HAL
open science

Contributions of atmospheric forcing and chaotic ocean variability to regional sea level trends over 1993-2015

W. Llovel, Thierry Penduff, Benoit Meyssignac, Jean-marc Molines, Laurent Terray, Laurent Bessières, Bernard Barnier

To cite this version:

W. Llovel, Thierry Penduff, Benoit Meyssignac, Jean-marc Molines, Laurent Terray, et al.. Contributions of atmospheric forcing and chaotic ocean variability to regional sea level trends over 1993-2015. Geophysical Research Letters, 2018, 45 (24), pp.13,405-13,413. 10.1029/2018gl080838 . hal-02003015

HAL Id: hal-02003015

https://hal.science/hal-02003015v1

Submitted on 28 Mar 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Contributions of atmospheric forcing and chaotic ocean variability to regional sea level trends over 1993-2015

William Llovel*[1] http://orcid.org/0000-0002-0798-7595 ,

Thierry Penduff[2] http://orcid.org/0000-0002-0407-8564,

Benoit Meyssignac[1] https://orcid.org/0000-0001-6325-9843,

Jean-Marc Molines[2] https://orcid.org/0000-0003-1665-6816,

Laurent Terray[3] https://orcid.org/0000-0001-5512-7074,

Laurent Bessières[3] https://orcid.org/0000-0001-6492-3427

and Bernard Barnier[2] https://orcid.org/0000-0002-7539-2542

*corresponding author william.llovel@legos.obs-mip.fr

1- LEGOS/CNRS/IRD/CNES/UPS, Toulouse, France.
2- Université Grenoble Alpes, CNRS, IRD, Grenoble-INP, IGE, Grenoble, France
3- CERFACS, CECI, Toulouse, France

Key points:

- Atmospheric drivers force regional sea level trends over most of the global ocean area since 1993
- Chaotic ocean variability may mask these atmospherically forced regional trends over a substantial fraction of the global ocean area
- In the latter regions, altimeter-derived regional sea level trends may not be representative of anthropogenic or atmospheric causes

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1029/2018GL080838

Abstract

A global ¼° ocean/sea-ice 50-member ensemble simulation is analyzed to disentangle the imprints of the atmospheric forcing and the chaotic ocean variability on regional sea level trends over the satellite altimetry period. We find that the chaotic ocean variability may mask atmospherically-forced regional sea level trends over 38% of the global ocean area from 1993 to 2015, and over 47% of this area from 2005 to 2015. These regions are located in the western boundary currents, in the Southern Ocean and in the subtropical gyres. While these results do not question the anthropogenic origin of global mean sea level rise, they give new insights into the intrinsically oceanic versus atmospheric forcing of regional sea level trends, and provide new constraints on the measurement time required to attribute regional sea level trends to the atmospheric forcing or to climate change.

Plain language summary

As a direct consequence of anthropogenic influences, global mean sea level rises in response to ocean warming and land ice melting. Since the early 1990s, satellite altimetry has revealed large regional contrasts in sea level trends, controlled by temperature and salinity changes, oceanic processes and atmospheric forcing. Using an ensemble of forced eddying ocean simulations, we show that regional sea level trends over the altimetric period are only partly determined by the atmospheric evolution (both natural and anthropogenic): nonlinear ocean processes produce additional sea level trends that are inherently random, which can compete in certain regions with the externally-forced trends. These results do not question the existence of global and regional sea level trends, but suggest that sea level trends may not be unambiguously attributed to external causes in certain regions.

1- Introduction

As a direct consequence of the ongoing global warming, global mean sea level has risen in response to land ice melt (as melt water flows from land to the ocean) and to ocean warming (thermal expansion, Church et al., 2013) and other lesser factors such as the impoundment of water by reservoirs.

Since the early 1990s, satellite altimetry has become the main observing system for continuously measuring the sea level variations. Satellite altimetry has revealed large regional contrasts in sea level trends.

Altimetry-based measurements of sea level trends are affected by various uncertainties (instrumental errors, perturbations of the radar echo travelling through the atmosphere and orbit determination). Efforts have been made to create a homogeneous sea level record with all available satellite altimetry data, to identify and reduce sea level trend errors. Regional satellite altimetry trend errors are on the order of 2-3 mm/yr over a long-term evolution (> 10 years; Ablain et al., 2017), but would need to be lowered down to $1 mm.yr^{-1}$ in order to assess regional sea-level trends on decadal time scales, and for the detection of climate change impacts and model improvements (see GCOS, 2011).

Ocean model simulations have been used to estimate the role of the atmosphere in forcing the regional patterns in sea level changes (Forget and Ponte 2015). Wind stress, buoyancy and mass air-sea fluxes explain large scale fluctuations of sea level at time scales longer than one month and spatial scales of 3° and larger, and have a substantial imprint on sea level trends.

Ocean model simulations, in particular in the eddying regime, also revealed the existence of another possible driver of regional sea level trends. A NEMO-based 1/4° global ocean/sea-ice simulation driven for 327 years by a repeated climatological atmospheric forcing has shown that a strong low-frequency chaotic intrinsic variability spontaneously emerges from the ocean (Penduff et al., 2011). Hydrodynamic instabilities spontaneously generate mesoscale eddies, whose mutual non-linear interactions may in turn feed chaotic fluctuations at longer time and space scales through spatio-temporal inverse cascade processes (Sérazin et al., 2018). This multi-decadal "noise" emerges from the turbulent ocean without any trend or low-frequency variability in the atmospheric forcing. These chaotic fluctuations may leave random imprints on decadal regional sea level trends, in particular in the Gulf Stream, Kuroshio and Antarctic Circumpolar Current (ACC) (Sérazin et al., 2016). Should these chaotic trends remain substantial in an ocean driven by the full range of atmospheric time-

scales, they may partially mask the regional sea level trends due to the atmospheric forcing, and constitute a source of uncertainty.

