# U.S. GLOBEC

# Global Ocean Ecosystems Dynamics

A Component of the U.S. Global Change Research Program

Implementation Plan and Workshop Report
for
U.S. GLOBEC Studies in the Arabian Sea

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This document is an implementation plan for U.S. GLOBEC research in the Arabian Sea. It developed from initial discussions at a U.S. GLOBEC Workshop on the Arabian Sea held in Denver, Colorado, USA on June 16-17, 1992 -- Sharon Smith, convener.

Working group reports from the meeting are included in this document as Appendices. The editorial and implementation committee for this document included Hal Batchelder, Charlie Miller, Don Olson, and Sharon Smith. We thank Karl Banse, Ann Bucklin and Mark Luther for their contributions to this document.

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*EXECUTIVE SUMMARY*

U.S. GLOBEC's goal is mechanistic understanding of population processes in the sea. The stimulus for pursuing that goal is the need to predict the consequences of global change for marine populations. Our pursuit will be fruitful if we find sites and problems offering natural experiments on population dynamics. The Arabian Sea offers two fine natural experiments of the sort U.S. GLOBEC requires:

(1) Because of the monsoonal alternation of the winds, it provides all the advantages for population studies of a seasonal climate, but provides them in a tropical setting. In addition, because the monsoons drive both coastal and separated oceanic upwelling regimes, there are a variety of contrasts among habitat types. The responses of the biota, particularly zooplankton and fish, to these seasonal and spatial variations cry out for study.

(2) Unlike many other major upwelling systems, the fish fauna of the Arabian Sea is dominated by myctophid fishes. One species, *Benthosema pterotum*, is arguably the largest single species population of fish in the world, with stock estimates ranging to 100 million metric tons. Possibly, their dominance derives from their ability to enter the suboxic middle depths so widely available across the Arabian Sea, and thus to obtain refuge from predation. Most exciting, this stock is annual, it turns over each year, perhaps faster. Thus, the productivity of *B. pterotum* is of the order of 100 million tons year$^{-1}$! Many things are known about these fish, opening the way for a full modern study of their population processes. The population biology of the copepod species that are the direct prey of Arabian Sea myctophids is essentially unexamined. It is a project perfectly suited to a U.S. GLOBEC effort.

The geographic domain of particular interest lies offshore from the Arabian Peninsula and stretches toward the Indus delta. During the southwest monsoon of summer months, a jet of wind from east Africa across the open Arabian Sea to India (the Findlater jet) generates strong wind stress curl and, therefore, open-sea upwelling in a 500 km wide belt. There is massive ensuing phytoplankton production under the steady, very strong winds. During this period, the open-ocean upwelling domain borders on its Arabian side a domain of seasonal coastal upwelling, and on its Indian Ocean side a downwelling domain. The downwelling grades into the persistent oligotrophy of the tropical oceans. The northeast monsoon of winter, with winds in the opposite direction, also produces a strong production response in surface layers. There are two periods of quiet winds and reduced productivity between the monsoons.

This situation is ideal for study of adaptations of planktonic and nektonic populations to strong physical oscillation in habitat features. U.S. GLOBEC should mount an investigation in the Arabian Sea to understand its dynamics in the Present, so as to anticipate the effects of climatic change here and in other areas of the sea. To an extent the effects of climate change will be foreshadowed in the variable responses of populations to the strong interannual variations in monsoon intensity. Thus the U.S. GLOBEC investigation ideally should extend over at least several years. However, our state of knowledge of population processes in the Arabian Sea is so primitive that any initial study, particularly of zooplankton, will be of value.

The present instant offers a special opportunity for a U.S. GLOBEC Arabian Sea program because it can be done in coordination with the U.S. JGOFS, ONR/ARI, and WOCE programs that are scheduled to work in the region in 1994-96. In this document, we propose that U.S. GLOBEC work along the same sampling lines as these programs, taking full advantage of the rich suites of habitat data they will develop. U.S. GLOBEC need by no means be parasitic in these relations, JGOFS, which focuses on the primary production of organic matter and vertical fluxes from the euphotic zone, would benefit greatly from investigation of growth processes and population dynamics of mesozooplankton and mesopelagic fishes.

This document reviews the ecological problems suitable for study by U.S. GLOBEC in the Arabian Sea. Then it offers two levels of implementation plan for U.S. GLOBEC studies: (1) A modest program scaled to the funds and ship resources believed likely to be available for U.S. GLOBEC's participation (in coordination with other programs (U.S. JGOFS, ONR/ARI, WOCE) in Arabian Sea studies during 1994-1996. (2) An ambitious program designed to answer some of the exciting questions presented by the pelagic population ecology of the Arabian Sea. The latter proposes deployment of a vessel equipped for modern study of fish stocks, together with supporting studies of zooplankton populations. Both plans fit the model for U.S. GLOBEC studies: (1) target species are designated, (2) population processes of those species are the principal foci, and (3) the studies will be designed to enable prediction of the impacts of global change on those key species.

## IMPLEMENTATION PLAN FOR A U.S. GLOBEC ADD-ON TO ANTICIPATED STUDIES IN THE ARABIAN SEA

The implementation committee proposes that U.S. GLOBEC sponsor a study that will take advantage of the ships and other logistics expected in the Arabian Sea region in 1994-1996. These include field programs of U.S. JGOFS, ONR/ARI, WOCE, and NOAA and imply the presence of three research vessels. U.S. GLOBEC should use some of the time still available in the schedules of those vessels. The Steering Committee should act now to obtain assignment of that time to U.S. GLOBEC.

Our interest in the Arabian Sea involves two major issues:

(1) The extraordinary temporal and spatial variation of physical forcing (monsoonal reversals, coastal and open-ocean upwelling) and its potential effects on the pelagic ecosystem, including the zooplankton and fish.

(2) The habitat features and population responses to them that results in the enormous stocks of myctophid fishes.

While myctophid biology and ecology in the Arabian Sea are its most attractive features for U.S. U.S. GLOBEC work, the "add-on" plan for 1994-1996 focuses on improving our understanding of the response of the zooplankton and fish to the time and space variation in monsoonal forcing. Specifically, we propose to study mesozooplankton and fish stocks (emphasizing larvae) along the U.S. JGOFS transect from Oman out into the central and southern Arabian Sea. We recommend:

(1) a study of population structure and population dynamics of three target groups of mesozooplankton (*Calanoides carinatus*, Arabian Sea euphausiids, and *Thalia democratica*);

(2) a general planktological reconnaissance of the northern Arabian Sea, including the open-ocean and coastal upwelling regimes; and

(3) a study of the biology, ecology, distribution, and systematics of the larvae and adults of the dominant species constituting the massive myctophid stocks of the region.

## IMPLEMENTATION PLAN FOR A FULL-SCALE U.S. GLOBEC STUDY OF PELAGIC POPULATIONS AND ECOSYSTEM DYNAMICS IN THE ARABIAN SEA

The implementation committee also recommends that the U.S. GLOBEC Steering Committee seek funding for an extensive, "full-scale" study of the dynamics of the interactions among the complex Arabian Sea physical regime, mesozooplankton stocks, and the massive stock of migratory myctophids. The principal focus should be understanding of the dynamics of the myctophid stocks together with their supporting food web and the relations of both to the special climatology of the region. An ambitious program of study can focus its seasonal comparisons along a single, onshore-offshore transect line, and the line out of Oman proposed for U.S. JGOFS work is an excellent choice. To provide a range of physical conditions and to investigate myctophids in both the coastal and oceanic upwellings, stations should be located on the shelf, over the slope, and along the line offshore. It should not be necessary to proceed beyond the limit of eutrophic conditions established by the SW monsoon beneath the Findlater jet. In addition, it will be necessary for studies to be dispersed alongshore, certainly at least from Cape Guardafi east to the southeastern limit of Pakistan. A tour of this perimeter on a seasonal basis would produce useful information on the response of the stocks to the variations of the monsoon regime.

The scale of this second-level plan remains within reasonable limits for a project funded primarily by the U.S., but it requires a dedicated ship, some specialized technology (particularly state-of-the-art sonar, a U.S. GLOBEC specialty), and a team of investigators working in the Arabian Sea for several years.

*GENERAL INTRODUCTION*

U.S. GLOBEC's interest in the biological and chemical environments of regions with strong physical forcing leads us to propose investigation of zooplankton and fish stock processes in the monsoon regime of the Arabian Sea. Strong, steady winds during the southwest (May-August) monsoon generate coastal and oceanic upwelling zones of great extent and upward transport. The biological response is dramatic, featuring intense phytoplankton blooms. The northeast monsoon (December-February) produces strong surface convection in the north and, again, blooms. There are regular lull periods between the monsoons in which the Arabian Sea transforms to a tropical-subtropical oligotrophic condition. The monsoonal oscillation makes the Arabian Sea a unique study case for mixed-layer development, adjustment of the interior density and current fields to onset of forcing, and (most important to U.S. GLOBEC) response of the pelagic ecosystem to changes in the physical environment. The massive downward flux of organic matter generated by the monsoonal blooms, coupled with the advection at depth, creates a suboxic mesopelagic zone between 180 and 1500 m, modifying the interaction between surface and mesopelagic communities, thus providing an opportunity for examining the role of mesopelagic processes in oceanic ecology generally.

The large vertical turn-over of dissolved carbon associated with monsoonal blooms makes the northwestern Indian Ocean a key site in the carbon budget of the global ocean. Thus, the region is important to global climate control and worthy of a prolonged research effort by the international oceanographic community. This should include a U.S. GLOBEC effort on zooplankton and fish stocks, parallel to the U.S. JGOFS and ONR efforts already planned for the middle 1990's. A workshop was held in June 1992 to explore the scientific issues and formulate a research plan for a U.S. GLOBEC effort in the Arabian Sea. Three working groups addressed questions associated with zooplankton, fish, and technology. Reports of the working groups and a workshop summary are included in this document as Appendices A-D. The U.S. GLOBEC Arabian Sea implementation plan described here developed from discussions initiated at that workshop.

In this document we review the physical setting of the Arabian Sea, detail the status of knowledge of mesozooplankton and fish stocks in the region, and lay out general implementation plans for two levels of U.S. GLOBEC effort in the Arabian Sea. The first level is to take advantage of and to supplement U.S. JGOFS and ONR efforts already planned for the middle 1990's. It focuses on processes affecting mesozooplankton stocks along the U.S. JGOFS transect from Oman out into the central and southern Arabian Sea. The scale of this first-level plan has been set by the amount of support considered likely for a U.S. GLOBEC Arabian Sea program at the time of writing (late 1992). It fits the model for U.S. GLOBEC studies in that (1) target species are designated, (2) population processes of those species are the principal foci of the program, and (3) the studies will be designed to enable prediction of the impacts of global change on those key species.

