The use of "CARAVELA 2000®" vehicles in operational oceanography

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World-wide, there has been increasing interest in the operational analysis of mesoscale ocean dynamics, which appear to hold the key for a correct description and prediction of ocean system behaviour (e.g. EuroGOOS goals). However, due to the three dimensional characteristics of the underlying phenomena, the characterisation of mesoscale ocean processes for numerical modelling and prediction purposes poses formidable challenges. This stems from the fact that the spatial and time scales of the phenomena involved span the ranges from 10km to 300km and a few days to some months, respectively. With currently available means, it is simply impossible (mainly for cost reasons) to obtain oceanographic data with the 3D space and time resolutions required for accurate large scale, high resolution, ocean modelling in a regular operational mode. Thus the urgent need to develop advanced technological systems for cost effective, automatic ocean data acquisition that will be able to accomplish with the 4D sampling requirements.

1. THE CARAVELA PROJECT (EUREKA–EUROMAR Σ!1850)

1.1. Project outline

As a contribution to the solution of this problem, the CARAVELA project (EUREKA–EUROMAR Σ!1850 and funded in Portugal through PRAXIS XXI 3.1b L-104) puts forward the development of an autonomous robotic research vessel named CARAVELA 2000®[1].

A major CARAVELA objective is to be able to perform, regularly the required ocean sampling at very low costs. Combining data from CARAVELA 2000 and from other sources with numerical models will be a straightforward step towards an operational large scale, high resolution, ocean forecasting facility with long-standing predictability.

[1] "CARAVELA 2000" is a Registered Trademark from CARAVELA Consortium.

The CARAVELA 2000 vehicle will be capable of performing a large number of oceanographic missions without support from a permanent, dedicated crew. Its self-righting body will be equipped with standard, well-tested oceanographic equipment operating in a standalone mode. The vehicle will be fully autonomous, yet capable of responding to commands issued from land or any sea platform via a remote RF/Satellite communication link. This link will provide a data channel for receiving mission sensor data from the vehicle, as well as sending operator generated commands to the vehicle to re-direct its mission, if required. At the heart of the CARAVELA vessel is an integrated navigation, guidance, and control system that will allow it to follow pre-determined trajectories with great accuracy, without outside intervention. A radar based safety system will enable the vessel to detect and avoid potentially harmful obstacles.

The range of operation of the prototype CARAVELA 2000 will be at least 2000 nautical miles. The propulsion system will consist of two electrical engines that will propel the vehicle at an average speed of 5 knots. The vessel's streamlined hull will be about 10 meters long, 2 meters wide, and 7 meters high. Maintenance shall be kept at a minimum when compared to that required for classical research vessels. A high day per year rate of vessel work at sea is expected since only interruptions for maintenance and improvement will be required.

Figure 1. Computer vision of CARAVELA 2000.

A major CARAVELA objective is to be able to perform, regularly, long range open ocean autonomous monitoring operations, similar to those performed by standard research vessels, but with total costs kept at very low levels when compared to those of standard cruises.

1.2. Project Consortium

An international consortium, which assembles together specialists from several different fields, have been put together. The consortium institutions are:

IMAR / University of Azores, Portugal (Project Co-ordinator)
ISR/Instituto Superior Técnico, Portugal
RINAVE, Portugal
CONAFI, Portugal
SIMRAD, Norway
System Technologies, United Kingdom
RDInstruments-Europe, France-USA

1.3. Innovation with the CARAVELA 2000 vehicle

The major technological achievements expected can be listed as follows:

i) Development of a standalone operation mode (pre-programmed or remotely controlled) for the presently available market of well tested and proved scientific equipment that will be installed in the vehicle.

ii) Development of inboard capacity for autonomous long range and long distance operation of the vehicle (either in pre-programmed mode or by remote control, through a satellite or Radio Frequency link).

iii) Development of the capacity for normal operation and data collection (including that of all transducers installed) under severe weather conditions.

iv) Development of an intelligent anti-collision and safety system.

v) Development of an inboard computer distributed network unit for an integrated management of all inboard devices (scientific, navigation, communication, propulsion, energy and safety).

vi) Development of an intelligent unit for the autonomous management of a multi-source (almost non-pollutant) energy generation and accumulation / distribution system.

vii) Development of a 'black-box' system for a security data backup of all inboard units during the whole mission.

viii) Development of a very resistant hull, with lifeboat like behaviour (self-righting capacity) and with very low friction to displacement at normal cruise speeds.

ix) Development of an autonomous operating CTD, equipped with standard sensors.

