Earliest local emergence of forced dynamic and steric sea-level trends in climate models

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Abstract
We investigate the impact of internal variability on the emergence of a forced local trend in steric and dynamic sea surface height in historical and future climate simulations. By analyzing the unforced control simulations, the magnitude of internally generated, local trends in sea surface height is quantified and compared to trends found in historical simulations and projections. We find that the timing of the emergence of a forced local signal depends strongly on the location and the year in which the trend computations are started. Starting in 1950, it takes at least 60 yr to detect a forced trend in regions of weak internal variability such as the tropical Atlantic Ocean while this period is reduced to 30 yr when starting in 1990. The detection of a forced trend is further delayed by several decades in regions of elevated internal variability.

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1. Introduction

Global sea level is rising (Church et al 2011) and is expected to continue to rise on a multi-centennial to millennial time scale (Yin 2012, IPCC 2013). Sea level is not rising at the same rate globally but exhibits significant spatial variations (Cazenave et al 2008, Cazenave and Llovel 2010, Stammer et al 2013). Superimposed on the long-term trend are large interannual and decadal fluctuations (Jevrejeva et al, 2006). These fluctuations may either arise from changes in the external forcing (natural or anthropogenic) or may be internally generated due to the highly complex and nonlinear nature of the climate system. Changes in the global circulation as well as the exchange of heat and momentum between atmosphere and ocean induce regional climate variability on interannual to multi-decadal time scales. Sea level is a sensitive parameter that responds to atmospheric changes and integrates changes in the entire water column. Therefore, regional and temporal variability is a common feature of the oceans surface. The focus of this study is on the impact of internal variability on the detection of forced long-term trends in sea surface height.

Detecting externally forced trends in sea level on a regional level is more challenging than on a global scale as internal climate variability introduces strong changes in regional sea level on time scales from years to decades. For example, Northern North Atlantic sea level is strongly coupled to changes in the North Atlantic Oscillation (Richter et al 2012, Calafat et al 2012) while sea level changes in the tropical Pacific Ocean are governed by climate modes such as the Pacific Decadal Oscillation (Merrifield et al 2012, Scafetta 2013). Meyssignac et al (2012) conclude that sea level trend patterns in the tropical Pacific Ocean are still dominated by internal variability rather than external forcing.

Calafat and Chambers (2013) showed that internal variability may induce strong acceleration in regional sea level on time scales of decades. They find that the acceleration is real but to assess whether or not it is anthropogenically forced, internally generated accelerations have to be taken into account. Houston and Dean (2013) argue that a minimum record length of 75 yr is necessary to detect an acceleration in regional sea level that is distinct from internally generated variability. Likewise, Dangendorf et al (2014) find a
significant long term persistence on time scales of up to several decades in regional sea level, unrelated to any systematic rise. In a recent study, Haigh et al (2014) stress the importance of understanding and accounting for internal variability when attempting to detect an acceleration in regional sea level rise. Using a 40-member ensemble of climate projections, Hu and Deser (2013) showed that the sea level trend uncertainty due to internal variability by the mid-21st-century can be as large as the greenhouse gas forced trend in some locations.

Thus, internally generated variability has the potential to mask forced changes in sea level on multi-decadal time scales. As already mentioned, we distinguish between forced and unforced (internal) variability in this study. Forced trends include anthropogenically forced trends as well as trends due to changes in natural external forcing such as volcanic eruptions or solar variability. Thus, natural sea surface height variability due to changes in volcanic or atmospheric forcing are not considered as internal variability. By analyzing control simulations of 19 climate models, we quantify the linear trends introduced by internal variability on time scales from 10 to 100 yr. The timing of a forced trend signal is subsequently identified by comparing simulated historical and projected sea surface height trends to the range of internally induced trends.

2. Data and methods

Detecting a forced trend requires to determine whether or not the observed trend is consistent with internally generated variability. To investigate and quantify changes in sea surface height due to internal variability, we analyzed control simulations from the fifth phase of the Coupled Model Intercomparison Project (CMIP5, Taylor et al (2012)). The control simulations are driven with non-evolving pre-industrial conditions. Thus, the simulated variability is only due to the interaction between the different components of the model climate system (e.g. atmosphere, ocean, land and sea ice) and is therefore purely internal and unforced. The models used in this study are listed in table S1 in the supplementary material together with the length of their respective control simulations. The majority of the control simulations are 500 yr or longer and therefore well suited to investigate variability on multi-decadal timescales. All data in this study is used at yearly resolution.

