Dear Prof. Meier,

thank you for publishing our manuscript in the OSD.

In the following we respond to the referees comments and provide the applied changes as you can see additionally in the marked-up version of the revised manuscript.

Please, note that to better explain the objectives of our study, as several reviewers suggested, we have slightly changed the title of the manuscript from ' Imprint of external climate forcing on coastal upwelling in past and future climate' to 'The importance of external climate forcing for the variability and trends of coastal upwelling in past and future climate'.

Reviewer #1:

I think this paper here is not very valuable for the discussion of EBUS sensitivity to climate change, as there are just too many uncertainties associated with past forcing, too many potential caveats in model simulations, and too simplistic of an analysis provided here.

The uncertainties in past external forcing in the pre-industrial era are known and acknowledged, but these uncertainties are not that large in the period after 1850. Even then, the uncertainties in the past external forcing prior to 1850, though important, are not a critical point in our reasoning. The uncertainties in past external forcing apply to the amplitude of the variations in this forcing. The CMIP5 models have included the best estimation to-date of these forcings. There are indeed other reconstructions of past solar variability that point to higher amplitude of variations (e.g. Shapiro et al., 2011) but these have been already considered inconsistent with reconstructions of past temperature (Judge et al., 2012).

Over the 20th and 21st century, this criticism does not apply. The uncertainties in the external forcing in the 20th century are relatively narrow, and in the 21st century the forcings are prescribed.

I wonder why the authors set out to write this paper in the first place. Given the evidence we have from other paleoclimate modeling studies, it seems naive at best to expect to find robust signals in models, let alone signals that can be backed up with proxy evidence (hence the lack of proxy evidence in this paper). So in that sense this paper is a model sensitivity study, and for that it provides not enough details about model mechanisms to be a significant contribution. To put it provocatively, one could have reached the same conclusions as this paper (probably even with the same confidence) by studying the existing literature.

The sensitivity of upwelling to variations in external forcings in the future has been so far framed by Bakun's hypothesis (Bakun, 1990; Bakun et al., 2015). This hypothesis has also been invoked to explain observed trends over the 20th century and to explain reconstructions of sea surface temperature over the past millennium in some EBUSs (McGregor et al., 2007). This hypothesis, in summary, states that an increase in external forcing causes a more intense warming over land than over the ocean, changing the sea level pressure gradient between both, and thus intensifying the alongshore winds that favour coastal upwelling. The formulation of this hypothesis is not dependent on a detailed mechanistic description of the winds along a narrow coastal channel, or on the small-scale ocean dynamics in the upwelling regions. It is formulated in terms of purely large-sale (thousands of kilometres) atmospheric dynamics (and additionally on the differences of atmospheric humidity over land and over ocean). It is also meant to be applicable to all EBUSs. This dynamics should be well represented in present climate models.

Therefore, we think it makes perfect sense to test this hypothesis in the context of global climate models, in the past centuries, in the 20th century and in the future assuming different scenarios of increase in radiative forcing.

In this study, we are not quantitatively estimating the sensitivity of upwelling to climate change, but investigating weather Bakun's hypothesis can be confirmed in simulation with state-of-the-art global climate models. It is, therefore, not totally critical whether or not global climate models faithfully represent the small-scale atmospheric or ocean dynamics. The testing of Bakun's hypothesis would be not meaningful if the connection between upwelling and SLP (or winds) in the models would be totally unrealistic. This is the reason why the 'validation of the models' in our study is limited to this aspect, which encapsulates the link between upwelling and atmospheric forcing in Bakun's hypothesis. Perhaps, the criticism raised by the reviewer stems from the fact that we did not clearly explain this focus of our study.

More so, the future part (where you could actually hope to find significant changes due to the strong rcp85 forcing) is covered more comprehensively by Wang et al. (2015).

This is not totally correct. Wang et al. (2015) analysed the strongest scenario rcp8.5 and calculated the trends since 1950 until 2099 assuming this scenario. Wang et al. (2015) did not analyse the weaker scenarios, not the 20th century simulations in isolation, so that from Wang studies it is not possible to know what level of external forcing is needed for Bakun hypothesis to be detectable. We analysed the weaker scenarios as well and found that, in these, the external forcing is still too weak. This is a novel result that could not have been guessed beforehand. Wang et al. (2015) did not analyse the past millennium simulations, and we may recall that also in this period variability in upwelling (derived from proxy records) has been interpreted as response to external forcing using very similar arguments as those included in Bakun's hypothesis (McGregor et al., 2007).

The set-up used by Wang et al. (2015) using 22 models may be considered more comprehensive, as the reviewer does, but it is also more difficult to interpret. Each of the 22 models is different, so that a disagreement among the simulated upwelling trends within the model ensemble could be, in principle, be also caused by the different model structure. Note also that the external forcing 'seen' by each model is also model dependent, since although the atmospheric concentrations of greenhouse gas is prescribed equally for all models, the radiative forcing depends on the mean climatology of atmospheric humidity and temperature of each model, among other factors. Here, we use more controlled conditions: only two models but for each model we analyse an ensemble of simulations driven by the same forcing. Under these conditions, we can indeed state that the disagreement in the simulated upwelling trends is purely due to internal climate variability and not to different model structure, as could be the case in Wang et al. (2015). We are also consistent in that we use the same ensemble size for all periods, past millennium, historical and future, whereas the full CMIP5 ensemble of future simulations include a different number of realisations for each model.

To put it provocatively, one could have reached the same conclusions as this paper (probably even with the same confidence) by studying the existing literature.

We respectfully doubt that this is correct. Bakun's hypothesis is being used in very recent papers (e.g. Sydeman et al., 2014). Trends in atmospheric circulation over the 20th century in other contexts different from upwelling are being explained as a response to external forcing, e.g. the poleward expansion of the Hadley cell (Lu et al., 2007), shifts in storm tracks (Ma and Xie, 2013). Our study finds that Bakun's hypothesis is not compatible with state-of-the art global climate modelling. To reach this conclusion without analysing the CMIP5 simulations could have been guessed, but it would remain a guess. To our knowledge, there are no systematic studies of the amount of forced response in the atmospheric circulation over the 20th century, and specifically of the SLP land-ocean contrast, as assumed in Bakun's hypothesis.

I recommend major revisions that should focus on providing more in-depth analysis of the mechanisms governing the variability and sensitivity of the EBUS in the models, since this would be a valuable contribution to the field.

The mechanism that give rise to variability of upwelling are well known. It is known that the coastal winds are the main drivers of upwelling. The details of the connection between winds and upwelling may be very complex at small scales, e.g. involving coastally trapped waves, small-scale turbulence, filaments, etc., (see for instance Fennel et al., 2007) but this link must be broadly driven by the large-scale atmospheric circulation and the SLP gradient between land and ocean. To investigate the small-scale mechanisms, it is clear that high-resolution ocean and probably atmosphere models are needed. But global climate models have to replicate the very basic link between SLP gradient and upwelling, and the imprint of the external forcing on upwelling must be mediated first by the modification of the SLP gradient. So we see little use in evaluating the detailed dynamics of upwelling in ocean models that will certainly not be able to replicate the small-scale wave dynamics and turbulence. This is why we analysed in our study the imprint of forcing on both the simulated upwelling and on the simulated SLP gradient in the context of Bakun's hypothesis.

P2904L25ff: how do these upwelling regions and seasons compare to observations? Maps

and time series of observations are needed to put the model performance into perspective. Also, why does the upwelling season change for Benguela in the future?

We have now included a high-resolution comparison of the sea surface temperature simulated by the MPI-ESM model and satellite data sets (Advance Very High Resolution Radiometer). This comparison is quite favourable regarding the spatial gradient, although for the regions in the Southern Hemisphere there is a large systematic bias, which is known to exist for many other CMIP5 models.

As there are no time series of upwelling intensity, it is otherwise difficult to validate the simulated variability of upwelling. This is a a problem common to the other cited studies that have analysed upwelling in global climate models, e.g. Wang et al (2015).

The Benguela upwelling season changes slightly between past and future. The reason for this change is that the main upwelling season in North Benguela is austral winter and spring (Tim et al., 2015). As it can be seen in the upwelling annual cycle, the maximum upwelling is around August and September. Thus, only slight changes in the intensity impacts in which of the three months seasonal mean (JJA or SON) the upwelling is stronger.

P2905L3f: how were the timeseries detrended? Linearly? Or with a trend estimated from the control run? How is the drift in the simulations?

The timeseries are linearly detrended.

P2905, the equations: where is this scheme applied later in the paper?

This mathematical description is the base for the whole the statistical analysis used here. This is why we compute the across-simulations correlations. Correlating the three simulations of an ensemble shows us if the external or internal forcing drives the temporal variations. The construction is used in the manuscript whenever correlating simulations of the same ensemble.

P2906L9ff: besides big differences in the mean upwelling in the different resolutions, there are also relative changes between the different regions visible in Fig. 2. Not all the regions increase by a factor of two. Why could that be? Is there a difference in variability associated with the changing resolution? These are all questions that I would hope to be answered in a model-only study. Currently, the discussion of the importance of differing model resolution is not very insightful.

In all four EBUSs the upwelling intensity is stronger in the past1000 simulation of the MPI-ESM than in the historical simulation. Changes are less intense in the Morocco (now Canary) upwelling regions. The atmospheric resolution of both simulations is equal, leading to the assumption that the oceanic resolution is the driver of these differences. We could only speculate on the origin of these differences. The oceanic response the atmospheric forcing seems to be more intense in the low resolution version.

We think that the analysis of the these differences, although indeed interesting, lies outside the scope of the present study. It should be included in a larger-scale comparative study of upwelling in all CMIP5 models.

I have doubts as to the usefulness of global models in studying EBUS. The winds that actually cause the upwelling can be very narrow (narrower than the model resolution) and coastal topography might play a role (which is not resolved well in global models). So I do not know how we can validate the models on something that they do not simulate well (strong narrow winds). It reminds me of the cloud feedback that gets studied a lot with GCMs, although they do not resolve most of the processes. One might be able to learn something, but one has to be extremely careful as to not over-interpret the model results. I think the authors here lack a little bit of this carefulness in their model validation and I would encourage them to expand that part – especially since there is no forced response to talk about anyway, they could spend more time on the model mechanisms and variability.
Bakun's hypothesis does not take into account the small-scale coastal topographic features. It is a robust and universal prediction that applies in principle to all EBUSs. The particular response of each EBUS in reality may indeed be dependent on these local details, but the sign of the response to external forcing is clearly stated in Bakun's hypothesis. We are careful not to make any predictions about the magnitude of the sensitivity of upwelling to external forcings in each particular EBUS based on these models results. This would be indeed adventurous. We, however, do indicate that the very basic mechanism incorporated in Bakun's hypothesis cannot be confirmed in present climate models, and that a very strong forcing would be needed to see any effect at all of the external forcing on the SLP gradient. This holds independently of the realism of the simulated upwelling, and even independently of the skill of the ocean model (provided that upwelling does not feedback onto the atmospheric circulation itself).

P2906L17ff: what the authors write here does not seem to hold for California (Fig. 3b). The correlation does not switch sign at the coastline as in the other three regions. In fact, the California system appears to act quite differently from the other systems. There is lots of literature on this (see Wang et al., 2015 and others). I think this would be interesting to explore.
Each Upwelling System hast its own particularities, but we think that this is not the proper study to deepen into the individual behaviour of the EBUSs. We find that, regarding the effect of the external radiative forcing, California behaves as the other EBUSs, namely not reflecting any discernible influence of the external forcing on the upwelling intensity. To analyse more closely the variability of the California upwelling system would not add any new information in this regard, as much as it can be very interesting for other goals.

P2909, first paragraph: I think this could go into the Introduction rather than the Results.
We leave this sentence in this section but describe the driving of the upwelling also in the introduction.

P2907L22ff: I do not think it is straightforward to understand the link between this paragraph and the one before. Are the authors saying that the PNA is internal variability, unaffected by external forcing, and therefore the California upwelling system will not/cannot be affected by external forcing? These would be a bit too far-reaching conclusions. I do not believe we understand the natural variability of the PNA very well. Pacific observations are worse than Atlantic ones and there are no credible PNA reconstructions back in time. But maybe I misunderstand this paragraph. In any case, some clarification would be helpful.
We have reformulated this paragraph to improve readability. We actually cite another study that links the trends in upwelling in California to the observed trends in the PNA over the last 30 years. The PNA is so far understood as a mode of internal climate variability, which is also linked to ENSO.

P2909L1ff: this is another example of the authors not making a huge effort to support their claims. They compare Wang et al. (2015), which used 22 models, to one model here.
The differences between our study and Wang et al.'s are now described in more detail.

P2909L24ff: there is some literature on past1000 simulations, showing that there is no discernible effect of external forcing on SLP variability (e.g., Yiou et al., 2012). I believe even under strong anthropogenic forcing people do not expect to easily see a forced response in SLP (Deser et al., 2012 and some of her following papers).
As noted before, this is not totally correct, specially in the tropical realm. Gillet and Stott (2009) could attribute the observed SLP trends, especially at low latitudes, to the external forcing in the 20th century. Also, the external forcing is indeed expected to impact, for instance, the ENSO state in the future and therefore the tropical SLP. The papers by Deser et al. referred to by the reviewer mostly analyse the mid-latitude realm. There are other studies, also by one of us (Gómez-Navarro and Zorita, 2013) that analysed the SLP response to external forcing at mid and high latitudes over the past millennium, also finding no clear response.
Therefore, we think that its is indeed meaningful to investigate whether the externally simulated trends and multidecadal variability of SLP over all these three periods project onto the land-to-ocean SLP gradient envisaged in Bakun's hypothesis. One conclusion of our study is that they do not, but this could not have been guessed beforehand.

P2910L18ff: "...has been so far overlooked but that has been found in previous analysis...." Has it been overlooked or not? Please clarify. In fact, I think besides Tett et al. (2007),

Lehner et al. (2015) also found a similar result, correlating CESM and MPI simulations.
Changed “far” to “mostly”

P2912L17: what is meant with “climate clouds”?
GCMs have difficulties in representing well stratocumulus clouds.

Fig. 1, bottom panel: please plot your own simulations and focus the figure on the time period covered in this paper. This panel has really not much to do with the paper here: it is not about global temperature, it does not go until 2300 but goes further back than 1850, and it does not use the same models. Like a number of other things in this manuscript, this leaves the taste of a rather carelessly put together paper.
This Figure has been now excluded

Fig. 2: please provide observations and indicate the upwelling regions that you average over on the map.
We include now a comparison between the sea surface temperature derived from satellite data and the modelled SST in the regions in which we define the upwelling indices. There are no time series of observed upwelling intensity in any of the regions, so that the comparison with observations must be limited to the gradients of the SST close to the coast.

Fig. 5: please provide reasoning for changing the filtering between past1000 and historical.
Done

Fig. 6 and 7: please provide indication of significant correlations.
Done

Fig. 9: this is an interesting figure! In addition you could answer: how is the correlation between the two different models (CESM and MPI)? I.e., how much of the correlation is due to structural similarities/differences between models and how much is due to common forcing?
The correlations between the two different models cannot only arise by chance, since even the correlations among the different simulations within each ensemble are not statistically significant. This is the main conclusion of the study: since this correlations are not large nor significant, the effect of the external forcing must be small.

General: I believe the “Morocco” system is called “Canary”, for example in Wang et al. (2015). I recommend using “Canary”, it seems more common.
Changed to Canary.

<u>Reviewer #2:</u>

The consideration of broad regions and the lack of careful analyses inhibit the ability to interpret results. The authors consider vertical transport in broad regions that are probably more sensitive to wind-stress curl over the open ocean than to alongshore winds.

The regions chosen as representative for the upwelling in the Eastern Boundary Upwelling Systems are not only a narrow band near the coast, but also include the adjacent ocean. This area is supposed to be still related to the alongshore winds as the jet of coastal parallel winds is slightly offshore and wind stress curl develops due to the relaxation of wind speed towards the coast. Therefore, the strength of upwelling in the whole region should be related to the alongshore wind, to the sea level pressure gradient and, thus, to the Bakun hypothesis (Bakun, 1990).

We checked that upwelling in the regions that were chosen for our study do present a uniform evolution of upwelling. We calculated the correlation between the latitudinal mean of the gridboxes which are closest to the coast with the latitudinal means of all other gridboxes. The correlations decay with the distance from the coast, and vanish at the edges of the chosen regions. Thus the regions used here do cover the area of upwelling and are suitable for representing the upwelling in the Eastern Boundary Upwelling Systems in the simulations. This is now included in the section defining the upwelling indices.

The main objectives of the analyses should also be stated more clearly. It is unclear whether the authors seek to investigate the impact of natural or anthropogenic external forcing on coastal upwelling, curl-driven upwelling, the validity of Bakun's 1990 hypothesis, or some combination of these options.

The main objective of the analysis is to test whether the upwelling in the Eastern Boundary Upwelling Systems shows a long-term trend and if these possible trends may be related to external climate forcing. This is obviously strongly related to the Bakun hypothesis. It is not our goal to investigate the mechanism (e. g. CO_2) that lead to changes in upwelling but to analyse if the upwelling has changed linearly over the last millennium, the last 150 years and if it will in the next 100 years.

The title of the manuscript and the introduction section have now been reworded to better explain the main objective of the study.

I appreciated the authors' mathematical description of forced and internal components of variability on p 2905. However, this construction did not appear to be utilised later in the analysis, and it did not incorporate the authors' filtering at various frequencies. Perhaps more significantly, the change in the months considered between the past and future simulations was not discussed or included in the mathematical analysis.

The mathematical description is the base of the statistical analysis used here. Correlating the three

simulations of an ensemble shows us if the external or the internal forcing drives the temporal variations. The construction is used in the manuscript whenever correlating simulations of the same ensemble.
This is now highlighted in the methods section.

