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Report of the Workshop on the Indices of Mesoscale Structures (WKIMS)

22–24 February 2006

Nantes, France

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

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Executive summary

Long-term indices of ocean climate are generally based on large scale features (e.g. NAO). Such indices are limited in providing insight on the possible response of fish because the scale of the physical processes described is far greater than the scale at which fish behaviour is understood. Process understanding of fish response to the environment is generally more obvious at the mesoscale (10–100 km, days-weeks) where oceanographic features such as fronts, plumes, upwelling or eddies occur. An understanding of fish response to climate compatible with process understanding requires that mesoscale oceanic features be detected and tracked over long period of times. The aim of the workshop was to apply automated detection of mesoscale hydrological structures in a number of coastal and oceanic systems in order to provide long-term time series of these indices. These new time-series would complement those of existing indices (e.g., regional SST, NAO, Baltic inflow, etc.). The ultimate goal is to relate time-series mesoscale indices to times series of fish populations on the basis of process understanding gained at the mesoscale by field/process studies. During the workshop, emphasis was first put on fronts and eddies which are found in many areas and are often associated with important biological processes (such as Bakun's triad of production, concentration and retention/transport). The work focussed on the identification of (1) the principal data types available for observing front and eddies, (2) the available techniques for detecting, characterising and tracking fronts and eddies, and (3) the possible indices which can be constructed in relation to front and eddies. For each, examples were provided and when possible, the method was applied to other datasets. In addition to front and eddies, indices which specifically deal with physical-biological interactions such as larval transport where considered.

The Workshop recommends that ICES oceanography committee (probably through WGPBI) should review progress in the development of tools for the identification and characterisation of mesoscale physical structures in the ocean and of indices of mesoscale oceanographic features; and that ICES should also ensure that the reliability of those indices is assessed for their use in explaining spatial and temporal variability in fish populations (possibly through WGRED).

1 Motivations for and use of indices of mesoscale structures

1.1 Physical and biological mesoscale processes

Mesoscale physical structures in the ocean are characteristics of processes which size is below that of large scale oceanic circulation and above that of turbulent or short lived phenomena. Typically, mesoscale structures range from tens to few hundreds of kilometres and last from few weeks to months. An important characteristic of mesoscale features is their common association with strong energetic interfaces. As stated by Bakun (in press), “such interfaces represent sites where the energy of the physical system becomes in some way available to augment the trophic energy of the biological system”. They thus constitute structures of particular importance for biological production in the ocean and most particularly for the time and location of key life-cycle events in fish populations. The most common mesoscale structures consists of fronts and eddies which may in turn result from a variety of generating processes. Frontal structures can result from upwelling, thermal or haline stratification, tidal mixing, mesoscale atmospheric forcing (e.g. clouds, catabatic wind systems) and eddies. Eddies can results from shear in the larger scale circulation and/or accidents in the ocean bottom topography. Both fronts and eddies can occur in shelf waters or in deeper part of the ocean (although they then have fairly distinct characteristics). Other oceanic processes which involve e.g. water mass intrusions, river discharge can also generate mesoscale structures.

What are ‘mesoscale biological structures’ is less well defined in the literature. However, one can assume that the mesoscale is the scale at which the spatial-temporal patterns in population dynamics can be resolved. Using this definition, the size of mesoscale biological structures will depend upon the size of the marine populations that are studied. This idea can be related to the concept developed by Sinclair (1988) on fish populations. One of its basic principles is that the size of the population is determined by the extent of larval retention areas. In such situation, mesoscale biological structures would be those that exert dominant controls on larval retention. The size of the mesoscale structure is then bounded by the geographical extent of the population (for the upper end) and by the size of fish aggregations or schools (for the lower end). In most cases, the spatial and temporal extent of biological mesoscale structures ranges from tens to hundreds of kilometres and from weeks to months which renders their scale comparable with that of physical mesoscale structures.

1.2 Mesoscale physical control of marine population

Mesoscale physical features are highly energetic and strong biological activity is generally observed at the location of these interfaces in the ocean. This makes mesoscale physical features to be a potential dominant controlling force on marine populations. However, in many instances, the study of physical controls on marine populations have focus either small scale phenomena which can be subjected to experimental studies, or to large scale phenomena for which observation exist. Often, atmospheric large scale indices such as the ENSO in the Pacific or the NAO in the Atlantic are used to characterise specific climatic and hence hydrodynamic states. Mesoscale physical features such has fronts or eddies are known to be determinant for fundamental processes such as biological production, concentration and retention/transport (termed ‘the fundamental triad’ by Bakun, 1996). The role of these mesoscale features on marine populations has been described for a number of systems around the world. Some more specific examples are provided in section 1.4. and throughout the present report.

1.3 Indices as the interface between physical and biological investigations

Biological and physical oceanographic investigations have there own methodologies, terminologies, observations and modelling techniques. Studying the relationships between physical and biological mesoscale processes requires joint efforts between physical and biological oceanographers and specific tools that allow for the connection between understanding gained separately in the two research fields. The construction of indices of mesoscale activity in the ocean is a way of synthesising and transferring into quantified information, the physical processes that are relevant for marine populations. The ultimate goal is to relate time-series mesoscale indices to times series of fish populations on the basis of process understanding gained at the mesoscale by field/process studies. During the workshop, emphasis was first put on fronts and eddies which are found in many areas and are often associated with important biological processes (such as Bakun's triad of production, concentration and retention/transport). The work focussed on the identification of (1) the principal data types available for observing front and eddies, (2) the available techniques for detecting, characterising and tracking fronts and eddies, and (3) the possible indices which can be constructed in relation to front and eddies. It is hoped that further development of such indices will promote the production of operational oceanography products which are relevant for fisheries assessment and management.

2 Fronts

2.1 Biological processes associated with fronts

Hydrographic fronts and adjacent stratified regions have been identified to have a key role in marine eco-systems and their importance in the modulation of biological processes is widely recognised. Literature on types of fronts, physical processes causing their variability as well as their influence on biological processes is exhaustive with implications for trophic levels from autotrophs to marine mammals (e. g. Le Fevre, 1986). The fronts act as enrichment, concentration and retention mechanisms, and their formation is associated to physical processes such as upwelling filaments, river plumes or the interaction between different water masses. These frontal structures affect ecosystem components at all levels, directly or through cascading across the food-web. For example, frontal processes have been linked to variations in the distribution, condition and growth of the critical early life history stages of a number of key fish species globally (e.g. Fiedler and Bernard, 1987; Röpke, 1993: Munk, 1995; Mendes *et al.,* 2002). The detection of frontal structures is thus critical for a better understanding of the spatial structuring of ecosystem properties and processes.

2.2 River plumes and tidal mixing fronts

Different types of dynamic frontal systems occur in the ocean. Pure tidal mixing fronts and river plume fronts predominate in shallow shelf seas, shelf break fronts in the proximity of sharp topographic gradients. River plume fronts are caused by density gradients between the fresh water runoff and salty oceanic water. In contrast, tidal mixing fronts are caused by density gradients due to temperature differences. Tidal mixing fronts separate the vertically well mixed colder waters from seasonally stratified waters with higher surface temperatures. In shallow waters of the North Sea tidal stirring counteracts buoyancy forces from sea surface heat flux and inhibits the development of a seasonal thermocline in the shallower water. Pure tidal mixing fronts are manifested, due to the regular tidal forcing, in relatively stable geographic positions. These positions can be predicted as a function of maximum tidal velocities and water depth. Early research in this area was carried out by Dietrich (1954), who developed a relationship between the buoyancy forcing, the maximum tidal velocities and the minimum water depth necessary for stratification. Later the widely used parameter for estimating the position of a tidal mixing front was introduced by Simpson and Hunter (1974). Using a potential energy model, they derived a stratification parameter, a function of maximum tidal current speed and water depth which successfully could describe the location of the tidal mixing fronts in the North Sea.

In contrast to tidal mixing fronts, the occurrence and location of river plume fronts is strongly influenced by wind forcing and volume of fresh water outflow and thus is highly variable (e.g. Dippner, 1993; St. John *et al*., 1992; Schrum, 1994; 1997a). Attempts have been made to develop an empirical parameter similar to the Simpson and Hunter parameter to estimate the position of plume fronts and mixed type of these, taking into account additionally wind forcing and air sea heat fluxes (Nunez-Vaz *et al.*, 1989). Despite of the usefulness of such a parameter for a qualitative understanding of the system, the complex nature of plume frontal systems requires additional information from 3D models. In particular these include the full equation of motion and are thereby better able to resolve the temporal and spatial variability of these frontal systems. In addition to wind forcing and local air/sea heat fluxes freshwater contributions, 3D advection and non-linear interactions are also considered in the 3D models, making them more likely to catch the variability of plume frontal systems and interacting tidal mixing/plume frontal systems (see e.g. Schrum *et al*., 2003).

A number of processes have been linked to the formation and maintenance of plankton aggregations in frontal systems, these include as outlined in Franks and Walstad, 1997 subduction of surface populations (Hood *et al*., 1991; Claustre *et al*., 1994a; Lohrenz *et al*., 1993; Washburn *et al*., 1991); physical accumulation due to interaction between current velocities and organism behaviour (e.g. Franks, 1992); enhanced growth in response to diapycnal or isopycnal nutrient fluxes (Hitchcock *et al*., 1993; Holligan *et al*., 1984); photo adaptation (Hood *et al*., 1991; Claustre *et al*., 1994b); and reduced grazing stress (e.g., Holligan *et al*., 1984). Following Bakun (1996), these can be grouped into two primary mechanisms contributing to enhanced biomass in frontal regions. The first mechanism is increased production of phytoplankton due to fluxes of limiting nutrients during the summer stratified period as well as increased population growth rates of zooplankton due enhanced feeding conditions (e.g. Kiørboe, 1993; Richardson *et al.,* 2000). The second mechanism is physical aggregation of plankton due to the interaction of vertical migration patterns, buoyancy and circulation and turbulence (e.g. Franks, 1992; Franks and Walstad, 1997, Martin, 2003; Martin *et al*., 2001). Furthermore, fronts are as well important for the third relevant process after Bakun (1996), impacting on ecosystem dynamics, the retention: Frontal jets associated with bank systems like the Dogger Bank or Georges Bank result in retention of larvae (cf. Section 4).

2.3 Upwelling systems

A specific type of fronts are upwelling fronts, found mainly along the west coasts of the continents in the major upwelling regimes but present as well on smaller scales in regional or marginal seas. Upwelling contributes to the nutrient enrichment and hence results in increasing lower level productivity and better feeding conditions for higher trophic level species. Tracking of upwelling processes and creation of index time series describing its local occurrence and its temporal-spatial variability and persistence therefore could provide a useful tool. As an example, during strong upwelling events and weak thermal stratification, phytoplankton is advected offshore, giving rise to maxima in the area of convergence or retention formed by the front of the filament associated to the upwelling processes. These maxima could be exploited by consumers such as zooplankton, which in turn could provide nourishment for fish larvae.

During the workshop examples of investigation and tracking of frontal systems for a selection of different frontal systems were presented. The examples shown comprised tidal mixing frontal systems (Miller and Holt, Workshop Contribution 3; Presentation at the Workshop by

C. Schrum), river plume fronts (Otero *et al*., Workshop Contribution 4) and upwelling frontal systems Examples of upwelling systems were discussed by Rodriguez-Sanchez *et al*. (Workshop Contribution 1) for the California Current system, Nieto Demarcq for the Humboldt current system. Rodriguez-Sanchez *et al*. (Workshop Contribution 1) discussed the distribution and abundance changes on sardine recruitment in relation to mesoscale variability in the California Current system (Figure 1) and related the latitudinal changes to El Niño, La Niña events.

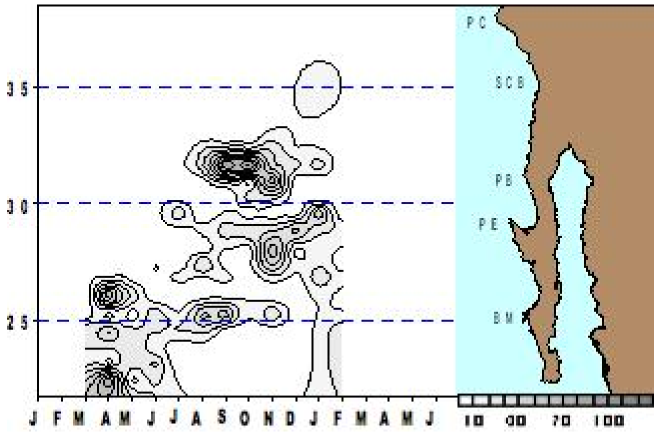


Figure 1. Distribution and seasonality of abundance of pacific sardines in the California Current system, here shown for the post-Niño year 1982.

The Chilean Humboldt subsystem is one of the most productive ecosystem in the world, but at the same time one of the least studied upwelling ecosystems. The area influenced by the Humboldt Current off Chile is known as Coastal Transition Zone. This zone extends from coast to 800 km offshore and can be separated in two latitudinal regions, the northern and central zone, with particular conditions of kinetic energy and wind stress (Hormazabal *et al*., 2004). The northern zone, between 19ºS and 29ºS, is characterized by low eddy kinetic energy and weak but persistent equatorward wind stress. In this area the upwelling process occur the whole year round, either as focal points or bands that covers a great part of the coast. The influence of the coastal upwelling is 20–25 nm (austral winter) and 30–40 nm (austral summer) and the upwelling events last from 4 (austral winter) to 15 (austral summer) days (Barbieri *et al*., 1995). In general, eddies occur only in summer but are not frequent. The central zone, between 29ºS and 39ºS, is characterized by high eddy kinetic energy and strong but variable equatorward wind stress. The upwelling process in this area is highly seasonal (Sept-Mar), main focus 30ºS and 37ºS, and the eddies activity is considerably more important that in the northern zone. The difference of the mesoscale processes in both zones is due mainly to the wind stress, kinetic energy and other factors less studied, like the topography, planetary waves influence, etc. On the other hand, the Chilean Humboldt subsystem support one of the most productive fisheries in the world, characterized by highly abundant pelagic fish species. In fact, more than the 90% of the total catch are pelagic fish, catched in almost half in the northern zone, between 18º–24ºS and the rest in the central zone, between 33º–39ºS. It's interesting to mention that different pelagic species dominate one and other one zone, being the anchovy the dominant species in the northern zone and the jack mackerel in the central zone. All the previous thing shows the need of studies to understand the dynamics of mesoscale processes and their effects on the biological processes and on the functioning of the links of the food web in this upwelling system.

2.4 Data types available to observe fronts

Different data types are available to assess frontal systems, and have been presented during the workshop. Sea surface observations as derived from remote sensing, were used by e.g. Miller and Holt. Remote sensing data thereby have two disadvantages, i.e. they resolve only the 2 dimensions and hence are only to a limited degree able to assess 3D mesoscale structures, further complementary information from e.g. in situ observations is necessary to assess the relevance of a detected surface structure for ecosystem functioning. Furthermore remote sensing of ocean colour or infrared radiations is cloud sensitive and hence only of limited usefulness in a many area.

Complementary information on the 3D structure of hydrographic characteristics mesoscale processes, resolved in time and space, could be obtained by using results from 3D models or in situ observations. Model data thereby enable derivation of process oriented index parameter like e.g. vorticity (relative, potential, planetary), Simpson-Hunter, baroclinic or barotropic instability contributions, Reynolds stress and spiciness, to allow for a better process oriented detection and tracking of relevant systems (Schrum, 1997; Flament, 2002). The concept of spiciness (based on in situ data) was presented at the workshop by E. Nogueira and discussed (Figure 2 and Section 4.1)

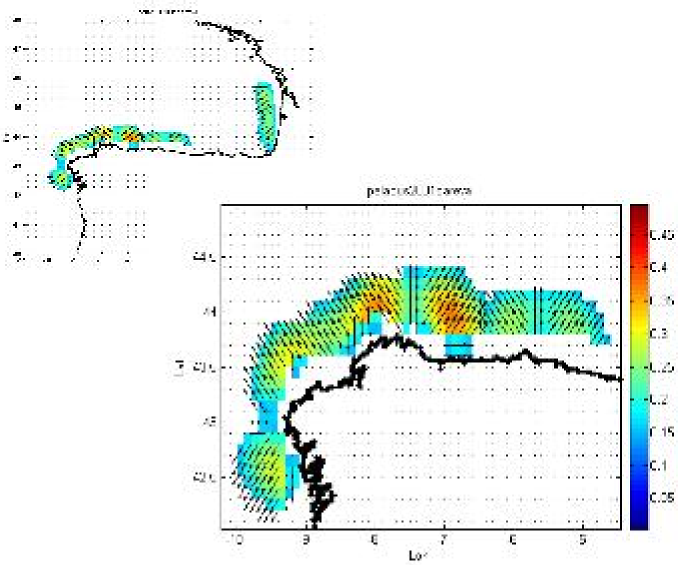


Figure 2. Careva cruise 04–2001. Frontal areas at 15m depth, Dmin[spiciness]= 0.15 in 10nm. Arrows indicate the direction of the maximum gradient.