The relevant model output consists of spatial fields of dynamic sea surface height that is related to changes in the thermohaline and wind-driven circulation as well as sea water density. In addition, the global mean change in steric height is provided. To account for local climate drift (Sen Gupta et al 2013), the linear trend was removed from all time series of the control simulations. The global mean was removed from the dynamic sea surface height at every time step prior to adding the global mean steric height change. This is to ensure that global mean sea level equals global mean steric height, which is not always the case for volume-conserving Boussinesq-models. The resulting variable is referred to as sea surface height in the remainder of the study. Historical simulations (1850–2005) and projections (2006–2100) were concatenated and processed similarly: climate model drift was accounted for by removing the respective linear trend found in the control simulations from each grid point, prior to forcing the global mean sea surface height to agree with the global mean steric sea surface height. For the 21st-century, we use the RCP4.5 scenario, an emission scenario with strong reductions in greenhouse gas emissions (Van Vuuren et al 2011). All spatial fields are remapped to a regular, horizontal grid with 1.0-by-1.0 degree resolution.

In the following, it is described how internal variability is quantified from the control simulations and identified in the scenario runs. Figure 1 illustrates the method using an arbitrarily chosen model and location. Linear trends are computed following the method of least squares. From the control simulations, we compute running linear trends using different multi-decadal windows starting from 10 yr and increasing the window length in steps of 5 yr up to 100 yr to assess and quantify linear trends that are generated by internal variability. By repeating the analysis with different window lengths, unforced trends can be quantified on various time scales. The range of internally generated (unforced) trends is then defined to be bound by the 5–95% percentiles of trends at each location for each time window (figure 1). The percentiles have a pentadal resolution (gray stars in figure 1) and are subsequently linearly interpolated to yearly resolution (gray lines). Forced trends in the historical and 21st-century
3. Results

3.1. Internal variability

To quantify the magnitude of local internal variability, maps of the sea surface height standard deviation were computed from the control simulations. Figure 2(a) shows the multimodel mean. Increased variability related to El-Niño Southern Oscillation and equatorial dynamics is evident in the Western tropical Pacific Ocean and the tropical Indian Ocean (although location and magnitude differ between models—see figure S1). The subtropical gyre region in the Western North Pacific also exhibits increased variability as well as the North Atlantic Current region. Relatively little variability is observed in the tropical and subtropical Atlantic and the Eastern subtropical Southern Pacific Ocean.

The uncertainty defined as the ratio of multimodel standard deviation to the multimodel mean of the temporal sea surface height standard deviation is largest in semi-enclosed basins such as the Mediterranean Sea, the Baltic Sea and Hudson Bay. However, these basins are not resolved by all models and are in fact closed basins in some models and results in those regions should be treated with caution. Relatively large uncertainties can be found in the Southern and Arctic Ocean where certain models exhibit almost no internal variability while some models show localized increased variability (figure S1). Away from regions of large variability, the uncertainty is relatively small.

3.2. Local trends induced by internal variability

Due to internal variability, linear trends in local sea surface height can be expected on different time scales even in the absence of an external forcing. The standard deviation presented in figure 2(a) represents a proxy of sea surface height variability in terms of white noise only. It provides no information on the time scales or persistence of multi-decadal linear trends. Figure 3 shows the multi model mean of the

![Figure 2](image-url)  
(a) Multi model mean of temporal standard deviation of sea surface height (in mm) in control simulations and (b) uncertainty defined as ratio of multi model standard deviation and multi model mean of temporal standard deviation.

![Figure 3](image-url)  
Multi-model mean of 95th percentile of running trends (mm yr$^{-1}$) using window lengths of (a) 20 yr, (b) 40 yr, (c) 60 yr and (d) 80 yr, respectively. The displayed trends represent the upper limit of trends that can be expected from internal variability on the respective time scales.
95th percentile of local sea surface height trends computed using moving windows of 20, 40, 60 and 80 yr, respectively. In this study, the 95th (5th) percentile is used as an estimate of the upper (lower) bound of unforced linear trends. The trend percentiles are mostly symmetric such that equivalent maps of 5th percentiles are very similar with opposite sign (not shown).

