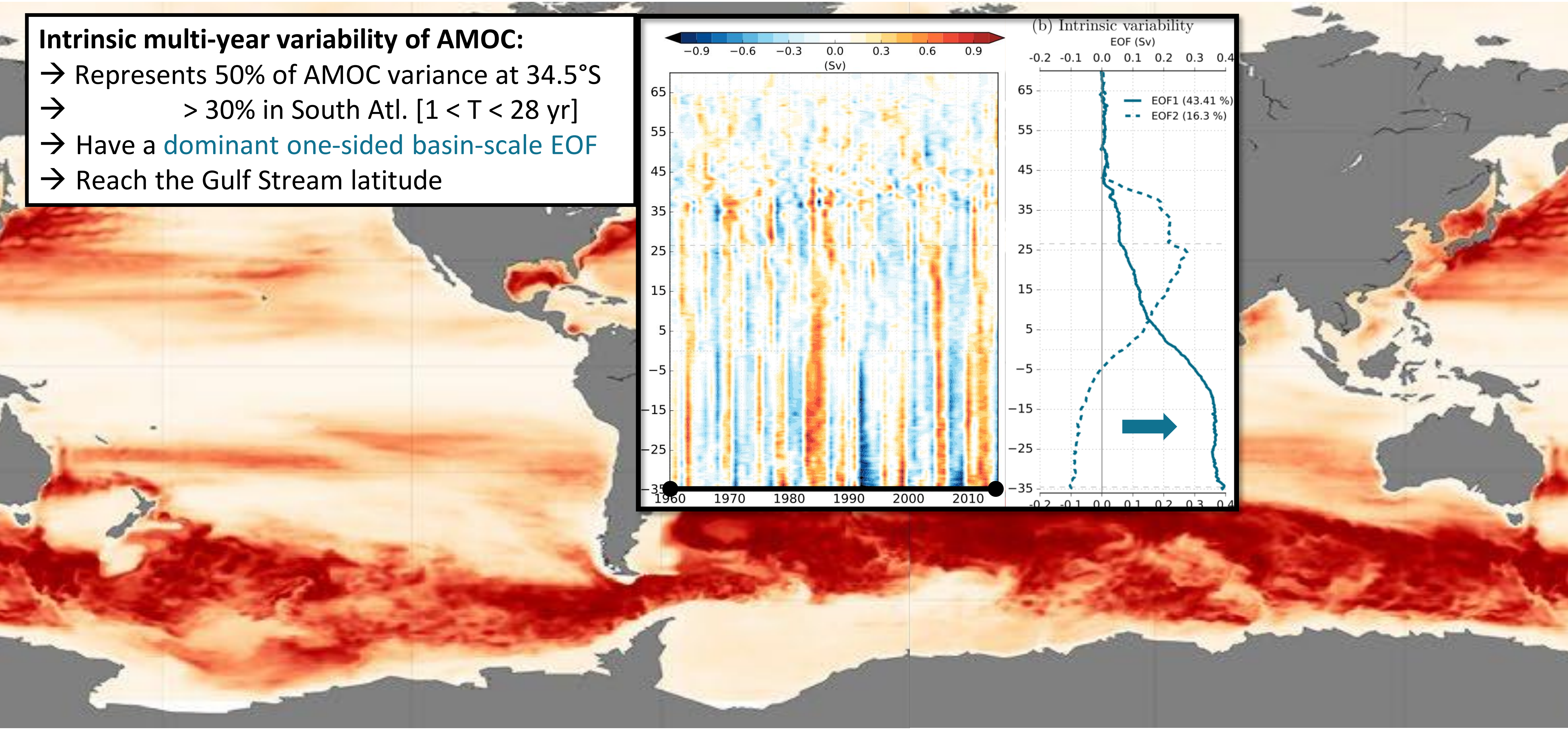
Intrinsic multi-year variability of AMOC:

→ Represents 50% of AMOC variance at 34.5°S

→ > 30% in South Atl. [1 < T < 28 yr]

→ Have a dominant one-sided basin-scale EOF

→ Reach the Gulf Stream latitude



Leroux et al (2018)