These results raise new questions for model simulations, and potentially for the real ocean: are the spatial patterns of sea level trends a direct response of the atmospheric forcing? How can we disentangle the atmospherically-driven and chaotic sea level trends? How many years of satellite altimetry measurement are needed to extract the atmospherically-driven sea level trends from their random counterparts? The purpose of this study is to answer these questions, to identify and quantify the respective contributions of atmospherically-forced and chaotic ocean variability to simulated regional sea level trends, and extend these results to those observed from satellite altimetry since 1993.

The paper is organized as follows. Section 2 describes the data sets and methods considered in the analysis. Section 3 presents and compares the imprints of the atmospheric forcing and of the chaotic ocean variability on regional sea level trends. In the last section we summarize the results, address the broader implications of the findings, and discuss the perspectives of this work.

2- Data and Methods

2.1 Satellite altimetry

We use the Climate Change Initiative (CCI) sea level products to evaluate sea level trends, and to assess the model simulation. The purpose of the CCI dataset is to provide an accurate and homogeneous long-term altimetry-based sea level record with two main specificities. First, all available satellite altimeters are taken into account, including the ESA missions (ERS-1/2-Envisat) along with the Topex/Poseidon and Jason reference missions. Second, all processing steps, including geophysical corrections are applied with coherent datasets over the whole period of the CCI product in order to meet the Global Climate Observing Systems requirements (Ablain et al., 2017). The CCI data set consists of monthly sea level anomalies on a global ¼° grid (Legeais et al., 2018) from January 1993 to December 2015.

2.2 The OCCIPUT ensemble simulation

We make use of the OceaniC Chaos – ImPacts, structure, predictability (OCCIPUT) ensemble of 1/4° ocean/sea-ice simulations (Penduff et al, 2014; Bessières et al., 2017). This ensemble consists of 50 global hindcasts at ¼° horizontal resolution performed over 1960-2015. The configuration is based on the NEMO 3.5 model and implemented on an eddy-permitting quasi-isotropic horizontal mesh whose grid spac-

ing is about 27 km at the equator and decreases poleward. The 50 members are initialized on January 1st 1960 from the final state of a 21-year one-member spinup. A small stochastic perturbation (Brankart, 2013) is applied within each ensemble member during the first year (1960) and switched off at the end of 1960, yielding 50 different oceanic states on January 1st 1961. Each member is then integrated until the end of 2015 with the same atmospheric forcing (DSF5.2, Dussin et al., 2016) based on the ERA-Interim atmospheric reanalysis. We therefore obtain an ensemble of 50 simulations with the same numerical model and forcing, but different initial conditions.

We also used a one-member 327-year climatological simulation based the exact same code and setup to estimate the spurious model drift. This simulation was forced each year with the same annual atmospheric cycle derived from DFS5.2 (Penduff et al., 2011). The spurious drift of simulated sea level was estimated at every grid point by computing sea level trends in the climatological simulation by considering the corresponding years of the 1993-2015 OCCIPUT simulations. This spurious trend map was then removed from the 50 trend maps derived from the ensemble simulation (Penduff et al., 2018).

As the NEMO model conserves volume rather than mass, the global steric effect is missing and the global mean sea level evolution is not properly resolved (Greatbatch, 1994). Global mean sea levels from 1993 to 2015 were thus removed from regional sea level trends within each member. For consistency, we have performed the same correction for the satellite altimetry data. Therefore, the trend maps discussed throughout the paper represent trend anomalies with respect to their global average.

2.3 Ensemble statistics

The processing steps presented above yields 50 simulated sea level trend maps. We use a Lilliefors test at each gridpoint to calculate the goodness of fit of the ensemble distributions of sea level trends against a Gaussian distribution with unspecified parameters. The gaussianity of these distributions is rejected (at the 95% significance level) over 7% and 5% of the global ocean area over 1993-2015 and 2005-2015, respectively. The use of ensemble mean and the standard deviation is therefore adequate to provide a meaningful description of the distributions in the following analysis as sea level trends follow a Gaussian distribution.

Therefore, over both periods of interest (1993-2015 and 2005-2015), the ensemble mean of the 50 sea level trend maps provides an estimate for the atmospherically-forced response (i.e. the trend common to all members), and the standard deviation

σ_I of these maps provide the uncertainty associated with the chaotic ocean variability (i.e. the "noise" associated with regional trends). This uncertainty is defined as:

$$\sigma_I = \sqrt{\frac{1}{N-1}\sum_{i=1}^{50}(T_{SLAi} - < T_{SLA} >)^2}$$

where N represents the total number of members (50), $<T_{SLA}>$ represents the ensemble mean sea level trend and T_{SLAi} the ith-member sea level trend. More details are given in Leroux et al. (2018).

The forced trend $<T_{SLA}>$ is considered as the "signal" in the following. We compare it to the "noise" via the signal-to-noise (SNR) ratio $|<T_{SLA}>|/\sigma_I$. We will consider in the following, as in Sérazin et al. (2017), that regional sea level trends picked from a given realization (one ensemble member for instance) cannot be unambiguously attributed to the atmospheric forcing in regions where the SNR is smaller than 2, unless otherwise stated. This corresponds to the 95% confidence level. Note that our external forcing includes the atmospheric part of the natural variability (internal atmospheric variability, atmospheric part of the coupled variability, fluctuations and trends in solar radiation, volcanic eruptions, Earth's orbital cycles, etc) and of anthropogenic influences (i.e. increasing greenhouse gases). The goal of the paper is to disentangle the forced regional sea level trends that are directly driven by these external drivers altogether, from their chaotic counterparts that spontaneously emerge from the oceanic non-linearities.

2.4 Time of emergence

We finally evaluate the time needed for the atmospherically forced trend to emerge from the chaotic ocean variability: the time of emergence is the time needed for a given forced trend signal to exceed (and remain above) the noise of the system (Lyu et al., 2014) at the same location. In other words, forced regional sea level trends are computed over 1993-2015, and the time of emergence corresponds to the year when the absolute forced sea level trend time series exceeds twice the 1993-2015 standard deviation (noise σ_I); the factor two corresponds to the 95% confidence level.

