

Water Mass Dynamics At The Northwest Iberian Margin

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1. INTRODUCTION

During the first year of OMEX II-II, the contribution of Instituto Hidrográfico, in the domain of physics (partner 8a), was aimed to understand some of the dynamical processes that are relevant on the northern Portuguese continental margin. This objective involved the two following studies:

- 1) Atmospherically forced low-frequency variability during the upwelling season - a process oriented study on this subject was carried through, based on the analysis of an extensive data set obtained by IH in 1987.
- 2) Winter dynamics and related SPM transport - this study used the observations made during the two winter cruises conducted by IH in the framework of OMEX II-II (CORVET 96 and CLIMA97 cruises).

The processes studied, not only play an important role in the ocean-margin exchanges off northern Portugal, but also affect the dynamics and sedimentary conditions of regions located further North. In that way, they must be viewed as part of the southern boundary conditions for the OMEX region off Vigo.

2. THE SUMMER (UPWELLING) REGIME OFF NORTHERN PORTUGAL.

2.1 Objectives

Some of the most extensive observations on the dynamics of the northern Portuguese margin were conducted during the summer and early fall of 1987, jointly by IH and IPIMAR. These observations included long-term current meter measurements, coastal wind measurements and hydrographic and biological surveys. They were part of a research program conducted, from 1986 to 1989, by the two institutions, aimed at the study of the physical and biological aspects of the Portuguese upwelling system.

The present work results from a re-analysis of the 1987 data with the objective of characterise the seasonal evolution of currents off northern Portugal and study of the wind-forced dynamics during the upwelling season.

2.2 Data and methods.

The physical program conducted by IH, during the summer and fall of 1987, focused the area between 39° 30'N and 42°N. This program included the deployment, in the first week of May, of three current meter moorings along a cross-shore section at latitude 41° 05'N (figure 1). The moorings were maintained until the end of October and included Aanderaa RCM-4 current meters at selected depths (see table 1 for details about moorings). Each current meter measured the current, temperature and conductivity with a 30 minute sampling rate. Some of the meters were also equipped with a pressure sensor which provides useful indications about eventual mooring motions. No contamination due to mooring motion was detected on the 1987 data set.

Coastal winds were measured in a weather station maintained by IH at Ferrel (39° 23'N). The meteorological observations cover the total period of current meter measurements, with a gap in the first week of July due to an intervention on the station. Meteorological data was obtained with an Aanderaa AWS/DL1 station, with 30 minutes sampling rate. Wind stress was calculated using a constant drag coefficient (1.2×10^{-3}). Using the data collected by Instituto Nacional de Meteorologia and Geofísica at Pedras Rubras (Porto), and published in its daily reports, was concluded that the measurements at Ferrel were fairly representatives of the meteorological conditions on the NW Portuguese coast.

Both current meter and meteorological time series were analysed for isolated errors, filtered with a low-pass Butterworth filter of order 7 and cut-off period of 2 hours and finally decimated to hourly values. Low-frequency (residual) time series were obtained by filtering the hourly time series with a low-pass Butterworth filter of order 7 and cut-off period of 35 hours. This period corresponds, for the

majority of the spectra of the time series, to an energy gap between the band of subinertial motions and the bands of quasi-inertial and tidal motions.

During the summer 87 IH promoted two hydrographic surveys, CECIR XII cruise (23 April to 11 May 1987), during which the moorings were deployed, and CECIR XIII cruise (10 to 28 August 87). In both surveys the hydrographic observations were made using a Neil Brown (NBIS) MKIIIb equipped with a General Oceanic 101512, 12-bottle rosette. A description of the data obtained in these surveys is given by *Jorge da Silva* [1992a, b].

2.3 Seasonal evolution.

Some of the basic features of the northern Portuguese margin dynamics, observed during the summer and early fall of 1987, can be discussed using the filtered time series presented in figures 2a and 2b. These figures suggest that the observations cover the complete upwelling season and that they extend over the transition period to winter conditions.

Upwelling season

From May to mid-September northerly (upwelling favourable) winds were dominant along the northern Portuguese coast. The most intense and persistent upwelling favourable winds occurred during the first two months of observations, with events of 10-15 days of sustained northerly winds. Shorter events of intensification/relaxation of those winds, with time scales of 5-7 days, were also observed. From July to mid-September the winds remain upwelling favourable but weaker and more variable, again showing fluctuation with scales of 5-7 days.

Marked differences were observed between the shelf and slope dynamics during this period. The residual flow over the inner-shelf and mid-shelf was essentially characterised by fluctuations with time scales of 5-15 days. These fluctuations show a clear relation with the variability in the coastal winds (figure 2a). Mean currents, both at seasonal or at monthly time scales, were very weak (table 2). Over the upper slope, by contrast, a mean baroclinic flow was observed during all the upwelling season, with equatorward flow at surface levels and a mean poleward flow present at deeper levels (table 2).

The association of current meter measurements with the hydrographic observations made during the summer 87 allowed to follow the evolution of the upwelling season. At the beginning of the observation period isopycnals run horizontally over the slope and outer shelf (figure 3a) and poleward flow was observed at all levels over the upper slope and mid-shelf. The equatorward flow observed over the inner-shelf and the upward slope of the isopycnals near the coast suggested that upwelling was occurring in a region of 20 Km from the coast. Low salinity (less dense) waters, associated with the Douro river plume, were observed in the first 20-30m depth over the shelf and extended to the shelf-break region.

After a week of sustained northerly winds, the low salinity waters were pushed offshore of the shelf break and an upwelling front was found over the outer shelf and (figure 3b). The offshore displacement of the associated equatorward jet was followed in the stick diagrams of currents, which show equatorward flow progressing from the inner shelf to the mid-shelf and finally reaching the upper-slope. Below 50-60m, however, the isopycnals still run horizontally. The observations during this first week are illustrative of the onset of upwelling conditions on the northern Portuguese margin. During this phase, events of relaxation or even inversion of the northerly winds caused an inversion of the equatorward flow at all locations (figure 2a).

With the persistence of upwelling winds for more than one month, a sustained equatorward flow appeared over the upper slope and extended itself over the first 120-170m depth. During a few periods of intensification of the upwelling favourable winds, this flow reached all the water column. The August survey showed a general upward slope of the isopycnals, both over the shelf and slope regions, to depths of 150-200m (figure 3c). These observations corresponded then to a more mature phase of upwelling. In this phase, events of relaxation/inversions of the upwelling winds modulated the intensity and depth penetration of the equatorward jet, but no longer conducted to flow inversions at the surface layers over the upper-slope. Over the shelf, however, current inversions are still observed in response to relaxation of northerly winds.

A poleward undercurrent persisted during the total upwelling season over the upper slope (with two short disruptions associated with strong northerly winds' events). From August to mid-September,

northerly winds become weaker and more variable and the equatorward flow rested confined in a shallower layer, or was no longer identifiable as a persistent flow. Over the upper slope the poleward undercurrent becomes shallower during this period and even extended to all the levels observed during particular events of relaxation of the northerly winds.

Reflecting the prevailing upwelling conditions, a systematic decrease was observed in the temperature at all levels in the two moorings. At the mid shelf mooring temperature dropped about 1°C at all levels from May to end of July and begins to rise at depth from August. Over the upper slope temperature also decreased about 1°C at all depths, until the beginning of July (i.e. during the period of persistent upwelling winds). After that, temperature at the lower levels beggined to rise. From August to mid October temperature increased almost 1°C at the three deeper levels, but more than 3°C at the surface level.

Transition to the winter regime

By mid September marked changes on the winds and currents were observed. A period of several days of sustained south-westerly winds occurred and was followed by the passage of a low pressure system which originated a complete rotation of winds. By this time a persistent poleward flow was observed over the mid-shelf and upper slope at all levels (figure 2a) with maximum poleward flow occurring at mid-depths (120-170m) over the upper slope. Substantial temperature changes, at all levels, were also registered. These changes are consistent with the shallowing of the poleward slope current and with the invasion of the shelf by warm oceanic waters, due to the prevailing downwelling conditions. Between mid September and mid October, the temperature increased almost 3°C at 40m over the mid-shelf, while at deeper levels this increase was about 0.8°C. Over the upper slope a systematic rise of temperature also occurred at all levels.

The last month of measurements seems to reflect a highly variable regime, with sustained periods of winds with a southerly component. These conditions are typical of the winter regime off the western Iberian coast [Fñúza *at al.*, 1982].

The discussion in the next sections concerns only the 87 upwelling season.

2.4 Flow variability during the summer circulation.

With the objective of analyse in some detail the characteristics of the flow variability, during the summer period, spectra of currents were calculated using rotary spectral analysis methods(Gonella [1972], Mooers[1972]). Spectra were calculated by the Welsh method with 8 degrees of freedom using 4 non-overlapping blocks of data. The spectral resolution is 0.0234375 cpd.

The total (kinetic energy) spectra for currents over the mid-shelf and upper slope are presented in figures 4a and 4b. In each figure the individual spectra are shifted by one decade, starting at the uppermost levels, to allow a better identification of the energetic peaks. Confidence intervals to 95% of significance are also show. Three bands of energetic motions are identified in these spectra: the tidal band (periods lower than 15 hours), the quasi-inertial band (periods from 15 to 35 hours) and the subinertial band (periods longer than 35 hours). By appropriately filtering the time series it was possible to separate the contribution of each one of these bands.

The basic results concerning the inertial and tidal bands are summarised next. Those concerning the subinertial band will be object of a more detailed analysis in the next sections. Tidal motions contain a significant fraction of the flow variability over the shelf and slope regions. The dominant contribution in this band came from the M₂ tide (12h 25m) with a secondary contribution from the S₂ tide (12h). Over the upper slope the semi-diurnal signal is bottom intensified and a 6 hour's harmonic becomes increasingly important with depth. Tidal ellipses (figure 1) in this region are polarised along the local direction of the topography except near the bottom where the current variability is fairly isotropic. Over the shelf, tidal motions exhibit a rather barotropic structure. Tidal ellipses are polarised, over the mid-shelf, in a direction similar to the direction of the shelf break line and in a direction normal to the local isobaths over the inner-shelf. In both cases tidal motions over the NW Portuguese shelf originate important cross-shore motions.

In the diurnal and near-inertial band the energy is essentially associated to motions with periods near or slightly lower then the local inertial period (18 hours 37m). The energy associated with these near-

inertial motions is almost as great as the one in the tidal band. These motions decay with depth but can still be identified at the 280m, over the upper slope. At mid-shelf, the quasi-inertial energy is completely dissipated near the bottom. The correspondent current ellipses (not shown) reveal a fairly isotropic character at all locations.

2.5 Subinertial variability (low-frequency variability)

In section 2.3 it was pointed the fact that current fluctuations with time scales of several days were observed during the summer of 87. The energy of these subinertial motions increases for longer periods, reaching an energetic plateau for periods of 15 days (figure 4a). The energy levels of these motions are comparable, over the mid-shelf, with those of tidal motions but over the upper-slope are somewhat weaker. The correspondent current ellipses (not show) are roughly aligned along the local isobaths but veer in the counter-clockwise sense when approaching the bottom as a result of frictional effects.

Several energetic peaks with periods between 2 and 10 days can be identified in the spectra of figure 4. A particular attention is paid to motions with time scales between 4-6 days, which show energy both over the mid-shelf as over the upper-slope (although being more confined to the surface levels at the latter location). The rotation coefficients [Gonella, 1972] for these time-scales (figure 4) are positive, revealing that the motions have a predominant anticyclonic character.

