DYNAMICS OF UPWELLING IN THE ICES AREA

Selected papers presented at Theme Session O at the ICES Statutory Meeting
23 September–1 October 1993

Edited by
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Dynamics of Upwelling in the ICES Area

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Conseil International pour l'Exploration de la Mer

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Upwelling in the ICES area

Introduction

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Although there have been some international interdisciplinary efforts in the recent past to improve understanding of coastal upwelling and associated processes, the subject of upwelling has been a minor one on the ICES agenda since the 1970s. This prompted, in 1991, the ICES Working Group on Shelf Seas Oceanography to propose a Theme Session on the "Dynamics of Upwelling in the ICES area". The 81st Statutory Meeting, which took place in 1993 in Dublin, Ireland, provided the venue for such a session.

Since the early 1970s, an impressive amount of knowledge on the physical processes involved in coastal upwelling and their consequences for marine productivity has been accumulated by large field campaigns, including the following:

- the interdisciplinary programme denoted "Coastal Upwelling Ecosystems Analysis" (CUEA), carried out off Oregon in 1972/1973;
- "Cooperative Investigation of the Northern Part of the Eastern Central Atlantic" (CINECA), co-sponsored by ICES, which revealed interdisciplinary relationships in the food web of upwelling systems during 1970-1975;
- the interdisciplinary Joint Action (JOIN T-I, II) programme carried out within the framework of CUEA to study dynamics in large upwelling areas not only off Northwest Africa but also off Peru, in 1974--1976.

Inter alia, the international co-ordination of all these activities was supported by the Scientific Committee on Oceanic Research (SCOR) Working Group 36 during 1974--1976.

Twenty-one papers and one poster were presented at the Theme Session, covering the following topics:

- physical observations and modelling,
- phytoplankton and zooplankton ecology,
- effects of harmful algal blooms dynamics,
- fish recruitment strategies, and
- multidisciplinary programme achievements.

The state-of-the-art was also discussed at a regional level, such as, for instance, the Irish Sea, off the Iberian Peninsula, and off Northwest Africa. Partial overviews were given of the latest developments in the understanding of upwelling as well as of the on-going research activities of ICES scientists. An important question the session attempted to address concerned the manner in
which we might organize interdisciplinary programmes in the future.

The key to high biological productivity lies in the upwelling of "new" nutrients from intermediate waters into the euphotic zone. Stratification in the water column makes it possible to observe the retention of phytoplankton in the well-lit near-surface water. Wind-induced mixing modifies the patterns generated by breaking down stratification, which is usually re-established soon after the wind abates.

Since ecosystem upwelling is "embedded" in a fluid medium, both marine chemistry and biology require from physical oceanographers a description of the temporal and spatial variations within the mass and current field for different scales, both in space and in time. From observations in the upwelling areas of Eastern Boundary Current (EBC) systems we can summarize the following:

- Fishing yields per hectare are at least a thousand-fold higher in coastal upwelling areas than in oceanic regions. At present, the factors controlling the fishery resources are not well known.
- Coastal upwelling occurs at a series of spatial and temporal scales with a stochastic component.
- The main upwelling zones lie on shelves with an offshore extension of 15-30 km determined by the baroclinic radius of deformation.
- The spatial extension of large-scale winds lies in the order of 1000-2000 km.
- Local wind fields are very dependent on larger-scale wind fields but can be drastically influenced by the coastal orography.
- Climatic wind-stress curl shows a negative sign, producing Ekman pumping up to ashore distance of about 200-300 km.
- Monthly windstress is about 0.1 N/m², while several-day time scales involve intermediate values (0.1-0.3 N/m²).
- The alongshore wind component is the driving force for coastal upwelling.
- Two well-mixed layers occur near the sea surface and above the bottom, with a thickness of 2 to 30 m, depending on the strength of surface currents and of the movement in deep layers. Here, we have a major gap in our knowledge!
- Temperature-salinity relationships suggest water-mass transformation within regions of active upwelling.
- The biological upwelling intensity is determined by primary production, which exceeds that of neighbouring areas by a factor of 10 or more.
- There is an equatorward-going coastal jet with core velocities of about 20-40 cm/s, an offshore width of 10-20 km, and a thickness between 20 and 50 m; the coastal jet is embedded in a surface frontal zone following the continental slope and separating the upwelled water on the shelf from offshore waters.
- A poleward-flowing undercurrent follows alongshore pressure gradients at depths between 100 m and 500 m and shows core velocities of about 5-25 cm/s; its shore width varies zonally from 20 to 80 km and vertically from 50 to 200 m.
- Both alongshore currents and the near-surface frontal zones exhibit meanders generating eddy-like features determined by irregularities in the bottom topography.
- There is some evidence that both the southward-going coastal jets and northward-flowing undercurrents are ingredients of seasonally forced Rossby waves with an offshore radiation after a critical time of about half a year.
- The coastal parallel windstress drives an offshore transport with speeds of 10-30 cm/s within the near-surface layer.
- Onshore currents flow at speeds of 1-15 cm/s in intermediate layers.
- Upwelling velocities lie in the range $10^{-3}$- $10^{-5}$ cm/s.
- Current measurements show some peaks at semi-diurnal, diurnal, several-day, semi-annual, and seasonal cycles, with energy gaps between several-day periods and the seasonal cycle.
- Variations in sea level indicate changes between 2 and 20 cm with periods of 2-7 days; they propagate polewards with properties of barotropic continental shelf waves and show a strong correspondence with changes in the local wind field.
- Although coastal upwelling areas are notable for their high productivity there are comparatively simple structures in the food web.

The conventional view of upwelling as bands of nutrient and phytoplankton-rich water parallel to the coastline...
has been modified recently, mainly by means of synoptic satellite images of the sea surface temperature and the chlorophyll patterns (Coastal Zone Color Scanner). The upwelled water and the related production are most apparent in discrete relatively stable "tongues" extending into both near-surface and subsurface currents. These features are locally fixed and, among other things, controlled by irregularities in the continental slope and coastal configuration. Acoustic Doppler Current Profiler (ADCP) measurements have shown that the filament structure may simply result from the equatorward-going coastal jet along the continental slope. Such topographically trapped filaments display meanders as far as 300 km offshore, leaving no surface signature when bending coastward.

One quite puzzling observation in upwelling areas concerns the sometimes positive and sometimes negative relationship between windstress and recruitment strength. This phenomenon was explained by the concept of the "Optimal Environmental Window", according to which concept, recruitment is at its maximum at a moderate value of windstress, roughly corresponding to a wind-speed of 6 m/s. Such windspeeds are usually observed in monthly means for the large-scale upwelling areas in EBC systems, where this concept has proved quite useful. On the other hand, there are some indications from the Cantabrian area and the Portuguese west coast that in other regions, different mechanisms must be dominant. The concept discussed depend on the underlying assumptions about recruitment conditions. For instance, it was apparent that these assumptions should be carefully specified for each separate region. The application of the OEW concept to the ICES area was one of the highlights of the Theme Session.

In the near future, topics to be considered could focus on the generative mechanisms for:

- upwelling filaments,
- pole-ward going undercurrents,
- open ocean frontal zones and associated eddy-like features,
- different circulation patterns over both wide and narrow shelves,
- dynamics within the bottom boundary and wind-mixed layer, and
- factors controlling primary and secondary production.

Furthermore, we do need explanations concerning the:

- modification of the windstress by coastal orography,
- role of local and remote forcing on different temporal and spatial scales, and
- "Optimal Environmental Window" in regions relevant to ICES.

After the Theme Session it was decided that selected papers should be published. Given space limitations the ICES Cooperative Research Report series, only those papers reviewing discussion topics could be included.

In order to illustrate the wide range of interest and interdisciplinary work carried out at different scientific levels, all abstracts are included.

Finally, we should like to express our gratitude to the authors and speakers at the Theme Session as well as to the ICES Secretariat for its practical support in all open questions, especially Dr Harry Dooley for his permanent efforts to realize the update in coastal upwelling dynamics in the ICES area.

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Upwelling Along the West Coast of Ireland: What can we learn from the experience in the Benguela Upwelling System?

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Abstract

Intensive interdisciplinary studies of the Benguela Current upwelling system off the south west coast of southern Africa were done for many years by groups closely connected to research staff of the South African Sea Fisheries Research Institute. The upwelling in this region is particularly intense and many complex processes can be identified and modelled. These findings may therefore provide as a useful model for setting up a sampling strategy for study of the upwelling processes which occur off the west coast of Ireland, or off Northern Europe.

Introduction

Upwelling may be simply defined as the process whereby deeper-lying sea water is uplifted to surface or to near-surface layers (Smith, 1968; Pond and Pickard, 1991). There are many definitions; this was chosen as a simple, descriptive definition.

Upwelling is one of the major physical processes in ocean mixing, bringing deeper water into closer contact with the atmosphere where the air-sea exchange processes so critical in study of the fluxes between the ocean and the "sea of air" above it, can take place.

Physical/chemical effects

Deeper water is nearly always colder than surface water (op.cit.) and upwelling is readily detected either by remote sensing of the resultant cooler patches of surface water, or by standard ship-borne temperature and salinity measurements. Depth profiles obtained by CTD are needed to identify the upwelling stream if it does not reach the surface layer.

Displacement of the upper layers by upwelling breaks down stratification. Fronts, often with strong vertical and horizontal gradients, develop between the upwelled water and those water masses previously present.

Depending on the subsurface salinity distribution, upwelling is detected also by surface water salinity changes-frequently the upwelling creates a less saline patch, which is more readily measured since its properties are not as easily altered as temperature. For example, recently upwelled, cool water may quickly be warmed by solar heating and its signature blurred, while the salinity may change little since the accompanying evaporation effects, which increase salinity, change salinity much less. Effects of terrestrial freshwater run off will, however, bias salinity distribution by dilution. As with temperature, salinity fronts are often associated with the upwelling system.

Upwelled water usually differs markedly in chemical composition from the water it displaces. Nutrient concentrations, including the vital nutrient elements carbon [as "dissolved" carbon dioxide- at the pH of sea water mainly bicarbonate (HCO₃⁻ ion)], phosphorous, nitrogen, silica, and essential trace elements are generally higher, and dissolved oxygen (DO) lower, in the deeper layers from which the upwelling stream originates. These differences in chemical properties may also be used as tracers for upwelling water. "Chemical" fronts develop along the boundaries of the upwelled water.
Biological effects

The injection of nutrient-rich upwelled water into the euphotic zone, where sufficient light is available, can greatly accelerate primary production and hence set up an enhanced food chain of secondary producers, together with grazers from zooplankton up to fish, marine birds and mammals. A consequence of increased production of new, living organic material is the synthesis of plant pigments, particularly chlorophyll. The resultant distinctive coloration of the water is a further indicator of upwelling (Shannon et al., 1985).

Considerably enhanced biological activity hence accompanies the physical process of upwelling and underscores the importance of this process in oceanography. Economically important fisheries are frequently located in upwelling regions (e.g., Shannon, 1985).

Processes of upwelling

In the open ocean, upwelling is associated with two-sided divergence, i.e., where current components are such as to advect surface water away from a region and deeper water then wells up to take its place (Pond and Pickard, 1991). When the divergence is one-sided, such as along a coast with a divergent water movement away from shore, upwelling of deep water is observed. Momentum currents in the ocean are associated with a density distribution such that lighter, warmer water lies on the right hand side of the current direction (in the Northern Hemisphere; to the left in the Southern Hemisphere) and cooler water, due to the slope of the isopycnals, lies on the left, and apparent "upwelling" of cooler water is seen.

Cool water patches at the surface may also be the result of the turbulent mixing upwards of deeper water when internal waves break or due to tidal turbulence, particularly associated with bottom topography near the shelf break or closer inshore. Cooler patches of water in otherwise warmer waters may not necessarily be associated with upwelling-cooler water is present in the central region of transient cyclonic eddies and is found in areas of intense tidal mixing mentioned above.

Traditionally, upwelling is linked to wind-driven transport setting up an offshore component of motion in the surface layers and deep water upwells to take its place. By its nature, upwelling is a periodic phenomenon and the processes involved have been extensively studied (e.g., Smith, 1968). The upwelling water may not reach the surface and may advect onto the shelf in coastal regions. When nutrient-rich upwelled water mixes upwards into the lower layers of the euphotic zone through other physical processes, such as by wind- or tidal-induced turbulence, phytoplankton production is stimulated. In other words, a "cold signature" at the surface, where it is readily indicated by satellite imagery, is not necessarily observed but productivity nonetheless increases and is accompanied by an increase in upper layer chlorophyll concentrations.

Upwelling has been extensively investigated in the Benguela Upwelling System (Shannon, 1985) and a great deal learned about the processes involved since upwelling is so intense in this region. The knowledge gained from studies where upwelling is enhanced can be used in areas with less intense upwelling to understand processes which may be more subtle and difficult to establish.

With this in mind, the areas of upwelling off the West of Ireland can, in the author's opinion, be studied more efficiently, and suitable sampling strategies designed, by using the well-documented Benguela system (Shannon, 1985) as a "model".

Assuming that coastal wind-driven upwelling is the mechanism involved, and that the ocean is initially at rest, a wind blowing in a direction such that an offshore transport of surface water occurs will set up the movement of deeper water closer to the surface and upwelling occurs. This process is dynamically complex and the original reference (Shannon, 1985) should be consulted for details.

Parrish et al. (1983) (see Figure 14 in Shannon, 1985), show that in the southern summer (upwelling) months the mean sea surface temperature anomalies along the south west coast of Africa vary between 0°C at 35°S to -6°C off Luderitz Bay (~25°S) and only reach 0°C again as far north as 15°C again as far north as 15°C. A band of cold, upwelled water, with anomalies generally from -1°C to -4°C lies between the coast and a region just off the edge of the Continental Shelf. In complete contrast, the warm Agulhas Current to the south of Africa has a positive anomaly of between +2 and +4°C. Even in the southern winter, when upwelling is at a minimum, anomalies off the west coast remain in the -1 to -4°C range north of about 32°S.

Satellite infra-red images confirm this temperature distribution, and show the complexities of the frontal region between the cold upwelled water and warmer offshore waters (Figure 15 in Shannon, 1985) with intertwined filaments and rings of warm and cold water and a very sharply demarcated front in some places.

Shannon (1985) describes the area in considerable detail including the distribution of offshore water movements, but for the purposes of this paper, the diagram of Barange and Pillar (1992) based on a conceptual 3-dimensional model is most useful. This diagram has
been re-drawn to simulate upwelling off a west coast in the Northern Hemisphere (Figure 1).

Results and discussion

The results enable an estimate to be made of processes off Ireland (or the west coast of Europe) when wind-driven upwelling occurs, during northerly winds. A wide shelf with a steep slope is assumed.

Near the coast, cold upwelled surface water flows poleward (northwards), modulated by coastal trapped waves, separated by the "Upwelling Front" from somewhat warmer water flowing equatorward (southwards) a short distance offshore. The colder inshore water sinks beneath this warmer water at this front, some mixing with the upwelling stream beneath and some moving further from the coast. The upwelling stream has a poleward component along the near bottom region on the shelf and upper part of the slope (to depths of about 200 m or so). A further front may develop over the shelf break and frequently merges with the "upwelling front" after upwelling has continued for some time. Sinking and turbulent mixing occurs beneath this front, with a current shear developing between surface water and water below about 100 m. When warm offshore water is encountered, the remnants of the upwelled water sink beneath this at the "Oceanic Front".

A conceptual understanding of the physical processes during upwelling events assists the chemists, biologists and marine sedimentary geologists in incorporating their observations into the physical "framework" and should lead to a better understanding of the upwelling region as a whole, culminating in an ecosystem approach.