The second significant issue that prevents clear interpretation of the results is the muddled investigation of the "imprint of external forcing on the drivers of upwelling" (manuscript section 5, p 2909). Here the authors attempt to explore whether the absence of common trends in upwelling can be explained by a lack of common response of sea-level pressure gradient to external forcing. The authors have skipped a few critical steps in this analysis. First, the relationship between the authors' metric of upwelling and winds was not well described. Second, the regions considered in the analysis of sea-level pressure are vaguely mentioned as "the regions most closely correlated with the upwelling indices." More explanation is necessary to interpret the analyses performed. Perhaps these regions be indicated on Figure 3 and their choice better justified.
The definition of the upwelling indices is now hopefully better justified, as the coastal regions where upwelling behaves coherently, i.e. positively correlated to the upwelling in grid-cells most closely located to the model coast.
The upwelling in the Eastern Boundary Upwelling Systems are driven by the trade winds. The strength of the trade winds is clearly related to the sea level pressure gradient. Thus, investigating the importance of external climate forcing on the sea level pressure gradient and the wind stress is a logical step.
A description of the calculation of alongshore winds and the regions for the SLP gradient has been now included.

Section 6 of the manuscript ("Imprint of external forcing on stratification") was unexpected. If stratification is to be considered as part of the analyses, perhaps it should be introduced earlier in the manuscript. However, the authors do not perform an analysis of stratification; instead, global patterns of SST are considered. These SST patterns are not compared with upwelling.
We included the analysis on stratification to investigate a more indirect impact of external climate forcing on upwelling, too. The correlation pattern of two simulations of the ensemble provide a map on where the impact of the external climate forcing on the SST is large, larger than the impact of the internal forcing. Thus, figure 9 (now figure 10) indicates that the impact of the external climate forcing on the sea surface temperature and therefore on the stratification is lower in the EBUSs compared to other regions of the same latitude. We present global patterns here only to show all regions simultaneously, but the arguments refer only to the upwelling regions. We see no correlation of SST across simulations in the upwelling regions, i.e. in the regions where SST is

mostly controlled by upwelling. indicating that the stratification is not influenced by the external forcing either.
Section 5 and 6 are combined now to make our procedure more clearly.
The section is now introduced in the introduction.

Both sections 5 and 6 which consider the external forcing appear to be limited to external forcing the past1000 and historical periods. The response of upwelling drivers and surface temperatures to future external forcing was not considered. This should be made clear, as the future change in external forcing is expected to be much larger than that of the past, but the authors' findings in sections 5 and 6 should not be interpreted as applicable to future periods.
We made this more clear in the revised version by changing the title and add further descriptions.

The "Discussion and conclusions" (section 7, pp 2911 and 2912) can be improved with more attention to detail. The current discussion does not consider the distinctions between coastal and curl-driven upwelling, but I think this discussion would be essential to the authors' interpretation. The authors note that the trends noted are consistent "in all three simulations in the ensemble" but "are not always consistent with the expectation of upwelling, with some regions showing an intensification but others showing a weakening." Neither of these statements appear to be precise, as trends in the Humboldt system do not appear to be consistent in the ensemble, and only in one of the regions (Benguela) are the trends consistent with the authors' expectation of intensification. The authors note that their "results generally agree with the ones obtained by Wang et al. (2015)." I found this statement surprising, as Wang et al. (2015) found support for Bakun's 1990 hypothesis of intensification (as the authors note on P 2901, lines 26-27). Here, the analyses seem to offer superficial support for Bakun's hypothesis only in the Benguela region, and the authors note that their results "are in contrast with the hypothesis of a discernible influence of the external forcing on coastal upwelling intensity" during historical and future periods.
We changed the discussion of the results of Wang et al. (2015) and Rykaczewski et al. (2015).
We include a brief discussion in the introduction about the coastal and wind stress curl upwelling. This is also related to the definition of the upwelling regions. As explained before, these regions display a spatially coherent behaviour of upwelling although the immediate mechanisms (alongshore wind stress on the one hand and wind stress curl on the other hand, are different. However, the are both correlated, and this is plausible because both are related to the intensity of the oceanic high-pressure cells. The wind stress curl driven upwelling is related to the alongshore wind jet too as it develops due to the decrease of wind speed from the jet towards the coast.

Finally, I suggest the authors highlight the differences between use of a single model

ensemble and the multi-model analysis of Wang et al. (2015). Comparing the future projection of one model to that of multiple models, as is done here, is one option for discussion. However, the real strength of using a single-model ensemble is the ability to more clearly distinguish internal variability from the forced response.
Done.

Currently, the analyses appear to be weighted towards the past1000 and historical simulations, with only one paragraph of the results dedicated to the future time period. However, the bulk of the introduction and discussion appear to be focused on comparing results of the current project with previous efforts that focused on analyses of the future period.
Our focus is not only the future scenarios, as in Wang et al. (2015), but also the paleo climate context, where ocean sediment cores indicative of upwelling intensity have also been interpreted as a response to external forcing. This point is key of our analysis, leading to the possibility to directly detect the influence of the external climate forcing on the upwelling in the EBUS.
We changed the introduction and discussion to be weighted more towards the past1000 and historical simulations.

P 2900, lines 5-10: The description of the project in the abstract is a bit incorrect. Here, it is noted that the ensembles included simulations of three time periods: past1000, historical, and future. However, only one ensemble included these three time periods.
Done.

P 2900, lines 20-21: I am unsure if intensification of the oceanic high-pressure systems is a significant aspect of Bakun's 1990 hypothesis. Clarify this point.
Done.

P 2901, lines 10-11: "Also, other long-term records of upwelling intensity are indirect, and sometimes even based on wind records themselves." I found this statement confusing, as I am unaware of methods to directly observe upwelling (as the rate is much smaller than can be detected by direct measurement). All studies of long-term variability in upwelling intensity are indirect. Those that report vertical velocities typically infer those vertical velocities from some simple Ekman relationship or use a model that incorporates wind forcing as a significant influence on circulation.
"other" deleted.

P 2901, lines 20-21: There are a number of other analyses that have examined the effect of increasing greenhouse-gas concentrations on upwelling that may be worth noting. Some of

these include Hsieh and Boer (1992), Mote and Mantua (2002), Diffenbaugh (2005), and Rykaczewski et al. (2015). I am not one to require an exhaustive review of literature in an introduction, but the authors may benefit from awareness of the methods and discussions of these other efforts.
Done.

P 2902, lines 5-7: These two sentences appear to be contradictory. The first sentence suggests that verification of Bakun's hypothesis in the recent past is critical if it is to be considered valid for the future period. The second sentence suggests that the hypothesis may be valid regardless of whether or not it can be verified for the past period.
Changed.

P 2904, lines 17-18: If the authors believe that the resolution of the models they utilize can realistically represent wind-stress curl in these regions, they should provide a reference. The publication that comes to mind that has raised scepticism is Capet et al. (2004) which suggests that models of 1 degree horizontal resolution would not represent wind-stress curl appropriately, but the authors may know of a more applicable publication.
We cannot be completely sure whether the 1.9 degree resolution of the MPI-ESM is high enough to realistically represent the connection between the wind stress curl and upwelling. We did test the connection of wind stress and upwelling in the EBUSs and the connection of alongshore wind stress and SLP gradient. Alongshore wind stress and SLP gradients are significantly correlated and their connection to the upwelling is strong. The strength and location of the jet seems to be impacted by the atmospheric model resolution (Small et al. (2015)). This publication indicated that an atmospheric resolution of at least 1 degree would be better and would represent the jet better. But this is just one study with one model. Unfortunately, no higher resolution version is available for any of the CMIP5 models covering these long time-scales. This must remain an open question, and our results are of course dependent on the realism of current global models to represent the upwelling dynamics.

P 2906, lines 1-9: Here, the authors provide a qualitative comparison between the models and observations. The authors should provide, at the least, references for temperature and wind observations against which they are comparing model simulations.
Done.

P 2907: The authors discuss the prehistorical evolution of global temperatures as a result of external forcing (as interpreted from proxy reconstructions) and then compare this evolution with the modelled upwelling. A necessary intermediate step here is as assessment of whether the two models considered here simulate the global variation that is

described. As mentioned earlier, justification for filtering of time series would aid in understanding.

A figure is now included representing the evolution of the global mean temperature in both ensembles.

P 2908, lines 7-10: The “general” result here is one of trends of opposite sign, but California and Morocco are two “exceptions.” It is not clear to me why the two regions exhibiting opposite signs were considered “the general result” and the two regions exhibiting similar trends were considered “the exception.”

Changed.

P 2909, lines 1-2: Here, when comparing the results of the current analysis to that of Wang et al. (2015) the authors focus on their consideration of different forcing scenarios and the detectability of upwelling responses. However, nothing is noted about the difference in the sign of the projections. I would expect that a disagreement in the sign of projected trends between Wang et al. (2015) and the current analysis would be worth noting.

Now included.

P 2911, lines 2-4: The manuscript confuses coastal and curl-driven upwelling, and so I am unsure whether the authors should conclude that their findings are specific to coastal upwelling.

We include now a more detailed discussion about this difference, which is also related to the definition of the upwelling regions. The reviewer is right that the physical mechanisms are, strictly considered, different, but both are related to the intensity of the oceanic high-pressure cells. The chosen upwelling regions display a coherent behaviour of upwelling, i.e. upwelling in the grid-cells within each region are positively correlated to upwelling in the grid-cells closest to the coast.

P 2912, lines 1-4: My interpretation of the results of Rykaczewski et al. (2015) is that they found most IPCC AR5 models simulated an increase in upwelling-favourable winds in the Canary and Humboldt systems, but no consistency across models in the Benguela system, and a decrease in winds in the California system.

Changed.

P 2908, line 4: I interpret table 8.6 in Chapter 8 of the AR5 (Myhre et al., 2013) to suggest that the increase external forcing over the past 250 years is 2.3 watts per square meter rather than 1.6 watts per square meter.

We mentioned here the 1.6 watts per square meter because its the RF (radiative forcing), as described by the IPCC. The quoted 2.3 watts per square meter in Myhre et al. (2013) is the ERF (effective radiative forcing), which also includes rapid changes in the surface and tropospheric conditions. To correct figure to compare with the radiative forcing in the past mentioned by Schmidt et al. 2011. is the radiative forcing.

The first sentence of section 4 (P 2906) in indecipherable.
Changed.

Reviewer #3:

It is interesting to look specifically at upwelling systems because global models still tend to behave rather poorly in these areas, compared to observed data. But doing such an ensemble analysis with 3 members for one forcing is, even though right now state of the art, just not enough to conclude anything substantial.

We analyse ensembles of three simulations with the Max-Plank Institute (MPI-ESM) and the CESM-LME with different initial conditions. Analysing these three with regard to their temporal evolution and their similarities in this aspect, provides a robust tool to evaluate whether the external or the internal forcing dominates the upwelling variabilities. Using more than three simulations would not lead to another result.

We think that the use of just three simulations is indeed enough for our purposes. The reviewer may be perhaps aiming at identifying and attributing the spatial pattern of upwelling that is driven by the external forcing and for this purpose a large number of simulations would indeed filter out the noise and leave a clearer signal. However, our purpose is different. It is to test whether the interpretation of single upwelling records (from observations or from proxy data) as driven by external forcing is justified. If, as in our case, two simulations driven by the same external forcing produce different time evolutions of upwelling in terms of long-term trends, it is clear that model results are not compatible with this interpretation. For our purposes, even two simulations would be enough.

As far as I can see it, the main method hinges on splitting up a certain solution quantity in a part caused by initial conditions and a part caused by the forcing (eq.(1),(2)). The underlying assumption being that the part of forcing for a certain quantity doesn't change when only the initial conditions are changed. And that the time scale of the internal variability of the system is much smaller than the variability due to forcing. Making it possible to set variance terms of the form y i , y f to zero. Is this really the case here? In particular regarding the upwelling index. On what time scales does the forcing change?

The equations show that with two simulations which have the same forcing but different initial conditions the ratio of the variance of the forced component and the variance of the time series is the same as the correlation between both time series. This is true because of the assumption that the variance of the internal components of both time series are uncorrelated. The forcing is

externally prescribed and, thus, cannot be influenced by the initial conditions. Correlations are performed after time filtering of 10 years (historical and future) and 30 years (past1000) because we are interested in decadal and multidecadal variabilities and trends. Therefore, forcing variabilities on these and longer time scales are investigated not variabilities of higher frequencies.
Our analysis does not depend on whether the time-scale of internal variability are shorter than the time scales of the forcing. Actually, they could be the same. The key point is only that the internal variability is uncorrelated in the different simulations of one ensemble, which is assured by the random selection of the initial conditions.

On another note. These two equations are never mentioned later on. Even though it is clear after a second read through, what was calculated with them. The paper might benefit from mentioning these quantities just after the equations thus removing any possible confusion later on.

This mathematical description is the base for the whole the statistical analysis used here. This is why we compute the across-simulations correlations. Correlating the three simulations of an ensemble shows us if the external or internal forcing drives the temporal variations. The construction is used in the manuscript whenever correlating simulations of the same ensemble.
We explained this point clearer in the revised version.

Could you elaborate more on the setting of the initial conditions. What was randomly changed?

The initial conditions were taken from another pre-industrial control simulation with the same model randomly choosing different steps as starting conditions. This is the standard practice to construct ensemble of global climate simulations that are not aimed at decadal or seasonal climate prediction.

2904 line 24: As there seem to be other definitions of the upwelling index, could you please write out the formula for yours.

We calculated the field mean and the seasonal means of the vertical mass transport at 52m depth of the MPI-ESM and of the vertical velocity at 50m depth of the CESM-CAM5. Using the Climate Data Operator (CDO), this is done by applying the functions fldmean, seasmean, and splitseas.

2903 line 14 The width of the probability distribution (volcanic ash) is mentioned. How big were the differences between the models?

The difference lies in the width of the distribution of the sulphate aerosols size (not volcanic ash), which is 1.2 micrometers in r1 and 1.8 micrometers in r2 and r3.

2903 line 10: Information in what order the simulations were started is not really useful.

We do not understand this comment.

2909 line 15: ’ areas most closely correlated’: So the area, where the upwelling index was calculated differs from the area, where the SLP gradient was calculated (ocean)? Why would one do that?

There areas chosen for the SLP gradient are not the upwelling regions. The wind that drives upwelling is linked to the gradient of the SLP, and therefore the SLP regions must encompass a wider a different area that the upwelling regions. We chose the areas which are highest correlated to the upwelling. These areas include the at mainly large parts of the areas of the location of the climatological mean of the subtropical oceanic high and continental low. Correlating the SLP gradients with the areas of the climatological mean do not change the results of this analysis.

2922: Figure 1 really doesn’t tell me much. Except that that these kind of rcp scenarios exist.

Figure has bee now excluded.

There are a couple of small things. I couldn’t find information about the physics of the CESM-CAM5 version. In particular the ocean model. A reference in the text, when mentioned first, would help very much.

Done.

2905 line 8: no ’the’ in ’the initial conditions’

Done.

2909 line 2: found instead of find

Done.

2919 line 9: ’to be kept in’ instead of ’to kept in’

Done.

<u>Reviewer #4:</u>

There is no observation at all to refer with in this paper. I think the author should at least find ocean reanalysis data for Fig. 2, in order to properly evaluate their simulations.

Of course it would be a great benefit having observations to evaluate our model results. Unfortunately, there are not time series of directly measured observed upwelling. Observational data sets regarding upwelling are proxies of the upwelling itself like sea surface temperature and wind stress. Furthermore, these data sets are not covering large spatial and, even more important, temporal scales. When analysing the last hundreds or thousand years, sediment cores are used as proxies. These are locally restricted and the derived variable is not the upwelling itself but e.g. temperature, nutrients or species which could be influenced by other factors, too. Thus, it is very difficult to evaluate earth system model results with observations when analysing upwelling of the last thousand years.

The reviewer suggests to compare with ocean reanalysis, but this comparison would not be between model versus observations, but rather model versus model. The ocean model used in ocean reanalysis is also driven by atmospheric (and oceanic) data sets that do not have a very fine resolution, also that the caveat always remains whether the wind forcing would be adequate to realistically represent coastal upwelling. The amount of ocean observations in the EBUSs is also quite limited, with the exception of the California upwelling system. All in all, the upwelling simulated in ocean reanalysis would rather be a model product, only very weakly constrained by ocean observations, if at all.

The reviewer is right that it is difficult to validate the realism of the simulated upwelling, other than comparing the sea surface temperature fields with observations. It is, however, well known that all climate models display a temperature bias in the EBUS, the origin of which is not well known. This is an open question that cannot be resolved here.

Nevertheless, we include now a comparison of the simulated sea surface temperatures with high resolution satellite products from AVHRR. This comparison indicate that the mean SST structures are rather well reproduced by the MPI-ESM model, although the two regions in the Southern Hemisphere the well know SST bias is very apparent. We conclude that the basic mechanisms of upwelling must be rather realistically simulated in the models, but that likely other processes, like the simulation of boundary layer clouds is a major deficiency of the CMIP5 models.

The statistical analysis is not very clean. The statistical significance of the different correlation computed should be systematically given with a threshold clearly stated, and with an appropriate way to account for the number of degrees of freedom including auto-correlation in the time series. This is true for Fig. 3, 5, 6, 7 and 9. Also the “statistical model” from page 2905 should be better depicted with assumptions clearly explained.

