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Imprint of external climate forcing on coastal upwelling in past and future climate

N. Tim¹, E. Zorita¹, B. Hünicke¹, X. Yi¹, and K.-C. Emeis^{1,2}

¹Helmholtz-Zentrum Geesthacht, Institute of Coastal Research, Max-Planck-Strasse 1,
21502 Geesthacht, Germany

²University of Hamburg, Institute of Geology, Bundesstrasse 55, 20146 Hamburg, Germany

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Correspondence to: N. Tim (nele.tim@hzg.de)

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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. 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 two Earth System Models. The ensembles contain three simulations for each time period which cover the past millennium (900–1850), the 20th century (1850–2005) and 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. Our analysis shows that the variability of the simulated upwelling is to the most driven internally and that there are no significant trends except for the scenario with the most dramatic increase of greenhouse gas concentrations.

1 Introduction

Eastern Boundary Upwelling Systems (EBUs) are highly productive coastal ocean areas where nutrient rich, cold water upwells by the action of favourable winds. The link between external climate forcing, such as greenhouse gases and solar activity, and coastal upwelling has primarily been framed by the theoretical considerations put forward by Bakun (1990). 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 a strengthening the upwelling-favourable winds (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 as indicative of upwelling intensification due to stronger external climate forcing. 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 cli-

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mate forcing, mainly solar irradiance and volcanism. However, the empirical evidence for a long-term intensification of coastal upwelling over the 20th century is not clear-cut. 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; Gutierrez et al., 2011; Santos et al., 2012), but others have not (Rykaczewski et al., 2010; Pardo et al., 2011). 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 Niño-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 effect of increasing greenhouse gas concentrations on upwelling regimes in future scenarios has been investigated by Wang et al. (2015). They 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 W m^{-2} by the year 2100. They found that in most of the EBUs models tend to simulate an intensified upwelling and longer upwelling seasons under climate change.

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

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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.

- 5 The verification of Bakun's hypothesis in the recent past is critical to establish its validity for the future. Even if Bakun's hypothesis is correct, it is not clear whether past variations in external forcing 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
10 by chance. The analysis of the recently available ensemble of climate simulations with CMIP5 models over the recent past can shed light on this question. If the upwelling is mainly externally driven, all simulations should show approximately the same time evolution of upwelling.

15 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. Their analysis indicate 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
20 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.

2 Data and methods

- 25 We analyse here ensembles comprising three simulations of two different Earth System Models, the MPI-ESM and the Community Earth System Model – Community Atmosphere Model version 5 (CESM-CAM5).

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The simulations with the MPI-ESM, a model developed by the Max Planck Institute for Meteorology in Hamburg (Giorgetta et al., 2013), cover the periods 900–1850 (past1000), 1850–2005 (historical), and 2006–2100 (future). For the future, we analyse here three scenarios with different strength in greenhouse gas forcing, rcp2.6,

5 rcp4.5, and rcp8.5, where the numbers indicate the anthropogenic radiative forcing in Wm^{-2} reached by the year 2100 (Fig. 1). 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. These data can be downloaded from the CMIP5 web
10 site (<http://cmip-pcmdi.llnl.gov/cmip5/>). Two additional past1000 simulations 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 distribution of the volcanic aerosol size slightly differs in the last two past1000 simulations). The forcings (Schmidt et al., 2011) prescribed in the past1000 and historical simulations include the orbital forcing, variability in solar irradiance (Vieira et al., 2011), seasonally varying natural tropospheric aerosols, stratospheric aerosols from volcano eruptions (Crowley et al., 2008), and five well-mixed greenhouse gases: CO_2 , CH_4 , N_2O , CFC-11, and CFC-12, as well as O_3 , anthropogenic sulphate aerosols, and changes due to anthropogenic land use (Pongratz et al., 2009). In the scenario simulations, only changes in anthropogenic forcing were prescribed according to the Representative Concentration Pathways (rcp) scenarios.