Several physical processes can explain the flow variability at these scales. For example they can be assumed as the manifestation of mesoscale eddy activity in the study area. Alternatively they can express the response of the coastal ocean to the variability in local or remote wind forcing. The latter hypothesis was already suggested in section 2.3, based on the analysis of the stick diagrams of wind and currents, and is now further explored.

The total spectra of wind stress at Ferrel (figure 5) reveal that wind variability was associated with periods of 3 days, 4-6 days and 11-15 days. A minor energetic peak is also observed at the diurnal period and corresponds to the sea-breeze diurnal cycle. A separated analysis shows that these bands of variability were dominant in the period between May and July and decay on the last two months. However wind fluctuations with periods of 4-6 days remain during the total period as a well defined energy peak although more important in the first two months.

Coherence between the current and the North-South (longshore) component of the wind stress at Ferrel (figure 6a) is high for time scales of 4-6 days, particularly for anticyclonic motions (corresponding to negative frequencies). The phase between current and wind stress fluctuations in this band (figure 6b) is about 60° , which implies that currents lag the longshore wind stress at Ferrel by about 20 hours.

The previous results are consistent with the interpretation of current fluctuations with time scales of 4-6 days as being part of the response of coastal ocean to local wind forcing events. The observed phases between currents and winds (which were measured almost 160 Km to the south of the latitude of current measurements) indicate that this response propagates northwards along the northern Portuguese shelf, with a phase velocity of about 2-2.5 m/s.

2.6 Vertical structure of low frequency motions

The stick diagrams of figure 2a reveals subinertial current fluctuations that are fairly barotropic over the mid-shelf, but have a weak baroclinic character over the upper slope. The barotropic and baroclinic contributions to currents at both locations have been separated with a methodology similar to the one discussed by Kundu *et al.* [1975]. A simplified model of the subinertial dynamics of a coastal region is used as the adequate framework to decompose the vertical structure of currents. The consistency of the basic assumptions on which the model relies, as well as its limits of validity, are checked *a posteriori* by comparing the calculated structures with the statistical properties of the data.

The simplified model will describe the linear dynamics of a stratified, inviscid Boussinesq fluid in rotating uniformly. Solutions are assumed to be in the form of longshore propagating waves. Although extremely simplified, the problem remains of difficult resolution for general topography and stratification profiles since the vertical and horizontal structures of the solutions are coupled through the bottom boundary condition. To overcome this difficulty a further assumption must be introduced, namely that the topographic changes are small in the scale of the baroclinic response (i.e. the internal Rossby radius). In this case the bottom boundary condition for the baroclinic problem can be replaced by that of plane

bottom (zero vertical velocity at bottom) and a separation of variables technique can be used to separate the horizontal and vertical structures. However this assumption breaks at those regions, such as the continental slope, where topographic gradients are strong. As before we proceed by using the assumption and rely on the data and its statistical properties to *a posteriori* check its adequacy.

With the above assumptions the vertical structure functions (dynamical modes) were found as the solutions of a Sturm-Liouville problem. This problem was solved numerically using the mean profiles of Brunt Vaisala frequency, obtained from the CTD cast made in the proximity of each mooring during CECIR XII and CECIR XIII cruises.

The first three normalised dynamical modes, at each mooring, are represented in figure 7 (the barotropic mode as no vertical node, the n^{th} baroclinic mode as n vertical nodes). It can be concluded, from this figure, that the baroclinic structure was not resolved with the mid-shelf mooring. All the current meters in this mooring (represented by blue dots in the figure) were located below the node of the first baroclinic mode and so aliasing of the barotropic mode by the baroclinic structure will occur.

Over the upper slope, however, the position of the current meters in the mooring was such that at least the first baroclinic mode was adequately resolved (but not the second mode). In this case a separation between the barotropic and first baroclinic contributions is possible. This separation is done by least squares fitting the filtered currents to the previously computed dynamical modes, which allows to obtain the amplitude of the contribution of each mode (function of time). The two components of current are fitted separately. A new co-ordinate system is defined from the mean principal direction of filtered currents in this mooring. This new system is rotated 24° clockwise relative to the geographic co-ordinate system and traduces the general orientation of current at each level along the local topography (figure 2a). The flow is then decomposed in a cross-topography component (U component) and an along-topography component (V component).

Results of the adjustment of the upper slope currents with the first two modes (barotropic and first baroclinic) are show in table 3. The quality of the adjustment procedure is judged by two different criteria, the relative residual to the adjustment and the correlation coefficient between observed and adjusted currents. The adjustment with two modes is very good for the along-topography component but less good for the cross-topography. This suggests that the simplified model contains the essential dynamical balances for the along-topography flow, but lack part of the dynamics involved in the cross-topography flow.

For the along-topography component the mean barotropic is positive while the mean amplitude of the first baroclinic mode is negative (table 3). This indicates the existence of a mean poleward barotropic flow that is modulated by a mean vertical shear for which the surface flow is directed equatorwards while the deep flow is directed polewards. The variability with time scales of 4 to 15 days is dominated by the barotropic contribution (figure 8). The motions with periods of 4-6 days, which have been discussed in previous sections, the contribution of the barotropic mode is four times greater than that accounted by the first baroclinic mode.

To check the consistency of the dynamical mode decomposition, the vertical structures are compared with the vertical empirical orthogonal functions (EOF) of the current fluctuations (figure 7). EOF's correspond to the eigenvectors of the cross correlation matrix and so provide a type of modal decomposition that is based only on the statistics of the data and not on a particular dynamical model. Each vertical EOF explains a fraction of the total variance that is observed in one component of the flow in a particular mooring. The results present in table 4 indicate that the first two EOFs explain almost all the variance in the V component, both over the shelf and upper-slope. Higher EOF modes must be retained for the U component. An important aspect is that the vertical structure of the EOFs for the along-topography component closely resemble the dynamical modes. In particular for the upper slope mooring, 93% of the variability in the along-slope flow is explained by the two first EOFs. For this case the first mode is almost four times more important than the second one. The first EOF is fairly barotropic while the second EOF mode is very similar to the first baroclinic mode. The very good similarity between the EOFs and the dynamical modes, strongly suggest the validity of the simplified model previously used to obtain the vertical structure of the along-topography flow over the upper slope.

2.7 - Theoretical solutions

Solutions of the simplified dynamical model were obtained by numerically solving the coupled partial differential problem by the method of resonance iteration, using the routines of *Brink and Chapman* [1987]. The numerical domain considered extends 200 Km offshore and 4000m depth and uses the bottom topography profile at the latitude of the moorings line (figure 9). A Brunt-Vaisala profile to 1600m obtained during CECIR XIII (August 87) was used to define the stratification conditions. This profile was extended to 4000m by fitting an exponential decay with a vertical scale of 1500m. The problem was solved in a grid of 101 point in the horizontal and 35 points in the vertical. A stretched vertical co-ordinate is used to allow a high resolution over the shelf.

The solutions of the problem are in the form of discrete coastal trapped wave (CTW) modes. The dispersion curves of the first five CTW modes are presented in figure 10 (curves in red). The solutions of the corresponding barotropic problem (continental shelf waves) are also represented in the figure in blue colour. It can be concluded from this figure that wind forcing patterns with time scales between 4-5 days and spatial (longshore) scales longer than 500 Km can excite the two lower CTW modes. The first mode (noted A) has a phase velocity of 4.5-5 m/s while the second mode (B) presents a phase velocity of 2.2 m/s.

The pressure perturbations associated with each one of these solutions are represented, for the upper 1000m depth, in figure 11. It can be noted that both modes are fairly barotropic over the shelf. The first CTW mode remains barotropic off the shelf-break, but the second mode reveals there some baroclinic character.

3. WINTER DYNAMICS AND RELATED SPM TRANSPORT PROCESSES.

3.1 Objectives

Off the northern Portuguese margin a muddy complex is observed over the mid-shelf, following roughly the 100m isobath and extending northwards from about 41°N - the Douro muddy complex (DMC) [*Drago et al.*, 1998]. A number of studies indicate the Douro river (the major fluvial contribution to the NW Iberian region) as the main source of the sediments for this complex.

Several questions remain open about the dynamical background that lead to the formation of the DMC over the mid shelf and to its orientation northwards of the likely source. Recent studies [*Drago et al.*, 1989] pointed, in particular, to the important role that winter circulation has in defining the main characteristics of the DMC. The winter regime off the northern Portuguese margin is characterised by high variable winds with frequent period of south-westerly winds [*Fiúza et al.*, 1982]. Under these conditions, downwelling occurs and an associated northward flow must be present over the shelf. Along the continental slope the observations show a surface intensified poleward slope current [*Frouin et al.*, 1990, *Haynes and Barton*, 1990] that eventually extends over the outer shelf. The wave regime is highly energetic during this period. Waves with heights in excess of 5m and periods greater than 13s are directed predominantly from NW and W, and are associated with the distant fetches in the North Atlantic [*Powaves group*, 1994].

With the general purpose of characterising the winter conditions and study its role on the SPM distribution in this region, IH conducted an observational program during the 96 and 97's winters. Part of the results obtained by this program will be now discussed.

3.2 The observational program

The program focused the area between 41°N and 42°N and integrated two hydrographic and sedimentary surveys and a period of two months of continuous wave and current observations at one mid-shelf location. The University of Bordeaux (Prof. J.M.Jouaneau, Dr. Olivier Webber) and IPIMAR (Dr. Carlos Vale) were directly involved in this program.

Corvet 96 cruise

During November 1996 an hydrographic/sedimentary survey - CORVET 96 cruise - was conducted by IH, with the general objective of study several aspects of the western Iberian margin. Part of the work plan of this cruise consisted on what was called the "local study". This study was made on the area referred above and was intended to provide some preliminary observations to the IH contribution to

OMEX II-II.

The local study was held between 12 and 22 November 96, during a period characterised by the influence of two major storms that affect the western Iberian margin. In the first part of this study, samples of bottom sediments were collected in several locations over the Douro and Minho muddy complexes with a multi-corer from University of Bordeaux. After that, two moorings were deployed over the DMC, at the mid-shelf (84m) off Leixões (41° 19'N - see figures 1 and 12) and close to a WAVEC wave buoy maintained by IH. One of the moorings was a classical mooring included 4 current meter Aanderaa RCM-7 at 29, 53, 76 and 82 m depth (sampling rate 20min) and an electromagnetic current meter SEAPAC 2100 at 24m depth. The second mooring consisted of a tripod with an electromagnetic current meter PACER 621 planned to provide high frequency measurements (9 minutes burst of measurements at 2 Hz every hour) at 2m above the bottom. Due to malfunction of the equipment, however, no data was available from the electromagnetic current meters.

After mooring deployment, a hydrographic/SPM coverage was conducted (figure 12a). A total of 54 CTD/nephelometry stations were occupied. In all stations the observations were made with a Neil Brown (NBIS) MKIIC CTD equipped with a nephelometer and a General Oceanic 101512, 12-bottle rosette. Water samples were collected with the rosette for CTD calibrations at selected depths. Water samples for SPM evaluation were collected near the bottom (or at 500m if bottom is deeper) with the rosette system and at 5m depth with a pump. Water samples for nutrient evaluation were collected at the surface.

Clima 97 cruise

The second cruise - CLIMA97 - was held between 6 and 14 December 1997, under moderate winter conditions. A total of 120 hydrographic/SPM stations were covered to a maximum depth of 1500m (figure 12b). A system of two coupled CTDs was used. One of the CTDs was a Neil Brown (NBIS) MKIIC CTD, equipped with a nephelometer and a General Oceanic 101512, 12-bottle rosette. The other was an Idronaut CTD, equipped with OBS, O₂, pH and Redox sensors and with an ultra-sonic current meter. Water samples were collected for CTD calibrations and nutrients at selected depths. Water samples for SPM evaluation were collected near the bottom (or at 500m) with the rosette system. Water samples at 5m depth were also collected with a pumping system for SPM and nutrient evaluation.

