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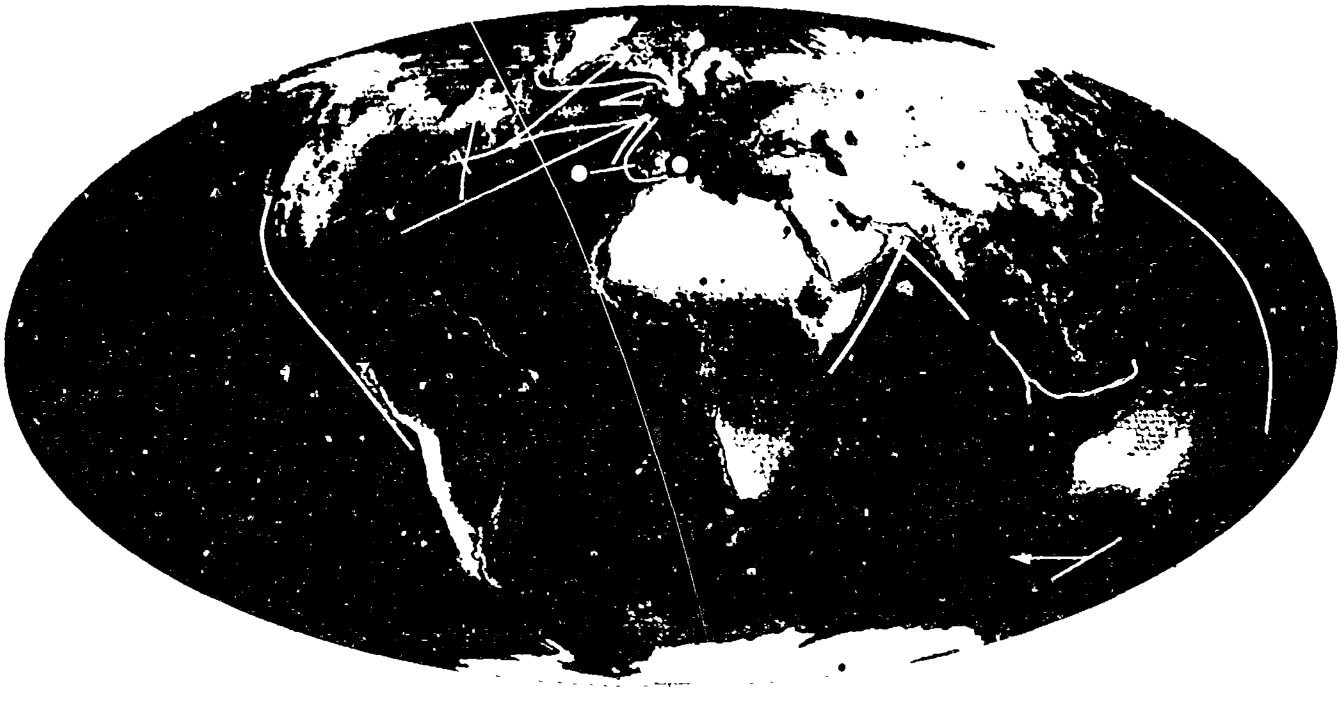
THE INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION
AND
THE SIR ALISTER HARDY FOUNDATION FOR OCEAN SCIENCE

MONITORING THE HEALTH OF THE OCEAN: DEFINING THE ROLE OF THE CONTINUOUS PLANKTON RECORDER IN GLOBAL ECOSYSTEM STUDIES



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SC-92/WS-8

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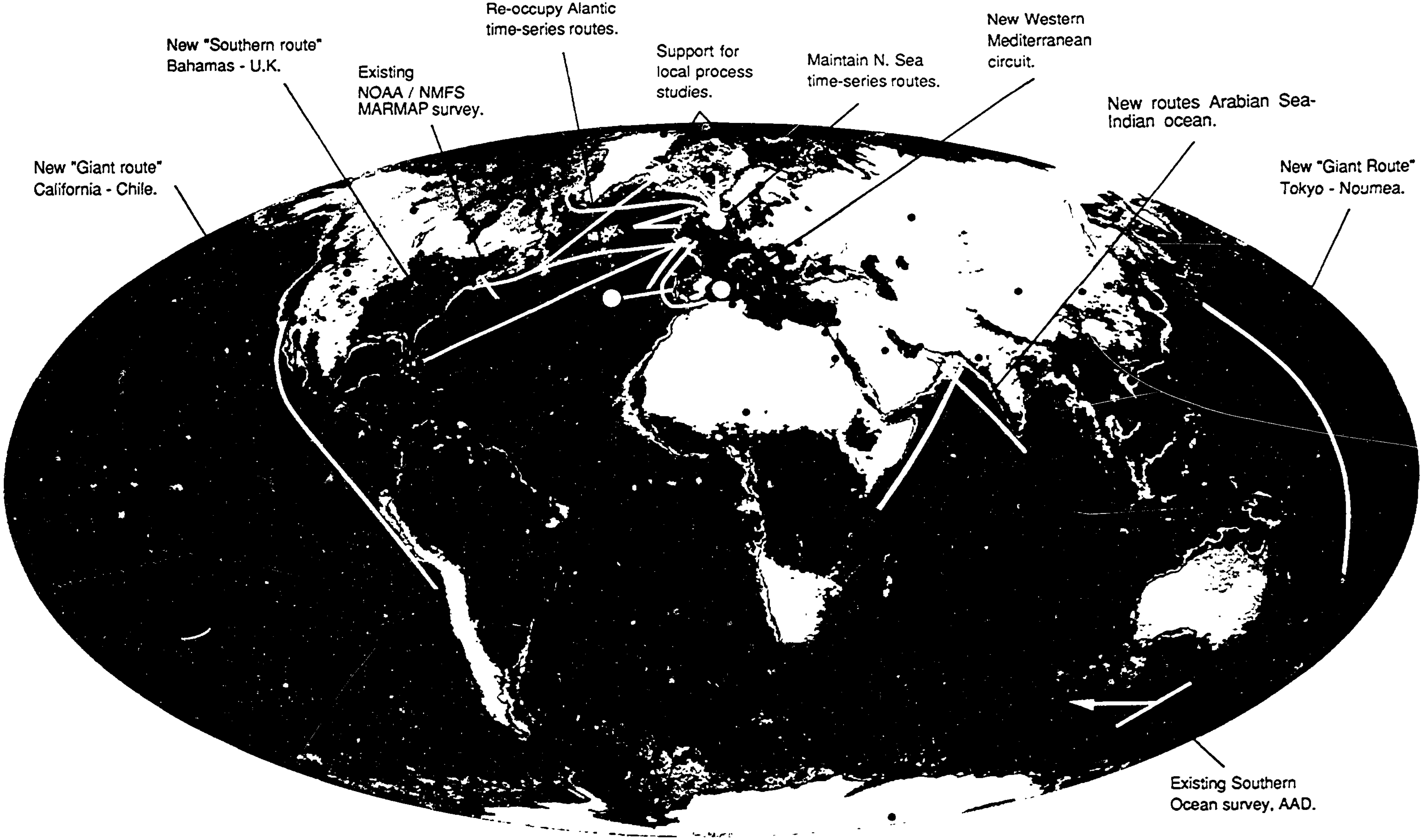

Towards Global Ecosystem Monitoring: The Developing CPR Survey.

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FOREWORD

As the Global Ocean Observing System of the IOC, UNEP and WMO moves towards implementation (IOC 1990, 1991b), it is an essential part of the planning process to stimulate the fullest possible discussion of what the Implementation Plan should contain.

Though the Observing System is being set up to meet a list of *global* objectives, -- principally those which enable us to distinguish the global-climate signal from that due more-directly to Man -- it is obvious from the outset that the type of climatic impact, the nature of Man's interference with the marine environment, and the amplitude of both will differ from one region of the World Ocean to another.

Thus, to be effective in following these changes, predicting their effects and identifying appropriate counter measures, the Global Ocean Observing System that we set up should not be wholly rigid in its content, but should be sufficient flexible to apply a variable mix of methods and techniques, and a varying sampling strategy to the differing anthropogenic problems and climatic impacts of individual regions.

It follows that the evolution of the GOOS plan is probably best achieved through inter Governmental discussions which are structured not only by scientific discipline or observing method but also by geographical sector, in order that the mix of programme components which Governments select for inclusion and support form a *global* survey that is relevant to *regional* problems.

This report concentrates on just one component of the present draft Plan - the use of *"instrumented towed vehicles from selected ships-of-opportunity for collection of plankton and marine environmental data"* (IOC 1991b, P13) - to illustrate ways in which the Continuous Plankton Recorder survey might be adapted and expanded to meet a range of perceived regional problems, and at what cost. As such it is not intended to dictate an observational strategy for GOOS, but to stimulate the discussion from which such a strategy might evolve. Similar reports covering other subject-areas are planned by IOC in due course. The IOC is indebted to R. R. Dickson who prepared this document.

1. Introduction: The aim of this document is to demonstrate that an expanded and developing CPR system is an appropriate device for monitoring the health of the oceans.

In Section 1 we briefly describe a range of global problems in which those components of the plankton that are well-sampled by the present Continuous Plankton Recorder play a controlling or modifying role.

1.1 El Nino and the East Pacific Ecosystem
1.2 Coastal upwelling and climatic change
1.3 Arabian Sea productivity and the changing monsoon
1.4 CO_2 drawdown and global warming
1.5 Cod and climate
1.6 Abnormal plankton blooms, and avoidance by grazers
1.7 Large-scale routine survey

Section 2 then describes what we mean by the "developing CPR" programme. Briefly, the point we make is that there is no requirement to regard the existing CPR instrument as the sole and unchanging vehicle. Today, when exploring new areas for plankton monitoring we would undoubtedly assess the zoogeography with a mix of techniques, including undulating recorders, before settling down to monitor long-term at fixed depth. For the future, there is equally no requirement that we retain the same system forever. A range of exciting new methodologies are becoming available for continuous plankton monitoring (acoustic, optical or some combination) that do not necessarily require counting to species and the challenge will be to map the way forward from the present technology to some future technology without losing the main accumulated asset - the multidecadal time series.

Section 3 briefly describes the current major ecosystem studies in which plankton monitoring by the CPR system will be of crucial significance. The point here is that even although the time scales of these studies may be finite they all benefit from the longer-term context which the "developing CPR" programme will provide. Current and future initiatives are

- LME's of NOAA
- GOOS/COOS of IOC-UNEP-WMO
- OMEX of CEC
- GLOBEC of SCOR and IOC-FAO/OSLR

Finally, in Section 4 we attempt to describe the mix of regional monitoring efforts that we can envisage within the next decade. This highlights for discussion - and possible alteration - the priorities for deploying a finite resource to address global problems, the expected cost of doing so, and the administrative structure required.

F1

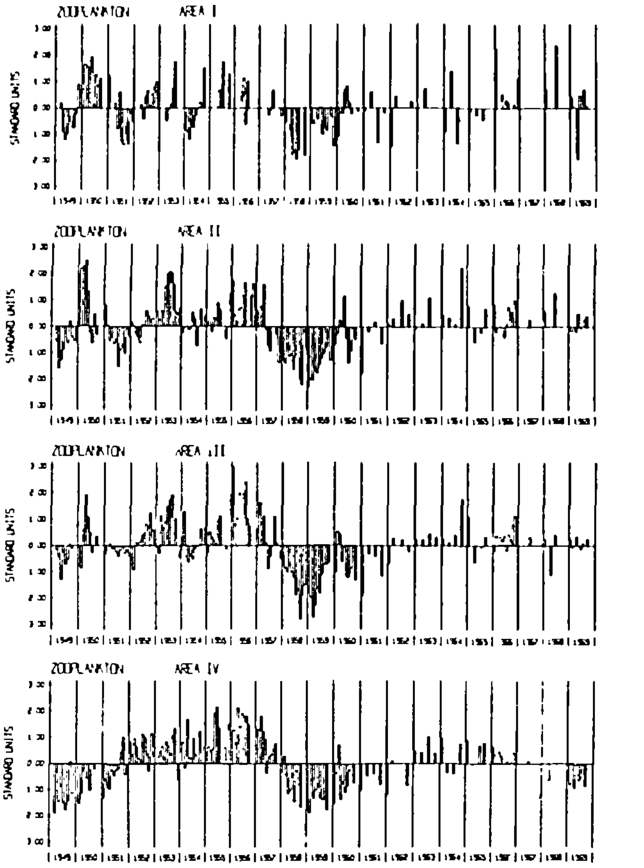


Figure 6. Seasonally corrected time series of zooplankton biomass. These are anomalies calculated as difference with respect to corresponding long term monthly average. Magnitude of this variable given in standard units. Hence value of 1.00 is equivalent to one standard deviation from the mean. (From Bernal 1980.)

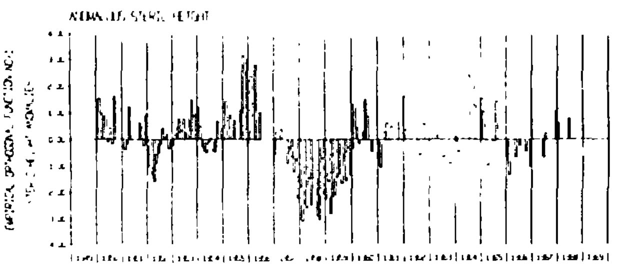


Figure 13. Time series of the monthly amplitude of the first Empirical Orthogonal Function. Coefficients, according to the sign convention used in Figure 12, are positive when flow is southward along EOF contour lines, negative when flow is reversed. (From Bernal 1980.)

F2

F3

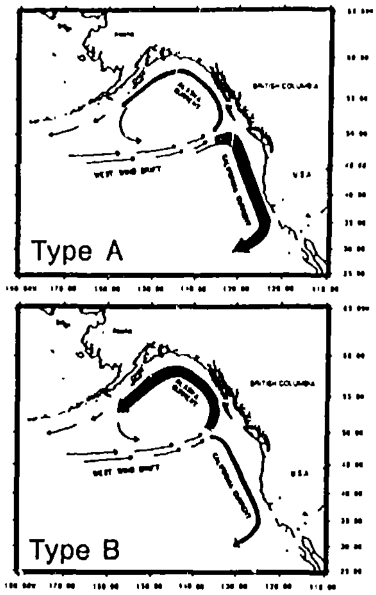
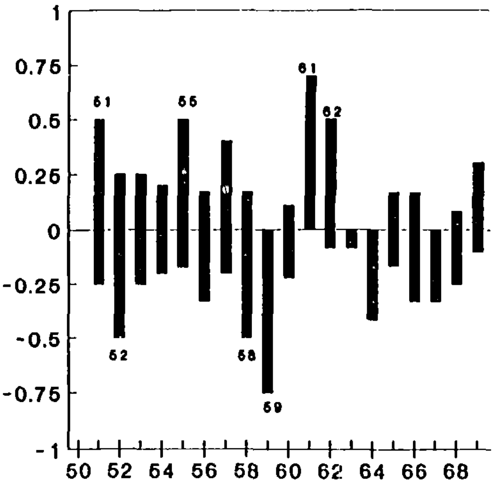


Figure 4. Diagram of circulation patterns associated with type A and type B ocean conditions.



Proportion of Strong or Weak Recruitment

F5

Case 1.1 El Nino and the East Pacific Ecosystem

- The analysis of the multi-decade CalCOFI data set reveals the presence of a dominant low-frequency signal in the entire pelagic ecosystem of the California Current (Bernal, 1981). F1

- This low-frequency response of the ecosystem is coherent with changes of the flow pattern occurring in the whole eastern boundary current (Chelton, 1981).

- Chelton shows that the observed variations to the large-scale zooplankton biomass offshore cannot be explained solely on the basis of coastal upwelling. However, the large-scale advection in the California Current appears to be linked to the large-scale zooplankton variability over inter-annual time scales. Increased equatorward transport brings increased zooplankton biomass. F2

- A poor correlation with longshore wind stress indicates that these fluctuations are not forced by local windstress. (The scales of the physical and biological fluctuations are much longer than those of the wind stress).

- In many cases the variations bear a strong resemblance to El Nino events in the eastern tropical Pacific with a time-lag of several months, consistent with the view that the El Nino signal propagates poleward as coastally trapped waves which lead to anomalously strong poleward geostrophic flow (McCreary, 1976).

- However, the CalCOFI record shows occasional strong events with no eastern tropical Pacific counterpart (Chelton, 1981).

