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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

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Contributions of Atmospheric Forcing and Chaotic Ocean Variability to Regional Sea Level Trends Over 1993–2015

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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 traveling 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/year over a long-term evolution (>10 years; Ablain et al., 2017) but would need to be lowered down to 1 mm/year 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 & Ponte, 2015). Wind stress, buoyancy and mass air-sea fluxes explain large-scale fluctuations of sea level at time scales longer than 1 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 nonlinear interactions may in turn feed chaotic fluctuations at longer time and space scales through spatiotemporal inverse cascade processes (Sérazin et al., 2018). This multidecadal "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 timescales, 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 data set 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 data sets 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 (Bessières et al., 2017; Penduff et al., 2014). 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 spacing is about 27 km at the equator and decreases poleward. The 50 members are initialized on 1 January 1960 from the final state of a 21-year one-member spin-up. 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 1 January 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 grid point 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

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

where N represents the total number of members (50), $<T_{SLA}>$ represents the ensemble mean sea level trend and T_{SLAi} the *i*th-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 ratio (SNR) $| < T_{SLA} > |/\sigma_I$. 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 nonlinearities.

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 two other observing systems allow certain authors (Chambers et al., 2017; Llovel et al., 2014; 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 2,000 m 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

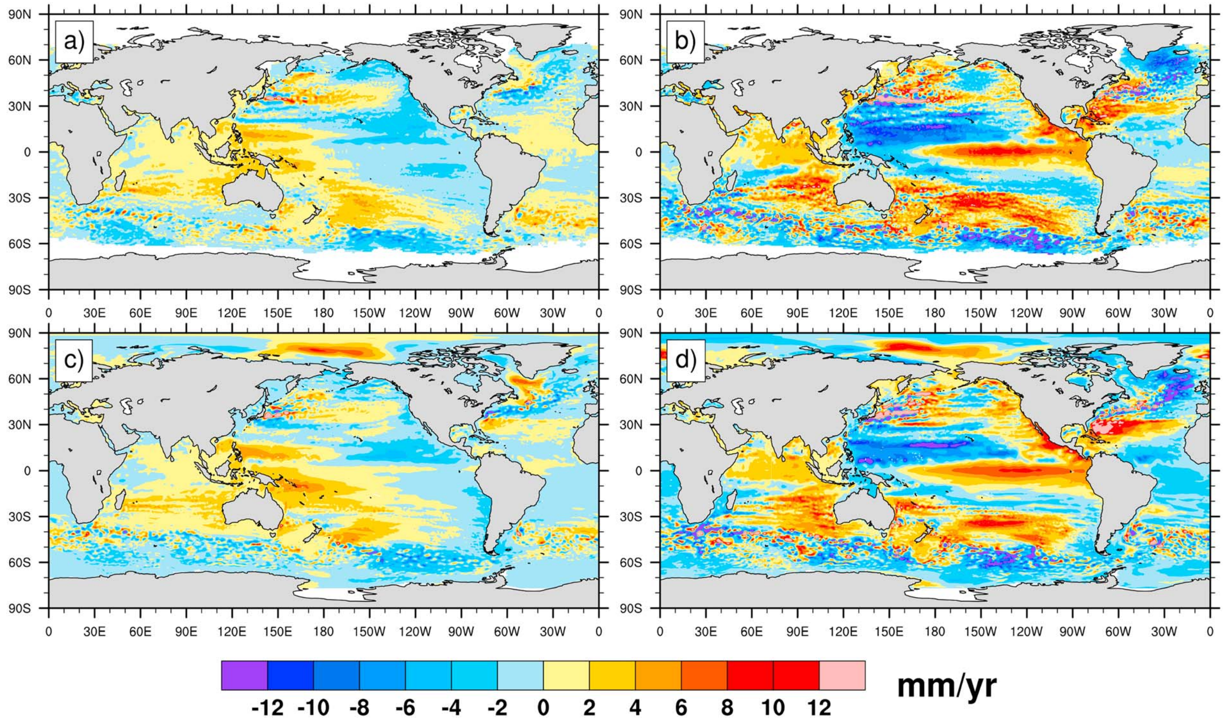

Figure 1. Observed sea level trend maps from satellite altimetry (CCI product) over (a) 1993–2015 and over (b) 2005–2015. Simulated sea level trend maps from member #1 of the OCCIPUT ensemble simulation over (c) 1993–2015 and (d) 2005–2015. In the four trend maps the global mean sea level time series has been removed. Annual and semiannual signals have also been removed.