We calculate correlations in different settings. In one setting we calculate correlation patterns across simulations. In other settings we calculate correlations between individual time series. The requirements to show the statistical significance are different. When we show correlation patterns, for instance the correlation pattern between a upwelling index and the SLP field, it is the physical plausibility and interpret ability of this pattern what is more relevant. There will be correlations with gridpoints that are statistically significant, but for others this correlation will be non-significant. This will be necessarily so. For instance, upwelling will be more strongly correlated with the coast-parallel winds, which means that the correlation to the SLP field will be zero on those locations (where the SLP gradient is highest). This illustrates that the interpretation of a correlation pattern is more based on physical reasoning.

In other settings we do calculate the correlation between individual time series, for instance between the upwelling indices in the different simulations (Fig. 4 and Fig. 8). As we claim that there is no connection between these indices, we have to put care in this case in establishing the statistical significance. For this we do not rely on the estimation of an effective number of degrees of freedom, but rather on Monte Carlo simulations, in which we produce synthetic time series that have the same serial correlation structure as the original series, but that are otherwise uncorrelated in time (see e.g. Ebisuzaki et al. J. of Climate, 1997, A Method to Estimate the Statistical Significance of a Correlation When the Data Are Serially Correlated). Since we calculate the correlations after different degrees of time series smoothing, this method takes care. The threshold of significance in this calculation is 0.95 for all correlations and trends.
The mathematical description is the base of the statistical analysis used here. Correlating the three simulations of an ensemble shows us if the external or internal forcing drives the temporal variations. The construction is used in the manuscript whenever correlation simulations of the same ensemble. We explain this point more clearly in the revised version.
We explain these technical details in a more detailed fashion in the revised version.

Why are your results so different than Wang et al. (2015)? Do you use the same boxes? Is MPI an outlier in the CMIP5 database? According to his Extended Data Table 2, this does not seem to be the case. Please clarify this point. More specifically, the sign of the trends were the same in the different regions in Wang et al. (2015), while here for your RCP8.5 you find either positive or negative trends. Why do you limit your table 3 and 4 to past1000 and historical and not to RCP8.5 to confirm mechanisms proposed by Wang et al. (2015) within your framework?
We included a more detailed discussion of the differences and similarities of our results compared to Wang et al. (2015). However, we are surprised by the comment of the reviewer. In the paper of Wang et al. (2015), extended data figure 3, the long-term trends in the period 1950-2099 in the EBUSs are shown. For all regions there are positive and negative trends (blue and red squares), so that clearly not all models agree in the sign of the trend. Wang et al. (2015) define a level of consensus among models (e.g. if 80% of the models agree) to claim robust trends. In our study, we calculate the trends in the period 2006-2100 (in contrast to 1950-2099 in Wang et al. (2015)). We additionally show that for some regions, e.g. Humboldt, this discrepancy in the trend may be due not the different model structure, but also to internal variability, as we find in the MPI-ESM model. It is not easy to identify the trends simulated in individual models, as their figure 2 show only the ensemble-mean together with confidence intervals, specifically for California, the long term trend seems to be mainly not robust across the models.
We agree with the reviewer that our manuscript should explain more clearly the differences between the Wang et al. (2015) study and ours and also how our conclusions complement the conclusions reached by Wang et al. (2015).

P. 2900, l. 11-12: you should specify for which period you are talking about. This last sentence could be improved.
Done.

P. 2900, l. 24: please specify "stronger" than what?
Done.

P. 2901, l. 4-5: in the following you refer to Humboldt and Canary by Peru and Morocco. It would be nice to keep the same terminology in the all the paper.
When referring to a publication, we call the regions like the authors of the original paper.

P. 2901, l. 27: "lack of observations" where and when? I can't believe there is absolutely no source of instrumental observations in the analysed regions.
Changed to "lack of long-term observations".

P. 2902, l. 4: replace "external" by "radiative".
Done.

P. 2902, l. 5: please state clearly what you have in mind by "Bakun's hypothesis" in a sentence. Is it that "upwelling should answer to external forcing", or that "external forcing may change land-sea contrast and therefore wind stress and upwelling". This is important to clearly define here what you meant.
We clarified in the introduction what is meant by "Bakun's hypothesis". We mean both: the external forcing may change the land-sea contrast of SLP and therefore wind and upwelling which in turn imply an answer of the upwelling by external forcing.

P. 2902, l. 11-13: "if the upwelling. . ." this question is a bit different than the one stated l. 6-8. Indeed, the external forcing can act as a pacemaker for internal variability, without leading to variations that goes beyond the internal variability (cf. Ottera et al. 2011, Swingedouw et al. 2015). What is your point here? I believe it is looking at external forcing playing as a pacemaker, but please clarify your main question to be analysed here.
Done.
If the correlations between the simulations are low the upwelling is not driven externally. This means the external forcing is too weak to dominate the internal variations or its has no influence on the upwelling.

P. 2902, l. 14-23: I think this paragraph should come before the former one. The paragraph l.

5-14 should end with presentation of the plan of the paper I believe.
Done.

P. 2903, I. 6: In Fig. 1, you only depict the upper panel. You do not use the lower panel, which is misleading, since in the present study, you're not looking at all CMIP5 models, but just two. Please remove lower panel, or replace it by the models you are looking at.
Figure is now excluded.

P. 2903, I. 15-17: It should be stated how strong is this solar forcing, given the debates that exist on the scaling. What is the difference between Maunder Minimum and present day for instance? I assume this is a weak solar forcing, but please clarify this.
Done.

P. 2904: please describe rapidly CESM-CAM5 model.
Done.

P. 2904: I.25 - p. 2905, I. 2: this is depicting a first result and not really "data and methods". So I think, this should move in section 3, and state Fig. 2 as a support for this result.
We left this part in the "data and methods" section because it is part of the description how the upwelling index is calculated.

P. 2905, I. 15: "proportional to the external climate forcing". I disagree with this statement since the response to external forcing could be lagged by a few years. Indeed, you analytical strategy would account for that, so this is mainly an issue with the word "proportional to". What about "Related with"?
Done.

P. 2905, I. 23-27: Here I think more details should be given. I assume the results proposed assumed that correlation between yji and yf is equal to zero, which won't be the case empirically. Please clarify.
The true correlation between the internal variability in the different realisations will be zero, as the initial conditions are chosen at random. The reviewer is right that the 'sample correlation' derived from the data depends on the realisation at hand, but the statistical analysis presented here related to the true statistics, not the sample statistics. The main result is that the true ratio between forced variance and total invariance is given by the true correlation between members of the ensemble. This is an exact result, which has to be later tested with the sample statistics estimated from the model at hand.

P. 2906, l. 8: “”observations”. Which? Can you at least provide a reference?
Done.

P. 2906, l. 9-10: “lower resolution”. Here I’m really confused. What do you mean by lower resolution? Are projections and last millennium simulation not using the same model that you loosely called MPI-ESM? Indeed, different versions of this model exist (MPI-ESM-LR and MPI-ESM-MR). Even though these models do share lots of element, the difference in resolution is paramount, and makes these two models different. I can’t find any mention of different version of MPI model used in section 2. This should be clarified by using the CMIP5 name for the models.
Done.

P. 2906, l.23: the first sentence is too general and not necessarily true: you have not proven it and no references substantiate it.
The explanation and references are the ones cited in the following sentences.

P. 2907, l. 4-5: I think a better or additional reference to Fernandez-Donado et al. (2013) will be Schurer et al. (2015)
Done.

P. 2907, l. 6-7: “These high temperatures. . .”. I do not think there is any consensus at the moment on what caused the MWP. Indeed, as stated before, solar activity is now believed to be very small and not large enough to cause by itself the MPW. There have been lots of volcanic activity around the 13th centuries, so that your definition of the MWP as 1000-1300 AD is problematic in this respect. Please clarify and give references to support this strong sentence.
Done.

P. 2907, l. 16: “mostly not statistically no significant”. Please state the level and the test used, and how you compute the degrees of freedom. Such an estimation of significance should be done everywhere.
This now explained in more detail in the method section. The test are not based on any effective number of degrees of freedom, since the time series present serial correlations in all cases. The test are based on Monte Carlo calculation that take into account this serial correlation.

P. 2909 l. 22- 24: “These expected trends. . .” This sentence is not clear to me. Please clarify. To which Table or figure are you referring? Table 2 I assume. But why have such expectations. Recent McGregor et a. (2015) paper rather argue that it is the volcanic forcing

that leads the decreasing trend over last millennium. And since the trends are not significant in Table 2, what can we say from that? Just that signal (if any) to noise is too small?

According to Bakun's hypothesis, the expected trends are negative in past1000 due to the long-term orbital forcing, and positive due to the increasing greenhouse gas forcing.

P. 2910, l. 23-24: Indeed, internal variability may have played a very big role over the last millennium, notably to explain MWP (cf. Goosse et al. 2012). This is why you should avoid strong statement as p. 2906, l. 23

Sentences on P2906 L23 changed.

P. 2911, l. 15: please be more specific: Benguela has a positive trend, while California and Morocco a negative one and Peru no significant one.

Done.

P. 2912, l.1-8: following my main issue no 3, you should specify here more clearly the differences in which regions compared to your results.

Done.

P. 2912, l. 23: add “two” before “state-of-the art” to be more specific.

Done.

Table 1,3 and 4: p-values? 10 and 30 should be reversed at the end of the legend I assume.

Table 1 was excluded because the histogram contains the same information. All correlations in table 3 and 4 are not significant. 10 and 30 low-pass filter was reversed.

Table 2: star are not defined:

Table 2 excluded.

Fig. 2: keep the same scale for b and c. Why are such differences? Two versions of the MPI model? Is it possible to have an idea of observations?

If we would keep the same scale for b and c, one could not see the annual cycle that clearly as now. The historical period is the MPI-ESM-MR and the past1000 the MPI-ESM-LR. For both, the atmospheric horizontal resolution is the same (1.9 degree), whereas the oceanic horizontal resolution is finer in the MR version. This seems to induce the differences in the strength of the upwelling.

To our knowledge, there are no direct observations of vertical velocities over a relatively long-period of time. Upwelling in the models is also subject to high interannual variations, so that a comparison with point measurements obtained in one particular year would not be meaningful to derive a long-term mean statistics. Unfortunately, inference about the upwelling intensity must rely on indirect indicators, like SST or algae blooms but from this it would be very difficult to derive absolute values of the mean vertical velocity.

Fig. 3: remove non-significant regions?

There will be correlations with gridpoints that are statistically significant, but for others this correlation will be non-significant. This will be necessarily so. For instance, upwelling will be more strongly correlated with the coast-parallel winds, which means that the correlation to the SLP field will be zero on those locations (where the SLP gradient is highest). This illustrates that the interpretation of a correlation pattern is more based on physical reasoning.

Fig. 6: Is it the same for the other regions?

Figure changed to include all regions.

Fig. 7: Why can't we find the same vertical bar as in Fig. 5?

Done.

Fig. 9: legend: What is skin temperature? Why showing only two members? Remove non-significant correlation?

The skin temperature is the surface temperature of land and ocean. We show two member here as an example for the correlation between the simulations of an ensemble, but the results of the correlations calculates over such long-period of time is essentially identical using any other pair of simulations.

We did not remove the non-significant correlations for the same reason as mentioned for Fig. 3 (see above).

P. 2900, l. 1: please remove the capital to "eastern boundary upwelling systems"

Eastern Boundary Upwelling Systems is a capitalised term in our manuscript.

P. 2900, l. 6: "volcano" should be "volcanic"

Done.

P. 2900, l. 6: "simulations of ensembles" should be "ensembles of simulations"

Rewritten.

P. 2900, l. 15 "EBUs" why is the final "s" not in capital letter? This should be "EBUSs"

according to Want et al. (2015). Correct everywhere in the ms.
Done.

P. 2901, l. 26: add a coma after "EBUs"
Done.

P. 2905, l. 8: remove "the" before "initial conditions"
Done.

P. 2909, l. 2: replace "find" by "found"
Done.

P. 2912, l. 9: add a "be" after "has to"
Done.

P. 2912, l. 23: "state-of-the art" should be "state-of-the-art"
Done.

Reviewer #5:
My first concern is on the goals of the paper which are not clearly stated in the introduction. A focus seems to be made on the comparisons of results from this study with previous efforts in the introduction and conclusion, which does not help the reader to find the link between the different parts of the paper. For example, Chapter 6 on the imprint of external forcing on stratification does not appear to be connected with the rest of the paper.
This concern is common to the opinion of several other reviewers. We have rewritten parts of the introduction to state more clearly the goals of the analysis and remove the sources of misunderstanding.

The authors claim to focus on coastal upwelling, however in this paper they consider upwelling in offshore regions so that the processes at play may differ.
The chosen regions include not only the upwelling directly at the coast, this is true. Nevertheless, the upwelling is forced by the trade winds in the whole regions selected here. These areas are still related to the alongshore winds as the jet of coastal parallel winds are slightly offshore and wind stress curl develops due to the relaxation of wind speed towards the coast. Therefore, the strength of upwelling in the whole region should be related to the alongshore wind, to the sea level pressure gradient and, thus, to the Bakun hypothesis (Bakun, 1990).
We checked that upwelling in the regions that were chosen for our study do present a uniform evolution of upwelling. We calculated the correlation between the latitudinal mean of the gridboxes

which are closest to the coast with the latitudinal means of all other gridboxes. The correlations decay with the distance from the coast, and vanish at the edges of the chosen regions. Thus the regions used here do cover the area of upwelling and are suitable for representing the upwelling in the Eastern Boundary Upwelling Systems in the simulations.

There is no mention of model validation in this paper, nor reference to observation. Are the models able to realistically represent wind-stress curl in these regions at that resolution? The authors appear to be honest about the presence of large uncertainties in the simulated results, would it be possible to describe the underlying assumptions and the nature of those uncertainties?

Comparing the upwelling itself to observations is very difficult due to the lack of measured vertical velocities. Also, the spatial resolution of the atmospheric submodels may be not enough for a realistic representation of the wind stress forcing. This is a caveat that we have to accept until high-resolution simulations over centennial times scales become available.

We include now a comparison of the simulated mean sea surface temperature in the upwelling regions with the sea surface temperature derived from satellite products (AVHRR). We find that the spatial gradients of the mean SST are rather well simulated, although in the upwelling regions of the Southern Hemisphere the models show a large systematic bias, which is already known for all CMIP5 models (see for instance the cited paper by Richter, 2015). In addition, we also investigate drivers of upwelling by analysing the connection between simulated upwelling and the simulated wind stress. We find that this link is quite compatible with the well-known link derived from observations at least at larger spatial scales. The correlation patterns in Fig. 3 show the realistic representation of the sea level pressure patterns connected to upwelling in the EBUSs. Furthermore, the annual cycle of the upwelling is realistically represented in the earth system model. Small scale features of wind variability are surely not resolved in these models but the large-scale pattern and, evidently, its relation to the upwelling is.

The uncertainties are related to the realism of the models in simulating upwelling dynamics. Although our analysis does indicate that the basic upwelling mechanisms are well represented in the models, there will certainly be small-scale processes that cannot be captured in this simulations. To what extent these processes may be relevant for the trends in upwelling remains an open question. On the other hand, we also look for the connections between the external forcing and the main driver of upwelling, namely the wind stress. It can be argued that the atmospheric resolution is not suitable to represent the small-scale coastal wind stress, but on the other hand Bakun's hypothesis is formulated in terms of large-scale atmospheric dynamics as the differential response of the oceans and land to increased radiative forcing. This is quite well represented in current climate models.

The differences with the previous work by Wang et al. (2015) are not very well explained. The authors could clarify why they obtain different results, for example why the signs of the trends differ.

We included a more detailed discussion of the differences and similarities of our results compared to Wang et al. (2015). In Wang et al. (2015), extended data figure 3, the long-term trends in the period 1950-2099 in the EBUS are shown. For all regions there are positive and negative trends (blue and red squares), so that clearly not all models agree in the sign of the trend. Wang et al. (2015) define a level of consensus among models (if 80% of the models agree) to claim robust trends. In our study, we calculate the trends in the period 2006-2100 (in contrast to 1950-2099 in Wang et al. (2015)). We additionally show that for some regions, e.g. Humboldt, this discrepancy in the trend may be due not the different model structure, but also to internal variability, as we find in the MPI-ESM model. It is not easy to identify the trends simulated in individual models, as their figure 2 show only the ensemble-mean together with confidence intervals, specifically for California, the long term trend seems to be mainly not robust across the models.

We agree with the reviewer that our manuscript should explain more clearly the differences between the Wang et al. (2015) study and ours and also how our conclusions complement the conclusions reached by Wang et al. (2015).

P. 2904, l.24 : The upwelling indices used in this paper should be better described. Also, the relationship between the metric of upwelling and winds could be better described.

The method section now includes a more detailed description of the definition of the upwelling indices, as this is also related to the two mechanisms that drive upwelling, namely the alongshore wind stress and the offshore wind stress curl. Both are physically related to the intensity of the oceanic high-pressure cells. The regions selected to derive the upwelling indices represent oceanic areas with coherent upwelling evolution, i.e. upwelling in the grid-cells included in the regions is positively correlated to the immediate coastal upwelling in the model.

Table 1: the meaning of (r1, r2, r3) has to be better defined.

Table excluded but done for table 3 and 4.

p. 2902, l. 5: an explanation of “Bakun’s hypothesis” would be appreciated.

Done.

Fig. 5: why is there a different filter between past1000 and historical simulations?

The different filter is mainly related to the different length of the simulations (950 years, versus 156 years) and to the objective of filtering out as much as possible interannual variations that may mask the influence of the external forcing.

Fig. 9: the "skin temperature" is referred to without any mention on how this was computed. Please explain.
Done.