Relatively large trends can be expected in regions of elevated variability (compare figure 2) on all time scales. Within a 20 yr period, localized trends of around ±7 mm yr\(^{-1}\) are still within the range of internally generated trends in the Western boundary current regions of the North Atlantic and North Pacific Ocean (see also figure S2). In regions of weak internal variability, 20 yr trends may reach up to ±2 mm yr\(^{-1}\). On longer time scales, the magnitude of internally generated trends is reduced yet the pattern is similar for all time scales. One notable exception are the relatively larger trends in the Arctic and Southern Ocean on multi-decadal time scales (figures 3(c) and (d)).

### 3.3. Emergence of a forced linear trend

The multi-model mean period necessary to detect a forced trend in the historical and 21st-century simulations is shown in figure 4 for selected starting years. These start years are representative for the evolution of the detection timing with progressing start years. In all cases, a forced trend is first to be seen in the tropical Atlantic Ocean, a region of very low internal variability (compare figure 2). Depending on the start year, it takes at least 60 (1950), 40 (1970), 30 (1990) and 20 (2010) years, respectively, for a forced trend to emerge from internal variability in this region.

Starting in 1950, the forced trend can only be detected after 80 yr in regions of enhanced internal variability such as the Western Pacific Ocean and the North Atlantic Current region. Note that this estimate is biased low as not all models detect a forced trend within 100 yr which is the largest window used in this study. It is also noteworthy that the delayed detection of a forced trend in these regions is confined to the offshore regions. In shallower coastal areas such as the Northeastern American coast, a forced trend can be detected decades before the signal emerges offshore. This is a direct result of the weaker internal variability along the coastal regions as simulated by the models (figures 2(a) and 3).

Shifting the starting year progressively forward by 20 yr reduces the necessary time period continuously. By 1990, a forced trend is detected by all models in the tropical ocean regions after at most 60 yr (figures 4 and S3). Not all models detect a forced trend in the Arctic and the Southern Ocean, independently of the starting year. This result reflects the large uncertainties (figure 2(b)) in the two regions. However, those models that find a forced trend also show a decrease in the timing with a later starting year. The results remain unchanged when the higher emission scenario RCP8.5 is used (not shown).

It is also those two regions that show the largest uncertainty in the timing of a forced trend (figure 5). In particular, the uncertainty increases in the Southern Ocean with a later starting year. This is also true for regions of enhanced internal variability such as subpolar North Atlantic and Pacific Ocean. The agreement between the models is highest, and increases with a later starting year, in the tropical Atlantic and Eastern Pacific and Indian Ocean with a standard deviation of less than 10 yr.

### 4. Discussion

By comparing local linear trends found in unforced control simulations with linear trends in historical and 21st-century simulations, we estimated the time span necessary for a forced
trend to emerge from the noise of internal variability. The timing of the forced trend depends on the magnitude of the local internal variability and on the magnitude of the forced trend itself. We found that, in regions of elevated internal variability, a forced trend is masked significantly longer than in regions of low internal variability. The tropical Atlantic Ocean and tropical Indian Ocean, two regions with relatively low internal variability, are the regions where a forced trend is first detected. In contrast, in the regions of the Western boundary currents and subpolar gyres in the northern hemisphere, elevated variability masks a forced trend for several decades after it has been detected in the tropical oceans. It should be noted that the applied external forcing in the historical and 21st-century simulations not only induces a long-term trend but may also change the magnitude of the background variability. These changes may be permanent or part of a long-term adjustment to the changing external forcing. However, with the exception of the polar regions the multi-model mean change in background variability is relatively small (within ±10% of the variability found in the control simulations) and therefore not significantly different from zero (figure S4).

The timing of emergence of a forced trend strongly depends on the start year of trend computation. This result indicates a change in the magnitude of the linear trends with time. The later the start date, the faster is the emergence of a forced trend in all regions, pointing towards an acceleration in sea surface height trends in the model simulations. The Southern Ocean is the region where the detection of a forced trend takes longest and where the largest number of models do not detect a forced trend at all (figure S3). The reason for this is twofold. Firstly, the variability in the Southern Ocean is elevated particularly on longer time scales (e.g. figures 3(c) and (d)). Secondly, the trend increase in global sea surface height is counteracted and even reversed by a decrease in dynamic sea surface height (e.g. Yin (2012)) leading to an overall small change in total sea surface height. Therefore, in the case of the Southern Ocean it might be more appropriate to investigate linear trends of dynamical sea level changes in order to detect an externally forced trend (Lyu et al 2014).

