Climatological space and time variation of the Portuguese coastal upwelling

Upwelling
Portugal
Coastal winds
Sea surface temperature
Sardine

Upwelling
Portugal
Vents côtiers
Température de surface de la mer
Sardine

A. F. de G. Fiúza, M. E. de Macedo, M. R. Guerreiro
Oceanography Group, Department of Physics/Geophysical Centre, Faculty of Sciences, University of Lisbon, Rua da Escola Politécnica, 58, 1200 Lisbon, Portugal.

Received 21/5/81, in revised form 22/6/81, accepted 5/7/81.

ABSTRACT

In order to establish the climatic framework of coastal upwelling off Portugal, an analysis is made of monthly averages (30 years) of winds measured at Portuguese coastal stations and of sea surface temperatures (SST) taken from an atlas of the North Atlantic. The spatial resolution is 1° latitude for the SST and 50-100 km for winds. The monthly regime of the winds is strongly dependent on the evolution of the atmospheric circulation on regional scales, being related with the latitudinal migration of the subtropical front and with the dynamics of the Azores anticyclonic cell. It is concluded that upwelling, as indicated by the deviations of the SST at the coast relatively to the central North Atlantic, migrates seasonaly from the south of Morocco to the north of Portugal, with very well defined maxima off the west Portuguese coast in July, August and September. The average regime of the upwelling favourable northerly winds also presents a summer maximum but 1 month out of phase relative to the temperature anomalies.

Employing monthly averages of winds and SST measured at Portuguese coastal stations during 1959-1969, a study is also made of the year to year upwelling variations. The monthly anomalies of the coastal SST relative to a station at the Azores are well correlated with the stress of the north wind, their maxima occurring again generally one month after the maxima of the favourable winds. The interannual variability of these upwelling indices is small during the summer but high in winter. Monthly averages of this 11 years series are close to the climatological values (30 years means) for the winds but indicate some differences in the case of the thermal anomalies, the reason for these lying in the differences between the time and space scales of the data bases used in each case.

Using statistics of sardine landings at Portuguese fishing ports, relative to the period 1939-1974, it is found that the monthly average catches are strongly correlated with the climatological upwelling indices, with maxima occurring 2 months after the maxima SST anomalies and 3 months after the north wind maxima.

Oceanol. Acta, 1982, **5**, 1, 31-40.

RÉSUMÉ

Variation spatio-temporelle de l'upwelling portugais à l'échelle climatologique

Afin d'établir le cadre climatique de l'upwelling côtier du Portugal, on analyse des moyennes mensuelles (30 ans) des vents des stations côtières portugaises et de la température de surface de la mer (TSM) d'un atlas de l'Atlantique Nord. La résolution spatiale est de 1° de latitude pour la TSM et de 50-100 km pour le vent. Le régime mensuel des vents dépend étroitement de l'évolution de la circulation générale de l'atmosphère, particulièrement de la migration latitudinale du front subtropical et de la

dynamique de la cellule anticyclonique des Açores. On conclut que l'upwelling climatique, indiqué par les écarts entre la TSM sur la côte et au milieu de l'Atlantique Nord a une migration saisonnière dès le sud du Maroc jusqu'au nord du Portugal avec des maximums bien définis au large du Portugal en juillet, août et septembre. Le régime moyen du vent du Nord (favorable à l'upwelling) présente aussi un maximum en été, mais celui-ci est déphasé de 1 mois relativement aux anomalies thermiques.
En utilisant des moyennes mensuelles des vents et des TSM mesurés sur la côte portugaise pendant la période 1959-1969, on a aussi étudié la variation interannuelle de ces indicateurs d'upwelling. Les anomalies mensuelles des TSM côtières relativement aux mesures obtenues dans la station de Flores (Açores) sont correlées avec la tension du vent du Nord, et présentent aussi des maximums 1 mois après les maximums des vents favorables. La variation interannuelle de ces indicateurs d'upwelling est réduite pendant l'été, mais atteint des amplitudes considérables en hiver. Les moyennes mensuelles obtenues de la série de 11 années sont très proches des moyennes climatologiques (30 ans) dans le cas du vent, mais elles présentent quelques écarts pour les anomalies thermiques. Cette divergence est due aux différences entre les échelles de temps et d'espace utilisées dans chaque cas.
Avec des statistiques des débarquements de sardine dans les ports de pêche portugais, relatives à la période 1939-1974, on a trouvé de fortes corrélations entre les captures mensuelles moyennes et les indicateurs climatologiques d'upwelling analysés. Les captures atteignent leurs maximums 2 mois après les anomalies thermiques extrêmes et 3 mois après les maximums du vent du Nord.

Oceanol. Acta, 1982, **5**, 1, 31-40.

INTRODUCTION

A study of coastal winds and sea temperatures as indicators of the Portuguese coastal upwelling is presented here for large space-time scales. Climatological time series are used together with space scales comprised between the mesoscale (10-100 km) and the regional scale 0(1 000 km).

In what concerns the wind influence on coastal upwelling, the main point here will be to characterize the wind component along the coast since, in the light of the elementary theory of Ekman (1905), it is the responsible for the existence of one-sided coastal divergence or convergence. According to this theory, there will be divergence at the eastern coast of an ocean (i. e., upwelling of cool subsurface waters) if the wind stress acting on the sea surface is oriented towards the equator, and convergence (i. e., downwelling) if the stress is polewards.

Another useful index for upwelling intensity is the nearshore sea surface temperature or, even better, the difference between this temperature and that observed offshore, in relatively stable areas such as those along the meridional axes of the large oceans at mid-latitudes.

The aim of this report is the establishment of a general framework of the Portuguese coastal upwelling and for that purpose it is convenient to use time scales that filter synoptic variability (a few days) but keep seasonal and annual fluctuations and for which the data are in an easily available form. As the period of one month satisfies these requisites, monthly means of the pertinent parameters will be extensively used here.