25 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.

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 were conducted after

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the CMIP5 project was closed. The CESM-CAM5 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 forcings, natural and anthropogenic (denoted as “all-forcings” in the CESM-CAM5 Last Millennium ensemble project Otto-Bliesner et al., 2015 (<https://www2.cesm.ucar.edu/models/experiments/LME>)). The CESM-CAM5 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. Unfortunately, no future simulations with this model are publicly available (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 are similar to the resolution of the CMIP5 models used by Wang et al. (2015). Although ocean processes of spatial scales of a few kilometres are only imperfectly resolved, this resolution should be fine enough to realistically represent the basic relationship between upwelling dynamics and the large-scale wind forcing, including the shoreline-parallel winds and the wind stress curl.

Upwelling intensity in each of the four upwelling regions is defined by the vertical mass transport (wmo) at the ocean model layer at 52 m (MPI-ESM) and the vertical velocity (wvel) at 50 m (CESM-CAM5) (close to the modelled mixed layer depth), and averaged over each of the upwelling regions: Benguela ($8\text{--}30^\circ E$, $15\text{--}28^\circ S$), Peru ($80\text{--}70^\circ W$, $20\text{--}10^\circ S$), California ($130\text{--}110^\circ W$, $20\text{--}50^\circ N$), and Morocco ($20\text{--}10^\circ W$, $20\text{--}34^\circ N$). Upwelling indices are here defined as the seasonal means over the main upwelling season in each region. 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 simulations, the main upwelling

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season is September–November in Benguela and Peru and June–August in California and Morocco.

If it is not explicitly stated, all correlations have been calculated with long-term detrended series.

5 Here, we show results from three of the available simulations from the CESM-CAM5 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.

10 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 model of the variations of a climate record that decomposes its variability into a sum of a forced component, proportional to the external climate forcing, and an internal component caused by the non-linear interactions within the climate system:

$$y = y^f(t) + y^i(t) \quad (1)$$

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:

$$y_1(t) = y^f(t) + y_1^i(t) \quad (2)$$

$$y_2(t) = y^f(t) + y_2^i(t) \quad (3)$$

where the forced components are by construction equal in both simulations and the internal components are uncorrelated in time. 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

$$r = \langle y_1, y_2 \rangle / \langle y_1, y_1 \rangle = \langle y^f, y^f \rangle / \langle y_1, y_1 \rangle \quad (4)$$

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

3 Representations of upwelling and its drivers in the model

The patterns of long-term mean sea surface temperature (SST) (June–August, main upwelling season in three of the four regions) display depressed values in the areas
5 of upwelling relative to the zonal SST mean at the same latitude, although the fine spatial structure appears smoothed due to the model resolution (Fig. 2a). The shape of the modelled seasonal cycle of upwelling generally agrees with what is known from observations (Fig. 2b and c), with upwelling being more intense in the boreal warm half-year. The mean upwelling is, however, about a factor two more intense in the lower
10 resolution past1000 simulations, 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 simulated by many climate models (Wang et al., 2014).

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
15 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) realistically show regions with negative correlations over land and positive correlations off-shore (Fig. 3), indicating that the across-coastline SLP
20 gradient is conductive for alongshore wind stress through the geostrophic relation.

4 Imprint of external forcing on coastal upwelling

4.1 Past1000 and historical simulations

In the last millennium, the climate changed driven by the external climate forcing. The main external climate drivers over this period were volcanic forcing, solar variability,

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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-

5 Donado et al., 2013). 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 caused by high solar and low volcanic activity. 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
10 result of higher concentration of greenhouse gases (Fernández-Donado et al., 2013).

For both ensembles of simulation of the past, the decadally smoothed time series of regional upwelling extracted from each of the three simulations display different time evolutions (Fig. 4) and do not show a centennial evolution comparable to the global mean temperatures or the global mean external forcing as just described. The correlations
15 between these series for each region are correspondingly low (Table 1, Fig. 5) and mostly statistically not significant. These correlations remain low and non-significant for stronger low-pass time filtering up to 50 years (Fig. 6a). 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 up to multidecadal timescales over the past millennium.

