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Trends of the Galician upwelling in the context of climate change

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ABSTRACT

Coastal upwelling is a phenomenon of great importance both for the study of ocean dynamics and for the development of fish production in some coastal regions. Our study region, the Galician coast, lies at the northern end of the Canary–Iberian Peninsula upwelling system. Knowing the changes provoked by climate change on this upwelling system is particularly relevant for the future of this area taking into account the social and economic importance of fishing activities in this region. In this paper we study the trends in the intensity and frequency of upwelling in the Galician coast and the expected changes in this phenomenon for the next decades using three regional models implemented within the European project ENSEMBLES. As a main result, we observe that the models show a positive trend in both the intensity and frequency of upwelling phenomenon for the future, particularly significant in spring and summer which are the seasons favorable for upwelling. In autumn and winter there are no significant changes.

1. Introduction

Around 90% of the world's fishing areas are concentrated in 2–3% of the total area of the oceans, mostly coastal areas where situations of upwelling occur. The upwelling process brings cold, nutrient rich water to the surface in coastal areas. These waters in turn support a diverse marine fauna. To know in detail where, when and how these events take place is critical for the proper development of fisheries (Álvarez, 2005). The study of the direction and intensity of the wind is very important to characterize the upwelling events. According to Bakun (1990), due to global warming and increased greenhouse gases, a higher thermal gradient between the land and water masses could take place to intensify upwelling favorable winds; so it will intensify upwelling in the Canary Current System, the California Current System, the Benguela Current, and the Peru–Humboldt Current. This effect has been corroborated for the case of California (García-Reyes and Largier, 2010) and northwest Africa (McGregor et al., 2007; Narayan et al., 2010). Contrary to this study, several recent trends in wind and temperature suggest a reduction of upwelling in the NW Iberian coast (Álvarez et al., 2008; Álvarez-Salgado et al., 2008; Alves and Miranda, 2013; Lemos and Pires, 2004; Lemos and Sansó, 2006). In addition, Ruiz-Villarreal et al. (2009) indicate a decrease in the intensity and duration of upwelling in the last 40 years due to changes in wind patterns, with a significant reduction in the duration of upwelling favorable conditions by 30% and its intensity by 45%.

In this paper we focus the study on the future climatic changes in the upwelling of the northwestern Iberian coast, in a global warming scenario. The region under study, which is part of the Canary Upwelling System, is characterized by upwelling during the months of April through September, being more intense during the summer. The onset of the upwelling is gradual, starting in March/April to attain values in June/July. Besides this spring–summer upwelling, this phenomenon can also occur in winter (Álvarez et al., 2003). This winter upwelling occurs under the same conditions as in summer generally with northerly winds, so it occurs less frequently. Changes in frequency and intensity of these events can have a profound effect on ecosystems, even if characteristics of upwelled water do not change, and can result in large and significant changes in the productivity of fisheries. Obviously, upwelled water characteristics can also vary, but this topic is out of the scope of this paper.

The objective of this study is to examine the behavior of upwelling in the period 1961–2090 through the results of different climate models and compare it with the 1961–1990 period. For this study, we will make use of three regional climate models (RCMs) from ENSEMBLES project. It must be taken into account that wind projections given by different models have a degree of uncertainty that will be transferred to upwelling index. The upwelling index (UI) values will be studied at three points of the Galician coast analyzing annual and monthly behavior in the different periods of upwelling (April to September) and no upwelling (October to March). This will be done for the last decades of this century (2061–2090) and compared with the values of

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the last decades of the last century (1961–1990). The entire series between 1961 and 2090 will also be examined to assess trends in the future.

2. Data and methods

Our analysis focuses on the coastal-upwelling areas off Galicia (NW Iberian Peninsula). The Galician coast is at the northernmost limit of the eastern North Atlantic upwelling system (Wooster et al., 1976). It can be subdivided into three domains (Fig. 1): the west coast, south of Cape Finisterre; the central coast, from Cape Finisterre to Cape Ortegal; and the north or Cantabric coast, east of Cape Ortegal.