THE SURFACE WIND FIELD

Regional setting

The geographical location of Portugal determines the large scale features of the wind climate along its coast. The west coast extends along the 9°W meridian between 37°N and 42°N (Fig. 1). The south coast (Algarve) is oriented along 37°N, between 7°20′W and 9°W. Portugal is thus located in the northern part of the climatic subtropical high pressure belt of the northern hemisphere.

Crowe (1949) presented monthly charts with frequency isopleths of the trades based on climatological means of winds (> 30 years) measured at sea by British ships and relative to Marsden squares. These charts show, besides a seasonal latitudinal migration *cum sole* of the maxima of these frequencies, a typical "root" structure to the eastern side of the oceans (Fig. 1, inset). This

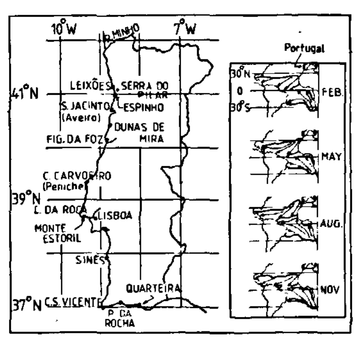

Figure 1

Distribution of Portuguese meteorological coastal stations. Inset: examples of the limits of the areas covered by the trade winds over the Atlantic Ocean as given by the 50% wind direction constancy isopleths (adapted from Crowe, 1949).

feature has a close connection with the continental masses existing there and is more pronounced polewards during the summer in each hemisphere. According to Crowe, this phenomenon of the meridional extension of the trades in the vicinity of the eastern coasts of the large oceans has long been known by North Atlantic navigators who, significantly, called them "Portuguese trades".

Another classical work with interest in this context is that of Chase (1956) where climatic charts (40 years averages) are presented of the atmospheric surface pressure distributions in the North Atlantic for the months of January, April, July and October. At the climatic scale, the pressure field is dominated by the Azores anticyclone and, to a smaller extent, by the Iceland low. From March to August, the anticyclone centre moves along the 38°W meridian from 27°N to 33°N, respectively. From November to February it moves eastwards from 38°W and reaches 23°W in January, as a consequence of the relative increase of the winter high pressures located over Europe and Africa. Besides the pressure contrast between the centre of the anticyclone and its European edge (Portugal) being larger in summer ($\simeq$ 8 mb) than in winter ($\simeq$ 1 mb), the pressure at its centre is higher in summer (1 027.5 mb) than in winter (1 023 mb). Therefore, the atmospheric current carried in the circulation of the Azores climatic anticyclone corresponds, in the Portugal area, to weak mean W winds in winter (as the strong synoptic perturbations are filtered out) and to relatively strong mean N and NW winds during the summer.

In a study on the seasonal cycle of the upwelling along the eastern margin of the North Atlantic between 7°N and 44°N, Wooster *et al.* (1976) used wind observations over the sea for the period 1850-1970 to compute the alongshore wind stress on the ocean (τ) and, from it, the Ekman transport (τ/f, where f is the Coriolis parameter) perpendicular to the coastline. From their distributions of offshore Ekman transports it can be concluded that: 1) south of Cape Verde the wind blows southeastwards in winter and northeastwards in spring and summer; 2) from Cape Verde to the Canary Islands the maxima of the N-NE winds (dominant all year round) occur progressively later in the year reaching Cape Blanc (21°N) at the beginning of spring and the Canary at the end; 3) from the Canary to northern Portugal there are north wind maxima during the summer, while at the north of Portugal and Galicia south mean winds occur during autumn and winter.

From the detailed discussion of the climatic normals of several atmospheric parameters presented by Defant and Mörth (1978), one may conclude that the seasonal migration of upwelling favourable winds along the North Atlantic eastern coasts is related to the meridional evolution of the subtropical front. In fact, this front, besides separating the tropical and the mid-latitude air masses, also corresponds to the transition between the planetary circulation regimes of the westerlies to the north and of the trades to the south, shifting from a mean position at 29°N, in January, to 35°N in April, 46° N in July, and 37°N in October. It is interesting to note that the position of the subtropical jet stream associated with the strong baroclinicity of this front follows closely the northern limit of the latitudinal belt of upwelling favourable winds indicated by Wooster *et al.* (1976), with an average displacement from 27°N in January on the Atlantic eastern margin (Canary) to about 43°N on the northern limit of the Portuguese coast in July.

Climatological means of Portuguese coastal winds

The wind regime along the Portuguese coast was analyzed using climatological averages (1931-1960) of the mean monthly values of speed and frequency of occurrence of the winds in each month, as published in *O Clima de Portugal* (Serviço Meteorológico Nacional, 1965). Normals from the following coastal meteorological stations (Fig. 1) were processed: Porto-Serra do Pilar, Aveiro-Barra, Dunas de Mira, Figueira da Foz, Cape Carvoeiro, Cape Roca, Monte Estoril, Lisboa and Cape São Vicente. From these data wind roses were drawn for each month with components along the main eight directions as well as their respective percentages. The corresponding vectorial mean, the "resultant wind", was also computed by using the trigonometric method of Brooks and Carruthers (1953).

The station of Dunas de Mira presented anomalously low wind speeds relatively to nearby stations because its anemometer is located at low height within a forested area. This station was therefore excluded from the subsequent analysis.

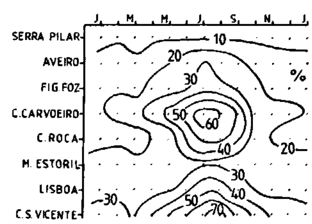

Figure 2
Isolines of the frequencies of wind from the north octant (climatological data, 1931-1960).