This finding supports previous studies derived from observed records, that 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,
25 probably linked to the dynamics of the Tropical and mid-latitude Pacific Ocean (Macías et al., 2012).

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 years is stronger

than the variations in the forcing prescribed in the past 1000 simulations. For instance, the amplitude of decadal variations of the preindustrial external forcing is of the order of 0.3 Wm^{-2} (Schmidt et al., 2011), whereas the increase in the external forcing over the past 250 years is 1.6 Wm^{-2} (Myhre et al., 2013).

- 5 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 trends are small, mostly statistically not significant, and generally display opposite signs in the different simulations (Fig. 4). The two exceptions here are California and Morocco in
10 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 confirms the results with the MPI-ESM. The simulated upwelling velocity in three simulations are weakly correlated with each other (Fig. 7) and the trends are
15 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, 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
20 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 2, Fig. 8). The trends are negative in California and Morocco and positive only in Benguela. In Peru no significant trends can be seen. This supports our results obtained for the past millennium, indicating that the external forcing has
25 not been intense enough in the past to force the upwelling significantly. Furthermore, the expected positive trend only occurs in one of the four regions, underlining the local differences among the EBUs. These results do not fully support the ones obtained by Wang et al. (2015). They analysed the trend for another period (1950 to 2099) and only

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the rcp8.5 scenario. They concluded that a clear connection between external forcing and upwelling could be find. 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.

5 Imprint of external forcing on the drivers of upwelling

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 is related to the SLP gradient between land and ocean (Tomczak and Godfrey, 2003; Mackas et al., 2006). 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).

As in the case of the upwelling indices, the correlations between the time series of wind stress and SLP gradients across the simulations in the ensemble are all low (Tables 3 and 4). These correlations also remain low regardless of the time filtering (Fig. 6b). 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 increase in greenhouse gas forcing. Therefore, even if the connection between the atmospheric drivers and upwelling were not 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 simula-

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tions 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.

5 6 Imprint of external forcing on 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 Kenny, 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. 9). 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. The reason is that at high latitudes the internal variability is also larger than at low latitudes. The ratio between both, external forcing signal and internal variability, which is encapsulated by the correlation patterns show in Fig. 9, is therefore highest in the tropics, a feature which has been so far overlooked but that has been found in previous analysis of paleoclimate simulations (Tett et al., 2007). In the EBUs, the correlations between the simulated SSTs are all positive, of the order of 0.2–0.3 after 10 year low-pass filtering. Therefore, the external forcing has some influence on the SST variability in these regions but most of the multi-decadal variability is internally generated.

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7 Discussion and conclusions

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 5 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 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 10 intensification or weakening.

For the future, the effect of external forcing on the EBUs 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 15 in the ensemble display consistent trends, but these trends are not always consistent with the expected intensification of upwelling, with some regions showing an intensification but others 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 (18.5–10.5° W, 16.5–42.5° N), South Benguela (8–20 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 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 agree with the ones obtained by Wang et al. (2015) on the 25 influence of a strongly increased future greenhouse gas forcing on upwelling intensity in the EBUs. However, our results indicated 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 the evo-

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lution of upwelling over the past millennium. The same can be said on the study of Rykaczewski et al. (2015) where again only the upwelling in the EBUs in the rcp8.5 scenario is analysed. 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 the differences between the upwelling regions, and indicate the complexity of the upwelling by the different results depending on the analysed model – but stress the impact of the external forcing on upwelling in the rcp8.5 scenario.

It has to 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 the strongest influence on the simulated coastal upwelling. Furthermore, the current global coupled climate models still display a strong SST bias in the EBUs. The cause of this bias is not completely understood, it may be related to a deficient representation of coastal upwelling but it may have other causes, for instance related to biases in the climate 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.