Acknowledgements

I thank Miriam Moloney for the diagram.

References


CONCEPTUAL MODEL OF CIRCULATION DURING UPWELLING OFF THE EUROPEAN WEST COAST

Modified from Barange and Pillar (1992)

Figure 1. Conceptual model of circulation during upwelling off the European west coast.
The Benguela Ecology Programme: An example of a successful interdisciplinary study of upwelling and its biological consequences

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Abstract

The Benguela Ecology Programme (BEP) is a regional co-operative marine ecological research programme. Launched in 1982, the BEP is now in its third five-year phase. Its original objective was to provide scientific information on the structure and functioning of the ecosystem to facilitate wise management of the living resources of the Benguela Current region. Research has focused increasingly on the pelagic environment and the objectives of Phase III aim to make a reasonable contribution to the optimal utilization and management of anchovy, sardine and squid through appropriate process studies, to encourage national and international co-operation among marine scientists (and maintaining close ties with a number of international programmes) and to provide opportunities for appropriate training of young marine scientists. In this paper we outline the development of the BEP, highlight its principal features and successes and comment on this type of approach to the study of upwelling systems.

Introduction

The Benguela Ecology Programme (BEP) was established in 1982 as a co-operative scientific enterprise under the auspices of the South African National Committee for Oceanographic Research (now the Committee for Marine Science). The idea behind the creation of regional ecological programmes such as the BEP was to make best use of expertise available in research organisations, universities and museums through a co-ordinated approach, focusing on complex problems which might otherwise be insoluble. The scientific coordination of the BEP is undertaken by the Foundation for Research Development, which body also provides a significant level of funding to support participating staff at universities and museums. The organisations which have participated in the BEP include the Sea Fisheries Research Institute, the Foundation for Research Development, the universities of Cape Town, Port Elizabeth, Pretoria and the Western Cape, the South African and the Port Elizabeth museums, and the CSIR. Approximately 200 scientists have been associated directly or indirectly with the BEP since its inception, and approximately R25 million ($8 million) has been spent on the programme to date. International collaboration and exchange are a high priority and close ties are maintained between the BEP and a number of overseas scientists and research initiatives. Shannon et al. (1988) provided an assessment of the first five year phase and commented on the contributions of the BEP to science, to resource management and to the development of manpower. In 1991 the BEP successfully concluded its second phase, culminating in the Benguela Trophic Functioning Symposium in 1991, the proceedings of which were published after international peer review in the volume 12 of the South African Journal of Marine Science (Payne et al., 1992). In their evaluation of the second five year phase Rothschild and Wooster (1992) lauded the evident successes of the Programme but also pointed out a number of shortcomings. Some of the latter are being addressed in Phase III of the BEP which commenced in 1992.

Objective of the BEP

The overall and ultimate objective of the BEP is "... to provide scientific information on the structure and functioning of constituent ecosystems, to complement the knowledge which is required for the management of the renewable resources of the Benguela Current region" (Siegfried and Field, 1981). As the BEP evolved, research has focused increasingly on the pelagic environment, where the important short-lived species such as anchovy and sardine, as well as chokka squid are found. Because of their short life spans, the abundance of these species can fluctuate considerably from year to year, particularly in response to environmental changes. This
is recognised in the specific objective of Phase III of the BEP, which can be summarised as follows:

1) To make a measurable contribution to the optimal utilization and management of anchovy, sardine and squid through the following research.

   1.1 To describe the characteristics and variability of the physical environment, primary production and zooplankton production and their impact on the key resources.

   1.2 To improve existing knowledge of the nature and causes of long-term changes in the ecosystem.

   1.3 To supplement the existing knowledge on resource dynamics required for immediate resource management.

2) To encourage national and international co-operation among marine scientists.

3) To provide opportunities for appropriate training for young marine scientists.

Research structure of the BEP

The research structure of the Programme has evolved since its inception in 1982, and Phase III is more streamlined and focused than the preceding phases whose structures were described by Siegfried and Field (1981) and Shannon et al. (1988). The research structure of the latest phase of the BEP is illustrated in Figure 1 diagrammatically.

Details of the nine distinct but inter-related components of the Programme are briefly as follows:

Physical processes and remote sensing

This project aims to investigate, through on-going shipboard sampling, analysis of existing data and remote-sensing, the vertical and horizontal circulation, stratification and mixing of the coastal waters of the Benguela ecosystem. The information generated by remote sensing and processed in this project is important to several components of the Programme.

Biogeochemical processes

This project is examining the primary production of phytoplankton, which underlies all other production. Using direct measurements and remote sensing, it focuses particularly on the relative quantities of "new" production arising from the introduction of nitrogen from upwelling, and "regenerated" production from nitrogen cycling within the system. The relevance of this project to resource management lies, inter alia, in the hypothesis that sustainable yields in the system will be related to the rates of new production rather than total production.

Zooplankton and the recruitment of pelagic fish

Initial results have suggested that the number of anchovy recruits each year may be closely related to the availability of food, particularly copepod zooplankton, on the spawning grounds. The project aims to test this hypothesis through studying zooplankton production and pelagic fish feeding and their variability between and within different spawning seasons.

Factors affecting the abundance and distribution of Chokka squid

The overall objective of the project are to increase knowledge of the biology of the species to improve upon the current management procedure, and to link the distribution of squid and its availability to the South Coast jig fishery to environmental parameters. This project, involves localized environmental studies, research cruises, diving surveys and simulation modelling.

Long-term trends in the abundance of dominant resources in the Benguela ecosystem

Upwelling ecosystems are not stable assemblages of species. For example, anchovy and sardine abundances in at least some of these systems have been found to have fluctuated over decades, with the species alternately dominating the pelagic ecosystem. This project is attempting to identify the environmental parameters regulating changes in dominance, and is investigating the feasibility of predicting such changes. Such knowledge could help to forecast or at least provide early warning of shifts in ecosystem state.

Stock assessment

Variability in stock abundance and uncertainties associated with measuring abundance and key production parameters require sophisticated modelling techniques to
ensure stocks are properly utilized without undue risk of adverse depletion. This project is exploring possible improvements to the way stocks are assessed, and how the results can be translated into the best management advice. The results of this component play an important role in the ongoing management of the exploited, living resources of the Benguela.

Variability of pelagic fish and squid and the environment

This project is integrating the results from the Programme to identify those abiotic and biotic factors which drive the spatial and temporal variability of pelagic fish and squid. The relationships between these factors and the resource populations are being quantified. Coupled physical-biological models are being used to simulate the interactions between the driving variables and the dependent populations.

Resource management

Rothschild and Wooster (1992) stressed the need for a synthesis or syntheses of what is currently known about the Benguela ecosystem. This component, with several different facets, sets out to achieve such syntheses and, specifically to apply these broader insights to better management and utilization of the pelagic resources. Thus, for example, one study, is investigating short-term forecasting of anchovy recruitment success while another attempts to improve the accuracy and precision of hydro-acoustic surveys for sardine.

Principal achievements

The principal achievements of the BEP are highlighted below. Readers are referred to Payne et al. (1987), Shannon et al. (1988), Payne et al. (1992) and Rothschild and Wooster (1992) for more comprehensive information and assessment.

Scientific

- To date approximately 1 200 papers emanating from BEP-linked research initiatives have been published in the international literature. Included among these are a suite of 7 major syntheses which have appeared in Oceanography and Marine Biology: An Annual Review and the review papers which were published as part of "The Benguela and Comparable Ecosystems" volumes (Payne et al., 1992).

Management

- Perhaps the most successful component of Phase I of the BEP was the research dealing with nutrients, bacteria and phytoplankton, and the clear demonstration of the importance of the microbial loop in the Benguela food chain (e.g. Probyn and Lucas 1987, Armstrong et al., 1987, Brown and Hutchings 1987).

- Benguela scientists were among the first to demonstrate the utility of the remote sensing of ocean colour and to apply this together with thermal imagery in the study of fisheries related processes. The satellite imagery was helpful in developing concepts about the system response to large scale events such as the intrusion of Agulhas Current water into the southern Benguela region via rings and filaments (e.g. Shannon et al., 1990).

- Studies on feeding energetics have characterized a major thrust of Phase II of the BEP and have demonstrated the importance of zooplankton production, in particular copepod production on the Agulhas Bank in the life history of the anchovy. In particular the understanding of the partitioning of energy between gonad and somatic biomass is crucial for any multi-species yield-per-recruit modelling. A consequence of this is that the study of the Agulhas Bank ecosystem has become a key component of Phase III.

- A distinguishing feature of the BEP in comparison with other similar studies has been the focus on studies of the key processes determining the population dynamics of the target species within the contexts of their biotic and abiotic environments, rather than treating them as environment-independent rates. This approach, pioneered by the BEP, is yielding results which have materially added to our conceptual understanding of the system. These insights have formed valuable background to decisions made on the management of pelagic species during a period of considerable inter-annual variability.
try. The work on fish scale deposits and studies which compare trends, variability and change in the Benguela with other harvested upwelling systems are viewed as important for the longer term management of Benguela resources. The contribution of Professor D.S. Butterworth and his team to the development and application of appropriate resource models and management procedures is internationally recognised. The BEP Seal Workshop held in 1991 to address the issue of seals/fishery interactions addressed issues related to conservation and multi-species management.

The BEP since its inception has striven to maintain a reasonable balance between applied/focused research and investigator-initiated research. It is our view that the Programme has been most successful in this respect, in spite of criticism which has been levelled at those who guide the BEP that too much of the research has been academic or not relevant. We believe that the maintenance of a fine balance has enabled the Programme to survive for over a decade as a respected science-driven initiative which is responsive to the needs of wise management. Indeed Rothschild and Wooster (1992) have stated "In our opinion the BEP is close to solving the recruitment problem of the anchovy - a remarkable achievement, the value of which would be enhanced by a better understanding of physics of the system, a fact which also seems to be in prospect given the improved understanding of large-scale circulation features such as El Niño and the Southern Oscillation."

Training and other benefits

* To date the BEP has produced 27 PhD and 24 MSc graduates over a broad spectrum of the natural sciences.

* Regular (weekly) seminars, frequent workshops and the less frequent scientific symposia have played a vital role in the communication process and in informal education and training, as has the contact with overseas scientists.

* Bridges have been built between the Sea Fisheries Research Institute and museums and universities, in particular the University of Cape Town. These have resulted in less tangible but perhaps the most significant of all benefits, in that the contact has contributed to the improvement of State funded science and at the same time the increased relevance of university research and education.

Concluding remarks

The BEP has proved to be a most successful and cost-effective venture in terms of the science, improved management of Benguela resources and development of skilled manpower. The experience, knowledge and understanding gained has facilitated the optimal utilization of a number of living resources, in particular anchovy, sardine and hakes (Punt 1992) during a period which has been characterised by large fluctuations in the environment and in the fisheries. As a consequence of the interdisciplinary approach which has been followed by the BEP we are now much closer to being able to predict recruitment of the key pelagic species.

It is our view that a BEP-type approach could serve as a model for the study of other coastal upwelling systems.

References


Figure 1  Research Structure of the Benguela Ecology Programme.
On the Process of Upwelling: New observations and understanding

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Abstract

Sverdrup (1938), in the first 'modern' paper on upwelling, stated the hope "that in the future it will be possible to undertake special series of observations during periods of upwelling in order to obtain better knowledge of the phenomenon and to answer many questions which now must be left open." During the past decade several major oceanographic experiments were conducted over the continental margins in coastal upwelling regions. The studies extended farther seaward than the continental shelf and often extended over the seasons. Our understanding of the processes associated with coastal upwelling, especially the Ekman transport in the surface layer and the processes affecting the ocean farther seaward, has increased. The wind-driven cross-shelf transport in the surface mixed layer agrees well in magnitude and variability with the Ekman transport estimated from the wind stress. The cool 'filaments' conspicuous in satellite images of SST during the coastal upwelling seasons off northern California, Portugal and Africa, have been studied; these cool filaments are usually the jets along the boundary (front) between recently upwelled water and the warmer adjacent ocean water. Sverdrup wrote: "One may ... raise the question whether a boundary region of the nature described can exist on a long horizontal distance ... it appears indeed likely that on a long distance it must be broken up owing to the intensive mixing processes, and that horizontal eddies of considerable dimensions may break away from the boundary region." Although the question remains, observations with new techniques suggest that the boundary is maintained over long horizontal distances as the jets meander equatorward, but that eddies may break away. The upwelled water (and the front associated with coastal upwelling) can extend farther offshore than previously realized. Cross-isobath flow, although generally small compared to the along-isobath flow over the continental margins, is of crucial importance to the physics and ecology of both the coastal ocean and the ocean boundary currents seaward of the shelf; this topic, especially over the inner shelf and in the bottom boundary layer, will be the focus of much future research, as will the problems of cross-frontal exchange and the adjustment of flow to spatial variations in wind and topography.

Introduction

A review of "the state of the art of upwelling understanding" was suggested as the topic for this paper and, at the risk of being parochial, I thought a review of what we have learned about coastal upwelling in the California Current region, i.e., along the west coast of North America, might be of interest to ICES oceanographers. Studies of the physical dynamics along the eastern boundary of the North Pacific since 1980 have caused physical oceanographers to think anew about coastal upwelling regions and, in particular, about interactions between the coastal ocean and the larger ocean seaward of the continental shelf (Smith, 1992). The observational and modelling results should be important for both contemporary fisheries problems and the interpretation of the sediment record - the focus of both are often seaward of the continental shelf but greatly influenced by processes over the shelf. Before discussing recent experiments in which the focus was offshore of the shelf-break, one important achievement of the earlier experiments that focused on the continental shelf should be mentioned: understanding of the surface boundary layer.

The divergence of the Ekman transport in the surface boundary layer drives coastal upwelling, but there have been relatively few studies of the surface boundary layer in the coastal ocean since such studies involve expensive moorings and considerable effort to obtain the wind field. Two major physical oceanographic studies that were conducted over the continental margins along the ocean's eastern boundary did make detailed measurements in the surface boundary layer: the Coastal Upwelling Ecosystems Analysis (CUEA) program, with experiments off Oregon (1973) near 45°N, Northwest Africa (1974) near 22°N, and Peru (1977) near 15°S, and the Coastal Ocean Dynamics Experiment (CODE) off northern California (1981 and 1982) near 38°N. In each of these regions, the wind, currents, and tempera-
ture were measured from moorings near mid-shelf; all four regions had mean equatorward wind stresses and large mean heat fluxes into the ocean during the observation periods. Lentz (1992), in a paper on the surface boundary layer in coastal upwelling systems, examined the observations and found that the offshore-onshore Ekman transport estimated from the wind stress agrees well, both in magnitude and variability, with that directly measured by current meters in the surface boundary layer. The agreement can be seen in Figure 1, from Lentz (1992), which shows the time-series of the cross-shelf transport in the surface boundary layer and the Ekman transport computed from the wind stress. Lentz found that the surface mixed layer, which responds to the wind in a slab-like manner, does not contain all of the wind-driven transport; the Ekman transport layer is deeper than the mixed layer and up to half the wind-driven transport occurs in a transition layer below, and about half as thick as, the mixed-layer. On the basis of five experiments in four coastal upwelling regions, one can say that the wind-stress alone seems to determine most of the offshore transport at mid-shelf. Because of the coastal boundary, offshore transport causes a divergence in the horizontal flow and upwelling occurs between the coast and mid-shelf.

