

Acoustic Tomography Ocean Monitoring System (ATOMS)

Contract number: PDCTM/P/MAR/15296/1999

Final Report

Coordinating Institution: CINTAL - Centro de Investigação Tecnológica
do Algarve

Partners: Instituto Hidrográfico
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Part A - Coordination Report

1 Progress

Project “ATOMS - Acoustic Tomography Monitoring System”, here below designated as ATOMS, was initially scheduled to last for 3 years. Due to two successive extensions of 6 months and one of 3 months, the actual project duration was 4 years and 3 months, finally ending on December 31, 2004. The justification for the extensions was the completion of the technical program, namely the sea trial (task A.3.2) and the associated data analysis (tasks A.4.1 to A.4.4). The sea trial was first scheduled to take place in July 2004 and was then postponed, due to unreadiness of the ship, to the month of October (which justified the last three month extension). The ATOMS sea trial finally took place between 22 and 26 October 2004, for a total of 5 days. Unfortunately, the weather conditions on the area at that time of the year were such that, in agreement with the D. Carlos I commanding officer, no acoustic equipment could be deployed and therefore only non-acoustic (environmental) measurements such as CTD, currents and water sample data could be collected during the cruise.

Taking into account that no acoustic data was collected, tasks A.4.1 and A.4.3 could not be achieved, also task A.4.2. was only superficially performed in the very short two months period left between the sea trial and the project termination. That data set has, however, a potential for further in depth analysis in the months and maybe years to come. Apart from the last two months where CIMA was working full time on the analysis of the data gathered during the sea trial, the other teams were mostly involved with the preparation of the sea trial: first for the July trial, then aborted, and later on for the October sea trial. Extremely long equipment testing in the lab was performed. This involved the acoustic source and respective cable (purchased and build on purpose for the ATOMS sea trial), the acoustic power amplifiers, a courtesy loan from CMO/SHOM (Brest, France), and the ULVA receiving array.

The data gathered during the sea trial consists in a impressionant data set for the observation of the Cape São Vicente filament area, which is one of the most developed and recurrent existing filament system and has important implications in the biological and chemical exchanges between the coastal and offshore ocean. Preliminary results show that the filament was present during the period of observation and the data set has a potential for more in depth analysis in the years to come. During this year there were two national conference presentations, one international conference one Ph.D. thesis, one international journal paper published and one submitted for publication.

2 Tasks under completion

Task 3: Sea trial

Sub-task A3.2: Full scale sea trial

Responsible: IH

Duration: month 12 - 18 (initial schedule)

The sea trial took place for 5 days between October 22 and 26, 2004. These 5 days were reduced to 4 effective days on site (1 day transit), during which no acoustic equipment was deployed due to sea state and therefore only the oceanographic and chemical data survey could be achieved.

Task 4: Data analysis and validation

Sub-task A4.1: Application of optimized methods to acoustic data

Responsible: CINTAL

Duration: 12-36 months (initial schedule)

There was no acoustic data to perform this task.

Sub-task A4.2: Analysis of acquired oceanographic data

Responsible: CIMA

Duration: 12-36 months

Direct observations performed during the sea trial cruise concerning the oceanographic characterization of the upwelling filament off Cape São Vicente, under the responsibility of CIMA/UAlg, were:

- CTD and ADCP data
- Meteorological and thermo-salinometer data
- Monitoring of satellite data
- Collection of water samples for chemical and biological characterisation of the filament

The sea trial was undertaken in the period from 22 to 26 of October of 2004, during an extent of approximately 84 hours, in which 42 oceanographic stations were executed (Fig. 3).

Sub-task A4.3: Comparison of direct and inverted data for validation

Responsible: CIMA

Duration: 30-36 months

No comparison could be performed since there was no acoustic data to perform the inversion.

3 Conclusion

From the coordination point of view this project was deeply marked by the availability of the research vessel for the main full scale sea trial - the NRP D. Carlos I. The sea trial was initially scheduled for project year two and finally took place more than four years after project start. This means that there was absolutely no time for data analysis within the project allocated time and therefore most of project resources were spent on sea trial preparation, running algorithms on simulations and analysing data from other cruises. Moreover, the ATOMS sea trial did provide a large amount of temperature, current and biological data but did not allowed to make simultaneous acoustic observations of the filament structure. However, the acoustic tomography equipment developed in the present project was used in the framework of other projects run by the same team and proved successful. The acoustic data analysis developed on simulated data for ATOMS were also applied and tested in other data sets. The large number of both international conferences and journal publications that were made under this project, represent the final recognition of the amount and quality of the work performed.

Future projects involving sea trials and specific data gathering platforms should require a better coordination between the project requirements and the resources availability.

Part B - Scientific Report

1 Introduction

Filaments of upwelled waters are recognized to be of strong hydrodynamic activity and flow patterns, accompanied by changes in the biological and chemical fluxes. High concentrations of chlorophyll due to an excess of nutrients are observed and consequently primary production is high. The offshore transport in the filament structures may represent an efficient way of exchange of mass with the open ocean. The Cape São Vicente is an upwelling center under wind favourable conditions and is the origin of one of the major and more recurrent cold filament observed along the coast of Iberia. The fact that Cape São Vicente has associated to singular cold filaments makes it an interesting target region to investigate such features. In addition, a description trough in situ sampling of a filament feature off Iberia has never been succeeded and the past research was based in remote sensed data. Furthermore a multidisciplinary approach of characterization of cold water filaments in the Portuguese coastal transition zone using standard and/or tomography techniques was never done. Employing remote sensing acoustic techniques for resolving the filament structure and its evolution through time constitutes undoubtedly a world premiere. The excess of offshore transport of mass, nutrients, and phytoplankton due to these features was never estimated for filaments off Portugal. Consequently, the description of the structure and dynamics of a filament off Iberia and its implications in chemical and biological cycles would be a valuable contribution for that purpose.

Detecting the onset and offset of an upwelling filament is an interesting, yet difficult problem in operational oceanography. Even if satellite imagery is a powerfull tool for detecting and approximately localizing the filament, its dynamical behaviour in the vertical and cross planes can not be precisely and timely assessed with current oceanographic sampling techniques. Ocean Acoustic Tomography (OAT) is the technique of choice for determining temperature disturbances along depth withing the acoustic propagation path between source(s) and receiver(s). Classic OAT, as originally proposed by Munk it et al. [1, 2], mostly deals with deep water long range estimates using travel time tomography. The basic idea is that the acoustic signal is deflected by the ocean stratification in a unique way, such that the travel times of the various rays reaching a given receiver represent an inprint that can be associated to one and only one water mass stratification profile. With various sources and various receivers the ocean volume is crossed by multiple rays at a given time so it becomes possible, in a similar way then with biomedical tomography, to obtain an image of the temperature over the ocean volume in depth, range and cross-range. There are numerous publications showing the application of OAT and its derivatives (such as Matched Field Tomography - MFT) to invert for a number of oceanographic features and environmental situations (see intermediate ATOMS reports for an extensive list

of references in the subject).