The region is located in the mid-latitude belt of north Atlantic. This means that in autumn and winter it is submitted to the passage of lows that travel between the east coast of North America and the western coast of Europe. Therefore prevailing winds have a west component (Lorenzo et al., 2011), which inhibit upwelling. On the contrary, when spring comes to the northern hemisphere, low pressure systems move to the north and the Iberian Peninsula is affected by the Azores High, which means that prevailing winds are north-easterly. These winds favor coastal upwelling.

To make this work results from the ENSEMBLES project have been used. Specifically, we have used three RCMs driven by a single global climate model (GCM) and the same three models driven by the ERA-40 reanalysis. The GCM driving the different RCMs is the ECHAM5 model developed by the Max Planck Institute for Meteorology in Hamburg, because the results of this model in the mid latitudes of the North Atlantic are quite remarkable (Van Ulden and Van oldenbourgh, 2006). Moreover other previous works have also used ECHAM5 as GCM to calculate wind because of the good representation of circulation made by this model over the north Atlantic area (Pryor et al., 2012). The regional models chosen were the RACMO, developed at the Royal Netherlands Meteorological Institute, the REMO of the Max Planck Institute for Meteorology in Hamburg, and the RCA, developed at the Rossby Centre of the Swedish Meteorological Center. We analyze and compared the results of models driven by ECHAM5 with those obtained when the boundary conditions of the RCMs are given by the ERA-40 reanalysis. In this last case, the results can be considered similar to real values, because the reanalysis data can be considered as the best choice to simulate real climate. The period considered by the comparative study was 1961–1990 and the future scenario analyzed was the A1B for the period 2061–2090.

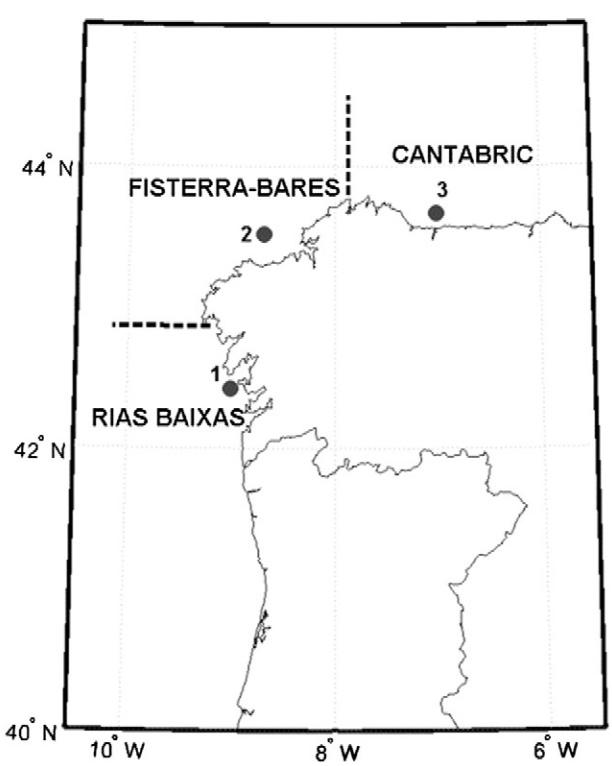

Fig. 1. Study area with three regions chosen for study.

The data taken from the models for the study are the zonal (W_x) and meridional (W_y) components of wind, in order to calculate the Ekman transport and upwelling index. This analysis will be done for the mentioned periods and for the complete period 1961–2090 in order to analyze the future trends. The Ekman transport can be calculated in terms of the wind speed, W, by means of the following equation

$$Q_x = \frac{\rho_a C_d}{\rho_w f}\left(W_x^2 + W_y^2\right)^{1/2} W_y \text{ and } Q_y = -\frac{\rho_a C_d}{\rho_w f}\left(W_x^2 + W_y^2\right)^{1/2} W_x \quad (1)$$