3.3 Storm impact (a view from CORVET 96 cruise)

The meteorological context in which the 96 cruise took place was rather untypical of the winter conditions of the western Iberian margin. A high pressure system persisted, during the fall and early winter, at an anomalous high latitude. Therefore this area was influenced by northerly winds and the upwelling conditions were maintained until the first week of November. By the 11th of November, however, a low pressure system passed over the northern Iberian region and induced severe storm conditions. A week later, by the 19-20 November, a second low pressure center moved across the Biscay Bay, also promoting storm conditions off northern Portugal.

Since the local study occurred during the period of influence of these two major events, the opportunity appeared to direct the observations onto the search of their impact on the hydrographic and sedimentary conditions. In particular, a hydrographic/SPM section off Viana do Castelo was repeated (figure 12a), with one coverage just before the passage of the second storm (Section 7) and the other soon after (Section 8).

Section 7, covered between 18-19 November, revealed hydrographic conditions consistent with previous upwelling conditions (figure 13a). A marked thermal front (2 °C in 5-10Km) occurred over the shelf-break and separated warm oceanic waters from the shelf waters. Low salinity waters were present at the surface levels over the mid-shelf and without continuity with the coastal region. These waters are the expression of the Douro river plume, that seems to have been displaced over the mid-shelf by offshore (Ekman) transport at the surface layers, during the period of prevailing upwelling conditions. Another interesting aspect is the presence of a warm anomaly, below the low salinity region, which shows some continuity with the warm waters offshore of the shelf break. An interpretation for this feature will be given below. The SPM distribution before the passage of the storm was characterised by a surface nepheloid layer (SNL), 20-30m thick, which extended over the shelf, and a bottom nepheloid layer, which was confined inshore of the mid shelf. The highest values of SPM were confined to 10 Km from

the coast.

After the passage of the storm (section 8, covered by the 21 November) profound modifications were observed in all the fields (figure 13b). At the surface layers, the warm water that once was confined off the shelf-break now extends over the mid-shelf. At deeper levels the thermal front extends deeper, below the shelf break. The low salinity region that once was located over the mid-shelf was eroded by increased mixing, and there is a suggestion from figure 13b that a low salinity tongue follows the offshore boundary of the thermal front. The river plume is now confined close to the coast.

The previous observations could reflect the establishment of a downwelling circulation over the shelf, characterised by onshore transport in the first 20-30m and a compensatory offshore flow at the levels below. The warm feature observed before the storm could have resulted from a similar circulation pattern (established possibly during the first storm), which induced the inshore movement of warm waters. This was followed by a new period of upwelling, during which the front was pushed offshore at the surface levels and warm waters were left behind at deeper levels.

Marked differences are also observed in the SPM distribution. As the result of increased mixing, the SNL was completely eroded. A thick (30m) BNL now extends over the continental shelf and across the shelf break. High SPM values occurred both at the coast as over the mid-shelf. The observations suggest that these two regions of high SPM values are not connected, the one located over the mid-shelf is probably the result of local resuspension of bottom sediments.

3.4 Wave conditions off the northern Portuguese coast

A much extended view of the impact of these storm events on the northern Portuguese shelf was provided by combining wave and current measurements. Data from the wave buoy corresponds to the period from 15 July to 31 December of 1996 and so covered the summer and winter regimes. In this work only significant and maximum wave height and mean period are discussed. The directional information, although measured, was not yet analysed.

The time series of wave measurements reveal substantial changes occurring in the wave regime by September (figure 14). These mean values of significant wave heights increased from 1.5m, observed during the summer, to 2.5m observed during fall and winter. Correspondingly the mean values of the mean periods increased from 8s to 11s. For the stronger events observed during the summer period, the significant wave heights do not exceed 3m and maximum wave height is below 5m. During the fall and winter the significant wave height associated with the stronger events frequently exceed 4m and the maximum height attains 8m. In two occasions, however, the significant wave height was observed to exceed 6m with maximum wave height over 10m. The associated mean periods were higher than 14s and 12s respectively. These were the two major storms that were covered during the CORVET 96 cruise.

The orbital velocities induced by the waves near the bottom (84m) were calculated for the observed wave conditions, using the classical results from the theory of surface gravity waves and are presented in figure 14c. The corresponding shear velocities were also calculated (figure 14d).

During the summer "mean" orbital velocities (corresponding to significant wave heights) were low, and only in one occasion exceed 10 cm/s and the maximum orbital velocities (corresponding to maximum wave heights) reached 30 cm/s. The corresponding maximum shear velocities, during this period, did not exceed 1.15 cm/s.

In contrast, during the winter period, mean orbital velocities frequently exceed 20 cm/s and maximum orbital velocities exceed 40 cm/s. The maximum shear velocity attained 1.5 cm/s for the great majority of the stronger events observed during this period. However, during the two major storms, mean orbital velocities of 40 cm/s and maximum orbital velocities in excess of 70-80 cm/s were observed. The maximum shear velocity then attained 1.8-2 cm/s. The results from the sedimentary characterisation made during the CORVET 96 cruise revealed that these values are sufficiently high to induce resuspension of bottom sediments [*J.M. Jouanneau*, personal communication].

3.5 Combined action of waves and currents during winter.

During the period from 17 November to 31 December the observations of the high frequency dynamics provided by the wave buoy were complemented with current measurements at four levels from surface to bottom. All along this period, currents were essentially characterised by variability, with mean

values being weak at all levels (table 5). Three contributions to flow variability has been separated by selectively filtering the data. These corresponded to tidal motions (with periods lower than 16h), diurnal and quasi-inertial motions (with period between 16h and 25h) and subinertial motions (with periods longer than 25h).

Tidal motions present some bottom intensification and are polarised in a direction transversal to the isobaths, which is very similar (particularly near the bottom) with the general orientation of the Porto Canyon axis (figure 1). This canyon is a major topographic feature of the of NW Iberia and the observations suggest that it plays an important role by promoting significant cross-shore motions.

Quasi-inertial motions reveal an interesting evolution during the two months of observations. Periods of bottom intensification, during which the current ellipses below 29m are polarised along the isobaths, are observed (figure 15). More frequently the fluctuations remain fairly isotropic and decay with depth. At the shallowest level quasi inertial motions remain isotropic during the all period.

Subinertial (residual) motions are polarised in the direction of topographic contours and veer in counter-clockwise sense as approaching the bottom, as a consequence of interaction with the lower Ekman layer (figure 15). The poleward residual currents observed over the shelf then show a reinforcement of the offshore transport near the bottom.

In figure 16 the time series of residual currents (longshore and cross-shore components) are displayed together with the time series of wave orbital and shear velocities. The upwelling conditions observed before the current measurements persisted almost continuously until mid December, with some interruption due to the highly energetic storm covered by the CORVET 96 cruise. Important upwelling events occurred during the first half of December and were associated with equatorward flow extending over all the water column (although more intense at the mid column levels). During these events offshore flow is observed in the first 30m depth (sometimes even less) and onshore compensatory flow occurs below, being more intense near the bottom. Reflecting the upwelling situation, a consistent drop of temperature was observed at all levels from November to mid December (figure 16c), with a drop of 2°C at the surface level. By the end of the first week of December the water column is almost homogeneous with cold waters occurring at surface. These cold surface waters must correspond to waters of fluvial origin (the Douro plume), which were pushed over the mid-shelf by the prevailing upwelling conditions, as discussed previously.

After mid-December a more typical winter regime with downwelling conditions prevailed. These conditions are associated with onshore flow at the upper layers and offshore (compensatory) flow at the lower levels and a poleward flow. This circulation pattern favoured the extension of warm oceanic waters over the shelf and the re-establishment of the thermal stratification.

The strongest upwelling events are associated with relatively moderate wave regimes, with weak orbital velocities at the bottom. In these conditions the resuspension of bottom sediments is not favoured. The periods characterised by an energetic wave regime seem to be essentially associated with downwelling conditions. This kind of conditions, although more persistent during December, were also observed to occur during the days of passage of the storm of 19-20 November.

4. OVERALL DISCUSSION.

Some of the results about the dynamics of the northern Portuguese margin that were obtained during the first year of OMEX II-II can now be summarised.

- Both the 87 and 96 data consistently revealed the occurrence of weak mean flows over the shelf during upwelling conditions. The residual flow in these periods is there essentially characterised by several days variability, which is associated with events of intensification/relaxation of upwelling winds, even after a well developed upwelling regime was established.
- Over the upper slope, by the contrary, the persistence of upwelling conditions built a mean baroclinic current, with equatorward flow at surface and a poleward undercurrent. With the transition to winter, the equatorward flow at surface weakens and the poleward slope current becomes shallower and occupies all the water column. This seasonal evolution of the mean flow over the upper slope is consistent with a combination of baroclinic (JEBAR) forcing, which persists over great part of the year, and wind forcing, that modulates the current at surface levels. This interpretation was previously proposed to this region by *Frouin et al.* [1990] and *Haynes and Barton* [1990].

- Another important feature of the surface circulation in this region is the Douro river plume. The observations revealed that during upwelling conditions its signature at the surface layers extends over all the continental shelf. During downwelling conditions, by the contrary, the plume is confined near the coast.
- During the 87's upwelling season a significant fraction of current variability over the shelf and slope was characterised by time scales of 4-6 days. These motions were polarised along the isobaths, had an anticyclonic character and showed a remarkably barotropic structure. They were highly coherence with the events of intensification/relaxation of upwelling favourable winds, observed 160Km further south. The lags between currents and winds suggested that the response of the coastal ocean to the local wind forcing was propagating northwards with a phase velocity of 2 m/s.

These results were found to be rather consistent with a response to the local wind forcing in the form of a second mode of coastal trapped waves (CTW). This mode can be excited by fluctuating wind patterns with spatial scales between 500 and 1000Km, which are rather typical of the atmospheric synoptic systems, and then propagates northwards the response to wind forcing. Consequently, they will play a role in the dynamics of the western Spanish margin that includes the OMEX study area. Although an extremely simplified, linear and inviscid model apparently had success in reproducing the basic characteristics of the observed motions. The reason for this relies, probably, on the fact that measures were made in the forcing region, which is also an area of relatively regular topography. As the waves propagate northwards they will be increasingly affected by bottom friction and they will find a more complex topography. The complex dynamics that will develop in these regions can be studied with numerical simulations. Also the motions associated with the waves can be relevant to the upwelling dynamics in general and to filament dynamics in particular.

- A few extreme events affect the NW Iberian coast during winter and have profound impact on the bottom sedimentary. Two of such events were observed during the winter 96 and were able to promote resuspension of sediments over the mid-shelf at the Douro muddy complex. The observations show that they were associated with dominant downwelling conditions, with poleward flow extending from surface to bottom. The onshore surface Ekman transport is compensated at depth by an offshore transport extending over 30m. During these highly energetic events, then, waves and currents concur to resuspend sediment and transport them in the poleward and offshore direction. This could then explain the orientation of the complex relatively to the source.
- Tidal motions over the NW Portuguese shelf are associated with important cross-shore motions. In particular it was suggested an important role of the Porto Canyon in focusing tidal currents onto the shelf.