In order to obtain an idea of the regime of upwelling favourable winds along the west coast of Portugal and for evaluating the representativity of the coastal stations, the diagram of Figure 2 was drawn where frequencies of the wind from the north octant are represented. The stations Serra do Pilar, located in the river Douro valley (oriented E-W), and Monte Estoril, on a hillside facing the south, may not be very representative of north winds. The Lisbon station, within a large town, seems to have an intermediate representativeness. The annual variation of the percentages of upwelling favourable winds at the west coast of Portugal shows clearly a maximum (> 50%) from July to September (particularly southwards of Cape Carvoeiro, 39.3° N) which is in accordance with the previous references to the large scale phenomenology.

The annual variation of the sum of the percentages corresponding to the three octants with north wind components (NW, N and NE) are presented in Figure 3*a*. The general configuration of Figure 2 is maintained but the percentages show now higher values reaching almost 90% in July at the capes. Figure 3*b*

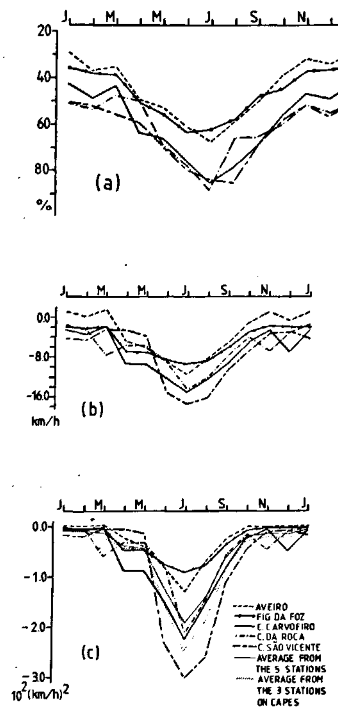

Figure 3

Climatological monthly winds (1931-1960) at Portuguese coastal stations: a) *sums of the frequencies of the winds from the NW, N and NE octants;* b) *N-S wind components (the minus sign indicates southward winds);* c) *N-S wind "stresses" (squared climatological N-S components).*

illustrates the evolution of the N-S component of the "resultant mean wind" for the more representative stations (in this report, values below the horizontal axis of zero velocities represent southward components). As can be seen, the speed of the north winds along the Portuguese coast also shows maxima from July to August, with an extreme in July. It is interesting to note a predominance of southerly components as the northernmost station (Aveiro) during autumn and winter, in remarkable agreement with the conclusions of Wooster *et al.* (1976).

These data were used for computing wind stresses which were employed as upwelling indices. An adequate approximation for calculating the wind stress from climatological data is the so-called bulk parameterization, represented by $|\vec{\tau}| = \rho_a C_D |\vec{c}| v$ (e.g., Halpern, 1976) where ρ_a is the air density, $\vec{c}$ the wind velocity vector, v the wind component along the direction of interest (N-S in this case) and C_D the drag coefficient. In the present case, the diversity of the instruments used, and of their exposure and location, makes unnecessary such a detailed computation. Wind roses constructed for these Portuguese coastal stations show that the N-S wind component (v) is generally much greater than the W-E component (u) and thus it will be sufficient to use the square of that component (v^2) for representing the meridional wind stress.

Squares of the N-S monthly means obtained at the more representative coastal stations were computed as well as averages relative to selected groups of stations (Fig. 3 *c*). The summer intensification of v^2 (with maxima in June, July and August) is very obvious, mainly along the southern half of the Portuguese west coast.

Excepting the northernmost station (Aveiro), to which coastal convergence corresponds during winter and autumn, the mean winds always imply more or less pronounced situations of coastal divergence (upwelling).

Interannual variation of mean monthly winds

A more detailed investigation of the mean wind field along the west coast of Portugal will now be carried out with an analysis of the data relative to the 11 years period 1959-1969 (Yearbooks of the "Serviço Meteorológico Nacional", Lisbon). This period was chosen as it is the same for which there are also available monthly mean values of sea surface temperatures measured at several places at the Portuguese coast, which will be used below in the computation of another upwelling index.

In these Yearbooks the only coastal stations with meaningful wind data are those at Cape Carvoeiro (Peniche) and at Cape Roca which are very close to each other (Fig. 1). Since the climatological values previously analyzed indicate that the wind data from Cape Carvoeiro are more representative (Fig. 3 *b* and *c*), only this station is used in the following. The monthly mean

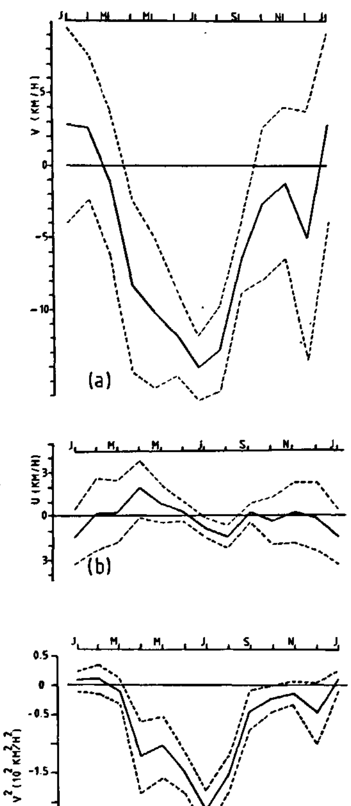

Figure 4

Statistics of monthly mean winds at Cape Carvoeiro for the period 1959-1969 *(averages are represented by full lines, standard deviations by dashed lines):* a) *N-S wind components;* b) *W-E wind components;* c) *N-S wind "stresses".*

intensities and frequencies were processed and wind vectors were obtained for each month of the 11 years 1959-1969 period. Graphical representations (not shown) of the time series of N-S and W-E components of these resultant winds lead to some conclusions with interest: 1) the mean monthly meridional component is generally southwards, except in winter when it is frequently northwards, with considerable higher maxima ($\simeq$16 km/h) in summer; 2) the zonal component is very reduced (0-2 km/h) in the summer months but in winter it reaches the same order of magnitude as the N-S component (4-8 km/h); 3) westerlies are dominant from November to February, although easterlies prevail sometimes.