P. 2900, l. 6: "volcano" should be "volcanic"
Done.

P. 2900, l.15: why does the final "s" in "EBUs" is not capital letter?
Done.

P. 2904, l.5: remove reference to "Otto-Bliesner et al., 2015"
Done.

P. 2905, l.8: "with different THE initial conditions", remove "the"
Done.

P. 2911, l.28: "not the evolution of upwelling" should be "nor the evolution of upwelling"
Done.

Fig. 1, last sentence of legend: "how many model are", "model" should be "models"
Figure excluded.

<u>Reviewer #6:</u>
The main and big problem of the paper is that the authors do not go enough into details in their explanations and reasoning. The reader needs to make a strong effort to understand the logical reasoning and the conclusion induced by a given explanation. A big effort of explanation and clarity is necessary, requiring to explain clearly the objective of each section, to provide more details, to go deeper in the analysis and to improve the link between sentences, paragraphs and sections. This is true throughout the whole paper.
This concerns has been shared by most of other reviewers and we tried to produce a manuscript that can be read from a large fraction of the scientific community, we rewrote and clarify our explanations and reasoning throughout the whole manuscript.

The results found by the authors for the evolution of EBUS in the rcp8.5 scenario are not in agreement with previous studies made with other models (Wang et al., 2015, Rykaczewski et al., 2015). First, it is necessary that the authors develop their discussion about these differences, trying to understand them.

We included a more detailed discussion of the differences and similarities of our results compared to Wang et al. (2015). Wang et al. (2015), extended data figure 3, the long-term trends in the period 1950-2099 in the EBUS are shown. For all regions in the analysis of Wang et al. there are positive and negative upwelling trends (blue and red squares in their figure), so that clearly not all models agree in the sign of the trend. Wang et al. (2015) define a level of consensus among models (if 80% of the models agree) to claim robust trends. In our study, we calculate the trends in the period 2006-2100 (in contrast to 1950-2099 in Wang et al. (2015)). We additionally show that for some regions, e.g. Humboldt, this discrepancy in the trend may be due not the different model structure, but also to internal variability, as we find in the MPI-ESM model. It is not easy to identify the trends simulated in individual models, as their figure 2 show only the ensemble-mean together with confidence intervals, specifically for California, the long term trend seems to be mainly not robust across the models.
We agree with the reviewer that our manuscript should explain more clearly the differences between the Wang et al. (2015) study and ours and also how our conclusions complement the conclusions reached by Wang et al. (2015).

Second, this suggests that the choice of the model is a source of uncertainty resulting in a range of variability that can be as large as the one associated to the variability of external or internal origins. The authors should therefore examine the possibility to extend their study to other models of CMIP5, that gathers 20 modeling groups (as seen on Fig. 1, 42 models were used to perform historical simulations, and 25 to 42 to perform scenarios simulations). This does not require to run additional simulations, but to gather 2D fields of SST, mean SLP, velocity/transport at 50m depth and wind stress. This would greatly increase the robustness of their conclusions. It seems possible to use other ensemble to estimate effect of external forcing (for example by comparing trends) even if initial conditions differ across models. The authors could examine the correlation between simulations performed with different models, as they do here for simulations performed with the same model. Note that the authors mainly use here results from MPI-ESM, and do not discuss a lot results from CESM-CAM5, though they say at the beginning that they will examine the effect of the model.
We only used these two earth system models because these are the only ones available with ensembles of simulations where the simulations are driven by the same model and the same external forcing over the past millennium. Our focus is not only the future scenarios, as in Wang et al. (2015), but also the paleo climate context, where ocean sediment cores indicative of upwelling intensity have also been interpreted as a response to external forcing. This point is key of our analysis, leading to the possibility to directly detect the influence of the external climate forcing on the upwelling in the EBUS. Therefore, analysing other models would not be a benefit for this purpose

In addition, there seems to be a misinterpretation of the Wang et al. (2015) study, as the reviewer seem to indicate that virtually all CMIP5 models used in Wang et al. (2015) agree in the sign of the simulated upwelling trend in all EBUS. This is not the case, as it can be seen in the Extended Figure 3 of Wang et al. (2015). The agreement between CMIP5 models is not as strong, although the ensemble mean does indicate a general intensification of upwelling.

In our study, by using ensemble of simulations, we expand the conclusions reached by Wang et al. (2015), by showing that model disagreement can be due not only to different model structure but also simply to random trends caused by internal climate variability.

The suggestion of the reviewer to also calculate correlations across models does not seem meaningful (we may have misunderstood this part of the comment). If simulations within an ensemble performed with the same model already appear uncorrelated, indicating that the role of the external forcing must be very small, there cannot be physically meaningful correlations between simulations with different models, which inly share the prescribed external forcing. We do not see any additional information in this type of calculation.

The authors show that the variability of the upwelling over the past periods in mainly internally driven. They should explain more clearly what are the mechanisms involved (some of the explanation is already present in Sections 5 and 6, but needs to be developed).

We further tried to expand this in the revised version, but the core of this concern is very difficult to address here. The main reason why upwelling is not responding to the variations of external forcing is that the atmospheric circulation, the wind stress, has a very small signal-to-noise ratio. In other words, it is the atmospheric dynamics that does not respond to the external forcing as other thermal variables do. For instance, focusing on the simulated trends in the large-scale atmospheric circulation patterns like the North Atlantic Oscillation or the Antarctic Oscillation, models tend to produce future trends of different sign, although in general, taken the CMIP5 model as an ensemble, the tendency is towards an intensification of these modes. However, there is a non-negligible number of models that do not agree, even more so when considering not only the atmospheric circulation at the surface but in the mid- troposphere as well. Related to this, these large-scale circulation patterns have displayed large-decadal variations over the 20th century that cannot be attributed to the external forcing. Detection and attribution studies do find a response of the atmospheric circulation to future forcing, but this response is weak and rather limited to the low-latitudes (see e.g. Gillett and Stott, doi:10.1029/2009GL041269).

Abstract P 2900 L 12 : Conclusions of the type "except for" or "only for" are too strong since there are only 4 cases (of upwelling or scenario). Moreover scenario rcp 8.5 may be the most realistic one in terms of GHG emissions ...

Done.

1- Introduction L24 : "stronger external climate forcing". Please be more precise (stronger trade winds ?). In general in the paper the authors mention the increase or evolution of external forcing, they should be more precise.

Changed to: “stronger external climate forcing in the recent past and future “

P2901

L1 : What about the conclusions ? "Solar irradiance and volcanism": please briefly explain how.

Description added: ….have been interpreted as a response to past variations in the external climate forcing, mainly solar irradiance and volcanism, with weaker upwelling during the Little Ice Age and stronger upwelling during the Medieval Warm Period.

L 3: Could you please give some details about the « metadata analysis ». What it is based on ?

This is a reference to another study. Meta-data analysis is the analysis of already existing publications, in this case the publications that claim to have found (or not found) a trend in the upwelling-favourable winds.

L 4: Same comment as p 2900, I would remove "only" since it concerns 3/4 of the cases.

Done.

L 5-10: This part should be developed, giving more details about upwelling intensity indicators used (wind?). L8-9 does indeed make sense only if this is based on wind indicators.

Done.

L 14-19: The effect of El Niño is not clearly explained. Please explain more precisely the relationships (El Nino -humidity- radiative forcing- land ocean thermal contrast- wind ?).

Done.

L 17-19, what is the "changing frequency of ENSO"?

Done.

L 25 : rcp 8.5 is the scenario that results in the strongest warming. The result of Wang et al. (2015) is in contradiction with the result of the present study, this should be investigated deeper in this paper (did they use the same indicators ? What was the analysis that support their conclusions ? What were the differences between the configuration of the models that they used and the one used in the present study ?...)

Done.

L 28-4 : This should go after L 2 , since it deals with uncertainty associated to upwelling evolution estimations in the past.
Done.

P 2902
L14-23: this part should not be here but in the part about models configuration, and should be clarified. What is the criteria for high resolution of atmospheric model, and is it met in the present study ?
Done.

L 22-23: what does that imply ?
Done.

End of part 1: in the introduction, the authors presented the context of their study. At the end of this introduction they should clearly state the specific scientific questions they are addressing, and how (L 10-13 only gives the reader a hint), and present the structure of the paper.
Done.

2- Data and methods
For the sake of clarity, I would add subsections (2.1 Models and simulations, 2.2 Upwelling index, 2.3 Methodology).
Done.

P 2902
L 25: The acronym of CESM-CAM5 are explained and not MPI-ESM. This is not consistent .
Done.

P 2903
The description of the model and simulations should be much developed : what are the atmospheric and oceanic models, resolution (that is detailed on page 2904), etc ...
Done.

L 5: a reference is missing for the CMIP5 scenarios description, while Fig 1 is not very useful. It would be more informative to briefly explain that it is a part of the CMIP5 project, to explain what is rcp (useful for l 22), to provide a reference and to just indicate the

average delta T by 2100 and 2300 for each rcp. Adding something about the current level of GHG compared to those scenarios could also be informative …
Figure excluded.

L 7 : please check English, "contributing" is strange
Correct.

L 16 : « include ». Does that mean that there are other forcings not mentioned here ?
No, changed to “comprise”.

L 17 : A reference for tropospheric aerosols is missing.
Done.

L 19 : please check
Done.

L 22 : please provide a reference for GHG concentration sources, as well as for each forcing, that should be clearly stated : it is not clear if the forcings taken into account for past1000 and historical simulations are also included in future simulations.
Done.

L 23 : how do initial conditions differ ?
The initial conditions in the CMIP5 simulations are randomly chosen fro a long pre-industrial control run. The initial 3-dimensional fields of all model variables are therefore different. It is not possible to briefly describe the difference in initial conditions: they correspond to different time steps, hundred of model yeas apart, of a control simulation.

28 : the authors used the result of simulations performed with a second model to assess the impact of the model on the results, however in the rest of the paper nothing is said about this. Is it really sufficient to use those simulations (who do not include future simulations) ?
These two models are the only ones that provide ensemble of simulations over the past millennium. All other CMIP5 models provide just one realization over this period. The results obtained with model models, i.e. the lack of a coherent influence of the external forcing, lack of within-ensemble correlations, inconsistent long-term trends are found in both models.
This result is already significant for other studies. For instance, in the Wang et al (2015) study, the upwelling trends found under scenario RCP8.5 are not in agreement for all models, but rather a trend is considered to be robust when at least 80% of the models agree in the sign of the simulated

upwelling trend. Our results indicate that the analysis of ensemble of simulations, instead of a single simulation per model, could potentially reduce further the level of inter-model agreement.

P 2904:

L 6: A «) » is missing

Done.

Again it is necessary to describe better the model configuration (resolution of ocean and atmosphere models, etc...) and the characteristics of the CEMS-CAM5 simulations. The description of the forcing is very vague and similarities and differences between both models should be clearly stated. For example are "All forcing" the same as the ones used for MPI-ESM?

A more detailed description was added. Describing exact differences in the radiative forcing and differences due to the model design goes beyond the slope of this manuscript.

L 10-18 : this paragraph about the model configuration should go on the previous page with the 1st paragraph.

Done.

On p 2902 the authors cite Small et al (2015) about the necessity to use a high resolution atmospheric model. Does the 2 degree resolution used here corresponds to this criteria ?

A brief description is now included.

L 15-18. This needs to be justified.

Done.

L 19: Please provide some reference and justification for the choice of upwelling indicator, which is a key point of the paper since it is used to base the results and conclusions of this paper. Why are 2 different indicators used (mass transport and velocity). It would help show the spatial boxes on a map for example on Fig 1 and 9.

The vertical mass transport of the MPI-ESM and the vertical velocity of the CESM-CAM5 are the variables of the model output that represent the upwelling. Upwelling is the vertical displacement of water from deeper layer to the euphotic zone. Thus, these are the two variables most directly related to upwelling, or even the upwelling itself.

We are constrained by the publicly available output of the simulations, so that the indicators are slightly different. However, they both physically represent upwelling.

L 25 - L 2 p 2905 : What about the realism of those upwelling seasons ?
Done. See: “Representation of upwelling and its drivers in the model”.

P 2905: How is the detrending made?
Linearly long-term detrended.

L 5-7: I don’t understand this sentence.
Analysing three simulations with regard to their temporal evolution and their similarities, provides a robust tool to evaluate whether the external or the internal forcing dominates the upwelling variabilities. Using more than three simulations would not lead to another result.

L 7-9 : If initial conditions and models are different but forcings are similar, comparing the simulations should also show the effect of internal forcing and model choice no?
This comment is somewhat unclear. We interpret that the reviewer means to compare simulations conducted with different models. Yes, the reviewer is right, but it would not add new information. We show that the simulations within an ensemble are uncorrelated or display not consistent trends. Since the model is the same, the only explanation is that the effect of the forcing is very small. If we had looked at correlations between simulations conducted with different models and we had also found that these were uncorrelated, the explanation would not be clean. It could be because the influence of the forcing is low, or because the models are different. The analysis would be inconclusive. It is much more logical to look at correlations between simulations conducted with the same model if the objective is to detect the effect of the forcing.

From L10, it should be clearly stated here that the authors are presenting the equation on which all their reasoning is based in the following sections.
Done.

L 24-26 and Formula 4: This should be explained more in details, in particular the assumptions made. (yf and y'1 and y'2 are uncorrelated, hence their covariance is 0, <x,y> is the covariance of variables with mean equal to 0, and it is assumed that the internal and external variability do not interact (the decomposition is linear)). The conclusion of this formula should be explained : if the correlation y1,y2 is weak, the variance of yf is much weaker than the variance of y1, meaning that the effect of internal variability is much stronger than the effect of external forcing. This formulae is never referred to hereafter in the paper.
Done.

P 2906

3- Representation of upwelling and its drivers in the model This part about the ability of the paper to represent correctly the EBUS is much too succinct.

We have now expanded this part of the study comparing the mean sea surface temperature in the main upwelling season with high-resolution satellite product. We find that the spatial gradients of SST are quite reasonable simulated by the MPI-ESM model although the known large systematic biases are apparent, in particular in the Southern Hemisphere region

L 6-9: Those affirmation need to be justified through references, and possibly figures of observations.

Done.

L 10: I would add « than in the historical simulation ».

Done.

L 10-12: Not only the resolution changes between 2 simulations. When referring to Wang et al. (2014) the resolution of the models used in this study should be compared to the resolution of the model used here.

Wang et al. (2014) analysed the SST bias of 22 models, also including the very same simulations analysed here with MPI-ESM-LR and MPI-ESM-P.

L 13: It would however help to show the figure

We would rather maintain the figure as it is now, showing the correlation pattern between the upwelling index and the SLP field. The correlation with the wind stress would not provide additional information as the wind stress is largely influenced by the atmospheric pressure fields through the geostrophic relation.

L 17-20: This needs to be better explained and justified.

Done.

4 Imprint of external forcing on coastal upwelling

4.1 Past1000 and historical simulations

P 2907:

First paragraph until l 7. It would help to present the evolution of mean temperature during this long period, which would support l 14-15 « do not show a centennial evolution comparable to the global mean temperatures or the global mean external forcing as just described. »

This is now shown in a new figure.

L 12 : regional upwelling INDEX.
Done.

L 19 : Here it should clearly stated that this results from Formula 4.
Done.

L 22-26: The sentence above does not necessarily lead exactly to this conclusion, I would rather say that results are consistent with the previous study rather than they support it...
Done.

P 2908:
L 1-4: to what variable is the « external forcing » of 0.3 and 1.6 W.m-2 referring to ?
It is referring to the total external forcing. The RF, the radiative forcing.

L 9-12 : Again I think that one can not really speak about « exceptions », but rather about « cases »: California is the only case over 4 where there is a significant trend in historical that can be attributed to external forcing.
Done.

4.2 Scenarios
L 23 : remove « only »
Not here, because the underlying Bakun's hypothesis is that all trends must be positive.

L 23-24 : « This support our results » : please explain better why
Done.

The discussion about the disagreement with Wang et al. (2013) results should be developed.
Done.

5 Imprint of external forcing on the drivers of upwelling
P 2909: Please provide some details about the SLP computation (area...). Otherwise it will not be reproducible.
Done.

Since authors compute both wind stress and SLP, they should check that these 2 variables are indeed correlated, to support l 8-9.
Done.

L 8: explain briefly
Done.

L 17: low and not significant
Done.

L 19-24 (« Regarding ... forcing . »). This should be explained more precisely The main conclusion of part 5 seems to be that the impact over the last centuries of external forcing on the atmospheric drivers of upwelling (wind stress and SLP) is not significative, therefore that no matter the quality of the upwelling representation in the coupled model, one could not detect any impact of external forcing on the upwelling.
Done.

6 Imprint of external forcing on stratification
Parts 5 and 6 should be merged in a section about the imprint of external forcing on atmospheric and oceanic factors implied in upwelling, with a first part about atmospheric drivers and the second about stratification. It should be explained at the beginning of this section that the authors want to determine why the imprint of the external forcing on coastal upwelling is weak over the past periods, looking at the imprint of the external forcing on processes involved in the functioning of upwelling.
Done.

P 2910
L 15-17 : references are needed
Done.

Once again, this part needs to be developed and explained more clearly. It would be interesting, together with the value of the correlation, to indicate the level of significance.
Done.

7 Discussion and conclusions
P 2911:
The context, objective and methodology of the study should be clearly reminded. For example, it is not completely clear if L 1-10 concerns past or present study (or both).
The authors need to develop the discussion about the obtained trends for the future scenarios. In particular, they should explain why these trends are obtained, by examining the evolution of the atmospheric and oceanic drivers of the upwelling. They began to do

that for the past periods in parts 5 and 6, but not at all for the future period.
More generally the authors should do a strong effort to develop this part and improve its structure (for example I don't think that the paper can finish on a last sentence like the one on L 22-23).
Done.

L 8-10 : this is not true for California.
Done.

L 14-15 : « these trends are not always consistent with the expected intensification » : why is intensification expected ?
Now explained.