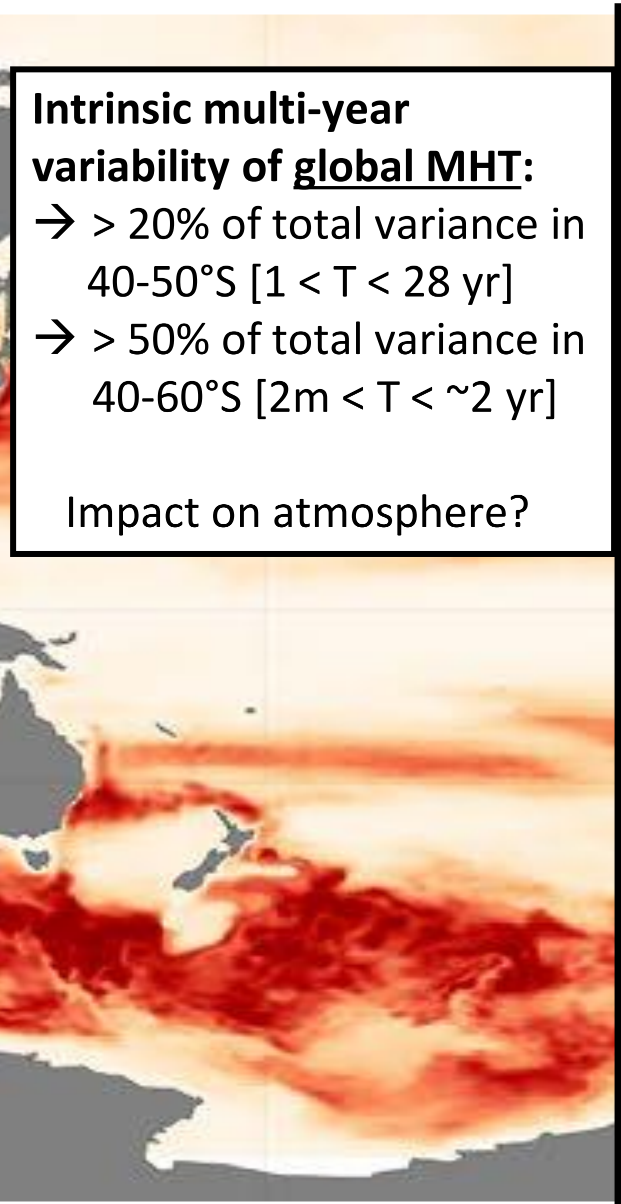
Large scale impacts of S.O. intrinsic variability : global MHT

Intrinsic multi-year variability of <u>global MHT</u>:

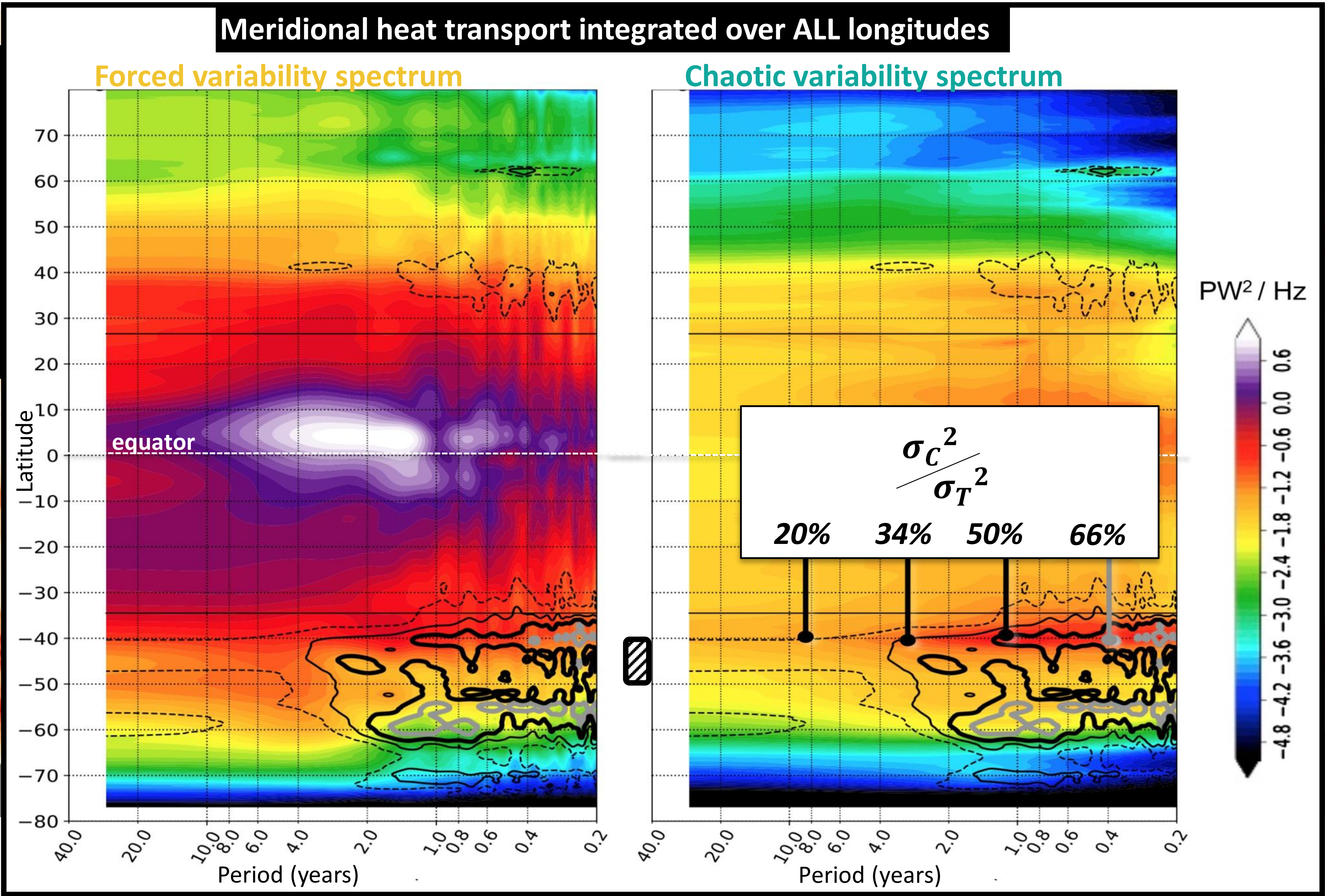
→ > 20% of total variance in 40-50°S [1 < T < 28 yr]