In order to quantify the interannual variability, monthly means and their corresponding standard deviations were calculated for the eleven years series. Despite the low significance of these second order moments as they refer to a short series, the results obtained (Fig. 4*a* and *b*) show reasonable internal consistency.

The averages of the N-S components (Fig. 4*a*) are extremely similar to the climatological means (30 years) of Figure 3*b*; their standard deviations present minima in summer and maxima in winter, in agreement with the evolution of the meteorological systems prevailing in these seasons over Portugal: westerly perturbed currents in winter and northerly semipermanent circulation associated with the eastern margin of the Azores anticyclone, in summer. The means of the E-W components (Fig. 4*b*) show values generally nearly zero, and their respective standard deviations have a much larger relative importance than in case of the N-S components, also with summer values rather lower than those observed in winter.

In view of the large preponderance of the mean meridional wind component (v) over the zonal component (u) at Cape Carvoeiro, the N-S wind stress may also be approximated here by v^2. From the time series of the squares of the averages of the monthly mean values of v from January 1959 to December 1969 (not shown) it was concluded that maxima of upwelling favourable wind "stresses" occur from once to twice a year during that period. These are generally stronger from May to August with the largest amplitudes in July and August (higher values were measured in 1960-1963 and 1965-1967). However, in some years (1963, 1964, 1965 and 1969) an early maximum occurs in the spring, in April or May. In some cases, maxima are also observed in December (1959, 1960, 1967 and 1969).

The means of v^2 relative to the 11 years series and their standard deviations were also computed (Fig. 4*c*). The progression of the mean values for the 11 years is very similar to that of the climatological values represented in Figure 3*c*. The means of v^2 in Figure 4*c* show an upwelling favourable absolute summer maximum (June-August) and also secondary maxima in April and in December. In January and February small northward resultants do occur. The standard deviations are largest in April, May and December. Relatively to the magnitudes of the mean values of v^2, the deviations are less important in the summer than in the other months.

THE SEA SURFACE TEMPERATURE

Evolution of SST at the regional scale along the eastern edge of the North Atlantic

Essentially two approaches have been used for the utilization of SST as an upwelling index. One consists in analyzing the results of oceanographic cruises conducted in the area of interest and the other in studying climatological data obtained from observations of merchant vessels. The first was used for characterizing systematically the evolution of upwelling along the NW coast of Africa by Schemainda and Nehring (1974) and by Schemainda *et al.* (1975), and the second has been employed, for the same area, by Speth *et al.* (1978) and, for the whole coast of the NE Atlantic between 7°N and 44°N, by Wooster *et al.* (1976).

Schemainda and his collaborators used the results of several cruises in the upwelling area off NW Africa to investigate the seasonal evolution of upwelling between 8°N and 27°N and concluded that the coastal strip affected by this phenomenon is limited in the south by a boundary coinciding with the southern edge of the NE trades belt, moving from 9-10°S in February to 20-21°N in August. They also suggested that the northern limit of this upwelling region is related to the northern margin of the trades which they considered to reach 25°N in February and 33°N in August. This is not very correct since, as was seen above, these upwelling favourable winds reach much higher latitudes in summer.

Wooster *et al.* (1976), used 120 years (1850-1970) of SST observations near the coast and values from climatological tables relative to the central Atlantic for computing the deviations of coastal temperatures relative to ocean temperatures. They concluded that there is a permanent meridional strip of relatively strong coastal upwelling (anomalies over -3.5°C) with an extension of about 15° latitude, which migrates from 10-25°N in February-March to 21-32°N in August. Between 32°N and 37°N (Mogador and Cape São Vicente, respectively) nearshore temperatures are always lower than in the open ocean with a maximum deficit of about -2.5°C between June and October; along the Portuguese coast (37°N to 34°N) the deficit is much larger during these months, exceeding -4.5°C from July to September to the south of Figueira da Foz (40°N) with a maximum of more than -5.5°C off Lisbon, in August. Wooster *et al.* (1976) also concluded that the patterns of the seasonal variations observed in the fields of thermal anomalies and of longshore wind stresses are extremely similar, particularly off NW Africa between 20°N and 25°N and off the Portuguese coast, but generally slightly out of phase, the maximum stresses occurring 1 to 2 months before the anomaly extrema.

In a study aimed to finer time scales, Speth *et al.* (1978) used SST data along the NW African coast relative to consecutive blocks of 5 days, for the period 1968-1976. Using the same central Atlantic band as Wooster *et al.* (1976), but using data from oceanographic atlases, they also examined the seasonal variation of the coastal thermal anomalies and obtained essentially the same results. Speth and his collaborators included in their analysis surface atmospheric pressures inland and offshore, and used their differences as indicators of the strength of the atmospheric circulation along the coast. The fluctuations in these pressure differences and in the temperature anomalies are strongly correlated, 2.5 days out of phase, suggesting that the coastal ocean responds with upwelling "events" to favourable pulses of the wind within 2.5 days.

Marine thermal anomalies along the Portuguese coast at climatological scales

With the aim of analyzing the behaviour of coastal thermal anomalies as indices of the Portuguese upwelling, we conducted independently in 1975 a study similar to that made by Wooster *et al.* (1976). In this study we used climatological data extracted from the atlas "Monthly Sea Surface Temperatures of North Atlantic Ocean" (Meteorological Office, 1949). This atlas is composed of monthly charts with isotherms drawn from mean values taken over 1° "squares" relative basically to the periods 1887-1899 and 1921-1938. For reference temperatures, values along the 30°W meridian were chosen as at this longitude the mean isotherms present consistently a quasizonal orientation. Besides, this is approximately the longitude of the Azores archipelago, being thus advantageous for comparison with the analysis to be made below of the interannual variation of the anomalies of the temperature near the Portuguese coast relative to temperatures measured at an Azores station.