L 19-20 : again show these boxes on Fig. 9
The upwelling areas are now illustrated in the new figure showing the comparison between the simulated sea surface temperature and the AVHRR sea surface temperature.

L 24-26 : the intensity of the upwelling decreases in rcp 8.5 for California and Morocco upwelling in the present study, so the authors can not reasonably conclude that their « results generally agree with the ones obtained by Wang et al. (2015) on the influence of a strongly increased future greenhouse gas forcing on upwelling intensity in the EBUs. »
Done.

P2912
L 5: Again, the conclusion can not be that « These results agree partly with our findings ».
Done.

L 9: be kept in mind
Done.

Figures and Tables
Fig 1: I don't think it is really necessary to include this figure.
Figure has been excluded.

Fig 2: Could it be possible to indicate the mean over the ensemble and, for b and c, the enveloppe?
The within-ensemble standard deviation of upwelling is very small, about 0.2 m/month for both ensembles (past1000 and historical) and regions, so that the mean climatology of upwelling is

virtually identical in all members of the ensemble.

Fig 3: What is the level of significance of correlation ? Is the map for one simulation representative of all the situations ? Could the authors try to produce a figure that uses all the simulations to make this map more robust ?

The climatological seasonal mean of one simulation is representative of all the simulations. The level of significance is 0.95.

Fig 4 : I suggest to merge this figure with Fig. 8 (same plot but for scenarios instead of past1000 and historical), and to remove Tab. 2 that does not provide any additional information.

We removed table 2 but combining figure 4 and 8 seems to be not appropriate. It would make the figure too large and unclear.

Fig 5 and 7, and Tab 1.

Tab. 1 and Fig. 5 show the same information, so I suggest removing Fig. 5 (values outside the

5-95% significance range could be put in italics in Tab. 1) and add the same information for CESM-CAM5 in Tab. 1.

We removed table 1 and kept both histograms.

Fig. 6 : it would be nice to write the name of the variable on the graphs title.

Name of variable is included in the caption.

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~~Imprint~~ The importance of external climate forcing ~~on~~ for the variability and trends of coastal upwelling in past and future climate

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Abstract

The Eastern Boundary Upwelling Systems~~are the major coastal upwelling regions. The trade winds are driving these upwelling regimes.~~, located in the subtropics at the eastern boundary of the Atlantic and Pacific ~~Ocean~~Oceans and mainly driven by the trade winds, are the major coastal upwelling regions. Previous studies have suggested that the intensity of upwelling in these areas in the past centuries may have been influenced by the external radiative forcing, for instance by changes in solar irradiance and it will also be in the future by the increasing atmospheric greenhouse gases. Here we analyse the impact of the external climate forcing ~~, e.g. the greenhouse gas concentration, solar activity and volcano eruptions,~~ on these upwelling systems in ~~simulations of ensembles of~~ ensembles of simulations of two Earth System Models. The ensembles contain three simulations for each time period which cover the past millennium (~~900–1850) ,~~ 900–1849) and the 20th century (1850–2005)~~and~~ . One of these Earth System Models additionally includes the near future (2006–2100). Using a set of simulations, differing only in their initial conditions, enables us to ~~detect whether the variability is driven internally or externally~~test whether the observed variability and trends is driven by the external radiative forcing. Our analysis shows that the variability of the simulated upwelling is ~~to the most driven internally and that~~ largely not affected by the external forcing and that generally there are no significant trends ~~except for the scenario with the most dramatic~~ in the periods covering the past and future. Only in future simulations with the strongest increase of greenhouse gas concentrations ~~.~~ the upwelling trends are significant and appear in all members of the ensemble.

1 Introduction

Eastern Boundary Upwelling Systems (~~EBUs~~EBUSs, the California, the Canary, the Benguela, and the Peru upwelling system) are highly productive coastal ocean areas where nutrient rich, cold water upwells by the action of favourable winds. The ~~link between~~ easterly trade winds which dominate these subtropical regions cause Ekman transport from the coast to the open ocean, perpendicular to the wind stress forcing, leading to upwelling at the coast. In addition, the wind stress curl between the jet of the trades and the coast induced by to the relaxation of wind speed towards the coast, causes upwelling further offshore.

It has been suggested (Bakun, 1990) that changes in the external climate forcing, such as greenhouse gases and solar activity ~~, and coastal upwellinghas primarily been framed by the theoretical considerations put forward by Bakun (1990) . Surface~~ can influence the intensity of coastal upwelling. Bakun's hypothesis states that surface temperature over land should warm faster than over the oceans under increased radiative forcing, leading to an intensification of the subtropical continental lows and the oceanic highs~~and~~, to an intensified cross-shore air pressure gradient, and to a strengthening the upwelling-favourable winds~~(Bakun, 1990) .~~. (Bakun, 1990) .

Some observations over the 20th century (Narayan et al., 2010) and simulations of the 21st century (Wang et al., 2015) have been interpreted, according to this hypothesis, as indicative of upwelling intensification due to stronger external climate forcing in the recent past and future. Also, coastal sediment records covering the past millennium and indicative of upwelling (McGregor et al., 2007) have been interpreted as a response to past variations in the external climate forcing, mainly solar irradiance and volcanism~~. However, the empirical evidence for a~~, with weaker upwelling during the Little Ice Age (centuries around 1700 AD) and stronger upwelling during the Medieval Warm Period (around 1100 AD). Although not totally ascertained, it is generally assumed that the Little Ice Age was mainly driven by a weaker solar activity and increased volcanic activity, which lead to reduced radiative forcing (Hegerl et al., 2006) . For the Medieval warm period, this attribution is not as clear, but proxy records indicate a stronger solar activity than during the subsequent Little Ice Age (Usoskin et al., 2004) .

For the past millennium, sediment cores are used as proxy for upwelling due to the lack of direct long-term ~~intensification of coastal upwellingover~~ observations (McGregor et al., 2007) . Though, not the upwelling itself is derived from the sediment cores, but rather indirectly indicated on the basis of the water temperatures, assuming that cooler temperatures are indicative of stronger upwelling. This assumption could lead to a misinterpretation because temperature changes could also have been driven by the direct effect of the radiative forcing itself, in addition to any possible influence of the radiative forcing on upwelling.

For the 20th century~~is not clear-cut. A~~, a meta-data analysis has found a significant intensification of wind stress in ~~only~~ three of the four major coastal upwelling systems (California, Benguela, and Humboldt but not Canary) (Sydeman et al., 2014). Previous studies have detected increasing upwelling intensity over the past century (Di Lorenzo et al., 2005; Gutiérrez et al., 2011; Santos et al., 2012), but others have not ~~(?Pardo et al., 2011)~~ (Pardo et al., 2011) , using observations, reanalysis, and model data. A possible cause may lie on insufficient data homogeneity in long-term wind station records and in meteorological reanalysis, which may blur the identification of long-term trends (Sydeman et al., 2014). Also, ~~other~~ long-term records of upwelling intensity are indirect, and sometimes even based on wind records themselves (Bakun et al., 2010).

~~The direct evidence for upwelling intensification is, therefore, still not conclusive. For instance, the Benguela upwelling system does not exhibit a long-term intensification in the recent decades (Bakun et al., 2010) . This has been explained by the counteracting influence of El Nio-Southern Oscillation (ENSO) on humidity in the Peru and Benguela EBUs regions, which would also influence the regional radiative forcing and modulate the land-ocean thermal contrast (Bakun et al., 2010) . According to this explanation, the upwelling trend due to stronger external radiative forcing would be biased by a changing frequency of ENSO events in the recent past.~~

~~The~~ For the future, the effect of increasing greenhouse gas concentrations on upwelling regimes in future scenarios has been investigated by ~~Wang et al. (2015) . They~~ several authors. Wang et al. (2015) and Rykaczewski et al. (2015) analysed the simulated trend of upwelling in several simulations included in the Climate Model Intercomparison Project (CMIP5) (Taylor et al., 2012) driven by the Representative Concentration Pathways (rcp) 8.5 scenario, a scenario with an increase of the globally averaged external radiative forcing of 8.5 $\mathrm{W\,m^{-2}}$ by the year 2100. They found that in most of the ~~EBUs~~ EBUSs, models tend to simulate an intensified upwelling and longer upwelling seasons under climate change. In contrast, the studies of Mote and Mantua (2002) (21th century simulation) and Hsieh and Boer (1992) (double carbon dioxide simulation) found only a weak or no trend in future coastal upwelling.

~~Due to the lack of direct observations, sediment cores are used as proxy for upwelling(McGregor et al., 2007) . Though, not the upwelling itself is derived from the sediment cores, but rather indirectly indicated on the basis of the water temperatures, assuming that cooler temperatures are indicative of stronger upwelling. This assumption could lead to a missinterpretation because temperature changes could have other origins than upwelling, for instance due to variations in the external forcing~~The evidence for effect of radiative forcing on upwelling is, therefore, still not conclusive. For instance, the Benguela upwelling system does not exhibit a long-term intensification in the recent decades (Bakun et al., 2010) . This has been explained by the counteracting influence of El Niño-Southern Oscillation (ENSO) on humidity in the Peru and Benguela EBUSs regions, which would also influence the regional radiative forcing and modulate the land-ocean thermal contrast (Bakun et al., 2010) . During an El Niño, the Benguela region is less humid which causes a reduction of the greenhouse effect due to the less water vapour, the most important atmospheric greenhouse gas (Bakun et al., 2010) . According to this explanation, the upwelling trend due to stronger external radiative forcing would be biased by a higher frequency of ENSO events in the recent past.

The verification of Bakun's hypothesis in the recent past ~~is critical to establish its validity for the future~~and future is of major importance for the EBUSs. Even if Bakun's hypothesis is correct, it is not clear whether past variations in external forcing could have been strong enough to drive upwelling intensity beyond the range of variations caused by internal chaotic climate variability. Hence, an apparent agreement between the ~~predicted and observed trend could just occur by chance~~sign of predicted and of the observed trend cannot be considered a conclusive proof of Bakun's hypothesis until those observed trends cannot be attributed to the external forcing. The analysis of the recently available ensemble of climate simulations with CMIP5 models over the recent past can shed light on this question. Firstly, they comprise different climate periods in which the external forcing has first varied little -the past millennium -, then more strongly, as presently, and much more strongly in the scenario simulations. Secondly, the use of ensembles of simulations with the same model offers the advantage of a much easier identification of the effect of the external forcing than the analysis of a single simulation. If the upwelling trends and multidecadal variability is mainly externally driven, therefore determining the upwelling variations, all simulations should show ~~approximately the same time~~ a similar evolution of upwelling ~~.~~

~~A recent paper by Small et al. (2015) investigated the relevance of model resolution for the question of the warm bias that global climate models usually display in~~ over time, since all simulations have been driven by the ~~Eastern ocean basins (Richter, 2015) . This bias may be related to the simulated upwelling intensity. Their analysis indicate that a high atmospheric horizontal resolution is of larger importance than the horizontal resolution of~~ same prescribed external forcing. If, in contrast, upwelling variations and trends are mainly a result of stochastic internal dynamics, the evolution of upwelling in the different simulations of the ensemble will tend to be uncorrelated in time, and the long-term trends will show different signs in the different simulations. This reasoning is more formally explained in subsection 2.3.

Bakun's hypothesis includes a physical mechanism by which upwelling may be driven by the external forcing, namely by the intensification of the sea level pressure (SLP) difference between the continents and the oceans adjacent to the upwelling regions. We also test in the climate model simulations whether the variability and trends of this air pressure difference, and of the associated alongshore wind stress, is correlated across the members of the ~~ocean model. The most realistic wind stress curl and upwelling was simulated with a high resolution nested regional atmospheric model coupled with an eddy-resolving ocean model, resulting in more intense values of wind stress and shifted towards the coast. Restoring the SST of Benguela further reduce the typical warm bias in these upwelling regions because the model improvement also impact the shortwave radiation~~ensemble of simulations. Additionally, another mechanism by which the external forcing could affect upwelling is through the ocean stratification. Global warming would lead to a warmer ocean surface, generally increasing the stability of the water column, with a shallower thermocline. This would hinder the upwelling (Hsueh and Kenney, 1972) .

In summary, the main objective of the analysis is to test whether the external forcing prescribed in a set of ensembles of climate simulations is strong enough to drive upwelling in the four EBUSs, and whether, accordingly, there are significant long-term trends in upwelling over the last millennium, the last 156 years and the near future that appear common to all simulations. This is obviously closely related to Bakun's hypothesis.
It is not our goal here to investigate the detailed mechanistic chain by which external forcing drives upwelling mechanism in the models used. This task would be in any case not meaningful, since the main result of our study is that the external radiative forcing has not varied strongly enough over the past millennium, including the 20th century, to drive the upwelling variability over this period. Even the simulations for the future do not indicate that a moderate greenhouse gas emission scenario would be strong enough to unmistakably drive upwelling intensity.

In the following section we present the data and the methods used for this analysis. In the main sections we compare some model results with the few available, mostly indirect, observations of upwelling. Later, we analyse the link between external forcing and the upwelling itself and with the immediate atmospheric drivers of upwelling. We finalise the study with a discussion and conclusion sections.

2 Data and methods

2.1 Models and simulations

We analyse here ensembles comprising three simulations (r1, r2, and r3) of two different Earth System Models, the Max-Planck Institute – Earth System Model (MPI-ESM) and the Community Earth System Model – ~~Community Atmosphere Model version 5 (CESM-CAM5~~Last Millennium Experiment project (CESM-LME).

The ~~simulations with the~~ MPI-ESM ~~, a model developed by the Max Planck Institute for Meteorology in Hamburg (Giorgetta et al., 2013) ,~~ includes the ECHAM6 model (Stevens et al., 2013) for the atmosphere, the MPI-OM model (Jungclaus et al., 2013) for the ocean, the JSBach model (Reick et al., 2013) for the vegetation, and the HAMOCC5 model (Ilyina et al., 2013) for the marine biogeochemistry (Giorgetta et al., 2013) . The simulations of the MPI-ESM cover the periods ~~900–1850~~ 900–1849 (past1000, MPI-ESM-P), 1850–2005 (historical, MPI-ESM-MR), and 2006–2100 (future, MPI-ESM-LR). For the future, we analyse here three scenarios with different strength in greenhouse gas forcing, ~~rcp2.6~~Representative Concentration Pathways (rcp) 2.6, rcp4.5, and rcp8.5, where the numbers indicate the anthropogenic radiative forcing in $\mathrm{W m^{-2}}$ reached by ~~the~~ year 2100 ~~(Fig. **??**)~~(Taylor et al., 2012) . The horizontal resolution of the atmospheric model of the MPI-ESM is about 1.9° (spatially varying) with 95 levels for the historical period and 47 levels for the past1000 and future period, whereas the ocean model resolution is approximately 1° (past1000 and future) and 0.4° (historical), including 40 ocean layers. The climate model MPI-ESM participated in the CMIP5 project (Giorgetta et al., 2013), contributing three simulations to the historical ensemble, three simulations to the future ensemble and one simulation for the past1000 period (r1). These data can be downloaded from the CMIP5 web site (http://cmip-pcmdi.llnl.gov/cmip5/). Two additional past1000 simulations (r2 and r3) were later conducted with the MPI-ESM and were kindly provided by the Max Planck Institute for Meteorology.

The simulations in each ensemble were driven by almost identical external forcing~~(only the width of the probability~~ . Only the volcanic scheme in the past1000-r1, and in the past1000-r2 and past1000-r3 experiments differ in prescribed distribution of the volcanic aerosol size~~slightly differs in the last two past1000 simulations)~~. This distribution is assumed to be log-normal, with a standard deviation of 1.2 μm in r1 and 1.8 μm in r2 and r3 (Jungclaus et al., 2014) . The forcings ~~(Schmidt et al., 2011)~~ prescribed in the past1000 ~~and historical simulations include the orbital forcing~~(Masson-Delmotte et al., 2013) follow a standard protocol defined by the project CMIP5 and comprise orbital forcing (Berger, 1978) , variability in solar irradiance ~~(?) , seasonally varying natural tropospheric aerosols, stratospheric aerosols from volcano eruptions (?) , and five well-mixed greenhouse gases: , . CFC-11, and CFC-12, as well as , anthropogenic sulphate aerosols, and changes due to anthropogenic land use (Pongratz et al., 2009)~~ (Vieira and Solanki, 2010) , volcanic activity (Crowley and Unterman, 2013) , greenhouse gas concentrations (Flückinger et al, 1999; Hansen and Sato, 2004; MacFarling Meure et al., 2006) , and land-use changes (Pongratz et al., 2009) . The external forcing of historical simulations comprise the same variables and are described in IPCC, Annex II (2013) . The reconstructed changes in the solar forcing have been disputed over the past decade, but the CMIP5 protocol agreed that small solar variations are likely more realistic. In these simulations they are rather small, with an increase of about 0.15% from the Maunder Minimum (around year 1700) to present time. In the scenario simulations, only changes in anthropogenic forcing were prescribed according to the ~~Representative Concentration Pathways (rcp) scenarios .~~

~~Within each ensemble of simulations (past1000, historical, and future), the simulations differ in their initial state. Thus, a coherent evolution of upwelling in all simulations with an ensemble would suggest a quantifiable influence of the external forcing, whereas a lack of correlation among the simulations would clearly indicate a preponderance of internal dynamics~~rcp scenarios (Taylor et al., 2012) .