$\rho_a = 1.22\ \mathrm{kg\ m^{-3}}$ is the air density, $\rho_w = 1025\ \mathrm{kg\ m^{-3}}$ is the sea water density, $C_d = 1.4 \times 10^{-3}$ is a dimensionless drag coefficient and f is the Coriolis parameter defined as twice the vertical component of the Earth's angular velocity, Ω, about the local vertical given by $f = 2\Omega \sin(\theta)$ at latitude θ. The subscript x corresponds to the zonal component and the subscript y to the meridional one. The upwelling index (UI) can be calculated as the Ekman transport component in the direction perpendicular to the shoreline (Bakun, 1973; Gómez-Gesteira et al., 2006; Nykjaer and Van Camp, 1994) using the following formula:

$$UI = Q_{\perp} = -Q_x \sin\theta + Q_y \cos\theta \quad (2)$$

where $\theta = \pi/2 + \varphi$, and φ is the angle of the unitary vector perpendicular to the shoreline pointing landwards. Positive (negative) UI values mean upwelling-favorable (-unfavorable) conditions. UI was measured in three points located along the Galician coast and representative of the three regions considered (Fig. 1).

Mean values have been calculated as the mean of the three models, calculated all along the year or separately on the period favorable and unfavorable, while the standard deviation comes from the differences between each model, representing inter-model variability.

To calculate the frequency of appearance of upwelling, we have taken into account only the episodes of strong upwelling, considering that the upwelling is strong if the UI value is greater than the average plus the standard deviation of the series.

The Mann–Kendall trend test (Kendall, 1975; Mann, 1945) was applied to analyze the significance of the trends. This non-parametric test uses a correlation between the ranks of a time series and their time order and it is widely applied to time series of environmental data.

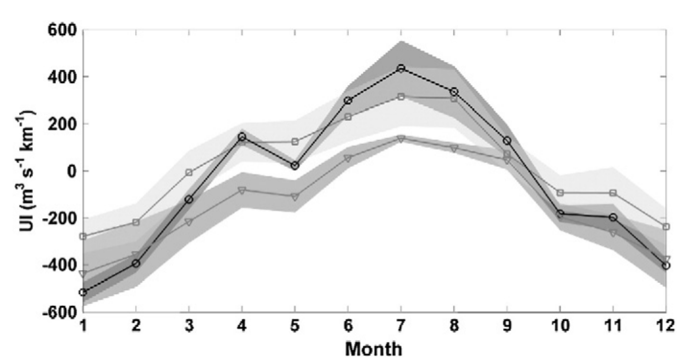

Fig. 2. The mean UI (solid line) and its standard deviation (shaded region) for each point are illustrated with the three RCMs driven by ERA-40 for the period 1961–1990 (squares—Rias Baixas region, circles—Fisterra-Bares region and triangles—Cantabric region).

Table 1
Average annual UI ($m^3\ s^{-1}\ km^{-1}$) for the period 1961–1990 with RCMs driven by ECHAM5 model and the ERA-40 reanalysis.

Regions	Models	ERA-40	ECHAM5	Difference
Rias Baixas	RACMO	43.04	−9.53	52.57
	RCA	−75.63	−116.77	41.14
	REMO	93.39	−34.93	128.32
Fisterra-Bares	RACMO	−24.52	−315.75	291.23
	RCA	−77.84	−276.97	199.13
	REMO	−9.46	−353.54	344.08
Cantabric	RACMO	−205.83	−489.07	283.24
	RCA	−67.39	−233.87	166.48
	REMO	−149.19	−421.33	272.14

Table 2
Annual frequency of strong upwelling events (%) for the period 1961–1990 with RCMs driven by ECHAM5 model and the ERA-40 reanalysis.