The second-level plan is for a study adequate to examine the dynamics of the interaction between mesozooplankton stocks and the abundant mesopelagic fish, primarily migratory myctophids, which feed upon them in the Arabian Sea. The scale of this second-level plan has been kept within reasonable limits for a project funded primarily by the U.S., but it requires a dedicated ship, some specialized and expensive technology, and substantial numbers of personnel working in the Arabian Sea for a period of several years. Again, population processes of the target species are the focus, and the studies are designed to enable the prediction of the impacts of global change on those animal stocks. Because the target species can be designated with much more confidence in the case of the second-level plan, this study can be designed more explicitly and promises greater returns than the first-level plan.

*Physical Preliminaries - The Arabian Sea: A Monsoon-Driven Environment*

## Introduction

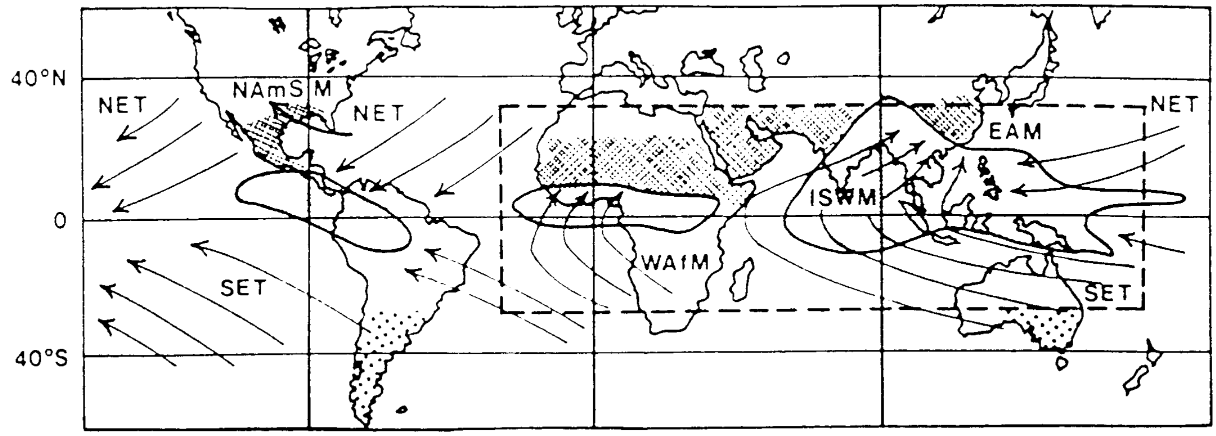
The intent here is to review the northern Arabian Sea ecosystem in relationship to the region's climate and both its monsoonal, wind-driven and thermohaline ocean circulation components. An attempt is made to lay out in one place the background for an Arabian Sea U.S. GLOBEC effort and to provide an introduction to the literature. With regard to the overall literature it is worthwhile mentioning several general sources. The reader is directed to the volume edited by Fein and Stephens (1987) for an up-to-date discussion of the various aspects related to the monsoon in meteorology, literature, history, climatology and oceanography. The International Indian Ocean Expedition (IIOE) hydrographic atlas compiled by Wyrtki (1971) is an excellent source on water mass distribution and the overall ocean circulation. Qasim (1982) and Swallow (1984) provide recent reviews of the regions general oceanography. The best single sources on the biology of the Indian Ocean can be found in the volume compiled by Zeitzschel (1973) and the National Institute of Oceanography at Goa's 25th anniversary volume (Desai, 1992). The reader should also consult the U.S. JGOFS Arabian Sea Process Study document (Smith et al., 1991) for reviews of the regional processes. Finally there is a special issue of Deep-Sea Research on the northern Arabian Sea based in part on British, U.S. and German work there in 1986-87 which is in press.

This review will begin with some basic aspects of the monsoons and their climatic variability. The basic physics of the surface layers of the Arabian Sea and their relation to primary production are then treated. This is followed by a discussion of the intermediate-depth low-oxygen layer and its relationship to the circulation and biogeochemical balances.

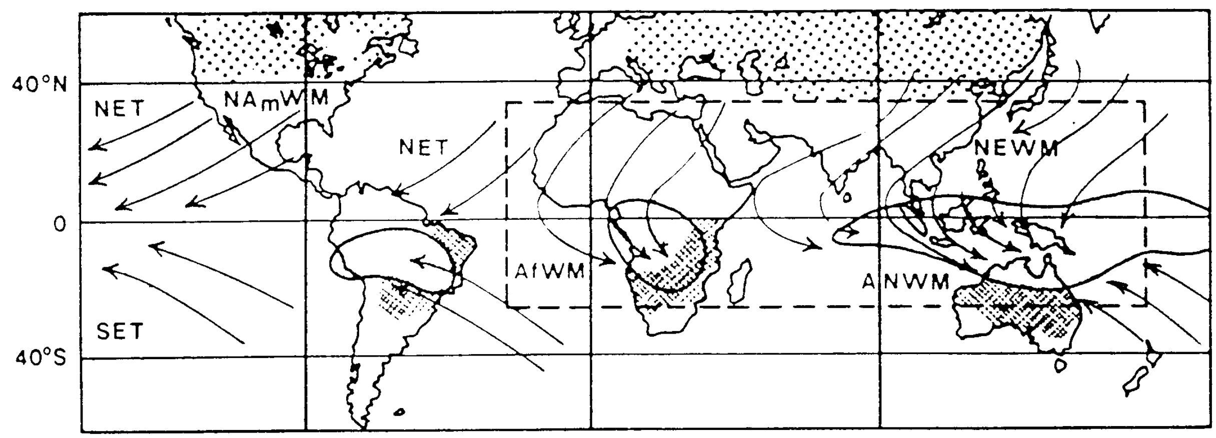
## Monsoon Systems

Monsoon systems are planetary-scale, seasonal cycles in atmospheric circulation associated with ocean-continent thermal contrasts and typically movements of the intertropical convergence with its characteristic band of convection (Webster, 1987a; Fig. 1). The role of the land-sea temperature difference to these planetary "sea-breezes" was first appreciated by Halley (1686). Hadley (1735) pointed out the importance of the earth's rotation in determining the nature of the resulting winds. As pointed out by Webster (1987a) the only major process not covered in these two pioneering works was that of convection; i.e. the importance of evaporation and precipitation to the monsoon. The strongest monsoon system occurs between the continent of Asia and the Indian and western Pacific Oceans. These consist of the northern winter monsoon with flows off of the Asian continent and a northern-hemisphere summer monsoon with flows of moist maritime air onto the continent. A weaker system, the West African monsoon, occurs in the Gulf of Guinea (Halley, 1686; Hamilton and Archbold, 1945; Webster, 1987a).

The Asian monsoon, which can be broken into an eastern and Indian branch, consists of a build-up of high pressure over the Asian highlands in the northern-hemisphere winter. This produces the northeast Indian monsoon (NE monsoon) with near-surface winds which flow out of the northeast over the Indian subcontinent and out across the Arabian Sea. The other branch brings flow off the Chinese mainland out over the island archipelagos of the Philippines and Indonesia. Both branches cross the equator and push the intertropical convergence into the southern hemisphere. The situation reverses with the build-up of high pressure south of the equator in the Indian Ocean in April and lowering of surface pressure over the Asian highlands as summer approaches. This leads to a reversal in the winds proceeding first along East Africa and then across the center of the Arabian Sea and onto the Indian Subcontinent. The flow across the Arabian sea within this southwest monsoon takes the form of an intense low-level jet, known as the Findlater jet after Findlater (1969). As depicted in Findlater's (1969) work the jet typically bifurcates before it reaches the Indian coast into two branches which are denoted as the Somali and




(a)




(b)

Figure 1. Surface-level circulation in the various monsoon regions. (a) Northern-hemisphere summer. (b) Northern-hemisphere winter. Hatched areas denote heated continental regions while dotted ones are cooled. Regions enclosed in solid contours are those with heavy monsoon rains. The abreviations denote the northeast trades (NET), southeast trades (SET), North American summer and winter monsoons (NAmSM, NAmWM), West African monsoon (WAfM), African winter monsoon (AfWM), Indian summer monsoon (ISWM), East Asian monsoon (EAM) and northeast winter monsoon and Australian winter monsoon (ANWM). The components over the Arabian Sea are typically referred to as the northeast and southwest monsoons (NE, SW). Original figure is from Webster (1987a).

Split jet. The placement and time dependence of this split is important in setting the bounds of the wind stress curl induced open ocean upwelling which is a dominant feature of the Arabian Sea monsoon response. The NE and SW monsoons are separated by transition periods or monsoon lulls during which the wind speeds drop and the sea surface heats.

A major factor controlling the air-sea interaction during the monsoon and the structure of the near-surface ocean responses to this cycle is the alternate temperature rise to nearly 30°C during the lulls and the cooling which occurs through air-sea heat exchange during the high-wind periods. The phenomenon known as Arabian Sea cooling (Düing and Leetmaa, 1980, McCreary and Kundu, 1989) is most intense in the SW monsoon when the northern and western Arabian Sea are dominated by upwelling. This involves coastal upwelling along both the Arabian and Somali coasts (Currie et al., 1973; Schott, 1983; Currie, 1992), and open-ocean upwelling in the mid-basin associated with the wind-stress maximum under the Findlater jet (Smith and Bottero, 1977; Swallow, 1984; Bauer et al., 1991). The upwelling and surface heat exchange creates thermal anomalies in the western Arabian Sea which vary from year to year (Brown and Evans, 1981). While it has been suggested that these in turn modify the monsoon rainfall over India (Shulka, 1975; Raman et al., 1992), this effect is not seen in all models (Washington et al., 1977). During the SW monsoon, large-scale upwelling also occurs off southwest India (Banse, 1968; Shetye, 1984).

**Monsoon Variability**

The Indian monsoon is highly variable over a range of time scales (c.f. Kutzbach, 1987; Webster, 1987b). The variability is of interest to U.S. GLOBEC both in the context of climate variations and for operational reasons. Shorter-term variability within a monsoon is addressed first, followed by a discussion of the longer-term variations between monsoons.

The onset of the SW monsoon is variable but usually takes place between mid-May and mid-June. Southern regions have a larger range of onset dates than more northerly ones (cf. Krishnamurti, 1987). Onset in Bombay between 1977-1980 occurred within 7 days of June 15th (Krishnamurti, 1987). Onset over the northern Arabian Sea is essentially a tropical storm, the "onset vortex", which varies in intensity, but is strong enough to be a danger to shipping. The onset in Bombay is a good indication of the presence of the onset vortex, although Bombay is not necessarily affected in any given year. The monsoon is interrupted by lulls in rain and wind known as monsoon breaks. An example of these cycles between active monsoon periods and breaks in two normal monsoon years (see longer term variability below) is given in Fig. 2. It is not clear to what degree breaks involve wind reduction over the Arabian Sea. The monsoon breaks seem to be related to the passage of individual convective complexes (cloud bands) (Webster, 1987). At a slightly longer period there are 30-50 day oscillations in the monsoon (Krishnamurti et al., 1985a,b) which correspond to a global-scale oscillation in the tropics.

