The PIRATE OST/ST project.
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1 - General objectives and approach

The main goal of the PIRATE (*Probabilistic InteRpretation of Altimeter & in-siTu obsErvations*) OST/ST project is to study the intrinsic vs extrinsic sources of the ocean variability observed by altimeter and in-situ. We consider real observations and the OCCIPUT ensemble of ocean/sea-ice simulations to disentangle and characterize 2 components of the oceanic variability for several variables, focusing on interannual-to-decadal timescales: the first component is the Atmospherically Forced Variability (AFV) that is directly driven by the fluctuating atmospheric forcing; the second component is the Chaotic Intrinsic Variability (CIV) that is spontaneously generated by the eddying ocean, whose phase is random, and is independent of the phase of the atmospheric variability.

OCCIPUT is a pioneering multi-decadal (1960-2015) global ocean/sea-ice eddy-permitting (1/4° resolution) large (50-member) ensemble simulation that has been performed in 2015-2016 in the framework of a French ANR/PRACE project. These 50 ensemble members were perturbed initially to generate an ensemble spread, then forced over these 56 years by the same realistic fully-varying atmospheric forcing deduced from atmospheric reanalyses. Ensemble synthetic (i.e. model-derived) observations have also been generated during the 50-member integration, providing 50 equiprobable numerical counterparts of the Jason-2 along-track altimeter dataset and of the EN4 collection of local temperature and salinity profiles (including Argo, CTDs, TAO, XBTs, etc).

In PIRATE, we have disentangled the extrinsic and intrinsic sources of ocean variability in 2 ways. [1] we have first split the total model variability into AFV and CIV from simple and classical ensemble statistics: the fluctuations of the ensemble mean were used to estimate and characterize the AFV, and the deviations of each member around this ensemble mean provided us with the CIV. [2] Then we have acknowledged that this pragmatic, usual splitting of the variability into both components is not consistent with the Dynamical Systems Theory (DST): we have thus developed more mathematically-consistent diagnostics to characterize the ocean variability, now properly seen as an ocean-driven CIV modulated by the atmospheric variability throughout the integration.

The first method allowed us to confirm that the imprint of the interannual-to-decadal CIV on many observed variables (sea level, Ocean Heat Content, Atlantic Overturning, etc) can be as strong as the imprint of the AFV in several eddy-active regions: these CIV-related random low-frequency fluctuations cannot be neglected when interpreting the global ocean simulated or observed variability. We also showed that CIV may hamper in several regions the detection and attribution of externally-driven long-term trends (i.e. anthropogenic sea level, Ocean Heat Content). We have recently shown that the second method is compatible with the first one, while providing additional views on the determinism of the ocean variability (connection with DST, access to the temporal evolution of the atmospheric contraint on the oceanic chaos, validity in non-Gaussian cases, etc).

It is worth noting that [i] the oceanic CIV is strongly underestimated when the mesoscale in not resolved (i.e. the coupled models used in climate projections are mostly devoid of this active source of uncertainty), and that [ii] the contribution of CIV to the total variability only increases moderately when switching from 1/4° to 1/12° resolution (i.e. the 1/4° OCCIPUT ensemble likely provides a quite robust estimate of this ratio, which indicates the degree of chaoticity in the ocean).

2 - Specific objectives and exemples of results

The figures below illustrate some results obtained with both methods, in response to 4 specific questions addressed during the project:

- **« Which observations/locations/timescales are most affected by Low-Frequency (LF) CIV?»**