Numerical models do have the disadvantage of being only a system approximation which has to neglect a variety of processes. They are furthermore limited by numerical errors and/or model errors, hence making detailed validations of models very necessary. Model validations are typically performed as snap shot validations, e.g. used to validate single events as observed and conclusions are drawn by extrapolating the results of such an validation to the general model performance, raising the question of statistical significance of the validation performed. More detailed validations using long-term data sets and allowing for a quantification of model performance have only been performed for few regional models (Janssen *et al*., 2001; Janssen, 2002). A new method for validation of mesoscale processes as resolved by models was presented in the frame of the workshop (Miller and Holt, Figure 3). Here a frontal detection method was applied to both, model results and remote sensing SST images. Comparison of detected structures in model results and observations allowed for identification of problems in the model.

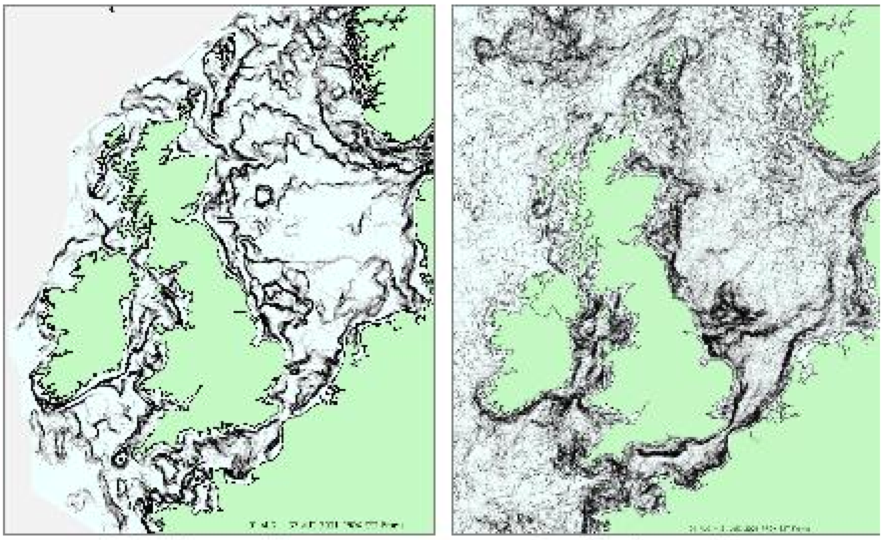


Figure 3. Detection of oceanic fronts on SST from (a) remote sensing and (b) model, for model validation and generation of mesoscale indices (Miller and Holt).

2.5 Techniques for detecting frontal structures

Methods presented here were based on detection of horizontal gradients or boundaries between water masses with different properties. Techniques have been developed for increasing the value of cloud-affected sequences of Earth Observation (EO) thermal and colour data for visualising dynamic physical and biological oceanic processes such as fronts and eddies. The composite front map approach is to combine the location, strength and persistence of all fronts observed over several days into a single map, which allows intuitive interpretation of mesoscale structures (Miller, 2004). This method achieves a synoptic view without blurring dynamic features, an inherent problem with conventional time-averaging compositing methods. Such techniques enable us to summarise mesoscale indices from the massive datasets acquired by an increasing number of multispectral EO sensors.

There was general approval of the 'composite front map' technique (Figure 4) as a generic tool for detecting fronts in time sequences of 2D fields (Miller, 2004). These fields may be Earth Observation (EO) surface maps of SST, chlorophyll, etc. or surface or deeper layers of any field simulated by a high resolution 3D hydrodynamic model. The technique uses the Cayula and Cornillon SIED method (Cayula and Cornillon, 1992; Diehl *et al*., 2002) to detect fronts on individual daily data, then combines the locations of fronts over a week or month with weightings based on front gradient, persistence and proximity to other fronts. This indicates the most persistent and significant fronts, and some visual information on whether fronts are static or dynamic. In the case of EO data, composite front maps also provide the best spatial integration of a sequence of partially cloud-obscured data without introducing smoothing or artefacts that can occur with composite SST maps.

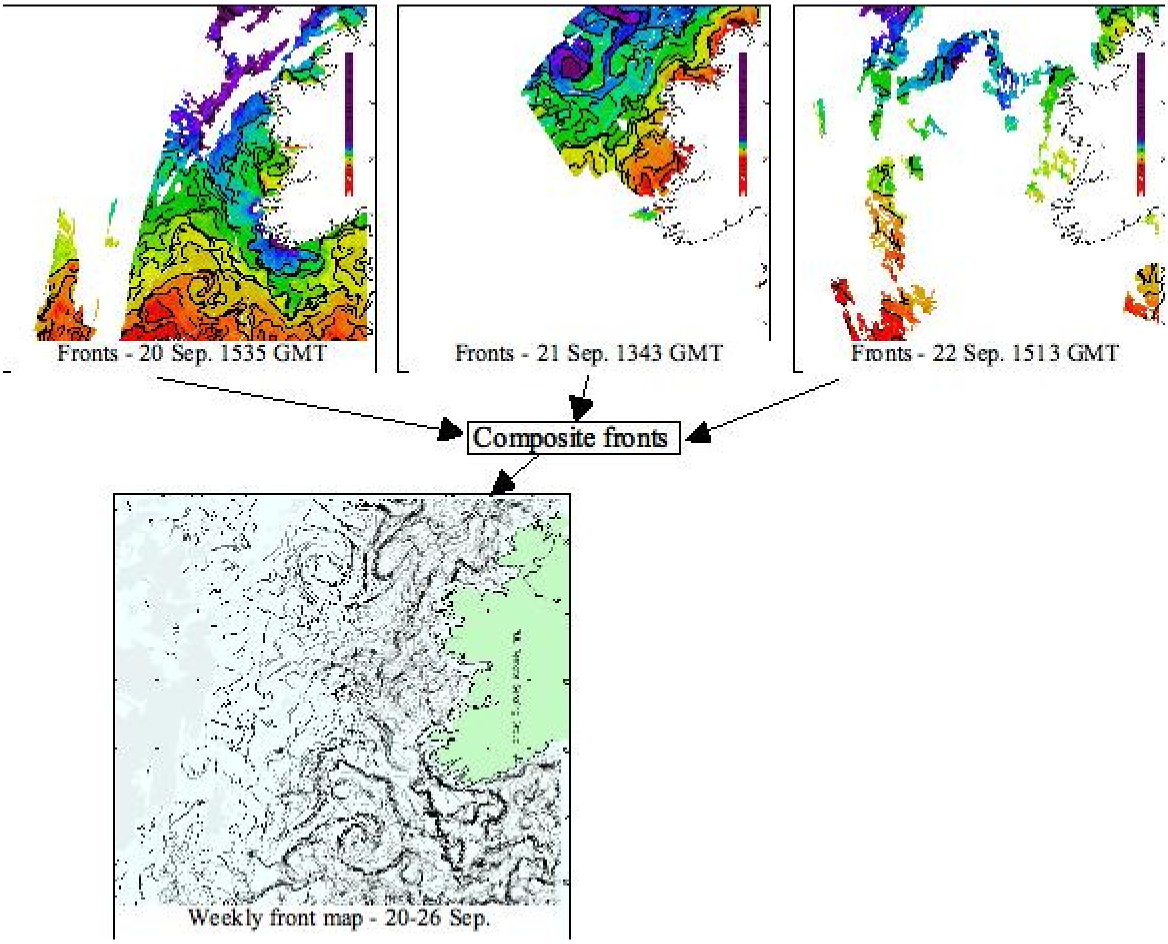


Figure 4. Schematic diagram showing composite front map method for automated front detection. Front contours are detected on individual SST maps over 7 days, then their location, gradient magnitude and persistence are combined to highlight the significant structures (Miller, 2004)

Otero *et al*. (Workshop Contribution 4), presented different methods of frontal detection (Figure 5). In the Northwest Iberian Upwelling System, river plumes can act as a retention or concentration mechanism with important implications in biological processes. This low-salinity structure is enhanced during the winter period, when river runoff is at maximum. Furthermore, this structure confines to the coast or expands offshore in response to wind in the scale of hours. To better understand the behaviour of the river plume a numerical model is employed allowing for taking into account the high temporal and spatial resolution.

A front detection algorithm is automatically applied to model outputs to delimit the edge of the river plume. The technique is based on the vertical density structure, allowing to construct a map of mixed layer depths. Classical image detection techniques are used to filter and enhance the presence of the front. Density is preferred instead of salinity to take advantage of the low temperature of the river outflow in winter period. In spite this technique has presented good results when compared with remote sensing imagery, problems are known when strong winds blow on the area and extremely confinement or detachment of the plume is reported.

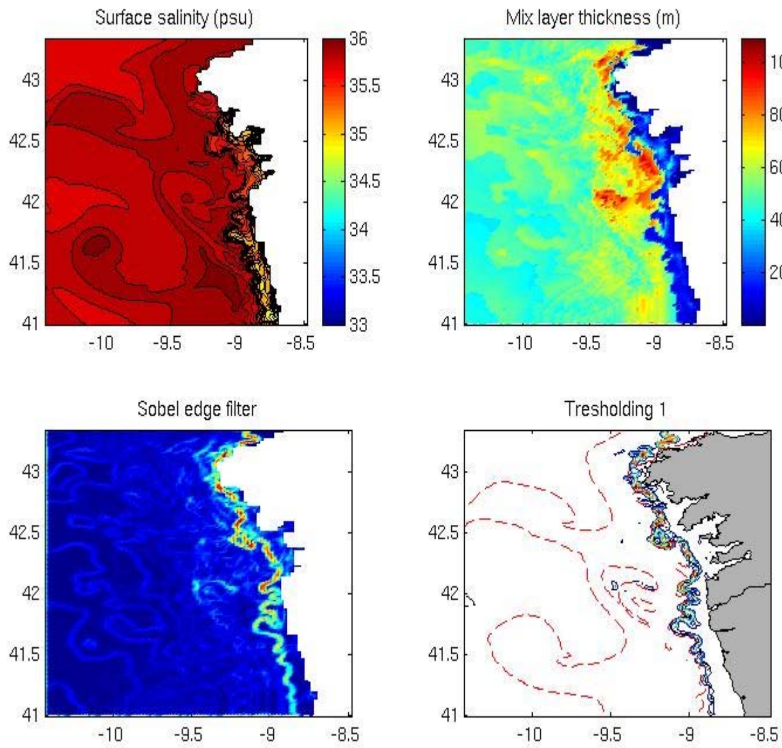


Figure 5. Comparison of frontal detection methods by different methods, surface salinity, Mixed layer thickness, Sobel edge filter, Tresholding (Ortero *et al.*, Workshop Contribution 4), 2 different wind cases.

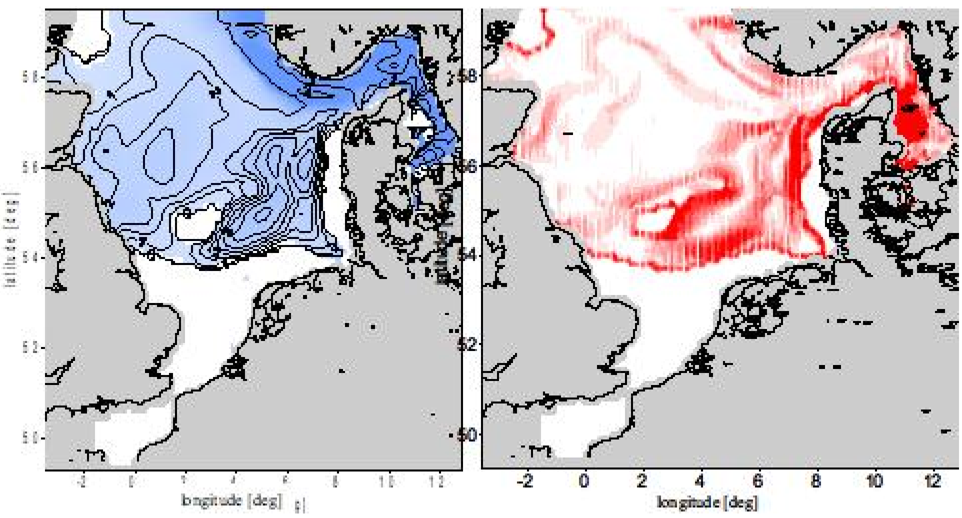


Figure 6. Density of stratification fronts in the North Sea (Presentation at the Workshop by C. Schrum)

2.6 Frontal indices

2.6.1 Deriving indices from detected frontal structures

To date composite front maps have been used primarily as a visual tool to help identify fronts, eddies and upwelling processes. However they are unsuitable as an index because of the spaghetti-like confusion of strong and weak fronts and clusters of strands indicating multiple observations of a dynamic front during the time period. So how may we derive indices from spaghetti? We have to simplify spaghetti into main front contours before we may derive structure indices.

Through analysis of a monthly front map we can infer the most likely contours of the main fronts, and thus greatly reduce the number of lines on the map. Each front contour would then be described using structure indices.

There are several possible methods for simplification. Manual annotation: this will produce the most structurally realistic contours, but is time consuming and subjective. Thresholding the front strands based on gradient, persistence, etc. to leave only the strongest fronts (Figure 9); though clusters of strands associated with strong fronts will remain. Miller has developed a straightforward automated simplification algorithm which generates contour segments; these may not always match a manual annotation, though may be adequate as a starting point (Figure 8). There are doubtless many other image analysis techniques that could be applied to this problem. For instance, a map of mean strand angle may be a useful first step.

An alternative approach is to describe the properties of each strand, and record these in all cells of the grid covered by the strand. The average value within each cell would form the gridded index of e.g. frontal gradient, persistence direction, or shape. This approach has been used in several published papers (e.g. Kahru *et al.,* 1995; Ullman and Cornillon, 1999).

Finally, more complex statistical methods are useful tools to compress high resolution information. One of the examples applied to frontal structures was the EOF analysis(Empirical Orthogonal Functions). EOF is a method of data reduction applied in first for geophysical data by Lorenz (1956) for the purpose of statistical weather prediction. The interest of EOFs is to summarise the information by reducing the number of dimensions of the data. The objective is to find simple patterns (space dimension) representing a maximum of variance of the data. The numerical method is described by lots of authors (Hannachi, 2004; Eslinger *et al*, 1989).

One example of EOF application presented at the workshop was realised in the north of the Mozambique channel (TewKai). The two modes representing respectively 37.69% and 11.45% of the variance and patterns are similar. The spatial mode presents few negative values, and they are along the northwest coast of Madagascar. This EOF describes a phytoplanktonic enrichment coming from the north of the channel with the strongest values (>0.04 mg Chl.m-3) organized along an anticyclonic cell. The time series presents a seasonal cycle with positive values from May to October (maximum in June) and negative values from November to April, with a minimum in January.

The EOFs are good methods to summarise the information and allow the spatial and temporal (seasonal, interannual) approach. Unfortunately, this statistical method needs to have all the data. So, if we use remote sensing data as SST or Ocean Colour, the problem of clouds is not negligible. We need to estimate the missing value due to the presence of clouds. Even if the treatments to estimate the missing values are robust, as the kriging they are restrictive and smooth the data. This kind of statistical methods are very useful to have spatial and temporal trend, but they are not good to the mesoscale detection. Further methods of data compression and identification of basic structures have been presented during the Workshop in context of identification of eddy structures (cf. Section 3).