- Chelton et al. (1982) propose that the Alaska and California currents fluctuate out of phase in response to large scale changes in the Pacific windfield. Enhanced circulation in the Alaska gyre is accompanied by reduced southward transport in the California current and vice versa. F3

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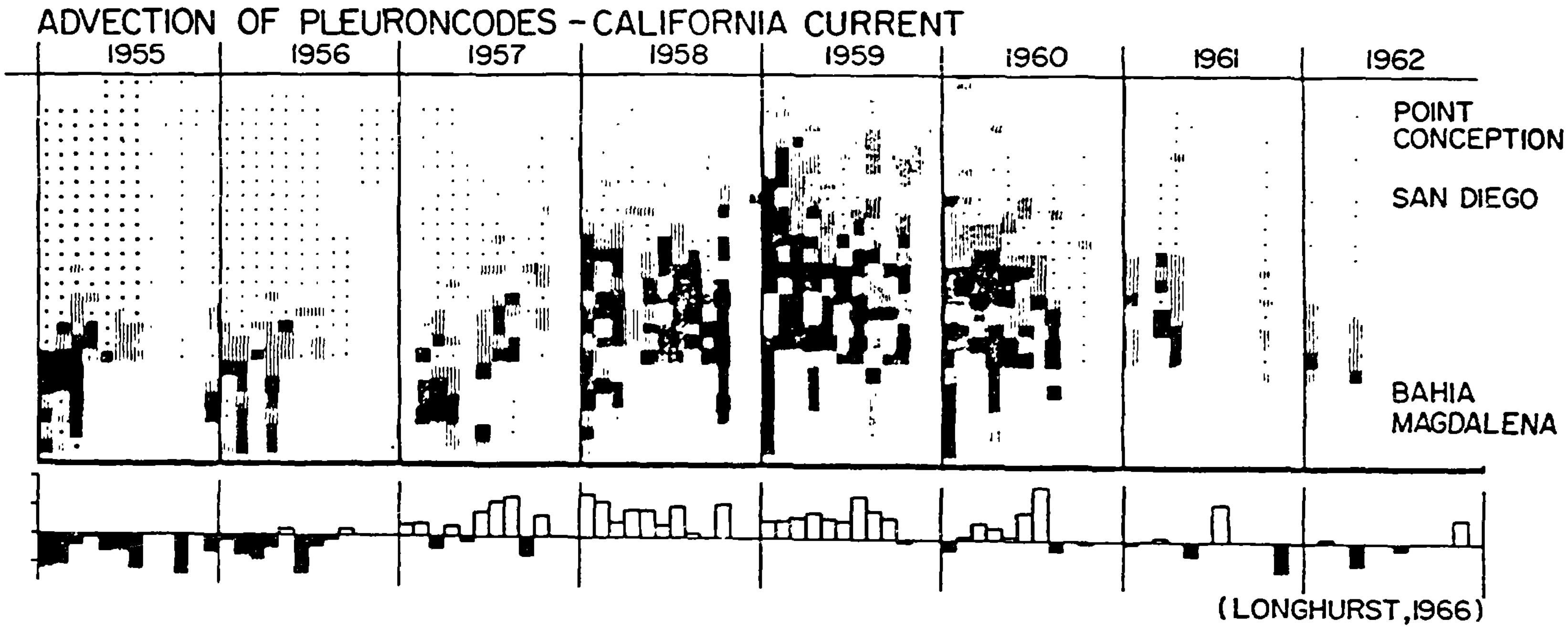
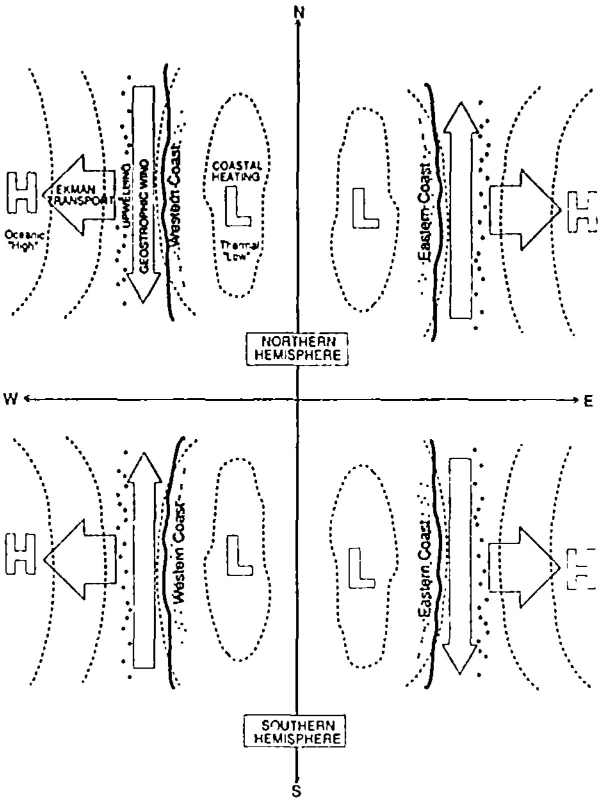
Summary. The circumstances of this case are unique in more respects than the impressive quality of the data-set. Adding Longhurst's (1966) story of the northward advection of the pelagic crab Pleuroncodes (F4) and other massive invasions of warm water organisms during El Nino/weak-California Current episodes, and the recent evidence of synchronous strong recruitment in a range of NE Pacific fish stocks (F5, Hollowed and Wooster, 1991), the picture is one of coherent long-period ecosystem change over a wide latitude range. McGowan has proposed that in ecosystem changes like this, classic biological interactive processes such as

F4


ADVECTION OF PLEURONCODES - CALIFORNIA CURRENT
1955
1956
1957
1958
1959
1960
1961
1962
POINT CONCEPTION
SAN DIEGO
BAHIA MAGDALENA
(LONGHURST, 1966)

4

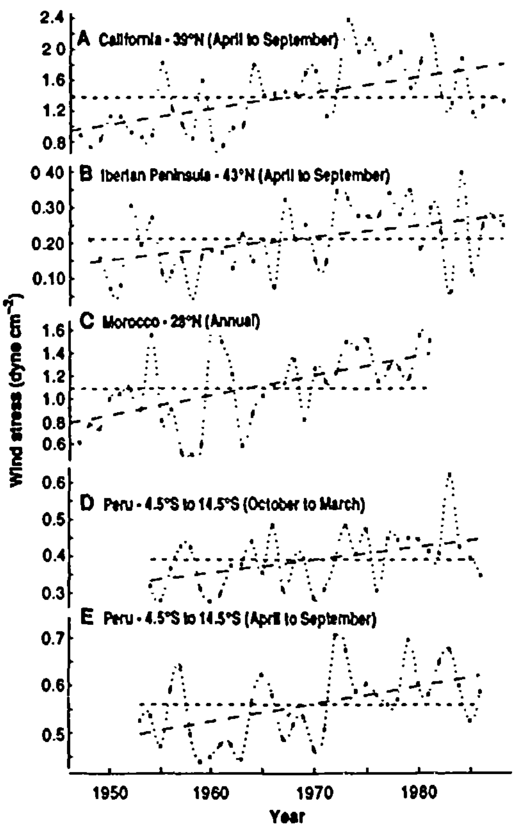
competition and predation will be secondary as regulatory mechanisms to the disruptive effects of the physical conditions themselves (see Bernal, 1981). However, although the zooplankton community is at the heart of these changes little is known of the mechanisms which link the planktonic variation to the physics. Do the changes in zooplankton volume reflect an advecting population or the in situ effects of "dynamical upwelling" as the California Current strengthens? (Chelton 1981). While the CalCOFI coverage is more than adequate to cover its own domain and interests it would nevertheless be valid and valuable to connect the CalCOFI area, the Costa Rica dome, the eastern root of the El Nino signal in the eastern tropical Pacific and the upwelling centres off South America on a routine basis even if the CPR coverage (because of the great distances) was forced to be discontinuous. The aim would be to extend our knowledge of the coherence of these ecosystem changes, first, and to seek to illuminate their dynamics second.



F6

Proposed mechanism. Increased seasonal heating due to atmospheric greenhouse effect increases temperature contrast between continental land mass and coastal ocean. The thermal low pressure cell in the continental interior is intensified, increasing the cross-shore pressure gradient between the spring-summer continental "Low" and the offshore oceanic "High". This increased pressure gradient supports an intensified alongshore geostrophic wind directed such that, with respect to a person facing downwind, low pressure would be on his left in the northern hemisphere and on his right in the southern hemisphere. Correspondingly increased Ekman transport, directed 90° to the right of the wind in the northern hemisphere (to the left in the southern hemisphere), leads to enhanced coastal upwelling which may feed back as further enhanced land - sea temperature contrast.

(Bakun 1991)



Bakun 1990

F7

Within-year averages of monthly estimates of alongshore wind stress off (**A**) California, (**B**) the Iberian Peninsula, (**C**) Morocco, and (**D** and **E**) Peru (in D, each mean value for October to March is assigned to the year in which the January to March portion falls). Short dashes indicate the long-term mean of each series. Longer dashes indicate the linear trend fitted by the method of least squares.

Case 1.2 Coastal upwelling and climate change

- Early simulations of global warming emphasised changes in the strength and position of global windbelts that might arise through change in the thermal contrast from equator to pole.

- Bakun (1991) proposes an alternative response in which increased seasonal heating due to the greenhouse effect increases the temperature contrast between the continental land mass and the coastal ocean, intensifying the cross-shore pressure gradient and thus augmenting the long-shore geostrophic wind in the sense that upwelling is stimulated along both the west and east sides of continents and in both hemispheres. F6

- Bakun (1990, 1991) provides evidence that longshore wind stress has been showing an intensifying trend over the last several decades off California, Iberia, Morocco and Peru. F7

- Though an artificial "anemometer effect" exacerbated by a "stable atmosphere effect" will have acted in the same sense, Bakun (1991) concludes that this could account for only a fraction of the observed trend, i.e. the trend appears real, and this signal seems likely to increase with time.

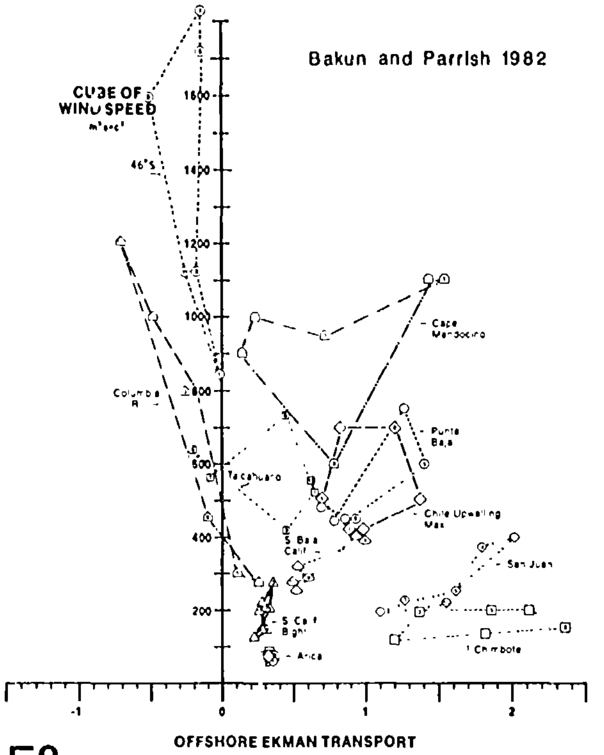
- If real, then a change in the location onset and/or amplitude of upwelling is likely to bear major implications for upwelling ecosystems.

    - Cushing (1971) showed that production in the rising water is strongly rate dependent, with maximal production obtained at moderate to low upwelling velocities (< 0.5 md^{-1}); then the zooplankton grazing capacity is allowed to develop fully within the upwelling plume while at greater vertical velocities grazing balance may not become established until the production reaches the surface and drifts offshore.

    - Bakun and Parrish (1982) showed how intimately the life history of pelagic fishes in the California and Peru current systems were bound up with the 3 related parameters of turbulent mixing (food concentration), offshore transport (losses of spawning products) and upwelling (system productivity). F8

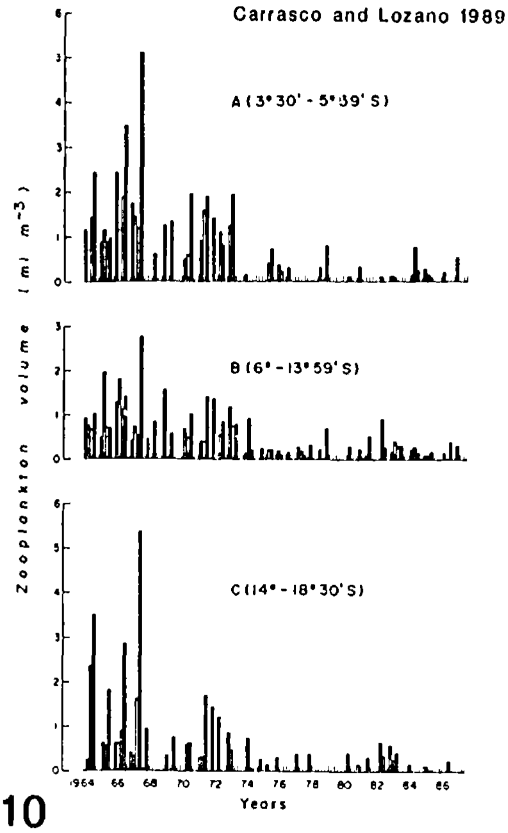
    - Cury and Roy (1989) introduced the concept of an optimum "window" of upwelling rates for reproductive success of pelagic fishes in upwelling regions; winds must be neither so weak that there is insufficient upwelling to enrich the food levels nor so strong that turbulent mixing disrupts the concentrations of food organisms essential for larval survival. F9

    - Dickson et al (1988) describe the response of the California Sardine to such effects in showing a dramatic shift in their time of peak spawning during a major intensification of upwelling in the 1950s.



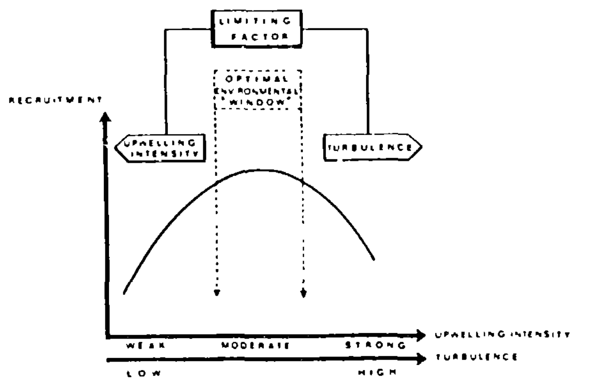
F8

Characteristic seasonal relationship of turbulent mixing energy production (proportional to cube of wind speed) and offshore-directed Ekman transport for various locations off the west coasts of North and South America. Each numbered symbol represents a 2-month sample, with the number corresponding to the first month of the two (e.g. 1 represents Jan.-Feb., 3 represents Mar.-Apr., etc.)

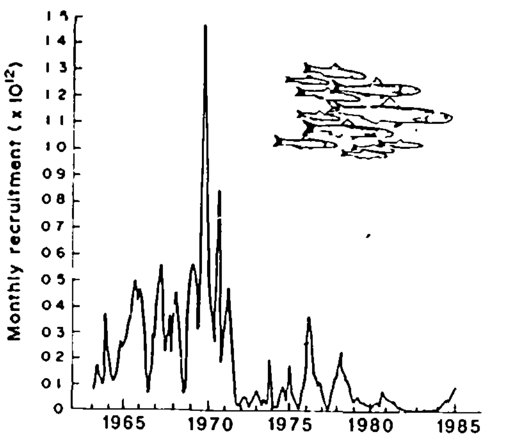


F10

Trend of zooplankton abundance off Peru, 1964 to 1987. Note strong decline in all three zones and overall lower biomasses in area B



F9 Theoretical relationship between recruitment and environmental factors in upwelling areas (Cury and Roy 1989)



F11 Time series of recruitment (of fish ranging from 3.75 to 4.75 cm, slightly less than 3 months old) into the anchoveta stock, January 1953 to December 1985. Above: monthly recruitment showing increasing variability, from the late 1950s to 1970, probably due to increasing fishing pressure and leading to recruitment collapse in early 1971, prior to the onset of the 1972-1973 El Niño

Pauly and Palomares 1989

- The parallel decline of the zooplankton (Carrasco and Lozano 1989) and the anchoveta (Pauly and Palomares 1989) off Peru since the late '60s appears equally clear evidence of a whole-ecosystem response, with zooplankton at its core. F10 F11

- At their peak the world's great pelagic fisheries have concerned an annual total production of 30 Mt or about one-third of the total global fish catch. The variability (Σ max - Σ min) is almost as great (Lluch-Belda et al, 1989).

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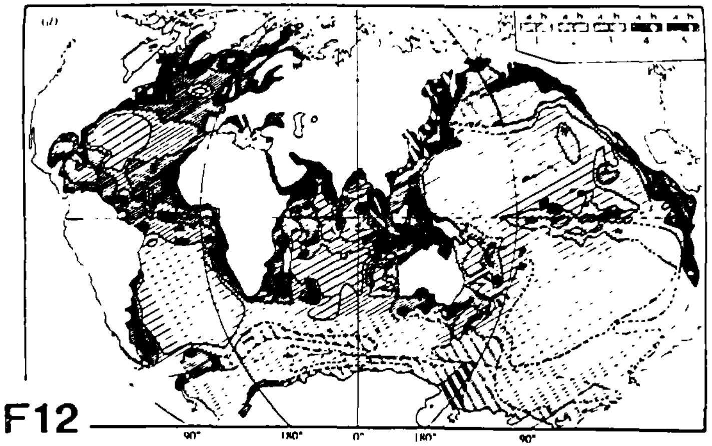
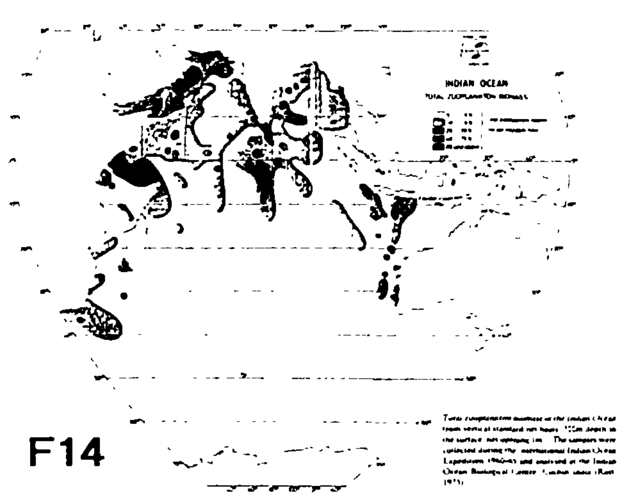
Summary. "Greenhouse-related wind changes would seem capable of rearranging the geography of suitable spawning habitat "in coastal upwelling systems (Bakun, 1991). Though the assumption has been that such tropical coastal upwelling systems are nutrient-driven, there remains a less vociferous assertion that the important factors are more complex, involving a link between the physical rates of upwelling and the gradual development of grazing power in the upwelling community. If so the zooplankton form a central and sensitive link in the translation of environmental change into changes in the world's major pelagic fish stocks. Long-term CPR monitoring is important both for recognising the fact of ecosystem change and more generally for (gradually) reducing our ignorance of the factors controlling trophic dynamics.