Our chosen spatial resolution was 1° latitude (nearly 111 km), from the NNW extremity of Galicia (43°30′N) to 31°N (South Morocco), in the southern limit of the charts in the atlas. The values of the temperatures were obtained by interpolation from the intersections of the isotherms with the coast or with the 30°W meridian, for each parallel at every degree of latitude.

Graphs (not shown) of the yearly variation of SST along the 30°W meridian present an yearly thermal wave typical of the central areas of subtropical oceans as well as a latitude effect. The corresponding SST curves along the coast have, during winter and autumn, a "normal" evolution and the latitudinal effect is clearly noticeable; however, after the beginning of spring and mainly in summer, the thermal wave appears truncated, even with inversions in the latitudinal sequence. The temperature values near the coast are always smaller than offshore, and this difference is frequently more pronounced in summer. This leads to the most remarkable feature of the graphs representing the anomalies $T_{coast} - T_{30°W}$ shown in Figure 5. On the Galician coast (43° and 43°30′N) the summer maximum does not take place, the anomaly lies between −0.5 and −2°C and an yearly minimum is actually observed in July at 43°30′N. Along the whole of the Portuguese coast, from the mouth of the Minho river (42°N) to Cape São Vicente (37°N), the anomaly has a band of very well defined maxima in July, August and September with values of more than −2.5°C and a maximum of −4.2°C off Sines (38°N) in August. South of São Vicente the summer maximum vanishes in the Gulf of Cadiz, only appearing again clearly at the latitudes of 31°N and 32°N, in September.

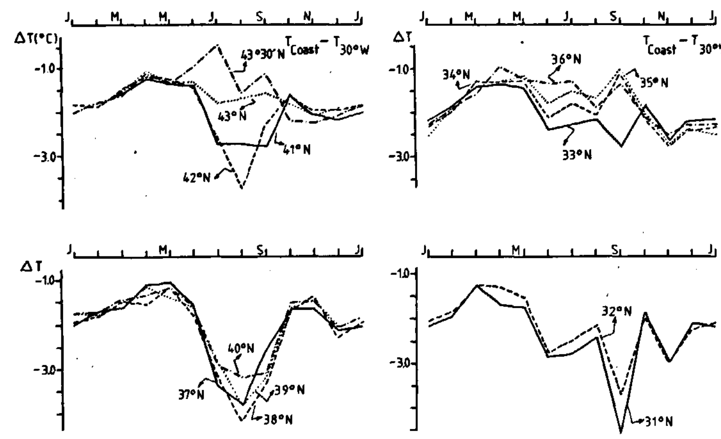

Figure 5
Climatological mean SST anomalies along the eastern coast of the North Atlantic.

Thus, the climatological SST anomalies indicate absence of upwelling northwards from the N Portuguese border and in the Gulf of Cadiz, and point to the occurrence of a pronounced seasonal upwelling regime along the western coast of Portugal in July, August and September, mainly in its southern half. Almost simultaneous transitions occur in the whole region, around March, from the winter regime (with a moderate secondary upwelling in December) to the spring minimum, and in June, from this to the yearly summer maximum. The summer-winter transition is generally less well defined except off Portugal where the average upwelling decays suddenly from September to October.

Considering the previous description of the wind field and of its evolution over the eastern shores of the North Atlantic and the configuration of these coasts (Fig. 1), the existence of strong correlations between upwelling and favourable wind components becomes obvious. During the summer, the Portuguese west coast is under a N wind regime. In the Galicia area this gives place to a mean westerly circulation. The same summer regime of north winds is generally maintained to the south, over the coasts of the Gulf of Cadiz (SW Iberian Peninsula and NW Morocco), as far as about 30°N, from where NE winds prevail. The orientation of the coast between Cape São Vicente and Mogador, first W-E, then NW-SE, and finally NE-SW, does not favour Ekman upwelling under north winds and this justifies its reduced intensity in that area. To the southern limit of the study area the coast is again oriented meridionally, favouring upwelling under N-NE winds.

The magnitude of the climatological thermal anomalies obtained here is about 1.5°C less during the summer than those of Wooster *et al.* (1976). Winter values, however, are similar. This disagreement may indicate a temporal variation in upwelling intensity as they used a much longer time series (120 years) than us (13+18 years). Strict comparison between both series would need an analysis of their data by the corresponding 10 years or 20 years segments. Apart from the quantitative summer deviation, both patterns show excellent qualitative agreement, the present results having perhaps a greater detail than in the paper by those authors, allowing, for instance, to a clearer spatial definition of the Portuguese coastal upwelling.

In order to get a quantitative idea of the relation on a climatological scale between wind and upwelling off the Portuguese coast, correlation coefficients were computed between the mean values of the N wind "stress" (approximated by v^2) and of the SST anomalies at the coast relative to 30°W (ΔT). First the correlation between the averages of the different monthly ΔT for the whole Portuguese coast and the corresponding averages of v^2 from coastal meteorological stations (Aveiro, Figueira da Foz, Cape Carvoeiro, Cape Roca and Cape São Vicente) was computed and the value 0.67 was obtained. Considering the possibility of a finite response time of the coastal ocean to the wind forcing, lagged correlations were also calculated, leading to the values: 0.84 for a 1 month lag, and 0.59 for a 2 months lag. These series were also correlated using only the wind observations at the capes, more exposed and so more representative for sea winds. The results were 0.69 and 0.91, respectively for non-lagged correlation and for a 1 month lag. The consistency of these results suggests that, at the scale of monthly climatological means, the upwelling regime off the Portuguese W coast is intimately dependent on the wind field, presenting, at that scale, a response time of 1 month. Obviously this applies on "seasonal" scales. Once the upwelling season becomes established, the oceanic response to favourable winds at synoptic time scales is rather fast, e. g., 2.5 days as found by Speth *et al.* (1978) for the semi-permanent upwelling off NW Africa, or 0 (1 day) off Portugal during the summer, from the personal experience of the present authors with airborne remote sensing of SST.