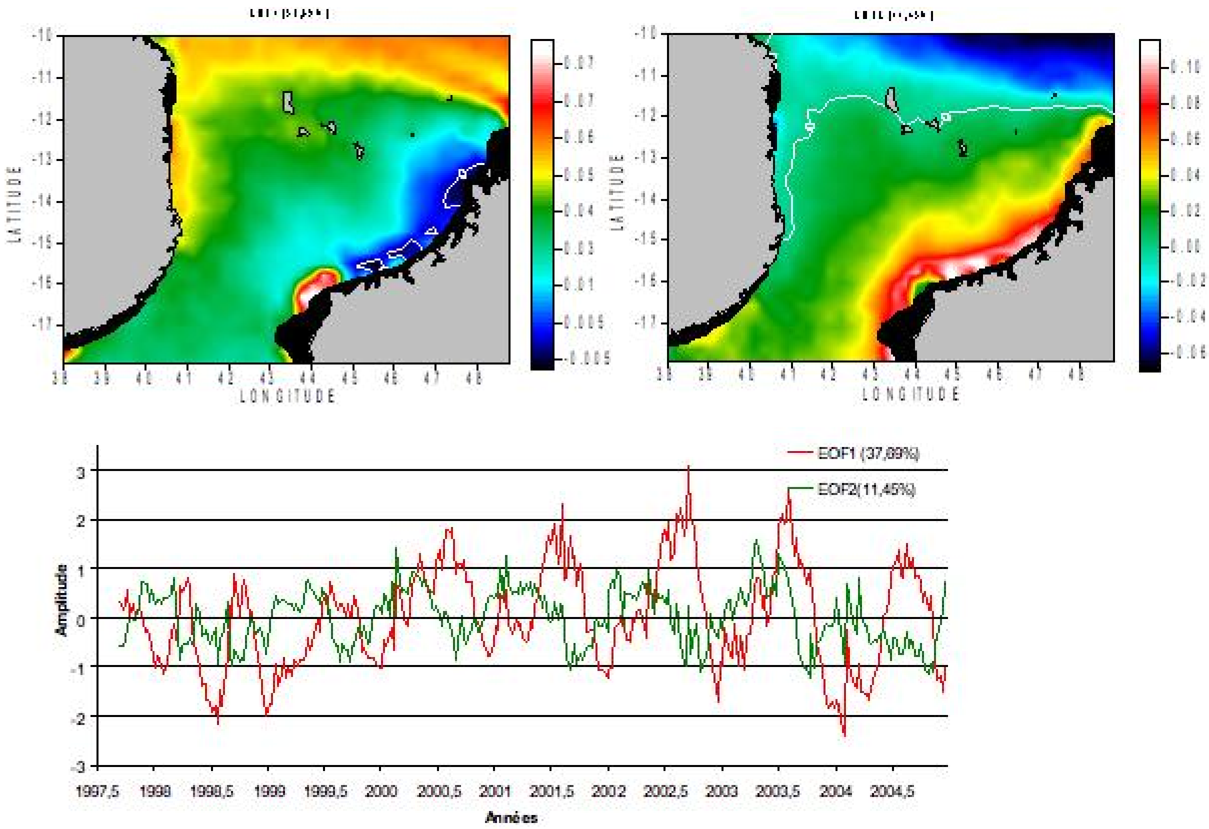


Figure 7. First and second component of EOF realized in the north (-10°S/-18°S, 30°E/50°E) of the Mozambique channel from 1997 to 2004.

2.6.2 Frontal indices of biological relevance

It is important to consider the different forms of mesoscale index which can be used to relate ecosystem processes and hydrodynamics on different spatial and temporal scales:

Gridded index: a sequence of 2D maps (or an average of these) of values indicating some statistic for a given cell for each time step. For example, the density of fronts observed within a 10km grid cell during each month. This form of index would be suitable for correlating with a time-series of gridded biological data, e.g. primary production or CPUE. Gridded indices which have been used successfully to relate biological structures to ecosystem processes are the magnitude of frontal gradients. Further potentially useful indices are frequency/density and direction of frontal gradients; frontal persistence or a combination of gradient, persistence, proximity and shape. Furthermore the distance to the nearest front could be potentially useful for the explanation of biological structures found in the field. All indices require at least temporal mean and SD, e.g. to distinguish between weak persistent and strong episodic fronts. Further indices derived from e.g. 3D models are e.g. most common type of front (see below); mean frontal depth, depth of the mixed layer, fresh water content and others.

Description of water masses on either side of a front and the area of each water mass (e.g. stratified area) have been suggested of being of use for specific types of applications. Further indices from 3D model information: velocities across front/along front/vertical; depth profile of front; stratification parameters. The choice of parameters is site dependent and clear identification of frontal types (e.g. tidal mixing front, river plume front, shelf break front, upwelling) is pre-requisite of derivation of biological relevant indices, since different frontal types have different dynamic consequence and hence different biological implications.

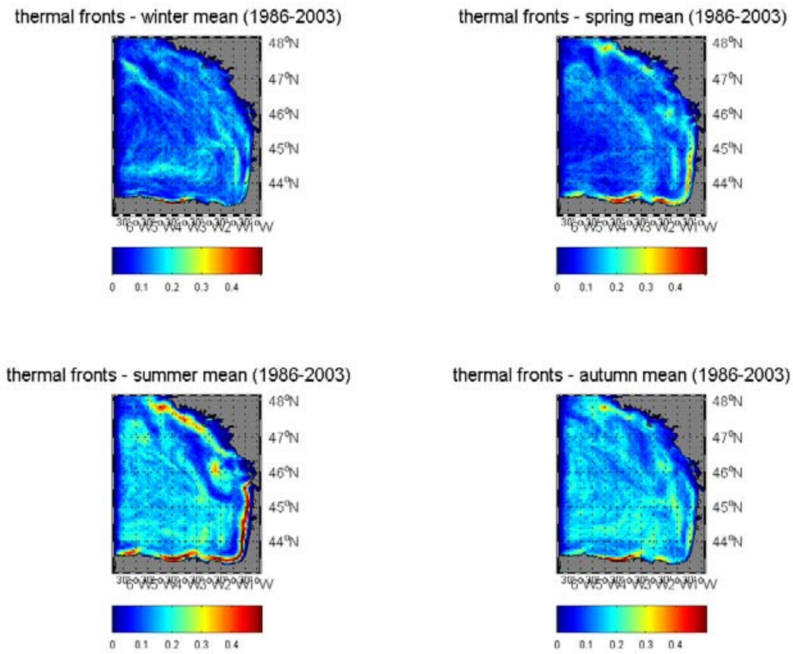


Figure 8. Spatial indices of surface thermal fronts in the Bay of Biscay. Colour scale indicate the relative frequency at which thermal fronts are detected for a given season. Note the recurrent fronts on the shelf during spring and summer months.

Structure index: a set of values describing different instances of mesoscale structures observed in a region. For example, the start and end date the front existed, length, position, advection path, etc. This form of index may help to explain a particular anomaly in biological data, or could be used to generate a census of structures of interest. Location, duration, advection, length, gradient magnitude and direction, contour mean angle, shape (e.g. Curvature, bending energy), angle relationship to coast (parallel, perpendicular, neither), distance from coast are potentially useful further information. For instance, increasing bending of an upwelling front may indicate when it will break down to form filaments.

Process index: a time-series describing the change in a mesoscale process of relevance to a particular region. For example, the strength or direction of a certain current, the outflow of a river, the distance from coast or volume within a river plume front. This form of index could be compared with a regional biological index, e.g. fish recruitment or abundance in that region.

Process indices will usually be region-specific, so are difficult to list in a generic form. Perhaps the presence, location, persistence or gradient of a *particular* front that is important to enhanced productivity or retention in a region. Or the summation of a gridded index over a larger box with which to compare a fisheries time series.

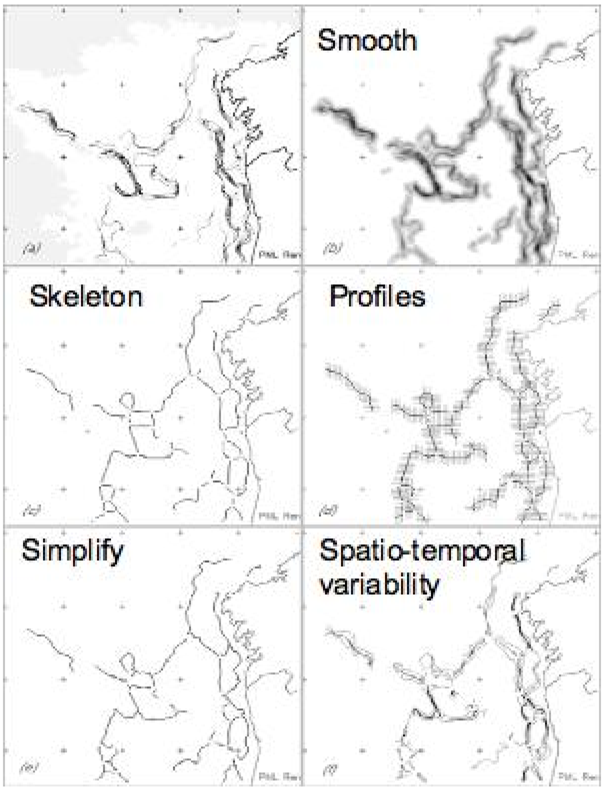


Figure 9. An automated method for simplifying front maps into main contours (Miller and Holt): (a) Daily SST front map for 17 Jan. 2000; (b) after smoothing; (c) after skeletonisation; (d) profiles used to calculate weighted mean position of front; (e) simplified front contours; (f) visualisation of spatio-temporal variability along front contours.

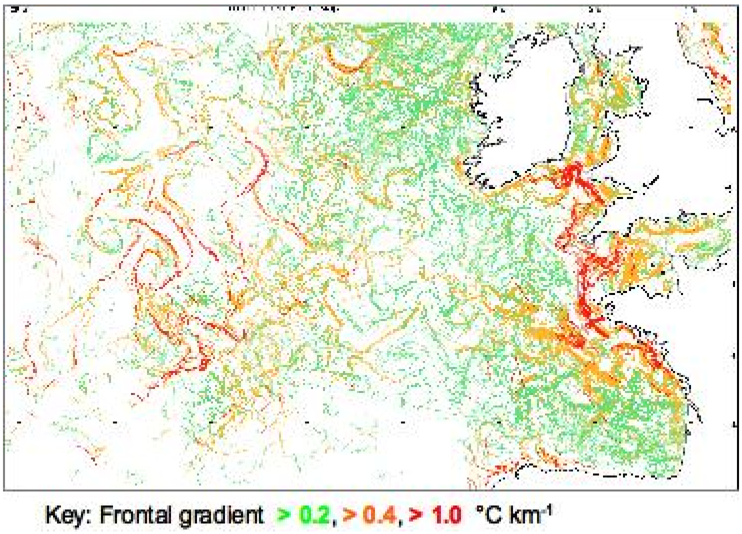


Figure 10. Traffic light front map for part of NE Atlantic, 08–14 Sep. 2002 (Miller and Holt, Workshop Contribution 3). Green, amber and red lines indicate fronts of horizontal thermal gradient of at least 0.1, 0.2, 0.4°C km-1 respectively.

3 Eddies

3.1 Biological processes associated with eddies

Mesoscale eddies can be defined as rotating structures at scales ranging from few tens to few hundreds of kms. Water masses at the core of the eddy may conserve there hydrological properties over time. The vertical range of mesoscale eddies may vary depending on there origin and geographical location. Shelf seas structures which are rotating but have a limited vertical extent have also been considered in the present section.

Mainly, three biological processes can be affected by eddies: (1) biological production, (2) retention of organisms within the eddy and (3) transport of organisms by the eddy following the eddy displacement. Two examples of eddy influence on biological processes are given below: swoddies in the Bay of Biscay and eddies in the Mozambique Channel (Figures 11 and 12).

In the Bay of Biscay, Slope Water Oceanic eDDIES (called SWODDIES by Pingree and Le Cann, 1992) are generated on the continental slope. They can trap and transport biological material from the shelf and slope and therefore influence widely the pelagic ecosystem in their area with respect to the recruitment and retention of fish larvae from shelf spawning grounds. In recent years, detailed observational and modelling investigations have stressed the significant role of eddy dynamics upon the injection of nutrients into the photic layer and, ultimately, on the magnitude of new production in the open ocean (Fernandez *et al.*, 2004). Through the upward displacements of the pycnocline, swoddies have several effects on biological production: an upward flux of new nutrients into the photic layer initiated by tilting of isopycnal surfaces; enhanced PAR (Photosynthetically Active Radiation) irradiance levels, thereby enhancing primary production rates (Smith *et al.*, 1996) and carbon uptake by the ocean; and higher subsurface oxygen concentrations (Fernandez *et al.*, 2004). As a consequence, the irradiance at the subsurface chlorophyll-a maximum is approximately a two-fold factor higher inside than outside the swoddy centre. An increase of the contribution of large plankton cells (>10µm) to total phytoplankton chlorophyll can be noticed. The higher biomass of larger primary producers directly propagates through the food web, favouring enhanced growth rates of large-sized mesozooplankton species (Fernandez *et al.*, 2004).

The Mozambique channel (10°S–30°S/30°E–50°E) is characterised by a strong mesoscale activity. Some authors detailed the oceanic circulation in the Channel (Quartly and Srokosz, 2004; Schouten *et al.*, 2003; Riddenkhof and Ruijter, 2003; Di Marco *et al.*, 2002). Several eddies were observed using Sea Level Anomaly and SeaWiFS data in the westside of the channel and in the south of Madagascar. Eddies in the Westside of the channel move southward, and eddies in the south of Madagascar are generated by the retroflection of East Madagascar Current. The mesoscale activity is independent of the seasonal variability, and four eddies in the westside of the channel are generated per year. Moreover it's important to underline that mesoscale circulation induce a significant proportion of the variability of chlorophyll distribution in the Mozambique channel. Using remote sensing sensor (SLA and SeaWiFS), the influence of mesoscale eddies on the distribution of chlorophyll has been shown. Comparisons between the Sea Level Anomaly and ocean colour have shown that the anticyclonic eddies seem to have a maximum of chlorophyll concentration at their periphery. This is probably due to the convergence of water mass which induce a process of warm and light water accumulation in the centre of the eddy. The cyclonic eddies seem to enhance phytoplanktonic production in their centre. This can be explain by the fact that this kind of eddies are divergent eddies, which allows for the upwelling of rich water toward the euphotic zone (Levy, 2003; Kang *et al.*, 2004; Falkowski *et al.*, 1991). There are other consequences of eddies on the distribution of phytoplankton. Indeed, eddies can contribute to export organic material from the coast to the offshore, and so contribute to the enrichment of biological production in the upper ocean. Some authors have discussed about the role of mesoscale eddies in the transport and retention of particles, for example in larval transport toward the offshore and their role in their retention, growth and larvae survival until recruitment (Garcon *et al.*, 2001; Mackas and Galbraith, 2002. In the Mozambique channel chlorophyll distribution is influenced by the mesoscale eddies moving southward. Weimerskirch *et al.* (2004) have shown that seabirds (Fregata minor) follow the boundary between two eddies. Birds are located specially on the westside of the channel, where mesoscale eddies are located and the trajectories followed by the seabirds are not concentred at the centre of cyclonic or anticyclonic eddies, but at their periphery. These examples show that mesoscale eddies have probably an important role on the biological processes and food web, on the coast and the upper ocean. Unfortunately, the relationships between eddies and biological variability, are not well studied. There is a need for tools such as automatic detection of eddies, and for the development of indices, in order to understand how mesoscale eddies can affect the distribution and the biomass of the biological compartment.

Figure 11. Satellite derived ocean colour showing high concentrations of phytoplankton (likely cocolithophores) in the southern Bay of Biscay. The shape of the colour patterns reveals the existence of cyclonic and anti-cyclonic eddies in the deep part of the area.

(a) **(b)**

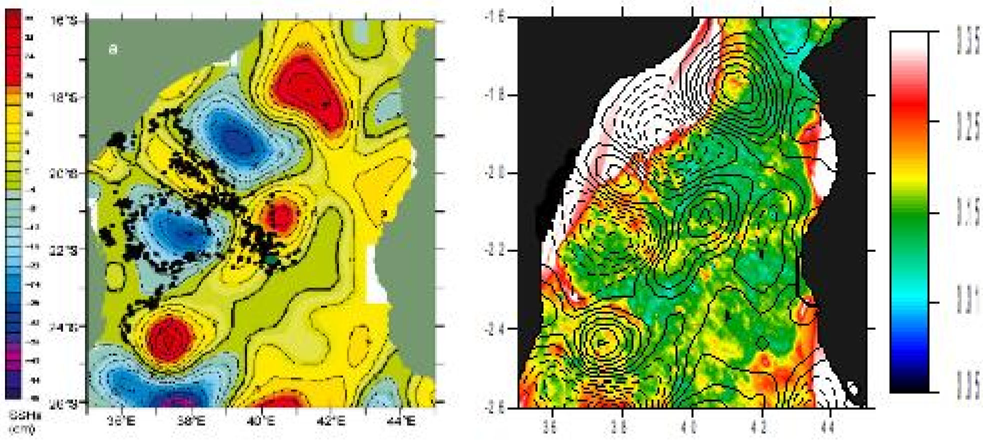


Figure 12. (a) Sea surface height anomalies in the Mozambique Channel between 13 and 18 September 2003 and locations of frigate birds during this time (from Weimerskirch *et al.*, 2004). (b) Map of Sea surface chlorophyll in the same time.

3.2 Data types available to observe eddies

Eddies have been observed through a range of available techniques and data types. Typically, remote sensing information, in situ data and model simulations can be used to observe eddies.

Remote sensing provides 2D surface fields and allow to follow them with time. This data type offers the advantage of providing synoptic or quasi-synoptic observations of surface parameters (temperature, colour, elevation, see below). It is limited by cloud interferences and does not provide direct observations of deep layers.

In situ data provide direct measures of the water hydrography (temperature, salinity, density) as well as dynamics (e.g. velocities measured with Acoustic Doppler Current Profiler). They provide sea-truth information but are limited in there spatial and temporal extent and resolution.

Model simulations provide the most comprehensive set of data with 3D fields, and there evolution in the time domain. Most of the parameters and techniques available to detect and characterise eddies can be applied to simulation outputs, assuming that the models can provide realistic simulations of the processes studied.

