Work Package I

Temporal evolution of surface production and fate of organic matter

Executive Summary of Scientific Achievements

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Introduction

WP I had a most productive 12-24 months period. The most important event was the efficient cruise *CD114* which, despite of the lack of sufficient berths, prepared the base for probably the most complete and balanced data set of an upwelling situation, including a filament, on a shelf. The period following *CD114* was intensive to work up and make available the wealth of data, which were derived during the cruise. Two workshops where modelling work was the focus, were organised. Most of the WP I participants took lace in the OMEX II-II workshop in Plymouth. Much progress has been made, but the lack of ship time for a downwelling cruise created some problems, which were discussed by the various WP I participants, also in concert. The solution to compensate for the lacking second cruise has been solved in different manners (see more about this in the management report). Several partners of WP I participated in non-WP I cruises at appropriate times in order to compensate for this lack in sampling. Thus every now and then reference is made to non-WP I cruises in the present executive summary.
The summary follows the structure of the Technical Annex objectives. In some cases several objectives are presented in concerted because the work carried out was so integrated that a split up did not seem appropriate.

Task I.1 **On-, off- and along-shelf transport of water, filament transport and turbulence**
Partners: *UWB (6a) responsible, UWB (6b), NSS (9)*

Objectives:

(a) To measure the net transport associated with an upwelling filament

The main task was the description of the 3-D structure of the 42°N upwelling filament. This was completed during the *CD114* cruise fulfilling our original objectives, like determination of the 3-D structure and flow regime of the filament, its net transport, mixing and Lagrangian observations within the filament structure. The winter cruise on board the *Meteor* (*M43/2*) provided further data for studying the seasonal variability of the filament area and gave the opportunity to sample the winter regime both with ADCP and CTD. Four ARGOS drifters were released to provide a quantitative description of the meso-scale structure and seasonal variability of the circulation in the upper layer of the ocean within the OMEX II-II region.
The drifter data set has been further analysed. Single particle Lagrangian statistics were performed separately for the summer and winter deployment from the dispersion of the drifters. Assuming homogeneous isotropic turbulence from Taylor's theory, eddy diffusivity was calculated, indicating distinctive regimes in the two seasons. In summer, the presence of filaments gives rise to a rich meso-scale field which actively links the shelf and the open ocean at a large variety of time scales but with no clear net transport Eddy diffusion estimates were high and isotropic (zonal $K = 9\ 10^6\ cm^2\ s^{-1}$, meridional $K = 9.7\ 10^6\ cm^2\ s^{-1}$). In winter there is a clear inhibition of the shelf-ocean exchange seen during the summer deployment and drifters are restricted to the shelf with a larger meridional dispersion. Eddy diffusion estimates were smaller than in summer, (zonal $K = 1.9\ 10^6\ cm^2\ s^{-1}$ and meridional $K = 3.3\ 10^6\ cm^2\ s^{-1}$). A further calculation was performed with all the drifter data available giving bulk values for the area (zonal $K = 5.6\ 10^6\ cm^2\ s^{-1}$ and meridional $K = 8.5\ 10^6\ cm^2\ s^{-1}$).
Most publications on filaments describe the structures as narrow surface intensified baroclinic jets flowing offshore with an associated total offshore transport of a few Sverdrup with a return flow further south. Our results showed a surprisingly different picture: the filament was mainly superficial, with very weak velocities and long return flow time scale. It would have a limited export capability in terms of

advection but the slow return flow would allow for sinking of fast material to occur on the slope and deep ocean rather than on the shelf.
Although weather conditions proved to be very similar during the two drifter deployments there are clear differences in drifter behaviour in the summer and winter periods which were confirmed by the statistical analysis. The activity of upwelling filaments marks the summer surface circulation and they act as an active link between the shelf and open ocean but the associated return flow inhibits a net offshore flow of shelf waters. During winter, filaments did not occur, even though upwelling conditions persisted, and shelf waters were isolated from the ocean. During this exceptional winter, there has been a net southward transport over the slope contrary to previous evidence of persistent winter poleward flow.

(b) To measure turbulent dissipation in the upper 250 m and quantify vertical mixing
The FLY probe is a free falling instrument which can be used to measure turbulent dissipation which can, in turn, be converted to an estimate of vertical diffusion, K_Z, from a knowledge of the vertical density structure. The method operation of the probe, which is periodically dropped from behind a slowly moving ship, was described in the first year annual report. Within WP I the aim is to make measurements coincident with the drifting buoy experiment for comparison with the *in situ* biological measurements and the accompanying modelling exercises.

