

## Importance of the mesoscale in the decadal changes observed in the northern Canary upwelling system

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Received 10 August 2009; revised 17 September 2009; accepted 21 October 2009; published 19 November 2009.

[1] Analysis of sea surface temperature (SST) time series since 1960 from existing data bases shows a generalized warming trend in the northern Canary upwelling system. The field of the satellite-derived SST trends off Western Iberia was built at the pixel scale ( $4 \times 4$  km) for the period 1985–2008, revealing significant spatial differences in the warming rates. Weaker warming trends fit to the known upwelling pattern off the southern part of the Western Iberia, pointing out the intensification of this feature since 1985, particularly during the peak summer months. A more regular behavior is found further north suggesting significant decadal changes in the mesoscale patterns of the northern Canary upwelling system. **Citation:** Relvas, P., J. Luís, and A. M. P. Santos (2009), Importance of the mesoscale in the decadal changes observed in the northern Canary upwelling system, *Geophys. Res. Lett.*, 36, L22601, doi:10.1029/2009GL040504.

### 1. Introduction

[2] The Western Iberia (WI) constitutes the northern limb of the Canary Current Upwelling System (CCUS), one of the four Eastern Boundary Upwelling Systems of the world ocean. The strong dynamic link between the atmosphere and the ocean makes these systems highly sensitive to global change, ideal to monitor and investigate its effects. A distinctive characteristic of the CCUS is the discontinuity imposed by the Mediterranean entrance that separates the North African from the Iberian segment, where the upwelling regime has a seasonal prevalence, roughly from April to October. The circulation in the Coastal Transition Zone (CTZ) off WI is characterized by a southward surface flow of cold upwelled water associated with the summer upwelling regime and a generalized northward flow during the winter [Fiúza *et al.*, 1982].

[3] Recent works suggest that at the synoptic scale the climatological pattern is modulated by mesoscale processes that dominate the oceanography off the WI [Relvas *et al.*, 2007]. Some mesoscale features are recurrent and identified in the literature, such as the Iberian poleward current, warm coastal counter-currents, buoyant plumes [Peliz *et al.*, 2005], or features associated with the upwelling pattern, like filaments rooted in the main capes [Haynes *et al.*, 1993]. Others have a more erratic behaviour, such as the offshore eddy field and the meanders that result from their interaction with the upwelling front.

[4] There is the perception that a warming trend is occurring in the Eastern North Atlantic as a whole [e.g., Casey and Cornillon, 2001] and in the coastal regions in particular [e.g., Lemos and Sansó, 2006] and some consequences, as a northern distribution of more tropical fish species, were already observed in the NE Atlantic coasts [e.g., Brander *et al.*, 2003]. Decadal shifts in upwelling intensity were already described for the CCUS and their consequences for the fluctuations in small pelagic fish productivity [e.g., Santos *et al.*, 2005]. This large-scale variability at decadal scales is of the most importance for marine ecosystems since it can reorganize communities and trophic relationships.

[5] The question addressed in this research is: How does the WI upwelling system respond to the basin scale warming observed during the past decades? To answer to this question we use available time series of sea surface temperature (SST). Emphasis will be given to satellite SST observations because they are the most suitable data for mesoscale analysis due to their good time-space resolution and are long enough to attempt the analysis of long term changes.