Interannual variations in monsoon strength appear from the scale of the bi-annual oscillation in the tropical atmosphere (Cadet and Diehl, 1984; Dube et al., 1990) to longer-period variations related to cycles ranging from ENSO (El Niño/Southern Oscillation) to glacial-interglacial time scales. The origin of the Southern Oscillation index stems from Walker's (1910, 1924) work on monsoon prediction. The result was a system more in tune to a Pacific basin phenomenon which became a major focus in oceanography in the 1970's (Bjerknes, 1969; Wyrtki; 1975). The ENSO phenomenon has seen a wealth of quantification over the last two decades. The connection between the ENSO and monsoons over the Arabian Sea, however, remains unclear. Barnett (1985) and Webster and Yang (1992) are but two of several attempts to consider the interaction between monsoon and ENSO. The latter authors suggest a selective coupling between the onset phase of the Asian summer monsoons and global-scale summer circulation patterns with weak global trade winds being tied to weak Asian monsoons. Although the exact nature of the latter coupling is uncertain in the sense of whether or not ENSO events start in the Indian sector, it

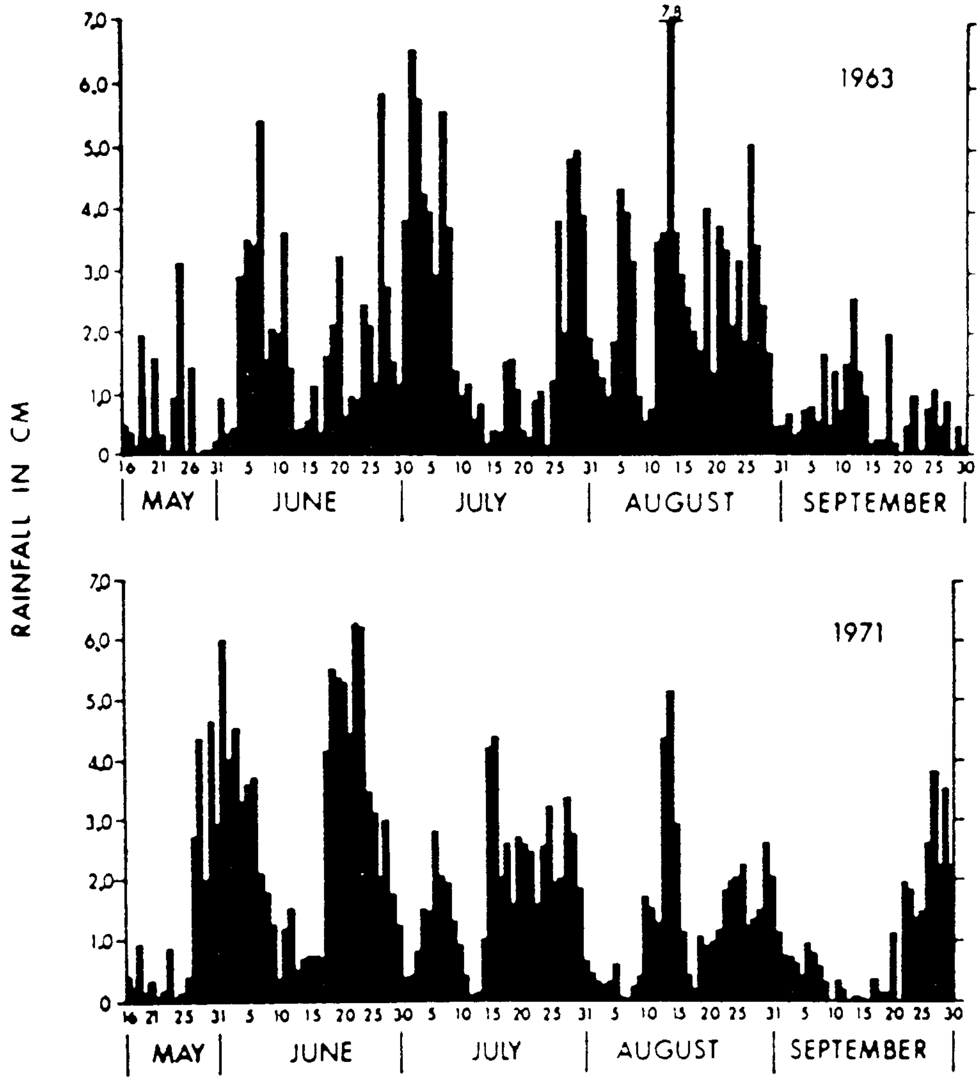



Figure 2. Rainfall along the western Indian coast during 1963 and 1971 from Webster (1987b). These are two fairly normal monsoon years as shown in Fig. 3.

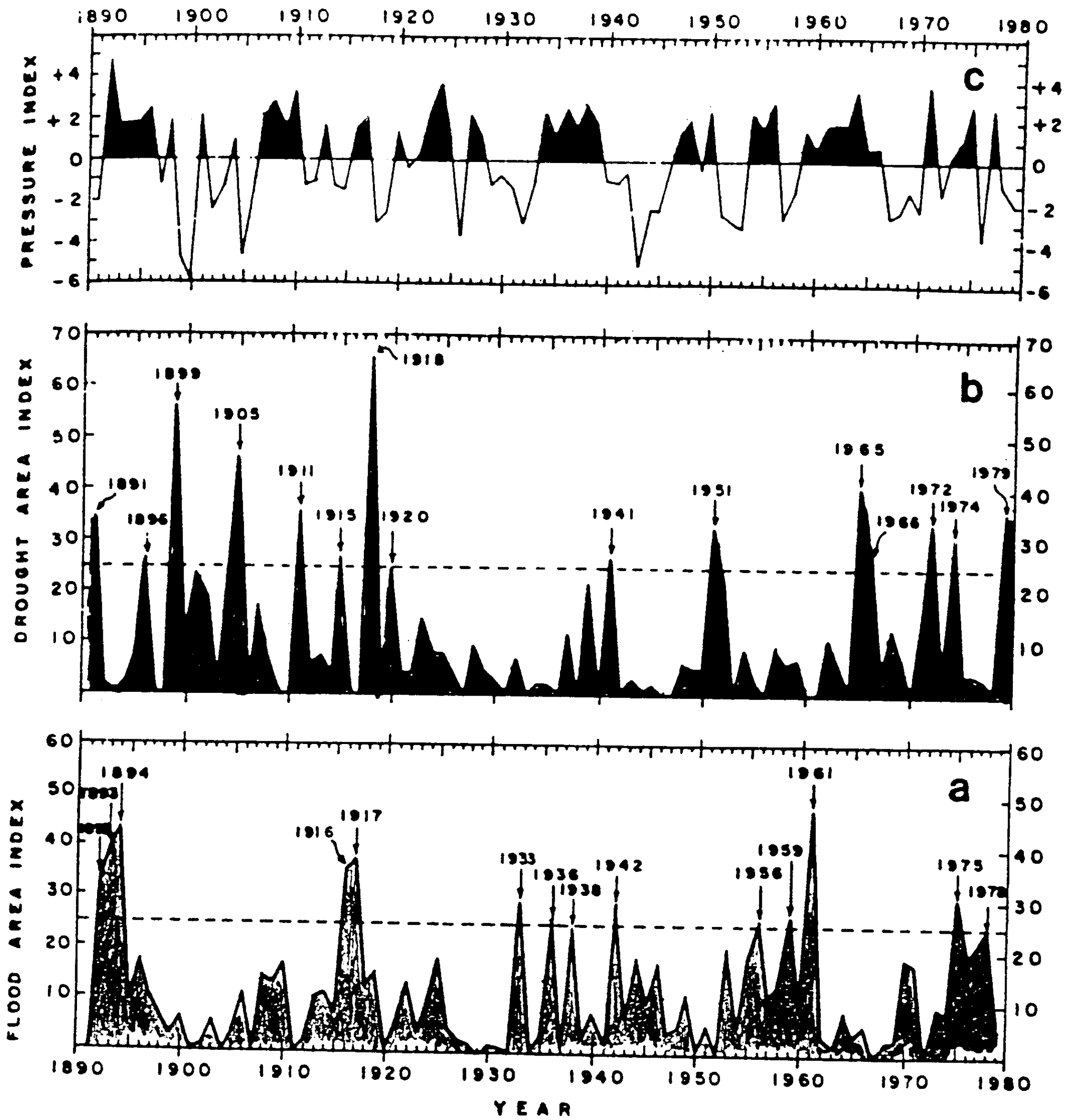



Figure 3. Rain and drought indices for India based on area effected. Figure shows clusters of years dominated by either dry or wet conditions over a decade time scale (from Bhalme et al., 1983).

is clear that Indian rainfall is less following ENSO events and heavy during anti-ENSO periods. A good example is the 1987 monsoon which had almost no rain over portions of India (Krishnamurti et al., 1989). It is important to note that much of the change in this monsoon involved low winds south of the equator and along the Somali coast. Winds over the central Arabian Sea were near climatological values (Bauer et al., 1991). There is little discernible trend in monsoon rainfall records over the last hundred years, but there is considerable interdecadal variation. The 1900's, 1920's, and 1960's all had lower rainfall, while the 1910's, 1930's, 1940's, 1950's, and 1970's saw higher rainfall (Fig. 3).

Finally, paleoceanographers have been able to use sediment records from the northern Arabian Sea to consider the longer-term variations tied to ice age cycles with their associated solar radiation forcing, and longer-term events such as the rise of the Tibet-Himalayas massif (Prell, 1984; Kutzbach, 1987; Prell and Kutzbach, 1987). Sediment records and modelling (Luther et al., 1990; Prell et al., 1990) suggest weaker monsoons at the height of the last glaciation (18 Kyr BP) and stronger monsoons at the interglacial maximum (9 Kyr BP).

**Surface Layer Response**

The physical response of the surface layers of the northern Arabian Sea to the monsoon cycle is important to understanding the operation of the region's pelagic ecosystems. Basic descriptions of the surface forcing fields and the nature of the mixed layer can be found in Cadet and Diehl (1984), Hastenrath and Lamb (1979), and Molinari et al. (1986). Surface currents are discussed in Cutler and Swallow (1984) and Molinari et al. (1990). Here the principal features are covered along with a description of conditions along ~65°E during the NE monsoon of 1986-87 and the SW monsoon of 1987 (Bauer et al., 1991). The wind patterns for the month of December and August are shown in Fig. 4.