However, there is an important impairment with these OAT techniques when attempting to invert for a feature such as a filament: is that the inverted image obtained from a source - receiver pair is an integral measurement of the temperature profile along range between that particular source and receiver. In other words: classic OAT is not range-dependent. This last topic has received particular attention in ATOMS since the problem at hand, namely determining the upwelling filament onset and offset, define a strongly range-dependent acoustic propagation channel. One of the most stringent tasks in producing range-dependent tomographic estimates is the choice of the parameterization of the medium of propagation, that is a compromise between a high flexibility, to accurately represent the phenomena, and a low number of parameters being manageable in the inversion process. Such a parameterization was proposed in [3] and was showed to allow a high flexibility in modelling the California Coastal System upwelling. An alternative parameterization is now proposed in [5] and is discussed in greater detail in section 2.

Another important question to be taken into account in MFT is the choice of the objective function to be optimised. The crucial question here is to define the best representation in the optimization space that allows the most sensitive estimation of the parameter set. This is a particularly hard problem in presence of noise and model mismatch. In practice model mismatch can not be analitically handled while the presence of noise in the data is normally introduced by considering a deterministic observation corrupted by additive noise and defining a minimal statistic for the parameter vector. Such derivation is further complicated when the data available mixes different data types, such as the data observed in the spatial domain and in the frequency domain. An interesting derivation of such an objective function that allows a simple optimization procedure is proposed in [4] and is also summarized in section 3.

The final scope of estimating oceanographic features from indirect acoustic measurements is to be able to incorporate that information into actual directly measured oceanographic data. The objective is to complement *in situ* measurements with acoustic remote data, to obtain a full picture of the oceanic volume mass. There are a number of techniques, known as data assimilation, that aim at coherent integration of data of different nature and from a variety of sources, to describe the same phenomena. Such an effort is underway in a study carried out at CINTAL's SiPLAB laboratory that could be applied to the upwelling filament observations under ATOMS [6]. Acoustic and direct oceanographic observations are being associated with temporal and spatial correlation lengths and their respective estimates through time and space interpolated within a state space representation model and optimal Kalman predictors. These techniques draw their roots from the work of Elisseff [7] and Lermusieux [8].

In order to demonstrate the feasibility of the ATOMS project, an experimental test including a research cruise, was planned to characterize the upwelling filament

structure of the Cape São Vicente. Due to a second postponement of the ATOMS sea trial scheduling changed from 2003 to the summer 2004. However, another delay occurred associated with the availability of the oceanographic vessel resources, but at last during October of 2004, a sea trial was performed. The previous monitoring of the study area by observation of satellite imagery of sea surface temperature revealed the presence of an upwelling filament structure in the region. Such event is not frequent during this time of the year. Its presence did allow to fulfil one important objective of the sea trial. Unfortunately, due to bad weather conditions, no work concerning OAT was undertaken at sea during the cruise and consequently no validation with the physical (CTD and ADCP), chemical and biological data (from water samples collected) was carried out.

2 Range-dependent acoustic tomography

Acoustic tomography in range-dependent waveguides using a source-array pair represents an inverse problem with potentially many solutions. One of the aspects contributing to a successful inversion is the ability to correctly model the environmental variation through range: the suited model is the one that provides the best fit with the data and has the minimum number of coefficients. Obviously these are two contradictory requirements that call for a case dependent compromise. The present problem is to model an upwelling filament which is a localized uprise of cold water, introducing a high degree of range dependence. In this study a parameterization scheme with a reduced number of parameters is proposed in order to represent the spatial evolution of the filament using an asymmetric Gaussian function parameterized by two variances, an amplitude coefficient and a mean value. Using a real data example of the filament of the California Current System (CSS), this modeling scheme was tested on semi-synthetic data [5]. The results indicate that such an approach can be considered for an efficient modeling of a complex oceanographic feature.

3 The inchoerent cross-frequency processor

Matched-field based methods always involve the comparison of a physical model output and the actual data. The method of comparison and the nature of the data varies according to the problem at hand, but the result becomes always largely conditioned by the accurateness of the physical model and the amount of data available. The usage of broadband methods has become a widely used approach to increase the amount of data and to stabilize the estimation process. Due to the difficulties to accurately predict the phase of the acoustic field the problem whether the information should be coherently or incoherently combined across frequency has been an open debate in the last years. The work performed on this subject by Soares *et. all.* [4], provides a data consistent model for the observed signal, formed by a deterministic

channel structure multiplied by a perturbation random factor plus noise. The cross-frequency channel structure and the correlation of the perturbation random factor are shown to be the main causes of processor performance degradation. Different Bartlett processors, such as the incoherent processor [9], the coherent normalized processor [10] and the matched-phase processor [11], are analysed and compared in light of the optimum processor performance. Finally a cross-frequency incoherent processor is proposed that is analytically shown to have the same performance as the matched-phase processor with however an extremely low computation complexity.

4 Modeling of the Cape São Vicente Filament

4.1 ROMS: The Regional Ocean Modeling System and the Cape São Vicente region

The Regional Ocean Modeling System (ROMS) is a free surface primitive equations ocean model being used by a rapidly growing user community for applications from the basin to coastal and estuarine scales (e.g. Marchesiello et al. [17]). Model features are described elsewhere (Shchepetkin and McWilliams [21]). A major advance is the implementation of conservative parabolic-spline discretization in the vertical, which has greatly reduced the pressure-gradient truncation error that has plagued previous terrain-following coordinates models.

ROMS has been configured for a region of the southeastern Iberian Peninsula. Using the ROMS model, ocean conditions in the environs of the Cape São Vicente, with particular devotion to the development of the Cape São Vicente filament, are studied. To provide useful pictures of the regional circulation, ROMS should capture the essential features of the 3-dimensional heat transport on diurnal to several day time-scales, and spatial scales of order 5 km. To achieve this, we have employed a high degree of realism in the configuration of model bathymetry and forcing. The present model has fine grid spacing (5 km) and realistic bathymetry from the Sandwell/Smith 2x2 min data set. Air-sea heat and momentum fluxes are calculated by the bulk formulae of Fairall et al. [15] using the model sea surface temperature and external forcing. The external forcing is given by momentum, heat, freshwater flux at the surface and adaptive nudging to gyre-scale fields at the boundaries. The fluxes are sea level air temperature, pressure, relative humidity and downward long-wave and short-wave radiation obtained from NCEP, and 10-meter winds obtained from either NCEP or QuikSCAT.