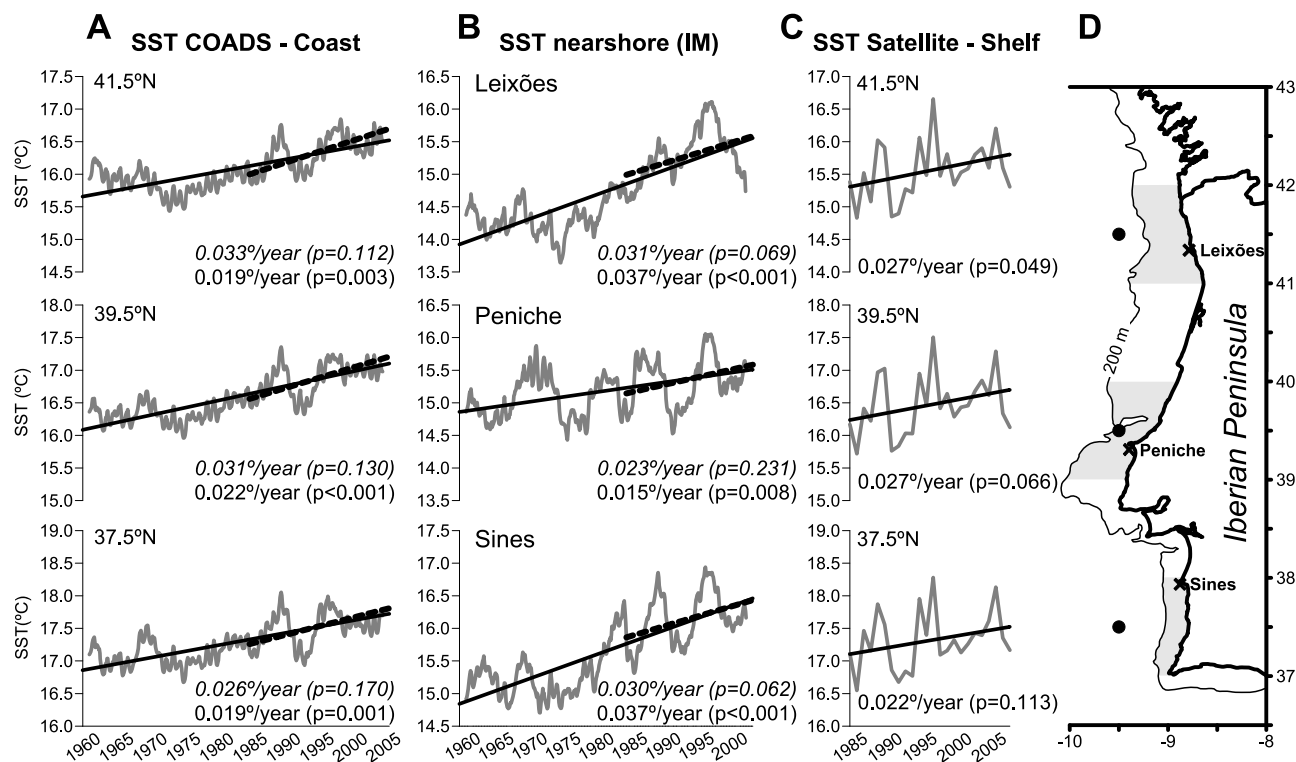
### 2. Data and Processing

[6] Three independent sources of observed SST were analyzed: a) monthly mean SST for the period 1960–2005 from the one degree enhanced International Comprehensive Ocean-Atmosphere Data Set (ICOADS), b) monthly mean near-shore temperatures for the period 1960–2003, collected daily from the seashore by the Portuguese Meteorological Office (IM), and c) monthly mean SST data from the Advanced Very High Resolution Radiometer (AVHRR) on board NOAA series satellites, with a spatial resolution of  $4 \times 4$  km, provided by the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the Jet Propulsion Laboratory. SST estimates were derived from the Pathfinder Version 5 algorithms, extending from 1985 up to 2008. The time series were limited to the nighttime passes to avoid the solar heating effect.

[7] Based on a hierarchical suite of tests, Pathfinder V5 Project provides a quality flag assigned to each SST pixel that varies from 0 to 7, with the latter being the highest quality. We did use only SST values with quality 6 and 7, as they are the most appropriate for quantitative climate analysis [Kilpatrick *et al.*, 2001]. However, this procedure creates voids on the SST grids on the node positions corresponding to the rejected values. The voids, originated primarily on weather conditions of strong cloud cover and fogs, are located on variable positions on the grids depending on the month the grid refers to. This is particular evident on the winter months where large areas of the ocean did not have any reliable measure, even on a monthly average.