Extremes of near-surface thermal stratification at the heights of the two monsoons are shown in Fig. 5. Note the overall shift in the slope of the thermocline; the large scale gradients of the thermocline are changed throughout the depth of sampling. Currents in the NE monsoon case are to the west (into the page). The flow reverses in the SW monsoon such that the flow is eastward and slightly stronger than in the northern winter. The SW monsoon section reveals a major mid-ocean upwelling zone separated from the coastal upwelling zone by a reversed flow. Smith and Bottero (1977) first suggested a separation of these two upwelling domains. The reversal can be interpreted as the westward end of a permanent anticyclonic circulation over the Murray Ridge (Quraishee, 1984, Bauer et al., 1991). Connections between these two upwelling systems in three dimensions remain to be fully established. This has ecological implications, particularly in respect to the coupling between coastal upwelling and mid-ocean conditions. This is one of the many cases where the Arabian Sea is a model in which to understand interactions between physics and biology in other flow-coupled pelagic ecosystems.

Mixed layers are deepest in the NE monsoon in the northwestern area (average about 125 m, Banse 1984; see also Fig. 5). During this season, they shoal to less than 20 m around 5°N (Bauer et al., 1991). Conditions during the SW monsoon in 1987 show the deepest mixed layers (~60 m) around 15°N with a minimum in mixed layer depth under the Findlater jet. The shallow mixed layers under the maximum winds are coincident with the upwelled dome of fluid in the SW monsoon (Fig. 5). Deepening of the mixed-layer by wind stirring is curtailed by the upwelling of the thermocline at rates of order $10^{-5}$ m $s^{-1}$ (Bauer et al., 1991). The deep mixed layers to the south of the wind maximum can only be explained through advection of dense mixed layers southward in the Ekman layer and the subsequent downward motion of the thermocline associated with Ekman pumping, with maximum vertical velocities of $-2.5 \times 10^{-5}$ m $s^{-1}$ (Bauer et al., 1991). The simple two-dimensional mixed-layer model of Bauer et al. (1991) suggests that the upwelled structure reaches an equilibrium in mixed-layer depth where the upward motion balances

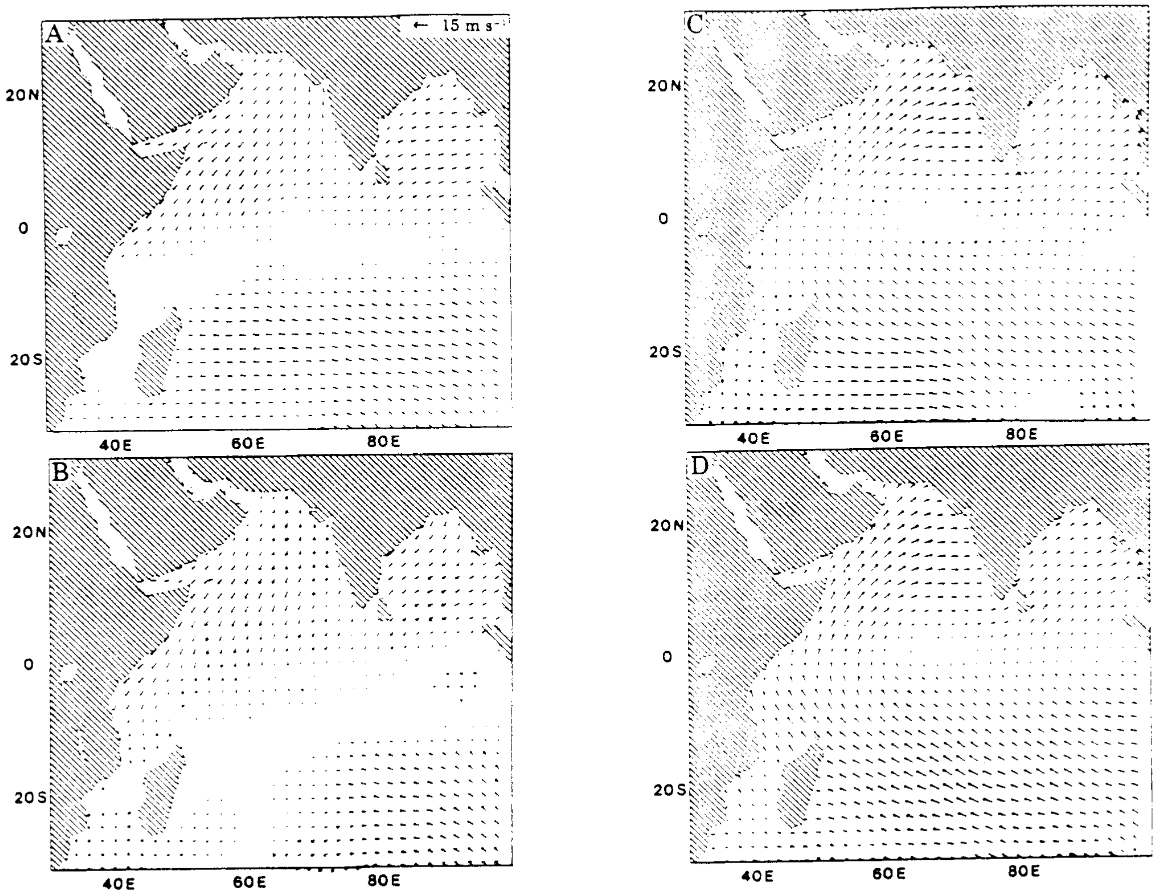



Figure 4. Monsoon winds for (A) December 1986, (B) January, (C) July, and (D) August 1987 from Bauer et al. (1991). The original data are from the COADS data set. Scale for the wind vectors is shown in panel (A).

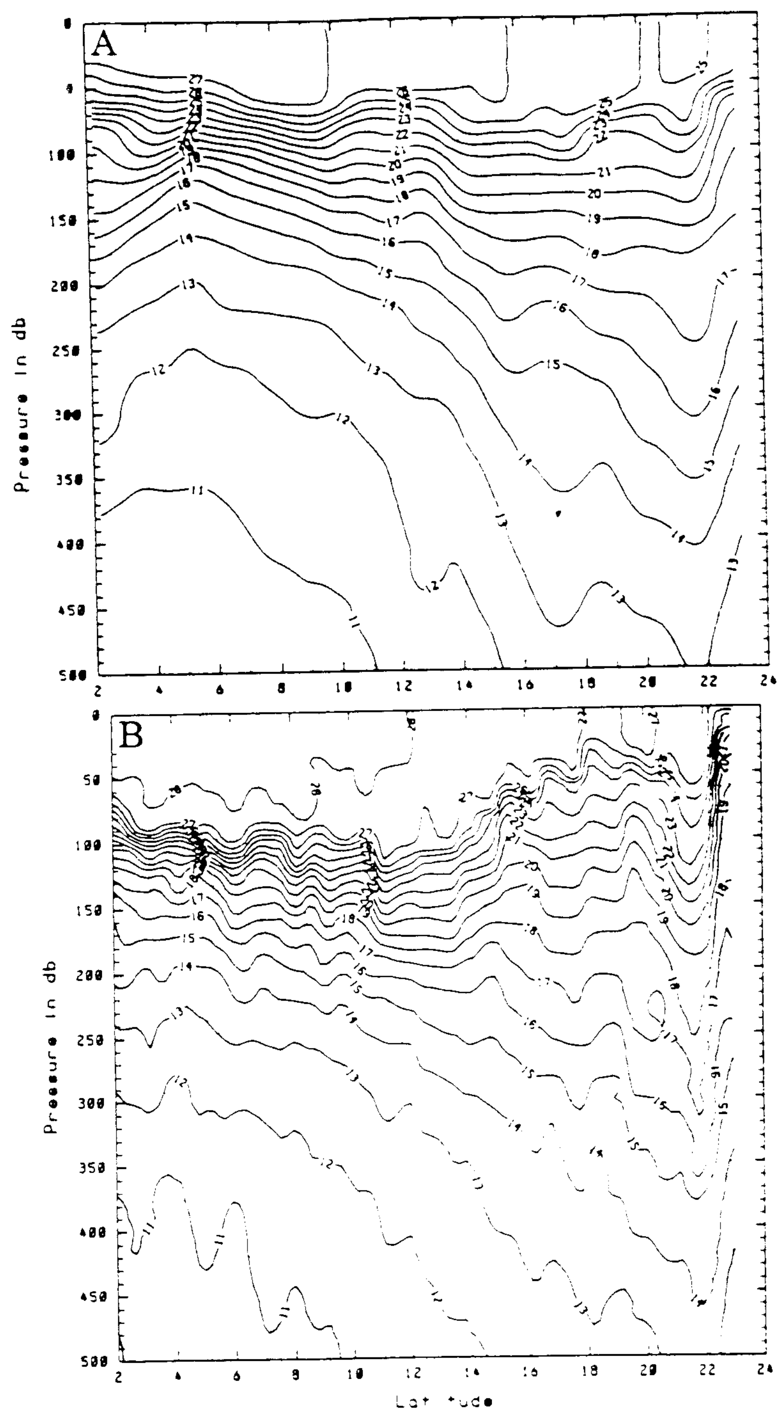



Figure 5. Temperature sections through the central Arabian Sea (60-64°E) in December 1986 and August 1987. Only the upper 500 db are shown although the effect of the monsoon forcing was evident to the 1200 db depth of the CTD casts. Data was taken on the RRS *Darwin.* See Bauer et al. (1991) for further discussion.

the turbulent entrainment rate. The deep mixed layers to the south continue to deepen in the simple model since turbulent entrainment and downwelling both act to increase mixed-layer depth.

**Phytoplankton Response**

During the SW monsoon, the combination of vertical motion and entrainment causes a very abrupt transition in phytoplankton biomass and productivities along an axis from the oligotrophic deep mixed layer up across the wind maximum into the mid-ocean upwelling region. This effect is obvious in chlorophyll sections along 65°E (Fig. 6). in which the coastal upwelling zone (with even higher phytoplankton biomass and productivity) is not shown. Chlorophyll biomass and $C^{14}$ productivities during these sections ranged from lows of 15-30 mg $m^{-2}$ and 0.3-0.6 g C $m^{-2}$ $day^{-1}$ in the deep mixed layer regime south of 15°N to extremes of 40 mg $m^{-2}$ and 1.1 g C $m^{-2}$ $day^{-1}$ in the mid-ocean upwelling region. These values agree with estimates from the IIOE work (Banse, 1988). It is the two dimensional development of the mixed layer associated with Ekman transports that lead to this coupled bloom and oligotrophic region. See Yentsch and Phinney (1992) for a similar explanation making use of the geostrophic relation in the thermocline. Quantities are even higher in the upwelling plume off Ras al-Hadd where in the 1987 cruise Chl-*a* biomass was 80 mg $m^{-2}$ and productivities were 2.5 g C $m^{-2}$ $day^{-1}$ (Hitchcock and Frazel, 1989). In contrast, the NE monsoon period (Fig. 6a) exhibits a lower Chl-*a* biomass over the entire region and lower productivities.