3.3 Parameters and techniques available to detect and characterise eddies

3.3.1 Parameters

3.3.1.1 Vorticity

Eddies are most easily characterized by their vorticity, a vector field that measures the rotation in the fluid and defined as the curl of velocity: Ω=rot(U). Vorticity is positive (negative) for a cyclonic (anticyclonic) rotation which corresponds to an anti-clockwise (clockwise) rotation in the Northern Hemisphere.

3.3.1.2 Temperature, sea level height and chlorophyll-a

The temperature signature of an eddy can vary in space and time: the development of a seasonal thermocline above a vertical structure can for example change its temperature signature. The sea level height anomaly is negative for a cyclone and positive for an anticyclone that is to say opposite to the sign of vorticity. Temperature (or sea level height) and chlorophyll-a may show good correlation at the mesoscale but it is not always the case: in particular nutrients are shown to not necessarily follow isopycnal surfaces (Levy, 2003).

3.3.1.3 Trajectories

Eddies trajectories can be measured by drifting buoys tracked by satellite. Eddy dynamics is highly influenced by topography (they can in particular be trapped by topography, increasing the persistence time in the area), but also by the presence of other vortical structures and strong currents in their surroundings.

3.3.1.4 Forced / Free eddies

Both cyclonic and anticyclonic eddies can be forced or decaying according to the sign of the net frictional force they sustain (see Bakun, in press for a detailed review). The most interesting situations in term of increase of biological production increase are the forced cyclone and the decaying anticyclone that both correspond to an upwelling flow of water, associated with a divergence in the upper layer and a convergence in the deep layer. In the contrary, forced anticyclones and decaying cyclones correspond to a downwelling flow of water, associated with a convergence in the upper layer (that can highly favour the increase of concentration at the surface) and a divergence in the deep layer. An exception to that rules needs to be noticed: divergent forced anticyclonic eddies can appear if (Ω + f) becomes negative which can occur when either 1) the eddy has a very small diameter; 2) the eddy is rotating very rapidly; 3) the eddy is located near the equator (see Bakun, in press for a detailed review).

3.3.2 Techniques

3.3.2.1 Visual observation

The most commonly used technique for eddy identification is expert visual observation. Eddies have been described from satellite observations of sea surface temperature, chlorophyll and elevation fields. The technique is valid when the identification (and tracking) is done on a limited number of structures that are well defined.

3.3.2.2 Wavelet analysis

Wavelet analysis provides methods for efficient data compression of variety of signals such as images or sounds. It consists of decomposing the signal into orthogonal, multiresolution wavepackets to isolate contributions from a range of scale and filter the smaller scales dominated by noise. One can use wavepackets to decompose successive horizontal maps of relative vorticity and extract localized structures in space. In a fixed area of the domain in study, the wavelets allow the identification of several structures, for each of which the centre is defined as the point of maximum relative vorticity or minimum velocity. The criterion is adjusted to allow the longest possible tracking.

Time and vertical tracking of eddies can be achieved by requiring successive eddy centres to belong to the eddy envelopes identified at the prior step of the analysis.

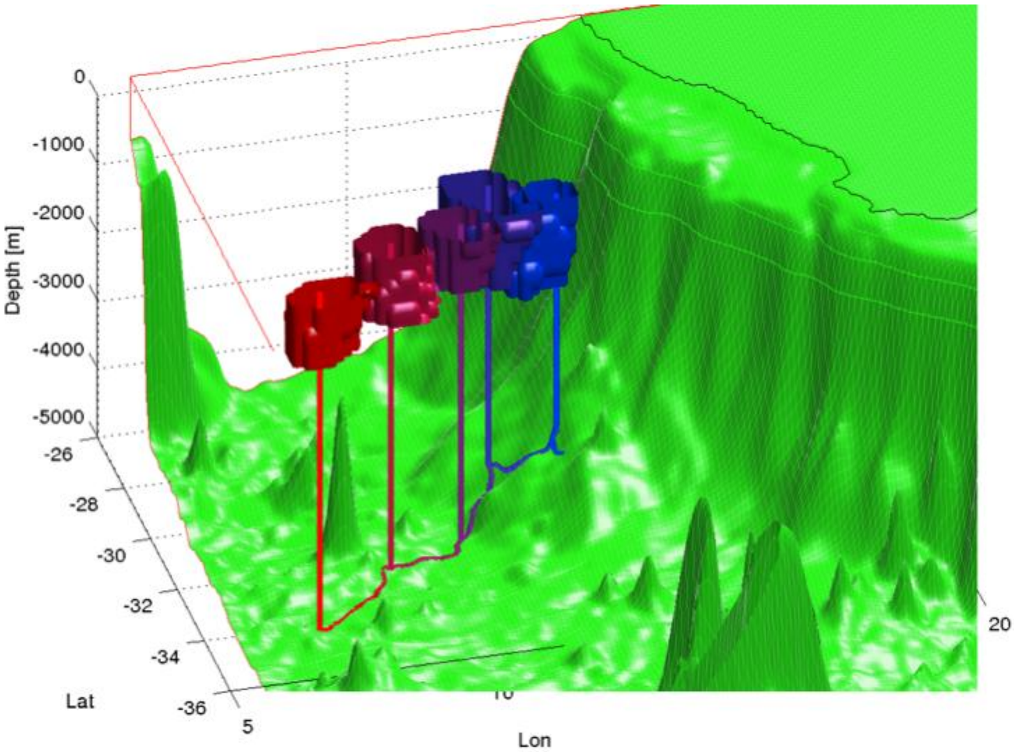


Figure 13. Example of eddy displacement. Coloured surfaces show eddy volumes and denote time, from blue (freshly-formed eddy) to red (ageing eddy)

3.3.2.3 Streamlines

The streamlines method is a deterministic detection method that builds streamlines using an interpolation of a vector field. The principle of this technique is simple: individual particles are dropped on the vector field. The particles follow the direction of the stream, taking into account its velocity and by doing so, they construct a streamline. When a particle has a looping trajectory, it is assumed that an eddy has been detected and the construction of the streamline is terminated. To build all the streamlines on a map, particles are dropped at every grid cell location. More or less particles can be dropped per cell, depending on the precision of the detection needed. Increasing number of particles increases computation time.

The trajectory of a particle is calculated using a Runge Kutta 2 integration. To be able to perform this integration, the position of the particle has to be known at any time. Exact location of particles (i.e. Between grid points) are interpolated.

This method requires 3 parameters to be set: the number of particles for a cell (called precision), a critical point and a looping threshold. The critical point is the minimum distance between successive positions of a particle. As a particle moves according to stream velocity, if the velocity is very low, the particle will not move a lot. If it moves of a distance that is lower than the critical point, the streamline is stopped. The looping threshold is used to detect eddies. As the trajectory of a particle is pseudo-continuous, there is a very low probability for a particle to loop at exactly the same point. The looping threshold is therefore the maximum distance between two points of a trajectory under which the algorithm has detected an eddy.

The streamline method is efficient but it is difficult to tune (i.e. Find the best combination of the above three parameters). It can have a very low detection noise but also a low success rate and when success rate increases, detection noise also increases badly. This is due to the fact that it focuses only on the stream direction and velocity but it is not able to take into account the retentive aspect of a structure that may rely on more global information.

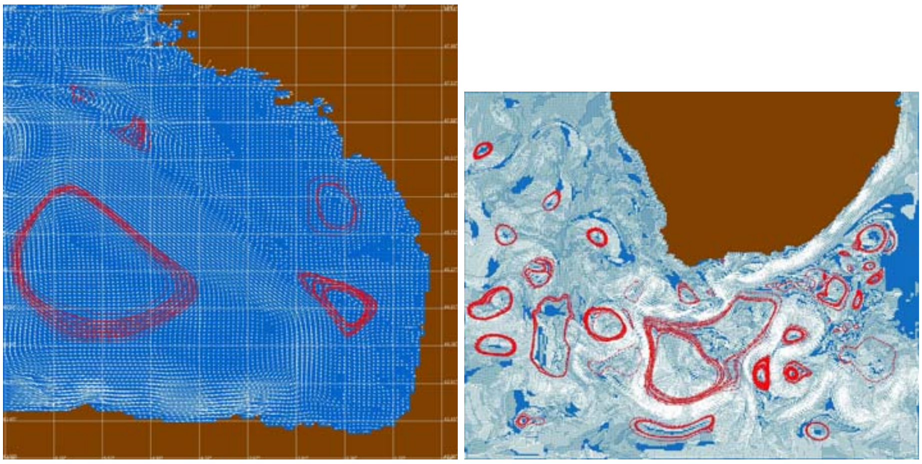


Figure 14. A vortex detection performed using the streamlines method within the software Marsouin. Velocity field results from hydrodynamic simulation from MARS3D model in the Bay of Biscay (left) and from ROMS model in the Cape basin region, South of Africa (right).

3.3.2.4 Ant-based algorithms for the detection of vortices

Ant algorithms were introduced in computer science by Dorigo (1992). The main idea of such algorithms is to use the ability of ants colonies to generate emergent 'intelligent' behaviour using only a small set of individual rules and simple interaction between individuals, through their environment. Classical applications of such algorithms are finding the shortest path to a goal, network routing, combinatorial optimisation, etc.

In the present case, this type of algorithm is adapted to fit a detection problem: the identification of retentive structures in coastal waters. This kind of detection can be performed by classical deterministic vector field analysis methods such as vorticity thresholding or streamlines building (see sections above). However, these methods may not always be efficient in coastal waters due to their high sensitivity to stream perturbations. In particular, vorticity based methods are not able to differentiate between meanders and true vortices.

The ant algorithm works in 3 steps: first, ants are dropped randomly on the vector field. The needed number of ants is automatically calculated by the algorithm taking into account the size of the grid. The second step is ants moving. Ants move using a stochastic rule to determine which cell they choose to go to. This rule has 3 parameters: pheromone concentration and stream velocity in each candidate cell and stream direction in the current cell. Using these 3 parameters, each candidate cell is given a « fitness » value and the next cell for an ant is chosen randomly between these candidate cell. A cell that has a good fitness value has a higher probability to be chosen than a cell that has a low fitness value.

The third step is eddies detection. During its move, an ant checks if its trajectory loops. If it does, then an eddy is detected and stored into the memory. When the algorithm ends, eddies are filtered so that extreme large or small eddies are rejected. If the same eddy has been detected several times with a different envelop, only the largest envelop is retained.

The ant algorithm can be used to perform detection and tracking of retentive structures on any suitable 2D vector field, taking in account stream strength and direction. Due to its high flexibility, it can easily be applied to the detection of other kind of eddies, at any scale, as it is only relying on the scale and mesh of the vector field given to the algorithm. The algorithm can be applied on other parameters such as wind, salinity, bathymetry, to perform a special detection task. More precise references can be found in Segond (2004) and Segond *et al.* (2003).

The algorithm has been implemented in a detection software called Marsouin. The software is designed to be an easy to use tool able to load and perform detection an tracking on any vector field that respects some rules to be opened. The Marsouin software is able to use both streamlines detection and ant based detection. Having done this detection, tracking of detected eddies can be done and eddies concentration maps can be generated. All these data can be exported as images or « .csv » files in order to be used in other dedicated softwares.

Additional information as well as download links can be found at the following address: http://lil.univ-littoral.fr/~segond/EN/Marsouin.html

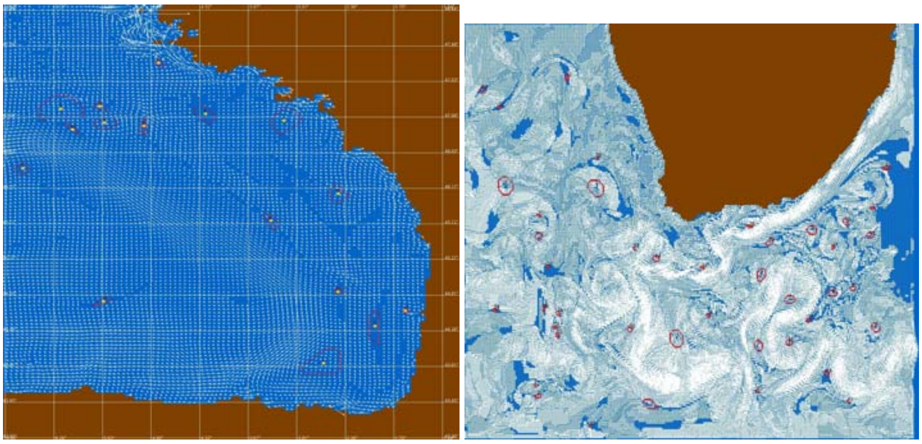


Figure 15. Application of the automatic detection of eddies to a MARS3D model output in the Bay of Biscay (left) and ROMS simulation output in the Cape basin region (right). Velocity field is shown in white arrows. Vortices are indicated by red lines.

3.4 Eddy indices

As for frontal structures (Section 3), the detection and characterisation of eddies and vortices needs to be complemented by the definition of indices which can summarise the information about eddy activity in a useful manner. Two types of indices may be considered: first, structure indices which describe the properties of individual eddies; second, aggregated indices which describe the properties of the eddy field or of an ensemble of eddies.

Structure indices may comprise: eddy size (contour/surface/volume), rotational direction (cyclonic/anticyclonic), revolution speed, displacement speed and direction, trajectory, life-time, point of origin,

Aggregated indices may comprise: spatial map of eddy density averaged over a period of time (see e.g. Figure 16), time-series of eddy density averaged over a given geographical area, ensemble of eddy trajectories, Eulerian map of eddy mean transport direction an velocity.

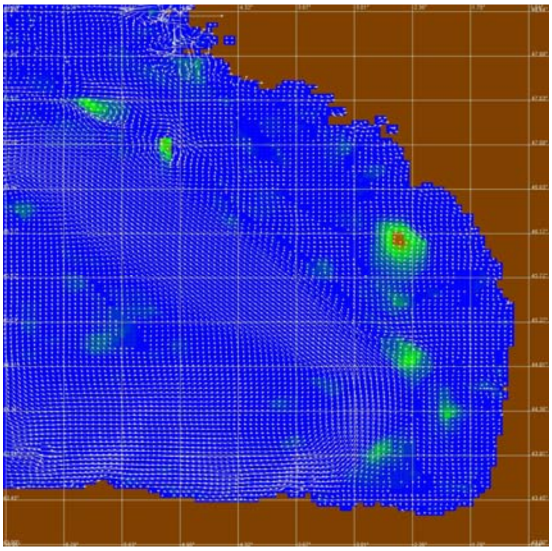


Figure 16. An example of eddy index derived from the software Marsouin applied to MARS3D simulations for the Bay of Biscay region. The index shows the frequency at which each individual location (pixel) belongs to a vortex-like structure and ranges from blue (zero) to red (maximum). Average flow field is shown in white arrows. Note the presence (in red) of a persistent vortex-like structure in the centre of the map which correspond to a topographic anomaly (the bank of 'Rochebonne').

4 Hydrodynamic transport of eggs/larvae

4.1 Circulation and water mass characterisation in relation to transport processes

It is considered that the spatial structuring and functioning of marine biological communities is markedly controlled by the dynamics of water masses and circulation, and therefore the characterisation of this physical processes is a key factor for the comprehension of the spatial distribution of ecosystem properties. For instances, in the NW and N Iberian shelf, the intrusions of warm and salty (thus ‘spicy’) waters associated to the Iberian Poleward Current (IPC) into the southern Bay of Biscay shelf, play a major role in structuring spatially the biological communities, since the poleward advection associated with the IPC transports northward biological communities of southern origin (upstream influence). It is thus important to derive indices related to the strength and northward extension of this poleward transport. We can derived these indices from remote sensing observations (i.e. satellite images of SST) or from the thermohaline field, from which we can estimate the position of the frontal area that separates the water masses from different origin.

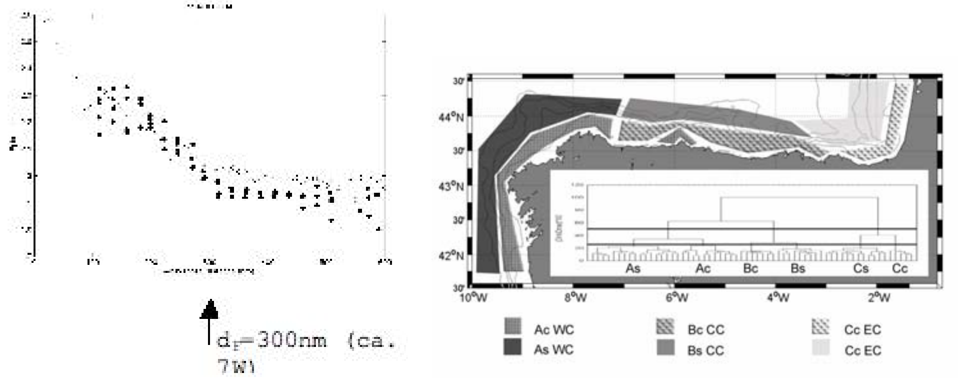


Figure 17. Relationship between dF (an index that defines the penetration of the Subtropical mode of Eastern North Atlantic Central Water associated with the Iberian Poleward Current front, defined from the analysis of the along-shelf variation of the spiciness value of subsurface, 75–80m depth, layer) and the spatial distribution of zooplankton assemblages. Note that the spatial distribution of zooplankton is delimited up to the extension of the IPC intrusion (around 7W) (from Cabal, Gonzalez-Nuevo and Nogueira, 2006)

Another example comes from the interannual variability of some demersal resources around the Balearic Islands. It is hypothesised that these resources may be related to the different reported regional circulation patterns in the area. These patterns seem to be associated with the presence/absence of winter intermediate waters (WIW) in the Balearic channels in late spring. So tracing the presence of these waters in the Balearic channels may be a good indicator of the regional circulation and then of the resources variability. For this case a possible index identifying WIW waters by its characteristic temperature at intermediate levels may be defined. This characterization may come from in situ data or numerical modelling.