***CD114* Leg A.** Direct observations of dissipation and mixing rates were made on the Iberian shelf in August 1998. In Leg a, a six-day Lagrangian experiment was undertaken, following an instrumented drifting buoy. Leg b was an Eulerian internal wave experiment lasting 36 hours, during which a thermistor chain along with a near surface current meter mooring were deployed. During both phases repeated turbulence measurements were made from the ship to quantify the vertical drag. All data have been calibrated and quality checked using the SPIDER software suite. Leg b data have so far been analysed in greater detail than data from Leg a, and the results of this analysis are presented below.
Approximately half the data were processed onboard to the level of turbulence dissipation rates using the SPIDER processing software. The instrument appeared to behave well, with data quality looking good. An accident, which resulted in the FLY cable becoming entangled with the ship's propeller, curtailed FLY usage for Leg a but fortunately did not result in equipment loss and it was able to be used again in Leg b. As a consequence of the accident an experiment planned to measure internal waves at three locations as they propagated on-shelf was abandoned. However, a 24-hr long FLY station was completed on 8 and 9 Aug. The measurements were made at 41°55.1'N, 9°19.3' W in about 167 m of water close to a mooring which comprised 9 Minilog thermistors deployed between 15 m and 100 m and an Inter Ocean S4 current meter located 10 m from the surface. These observations have revealed valuable information about the relationship between internal waves and mixing in the region.
SAR satellite images received at RSDAS during the cruise showed the complex nature of the internal wave field in the region. Near the measurement site the orientation of waves in the images is in good agreement with that estimated from the *in situ* current measurements with an onshore propagation direction of about 14°N. The temperature record from the mooring shows a 12.4-hr period (M2) internal tide with an amplitude of approximately 25 m. Superimposed on this wave was a highly energetic, high frequency internal wave field, with a dominant frequency of approximately 3 cph and amplitudes of up to 25 m. High frequency internal wave amplitudes were generally greater in the trough of the internal tide. These observations are significantly different from those observed further south at 41°N during the MORENA project where waves of order 45 m appeared in discrete packets every tidal cycle.
High turbulent kinetic energy dissipation rates (ε, of order $5\ 10^{-4}$ W m^{-3}) were observed within the thermocline and were associated with the high frequency waves. Fine scale temperature inversions were frequently observed. These inversions convert into overturning length scales of up 5.2 m which imply turbulent kinetic energy dissipation rates in excess of $3\ 10^{-3}$ W m^{-3}, *i.e.*, two orders of magnitude greater than the background value. The importance of internal waves in dissipating tidal energy is as great as the bottom friction layer which is in contrast to the Malin Shelf, where bottom friction accounts for a far greater portion of the total dissipation.
***CD114* Leg B.** The second part of *CD114* involved a drifter study in an offshore filament. During this study the FLY probe was deployed along a series of sections across the filament at about 42°N. Two series taken on contiguous days (17th and 18th Aug.) along the 10°W meridian reveal the essential dissipation structure in the filament. The coolest surface water is located at about 41.9°N with a strong frontal structure to the north, and a weaker one to the south. In general the highest levels of dissipation

where found in the frontal regions, particularly to the north of the filament where values of about 3 10^{-5} W m^{-3} were observed at 20 m. This is not surprising, since ADCP measurements (not shown here) suggest that this is the region of greatest vertical shear. Below about 80 m dissipation levels were generally small (less than about 3 10^{-6} W m^{-3}) under the cool surface expression of the filament, but were up to an order of magnitude larger than this at 100 m on the southern side.
The contractual requirements to make observations to map the turbulence dissipation have been fulfilled and its distribution is being investigated at present. The highest values of dissipation (about 3 10^{-3} W m^{-3}) were measured in the seasonal thermocline during the internal wave experiment, although comparable values about 10^{-3} W m^{-3} were measured in the upper mixed layer of the ocean during the winter cruise of *CD110*. In the filament mixing levels were typically one to two orders of magnitude smaller than these values.

(c) Continuous data processing of AVHRR and SeaWiFS data for observation of upwelling episodes, filaments, fronts, eddies and currents and surface phytoplankton pigment concentrations
Routine processing of AVHRR and SeaWiFS data takes place. Approximately 2000 SST images and 350 ocean colour scenes were processed this year for the OMEX II-II region on the same day as reception, and made available over the World-Wide-Web.

(d) Support ships at sea with near-real time remote sensing images from AVHRR and SeaWiFS
Remote sensing support during the 1998 upwelling season has been of crucial importance to the success of several cruises studying the exchange generated by dynamic and transient upwelling filaments. In particular, the *CD114* cruise during August used satellite data and drifting buoys to track the change in physical and biological processes associated with the flow within a filament. SeaWiFS chlorophyll maps representative of the two legs of the *CD114* cruise. Leg 1 was characterised by strong upwelling and high phytoplankton (> 1 mg Chl. m^{-3}) on shelf, with two significant filaments between 42-43°N. One filament is seen to interact with an eddy near 42°N, 10°W, entraining high-chlorophyll water into an anticyclonic spiral. The Lagrangian experiment took place along this filament during Leg b, and experienced both lower biological activity and horizontal currents than expected. The mosaic of chlorophyll maps between 18 and 21 Aug. indicates lower levels of phytoplankton abundance on the shelf and within the filament than during Leg a. The wind plot shows a major relaxation in upwelling winds at the end of Leg 1 (7-10 Aug.) and a minor relaxation during Leg 2 (13-17 Aug.); this is the probable cause of the lower chlorophyll concentrations near the coast, and reduced flow from the upwelling zone into the filament.

(e) Analysis of archived Coastal Zone Colour Scanner data
Approximately 2000 SST images and 350 ocean colour scenes were processed this year for the OMEX II-II region on the same day as reception, and made available over the World-Wide-Web. Unusually, upwelling conditions were sustained by predominantly northerly winds until early December 1998. The SST for 6th Nov. shows a defined upwelling zone and several small filaments. The extended upwelling season postponed the formation of the northward Navidad current shows strong upwelling (with ~3 mg Chl m^{-3}) and well-developed filaments in a SeaWiFS chlorophyll image from 17 Mar. 1999, several months earlier than expected. The spring bloom normally produces high chlorophyll concentrations near to the coast or in isolated patches.

(f) Detection, classification and statistical analysis of surface temperature and ocean colour phenomena
To be approached in the final year

(g) Analysis of Synthetic Aperture Radar imagery from ERS-1/2
The *CD114* cruise during August explicitly used satellite data and drifting buoys to track the change in physical and biological processes associated with the flow within a filament. Synthetic Aperture Radar (SAR) data were also supplied during this cruise to locate the internal waves for investigation and comparison with measurements using the FLY turbulence probe, though high winds limited the visibility of the internal wave signal.