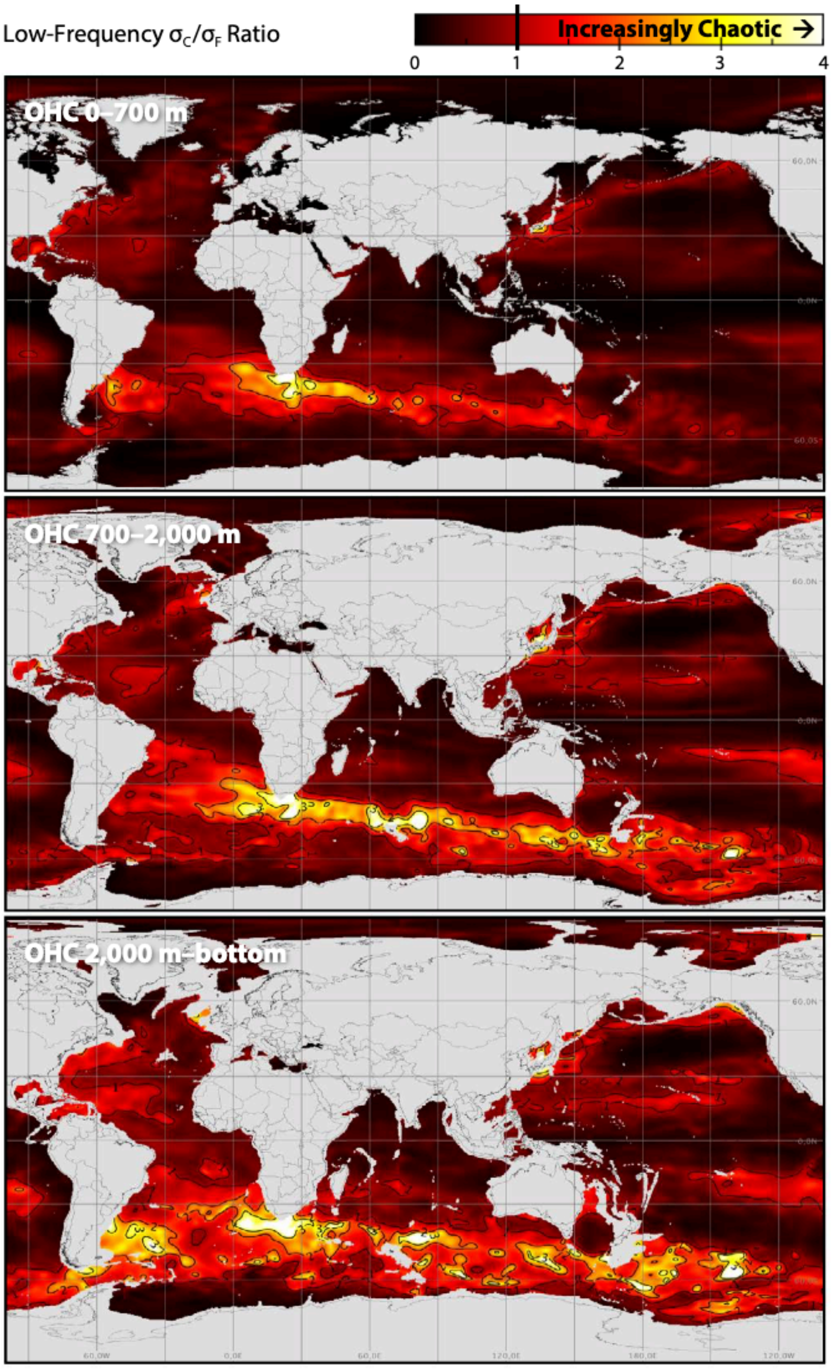

Figure 1 shows an example of the imprint of LF CIV on a key climate-relevant oceanic index: the large-scale interannual-to-decadal variability of Ocean Heat Content (OHC) over 3 depth ranges. This variability is dominantly chaotic within contoured regions, where its attribution to the atmospheric fluctuations is therefore very questionable. Estimate obtained with the first method. See Penduff et al (2018) for details.