As sardine is a species associated with upwelling areas that lies at low levels of the trophic chains (being thus strongly dependent on the physical environment), an attempt was made to relate the abundance of the Portuguese race of *Sardina pilchardus* (Walbaum) with the upwelling indices under discussion. Using unpublished data on the catches of this species off the Portuguese coast in the period 1939-1974 (made available by the Portuguese State Bureau for Fisheries), average monthly percentages relative to the annual totals were calculated. A graph of the variation of these values is shown in Figure 6, together with curves of the mean ΔT for the

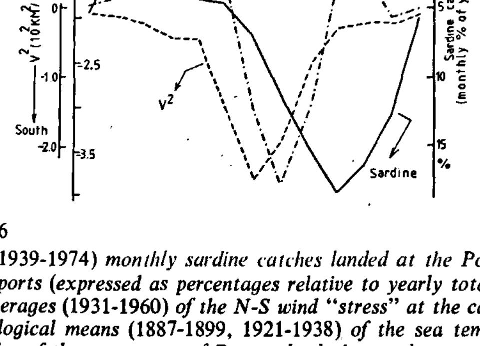

Figure 6

Mean (1939-1974) *monthly sardine catches landed at the Portuguese fishing ports* (*expressed as percentages relative to yearly totals*), *long term averages* (1931-1960) *of the N-S wind "stress" at the capes, and climatological means* (1887-1899, 1921-1938) *of the sea temperature anomalies of the west coast of Portugal relative to the central North Atlantic.*

Portuguese coast and of average of v^2 for the meteorological stations located on capes. The visual relation between these different curves is immediate and the following correlation coefficients were computed between the percentages of the sardine catch and ΔT: non-lagged, 0.34; with 1 month lag, 0.66; 2 months lag, 0.77; 3 months lag, 0.64.

In view of the relation between the series of v^2 and ΔT, the sardine percentages were also correlated with the "stresses" and a maximum coefficient of 0.91 was obtained for a 3 months lag.

These results are interesting as they allow, to a certain extent, to establish average cause and effect relationships between upwelling intensity (quantified either by the favourable wind intensity or by the thermal anomalies) and abundance of sardine off Portugal. The sequence: maximum of favourable winds (June, July, August), maximum of upwelling (July, August, September), maximum of sardine catch (September to November), is logical and quite understandable in the light of the simpler dynamics of the trophic web. Vertical advection due to the upwelling regime carries large quantities of nutrients to the euphotic zone and, in association with the mixing resulting from the high levels of turbulence induced by the relatively strong and steady northerly winds, provides optimum conditions for the phytoplankton bloom (primary production). If the upwelling rhythm is kept for sufficient time, the zooplankton bloom (secondary production) will take place, about 1 month later. As zooplankton seems to constitute the preferred part of the sardine diet (e. g., Cushing, 1978), the abundance of this species is thus justified.

Interannual variation of monthly thermal anomalies

In the Climatological Yearbooks of the Portuguese Meteorological Office relative the years 1959 to 1969, monthly means of daily measurements of sea temperature are listed for several stations on the west coast (Leixões, 41°10′N; Peniche-Cape Carvoeiro, 39°20′N; Sines, 38°N) and on the south coast (Praia da Rocha, 8°30′W, and Quarteira, 8°10′W), and also on the Azores (Santa Maria, Angra do Heroísmo, Ponta Delgada, and Santa Cruz das Flores) and Madeira (Funchal). These series were used for a study of the interannual variation of the SST upwelling index. The station of Funchal was excluded from the analysis as it is at a much lower latitude than the continental stations.

The data from the Azores stations were examined in order to evaluate their representativity as oceanic stations. For this purpose, graphs were drawn of the seasonal variation of these data which demonstrate that the station presenting larger amplitudes and more regularity, with a well-defined oceanic thermal wave, is that of Santa Cruz das Flores. This is not surprising as this station is located at a more exposed position than the others. Moreover, Flores is the westernmost of the Azores islands, closer to the North Atlantic central region. For these reasons, the station of Santa Cruz das Flores was chosen as representative of open ocean temperatures, far from the influence of the Portuguese coastal upwelling.

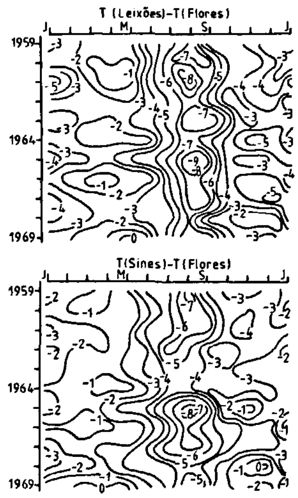

Figure 7
Evolution of the monthly mean SST anomalies at several stations at the west coast of Portugal during the period 1959-1969.

The temperatures from the stations in Algarve (Quarteira and Praia da Rocha) present an evolution almost of the same type as observed in the open ocean (Flores), whereas the series relative to the W coast of Portugal show much lower thermal amplitudes, always with smaller SST than those in the mid ocean, and this difference is even more pronounced in summer. An explanation for this temperature behaviour, besides the summer upwelling effect, may lie in the fact that the W Portuguese coast is under the direct influence of the eastern part of the large anticyclonic North Atlantic circulation – the Portugal Current – which advects colder water from higher latitudes. The zonal coast of Algarve is sheltered from this circulation and upwelling effects are felt there with much less intensity.