The boundary region

The boundary between the cold, saline and nutrient-rich upwelled water and the warmer, lighter and nutrient-depleted oceanic surface water is often sharp, forming a 'coastal upwelling front' conspicuous in satellite imagery of temperature and colour. The coastal upwelling front is a manifestation of the divergence of the surface Ekman layer forced by the coastal boundary: the vertical stratification (in temperature, density, nutrients) is folded into a horizontal stratification. Because of the strong density gradient across the front, a strong geostrophic current sets up along the front (the thermal wind effect of meteorology).

Sverdrup (1938), in a paper entitled "On the process of upwelling" reporting on observations off southern California near 34°N, noted that "between the heavier upwelled water and the light offshore water a boundary region forms with a strong current parallel to the coast". Sverdrup speculated on the fate of this coastal upwelling front and jet after the initial stage of coastal upwelling and, in a later paper (Sverdrup and Fleming, 1941), questioned "whether a boundary region of the nature described can exist on a long horizontal distance. It appears likely that on a long distance it must be broken up owing to intensive mixing processes, and that horizontal eddies of considerable dimensions may break away from the boundary region ..., but what actually happens can be determined only by surveys more extensive and detailed than the present one".

Satellite observations of the waters off California provided some of the first "surveys" adequate to the task and showed the inhomogeneous nature of the boundary region between coastal and offshore waters during the upwelling season, including long tongues or filaments of cold or high chlorophyll water extending from the coastal zone to more than 200 km from shore (Bernstein et al., 1977; Abbott and Zion, 1985; Kelly, 1985). Examples of SST (sea surface temperature) maps of the eastern North Pacific from satellite images are shown in Figure 2; oceanographic observations from ships at the time of these images will be discussed later. Similar features are seen in the satellite images of other coastal upwelling regions, especially in the Benguela Current region off South Africa (Lutjeharms et al., 1991) and off the Atlantic coast of the Iberian peninsula (Haynes et al. 1993).

Extensive systematic surveys of temperature, salinity and velocity were made over the shelf and slope off northern California during CODE in the upwelling season (spring and summer, 1981 and 1982) and extended to the transition zone between the coastal and offshore waters (Huyer and Kosro, 1987). The results from CODE showed (e.g., Davis, 1985; Kosro, 1987; Send, 1989) that the flow patterns could be much more complex than inferred during earlier studies of coastal upwelling and demonstrated that the observational effort must extend farther seaward. During CODE, shipborne and drifter observations off northern California, coupled with satellite observations, showed that at least some of these cold tongues and filaments are associated with strong (>0.5 m s⁻¹) narrow (~30 km) seaward currents, (Flament et al., 1985; Kosro and Huyer, 1986). Surface drifters deployed over the shelf near Pt. Arena (39°N) suggested that freshly upwelled waters may "squirt" directly offshore, after undergoing little or no alongshore displacement (Davis, 1985). Other observations, including a July 1982 survey of waters offshore of Pt. Arena using closely spaced CTD (conductivity-temperature-depth) casts and a shipborne ADCP (acoustic Doppler current profiler), suggested that the seaward jet off Point Arena is a continuation of a strong alongshore "coastal jet" that flows generally southward along the upwelling front between warmer offshore waters and cold, freshly-upwelled coastal waters (Kosro and Huyer, 1986); this view was supported by the track of a drifter which moved rapidly southward at about 125°W between 45°N and 35°N in August and September 1984 (Thomson and Papadakis, 1987). Still other observations (Mooers and Robinson, 1984) off northern California suggested that pairs of oppositely-rotating eddies might interact to produce intense current jets and to extract filaments of cold coastal upwelled water out to sea (i.e., the eddies might act as roller bearings extracting filaments of cold water seaward from the continental margin). The resolution of the ontogeny of the 'cool filaments' required surveys that were more extensive and detailed,
and this was accomplished with the Coastal Transition Zone Experiment.

The Coastal Transition Zone

The Coastal Transition Zone (CTZ) study was initiated with the explicit purpose of studying the structure and dynamics of the boundary region between the coastal and oceanic water, and the characteristic 'filaments', 'squirts', and 'jets' that lie within it (Coastal Transition Zone Group, 1988). The region chosen for the CTZ study was centred off northern California at about 39°N, offshore of the site of the CODE experiment. The CTZ experiments took place during the summers of 1987 and 1988 (CTZ Group, 1988; Strub et al., 1991), the season when the alongshore wind-stress exceeds 1 dyne cm⁻² and the resulting seaward Ekman transport exceeds 1 Sv (1 Sv = 10⁶ m³ s⁻¹) per 1000 km of coastline.

The 1987 experiment looked at the larger scale (42 to 37°N) and provided evidence that the structures seen in the satellite images were not simply upwelling 'squirts' or a field of oceanic mesoscale eddies interacting with the coastal ocean, but the result of a strong alongshore jet meandering equatorward, perhaps starting as a coastal current velocity structure observed during the upwelling season (spring through summer) is seasonal, since the cold upwelled water which serves as a "dye" or tracer is present only during seasons of coastal upwelling. On the basis of limited winter cruises, these strong narrow currents seem to occur only during the seasons of persistent coastal upwelling, i.e., strong equatorward winds (Kosro et al., 1991).

Since the jet flows rapidly equatorward, it efficiently advects water with upstream properties. Off northern California the jet carries water of lower salinity than that present either offshore or onshore at that latitude (Huyer et al., 1991). The TS (temperature-salinity) distribution for the several surveys of the CTZ jet during June to August 1988 is shown in Figure 9, from Huyer (1991). It is clear that the water in the jet is not a mixture of the water on either side of the jet in the survey region; it must be advected from upstream. On Figure 9 is also plotted the TS characteristics from Station 130 in June 1987 (see Figure 4) which is just offshore from the shelf break in 300 m of water at 43.1°N. Mixing along isopycnals of this water with inshore water, which has been more recently upwelled, can clearly yield the water properties seen in the jet 300 km to the south. This further supports the hypothesis that the jet and front observed a couple of hundred kilometres off the coast at 38°N is connected to the coastal upwelling front and jet over the shelf several hundred kilometres to the north.

The results of the CTZ program show that the upwelling front may advance seaward a couple of hundred km beyond the continental shelf as the jet continues to flow equatorward for several hundred km without breaking up. The jet itself is not a region of abundant nutrients and phytoplankton, but the boundary separating upwelled water from the nutrient poor water seaward (Chavez et
al., 1991). The jet and front remain a boundary, albeit an active one with some exchange across the front, perhaps by upwelling and downwelling along the jet's edges. As the upwelling front meanders much farther seaward, the upwelling 'signal' extends much farther seaward than earlier thought likely; this must have a significant effect on fisheries recruitment and the sediment record.

Present

A major field study has recently been completed (1992-1994) off northern California, extending from the inner slope to 128°W between 36° and 39.5°N. The goal of this EBC (eastern boundary current) study is to understand the physical and biological dynamics of the mesoscale interactions in what is assumed to be the weakly nonlinear flow regime of eastern boundary current regimes. Although the California Current is the most studied of the eastern boundary currents, its large variability and the difficulty of quasi-synoptic sampling leave many questions about the mesoscale flow field unanswered. The CTZ experiment showed that mesoscale eddies, that deform the main thermocline by 100 to 200 m vertically and have horizontal scales of 10 to 100 km, and a jet-like flow of width about 40 km and transport of about 4 Sv, that meanders on scale O(>100 km), are superimposed on the long term mean California Current which has been characterized as a broad (~1000 km) southward drift with a transport of about 10 Sv (Wooster and Reid, 1963). Lynn and Simpson (1987), analysing 23 years of hydrographic data, noted that a high-velocity low-salinity core of the California Current was coincident with an eddy-dominated transition zone; because of the coarse spatial and temporal resolution of that data, they deduced a broader (>100 km) transition zone with speeds less than 20 cm s⁻¹. Among the hypotheses are that eddies have their origin on the continental shelf or inner slope (eddies are perhaps 'spun off' the meandering jet as it transits the slope) and that the circulation accompanying the meanders has a significant vertical component. No direct measurements of these features had been made over their 'lifetimes' (the duration of the CTZ experiments was on the order of one month) so we have little knowledge of their dynamical and energetic interactions, nor had the development of the jet(s) over an annual cycle been observed. For the EBC study, moored arrays of current meters have been deployed for two years (1992-4), extending from just seaward of the continental shelf break to about 300 km offshore over the abyssal plain. Lagrangian drifters, towed CTD systems, and satellite derived SST and sea surface altimetry have also been employed. The current meter mooring array, near-surface drifters, and satellite SST and altimetry should allow the seasonal variation of the features to be observed and, in particular, to verify that the development of the "California Current" jet follows the development of coastal upwelling. Since the field experiment ends during the second half of 1994 it is too early to discuss anything except for some preliminary results from surveys in 1993.

The CTD surveys in June and August 1993 were done with an towed undulating vehicle (SeaSoar) moving at 8 knots. The temperature and salinity fields were mapped to 250 m with an along-track resolution of about 3 km, with track separation of 28 km (0.25° latitude). The geopotential anomaly maps (dynamic height) at 25 m relative to 199 m are shown in Figure 10. The winds in the region were often in excess of 30 knots during both cruises. The dominant feature is the alongshore baroclinic jet which is continuous through the region and over the three months; it is along the boundary of the cold water in the satellite image for 27 August 1993 (Figure 2). In June, the jet had one gentle meander in the vicinity of the cyclonic eddy near 38.3°N, 125.2°W. By August, the jet had developed intense meanders and part of it reaches 400 km offshore; the cyclonic eddy was at 37.8°N, 127°W. This cyclonic eddy, first observed in satellite images over the inner slope in April, was first surveyed with a CTD grid and ADCP transects in May when it was centred at 38.6°N, 124.3°W. The cyclonic eddy remained on the coastal side of the jet throughout the six months, having moved WSW at 0.05 m s⁻¹.

The preliminary results confirm the significance and persistence of the jet, and the difficulty of making a meaningful distinction between it as a feature associated with an eastern boundary current and as the coastal upwelling front and jet. These preliminary results suggest that although eddies are present and the jet (front) meanders, the boundary between the coastal upwelled water and the oceanic water is not "broken up" by large eddies, as Sverdrup guessed, but persists over very long horizontal distances. Indeed the jet seems to act as a barrier to cross-margin exchange by large eddies. However, a cyclonic eddy, which developed out of the meandering coastal jet between 42° and 43°N, was observed to separate from the coastal jet and move offshore while the coastal jet re-connected (Barth et al., 1994). Exchange across the jet may take place more commonly by subduction and vertical motions near the front - or with short-wavelength instabilities. Barth (1994) has modeled the short scale, O(20 km), instabilities on coastal jets; an example of wave-like perturbations along the coastal upwelling front and jet off Oregon is shown in Figure 11, from Barth (1994). The present studies do support the view expressed in the final sentences of Sverdrup (1938): "...as the boundary region moves out conditions become more and more unstable and large eddies develop on the coastal side of the boundary. The processes are far more complicated than assumed on the basis of earlier data."
Future

Future studies, I expect, will again focus on the shelf and processes not yet adequately understood: the inner shelf, inshore of the mid-shelf moorings used by Lentz (1992) in his study of the surface boundary layer, is where the cross-shelf divergence of the surface Ekman transport, and hence upwelling, occurs. Although the bottom boundary layer is of importance in cross-shelf transport, and in many models of coastal upwelling, measurements in it have not been adequate to even test the Ekman transport in the bottom boundary layer (Lentz and Trowbridge, 1991). The behaviour of coastal upwelling fronts and their presumed transition from the shelf to the open ocean needs further study: How does the front over the continental margin respond to wind variability? Does the front over the shelf at higher latitudes (e.g., north of the critical latitude for annual baroclinic Rossby waves)? How does it 'regulate' the distribution and transport of planktonic forms?

Another topic deserving of study are the ubiquitous poleward currents (Warren, 1990), usually subsurface over the inner slope and outer shelf, that are observed in all coastal upwelling regions in spite of equatorward winds (Neshyba et al., eds., 1989). A companion experiment to CODE, monitored the currents along the North America continental shelf from 35\(^\circ\)N to 50\(^\circ\)N to define the seasonal cycle; the tendency for subsurface poleward flow over the continental shelf was ubiquitous and the mean poleward flow actually increased at lower latitudes in spite of the increased equatorward mean wind (Strub et al., 1987). There is not yet a satisfactory model for poleward undercurrents. They may be a source of upwelling water, and they may provide a 'recycling conveyor belt' for nutrients and biota. Unlike the jets of the coastal transition zone, the poleward undercurrents seem trapped to the continental margin. The time scale of the undercurrents variability over the slope is greater than that of typical shelf currents responding to the local wind. Although there is evidence for the existence of poleward undercurrents along the eastern boundaries of the Atlantic and Pacific Ocean in both hemispheres, there has been no definitive study of their continuity over even a few hundred kilometres. It is to be hoped that in the future it will be possible to undertake special series of observations in upwelling regions of eastern boundary currents in order to obtain better knowledge of the phenomena and to answer the many questions which now must be left open.

Acknowledgements

The Office of Naval Research Coastal Dynamics Program Grant N00014-92-J-1177 and National Science Foundation Grant OCE-9103034 have supported my interest in coastal upwelling. Continuing research on the ontogeny of the fronts and jets associated with coastal upwelling and eastern boundary currents is being supported by ONR Grant N00014-92J-1348 and NSF Grant OCE-9314370. I thank my colleagues Jack Barth, Raleigh Hood, Jane Huyer, Corinne James, Mike Kosro, Steve Lentz, Steve Pierce, and Ted Strub for sharing ideas and figures.