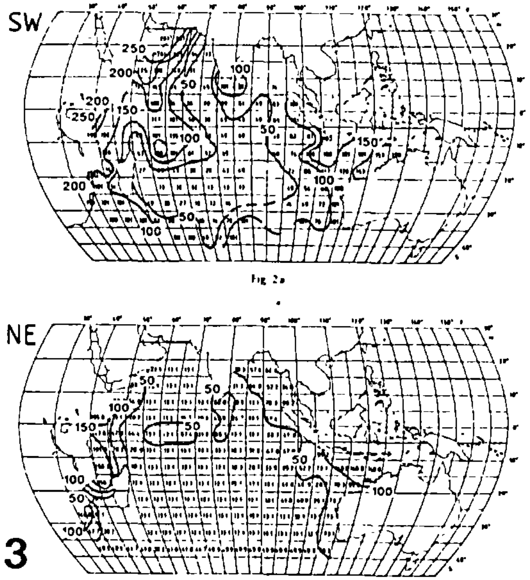


F12

. Distribution of radiocarbon in the surface waters of the world oceans (Koblentz-Mishke *et al.*, 1970); in mg C/m^3 per day; (1) < 100; (2) 100–150; (3) 150–250; (4) 250–500; (5) 500+.

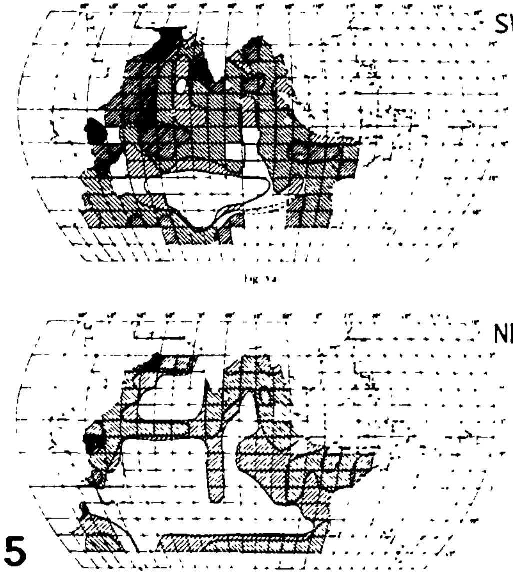


F14



F13

Fig 2 Primary productivity in the Indian Ocean in gC m^{-2} 180 day^{-1} a) in the SW monsoon, b) in the NE monsoon



F15

Fig 3 Tertiary production in the Indian Ocean in tons wet weight a) in the SW monsoon b) in the NE monsoon

Case 1.3 Arabian Sea productivity and the changing monsoon

- In their early attempt to piece-together a global map of marine productivity, Koblenz-Mishke *et al.* (1970) show that the extent and intensity of production reaches a global maximum in the Indian Ocean sector. F12

- Later, improved data-sets show that within this sector, the intensity of primary, secondary and tertiary production all reach their regional maximum in the Arabian Sea (see separate contributions by Cushing, Krey and Rao in Zeitschel, 1973). F13 F14 F15

- The causes are unknown in detail, but production reaches a temporal maximum during the SW monsoon, reflecting some aspect of that persistent circulation or the changes it induces in the upper ocean.

- The SW monsoon seems set to change with global warming. Though discrepancies exist between models the IPCC Report (1990; p146) suggests that most models anticipate a strengthening of the SW monsoon through a strong positive cloud feedback. Decreases in cloud-cover over Eurasia in summer enhance the solar heating of the surface, thus increasing the land-sea temperature contrast which drives the summer monsoon.

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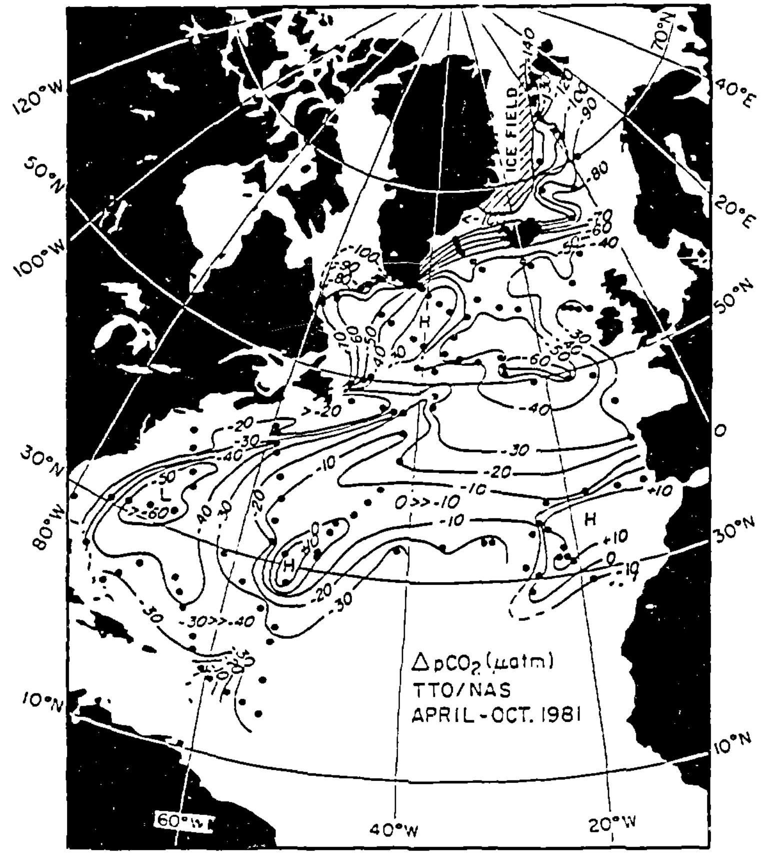
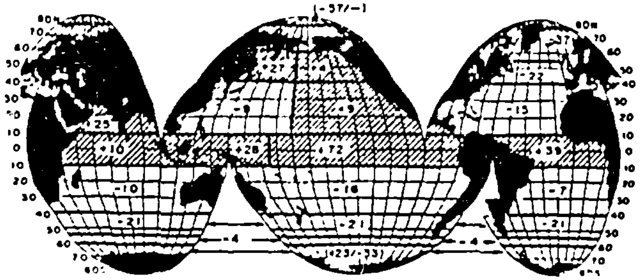
Summary: Though we are unsure of the mechanism that connects the production maximum of the Arabian Sea with the SW monsoon, and even less sure of its future course, the productive significance of this area is such as to justify the initiation now of a sufficient effort in plankton monitoring to establish the baseline against which the effects of climate change may be detected, and with which the mechanism of change can be understood.

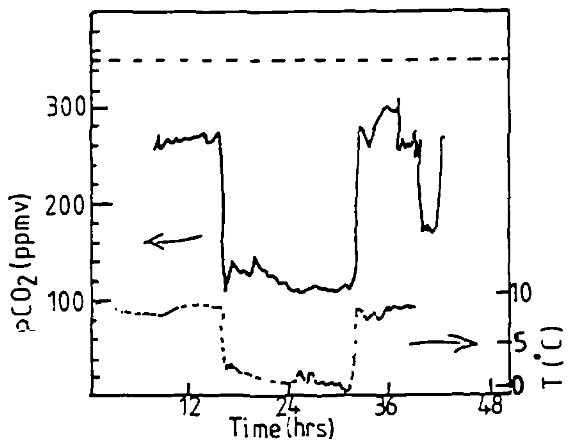


F16 - Distribution of the sea-air pCO_2 difference observed during the TTO/North Atlantic Study Program in April through October, 1981. Note that the proposed 20°W COFS section passes through one of the most prominent low pCO_2 areas centered around 50°N and 20°W. The data are listed in Takahashi et al. (1982).

F17

Mean annual differences of the CO partial pressures between surface ocean water and overlying air (ΔpCO_2) The values are in microatmospheres, or a millionth of an atmosphere at sea level The positive values (and the hatched areas) indicate that the ocean is a source of atmospheric CO_2, and the negative values indicate that the ocean is a CO_2 sink





F18

Case 1.4 CO_2 drawdown and global warming

- Since the 1981 Transient Tracers in the Ocean (TTO) expedition, it has been known that the largest sea-air pCO_2 difference in the north Atlantic lies in a relatively narrow band (300 km wide or so) along the eastern margin of the East Greenland ice from Cape Farewell to Spitsbergen. There, Takahashi shows ΔCO_2 values as low as -140 µatm in summer. F16

- The annual mean ΔpCO_2 values estimated for this zone are naturally lower (-37 in the large region which includes this zone) but are nevertheless of Atlantic - and therefore of global significance, since much of the hemispheric drawdown of CO_2 occurs in the north Atlantic. F17

- These TTO estimates may well underestimate the importance of this zone. On RV CIROLANA in June 1988, ΔpCO_2 values of -230 units were encountered along the ice edge north-west of Iceland, the largest difference from atmospheric concentrations (implying the largest CO_2 drawdown) yet observed anywhere. F18

- Several factors peculiar to this zone appear to be responsible, and none seem to be of particularly restricted distribution.

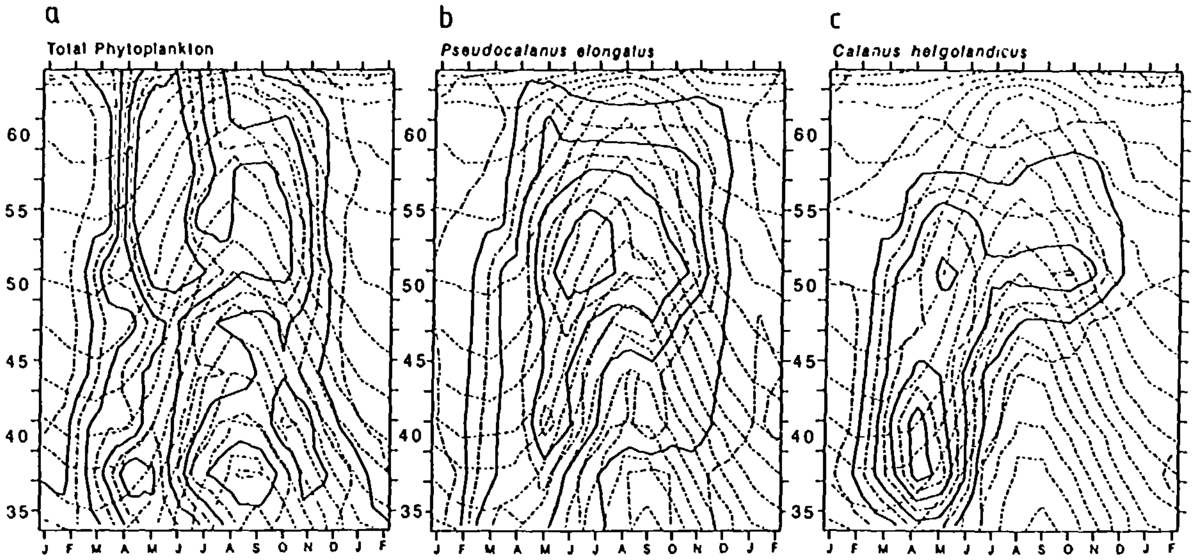
  - The abrupt onset of biological spring as the ice cover rolls back. At each point between the seasonal max and min ice limits, the retreating ice-margin brings an instantaneous increase in illumination and a rapid increase in water column stability (through ice-melt).

  - This disrupts the link with grazers, permitting a large amplitude bloom with a massive CO_2 drawdown until grazing control becomes re-established. The lag in the mobilisation of grazing power is much greater in the Arctic, where Calanus spawn in response to the bloom, than in the Antarctic, where krill-swarms overwinter under the ice-cover entering meltwater zones during spring, anticipating the bloom and therefore immediately able to control production. The amplitude of the bloom, the degree of nutrient depletion and the CO_2 drawdown in Arctic and Antarctic all reflect this differential delay.

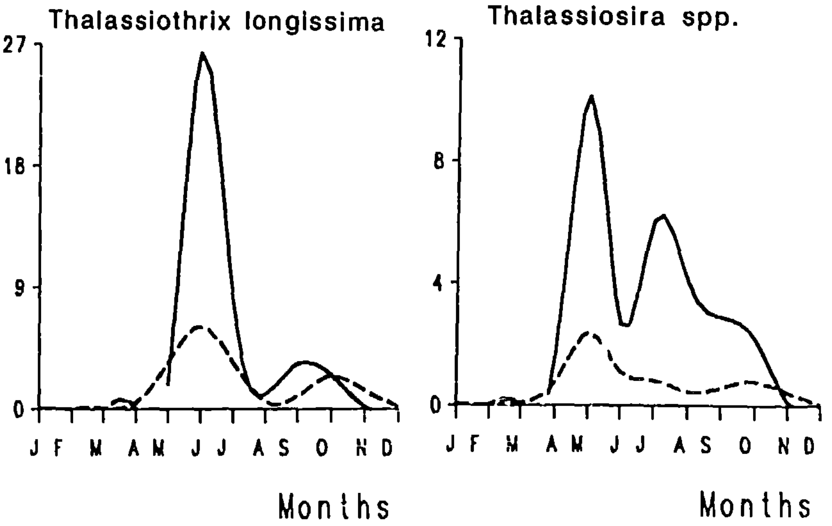
  - In conjunction with this "biological pump" the rapid cooling of surface waters as they circulate in towards the ice margin acts as a "chemical pump" for the drawdown of CO_2 since, for a given piston velocity (proportional to windspeed), the inward flux of CO_2 is proportional to ΔpCO_2 which is a strong function of temperature.

- The factors which promote such a radical drawdown are all peculiar to the marginal ice zone (i.e. they all require the presence of ice) and although similarly-large ΔpCO_2 values are now being reported from the seas bordering Antarctica (Karl et al., 1991), the narrow strip of thin ice bordering East Greenland must be more sensitive to global warming than the bulk of the Arctic or Antarctic ice sheets.

- In addition to the waters around Greenland, the north-east Atlantic between about 55°-63°N and out to about 20°W may also serve as a locally-enhanced CO_2 sink, but for



F19 Mean monthly plankton abundance (solid lines) and sea surface temperature (dashed lines) versus latitude for a meridional strip of the NE Atlantic. For details, see Colebrook, 1991.



F20 Seasonal cycles of abundance, data from the CPR survey, of the diatoms *Thalassiothrix longissima* and *Thalassiosira* spp. south of Greenland (solid lines) compared with the open Atlantic to 50°N. For both species the peak of the seasonal cycle in Greenland waters is about four times that in the open ocean.

different reasons (Colebrook, 1979, 1982, 1991). The CPR survey tends to show an enhanced algal biomass north of 55°N in spring and early summer. F19a

While this may be an artefact of the fixed depth of CPR sampling, it may also reflect some local relaxation of grazing control. In the south the copepod *Calanus helgolandicus* can overwinter in sufficient numbers to increase in phase with the phytoplankton but at about 50°N it is approaching the northerly limit of its distribution. (F19c) *Calanus finmarchicus* tends not to become dominant until > 60°N in this sector. Between 50°N and 60°N the dominant summer copepod is *Pseudocalanus elongatus* but the overwintering stocks are such that it does not reach its seasonal peak until June and July, towards the end of the phytoplankton bloom. F19b

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Summary

Although the ice migration zone of the Arctic is of limited extent, it results in extreme CO_2 drawdown. Even by the available evidence, this zone appears to have global significance as a CO_2 sink and the chances are that its role as a sink has been underestimated. A rapid onset of biological spring as the Arctic ice retreats is followed by only a sluggish development of grazing pressure permitting an excessive algal biomass and an extreme CO_2 drawdown to develop in the interim. These processes and this drawdown are sensitive to any lessening or loss of East Greenland marginal ice through climatic change. A complex and prolonged planktonic/pCO_2 survey is required to integrate the present drawdown during the whole space-time domain occupied by the westward retreat of the ice margin and the northward march of production. This assessment will determine the scale of the potential change to the global sink of CO_2 but it already appears evident that it will act via a change in the effectiveness of zooplankton grazing. Re-deployment of the long-established CPR "G" route to South Greenland will be of value since a greatly-amplified production is also observed off Cape Farewell but monitoring for such changes can only be effectively conducted via regular R/V and S.O.O. tracks along and normal to the ice zone. The autonomous hull-mounted pCO_2 sensor under development by PML/MAFF will be essential ancillary equipment.

It is clear that the processes involved in the CO_2 sink of the NE Atlantic are quite different to those off Greenland, related to the range and overwintering strategies of the dominant grazers. Monitoring of changes in this zone will be much more easily addressed by the conventional CPR coverage once that becomes re-established in the North Atlantic.

F21

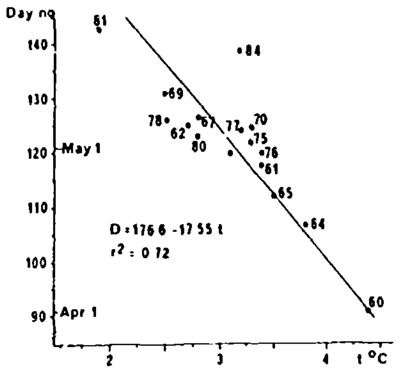
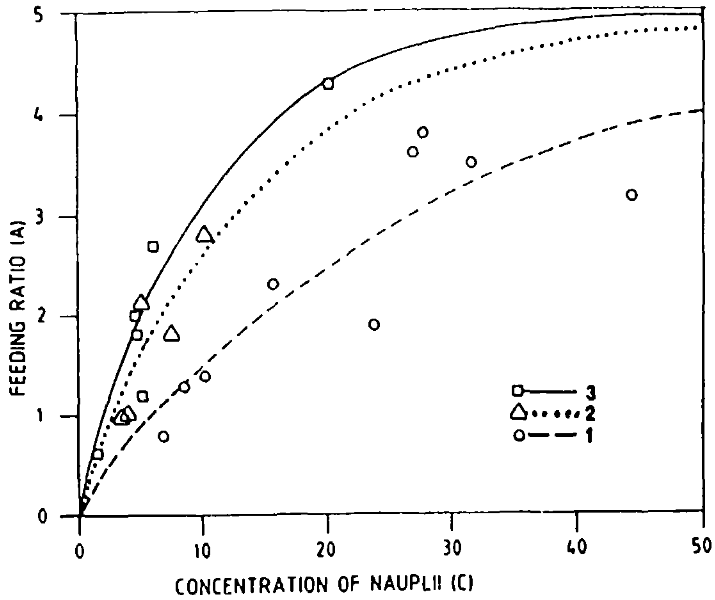
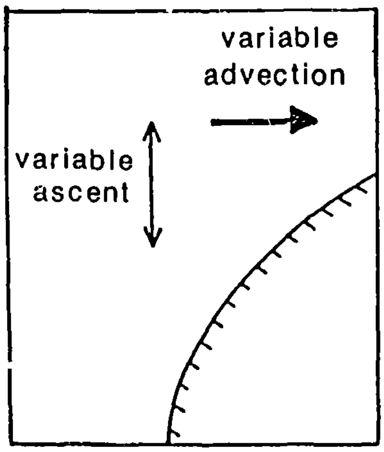


Figure 2.15. Time of maximum occurrence of *Calanus finmarchicus* copepodite stage I versus temperature

F23



Relation between the feeding ratio and the nauplii concentration for three conditions of turbulence from low (1) to high (3). (Sundby and Fossum 1989).