In order to evaluate upwelling intensities, SST differences (ΔT) between the continental stations and that of Flores were computed. At Praia da Rocha and Quarteira positive anomalies are observed, generally from March to June. This means that during these months the average SST in Algarve is generally higher than in the central North Atlantic. At the W coast, the effect of coastal upwelling is pronounced, thermal anomalies even reaching maxima of −8°C, generally in August, as can be seen in Figure 7. Stronger summer upwelling occurred in 1960-1961 and 1965-1967 clearly in consequence of maxima in the mean monthly favourable winds as measured at Cape Carvoeiro one or two months earlier. There is a band of annual ΔT minima in March-April, and zones of strong variation in May-June and September-October. Sporadic relative maxima of thermal anomalies in December and January (generally related to northerly wind maxima, e. g., January 1960, 1961, 1968) are noticed, indicating a secondary wind-induced upwelling during winter.

Similarly to what was done for the winds observed at Cape Carvoeiro in the period 1959-1969, means and standard deviations were also computed for the series of monthly SST values measured at the same location, and for their deviations relative to observations from the Flores station. The mean SST values (Fig. 8 *a*) measured at Peniche (Cape Carvoeiro) during this period present an annual amplitude of only 4.1°C in consequence of the summer upwelling; their standard deviations indicate stronger variability in the "transition" months: April-May and September. In what concerns the SST anomalies (Fig. 8 *b*), maxima annual values are reached from July to September and minima in April-May, a small relative maximum occurring in December-January. The standard deviations of the anomalies are higher than those of the SST at Peniche (as a matter of course since they refer to differences between two SST series, each with its own variability) and their magnitudes present a similar seasonal progression. Nevertheless, the relative importance of the fluctuations is much less emphasized in the summer than during the rest of the year.

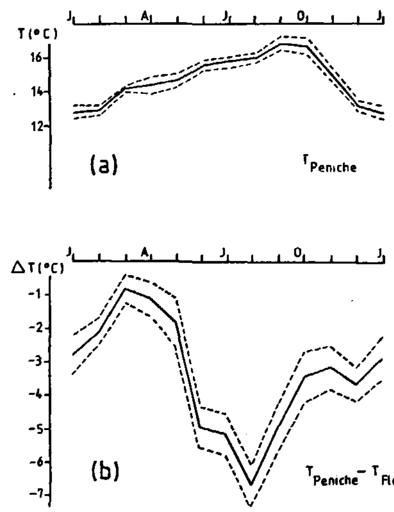

Figure 8
Monthly averages (1959-1969) *of:* a) *SST measured at Peniche;* b) *Peniche SST anomaly relative to Flores (Azores). The dashed lines represent the standard deviations.*

Comparison of the climatological SST with those from the period 1959-1969

Averages of the monthly mean SST anomalies relative to the Flores station and concerning the observations made at all the available stations during 1959-1969 are shown in Figure 9 *a*. The differences between the S coast stations and those on the W coast are very clearly illustrated here.

Figure 9 *b* shows the variation of the climatological means of ΔT (coast −30°W) obtained in this work. Comparing Figures 9 *a* and *b*, one concludes that our climatological values are generally lower and present smaller amplitudes than those from the eleven years average, although the course of both families of curves is qualitatively fairly similar (upwelling in the summer and in December, etc.). These differences may be due to smoothing effects resulting from the use of a larger number of years and of averages over 1° latitude × 1° longitude "squares" in the climatological computations; for instance the zonal gradients existing during the upwelling season are thus filtered, and so the climatic values should be less pronounced than those observed right at the coast.

The evolution of the average SST (1959-1969) for the coastal stations is shown in Figure 9 *c*. Their values are 1 to 2°C lower than those of the climatological means, probably because they refer to shallow coastal waters where the effects of summer upwelling and winter cooling are stronger than offshore.

Returning to Figure 9 *a*, it shows a latitudinal distribution of the upwelling intensity maximum inverse of the sequence found in the discussion of the climatological averages, which indicated stronger upwelling in the southern part of the Portuguese W coast. Considering that in the eleven years series only one station (Flores) at a single latitude (nearly that of Peniche) was used as reference for the calculation of the anomalies, it is concluded that a correction should be introduced in order to account for the different latitudes involved in the 1959-1969 anomalies. Therefore, taking the corresponding meridional gradients along 30°W, a correction was applied to the ΔT values relative to the stations of Leixões and Sines. The resulting sequence (Fig. 9 *d*) is more compatible with the climatological means, indicating that the average coastal upwelling regime seems to be more intense in the southern half of the W coast of Portugal.

Figure 9 *e* shows climatological thermal anomalies built with values extracted from the paper by Wooster *et al.* (1976). These are very similar to our climatological computations (Fig. 9 *b*) except for the already mentioned summer deviations of 1 to 1.5°C. Comparing the data in Figure 9 *e* with the 1959-1969 averages (Fig. 9 *d*), it can be seen that these climatological data also present a smaller amplitude than the 11 years series. Recalling the hypothesis advanced previously above about a possible climatic variation in upwelling intensity, if we take the 11 years average to be stable enough for comparison with the other longer term averages, the confrontation of Figures 9 *b* and 9 *e* suggests that upwelling may have undergone an intensification off Portugal since the beginning of the century.