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/year 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 ensemble 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 (Figure 2a) and over 2005–2015 (Figure 2b). Large values, exceeding 12 mm.yr^{-1} for both periods, are found in western

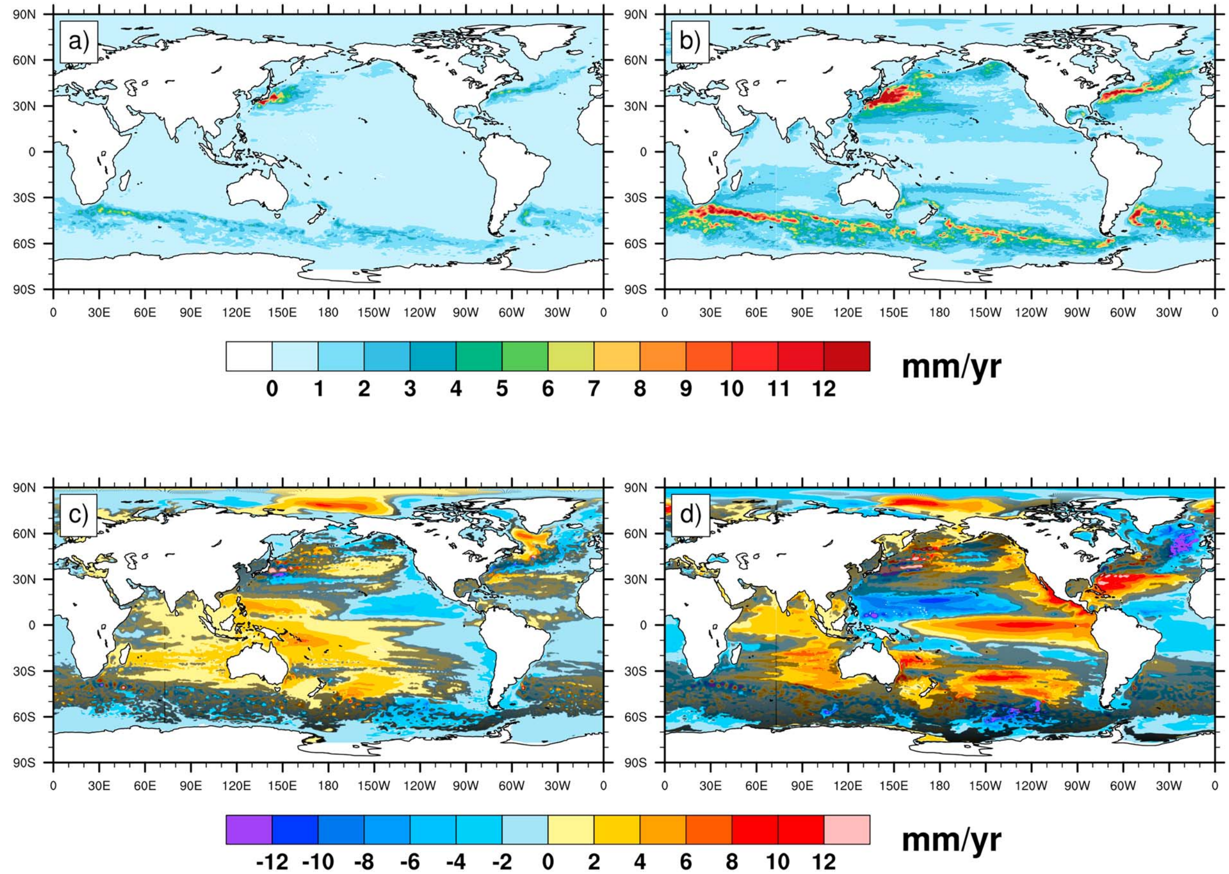

Figure 2. Imprint on sea level trends of the chaotic ocean variability in the ensemble simulation. Ensemble standard deviation of sea level trends from the 50 members over (a) 1993–2015 and (b) 2005–2015. Atmospherically forced sea level trend maps over (c) 1993–2015 and (d) 2005–2015. Black dots represent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

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/year over 1993–2015, and 2–5 mm/year 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 Meridional Overturning Circulation interannual variability (Leroux et al., 2018).