The description based on single sections through the region in single years cannot give a reasonable picture of the fields in light of the evidence discussed above for interannual variations. A powerful tool for quantifying the representative nature of limited ship based measurements is remote sensing. A series of papers (Banse and McClain, 1986; Brock and McClain, 1992; Brock et al., 1991) describe phytoplankton blooms in the Arabian Sea from CZCS data. There are blooms in *both* monsoons in the northern extreme of the basin (Banse, 1987), presumably caused by mixing related to cooling over the Gulf of Oman and Murray Ridge. Brock and McClain (1992) suggest interannual variability, which might be driven by the biannual oscillations in the forcing as discussed above. The reliable record, however, is very short. This should be improved with the SeaWiFS deployment in the time frame of the proposed Arabian Sea efforts.

**Thermohaline Circulation and Water Masses**

In most of the world's ocean the intermediate to deep circulation driven by water mass formation is of little direct consequence to the near-surface ecosystem. This is not the case in the Arabian Sea, where a layer over a kilometer deep is depleted in oxygen (Fig. 7). It is "suboxic", not anoxic; it does not usually contain hydrogen-sulfide. It does, however, have essentially no oxygen as evidenced by the depletion of nitrate in the water column (Deuser et al., 1978; Broecker and Peng, 1983; Naqvi, 1987; Naqvi, 1991; Naqvi et al., 1992). Recognition of the influence of this low oxygen layer on the biology of the region goes back at least to Gilson (1937) and the later Soviet work of Vinogradov and Voronina (1962a) and has formed one focus of studies in the region.

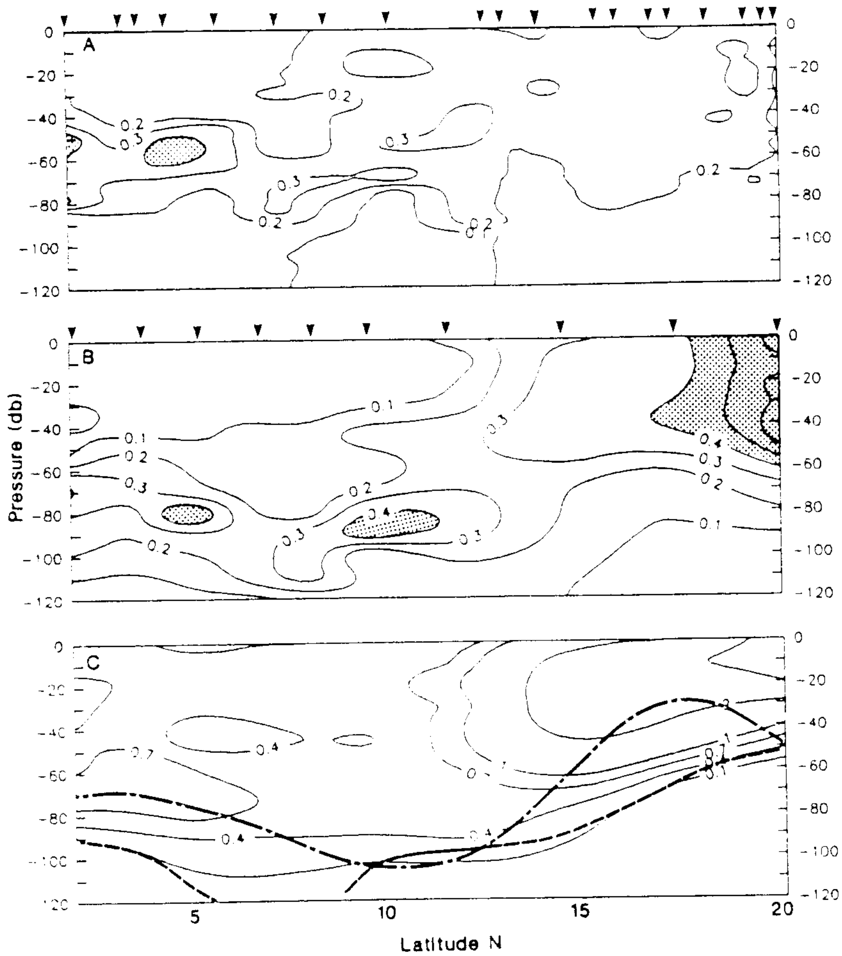



Figure 6. Chlorophyll in the northern Arabian Sea from the (A) December and (B) August *Darwin* cruises (Bauer et al., 1991). Stippled regions denote concentrations in excess of 0.4 mg $m^{-3}$. Panel (C) shows productivity estimates (mg $m^{-3}$ $h^{-1}$) from deck incubations during the SW monsoon in 1987. The dashed line is the depth of the one percent light level while the dot-dashed line provides an estimate of the depth of the nitracline.

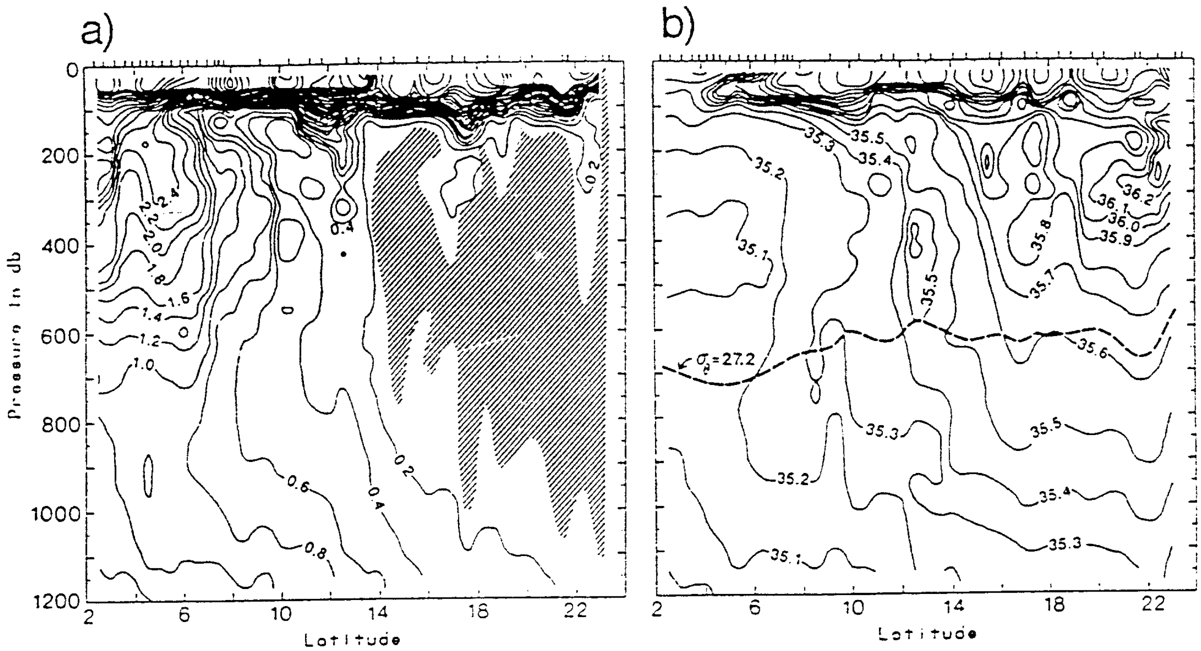



Figure 7. Sections showing the distribution of oxygen (ml $l^{-1}$) and salinity (ppt) along the *Darwin* cruise track in the Arabian Sea (December, 1986). The high-salinity water at the northern end of the section is Persian Gulf Water. Note that it is slightly oxygenated. The hatched region in the oxygen section has concentrations <0.1 ml $l^{-1}$. (see also Olson et al., 1993).

The physical and biological dynamics responsible for the oxygen minimum involves a complicated balance between the advection or mixing of oxygen into the layer and the removal of oxygen in the water column by respiration. Oxygen is added to the Arabian Sea by inflow of cold oxygen rich waters from the south up either the Somali or Indian coasts or by horizontal mixing between the Arabian Basin and the equatorial zone. Some oxygen is added through the introduction of warm, low oxygen waters from the marginal basins, the Red Sea and Arabian or Persian Gulf (Banse, unpubl.; Olson et al., 1993). Alternatively, oxygen can mix into the intermediate layers from the shallower or deeper adjacent waters (Swallow, 1984; Naqvi et al., 1992). The biological uptake of oxygen to balance these inputs depends ultimately on the primary production and how it is utilized. The available data suggests that the total phytoplankton production on an annual basis is not extraordinary (Olson et al., 1993) although the intense bloom and decay cycles may enhance the ratio of new to old production. A key issue in understanding the bloom and decay cycle involves better quantification of the grazing down of the phytoplankton stocks during the monsoons and the details of the trophic dynamics during the oligotrophic monsoon lulls.

There are many indications that the low-oxygen zone may be very variable and that it has varied considerably in the past. There are at least two studies that suggest the time scales for respiration versus oxygen input are very short compared to intermediate and deep water circulation times. Using anthropogenic chloroflurocarbon F-11 as an inert tracer, high-quality oxygen measurements and the productivity work quoted above, Olson et al. (1993) estimate that the time scale of oxygen renewal in the Arabian Sea is 23 years. A similar calculation based on the nitrogen cycle rather than that of oxygen gives time scales on the order of a year for the near surface portions of the low oxygen layer (Naqvi et al., 1992). Either estimate is very short relative to the time scales estimated for chlorofluorocarbons for the geographically analogous oxygen minima in the eastern North and South Atlantic Oceans (Doney and Bullister, 1992; Warner and Weiss, 1992). These time scales suggest that the oxygen minimum layer might be sensitive to decadal variations in the monsoonal forcing of surface productivity and circulation and to changes in the input from the marginal seas.

**Fisheries of the Arabian Sea**

In closing it is worthwhile to briefly explore the major pelagic fisheries of the Arabian Sea. The Indian Ocean is has one of the last under-exploited tuna fisheries (Rothschild and Yong, 1970; Sharp, 1992). As mentioned above, however, the extensive low oxygen zone apparently restricts all but some of the smaller tuna and occasional yellowfin. The southern coast of Oman supports a fishery for Indo-Pacific spanish mackerel (*Scomberomorus commerson*) with maximum landings in February to April (Dudley et al., 1992). Otolith analysis suggests that these fish grow up to 80 cm in their first year (Dudley et al., 1992). An old fishery centered in Salalah exploits the oil sardine (*Sardinella longiceps*) for camel fodder; the same species is a major contributor to the Indian fish catch. This species recruitment has been studied relative to the on set of the monsoon and coastal upwelling off southwestern India by Longhurst and Wooster (1990) but similar studies have not been carried out farther north on the Indian coast or off Oman. Their conclusion that the stocks of sardine are tied to the onset time and strength of remotely forced upwelling might also be applicable to the Omani coast. Mackerel, sardines and demersal fish (Banse, 1959) are all susceptible to upwelling of low oxygen waters into the coastal environment. The mackerel and sardine catches show marked interannual variations which are probably tied to variations in the physical forcing as suggested by the correlation between sardine catches at Cochin and sea level (Longhurst and Wooster, 1990). There is also evidence of a connection between the strength and onset of the monsoon and sardine catch (Murty and Edelman, 1971; Longhurst and Wooster, 1990) although further work with longer records is required to further quantify the connection. Fluctuations in mackerel catch in the same fishery are not correlated with deviations in sardines (Longhurst and Wooster, 1990). The variations in overall Indian mackerel catches are approximately decadal (Noble, 1992) with no long term trends. The final stock worthy of mention are the myctophid stocks in the Gulf of Oman. They are not currently being exploited although it has been suggested that they are exploitable (Gjøsæter, 1984).