3- Results

We focus on two time periods: over 1993-2015 and over 2005-2015. The latter period is chosen since 2 other observing systems allow certain authors (Llovel et al.,

2014; Chambers et al., 2017, WCRP Global Sea Level Budget Group, 2018) to split sea level trends into mass and steric components: the Gravity Recovery and Climate Experiment (GRACE) mission records the net ocean mass changes to sea level, and the Argo float network records temperature and salinity changes of the oceans for the upper 2000m depth. The decomposition of forced and chaotic sea level trends into mass and steric parts is left for future studies.

3.1 Model assessment

Observed sea level trend maps exhibit marked regional contrasts over 1993-2015 (Figure 1A) and over 2005-2015 (Figure 1B). Positive trends are found over 1993-2015 in the western tropical Pacific and its subtropical gyres, in the Indian ocean and the south Atlantic subtropical gyre, while negative trends are found in the eastern tropical Pacific and in the northern subtropical Atlantic. The spatial patterns are different over 2005-2015 from those over 1993-2015, denoting that they are not stationary (with opposite signs in certain regions such as the tropical Pacific and Atlantic). The trend values are larger for the shorter time period. As ice covered regions are partly sampled by satellite altimetry data (no data are available during the winter time), we do not provide any trend estimates for polar regions.

Each of the 50 OCCIPUT ensemble members simulates one possible realization of the ocean evolution over the last decades given the atmospheric evolution. In Figure 1, we compare the regional sea level trend within one member (member #1) with satellite observations over 1993-2015 and 2005-2015. The model reproduces the observed sea level trends over the altimetry era within most regions. Interestingly, the simulation reproduces the observed sea level rise in the Beaufort gyre that has been speculated to be linked to the shrink of the Arctic floating sea ice resulting in salinity-driven sea level change (Carret et al., 2017). Some discrepancies however can be seen in the north Atlantic subpolar gyre (especially in the Labrador sea) and in the southern ocean, possibly due to missing physics in the model, biases in the forcing, or in the observed sea level fields.

More quantitatively, the root mean square difference (rmsd) between observed and ensemble mean (forced) regional sea level trends turns out to be 2.56 $mm.yr^{-1}$over the period 1993-2007 and the ice-free ocean (1.57 $mm.yr^{-1}$ over the period 1993-2015). This rmsd is actually smaller than for any forced ocean numerical model considered in the CORE exercise (see Table 2 in Griffies et al., 2014). In other words, the OCCIPUT ensemble provides reliable estimates of regional sea-level trends, and its 50 realizations may be used to investigate the respective contributions of atmospherically-driven and chaotic ocean variability on this field. As the simulated sea level trends from the 50 members are normally distributed at each grid point, the en-

semble mean trends gives an adequate estimate of the forced trends, and the ensemble standard deviation of chaotic trends.

3.2 Forced and chaotic simulated trends

Figure 2 displays random sea level trends due to the oceanic chaos over 1993-2015 (fig. 2A) and over 2005-2015 (Fig. 2B). Large values, exceeding 12 $mm.yr^{-1}$ for both periods, are found in western boundary currents and in the ACC. Overall, the sea level trend ensemble standard deviation is larger over 2005-2015 than over 1993-2015: in the subtropical gyres for instance, it reaches about 1$mm.yr^{-1}$ over 1993-2015, and 2-5 $mm.yr^{-1}$ over 2005-2015.

These results are consistent with Sérazin et al. (2016), who examined the features of 20-year random sea level trends under a purely climatological forcing. In other words, the use of a reanalyzed forcing (driving an ensemble) instead of a climatological forcing (driving one simulation) allows the separation of forced and chaotic signals, and shows that the latter is barely affected by atmospheric fluctuations. This substantial insensitivity was also reported for the Atlantic Meridionnal Overturning Circulation interannual variability (Leroux et al. 2018).

Figure 2 also presents the atmospherically-forced trends over 1993-2015 (fig. 2C) and over 2005-2015 (Fig. 2D). These trend maps are in good agreement with observed sea level trends from satellite altimetry over both time periods. Black dots denote regions where forced trends are not distinguishable from their chaotic counterpart (SNR < 2). Over both periods, these regions are not limited to the western boundary currents and the ACC. Interestingly, the chaotic variability is likely to mask the atmospherically forced sea level trends over most of the Atlantic subtropical gyres over 1993-2015. These plots also show regions where sea level trends are not statistically different from zero and therefore, are within the ensemble standard deviation. Over the 2005-2015 period, the chaotic variability may mask the forced signal over larger regions, in particular in the South Atlantic, the Gulf Stream, the ACC, and the north Pacific subtropical gyre. Some coastal regions (such as the Yellow sea and gulf of Tonkin) and semi-enclosed seas (such as the Gulf of Mexico and the Japan sea) also exhibit dominant imprints of chaotic ocean variability over both periods.

Forced sea level trends display large-scale spatially coherent patterns in the tropical Pacific and Indian oceans, in line with the literature. The wind stress was indeed shown to drive a substantial sea level rise seen here in the western tropical Pacific ocean (Merrifield et al., 2011; England et al., 2014), the equatorial and north Indian ocean (Thompson et al., 2016) over 1993-2015, and in the south subtropical gyres of

the Pacific and Indian oceans (Llovel and Terray, 2016; Volkov et al., 2016) over 2005-2015.

In contrast, the simulated 1993-2015 sea-level trends cannot be unambiguously attributed to the atmospheric forcing over 38 % of the global ocean area because of the intrinsic variability. Over 2005-2015, almost half (47%) of the global ocean area is concerned by this uncertainty. If we exclude the regions where forced sea level trends are not statistically different from zero, the fraction of the global ocean area where trends cannot be attributed to the forcing amount to 19% over 1993-2015, and to 22% over 2005-2015. These model results therefore suggest that altimetry-derived regional sea-level trends are not mostly due to the external forcing over a large part of the global ocean, but may have a random nature because of the chaotic ocean variability.