Figure 2 also presents the atmospherically forced trends over 1993–2015 (Figure 2c) and over 2005–2015 (Figure 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 semienclosed seas (such as the Gulf of Mexico and the Japan sea) also exhibit dominant imprints of chaotic ocean variability over both periods.

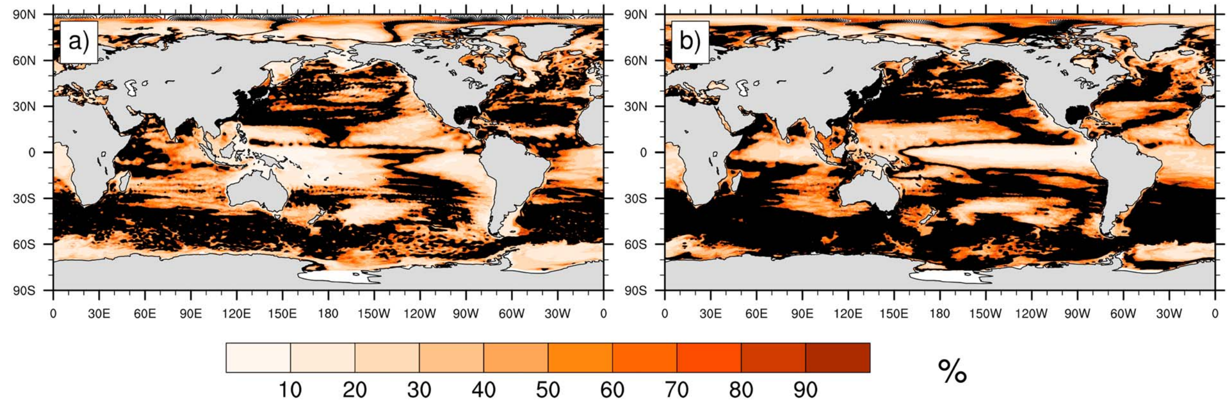

Figure 3. Inverse of the SNR of sea level trends over (a) 1993–2015 and over (b) 2005–2015. Black dots represent inverse SNR > 0.5 denoting forced trends not statistically different from the oceanic chaotic variability (at the 95% confidence interval). For clarity, we express the ratio in percentage.

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 (England et al., 2014; Merrifield, 2011), 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 & Terray, 2016; Volkov et al., 2017) 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, midlatitude 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.

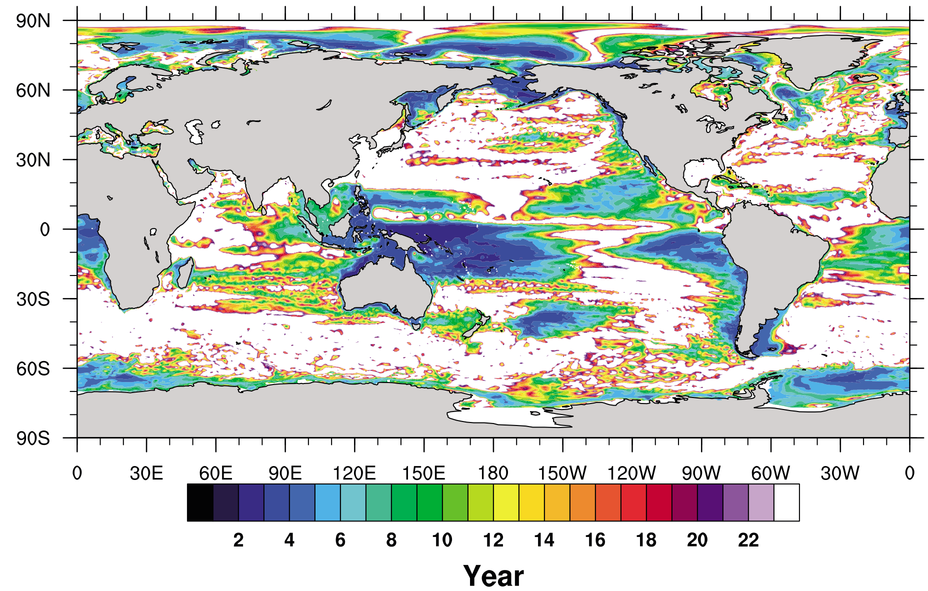

Figure 4. Time of emergence. Time length needed for the atmospherically driven sea level trend over 1993–2015 to exceed and remain above 2 standard deviations of the ensemble of the 1993–2015 sea level trends (at each grid point). White areas represent time length longer than over 1993–2015.