Task I.2 **Inorganic carbon biogeochemistry and atmospheric CO_2 uptake and release**
Partners: *ULg (22) responsible, RISØ (10), SINTEF (18)*

Objectives:
(a) To understand the inorganic carbon dynamics and identify sources/sinks for atmospheric CO_2
Underway measurements of pCO_2 were carried out throughout the *CD114 a* and *b* cruise (29th July to 24th August 1998); vertical profiles of pH, Total Alkalinity and dissolved oxygen were obtained at 33 stations (229 depths). The comparison of atmospheric pCO_2 and dissolved pCO_2 shows throughout the transect of *CD114* Leg a under-saturation with respect to atmosphere, related to important primary production as shown by the O_2 distribution. However, close to the coast equilibrium with the atmosphere was observed. This can be related to upwelling (as shown by the distribution of temperature) that brings water with a high content of inorganic carbon. The salinity distribution suggests that the coastal water (between 9.1°W and 9.3°W) where these important gradients of pCO_2 were observed could be related to outwelling from the Ría of Muros. The Lagrangian experiment of Leg a (3-7. Aug. 1998) begun on the shelf and the buoy drifted into an upwelling filament. During Leg b, the Lagrangian experiment (14-19 Aug. 1998) was carried out in the upwelling filament and the buoy drifted along the northern boundary of the filament except in the last day when the residual current turned inshore and the buoy shifted into the southern boundary of the filament. The third Lagrangian experiment consisted in a daily cycle (9-10 Aug. 1998) carried out over the continental shelf. The evolution of subsurface underway parameters during the Lagrangian experiments carried out during Leg a, Leg b and the daily cycle.
During the three experiments, temperature variations were very important. Temperature affects pCO_2 by altering the equilibrium constants of the inorganic carbon system among which the solubility coefficient of CO_2. To filter this factor and concentrate on the effect of biological effects, the pCO_2 values were normalised to an average temperature of 17°C. During Leg A, the overall evolution is the decrease of pCO_2 (17°C) values and the increase of oxygen saturation values, showing that primary production affected these parameters in a significant way. During the first two days of Leg a, it is clear that pCO_2 and dissolved O_2 evolve in periodical way. This can be related to the diel cycle of primary production and respiration. Indeed, the periodical signal of pCO_2 and O_2 is well correlated to the daily signal of light. The fact that this periodical signal disappears after two days can be explained by the fact that during the experiment the maximum of phytoplankton biomass shifted from the subsurface to around 30 m. In parallel, the mixed layer became shallower, shifting from 15 to 5 m. Thus, during the last two days of the experiment, the diel cycle of primary production and respiration was not affecting the surface values of pCO_2 (17°C) and O_2 in a periodical way and these parameters tended to stabilise.
During Leg b, pCO_2 (17°C) and O_2 were quite stable in comparison to Leg a. This is coherent with other partners' data that show that the mixed layer was nutrient depleted and primary production low. The most noticeable variation was observed in the last day of the experiment when the shift from the northern to southern boundary of the upwelling filament occurred. At this occasion, the oxygen saturation decreased and temperature increased, as water with more offshore characteristics was sampled. During the daily cycle experiment, pCO_2 (17°C) and the dissolved O_2 show a distinct periodical signal with an amplitude of the same order of magnitude as the signal observed during the first two days of the Lagrangian experiment of Leg a. The presence or the absence of a daily periodical signal of subsurface pCO_2 (17°C) and oxygen saturation seems to be related to the amount of phytoplankton close to the sea surface. Indeed, during first two days of the Leg a and during the daily cycle Lagrangian experiments, a daily periodical signal is apparent and the chlorophyll *a* concentration within the first 10 m is respectively of 1.0-1.3 and 0.8 µg l^{-1} as opposed to 0.2 µg l^{-1} during the Leg b Lagrangian experiment when a daily periodical signal was absent.
The order of magnitude of the variation of pCO_2 at daily scale (~10 µatm is smaller than at seasonal scale (~200 µatm). The dynamics of subsurface pCO_2 are related to the daily cycle of biological activity (photosynthesis and respiration) when the phytoplankton biomass is located close to the sea surface. This depends on nutrient availability in the mixed layer so directly depends on upwelling. The temperature variation in surface water, related to heat exchange, has also a strong effect on the variation of subsurface pCO_2.
The pattern of the distribution of subsurface pCO_2 in the OMEX II-II box during summer is complex but reproducible from one cruise to another: over-saturation at Cape Finisterre, under-saturation off the Rías Baixas area and values close to saturation offshore. This pattern is imposed by the input of over-saturated water by upwelling, primary production, outwelling from the rías and seawater temperature

variation. The variability from one cruise to another is imposed by the intensity of upwelling. The variability consists in the intensity of the pCO_2 gradients, the extent of spatial features, the presence of upwelling filaments and the outwelling from the rías either of over-saturated or under-saturated water.
During winter in the OMEX II-II box, under-saturation of pCO_2 is observed in relation to cooling of surface seawater. The presence of different water masses related to the poleward slope current also induces variability, the saltier and warmer ENAW tropical end member being characterised by lower pCO_2 values than the polar end member of ENAW. The variability from one cruise to another depends on the intensity of the poleward slope current related to general meteorological conditions.

(b) To convert measured pCO_2 values to air-sea fluxes
The process modelling work gave rise to several results. For variations in the ocean CO_2 concentration of length scales larger than a couple of kilometres there is no significant influence on the surface flux from the advection and diffusion of the CO_2 concentration in neither the water nor the air. The reason for this is that the carbonate buffer controls almost completely the water concentration, irrespective of advection or turbulence diffusion. These fluxes can therefore be computed by one or several of the standard exchange coefficient methods. However, such methods include uncertainties of the order of a factor 2-5 between the lowest accepted values to the largest accepted values. These uncertainties however can not be explained by the diffusion. They may possibly be associated with the behaviour of the aqueous pCO_2 very close to the surface, and with ill defined experimental conditions.
For smaller scales of the variation, less than a km or so, the different processes start interacting. However, generally the micro-meteorological derived flux is more likely to deviate from the true interfacial flux, than is the boundary flux. Changes in the water concentration of CO_2, due temperature, alkalinity, salinity etc. will create differences between the true interfacial flux and the boundary flux. Therefore it is important to try to extrapolate the CO_2 concentration to the surface, taking into account the vertical variation of these parameters. For other trace gases in the water, the diffusion plays a much large role than for CO_2, since these gases are without a controlling buffer.
Simultaneously field data from the first OMEX II-II cruises on pCO_2, as obtained by ULg and the transformation of these data to surface fluxes has been initiated. The initial results show very indicate small deviations from the transfer-coefficient predictions only.