References


Figure 1  Time-series of the cross-shelf transport in the surface boundary layer (from Lentz, 1992) on the continental shelves of Oregon (1973), Peru (1977) and California (1982). Solid line is the transport measured in the surface boundary layer (mixed layer plus the transition layer) and dashed line is the Ekman transport computed from the wind-stress \( U_E = \tau/\rho_0 f \).
Satellite sea surface temperature (SST) images of the coastal upwelling region off the west coast of North America at the time of three shipborne experiments, all of which included observations in the vicinity of 39°N, 125°W; crosses mark odd latitudes at 125° and 130° W. The seasonal coastal upwelling had begun at least 3 months prior to time of each image; the onset of sustained upwelling favourable winds had been unusually late in 1993, but winds were subsequently unusually strong. The association of westward meanders with capes, and the repeatability of the structure, is suggested by the images from June 1987 and August 1993. Geopotential anomaly (geostrophic current) maps from the time of the images are shown in Figures 3, 6, and 10. Satellite images were provided by Corinne James and P.Ted Strub.
Figure 2 (c)
Figure 3  Geopotential anomaly (m$^2$ s$^{-2}$), or dynamic height, of surface relative to 500 db from cruise 9-18 June 1987. Compare with the SST image from June 1987 (Figure 2), and Figure 4, which presents data along 41.5° and 40°N in sections. Figure from CTZ Group, 1988.
Sections of alongshore velocity from shipborne ADCP (top row), temperature (middle row) and salinity from the cruise during June 1987 (Figure 3): Across the shelf at 43°N off Oregon (left panels), off northern California at 41.5° (middle) and 40°N (right). Northward velocity is positive, units are m s\(^{-1}\), and distances in kilometers from the coast; the innermost stations of the two southern sections are in deep water seaward of the shelf break. The equatorward jet is associated with a temperature front (which is also a density and salinity front) near the 13°C isotherm at all three latitudes.
Figure 5  Potential density (sigma-theta), chlorophyll-a, alongshore geostrophic velocity, and particle volume along the cross-margin section at 41.5° N shown in Figure 4; station numbers as in Figure 4 but distance scale in Figure 5 is relative to most inshore station, which is 50 km offshore. Figure is adapted from Hood et al., (1991).
Figure 6  Geopotential anomaly (m² s⁻²), or dynamic height, of surface relative to 500 db, and surface salinity, from cruise 13-18 July 1988. Note that the jet is advecting water of minimum salinity. The TS diagram for the occupations of this station grid during June-August 1988 is shown in Figure 9. Figure 2 shows a SST image from 16 July 1988, and Figure 7 and 8 present velocity data from the current meter moorings indicated by the stars in Figure 6. Figure from Huyer et al., 1991.
Figure 7  Low-pass-filtered (half-power at period of 35 hours) velocity from moorings indicated (stars) in Figure 6. Most northern mooring is D5/6; most southern mooring is D7/8. Top panel shows velocity vectors at about 90 m below surface. Bottom panel shows vectors from selected depths at D5/6; measurements at 100 m and above are from an ADCP. Figure from Huyer et al., 1991.
The velocities at 20 m from moored and shipborne ADCPs from July 1988. The upper panel shows time series from moorings D5/6 and D7/8, the northern and southern moorings shown in Figure 6. The lower panel shows velocities at 20 m during repeated transects across the jet; the ship track was along 330° - 150° T through the moorings shown in Figure 6; the location of the moorings are indicated by the dashed horizontal lines. The jet wiggled in direction but the volume transport estimated from moorings, ADCP transects and geostrophic computations varied little. Figure provided by Stephen Pierce.
Figure 9  Average T-S curves for three groups of stations from 5 complete surveys of the grid shown in Figure 6. The groups are defined by ranges of dynamic height (geopotential anomaly units m² s⁻²) of the sea surface relative to 500 db and represent locations inshore of the jet core (values < 7.6), offshore (>9.6) and within the jet core (8.6 to 9.4). The shaded areas represent on-half standard deviation of the means. Note that the core is less salty at all densities and so can not be simply a mixture of the inshore and offshore waters. The T-S curve from station 130 in Figure 3, near shelf edge at 43.1°N, is plotted to shown that it could be a coastal upwelling parent to water in the jet core. Figure from adapted from Huyer et al., 1991.
Figure 10  Geopotential anomaly (m$^2$/s$^2$), or dynamic height, of 25 db surface relative to 199 db from the EBC cruises in June and August 1993. Figure 2 shows a SST image from the time of later cruise (27 August 1993).
Figure 11  Satellite derived images of sea surface temperature (SST in °C) off Oregon on 2 June 1992 (from Barth, 1994), showing the coastal upwelling front and jet. The right panel shows SST anomalies (maximum of 0.35°C) obtained by removing spatially averaged (cosine filter width of 20 km) SST. According to Barth (1994), these wave-like features appear to grow rapidly and propagate swiftly in the direction of the jet.
Harmful Algal Blooms in Relation to Wind Induced Coastal Upwelling and River Plumes

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Abstract

Most harmful algal blooms are produced by dinoflagellates. In coastal upwelling areas, diatoms are usually associated with active upwelling, while during relaxations or reversals, dinoflagellates replace diatoms. Presumably, this change is caused not only by the changes in nutrients and turbulence, but also by the influence of river plumes that flow along the coast when upwelling relaxes. In typical coastal upwelling areas, rivers are not common as they are usually associated with deserts (e.g. Sahara, Atacama, California, Kalahari). Nevertheless, on the Iberian Atlantic coast, an area where algal blooms are frequent, both coastal upwelling and river discharges are important. The longshore transport of initial population for developing a dinoflagellate bloom is considered important in upwelling systems. The concept of optimal environmental window could be applied, in a broad sense, to dinoflagellate blooms in upwelling areas. The effect of global climate change on harmful algal blooms occurrence in upwelling areas is considered: as wind induced upwelling may increase due to the "greenhouse effect", dinoflagellate blooms related to upwelling are expected to change their incidence.

Introduction

Most harmful algal blooms are caused by autotrophic dinoflagellates, or other organisms with similar characteristics: autotrophy and the capacity to perform active vertical displacements. Nevertheless, some diatoms may also cause harmful blooms due to their capacity to produce phyctotoxins that can be transferred through the marine food web and cause human poisoning. This is the case of the pennate diatom Pseudonitzschia pungens f. multiseries (Subba Rao, et al., 1988). Other diatoms, like Chaetoceros convolutus can cause physical damage to fish cultured in cages that cannot avoid the algae (Taylor, 1993). This paper deals only with those blooms caused by motile autotrophs in areas of wind driven upwelling.

Winds act on the upper layer of the water column. This layer, in which the applied wind stress is absorbed is called the surface Ekman layer and is the part of the water column where turbulent shear stress is non-negligible. (Brink, 1983). When this layer is affected by longshore winds with the coast on their left, it is moved offshore due to the Coriolis effect (the opposite in the Southern hemisphere). The water of this upper layer is then replaced by subsurface water, rich in nutrients, which rises near the coast. Diatoms are the phytoplankters best adapted to this situation, in which both turbulence and nutrient levels are high (Margalef, 1978). This is the reason why most of phytoplankton studies in upwelling areas, consider diatoms to be the major component of the phytoplankton in those areas. Nevertheless, Blasco (1975; 1977) showed that dinoflagellate blooms also make an important contribution to primary production in upwelling areas and pointed to the high frequency of "red water" events in upwelling regions. Small (1973), as cited by Small and Menzies (1981), even suggested that greater productivity can be achieved during upwelling relaxation than during strong upwelling. Although they did not mention the organisms responsible for that production, they are probably dinoflagellates. Seliger (1993) discussed the spatial and temporal scales of red tide mechanisms, gave special attention to coastal upwelling fronts, and considered alongshore transport as an inoculation mechanism.

Discussion

Seasonality

The seasonality of upwelling in the Northeast Atlantic was described by Wooster et al. (1976) based on observations of sea surface temperature and winds obtained from ship's reports. They found three types of upwelling
seasonality in that area. In the South, from 12° to 20°N, upwelling occurs from January through May, from 20° to 25°N, upwelling is strong throughout the year, and between 25° and 43°N it takes place from June through October. This seasonality is also well expressed by the annual evolution of the upwelling index in these regions (Bakun, 1973). As a consequence of this upwelling seasonality, we expect a strong influence on the annual phytoplankton cycle in the affected areas caused by the differences of turbulence and on the supply of nutrients to the photic zone. Margalef (1978) states that primary production appears simply as a function of the external seasonality on the blooms. The Rias Baixas of Galicia, differences of turbulence and on the supply of nutrients as the Northern prolongation of the Sahara system. In these regions, the estuarine circulation, reinforced by local winds, makes the upwelled water enter along the bottom and causes very high primary production. These rías are one of the most productive areas in the world and shellfish culture is a major industry that is jeopardised every year by harmful algal blooms. Here, the seasonality of blooms is clear: some species like Mesodinium rubrum usually bloom in summer during the upwelling season, while blooms of others such as Gymnodinium catenatum and Alexandrium affine, are more frequent after the summer (Fraga, 1989). In the case of summer blooms, they are usually more local phenomena, sometimes restricted to small inlets inside the rías. Although upwelling is the main factor driving the hydrography of the rías, these summer blooms do not depend as directly on upwelling as the autumn blooms that usually occur near the mouths of the rías. In the Rías Baixas, autumn blooms have been associated with upwelling relaxation that happens after the summer, when the area is no longer under the influence of the Azores high that produces upwelling favourable longshore winds on the western coast of Iberian peninsula. When the first low pressure announces the end of the summer, winds change from Northerlies (upwelling-favourable) to Southerlies (downwelling-favourable). This change in winds causes upwelling relaxation and advection of warmer surface water towards the coast, that coincides with dinoflagellate blooms. (Fraga et al., 1988; 1990; 1993).

Similar mechanisms have been described in other parts of the world. In the South African system, Horstman (1981) reported a bloom of the toxic Alexandrium catenella after two weeks of continuous Southerly winds (upwelling favourable on west coasts in the Southern hemisphere). He also says that blooms of toxic and non-toxic dinoflagellates occur frequently along the west coast of South Africa, but only when wind-driven upwelling is inactive for at least a few days. Pitcher et al. (1993) in the same area also associated downwelling periods with warmer temperature and dinoflagellate blooms, and upwelling periods with colder temperature and diatom blooms.

Alongshore transport

One problem that arises when an algal bloom is studied, is the identification of the seed population. Three origins can be considered: a) in situ populations of residual vegetative stages that need considerable time to increase their concentration by vegetative growth only; b) benthic resting cysts that may excyst simultaneously leading to a larger initial population; c) advected populations that increase their concentration by accumulation in convergence areas.

The first mechanism is not probable in a wind induced upwelling area, as turbulence will disperse the flagellate populations. Excystment does not look probable either as if there is no accumulation area, the recently excysted cells should also be dispersed by upwelling. The rapid appearance of blooms in upwelling regions could only be explained by advection and accumulation of a dispersed initial population to centres of convergent flow. These, at least occasionally, are the upwelling fronts (Brink, 1983).

The coastal longshore transport of water in upwelling systems is well known. Evidence exists also that longshore poleward currents lie over the slopes of continental shelves (For review, see Neshyba et al., 1989). Although the poleward surface flow of warm water off northwest Spain in winter is a conspicuous (by satellite imagery) phenomenon (Frouin et al., 1990; Pingree and Le Cann, 1990) called by Pingree and Le Cann (1992) "Navidad" (Christmas in Spanish), and HAB events are usually summer/autumn events, poleward currents are important in the developing of blooms in this area. Haynes and Barton (1990) studied this current in September 1986 at the time of an intense G. catenatum bloom in the Galician Rías. They found an offshore poleward current that advected higher salinity water 70 km northwards in only three days during an upwelling relaxation. The longshore poleward transport of water during upwelling relaxations is considered by Send et al. (1987) as even more important for coastal warming than offshore-inshore advection. When upwelling is strong, this poleward current still flows on deeper waters. According to a numerical model (Batteen et al., 1992) a steady band of equatorward winds which are uniform longshore but with an anticyclonic wind stress curl results in a equatorward coastal surface current nearshore and a poleward surface current offshore, developing eddies. The importance of poleward flows in wind-
driven upwelling systems was probably underestimated in the past, as was the case in the California Current system, where they dominate the circulation in its easternmost part (Bray and Greengrove, 1993).

Signs of a poleward along-shore transport of initial populations for an algal bloom in Galicia were reported by Estrada et al. (1984) when *G. catenatum* and two species of *Prorocentrum*, not previously recorded in the area, were observed south of Lisbon, and a month later bloomed in Galicia. Moita (1993) also suggests a transport like this for 1985, when *G. catenatum* was observed in August off Cape Roca, and bloomed off the north of Portugal and off Galicia in November. A bloom of the toxic dinoflagellate *G. catenatum* was observed centred over the shelf-break off Figueira da Foz (Portugal) in May 1993 (unpublished data), during a cruise off the coast of Galicia and Northern Portugal, and at the same time that no toxicity was detected in shellfish near the coast (M.A. Sampayo, personal communication). Approximately ten days later, this species was detected in the plankton of the Galician rías, around 200 km to the North, causing toxicity to mussels.

Equatorward currents have also been related to algal blooms. A longshore transport of cells was suggested by Blasco (1977) to explain a bloom of *Gonyaulax polyedra* in the upwelling region of Baja California, based on parallels between the distribution of dinoflagellates and low salinity water. Franks and Anderson (1992) also suggested transport of *Alexandrium tamarense* along the coast of the Gulf of Maine.

Harmful algal blooms are generally short term events, but their generation time could be much longer than the conspicuous event, which is the end of the whole process. We include here, in their generation period, the alongshore transport of initial populations. The longshore currents are most responsive to large-scale winds, while cross-shelf currents are much more responsive to shorter scale wind fluctuations (Brink et al., 1987, 1994). These two scales are important in developing blooms, and both processes are essential. Longshore transport better explains the interannual variation of HAB events in a wind driven upwelling system, as it depends mostly on large-scale winds, while the short-scale winds are more responsible for the triggering of blooms. On short-time scales, reversal or relaxation of upwelling favourable winds not only can cause reversal of the longshore currents, but the passage of coastal trapped waves may also cause reversal (Boyd and Smith, 1983).

River plumes

The most important coastal upwelling regions in the world are those in the eastern boundaries of the Oceans, like the western coast of USA, Peru, Western Sahara or Namibia, due to the important longshore equatorward winds. Deserts are common on the continents near the coasts of the upwelling areas, like California, Atacama, Sahara and Kalahari deserts, and river discharges are then very unusual in upwelling systems. Nevertheless, there are some cases in which rivers exist, like the Columbia River on the Northwest coast of USA, or the Tagus, Duero and Miño rivers on the west coast of the Iberian peninsula.

The Columbia River plume has been well studied. Huyer (1977) pointed out the importance that the Columbia river plume has on the salinity over the continental shelf off Oregon and Washington. During winter, winds are poleward and the surface currents are northward and close to the coast. When the Columbia River water enters the shelf waters, it turns to the right due to the Coriolis effect and flows along the coast of the state of Washington. In summer, with upwelling-favourable southerly winds, the plume lies southward off the Oregon coast. Fiedler and Laurs (1990) studied the variability of the Columbia River plume with the aid of satellite imagery, and found that it is easier to follow its evolution with images from the Coastal Zone Colour Scanner (CZCS), which reflects both sediments and phytoplankton pigments. With an appropriate pigment algorithm their pictures show dramatically the strong influence of the river plume variability, according to winds, on the distribution of the phytoplankton biomass in the region. Small and Menzies (1981) stated that the Columbia River plume, close to the coast during upwelling relaxation, compresses the biomass towards the shore. This fact was also observed by Fiedler and Laurs (1990), who suggest that during wind reversals, even if they are very weak and brief, the plume moves to the North with the Coriolis deflection much more readily than to the South. During upwelling events, when the river plume flows southward parallel to the coast, if it is not too far from it, its inshore boundary coincides with the offshore boundary of the upwelled water, the upwelling front. There is some evidence that the front may not have a very strong kinematic effect during active upwelling, while during relaxation, the front appears to have a dramatic effect on the near-surface flow field (Brink, 1983). Small and Menzies (1981) found evidence that relatively high biomass can move towards the shore under strong, rapid wind reversals to upwelling-unfavourable winds, and that these changes in biomass distribution occur quickly. This is an important fact, and can explain the sudden appearance of dinoflagellate blooms close to the shore.

Unfortunately, the river plumes of the West coast of the Iberian Peninsula have not been studied so intensely, but features similar to those of the Columbia River plume can be observed in satellite pictures. Mourino and Fraga (1982) reported that in the mouth of the Ría de Vigo, the salinity decreased after Southerly winds, not as a result
of fresh water discharge from the ría, but due to the River Miño plume moving towards the North along the coast in a similar way to the Columbia River plume off the coast of Washington. Fraga et al. (1993) have associated a bloom of G. catenatum in Ría de Vigo in 1990 with a reversal of the upwelling-favourable winds, that moved warm offshore water towards the coast, where apparently its salinity was lowered by mixing with the river discharge. When the Columbia River plume flows towards the north, it is probably mixed with oceanic surface water driven onshore (Fiedler and Laurs, 1990). Moita (1993) described the evolution of a bloom of G. catenatum off Porto that looks as if it was associated with the Duero River plume, whose mouth is not very far from the transect studied.

Figure 1 shows a conceptual diagram of the evolution and interaction of the River Miño plume with the upwelled water, the outflow of heated water from the Rías Baixas, and offshore warm surface water. At the end of the summer, when upwelling is still active, these four bodies of water are more or less separated moving southwards offshore, except the warm offshore water beyond the upwelling front. When winds reverse to Southerlies, the river plume flows northward along the coast until it meets the warm outflow of the Ría de Vigo. At the same time the warm offshore water moves inshore covering the upwelled waters until the three lighter bodies of water meet forming strong gradients and mix laterally.