4. Conclusions and Discussion

Satellite altimetry has revolutionized our understanding of ocean circulation, large-scale and mesoscale dynamics and revealed the large regional variability in sea level trends (Cazenave & 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/year 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). While the chaotic variability distribution and intensity are rather stationary over time, the atmospherically forced trend map depends on the time period considered. 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 & Llovel, 2010), with a large contribution of temperature changes (Levitus et al., 2012; Llovel & Terray, 2016) compared to salinity changes (Llovel & 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 data sets as well. This should be kept in mind when attributing regional altimeter trends to atmospheric causes.

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References

Ablain, M., Legeais, J. F., Prandi, P., Marcos, M., Fenoglio-Marc, L., Dieng, H. B., et al. (2017). Satellite altimetry-based sea level at global and regional scales. *Surveys in Geophysics*, *38*(1), 7–31. https://doi.org/10.1007/s10712-016-9389-8

Bessières, L., Leroux, S., Brankart, J.-M., Molines, J.-M., Moine, M.-P., Bouttier, P.-A., et al. (2017). Development of a probabilistic ocean modelling system based on NEMO 3.5: Application at eddying resolution. *Geoscientific Model Development*, *10*(3), 1091–1106. https://doi.org/10.5194/gmd-10-1091-2017

Brankart, J.-M. (2013). Impact of uncertainties in the horizontal density gradient upon low resolution global ocean modelling. *Ocean Modelling*, *66*, 64–76. https://doi.org/10.1016/j.ocemod.2013.02.004

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

Cazenave, A., & Llovel, W. (2010). Contemporary Sea level rise. *Annual Review of Marine Science*, *2*(1), 145–173. https://doi.org/10.1146/annurev-marine-120308-081105.

Chambers, D. P., Cazenave, A., Champollion, N., Dieng, H., Llovel, W., Forsberg, R., et al. (2017). Evaluation of the global mean sea level budget between 1993 and 2014. *Surveys in Geophysics*, *38*(1), 309–327. https://doi.org/10.1007/s10712-016-9381-3

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., et al. (2013). Sea level change. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (chap. 13, pp. 1137–1216). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Dussin, R., Barnier, B., Brodeau, L., & Molines, J.-M., 2016. The making of Drakkar forcing set DFS5, DRAKKAR/MyOcean Report, 01-04-16, LGGE, Grenoble, France.

England, M. H., McGregor, S., Spence, P., Meehl, G. A., Timmermann, A., Cai, W., et al. (2014). Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change*, *4*(3), 222–227. https://doi.org/10.1038/nclimate2106

Forget, G., & Ponte, R. M. (2015). The partition of regional sea level variability. *Progress in Oceanography*, *137*, Part A, September 2015, 173–195.

GCOS: Systematic Observation Requirements for Satellite-Based Data Products for Climate (2011). *Supplemental Details to the Satellite-Based Component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)", GCOS-154*. Geneva, Switzerland: WMO.

Greatbatch, R. J. (1994). A note on the representation of steric sea level in models that conserve volume rather than mass. *Jounal of Geophysical Reseach*, *99*(C6), 12,767–12,771. https://doi.org/10.1029/94JC00847

Griffies, S. M., Yin, J., Durack, P. J., Goddard, P., Bates, S. C., Behrens, E., et al. (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

Legeais, J.-F., Ablain, M., Zawadzki, L., Zuo, H., Johannessen, J. A., Scharffenberg, M. G., et al. (2018). An improved and homogeneous altimeter sea level record from the ESA Climate Change Initiative. *Earth System Science Data*, *10*(1), 281–301. https://doi.org/10.5194/essd-10-281-2018

Leroux, S., Penduff, T., Bessières, L., Molines, J., Brankart, J., Sérazin, G., et al. (2018). Intrinsic and atmospherically forced variability of the AMOC: Insights from a large-ensemble ocean hindcast. *Journal of Climate*, *31*(3), 1183–1203. https://doi.org/10.1175/JCLI-D-17-0168.1