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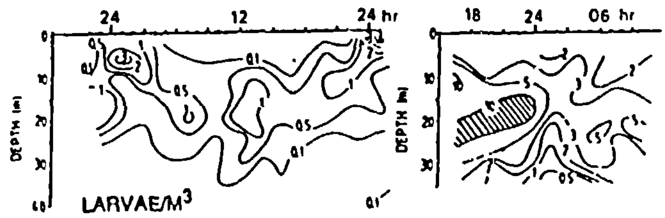


F24

Figure 2.8. Under extremely calm wind conditions (left), the larvae are able to show vertical migration. Under less calm conditions, the larvae are more evenly distributed (right). (From Ellertsen *et al.*, 1984.)

Case 1.5 Cod and Climate

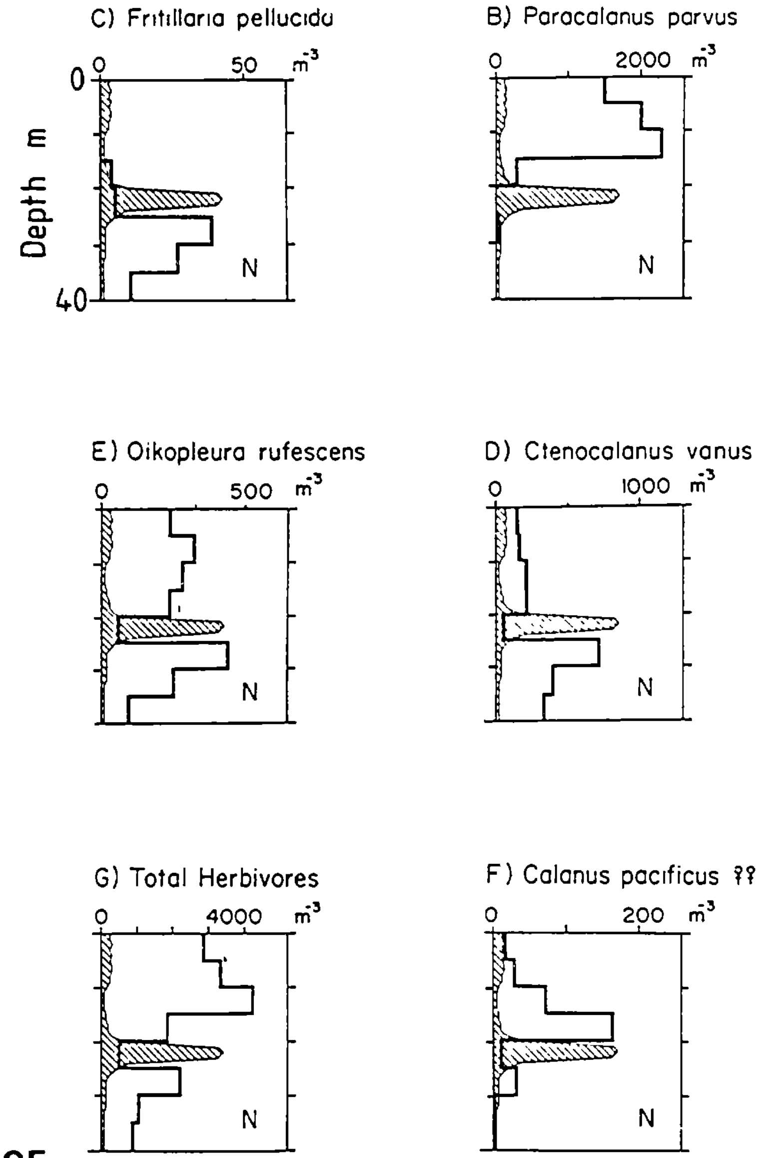
- A century of fishery investigations has identified the interactions between zooplankton (particularly copepods) and larval cod as the prime unknown in determining subsequent recruitment. A range of factors control the efficiency of this interaction. (Illustrated opposite):

- While cod tend to be fixed in their time of spawning within 10 days or so (Cushing and Dickson, 1976), there is a remarkable dependence of the maximum occurrence of C *finnmarchicus* copepodite stage I on temperature. Ellertsen et al, 1990 conclude (p32) that "the temperature dependent spawning of C. *finnmarchicus* found in Lofoten, causing a delay in spawning of about 1.5 months in the coldest year (1981) compared to the warmest (1960) may be the most important process to cause variable larval survival". F21

- The relationship between the time of ascent of overwintering stages from deep water and the onset of winds favouring their advection onto the shelf is a second key control on the "match" of cod and Calanus (Skjoldal, 1991). F22

- Once present in the same location the key time-varying factor controlling their interaction is wind-induced turbulence which (up to a certain level) can increase plankton contact rates (Rothschild and Osborn, 1988; Sundby and Fossum, 1989), or alternatively mix-out high-concentration patches and layers and perturb both the vertical migration and the concentration of cod larvae (Ellertsen et al, 1984). F23 F24

Summary. Though the circumstances which control the interaction of larval cod and copepods will differ in detail from one stock and region to another, the principal common thrust of the International Cod and Climate programme is agreed to be the investigation of Calanus dynamics - namely the time-varying balance between their roles as predators and prey which determines their production and availability, as well as the time-varying physical factors which control their advection from deep water onto the shelf. The routine multi-year operation of CPR and UOR in the relevant season and at a range of selected sites would be an ideal means of providing basic but essential information on interannual changes in the space-time distribution of Calanus concentration, in support of regional process studies of Calanus dynamics.



F25

F26

	Night			
	Filtration rate (ml/ind/d)		% gut fullness	
	G. layer	outside	G. layer	outside
Paracalanus parvus	4.4	8.6	6.2	19.4
Acartia tonsa	1.0	2.0	3.8	14.6
Calanus pacificus	1.5	8.4	9.2	27.0
Ctenocalanus vanus	1.4	2.6	6.7	7.2

Only 4.2% of all herbivores sampled belonged to zooplankton groups that did not exhibit the patterns of avoidance behaviour implied by the distributions illustrated.

Case 1.6 Abnormal plankton blooms, and avoidance by grazers

- A recent Canadian report by Frank, Perry, Drinkwater and Lear (1988) is typical of many reviews in anticipating that global warming in temperate and subarctic waters may act to favour components of the summer plankton, particularly the dinoflagellates:

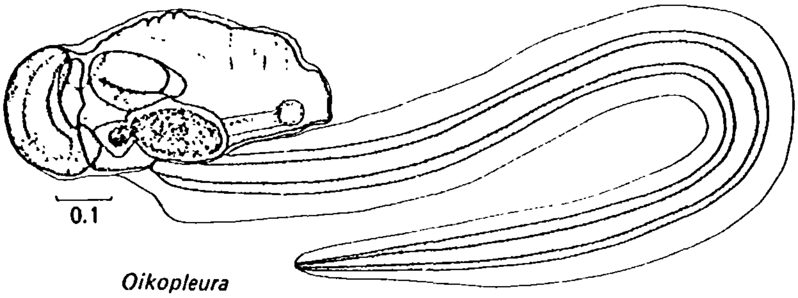
  "Associated with a doubling of atmospheric CO_2 is increased vertical stratification of the water column due to higher freshwater discharge, higher temperatures and lower winds.... The net effect of increased water column stratification would shift the growth advantage from large diatoms to smaller (5-25 μm) dinoflagellates and microflagellates that .... are better able to maintain their vertical position in a stratified water column and utilise nutrients effectively at low concentrations.... Maintenance of an annual time-series of the seasonal diatom: dinoflagellate ratio in continental shelf waters could provide an early warning signal for significant environmental changes"...

- However, summer is also the season when nutrient limitation of algal growth is likely to be at its most widespread, and therefore when changes in anthropogenic nutrient inputs are likely to have their maximal effect on the plankton. For this reason a summer increase in dinoflagellate bloom prevalence is also an expected result of anthropogenic eutrophication in coastal waters. Thus the same relative shift in the comunity structure of the summer plankton is expected for both climatic and anthropogenic reasons.

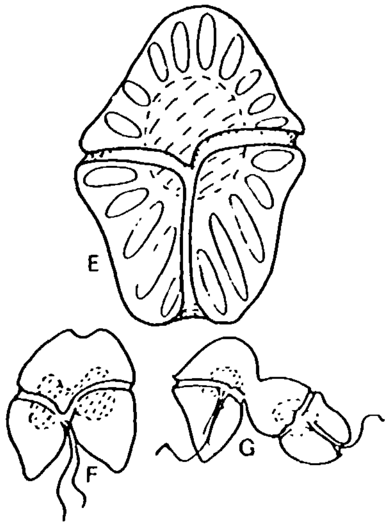
- We envisage 2 roles for a plankton surveillance system in monitoring for this particular change in the health of the ocean. First it should inform us objectively whether the prevalence, timing or amplitude of a particular nuisance bloom has changed over the years (i.e. not just the result of more people looking; Le Fevre, 1979; Mommaerts, 1986). The CPR collects only some of the dinoflagellates quantitatively (e.g. Ceratia), and although a useful proxy measure is available for Phaeocystis, it would require some future development to monitor effectively for small naked flagellates.

- One of the key unresolved issues relating to the dynamics of abnormal algal blooms concerns avoidance by zooplankton, and here we envisage a support role for the existing CPR system, particularly one with depth-resolving capabilities such as the UOR.

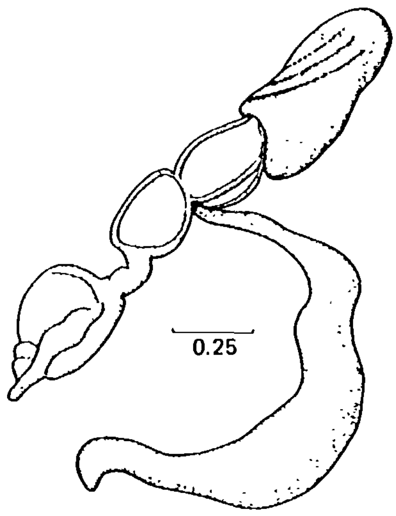
- Though avoidance by grazers has tended to be discounted as a primary control on the amplitude or prevalence of noxious algal blooms - compared, for example with their nutrient relations and eutrophication - Fiedler (1982) and others have shown that it may be of widespread and fundamental importance. The Gymnodinium case, opposite shows that the avoidance is plainly intentional, that the vast majority of the grazers took part, and that the effect is compounded by a reduced grazing efficiency on the part of herbivores which failed to avoid the Gymnodinium layer. F25 F26 F27



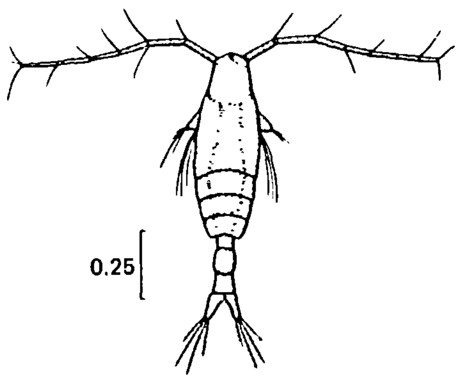
Oikopleura



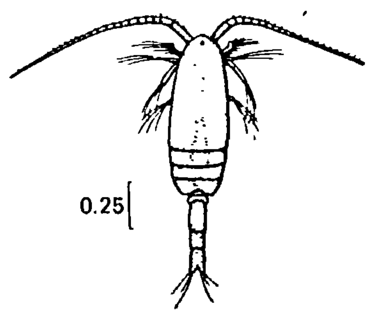
E. *G. splendens* F. G. stages of division



Fritillaria



Acartia



Paracalanus

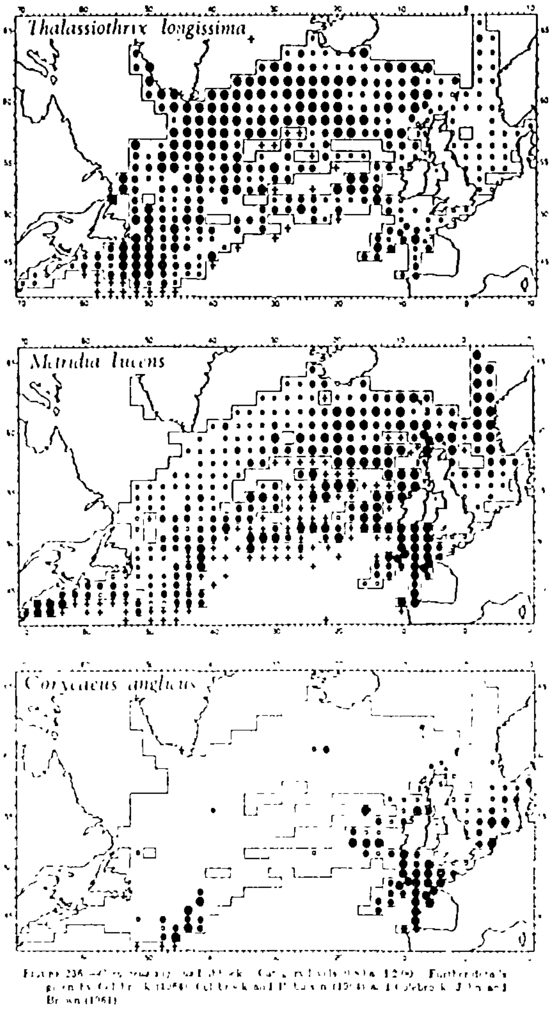
F27

- There is less information on the number of noxious algal species which provoke avoidance but it is likely to be high (see Huntley *et al.*, 1986, 1987; Sykes and Huntley, 1987). We glimpse its effect in the Chrysochromulina report (Skjoldal and Dundas, 1989, p41), and in a very recent PML contract report, Joint, Davies and Harris (1991, unpublished ms) present Irish Sea results which "demonstrate that the presence of Phaeocystis can have a negative effect on copepod feeding and production, and this may contribute to the development of the Phaeocystis bloom by reduced grazing mortality and decreased copepod reproduction, and hence grazer abundance".

- Wherever the grazing pressure is significantly reduced or suspended, it must fundamentally shift the role of nutrients from one of potential trigger (initiating the bloom) to one where nutrient depletion becomes the only available means of bringing the bloom to an end.

Summary. There is a general expectation that in the populated coastal zones, a continued increase in nutrient inputs will sooner or later lead to eutrophication in areas of reduced dispersion and hence to an increased amplitude, an altered toxicity and an increased prevalence of noxious algal blooms and the deoxygenation effects that they may generate. We do not even have in place an adequate and objective monitoring system to establish the fact of change unambiguously. Though this may seem an algal problem, many noxious blooms owe their towering amplitude not merely to nutrient supply, but to relaxation of grazing pressure through avoidance by grazers. Elaboration of the interplay between phytoplankton, zooplankton and the changing physical environment is crucial to understanding the problem and crucial to the application of appropriate rather than irrelevant or ineffective countermeasures. The CPR would be used to monitor for the fact of change, would hopefully be developed or complemented to monitor dinoflagellates more effectively, and act in support of process studies of finite duration.