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

Thus, the circumstantial evidence linking the recent observed trends in EBUs upwelling to external climate forcing is in conflict with state-of-the art climate simulations.

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Table 1. Correlation coefficients of the simulations of the upwelling indices of all upwelling regions for the past1000 and historical simulations with the MPI-ESM model with 10 and 30 year filter, respectively.

	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

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Table 2. 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.

	California	Morocco	Benguela	Peru
past1000:				
<i>r1</i>	-	-	-	+
<i>r2</i>	-	+	+	+
<i>r3</i>	+	+	+	-
historical:				
<i>r1</i>	-	-	-	+
<i>r2</i>	-**	-	+	-
<i>r3</i>	-**	-	-	-
rcp2.6:				
<i>r1</i>	-	-	-	-
<i>r2</i>	-	-	+	+
<i>r3</i>	-	-**	+	+
rcp4.5:				
<i>r1</i>	-	-**	-	-
<i>r2</i>	-	-	+	-
<i>r3</i>	-**	-**	+**	+
rcp8.5:				
<i>r1</i>	-**	-**	+**	+
<i>r2</i>	-**	-**	+**	-
<i>r3</i>	-**	-**	+**	-

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Table 3. 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 30 year filter, respectively.

	California	Morocco	Benguela	Peru
past1000:				
$r1-r2$	+0.12	+0.04	-0.03	+0.11
$r1-r3$	+0.21	+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	+0.13	-0.09

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Table 4. Correlation coefficients of the simulations of alongshore wind stress of all upwelling regions for the past1000 and historical simulations with the MPI-ESM model after 10 and 30 year filter, respectively.

	California	Morocco	Benguela	Peru
past1000:				
$r1-r2$	-0.02	-0.22	+0.001	+0.07
$r1-r3$	-0.05	+0.09	-0.13	+0.09
$r2-r3$	+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

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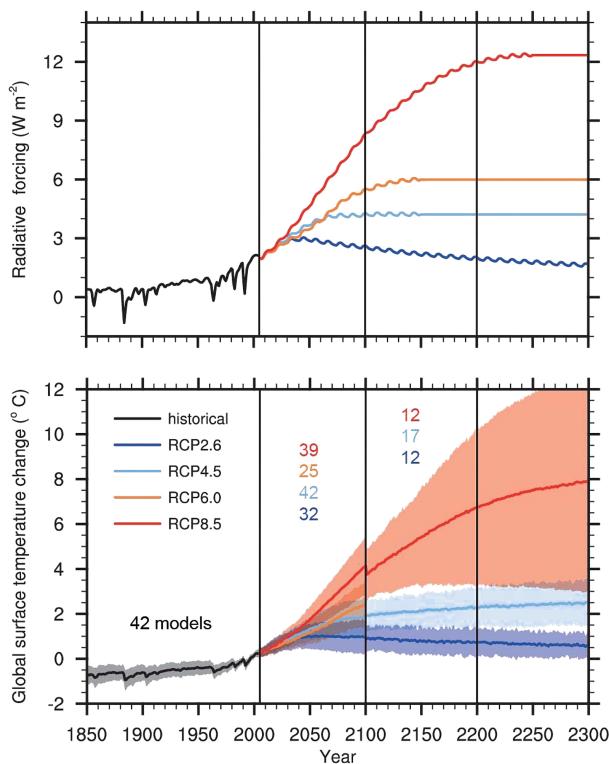


Figure 1. Global mean radiative forcing for the Representative Concentration Pathways (rcp) scenarios (Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC)) (upper panel). Multi-model mean (solid line) and spectra of all models (shaded) time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 simulations (lower panel). The numbers indicate how many model are available for the corresponding time period and scenario. Source: Stocker et al. (2013).