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Mooring (Bottom depth)	Position	Current meter	Meter depth (m)	Period of observation
A (39m)	41° 04.2' N 8° 48.4' W	RCM4 - 5056	36	7/5/87-15/8/87
B (103.4m)	41° 05.3' N 9° 03.5' W	RCM4 - 6065	46	8/5/87-24/10/87
		RCM4 - 5185	73.4	8/5/87-24/10/87
		RCM4 - 5179	100.4	8/5/87-24/10/87
C (302m)	41° 05.9' N 9° 20.2' W	RCM4 - 5152	38	8/5/87-24/10/87
		RCM4 - 5180	119	8/5/87-24/10/87
		RCM4 - 5187	171	8/5/87-24/10/87
		RCM4 - 5178	282	8/5/87-24/10/87
Weather Station	Position	Equipment	Sensors height above ground (m)	Period of observation
Ferrel	39° 23.3' N 9° 17.5' W	AWS/DL1	17	8/5/87 - 24/10/87

Table 1: Details about the measurements made during the summer and early fall 1987.

	11/5 - 15/6		15/6 - 15/7		15/7 - 15/8		15/8 - 15/9		15/9 - 14/10	
	U	V	U	V	U	V	U	V	U	V
INNER SHELF										
5056	0.70 (2.10)	-2.22 (6.51)	0.51 (1.52)	-1.91 (5.33)	-	-	-	-	-	-
MID-SHELF										
6065	1.05 (1.77)	-3.12 (5.12)	2.16 (2.26)	-0.19 (5.11)	0.60 (0.97)	0.97 (4.49)	0.62 (1.48)	0.39 (5.00)	2.54 (1.64)	5.01 (8.49)
5185	0.32 (1.37)	-2.93 (4.48)	0.60 (1.29)	0.83 (4.38)	0.34 (1.00)	1.58 (4.89)	-0.11 (1.04)	1.12 (4.95)	0.14 (1.50)	5.39 (6.03)
5179	-0.18 (0.93)	-2.48 (3.83)	-0.05 (0.76)	0.56 (3.84)	0.04 (0.60)	0.06 (2.55)	-0.16 (0.73)	-0.25 (2.83)	-0.63 (1.01)	1.70 (4.54)
UPPER - SLOPE										
5152	0.63 (4.26)	-3.04 (4.67)	-0.68 (2.87)	-4.67 (3.69)	1.24 (1.81)	-1.02 (2.54)	2.05 (2.25)	-1.38 (3.09)	1.80 (2.70)	2.22 (5.06)
5180	0.62 (2.16)	-0.33 (3.38)	0.58 (2.75)	-1.10 (4.09)	2.46 (1.71)	2.31 (3.12)	3.04 (1.28)	3.30 (2.82)	4.46 (2.22)	7.97 (4.74)
5187	1.68 (2.43)	1.02 (4.01)	2.00 (2.60)	1.85 (3.40)	3.54 (1.91)	4.03 (3.60)	4.77 (1.85)	6.20 (2.91)	6.13 (2.70)	10.93 (4.84)
5178	-1.70 (1.70)	3.82 (4.32)	-0.27 (2.48)	5.90 (2.24)	-1.29 (1.66)	5.71 (3.00)	0.83 (2.07)	8.37 (3.20)	0.68 (2.28)	8.34 (4.18)

Table 2. Monthly statistics for the filtered (residual) current components measured during the summer and early fall 1987. For each current meter, both the mean and standard deviation (in parenthesis) of the E/W component (U) and N/S component (V) are shown.

	U (across-topography)	V(along-topography)
Barotropic		
Mean \pm mean std. error	0.32 \pm 0.02 (cm/s)	2.22 \pm 0.07 (cm/s)
Standard Deviation	1.05 (cm/s)	3.62 (cm/s)
1st Baroclinic		
Mean \pm mean std. error	1.28 \pm 0.02 (cm/s)	-3.21 \pm 0.04 (cm/s)
Standard Deviation	1.19 (cm/s)	1.94 (cm/s)
Relative residual	4.1%	0.5%
Correlation	0.66	0.94

Table 3. Dynamical mode decomposition: basic statistics of amplitude functions and criteria for the quality of adjustment with 2 modes (barotropic and first baroclinic).

	MID - SHELF		UPPER - SLOPE	
	U	V	U	V
Mode 1	69.2 %	95.8 %	44.5 %	75.9 %
Mode 2	23.1 %	2.2 %	34.2 %	17.0 %
Mode 3	7.7 %	2.0 %	14.8 %	4.8 %

Table 4. Fraction of variability explained by the three first vertical EOFs for the E/W component (U) and N/S component (V) of current at the mid-shelf and upper-slope. For details see text.

Depth (m)	$U_{med} \pm \epsilon_u$ (cm/s)	σ_u (cm/s)	$V_{med} \pm \epsilon_v$ (cm/s)	σ_v (cm/s)	θ	$T_{med} \pm \epsilon_T$ ($^{\circ}$ C)	σ_T ($^{\circ}$ C)
29	1.03 \pm 0.04	2.05 (50.2%)	-0.33 \pm 0.16	8.71 (97.1%)	84	14.043 \pm 0.009	0.477
53	1.59 \pm 0.04	2.25 (50.1%)	0.94 \pm 0.18	9.94 (94.4%)	92	13.771 \pm 0.007	0.388
76	0.68 \pm 0.06	3.13 (55.2%)	2.04 \pm 0.21	11.28 (96.8%)	98	13.528 \pm 0.005	0.278
82	0.24 \pm 0.06	3.18 (58.4%)	1.76 \pm 0.18	9.96 (97.1%)	102	13.573 \pm 0.005	0.283

Table 5. Basic statistics for the filtered time series of the E/W component of current (U, positive eastwards), the N/S component (V, positive northwards) and temperature (T) obtained with the mooring deployed in November 1996, off Leixões (41° 19'N). Represented the mean and standard error of the mean (ϵ), the standard deviation (σ) and the principal direction (θ - measured counter-clockwise from east). U is the E/W component of current (positive eastwards) and V is the N/S component (positive northwards). For the current components the percentage of variability explained by the residual flow is also included.

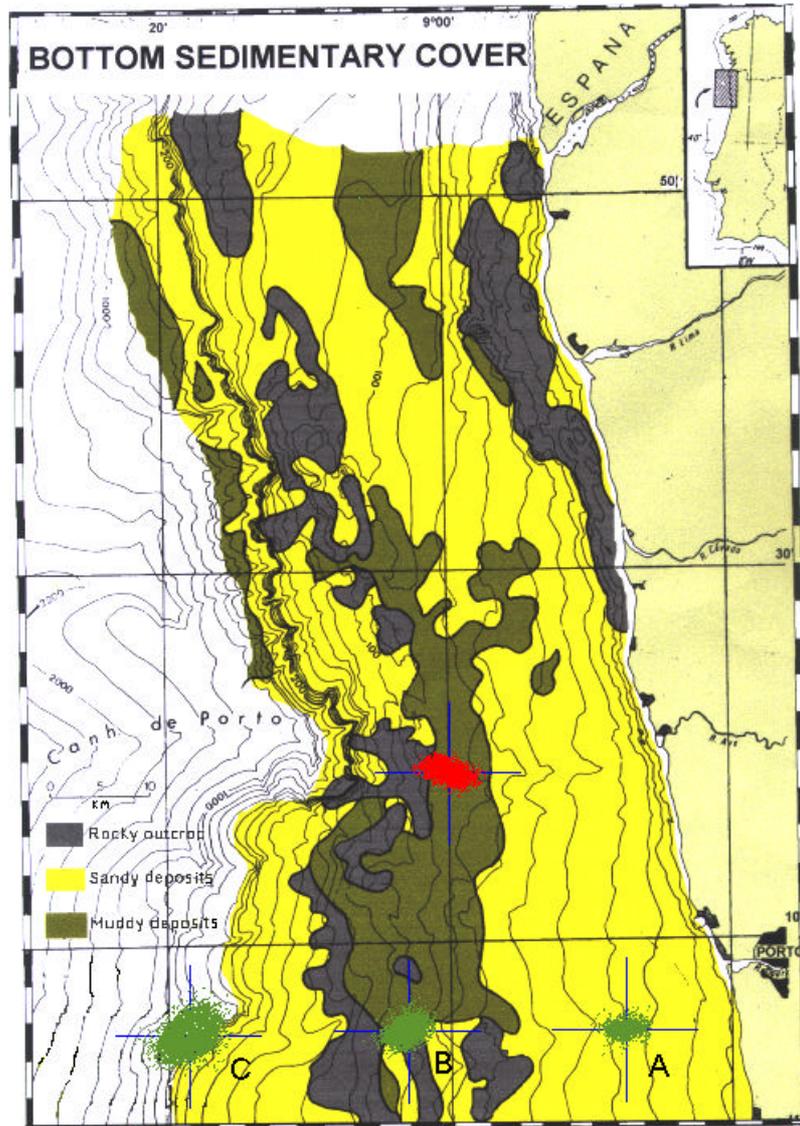


Figure 1. Tidal ellipses obtained from the observations made during the summer 1987 (in green) and winter 1996 (in red). The 1987 moorings are labeled as in table 1. Axis cover the interval $[-30,+30]$ cm/s. The sedimentary chart is adapted from Rodrigues et al. [1991].

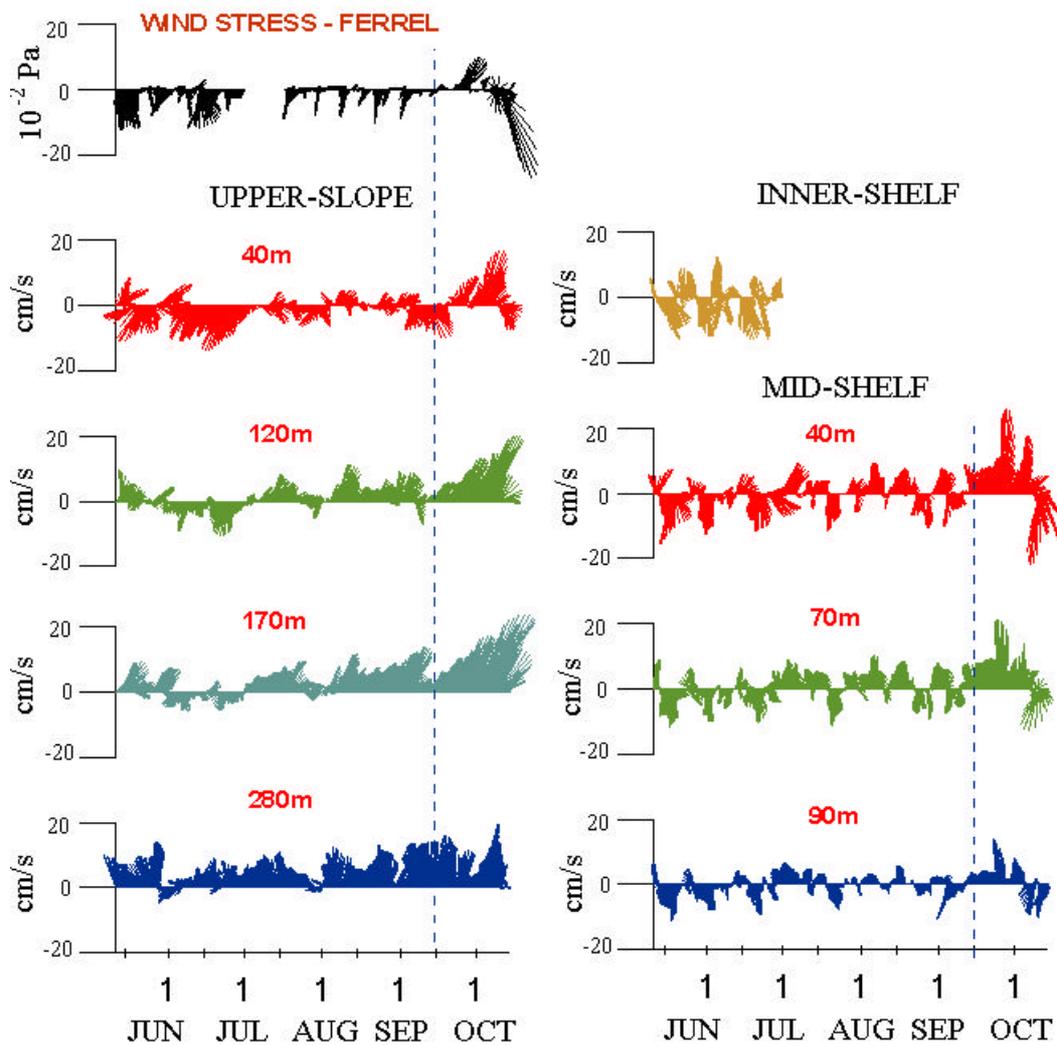


Figure 2a. Stick diagrams of wind stress at Ferrel ($39^{\circ} 23.3'N$) and of currents at the three moorings - inner-shelf (A), mid-shelf (B) and upper slope (C) - maintained off Porto ($41^{\circ} 05'N$) from May to October 1987. The discontinuous line mark the end of the summer period discussed in the text.