F28



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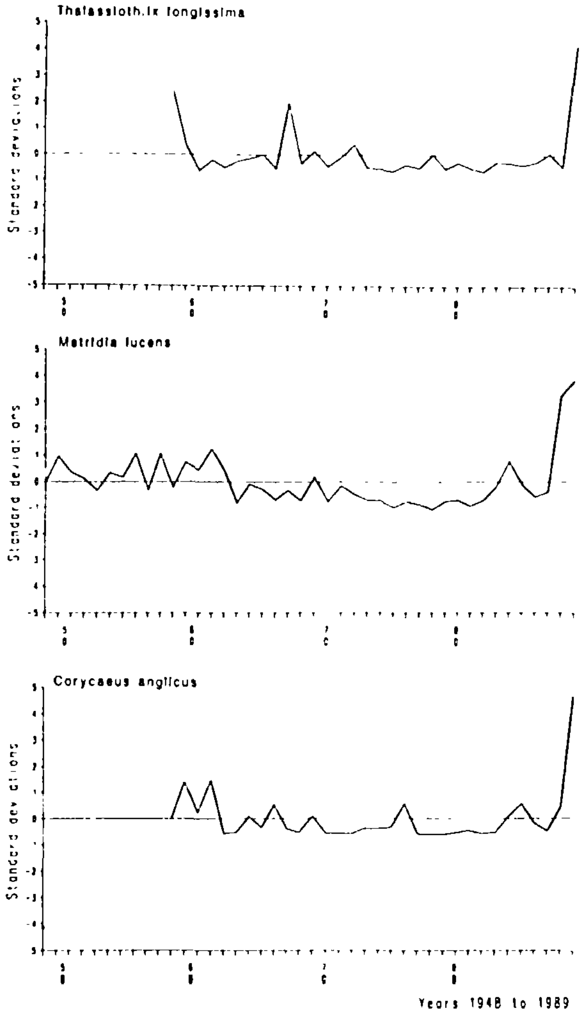
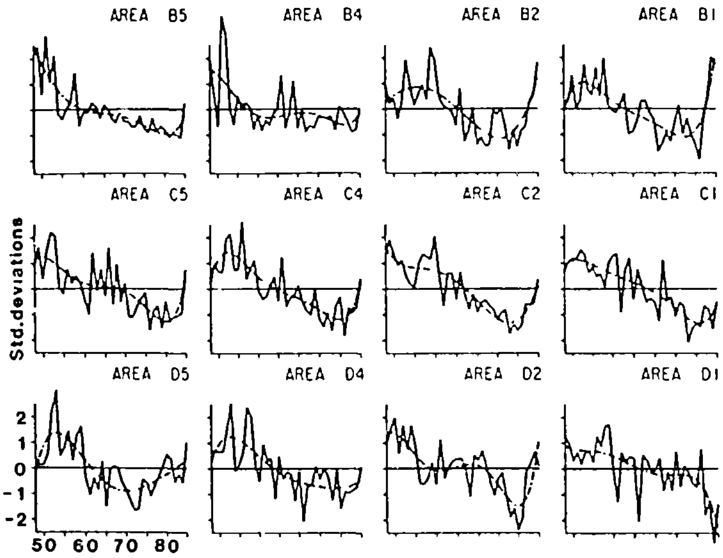
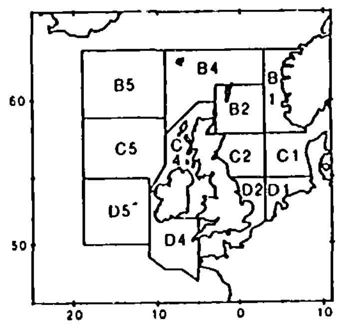






F30

Fig. 7. Trends of zooplankton abundance in 12 CPR Standard Areas around the British Isles Locations are shown in Figure 2b

Case 1.7 Large-scale routine survey

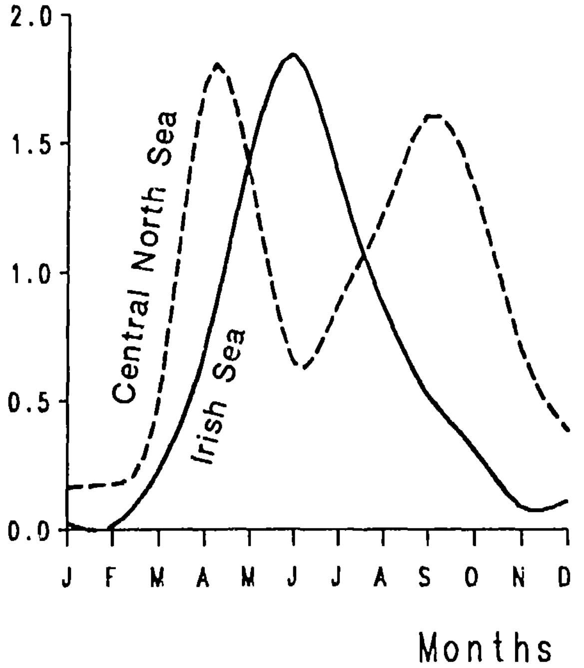
In many of the above cases, the role of the CPR has been to act in support of process studies in zooplankton dynamics which are of finite duration and extent. There remains a need, nevertheless for the long-established CPR role in large-scale routine survey, and that need is growing:

- At the time of its inception, 60 years ago, the concept which motivated the CPR was one of establishing a baseline against which anthropogenic impacts might later be detected. Subsequent experience has shown that no such fixed planktonic baseline exists, but a derivative of the concept continues to be of value in two main ways.

    - As an "alarm bell". If, for the concept of a rigid baseline, we substitute the concept of a normal range of variation, it remains of considerable practical value to be alerted to any grossly abnormal behaviour in the plankton. The annual fluctuations in abundance of Thalassiothrix, Metridia and Corycaeus in the North Sea over 4 decades make an obvious case in point. Thought there is no dynamical information in such a trend, it can frequently be interpreted as to cause, or justify the mobilisation of an adequate investigative effort. F28 F29

    - As a "control". The Coastal Ocean Observing System of the IOC, UNEP and WMO (COOS) differs from its Global Ocean Observing System (GOOS) in at least one important respect. It is attempting to identify a climatic signal of maximum socio-economic importance against a shelf-seas background of maximum anthropogenic noise. The nascent Ocean Margin Exchange Experiment (OMEX) of CEC has a similar aim and problem. Though the limitations of the available observing effort will force these studies to focus on selected cross-shelf transects (see e.g., IOC 1991a), it is nevertheless important that they retain pan-oceanic coverage as a control. The fact that the same post-war trend has dominated zooplankton abundance in all 12 CPR statistical areas around the UK including the eastern Atlantic, not only suggests the trend is real but confirms a non-anthropogenic cause. F30

- Winkling dynamics out of satellite imagery is a further role for large-scale, routine CPR survey. SEAWIFS, ADEOS and other new ocean colour satellites are due for launch in 1993-95. Only they can make the leap to near-global coverage of plankton by providing high quality pigment discrimination data in near-real-time. In the past they have successively (via CZCS) pieced together oceanic and global maps of phytoplankton standing stock; CZCS data has shown the potential to discriminate phaeocystis from diatom blooms using relatively crude 3-band comparisons (albeit from a strong shelf-seas signal); Platt and Sathyendranath (1988) later showed how the same colour data might yield net primary production. The next step requires extensive regular continuous plankton monitoring. Adding zooplankton biomass to satellite net primary production provides grazing mortality and hence a measure of apparent phytoplankton growth rate that can be matched to the distribution of light, wind turbulence, nutrients or any other production variable.



F31

The seasonal cycle of the plankton of the Irish Sea is markedly different from adjacent areas. The graphs, based on data from the CPR survey, show that compared with the central North Sea, the peak of the spring bloom in the Irish Sea is about two months later and the autumn peak is absent.

- Regional model validation. As Brander points out in his proposal to model the large marine ecosystem of the Irish Sea "It is very unlikely that reliable predictions of the effects of physics on recruitment and fish production can be obtained without models which incorporate some of the intervening planktonic processes". There is currently considerable international interest in developing and incorporating regional models of copepod production. Only regular routine survey by some form of continuous plankton recorder can provide the validation for such models. F31

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Summary. There appears to be little lessening of the need for the extensive routine zoogeographic survey data that forms the traditional product of the CPR survey. On the contrary its multi-decadal time-series are a principal means of recognising what is grossly abnormal in the observed continuum of planktonic variation; it will provide the oceanic 'control' against which anthropogenic changes on the shelf can be gauged, it has potential in eliciting plankton dynamics from satellite imagery and it could serve to validate the copepod models which form an increasingly important component of large marine ecosystem models.

2. <u>The "Developing CPR" programme</u>

These case studies are chosen to illustrate a range of global problems in which we expect a particular and significant ecosystem response and/or feedback. In each case the zooplankton appear to have a definable role in mediating the response or controlling the feedback. That role differs from case to case and, to be realistic, the role we assign the CPR in monitoring for these changes is case-dependent also.

The reason we assign a role to the CPR at all is threefold. First, it is the only system currently available for widespread, long-term, routine, cheap, plankton survey. Second, it does a good job of monitoring the zooplankton. Third it has already established the patterns of spatial and temporal change in the zooplankton in one ocean area (the North Atlantic) over many decades.

Nevertheless, like every other system that we can envisage, there are limitations to what the present CPR instrument can do. The instrument which forms the workhorse of the Atlantic survey operates at fixed depth (10 m), and though its 'silks' are counted to 393 separate species or entities, it has upper and lower bounds for quantitative collection which are set by the size and fragility of the species concerned. Frequently, - whether we are talking about large ctenophores as dominant predators, or small dinoflagellates as 'nuisance' species - our interests lie outside these bounds.

For this reason, when exploring new areas for plankton monitoring or even when re-occupying old routes, we should undoubtedly use a mix of present techniques to assess the zoogeography, to establish the 'watercolumn' representativeness of the changes that the CPR observes at fixed-depth and to assess those classes of plankton that are not well - or quantitatively - measured by the CPR. Coupled with the CPR, the undulating oceanographic recorder (UOR), with the range of sophisticated optics and other sensors that it now carries (Aiken and Bellan, 1990) would make a powerful combination, able to meet both these aims, and with some sensors (e.g. bioluminescence) providing useful proxy data on the presence of certain dinoflagellates even when the plankton themselves elude quantitative preservation.

Thus in defining a global role for the CPR we are really establishing such a role for continuous plankton recorders in general, albeit with the existing CPR survey system as its main prop and stay for the present and immediate future.

In the longer term there is equally no reason that we should retain the same system forever. In the outlook period (say 5 years) we can envisage the availability of a wide range of powerful new technologies, ranging from the multi-frequency acoustic (Tracor Corp; or Jaffe's SIO system), the high resolution optic/acoustic (Kils' IFMK system), and the laser-holographic (the Johns Hopkins system) to the size-frequency distributions provided by the Optical Plankton Counter of Herman, BIO (Focal Technologies, N.S.).

Like the original CPR system, all of these new methods will have their good and bad features, their different ranges or volumes sampled, their relative degrees of myopia, their upper and lower bounds of species discrimination, their own imperatives set by data-rate, data volume, data transfer, technical support and analytical effort - and hence their own individual mix of cost and effectiveness. One or a combination of these can be expected to take over the principal monitoring effort in the longer-term but only after parallel use has determined their relationship to the time-series provided by the past and present CPR survey. And although sophistication can bring great benefits, it must be provided at low cost and high reliability before it can be deployed for anything other than local and temporary coverage. In "monitoring the health of the ocean" we are referring to the sustained monitoring of a global scatter of large-regional ecosystems at reasonably high frequency (~ monthly), and at an accessible cost.

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Summary. In seeking a more-global deployment of CPR monitoring, there is no requirement to regard the existing instrument either as the sole or the unchanging vehicle. A mix of present day techniques is essential when exploring new areas for plankton monitoring (we suggest CPR and UOR in combination), and there will be a continuing need to seek and implement newer methods, when their cost-effectiveness exceeds that of the present system in meeting a particular purpose.

There will be two tricks to all of this however, both of them difficult. The first challenge will be to map the way forward from the present technology to some future technology without losing the main accumulated asset - the multidecadal time-series. It will be no advance to monitor the health of the ocean using a set of techniques which are not comparable from one location to another and which vary uncertainly with time. The second challenge will be to fit 'process' to large-scale monitoring in some comformable way. The trends identified by the latter are not necessarily identifiable as to cause without investigation of the underlying dynamics; the local complexities of process studies require the context of monitoring to establish their space-time validity. Despite this, it will not be a trivial task to extrapolate how the dynamics of a copepod population (say) - investigated by the traditional means of laboratory incubation or Lagrangian patch-following - can be used to interpret the long-term fluctuations of an entire population on the scale of a large marine ecosystem.

Understanding, rather than merely monitoring the health of the ocean will depend on meeting both these challenges.

3. Current major ecosystem studies

The four examples briefly described below are selected for their global scope and for the fundamental differences in their approach. The LME concept relies on developing a knowledge of the entire ecosystem and the principal forces that drive them in a global scatter of differing ocean regions. The GOOS programme is the only observing effort that combines a full range of physical and biological observation with a truly global coverage. The Integrated Atlantic Project of the CEC is based on perhaps the most intensive study of physical, biological and sedimentological transfers across an ocean boundary, and the International GLOBEC initiative will represent the most intensive study ever in the neglected field of zooplankton dynamics.

3.1 The LME Concept

Large Marine Ecosystems are extensive regions, typically over 200,000 km^2, each with a distinctive hydrography, topography, productivity, and ecological structure. It is central to the LME Concept that in each such region there is a definable set of forces which drive the principal changes in the living marine resources and thus determine their management. The rationale of studying a wide range of such regions hinges on the idea that the principal 'driving forces' differ from one LME to another, and that progress in the research and management of these marine resources and their yields can be enhanced by comparing the multiple stable states that develop differently in each, according to the imposed stress on the system, and the feed back of the system on the stress.

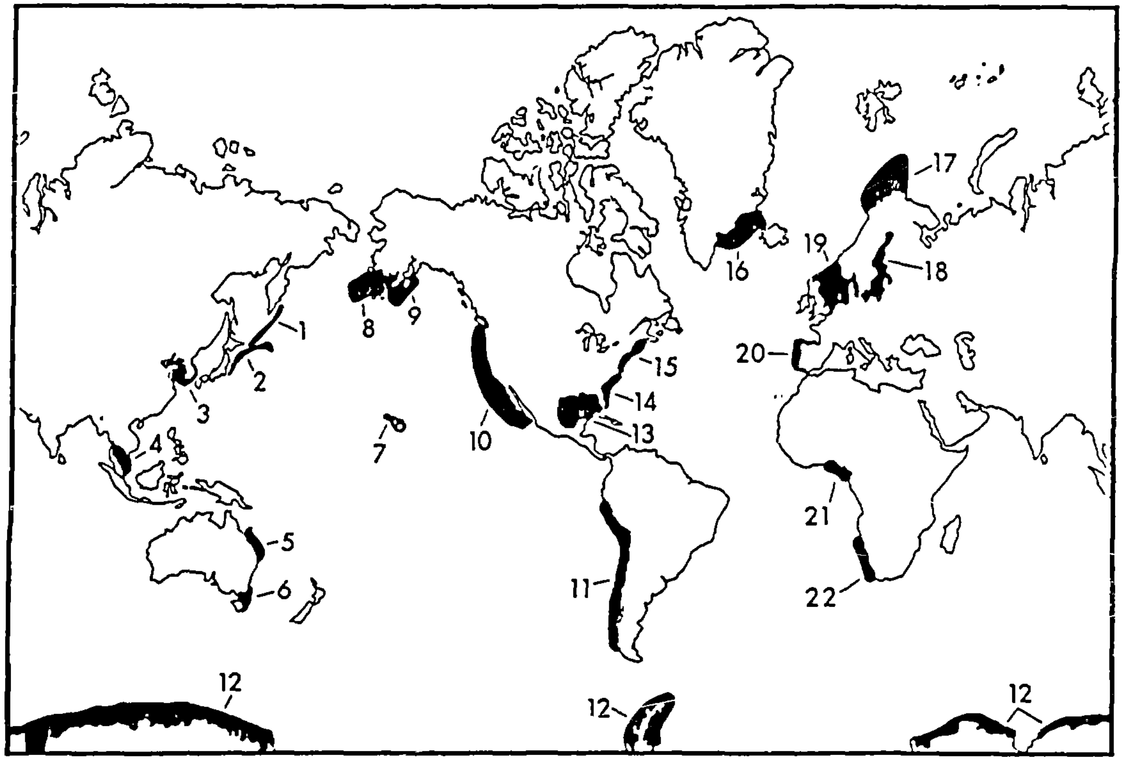
Thus the LME concept relies upon the identification, study and comparison of a globally-extensive set of differing unit regions. In contrast to the traditional preoccupation with single-species stock assessments, each LME aims to elaborate the entire trophic chain from plankton to fish and cetaceans, since environmental and anthropogenic perturbations of a given LME are likely to be partitioned throughout the food chain in one form or another, with changes rippling through the system as one dominant species is affected and succeeded by another.

Since these driving perturbations may be of natural or anthropogenic origin the structure of each study must have adequate scope to recognise and cover both climatic effects, (e.g. changes in water column stability, current structure, cloud cover, etc) and those due to man, (e.g. effects of nutrient loadings on dinoflagellate bloom timing, amplitude, prevalence or toxicity).

However, the ecosystem is never static and even its planktonic component can be shown to exhibit a continuum of change over a wider range of time and space scales. Thus the recognition of change in itself is not enough. It must be sufficiently protracted to recognise the 'normal' range of variation in the planktonic community (say) against which the grossly abnormal can be identified and, perhaps attributed as to cause. And it must be sufficiently 'routine' to overcome the problem - encountered in many of the more 'targetted' observing efforts - that the prevalence of the change you wish to measure becomes correlated with the amount or effectiveness of the observing effort deployed (Le Fevre, 1979; Mommaerts, 1986).

Figure 32 illustrates the global spread of the LME's identified for study (from Sherman, 1991). Although each study will demand intensive process-orientated research over an entire

LARGE MARINE ECOSYSTEMS



1 OYASHIO CURRENT ECOSYSTEM (0)
2 KUROSHIO CURRENT ECOSYSTEM (0)
3 YELLOW SEA ECOSYSTEM (X)
4 GULF OF THAILAND ECOSYSTEM (X)
5 GREAT BARRIER REEF ECOSYSTEM (X)
6 TASMAN SEA ECOSYSTEM (+)
7 INSULAR PACIFIC ECOSYSTEM (+)
8 EAST BERING SEA ECOSYSTEM (+)
9 GULF OF ALASKA ECOSYSTEM (+)
10 CALIFORNIA CURRENT ECOSYSTEM (0)
11 HUMBOLDT CURRENT ECOSYSTEM (0)
12 ANTARCTIC ECOSYSTEM (+)
13 GULF OF MEXICO ECOSYSTEM (+)
14 SOUTHEAST CONTINENTAL SHELF ECOSYSTEM (+)
15 NORTHEAST CONTINENTAL SHELF ECOSYSTEM (X)
16 EAST GREENLAND SEA ECOSYSTEM (+)
17 BARENTS SEA ECOSYSTEM (0)
18 BALTIC SEA ECOSYSTEM (P)
19 NORTH SEA ECOSYSTEM (+)
20 IBERIAN COASTAL ECOSYSTEM (0)
21 GULF OF GUINEA ECOSYSTEM (+)
22 BENGUELA CURRENT ECOSYSTEM (0)

F32

ecosystem, there is an obvious need for the large-scale, long-term, routine, context that the CPR (or its derivatives) is capable of providing in most of these systems.

These studies are lent urgency by the fact that as the climatic and anthropogenic perturbations grow, our ability to define the 'normal' range of variation and hence our ability to appreciate the amplitude of the effect, will both diminish.

3.2 <u>GOOS/COOS of IOC-UNEP-WMO</u>

The objective of the Global Ocean Observing System (GOOS) is to provide the data and information required from coastal and oceanic regions, including the enclosed and semi-enclosed seas, to address issues related to changes in regional and global environments (IOC, 1990,1991b).