Figure 1: *Ratio R between the CIV and AFV amplitudes at interannual-to-decadal timescales ($R = \sigma_C/\sigma_F$) for the Ocean Heat Content (OHC) at scales larger than 1000 km. From top to bottom, layers 0–700 m, 700–2000 m, and 2000 m–bottom. All time scales longer than 15 years (hence, the trends as well) were first removed from the 50-member yearly OHC fields in the 3 layers. Result obtained from the OCCIPUT ensemble simulation. From Penduff et al (2018).*

- **« Did the decadal CIV influence the global warming hiatus in the 2000's ? »**

The analysis of OCCIPUT shows that the decadal oceanic CIV has had a substantial impact on another crucial global climate-relevant index: the change in global ocean heat uptake between the 1990's and the 2000's during which the atmospheric global warming experienced a hiatus. Fig 2b shows that the decadal CIV (whose phase differs among the members) has affected the decadal migration of the main currents (in particular the Kuroshio) and yielded a change in global ocean heat uptake (Fig 2a): this uptake differs by up to 20% among the members. This suggests that decadal CIV generates an uncertainty in the extra ~0.47 W.m^{-2} that has been stored in the ocean during the 2000's. Estimates obtained with the first method by Sinha et al (in preparation).

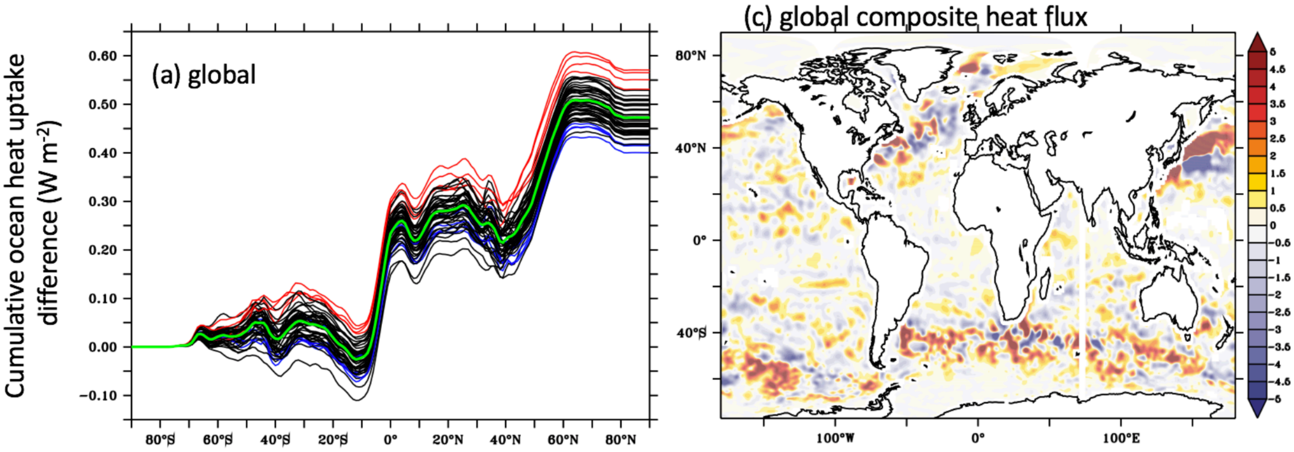

Figure 2: *(a) Decadally averaged, zonally integrated and meridionally accumulated ocean heat uptake scaled by the global ocean area (W.m^{-2}). Plotted is the change between 2000-2009 and 1990-1999: ensemble mean change (atmospherically-forced, green line), four members with highest global heat uptake change (red), four members with lowest heat uptake change (blue), and 42 other ensemble members (black). (c) Local change in decadally averaged heat uptake (2000-2009 minus 1990-1999) between four ensemble members with highest and lowest global heat uptake. From Sinha et al (in preparation).*

- **« Can the CIV signal be attenuated in observational data? »**

The CIV induces substantial multi-scale random fluctuations in simulated ocean variables, including sea level. Here we jointly address 2 open questions: [1] can we confirm that the CIV also impacts the *real* ocean? [2] is it possible to take advantage of the OCCIPUT ensemble analyses to attenuate the CIV imprint on *actual* sea level observational data and unveil its deterministic (forced) part?