When the origin of the water mass is clear one may try to get an index related to this water formation. WIW waters are generated by deep convection in winter in the Gulf of Lions, when air-sea fluxes are negative enough, particularly during cold winters. A simple index based on temperature anomalies in this region seems to be enough for this case, but one may also think in some more sophisticated way to indicate this water formation by investigating the actual heat fluxes between the ocean and the atmosphere.

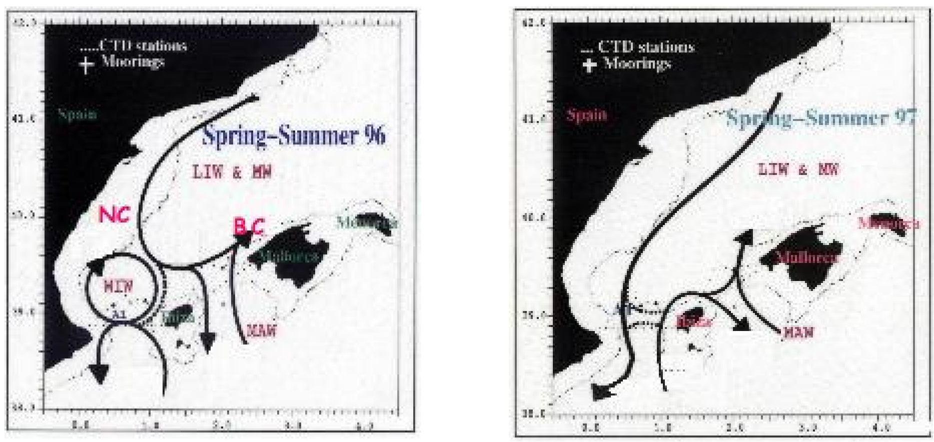


Figure 18. Circulation in the West Mediterranean Sea under cold (left) and mild (right) winter conditions. Note the presence of Winter Intermediate Waters (WIW) under cold winter conditions.

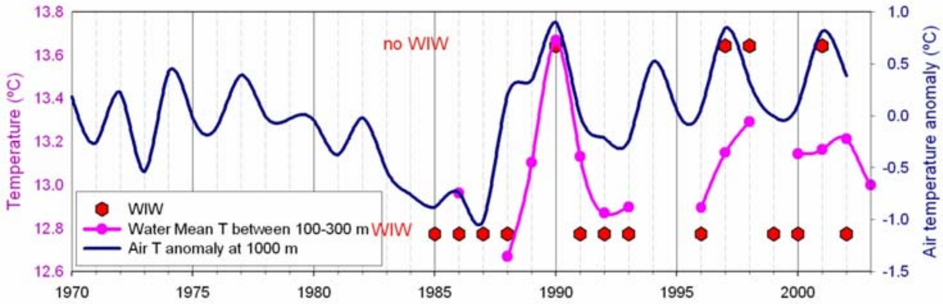


Figure 19. Time series of Winter Intermediate Water (WIW) (binary, presence-absence) present in the studied domain, water mean temperature between 100–300m depth and air temperature at sea level. Note that the years with no presence of WIW match those years of higher temperature, both at the intermediate water levels and at sea level in the atmosphere.

4.2 Transport enrichment and retention tracked with coupled hydrodynamic and IBM models

4.2.1 Modelling transport success in the Southern Benguela

The life history of anchovy (*Engraulis capensis/encrasicolus*) in the southern Benguela is characterized by a spatial discontinuity between the spawning grounds on the Agulhas Bank and the nursery grounds off the West Coast. Anchovy spawn in late spring-early summer on the western side of the Agulhas bank. A few day after spawning, eggs and early larvae are transported to the West Coast upwelling region by a narrow and intense jet that flows along the Cape Peninsula (Figure 20). Transport is considered a major ingredient of anchovy recruitment variability in this region (Hutchings, 1992). Correlations found between anchovy recruitment interannual variability and proxies of the jet behaviour further support the importance of transport processes in the southern Benguela (Boyd *et al*., 1998; Roy *et al*., 2002).

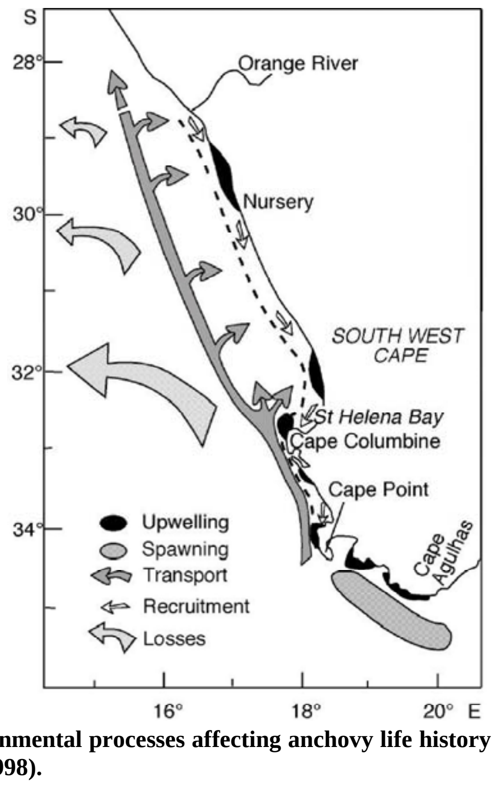


Figure 20. Major environmental processes affecting anchovy life history in the southern Benguela (from Hutchings *et al.*, 1998).

A modelling approach was designed to further investigate the effect of transport on anchovy recruitment variability (Huggett *et al*., 2003; Mullon *et al.*, 2003). It involved an IBM that allows to track particles released within the 3D currents fields provided by an hydrodynamic model of the southern Benguela region (Penven *et al*, 2001). This allows the quantification of different factors such as the timing and precise location of spawning activity, the frequency of spawning activity within a month, the level of aggregation of the spawning stock, and the interannual variability of transport due to the contribution of mesoscale processes.

The method used is described in the following section (extracted and adapted from Huggett *et al.*, 2003). The model was designed to simulate the Lagrangian transport of particles (anchovy eggs that subsequently develop into anchovy larvae) from the Agulhas Bank spawning grounds to the west coast nursery area. The particle tracking algorithm is based on a Eulerian scheme. It samples the output of the hydrodynamic model every 48 h but interpolates the data at 5 time steps during each 48 h period. This time step was selected after checking the sensitivity of the model to this interval. The algorithm does not include any turbulent diffusion; visualisation of the relative displacement of the particles obtained with passive transport indicated that the currents were very ‘diffusive’ without explicit diffusion. There was a set of fixed parameters: (1) the release of 10 000 particles per run in order to ensure stability in the outputs of the model despite the incorporation of random factors, (2) a random vertical distribution of the particles between the surface and 60 m, (3) a spawning period of 1 month repeated 12 times in order to investigate transport success all year round, and (4) a tracking period of 60 days. Transport success was defined as particles that were passively transported to the nursery area within a time interval of 14 to 60 d after release. The lower limit corresponds to the minimal swimming ability required to avoid advection upon arrival in the low-current nursery area, whereas the upper limit corresponds to the maximum swimming ability at which the fish may still be considered as a passive particle in an area of strong flow. The nursery area was divided into 2 regions: the inshore nursery located within the 0 to 200 m isobath between Cape Columbine and the Orange River, which is considered to be the core of the nursery area; and the offshore nursery located within the 200 to 500 m isobath between Cape Columbine and the Orange River. Variable parameters were: Particles were released from 5 different spawning areas: (1) the western Agulhas Bank (WAB) between Cape Point and Cape Agulhas from 0 to 500 m depth, (2) the inshore central Agulhas Bank (CAB in) between Cape Agulhas and Mossel Bay, from 0 to 100 m depth, (3) the offshore central Agulhas Bank (CAB off), as above, but from 100 to 500 m depth, (4) the inshore eastern Agulhas Bank (EAB in) between Mossel Bay and Cape St Francis, from 0 to 100 m depth, and (5) the offshore eastern Agulhas Bank (EAB off) as above, from 100 to 500 m depth. These areas cover the main spawning grounds of anchovy and their boundaries are inspired by current convention in the region. The 100 m depth contour is used on the central and eastern Agulhas Bank to split these areas into low spawning-intensity coastal zones and high spawning-intensity offshore zones. Other variable parameters included month of particle release or ‘spawning event’ (‘Month’, varying from January to December), the successive year of the simulation model (‘Year’, varying from 4 to 8), particle patchiness (‘Patchiness’, discrete values of 1, 10 or 100 corresponding to 10 000 random releases of 1 particle in the spawning area, 1000 random releases of 10 particles in 1 km2 and 100 random releases of 100 particles in 1 km2, respectively), and frequency of ‘spawning event’ (‘Frequency’, discrete values of 1, 3 or 10 corresponding to the release of particles every 1, 3 or 10 d mo–1, respectively). Due to the limited knowledge of the spawning behaviour of anchovy, patchiness and frequency were incorporated in the model in order to test the effect of non-randomness in the spatial and temporal distribution of particle release. Three trials of each permutation were run, resulting in 8100 simulated spawning events and a total of over 24 million particles released.

A number of implicit and explicit assumptions were made:

- The resolution, forcing, and topography employed in the hydrodynamic model produced sufficiently realistic circulation patterns; short-term (<1 month) wind events did not significantly affect the transport of spawning products from the spawning grounds to the nursery area.
- Significant spawning (in terms of reproductive success) only occurs on the Agulhas Bank, from Cape Point to Cape St Francis between the coast and the 500 m isobath.
- The subdivision of the spawning area into 5 subareas was adequate to explore the influence of spatial variability on reproductive success.
- The vertical distribution of eggs released by fish was assumed to be homogeneous in the upper 60 m, and any departure from this assumption would not significantly affect transport success.
- Eggs and larvae are mainly transported in a Lagrangian mode and the effects of ichthyoplankton density, diffusion and active movement are negligible in comparison to this fast mode of transport.
- Transport success was achieved when particles reached the nursery area within a time interval of 14 to 60 days after release.
- The release of 10 000 particles in the model during each run was sufficient to ensure stability in the outputs of the model (i.e. variability due to random factors in the model was taken into account).

A sensitivity analysis of transport success as the dependent variable was performed on the 5 independent class variables using multifactor analysis of variance (ANOVA). Results of the ANOVA were interpreted in the context of observed distributions of anchovy eggs during annual surveys of spawner biomass on the Agulhas Bank, as well as of seasonal spawning patterns from the literature and ongoing monitoring programmes. The model output was compared to monthly patterns of anchovy egg abundance from 2 historical ichthyoplankton surveys, namely the 'early routine' surveys and the Cape egg and larval programme (CELP) survey, plus one monitoring line, the sardine and anchovy recruitment programme (SARP) line. As the methods varied in all of these surveys, monthly egg abundance was expressed as a percentage of total annual abundance.

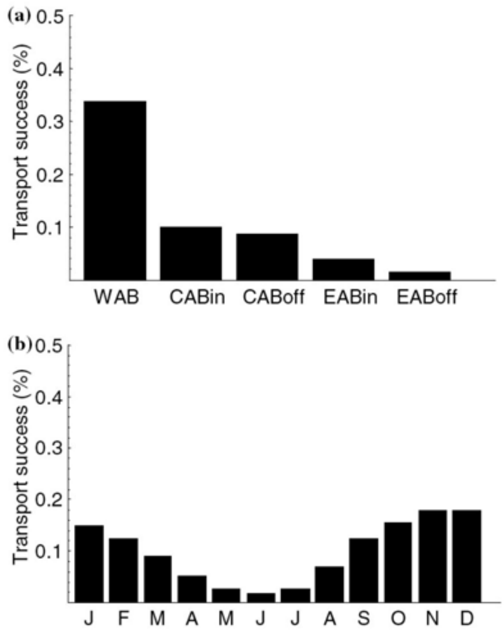


Figure 21. Transport success (%) in relation to (a) spawning area and (b) month of spawning given by the individual based model (IBM). From Mullon *et al.*, 2003.

Results from the model indicate that spawning season and area have a major effect on transport success. The most favourable period for spawning was September to March, peaking in November, and the western Agulhas Bank was the most favourable spawning area. A low success rate of passive transport to the core inshore nursery area in the model suggests that additional processes such as swimming or advection are required for larvae to reach this area. In general, there was good agreement between observed spawning patterns and the optimal temporal and spatial strata where particle transport was most successful, suggesting that the spawning strategy of anchovy is mainly the result of an adaptation to the circulation patterns in the region. Nonetheless, some discrepancies were observed between the success of transport and actual spawning patterns, and temperature may also be an important factor to take into consideration to fully explain how this originally temperate species is able to survive in an area of highly contrasting temperatures.

4.2.2 Modelling enrichment and retention processes in the Southern Benguela

Environmental processes that are believed to be important for the survival and recruitment of early life stages of pelagic fishes have been synthesized through Bakun’s fundamental triad. These three processes are : 1)-enrichment of surface waters by upwelling of nutrients rich waters from deeper layers, 2)-concentration of planktonic organisms on which larvae feed and 3)-retention of eggs and larvae within favourable areas (Bakun, 1996). These three processes are particularly relevant since they have implications from both a physical and a biological viewpoint. Agostini and Bakun (2002) already proposed a simple empirical method for quantifying the triad processes using surface wind stress as a proxy to estimate flow divergence (causing enrichment), flow convergence (responsible for concentration and retention) and Ekman transport. Indices based on sea surface temperature data have also been used as proxies to estimate enrichment and retention (Demarcq and Faure, 2000).

A method for quantifying two of the triad processes, enrichment and retention, has been developed (Lett, *et al*, in press). It is based on the Lagrangian tracking of particles transported within water velocity fields generated by a three-dimensional hydrodynamic model. The southern Benguela system was used as a test case. When designing this studies, the following assumptions were made :

1) The regional configuration of the hydrodynamic model provides realistic three-dimensional dynamics of water masses, at relevant spatial and temporal scales to study enrichment and retention processes.

2) The archiving frequency of hydrodynamic simulations, the integration scheme and the time stepping used in the Lagrangian model are such that trajectories of particles in Lagrangian simulations follow water mass displacement as simulated by the hydrodynamic model.

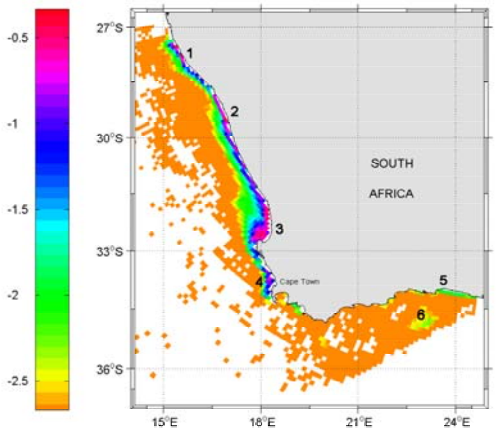
3) Nutrient-rich water parcels and fish eggs and early larvae are passively transported by water masses.

4) The procedure used to quantify enrichment and retention and the range of parameter values investigated allows characterisation of the broad patterns of these processes in the region.

5) The number of simulations performed and the number of particles used for each simulation is sufficient to provide an adequate representation of the spatial and seasonal variability of the simulated processes.

Simulations of the three-dimensional water velocity fields were given by a hydrodynamic model of the southern Benguela based on the Regional Ocean Modelling System (ROMS) numerical code (Penven *et al*., 2001). The Lagrangian model tracks particles using water velocity fields extracted from the archived hydrodynamic simulations. Transport of particles relies only on advection (or drift) as no diffusion term is introduced. Linear interpolations in time and space of the velocity fields are performed 30 times within 2-day time-steps. Under these conditions, the ‘well-mixed condition test’, stating that an initially uniform distribution of particles maintains uniformity was visually estimated as being satisfied.