In the Gulf of Maine, Franks and Anderson (1992) showed an association of a bloom of the toxic dinoflagellate Alexandrium tamarense with a buoyant current flowing southward parallel to the coast. The behaviour of this water is, in some way, similar to a river plume. Upwelling forces this current offshore while downwelling-favourable winds moved this current towards the coast causing seasonal toxicity to shellfish on the shore.

Optimal environmental window

In wind induced coastal upwellings, (Ekman-type) the intensity of upwelling is proportional to the wind stress, so it will be also proportional to the turbulence. Curry and Roy (1989) introduced the concept of the "optimal environmental window" to explain the relation between recruitment variability of pelagic-spawned fish and upwelling indices. They found that this relation is dome shaped. There are two different limiting factors that affect recruitment. During weak upwelling intensity the lack of nutrients in the photic zone limits production of food for the larvae, and during strong upwelling, the high turbulence has a negative effect on the survival of the larvae. In a much broader sense, and adding a temporal dimension, this idea can also be applied to dinoflagellate blooms. Eppley et al. (1968) and Eppley and Harrison (1975) related dinoflagellates with weak upwelling, so the nutrient rich water did not reach the surface. In Ría de Vigo, in 1986 a big bloom of Gymnodinium catenatum took place. The bloom started when summer upwelling relaxed, and warm offshore water was advected towards the coast. Once an initial population was established by advection, a very short upwelling event injected cold and nutrient rich water along the bottom of the Ría. This water did not reach the surface that remained warm, and it was too deep for diatoms, but it was a nutrient source for developing a dinoflagellate bloom (Fraga et al., 1990). In another study of this same bloom, (Figueiras and Fraga, 1990; Fraga et al., 1992) the transport of nutrients from lower to higher layers by vertical migration of G. catenatum was demonstrated based on the variations of the parameters 'NO', 'PO' and 'CO' based on Broecker's 'NO' (1974) that are characteristics of each water type. In this case their variations can only be explained if G. catenatum takes up nutrients at depth and photosynthesizes near the surface. If the short upwelling event that brought the nutrients to a depth accessible only to vertical migrants were stronger, dinoflagellates would be dispersed and replaced by diatoms. Figueiras and Rios (1993) observed that 10m is a critical depth for the nutricline. If upwelling is intense it will rise and provoke diatom growth, and if upwelling is too weak, the nutricline will be at a depth which the organisms are unable to reach. We may apply, in a broad sense, the optimal environmental window concept to dinoflagellate blooms with the aid of Margalef's phytoplankton mandala (Margalef et al., 1979) (Figure 2). The x-axis can be proportional to the intensity of an Ekman-type upwelling in which nutrients and turbulence go together, and represents also the production potential. The y-axis represents a gradient. Following what they call the "main sequence" of phytoplankton, weak winds correspond to phytoplankton communities dominated by flattened dinoflagellates, and as wind increases and hence upwelling, the phytoplankton changes to diatoms. In the case of upwelling relaxation, phytoplankton will be dominated by dinoflagellates again. The "red tide sequence" appears on the top of the figure at a higher gradient and in an intermediate position over the range of potential production. To go from the "main sequence" to the "red tide sequence", an extra supply of nutrients not related to turbulence is necessary. In wind-driven coastal upwelling ecosystems where river discharges are important, this supply of nutrients could be supplied by the freshwater (they could be just humic substances) or by short and weak upwelling events. When upwelling is strong, nutrients of the river plume are moved offshore and added to the high turbulence-related nutrients. When upwelling relaxes and the river plume lies offshore, gradients are stronger and the freshwater nutrients can change phytoplankton succession from the "main sequence" to the "red tide sequence". According to this model, the environmental window for dinoflagellate blooms, should
be wider with greater supplies of extra nutrients not related to turbulence. Then, we can expect more frequent harmful algal blooms in coastal upwelling systems having river plumes, than in those lacking them.

Greenhouse effect

If dinoflagellate blooms in upwelling areas depend on the intensity and timing of upwelling, any change in these variables will have an effect on the dinoflagellate blooms. One of the effects of global climatic change is an increase in the temperature difference between continents and oceans due to heating of the land. This difference will increase the longshore winds favourable for upwelling (Bakun, 1990). The effects of this increase in upwelling intensity on algal blooms occurrences could be of opposite sign in different places. In areas dominated by strong upwelling most of the year, we can expect a decrease in the number of dinoflagellate blooms, as there will be less upwelling relaxations. Nevertheless in other areas were upwelling is more seasonal, an increase in the incidence of dinoflagellate blooms can be expected, as is the case of blooms of the toxic dinoflagellate G. catenatum on the coast of Galicia (Fraga and Bakun, 1993). Upwelling ecosystems are latitude-dependent. Near the tropics, upwelling is present essentially through the whole year, and with increasing latitude, the upwelling season becomes narrower (Bakun et al., 1991) An increase in upwelling intensity due to the "greenhouse effect" could extend the upwelling season in the high latitude extremes of upwelling regions with the subsequent effects on algal blooms.

Summary

a) In wind-driven coastal upwelling areas, upwelling relaxation causes warm offshore surface water to approach the coast and increase the temperature of inshore waters.

b) This movement of water produces dramatic changes in the phytoplankton, from diatom dominated communities to dinoflagellate dominated ones. This movement may cause coastal blooms in convergence areas.

c) Longshore advection of phytoplankton seems to be an important factor in seeding dinoflagellate blooms.

d) During upwelling events, river plumes are extended equatorward and displaced from the coast. After upwelling, with downwelling-favourable winds, river plumes lie along the coast, flowing poleward. When this happens, the freshwater runoff may favour the growth of dinoflagellates due to the supply of humic substances and to the increasing gradients.

e) The concept of optimal environmental window developed for understanding pelagic fish recruitment, can also be applied, in a much broader sense and adding a temporal dimension, to dinoflagellate blooms.

f) Upwelling systems are expected to be affected by global climate change, these harmful algal blooms related to upwelling are expected to change their incidence.

Acknowledgements

I acknowledge the comments of Dr. C. Roy on a previous version of this paper, and the editing of Dr. T. Wyatt.

References


Figure 1  Conceptual diagram of the interactions of different water bodies on shelf off Ria de Vigo and the River Miño, during upwelling (A), and after upwelling relaxation (B).
Figure 2  Optimal Environmental Window and Margalef’s phytoplankton mandala. Redrawn from Cury and Roy (1989) (top) and from Margalef et al. (1979) (bottom).
Modelling Coastal Upwelling

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Abstract

Upwelling in the ocean is concentrated in regions along the coast where winds are favourable, along the edges of the continental shelf, in equatorial regions, near the edge of ice sheets and in frontal zones. Models have to be adapted to the dynamics and physics of each region.

In the eastern North Atlantic, important coastal upwelling occurs along the North West African coast near the Canary Islands and along the Iberian Shelf when the trade winds are favourable with a component towards the equator. Shelf break upwelling is observed along the edge of the shelf as shown by satellite pictures. Shelf waves propagate along the coast and the upwelling is produced by a mixture of local and remote forcing.

Models of coastal upwelling need to take account of the variability of the wind forcing, the stratification of shelf and deep ocean, and the topography of the shelf and shelf break. Associated with coastal upwelling off the Iberian coast are jets and eddies in which upwelled water is carried beyond the shelf break. The region at the edge of the shelf is an interesting and important area as it is the boundary between the deep ocean circulation which changes slowly and the shallow shelf circulation which rapidly responds to changes in forcing.

It is a difficult region to model but is important for both coastal models and deep ocean circulation models. Such models form an important part of the MORENA project which includes in situ observations and satellite observations over the Iberian shelf and shelf break.

Introduction

Upwelling in the ocean is concentrated in regions along the coast where winds are favourable, along the edges of the continental shelf, in equatorial regions, near the edge of ice sheets and in frontal zones. Models have to be adapted to the dynamics and physics of each region. However, modelling techniques for each region have much in common and provide useful methods for use in other regions.

Near the equator, the upwelling is associated with the propagation of Kelvin waves along the equator from west to east and with equatorial currents and undercurrents. It has been described by McCreary (1985), and is driven by a combination of local winds through Ekman divergence away from the equator and of distant winds through the action of Kelvin waves.

Upwelling near the edges of ice sheets is associated with the change in the effect of the surface wind stress on the open ocean and on the ice covered ocean. The abrupt change in Ekman transport in the surface layers produces upwelling along the edge of the ice, and is mainly a product of local winds. Røed and O'Brien (1983) describe a model of upwelling in the marginal ice zone.

Modelling of upwelling in frontal zones is not very advanced. The difficult geometry caused by a moving front and the effects of non-linear advection make modelling difficult. An outline of the dynamics has been given by Mooers et al. (1976) and a contrary view using an unsteady model of a coastal upwelling front is presented by Chen and Wang (1990).

Coastal upwelling

In the eastern North Atlantic, important coastal upwelling occurs along the North West African coast near the Canary Islands and along the Iberian shelf when the favourable Trade winds are present with a component towards the equator. Mittelstaedt (1983) has described the North West African upwelling and Frouin et al.
(1990) discuss the seasonal reversal of the ocean circulation off Portugal with upwelling in summer, but not in winter. Shelf break upwelling is observed along the edge of the shelf as shown by satellite images.

Models of coastal upwelling need to allow (i) for the variability of the wind stress producing upwelling events after less than a day of favourable winds, (ii) for the stratification of the ocean, and (iii) for various aspects of the bottom topography. The stratification is particularly important in determining the cross-shelf flow and the density field, and causes most problems for modellers due to the non-linear advection. The bottom topography has to include the shelf break and major features such as canyons, ridges and headlands. A review of U.S. modelling studies of coastal-offshore processes is presented by Wroblewski and Hofmann (1989).

### Stratification

The inclusion of stratification has been attempted in various ways including normal modes (Gill and Clarke, 1974), spectral methods (Davies (1986)), separate barotropic and baroclinic time scales (Johnson (1982)) to overcome the intractability of the non-linear equations. None of these methods is entirely satisfactory, and numerical models have to be used to get realistic distributions.

Secondary upwelling may be generated at the shelf break where the deep water, which flows with long (greater than monthly) time scales and large length scales, meets the shelf currents with their short (almost daily) time scales and small length scales. In many circumstances a sharp shelf break can act as an effective barrier between the deep ocean circulation and the shelf circulation, as demonstrated by Johnson and Nurser (1984). The shelf break upwelling is strongest above sharp shelf breaks.

### Shelf waves

Unsteady models allow propagation of Kelvin waves and continental shelf waves that have important effects on the part of the upwelling signal that is not caused by local winds. Along an eastern boundary of the ocean, Kelvin waves propagate away from the Equator, but the direction of continental shelf waves depends on the wave length and may change due to reflection or scattering by irregularities in coastline and topography. The scattering of coastal trapped waves is modelled by Wilkin and Chapman (1990). A stochastic model of the wave field generated by a distribution of wind at different frequencies is described by Brink et al. (1987). Grimshaw et al. (1993) discuss the generation of edge waves by radiation stress caused by surface waves.

### Jets and eddies

Associated with upwelling off the Iberian coast, there are jets and eddies in which cool upwelled water is often carried offshore beyond the shelf break. Similar features are observed in the eastern Pacific off the California coast in which 20-50 km wide filaments of upwelled colder water extend 200-300 km offshore, as surveyed by Kosro and Huyer (1986). In some cases the position of the jets and cold filaments appears to be connected with topographic or coastline features such as ridges or headlands. In other circumstances the filaments form a regular pattern along the coast separated meridionally by 100-150 km.

Models of these jets, eddies and filaments are not yet very wide spread. An attempt to model this phenomenon has been made by McCreary et al. (1991) using a three layer model with two active upper layers. Instabilities occur in the coastal currents that resemble filaments but the generation time (greater than 60 days) is too long.

### The MORENA Programme

The MORENA project that is funded by the EC MAST II programme aims to measure, understand and model the shelf - open sea exchange in the coastal upwelling region off the Iberian peninsula. A multidisciplinary approach is used including physical, chemical and biological observations along specific sections across the shelf break, remote sensing to cover a broader region, and new numerical and laboratory models of the region.

The modelling tasks include primitive equation numerical models, reduced gravity models with both single and double active layers, and laboratory models using rotating stratified channels. These models are to be validated against both in-situ and satellite observations collected as part of the observation programme.

The primitive equation model extends from the Gulf of Cadiz almost to the Bay of Biscay and from the Iberian coast out beyond the shelf break. The extent of the model is shown in figure 1. The horizontal resolution is $\frac{1}{12}^\circ$ x $\frac{1}{12}^\circ$ and there are 32 levels in the vertical with the thickness changing from 10m in the surface layer to 233m in the deepest layer. The model is spun up from climatological temperature and salinity fields and forced by seasonal surface winds. There are open boundaries along the North, West and South sides of the model domain.

Figures 1 and 2 show the velocity and temperature fields respectively at level 2 at a depth of 32.2m on September 15 in year 3 of the numerical calculation. The south-
ward moving coastal current in Figure 1 is confined to the continental shelf and is associated with the cool upwelled water illustrated in Figure 2. In the deeper water offshore of the break, the principal flow is related to the bottom topography. Although some evidence of eddies may be noted in these figures, they are much clearer in a video sequence with two surface jets of cold water moving offshore at about 43°N and 39°N.

References


Figure 1  Velocity field at depth 32.2 m on September 15, year 3.

Figure 2  Temperature field at 32.2 m on September 15, year 3.
Near Surface Dynamics of Coastal Upwelling

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Abstract

Recent advances in the understanding of the dynamics of the Ekman layer in coastal upwelling regions are reviewed. In particular, the question of Ekman transport as a local indicator of the strength of upwelling is investigated. Results over the last decade have highlighted the inhomogeneous nature of the interaction between the coastal upwelling zone and the offshore oceanic waters. The role of upwelling filaments, their relation to eddy structures, and their importance in lateral exchanges of nutrients and biota are investigated.

Introduction

Understanding of the basic process of coastal upwelling is predicated on the work of Ekman (1905). There is a widespread, albeit implicit, acceptance of the Ekman model in conditions which do not comply with the simplified homogeneous, stationary, constant eddy viscosity situation considered by Ekman. Questions remain as to what is meant by the Ekman layer, how appropriate is the adoption of the Ekman transport and what are the implications of time varying wind stress. Moreover, recent observations show that upwelling regions are far from uniform alongshore though the predominant meteorological scales are considered to be long. What is the significance of these observations and what do they tell us about the nature of upwelling systems?

Ekman transport

The Ekman-Sverdrup model of coastal upwelling allows an estimate of upwelling intensity, i.e. offshore near-surface transport, from a knowledge of only the local wind stress $\tau$ (Sverdrup, 1938). The volume transport is given as

$$T = \frac{\tau}{\rho f}$$

where $\tau$ is the surface wind stress $\rho$ is the water density, and $f$ is the Coriolis parameter. The applicability of this index was demonstrated on the climatic time scale by Wooster and Reid (1963) in their review of the Eastern Boundary Currents. Since that time the use of the index has been extended by Bakun (1975) to weekly and daily mean conditions. Numerous studies in upwelling regions have demonstrated a close relation between local wind stress and upwelling activity indicated by sea surface temperature anomaly or other measure. However, the practical difficulties of making reliable current observations in the upper layers of the ocean have largely precluded testing in any systematic and quantitative way of the reality of this model.