(c) To establish a coupled hydro-biological model
This work will be carried out in the forthcoming year.

Task I.3 **Nutrient dynamics, primary production, biomass and phytoplankton**
Partners: *IIM (13) responsible, PML (4a and 4c), UITØ (3a)*

Objectives:
(a) To determine the nutrient availability in the surface layer during a Lagrangian experiment and (g) to estimate what is the importance of dissolved organic carbon on the total carbon budget during exchange processes
The size and quality (C/N ratio) of the dissolved (<1 µm) and particulate organic (<200 µm) matter pools transported by the filament was investigated during *CD114*. Three contrasting domains were defined: 1) upwelled ENAW; 2) thermocline waters (>15°C) of the coastal-start of the filament; and 3) thermocline waters (>16°C) of the ocean-end of the filament. The average TOC excess (TOC) in the filament at the coastal represents 23.7 µM C (61% as DOC, 39% as POC), with a surprisingly low C/N molar ratio of 7.0. This suggests that the filament is transporting labile materials recently formed on the shelf (time scale of a few days). The average TOC maintains 21.3 µM C (65% DOC, 35% POC) with a C/N molar ratio of 6.9, pointing to the persistence of the material formed on the shelf during transport to the ocean. It should be highlighted that the dominant contribution of DOC to the organic carbon excess observed in thermocline waters (~2/3 of TOC), which has to be considered in any assessment of carbon export mediated through filaments. In this sense, the horizontal export of primary production is mediated through DOC whereas the vertical export is mediated through sinking particles.
The DOM transported by the filament can be roughly partitioned into refractory, semi-labile and labile fractions under the following assumptions. a) Organic matter in ENAW is refractory and, it is not going to undergo any transformation (biological or photochemical) during upwelling to the surface and subsequent outwelling to the adjacent ocean. b) The POM accumulated in thermocline waters of the

filament (C/N = 6.8) can be considered as labile materials. c) There is a significant correlation between POC and DOC changes in thermocline waters of the coastal start of the filament (r = +0.65). The correlation between PON and DON is good (r = +0.70) as well. We consider that the fraction of DOC, which covaries, with POC (slope 1.1±0.2) and the fraction of DON which covaries with PON (slope 1.0±0.1) contributes to the labile fraction. We obtained that the 81 µM C exported across the shelf-edge consist of 1) 57 µM C of refractory DOC (70%, C/N ratio 19.0); 2) 5 µM C of semi-labile DOC (6%, C/N ratio of 10.0); 3) 10 µM C of labile DOC (12%, C/N ratio of 7.4) and 4) 9 µM C of labile POC (11%, C/N ratio of 6.8).

(b) To determine the utilisation of nitrate, ammonia, phosphate and silicate by phytoplankton assemblages and to estimate new production,
(c) to assess the importance of nitrification and ammonia regeneration and
(f) to estimate the short time scale variability on primary production and phytoplankton growth rates as induced by upwelling

Primary and new production were measured daily during both Lagrangian experiments. There were significant daily changes during the experiment in the upwelling region. Nitrate concentration declined over the first 4 days of the experiment and strong vertical gradients in nitrate concentration were found. There was clear evidence of nitrate utilisation with a deepening of nutrient depletion with time. The vertical distribution of chlorophyll concentration also changed with time. At the beginning of the experiment, most of the chlorophyll was in the upper 15 m but by Day 4, surface chlorophyll concentrations were reduced and the highest concentrations were below 10 m.

Primary production showed a similar change in depth profile with a general deepening of the region of maximum production. Primary production was usually measured by *in situ* incubations but on two occasions, on deck incubations were done when, for logistical reasons, it was not possible to do an *in situ* incubation. During the 5 days of the first drifting experiment, primary production increased from *ca.* 828 mg C m^{-2} d^{-1} to a maximum value of 1176 mg C m^{-2} d^{-1}. At the beginning of the upwelling experiment, the picoplankton fraction (<2 µm) was slightly more productive than the >5 µm fraction. However, there was little change in the production of the picoplankton during the experiment and most of the additional production was by the >5µm phytoplankton.

During the experiment in the offshore filament, production was less than half that in the upwelling region at the shelf edge. This was a region of oligotrophic conditions and nitrate concentrations were *ca.* 10 nmol kg^{-1}. Picoplankton was the most productive fraction but was about 60% of the activity measured during the upwelling experiment. The >5-µm phytoplankton fraction was much less active in the filament than in the upwelling water, suggesting that larger cells are less well adapted to low nutrient conditions than picoplankton.

During the upwelling experiment, nitrate uptake by different size fractions of phytoplankton was measured by *in situ* incubations with ^{15}N. There was good correspondence between the *in vitro* ^{15}N uptake rate and the observed change in ambient nitrate concentration on all but the first day of the experiment; it is possible that a different water mass was sampled on Day 1. The *f*-ratio declined from *ca.* 0.6 on Day 1 to *ca.* 0.1 at the end of the second experiment.

Nitrate was the dominant nitrogen source for phytoplankton. The uptake rates measured on successive days decreased as the nitrate concentration declined. The >5-µm phytoplankton was responsible for more than 50 % of the uptake. Most of the ammonium uptake (>65%) was by the small size-fraction and, although rates also decreased each day, ammonium became increasingly more important as a nitrogen source and *f*-ratio decreased from 0.7 to 0.5. As nitrate was used in the upper 10 m, the depth profile of *f*-ratio paralleled the changes observed in chlorophyll and primary production depth profiles.