The chaotic variability may remain substantial in regions where the atmosphere forces most of the sea level trends. We therefore use the inverse SNR sea level trends (Figure 3) for both periods to quantify the sea level imprints of the chaotic variability with respect to its atmospherically-forced counterpart. Note that the inverse SNR threshold is now 0.5 . The tropical Pacific is the main region where the ensemble standard deviation remains smaller than 20% of the forced trend (western basin over 1993-2015, central and eastern basins over 2005-2015). In contrast, this fraction exceeds 50% in the Indian ocean, and reaches about 50%-60% within most mid latitude basins over 1993-2015. In these regions, sea level trends can be mostly attributed to the atmospheric forcing, with a substantial fraction due to the chaotic variability. Over 2005-2015, mid latitude regions do not present large surface fraction of atmospherically-forced sea level trends.

3.3 Time of emergence

We finally estimate the time it takes for forced sea level trends to emerge from the chaotic ocean variability over the entire altimetry period (i.e., over 1993-2015). These times of emergence exhibit marked contrasts from one basin to another (Figure 4). In the western and eastern tropical Pacific and in the tropical Atlantic oceans, the forced sea level trends become distinguishable from the chaotic variability after only a few years. In general, in the Indian ocean, periods of at least 8-10 years are needed for the atmospherically-forced trends to emerge from the chaotic component. A few years are needed in the subtropical south Pacific ocean, but significantly more at the edges of the gyre where the forced trends are weaker. In the subtropical gyres of the north Pacific, north Atlantic and south Atlantic oceans, our results suggest that more than 23 years of observation are needed to disentangle the (relatively small) forced sea level trends from the chaotic variability. Finally, the western

boundary currents and the ACC present the longest time of emergence, consistently with the strong eddy fields found in these.

4- Conclusions and Discussion

Satellite altimetry has revolutionized our understanding of ocean circulation, large-scale and meso-scale dynamics, and revealed the large regional variability in sea level trends (Cazenave and Llovel, 2010). Recent investigations have been focused on determining observational budget errors for sea level trends and less attention has been put on the ocean dynamics' contribution. Based on the OCCIPUT ensemble simulation, we show that the ensemble standard deviation in sea level trends may reach 12 $mm.yr^{-1}$ in western boundary currents and in the ACC over 1993-2015. The standard deviation tends to be larger over 2005-2015.

We find in particular that the regional trends of sea level over the period 1993-2015 cannot be unambiguously attributed to atmospheric influences over 38% of the global ocean area; this fraction reaches 47% for the period 2005-2015. These fractions are large: the uncertainty of regional sea level trends due to chaotic variability is 3-5 times larger than the quoted observed sea level trend errors (Ablain et al., 2017) in eddy-active western boundary currents and in the ACC. These results suggest that the chaotic ocean variability must be considered along with instrumental uncertainties to realistically assess error budgets for regional sea level trends over the altimetry period.

The inverse SNR level trend ratio is not uniform: it remains smaller than 10% in the tropical Pacific (western basin over 1993-2015, central and eastern basins over 2005-2015), but exceeds 50% in the tropical Indian ocean and reaches about 50%-60% within most mid latitude basins. Substantial ratios are found in certain coastal regions as well.

The large contribution of chaotic ocean variability to regional sea level trends is likely relevant for the assessment and design of current and future sea level observing systems and the interpretation of sea level time series. It raises new concerns about the duration of satellite altimetry measurement that is requested to capture signals that are driven by the atmospheric evolution and anthropic influences. The ensemble simulation suggests that a few years of altimeter data are sufficient to capture these forced signals in the tropical Pacific, but 10-14 years are required in the eastern Indian ocean, 20 years in the north Pacific and Atlantic oceans (except in the subpolar gyre). Whilst the chaotic variability distribution and intensity are rather stationary over time, the atmospherically-forced trend map depends on the time period con-

sidered. Therefore, the time of emergence map is valid for 1993-2015, and would not necessarily apply over different (past or future) 23-year time periods.

It is important to note that our results absolutely do not question the attribution of the observed global mean sea level trends to global warming. They suggest that the regional patterns of sea level trends derived from existing altimeter data are not only due to the atmospheric evolution (variability or global warming). Longer altimetry-based sea level records will likely help isolate the forced part of sea level trends in regions where the imprint of chaotic variability is large.

Regional sea level trends have been largely attributed to steric effects (Cazenave and Llovel, 2010), with a large contribution of temperature changes (Levitus et al., 2012; Llovel and Terray, 2016) compared to salinity changes (Llovel and Lee, 2015). The net ocean mass change linked to fresh water exchange between oceans and continents also contributes to regional sea level trends. Based on the same ensemble simulation, Sérazin et al. (2017) showed that ocean heat content trends are also impacted by chaotic intrinsic variability over 1980-2010, at all depths. It is thus likely that chaotic intrinsic variability has an imprint on thermosteric regional sea level trends, but we leave these open questions for future investigations.

As in any model-based study, our results might be partly biased and must be interpreted with care: the robustness of our results needs to be assessed from other ensemble simulations, with different ocean models, forcing functions and resolutions. However, Figures 1 and 2, and the small rmsd found between observed and simulated fields show that our model simulates realistic sea level trends over most of the global ocean. It is moreover unlikely that the sea level intrinsic variability is overestimated in our 1/4° simulation, since it further increases when resolution reaches 1/12° (Sérazin et al., 2015). In summary, the exact amplitude and distribution of chaos-related uncertainties on regional sea level trends might well be model-sensitive; our results nevertheless suggest that this uncertainty may be large in observed datasets as well. This should be kept in mind when attributing regional altimeter trends to atmospheric causes.