The system involves long-term systematic measurements of physical, chemical and biological properties of the World ocean, analysis and distribution of data and data products according to a globally-coordinated scientifically-based strategy in order to support the evaluation of natural and human-induced environmental and climate changes and related variabilities and for the long-range forecasting of weather and climate over the whole planet, as well as regional predictions of ocean conditions for fisheries, coastal zone management, and pollution studies, for use by Member States.

The integrated, comprehensive (space- and ground-based) ocean observing system is needed to:

(i) develop, improve and test predictive ocean system models;
(ii) improve the understanding of the carbon cycle;
(iii) improve the capacity to assess the effects of global change at regional scales on intensively exploited and natural oceanic ecosystems and coastal zones;
(iv) provide data for the assessment of the state of the health of the marine environment and its resources.

As basic concepts the GOOS will consist of an internationally agreed scheme for data collection (measurements), data analysis, exchange of data and data products, technology development and transfer, it will be implemented through national facilities and services owned and operated by Member States of IOC and WMO under the leadership of IOC and in co-operation with WMO and UNEP, it will require wide international participation, with free and timely data exchange and will serve as the oceanic component of an observing system designed to meet specific aspects of global environment and climatic change.

So far as our present report is concerned the key points of GOOS are its global scope, its involvement of 'biology', its stated reliance on developed, proven technology and its fundamental aim of attributing observed change to its natural or anthropogenic cause.

The GOOS plan, moreover recognises the key importance of the inhabited coastal zone where any observing effort will be taxed with recognising (and correctly attributing) a complex climatic signal against a background of maximum anthropogenic noise.

For this reason the IOC has taken steps to examine the special requirements of a Coastal Ocean Observing System as a subset of GOOS. The first COOS planning document (Anon,

1990) not only recognises the importance of establishing plankton monitoring as part of the Global Ocean Observing System, but adds a requirement (in a Pilot Study) for the long-term CPR monitoring of the plankton along a range of ocean-margin transects - initially in the North Atlantic sector but later extending to the North Pacific (note the similar interests of CEC-OMEX; section 3.3 below).

Costings for the GOOS programme have not been published. However, if it is to meet its key aim of establishing, under the IOC, a global ocean equivalent of the World Weather Watch of WMO, it can be assumed to require an equivalent scale of funding (~ $2-2.5B) and therefore to be funded by Governments.

3.3 <u>The integrated Atlantic project of the CEC</u> (Mast II)

Following the EROS 2000 programme which focussed on biogeochemical exchanges and exchange processes at the river-ocean boundary, and JGOFS which seeks to quantify the time-varying fluxes of carbon and other biogenic elements in the water column of the open ocean, the CEC are encouraging the design of the crucial 'missing' programme that links the continental shelf to the open ocean by investigating the biological, chemical and physical processes which regulate the transport of organics and related substances across the ocean margin.

The eventual project will operate within the framework of the LOICZ core project and will form a contribution by European marine science to the IGBP, with two main aims:

(i) to assess the role of the coastal environment as source and sink of several critical elements and contaminants associated with global change but including the time-varying anthropogenic contribution.

(ii) to evaluate the socioeconomic consequences of global change, particularly those induced by climatic modifications.

Though an early 'illustration' of this nascent project has had a name - Ocean Margin Exchange Experiment or OMEX - and 5 suggested foci (the Iberian margin, the Biscay margin, the Celtic Sea margin, the North Sea-Faroes transect and the southern Norwegian Sea margin) these details are unimportant and may change. They served mainly to provide an initiating regional framework around which scientific studies with common aims might coalesce to form a major contribution and since the individual proposals have not yet been submitted, the ultimate shape of the whole is unknown.

The key point lies in its underlying purpose of forming an international, interdisciplinary, well-focussed and well funded[1] study of contrasting ocean - margin ecosystems around the eastern North Atlantic with the aim of identifying - and ultimately predicting - their climatic and anthropogenic perturbations. As such it forms an obvious complement to the IOC COOS pilot study, has an equal need to cover the planktonic ecosystem as a sensitive indicator for such

[1] 5-10 M ecu for the 'integrated project' over the initial 3-year period but with possible additional funding under the separate headings of 'supporting initiatives' and 'technological development'.

perturbations, and has some requirement for pan-oceanic 'control' if the 'local-antropogenic' signal is to be distinguishable from the 'global-climatic' in the changes observed at the margin.

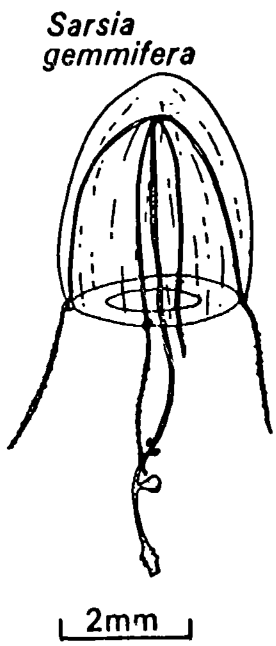
Depending on which transects of the littoral are ultimately selected for study, it is likely that the 'integrated project' will benefit from the multi-decadal data-set that the CPR survey has already collected and is continuing to collect along many of these transects. The two costings supplied in Section 4 are intended to supplement that coverage, and are presented as two options. The first estimates the cost of establishing additional CPR cover in all the suggested OMEX sites-of-interest, plus an appropriate degree of offshore 'control'. The second alternative anticipates that primary OMEX interest may be centred at the Armorican and Iberian margin, and represents a 'best-guess' option for a new route tailored to CEC aims by extending the S route from the Armorican shelf across Biscay, around the Iberian Peninsula to link with the Mediterranean study area of EROS 2000 (for which a 2nd phase has been proposed).

3.4 GLOBEC of SCOR-IOC/OSLR

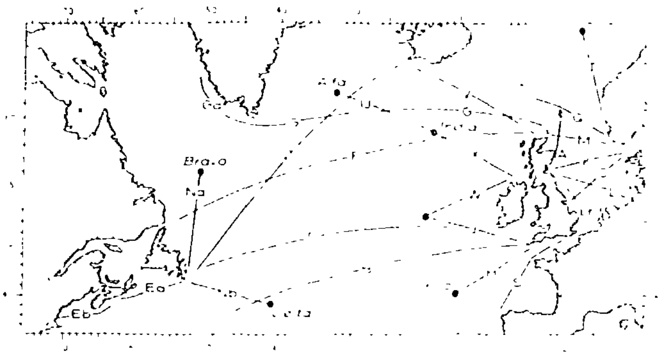
The central contention of the new International GLOBEC proposal, currently nearing completion, is that zooplankton population dynamics is the unique nexus through which the fields of phytoplankton production, fish recruitment variability, and environmental or climatic variation are related. An improved understanding of zooplankton dynamics would not only be of fundamental importance in its own right, but would act to complement and support other, existing international initiatives such as JGOFS and WOCE.

GLOBEC, then has the important and urgent aim of seeking to examine the contents of the "black box" which has hitherto represented the interactions of the zooplankton with their environment, predators and prey with special emphasis on the links between physics and biology at every scale and on the use of new technology to assess these. One question is identified as of particular importance since it underpins the dynamics of the entire marine ecosystem - the question of whether zooplankton grazing or nutrient limitation is the principal control on phytoplankton production. However, the more general GLOBEC goal of understanding all aspects of zooplankton dynamics means that it has a vital interest in each of the global problem-areas described in cases 1.1-1.7 above, including the effects of natural and anthropogenic change on the plankton, the feedback effects of the plankton on the environment and the translation of environmental change into variations in fish stocks. As such it would seem inevitable that the CPR or some derivative of it has a role to play in establishing 'context' in almost every aspect of the GLOBEC dynamics study.

The costs and other details of the GLOBEC plan are not yet available.


Sarsia
gemmifera
2mm

F33



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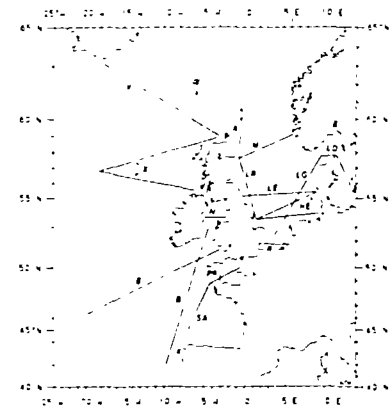

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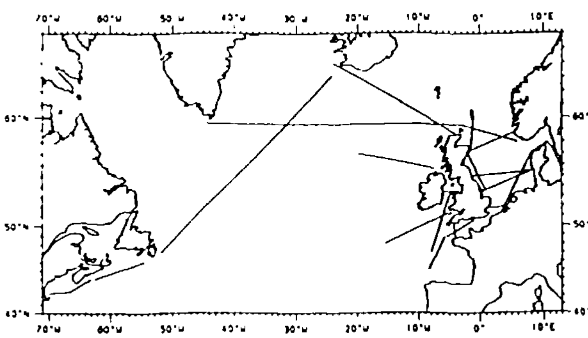

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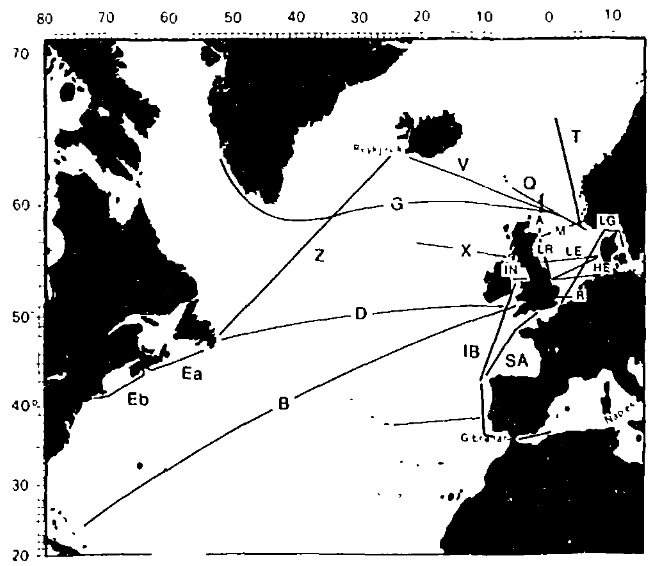


4. Towards a more global coverage

Each of the major ecosystem studies described above is of global scope. If the CPR or its derivatives are to be of more than local usefulness in support of such studies, then it also has to develop a more global scope. Realism however, requires that we move towards global coverage at an acceptable rate and cost. This chapter has the aim of identifying which global scatter of regional monitoring efforts might represent the most cost-effective means of addressing the important environmental questions using feasible routes at accessible cost.

4.1 Re-occupying the 'time-series' routes in the North Atlantic and North Sea

Figures F33-35 describe, respectively, the distribution of the CPR route network at its time of greatest extent in the 1970s, at its time of greatest retraction in the late 1980s, and the beginnings of its re-expansion in 1991. While it would be impracticable to attempt to re-work all of the old routes, (shipping practices change and the Ocean Weathership network has all but disappeared), figure F36 represents a realistic attempt to predict a necessary and sustainable network for the CPR in the Atlantic sector. The routes are costed below (Table 1). In each case the cost quoted is the net annual cost of providing data from that particular route to the point of entering the data set to computer-archive, and thus includes the cost of gear, ship support. analysis and overhead. New and old routes are already equipped for survey, and the equipment is durable; the cost listed is therefore the long-term annual running cost alone. In the case of new routes we list a setting-up cost in the first year that is higher (by the cost of the gear) than the running cost in subsequent years.

4.2 The Mediterranean

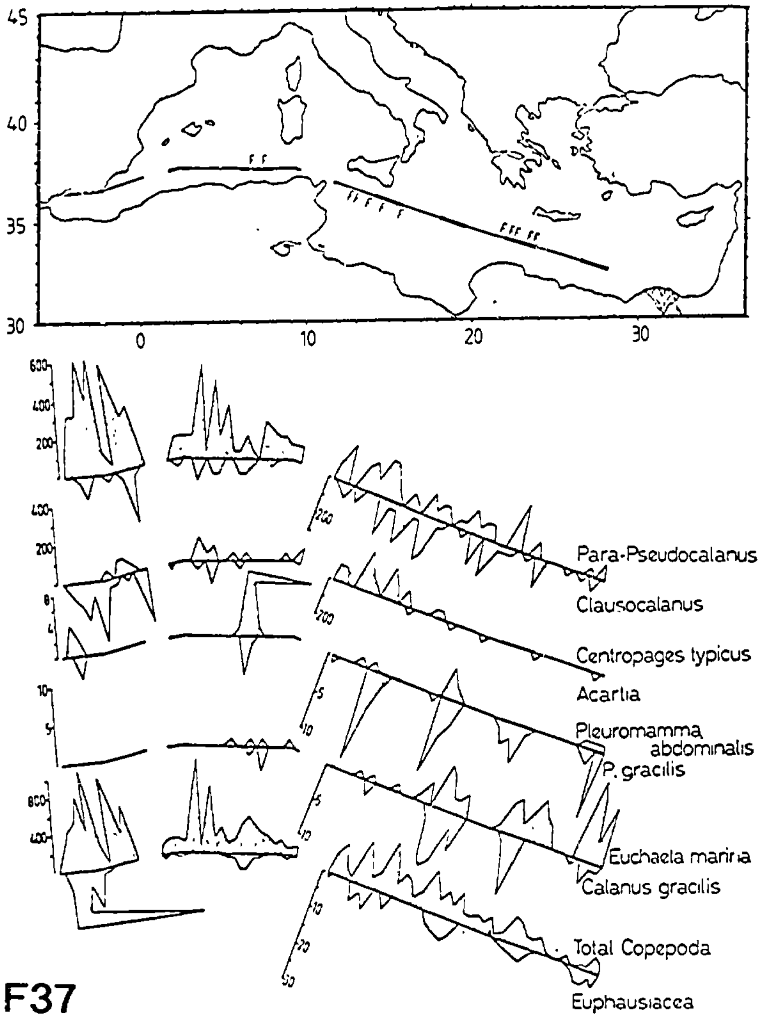
Extension of routine CPR survey to the Mediterranean is commended by three factors: it has a distinctive but relatively unknown planktonic community; the ecosystem is already believed to be suffering from the effects of heavy population pressure (eutrophication and contamination), in certain locations; the CPR is of proven effectiveness in these waters and could be introduced quickly and at moderate cost.

Figure F37 and Table 2 illustrate the results of a series of four CPR tows by RV METEOR between Suez and Gibraltar in May 1965. These provide an impression of the range of planktonic entities accessible to the CPR under routine survey conditions, and provide basic information on the characteristics of the plankton community.

- As expected, the plankton was less abundant than in the Atlantic or North Sea with an average of 24-128 copepods per 3 m^3 compared with a range of 28-2300 in Atlantic samples from the same month.
- Nevertheless the results show that the plankton is sufficiently abundant for CPR survey to be feasible (even with a ½" square aperture).

TABLE 1. ATLANTIC ROUTE COSTS

Route	Name	Shipping Company	Estimated annual cost £K 1st yr	Subsequent yrs
European shelf				
Liverpool-Dublin	IN	B and I line		3.6
Humber-Aberdeen	LR	Nor Cargo Ltd		9.8
Aberdeen-Stavanger	M	"		8.9
Aberdeen-Lerwick	A	P and O Ferries		6.4
N Shields-Esbjerg	LE	DFDS (UK) Ltd		12.1
Scheldt-Helsingborg	LG LD	Combi Shipping		20.4
Humber-F[illegible]e-Esbjerg	HE	Elbe-Humber Roline		10.8
Plymouth-Roscoff	PR	Brittany Ferries		3.6
Ipswich-Rotterdam	R	P and O Ferries		3.2
Shelf break transects (existing)				
Liverpool-Lisbon	IB	Cunard-Ellerman		17.0
55°30'N 7°W-OWS LIMA	X	Met Office		17.0
I of Wight-Ushant	S	Commodore Shipping		12.5
Ushant-Finisterre	S	"		12.5
Sule Skerry-62°30'N 18°W	V	HF Eimskipfelag		17.0
Shelf break transects (new)				
Norway-OWS MIKE	T	1 CPR + 1 Mech + 1 Davit	30.7	17.0
North Sea-Faroes (420 miles)	Q	1 CPR + 1 Mech + 1 Davit	30.7	17.0
Lisbon-Azores (720 miles)		1 CPR + 2 Mech + 1 Davit	45.4	27.2
Transatlantic (control lines)				
Denmark-Greenland	G	Royal Danish Lines 1 CPR + 3 Mech + davit	73.3	55.0
Liverpool-Newfoundland	D	ACL 1 CPR + 3 Mech + Davit	90.7	68.0
Reykjavik-Newfoundland	Z	HF Eimskipfelag 1 CPR + 2 Mech		51.0
Newfoundland-Halifax	Ea	"		17.0
Halifax-Boston	Eb	"		17.0
Barbados-UK	B	Geest Shipping Div (gear ex stock)		
		(i) Barry-14°W		17.0
		(ii) 14°W-Azores (40°N 32°W)		34.0
		(iii) Azores-35°N 39°W		17.0
TOTAL "2ND YR ON" COST				£492,000



F37

Figure 1. The Plankton Recorder in the Mediterranean. The chart shows the track of the tows made by F.F.S. METEOR on her return from the Indian Ocean in April 1965. The heavy lines indicate sampling by night (sunset to sunrise), the positions at which fish larvae were caught are shown by F.

The graphs show the numbers per sample of selected organisms in alternate 10-mile samples along the route.

Table 2

List of zooplankton found in Recorder samples in the Mediterranean in May 1965.

COPEPODA

- Paracalanus spp
- Pseudocalanus elongatus
- Temora stylifera
- Temora longicornis
- Acartia spp.
- Centropages violaceus
- C. typicus
- C. chierchiae
- Clausocalanus spp.
- Lucicutia flavicornis
- Scolecithricella spp.
- Ctenocalanus vanus
- Harpacticoida
- Corycaeus spp.
- Oithona spp.
- Oncaea spp.
- Calanus helgolandicus
- C. gracilis
- Nannocalanus minor
- Eucalanus crassus
- E. elongatus
- Rhincalanus nasutus
- Euchirella messinensis
- Undeuchaeta plumosa
- U. major
- Euchaeta hebes
- E. acuta
- E. marina
- Pleuromamma abdominalis
- P. gracilis
- P. piseki
- P. borealis
- Sapphirina spp.
- Heterorhabdus papilliger
- Candacia armata
- C. ethiopica
- Candacia spp.
- Scolecithrix danae
- Copilia spp.