The model configuration consists of open a domain along the box 34N 13W 41N 4.5W. Currently we are working with the N, W and S boundaries open and with a number of nudging conditions. In an initial approach we were applying a mean stratification characteristic of winter-spring conditions. In this stage of the works, we are applying active/passive inflow/outflow open boundaries (Marchesiello et al. [17])

incorporating somewhat more complex climatologies specially of the shelf circulation. These make the conduction of a twofold set of simulations possible. On one hand, the model starts from an equilibrium state, which is obtained from a multiple-year cyclic run of a sub-nested grid taken from a ROMS configuration running for the North Atlantic Ocean. This field is being taken as the initial and climatology reference values. This work is being conducted in a cooperative effort together with the Physics Department of the University of Aveiro. On the other hand, a finer scale Spring-Summer climatology prepared from NODC ([20]) is introduced and merged with larger scale climatologies obtained from other sources, either ocean models or in situ data (http://cls.mersea.eu.org/html/information/data_access.html)

Given that the wind stress is the primary forcing mechanism, several wind forcing patterns are being tested. The ROMS is being used to test the system response to four particular wind forcing conditions: spatially homogeneous constant/variable equatorward winds, spatially heterogeneous constant/variable equatorward winds.

The 160x148 resolution grid with 25 vertical levels requires approximately 50 CPU minutes per model day on single-processor AMD Linux-PC.

The solutions show realistic variability and the mesoscale structure of the circulation in the Cape São Vicente region as compared with the observations. The Figs. 1 and 2 represent the development of an upwelling filament at the Cape São Vicente. Some of the most frequently observed features of the filament can be observed. For instance the asymmetrical structure of the filament is closely reproduced. A vertical cross-section (Fig. 2) shows that the filament has indeed a consistent deep structure. The spatial asymmetry is also observed as the minimum SST is shifted with respect to the maximum uplifting of the pycnocline, as it has been observed from in situ data (e.g. this report).

The positive wind curl south of Cape São Vicente intensifies the local upwelling and also might introduce a domain scale pressure gradient which plays an important role in the shelf circulation. Currently the interaction between wind-driven circulation, the complicated bottom topography and the offshore eddy field is being studied with the aid of energy balances. Future analysis of the simulations will focus on critically comparing observed and modeled processes.

5 Sea Trial

The ATOMS sea campaign took place on board of the oceanographic vessel N.R.P D. Carlos I, from the Portuguese Navy, operated by the scientific staff of Instituto Hidrográfico and CIMA - Univ. Algarve.

Direct observations performed during the sea trial cruise concerning the oceanographic characterization of the upwelling filament off Cape São Vicente, under the responsibility of CIMA/UAlg, were:

- CTD and ADCP data

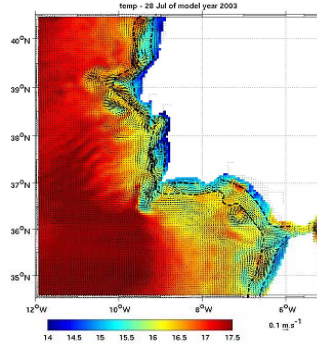


Figure 1: Results of a ROMS simulation for July 2003. The velocity vectors are also plotted. The presence of the Cape São Vicente and Cape da Roca filament is evident.

- Meteorological and termo-salinometer data
- Monitoring of satellite data

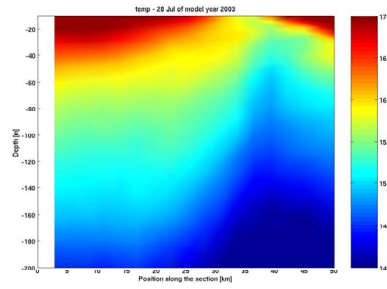


Figure 2: Simulated temperature cross-section of the Cape São Vicente filament. Note the strong uplift of the thermocline associated with the axis of the filament.

- Collection of water samples for chemical and biological characterisation of the filament

The sea trial was undertaken in the period from 22 to 26 of October of 2004, during an extent of approximately 84 hours, in which 42 oceanographic stations were

executed (Fig. 3).

22 of October of 2004

10:00 Departure: Navy Base of Lisbon

20:00 Transit time from Lisboa to working area

Start of the oceanographic survey for the filament characterization

25 of October

12:00 End of the oceanographic survey for the filament characterization

Start ADCP in transit

24:00 Stop ADCP in transit

transit to Lisboa

26 October

10:00 arrival at BNL

A complete data report of the ATOMS Sea Trial is being prepared.

6 Characterization of the upwelling filament off Cape São Vicente through *in situ* observations

6.1 Oceanographic Data Collection and Sampling

Monitoring of the evolution of the sea surface temperature (SST) patterns in the region started one month before the cruise time, through the analysis of AVHRR imagery. Images were downloaded at least two times a day from NERC - Remote Sensing Data Analysis Service (RSDAS) - Plymouth Marine Laboratory (PML), UK, following a protocol established with this institution. The acquisition of AVHRR imagery continued on board. Thus, the exact definition of the cruise track and sampling stations was guided, almost on real time, by the analysis of the SST patterns provided by the AVHRR images. A cold filament of upwelled water was identified in the region and a total of 42 stations were sampled in order to characterize the filament from the physical, chemical and biological point of view.

Geo-referenced wind speed data, corrected for the ship velocity, was continuously recorded from the onboard meteorological station (Fig. 4). Geo-referenced surface temperature (Fig. 5) and sound velocity were continuously recorded from the onboard probe at 5.1 meters depth. Combination of these two parameters will allow the determination of the surface salinity.

The flow field was measured along track through a 38 kHz RDI hull-mounted ADCP, operating in broad band. Most of the cruise was covered with bottom track calibration. A water track calibration was applied in the when bottom track was not available. Vertical bins were set to 20 meters.