Acknowledgements

This work is a contribution to the OCCIPUT and PIRATE projects. PIRATE (https://sealevel.jpl.nasa.gov/science/ostscienceteam/scientistlinks/scientificinvestigations2017/penduff/) is funded by CNES through the Ocean Surface Topography Science Team (OSTST). OCCIPUT (http://meom-group. github.io/projects/occiput) is funded by ANR through contract ANR-13-BS06-0007-01. This work was also supported by the French national programme LEFE/INSU. We acknowledge that the results

of this research have been achieved using the PRACE Research Infrastructure resource CURIE based in France at TGCC. William Llovel was supported by 'Louis Gentil – Jacques Bourcart' fellowship from the French 'Académie des Sciences' and by OVALIE project from ESA Living Planet Fellowhip fundings. The CCI product is freely available at http://www.esa-sealevel-cci.org/. The data set used for this study is freely available on http://zenodo.org (http://doi.org/10.5281/zenodo.1487983). We would like to thank two anonymous reviewers for their constructive comments and helpful suggestions.

References

1- Ablain M, et al. (2017) Satellite altimetry-based sea level at global and regional scales. Surv Geophys 38:7–31.
2- 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
3- Brankart, J.-M.: Impact of uncertainties in the horizontal density gradient upon low resolution global ocean modelling, Ocean Model., 66, 64–76, 2013.
4- Carret, A., Johannessen, J. A., Andersen, O. B., Ablain, M., Prandi, P., Blazquez, A., & Cazenave, A. (2017). Arctic Sea Level During the Satellite Altimetry Era. Survey of Geophysics,38 (1), 251–275. https://doi.org/10.1007/s10712-016-9390-2
5- Cazenave, A., Llovel, W., Contemporary Sea Level Rise, Annu. Rev. Mar. Sci. 2:143–173.doi:10.1146/annurev-marine-120308-081105, 2010.
6- Chambers, D. P., A. Cazenave, N. Champollion, H. Dieng, W. Llovel, R. Forsberg, K. von Schuckmann, and Y. Wada, Evaluation of the Global Mean Sea Level Budget between 1993 and 2014, Surv. Geophys. 38, 309-327, doi: 10.1007/s10712-016-9381-3, 2017.
7- Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
8- Dussin, R., Barnier, B., Brodeau, L., and Molines, J.-M.: The making of Drakkar forcing set DFS5, DRAKKAR/MyOcean Report, 01-04-16, LGGE, Grenoble, France, 2016.
9- England, M. H. et al. Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. Nature Clim. Change 4, 222–227 (2014).

10- Forget G. and R.M. Ponte: The partition of regional sea level variability, Progress in Oceanography, Volume 137, Part A, September 2015, Pages 173-195, 2015.
11- Greatbatch R.J., A note on the representation of steric sea level in models that conserve volume rather than mass, Jounal of Geophysical Reseach, vol. 99, No. C6, pages 12,767-12,771, June 15, 1994
12- Griffies, S.M., Yin, J., Durack, P.J., Goddard, P., Bates, S.C., Behrens, E., Bentsen, M., Bi, D., Biastoch, A., Böning, C., Bozec, A., Chassignet, E., Danabasoglu, G., Danilov, S., Domingues, C.M., Drange, H., Farneti, R., Fernandez, E., Greatebatch, R.J., Holland, D.M., Ilicak, M., Large, W.G., Lorbacher, K., Lu, J., Marsland, S.J., Mishra, A., Nurser, A.J.G., Salas y Mélia, D., Palter, J.B., Samuels, B.L., Schröter, Schwarzkopf, F.U., Sidorenko, D., Treguier, A.-M., Tseng, Y.H., Tsujino, H., Uotila, P., Valcke, S., Voldoire, A., Wang, Q., Winton, M., Zhang, X., 2014. An assessment of global and regional sea level for years 1993−2007 in a suite of interannual CORE-II simulations. Ocean Model. 78, 35–89. https://doi.org/10.1016/j.ocemod.2014.03.004.
13- Legeais, J.-F., Ablain, M., Zawadzki, L., Zuo, H., Johannessen, J. A., Scharffenberg, M. G., Fenoglio-Marc, L., Fernandes, M. J., Andersen, O. B., Rudenko, S., Cipollini, P., Quartly, G. D., Passaro, M., Cazenave, A., and Benveniste, J.: An improved and homogeneous altimeter sea level record from the ESA Climate Change Initiative, Earth Syst. Sci. Data, 10, 281-301, https://doi.org/10.5194/essd-10-281-2018, 2018.
14- 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 AM-OC: Insights from a Large-Ensemble Ocean Hindcast. J. Climate, 31, 1183–1203, https://doi.org/10.1175/JCLI-D-17-0168.1
15- Levitus S., J.I. Antonov, T.P. Boyer, O.K. Baranova, H.E. Garcia, R.A. Locarnini, A.V. Mishonov, J.R. Reagan, D. Seidov, E.S. Yarosh and M.M. Zweng, World ocean heat content and thermosteric sea level change (0-2000 m), 1955-2010, Geophys. Res. Lett., 39, L10603, doi:10.1019/2012GL051106, 2012.
16- Llovel, W., Willis, J. K., Landerer, F. K. & Fukumori, I. Deep-ocean contribution to sea level and energy budget not detectable over the past decade. Nature Clim. Change 4, 1031–1035 (2014).
17- Llovel, W., and T. Lee (2015), Importance and origin of halosteric contribution to sea level change in the southeast Indian Ocean during 2005–2013, Geophys. Res. Lett.,42, 1148–1157, doi:10.1002/2014GL062611.
18- Llovel, W., Terray, L., 2016: Observed southern upper-ocean warming over 2005–2014 and associated mechanisms. Environ. Res. Lett., 11, 124023
19- Kewei Lyu, Xuebin Zhang, John A. Church, Aimée B. A. Slangen & Jianyu Hu, Time of emergence for regional sea-level change, Nature Climate Change volume 4, pages 1006–1010 (2014)