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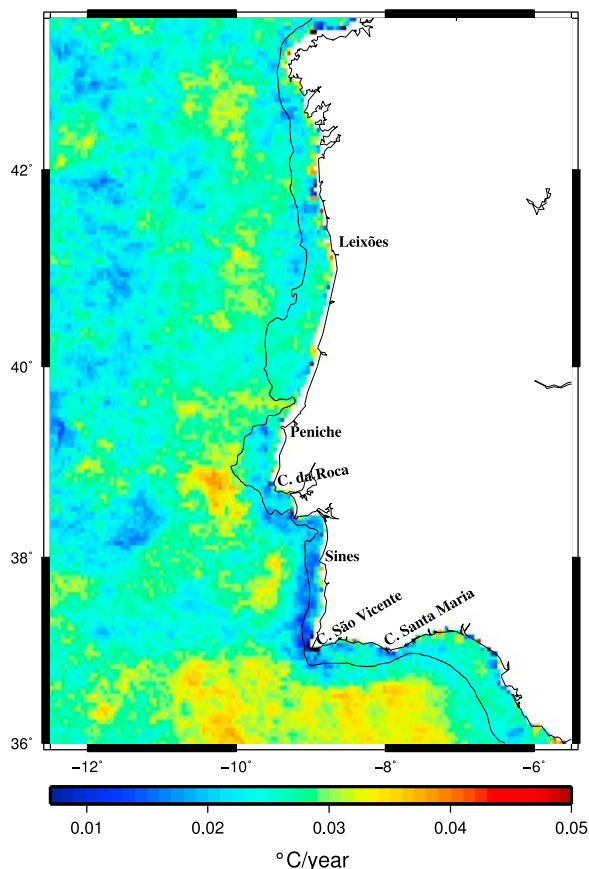
**Figure 1.** (a) Monthly mean SST time series from ICOADS data for the period 1960–2005. Data correspond to gridded cells of  $1^\circ \times 1^\circ$ , whose central points are  $9.5^\circ\text{W}$  of longitude and, top to bottom,  $41.5^\circ\text{N}$ ,  $39.5^\circ\text{N}$ ,  $37.5^\circ\text{N}$  of latitude. Running means spanning 25 months are displayed (grey lines), along with linear fits for the whole time series (solid lines) and for the 1985–2005 period (dashed lines). (b) Monthly mean SST measured directly from the seashore at three sites on the Portuguese coast, for the period 1960–2003. Top to bottom: Leixões ( $41.3^\circ\text{N}$ ), Peniche ( $39.3^\circ\text{N}$ ) and Sines ( $37.9^\circ\text{N}$ ). Running means spanning 25 months are displayed (grey lines), along with linear fits for the whole time series (solid lines) and for the 1985–2003 period (dashed lines). (c) Monthly mean satellite AVHRR SST for the period 1985–2008 and corresponding linear fits, averaged zonally from the coast offshore till the 200 meters isobath and meridionally at  $1^\circ$  latitude, centered at three latitudes along the western coast, top to bottom,  $41.5^\circ\text{N}$ ,  $39.5^\circ\text{N}$  and  $37.5^\circ\text{N}$  (grey lines). (d) Map of the Western Iberia coast, showing the location of the central points of the  $1^\circ \times 1^\circ$  ICOADS cells (dots) and the coastal sites: Leixões, Peniche, and Sines (crosses). The 200 meters isobath is shown. Gray shading represents the regions where the satellite AVHRR SST was spatially averaged. Numerical values of the trends are indicated along with the corresponding  $p$ -values (italic for the shorter time series).