To test the sensitivity of our results with respect to the choice of model, we also analysed simulations with the ~~CESM-CAM5 model . These simulations~~ CESM-LME model (Otto-Bliesner et al., 2015) . This model comprises for the atmosphere the Community Atmosphere Model version 5 (CAM5), for the ocean the Parallel Ocean Program version 2 (POP2), for the land the Community Land Model version 4 (CLM4), and for the sea-ice CICE4 (Hurrell et al., 2013) . The simulations with CESM-LME were conducted after the simulation time of CMIP5 project ~~was closed. The CESM-CAM5~~ and do not belong to that set of simulations. The CESM-LME ensemble comprises a large amount of simulations with different configurations of the external forcing and different initial conditions. Here, we analyse simulations driven by all external forgings, natural and anthropogenic (denoted as “all-forcings” in the ~~CESM-CAM5 Last Millennium ensemble project Otto-Bliesner et al., 2015~~ CESM-LME project (Otto-Bliesner et al., 2015) comprising the same set of external forcings as used in the MPI-ESM simulations (https://www2.cesm.ucar.edu/models/experiments/LME)~~. The CESM-CAM5~~). The CESM-LME covers the period 850 to 2005 with a horizontal resolution of the ocean of 1° ~~(Otto-Bliesner et al., 2015) . These simulations were driven by the same set of external forcings as used in the MPI-ESM simulations~~and of the atmosphere of 2° (Otto-Bliesner et al., 2015) . Unfortunately, no future simulations with this model are publicly available yet (Kay et al., 2015).

~~The horizontal resolution of the atmospheric model of the MPI-ESM is about 1.9(spatially varying) with 95 levels for the historical period and 47 levels for the past1000 and future period, whereas the ocean model resolution is approximately 1(past1000 and future) and 0.4(historical), including 40 ocean layers. These resolutions~~ A recent paper by Small et al. (2015) investigated the relevance of model resolution for the question of the warm bias that global climate models usually display in the Eastern ocean basins (Richter, 2015) . This bias may be related to the simulated upwelling intensity, but also to other physical processes, in particular to model clouds. The analysis by Small et al. (2015) indicates that a high atmospheric horizontal resolution is of larger importance than the horizontal resolution of the ocean model. The most realistic wind stress curl and upwelling was simulated with a high resolution nested regional atmospheric model coupled with an eddy-resolving ocean model, resulting in more intense values of wind stress and shifted towards the coast.

The model resolutions of the two Earth System Models used here are similar to the resolution of the CMIP5 models used by Wang et al. (2015). ~~Although~~ The strength and location of the jet seems to be impacted by the atmospheric model resolution (Small et al., 2015) . This study also indicated that an atmospheric resolution of at least 1° would be preferable for the representation of the jet. Unfortunately, no higher resolution version is available. Thus, although ocean processes of spatial scales of a few kilometres are only imperfectly resolved, ~~this resolution should be~~ the resolution of these two Earth System Models is plausibly fine enough to realistically represent the basic relationship between ~~upwelling dynamics and~~ the large-scale wind forcing and upwelling dynamics, including the shoreline-parallel winds and the wind stress curl. However, fine-scale ocean structures, like coastal filaments and wave dynamics cannot be realistic represented. Recalling that Bakun's hypothesis is formulated as the effect of external forcing on the atmospheric dynamics, the analysis of these simulations is an informative test of Bakun's hypothesis, until higher resolution multi-centennial simulations with coupled models become available.

Within each ensemble of simulations (past1000, historical, and future), the simulations differ in their initial state. The initial conditions for each simulation have been randomly chosen from a long pre-industrial control run, after which the model is allowed to run for several centuries driven by the (constant) forcing of, for instance, year 850 until a state of quasi-equilibrium is attained. From this point onwards the transient simulation starts with the prescribed temporally variable external forcing.

To validate the MPI-ESM simulations, we compared the simulated sea surface temperature (SST) with remotely sensed SST at 4 km resolution from the advanced Very High Resolution Radiometer (AVHRR; Casey et al., 2010) version 5.0, a radiometer onboard the National Oceanic And Atmospheric Administration (NOAA) satellites.

2.2 Upwelling index

Upwelling intensity in each of the four upwelling regions is defined by the corresponding model variable vertical mass transport (wmo) at the ocean model layer at 52 m (MPI-ESM) and the vertical velocity (wvel) at 50 m (~~CESM-CAM5~~CESM-LME) (close to the modelled mixed layer depth), and spatially averaged over each of the upwelling regions: Benguela (8–30° E, 15–28° S), Peru (80–70° W, 20–10° S), California (130–110° W, 20–50° N), and ~~Morocco~~ Canary (20–10° W, 20–34° N). Upwelling indices are here defined as the seasonal means over the ~~main~~ strongest upwelling season in each region. Seasonal averages are calculated using the standard seasons definition: December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON). In the MPI-ESM past1000 and historical simulations, the main upwelling season in Benguela is

September–November and June–August in all other upwelling regions. In the future simulations, the main upwelling season in Benguela is also June–August. ~~In the CESM-CAM5~~ Strongest upwelling in Benguela takes place between July and October (Tim et al., 2015) . The main upwelling season could be both of the standard seasons (JJA or SON), since the mean difference is small. In the CESM-LME simulations, the main upwelling season is September–November in Benguela and Peru and June–August in California and ~~Morocco.~~Canary.

As briefly mentioned in the introduction, upwelling directly at the coast is caused by the alongshore wind stress, whereas further away off the coast upwelling is driven by the wind stress curl. In the simulations analysed, the regions selected to define the upwelling indices present spatially coherent upwelling, i.e. the vertical velocities at 52 meter depth in each grid-cell are almost all positively correlated with upwelling at the grid-cells most closely located to the model land grid-cells. Only at the ocean-ward fringes of these boxes this correlation vanishes. Therefore, each geographical box encompass the set of grid-cells that show a coherent coastal upwelling, although the physical mechanism that drive upwelling as, strictly considered, not the same. This coherency is, however, reasonable since the strength of the alongshore wind stress directly at the coast should be correlated with the wind stress curl further offshore, both being generally driven by the ocean-to-land sea level pressure gradient, as also assumed in Bakun's hypothesis.

~~If it is~~

2.3 Methodology

When not explicitly stated, all correlations have been calculated with linear long-term detrended series. Low-pass time filters of 10 years for the historical and future data and low-pass time filters of 30 years for the past1000 data have been applied before correlating time series to filter out the high frequencies to focus on variations of decadal and multidecadal time scales. For the past1000 simulations, the filter is chosen to highlight the frequencies of variations in the external forcing. For the shorter historical period we are more interested in the long-term trends, since the external forcing, mostly anthropogenic, increases continuously. Applying a 30 years low-pass filter for a time series covering 156 years would leave out too many degrees of freedom to establish the significance of these trends.

For the analysis of the statistical significance of the long-term trends in the upwelling indices and the linear correlations between the ensemble members a two-sided significance level of $p = 0.05$ was adopted. All time series, and in particular the ocean time series, are affected by serial correlations that preclude the application of the usual statistical tests to establish the significance of trends or correlations. Here, we have applied a Monte-Carlo-based method (Ebisuzaki, 1997) . This method generates copies of the original time series with the same serial-correlation properties, but uncorrelated in time with the original series. For instance, to establish the significance of a correlation coefficients, 1000 surrogate pairs of series are generated and used to generate an empirical distribution of correlation coefficients under the null-hypothesis that the correlation is zero. In the case of linear trends, 1000 series are generated with zero long-term trend but the same serial-correlation as the original series, providing an empirical distribution of trends under the null-hypothesis of zero trend.

Here, we show results from three of the available simulations from the ~~CESM-CAM5~~ CESM-LME ensemble, as three simulations already confirm the results obtained with the MPI-ESM model. These two models used here are the only ones that provided an ensemble of simulations with basically the same forcing and with different ~~the~~ initial conditions, thus being suitable to detect the possible imprint of external forcing.

After assessing the realism of the connection between atmospheric drivers and simulated upwelling, we further evaluate whether the upwelling intensity in these regions displays any imprint of the external climate forcing. To estimate the ratio of forced variability to total variability we build a simple statistical model of the variations of a climate record~~that~~ , which decomposes its variability into a sum of a forced component, ~~proportional~~ related to the external climate forcing, and an internal component~~caused by the non-linear interactions within the climate system~~:

$$y = y^{\mathsf{f}}(t) + y^{\mathsf{i}}(t) \tag{1}$$

The same model can be applied to describe climate records simulated in two climate simulations driven by the same forcing and started with different and random initial conditions:

$$y_1(t) = y^{\mathrm{f}}(t') + y_1^{\mathrm{i}}(t) \tag{2}$$

$$y_2(t) = y^{\mathrm{f}}(t') + y_2^{\mathrm{i}}(t) \tag{3}$$

where the forced components are by construction equal in both simulations (the prescribed forcing is equal) and the internal components are uncorrelated in time. Since the response to external forcing could be theoretically lagged by a number of years, the time step (t') of the external forcing does not have to be necessarily the same as for the internal variability. The ratio between the variance of y^{f} and the variance of y_1, equal to the variance of y_2, can be shown to be equal to the correlation between y_1 and y_2

$$r = < y_1, y_2 > / < y_1, y_1 > = < y^{\mathrm{f}}, y^{\mathrm{f}} > / < y_1, y_1 > \tag{4}$$

where $\langle x, y \rangle = \sum_t x(t) y(t)$

The equations show that in two simulations that have the same forcing but different initial conditions the ratio between the variance of the forced component and the total variance is the same as the correlation between both time series. If the correlation y_1 and y_2 is weak, the variance of y^{f} is much weaker than the variance of y^{i}, meaning that the effect of internal variability is much stronger than the effect of external forcing. This is true because of the assumption that the variance of the internal components of both time series are uncorrelated. The forcing is externally prescribed and, thus, cannot be influenced by the initial conditions. This mathematical description is the base of the statistical analysis presented here. Correlating the three simulations of an ensemble shows us whether the external variability is an important component of the total variability. This statistical reasoning provides the rationale for the calculations of the correlations between the indices of different simulations within an ensemble, which is profusely used through the whole manuscript.

3 Representations of upwelling and its atmospheric drivers in the climate model

The patterns of ~~long-term mean sea surface temperature (SST) (June–August, main upwelling season~~ mean SST in the four main upwelling regions in their season with maximum upwelling simulated in one of the historical simulations with the model MPI-ESM-MR is compared with the corresponding data derived from the AVHRR in Fig. 1, both calculated for the overlapping period (1985–2005). The SST patterns display in ~~three of the four regions)display depressed values in the areas of upwelling relative to the zonal SST mean at the same latitude, although the fine spatial structure appears smoothed due to the model resolution~~general colder temperatures directly along the coast, with warmer temperatures offshore. The climate model is able to replicate these SST gradients remarkably well, in spite of the coarse spatial resolution. However, in the cases of Benguela (Fig. ~~2a) .~~ 1e and f) and Peru (Fig. 1g and h), the climate model shows an evident warm bias relative to the satellite data (Richter, 2015) . This indicates that the main mechanism of upwelling are likely reasonably represented in the model, though other important mechanism are not.

The shape of the modelled seasonal cycle of upwelling (Fig. 2) generally agrees with what is known from observations~~(Fig. 2b and c)~~, with upwelling being more intense in the boreal warm half-year (Fig. 7 in Chavez and Messié, 2009) . The mean upwelling is, however, about a factor two more intense in the lower resolution past1000 ~~simulations~~simulation (horizontal resolution of the ocean of 1° (past1000) compared to 0.4° (historical)), indicating that ocean model resolution is important to simulate the correct mean upwelling intensity, which may be relevant for the SST bias in the ~~EBUs~~ EBUSs simulated by many climate models (Wang et al., 2014). A reason for this difference is not clear-cut but it is also not essential for this analysis.

The link between each upwelling index and wind stress, calculated as the patterns of correlations between the index and wind stress in each model grid-cell (not shown), is also very realistic, displaying in each case a characteristic alongshore wind stress that favours Ekman transport, the main mechanism causing coastal upwelling (Tomczak and Godfrey, 2003). The correlation patterns between each upwelling index and the ~~sea level pressure (SLP)~~ SLP realistically show regions with negative correlations over land and positive correlations ~~off-shore~~ offshore (Fig. 3), indicating that the across-coastline SLP gradient, with an intense oceanic subtropical high and an intense continental low, is conductive for alongshore wind stress through the geostrophic relation.

4 ~~Imprint~~ Importance of external climate forcing ~~on coastal~~ for upwelling variations in the recent past and future

4.1 Past1000 and historical simulations

In the last millennium, the ~~climate changed driven by the~~ external climate forcing drove changes in the climate. The main external climate drivers over this period were volcanic forcing, solar variability, greenhouse gases, and land-use changes (Hegerl et al., 2006) and at millennium time-scale the slowly varying orbital configuration of the Earth (Laskar et al., 2004). These forcings had an effect on the global mean surface temperatures, both in climate simulations driven by these forcings as in proxy-based climate reconstructions (Fernández-Donado et al., 2013).
Schurer et al. (2014) found that the variability of the surface air temperature of the Northern Hemisphere was mostly driven by the greenhouse gas concentration and volcanic eruption in the last millenniums. There was a period of relatively high temperatures, the Medieval Warm Period with its maximum at around 1000–1300 A.D. These high temperatures ~~were~~ could have been caused by high solar and low volcanic activity but there is no consensus about the driver of the Medieval Warm Period, and internal variability could have had a role too. The Medieval Warm Period was followed by the Little Ice Age, a period of low temperatures caused by low solar and high volcanic activity. After the Little Ice Age, global mean temperatures rose mainly as result of higher concentration of greenhouse gases (Fernández-Donado et al., 2013). As illustration, Fig. 4 displays the multidecadal global mean temperature evolution simulated in the ensembles of simulations analysed in this

study. These temperature evolutions illustrate the common temperature response to the external forcing with the different climate sensitivities of both models, and also the internal variability of the global mean temperature at multidecadal time scales, since the simulations within each ensemble display slightly different temperature paths.

For both ensembles of simulation of the past, the decadally smoothed time series of regional upwelling index extracted from each of the three simulations display different time evolutions (Fig. 5) and do not show a centennial evolution comparable to the global mean temperatures or the global mean external forcing as just described. The correlations between these series for each region are correspondingly low (~~Table **??**,~~ Fig. 6) and mostly statistically not significant. These correlations remain low and non-significant for stronger low-pass time filtering up to 50 years (Fig. 7a). ~~This~~ Based on equation 4, this indicates that the upwelling variance shared by all simulations, which could only be due to the common external forcing, is also small. These simulations, therefore, do not support any significant imprint of the external forcing on upwelling in any of the ~~EBUs~~ EBUSs up to multidecadal timescales over the past millennium.

This finding ~~supports~~ is consistent with previous studies derived from observed records, ~~that~~ which identified a strong influence of the Pacific North American pattern on California upwelling. The Pacific North America pattern is a well-known mode of internal climate variability, unrelated to external forcing, and probably linked to the dynamics of the Tropical and mid-latitude Pacific Ocean (Macias et al., 2012). Thus, the influence of the Pacific North American pattern on the California upwelling supports our results of a dominant role of the internal variability.

At centennial timescales, the externally forced climate variability is a large portion of the total climate variability, as the random internal decadal variability is filtered out. Additionally, the increase in the external climate forcing over the past ~~150~~156 years is stronger than the variations in the forcing prescribed in the past1000 simulations. For instance, the amplitude of decadal variations of the ~~preindustrial~~ pre-industrial external forcing is of the order of 0.3 $\mathrm{W m^{-2}}$ (Schmidt et al., 2011), whereas the increase in the external forcing over the past 250 years is 1.6 $\mathrm{W m^{-2}}$ ~~(**?**)~~ (Myhre et al., 2013) .

Thus, the long-term influence of the external forcing – the strongest being anthropogenic greenhouse gases in the historical simulations – could be more easily detected in the form of common long-term upwelling trends. However, the simulated upwelling trends are small, mostly statistically not significant, and generally display opposite signs in the different simulations of the MPI-ESM ensemble (Fig. 5). The ~~two exceptions here are California and Morocco~~ are only two cases out of eight, California and Canary in the historical simulations, in which all members exhibit a negative trend (opposite to the expected strengthening), of which only two trends of the California upwelling ~~region~~ are statistically significant. Analysing the imprint of external forcing on upwelling with the ~~CESM-CAM5~~ CESM-LME confirms the results with the MPI-ESM. The simulated upwelling velocity in three simulations are weakly correlated with each other (Fig. 8) and the trends are either not coherent in the simulations or are not statistically significant.

4.2 Scenarios

Looking at the future development of the upwelling in the ~~EBUs~~EBUSs, we analyse the future simulations conducted with the MPI-ESM model under three different emission scenarios. An effect of the external forcing should be reflected in consistent centennial trends in upwelling in all members of each ensemble. Consistent significant trends in all three simulations of an ensemble only occur in the rcp8.5 scenario, the one with the strongest external forcing (~~Table **??**,~~ Fig. 9). The trends are negative in California and ~~Morocco~~ Canary and positive only in Benguela. In Peru no significant trends can been seen. This support our results obtained for the past millennium, indicating that the external forcing has not been intense enough in the past to force the upwelling significantly. Even the much stronger external forcing of the rcp2.6 and rcp4.5 scenarios, compared to the one of the past1000 and historical simulations, does not leave an imprint on the upwelling. Furthermore, the ~~expected positive~~ envisaged positive upwelling trend only occurs in one of the four regions, underlining the local differences among the ~~EBUs.~~EBUSs.

These results do not fully support the ones obtained by Wang et al. (2015)~~. They~~ , agreeing on the positive trends in Benguela and the negative trend California. For Peru (Humboldt in their analysis) and Canary they found an intensification in upwelling. However, they analysed the trend for another period (1950 to 2099) and only in the rcp8.5 scenario. They concluded that a clear connection between external forcing and upwelling could be ~~find~~found. However, when analysing the trends simulated in other scenarios, it turns out that in the weaker greenhouse gas scenarios this link is weaker, and it cannot be easily identified. As Wang et al. (2015) used a model ensemble with one simulation of each model and we use ensembles of simulation of two model, differences could come in by the methodology. This would indicate that either the trend differ between the models or that using only one simulation of each model could distort the result.