The study area was divided in 6 transects/sections across the filament, and the survey of temperature, salinity and depth/pressure (CTD) data extended from the surface to a maximum depth of 400 m, since upwelling is a superficial oceanographic

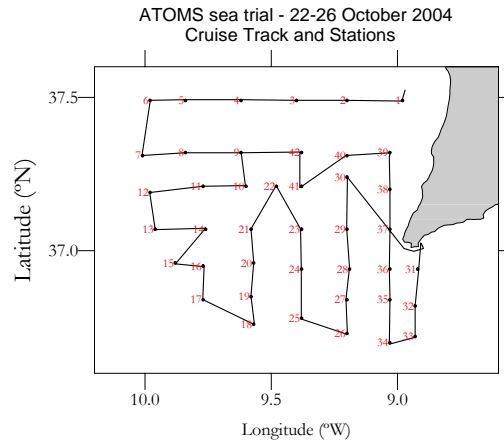


Figure 3: ATOMS Sea Trial - Cruise Track and Stations

process. CTD readings were monitored on real time from onboard. The recording of these parameters were achieved by a Idronaut OS316 CTD (2 sets of data per second, descending 1 m/s) coupled to a General Oceanics rosette with 11 Niskin bottles of 5 L to collect water samples at several depths in each station. The 10 selected levels for collection of water samples were: 5 (surface), 10, 20, 30, 50, 75, 100, 150, 200,

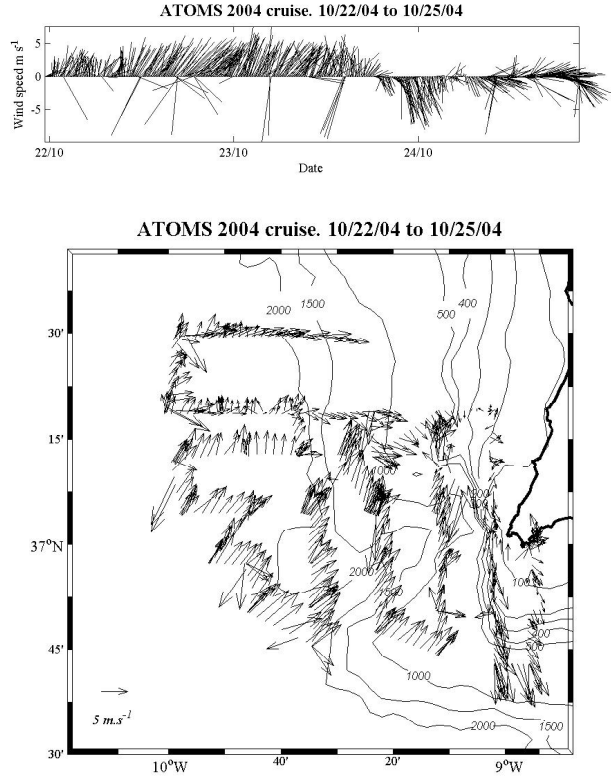


Figure 4: Wind vectors from the onboard meteorological station, displayed as a time series (top) and along-track (bottom).

400 meters depth.

The chemical parameters determined at each level of water sampling were: dissolved oxygen, suspended solids, nutrients of nitrogen (nitrate, nitrite, and ammonium), of phosphorus (phosphate) and of (silicate) while the biological ones were:

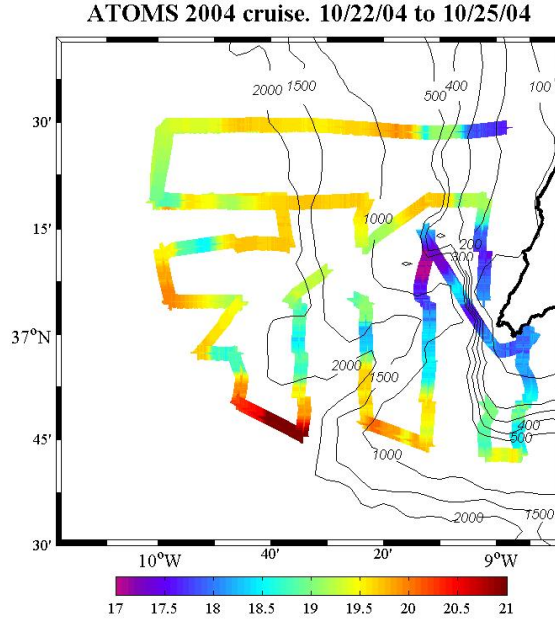


Figure 5: Along-track temperature at 5.1 meters depth from the hull mounted probe.

chlorophyll a and phaeopigments, and identification (qualitative and quantitative analysis) of major phytoplanktonic groups.

The Niskin bottles of 5 L in the rosette sampler coupled to the CTD were identified with the correspondent level of water collection (10 levels). At each level of the sampling stations, 2 flasks of 1L were filled, one for the determination nutrients

and suspended solids and the other for chlorophyll a and phaeopigments, and phytoplankton. 2 flasks of Winkler of ca. 100ml (duplicates) were also over filled with water for determination of dissolved oxygen. Each of the flasks was previously 3 times washed with the water sample, completely filled and stoppered. In relation to oxygen samples it was strictly avoided the entrance of air bubbles; samples were immediately stoppered and kept in a dark place. It must be mentioned that the 400 m level was not sampled for chlorophyll a, phaeopigments and phytoplankton since there there is no enough light to algae survive.

6.2 Work at the wet laboratory

All the water samples correspondent to the levels sampled were transported to a wet laboratory in the vessel. At this laboratory, after the homogenisation of the water samples of 1 L, there was a separation in sub-samples for different parameters. From the one of the flasks, there was the separation of suspended solids from the solution by the filtration of 500 mL of water in a polypropylene filtration apparatus system (1 L) connected to a vacuum pump, using pre-washed and pre-weighted membrane filters of 0.45 μ m. After the filtration the filters were kept in identified plastic Petri Dishes and sealed for the posterior gravimetric analysis. The filtered water samples were poured into acid-washed polyethylene cups and immediately deep-frozen on board at -20°C prior to analysis of nutrient concentrations that will be conducted at the laboratory of the University of Algarve. For the other flask of 1 L there was filtration of 250 ml of water samples (in duplicate) through GF/F glass fibre filters, in a 3 position (500 mL) PVC filtration apparatus system connected to a vacuum pump. After the filtration the filters were identified, kept in aluminium foil (to avoid light that can cause degradation of chlorophyll) and immediately deep-frozen at -20°C until further analysis of chlorophyll a and phaeopigments, conducted as soon as possible. The rest of the 500 ml were stored and preserved with neutral iodine solution - Lugol and stored in the dark until further examination.