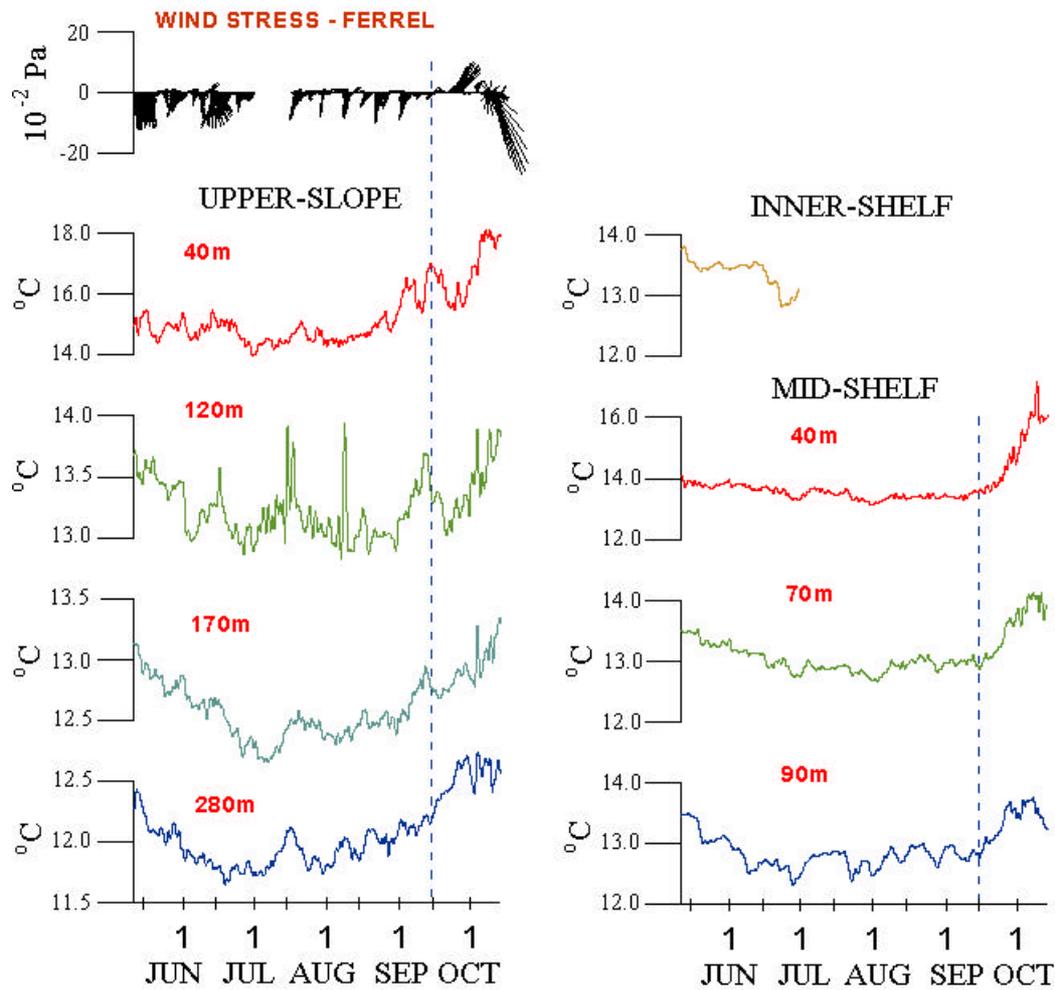


Figure 2b. Stick diagram of wind stress at Ferrel ($39^{\circ} 23.3'N$) and temperature time series at the three moorings - inner-shelf (A), mid-shelf (B) and upper-slope (C) - maintained off Porto ($41^{\circ} 05'N$) from May to October 1987. The discontinuous line marks the end of the summer period discussed in the text

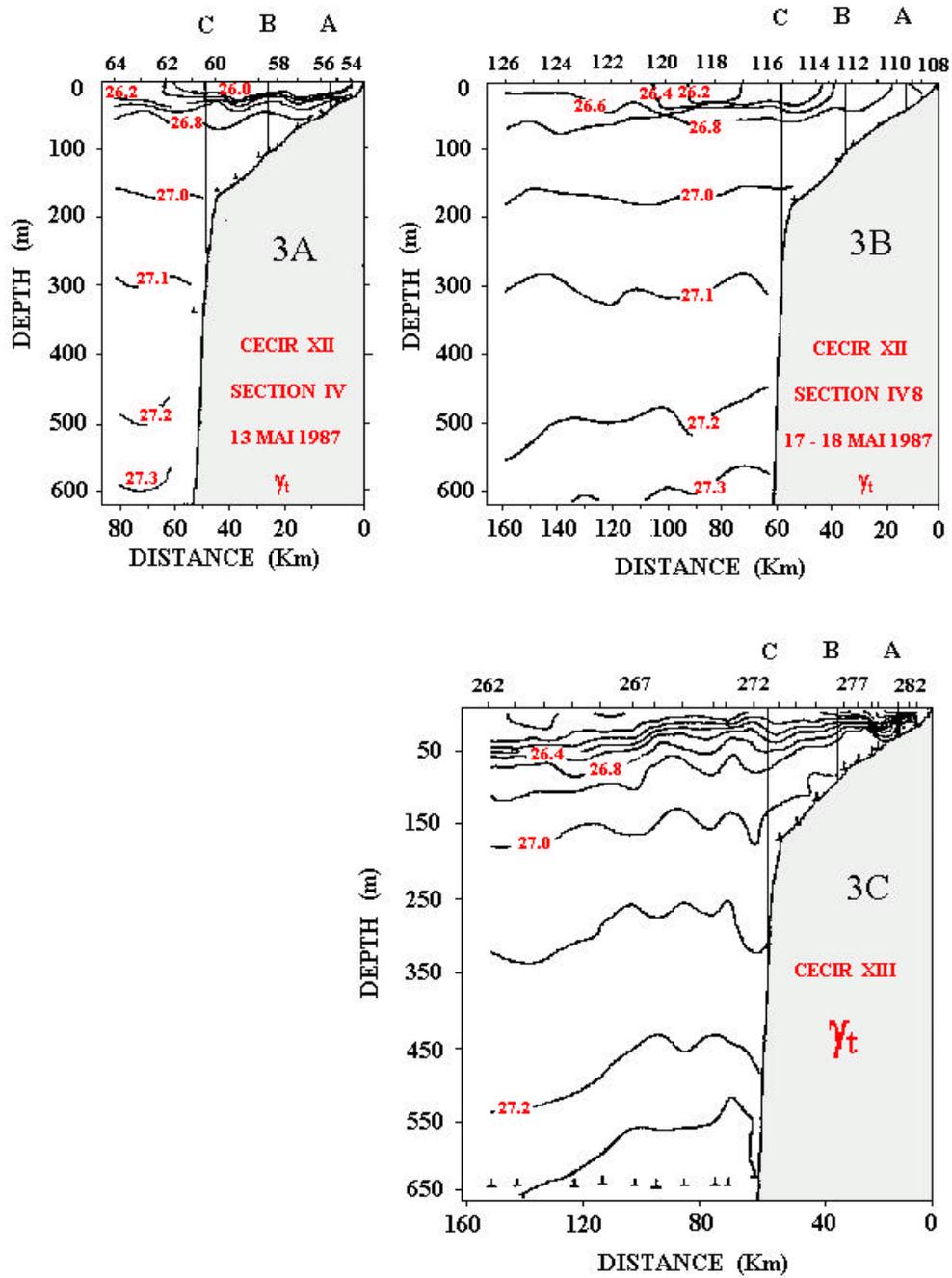


Figure 3. Density sections obtained during CECIR XII (May 1987) and CECIR XIII (August 1987) at the latitude of the moorings. a) 13 May 1987, b) 17-18 May 1987 and c) 21-22 August 1987. Adapted from Jorge da Silva [1992a,b].

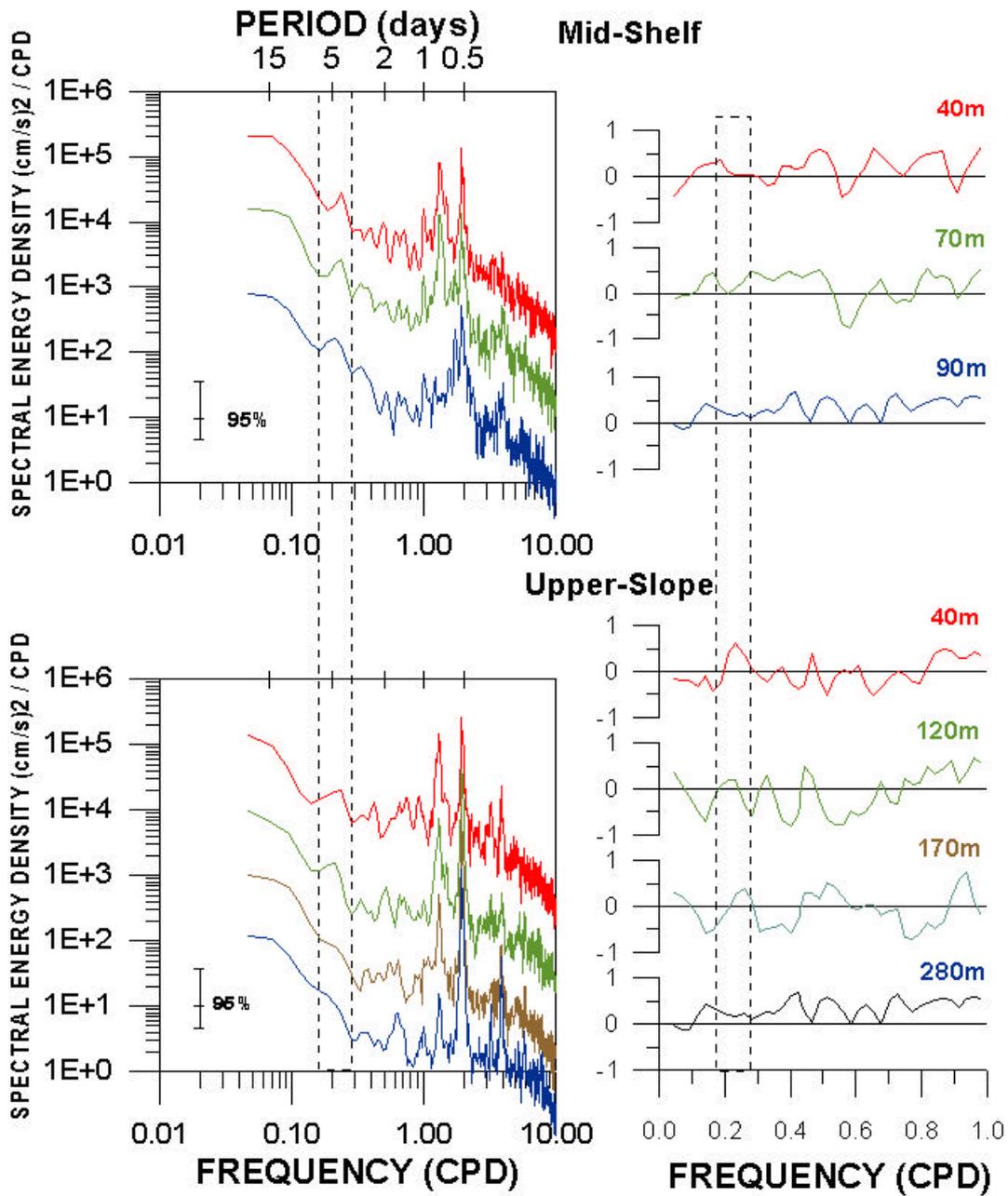


Figure 4. Total spectra of current (left) and rotation coefficients for periods greater than 1 day (right). Results for both the mid-shelf mooring (top - 4a) and upper-slope mooring (bottom - 4b) are show.