Experiments consisted of a series of simulations that were repeated every 2 weeks from 1992 to 1999. During each simulation, 200 000 particles were released and transported within the velocity fields, with their positions being tracked over 60 days following their release. Simulations were run with different initial conditions of particle release, one for the enrichment process and the other for the retention process. Different criteria were used to consider the particles as being upwelled (i.e. contributing to enrichment) and/or retained. The number of particles satisfying these criteria was counted and then plotted on a discrete spatial grid having the same resolution as the hydrodynamic model. It should be noted that the term 'particle' is used as a general term for anything neutrally buoyant and passively transported by the currents. In the context of this work, when focusing on the enrichment process, particles are nutrient-rich water parcels upwelled to the surface from deeper layers. For the retention process, particles represent fish eggs and early larvae.



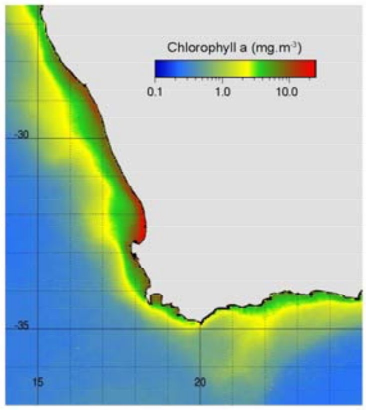


Figure 22. (a) Map showing the simulated pattern of enrichment intensity (log-scale, white is zero) averaged over years 1992–1999. (b) Composite map of annual average chlorophyll a concentration computed from SeaWiFS images (4.5 km resolution) from September 1997 to April 2002 (same as Figure 1c in Demarcq *et al.*, 2003 but with a focus on the region of interest).

In the southern Benguela system, upwelling occurs within the coastal domain, either at the shelf break or within the nearshore area. For these reasons, particles were only released within the continental shelf domain and its vicinity. At the beginning of a simulation, particles were randomly distributed at a depth between 100 and 300 m within an area delimited by the 100 and 500 m isobaths, which includes the depth range of the upwelled source waters. Particles were then transported by the simulated water velocity fields for 60 days, and were considered as upwelled as soon as they reached the upper 30 m of the water column, which corresponds approximately to the euphotic zone (or, at least, the upper, more active part of it) in the region. Once upwelled, particles were not transported anymore, to avoid showing particles away from their source as enriched. At the end of the 60-day period the number of upwelled particles within each grid cell was divided by the cell surface area to account for different surface areas among cells, and then mapped.

A proxy for retention was calculated using the following approach. For each simulation, particles were initially randomly distributed at depths between 0 and 100 m within the whole southern Benguela model domain. The criteria for particles to be considered as retained was that after 14 days of transport they should be less than 50 km away from where they were released. This empirical limit was chosen based on an averaged velocity of 4 cm s^{-1} over 14 days that is considered to be small regarding flow velocities in the region. Following the arguments developed by Parada *et al*. (2003), a period of 14 days correspond to the approximate age above which young larva showed swimming capabilities and may not be considered as passive. The proportion of released particles that were retained was averaged over depth within each grid cell, and then mapped.

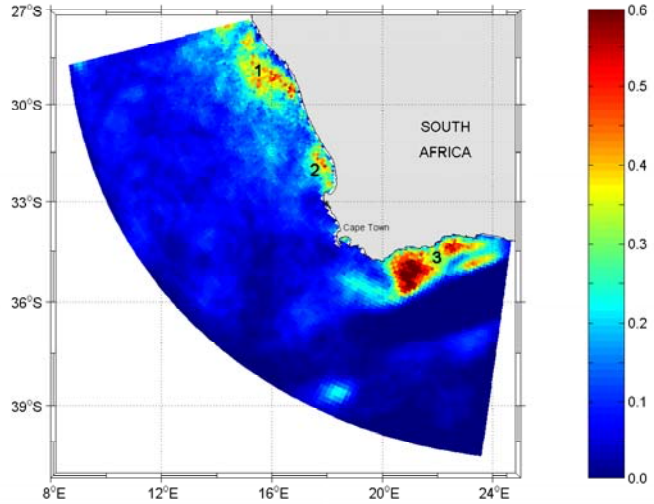


Figure 23. Map showing the simulated pattern of retention. Values correspond to the proportion of particles retained averaged over years 1992–1999 and depth

Maps showing the location and intensity of enrichment derived from our Lagrangian model are in agreement with field and other modelling observations of the southern Benguela (Shannon and Nelson, 1996). There is a close match between the distribution of the major coastal upwelling cells in the southern Benguela region deduced from the simulated enrichment map (labelled 1–5 in Figure 22) and descriptions derived from field observations. Observations as well as theory have often associated recirculation structures with shelf areas located downwind of major upwelling centres. Such recirculation structures are known to enhance both concentration and retention. Hence, retention in St Helena Bay (labelled 2 in Figure 22), which has often been mentioned in the literature, has been linked to a recirculation structure resulting from the interaction between the Cape Columbine upwelling plume, a strong wind curl and a sheltered shallow shelf inshore (Penven *et al*., 2000). The areas with high simulated retention values situated off the west coast (labelled 1 and 2 in Figure 22) broadly corresponds to the anchovy and sardine nursery area, where late larvae and juveniles have been found during larval surveys conducted in fall (March; van der Lingen and Huggett, 2003) and acoustic surveys conducted in winter (May; Barange *et al*., 1999), respectively. Enhanced retention on the Agulhas Bank (label 3 in Figure 22) undoubtedly plays a role in limiting dispersion in that region.

This simple approach did not allow us to consider the third triad process, concentration, because the hypothesis of fluid incompressibility underlying hydrodynamic models makes concentration impossible in models with passive particles. It would be necessary to consider particles that are not neutrally buoyant to investigate concentration that occurs at physical barriers like the surface, the bottom, or the pycnocline. Behaviour such as vertical migration is also thought to contribute to concentration in places such as the thermocline or the halocline (Batchelder *et al*., 2002).

Generic tools such as the one described here are particularly helpful in conducting comparative studies of small pelagic fishes in upwelling and other ecosystems. Our simulation tool requires three-dimensional water velocity fields as input. Such data are now available for many different systems, as can be seen from all the recently developed biological–hydrodynamic coupled models. Comparative studies are considered to provide a strong methodology for identifying the similarities and differences in the structure and functioning of comparable (e.g. upwelling) systems and in the reproductive strategies of small pelagic fishes occupying those systems. Identifying these similarities and differences will likely aid understanding of the dominant processes operating in individual systems.

4.3 Mesoscale indices and how to generate them

In early life stages, larvae and especially eggs are highly prone to variability in hydrographic conditions – they usually have very limited means of compensating for adverse conditions and buffering variability in the local environment. Especially, their absent or missing swimming abilities generally make recruitment success dependent of favourable hydrodynamic transport. Therefore, a key parameter in this context is basic hydrodynamic transport between spawn/hatch areas and nursery areas.

Compared to the other major targets of mesoscale indices covered in the work shop: eddy activity and frontal activity – transport indices can not fundamentally be derived from the physical conditions in the area and detached from biological parameters. The reason is that larvae/eggs of different species have different development schedules, activity patterns and physical properties (like buoyancy), and these issues affect the net transport significantly. Put in other words, each year, different species in a region will encounter different transport patterns, and it is likely that good transport conditions for one species could be bad for another, if there is sufficient interannual variability. The main advantage of transport indices is that they enter process-based recruitment models in a transparent way, because process-based recruitment models usually deals with population mass fluxes, which is exactly the target of transport indices.

Transport indices answers to main classes of questions:

1) Overlap between transported material and habitats (usually nursery area). This question usually derives from a match/mismatch hypothesis for recruitment.

2) Intra-habitat variability induced by life history variability along different transport paths. These questions usually derive from life-strategy contexts. These questions has not been in focus of the workshop, and therefore this class of questions is not elaborated further.

4.3.1 Indices for type 1 questions

Raw hydrodynamic transport is a multivariate distribution (6 degrees of freedom), which needs to be reduced to indices to be useful in improving biological understanding (the six degrees of freedom is transport starting position and time and transport ending position and time.)

The first step is to divide the region of interest into habitats of suitable size. No general rule for doing this can be stated, but as a rule of thumb, population distribution should be relatively homogeneous within a habitat. The aggregation into region immediately removes four degrees of freedom and leaves a matrix (transport between habitats) which depends parametrically on start and ending time. This hydrodynamically regional transport is denoted

$$H_{ij}(t_0,t_1)$$

Which is the transport probability from area *j* starting at time t0 ending at area i starting at time t1. *H* is a generic index (does only depend on hydrography). It is a probability distribution, because turbulent processes introduces randomness in the transport. The next step is to formulate a biological model, which provides the probability

$$B_j(t_0,t_1)$$

Which is the probability that transport from area *j* ending at area i starts at time t0 and ends at time t1. From this the net transport index between habitats in the region of interest becomes

$$T_{ij}=\int dt_0 dt_1 H_{ij}(t_0,t_1) B_j(t_0,t_1)$$

This is the maximum transport potential between habitats of interest. This conceptually demonstrates the linkage between hydrography and biology in determining the transport index. The most intuitive way to evaluate *Tij* is to couple a hydrodynamic model (providing *Hij*) with an individual-based model (IBM) which provides *Bij*, and release a large number of tracers in each hatching habitat.

4.3.2 Remarks on type 1 transport indices

Even though transport indices, *Tij* defined above, enter directly into recruitment models, one also needs to account for starvation/predation along the transport. This diminishes the fraction of successful transport between habitats of interest. If one neglects this factor when using the transport index directly into recruitment models, the implicit assumptions are spatially homogeneous starvation/predation loss and neglect of population density effects. We also notice that transport indices, *Tij* defined above, encompasses eddies/frontal issues dealt with more explicitly in other work shop sub groups.

Examples of transport indices: North Sea Sandeel larval transport

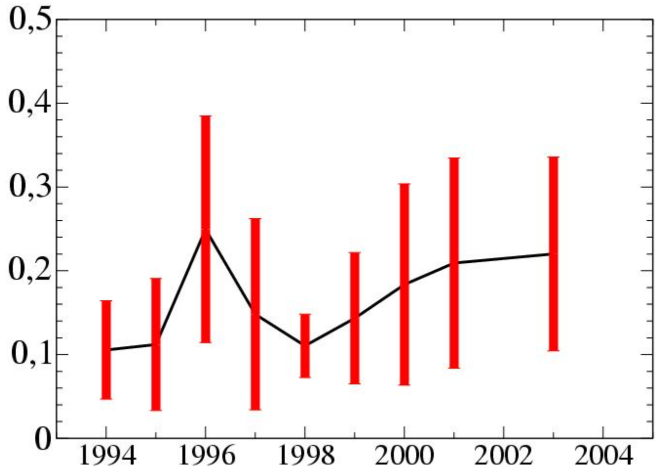


Figure 24. Average transport success () each year (full line) along with the spatial root mean square of transport success each year (when averaging over all hatching habitats). The figure demonstrates that there is considerable spatial and temporal variability in the transport index for this species in this region.

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6 References cited

Agostini, V.N., and Bakun, A. 2002. 'Ocean triads' in the Mediterranean Sea: physical mechanisms potentially structuring reproductive habitat suitability (with example application to European anchovy, (Engraulis encrasicolus). Fisheries Oceanography, 11: 129–142

Bakun, A. 1996. Patterns in the ocean. Ocean processes and marine population dynamics. California Sea Grant College. 323pp.

Bakun, A. (in press) Fronts and eddies as key structures in the habitat of marine fish larvae: Opportunity, adaptive response and competitive advantage. Scientia Marina.

Barange, M., Hampton, I., and Roel, B.A. 1999. Trends in the abundance and distribution of anchovy and sardine on the South African continental shelf in the 1990s, deduced from acoustic surveys. South African Journal of Marine Science, 21: 367–391.

Barbieri, M.A., Bravo, M., Farías, M., González, A., Pizarro, O., and Yáñez, E. 1995. Fenómenos asociados a la estructura térmica superficial del mar observados a través de imágenes satellitales en la zona norte de Chile. Investigaciones Marinas, 23: 99–122.

Batchelder, H. P., Edwards, C. A. and Powell, T. M. 2002. Individual-based models of copepod populations in coastal upwelling regions: implications of physiologically and environmentally influenced diel vertical migration on demographic success and nearshore retention. Progress in Oceanography, 53(2–4): 307–333.

Boyd, A.J., Shannon, L.J., Schulein, F. H. and Taunton-Clark, J.T. 1998. Food, transport and anchovy recruitment in the Southern Benguela upwelling system of South Africa. In : Durand M.H., P. Cury, R. Mendelssohn, C. Roy, A. Bakun and D. Pauly (eds). Global versus local changes in upwelling systems. Editions ORSTOM Paris, 195–209.

Cabal, J., González-Nuevo, G., Nogueira, E. 2006. Mesozooplankton species distribution related to hydrographic conditions in the NW and N Iberian shelf during spring 2004. X Symposium on oceanography of the Bay of Biscay, pp 3–6, ISBN: 84-689-6894-3.

Cayula, J.-F. and Cornillon, P. 1992. Edge detection algorithm for SST images. Journal of Atmospheric and Oceanic Technology, 9: 67–80.

Claustre, H., Kerhervé, P., Marty, J.C., Prieur, L., Videau, C., Hecq, J.H. 1994a. Phytoplankton dynamics associated with a geostrophic front: ecological and biogeochemical implications. Journal of Marine Research, 52: 711–742.

Claustre, H, Kerhervé, P, Marty, JC, Prieur, L. 1994b. Phytoplankton photoadaptation in relation to some frontal physical processes. Journal of Marine Systems, 5: 251–265.

Demarcq, H., and Faure, V. 2000 Coastal upwelling and associated retention indices derived from satellite SST. Application to Octopus vulgaris recruitment. Oceanologica Acta, 23: 391–408.

Diehl, S.F., Budd, J.W., Ullman, D. and Cayula, J.-F. 2002. Geographic Window Sizes Applied to Remote Sensing Sea Surface Temperature Front Detection. Journal of Atmospheric and Oceanic Technology, 19(7): 1115–1113.

Dietrich, 1954. Influence of tidal stirring on the hydrographic stratification in the North Sea (in German). Archiv für Meteorlogie, Geophysik und Bioklimatologie. Serie A, Band 7. Wien 1954 Springer, 391–405.

DiMarco, S., Chapman, P., Nowlin Jr, W., Hackerb, P., Donohuec, K., Lutherd, M., Johnsone, G., Toolef, J. 2002. Volume transport and property dstributions of the Mozambique channel. Deep-sea Research II, 49: 1481–1511.

Dippner, J.W. 1993. A frontal-resolving model for the German Bight. Continental Shelf Research, 13(1): 49–66.

Dorigo, M. 1992 Optimization, Learning and Natural Algorithms (in Italian). PhD thesis, Politecnico di Milano, Italia.

Eslinger, D. L., O'Brien, J. J., Iverson. R.L., 1989. Empirical Orthogonal Function Analysis of Cloud-Containing Coastal Zone. Color Scanner Images of Northeastern North American Coastal Waters. Journal of Geophysical Research, 94(C8):10,884–10,890.

Falkowski, P., G., Ziemann, D. Kolber, Z. 1991. Role of eddy pumping in enhancing primary production in the ocean. Nature, 352: 55–58.

Fernandez, Alvarez, Anadon, Barquero, Bode, Garcia, Garcia-Soto, Gil, Gonzalez, Iriarte, Mourino, Rodriguez, Sanchez, Teira,Torres, Valdes, M.Varela, R.Varela & Zapata. 2004. The spatial distribution of plankton communities in a Slope Water anticyclonic Oceanic eDDY (SWODDY) in the southern Bay of Biscay. Journal of the Marine Biological Associationof the United Kingdom, 84: 501–517.

Fiedler, P.C., Bernard, H.J. 1987. Tuna aggregation and feeding near fronts observed in satellite imagery. Continental Shelf Research, 7: 871–881.

Flament, P. 2002. A state variable for characterizing water masses and their diffusive stability: spiciness. Progress in Oceanography, 54(1–4): 493–501.

Franks, P.J.S. 1992. Sink or swim: accumulation of biomass at fronts. Marine Ecology Progress Series, 82: 1–12.

Franks, P.J.S., Walstad, L.J. 1997. Phytoplankton patches at fronts: a model of formation and response to transient wind events. Journal of Marine Research, 55:.1–30.

Garçon, V.C., Oschlies, A., Doney, S.C., McGillicuddy, D., Waniek, J. 2001. The role of mesoscale variability on plankton dynamics in the North Atlantic. Deep-sea research II, 48: 2199–2226.

Hannachi, A. 2004. A Primer for EOF Analysis of Climate Data.

Hitchcock, G.L., A.J. Mariano and T. Rossby. 1993. Mesoscale pigment fields in the Gulf Stream: observations in a meander crest and trough. Journal of Geophysical Research, 948: 8425–8445.

Holligan, P.M. 1981. Biological implications of fronts on the northwest European continental shelf. Philosophical Transactions of the Royal Society of London. Series A, 302: 547–562.