In Close et al (2020a), we analyzed the frequency-wavenumber spectral coherence between the total and forced OCCIPUT-derived sea level variabilities (first method). The results reveal that sea level variability is dominantly chaotic between 100 and 800 km at all time scales. We thus designed a band-pass spatial filter that attenuates this range of space scales, and verified that filtering out these scales indeed provides a very good estimation of the forced ocean variability (i.e. the OCCIPUT ensemble mean) from any *single* OCCIPUT member. We then applied this filter on the global AVISO altimeter product (top right panel in Fig 4) to produce an observational 1993-2017 product where the CIV signature is strongly attenuated (bottom right panel).

The middle panels in Fig 3 show that the percentage of interannual sea level variance explained by the NAO is small throughout the North Atlantic in the original AVISO data (top middle panel). Filtering out the CIV imprint in these observational data unveils the forced observed sea level variability, and strongly increases the sea level variance explained by the NAO (bottom middle panel). Accordingly, sea level interannual time series near the North American coast are strongly impacted by CIV and do not correlate with the NAO in the original AVISO data, but clearly follow these atmospheric fluctuations in the filtered AVISO dataset (left panels).

The answer to questions [1] and [2] above is thus yes to both. **This filtered 1993-2017 AVISO global sea level data set is freely available at https://zenodo.org/record/3707930#.X4B7zJOiGL4 (Close et al 2020b).**

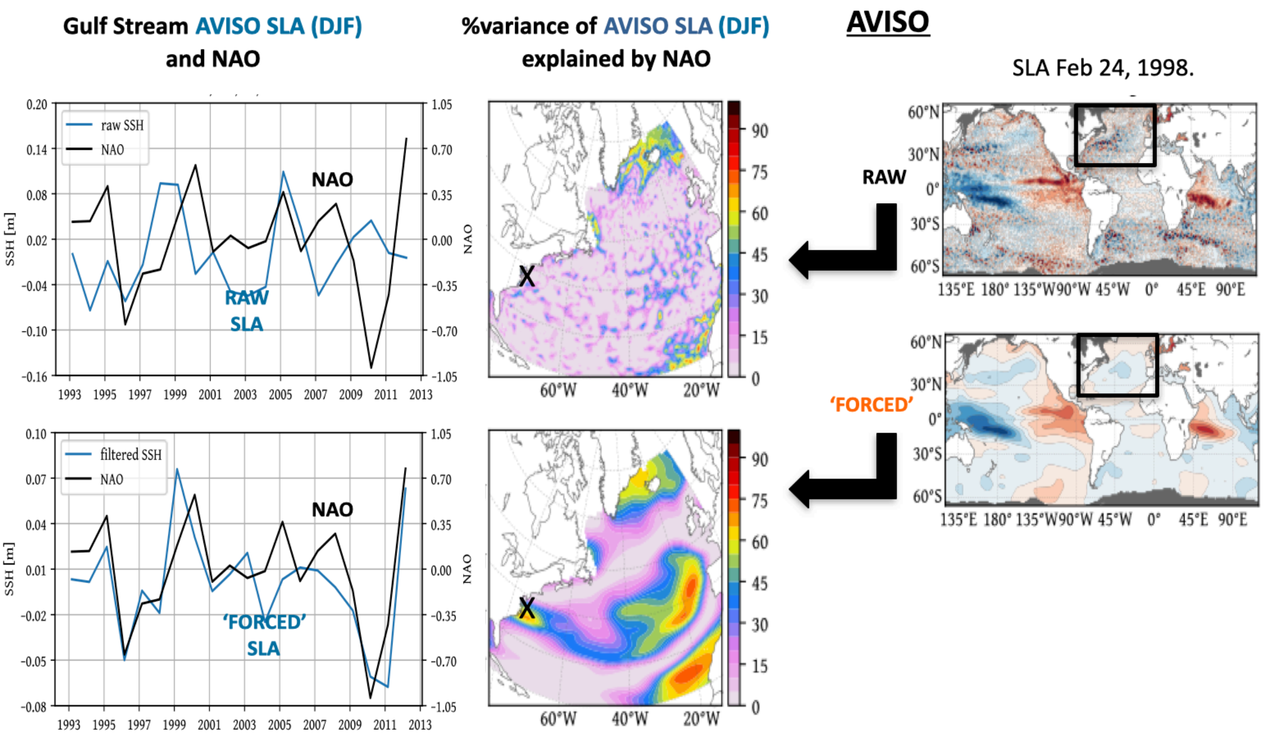

***Figure 3**:* *Right: snapshots of sea level in the original (top) and filtered (bottom) AVISO datasets. Middle: interannual North Atlantic sea level variance explained by the NAO in the original (top) and filtered (bottom) AVISO datasets. Left: sea level time series along the North American coast in the original (top) and filtered (bottom) AVISO datasets.*