2. TYPICAL MISSION TYPES FOR THE CARAVELA 2000

2.1. Small list of some mission types

There is a considerably large number of missions that one will be able to perform with the CARAVELA 2000 vehicle, either alone or organised in a small fleet. However, it is possible to equate immediately some typical missions:

1- High resolution bathymetric charting and bottom nature classification.

2- Synoptic 3D ocean mesoscale sampling for hydrodynamic and ecosystem numerical model assimilation to produce operational forecasting in: *i)* Ocean dynamics, *ii)* Biochemical and pollutant dispersal, *iii)* Ecosystem dynamics, *iv)* Fish stock assessment, *v)* Fishing fleet strategy. It will be possible then to build up *i)* a 4D data bank for climate assessment, *ii)* a reliable marine information system (MIS).

3- Satellite Sensor Calibration: *i)* Altimetric, *ii)* Thermal infrared, *iii)* Chlorophyll, *iv)* Atmospheric boundary layer wind vector and surface sea-state.

4- Oceanographic missions, with non operational purposes, as those presently performed with a normal research vessel.

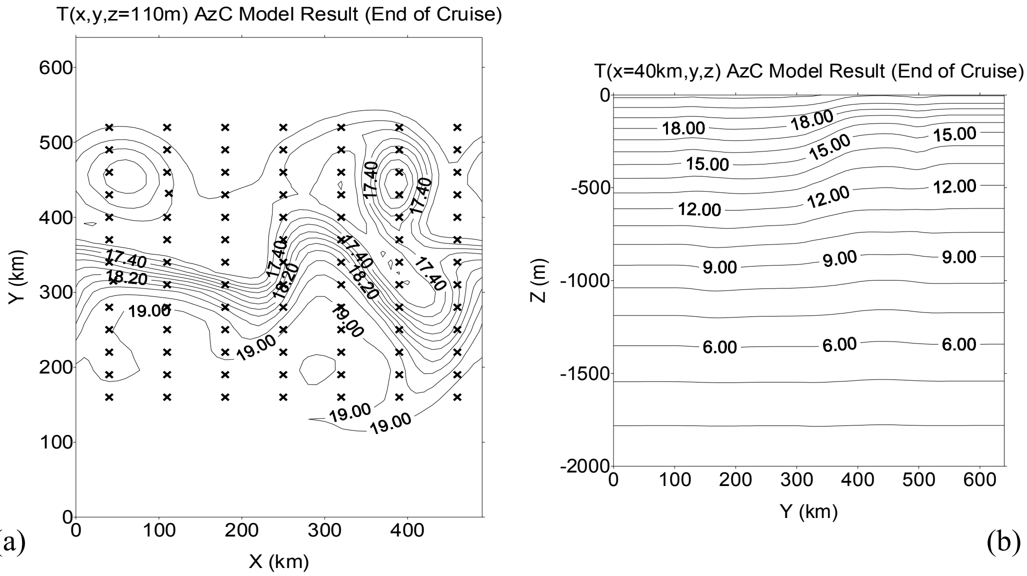
As an example of such a feasibility, we describe next how we expect that the CARAVELA 2000 vehicle alone will perform on the listed mission type 2. We note, however, that while performing a mission type 2 the vehicle will be able to perform simultaneously the mission type 3 and become part of mission type 4.

2.2. The CARAVELA 2000 Ocean Mesoscale sampling mission type

There is at present a growing recognition that mesoscale processes not only play an important role on geophysical fluid dynamics but also in the medium range climate evolution, which appears to be closely linked to the mesoscale geophysical turbulence rectification processes. Works like those of Palmer (1998), Feldstein and Lee (1998) or Alves and de Verdière (1999) are good examples of such a connection between climate and mesoscale.