Levitus, S., Antonov, J. I., Boyer, T. P., Baranova, O. K., Garcia, H. E., Locarnini, R. A., et al. (2012). World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophysical Research Letters*, *39*, L10603. https://doi.org/10.1019/2012GL051106

Llovel, W., & Lee, T. (2015). Importance and origin of halosteric contribution to sea level change in the Southeast Indian Ocean during 2005–2013. *Geophysical Research Letters*, *42*, 1148–1157. https://doi.org/10.1002/2014GL062611

Llovel, W., & Terray, L. (2016). Observed southern upper-ocean warming over 2005–2014 and associated mechanisms. *Environmental Research Letters*, *11*(12), 124023. https://doi.org/10.1088/1748-9326/11/12/124023

Llovel, W., Willis, J. K., Landerer, F. K., & Fukumori, I. (2014). Deep-ocean contribution to sea level and energy budget not detectable over the past decade. *Nature Climate Change*, *4*(11), 1031–1035. https://doi.org/10.1038/nclimate2387

Lyu, K., Zhang, X., Church, J. A., Slangen, A. B. A., & Hu, J. (2014). Time of emergence for regional sea-level change. *Nature Climate Change*, *4*(11), 1006–1010. https://doi.org/10.1038/nclimate2397

Merrifield, M. A. (2011). A shift in western tropical Pacific sea level trends during the 1990s. *Journal of Climate*, *24*(15), 4126–4138. https://doi.org/10.1175/2011JCLI3932.1.

Penduff, T., Barnier, B., Terray, L., Bessières, L., Sérazin, G., Gregorio, S., et al. (2014). Ensembles of eddying ocean simulations for climate, CLIVAR Exchanges. *Special Issue on High Resolution Ocean Climate Modelling*, *19*.

Penduff, T., Juza, M., Barnier, B., Zika, J., Dewar, W. K., Treguier, A.-M., et al. (2011). Sea-level expression of intrinsic and forced ocean variabilities at interannual time scales. *Journal of Climate*, *24*(21), 5652–5670. https://doi.org/10.1175/JCLI-D-11-00077.1

Penduff, T., Sérazin, G., Leroux, S., Close, S., Molines, J.-M., Barnier, B., et al. (2018). Chaotic variability of ocean heat content: Climate-relevant features and observational implications. *Oceanography*, *31*(2). https://doi.org/10.5670/oceanog.2018.210

Sérazin, G., Jaymond, A., Leroux, S., Penduff, T., Bessières, L., Llovel, W., et al. (2017). A global probabilistic study of the ocean heat content low-frequency variability: Atmospheric forcing versus oceanic chaos. *Geophysical Research Letters*, *44*, 5580–5589. https://doi.org/10.1002/2017GL073026

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. *Geophysical Research Letters*, *43*, 8151–8159. https://doi.org/10.1002/2016GL069273

Sérazin, G., Penduff, T., Barnier, B., Molines, J., Arbic, B. K., Müller, M., & Terray, L. (2018). Inverse cascades of kinetic energy as a source of intrinsic variability: A global OGCM study. *Journal of Physical Oceanography*, *48*(6), 1385–1408. https://doi.org/10.1175/JPO-D-17-0136.1

Sérazin, G., Penduff, T., Grégorio, S., Barnier, B., Molines, J.-M., & Terray, L. (2015). Intrinsic variability of sea-level from global 1/12° ocean simulations: Spatio-temporal scales. *Journal of Climate*, *28*(10), 4279–4292. https://doi.org/10.1175/JCLI-D-14-00554.1

WCRP Global Sea Level Budget Group (2018). Global sea-level budget 1993–present. *Earth System Science Data*, *10*, 1551–1590. https://doi.org/10.5194/essd-10-1551-2018

Thompson, P. R., Piecuch, C. G., Merrifield, M. A., McCreary, J. P., & Firing, E. (2016). Forcing of recent decadal variability in the equatorial and North Indian Ocean. *Journal of Geophysical Research: Oceans*, *121*, 6762–6778. https://doi.org/10.1002/2016JC012132

Volkov, D. L., Lee, S.-K., Landerer, F. W., & Lumpkin, R. (2017). Decade-long deep-ocean warming detected in the subtropical South Pacific. *Geophysical Research Letters*, *44*, 927–936. https://doi.org/10.1002/2016GL071661