Holligan, P.M.; Williams, P.J.Le B.; Purdie, D., Harris, R.P. 1984. Photosynthesis, respiration and nitrogen supply of plankton populations in stratified, frontal and tidally mixed shelf waters. Marine Ecology Progress Series, 17(2): 201–213.

Hood, R.R., Abbot, M.R., Huyer. 1991. Phytoplankton and photosynthetic light response in the coastal transition zone off northern California in June 1987. Journal of Geophysical Research, 96: 14769–14780.

Hormazábal, S., Shaffer, G., and Leth, O. 2004. Coastal transition zone off Chile. Journal of Geophysical Research, 109(C1): C01021.

Huggett, J., Fréon, P., Mullon, C. and Penven, P. 2003. Modelling the transport success of anchovy (Engraulis encrasicolus) eggs and larvae in the southern Benguela: the effect of spatio-temporal spawning patterns. Marine Ecology Progress Series, 250: 247–262.

Hutchings, L. 1992. Fish harvesting in a variable, productive environment – searching for rules of searching for exceptions ? *In* Benguela Trophic Functioning. Ed. by A.I.L. Payne, K.H. Brink, K.H. Mann and R. Hilborn. South African Journal of Marine Science, 12 : 297–318.

Hutchings, L., Barange, M., Bloomer, S.F., Boyd, A.J., Crawford, R.J.M., Hugget, J.A., Kerstan, M., Korrubel, J.L., De Oliviera, J.a., Painting, S.J., Richardson, A.J., Shannon, L.J., Schulein, F.H., Van de Lingen, C.D. and Verheye, H.M. 1998. Multiple factors affecting South African anchovy recruitment in the spawning, transport and nursery areas. South African Journal of Marine Science, 19: 211–225.

Janssen, F, Schrum, C, Hübner, U, Backhaus, J 2001. Validation of a decadal simulation with a regional model for North Sea and Baltic Sea. Climate Research, 18: 55–62.

Janssen, F. 2002. Statistical analysis of multi-year hydrographic variability in the North Sea and Baltic Sea. Validation and correction of systematic errors in a regional ocean model.Statistische Analyse mehrjähriger Variabilität der Hydrographie in Nord- und Ostsee. Möglichkeiten zur Validation und Korrektur systematischer Fehler eines regionalen Ozeanmodells. PhD Thesis, Fachbereich Geowissenschaften, Universität Hamburg.

Kahru, M., Hakansson, B. and Rud, O. 1995. Distributions of the sea-surface temperature fronts in the Baltic Sea as derived from satellite imagery. Continental Shelf Research, 15(6): 663–679.

Kang, J., Kim, W., Chang, K., Noh, J. 2004. Distribution of phytoplankton related to the mesoscale physical structure within the surface mixed layer in the southwestern East Sea, Korea. Journal of Plankton Research, 26: 1515–1528.

Kiørboe, T. 1993. Turbulence, phytoplankton cell size, and the structure of pelagic food webs. Advances in Marine Biology, 29: 1–72.

Lett, C., Roy, C., Levasseur, A., van der Lingen, C. D., Mullon, C. (in press). Simulation and quantification of enrichment, concentration and retention processes in the southern Benguela upwelling ecosystem. Fisheries Oceanography.

LeFevre, J. 1986. Aspects of the biology of frontal systems. Advances in Marine Biology, 23: 163–299

Lévy, M., 2003. Mesoscale variability of phytoplankton and of new production: Impact of the large-scale nutrient distribution. Journal of Geophysical Research, 18: C11.

Lohrenz, St.E., Fahnenstiel, G.L. and Redalje, D.G. 1993. Spatial and temporal variations of photosynthetic parameters in relation to environmental conditions in northern Gulf of Mexico coastal waters. Estuaries, 17: 779–795.

Lorenz, E. 1956. Empirical orthogonal functions and statistical weather prediction. Statistical Forecasting Project Rep. 1, Dept. of Meteorology, Massachusetts Institute of Technology, 49 pp. [NTIS AD-110-268.].

Mackas, D.L., Galbraith, M.D. 2002. Zooplankton distribution and dynamics in north Pacific eddy of coastal origin: Transport and loss of Continental Margin Species. Journal of Oceanography, 58: 725–738.

Martin, A.P. 2003. Phytoplankton patchiness: the role of lateral stirring and mixing. Progress in Oceanography, 57: 125–174.

Martin, A.P., Richards, K.J., Law, C.S., Liddicoat, M. 2001. Horizontal dispersion within an anticyclonic mesoscale eddy. Deep-Sea Research II, 48: 739–755.

Mendes, S., Turrell, W., Lütkebohle, T., and Thompson, P. 2002. Influence of the tidal cycle and a tidal intrusionfront on the spatio-temporal distribution of coastal bottlenose dolphins. Marine Ecology Progress Series, 239: 221–229

Miller, P.I. 2004. Multispectral front maps for automatic detection of ocean colour features from SeaWiFS, International. Journal of Remote Sensing, 25(7–8): 1437–1442.

Mullon, C., Fréon, P., Parada, C., van der Lingen, C.D. and Huggett, J.A. 2003. From particles to individuals: modelling the early stages of anchovy in the southern Benguela. Fisheries Oceanography, 12(4,5): 396–406.

Munk, P, Larsson, P.O., Danielsen, D., and Moksness, E. 1995. Larval and small juvenile cod Gadus morhua concentrated in the highly productive areas of a shelf break front. Marine Ecology Progress Series, 125: 21–30.

Nunes Vaz, R.A.; Lennon, G.W.; De Silva Samarasinghe, J.R. 1989. The negative role of turbulence in estuarine mass transport. Estuarine, Coastal and Shelf Science, 28(4): 361–377.

Parada, C., van der Lingen, C.D., Mullon, C., and Penven, P. 2003 Modelling the effect of buoyancy on the transport of anchovy (Engraulis capensis) eggs from spawning to nursery grounds in the southern Benguela: an IBM approach. Fisherie Oceanography, 12: 170–184.

Penven, P., Roy, C., de Verdiere, A.C., and Largier, J. 2000 Simulation of a coastal jet retention process using a barotropic model. Oceanologica Acta, 23: 615–634.

Penven P., Roy, C., Brundrit, G., Colin de Verdière, A., Fréon, P., Johnson, A., Lutjeharms, J., and Shillington, F. 2001. A regional hydrodynamic model of upwelling in the Southern Benguela. South African Journal of Science, 97: 472–475

Pingree, R. D. and Le Cann, B. 1992 Three anticyclonic Slope Water Oceanic eDDIES (SWODDIES) in the southern Bay of Biscay in 1990. Deep Sea Research I, 39: 1147–1175.

Quartly, G.D. and Srokosz, M.A., 2004. Eddies in the southern Mozambique Channel. Deep Sea Research II, 51(1–3): 69–83.

Richardson, K., Visser, A.W., Pedersen, F.Bo. 2000. Subsurface phytoplankton blooms fuel pelagic production in the North Sea. Journal of Plankton Research, 22: 1663–1671.

Ridderinkhof, H. and de Ruijter, W.P. 2003. Moored current observations in the Mozambique Channel. Deep Sea Research II, 50: 1933–1955.

Röpke, A. 1993. Do larvae of mesopelagic fishes in the Arabian Sea adjust their vertical distribution to physical and biological gradients? Mar. Ecol. Prog. Ser., 101: 223–235.

Roy, C., Fréon, P. and van der Lingen, C.D. 2002. An empirical model of anchovy recruitment variability in the Southern Benguela. *In* Report of a GLOBEC-SPACC/IDYLE/ENVIFISH workshop on Spatial Approaches to the Dynamics of Coastal Pelagic Resources and their Environment in Upwelling Areas (6–8 September 2001, Cape Town, South Africa), pp. 52–54. Ed. by C.D. van der Lingen, C. Roy, P. Fréon, L. Castro, M. Gutierrez, L. Nykjaer and F. Shillington). GLOBEC Report, 16.

Schouten, M.W., de Ruijter,W.P.M., van Leeuwen, P.J., Ridderinkhof, H. 2003. Eddies and variability in the Mozambique Channel. Deep-Sea Research II, 50: 1987–2003.

Schrum, C. 1994. [Numerical simulation of thermodynamic processes in the German Bight.]Berichte aus dem Zentrum fuer Meeres- und Klimaforschung der Universitaet Hamburg. Reihe E. Hydrobiologie und Fischereiwissenschaft.

Schrum, C. 1997. Thermohaline stratification and instabilities at tidal mixing fronts: Results of an eddy resolving model for the German Bight. Continental Shelf Research, 17(6): 689–716.

Schrum, C., Siegismund, F., St. John, M. 2003. Decadal variations in circulation and stratification pattern of the North Sea. Are the 90´s unusual?. ICES Symposium of hydrobiological variability in the ICES area: 1990–1999. ICES Marine Science Symposia, 219: 121–131.

Segond, M. 2004. Application d'un algorithme à colonies de fourmis à la détection de structures rétentives en eaux côtières, proceedings of Majecstic'04, Calais, France, October 2004.

Segond, M. S. Mahler, D. Robilliard, C. Fonlupt, B. Planque, P. Lazure. 2003 Ant Algorithms for Detection in Coastal Waters. Proceedings of Artificial Evolution, 03: 166–176.

Shannon, L.V., and Nelson, G. 1996 The Benguela: large scale features and processes and system variability. *In* The South Atlantic: present and past circulation, pp. 163–210.. Ed. by G. Wefer, W.H. Berger, G. Siedler and D.J. Webb. Berlin Heidelberg: Springer-Verlag,

Simpson J. H. and Hunter, J.R. 1974. Fronts in the Irish Sea. Nature, 250: 404–406.

Sinclair, M. 1988 Marine populations. An essay on population regulation and speciation. University of Washington Press. 252pp.

Smith, Richards and Fasham. 1996. The impact of mesoscale eddies on plankton dynamics in the upper ocean. Deep-Sea Research, 43: 1807–1832.

St. John, M.A.; Stevenson MacDonald, J.; Harrison, P.J.; Beamish, R.J.; Choromanski, E. 1992. The Fraser River plume: Some preliminary observations on the distribution of juvenile salmon, herring, and their prey. Fisheries Oceanography, 1(2): 153–162.

Ullman, D.S., and Cornillon, P.C. 1999. Satellite-derived sea surface temperature fronts on the continental shelf off the northeast US coast, Journal of Geophysical Research-Oceans, 104(C10): 23459–23478.

van der Lingen, C.D., and Huggett, J.A. 2003. The role of ichthyoplankton surveys in recruitment research and management of South African anchovy and sardine. *In* The Big Fish Bang. Proceedings of the 26th Annual Larval Fish Conference, pp. 303–343. Ed. by H.I. Browman and A.B. Skiftesvik. Institute of Marine Research, Bergen, Norway.

Washburn, L., Kadco, D.C., Jones, B.H., Hayward, T., Kosro, P.M., Stanton, T.P., Ramp, S., Cowles, T. 1991. Water mass subduction and the transport of phytoplankton in a coastal upwelling system. Journal of Geophysical Research, 96: 14927–14645.

Weimerskirch, H., Le Corre, M., Jaquemet, S., Potier, M., Marsac, F. 2004 Foraging strategy of a top predator in tropical waters: great frigatebirds in the Mozambique Channel.

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*conveners

Annex 2: Agenda

22/02/2006		
9h-9h15	Welcome	Planque
9h15-9h30	Presentation of wkims objectives and participants. Adoption of the Agenda	Planque & Schrum
9h30-9h50	The need of time-series of mesoscale oceanographic indices for understanding latitudinal abundance changes of Pacific sardine in the California Current system	Rodríguez-Sánchez, Villalobos and Ortega-García
9h50-10h10	Multi-image edge detection on SST and Chlorophyll satellite images: Interaction between physical and biological process in oceanic mesoscale structures	Nieto and Demarcq
10h10-10h30	Validation of a high-resolution ocean shelf model using automated front detection	Miller and Holt
10h30-11h00	Coffee break	
11h00-11h20	Detection of river plume fronts off NorthWest Iberia	Otero, Ruiz-Villarreal1 and Peliz
11h20-11h40	Mesoscale fronts in the NW and N Iberian shelf during the winter-spring transition	Gonzales Nuevo and Nogueira
11h40-12h30	Discussion	
12h30-14h00	Lunch break	
14h00-14h20	Eddy tracking in a regional model of the Cape Basin	Doglioli , Speich, Blanke and Lapeyre
14h20-14h40	Simulation and quantification of enrichment and retention processes in the southern Benguela upwelling ecosystem	Lett, Roy, Levasseur, Va der Lingen and Mullon
14h40-15h00	Mesoscale structures of sea surface chlorophyll measured by SeaWifs in the Mozambique Channel: seasonal and inter-annual variability	Tew Kai, Marsac and Demarcq.
15h00-15h20	Detection and tracking of retention structures in the ocean	Segond, Fonlupt, Robilliard, Planque and Lazure
15h20-15h40	Slope Water Oceanic eDDIES (SWODDIES) dynamics in the Bay of Biscay	Otheguy, Irigoien and Gonzalez
15h40-16h15	Discussion	
16h15-16h45	Coffee break	
16h45-17h05	Mesoscale larval transport indices in the North Sea	Christensen, Hochbaum, Alekseeva, Jensen, Mosegaard, St. John and Schrum
17h05-17h25	A mesoscale index to describe the regional ocean circulation around the Balearic Islands. Its impact on the population dynamics of demersal fishery resources.	Monserrat, López-Jurado, Marcos, Romero, Massutí, Oliver, Moranta and Morales
17h25-18h00	Discussion	
23/02/06		
9h00-10h30	ToR 1	
10h30-11h00	Coffee break	
11h00-12h30	ToR 1 continues	

12h30-14h00	Lunch break
14h00-15h30	ToR 2
15h30-16h00	Coffee break
16h00-17h30	ToR 2 continues
24/02/06	
9h00-10h30	ToR 3
10h30-11h00	Coffee break
11h00-12h30	ToR 3 continues
12h30-14h00	Lunch break
14h00-15h30	Writing & summing up
15h30-16h00	Coffee break / end

Annex 3: WKIMS Terms of Reference 2006

The **Workshop on Indices of Meso-scale Structures** [WKIMS] (Co-chairs: B. Planque, France; C. Schrum, Germany/Norway) has met in Nantes, France from 22–24 February 2006 to:

a) review numerical methodologies for the constructions of indices of meso-scale structures such as fronts, eddies, transport, upwelling, and vertical hydrographic changes.

b) disseminate available tools and software for the automatic detection of meso-scale structures

c) construct long-term (>10 years) time series of indices of meso-scale structures in a number of systems in ICES waters

WKIMS will report to the attention of the Oceanography Committee.

Supporting Information

PRIORITY:	The workshop is essential for supporting ICES progress in linking fish population response to climate change.
SCIENTIFIC JUSTIFICATION AND RELATION TO ACTION PLAN:	Long-term indices of ocean climate are generally based on large scale features (e.g. NAO). Such indices are limited in providing insight on the possible response of fish because the scale of the physical processes described is far greater than the scale at which fish behaviour is understood. Process understanding of fish response to the environment is generally more obvious at the mesoscale (10-100km, days-weeks) where oceanographic features such as fronts, plumes, upwelling or eddies occur. An understanding of fish response to climate compatible with process understanding requires that mesoscale oceanic features be detected and tracked over long period of times. The aim of the workshop is to apply automated detection of mesoscale hydrological structures in a number of systems in ICES waters in order to provide long-term time series of these indices. These new time-series would complement those of existing indices (e.g., regional SST, NAO, Baltic inflow, etc.). The ultimate goal will be to relate time-series mesoscale indices to times series of fish populations on the basis of process understanding gained at the mesoscale by field/process studies. This workshop is related to Goal 1 of the Action Plan: understand the physical, chemical and biological functioning of marine ecosystems.
RESOURCE REQUIREMENTS:	No specific resource requirements beyond the need for members to prepare for and participate in the meeting.
PARTICIPANTS:	These have included scientists working in WGPBI, SGRESP and scientists participating to GLOBEC/SPACC and EurOceans.
SECRETARIAT FACILITIES:	None.
FINANCIAL:	No financial implications.
LINKAGES TO ADVISORY COMMITTEES:	link with ACE through WGPBI and WGRED and ACFM through SGRESP and WGMHSA
LINKAGES TO OTHER COMMITTEES OR GROUPS:	The Group will deliver products to WGPBI, SGRESP, WGRED
LINKAGES TO OTHER ORGANIZATIONS:	The workshop has been endorsed by GLOBEC-Int and EurOceans.
SECRETARIAT MARGINAL COST SHARE:	None / National expenses

Annex 4: Recommendations

As the workshop was designed to be a single event. However, the work carried before and during the workshop revealed that much still need to be done before mesoscale indices become widely available useful operational tools. The workshop makes the following two recommendations to promote further developments and future improvements of indices of mesoscale structures in the ocean.