Regions	Models	ERA-40	ECHAM5	Difference
Rias Baixas	RACMO	12.7595	11.3552	1.4044
	RCA	11.1709	10.6790	0.4919
	REMO	12.2573	11.2999	0.9575
Fisterra-Bares	RACMO	14.2103	13.0613	1.1491
	RCA	12.9503	12.4491	0.5012
	REMO	13.8912	12.6133	1.2779
Cantabric	RACMO	10.3311	10.2856	0.0456
	RCA	11.2252	10.0207	1.2046
	REMO	10.5871	9.7561	0.8310

3. Results

In a first step, upwelling index was calculated using wind data from the RCMs with boundary conditions forced by the ERA-40 reanalysis. Fig. 2 shows the UI corresponding to the average of 1961–1990 period at 3 points shown in Fig. 1 for each month of year. It can be observed that the months in which the rate of upwelling is positive in the Rias Baixas take place between April and October, when the winds mainly blow from the north. This period of positive upwelling occurs only in the summer months when there is northeasterly wind in the area between Bares and Fisterra area and more weakly it is also observed in the Cantabric Coast when the wind blows from the east. The intensity is higher in the region of Fisterra-Bares, however the period favorable to upwelling is longer in the region of Rias Baixas. In this way, we can see that RCMs accurately simulate the seasonal contrast of wind stress curl.

In a second step we calculate the UI for the period 1961–1990 with the RCMs but now with the ECHAM5 model as boundary condition. In this way we can analyze the differences between the real conditions and the conditions forced by a general circulation model. Therefore we can obtain the deviations introduced by the GCMs in the calculations for the future periods. Table 1 and Fig. 3 show the results of annual UI when the models are forced by the reanalysis ERA-40 and when the models are forced by ECHAM5. In Fig. 3(a–c) we can see that upwelling index is underestimated in RCMs driven by ECHAM5 with respect to the results obtained by the same models driven by ERA-40. This effect has also been observed in similar studies of upwelling in other areas of the world (Snyder et al., 2003). The reason of this underestimation may be related to the spatial scale of the upwelling phenomenon. Even an RCM of 25 km of resolution can have difficulties to resolve completely such a local phenomenon. But the important thing is that seasonality of the phenomenon is well represented. Table 1 shows the numerical value of the difference between RCMs driven by ECHAM5 with respect to the RCMs driven by ERA-40. This bias underestimates upwelling intensity and this bias should be taken into account for future predictions. In Fig. 3(d–f) the frequency of appearance of strong upwelling is shown. In this case there is no underestimation, which means that the episodes of strong upwelling are fairly well represented. In Table 2 the mean value of the frequency of strong upwelling events is shown for the RCMs driven by ERA-40 and ECHAM5 respectively. Difference is also shown in the third column.

We haven't found any significant trends in upwelling indices during the period 1961–1990 (Fig. 3). However, the values for the period 1961–2090, Fig. 4(a–b), show significant trends both in the annual value of UI in the three regions and in the frequency of strong events (see Table 3). Moreover, if we split the annual period in period of favorable upwelling (April–September) and period unfavorable upwelling (October–March), we can see that the significant increase