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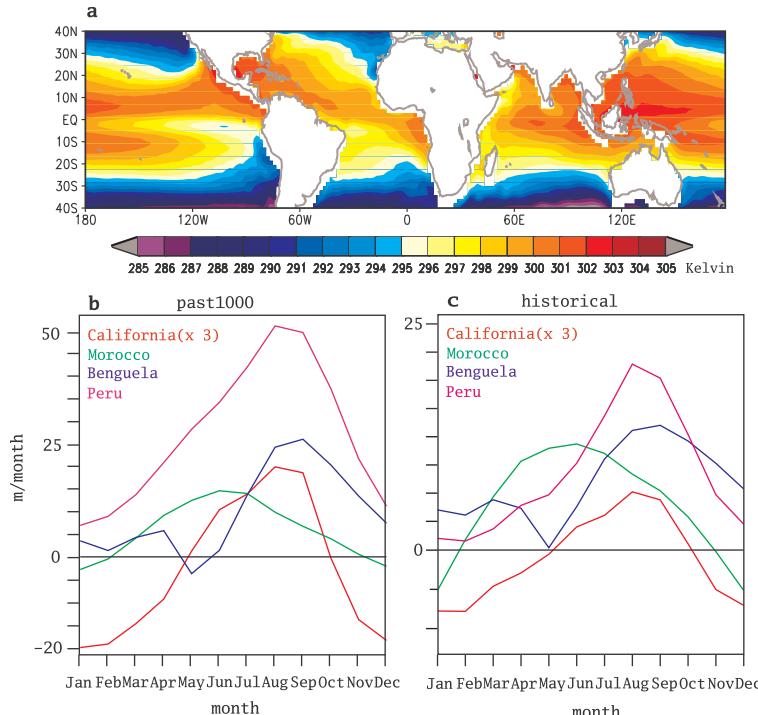


Figure 2. Mean sea surface temperature in June–August simulated by one past1000 simulation with the MPI-ESM Earth System Model in the tropics and subtropics (**a**). Monthly mean vertical velocity at 52 m depth in four main coastal upwelling regions simulated in one past1000 (900–1850) (**b**) and one historical (1850–2005) simulation (**c**) of the MPI-ESM. The values for California have been re-scaled for better visibility. Note the different y axis scale for each simulation.

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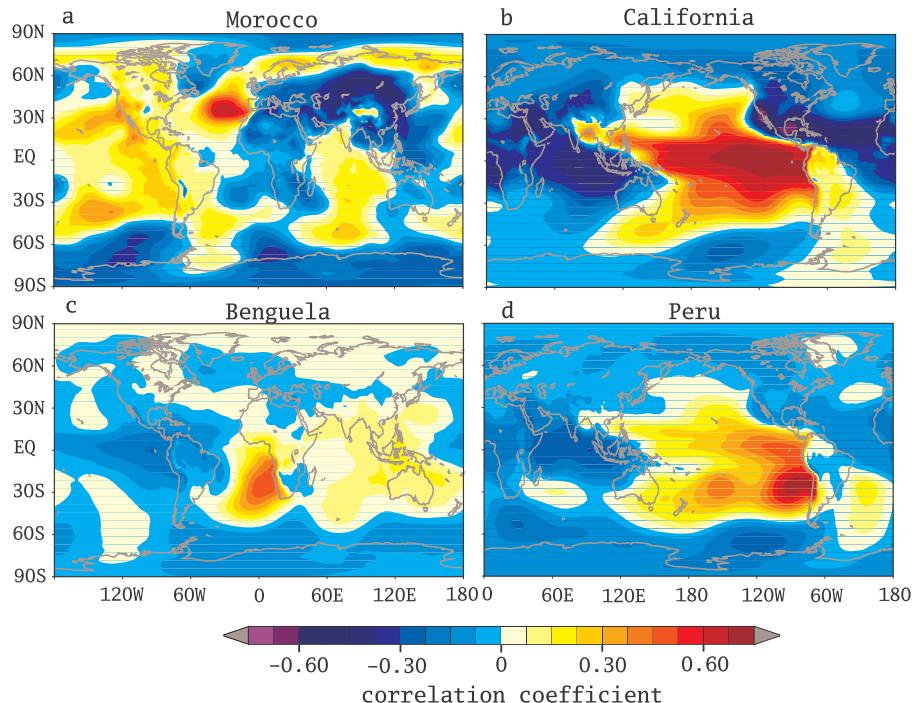