RADIOLARIA

FORAMINIFERA

TINTINNIDAE

COELENTERATA

ANNELIDA

- Polychaeta larvae
- Tomopteris spp.

CLADOCERA

- Evadne spp.
- Podon spp.

CIRRIPEDIA

OSTRACODA

ISOPODA

CAPRELLIDEA

GAMMARIDEA

HYPERIIDEA

MYSIDACEA

DECAPODA

EUPHAUSIACEA

CHAETOGNATHA

TUNICATA

LARVACEA

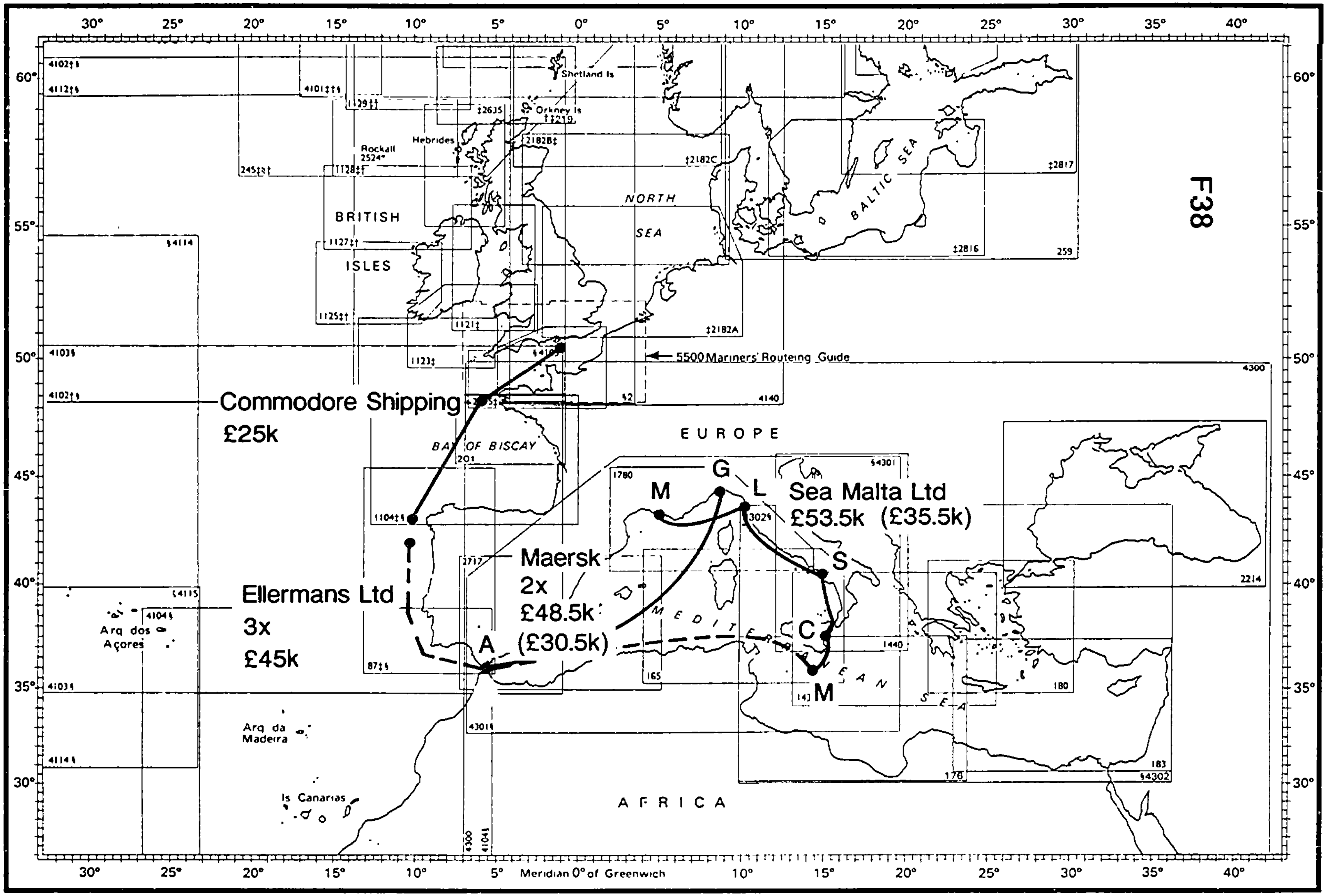
MOLLUSCA

- Thecosomata
- Pterotrachea coronata
- Lamellibranchia larvae

ECHINODERMATA - larvae

FISH EGGS

FISH LARVAE


F38
Commodore Shipping
£25k
Ellermans Ltd
3x
£45k
Maersk
2x
£48.5k
(£30.5k)
Sea Malta Ltd
£53.5k (£35.5k)
A
M
G
L
S
C
M
BRITISH
ISLES
NORTH
SEA
BALTIC SEA
BAY OF BISCAY
EUROPE
MEDITERRANEAN SEA
AFRICA
Shetland Is
Orkney Is
Hebrides
Rockall
5500 Mariners' Routeing Guide
Arq dos Açores
Arq da Madeira
Is Canarias
Meridian 0° of Greenwich

- There is a general increase of abundance from east to west, though a few species showed the opposite tendency (eg *Pleuromamma gracilis, Euchaeta marina*, and *Calanus gracilis*).

- Many of the large copepods and the euphausiids (mostly *Euphausia krohni*) showed very strong diurnal variations in abundance, presumed to reflect vertical migration since escape from the Recorder (unlike slow-moving nets) is unlikely.

- three patches of fish larvae were found.

Figure F38 represents an illustrative subset of the Mediterranean routes that are currently being formulated into an international MAST II proposal by Bob Williams, Plymouth Marine Laboratory. Williams' proposal envisages the working of a wider network of routes in both the western and eastern Mediterranean using more-sophisticated instrumented CPR's and UOR's (see Section 4.6) over an intensive study period of 2-3 years; our costings and our subset are in keeping with the intent of the present report in indicating the costs of longer-term monitoring of fewer key routes using standard CPR instrumentation. As usual, costs include complete analysis and computer archiving:

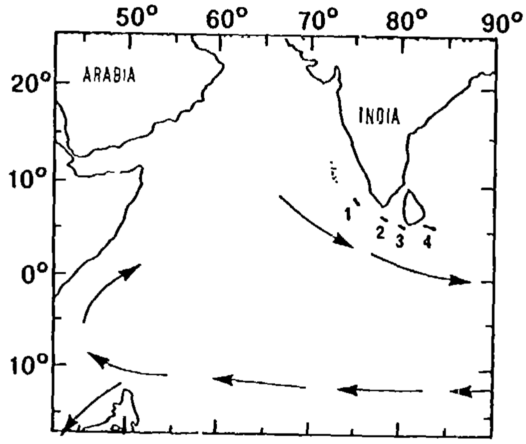
(i) **Finisterre-Malta**, Cunard-Ellerman Line, Triple[2], existing gear, monthly.
....£45k/a

(ii) **Algeciras-Genoa**, Maersk Line. Double. Costing includes 1 davit, 1 new CPR + 3 internal mechanisms plus transport to and from UK. Thus annual costs reduce from £48.5k/a in year one to **....£30.5k/a** thereafter.

(iii) **Marseille-Livorno-Salerno-Reggio Calabria-Catania-Malta**. Sea Malta Ltd. Double. Costing includes 1 new CPR + 2 internal mechanisms, plus transport to and from UK. Thus annual costs reduce from £53.5k for monthly operation in year one to
....£35.5k/a
thereafter.

These costing options are not in competition. In practice the intensive phase will determine the appropriate scale, type and location of the longer term monitoring effort.

[2] (i.e. three 450 mile units of tow).



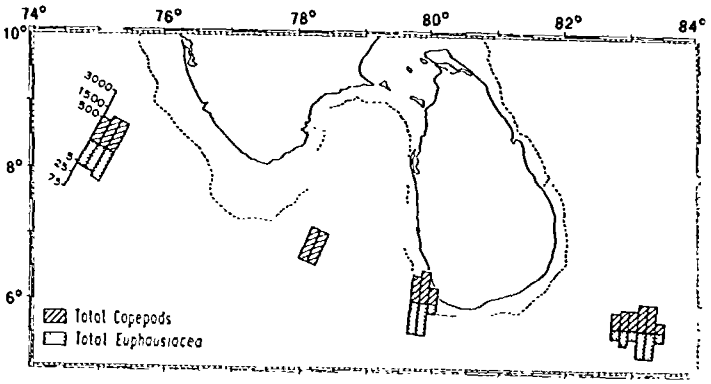


Figure 7 The distribution of Total Copepods and Total Euphausiids in tows 1-4 in the Indian Ocean. The histograms show the numbers per samp e in alternate 10-mile samples (See Figures 4 13)

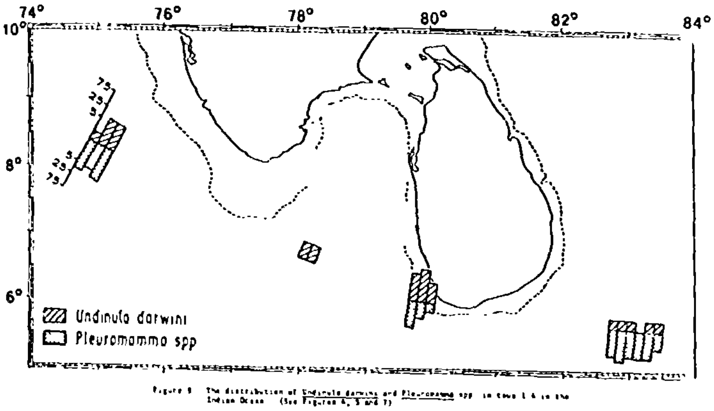


Figure 8 The distribution of Undinula darwini and Pleuromamma spp in tows 1-4 in the Indian Ocean (See Figures 4, 5 and 7)

Table 3

LIST OF SPECIES FOUND IN SAMPLES TAKEN BY THE CONTINUOUS PLANKTON RECORDER DURING TOWS IN THE INDIAN OCEAN IN JULY, 1967

DIATOMS	Bacteriastrum spp
	Chaetoceros spp - Hyalochaete
	Chaetoceros spp - Phaeceros
	Nitzschia delicatissima
	N seriata
	Rhizosolenia alata f. alata
	R hebetata f semispina
	Thalassionema nitzschioides
	Thalassiothrix longissima
DINOFLAGELLATES	Ceratium fusus
	C. carriense
	C. macroceros
FORAMINIFERA	
RADIOLARIA	
COPEPODA	Acartia amboinensis
	A danae
	A negligens
	Calanopia minor
	C elliptica
	Candacia pachydactyla
	Centropages calaninus
	C. furcatus
	C gracilis
	Clausocalanus spp
	Copilia spp
	Corycaeus spp
	Eucalanus spp (still to be identified)
	Euchaeta spp
	Farranula spp
	Harpacticoida
	Heterorhabdus papilliger
	Labidocera acuta
	Lucicutia spp
	Nannocalanus minor
	Oithona spp
	Oncaea spp
	Paracalanus spp
	Pseudocalanus sp
	Pleuromamma xiphias
	P abdominalis
	P indica
	P borealis
	P gracilis
	P piseki
	Pontellina plumata
	Rhincalanus cornutus
	Sapphirina spp
	Scolecithrix danae
	Temora stylifera
	T turbinata
	Undinula darwini
	U vulgaris
	Undeuchaeta plumosa
CLADOCERA	
EUPHAUSIACEA	
OSTRACODA	
GAMMARIDEA	
HYPERIIDEA	
SERGESTIDAE	
DECAPODA	
MYSIDACEA	
CIRRIPEDIA	
CHAETOGNATHA	
LARVACEA	
THECOSOMATA	
CTENOPHORA	
SIPHONOPHORA	
CEPHALOPODA	
PTEROPODA	
NEMERTINEA	
POLYCHAETA	
THALIACEA	
PISCES	Young stages

F39

4.3 Arabian Sea

The justification for monitoring planktonic changes across the global production centre of the Arabian Sea has been described. The need is to lay down a system capable of recognising the ecosystem effects that are expected to arise through climatic modulation of the SW monsoon.

Two orthogonal routes are selected to address this problem (see the color map on the back of the faceplate), the first running from East Africa to the Persian Gulf, the second running from the Gulf to the southern tip of India at Cape Comorin and beyond to Sri Lanka. These routes offer 3 main benefits. They use frequently-travelled and therefore easily-worked shipping routes; they transect the two main local production centres of the northern Arabian Sea and around Cape Comorin; they provide both the large-scale context and the "open ocean" contrast for one of the likely key sites of the Large Marine Ecosystem study (the East Africa-Somali Current Domain); and we already have a small but sufficient number of CPR tows from this route to confirm the validity of the CPR survey technique in these waters.

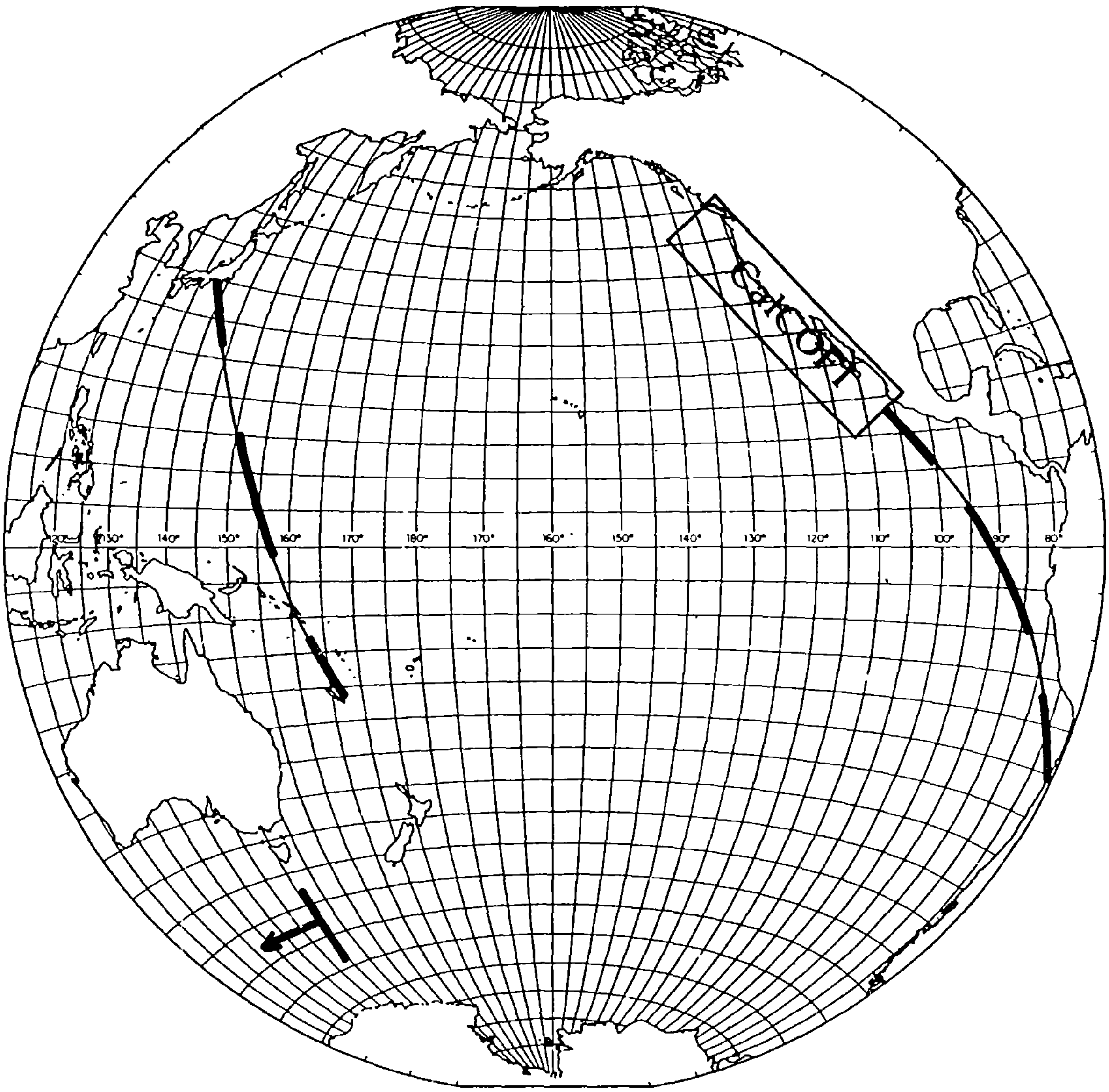
Figure F39 and Table 3 use 4 short CPR tows by RV OCEANOGRAPHER in July-August 1967 to illustrate the range and abundance of species accessible to the CPR during the SW monsoon.

Compared with the 4 tows through the Mediterranean (described earlier), copepod abundance was very much greater at 280-1300 per 3 m^3 sample than the 24-128 observed in the Mediterranean, and were evenly distributed by day and night. Numbers of copepod species were the same (39) in the Mediterranean and Indian Ocean tows and, as expected, were very much greater in these warm water areas than the 10-25 spp normally encountered in the cold-water Atlantic north of 50° N (for example). Comparison of species composition and abundance with two further CPR tows NW of Australia appears to highlight similarities rather than differences over this vast area.

The costs per route for these two key transects are given below, with the following provisos: (i) with one route running coastwise along the axis of maximum production, and the other providing an "open ocean" contrast between production maxima (F12-15), both routes are of separate value, with little redundancy; (ii) as new routes in a remote ocean area, costings must be regarded as approximate; (iii) since the physical changes associated with the monsoon will be immense yet the provision of environmental data will be poor, we regard it as axiomatic that we must equip these routes with instrumented CPRs from the outset if we are to interpret as well as describe the trends of change in the plankton.