*Modelling Studies of Arabian Sea Physics*

Shipboard and moored measurements can only sample the ocean at fixed times or locations. A numerical model that is adequately verified by *in situ* measurements can extend, interpolate, and extrapolate these measurements in time and space. Moreover, numerical models can be used to plan *in situ* measurement strategies to ensure that the relevant features of the ocean are adequately sampled. A coupled physical-biological model provides a mechanism for integrating satellite altimeter, SST and ocean color data with *in situ* measurements into a common coherent framework for analysis and interpretation. This will become particularly useful with the launches of the Topex-Poseidon altimeter and the SeaWiFS ocean color sensor. A coupled model will allow the maximum exploitation of the satellite ocean color data and other remotely sensed variables.

Numerous modelling efforts have sought to explain the observed flows in the tropical and subtropical northern Indian Ocean, with particular attention given to the semi-annual reversals in the Somali Current along the east coast of Africa (e. g. Cox, 1970, 1976, 1979; Hurlburt and Thompson, 1976; Lin and Hurlburt, 1981; Luther and O'Brien, 1985; Luther et al., 1985; McCreary and Kundu, 1988, 1989; Kindle and Thompson, 1989; see Luther (1987) or Knox (1987) for a review).

Luther et al. (1990), Prell et al. (1990), and Brock et al. (1991), using a reduced-gravity ocean circulation model of the Arabian Sea, were able to qualitatively reproduce much of the spatial and temporal variability observed in upwelling/downwelling and primary production. Reduced gravity models are efficient in that they retain the physics necessary to reproduce many of the observed features of ocean circulation while remaining relatively simple to analyze. In these simulations, nutrient injection into the photic zone and biological activity are inferred from upward movements of the model pycnocline, since the model does not include active thermodynamics or mixed-layer processes. Biological activity, particularly primary production, will be better quantified by the addition of mixed-layer physical dynamics and biological processes to the numerical models.

The ocean circulation model developed by Luther and O'Brien and collaborators (Luther and O'Brien, 1985; Luther et al., 1985; Simmons et al., 1988; Woodberry et al., 1989; Luther and O'Brien, 1989; Jensen, 1991; Potemra et al., 1991) is being coupled with the photosynthesis-irradiance (P-I) model of Platt and Sathyendranath (Platt and Sathyendranath, 1988; Sathyendranath and Platt, 1989; Sathyendranath et al., 1989; Platt and Sathyendranath, 1991). John Brock, Trevor Platt, and Shuba Sathyendranath of the Bedford Institute of Oceanography are collaborating with Mark Luther in this effort. A mixed layer parameterization with active thermodynamic forcing as in McCreary and Kundu (1989) is being added to the ocean circulation model in cooperation with J. P. McCreary at Nova University. The inclusion of mixing and thermodynamic processes in the ocean circulation model is essential for the accurate determination of sea surface temperature and for the determination of the parameters needed by the P-I model.

Modelling efforts for the Indian Ocean are also underway by J. P. McCreary and P. Kundu at Nova University (McCreary and Kundu, 1988, 1989), by J. C. Kindle at the Naval Research Laboratory (Kindle and Thompson, 1989), and by D. L. T. Anderson and collaborators at Oxford University, and G. R. Bigg and collaborators at East Anglia University (Anderson et al., 1991; Bigg et al., 1992). The Nova and NRL models are very similar to the Luther and O'Brien model. All three models use a layered, reduced-gravity formulation with very high horizontal resolution (order 10 km). The major differences among the models are in the mixing parameterizations and the boundary conditions. Luther, Kindle, and McCreary are collaborating to evaluate the effects of these differences and to improve the mixed-layer formulations in the models. Kindle and McCreary are also incorporating active biological processes in their models. The Anderson and Bigg model is a variation of the Bryan-Cox-Semtner model developed at the Geophysical Fluid Dynamics Laboratory. It has high vertical but coarse horizontal resolution (order 30 to 100 km).

Therefore, the model does not adequately resolve the sharp gradient in wind stress curl found in the Findlater Jet that drives the corresponding gradient in open-ocean upwelling in the Arabian Sea.

## Introduction

The intent of this section is to review briefly current knowledge of the structure and dynamics of the mesozooplankton of the Arabian Sea. The reader is referred to Peterson's (1991) contribution to the U.S. JGOFS Arabian Sea Process Study Report. This essay will not repeat many facts stated there.

Monsoonal changes in wind strength and direction in the Indian Ocean result in dramatic seasonal changes in mixed-layer depth and phytoplankton concentration. During the SW monsoon, coastal upwelling occurs within 50 km of the Arabian peninsula. Further offshore, spatial gradients in the strength of the Findlater Jet during the SW monsoon cause Ekman upwelling and shoaling of the nutricline in the northwestern portion of the Arabian Sea. Coastal Zone Color Scanner images of chlorophyll-a just prior to and following the strong southwesterly winds of the summer monsoon show the development of intense blooms of phytoplankton from the coast of Arabia to 500 km offshore. The seasonal bloom of phytoplankton biomass is so extensive and of such high magnitude that it must be of ecological importance to the zooplankton species and populations of the northern Arabian Sea. We find nothing in the literature which describes or quantifies that ecology.

## Zooplankton Biomass

Much of the available data on zooplankton and fish distributions over the entire Indian Ocean comes from the International Indian Ocean Expedition (IIOE) (cf. Zeitzschel, 1973). Samples obtained during the (IIOE) of 1960-65 indicate that zooplankton biomass is highest in the northern and western Arabian Sea (IOBC, 1968a; IOBC, 1968b; Prasad, 1969; Rao, 1973; see also figure on inside front cover of Zeitzschel, 1973). Highest zooplankton biomasses occur near the coasts of Somalia and Arabia, and also on the southwest coast of India. The central region of the Arabian Sea has generally lower zooplankton biomass. Rao (1973) provides maps of the distribution of zooplankton biomass for the northeast monsoon (December-February) and southwest monsoon (July-September) periods (Fig. 8). Seasonal changes (between NE and SW monsoons) of zooplankton biomass off the coast of Arabia and in central and northern oceanic realms of the Arabian Sea are difficult to evaluate from the IIOE data due to the incomplete seasonal coverage of those regions (see Banse, 1991). The best seasonal data exist for the Indian Exclusive Economic Zone and contiguous waters, which approximately extend to the position of the eastern JGOFS time series station (roughly at 15°N, 70°E, Fig. 18). Mathew et al. (1990a) have summarized zooplankton biomass data obtained with a 60 cm diameter net of the same mesh size as the IIOE net, towed from 150 m to the surface and differentiated both seasonally and latitudinally. Offshore and north of 20°N, the time before the SW monsoon exhibits highest biomass (an after-effect of the high primary production of the NE monsoon?) while to the south, it is the SW monsoon season. The latter is in accord with the sediment trap data of Nair et al. (1989) near the eastern JGOFS time-series station. During June-October, but especially in July and August, coastal upwelling occurs along the west coast of India; highest zooplankton biomass occurs during upwelling periods and maximum fish harvests occur during or soon after upwelling. Figure 9 shows the close temporal correspondence between coastal upwelling and zooplankton biomass at four latitudes along the west coast of India from 16°N south (Menon and George, 1976). The effects of upwelling off the west coast of India are restricted to near-shore regions; zooplankton biomass adjacent to the coast during the SW monsoon upwelling was 4-10 times higher at stations within 10 miles of the coast than at stations farther than 30 miles offshore where bottom depths exceed 200 meters (Madhupratap et. al., 1990; Menon and George, 1976). However, seasonal contrasts appear to be greatest in the coastal upwelling regions off Somalia and Oman. Rao (1973, p. 251), in his discussion of zooplankton biomass distribution in the Arabian Sea, reports:

> From the above account of the seasonal distribution of the biomass, it is evident that the areas adjacent to the Saudi* Arabian coast consistently show very high ranges of productivity during the prolonged SW monsoon period. A comparison of the biomass distribution with the surface thickness layer distribution makes clear that high biomass values overlap areas of no surface layer or regions of upwelling. In this respect the Saudi Arabian coast is unique....All these circumstances combine to make the Saudi Arabian coast the richest area for secondary production in the north Indian Ocean. [*Note: Saudi Arabia does not border the Arabian Sea; however Yemen and Oman on the *Arabian Peninsula* do].

As discussed in the section on physics, more recent studies (Bauer et. al., 1991; Smith and Bottero, 1977) suggest that high phytoplankton biomass off the Arabian peninsula result from two distinct SW monsoon upwelling regions: a coastal upwelling domain of ca. 50 km width, and a north central Arabian Sea upwelling domain (of ca. 500 km width).

## Zooplankton Species Composition

The International Indian Ocean Expedition (IIOE) of 1960-1965 was arguably the first attempt to describe the quantitative geographic distribution and abundance of zooplankton in the Arabian Sea. Ships from several countries collected 1548 plankton samples using the Indian Ocean Standard Net (Currie, 1963). Copepod distributions from the IIOE can be found in Kasturirangan et al. (1973), Fleminger and Hulsemann (1973), Stephen et al. (1992), and Gopalakrishnan and Balachandran (1992). Most of the available data cover the large calanoid copepods, due to the large mesh nets used in IIOE (> 300 µm). The samples also are typically limited to the 0-200 m strata and therefore underrepresent forms which have deeper distributions. Chaetognaths are covered by Nair and Rao (1973). Brinton and Gopalakrishnan (1973) review the euphausiid distributions. Other zooplankton groups are discussed in Zeitzschel (1973) and Desai (1992). Apart from the IIOE collections, other, more localized regions of the Arabian Sea have been sampled for zooplankton. Some of the local studies provide better seasonal coverage and more complete taxonomic analysis than has been done to date with the IIOE collections. The species composition, abundance and distribution of zooplankton are reasonably well known for coastal regions of the Arabian Sea, especially the regions adjacent to Somalia (Smith 1982, 1984), India (among more recent papers, see Mathew, 1980, 1985; Madhupratap et al., 1990; Srinivasan, 1976), and Pakistan (Haq et al., 1973; Srinivasan, 1981). Likewise the zooplankton of the Red Sea and, to a lesser extent, the Gulf of Aden (Halim, 1969; Rudyakov and Voronina, 1967) are known. Madhupratap and Haridas (1986) provide a list of zooplankton species and show abundances of copepod taxa from a transect within the oceanic region of the western Indian Ocean. Unfortunately, their transect did not continue north into the central Arabian Sea. The cruise tracks of Soviet research vessels in the Arabian Sea show that Soviet oceanographers have collected many zooplankton samples throughout the northern and central Arabian Sea. Except for a few reports published (e.g., Vinogradov and Voronina, 1962a) or translated (papers in Oceanology) to English, the results are either unpublished or available only in Russian (e.g., Grobov, 1968; Vinogradov and Voronina, 1962b; Voronina, 1962), and are generally unavailable. The species composition and distribution of zooplankton of the coastal waters off Arabia and of the oceanic central Arabian Sea are poorly known.