→ > 50% of total variance in 40-60°S [2m < T < ~2 yr]

Impact on atmosphere?



Zanna et al (2020)



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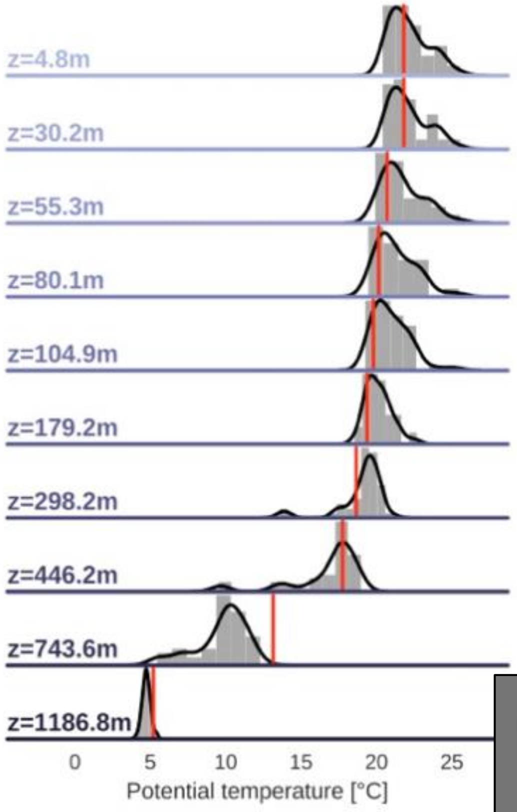
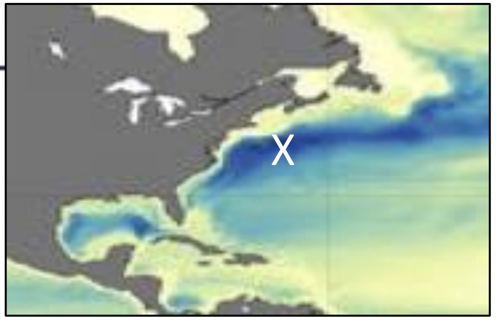
Other results — Perspectives

CIV enerates uncertainty in model outputs
→ representativeness of simulated/observed data?



Red : Argo T(z) profile within the Gulf Stream: June 1st (5:44am), 2014

Grey : OCCIPUT instantaneous E- PDF (same time and location)



Penduff et al (2018)

A few other results — Perspectives

Chaotic Intrinsic Variability (CIV)

We have **separated** CIV & the forced variability via Emean/E-std (easy, classical). OK when E-pdf(t) remains close to Gaussian (?)

But CIV should **NOT be separated** from the forced variability… : CIV is in fact modulated by the atmospheric forcing.