[8] Our strategy to fill data gaps followed a two steps procedure. First we filled only the gaps with a number of cells smaller than 200, since the temperature is a relatively smoothly varying parameter and one can safely interpolate the small data holes. We used the minimum curvature interpolation algorithm as implemented in the Generic Mapping Tools (GMT) surface program [Smith and Wessel, 1990]. However, the interpolation still left areas with no data, particularly on winter months grids. Although one can compute averages by taking into account where the voids are, they are biased towards the seasonally more abundant summer data, when the sky is considerably clear. To overcome this difficulty we made a second interpolation, now in the time direction. We took the whole data set, the 12 month  $\times$  23 years, and stacked them in a 3D grid with the third dimension corresponding to the time. Next, for each cell, a spline interpolation was used to fill in the missing data. By doing so along the stacked grid we assured that seasonal temperature variation, roughly with a sinusoidal shape, was preserved on the interpolation scheme. This way, though based on variable number of interpolated values depending

on the geographical location, we guarantee that the annual and seasonal averages are not biased towards summer temperatures. All these numerical procedures were carried out in MATLAB within the Mirone suite [Luís, 2007].

### 3. Results

[9] A generalized warming trend is detected in the coastal waters off WI during the last decades, no matter which data set we analyse (Figure 1). SST trends from three different sources, at roughly concurring sites, are compared: a) monthly mean ICOADS SST time series, from 1960 till 2005, at three locations along the WI, in which a separate analysis is done for the period 1985–2005 to allow comparisons with the SST satellite data, b) time series of monthly mean SST, measured directly from the seashore between 1960 and 2003, at three sites along the Portuguese coast (Leixões, Peniche and Sines), in which an analysis for the period 1985–2003 is done too, and c) time series of monthly mean satellite AVHRR SST, spatially averaged over the continental shelf (roughly the 200 meters isobath corresponds to the shelf break) at 1 degree of latitude, centered at the three ICOADS



**Figure 2.** Image of the coastal ocean off the Western Iberia showing the SST trend, in  $^{\circ}\text{C}/\text{year}$ , from 1985 till 2008. The p-values were typically below 0.10 in more than 90% of the domain and above 0.50 in the dark blue upwelling region off SW Iberia. The 200 m isobath is represented.

latitudes. Refer to Figure 1 caption for extra explanation on the time series presentation.

[10] All the three independent SST data series show consistent positive trends, ranging from  $0.015^{\circ}\text{C}/\text{year}$  to  $0.037^{\circ}\text{C}/\text{year}$  for the period starting in 1960, or from  $0.022^{\circ}\text{C}/\text{year}$  to  $0.033^{\circ}\text{C}/\text{year}$  if the time series start in 1985, including here the satellite SST time series. Although the different nature and geographic areas covered by each SST data set, the overall trend indicates a generalized warming of a few hundredth of degree a year. The point now is to understand the effects of this positive SST trend on the coastal and upwelling patterns off WI.

[11] To meet this goal a robust linear fit was applied to each individual pixel, crossing along the time the same  $4 \times 4$  km pixel in all the processed monthly mean AVHRR SST images from 1985 until 2008. Figure 2 was created upon the slopes of the linear fits applied to each pixel, in a way that the value associated to each pixel represents the SST trend from 1985 to 2008 in  $^{\circ}\text{C}/\text{year}$ .

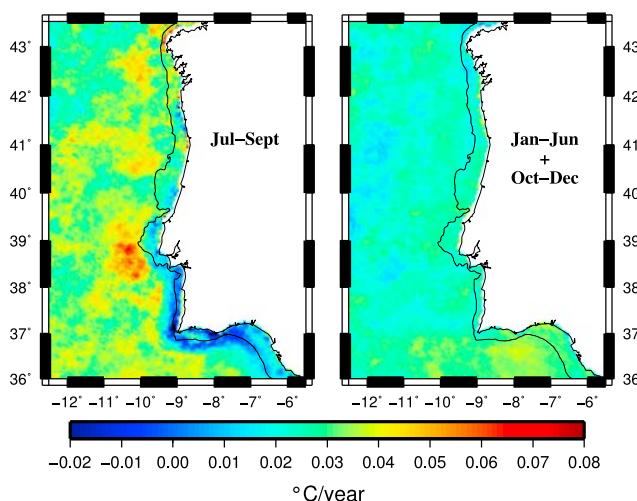
[12] The field of the SST trends reveals regions with clear contrasting warming trends (Figure 2). In general we can discern that the coastal ocean off WI experienced the stronger warming in the central part, roughly between  $39\text{--}41^{\circ}\text{N}$ , and the weaker warming in the southern part, while an intermediate warming trend occurred in the northern part. Offshore, alternate patches of stronger and weaker warming are observed.