Relatively to the dissolved oxygen, it was determined on board following the Winkler method, modified by Carrit and Carpenter (1966), as described in Grasshoff et al., 1983. Dissolved Oxygen samples were immediately fixed after collection with 1 mL of a divalent manganese solution followed by 1 mL of a strong alkali after agitation of the flasks (at least 10 times). A precipitation of a complex was formed. After the settling of this complex, it was dissolved by the addition of sulphuric acid and iodine is liberated, equivalent to the original dissolved oxygen content of the water. The amount of iodine is then determined by titration using an automated microtitration apparatus (Methrom), with standardised thiosulphate solution. The iodine is reduced to iodide and the thiosulphate is in turn oxidised to the tetrathionate ion. The concentration of thiosulphate solution used for the titration must be known precisely. The endpoint of the redox titration is detected visually by a starch indicator, which is clearly marked by the change from blue to colourless. The calculation of

dissolved oxygen concentration is as follows:

$$O_2 = \frac{(v - a) \times f \times 0.16 \times 10^3}{V - 2}$$

$$f = \frac{5}{T}$$

where: O_2 =dissolved oxygen concentration (mgL^{-1}); v =volume of thiosulphate used in titration of the sample (mL); a =volume of thiosulphate used in titration of the blank (mL); f =standardisation factor of thiosulphate, where T =volume of thiosulphate used in standardisation titration of 10 mL of the primary standard of iodine-potassium iodine (mL); V =volume of sample bottle (mL); 2=correction volume of the addition of reagents (manganous and iodine). The standard deviation for the duplicates was always lower than 5%. All the identification and data relatively to chemical and biological samples were registered in the logging book.

6.3 Laboratorial Analysis

After the cruise, the determination of the chemical biological analysis was performed as soon as possible, at the laboratory of the University of Algarve:

- **Suspended Solids** - The suspended solids from a single sample of 500 mL was determined by the gravimetric method described by A.P.W.A. (1992). The sample was well mixed and filtered through a pre-washed and pre-weighed 0.45 μm filter, and the filtered volume registered. The residue retained on the filter is dried at 103-105°C for at least 1 hour and then cooled in a desiccator before weighing. The cycle of drying, cooling, desiccating, and weighing is repeated until a constant weight is obtained or until the weight loss is less than 5% of the previous weight or 0.5 mg, whichever is less. The increase in weight of the filter represents the total suspended solids. The calculation of Suspended Solids is determined as following:

$$S.S = \frac{(FW - IW) \times 10^3}{V}$$

where: $S.S$ = suspended solids (mg L^{-1}); FW = final weight of the filter (weight of filter + dried residue (g)); IW = initial weight of the filter (weight of filter (g)); V = volume filtered of the sample (L^{-1}).

- **Nutrients** - The nutrient concentrations of ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}) and silicate (SiO_4^{4-}) were determined by spectrophotometric/colorimetric methods, based on calibration curves of standard solutions according to the methods described by Grasshoff et al. (1983).

For those analysis a Spectronic UNICAM Spectrophotometer, UV-300 was used. The general formula of nutrient concentration determination was:

$$Nutrient\ concentration(\mu M) = \frac{(ABS - a)}{b}$$

where: ABS = absorbance of the sample; a = intercept of the regression line obtained from the calibration curve; b = slope of the regression line obtained from the calibration curve.

The Marine Nutrient Standard Kit was used as reference material, produced by the *Ocean Scientific International Laboratory* (Southampton, United Kingdom). The standard deviation with respect to the mean calculated for all samples of the study was always less than 5%. The precision as well as the limit of detection for the nutrients were also carried out.

- Chlorophyll a and phaeopigments - concentrations were determined in the subsequent week after the cruise, at the IPIMAR- Lisboa, based on the extraction of chlorophyll a from the GF/F filters in 90% acetone during 24 h, after this period the filters were grinded and centrifuged during 10 minutes at 3000 rpm and chlorophyll a and phaeopigments quantified in a Perkin-Elmer spectrofluorometer, as described by Yentsch and Menzel, 1963. The Perkin-Elmer spectrofluorometer was calibrated with a dilution series of a standard chlorophyll a solutions quantified spectrophotometrically.
- Quantitative and Qualitative analysis of phytoplankton - Phytoplankton samples (500 mL) preserved with Lugol's were stored in the dark until further examination. The identification and quantification of the phytoplankton cells was made using the [26] technique. Samples were concentrated by settling 50 mL for 24 hours minimum, in sedimentation chambers. Phytoplankton samples were counted and identified to genus level whenever possible, under a Zeiss Axiovert S100 inverted microscope, using a magnification of 400x. Identification was made with reference to [25], [13], [14], [22], [19], [23] and [24]. In each sample 50 fields were observed, to ensure the count of a minimum of a 100 cells, so that the 95% confidence limits approximate $\pm 20\%$ of the mean (Margalef, 1983). The total numbers were expressed as abundance values (N. cells/mL), according to APHA (1992):

$$Abundance(N.Cel/mL) = \frac{C \times A_t}{A_f \times F \times V}$$

where: C is the number of cells counted; A_t is the total area of the bottom of the settling chamber (mm^2); A_f stands for the area of a field (mm^2); F is the number of counted fields; V stands for the volume of sample settled (mL).

6.4 Preliminary Results

The research cruise, initially scheduled for the second year of the ATOMS Project, took place only in the fourth year. Meanwhile, the completion of the Project was extended to encompass the sea trial. Thus, the cruise was carried out two months before the end of the project. Although this small time span since the end of the *in situ* observations, it is already possible to present some results. However, these results must be regarded as "preliminary" and not analysed results.

6.4.1 Hydrography

The horizontal fields of temperature and salinity at 30 meters depth are represented in Fig. 6. For comparison, the AVHRR image of the sea surface temperature of 23 October 2004 is shown too. Vectors of the computed geostrophic velocities are superimposed in the temperature and salinity fields, showing the offshore excursion of the cold upwelled water within the filament structure. Vertical fields of several parameters (temperature, salinity, sigma-t, buoyancy frequency and turbidity), along a transect crossing the filament, represent the subsurface structure of the cold filament down to 200 meters depth (Fig. 7) and reveal the strong subsurface anomalies associated with the structure.

6.4.2 Velocity fields

Examples of the direct measurements of the horizontal water flow field are represented in Fig. 8. The along track velocity vectors, averaged for the 25-65 meters layer and 45-105 meters layer, processed from the vessel mounted RDI 38 kHz ADCP data are shown. The vectors are superimposed to the sea surface temperature satellite image. The flow field associated with the filament structure is complex, suggesting a filament jet with an anticyclonic circulation to the north and a cyclonic circulation to the south. The intensity of the flow is seen to decay in depth.

6.4.3 Chemical and biological distributions

The quantification of chlorophyll *a* and phaeopigments, suspended solids and dissolved oxygen as well as the calculation of percentage of dissolved oxygen saturation and AOU were already carried out. The dissolved oxygen percentage saturation was calculated using the algorithm given by UNESCO (1973):

$$\ln C = A_1 + A_2(100/T) + A_3 \ln(T/100) + A_4(T/100) + S[B_1 + B_2(T/100) + B_3(T/100)^2]$$

where: $\ln C$ = logarithm of the oxygen concentration $A_1 = -173.4292$; $A_2 = 249.6339$; $A_3 = 143.3483$; $A_4 = -21.8492$; $B_1 = -0.033096$; $B_2 = 0.0142259$; $B_3 = -0.0017000$ T and S are the absolute temperature (K) and salinity respectively.