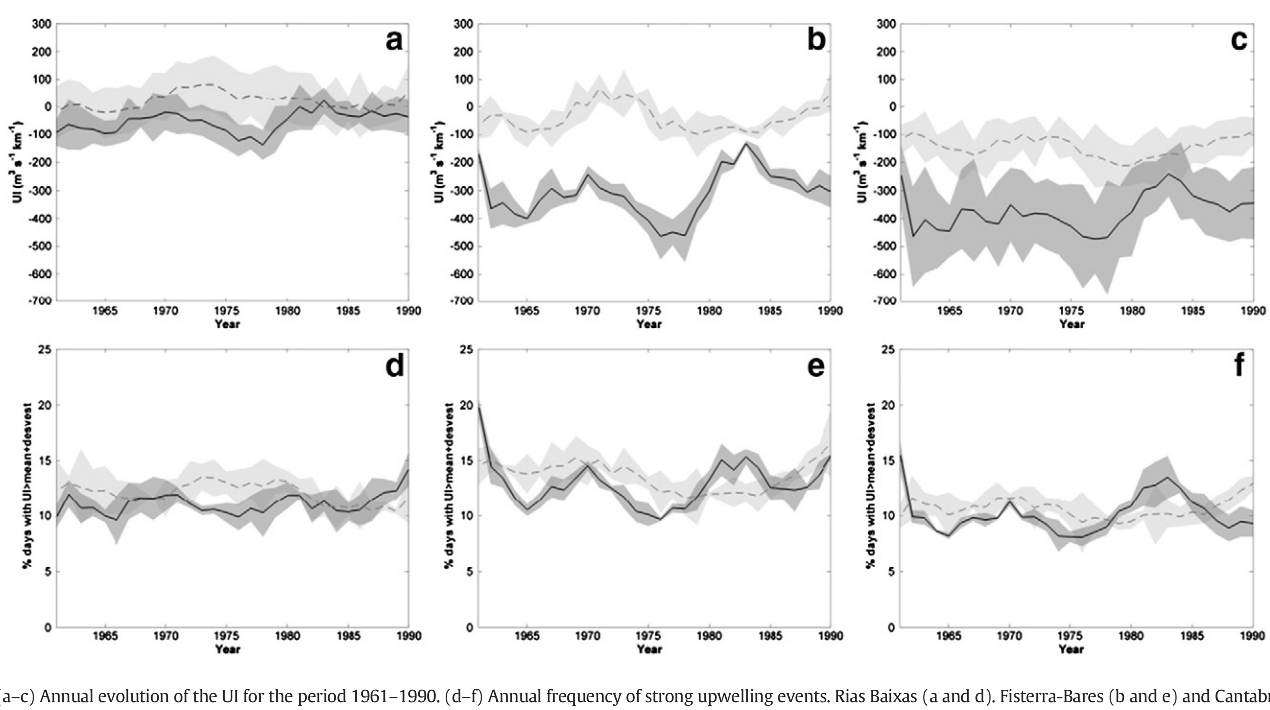

Fig. 3. (a–c) Annual evolution of the UI for the period 1961–1990. (d–f) Annual frequency of strong upwelling events. Rias Baixas (a and d). Fisterra-Bares (b and e) and Cantabric coast (c and f). The mean UI (solid and dashed line) and its standard deviation (shaded region) for each point are illustrated with the three RCMs driven by ECHAM5 in dark gray and with the three RCMs driven by ERA-40 in light gray.

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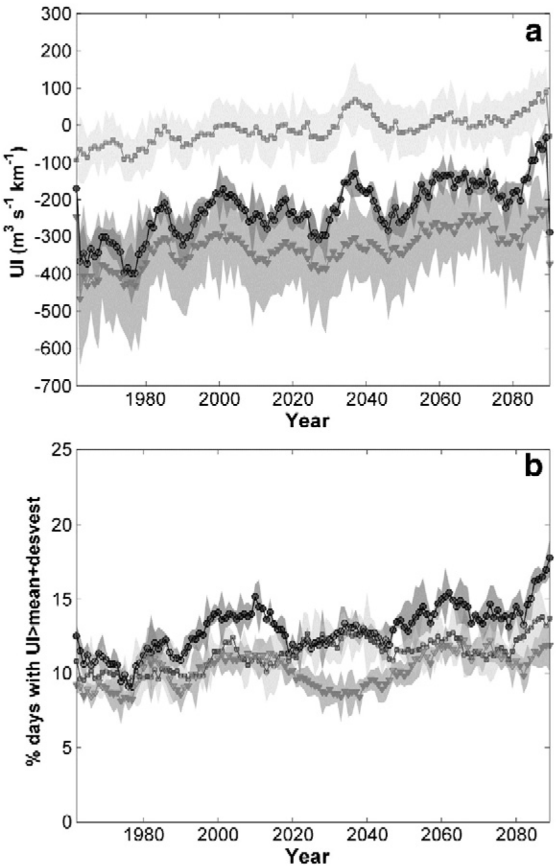

Fig. 4. (a) Annual evolution of the UI for the period 1961–2090. (b) Annual frequency of strong upwelling events for the period 1961–2090. The mean UI (solid line with symbols) and its standard deviation (shaded region) for each point are illustrated with the three RCMs driven by ECHAM5 (squares—Rias Baixas region, circles—Fisterra-Bares region and triangles—Cantabric region).

occurs in the period from April to September, while the period from October to March shows no significance. For this reason the trend values are not included in the tables. This result means that winds will tend to increase upwelling in spring and summer.