20- Merrifield, M. A. (2011). A shift in western tropical Pacific sea level trends during the 1990s. Journal of Climate, 24, 4126–4138. doi.org/10.1175/2011JCLI3932.1
21- Penduff T, Juza M, Barnier B, Zika J, Dewar WK, Treguier A-M, Molines JM, Audiffren N (2011) Sea-level expression of intrinsic and forced ocean variabilities at interannual time scales. J Clim 24:5652–5670.
22- Penduff, T., Barnier, B., Terray, L., Bessières, L., Sérazin, G., Gregorio, S., Brankart, J., Moine, M., Molines, J., and Brasseur, P.: Ensembles of eddying ocean simulations for climate, CLIVAR Exchanges, Special Issue on High Resolution Ocean Climate Modelling, 19, 2014
23- Penduff, T., G. Sérazin, S. Leroux, S. Close, J.-M. Molines, B. Barnier, L. Bessières, L. Terray, and G. Maze. 2018. Chaotic variability of ocean heat content: Climate-relevant features and observational implications. Oceanography 31(2), https://doi.org/10.5670/oceanog.2018.210
24- Sérazin, G., T. Penduff, S. Grégorio, B. Barnier, J.-M. Molines, and L. Terray. 2015. Intrinsic variability of sea-level from global 1/12° ocean simulations: Spatio-temporal scales. Journal of Climate 28:4,279–4,292.
25- Sérazin, G., Meyssignac, B., Penduff, T., Terray, L., Barnier, B., Molines, J.M., 2016: Quantifying uncertainties on regional sea level change induced by multi-decadal intrinsic oceanic variability. Geophys. Res. Lett., 43, pp. 8151–8159.
26- 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.
27- Sérazin, G., T. Penduff, B. Barnier, J. Molines, B.K. Arbic, M. Müller, and L. Terray, 2018. Inverse Cascades of Kinetic Energy as a Source of Intrinsic Variability: A Global OGCM Study. J. Phys. Oceanogr., 48, 1385–1408, https://doi.org/10.1175/JPO-D-17-0136.1
28- Systematic Observation Requirements for Satellite-based Products for Climate Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC: 2011 update.
29- Thompson, P. R., C. G. Piecuch, M. A. Merrifield, J. P. McCreary, and E. Firing (2016), Forcing of recent decadal variability in the Equatorial and North Indian Ocean, J. Geophys. Res. Oceans,121, 6762–6778,doi:10.1002/2016JC012132.
30- Volkov, D. L., S.-K. Lee, F. W. Landerer, and R. Lumpkin (2017), Decade-long deep-ocean warming detected in the subtropical South Pacific, Geophys. Res. Lett., 44, 927–936, doi:10.1002/2016GL071661.
31- WCRP Global Sea Level Budget Group: Global sea-level budget 1993–present, Earth Syst. Sci. Data, 10, 1551-1590, https://doi.org/10.5194/essd-10-1551-2018, 2018.