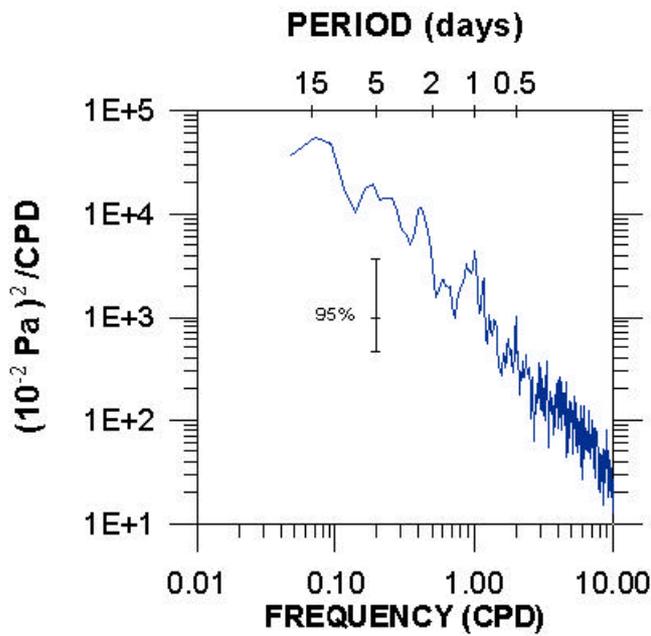


Figure 5. Total spectra of wind stress at Ferrel obtained with 8 degrees of freedom.

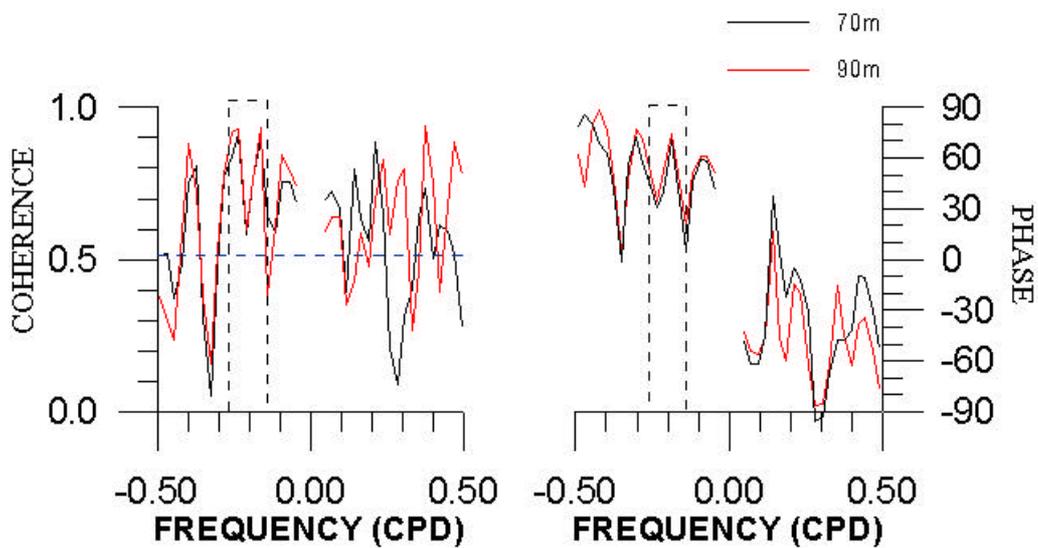
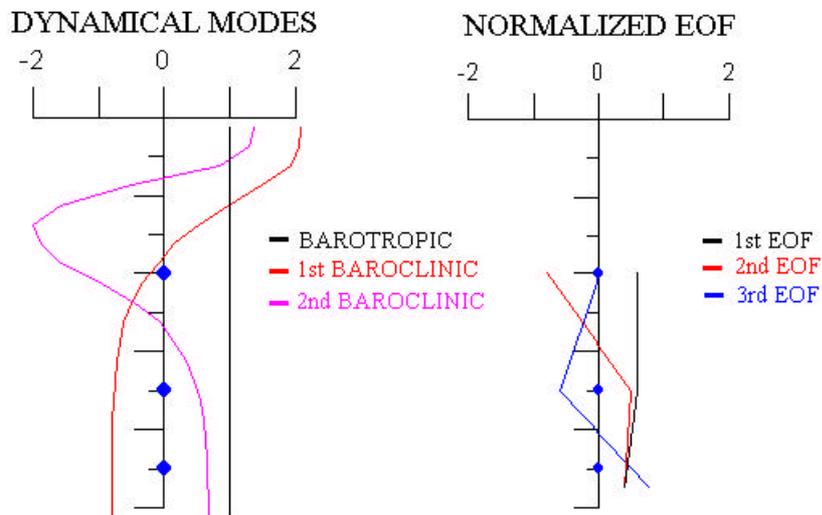


Figure 6. Coherence (left-6a) and phase (right - 6b) between current at 70 and 90m over the mid-shelf and the longshore component of wind stress at Ferrel (8 degrees of freedom). The level of zero coherence at 95% signif. is show.

MID-SHELF



UPPER SLOPE

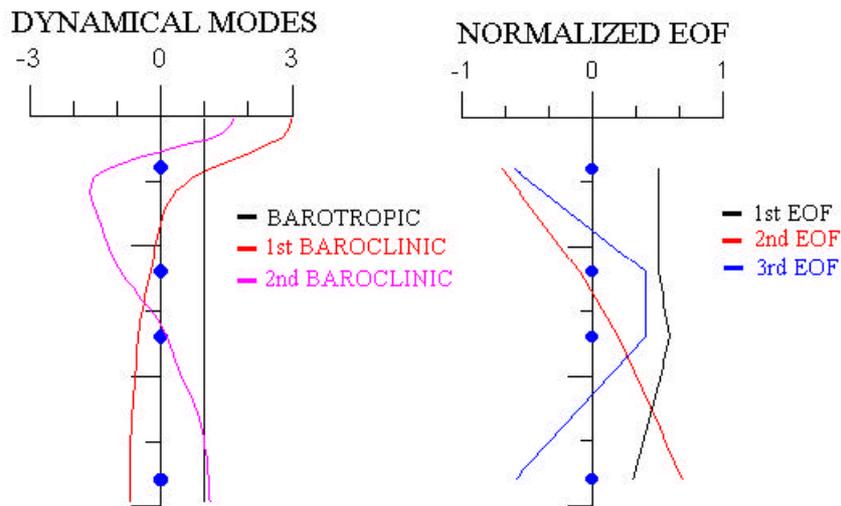


Figure 7. Left -Dynamical modes (left) obtained from the mean stratification conditions at the upper-slope mooring. Right - Vertical EOFs for the along-topography (V) component of current at the upper-slope mooring. The blue dots indicate the position of current meters.

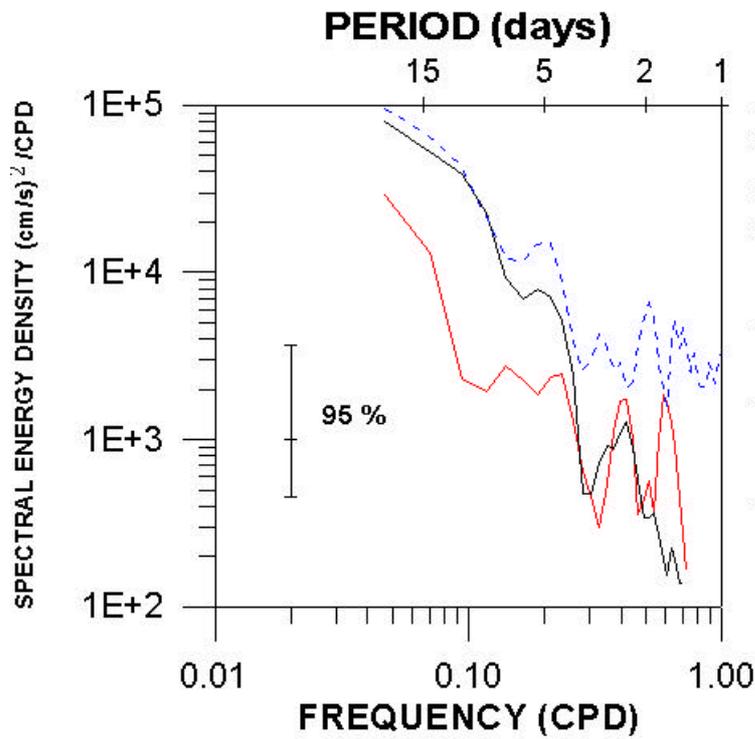


Figure 8. Spectra of the barotropic (in black) and first baroclinic (in red) modal amplitudes, for the along-topography (V) component. The spectra were obtained with 8 degrees of freedom. The total spectra of current at 120m over the upper slope is also included (in blue).

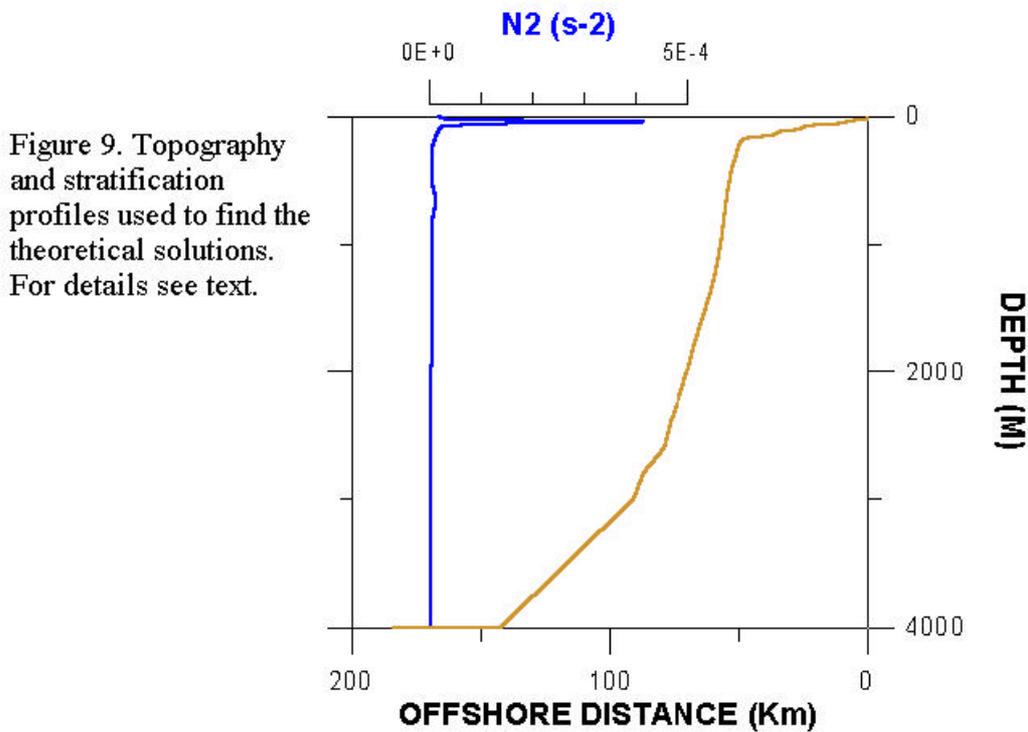


Figure 9. Topography and stratification profiles used to find the theoretical solutions. For details see text.