Pierini (2020); Fedele et al (2021)

Conclusions

Southern Ocean variability in the eddying regime

- ACC band = main CIV hotspot in the global ocean
- CIV competes with (locally exceeds) the forced variability
- CIV reaches basin-scale & multiple decades (& trends)
- CIV affects many climate-relevant indices
- Observations : one pick among many possibilities → ensemble simulation

Perspectives

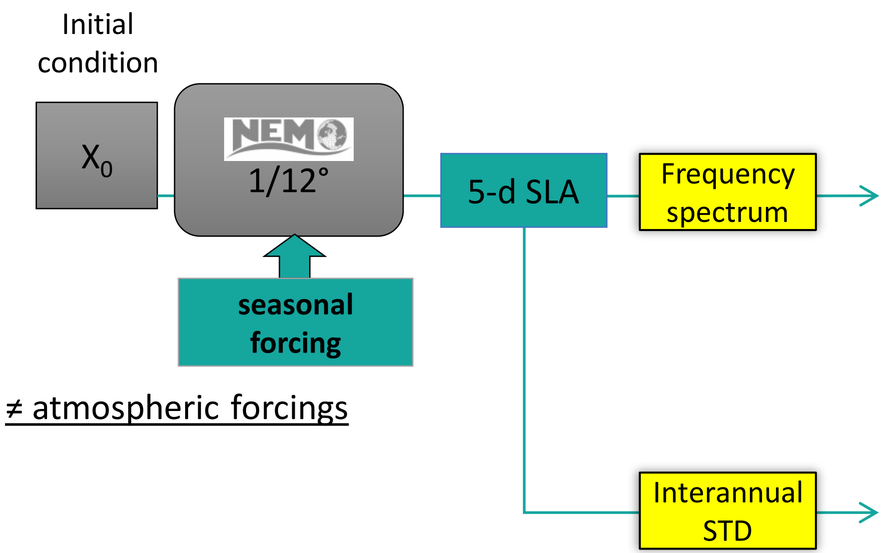
- Replace forced/intrinsic splitting by non-autonomous DS approach. Entropy ?
- Attenuate CIV in observational data (beyond SLA)
- Impact of ocean CIV on atmosphere and climate ?

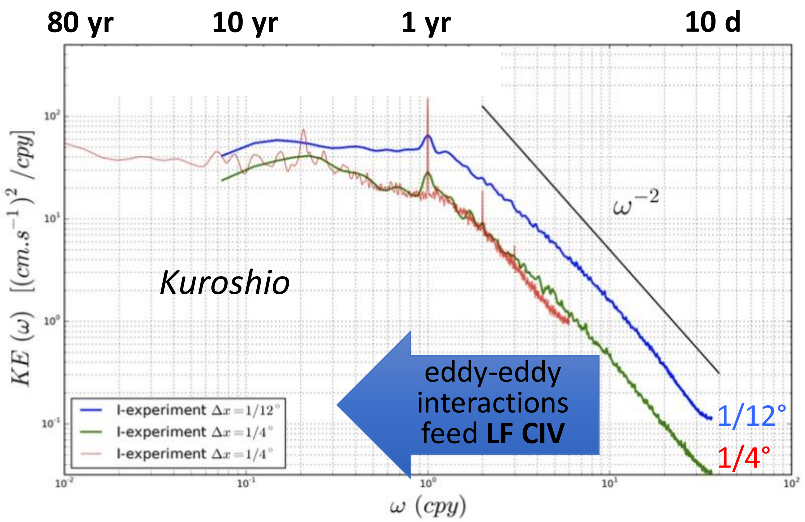
oceanic predictability ? IPSODES project

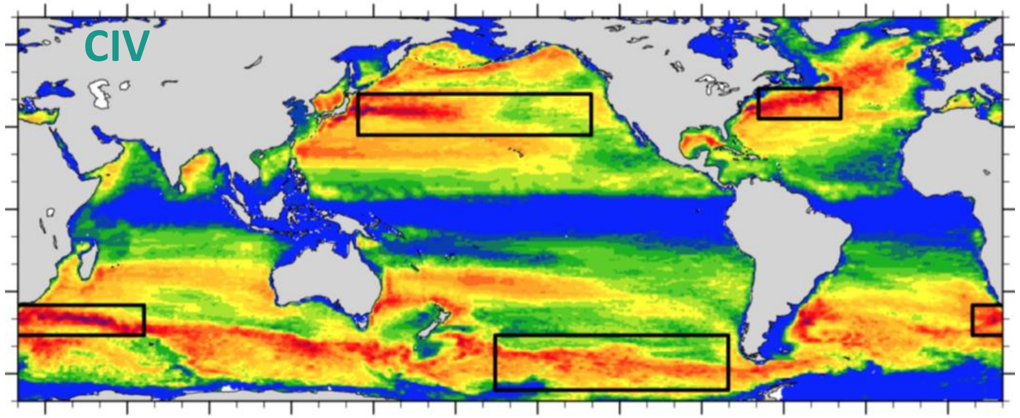
More details in https://meom-group.github.io/projects/occiput/