Table 4 shows the average differences between UI of the period 1961–1990 and UI of the period 2061–2090 for the months of the year with upwelling, no upwelling, and annual. The results indicate that the differences between both periods are higher in the period of favorable upwelling, although in all cases an increase of the averaged UI is observed. The Rias Baixas region is the one with a smaller increase while Fisterra-Bares is showing a greater increase. Nevertheless we must remind that Rias Baixas is the region with greater values of upwelling index and therefore any statistically significant increment is relevant in this area. A similar behavior is found for the frequency of strong upwelling events (Table 5). Models show an increase for the three areas of the frequency of strong events in the months with favorable characteristics for upwelling, while in other periods of the year the increments are smaller or even negative.

Fig. 5 shows the monthly results of the UI in the periods 1961–1990 and 2061–2090, for each region, with the RCMs driven by the ECHAM5 model. In this figure we can see that the RCMs accurately simulate the seasonality and seasonal contrast of wind stress curl and upwelling observed in Fig. 3, even if the values are underestimated.

In the three regions the summer months are those with a higher value of the UI and these values will increase in the future. The largest increase is observed in the Fisterra-Bares region. This may be because in the future the models forecast more situations of N, NE and E in summer (Lorenzo et al., 2011). However, Rias Baixas is the region with higher values of the annual UI, followed by Fisterra-Bares and Cantabric regions (see Fig. 4) because it has a wider period of favorable upwelling. In the remaining months of the year (except in December and January) the upwelling index is also somewhat higher in the future than in the past, but not as much as in summer. These increases could have a positive effect on the fisheries of Galician with a higher primary productivity.

4. Conclusions

In this work we have studied the changes expected on the upwelling index at the coast of Galicia. Studies have been done using three RCMs of ENSEMBLES project under the A1B scenario driven by a GCM and driven by the ERA-40 reanalysis. In the study of the behavior of upwelling in the end of the last century, 1961–1990, the conclusion is that no trends are observed by the models in any case; neither in the simulation with the best available boundary conditions (ERA-40) nor in the simulation with boundary conditions given by a GCM (ECHAM5). However, it is observed that the RCMs driven by the GCM underestimate the upwelling index value although qualitatively they represent in a suitable way the behavior of the index in the three regions considered at the Galician coast. This bias must be into account in the future in quantitative studies.

In the study of the period 2061–2090 the results show that the upwelling phenomenon between April and October will increase on

Table 3
Trends intensity ($m^3 s^{-1}$ km^{-1}) and frequency per decade for the period 1961–2090 differentiating both upwelling period and the whole year. These trends have been calculated using the Mann Kendal test and are significant at the 0.05 level.

Regions	RCMs	Upwelling trends		Strong events trends	
		April–Sept	Annual	April–Sept	Annual
Rias Baixas	RACMO	15.10	8.01	0.79	0.36
	RCA	11.34	7.39	0.41	0.20
	REMO	13.74	8.87	0.36	0.14
Fisterra-Bares	RACMO	28.86	17.45	0.72	0.38
	RCA	20.40	12.18	0.52	0.27
	REMO	26.14	17.73	0.53	0.30
Cantabric	RACMO	17.82	12.52	0.35	0.17
	RCA	8.54	5.86	0.25	–
	REMO	15.22	11.29	0.36	0.2

Table 4
Differences of averaged UI ($m^3 s^{-1}$ km^{-1}) between 1961–1990 and 2061–2090.