- **« How is the oceanic CIV modulated by the atmosphere? »**

The eddying ocean produces a multi scale CIV under constant atmospheric forcing, as autonomous dynamical systems do. When the forcing varies as in OCCIPUT, the dynamical systems theory does not formally allows to split the AFV and the CIV as done with the first method: as for non-autonomous dynamical systems, one should instead characterize the modulation of CIV (in strength and structure in phase space) by atmospheric fluctuations.

This paradigm has been adopted for the analysis of two regions from the OCCIPUT ensemble and altimeter observations: the Gulf of Mexico where the highly chaotic loop current is partly impacted by fluctuating winds (Garcia Gomez, 2020), and in the Northwestern Pacific where the atmospheric variability influences the Kuroshio extension chaotic interannual-to-decadal variability.

Fig 4 illustrates the joint evolution of the Kuroshio latitude and velocity in the OCCIPUT ensemble in a probabilistic way. The gray shadings represent the time-evolving probability of the Kuroshio state during 35 years in this 2D phase space. This figure reveals the complex (non-Gaussian, changing) shape of CIV year after year, and its modulation by the interannually fluctuating atmospheric forcing. Various statistical features of the ensemble variability match altimeter observations. Complementary analyses of a quasi-autonomous model counterpart (pseudo ensemble built from a long seasonally-driven 1-member global run) demonstrated that the interannal atmospheric variability narrows the part of the phase space visited by the system. Diagnostics by Fedele et al (submitted to Climate Dynamics) using the second method.