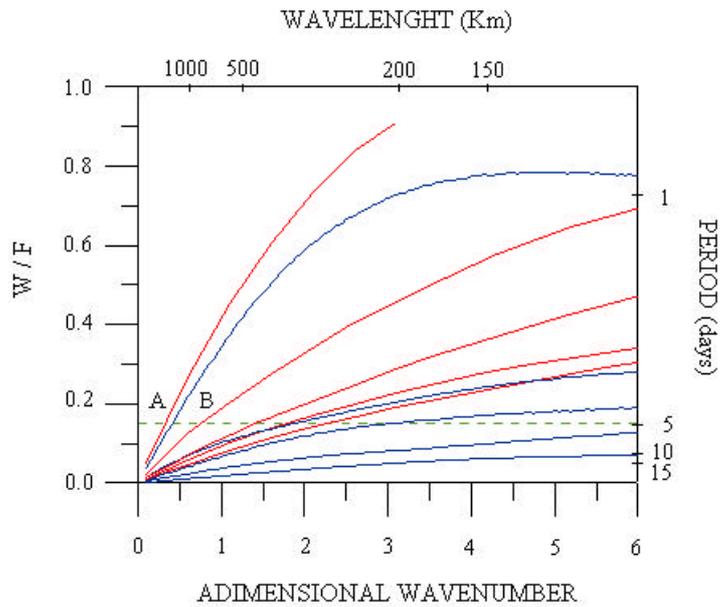


Figure 10. Dispersion diagram of the CTW modes found for the northern Portuguese coast, at the latitude of the 1987 moorings (in red). Also shown the correspondent barotropic solutions (in blue). The discontinuous green line corresponds to the region of atmospheric forcing discussed in the text. The typical spatial scale is $L=100\text{Km}$.

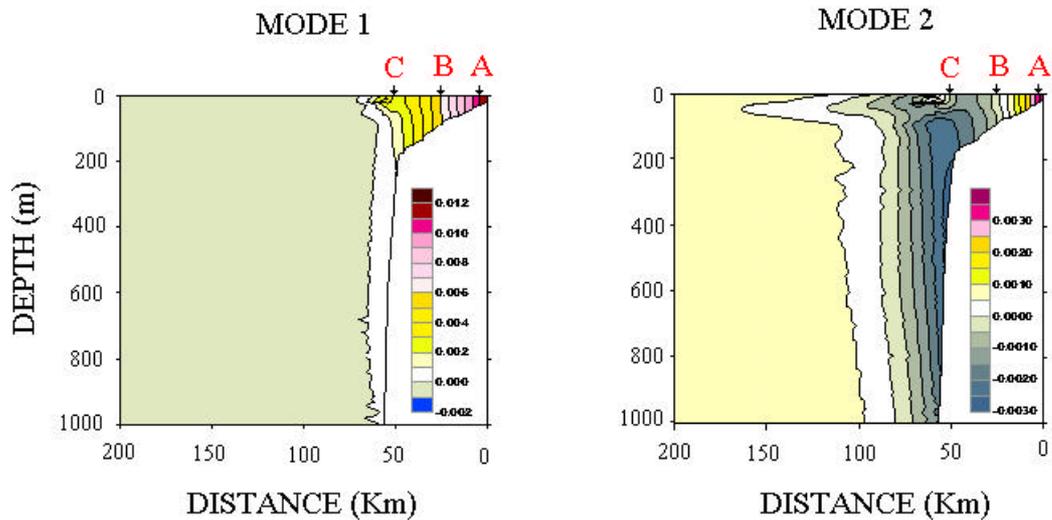


Figure 11. Pressure perturbation for the first CTW modes excited by fluctuations in the atmospheric forcing with time scales of 4-5 days. Left - Mode 1 (solutions A in figure 10). Right - Mode 2 (solution B in figure 10). For details see text

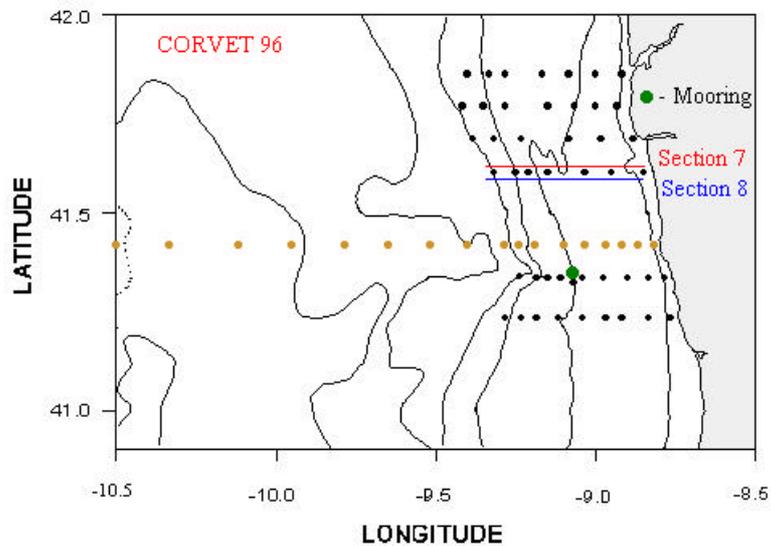


Figure 12a. Part of the hydrographic/SPM stations covered during the CORVET 96 cruise (6-23 November 96). Brown dots are stations made during the first phase of the cruise. Black dots are stations made during the local study (12-22 November). The two repeated sections (sections 7 and 8) are indicated with different colours. Also show the location of the current meter mooring deployed at the beginning of the local study

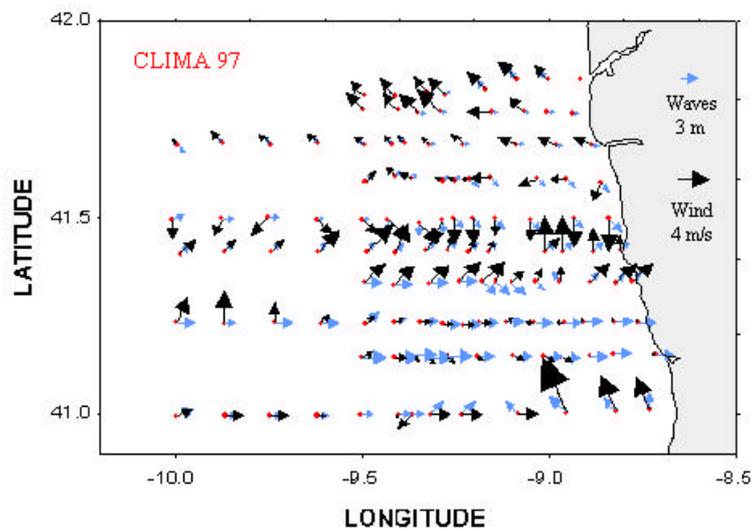


Figure 12b. Hydrographic/SPM stations achieved during the CLIMA 97 cruise (6-14 December 1997). The observations of wind and waves made at each station are also included.

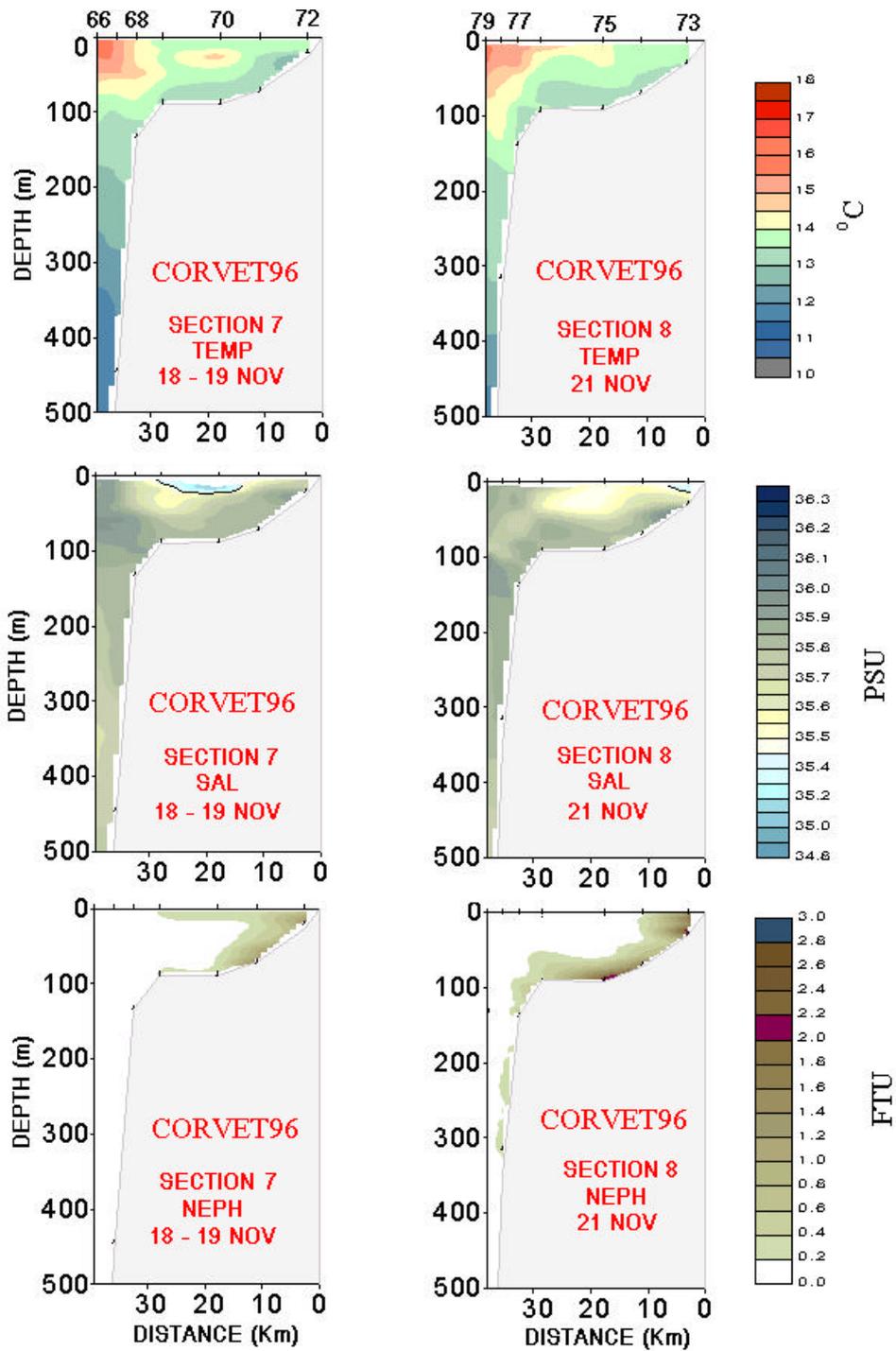


Figure 13a. Temperature, salinity and nephelometry sections before the storm of 19-20 November.