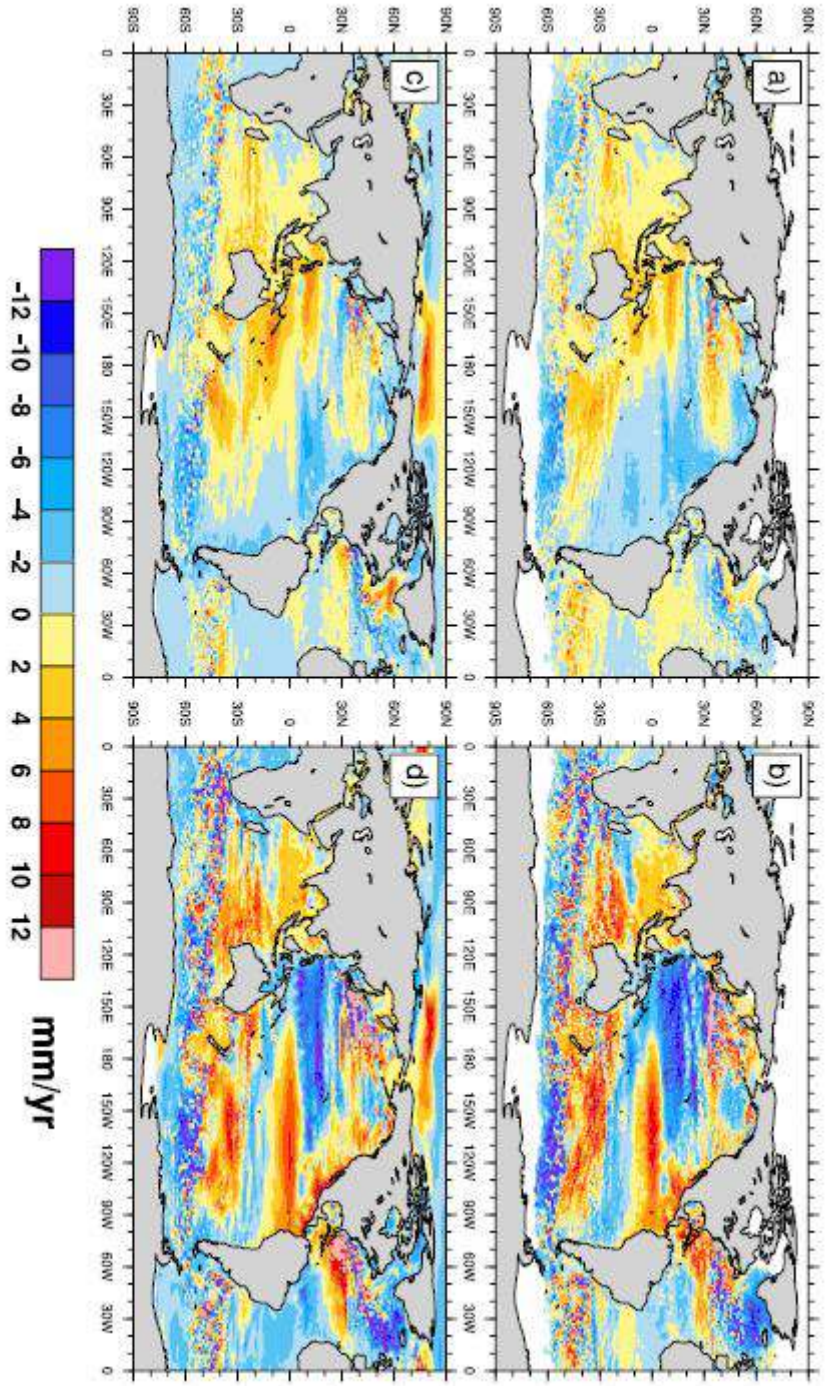

Figure 1: Observed sea level trend maps from satellite altimetry (CCI product) over A)1993-2015 and over B)2005-2015. Simulated sea level trend maps from member #1 of the OCCIPUT ensemble simulation over C)1993-2015 and D)2005-2015. In the 4 trend maps the global mean sea level time series has been removed. Annual and semi-annual signals have also been removed.

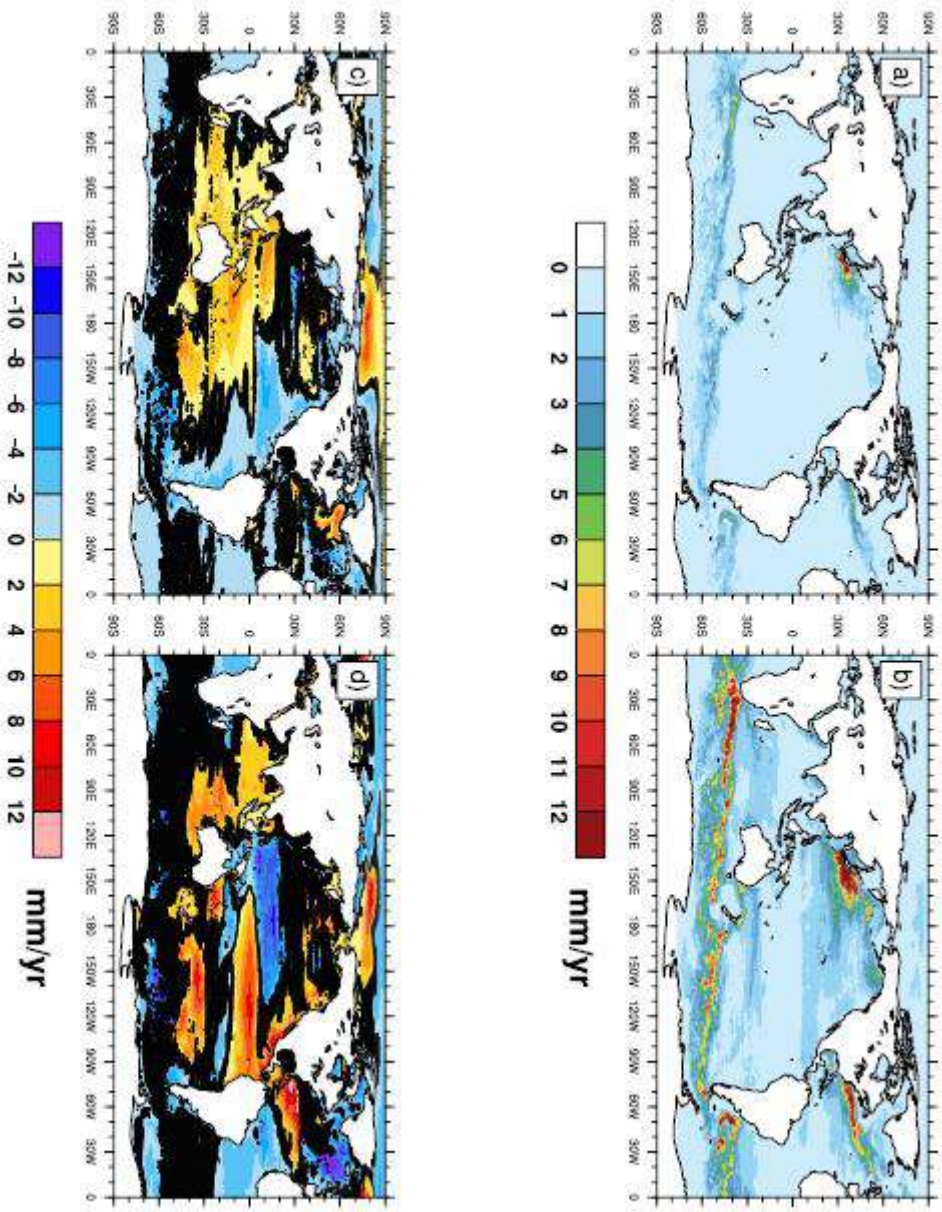

Figure 2: Imprint on sea level trends of the chaotic ocean variability in the ensemble simulation. Ensemble standard deviation of sea level trends from the 50 members over A)1993-2015 and B)2005-2015. Atmospherically-forced sea level trend maps over C)1993-2015 and D)2005-2015. Black dots represent SNR<2 denoting atmospherically-forced trends not statistically different from the oceanic chaotic variability (at the 95% confidence interval).