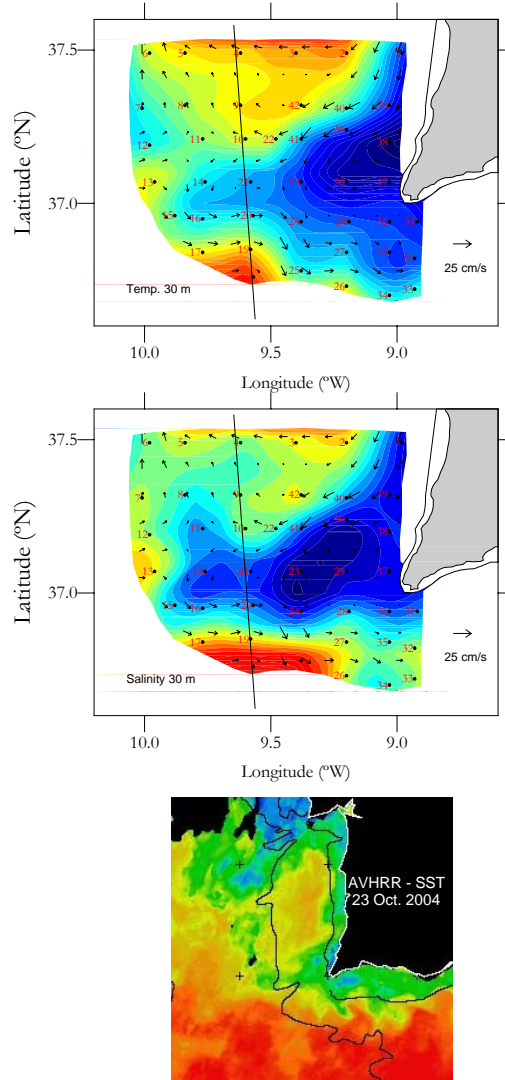


Figure 6: Horizontal fields of temperature (top) and salinity (middle) at 30 meters depth with the vectors of the geostrophic velocities superimposed and SST satellite image (bottom).

The apparent oxygen utilization (AOU), defined by the deficit of oxygen concentration with regard to the saturation concentration in equilibrium with normal

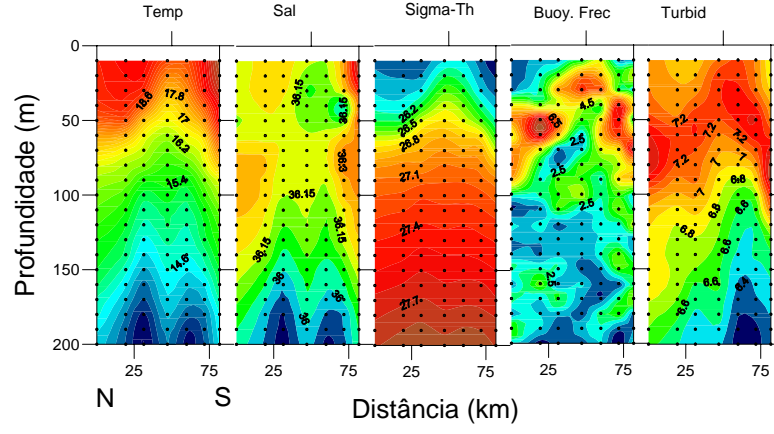


Figure 7: Vertical fields of temperature, salinity, sigma-t, buoyancy frequency and turbidity, along a transect crossing the filament and represented in the previous figure.

atmospheric pressure, was also calculated as:

$$AOU = O_2\text{saturation} - O_2\text{observed}$$

where: $O_2\text{saturation}$ = dissolved oxygen concentration in equilibrium with normal the atmospheric pressure; $O_2\text{observed}$ = determined dissolved oxygen concentration.

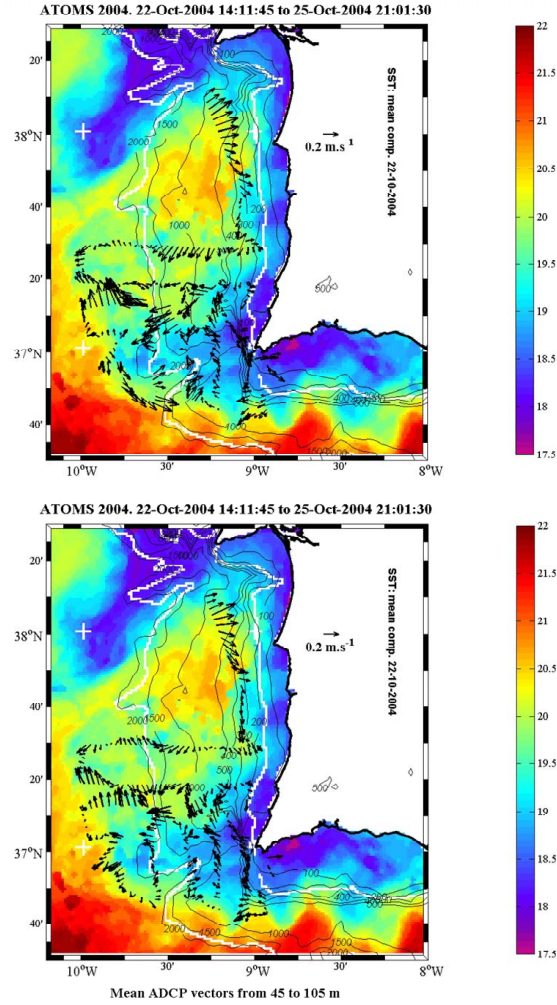


Figure 8: Along track water velocity vectors, averaged for the 25-65 meters layer (top) and 45-105 meters layer (bottom), processed from the vessel mounted ADCP.

Contour mapping of these parameters are being produced based on the calculation of areal integrals by kriging interpolation method.