It is often tacitly assumed that the surface mixed layer, which develops in response to the strong surface wind stress, is identifiable with the Ekman layer or layer of offshore transport (e.g. Brink, 1982), and is of constant depth. It has to be noted, however, that the surface mixed layer is not of fixed thickness, but varies significantly as the wind forcing changes. Secondly, there is little a priori justification for equating the mixed layer with the layer of Ekman transport. These issues have been explored by Lentz (1992) on the basis of observations carried out off Peru, Northwest Africa and Northwest America during the major upwelling experiments of the 1970s and early 1980s. Using data from current meters and temperature sensors covering the upper layer with at best 5 m resolution and meteorological information from adjacent surface buoys, he investigated the properties of the surface mixed layer and the related current structure.

The results show that the mixed layer depth is distributed approximately as chi-squared with, obviously, a
predominance of near zero values. The depth of the mixed layer in the various regions varied between zero and almost 60 m, greater depths being associated with stronger wind stress. It was found that a good parameterisation of the depth was given by

$$h = A u' / (N f)^{1/2}$$

where $A = \text{empirical constant}$, $u'$ is the friction velocity and related to wind stress by $u' = (r/\rho)^{1/2}$, $N$ is the Brunt-Väisälä frequency at the base of the mixed layer, and $f$ is the Coriolis parameter. This formulation arises from one dimensional mixed layer models which neglect the effect of both surface and lateral heat fluxes (e.g. Pollard et al., 1973). Since significant surface heat flux is normal in coastal upwelling regions, it seems to be the case that the lateral advection of heat is sufficient to compensate.

Given a time varying surface mixed by layer depth, the question of how this relates to the Ekman transport arises. Combining both formulæ we may expect

$$H_{\text{mix}} = A (\frac{T}{N})^{1/2}$$

Attempts have been made to compare the theoretical Ekman transport to the observed offshore flow in the near surface layer assuming a constant mixed layer depth (e.g. Smith, 1981). In the mean, it was demonstrated that there was "fair agreement" between the calculated Ekman transport and the offshore transport estimated from the near surface observations. In the three cases considered, the Ekman transport was 26% less, 89% more and 72% more than the estimated transport. The magnitudes of the standard deviations differed by 36%, 8% and 72%. Correlation of the time varying Ekman transport with the offshore transport (both de-meaned) in the constant thickness near surface layer was significant in all cases at better than the 99.9% confidence level, while the corresponding regression did not differ from unity by more than the standard error. Thus the variability, at least, of the offshore transport was similar to that of the Ekman transport.

Lentz (1992) noted that since the mixed layer depth varied through the observation period, the above method often excluded observations actually in the layer or included observations below it. By calculating the theoretical Ekman transport from hourly wind values and observed transport from hourly current meter observations within the actual observed mixed layer and then low pass filtering the series, he obtained better correlations (in the range 0.8-0.9 compared to Smith’s 0.5 to 0.7). However, the results showed that the observed transport was consistently smaller than that predicted. He was able to show from the current observations that the layer of offshore flow, the depth of which also varied with the wind stress, was actually thicker than the mixed layer depth, by a factor of roughly 1.5. Repeating the calculation over this expanded depth range, including the "transition layer", provided better agreement between the predicted and observed transports.

Although it was concluded that the transports "agreed well", the mean observed value amounted to only 59% of the predicted value, averaged over all the observation sites used (Figure 1). Excluding comparisons believed less reliable increases the observed to 66% of the predicted value. Lentz (1992) points out that the transition layer thickness was not adjusted for optimal agreement at each study site, so that an improved result could be obtained. So, the best estimates of actual and predicted offshore transport agree to better than a factor of two. Reasons why agreement is not even better are numerous.

The problem of defining the "offshore" direction is not trivial. Any mis-orientation of the axes can severely affect the estimate of offshore flow because the alongshore flows are so much stronger. Local depth contours may not parallel the coast line or other contours and may change direction irregularly alongshore, compounding the difficulty of selecting the length scale over which the directions should be defined. Generally, the definitions are derived from the data in the sense that some measure of the direction of maximum current variance is used to define alongshore flow. Good vertical resolution of the currents throughout the water column are needed to provide a reliable estimate in this case. Smith (1981) showed that defining offshore as the direction of zero net transport produced inconsistent results, probably a result of poor coverage of the entire water column or local lack of two dimensional mass balance.

Another difficulty is that upwelling is not only a surface boundary phenomenon but also a lateral boundary one. Upwelling is supposed to take place within a distance of the coast defined by the Rossby internal radius of deformation. Any surface transport measurements made within this distance will not include the total Ekman transport since some water is being upwelled further offshore. Lentz (1992) suggested some of his poorer agreements might be due to the proximity of the mooring to the coast. He also noted that the surface mixed layer (and presumably offshore flow) depth in general decreased shoreward as bottom depth decreased.
The practical difficulties of measuring currents in the near surface layer again impose a major constraint on the reliability of these estimates. The effect of strong wave currents and surface buoy motion can have significant effect on the current measurements. Moreover, in many cases the current meter spacing has been irregular, due to instrument failure, and coarse in relation to the thickness of the surface layer so that vertical resolution of the flow has been poor.

In view of these considerations and noting that Ekman’s formulation was for stationary conditions, it may be remarkable that the theory has proven so applicable. Nevertheless, Acoustic Doppler Current Profilers now allow us to measure the velocities at high accuracy and good spatial and temporal resolution through the major portion of the water column, while modern current meters make possible measurements in the near surface layer. Perhaps, the time is now opportune for renewed attempts to refine our understanding of the Ekman response in the context of the several continental shelf experiments proposed for the near future.

Filament structures

Granted the validity of the Ekman transport mechanism and the extended scale of the predominantly trade wind systems which drive it, one might expect that coastal upwelling would be quite uniform over long stretches of the eastern boundary. Satellite imagery of any coastal upwelling region, showing AVHRR sea surface temperatures or chlorophyll-like pigment from CZCS, reveals that there is little evidence of uniform conditions along the shelf. Instead, the impression is one of a contorted boundary between upwelling and oceanic waters, localised areas of stronger upwelling and tongues of cool, high chlorophyll water extending hundreds of kilometres offshore from the coastal zone. The tongues of cooler water, which are typically narrow, defined by strong lateral temperature gradients, and often terminate in eddy-like structures, are termed filaments (Brink and Cowles, 1991). This region of interaction between the coastal upwelling and the offshore waters is known as the coastal transition zone. Figure 2 shows a dipolar filament off southwest Portugal.

Upwelling is generally a seasonal phenomenon. For example, off the Iberian peninsula it develops in late spring as a response to the onset of the Portuguese Trade winds. Brief episodes of near-shore upwelling may develop in winter as a result of short lived favourable winds, but it is not until the summer when persistent upwelling is found. Typically, in May or June a narrow band of colder water, often of quite uniform width, is produced along much of the coast. This band often appears to be edged by many narrow “fingers” of cool water extending 20-30 km offshore. If the winds relax or become poleward, this narrow band may disappear temporarily. As the season progresses, major filament structures develop and extend offshore.

A statistical analysis of the archive of AVHRR scenes for the Iberian region for the years 1982-90 shows the seasonal development of filaments (Haynes et al., 1993). There were fewer images available in winter than in summer because of persistent winter cloud cover, but the relative frequency of occurrence of filaments in winter was small compared to other times of year (Figure 3). The filaments grow to identifiable lengths of 80 km by about the start of July (day 180). At this time the width of the band of upwelling is around 50 km, so the filaments extend some 30 km seaward of the upwelling boundary. They grow over the following weeks to reach a maximum mean length of around 130 km in late September (day 270). The maximum observed filament lengths show the same growth trend, increasing from about 120 km at the start of July to over 270 km in late September. After this, both mean and maximum lengths decrease until the filaments become less common in October (around day 300). Their ultimate fate is not well documented since cloud cover obscures the region as soon as winds become unfavourable. However, it is probable that, once upwelling ceases to renew the filament waters near to shore, surface warming due to insolation quickly destroys their surface manifestation.

A sequence of images off Iberia from 1982 shows the later stages of development. On 9 August, nascent filaments were evident as bulges in the upwelling front at 42 30’N, 41 10’N and 40 20’N. Traces of the small scale fingers remain at this time. By 20 August, the bulges had extended offshore by about 100 km to form identifiable filaments. The offshore progress of the filaments continued until 2 September, when the longest filament had reached about 200 km extent. The observed rate of advance of the filament offshore was about 10 cm/s. After 2 September, warming commenced in the southern part of the region as a result of weakening winds. Cloud cover then increased and the structures had disappeared by the time of later images in October.

What is the significance of these features in terms of onshore-offshore transport? Although there are few in situ observations of filaments off the Iberian peninsula, recent work carried out off NW Africa reveals something of the structure of this type of feature. Satellite sea surface temperature imagery show an extended cool feature reaching from between Cabos Juby and Bojador towards the island of Gran
Canaria. The filament is over 120 km in length and appears to terminate in a cyclonic eddy. The subsurface distributions associated with the feature were mapped by CTD survey data (Figure 4), in which can be seen the partial separation of the eddy from the main structure. Detailed cross sections normal to the filament show that the isolines upwarp strongly near-surface but also that a signal is still evident as deep as 200 m (Figure 5). The steep inclination of the isopycnal surfaces indicates intense offshore baroclinic flow associated with the cool feature. This is confirmed by Acoustic Doppler Current profiler data from the cruise. High chlorophyll (fluorescence) values occur in relation to the feature. The chlorophyll structure in the surface layer could be compatible with subduction on the anticyclonic side of the filament, as has been observed in the California Current region (Kadko et al., 1991).

Large offshore transports occur in relation to the filament, many times greater than the Ekman transport. The filament therefore represents a potential mechanism for removing cool nutrient rich water and its constituent biota from the coastal region, if mixing takes place across the filament boundaries. In the present case, a cyclonic eddy of significant dimension terminates the eddy. The higher chlorophyll fluorescence values in the eddy are indicative of the export from near shore. Since the eddy is essentially a dissipative feature, the filament is producing a one way transport from the coastal upwelling region into the oligotrophic offshore areas. This mechanism is thought to be partly responsible for enhanced primary production around the Canary Islands.

Discussion

Considerable effort has been expended in testing the applicability of the Ekman transport to coastal upwelling, with encouraging, but not close quantitative, agreement between theoretical and observed offshore surface layer transports. Further investigation of the near surface transports with modern techniques are required for better understanding of the time and space varying response. Once upwelling is established, the development of a field of filaments and eddy structures occurs. The strong horizontal flows in filaments coupled with dissipative eddies may be the predominant mechanism for export of upwelled water and its properties out of the coastal region to enrich the offshore oligotrophic zone.

Acknowledgements

The African field work was funded by the Spanish Consejo Superior de Investigaciones Cientificas and MAST-I Project 0031.

References


Figure 1  Mean theoretical Ekman transport vs. mean observed offshore transport (m$^3$s$^{-2}$) in the near surface mixed layer and transition layer (Data from Lentz, 1992).

Figure 2  A filament of cooler (darker tones) water extending offshore of Cabo Sao Vicente, Portugal. The temperature range is from 17 C to 22 C approximately.
Figure 3
Seasonal variation off Iberia for period 1982-90 of: (Top) mean filament length (solid fill) and maximum filament length (grey fill) and (Bottom) number of available images (open boxes) and number of filaments (solid fill).
Maps of temperature, salinity, density and chlorophyll content at 50 m depth off NW Africa in August 1993 showing filament extending up to 200 km offshore and terminating in a large cyclonic eddy structure.

Figure 4
Figure 5  
Vertical section of temperature, salinity, density and chlorophyll content across the filament of Figure 4 along the second line of stations. Station positions are marked by a grey line.
The Optimal Environmental Window Hypothesis in the ICES Area: The example of the Iberian sardine

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Abstract

In upwelling areas, the relationship between upwelling intensity and pelagic fish recruitment success appears to be sometimes positively and sometimes negatively correlated. The Optimal Environmental Window (OEW) hypothesis offers an interpretation for these apparently contradictory results. The OEW hypothesis suggests that a dome shaped relationship exists between recruitment success and upwelling intensity: recruitment success increases with upwelling intensity in areas where wind speed is low or moderate, food availability is then the limiting factor; recruitment success decreases with upwelling intensity in areas of strong wind where physical constraints are the main determinants of larvae mortality rates. Several studies have shown that the relationship between recruitment success of small pelagic fish stocks located in upwelling areas is dome shaped and in agreement with the OEW hypothesis. The limiting factors defined by the OEW hypothesis are also able to account for apparent contradictory patterns observed between reproductive strategies of related species located in geographically distinct areas.

The OEW hypothesis applies to eastern boundary current ecosystems located in tropical or subtropical areas where trade winds are responsible for the upwelling process. The applicability of the OEW to higher latitude areas like the ICES regions is discussed and an example of an ICES region where upwelling events take place is presented.

Introduction

Many attempts have been made to correlate environmental fluctuations to recruitment indices. For the pilchard (Sardinops ocellatus), a relationship between year-class strength and sea-surface temperature is found to be positive in the southern Benguela (Shelton et al., 1985) but for the same species a negative one is found in the northern Benguela (Shannon et al., 1988). For the Iberian sardine (Sardina pilchardus), Dickson et al. (1988) found a negative correlation between catch and upwelling indices (Figure 1). In a nearby area, Belvéze and Erzini (1983) found a positive relationship between the catch of the Moroccan sardine (Sardina pilchardus) and upwelling (Figure 1).

These results question the existence of a unified theory relating recruitment with the environment in upwelling areas. However, positive and negative correlations may both be valid if the relationship between recruitment and upwelling intensity is dome shaped as suggested by the "Optimal Environmental Window" (OEW) hypothesis (Cury and Roy, 1989). The applicability of the OEW to temperate latitude areas is discussed and the Iberian sardine is presented as an example of an ICES region where upwelling events take place.

An Optimal Environmental Window for recruitment success in upwelling areas

Food availability and physical constraints such as wind mixing or offshore transport are considered important factors that affect larval survival and pelagic fish recruitment. Acceptable food concentrations associated with stable ocean conditions must be present in the larvae's environment for survival (Lasker, 1981). Small-scale turbulence that increases the encounter rate between food particles and larvae (Rothschild and Osborn, 1988; MacKenzie and Leggett, 1991) may also be beneficial to larval survival. Strong mixing generated by high wind speed has a negative effect on larval survival by desaggregating food and larvae patches (Saville, 1965; Peterman and
Bradford, 1987) and may affect recruitment (Lasker, 1981). In an upwelling ecosystem, vertical advection, new inputs of nutrients and mixing are generally closely related to the magnitude of the wind speed (Figure 2). Increasing upwelling intensity from weak to moderate should have a positive effect on recruitment since increased primary production would enhance food availability with wind mixing remaining low. Strong upwelling should have a negative effect on recruitment because wind mixing is high even if primary production increases.

The Optimal Environmental Window (OEW) hypothesis (Cury and Roy, 1989) assumes that the relation between recruitment and upwelling indices is dome shaped (Figure 3). The non-linearity of the curve is explained by considering the positive or negative effects of several environmental factors. On the left side of the curve wind is weak or moderate; an increase in the wind speed may enhance food production or the encounter rate between larvae and food. On the right side of the curve the upwelling is strong so that wind-mixing and offshore transport are then detrimental factors. There is an "Optimal Environmental Window" for recruitment success in moderate upwellings where the effects of the limiting factors are minimized (Figure 3).

Ecological validations of the OEW recruitment variability

Four of the main pelagic fish stocks, all located in tropical or subtropical upwelling areas, were analyzed using an exploratory statistical method (Cury and Roy, 1989). For the Peruvian anchovy, the Californian sardine, the Moroccan sardine and the Senegalese sardinella, this comparative analysis shows that a dome shaped relation exists between recruitment and upwelling intensity (Figure 4). The non-linearity always appears for values of wind speed around 5-6 ms⁻¹ (Figure 4). This suggests that for different upwelling ecosystems there is a common and "optimum" wind mixing level in the stable layers of the upper ocean.