On this basis costs per route are as follows:

1. The - 1500 miles of each route are equivalent to three standard 450 mile CPR tows. Operational and analytical costs average £17k per 450 mile tow per year of survey, i.e. **£51k**
2. Realistic initial equipment costs for each route are likely to be 1 Recorder ex stock (zero cost) + 1 Recorder + 3 mechanisms new at an overall cost of £18k, plus 2


CalCOFI
120°
130°
140°
150°
160°
170°
180°
170°
160°
150°
140°
130°
120°
110°
100°
90°
80°

F40

environmental sensor/logger packages (£26k total), plus 1 tow-davit @ £4.7k, **but will apply to the 1st year only** **£48.7k**

3. Logistical costs of supply and return are estimated to total a further **£4k**

[While it is intended to organise a local base of operation as soon as practicable, the training and facility costs are likely to be at least equivalent to the costs of remote-supply for the outlook period].

Thus the estimated initial cost of initiating each route on a monthly and annual basis is likely to total £103.7k in the first year, reducing by the cost of equipment to £55k in subsequent years; operating costs can also be reduced if the decision is made to cover the route during the SW monsoon alone rather than over the full year, or if only one route is funded, or if local analytical support is developed.

4.4 West Pacific, East Pacific "Giant Routes"

The intention to cover both hemispheres in the west and east Pacific by means of two "giant routes" is deliberate. The space-time scale of the dominant ENSO climatic signal in the Pacific sector is known to be vast and has been associated with a greatly reduced phytoplankton biomass in both the western (Dandonneau, 1986) and eastern (Barber and Chavez, 1983) Pacific; the trends of change in the wind system which drive coastal upwelling are apparently co-linear from California to Peru; and the changes observed in the ecosystem of the eastern North Pacific appear to be coherent over the full latitude range. In confirming and extending our knowledge of the coherence of ecosystem change in the Pacific sector, there seems little point in being parochial in our monitoring!

The two giant routes from Tokyo to Noumea and San Diego to Peru or Northern Chile were chosen from other options since they appear to cover the principal sites of environmental change (the Kuroshio/Western Boundary Current and its fluctuating meander pattern, the core domain of the El Nino signal in the western and eastern tropical Pacific and the key coastal upwelling centres of the east Pacific rim), while connecting both of the sites of intensive past ecosystem monitoring, [i.e. The multidecadal CalCOFI investigations of the California Current, and the French transpacific zooplankton monitoring route from Panama to Noumea which was worked using the "small plankton indicator" between 1977 and 1982 (Dessier, 1983, 1988)].

Both of these 'giant routes' are around 4000 miles in length; to achieve a realistic balance between cost and effectiveness we assume that approximately half of each route will be covered by CPR, in three discontinous tows of 450, 1000 and 450 miles using two machines of differing type. Table 4 is used to illustrate the method and assumptions of costing the Tokyo-Noumea route, (and it also illustrates the itemised costing that forms the basis of every other cost estimate in this paper). As with the Arabian Sea example (Section 4.3 above) the expected dominance of physical/climatic controls in a region of poor data-coverage implies the use of instrumented CPRs on these routes from the outset. These costs are therefore included in Table 4.

TABLE 4. NOUMEA - TOKYO PROJECTED COSTINGS

ROUTE COSTS 12 X PER ANNUM, 2 CPR MACHINES	SILK	£COST
2 X 450 miles = 900 miles	£220	2300
1 X 1000 miles = 1000 miles	270	2800
	Total	£5100 /a

TRANSPORT COSTS	
Plymouth-Southampton return per annum	2076
P and O Container Line to Tokyo per annum	3674
	£5750

RUNNING COSTS	
Ship payments	1080
Computing	2000
Salaries (analysts etc)	32000
Nat. Ins.	2560
Superannuation	3200
Accommodation rental	8000
	£48840

GEAR COST (1st year only)	
New davit, fitted	4700
1 new recorder body + 2 mechanisms	13500
2 environmental sensor/logging packages	26000
	£44200

TOTAL per route, 12 tows/yr serviced from UK	YEAR ONE	£103,890
	SUBSEQUENT YEARS	£ 59,690

Options

Alternative transport costings per annum by air to Noumea via Sydney (£32k) and by air to Tokyo (£12k) rejected as too costly. But alternative shipping cost UK-Noumea via Bank Line look attractive (£5.8k for 12 return trips /a) and other alternatives by P & O CL to Noumea via Australia and by Compagnie General Maritime to Noumea are under investigation.

Thus, the cost of instituting full CPR coverage 12 times per year over half the route-length amounts to **£104k** per route in both the west and east Pacific in the first year but reducing by the cost of new gear (£44.2k per route) in 2nd and subsequent years to **£60k** per route.

Since the eventual aim is to operate and analyse each route locally, the above should be regarded as realistic initial costs which will reduce as soon as a local analytical and servicing effort can be mobilised. The feasibility of establishing local analysis centres at a range of sites is currently under investigation.

4.5 Southern Ocean

Since 1990, the Krill Research Group of the Australian Antarctic Division in Kingston, Tasmania, have operated 2 standard CPR units from two research vessels and one supply ship in a Southern Ocean programme designed to assess the distribution, relative abundance and development of the larvae of Antarctic krill (*Euphausia superba*). First surveys in the Heard Island-Kerguelen area in May-June 1990 confirmed that the CPR performed well in southern ocean winter conditions, provided 2500 nmi of data, and (notably) sampled euphausids up to 20 mm in size. A continuing programme of research survey is planned extending to study the distribution and abundance of krill larvae in the Prydz Bay Region, Antarctica. Costs are borne internally by AAD.

4.6 Miscellaneous/process-study support

In section 1, above, a range of process studies were identified which were more restricted in time and space than the long-term monitoring efforts which form the basis of this proposal but which would benefit from CPR support (e.g. the variable advection of *Calanus* onto the Barents Sea shelf in section 1.5; the seasonal development of zooplankton grazing power along the marginal ice zone in section 1.4; the need for the vaalidation of the zooplankton component of ecosystem models in section 1.7).

Rather than attempt to cost the variable requirements of each of these explicitly, it achieves much the same object to cost them generically, as an additional equipment cost to cover the more specialised gear that is likely to be required.

We envisage three main types of task. First, the ocasional use of the Undulating Oceanographic Recorder (UOR) on almost any one of the standard CPR 'time-series' routes to provide depth-validation of the data set collected at the fixed CPR depth of 10 m. Second, the initial use of UOR coverage to characterise the zoogeography of the plankton in any area for which new CPR coverage is proposed, thus providing the necessary information to design the most appropriate frequency and depth of cover for the local conditions. Third, the use of instrumented CPR's to provide a range of environmental parameters on a routine basis for interpreting the distribution and dynamics of the plankton.

(i) 'instrumented CPR'. As developed by the team at PML, this system with its solid-state logger package fits beneath the standard CPR and collects data on T, S, chlorophyll, upwelling and downwelling irradiance and depth, (as well as the normal phytoplankton and zooplankton samples via the standard CPR internal net mechanism). Compared with the standard CPR cost of £3.5k each for recorder and mechanism, this instrumented development costs an added £13k.

(ii) UOR II. The undulator with its full suite of instruments including C, T, D, fluorescence, P.A.R., up and down irradiance via 3 light channels, and newly developed nutrient or contaminant sensor options is a most sophisticated and powerful package (Aiken and Bellan op. cit.), with the capability of estimating potential productivity rather than phytoplankton standing stock by combining the depth distribution of chlorophyll with irradiance. It may also be equipped with the standard CPR internal mechanism to collect plankton. The initial equipment cost probably relegates the UOR to a support role in any monitoring effort of global scale, though when used in support the CPR and UOR form a most powerful combination for large marine ecosystem monitoring. We envisage a constant need for at least 3 such systems in support of the three aims outlined above. Though the costs vary with the sensor options and the options for the logging, shipboard delivery, or satellite transmission of the data, we assume a mean cost of £60k per instrument.

Ideally instrumented CPRs and UORs would be the preferred instruments on every route; in practice, in order to achieve a more-global coverage of plankton monitoring, we envisage the continued widespread use of the standard CPR for the present, with instrumented CPRs specified for certain new routes (see Sections 4.3 and 4.4 above) and with the UOR in support as required.

Plainly, we could achieve this mix of instrumentation by merely adding a number of each of the more-specialised instruments to the SAHFOS "fleet". The analytical and ship-support costs can be assumed to be already accounted-for in the costs for a given route (more or less), and the added cost of specialised equipment will be + £13k per environmental package and + £60k per UOR.

However, there are perhaps more efficient ways of meeting the standard and the more-specialised survey tasks (above) than by operating essentially-different gears for each task. Figure F41, for example, makes the simple point that if the Aquashuttle (UOR) body-shell could be made to "fish" identically to the present CPR, then one instrument becomes capable of all tasks, and all CPRs can become instrumented CPRs or UORs, temporarily or permanently, as required, simply by plugging in an environmental package, or an alternator and gear-box, or both.

This example is illustrative only. Clearly, to change from the long-established CPR body for any reason is to risk the continuity of the existing time-series, and would not be a sensible option unless and until it can be demonstrated to make no difference to the way the CPR tows and fishes. However, it does illustrate the type of trial that the Steering Council of the CPR may have to undertake if it is to maximise the effectiveness of its global coverage at minimum cost.

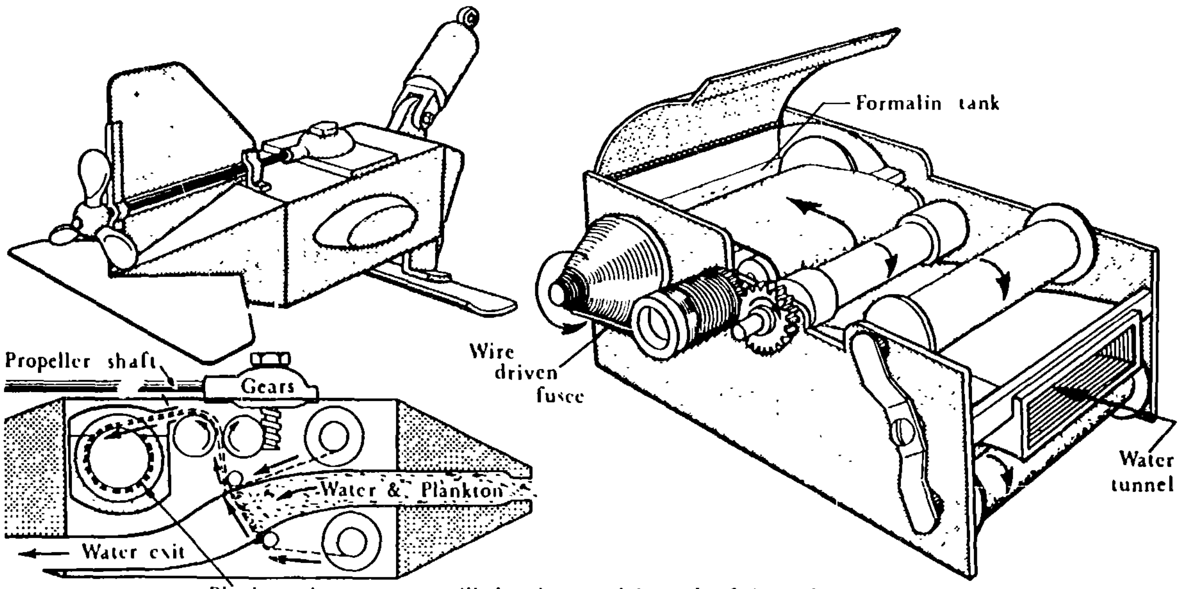
4.7 Total cost

The various route options listed in this proposal do attempt to match real or developing global problems with a global scatter of regional monitoring efforts and at a moderate cost. This paper is not so much a proposal however as an illustrative example of the type of cover that it seems feasible to achieve at present. While other better routes and techniques may emerge for this purpose it is probably of value to record the total cost of this particular sparse global scatter of routes, since it will provide an order-of-magnitude figure for the cost of any global monitoring effort of similar scope.

The following are the **long term annual running costs for the global CPR coverage** described in this document, area by area. As already explained, the setting-up costs are higher by the cost of new gear and these can be obtained from the regional subsections of the text. There will also be a general rather than a regional cost of purchasing UOR units for the purpose of checking up on the depth-validity of historic time-series routes, and for exploring new ones. [say two UOR units at £60k = £120k].

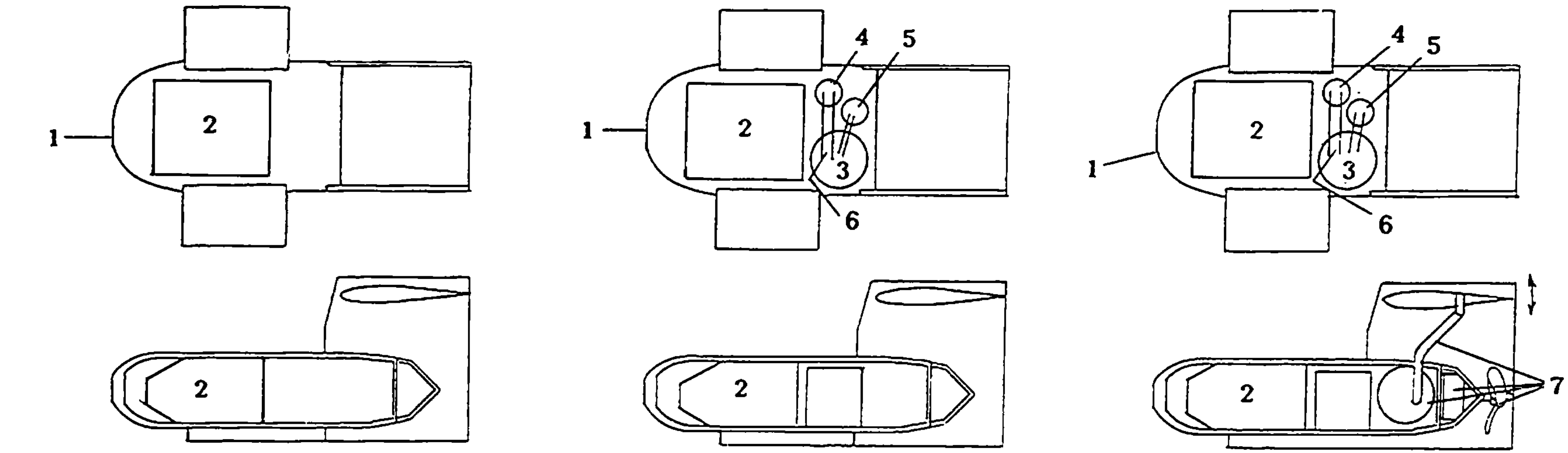
	£K
The NW European shelf and North Atlantic	492
The Mediterranean 'subset'	111
The Arabian Sea/Indian Ocean (two routes, instrumented)	110
The West and East Pacific (instrumented CPRs)	120
Total	£833,000

To achieve effective development towards this more global scope, it is already plain that the CPR will require the support of two quite different kinds of administrative structure. **Financially**, the requirement is not merely for an adequate funding base but for a continuity of funding that can enable time-series to grow. While the many current international initiatives in ecosystem dynamics - funded directly by Governments or indirectly through bodies such as the World Bank - have the interests and the resources to form a fruitful context for CPR growth, it is plain that the IOC will have a special coordinating role in view of its key aim of establishing, in GOOS, a global ocean equivalent of the World Weather Watch, of world-wide scope, indefinite duration and inter-governmental resource. **Scientifically** the administrative structure is already becoming established. Since its Incorporation on 29 November 1990 and its Registration as a charity on 12 December 1990, The Sir Alister Hardy Foundation for Ocean Science has operated as an International Charitable Trust under the aegis of the Marine Biological Association of the UK, and with laboratory and workshop facilities in its present



F41a The Standard CPR

Towed by ships-of-opportunity, monthly, along selected routes at a fixed tow-depth of 10 m. Plankton entering the 1.25 cm^2 aperture in the nose are trapped between two bands of 290 micron-mesh silk which unroll at a rate proportional to towing speed, and are then preserved in formalin. In the laboratory, the silk bands are cut into sections corresponding to 10-mile lengths of tow, counted under a microscope and entered to computer. In 60 years since 1931, ships of 10 nations have towed CPRs along a track-length of ~ 4 million miles.



a) Option 1

1. Basic Aquashuttle body (non-undulating) but suitable for upgrade to full Aquashuttle. £ 7,000
2. Plankton sampler Free

b) Option 2

Basic Aquashuttle Body with Equipment

Costs

1.	Basic Body	£ 7,000
2.	Plankton Sampler	Free
3.	Data logger with CTD	£ 5,995
4.	Fluorimeter	£ 5,995
5.	Battery Pack	£ 995
6.	Wiring Harness	£ 300

c) Option 3

Full Undulating Aquashuttle

Costs

1.	Basic Body	£ 7,000
2.	Plankton Sampler	Free
3.	Data logger with CTD	£ 5,995
4.	Fluorimeter	£ 5,995
5.	Battery Pack	£ 995
6.	Wiring Harness	£ 300
7.	Servo/gearbox/alternator/ impellor and crank	£14,000

Further options

Bioluminescence	£ 5,995
Upwelling and downwelling (3 channels each)	£ 7,995
Additional wiring harnesses	POA

F41b Could a single towed body with modular equipment perform as 'standard CPR', 'instrumented CPR' and 'UOR'? Costs of the three options are shown. (The Chelsea Instruments 'Aquashuttle' body is used in this illustration).

location within the Plymouth Marine Laboratory. The next step intended by the Trustees is the establishment of a CPR Council, and it will be this body - composed of the representatives of significant funding bodies, the Director of the CPR Survey and certain officers of the Foundation - which will have the responsibility of directing the future scientific development of the Survey, and for partitioning the available resources into (for example) maintenance of time-series routes, establishment of new routes, instrument development, training, data policy, data processing and data exchange. In brief, for matching facilities and analytical capacity to the changing resources, aims and scope of the Survey.

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