Typical oligotrophic conditions were found in the filament. Nitrate and ammonium concentrations were below detection limits (<0.05 µmol kg^{-1}) of standard autoanalysis and more sensitive methods were required to give accurate estimates of ambient nutrient concentration. Uptake rates of both nitrate and ammonium were 5 - 10 times lower than in the upwelling region. Primary production was approximately 0.2 - 0.5 that measured in the upwelling region and was dominated by pico- and small nano-plankton. The ratio of C:N uptake rates, based on the assumption that nitrate and ammonium are the only nitrogen sources, were 13 - 44. In comparison, the Redfield ratio is *ca.* 6.7. This suggests either severe nitrogen depletion or the phytoplankton were utilising an alternative source of nitrogen.

Phytoplankton cells have been known for many years to utilise urea as sole nitrogen source. Urea concentrations were determined on samples that had been stored frozen following GF/F filtration. In the

upwelling region, concentrations were generally low (<0.05 µmol kg^{-1}), although higher values were measured at the surface and the seasonal thermocline. In contrast, concentrations of urea in the filament were high throughout the water column (max. 0.6 µmol kg^{-1}). Since nitrate and ammonium concentrations were less than 0.05 µmol kg^{-1} in the upper 30 m, the high urea concentrations suggest that urea could be a dominant source of available nitrogen.
Microbial uptake of urea was greater than that of nitrate and ammonium by factors of 5 to 30. The *f*-ratio is 10 times lower if urea uptake is included. This raises several questions regarding the source of nitrogenous nutrients for phytoplankton, particularly during times of severe inorganic nitrogen depletion. It is probable that urea is an important nitrogen source for phytoplankton growth in the oligotrophic waters of the filaments.

(d) To evaluate the role of the short-time phytoplankton species succession and the corresponding suspended organic matter concentrations on primary production
During *CD114* Leg a the flagellates were also the most abundant phytoplankton group and accounted for 53% and 40% of the phytoplankton biomass during upwelling and wind relaxation events respectively, reaching a maximum of >75 µg l^{-1} on Day 2 of the Lagrangian experiment. Cyanobacteria constituted 40% of the total biomass during upwelling, with >85 µg l^{-1} on Day 1 of the experiment. There was a slight decrease in cyanobacteria during wind relaxation (max. 60 µg l^{-1}) when they formed 36% of the total biomass. The diatom biomass was initially low during upwelling (~ 1.0 µg l^{-1}) and made up only 2.5 % of the total biomass, but increased by >20 times (max. 30 µg l^{-1}). The dinoflagellates had the lowest biomass during upwelling and wind relaxation (max. 4 µg l^{-1} during upwelling, 6.45 µg l^{-1} during wind relaxation) which accounted for only 2% of the biomass.

(e) To characterise the photosynthetic response of phytoplankton as a function of underwater light field, nutrient availability and phytoplankton composition
The range in PP (PUR) during *CD114a* was 1780 to 3953 mg C m^{-3} d^{-1}. PP gradually increased during upwelling and significantly decreased during wind relaxation. The highest values during the upwelling event coincided with a short-term relaxation event on 5th August 1998. Most of the water column primary production was in the first 20 m of the water column on Day 1 and 2 and by Day 3 there was a maximum at 5 m. On Day 5, *in situ* primary production in the upper 20 m was reduced due to the deepening of the Chl *a* maxima to 30 m as the buoy moved off-shore. When PP (PUR) data from all hydrographic conditions was compared, PP (PUR) was significantly higher during upwelling, with a mean of 2921 (626 mg C m^{-2} d^{-1}).

(h) To investigate the fluxes of chlorophyll and carotenoid pigment distribution, production, sedimentation and degradation across the NW Iberian shelf
250 *CD114* samples from surface and vertical profiles have been analysed applying an HPLC. Analysis of chlorophyll and carotenoid pigments in the samples were completed and data reprocessing currently underway. Data from the cruise were used in chemotaxonomic interpretation, in calibration of *in situ* optical and fluorometric sensors and in the development of ocean colour remote sensing algorithms.
The vertical export of chlorophyll a was significant during both legs, but lower on *CD114* Leg b. The export of chlorophyll *a* on the shelf was about 1 mg m^{-2} d^{-1}, but an order of magnitude lower off-shelf. However, the vertical export of phaeopigments and chlorophyll equivalents was in the same order of magnitude in both areas, indicating that degradation of phytoplankton off the shelf is considerable.

(i) Undertake surface pigment and mapping for ground-truthing remotely sensed ocean colour satellite data
Data were delivered to NSS-NERC (see **Task I.1 (c)**)

Task I.4 Zooplankton and microbial cycling
Partners: PML (4b) responsible, UAL (14a), UITØ (3b), SAHFOS (12), SINTEF (18)

Objectives:
(a) To estimate bacterial biomass, production, respiration and growth during short-term Lagrangian experiments

Lagrangian sampling during an upwelling-relaxation period (*CD114a*) revealed an enhancement in both bacterial abundance and specific production (< 140 10^{-9} nmol leucine $cell^{-1}$ h^{-1}) during the transition between mixed and stratified conditions coinciding with increased primary production. This contrasted with further sampling of an upwelling filament (*CD114b*) where stratified waters yielded much lower values of specific production (< 60 10^{-9} nmol leucine $cell^{-1}$ h^{-1}).
Vertical profiles observed during summer upwelling (Prof. Shtokman) in N, P and S reference transects showed a sub-surface (5 to 50 m) maximum in bacterial abundance (and biomass) of 3-4.5 10^6 cells ml^{-1}. Values decreased rapidly with depth reaching a minimum of ca. 0.5 10^6 cells ml^{-1} below 250 m. During winter downwelling (*CD110b*), bacterial abundance were generally much lower (< 0.6 10^6 cells ml^{-1}). Very low frequency of dividing cells (<0.8%) were associated to downwelling conditions. Vertical structure in bacterioplankton distribution was much more apparent during upwelling than downwelling situations. Although bacterial abundance in surface waters did not vary significantly along an onshore-offshore gradient, surface bacterial production decreased markedly from 3.5-13.3 µg C l^{-1} d^{-1} onshore to 0.6-1.1 µgC l^{-1} d^{-1} offshore. This resulted in a marked offshore decrease of specific bacterial production, which suggests substantial enrichment in DOC on the shelf.