Using new estimates of recruitment for the Peruvian anchoveta, Mendelsohn (1989) found similar results. Using extended time series for the Pacific sardine, Ware and Thompson (1991) supported the existence of an optimal environmental window but at a wind speed value of around 7-8 ms⁻¹. Roy et al. (1992) show new evidence of a non-linear relationship between recruitment and upwelling for the Moroccan sardine. Recently, an analysis of the Californian anchovy larvae data also supported the existence of a dome-shaped relationship between larvae abundance and upwelling intensity (Cury et al., in press).

Reproductive strategies

Using a comparative approach as suggested by Parrish et al. (1983), Roy et al. (1989) investigated the spatial and temporal reproductive dynamics of some coastal pelagic fish off West Africa. The spawning areas are not continuously distributed along the coast and do not always coincide with the location of highly productive areas. Reproduction occurs in places where the continental shelf broadens or in coastal indentations like a bay or downstream of a cap: this strategy allows to minimize the detrimental effects of dispersion on larvae by reproducing where offshore transport is minimum. Similar patterns were also found in other upwelling areas (Parrish et al., 1983). Along the West African coast, contradictory patterns emerged when the timing of spawning is examined simultaneously with the timing of the upwelling. In some areas like Senegal or Ivory Coast, the spawning season coincides with the upwelling season, but in other areas like Sahara and Morocco spawning and upwelling are out of phase (Figure 5).

The OEW hypothesis was used to account for these contradictory patterns that have emerged (Roy et al., 1992). For the main reproductive areas off West Africa, the mean monthly wind speed is plotted versus the coastal upwelling index (Figure 5). This allows a comparison to be made between areas of the environmental patterns during and outside the reproductive seasons. For the four different areas, spawning peaks occur at a different value of the upwelling index (between 1 and 3.2 m²s⁻¹ m⁻¹), however high reproductive activity always coincides with time periods of wind speed of about 6 ms⁻¹ (Figure 5). The following scheme was proposed:

- in areas where wind speed during the upwelling season is close to, or lower than, the threshold value of 6 ms⁻¹, spawning occurs during the upwelling season, thus allowing larvae to benefit from the enhanced food production.

- in areas where wind speed during the upwelling season is higher than the threshold value, spawning occurs outside the upwelling season or when upwelling is minimum. This strategy minimizes the negative effect of strong wind mixing on larval survival.

For West African sardine and sardinellas, adequate spawning locations allow to solve the detrimental effect of offshore transport on larvae. Such a spawning habit leaves adjustment of seasonality as an avail-
able means for dealing with other factors such as the detrimental effects of turbulence. It appears that the tuning of the spawning season is not related to the seasonal occurrence of the upwelling. Rather, the spawning peaks coincide with the seasonal occurrence of wind speed of 6 m·s⁻¹. This reproductive strategy appears to be the result of a compromise between several antagonistic environmental factors. It has evolved in order to invest most of the reproductive effort in the areas where and seasons when the effects of the limiting factors for recruitment success are minimized. From an evolutionary point of view, this pattern can be interpreted as the response of a long term adaptation of reproduction to the environment for maximizing recruitment success.

The OEW hypothesis assumes that both nutrient enrichment (upwelling intensity), mixing and offshore transport are positively correlated with the magnitude of the wind (Figure 2). This is the case in tropical or subtropical Ekman-type coastal upwelling areas where trade winds are responsible for the upwelling process. In these regions, the positive correlation between the wind-mixing index, offshore transport and upwelling intensity is the result of the steadiness of the wind regime. The underlying assumption of the OEW hypothesis in this situation are: biological production, offshore transport and mixing are related to wind speed.

In tropical or sub-tropical areas, the seasonallity of the upwelling process is induced by the latitudinal migration of the atmospheric high pressure cells located over the oceans (Azores and Saint Helen Highs in the Atlantic); the duration of upwelling seasons varies from several months (California, Morocco, South-Africa, ...) to almost year-round durations in areas like Cap-Blanc (West-Africa) Baja California or Peru. It is expected that seasonal and interannual fluctuations of the wind create corresponding fluctuations of the ecosystem biological components.

### The OEW in ICES areas

In mid-latitude or temperate regions, biological productivity is highly seasonal and the annual production cycle is dominated by the plankton spring bloom. The initial peak in primary production is attributable to the onset of stratification in waters which were enriched with nutrients earlier in winter by wind mixing. Primary production typically falls during summer due to a pronounced vertical stratification and a shortage of nutrient supply; mid-latitude production is distinguished from that at lower latitudes by its discontinuities. Mid-latitude ecosystems differ from tropical or sub-tropical upwelling areas: temperature, nutrients, light, mixing and grazing are the expected limiting factors of biological production. In temperate areas, the limited duration of the growth season is also in total contrast with the almost permanent processes that occur in lower latitude areas (Cushing, 1971; Wyatt, 1980). This suggests that the underlying assumption of the OEW may not always apply in temperate areas.

### The upwelling off the Iberian Peninsula

The ocean dynamics and the biology in the ICES areas may differ from the dynamics of tropical or sub-tropical upwelling areas. However, upwelling locally occurs: coastal trapped waves, tidal energy, eddies, wind curl are known to induce upwelling along the shelf break (Pingree and Mardell, 1981; Bakun and Nelson, 1991; Mazé et al., 1986).

Along the West coast of the Iberian peninsula, northerly winds generates an Ekman type upwelling in spring and summer (Wooster et al., 1976). For the Iberian sardine (*Sardina pilchardus*), Dickson et al. (1988) showed that there is a negative correlation between upwelling indices and catch (Figure 1); increasing upwelling off the West coast of Portugal and Spain seems to be detrimental to sardine abundance. These results seems to be in agreement with the OEW hypothesis which suggests a negative correlation between wind and recruitment in areas with wind speed greater than 6 m/s. However, *S. pilchardus* reproduction occurs along the Atlantic coast but also in the Cantabrian sea; moreover, spawning activity is not synchronous along the Iberian peninsula coasts. Reproduction occurs in winter or early spring in the Cantabrian Sea and juveniles later migrate to the upwelling area off the West coast of Spain and Portugal (Garcia et al., 1988; Sola et al., 1992). Off Portugal, reproduction is maximum in winter with a second peak in early spring (Cunha and Figueiredo, 1988; Ré et al., 1990). Recruitment variability of the Iberian sardine appears to be correlated with winds occurring after the main spawning peak (Portugal) or outside of the spawning area (Cantabrian sea) (Robles et al., 1992). Therefore, it appears to be difficult to invoke the effect of wind on larvae to explain the observed relationship between recruitment and upwelling.
Identification of relevant processes for recruitment success: The Cantabrian Sea spawning area

Time series analysis has shown negative correlations between upwelling intensity and recruitment success of the Iberian sardine population (Dickson et al., 1988). However, the physical and biological processes involved remain unclear (Chesney and Alonso-Noval, 1989) and it is unlikely that purely empirical approaches will clarify the involved processes. Instead, relevant environmental processes for recruitment success of the Iberian sardine can be identified using the approach of Parrish et al. (1983). Since natural selection implies that reproductive strategies reflect responses to the most crucial factors regulating reproductive success, a joint investigation of the early life history of the fish and of the environment is likely to reflect important causal mechanisms. This approach also provides a guide for selection of relevant variables for time-series analysis in a way that makes improved use of the scarce degrees of freedom available (Bakun, 1986).

As an example we choose to investigate the reproductive pattern of S. pilchardus in the Cantabrian sea. Spawning of the Iberian sardine occurs in the Cantabrian sea while nursery and feeding grounds are located along the coast of Galicia and off the West Coast of Spain and Portugal (Porteiro et al., 1986; Garcia et al., 1991). Intense spawning occurs during spring in the Cantabrian sea outside the upwelling area (Garcia et al., 1991). Little reproduction occurs during spring in the highly productive upwelling areas off the Spanish West coast. The spawning peak occurs in the Cantabrian Sea between April and May; simultaneously, a sharp decrease of the wind mixing is observed in this area (the value of the wind speed decrease from 8.1 ms\(^{-1}\) in March to less than 5.5 ms\(^{-1}\) in June, a value below the threshold value of the OEW) (Figure 6). The resulting stabilization of the surface layer appears to set conditions for a phytoplankton bloom and high larvae survival. A similar relaxation occurs along the West coast of Spain but with a smaller amplitude; in that area, wind speed remains greater than 6 m/s during spring and summer. An interpretation of the reproductive patterns in the Cantabrian sea is that:

- the detrimental effects of dispersion (offshore transport) are minimized by reproducing outside the upwelling area;
- the timing of the reproductive season is set to take advantage of the annual spring bloom and also to avoid the detrimental effect of strong wind mixing on larvae.

Conclusion

Previous studies have shown that strong upwelling is detrimental for the recruitment success of the Iberian sardine population but the environmental process involved remains unclear. The coast of the Cantabrian sea is an area where high concentration of eggs and larvae are found; high reproductive activity occurs in spring when the wind speed reaches the threshold value of the OEW. Year to year fluctuations of the timing of the wind relaxation may occur. Larvae survival will be particularly affected by a delay of the wind relaxation or by the occurrence of late storms which will suddenly increase mixing in the surface layers. This suggests that a time series analysis of recruitment variability of the Iberian sardine should consider the interannual fluctuations of wind off the Cantabrian coast during spring and early summer as a relevant environmental variable. Following the OEW hypothesis, a negative relationship between wind and recruitment would be expected. However, the coast of Portugal is also thought to be an important spawning area for sardine; reproductive activity is maximum during winter when wind mixing generated by storms is high. Both areas may contribute to the overall recruitment of the Iberian sardine population.

The OEW may or may not apply to ICES areas depending on the validity of the underlaying assumptions of the OEW in the area under study. However, OEW hypothesis highlights some important characteristics on the way the environment can affect population dynamics:

- recruitment success does not always depend on a single environmental key factor but rather will be the result of the combination of different factors acting sometimes in opposite ways (i.e. upwelling intensity and wind mixing);
- non-linear relationships are to be expected between the environment and recruitment variability: upwelling can be either beneficial or detrimental, depending on its intensity. A scattergram that reveals no linear relationship does not necessarily mean the absence of a tight link and non-linear statistical techniques are needed to explore the effect of the environment on fish population (Mendelssohn, submitted; Cury et al., in press);
- changes through time or between areas may also occur: shift of the wind speed from one side to the other of the threshold value defined by the OEW will change the sign of the relationship between recruitment and the environment (Roy et al., 1992).
Acknowledgements

Comments by Roy Mendelssohn and Richard Parrish greatly improved the manuscript. Many thanks to M. E. Cunha for her comments. This is contribution n' 35 to the CEOS (Climate and Eastern Ocean Systems) program, a NOAA-ORSTOM-ICLARM cooperative project supported by the NOAA Climate and Global Change Marine Ecosystem Response project (USA) and by the TOA department of ORSTOM (France).

References


Mendelssohn, R. If the environment affects fish in a non-linear fashion. Submitted to Fish. Bull.


Figure 1  An example of positive and negative correlations between catch and upwelling index obtained for the same species (*Sardina pilchardus*) at two different locations: the sardine off Morocco (from Belvèze and Erzini, 1983) and the sardine off Spain (from Dickson *et al.*, 1988).

Figure 2  Relation between monthly values of (left) upwelling index and wind mixing or Nitrate concentration; (right) wind speed and upwelling index or wind mixing. Data from 1985 to 1989 at the Cap-Vert coastal stations (Sénégal). Mean calculated during the upwelling season from January through May (See Oudot and Roy, 1991 for details).
Figure 3  Theoretical relationship between recruitment and environmental factors in upwelling areas (adapted from Cury and Roy, 1989).

Figure 4  Optimal transformation obtained using the ACE algorithm (Breiman and Freidman, 1985) for the recruitment of sardine and anchovy in four different upwelling areas (from Cury and Roy, 1989).
Figure 5 Spawning activities of sardine and sardinella in relation to wind speed and upwelling for four regions off West Africa. Mean monthly upwelling indices are plotted against mean monthly wind speed for each region. The upwelling seasons are shaded and months with intense spawning are indicated by a black dot. Note that the black dots for all regions are clustered around 6 m/s (upper figure); this value corresponds to the average wind intensity of the OEW (lower figure). (from Roy et al., 1992).

Figure 6 Monthly mean wind speed off the Atlantic coast and North coast (Cantabrian Sea) of Spain. 1960-1990 mean from the COADS database.
Towards an Integrated Research Initiative

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South African marine science is characterised by its interdisciplinary approach and inter-institutional collaboration. An example of this is the successful Benguela Ecology Programme (BEP) which is now in its third five-year phase. (Readers are referred to a recent evaluation of the first 10 years of the BEP by Rothschild and Wooster, 1992). From the experience gained in the BEP and other South African marine initiatives, I believe that we now have a fair understanding of those ingredients which are vital for the success of joint ventures of this nature. What follows is thus a personal philosophy on what should be done when establishing a co-operative interdisciplinary research programme in an area characterised by pronounced variability and where a proper understanding of the processes is a prerequisite for the wise management of the environment and resources. Although the Benguela is an upwelling region I believe that the philosophy is equally applicable within the ICES area.

Twelve critical elements necessary for success of an interdisciplinary and inter-institutional research programme

1. There must be a well-defined problem or issue that requires addressing in order to provide a clear research focus. The nature of the problem or issue will determine the type and the mix of the research. Above all, its relevance (e.g. to ICES) must be apparent.

2. There should be critical mass within the participating disciplines. If there is not, it will be necessary to solicit or "buy-in" expertise in order to ensure disciplinary viability.

3. It is essential to have the ability for a substantial number of participants to meet regularly. The meetings should ideally take the form of seminars. Such seminars are useful not only for informing but also for developing research thrusts and for developing projects (even project proposals).

4. The programme needs to be driven by a small (± 5 persons) enthusiastic leadership team with vision. Large committees should be avoided except for perhaps one statutory meeting per year.

5. Good, full-time co-ordination and facilitation support is essential. (Don't expect the scientists to do this - it is a professional activity requiring special skills.) The right sort of co-ordination will ensure that the programme does not become dominated by one or two forceful individuals who are trying to pursue personal hobby horses.

6. There must be adequate funding and facilities - but not too much. It is my experience that being lean and hungry is preferable to having a surplus as it encourages efficiency of operation and helps to focus activities on the essentials.

7. The right mix of free thinkers and hard workers is desirable. By this I am not implying that free thinkers are incapable of hard work or that workers cannot think, but rather that the team should be balanced and capable of "delivering the goods".

8. There should be what I refer to as "balanced competition" between participants. If there is too little, there is little incentive for progress. Conversely if competition is too strong it can be destructive as participants will then not share their thoughts and ideas freely - until after publication. It is this pooling of ideas at the developmental phase of projects that can be most beneficial.

9. Participants should be prepared to devote a reasonable amount of their time to the overall programme.

10. There should be a mix of "establishment" scientists and academics. In my experience this not only improves the quality of the science but
also helps to improve the relevance of education and training.

11. Project proposals and progress must be peer reviewed.

12. Flexibility in operation is essential.

Some do's

* Do encourage creative thinking
* Do determine priorities

Some don’ts

* Don’t try to be inclusive
* Don’t get too large - avoid any temptation to try and cover everything (a recipe for disaster)
* Don’t build a program out of a collection of existing projects - be highly selective.