Figure 3. Correlation patterns between the seasonal (June–August, except for Benguela September–November) upwelling index in each Eastern Boundary Upwelling System and the simultaneous seasonal mean sea level pressure field simulated in one of the past1000 simulations (900–1850) with the Earth System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

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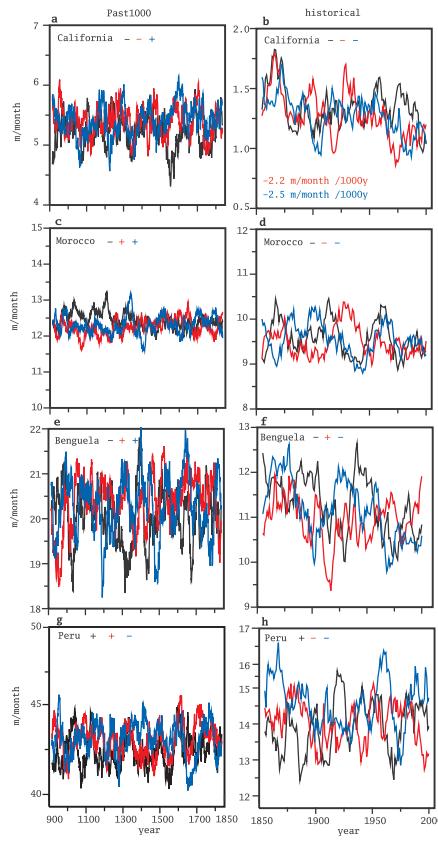


Figure 4. Time series of the simulated upwelling indices in each upwelling region simulated in two ensembles of climate simulations (three members each), denoted past1000 (900–1850) and historical (1850–2005), with the MPI-ESM model. The plus and minus signs in each panel indicate the sign of the long-term 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.

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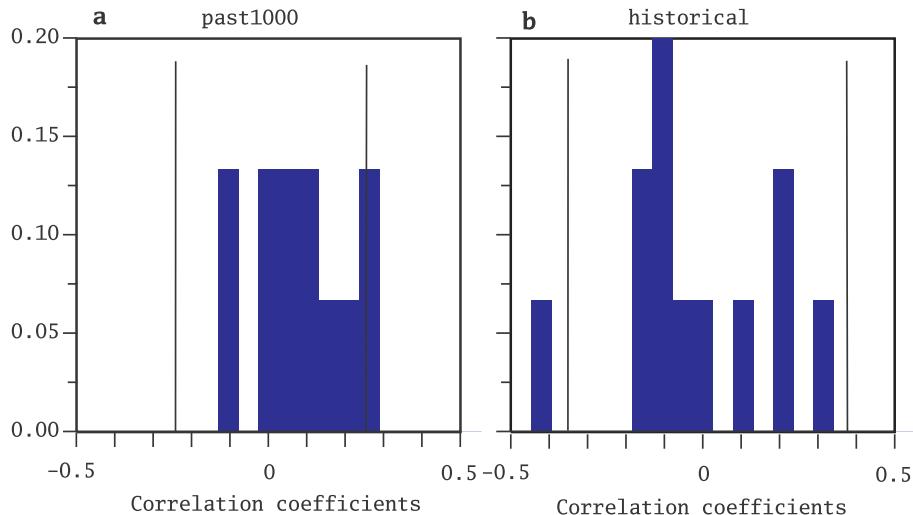


Figure 5. Frequency histogram in bins of 0.05 width showing the distribution of across-ensemble correlations between the upwelling indices simulated in each upwelling region for the ensembles past1000 (a) and historical (b) of the MPI-ESM, after low-pass filtering with a 30 year (past1000 simulation)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