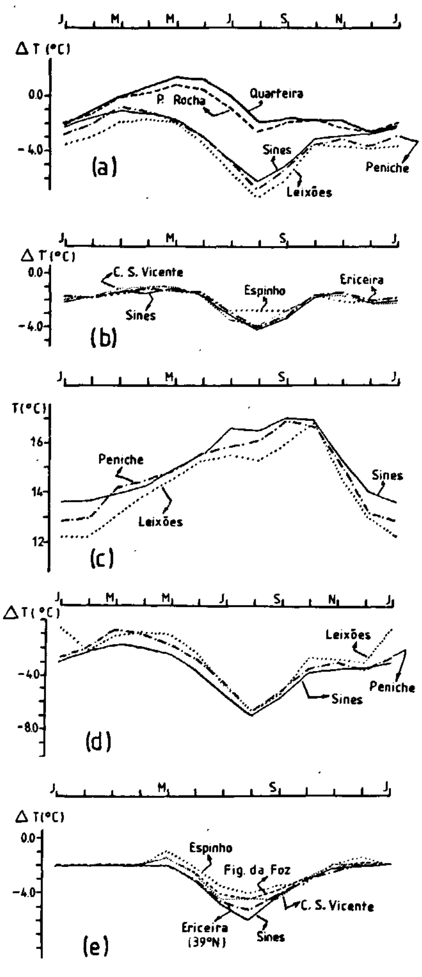

Figure 9

a) *averages of SST anomalies at Portuguese coastal stations relative to Flores (Azores) in the period* 1959-1969; b) *climatological means of Portuguese coastal SST anomalies relative to* 30° *W* (1887-1899, 1921-1938); c) *mean monthly SST at Portuguese coastal stations* (1959-1969); d) *averages of SST anomalies at the W coast of Portugal relative to Flores, corrected from the effect of latitude variation;* e) *climatological mean SST anomalies* (1850-1970) *near the Portuguese coast relative to the central area of the North Atlantic (adapted from Wooster* et al., 1976).

CONCLUSIONS

The average Portuguese coastal upwelling occurs from July to September in consequence of the increase in the intensity and steadiness of northerly winds in June, July and August, in connection with the dynamics of the Azores anticyclone and with the seasonal migration of the subtropical front.

Along the western coasts of Europe, average upwelling conditions are specifically restricted to the coast of Portugal, being more pronounced to the south of Cape Carvoeiro (39°20'N) with apparent intensity maxima in the coastal region of Sines (38°N). The climatological values of the SST anomalies (Fig. 5) seem to indicate a secondary maximum in August near the northern border of Portugal (42°N).

At the scale of monthly means, wind observations at Portuguese coastal meteorological stations and sea temperature measurements at exposed locations of the coast show mutual coherence in the light of wind-induced coastal Ekman divergence theory and seem representative of the atmosphere-coastal ocean boundary layer, comparing favourably with climatic results obtained with ship data analyzed by other authors and here.

SST values obtained at the Island of Flores (Azores) are fairly representative of the open ocean in the region where it is located.

The present analysis also points to the sporadic appearance of upwelling in December-January along the Portuguese coast, with smaller intensity than in the summer but also induced locally by favourable northerly winds. This pattern is strong enough to be noticeable in all the climatological averages of the upwelling indices looking thus as a seasonal feature. The average regime of coastal upwelling has, in this area of the North Atlantic eastern margin, an annual minimum between March and May, with a swift transition in June for the summer maximum which takes place in August.

The good correlation found between the evolution of the average sardine catch and the variation of the physical indices of upwelling off Portugal, confirms the importance of this phenomenon for the abundance of that component of the third trophic level.

Acknowledgements

This investigation was carried out as a part of the project "Dynamics and Hydrology of the Portuguese Coastal Waters" of the Oceanography Group, Geophysical Center of the University of Lisbon, and was supported by the Instituto Nacional de Investigação Científica (Portuguese National Institute for Scientific Research).

The authors are indebted to Dr. David Halpern for his comments on a preliminary version of this paper and to two referees who contributed for improving the clarity of the text.

REFERENCES

Brooks C.E.P., Carruthers N., 1953. *Handbook of statistical methods in meteorology*, Meteorological Office, Air Ministry, London.

Chase J., 1956. The Bermuda-Azores high pressure cell. Its surface wind circulation, in: *Miscelânea Geofísica*, 29-54, Serviço Meteorológico Nacional, Luanda.

Crowe P. R., 1949. The trade wind circulation of the world, *Transactions and Papers*, No. 15, Institute of British Geographers, 37-56.

Cushing D. H., 1978. Upper trophic levels in upwelling areas, *Upwelling ecosystems*, edited by R. Boje and M. Tomczak, Springer-Verlag, 101-110.

Defant F., Mörth H. T., 1978. *Compendium of Meteorology*, Vol. 1, Part 3, *Synoptic Meteorology*, World Meteorological Organization, Geneva, 276 p.

Ekman V. W., 1905. On the influence of the Earth's rotation on ocean-currents, *Arkiv for Matematik, Astronomi o. Fysik*, **2**, 11, 1-53.

Halpern D., 1976. Measurements of near-surface wind stress over an upwelling region near the Oregon coast, *J. Phys. Oceanogr.*, **6**, 1, 108-112.

Meteorological Office, 1949. *Monthly sea surface temperatures of North Atlantic Ocean*, Marine Branch, Meteorological Office, Air Ministry, London, 12 charts.

Schemainda R., Nehring D., 1974. Estimation of the mean duration of upwelling along the coast of NW Africa, International Council for the Exploration of the Sea, Hydrography Committee CM, 1974/C9, 8 p.

Schemainda R., Nehring D., Schulz S., 1975. Ozeanologische Untersuchungen zum Produktionspotential der Nordwestafrikanischen Wasserauftriebsregion 1970-1973, *Geod. Geoph. Veröff*, **R. IV**, H. 16.

Serviço Meteorológico Nacional, 1965. *O Clima de Portugal*, Fascículo XIII, Lisboa.

Serviço Meteorológico Nacional, 1959-1969. *Anuários climatológicos*, Lisboa.

Speth P., Detlefsen H., Sierts H. W., 1978. Meteorological influence on upwelling off Northwest Africa, *Dtsch. Hydrogr. Z.*, **31**, 3, 95-104.

Wooster W. S., Bakun A., McLain D. R., 1976. The seasonal upwelling cycle along the Eastern boundary of the North Atlantic, *J. Mar. Res.*, **34**, 2, 131-141.