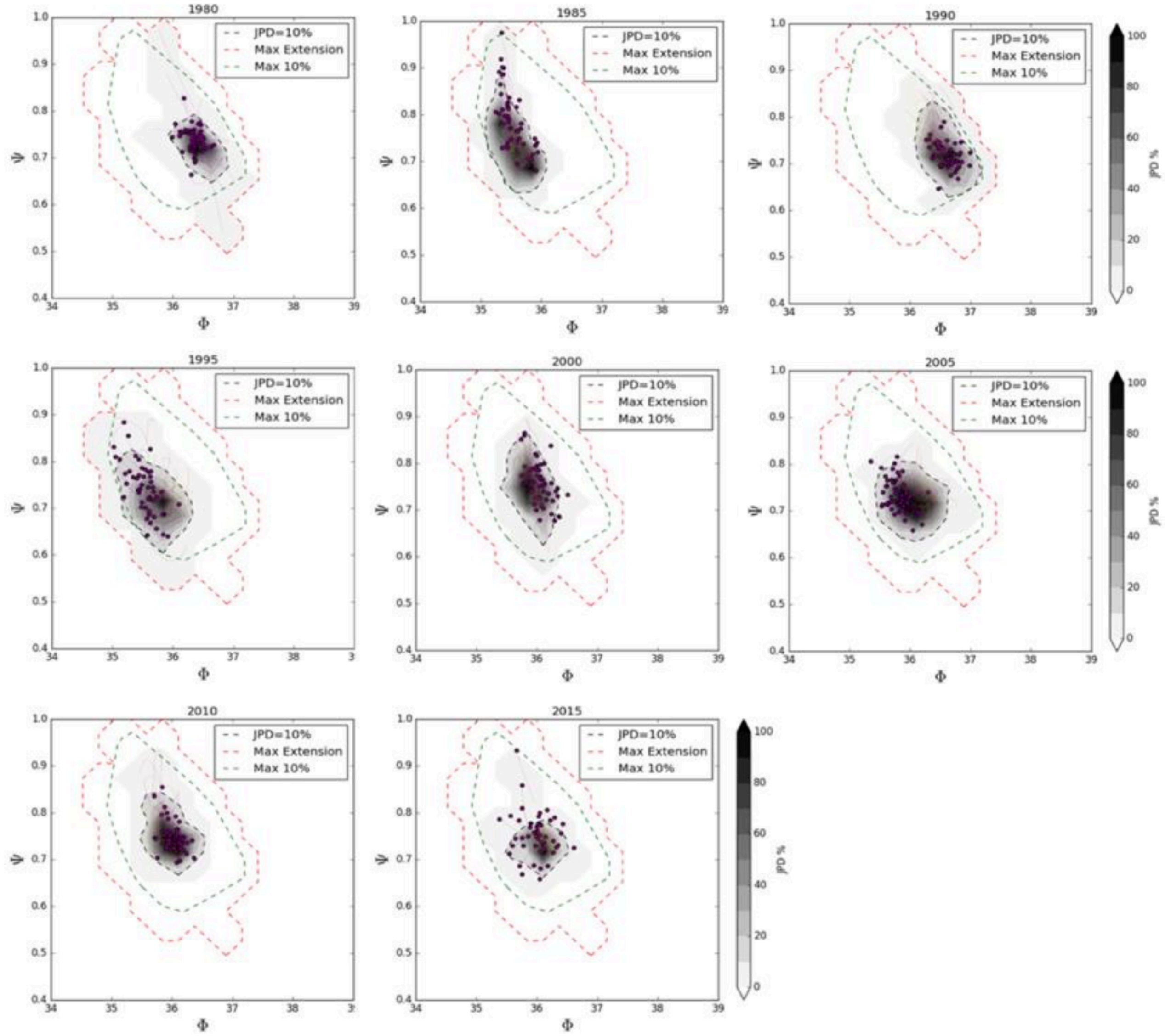

Figure 4: *Yearly Joint Probability Distributions (JPD, gray shading) of the Kuroshio latitudinal position (Φ) and velocity (Ψ) in the OCCIPUT ensemble every 5 year during 1980-2015. Yearly 10% deciles are shown as black dashed lines. The red and green dashed lines are the same in all panels and show the first decile of the Φ-Ψ JPD computed over the full 36-year period (0% and 10% isolines are shown in red and green, respectively). The purple lines show the evolution of the Kuroshio in this Φ-Ψ phase space for each of the 50 members during each selected year; the state of the current at the end of each selected year is shown for each member as purple dots.*

3 - PIRATE publications since 2017 as of October 2020

PUBLISHED

1. Bessières, L., Leroux, S., Brankart, J.-M., Molines, J.-M., Moine, M.-P., Bouttier, P.-A., Penduff, T., Terray, L., Barnier, B., and Sérazin, G., 2017: Development of a probabilistic ocean modelling system based on NEMO 3.5: application at eddying resolution, **Geosci. Model Dev.**, 10, 1091-1106, doi:10.5194/gmd-10-1091-2017.

2. Sérazin, G., A. Jaymond, S. Leroux, T. Penduff, L. Bessières, W. Llovel, B. Barnier, J.-M. Molines, and L. Terray, 2017: A global probabilistic study of the ocean heat content low-frequency variability: Atmospheric forcing versus oceanic chaos, **Geophys. Res. Lett.**, 44, 5580–5589, doi:10.1002/2017GL073026.

3. Leroux, S., T. Penduff, L. Bessières, J. Molines, J. Brankart, G. Sérazin, B. Barnier, and L. Terray, 2018: Intrinsic and Atmospherically Forced Variability of the AMOC: Insights from a Large-Ensemble Ocean Hindcast. **J. Climate**, 31, 1183–1203, https://doi.org/10.1175/JCLI-D-17-0168.1

4. Sérazin, G., T. Penduff, B. Barnier, J.M. Molines, L. Terray, and B. Arbic, 2018. Inverse cascades of kinetic energy as a source of low-frequency intrinsic variability: a global OGCM study. **J. Phys. Oceanogr.**, 48, 1385–1408, https://doi.org/10.1175/JPO-D-17-0136.1.