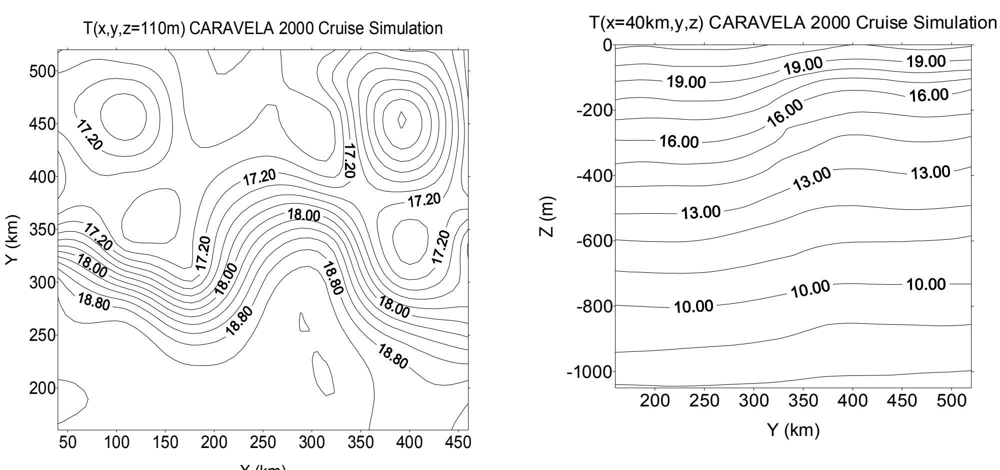
In order to evaluate the feasibility and performance of the CARAVELA 2000 vehicle in performing the required sampling strategy for ocean mesoscale processes characterization, we conducted a series of numerical cruise simulations under normal operation conditions (with no accidents or unexpected delays). In order to do that, a realistic Primitive Equation numerical model simulation of the Azores Current (AzC) have been used, whose details can be found in Alves and de Verdière (1999). The time and threedimensional space evolution of the model generated mesoscale features were considered as to be representative of a given observed AzC period. Doing so, we then conducted a numerical CARAVELA 2000 mission across the AzC. The AzC features and the vehicle evolve in the same time reference. This means that, as the time goes by during the vehicle mission acomplishment, the model is always running on and the mesoscale features are evolving. Our major question is now: is the CARAVELA 2000 vehicle able to perform the necessary mesoscale sampling during a time interval short enough that we can consider observations as synoptic to those scales? Another way to put this question is: what is the maximum area that CARAVELA 2000 can cover in resolving the AzC mesoscale and, at the same time, remaining still as synoptic? After a few numerical trials we came out with a typical sampling strategy whose pattern can be seen in Figure 2a). In this case, the mission plan was to cary out 91 CTDs, up to a depth of 1000m each (with its own multipurpose profiling device) and continously acquire, between CTD stations, the acoustic signals coming from a 75 kHz ADCP and biomass echointegrator through two transducers (120kHz and 38 kHz). Also, atmospheric and surface water quality parameters were continously recorded. Steaming at a mean cruise speed of 5 knots (no stop is required for the CTD cast), CARAVELA 2000 will take about 13 days to perform the overall program (about 1500 nautical miles) and more about 4 days of pure steaming between the AzC sampling area and its home port, if an overall distance of 500 nm is assumed (typical case if Horta, in Azores, is that port). Figure 2 a) also show the AzC temperature distribution at 110m depth as generated by the model run and coincident with the last cruise day (13th

day). A vertical cross section of the same temperature field and model run day across AzC (up to a depth of 2000m) can be apreciated in Figure 2 b.



(a) (b)

Figure 2 a) and b). Horizontal distribution of AzC temperature as generated by the model simulation at 110m depth and last cruise day, with CTD station position superimposed (a). For the same run, the vertical temperature distribution is shown (b).



(a) (b)

Figure 3 a) and b). After optimal reconstruction of the observed thermal distribution at 110m depth (a) and vertical cross section across the AzC system (b), its comparison with Figures 1 a) and b), respectively, clearly show that CARAVELA 2000 will have the capacity for ocean mesoscale sampling.

An objective analysis of the CARAVELA 2000 CTD measured temperature at 110m depth (with isotropic correlation function and an integral correlation space scale of 200km) allow us to reconstruct the thermal field of AzC. Figure 3 a) shows the resulting field. It is clear that we were able to reconstruct the model result only with minor differences. The same is true for the vertical temperature distribution as obtained from CARAVELA 2000 observations (Figure 3 b).

A normal RV would take a total of about 12 days to do the same described job (10 days in the working area and 2 days of transit).

We note that this simulation corresponds to push CARAVELA 2000 prototype to near its maximum range of operation (2000 nm mission, when only an extra 10% security margin is still available). However, it is clear than any shorter range cruise will still remain synoptic in what concerns ocean mesoscale. We conclude then that CARAVELA 2000 is suitable for such a sampling strategy.