In the ICES context

* In developing an interdisciplinary programme, check against the list of twelve critical elements. In particular the problem or issue must be carefully defined and it must be relevant to ICES.

* Decide whether a multi-state or interdisciplinary or inter-institutional approach is required or is viable.

Finally, the old saying "success breeds success" is equally true in the interdisciplinary context. In my experience people want to be associated with something good and which gives relevance to their efforts.

References

Abstracts of additional papers presented at Theme Session 0 at the ICES Statutory Meeting in Dublin, Ireland, 1993

C.M.1993/C:8 - Ref.: Theme Session 0

Cotos, J.M., Torres, Carollo A. and Hernández, C. (*Applied Physics Department, University of Santiago, 15706 Santiago de Compostela, Spain; 2Fundamental and Experimental Physics Department, University of La Laguna, Santa Cruz de Tenerife, Spain)

UPWELLING DYNAMICS IN SPANISH AND PORTUGUESE COAST. A PILOT STUDY FROM NOAA-AVHRR IMAGES AND GEOSTROPHIC WINDS

Upwelling dynamics in East Atlantic has a very big influence in the economic structure of the Northwest of Spain and in the West of Portugal because this event regulates the sardine fisheries in our coast, and is the responsible of the appearance of red tides (toxic algae bloom) that have a direct effect in the growing of shellfish.

We have developed a system to study the upwelling comparing the theoretical evolution from geostrophic winds and the mass of water displacement. Geostrophic winds are estimated from isobaric maps in an interactive program and upwelling area is evaluated from NOAA-AVHRR images. We can estimate the increase or decrease of upwelling via cross correlation algorithms in pairs of consecutive images (with one or two days between both).

The first image is divided into squares of 32 x 32 pixels; the program computes the correlation factor between this square and all possible ones in a 64 x 64 template in the second image. The maximum correlation factor give us the displacement that our square has suffered in the second. As our images have been registered we know their the spatial resolution and we can measure an average velocity of movement.

C.M.1993/C:30 - Ref.: Theme Session 0

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A CASE STUDY OF MESO-SCALE MOTION PATTERNS OFF THE PORTUGUESE WEST COAST

Repetitive sets of CTD- and current data reveal meso-scale circulation patterns offshore the Portuguese shelf. The data analysis refers to local winds, mapped sea surface temperature and salinity, geostrophic flow conditions between potential density surfaces of $\sigma_1 = 27.1$ (~200 m) and $\sigma_2 = 27.7$ (~1100 m), and geostrophic meridional currents during the season of climatic upwelling (September 1991) and "non-upwelling" (April 1991, January 1992) along the coast. The Tejo Plateau (39°N) subdivides the meridional subsurface currents along the continental slope into a northern and southern flow domain. North of the plateau meso-scale eddy-like subsurface currents controlled by the local slope topography seem to be dominant. South of the plateau the boundary flow is apparently more stable. In particular, the Mediterranean outflow water basically follows the continental slope and bifurcates into two branches with a noticeable west flow component between 37°N/38°N (C.S. Vincent) and 39°N/40°N (Tejo Plateau). Current data provide clear signals of barotropic poleward going subsurface flow along the continental slope above, within, and below the layer of the Mediterranean outflow. The results of current measurements at the northern Moroccan continental slope suggest that there must be a link between the poleward going subsurface flow from the south (Morocco) and along the south Iberian slope.

C.M.1993/C:34 - Ref.: Theme Session 0

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VARIABILITY OF COASTAL UPWELLING AND CROSS-SHELF TRANSPORT OFF THE NORTHWEST AFRICAN COAST

Satellite images, wind data and a hydrodynamic model have been used for studying the seasonal
variability of coastal upwelling along the Northwest African coast. The period studied is from 1981 to 1989. Upwelling indices have been derived from satellite data of sea surface temperature by extracting zonal temperature differences between shelf and open ocean water as a function of latitude in all available images. A similar but independent upwelling index is calculated from the wind data using classical Ekman theory. The seasonal variability of coastal upwelling is discussed from the 2 upwelling indices. In both data sets the known seasonal variability south of Cape Blanc and off northern Morocco is easily identified. Quasi-permanent upwelling throughout the year appears in the area immediately north of Cape Blanc. A hydrodynamic model is used for a specific analysis of the cross-shelf transport in that area for 3 different periods in 1983 and 1984 and the model results are compared to Ekman theory. It results that most of the cross-shelf transport is explained well with the simple Ekman theory, confirming the understanding of coastal upwelling as a wind driven phenomenon.

C.M.1993/L:17 - Ref.: Theme Session O

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UPWELLING AROUND THE SOUTHWEST IRISH COAST: NEAR-SURFACE DYNAMICS AND BLOOMS OF THE DINOFLAGELLATE GYRODINIUM CF. AUREOLUM (HULBERT)

An upwelling system has been described for coastal waters around southwest Ireland. Exceptional blooms, or "red tides", of the dinoflagellate Gymnodinium aureolum have frequently occurred in the region which have an origin in the adjacent shelf waters. The advection of these blooms towards the coast is a result of surface wind effects, which are more obvious in the large embayments of southwest Ireland which are axil to the prevailing south-westerly winds. In addition, this organism accumulates at the frontal zones between upwelled water and the adjacent stratified shelf waters, effectively a situation where the pycnocline is forced towards the sea surface.

The role of upwelling in promoting extensive populations of G. aureolum is examined. In particular, relationships between surface wind stress and both upwelling and surface advective bloom transport are discussed.

C.M.1993/L:18 - Ref.: Theme Session O

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UPWELLING AND THE PHYTOPLANKTON ECOLOGY OF SOUTHWEST IRISH COASTAL WATERS

Surface temperatures of coastal waters of southwest Ireland in the vicinity of the Fastnet Rock can be exceptionally cool (<11°C) in mid-summer. This is now known to be due to a coastal upwelling system which has only recently been identified. The upwelling is, however, highly variable both in its periodicity and magnitude, whereby events may prevail over time-scales of several days or weeks, providing an alternation of conditions between upwelling and fully stratified.

These events in mid-summer have a profound effect on the planktonic ecosystem. When upwelling is absent, the water structure is similar to that of the adjacent stratified Atlantic shelf and dinoflagellates, particularly Ceratium species are commonly found. When upwelling occurs to any extent diatoms flourish and typical spring bloom diatoms such as Thalassiosira roule/gravida, and Lauderia borealis can be surprisingly common. The more typical situation is intermediate between these two extremes and a variety of summer diatoms such as Chaetoceros spp., Rhizosolenia setigera and Nitzschia seriata are all common. The upwelling zone will be separated from the surrounding stratified water by a system of fronts. Their presence as the possible the source of red tides of Gymnodinium aureolum recorded from the area is discussed.

C.M.1993/L:32 - Ref.: Theme Session O

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VARIABILITY OF SURFACE PLANKTONIC COMMUNITY METABOLISM IN RESPONSE TO COASTAL UPWELLING EVENTS IN THE RIA DE VIGO (NW SPAIN).
Measurements of microbial photosynthetic and respiration rates based on oxygen light:dark incubations were carried out twice weekly, from April to November 1991, at a fixed station in the Ria de Vigo (N.W. Spain). Wind driven upwelling events in the Ria sustained high but very variable chlorophyll \( a \) biomasses (mean: \( 6.6 \pm 4.2 \), range: \( 0.2 - 17.5 \mu g \mbox{l}^{-1} \)), gross photosynthetic (GP) rates (mean: \( 37.4 \pm 30.2 \), range: \( 0.9 - 123.3 \mu mol \mbox{O}_2 \mbox{m}^{-2} \mbox{d}^{-1} \)), GP:Chl \( a \) ratios (mean: \( 5.2 \pm 2.3 \), range: \( 0.9 - 11.6 \mu g \mbox{Chl} \mbox{a} \mbox{m}^{-2} \mbox{h}^{-1} \)) and respiration rates (mean: \( 12.3 \pm 9.7 \), range: \( 0.6 - 46.5 \mu mol \mbox{O}_2 \mbox{m}^{-2} \mbox{d}^{-1} \) in the surface planktonic community. Chlorophyll increases were associated with both upwelling and relaxation conditions. During the spring-summer period dominated by regular upwelling and relaxation events, the GP:Chl \( a \) ratio (Productivity Index), showed consistent correlations with the density of the surface layer but was independent of temperature, nutrient and planktonic dominance. From April to the end of June, upwelling typically depressed photosynthetic activity while in July-August upwelling was associated with increases in autotrophic activity. Respiration rates showed a more complex pattern and varied on a shorter time-scale than did chlorophyll biomass or photosynthetic productivity suggesting a rapid growth or physiological response of heterotrophic organisms to very transient physical and biological situations.

The cross-shelf zonation and dispersal of fish larvae depended on the interaction of spawning bathymetry, vertical distribution of larvae and the hydrographical conditions in the respective range, but integrated time scales larger than the survey.

Soleid larvae living in less dense and less wind exposed coastal surface waters appeared to be retained there.

Surface living larvae of midshelf species showed dispersal offshore. For young anchovy larvae dispersal up to about 10 miles from the spawning grounds was directly related to the observed upwelling event, but for elder larvae up to 43 days old occurrences up to 37 miles from the respective zonal spawning depths were related also to two events north of the surveyed area during July.

Larvae from midshelf origin, but with a more extended vertical distribution including the thermocline showed reduced net offshore dispersal, particularly when they avoided the Ekman-layer as \textit{e.g.} \textit{Callionymus sp.} However, the bottom-near specimens of many taxa showed some advection from midshelf towards the coast.

The inshore boundaries of larvae of several slope or oceanic species were not always as anticipated from their vertical range, the reasons are discussed.

It is presumed that under normal summer conditions (with more consistent and stronger upwelling) all discussed dispersal patterns would become more pronounced.

C.M.1993/L:53 - Ref.: Theme Session O

Bode, A.\(^1\), Casas, B.\(^1\), Fernández, E.\(^2\), Marahón, E.\(^1\), Serret, P.\(^1\) and Varela, M.\(^1\) (\textit{Instituto Español de Oceanografía}, Apdo 130, E15080-La Coruña, Spain; \textit{Plymouth Marine Laboratory}, West Hoe, PLI 3DH, Plymouth, England; and \textit{Unidad de Ecología}, Dept. de Biología de organismos y Sistemas. Universidad de Oviedo, E33005-Oviedo, Spain)  

\textbf{VARIABILITY OF PHYTOPLANKTON BIOMASS AND PRIMARY PRODUCTIVITY IN THE SHELF WATERS OF THE UPWELLING AREA OF N-NW SPAIN}

Chlorophyll-a and primary productivity on the euphotic zone of the N-NW Spanish shelf was studied in 125 stations between 1984 and 1992. Three geographic areas (Cantabrian Sea, Rias Atlas and Rias Bajas), three bathimetric ranges (20 to 60 m, 60 to 150 m and stations deeper than 200 m), and
four seasonal periods (summer upwelling, spring and fall blooms, summer stratification and winter mixing) were considered.

One of the major sources of variability of chlorophyll and production data was seasonal, with equivalent mean and maximum values during bloom and summer upwelling periods. Average chlorophyll-a concentrations approximately doubled in every step of the increasing productivity sequence: winter mixing - summer stratification - high productivity (upwelling and bloom) periods. Primary production rates increased only 60% in the described sequence. Mean (±sd) values of chlorophyll-a and primary production rates during the high productivity periods were 59.7 ± 39.5 mg Chl-a m² and 86.9 ± 44.0 mg C m²·h⁻¹, respectively.

Significant differences in both chlorophyll and productivity resulted between geographic areas in most seasons. Only 27 stations showed effects of the summer upwelling that affected coastal areas in the Cantabrian Sea and Rias Bajas shelf, but also shelf-break stations in the Rias Atlas area. The Rias Baixas area resulted with lower chlorophyll than both the Rias Altas and the Cantabrian Sea areas during blooms, but higher during upwelling events. On the contrary, primary production rates were higher in the Rias Baixas area during bloom periods. Mid-shelf areas showed the highest chlorophyll concentrations during high productivity seasons, probably due to the existence of various fronts in all geographic zones considered.

The estimated phytoplankton growth rates were comparable to those of other coastal upwelling systems, with average values lower than maximum potential growth rates. Doubling rates for upwelling and stratification periods in the northern and Rias Altas shelf were equivalent, despite larger biomass accumulations during upwelling events. Low turnover rates of the existing biomass in the Rias Bajas shelf during upwelling suggests that phytoplankton exported from the highly productive rias accumulates near shore, and that in situ production is of less importance.

C.M.1993/L:64 - Ref.: Theme Session O

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Spatial Variability of Phytoplankton Communities in the Upwelling Region off Portugal

The composition and distribution of phytoplankton were studied during a cruise carried out off the coast of Portugal in August 1985. The structure of phytoplankton communities was related to the observed hydrographic conditions and to some geographic features of the area.

The distribution and abundance pattern of total phytoplankton and diatoms, mostly represented by chain-forming species, reflected the direct area of influence of the newly upwelled coastal waters. Small species of dinoflagellates and coccolithophores appeared to be adapted to warmer and more saline offshore waters of the western coast.

*Coccolithophorids* have been related to the northward decreasing influence of the subtropical branch of ENACW, being very abundant in the upwelling center of cape S. Vicente. Different assemblages were associated with different stages of upwelling development during sampling or different patterns of the upwelling process along the coast. Those assemblages were mainly composed by dinoflagellates observed north of cape Roca, e.g. toxic species, and by *coccolithophorids* observed in the south.

C.M.1993/L:66 - Ref.: Theme Session O

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Dynamics of Toxic Dinoflagellates During an Upwelling Event at the Northwest Coast Off Portugal

The dynamics of *Gymnodinium catenatum* and *Dinophysis acuta* was studied during the development of a weak upwelling event observed in a repeated coverage of a combined CTD/Plankton transect at 41°05' N, off the coast of Portugal. Both species were mainly distributed in the surface wind driven layer within the region of the equatorward coastal jet. Wind induced mixing, offshore transport and vertical motions were reflected in the distribution and the number of cells. It was generally observed that wind relaxation was associated with blooming conditions and shellfish toxicity, while active winds gave rise to dispersion of cells, reduction of their number and detoxification of bivalves.

C.M.1993/L:73 - Ref.: Theme Session O

Postel, L.¹, Arndt, E.A.² and Brenning, U.² (Baltic Sea Research Institute at the University of Rostock,
ROSTOCK ZOOPLANKTON STUDIES OFF WEST AFIRICA

Many cruises of the German r/v "A. V. Humboldt" operating from Rostock were carried out in the upwelling regions off West Africa since 1970. Zooplankton studies focused on quantitative, metabolic, taxonomic, and parasitological aspects. Biomass studies covered scales ranging in time from minutes to several years and in space from hundreds of meters to several thousands of kilometres. The epipelagic mesozooplankton of these upwelling areas mainly consists of calanoids with developmental times of about 20 to 23 days. In that time zooplankton dry mass pikes after an upwelling event, with a double dry mass. The upwelling phenomenon shows seasonality in most of the investigated areas. Typical time and space scales were described. There is a relationship between the duration of seasonal upwelling, that means the numbers of single upwelling events, and the cumulative growth of biomass. This net growth rate of zooplankton biomass is most pronounced at the shelf break, the area with the highest fish biomass, and in the upper 25 m. The large scale zooplankton biomass patterns are superimposed by mesoscale phenomenons, originated by e.g. long coastal parallel waves and eddies. Water masses, including upwelling source water, are to identify by indicator species, e.g. chaetognaths and calanoids. Comparisons of transport velocities and developmental rates of calanoids allows to explain the current regime as a suitable maintenance mechanism for this taxonomic group in the near coastal area.