Gregory (2010) and Gregory et al (2013) pointed out that the ocean heat uptake, and therefore the global thermosteric height change, in historical simulations is artificially reduced in models without volcanic forcing in their spin-up and control simulations. The sudden imposition of volcanic forcing in historical simulations represents a net negative radiative forcing that the climate system has to equilibrate with. The latest Assessment Report (IPCC 2013) accounted for the underestimation by adding a trend of $-0.1$ mm yr$^{-1}$ to the multi-model mean historical global steric sea level rise. To assess the impact on our results, we repeated the analysis, but replaced the individual global steric sea level rise in each model with the adjusted multi-model mean steric sea surface height (only in the historical simulations). Doing so reduces the multi-model mean timing by 10 yr at most (figure S5). The reduction is confined to the tropical Atlantic and and Southern Atlantic and Indian Ocean and applies only to trends starting in 1950. Therefore, the impact of the absence of volcanic forcing in the spin-up integrations on our analysis of appears to be minor.

The present study investigated the emergence of forced linear trends in local sea surface height, therefore including trends due to changes in volcanic and solar forcing that are considered as natural variability. To assess whether volcanically induced local sea surface height variability is within the range of internally generated variability as defined in this study, better knowledge about the impact of volcanic eruptions on local sea surface height trends is needed.

Our results agree well with a very recent study by Lyu et al (2014) who find that an externally forced trend is
detectable in steric and dynamic sea surface height by the early to mid 2040s in 50% of the ocean area relative to the 1986–2005 reference period with a similar regional pattern as presented in figure 4(c). In our study, an externally forced signal is already detectable in the early 2030s relative to 1990 in 50% of the ocean area. The reason for this is that Lyu et al. (2014) use a fixed signal-to-noise threshold to detect emergence while we also consider the dependence of the magnitude of internal variability on different time scales. This is of particular importance in regions like the tropical Western Pacific Ocean, where internal variability is large (figure 2(a)) on interannual time scales but decays relatively fast on decadal to multi-decadal time scales (figure 3).

5. Conclusion

We found that the record length needed to detect a forced linear trend in sea surface height does not only depend on the location but also on the time when the record started. The later the record starts the sooner (in relative terms) a forced linear trend can be detected. Independently of the start of the record, the tropical Atlantic is the region where a forced linear trend emerges first. Global coverage of sea surface height observations through satellite altimetry starts in the early 1990s. We find that, starting from 1990, it takes at least 30 yr for a forced linear trend to locally emerge distinctly from internal variability (figures 4(c) and S3) in the tropical Atlantic, and more than 60 yr in regions of large internal variability, such as the Western boundary current regions in the Northern hemisphere.

It should be noted, however, that the present study investigates the emergence of a forced linear trend on local scales. It can be expected that a forced trend emerges sooner when averaging over larger regions since internally generated variability is reduced when averaging spatially and the signal to noise ratio therefore enhanced. We only investigated changes in sea surface height due to ocean dynamics and steric changes. Contributions from melting land ice and changes in the hydrological cycle are not taken into account. Due to the gravitational fingerprint of melting land ice it can be expected that the signal to noise ratio is enhanced in the ocean interiors away from glaciated regions when melting glaciers are taken into account, thus enabling a forced linear trend to emerge earlier (Lyu et al. 2014).

In summary, the presence of internal variability can obscure a forced long term trend for several decades. However, if the dominating large scale climate phenomena are known in a certain region, it is possible to remove the respective unforced variability from the observed sea level. During the past two decades, the tropical Western Pacific Ocean experienced sea level trends several times larger than the global average. Two recent studies attribute a large part of the observed trends to variability related to the El Niño Southern Oscillation and the Pacific Decadal Oscillation (Zhang and Church 2012, Hamlington et al. 2014). By removing the variability associated with these two climate modes they found a residual trend that, as the latter study showed, could be linked to the anthropogenically forced warming of the tropical Indian Ocean. It can however not be excluded that the residual trend is still part of some unresolved low-frequency internal variability. The findings of those two studies, therefore, do not contradict the results of the present study, that finds detection times of 30–60 yr (starting in 1990) for the tropical Western Pacific Ocean. Rather, all of the studies emphasize that it is important to consider internal variability when investigating long term trends, either by choosing a data-set of appropriate length or by removing internally generated variability. This is of particular importance from a coastal management and planning point of view: even if the observed sea level trends are within what can be expected from internal variability, the presence of an underlying forced positive trend cannot be excluded. The question is not if but rather when an anthropogenically forced trend emerges from local internal variability. To take adaptation measures only once the anthropogenic signal is distinct might prove to be too late.

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