5 ~~Imprint~~ Importance of external climate forcing ~~on~~ for the drivers of upwelling in the past1000 and historical simulations

In this section, we want to determine why the imprint of the external forcing on coastal upwelling is weak over the past periods, by looking at the imprint of the external forcing on processes involved in the functioning of upwelling. These processes are, on the one hand, the atmospheric drivers of the upwelling and, one the other hand, the oceanic factors influencing the upwelling.

5.1 Atmospheric drivers

Upwelling in all four investigated regions is mainly driven by the wind stress curl that modulates upwelling in offshore regions and by the alongshore wind stress that drives the coastal upwelling. The ~~latter~~ upwelling in the four EBUSs is related to the SLP gradient between land and ocean ~~(Tomczak and Godfrey, 2003; ?)~~ (Tomczak and Godfrey, 2003) . The strength of this gradient impacts the intensity of the trades (Bakun, 1990) . We investigate whether the time evolution of this SLP gradient is consistent across the simulations and whether the lack of correlations between the upwelling indices across the ensemble may be due to a weak influence of the external forcing on wind stress and on the SLP gradient. The across-coastline SLP gradients in the simulations are calculated by subtracting the averaged air pressure over land from the averaged pressure over ocean in the regions identified as most closely correlated to the upwelling indices (Fig. 3). These areas are: Benguela: 15° W–10° E, 20–40° S (ocean), 18–25° E, 10–30° S (land); Peru: 75–100° W, 16–30° S (ocean), 60–70° W, 0–8° S (land); California: 130–160° W, 35–50° N (ocean), 110–120° W, 20–40° N (land); Canary: 20–40° W, 20–40° N (ocean), 0–10° E, 5–15° N (land). The results are not sensitive to the chosen regions. Using the position of climatological mean of the subtropical high and continental low do not change the results.

As in the case of the upwelling indices, the correlations between the time series of alongshore wind stress and SLP gradients across the simulations in the ensemble are all low and not significant (Tables 1 and 2). These correlations also remain low and not significant regardless of the time filtering (Fig. 7b). The alongshore wind stress was calculated as the wind stress over the ocean in the upwelling areas, with an angle of the shoreline of 15° for Benguela and 45° for the other regions. Correlating the time series of both drivers, the SLP difference between ocean and land and the alongshore wind stress, without low-pass filter shows their close relation with significant correlations for both periods, past1000 and historical, with correlation coefficients between 0.34 and 0.70. Regarding the longest time scales captured in the simulations, the long-term trends of the wind stress and of the SLP gradient within each ensemble have either inconsistent signs, or are not statistically significant, or are incompatible with the expected effect of the external forcing varying at centennial timescales. These expected trends are negative in past1000 due to the long-term orbital forcing and positive in historical due to the Bakun hypothesis (Bakun, 1990) based on the increase in greenhouse gas forcing. Therefore, even if the connection between the atmospheric drivers and upwelling ~~were not~~ might not be totally realistic in the Earth System Model, the lack of common time evolution of wind stress or SLP across the simulations clearly shows that, from the atmospheric perspective alone, the simulations do not support a discernible influence of the external forcing on the atmospheric drivers of upwelling over the last centuries. This implies that such an influence could not have been found even if the ocean model perfectly represented the real upwelling dynamics. No matter of the quality of the upwelling representation in the coupled model, one could not detect any

impact of external forcing on the upwelling.
For the future period, significant trends of the alongshore wind stress in all three simulations of an ensemble take place in the rcp8.5 with the same sign as for upwelling, negative for California and Canary and positive for Benguela. Additionally, there are significant negative trends in the whole ensemble in the rcp4.5 for the California upwelling region. This indicates that, again, the external forcing has to be very strong to be discernible.

6 ~~Imprint of external forcing on stratification~~

5.1 Stratification

Another possible mechanism by which the external climate forcing could influence upwelling involves the stratification of the water column. In periods with a stronger external forcing, the temperatures at the surface should warm more rapidly than in the deeper layers, increasing the stability of the water column, and hindering the mechanical effect of the alongshore wind stress (Hsueh and Kenney, 1972). The amount of variability in the SST that can be attributed to the variations in the external forcing can also be estimated by the correlation between the grid-cell SST series simulated in each members of the simulation ensemble (Fig. 10). The correlation patterns indicate that the SST variability is more strongly driven by the external forcing in the tropical belt and tends to the weaker in the mid and high latitudes. This occurs despite the strongest response of high latitudes to external radiative forcing, known as the Arctic amplification (Taylor et al., 2013) . The reason is that at high latitudes the internal variability is also larger than at low latitudes (Tett et al., 2007) . The ratio between both, external forcing signal and internal variability, which is encapsulated by the correlation patterns show in Fig. 10, is therefore highest in the tropics, a feature which has been so far mostly overlooked but that has been found in previous analysis of paleoclimate simulations (Tett et al., 2007). In the ~~EBUs~~EBUSs, the correlations between the simulated SSTs are all positive, of the order of 0.2–0.3 after 10 year low-pass filtering ~~. Therefore,~~ (Fig. 10). These relatively low correlations indicate that the external forcing

has some influence on the SST variability in these regions but most of the multi-decadal variability is internally generated.
The impact of the external forcing on the stratification in the future has not been analysed. There might be an impact due to much stronger increase in greenhouse gas concentrations in the 21th century, especially in the rcp8.5.

6 Discussion and conclusions

In this paper, the importance of the external climate forcing on the upwelling and its drivers in the four Eastern Boundary Upwelling Systems over the past millinnium and the 21th century is investigated. Regarding Bakun's hypothesis (Bakun, 1990) , the increase in radiative forcing linked to increased greenhouse gas concentrations would lead to an intensification of coastal upwelling.

The analysis of three simulation ensembles with the Earth System Model MPI-ESM over the past millennium and the future are in contrast with the hypothesis of a discernible influence of the external forcing on coastal upwelling intensity. ~~Uncertainties still remain. For instance, the magnitude of the external forcing variations over the past millennium is still not well established (Schmidt et al., 2011) , and larger variations than hitherto assumed may cause a tighter connection between forcing and upwelling . Over the past 150, however, the trends in external climate forcings are much more certain and over this period the historical simulations do not show any consistent sign of intensification or weakening.~~

Analysing ensembles of simulations enables us to distinguish between variations driven by internal and external variabilities.

For the periods covering the past, the past1000 and the historical simulations, no significant trends could be found in the upwelling itself, nor in its atmospheric drivers. Furthermore, correlations of the ensemble members are low indicating the missing imprint of external forcing on the upwelling and its drivers. The internal variability dominates the external one for both periods in all four EBUSs. These results are in conflict with Bakun's hypothesis of an intensification of upwelling due to climate change (Bakun, 1990) . The work

of Narayan et al. (2010) shows that the results of a trend analysis of observed upwelling differs with analysed period, data set, and analysed variable. Thus, it might not be the inability of the used models to represent the temporal development of the upwelling over the past century but its rather unclear due to the lack of direct measurements and long-term observations of upwelling.
A possible reason why upwelling does not show the signal of the variations of external forcing in the simulations, with the exception of the rcp8.5 scenario, may be that the atmospheric circulation has a large internal variability, in contrast to other variables like temperature more directly related to the external forcing. In general, detection and attribution studies of climate change detect weaker signal in atmospheric dynamical variables like SLP than in thermal variables.

For the future, the effect of external forcing on the ~~EBUs~~ EBUSs can be identified when greenhouse gas concentrations are assumed to follow the strongest scenario, rcp8.5, among the three Representative Concentration Paths analysed here. All three simulation in the ensemble display consistent trends, but these trends are not always consistent with the expected intensification of upwelling ~~, with some regions~~ due to the Bakun hypothesis (Bakun, 1990) , with only Benguela showing an intensification~~but others~~ . California and Canary showing a weakening~~.~~

~~The definition of the upwelling index can be sensitive to the region over which the vertical velocities are averaged. Redefining the subregions of the Eastern Boundary Upwelling Systems (EBUs) (Canary (18.5–10.5W, 16.5–42.5N), South Benguela (8–30E~~, ~~28–40S), Chile (80–70W, 20–40.5S)) does not change the main results of this study. The correlation between the three simulations remains low, for upwelling as well as for wind stress. Significant trends with the same sign in all three simulations do not occur, neither in the simulations of past periods nor in the future simulations.~~

~~Our results generally~~ and Peru no significant one.
Our results partly agree with the ones obtained by Wang et al. (2015) on the influence of a strongly increased future greenhouse gas forcing on upwelling intensity in the ~~EBUs~~EBUSs, agreeing in an intensification of the Benguela upwelling system and

a weakening of the California upwelling system. However, our results ~~indicated~~ indicate that the conclusion obtained from the analysis of only the rcp8.5 scenario cannot be extended to weaker scenarios of future greenhouse gas forcing nor to the trends observed over the 20th century ~~not~~ nor the evolution of upwelling over the past millennium. ~~The same can be said on the study of Rykaczewski et al. (2015)~~ Differences in the results obtained from Wang et al. (2015) compared to our study could be due to several factors: The analysed time period in their analysis differs (1950-2099) from ours. They analysed only one simulation of each model and not an ensemble of simulations. Using an ensemble of simulations allows to better identify the presence or absence of an externally forced signal. Furthermore, long-term trends in their analysis (extended data figure 3) show that there are positive and negative upwelling trends (blue and red squares in their figure) for all regions, so that clearly not all models agree in the sign of the upwelling trends. In addition, for some regions, e.g. Humboldt, this discrepancy in the trend may be due not the different model structure, but also to internal variability, as we find in the MPI-ESM model.

Compared to Rykaczewski et al. (2015) , where again only the upwelling in the ~~EBUs~~ EBUSs in the rcp8.5 scenario is analysed and one simulation per model, our results match theirs only for Benguela and California. They found significant positive trends in the upwelling-favourable winds in the Canary, Humboldt and Benguela systems and negative trends in the California system~~. These results agree partly with our findings, underline~~ , with trends in Benguela being less consistent among the models. This underlines the differences between the upwelling regions ~~, and indicate~~ and illustrates the complexity of ~~the~~ upwelling by the different results obtained depending on the analysed model – but ~~stress~~ also highlight the impact of the external forcing on upwelling detected in the rcp8.5 scenario. For the rcp8.5, there seems to be a difference between the EBUSs in the Northern hemisphere (showing significant negative trends) and the Southern hemisphere (showing significant positive or not significant trends). Differences could be caused by changes in the Hadley cell, which is expected to expand poleward as a consequence of global warming (Lu et al., 2007) . The temperature differences between the equator and the subtropics will decrease in the Northern hemisphere, due to the larger fraction of land on the Northern than on the Southern hemisphere, leading to a weakening of the Hadley cell and thus to weaker trades (Ma and Xi, 2013) . This effect may be smaller in the southern hemisphere due to a weaker warming of mid and high latitudes (Ma and Xi, 2013) .

Uncertainties still remain. For instance, the magnitude of the external forcing variations over the past millennium is still not well established (Schmidt et al., 2011) , and larger variations than hitherto assumed may cause a tighter connection between forcing and upwelling than the one found in the simulations analysed here, driven by relatively weak variations of the external forcing. Over the past 156 years, however, the trends in external climate forcings are much more certain and over this period the historical simulations do not show any consistent sign of intensification or weakening in an ensemble.

It has to be kept in mind that our results are based on the realism of the analysed Earth System Models. The relatively low model resolution of the atmosphere and of the ocean components could result in an unrealistic representation of the upwelling itself and/or its drivers. As stated by Small et al. (2015), especially the resolution of the atmospheric model ~~has~~ may have the strongest influence on the simulated coastal upwelling. Furthermore, the current global coupled climate models still display a strong SST bias in the ~~EBUs~~EBUSs. The cause of this bias is not completely understood, and it may be related to a deficient representation of coastal upwelling but it may also have other causes, for instance related to biases in the ~~climate~~ stratocumulus clouds (Richter, 2015). This caveat, nevertheless, also affects the recent studies by Rykaczewski et al. (2015) and Wang et al. (2015), since they are also based on the CMIP5 models.

The definition of the upwelling index can be sensitive to the region over which the vertical velocities are averaged. Redefining the subregions of the Eastern Boundary Upwelling Systems (EBUSs) to the latitudinal extend of the regions used in Wang et al. (2015) (extended Canary region (18.5–10.5° W, 16.5–42.5° N), South Benguela (8–30° E, 28–40° S), Chile (80–70° W, 20–40.5° S)) does not change the main results of this study. The correlation between the three simulations remains low for upwelling. Significant trends with the same sign in all three simulations do not occur, neither in the simulations of past periods nor in the future simulations.

Analysing ensembles of simulation of the Earth System Model ~~CESM-CAM5~~ CESM-LME over the past millennium supports the results of the MPI-ESM.

Thus, we conclude that the circumstantial evidence linking the recent observed trends in ~~EBUs~~ EBUSs upwelling to external climate forcing is in conflict with ~~state-of-the art climate simulations~~ the present analysis of ensemble of simulations with two state-of-the-art climate models.

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Table 1. Correlation coefficients of ~~the~~ three simulations of each ensemble (r1, r2, and r3) of the ~~upwelling indices~~ cross-coastline pressure gradient of all upwelling regions for the past1000 and historical simulations with the MPI-ESM model ~~with 10 and~~ after 30 and 10 year filter, respectively. All correlations are not statistically significant at the 95% level.

~~California Morocco Benguela Peru past1000: $r1$–$r2$ +0.07 −0.11 +0.05 +0.22 $r1$–$r3$ −0.04 +0.16 +0.04 −0.004 $r2$–$r3$ +0.14 −0.14 +0.06 +0.23 historical: $r1$–$r2$ +0.15 −0.14 −0.10 −0.18 $r1$–$r3$ +0.30 +0.14 −0.19 −0.09 $r2$–$r3$ −0.12 −0.38 +0.06 −0.03~~

~~Sign of trends of the upwelling time series of all upwelling regions for the past1000, the historical, and the scenarios (rcp2.6, rcp4.5, rcp8.5) simulations with the MPI-ESM model.~~

~~Correlation coefficients of the simulations of the cross-coastline pressure gradient of all upwelling regions for the past1000 and historical simulations with the MPI-ESM model after 10 and 30filter, respectively.~~

	California	~~Morocco~~ Canary	Benguela	Peru
past1000:				
$r1$–$r2$	+0.12	+0.04	−0.03	+0.11
$r1$–$r3$	+~~0.21~~ 0.05	+0.21	+0.28	+0.25
$r2$–$r3$	+0.32	−0.30	−0.18	+0.36
historical:				
$r1$–$r2$	+0.09	+0.10	−0.25	+0.26
$r1$–$r3$	−0.27	+0.27	−0.20	+0.06
$r2$–$r3$	−0.13	−~~0.13~~ 0.41	+0.13	−0.09

Table 2. Correlation coefficients of ~~the~~ three simulations of each ensemble (r1, r2, and r3) of the alongshore wind stress of all upwelling regions for the past1000 and historical simulations with the MPI-ESM model after ~~10 and~~ 30 and 10 year filter, respectively. All correlations are not statistically significant at the 95% level.

	California	~~Morocco~~ Canary	Benguela	Peru
past1000:				
$r1$–$r2$	−0.02	−0.22	+0.001	+0.07
$r1$–$r3$	−0.05	+0.09	−0.13	+0.09
$r2$–~~$r3$~~ $r3$	+0.27	−0.05	+0.22	+0.14
historical:				
$r1$–$r2$	+0.45	−0.01	−0.27	+0.19
$r1$–$r3$	−0.08	+0.09	−0.06	+0.04
$r2$–$r3$	+0.14	−0.02	−0.07	+0.23

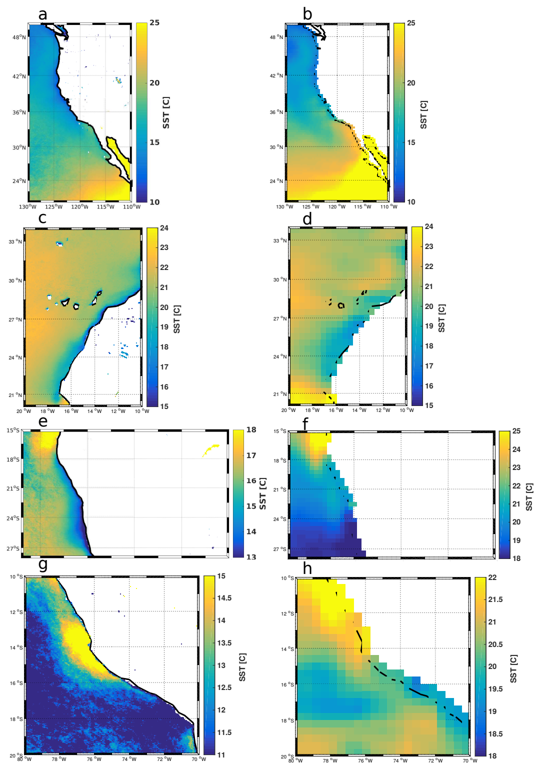
a
b
c
d
e
f
g
h
SST [C]

Figure 1. ~~Global mean radiative forcing for~~ Mean sea surface temperature in the ~~Representative Concentration Pathways (rcp) scenarios (Model~~ four upwelling regions in the corresponding main upwelling season for 1985-2005 simulated by the ~~Assessment of Greenhouse-gas Induced Climate Change (MAGICC)) (upper panel)~~Earth System Model MPI-ESM compared to satellite data from AVHRR. ~~Multi-model mean~~ California (~~solid line~~June–August) AVHRR **(a)** and ~~spectra of all models~~ MPI-ESM historical r1 **(b)**, Canary (~~shaded~~June–August) ~~time series of global annual mean surface air temperature anomalies~~ AVHRR **(c)** and MPI-ESM historical r1 **(d)**, Benguela (~~relative to 1986–2005~~September–November) ~~from CMIP5 simulations~~ AVHRR **(e)** and MPI-ESM historical r1 **(f)**, and Peru (~~lower panel~~June–August) AVHRR **(g)** and MPI-ESM historical r1 **(h)**. ~~The numbers indicate how many model are available for~~ Not the ~~corresponding time period~~ different temperature scale for Benguela and ~~scenario. Source: **?**~~ Peru.