Regions	RCMs	Differences		
		April–Sept	Oct–Mar	Annual
RB	RACMO	152.22	5.74	79.15
	RCA	115.52	34.07	74.89
	REMO	139.25	39.92	89.72
Fist-Bares	RACMO	301.40	74.31	188.13
	RCA	210.17	55.08	132.80
	REMO	267.06	115.70	191.56
Norte	RACMO	177.13	96.64	136.98
	RCA	81.05	49.99	65.55
	REMO	146.39	101.59	124.04

Table 5
Differences of frequency of strong events between 1961–1990 and 2061–2090.

Regions	RCMs	Differences		
		April–Sept	Oct–Mar	Annual
RB	RACMO	7.82	−0.72	3.56
	RCA	4.23	−0.04	2.10
	REMO	3.58	−0.84	1.37
Fist-Bares	RACMO	8.04	1.26	4.65
	RCA	5.69	1.01	3.36
	REMO	5.57	1.45	3.52
Norte	RACMO	4.04	0.96	2.50
	RCA	2.97	0.23	1.60
	REMO	3.73	1.30	2.52

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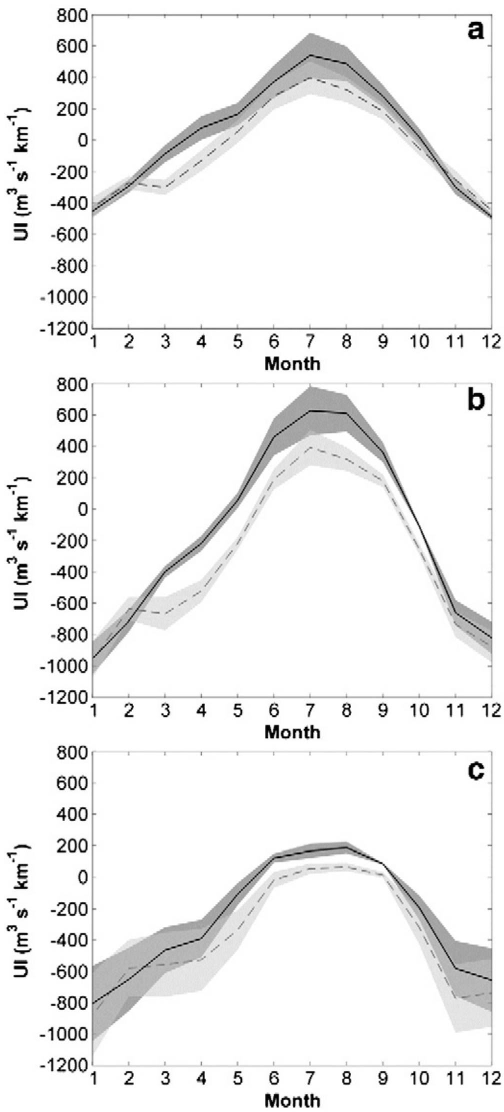

Fig. 5. Monthly evolution of the UI for the period 1961–1990 in light gray color and for the period 2061–2090 in dark gray color. Rias Baixas (a), Fisterra-Bares (b) and Cantabric coast (c). The mean UI (solid and dashed line) and its standard deviation (shaded region) for each point are illustrated with the three RCMs driven by ECHAM5.

the west coast and middle coast of Galicia. The Cantabric coast values of upwelling will continue to be the lowest values, and therefore the phenomenon will remain less frequent than in the Atlantic Coast. These results are in agreement with the increase in North and Northeast situations observed by the end of the century during the summer in previous studies (Lorenzo et al., 2011). The results also show that the differences between the current climate and the future occur mainly in the period between April and September, which is the period of favorable upwelling. As was highlighted in the introduction this result is significant because upwelling supports a productive system with high socio-economic impacts, and the area under study has an important seafood production and developed fishing industry. This work shows the result of three RCMs driven by a GCM, but the uncertainty of projected wind changes is relatively high. In this way projections made by other RCMs in the future must be studied to confirm this result. Moreover to study the socio-economical impacts other factors may be relevant, such as the characteristics of upwelled water that can also vary in the future.

Acknowledgments

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