Figure 13b. Temperature, salinity and nephelometry sections after the storm of 19-20 November.

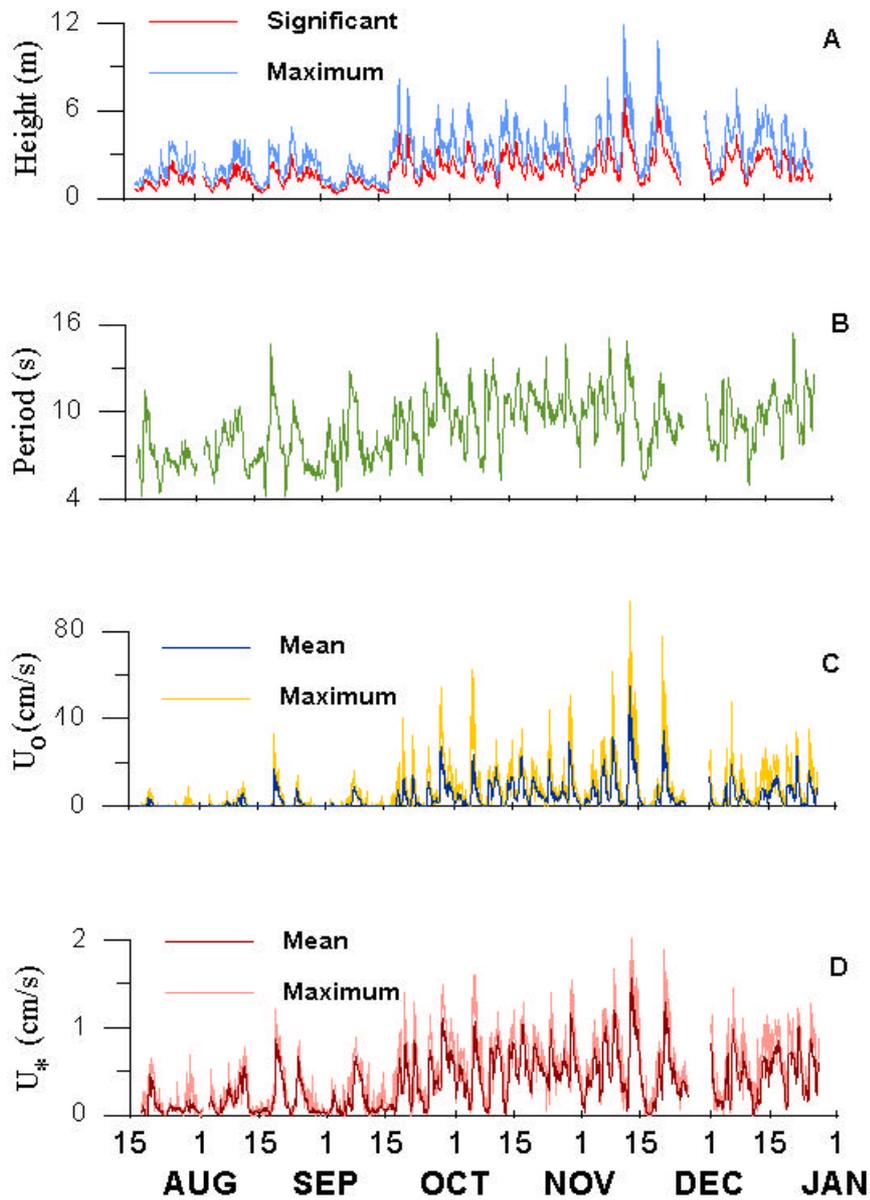


Figure 14. Characteristics of the wave field at the mid-shelf off Leixões (41° 05'N) measured by a WAVEC wave buoy. From top to bottom: A) significant and maximum wave height, B) mean period, C) mean and maximum orbital velocity at the bottom (84m) and D) mean and maximum shear velocity.

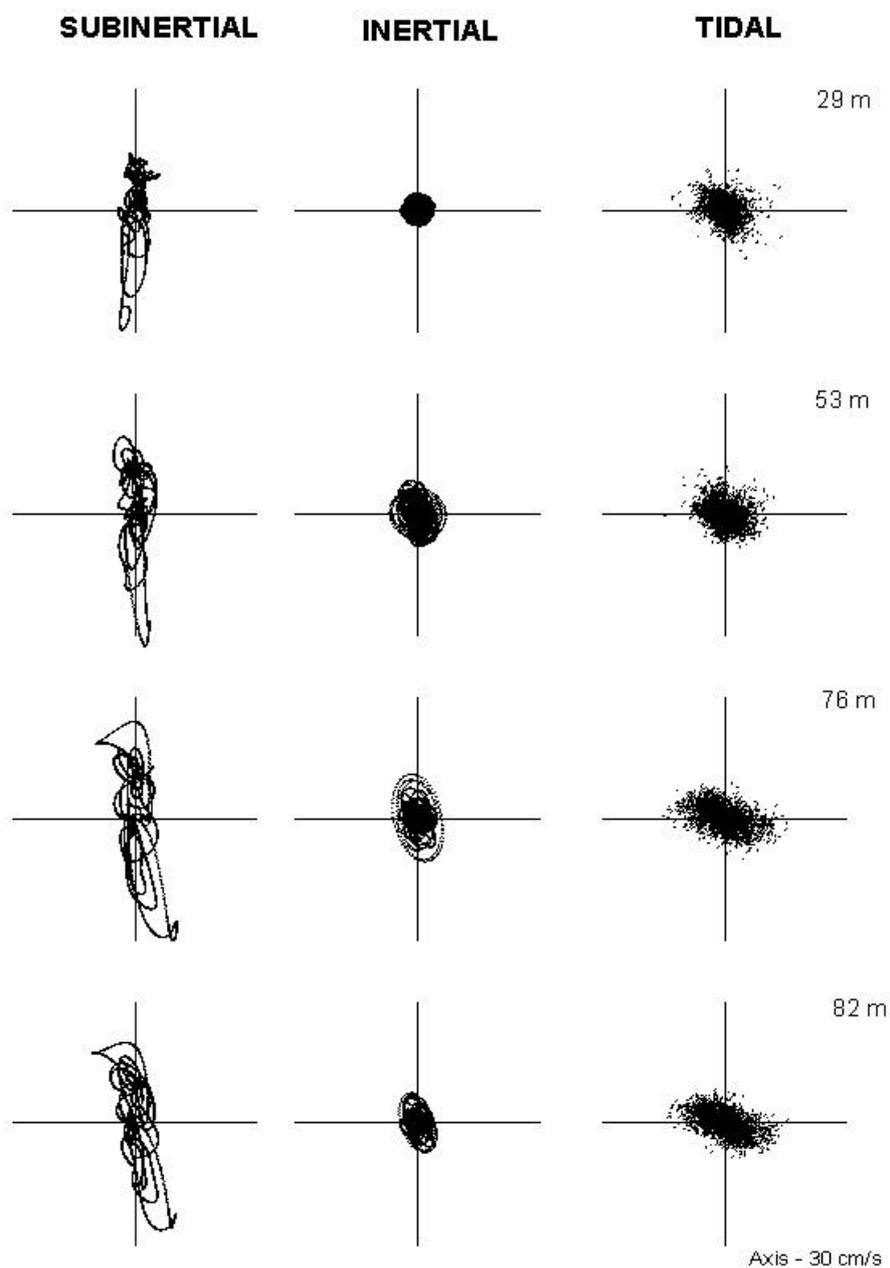


Figure 15. Scatter diagrams of currents measured at the mooring maintained, from November 1996 to January 1997, off Leixões (41° 19'N). The contributions of the three variability bands are presented separately. Axis cover the interval [-30,+30] cm/s.

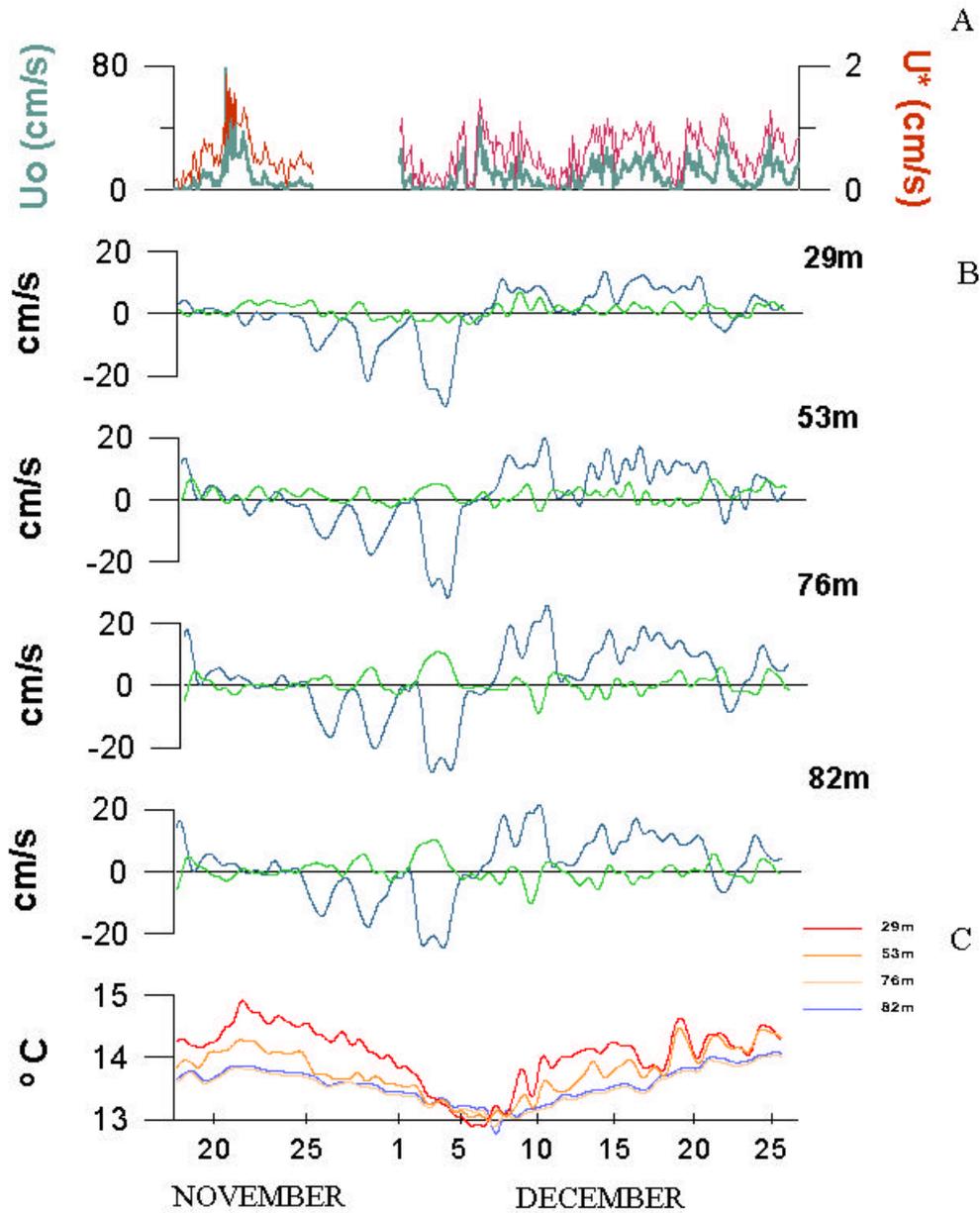


Figure 16. Continuous measurements of waves and currents at the mid-shelf off Leixões (41° 05'N) during the winter 1996. A) maximum wave orbital and shear velocities at the bottom (84m), B) Alongshore (blue) and cross-shore components of residual current and C) temperature time series.