(b) To quantify the role of bacteria and grazing on bacteria for the carbon flux on temporal and regional scales
During grazing experiments using <10-µm and <0.8-µm size fractions, bacterial growth rates were not significantly higher in the grazer free treatment suggesting more stringent substrate limitation in the absence of primary producers and predators. Furthermore, the relationship between primary production and specific bacterial production, combined with the significant correlation between bacterial production and bacterial abundance observed during Lagrangian sampling, are indicative of bottom-up control through DOC limitation. However, the importance of top-down control will be evaluated from the results of dilution experiments performed in Almeida Carvalho cruise.
In general, the fraction of respired ^{14}C-leucine varied from 11 to 68 % in surface waters with an increasing offshore trend. Bottom waters always exhibited higher values reaching a maximum of 100 % at an offshore station. The fact that large variations in the fraction of respired leucine were observed along horizontal and vertical profiles leads to the conclusion that single average values should not be used when modelling carbon fluxes in the area. Furthermore, the fraction of respired leucine was indicative of increasing DOC limitation offshore and in bottom waters. Routine screening of respired fraction may be warranted if accurate estimates of bacterial production are to be obtained in oligotrophic waters.
Finally, measurements of DOC uptake with concomitant increase in bacterial biomass yielded direct estimates of bacterial growth efficiency of ca. 20% at two intermediate stations (*OMEX0898* cruise). Although, these estimates are in agreement with those reported in the literature, more variation should be expected further onshore and offshore. More DOC uptake experiments will be carried out at stations located further apart along reference transects in future cruises (*Belgica*, 09/99 and *Thalassa*, 10/99) to provide a better assessment of spatial and temporal variability.

(c) To experimentally quantify the trophic impact of microzooplankton grazing on phytoplankton using short term shipboard experiments
Grazing rates in terms of the total amount of chlorophyll grazed per day have been determined from each experiment carried out on *CD114*. We have converted this to Carbon using a carbon:chlorophyll ratio of 68. From this data we were able to calculate the proportion of primary production grazed by the microzooplankton. The impact of microzooplankton on primary production was most pronounced at the beginning of the shelf experiment, thereafter decreasing from 80% to <40% of the production being grazed daily at the end of the drift experiment. Microzooplankton herbivory was much lower within the filament but the proportion of primary production consumed still in the region of 40% daily.

(d) To quantify microzooplankton distribution and standing stocks associated with Lagrangian drift experiments
Water samples for the determination of microzooplankton abundance and biomass were collected from 8 depths within the top 200 m of the water column from 12 dawn CTD casts. All HNF samples have been analysed and analysis of Lugol-fixed samples from 5 and 10 m and some deeper samples is also

complete. The vertical profile of protozoan and HNF biomass on Day 1 during the shelf study clearly shows maximum biomass at a depth of 10 m.
The microzooplankton community showed clear differences between the two Lagrangian experiments. Microzooplankton abundance was high, particularly in surface waters on the shelf where concentration of protozoa (10-200µm) ranged from 15,000 to 58,000 cells l^{-1} (mean 23095 cells l^{-1}) and concentration of HNF was between 200 and 700 cells ml^{-1} (mean 413 cells ml^{-1}). In the filament, HNF concentration averaged 248 cells ml^{-1} and mean protozoan concentration 3685 cells l^{-1}. Microzooplankton biomass increased from 16 to 44 mg C m^{-3} on the shelf but was much lower and less variable within the filament, around 10-12 mg C m^{-3}. It is interesting that the increasing trends in microzooplankton abundance and biomass do not match the decreasing grazing trend. This could be due to changes in the phytoplankton community and further analysis of the data should enable us to determine whether this is so.
The microzooplankton community during the shelf experiment, was dominated initially by HNF and HDINOS with OLIGOS and Other Ciliates increasing in importance with time and by 6/8 they comprised more than 50% of the biomass. One important finding during this study was the high contribution of the heterotrophic nanoflagellates to the total microzooplankton biomass. This was particularly pronounced within the filament where they comprised up to 90% of the total biomass. Tintinnids and other ciliates were very low in abundance in surface waters within the filament. The data also indicate that within the protozoan 10-200-µm size fraction, cells were larger, almost double, during the filament study.

(e) To quantify the copepod community in terms of biomass and standing stock during short-term Lagrangian experiments
The total abundance of mesozooplankton during *CD114* (averaged over the top 200 m) of "small" sized species known to feed on phytoplankton varied between 49 to 113 ind. m^{-3} (shelf) and 101 and 544 ind. m^{-3} (filament). In the small fraction the *Clauso*/*Calo*/*Cteno*/*Paracalanus* species contributed ~60% of the individuals, whereas *Oithona* spp. and *Acartia clausi* made up around 20 and 30%, respectively. In the "medium" size fraction abundance were between 4 and 13 individuals m^{-3}, with *Pleuromamma* spp. contributing between 20 and 50% in terms of abundance, together with *Calanus helgolandicus* (10-40%) and *Calanus tenuicornis* (10-30%) these were dominant. Abundance of "large" species ranged between 0 and 0.24 ind. m^{-3}, with *Euchirella curticauda* and *Heterorhabdus spinifrons* dominating. Our results also give weight to the idea that even when following a drifter it is not possible to follow a unified body of water and the organisms which live within it. The vertical distribution on the shelf is indicated, and shows that most of the copepods are concentrated in the upper 100 m of the water column at all times.