Relatively to chlorophyll *a*, the highest concentration ($3.6 \mu\text{g/L}$) was found the at the level of 20 m depth, particularly at the most nearest stations to the coast (36-38),

where concentrations varied from 0.6 to 3.6 $\mu\text{g}/\text{L}$ (Fig. 9). Concerning the vertical distribution at this section (vertical transept), it confirms that the highest concentrations were found at stations 37-38, between 10 and 50 m depth, while relatively high concentrations spreads horizontally offshore until station 13, between 20-75 m depth (Fig. 10). Concerning the phytoplankton, despite the analysis are not completed yet,

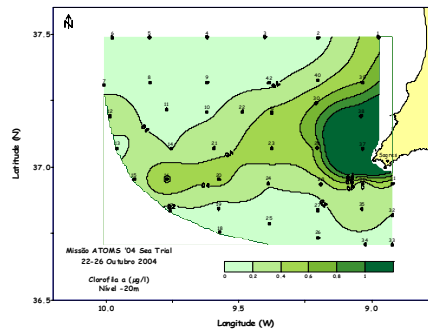


Figure 9: Horizontal distribution of the chlorophyll a at the level of 20 m depth, for the 42 sampled stations

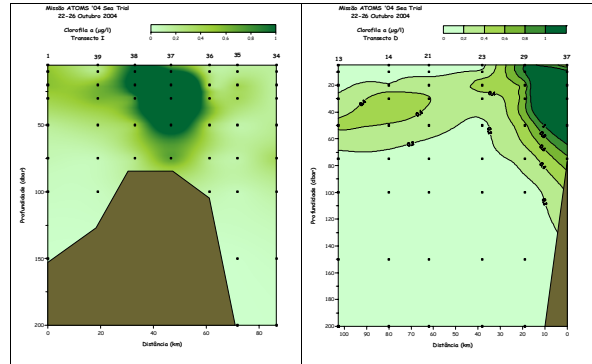


Figure 10: Vertical distribution of the chlorophyll *a* at: a) section I (stations 1, 34-39) and b) at transept D (stations 13, 14, 21, 23, 29, 27)

the main results is that qualitatively the major groups found are: diatoms, dinoflagellates and coccolithofores. Higher densities of phytoplankton match the stations where the highest chlorophyll *a* concentrations were found, particularly between 10 and 50 m depth.

With respect to dissolved oxygen, surface concentrations (Fig. 11a), despite higher

at the stations nearest to the coast, as found for chlorophyll *a*, were not maximal since the highest concentrations were found between 10-30 m depth, almost matching the highest concentrations of chlorophyll *a*. Relatively to bottom concentrations (Fig. 11b) as expected, due to absence of photosynthesis, oxygen concentrations were lower than at surface. It is interesting to show the horizontal concentrations at 75 m depth, where the highest gradient was found, recording the lowest concentrations at the stations close to the coast (Fig. 11c), that when expressed in percentage of saturation (Fig. 11d) revealed values between 90 and 105%. It is also presented the vertical distributions of dissolved oxygen at the vertical transept of the nearest stations to the coast (Fig. 11e) as well as at an intermediate horizontal section (C: 10-12, 22, 41, 30, 38), (Fig. 11f) that show oxygen concentrations decreasing from surface to the bottom, particularly in a drastic way at the shallowest stations, near the coast, below 30-50 m of depth. The horizontal distribution of the suspended solids at the surface (5 m depth), bottom level (400 m depth), 50 m depth and 75 m depth as well the vertical distribution at the meridional section I (stations 1, 34-39) and at the zonal section D (stations 13-14, 21, 23, 29, 37) is presented at Fig. 12.

As observed, the pattern of distribution of suspended solids, despite odd, can be considered relatively similar to that found for chlorophyll *a* distribution, particularly at the depth where the highest concentrations were registered. The horizontal distribution of total inorganic nitrogen (sum of ammonium, nitrite and nitrate) at the surface (5 m depth), bottom level (400 m depth), 30 m depth and 50 m depth as well the vertical distribution at the meridional section I (stations 1, 34-39) and at the zonal section D (stations 13, 14, 21, 23, 29, 37) is presented at Fig. 13. The same type of distributions in relation to the other nutrients of phosphorus (phosphate) and of silicon (silicate) are presented in Figs. 14 and 15, respectively.

Relatively to nutrients of nitrogen, phosphate and silicate, it can be observed in Figs. 13- 15 that both the horizontal and vertical distributions are similar. At surface the nutrient concentrations were low, particularly due to its consumption by phytoplankton whereas at the bottom the concentrations were maximal, associated with remineralization of nutrients, particularly where there is lack of phytoplankton activity due to light limitation. The major horizontal and vertical gradients of variation were observed between 50 m and 75 m depth.

7 Conclusion

One of the main reasons that have retained OAT to be widely used in ocean environmental monitoring is related to the difficulty of precisely controlling both the emitting and receiving systems and the inability to represent highly range-dependent features commonly present in the ocean. Both of these issues were investigated during ATOMS, demonstrating that it is indeed possible, at least with semi-synthetic data, to invert for the water column characteristics (mainly temperature profiles)

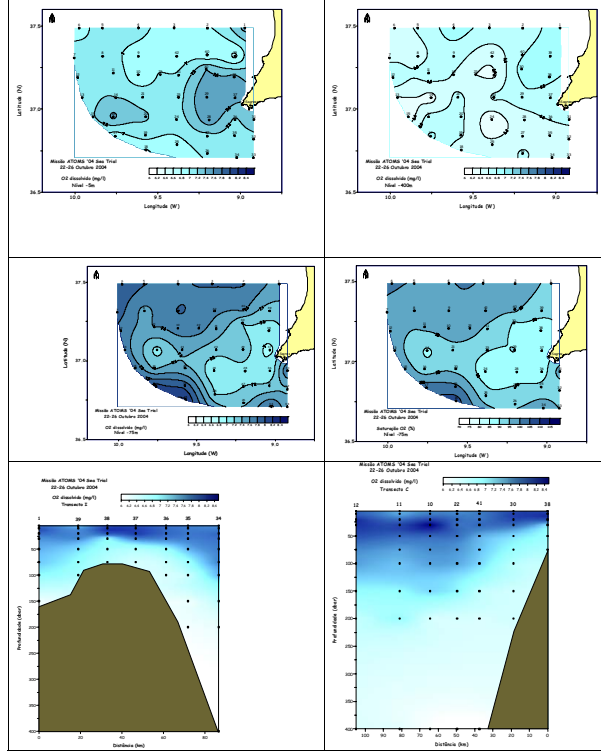


Figure 11: Horizontal distribution of dissolved oxygen concentrations at the: a) surface level (5 m depth), b) bottom level (400 m depth), c) 75 m depth and d) 75 m expressed in % of dissolved oxygen saturation, e) Vertical distribution of dissolved oxygen concentrations at section I (stations 1, 34-39) and f) at transept C (stations 10- 12, 22, 41, 30, 38)

without explicitly knowing relative source-receiver positions with great accuracy.