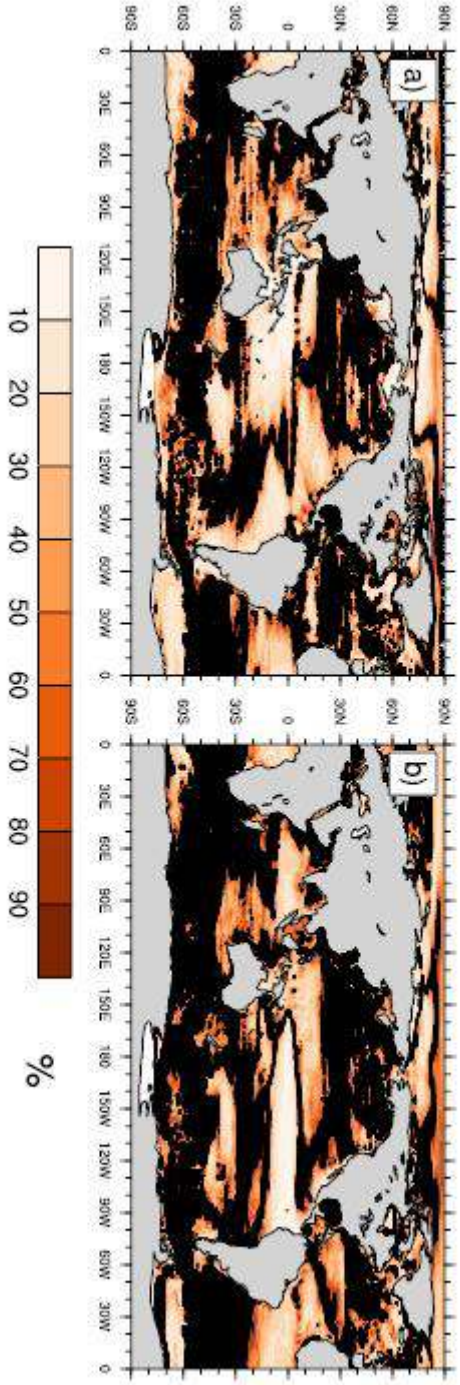

Figure 3: Inverse of the SNR of sea level trends over A)1993-2015 and over B)2005-2015. Black dots represent inverse SNR > 0.5 denoting forced trends not statistically different from the oceanic chaotic variability (at the 95% confidence interval). For clarity, we express the ratio in percentage.

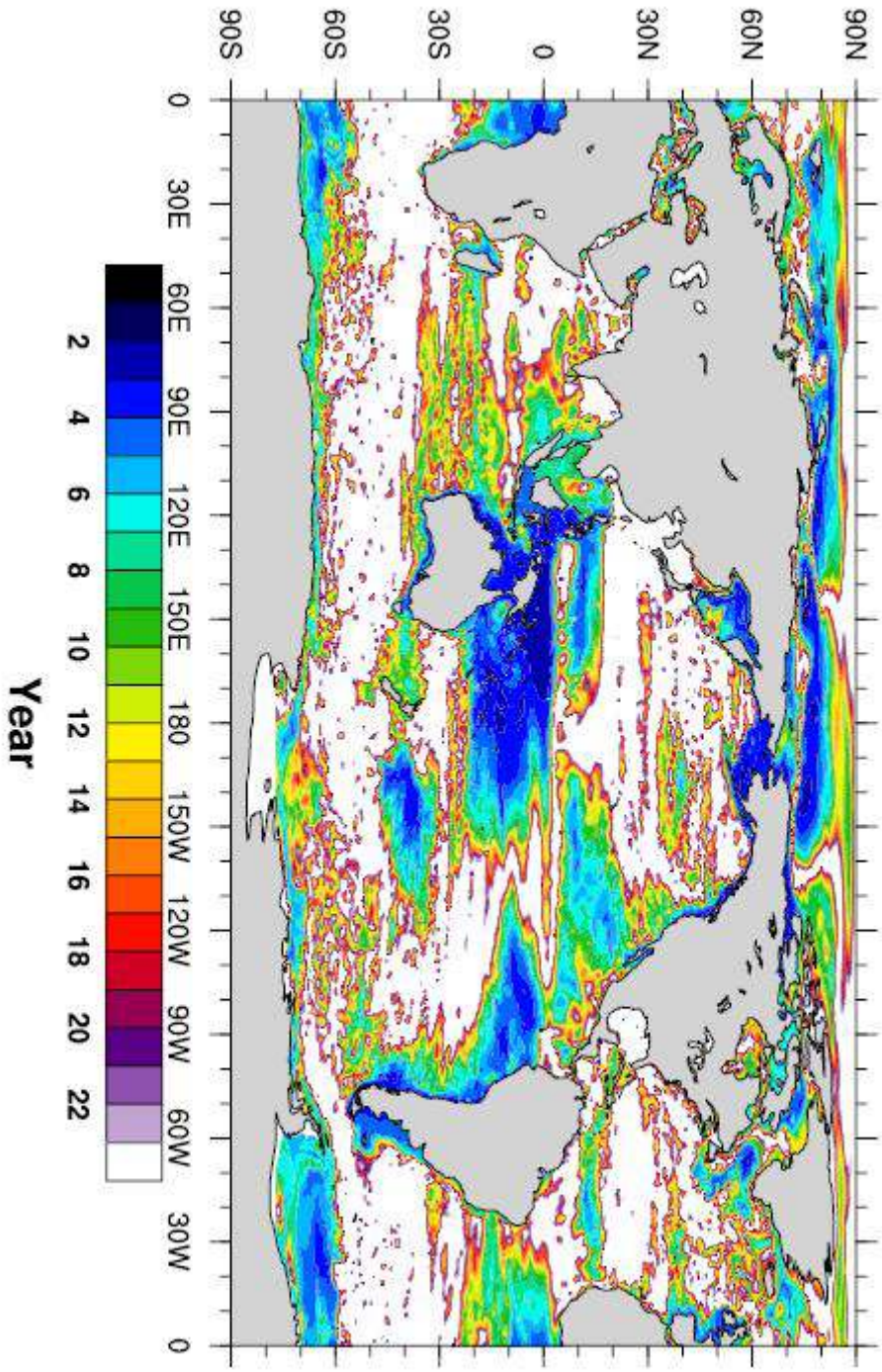

Figure 4: Time of Emergence. Time length needed for the atmospherically-driven sea level trend over 1993-2015 to exceed and remain above 2 standard deviations of the ensemble of the 1993-2015 sea level trends (at each grid point). White areas represent time length longer than over 1993-2015.