[13] Off the central and northern part of the WI, none of the characteristic structures of the coastal upwelling can be distinguished by their contrasting warming trend. Remarkably, off the southern part, the known upwelling pattern and associated features [Relvas and Barton, 2002] is clearly reflected in the warming field. Coastal waters upwelled south of Cape da Roca (approx.  $39^{\circ}\text{N}$ ) show a weak warming trend when compared with the offshore waters, pointing out an enhancement of the thermal contrast at the upwelling front and the intensification of the equatorward upwelling jet that turns cyclonic into the Gulf of Cadiz at the discontinuity imposed by the Cape São Vicente. A signal of weaker warming trend is also seen associated to the upwelling filament recurrently observed at the Cape São Vicente and stretching west into the open ocean [Sánchez et al., 2008]. Off the northern margin of the Gulf of Cadiz, west of Cape Santa Maria, the zone corresponding to the inshore warm counter-current that develops towards the Cape São Vicente [Relvas and Barton, 2005] shows a stronger warming trend, an indication of an increasing contrast with the upwelled water intruded from the west coast.

[14] If we assume that the SST contrast between coastal and offshore waters is a proxy for the upwelling intensity, then the result presented here shows that the upwelling regime off SW Iberia have experienced an intensification since 1985. However, the same conclusion is not clear for the coastal upwelling region further north. An analysis done on a monthly basis reveals that the peak months of the upwelling season (July to September) are the responsible for the coherent upwelling pattern observed off SW Iberia (Figure 3). Thus, the enhanced upwelling feature off SW Iberia shall be restricted to the central months of the classical upwelling season.

#### 4. Discussion and Conclusions

[15] Previous investigations have reached contradictory results about the temporal fluctuations of the upwelling in



**Figure 3.** Image of the coastal ocean off the Western Iberia showing the SST trend, in  $^{\circ}\text{C}/\text{year}$ , from 1985 till 2008, (left) considering only July, August and September, and (right) the remainder of the year. The 200 m isobath is represented.

the Canary Current Upwelling System during the last decades. Some authors found evidences of an intensification of coastal upwelling [Dickson *et al.*, 1988; Bakun, 1990; Santos *et al.*, 2005; McGregor *et al.*, 2007] but others a decrease [Lavin *et al.*, 2000; Lemos and Pires, 2004; Lemos and Sansó, 2006]. However, these different analyses used time series of different periods, lengths and sources, demanding for further studies. Our present results point out that the mesoscale activity, inherent to the coastal domain, can induce large changes in local SST that are not reflected in regional average trends. In Eastern Boundary Upwelling Systems, where mesoscale structures play a major role in the description of the upwelling regime, to rely on sparse spatial observations to hypothesize about the decadal behaviour of the upwelling intensity at the basin scale may be questionable. Also, the existence of an intense mesoscale field, with long time scales of variability, greatly complicates the efforts to discern long time scales shifts at the basin-wide scale [Wunsch, 2008].

[16] The conclusions of the present investigation can be outlined as follows:

[17] 1. A generalized warming of a few hundredth of degree a year is observed off Western Iberia during the last decades, no matter which data base we analyze.

[18] 2. The global warming affects the coastal ocean of Western Iberia, but the response is not spatially uniform. Different mesoscale features respond to the raise of the temperature in different ways.

[19] 3. The upwelling pattern off the southern part of the Western Iberian Peninsula underwent a substantial intensification since 1985, contrasting with a more regular behaviour further north. The intensification is particularly evident during the peak summer months (July to September).

[20] **Acknowledgments.** This is a contribution to the NoE EUR-OCEANS, GLOBEC and CLIBECO (FCT POCI/CLI/57752/2004).

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