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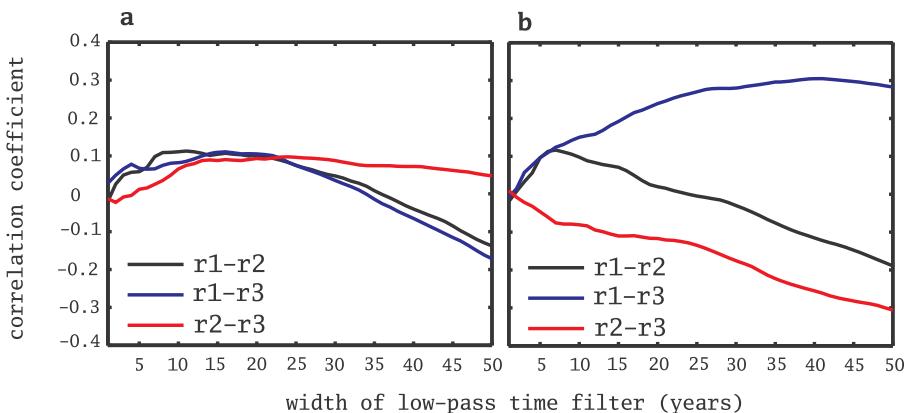


Figure 6. Correlations between the simulated upwelling indices in Benguela in three past1000 simulations with the MPI-ESM model after filtering the time series with low-pass filter of increasing period **(a)** and the same as **(a)** but for the time series of sea level pressure difference between land and ocean averaged over the areas most closely correlated with the simulated upwelling in this region **(b)**.

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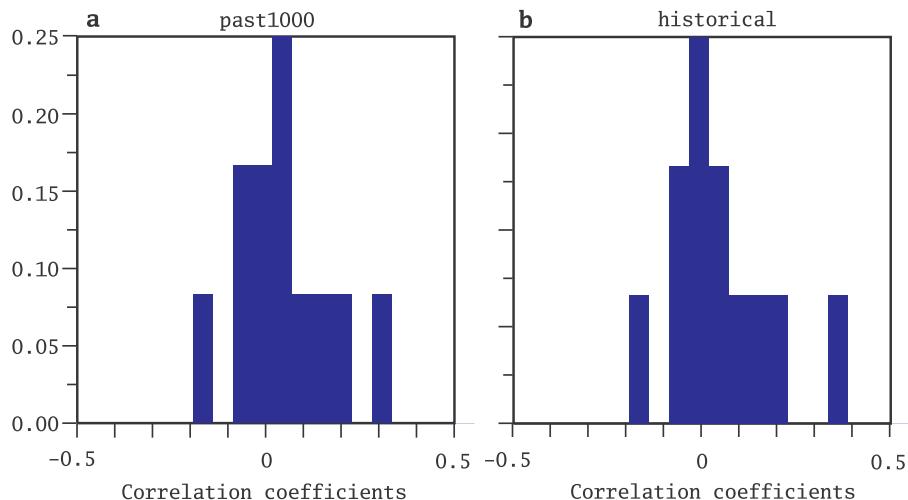


Figure 7. Frequency histogram in bins of 0.05 width showing the distribution of across-ensemble correlations between the upwelling indices simulated in each upwelling region for the ensembles past1000 (**a**) and historical (**b**) of the CESM-CAM5, after low-pass filtering with a 30 year (past1000 simulation) and a 10 year (historical simulation) filter, respectively.