(f) To quantify the role of mesozooplankton grazing for the carbon flux both on temporal and regional scales
Mean gut contents were almost an order of magnitude greater in the "medium" sized copepods in comparison to the "small" species. The average contents were 0.234 and 1.713 ng Chl *a* $copepod^{-1}$ in the "small" and "medium" groups respectively, and there was also no clear diel signal in these rates.
Estimates of total phytoplankton consumption by the copepod community over the top 200 m of the water column calculated from our herbivorous ingestion and abundance values varied from 660 to 1123 µg Chl *a* m^{-2} d^{-1}. The variability in grazing impact over the course of this study was predominantly attributable to differences in abundance of the small copepods, which had the greatest overall impact throughout the study period at 521 to 954 µg Chl *a* m^{-2} d^{-1}.

(g) Collect CPR samples each month on and off the Iberian shelf and analyse of phyto- and zoo-plankton species abundance
As at May 1999 21 successful CPR tows have been undertaken, with approximately 30 samples on each. Plankton abundance has been determined for all samples collected in 1997 and 1998. The tows were instrumented to record temperature, conductivity and fluorescence and all data, both biological and physical, collected during 1997 and up to July 1998 have been banked at BODC. The remainder of the 1998 data will be delivered imminently once quality control procedures are complete.

(h) Derive mesozooplankton biomass and grazing rates from CPR samples
Length and dry weight measurements have been made on individuals of key species collected on cruises in the area according to the methodology described in OMEX I. CPR abundance data collected during

the project will be converted to biomass and from this estimates will be made of mesozooplankton rate processes to compare with the experimentally derived grazing and respiration rates. This work is completed in year 3.

(i) Experimentally determine mesozooplankton grazing of microzooplankton
Initial chlorophyll determinations showed that chlorophyll levels were very low in the drift experiment (*CD114* Leg b), typically 0.2-0.3 mg Chl l^{-1} and were approximately an order of magnitude higher in experiment six. The initial ciliate and heterotrophic dinoflagellate biomass were determined and showed little variation between the experiments, typically 1.5 mg C l^{-1} for ciliates and 0.4 mg C l^{-1} for the dinoflagellates.
The relationship between copepod size and ingestion of microzooplankton differs between experiments, which may be caused by differing food concentrations and which will be examined further, however in order to initially estimate community grazing all of the experiments have been combined. These relationships were applied to the copepod abundance measured by UITØ-b, by assigning a size per copepod group, calculating the relevant rate from the line of best fit and multiplying the rate by the group's abundance.
The results suggest that the copepod community consumed a very small percentage of the initial standing stocks of microzooplankton, *e.g.*, 1.5% of the heterotrophic dinoflagellates. However, copepod numbers were found to be very low on this cruise and further work will be carried out to put these results into context.

Task I.5 **Suspended matter, aggregation potential, faecal pellet production and vertical flux**
Partners: *UITØ (3a) responsible, IIM (13), PML (4a and 4b), UITØ (3b), SINTEF (18)*

Objectives:
(a) Estimate the short-term vertical flux of organic matter and phytoplankton during the Lagrangian experiments and compare these with the suspended standing stock of organic matter and phytoplankton
Vertical POC export was moderately high and ranged between 140 - 260 and 60 - 230 mg C m^{-2} d^{-1} on and off the shelf, respectively. These rates are similar to vertical export estimates from boreal shelves. There was a general decline of POC export with depth, reflecting the mineralisation of biogenic matter, in particular below the upper layers. The POC/PON ratios (a:a) were on average around 8 and ranged between 6-9, indicating that vertical export is derived from reasonably fresh and marine sources and not particularly influenced by resuspension. Vertical export of pico-, nano- and micro-plankton reflected similar differences between the on- and offshore region, *i.e.*, higher phytoplankton export on the shelf compared to off-shelf. Flagellates dominated among the exported PPC (55-90 % of POC export). Of less significance were diatoms and dinoflagellates.
Cylindrical faecal pellets with a diameter between 40 and 100 µm, produced by reasonably small copepods and krill, contributed the most to the vertical export of faecal pellets, but there was much less export of faecal pellets off-shore compared to on-shore. It is important to notice that the FPC flux on *CD114* Leg b was an order of magnitude smaller compared to that on *CD114* Leg a. Obviously, coprophagy and related processes were of great significance off the shelf.

(b) Describe and quantify the spatial and temporal distribution of the zooplankton faecal pellets production with the goal to determine their role in material cycling and evaluate the role of zooplankton grazing and flux mediation
The suspended biovolume of various categories faecal pellets (FP) varied greatly between *CD114* Leg a and Leg b. The FPC concentration on *CD114* Leg b was far smaller compared to *CD114* Leg a. This does not reflect lack of producers, but is interpreted as a results of increased coprophagy etc. off the shelf. Most of the samples from the FP production experiments for the larger and dominating mesozooplankton species from *CD114* Leg b were quantified, but the rates are still not calculated. The rates will be available very soon.
The vertical loss rates of suspended FPC is difficult to estimate as there appears to exist a significant difference in suspended FPC during day and night, implying greater grazing activity in surface water at night of species producing the largest cylindrical faecal pellets. The specific vertical sinking rates on both legs varied between 25 - 50 d^{-1}, which reflects the rather small size of the dominating producers; *i.e.*,

copepods. Also, the appearance of large suspended FP at night indicates that there were differences in diurnal feeding. The large FP indicate that there are large zooplankton taxa, probably krill, which have not been quantified by the applied netting techniques.

(c) Estimate the amount of transparent exopolymeric particles (TEP) in the water column and the sediment traps; compare TEP concentrations with diatom distribution and vertical flux of phytoplankton cells and POC
TEP samples are analysed, but are not calculated and plotted as yet. A comparison with the diatom assemblages on both legs is also dependent on respective data availability from **Task I.3 (a)**.

(d) Evaluate the role of the short-time phytoplankton species succession and the corresponding suspended organic matter concentrations on primary production and on vertical flux of carbon
To be approached in the forthcoming year when the phytoplankton and suspended matter data are fully available

(e) Validate the physical and biological model of the Iberian margin on the basis of available and new data of nutrients, phyto- and zoo-plankton and vertical flux of organic matter
To be approached in the forthcoming year.