### *Basin Scale Zooplankton Distributions*

The basin scale distributions and abundance of total copepods (but with few exceptions, not individual species), ostracods (George, 1968), euphausiid species (Gopalakrishnan and Brinton, 1969; Brinton and Gopalakrishnan, 1973), appendicularian species (Bückmann, 1972; Fenaux, 1972), amphipods (Nair et al., 1973; Nair, 1976), total hydromedusae (Santhakumari, 1976), and chaetognath species (Nair and Rao, 1973; Nair, 1976a), as well as other, less abundant zooplankton taxa, have been described from the plankton collections of the IIOE. Of these groups the copepods and the euphausiids are likely the most important to the ecology of the large stocks of

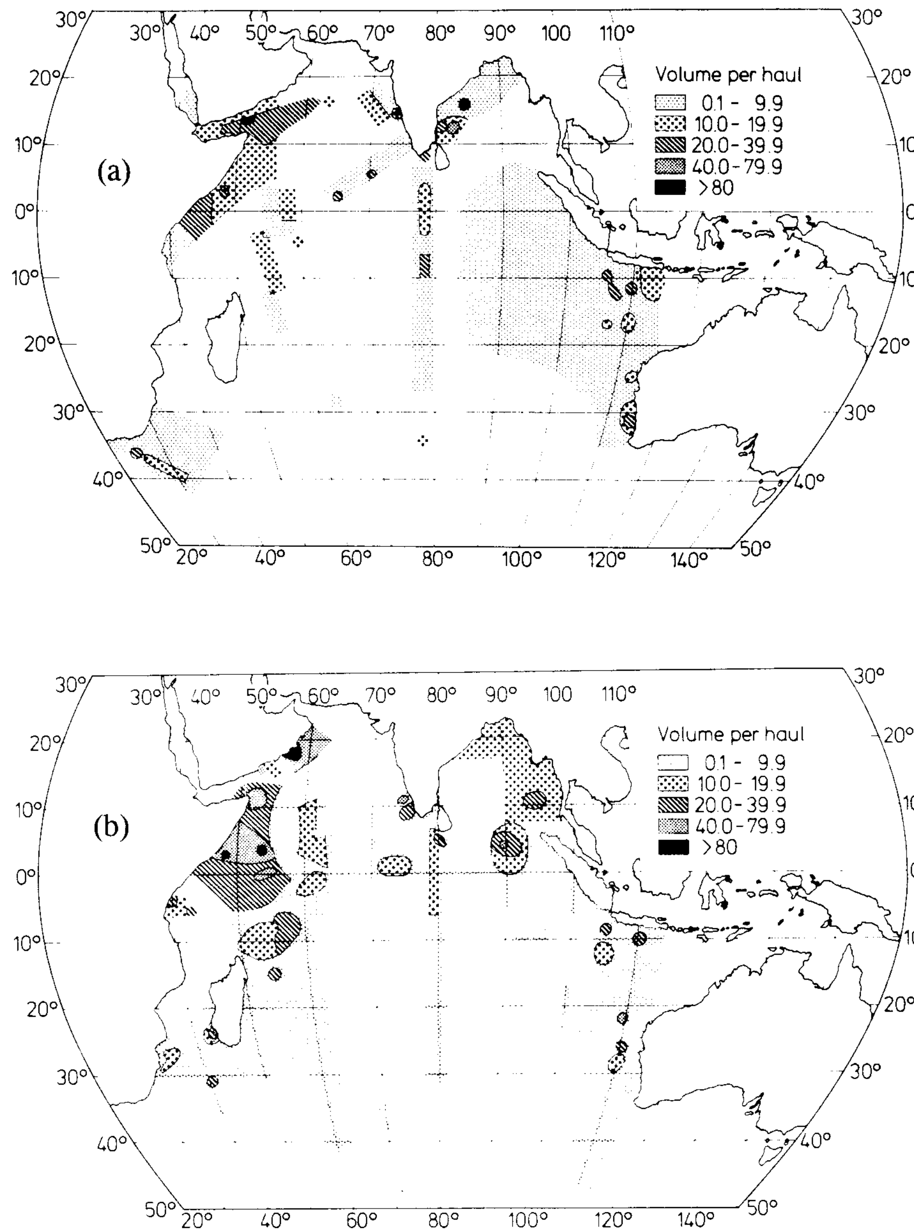



Figure 8. Regional and seasonal variation in zooplankton biomass (ml $m^{-2}$) for a 200 m water column in the Indian Ocean, (a) December-February (northeast monsoon), (b) July-September (southwest monsoon). (From Rao, 1973).

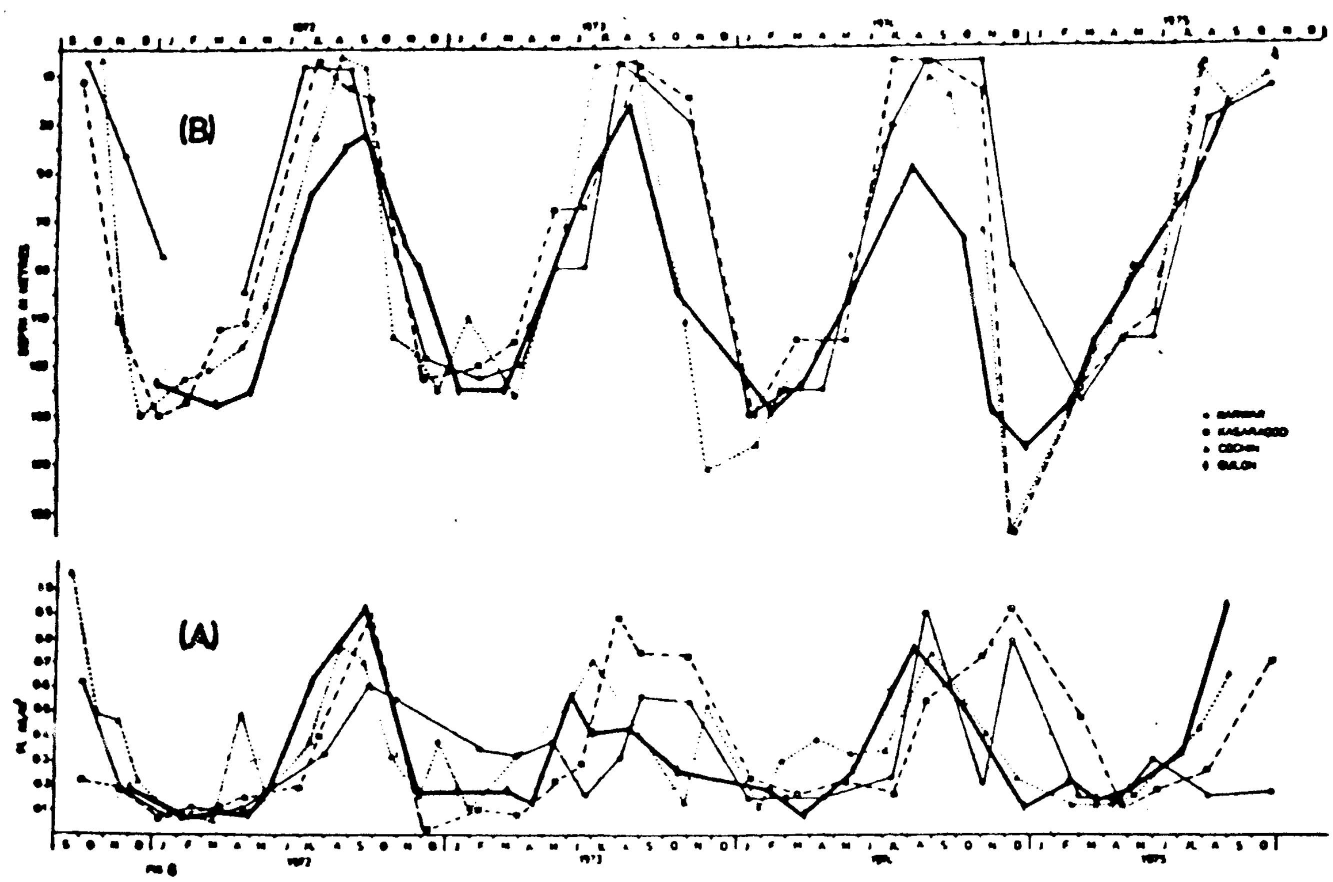


Figure 9. (a) Average zooplankton biomass (ml $m^{-3}$) at selected sections of the southwest coast of India for September 1971 to October 1975. (b) Plots of depths 1 ml $l^{-1}$ oxygen isoline (related to upwelling processes) for the southwest coast of India for September 1971 to October 1975. (From Menon and George, 1976).

mesopelagic fishes (myctophids) in the region.

The zooplankton biomass of the Arabian Sea is largely comprised of copepods. The seasonal change in total copepod abundance is shown in Figure 10 (Kasturirangan et. al., 1973). Highest copepod densities occur along the northwestern border of the Arabian Sea. During April-October (SW monsoon) peak copepod abundances occur in the upwelling regions off Somalia and Arabia, but high densities also occur far offshore of the Arabian peninsula. During October-April (NE monsoon) copepods are abundant off the Arabian peninsula and in the Gulf of Oman, but are somewhat less abundant (compared to the SW monsoon) off Somalia. Unfortunately, the IIOE plankton collections have not been mined as extensively as one would hope at the species level. The distribution and abundance of only a few copepod species have been reported, notably, *Gaussia princeps* (Saraswathy, 1973a,b), *Euchaeta* spp. (Tanaka, 1973), *Haloptilus* spp. (Sarala Devi et. al., 1979), *Pontella* spp. (Pillai, 1975) and *Candacia* spp. (Lawson, 1977). Nor have the plankton samples from the IIOE been mined in another, potentially more valuable, way; namely, identification and enumeration of the entire copepod assemblage from samples collected within a defined region and season. Consequently, the reported results from the IIOE plankton investigations leave us ill-prepared to specify with any confidence which copepod species are dominant regionally or seasonally.