Chaotic Intrinsic Variability (CIV): temporal scales

Sérazin et al (2018)



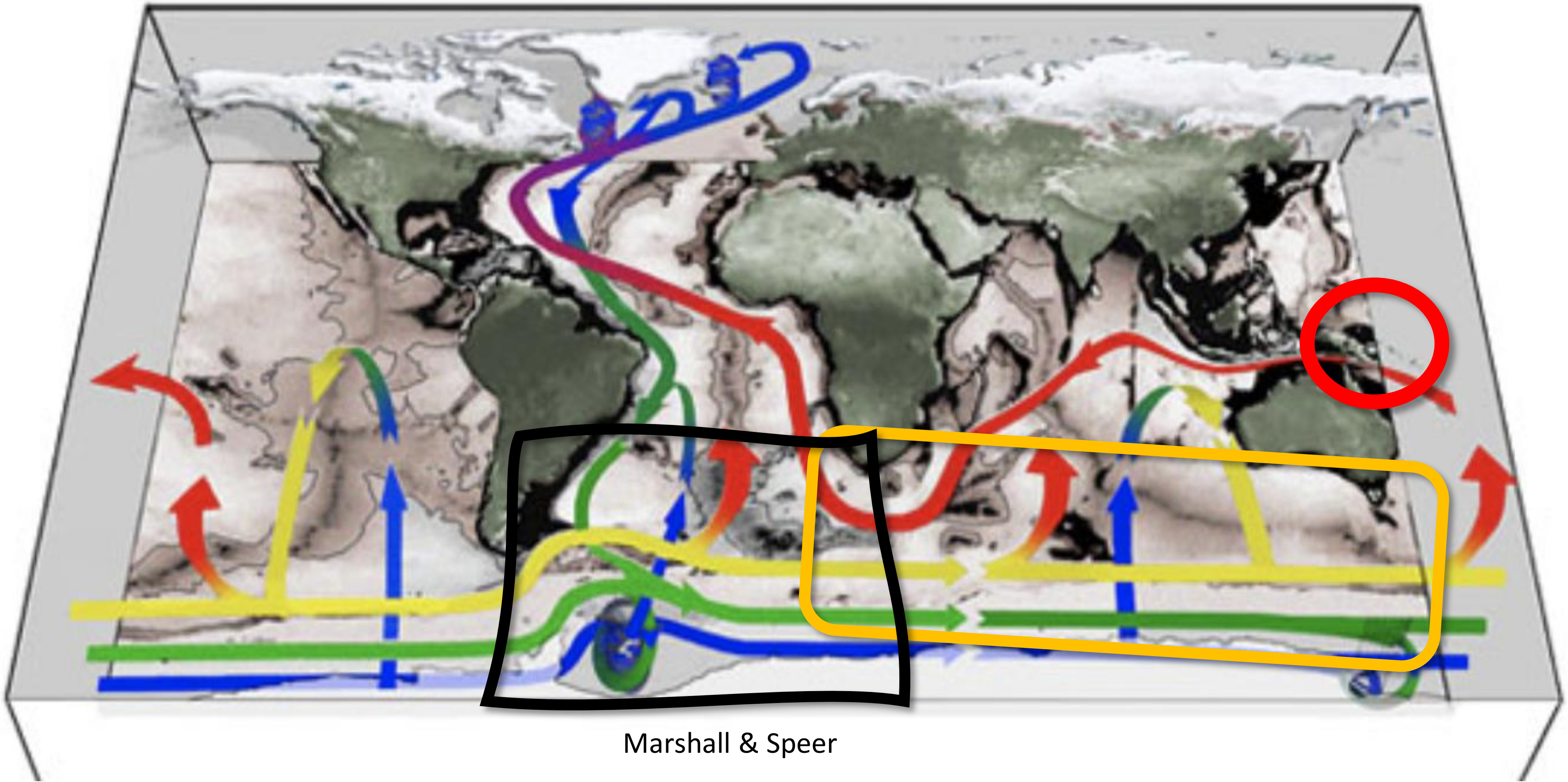




SLA interannual STD

Eddy-eddy interactions yield:

- Spatial & temporal inverse cascades
- multidecadal & gyre-scale **CIV**



Marshall & Speer

50 evolutions of yearly AMOC @34.5°S : largest impact of Chaotic variability within the Atlantic