5. Penduff, T., G. Sérazin, S. Leroux, S. Close, J.-M. Molines, B. Barnier, L. Bessières, L. Terray, and G. Maze, 2018: Stochastic variability of ocean heat content: Climate-relevant features and observational implications. **Oceanography** 31(2).

6. Zanna, L., J.M. Brankart, M. Huber, T. Penduff, and P.D. Williams, 2018: Model Uncertainty Quantification in Ocean Ensembles: From Seasonal Forecasts to Multi-Decadal Predictions. **Q. J. R. Meteorol. Soc.**, doi: 10.1002/qj.3397.

7. Llovel, W., Penduff, T., Meyssignac, B., Molines, J.-M., Terray, L., Bessières, L., & Barnier, B., 2018 : Contributions of atmospheric forcing and chaotic ocean variability to regional sea level trends over 1993–2015. **Geophys. Res. Lett,** 45. https://doi.org/10.1029/ 2018GL080838 [Editor's Highlight in EOS]

8. Ponte, R.M., …, T. Penduff, et al, 2019: Towards Comprehensive Observing and Modeling Systems for Monitoring and Predicting Regional to Coastal Sea Level, **Front. Mar. Sci.**, https://doi.org/10.3389/fmars.2019.00437

9. Penduff, T., W. Llovel, S. Close, I. Garcia-Gomez, and S. Leroux, 2019. Trends of Coastal Sea Level Between 1993 and 2015: Imprints of Atmospheric Forcing and Oceanic Chaos. **Surveys in Geophysics**, https://doi.org/10.1007/s10712-019-09571-7

10. Close, S., T. Penduff, S. Speich, and J.-M. Molines, 2020a : A means of estimating the intrinsic and atmospherically-forced contributions to sea surface height variability applied to altimetric observations. **Progress in Oceanography**. https://doi.org/10.1016/j.pocean.2020.102314

11. Close, S., Penduff, T., Speich, S., & Molines, J.-M. (2020b). Estimate of the atmospherically-forced contribution to sea surface height variability based on altimetric observations (Version 1.0) [Data set]. **Zenodo**. http://doi.org/10.5281/zenodo.3707930

12. Zhen, Y., P. Tandeo, S. Leroux, S. Metref, J. Le Sommer, and T. Penduff, 2020: An adaptive optimal interpolation based on analog forecasting: application to SSH in the Gulf of Mexico. **J. Atmos. Oceanic Technol.** 1–46. https://doi.org/10.1175/JTECH-D-20-0001.1.

SUBMITTED AND IN PREPARATION

13. Fedele, G., T. Penduff, S. Pierini, M.C. Alvarez-Castro, A. Bellucci, and S. Masina: Interannual-to-decadal variability of the Kuroshio extension: Analyzing an ensemble of global hindcasts from a Dynamical System viewpoint. Submitted to Climate Dynamics.

14. Sinha, B., A. Megann, T. Penduff, J.M. Molines, and S. Drijfhout: Internal ocean variability and the global surface warming slowdown of the 2000s. In preparation.

15. Close S., T. Penduff, S. Speich, C. Herbaut: Mesoscale variability hides the influence of the East Atlantic pattern on North Atlantic sea level anomaly in altimetric data. In preparation

16. Cravatte, S., G. Sérazin, T. Penduff, and C. Menkes: What drives the interannual variability of the transports in the Southwest Pacific? Atmospheric forcing versus intrinsic oceanic variability. In preparation for Ocean Science.

17. Carret, A., W. Llovel, T. Penduff, and J.M. Molines: Forced and chaotic interannual variability of regional sea level and its components over 1993-2015. In preparation.

OTHERS

Garcia Gomez, B. I., 2020. Intrinsic ocean variability modulated by the atmosphere in the Gulf of Mexico: an ensemble modeling study. PhD thesis, Université Grenoble Alpes, France.