3. INNOVATION AND CONSEQUENCES OF CARAVELA 2000 PHILOSOPHY

3.1. General statements

As a consequence of its mesoscale sampling capacities one can claim that the CARAVELA 2000 vehicle will allow one to innovate on the phylosophy of climate variability sampling through meoscale resolving strategies. Thus, we can enhance some of the expect new achievements on ocean sampling philosophy:

- Autonomous long-range operation according to a mission plan (up to 2000 nm).
- High rate of day per year operation at sea (up to 300 days per year).
- A small fleet of CARAVELA 2000 will multiply by its number the opportunities of ocean operation at a cost much lower than with conventional RV.
- Opportunity for the creation of new companies and services in ocean technology.
- Capacity of putting together several CARAVELA 2000 fleets for gathering worldwide ocean data for climate change.

We describe next two examples of such an observing philosophy.

3.2. The Portuguese EEZ case example

Having shown the capacity for the CARAVELA 2000 to deal with reliable sampling of ocean mesoscale processes, one can now apply this concept to some particular situations of great interest. The first selected case deals with the regular monitoring and forecasting of the full EEZ area of Portugal, which includes the Portuguese mainland area and Azores and Madeira autonomous regions. Figure 4 represents, in a sinthetic way, one of the possible modes of coordinated CARAVELA 2000 operation to achieve the regular mesoscale sampling of the whole area. Each of the rectangular zones are to be donne in one single cruise (of about 15 days). In order to ensure a regular 3D sampling each two months, two vehicles per EEZ zone are required (six for the total area). Six cruises are required for the Azores area, which means that the two vehicles will cover simultaneously two boxes, those with a line boundary of the same type in Figure 4 (full line, long dashed line and small dashed line boxes). The full Azores area will then be covered in 1.5 months, while, for a similar strategy, mainland and Madeira will need 1 month. If the same pattern is repeated each two months, then six 3D samples per year will be produced. Assuming that 2 month per year are required for maintenance, we see that after all 4 vehicles will remain available for about 4 months while for those in Azores we will have 1 month, that is, some 4*4+2*1=18 months per year that can be used on other mission types (e.g. bathymetric charting).

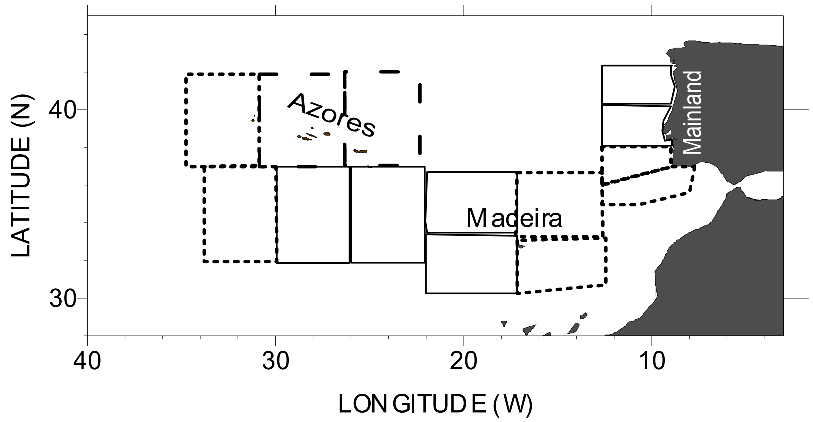


Figure 4. The full Portuguese EEZ area can be regularly sampled each 2 months for its mesoscale with a maximum of 6 vehicles. Zones with the same boundary line type are to be performed simultaneously by the CARAVELA 2000 fleet.

3.3. The North Atlantic case example

Similarly to what we have donne for the Portuguese EEZ case we can extend the concept of coordinated CARAVELA 2000 fleet operation to cover, regularly, six times per year the whole North Atlantic mesoscale in a 3D mode.