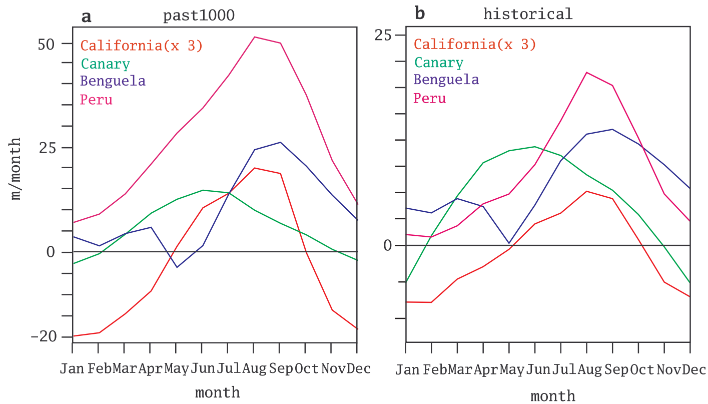

Figure 2. ~~Mean sea surface temperature in June–August simulated by one past1000 simulation with the MPI-ESM Earth System Model in the tropics and subtropics **(a)**.~~ Monthly mean vertical velocity at 52 m depth in four main coastal upwelling regions simulated in one past1000 (~~900–1850~~900–1849) ~~**(b)**~~ **(a)** and one historical (1850–2005) simulation ~~**(c)**~~ (r1) **(b)** of the MPI-ESM. The values for California have been re-scaled for better visibility. Note the different y axis scale for each simulation. As variations of the annual cycle are very small between the simulations of an ensemble, the annual cycle of r1 represents the simulated annual cycle of all simulations of the ensemble.

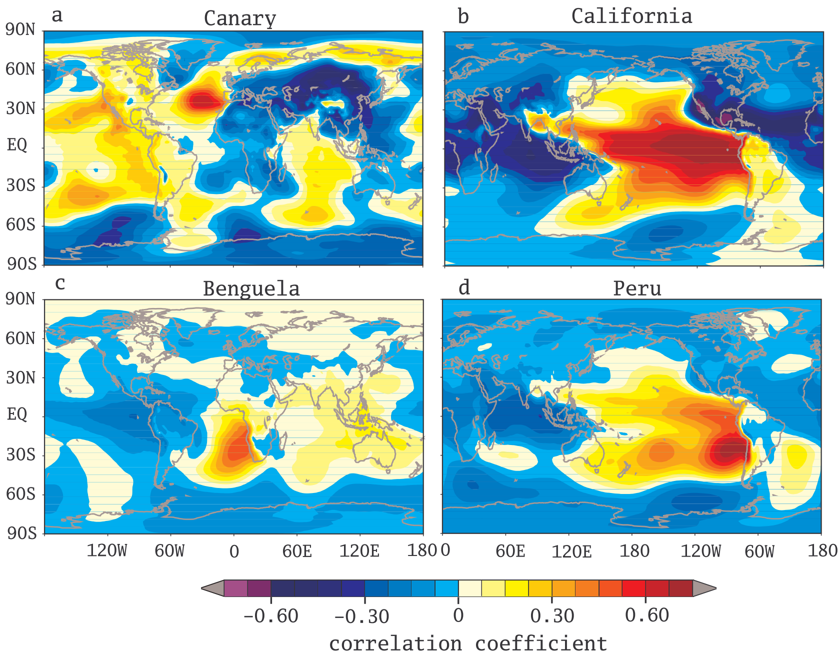

Figure 3. Correlation patterns between the seasonal (June–August, except for Benguela September–November) upwelling index in each Eastern Boundary Upwelling System and the simultaneous seasonal mean sea level pressure field simulated in one of the past1000 simulations (~~900–1850~~r1) (900–1849)) with the Earth System Model MPI-ESM.

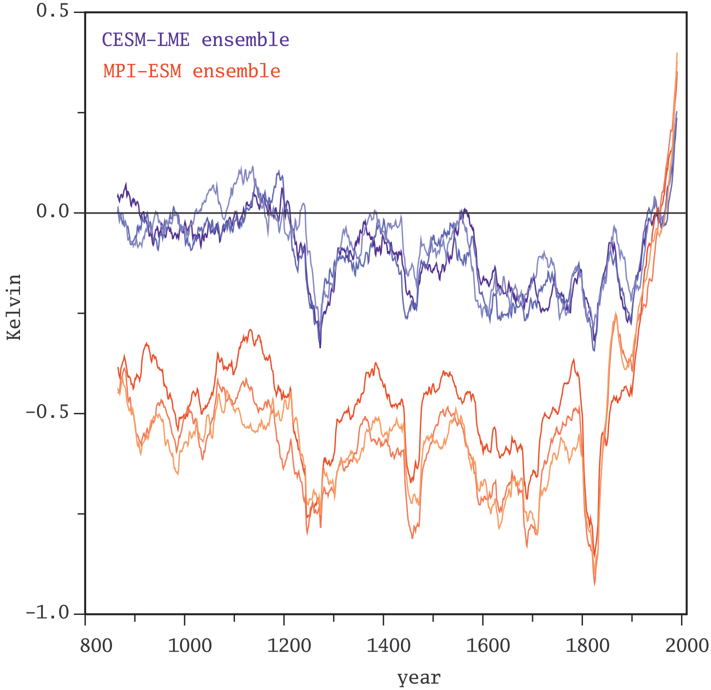

Figure 4. ~~Time series of~~ Global mean near-surface air temperature over the ~~simulated upwelling indices in each upwelling region~~ past millennium simulated in two ~~ensembles~~ ensemble of ~~climate~~ simulations ~~(three members each), denoted past1000 (900–1850) and historical (1850–2005),~~ with the Earth System Models MPI-ESM ~~model. The plus~~ and ~~minus signs in each panel indicate the sign of the long-term trend, their value being included whenever statistically significant~~CESM-LME. The time series ~~have been low-pass filtered with a 30filter for past1000 and a 10filter for~~ represent 31-year running mean of the ~~historical ensemble~~temperature anomalies relative to the 20th century mean.

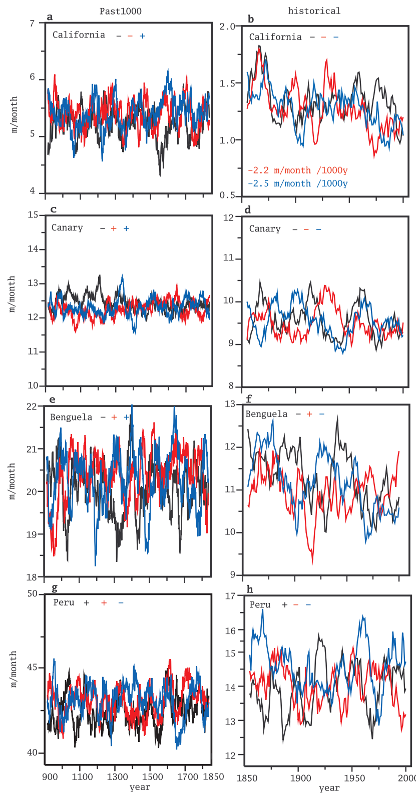
Past1000
historical
a
California − − +
b
California − − −
-2.2 m/month /1000y
-2.5 m/month /1000y
c
Canary − + +
d
Canary − − −
e
Benguela − + +
f
Benguela − + −
g
Peru + + −
h
Peru + − −
m/month
year
900 1100 1300 1500 1700 1850
1850 1900 1950 2000

Figure 5. Time series of the simulated upwelling indices in each upwelling region simulated in two ensembles of climate simulations (three members each), denoted past1000 (900–1849) and historical (1850–2005), with the MPI-ESM model. The plus and minus signs in each panel indicate the sign of the long-term trend, their value being included whenever statistically significant. The series have been low-pass filtered with a 30 year filter for past1000 and a 10 year filter for the historical ensemble.

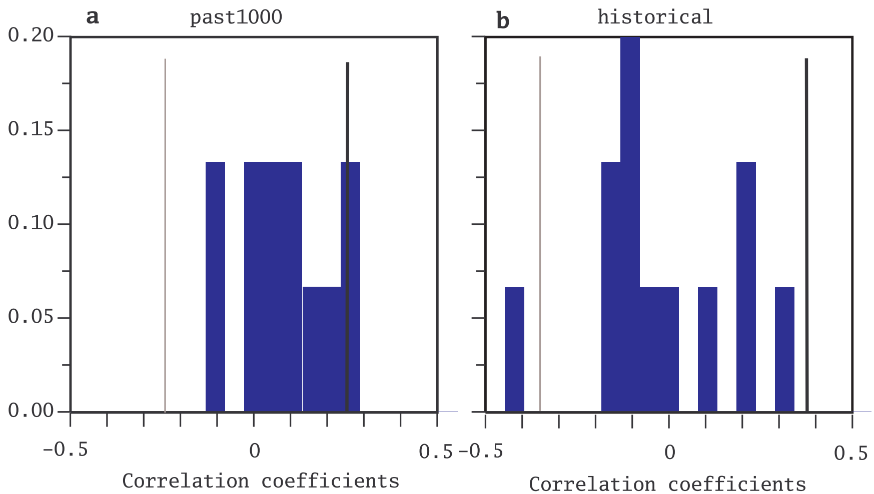

Figure 6. Frequency histogram in bins of 0.05 width showing the distribution of across-ensemble correlations between the upwelling indices simulated in each upwelling region for the ensembles past1000 **(a)** and historical **(b)** of the MPI-ESM, after low-pass filtering with a 30 year (past1000 simulation) and a 10 year (historical simulation) filter, respectively. The vertical black lines indicate the 5–95 % significance bounds taking the time filtering into account.

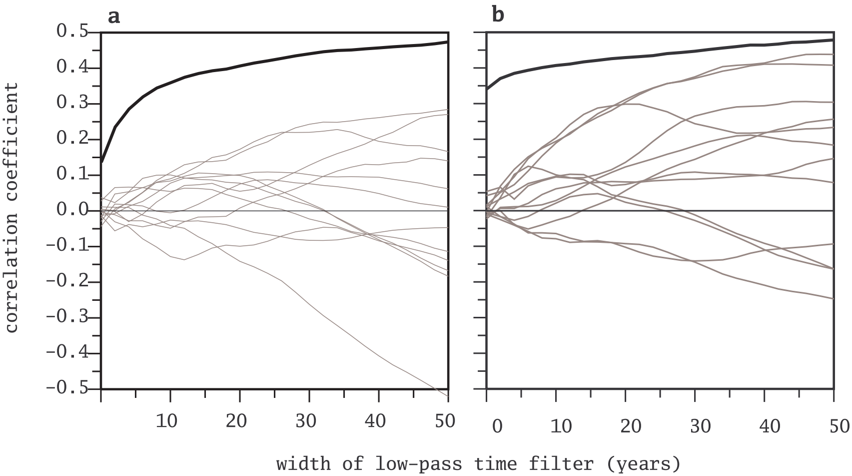

Figure 7. Correlations between the simulated upwelling indices in ~~Benguela~~ all four EBUSs in three past1000 simulations with the MPI-ESM model after filtering the time series with low-pass filter of increasing period **(a)** and the same as **(a)** but for the time series of sea level pressure difference between land and ocean averaged over the areas most closely correlated with the simulated upwelling in this region **(b)**. The 95 significance levels depend on which pair of series are being tested, since the test takes into account the serial correlation of each series. The figure shows, as an example, the significance levels for the correlations r1-r2 for Benguela, but all correlations shown here are not statistically significant at the 95% level.

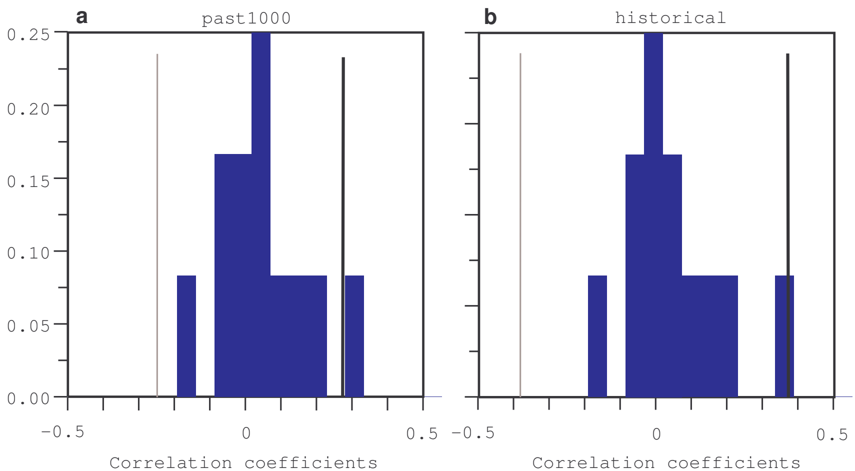

Figure 8. Frequency histogram in bins of 0.05 width showing the distribution of across-ensemble correlations between the upwelling indices simulated in each upwelling region for the ensembles past1000 **(a)** and historical **(b)** of the ~~CESM-CAM5~~CESM-LME, after low-pass filtering with a 30 year (past1000 simulation) and a 10 year (historical simulation) filter, respectively.

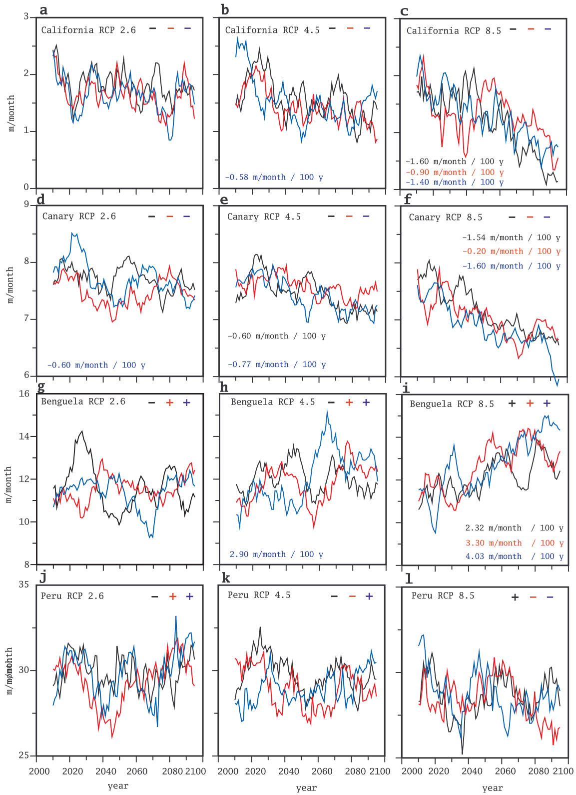

Figure 9. Time series of the simulated upwelling indices in each upwelling region simulated in three ensembles of climate simulations (three members each) for 2006–2100, rcp2.6, rcp4.5, and rcp8.5, with the MPI-ESM model. The plus and minus signs in each panel indicate the sign of the long-term trend, their value being included whenever statistically significant. The series have been low-pass filtered with a 10 year filter.

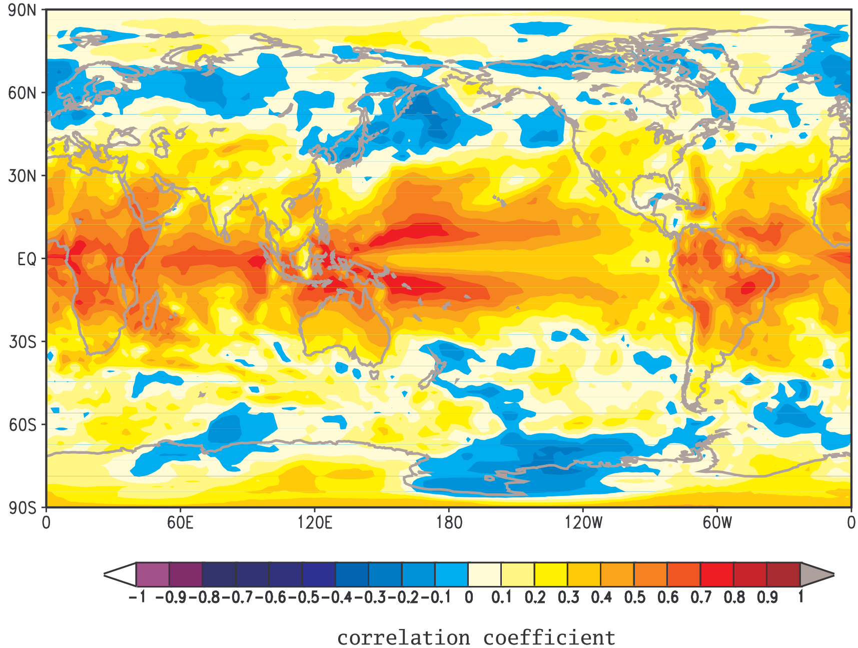

Figure 10. Correlation pattern between the global skin temperatures (temperatures of ocean and land surface) simulated in two past1000 simulations (~~900–1850~~r1 and r2) (900–1849) with the Earth System Model MPI-ESM in the June–August season after applying a 10 year low-pass filter.