Task I.6 2-way nested submodel, Lagrangian particle-tracking and ecological model
Partners: IST (11) responsible, SINTEF (18), UWB (6 a and 6 b), NSS (9)

Objectives:
(a) Development of a nested 3-D model allowing a resolution of the order of 1 km for the Galician area and
(b) Development of particle-tracking model and its use in conjunction with an ecological model in order to obtain a Lagrangian ecological formulation
A nested model module was implemented in MOHID3D. The utility of this module is the ability to simulate small specific areas without diminishing spatial step in the all modelled area. The kind of model implemented for now is a 1 way, meaning that information is passed only from the large-scale model to the small-scale model. In this implementation it is allowed that a run for the nested model is done separately from the regional model. This represents a considerable reduction in CPU and makes possible that another different team use the results of the regional model to run the nested model for is own purposes. In particular the nested model is available for SINTEF to run it coupled with biochemical model (see also **Task I.7**).
Preliminary results of a nested 3-D model allowing a resolution of the order of 1 km and of a particle-tracking model were presented. The nested model has a dimension of 10 x 10 grid cells in the large model. The reduction of grid cells in the nested model is 1/3 so that it has 30 x 30 grid cells.
Preliminary results from the particle-tracking model have been presented during workshops.
IST developed a biochemical "zero-dimensional" model. Each property knows only the values of the state variables determining its activity. A specific module performs the calculation of the state variable values. This module uses the hydrodynamics information provided by the circulation model, the internal transformations calculated by the biochemical model and the fluxes across the boundaries (free-surface, bottom and lateral boundaries). Fluxes across the bottom interface are calculated using a benthic diagenetic module developed using a similar philosophy. In the benthic module lateral transport is negligible and the calculation becomes one-dimensional. A clear splitting of the biochemical and transport processes allows the use of the most adequate numerical algorithm for transport in each situation and a simple exchange of biochemical modules among different teams. Simulations in the Goban Spur were carried out using both Eulerian and Lagrangian approaches for transport. Results show that both approaches can produce similar results

Task I.7 3-D nested model for the Galician shelf: ecological response and interannual variation in the carbon export
Partners: SINTEF (18) responsible, IST (11), UITØ (3 a and b), PML (4 a and 4 b), IIM (13), NSS (9), SAHFOS (12).

Objectives:

(a) Implement the existing SINTEF nested 3-D model in order to (*i*) establish a coupled hydro-biological model early in the project period, (*ii*) investigate, in co-operation with IST, the optimal way to establish the coupling between the hydrodynamical and the ecological models

The SINTEF hydrodynamic model was implemented for the Galician shelf during the first year. The SINTEF model comprises of a large-scale model having a grid point distance of 10 km and a nested model domain. Two nested domains have been tested: One having a horizontal grid point distance of 2 km and one having a grid point distance of 3.3 km. A relative large area has been chosen for the model set-ups. These areas will however be reduced in order to save computer time and thus be able to make more test runs. Both models have 23 horizontal levels of thickness (from surface to bottom): 8 x 5 m, 10 m, 4 x 25 m, 3 x 50 m, 100 m, 200 m, 400 m, 2 x 50 m, 1000 m, 2500 m. In order to improve the available data sets for the bottom topography on the shelf, bathymetry maps have been digitised.

The models have been run with the Levitus density fields and the sensitivity of the currents to the Galician shelf to change in the specified flow through the open boundaries has been investigated. Comparing the simulated flow field with observation showed relative good correspondence with a winter situation, but the important summer situation was in lesser agreement with the observations. The simulated surface current had a marked poleward flow during the upwelling season whereas the observations show a general southward flow of these water masses. The reason for this is difficulties with the open boundary specifications. Work is now carried out in order to solve this problem in the near future. The nested (3.3 km) model does however successfully simulate filament structures on the Galician shelf. It remains to verify details of their structure and to compare with real observations.

The ecosystem model assumes that nitrogen and silicate are the potential limiting nutrients and consist of eight state variables. These compartments are: nitrate (NO_3), ammonium (Na), silicate (Si), diatoms (Di), flagellates (F), microzooplankton (Mi), fast sinking detritus (Df), slow sinking detritus (Ds and mesozooplankton (Me). The basic unit used in the model is mmol N m^{-3}. Based on thorough discussions inside the frame of WP I during a specific workshop focused upon ecological modelling in February in Trondheim, the various functions of the ecosystem models were discussed. The result of these disputes is presented in the SINTEF annual report. It was concluded that some of the compartments could be lumped together in order to reduce the computer requirements. Typical candidates are nitrate and ammonium, which could be aggregated to an N compartment. However, the opportunity to calculate the new *vs.* total production is lost. Simulation experiments with the model show characteristic pattern with high production near the coast due to upwelling.

First simulation of the combined hydrodynamics and ecological model were carried out, with so far satisfactory results.

(b) Simulate response of the ecosystem as a consequence of wind events for the periods when data becomes available

First runs of the hydrodynamical model indicate clearly how wind influences the current regime in the region. Implementing the wind field during *CD114* produced a filament at the site were it was found during the cruise. The data were shown in public during a recent OMEX II-II meeting in Plymouth.

(c) Calculate possible variations in carbon export due to annual variation on wind forcing

To be carried out in the forthcoming year

(d) Establish a mathematical model for meso-zooplankton in the Galician shelf area that can be used in as well as large scale as nested ecosystem models

Model description and results from the first primary production, zooplankton and vertical flux test runs are in progress. This work will be intensified in the forthcoming period, in particular with regard to the one important grazer (*Acartia*) and its grazing effect. This will be performed by a particle-tracking model linked to a simple grazing model using the simulated flow fields. The biological component will have a simplified vertical behaviour and physiology, with grazing which mirror the field data obtained. The goal is to facilitate a high-resolution temporal and spatial grazing model for the Galician shelf based on a combined use of measurements being done within OMEX II-II and literature data.