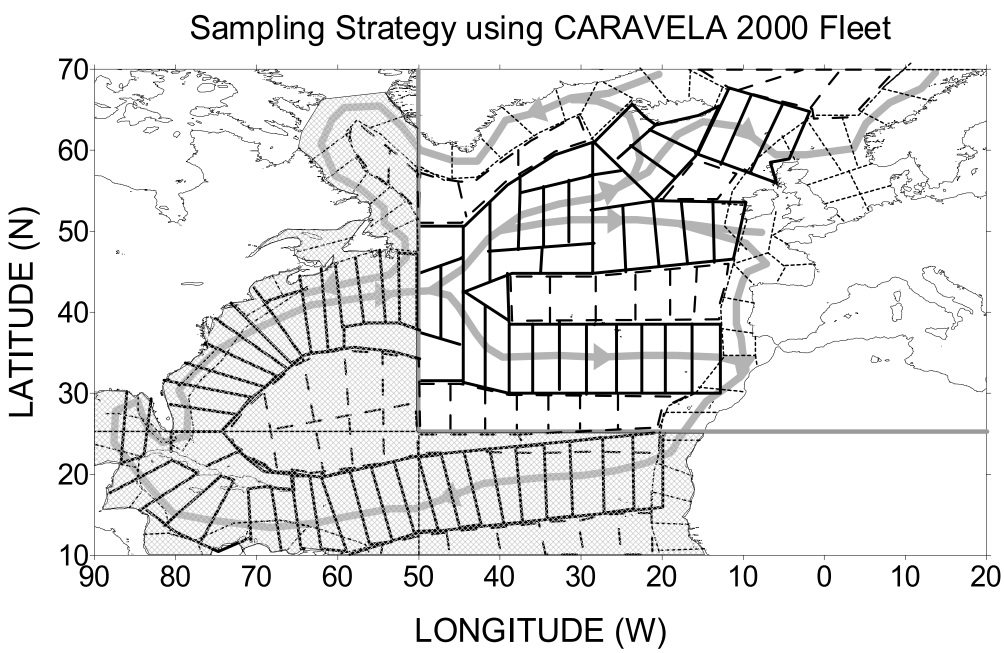


Figure 5. The whole North Atlantic can be regularly sampled each 2 months for its mesoscale with a maximum of 80 vehicles. Zones with the same boundary line type are to be performed simultaneously. We note that the distance between CTDs in the same section line and between sections is variable in accordance to the mesoscale signatures in each zone (coastal, main ocean current or adjacent current zones). The stipled area is the EuroGOOS adjacent zone

A total of 80 vehicles will be enough to achieve that. Figure 5 shows a possible coverage mode where the North Atlantic dynamic signatures are taken into account. The 80 vehicles will cover, simultaneously, the whole main current areas (full line box cruises in Figure 5) in about 15 days. From those, about 60 vehicles will be enough to cover the whole coastal zone area in another 15 day period (small dashed in Figure 5). During another 15 day period, 40 vehicles will cover the remaining areas (long dashed in Figure 5) and repeat the cycle each two month. The distance between CTDs in the same section and between sections is variable and may change, respectively, from 5km-40km in the coastal zone up to 40km-90km in the areas adjacent to the main currents. The total vehicle time that we can expect to have available in such a fleet is 80*10 = 800 month per year. Noting that to cover the whole North Atlantic (80*0.5+60*0.5+40*0.5)*6 = 540 months are required, we conclude that some 260 months will remain available for other mission types.

This may seem to be an ambitious goal but if we put forward the total estimated cost for such an operation in a regular basis during 10 years, with a full repetion each 2 months, then we will come out with a total cost, for the whole 80 vehicles, of about 100 Meuro (which includes vehicle construction cost (0.75Meuro each), its operation and maintenance during the 10 years and one technical specialist per vehicle).

A total rate per year of 100 000 CTDs and 1100 cruises is expected, together with continous remote acoustic profiling, continous surface water quality sampling, atmospheric boundary layer properties and regular satellite calibration. This is certainly a unique data basis for climate prediction at a cost that one can easily compare, for example, with the WOCE operation and take its own conclusions.

4. DISCUSSION AND FINAL REMARKS

Of course one can argue that all AUV's have the capacity of navigating at the surface, but certainly the operation philosophy of CARAVELA 2000 and the technological upgrades needed to go from a surface moving AUV to CARAVELA 2000 make it a unique solution at present and, at our knowledge, there is no such device available in the international market. In this sense, CARAVELA 2000 is an innovative concept, which will be able to mimic many of the classical oceanographic observational operations, usually performed on board of a Research Vessel. Its low cost operation will allow for economic, repetitive sampling strategies, making thus possible a reliable ocean monitoring scheme for numerical forecasting and operational purposes over wide areas.

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