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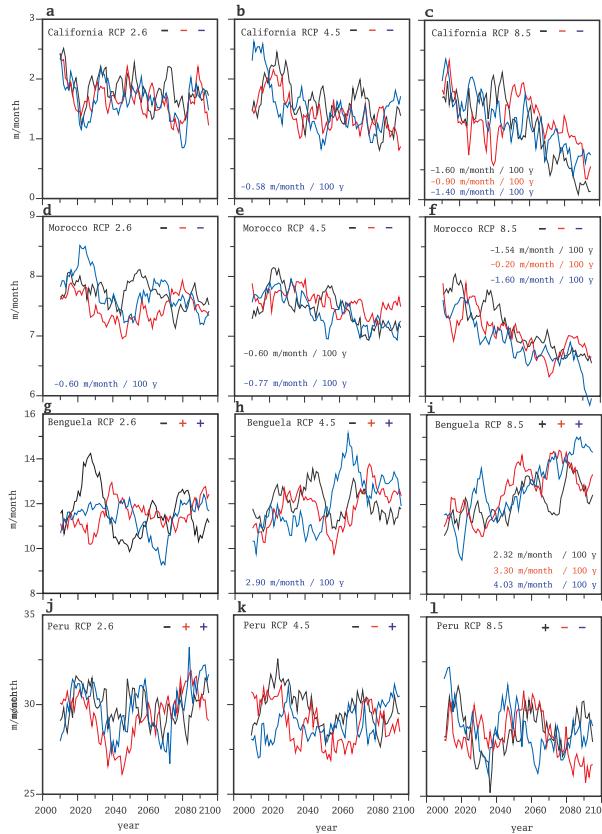


Figure 8. Time series of the simulated upwelling indices in each upwelling region simulated in three ensembles of climate simulations (three members each) for 2006–2100, rcp2.6, rcp4.5, and rcp8.5, with the MPI-ESM model. The plus and minus signs in each panel indicate the sign of the long-term trend, their value being included whenever statistically significant. The series have been low-pass filtered with a 10 year filter.

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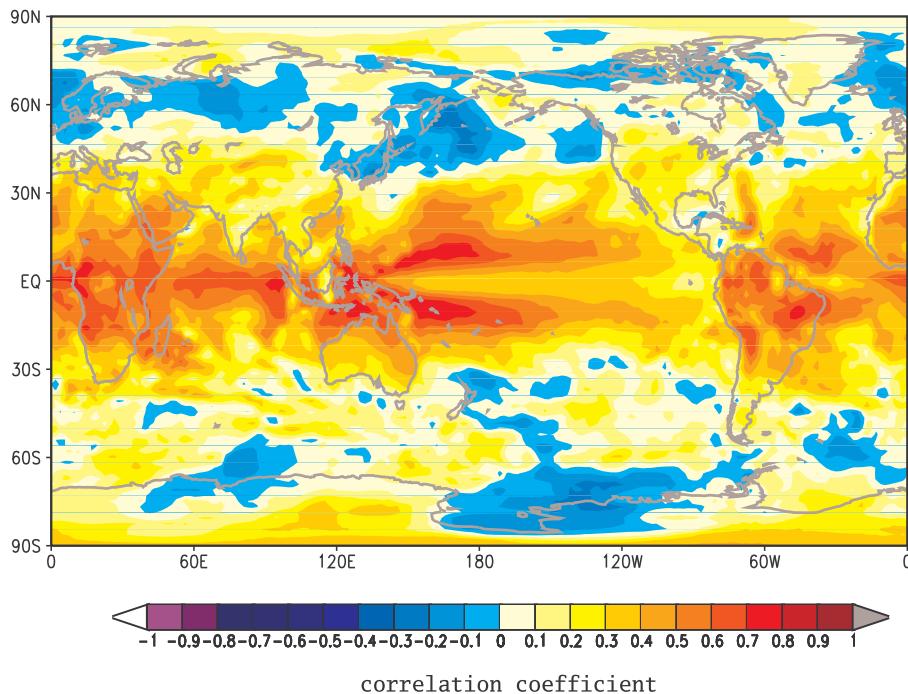


Figure 9. Correlation pattern between the global skin temperatures simulated in two past1000 simulations (900–1850) with the Earth System Model MPI-ESM in the June–August season after applying a 10 year low-pass filter.

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