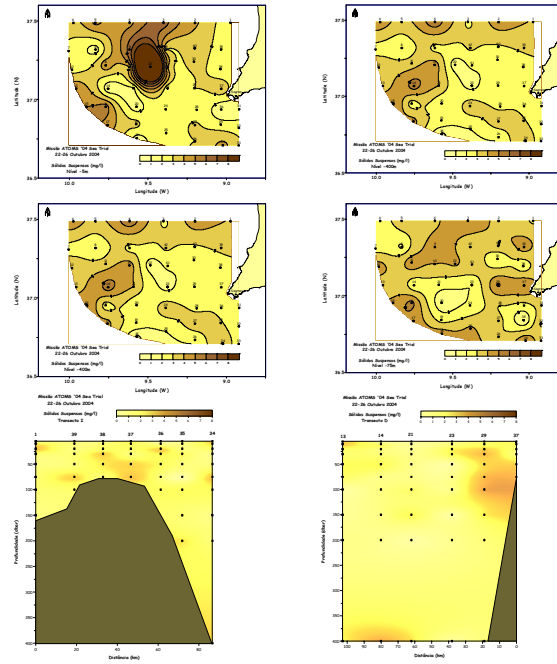


Figure 12: Horizontal distribution of suspended solids (mg/L) at the: a) surface level (5 m depth), b) bottom level (400 m depth), c) 50 m depth and d) 75 m depth and vertical distribution of suspended solids at meridional section I (stations 1, 34-39) and f) at zonal section D (stations 13-14, 21, 23, 29, 37)

To that end a few techniques were shown to be a significant step forward when attempting to optimally combining the cross-frequency information received at a ver-

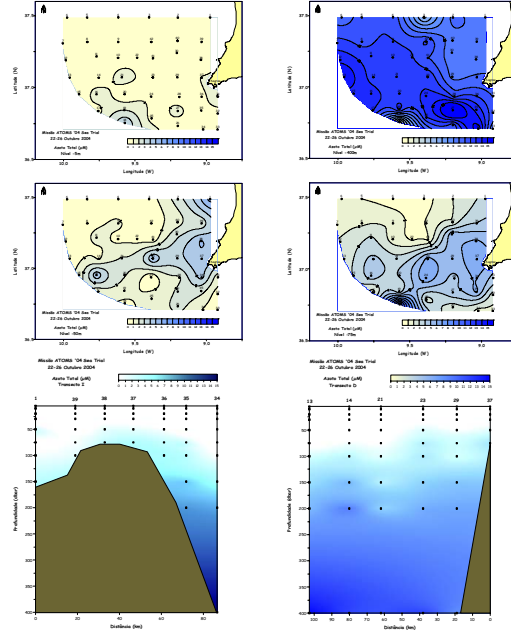


Figure 13: Horizontal distribution of the total inorganic nitrogen (sum of ammonium, nitrite and nitrate) at the surface (5 m depth), bottom level (400 m depth), 50 m depth and 75m depth as well the vertical distribution at the meridional section I (stations 1, 34-39) and at the zonal section D (stations 13-14, 21, 23, 29, 37).

tical array of sensors. Semi-synthetic data was also used to demonstrate, using two different techniques, that range-dependency along the source-receiver plane could be

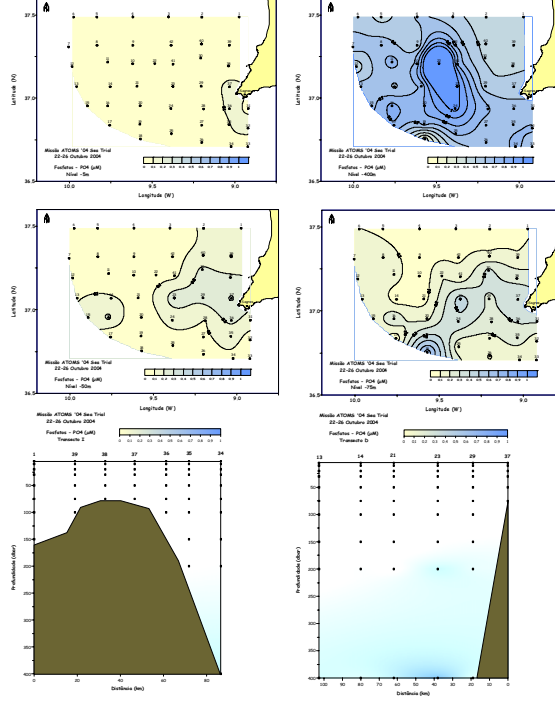


Figure 14: Horizontal distribution of phosphate at the surface (5 m depth), bottom level (400 m depth), 50 m depth and 75m depth as well the vertical distribution at the meridional section I (stations 1, 34-39) and at the zonal section D (stations 13-14, 21, 23, 29, 37).

accounted for with suitable environmental modelling. These semi-simulated tests may still be extended by testing with the temperature profiles recently acquired during

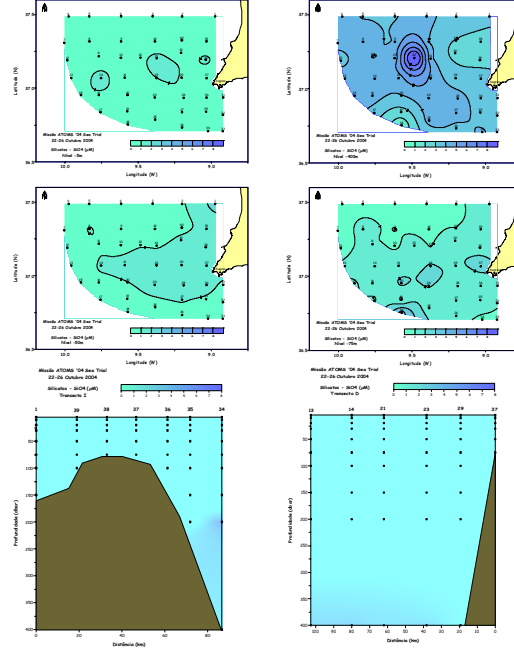


Figure 15: Horizontal distribution of silicate at the surface (5 m depth), bottom level (400 m depth), 50 m depth and 75m depth as well the vertical distribution at the meridional section I (stations 1, 34-39) and at the zonal section D (stations 13-14, 21, 23, 29, 37).

the ATOMS'04 sea trial where a upwelling induced filament was actually present as explained above in the analysis of the oceanographic data. It remains to be demon-

strated whether or not these ideas can be applied on actual experimental data, which could not be achieved during ATOMS due to the weather conditions off Cape São Vicente during the sea trial.

Regarding the oceanographic data description ...

During the ATOMS project

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