RECOMMENDATION	ACTION
1. review progress in the development of tools for the identification and characterisation of mesoscale physical structures in the ocean and of indices of mesoscale oceanographic features	ICES Oceanography Committee (probably through WGPBI)
2. ensure that the reliability of those indices is assessed for their use in explaining spatial and temporal variability in fish populations	ICES (possibly through WGRED)

Annex 5: Abstracts of contributions

Workshop Contribution #1

The need of time-series of mesoscale oceanographic indices for understanding latitudinal abundance changes of Pacific sardine in the California Current system

Rubén Rodríguez-Sánchez, Héctor Villalobos and Sofía Ortega-García
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We analyzed the patterns of latitudinal abundance-changes of Pacific sardine in the California Current system (CCS) during the most recent warming regime as a means to identify and propose possible mesoscale oceanographic process underlying seasonal and interannual sardine changes. Nevertheless, our findings need to be tested comparing our sardine indices with mesoscale oceanographic indices (to be developed in the workshop) that show some characteristics of interannual variability of fronts along the California-Mexico coast. Our previous results shown that the latitudinal distribution of monthly abundance indices (CPUE) for young sardine in the CCS seems to follow the seasonal advection changes of the current system, suggesting that recruits are related to the oceanographic front where the California Current (CCal) and the inshore California Countercurrent (CcC) converge parallel alongshore. For 1980 to1997, interannual analysis of the monthly spatial dynamic shows progressive changes in latitudinal distribution of relative abundances, which suggests poleward changes in the latitudinal position of favourable conditions for young sardine along the front. Recruitment increases where optimal levels were found and decline where they were suboptimal. Interannual changes in the latitudinal position of population levels along the front suggest empirical evidence of a progressive interannual increase of the northward CcC advection after the 1976–1977 regime shift, whereas the CCal southward advection weakened. Our preliminary results would appear to explain the return of the sardine population after the 1980s to the northern part of the California Current system.

Workshop Contribution #2

Multi-image edge detection on SST and Chlorophyll satellite images: Interaction between physical and biological process in oceanic mesoscale structures

Karen Nieto and Hervé Demarcq
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The aim of this research is to implement automatic front detection tools on a sequence of satellite images in order to characterize oceanic mesoscale structures in coastal upwelling areas and to explore some interactions between physical and biological processes. Maps of Sea Surface Temperature (SST) fronts and chlorophyll are presented, derived from a sequence of high resolution NOAA/AVHRR and SeaWiFS data. A combination of the Canny Edge Detector (1986) and Cayula & Cornillon Image Edge Detector (1992) algorithms are implemented using the Interactive Data Language (IDL) and applied to a set of satellite images from the north of Chile in the Humboldt Current System. Preliminary results shows the interest of combining classical gradient-based methods and more modern Edge detector methods whose advantages are largely complementary. Nevertheless, bridging the gap between multiple frontal detections and automatic pattern recognition is not straight forward and needs further research.

Workshop Contribution #3

Validation of a high-resolution ocean shelf model using automated front detection

Peter Miller
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Jason Holt
Proudman Oceanographic Laboratory, Liverpool.

Techniques have been developed for increasing the value of cloud-affected sequences of Advanced Very High Resolution Radiometer (AVHRR) sea-surface temperature data and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) ocean colour data for visualising dynamic physical and biological oceanic processes such as fronts and eddies. The composite front map approach is to combine the location, strength and persistence of all fronts observed over several days into a single map, which allows intuitive interpretation of mesoscale structures. This method achieves a synoptic view without blurring dynamic features, an inherent problem with conventional time-averaging compositing methods. Such techniques enable us to summarise mesoscale indices from the massive datasets acquired by an increasing number of multispectral Earth observation (EO) sensors.

This paper explores how composite front maps may be equally applied to surface maps simulated by a high-resolution (2 km) 3D hydrodynamic model. Visual and quantitative comparison of frontal locations in EO and modelled data are presented for the North Sea. This enables validation and improvement of parameters of the ocean model in terms of physical structures, which would not be possible using standard pointwise comparison of model simulations against EO or in situ data. This method also enables mesoscale indices to be derived from model hindcasts in an analagous manner to EO data.

Workshop Contribution #4

Detection of river plume fronts off NorthWest Iberia

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Freswater discharge from different rivers over the continental shelf off NorthWest Iberia generates a persistent buoyant plume enhanced during the downwelling season, when river discharge is maximum and a poleward current flows over the slope. To analyze the response of the plume to real forcing, we performed realistic simulations with a 3D high resolution numerical model that correctly represent river plumes. Results show how the plume confines to the coast and accelerates with southerly winds and expands offshore during both northerlies and relaxation events, when enhanced dispersion in the frontal area is found. In addition, a remarkable front between saltier ocean water and the fresher water of the plume is present. A simple and automatic detection of the edge of this front would be useful to analyze the extension and position of the plume. We will report advantages and disadvantages of different methods tested to detect these fronts. Furthermore, we will compare model results to AVHRR data and we will discuss the usefulness of isohaline coordinates in the analysis of the evolution of the plume.

Workshop Contribution #5

Mesoscale fronts in the NW and N Iberian shelf during the winter-spring transition

Gonzalo González-Nuevo y Enrique Nogueira
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The occurrence of mesoscale fronts in the southern Bay of Biscay shelf during the winter-spring transition was studied using data from 23 cruises carried out between 1987 and 2005. 'Spiciness', a state variable derived from temperature and salinity [Flament, P., 2002, Prog. Oceanog., 54: 493–501], was used to characterize the fronts. The Iberian Portugal Current (IPC) generated a sub-surface front that separates warm and salty water of subtropical origin and cold and low salinity water presented in the Bay of Biscay. This front was detected in all the cruises, but its position fluctuated from year-to-year between the capes Finisterre (ca. 9°W) and Peñas (ca. 5°W). In surface waters, the principal frontal structures were associated with runoff from the Rías in the NW part of the shelf and with the river plumes from the small Cantabrian rivers and the Adour in the Cantabrian Sea. However, these surface fronts associated with freshwater inputs did not appear in all the analyzed years.

Workshop Contribution #6

Eddy tracking in a regional model of the Cape Basin

Andrea M. Doglioli (SHOM-UBO/LPO), S. Speich (UBO/LPO), B.Blanke (CNRS/LPO), G. Lapeyre (CNRS/LMD)

Eulerian and Lagrangian observations, satellite data and numerical model have already shown the complexity of the turbulent interocean exchange between the Indian and the Atlantic Oceans, upstream and within the Cape Basin. Rings and eddies pinch off from the Agulhas retroflection, before they penetrate into the Atlantic. They interact with the Agulhas Current and its retroflection, as well as with neighboring mesoscale structures.

Satellite measurements allow a rough evaluation of the transport achieved by the eddy field, but gaps in knowledge of the full 3D identity of these structures are handicaps that prevent more accurate diagnostics. On the other hand, the Lagrangian analysis of eddies simulated by regional ocean models offers promising bases for the development of more robust estimates of the propagation and conservation of eddy properties. Our numerical simulations of the Cape Basin circulation were run with the ROMS model with an eddy-permitting horizontal resolution, and lead to a fair description of the crucial properties of the eddy field.

We use a technique based on wavelet decomposition to identify coherent structures in the model and to follow water mass properties along their tracks. Then we disseminate Lagrangian numerical particles in selected cyclones and anticyclones to diagnose remote water mass origins and to evaluate associated mass transfers. The results are here discussed in terms of transport and tracers temporal evolution, and are compared, where possible, with observations.

Workshop Contribution #7

Simulation and quantification of enrichment and retention processes in the southern Benguela upwelling ecosystem

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Important environmental processes for the survival and recruitment of early life stages of pelagic fishes have been synthesized through Bakun's fundamental triad as enrichment, concentration and retention processes. This conceptual framework states that from favourable spawning habitats, eggs and larvae would be transported to and/or retained in places where food originating from enrichment areas would be concentrated. We propose a method for quantifying two of the triad processes, enrichment and retention, based on the Lagrangian tracking of particles transported within water velocity fields generated by a three-dimensional hydrodynamic model. We apply this method to the southern Benguela upwelling ecosystem, constructing putative maps of enrichment and retention. We comment on these maps regarding main features of the circulation in the region, and investigate seasonal variability of the processes. We finally discuss the results in relation to available knowledge on the reproductive strategies of two pelagic clupeoid species abundant in the southern Benguela, anchovy (Engraulis encrasicolus) and sardine (Sardinops sagax). Our approach is intended to be sufficiently generic so as to allow its application to other upwelling systems. Preliminary results of an application of this methodology to other upwelling systems will be shown.

Workshop Contribution #8

Mesoscale structures of sea surface chlorophyll measured by SeaWifs in the Mozambique Channel: seasonal and inter-annual variability

E. Tew Kai, F. Marsac and H. Demarcq
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Ocean color allows the quantification of the phytoplankton abundance on a global or regional scale. Within the framework of this work, we studied the mesoscale structures of surface chlorophyll in the Mozambique Channel. This one (10°S–30°S/30°E–50°E) is located between the African East coast and Madagascar. The channel is characterized by a contrasted oceanic circulation, and particularly by the presence of mesoscale eddies moving from north towards the south of the channel. We used satellite data obtained by the SeaWifs sensor from 1997 to 2004. The interest of the study of chlorophyll distribution was to allow a direct observation of the zones of enrichment in phytoplankton. The objective was to identify the

major patterns in the space and the time of chlorophyll and to determine the various scales of variability in order to understand how the phytoplankton reacts to the seasonal climatology, and also how anomalies like El Niño would act upon its distribution. We used empirical orthogonal function (EOF) analysis on normalized monthly fields (after temporal and spatial means were removed) and centred data. The analyses showed the link between the seasonal climatic factors and the inter-annual climatic phenomena with phytoplankton biomass. We characterized the presence of a seasonal cycle of phytoplankton bloom in the channel, with intense flowerings in southern winter (June–September) and less flowerings during the southern summer (December–March). The impact of the climatic phenomenon, El Nino 1997/1998, on the phytoplankton biomass was determined, with the appearance of an abnormal summer bloom and a gap of bloom arrival of southern winter into 1998.

The influence of the mesoscale eddies on the distribution of surface chlorophyll was also raised. The descriptive comparison between sea level anomalies map and phytoplankton biomass showed that the dynamics of the phytoplankton distribution is closely related to the vertical movements induced by the presence of mesoscale eddies.

Workshop Contribution #9

Detection and tracking of retention structures in the ocean

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The presence and density of animal species in the ocean and coastal waters are often conditioned by the presence of physical structures, such as upwellings, temperature fronts, or vortices. In the case of the anchovy in the Gulf of Biscay, biologists from the Ifremer institute (French Institute for Exploitation of the Sea) want to investigate the relationship between the presence of such structures and fish demography. To verify this hypothesis, one difficulty is automatically and efficiently identifying such patterns in massive datasets, in order to match their presence against biologists' observations and fisheries statistics.

This problem is clearly difficult, since it partly relies on experts' advice on the significance of structures and thus it has no complete formal characterization available. Only local properties could be based on strong physical background, and these properties appeared too weak to correctly classify retentive structures: sensibility (true positive rate) is excellent, but specificity (false positive rate) is a lag behind. Moreover, due to the same cause, local based methods seem unable to accurately retrieve the global shape of structures. On the opposite, schemes based on the fusion of information at a more global level should prove more efficiency for outlining structure envelopes. The ant algorithm used here was easily designed because it allowed an intuitive approach, as is often the case with artificial ants when the problem can be expressed in term of "optimal movements over a discrete structure". The performance is very good, reaching 100% true positives for the lowest number of false positives. It should be noted that it is obtained by combining ten detections results, in a multi-start fashion that is familiar to practitioners of stochastic search. This is interesting since stochastic search was not favoured at first by oceanographers (for fear of the variability of results) and also because the problem appeared at first as oriented either towards machine learning or specialized physical method, whereas ant algorithms are seldom used besides the pure combinatorial optimization domain. This ant based software is in fact able to detect retentive structures in stream maps without falling into the classical tricks of this kind of detection, that is to say stream perturbations in coastal waters. This method has the advantage to be able to take in account both global and local information from the stream map to filter detection noise and focus on retentive structures as considered by the expert.

Workshop Contribution #10

Slope Water Oceanic eDDIES (SWODDIES) dynamics in the Bay of Biscay

Pantxika Otheguy, Xabier Irigoien, Manuel Gonzalez
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In the Bay of Biscay, Slope Water Oceanic eDDIES (called SWODDIES by Pingree and Le Cann, Deep-Sea Research, 1992a) are formed during warm winters as the result of the instability of a continental margin current (called Navidad) interacting with the bottom topography. These mesoscale eddies are anticyclonic, 100 km in diameter and extend from the base of the seasonal thermocline to approximately 500 m depth and have a turnover time of a few days. Swoddies either propagate westward at a velocity of 2 km a day or are trapped by topography. Because the fluid of eddy cores does not mix with the surrounding water, swoddies play a major physical role in transporting water properties and enhancing slope-ocean exchanges. For the same reason, they can transport biological material inducing a major impact on the marine ecosystem. They have been widely described by both buoy measurements and satellite images during the last decade. A recent observational programme (GIGOVI) provided high resolution observations, allowing to determine both the physical properties (Garciá-Soto *et al.*, 2002; Sánchez & Gil, 2004) and the biological properties (Fernández *et al.*, 2004) of swoddies. Nevertheless, their physical understanding is not as far completely achieved as neither their birth nor their evolution can be forecasted. The present study aims at improving this understanding of their dynamics by determining the governing factors. Swoddies are created on the continental slope so that they can trap and transport biological material from the shelf and slope and therefore influence widely the pelagic ecosystem on their areas. In particular, they are believed to affect fish recruitment through two mechanisms. First, as they are anticyclonic, they generate an upward flow of nutrients in the photic layer, increasing primary and secondary production of the system. Second, swoddies can function as “safe heavens” for fish larvae transporting them into oceanic areas with lower predation pressure, but at the same time maintaining a high enough food concentration.

Workshop Contribution #11

Mesoscale larval transport indices in the North Sea

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The most transparent coupling between oceanographic mesoscale features and and biological species happens at early life-stages, where behavioural patterns are simple and where individuals have very limited possibilities of compensatory actions for adverse oceanographic conditions.

We discuss how to clearly define mesoscale generic larval transport indices. We consider different Eulerian/Lagrangian approaches for calculating larval transport indices and how to separate hydrodynamical and biological contributions to larval transport indices.

We illustrate our approach with North Sea sandeels as model species and discuss the impact on recruitment models

Workshop Contribution #12

A mesoscale index to describe the regional ocean circulation around the Balearic Islands. Its impact on the population dynamics of demersal fishery resources.

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Historical oceanographic surveys carried out around the Balearic Islands (western Mediterranean) suggest two different scenarios for the regional ocean circulation. In one scenario, occurring during cold winters, cool water is formed at intermediate layers (150-500 m) in the Gulf of Lions. This Winter Intermediate Water (WIW) usually moves southward reaching de Balearic channels, deflecting the warmer Levantine Intermediate Water (LIW) coming from the eastern Mediterranean, and even stalling the Ibiza channel. On the other hand, during mild winters, less WIW is formed and then LIW flows through the channels, appearing at their characteristic depths. It has been hypothesized that the observed changes in the trends of catches and population dynamics parameters of some demersal species could be related to this inter-annual variability.

The oceanographic surveys around the Balearic Islands (1986–2004) have provided a qualitative index, indicating the presence or not of WIW in the Ibiza channel, based on the analyses of TS diagrams. In order to quantitatively relate oceanographic data and biological parameters, a better index for the WIW presence is advisable.

A quantitative index based on mean water temperature between 100 and 300 meters depth in the channels may also be defined. Both indexes, the qualitative and the quantitave, are well correlated for the period 1985-2004, however, both are short in time and gapped.

In order to obtain a longer and continuous index of presence of WIW and then of regional ocean circulation around the Balearic Islands, some atmospheric variables from the meteorological data base ERA-40 for the period 1970–2002 have been analysed. Mainly, the surface temperature (at 1000 hPa, the closest level to the surface) in 5 points (N, S, E, O and centre of the Western Mediterranean); and the magnitude of O-E and N-S low level fluxes from geo-potential height at 925 hPa.

The air temperature anomalies at 1000 hPa in the Gulf of Lions during winter (January-March) has been shown to be the best indicator of absence/presence of WIW in the Balearic Islands channels in late spring. Values over 0.4ºC of the temperature anomaly would indicate absence of WIW in the Ibiza channel. The high correlation obtained allows using this index as an indicator of presence of WIW backwards in time and in those years for which the oceanographic data are missing.

The WIW index has been compared with the abundance of hake at sea (number of individuals and biomass at sea by year class and year) obtained from Virtual Population Analysis (VPA) and with catch per unit effort indexes (CPUE) for those years when VPA is not aplicable.

As a result, a high correlation between hake dynamics and the WIW index in the Balearic Islands since 1980 is found, suggesting that a clear presence of WIW in the Balearic channel is an environmental favourable scenario for hake abundance in the area.