Of the large calanoid copepods the family Eucalanidae dominates the Arabian Sea with mean abundances of 3000 and 2250 per standard India Ocean haul (0-200 m) in the SW and NE monsoons, respectively (Stephen et al., 1992; these numbers are nearly identical to individuals per $m^2$). The genera *Euchaeta* (1500/1900 for SW/NE monsoons) and *Pleuromamma* (270/1100 for SW/NE monsoons) are also abundant. Other represented taxa include the genera *Lucicutia* and *Undinula*, and the families Centropagidae and Temoridae. Of these the Centropagidae and Temoridae are coastal, *Undinula* is distributed in the region of the open-ocean upwelling, and Eucalanadae and *Pleuromamma* are found throughout much of the northern Arabian Sea (Stephen et al., 1992).

Species level analyses of the IIOE data are not complete and there is still some uncertainty in some of the systematics. For the copepods, Gopalakrishnan and Balachandran (1992) present the Scolecithricidae species from IIOE. Saraswathy (1986), Saraswathy and Krishnaiyer (1986), and Goswami et al. (1992) present data on *Pleuromamma* from various cruises. *P. indica* replace *P. gracilis* as the dominant species north of 10°N. This is consistent with *P. indica* making up between 21 and 95% of the myctophid diets in the surveys of Kinzer et al (1993). Saraswathy (1986) suggests that *P. indica* is tolerant to oxygen concentrations as low as 0.1 ml $L^{-1}$ and is therefore adapted to the conditions in the northern Arabian Sea. Another species of interest is *Calanoides carinatus* which seems to dominate certain coastal upwelling systems at least episodically (Smith, 1982, 1984, 1992b). *Calanoides* is only found in 15 of the 340 IIOE stations sorted by Stephen et al. (1992). Only five of those stations are in the northern Arabian Sea; at one SW monsoon station 1175 individuals per standard haul were found. Two stations during the NE monsoon recorded 88 and 3 individuals.

The most thorough, IIOE-based study of Arabian Sea copepods at the species level is Lawson's (1977) work on *Candacia* and *Paracandacia*. Lawson examined essentially the entire IIOE sample set covering the Indian Ocean to 35°S for this distinctive and well-studied genus. Distribution patterns for the Arabian Sea show both endemic species and species excluded from the region that are broadly distributed in the rest of the tropical Indian Ocean (Figure 11). *Candacia samassae* is endemic in all waters north of 10°N in both the Arabian Sea and Bay of Bengal. *Paracandacia bispinosa* is found essentially throughout the Indian Ocean, including the Bay of Bengal, but it is absent from the Arabian Sea north of 10°N (several exceptional occurrences are shown by Lawson right inshore off western Oman; Figure 11). These patterns suggest that the Arabian Sea is a distinctive pelagic habitat in some respect. Moreover, it has hydrographically

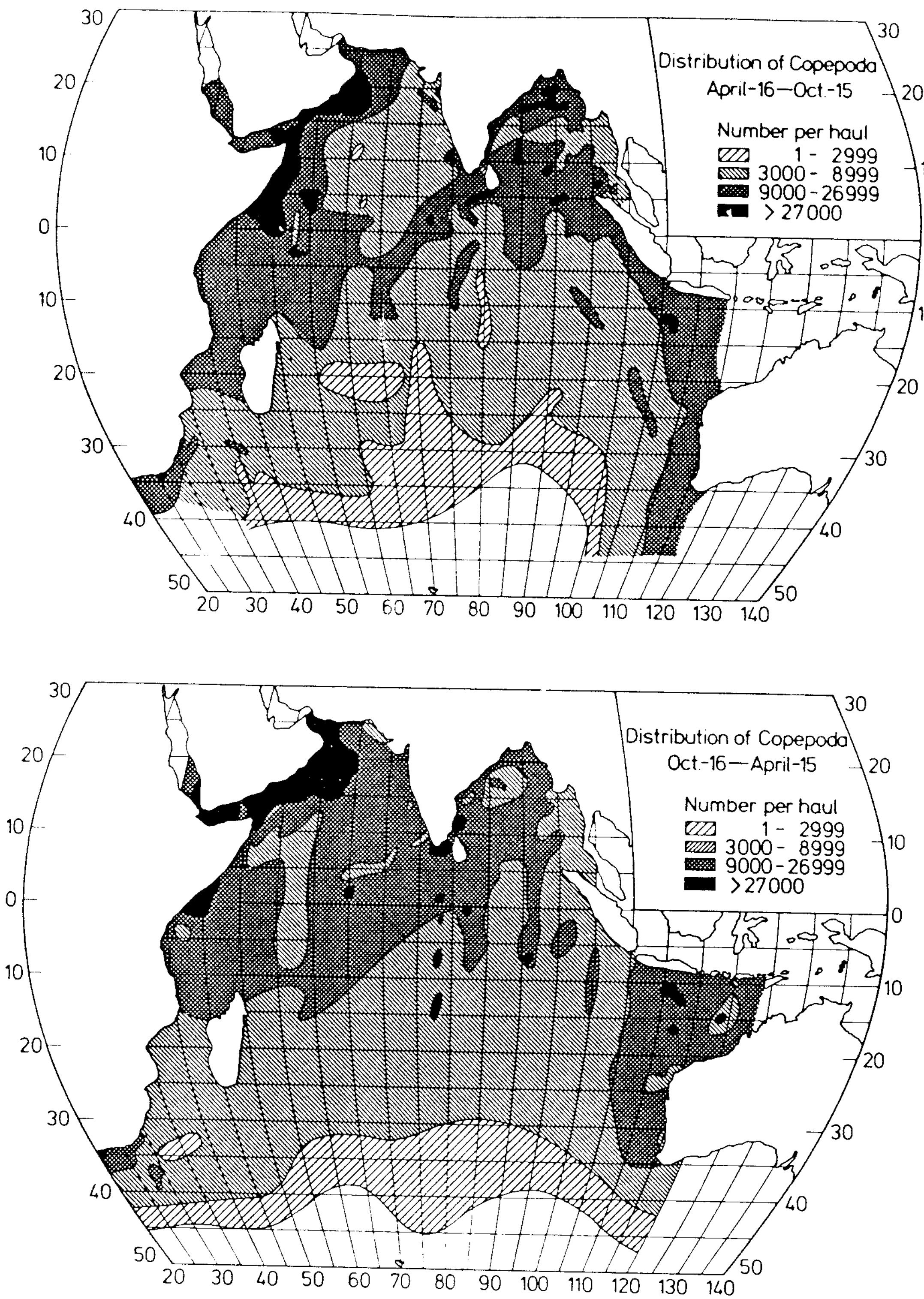



Figure 10. Distribution of Copepoda in the Indian Ocean from IIOE sampling, (a) 16 April to 15 October (southwest monsoon), (b) 16 October to 15 April (northeast monsoon). (From Kasturirangan et al., 1973; data originally from IOBC, 1970a).

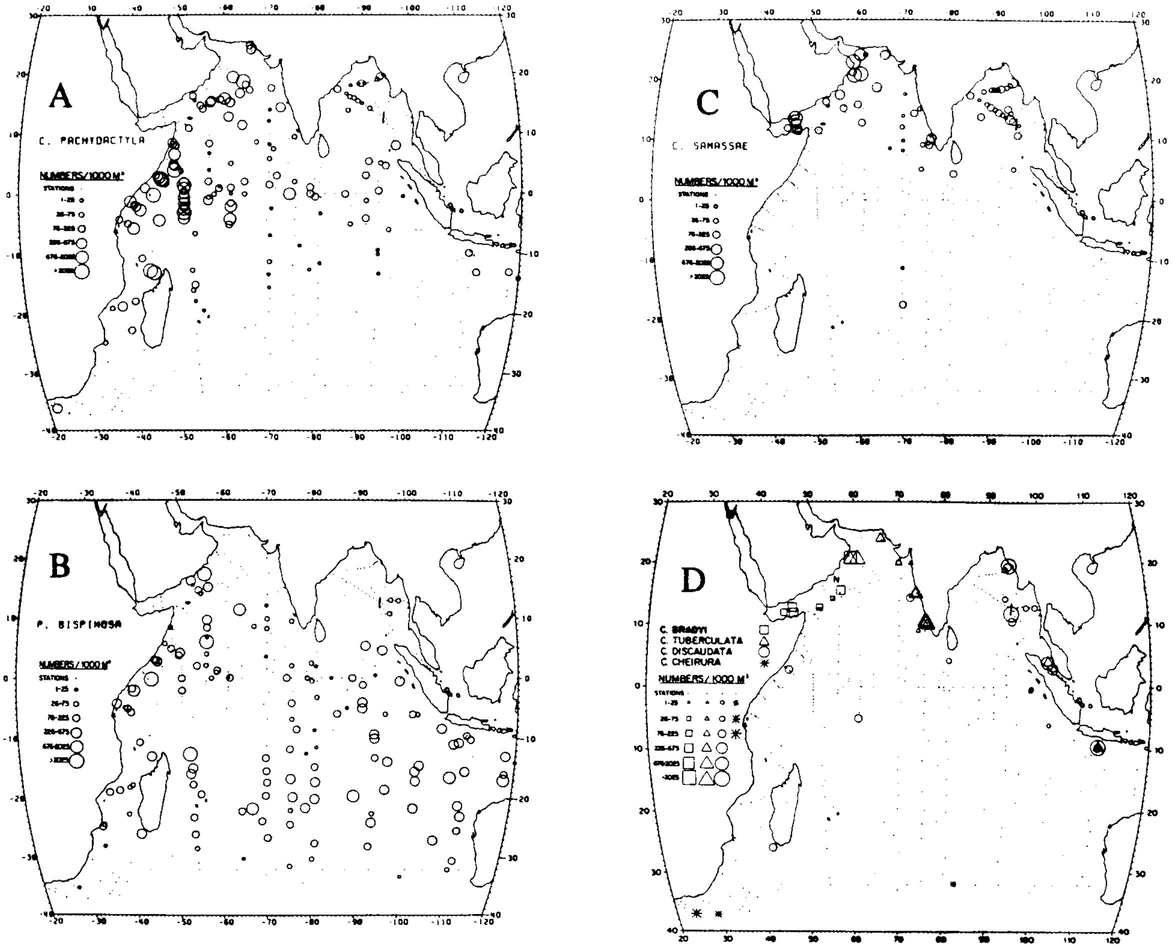



Figure 11. *Candacia* and *Paracandacia* spp. Distribution maps of selected species in the Indian Ocean. (From Lawson, 1977).

distinct subregions to which mesoplankton populations respond by stock development or failure. *Candacia bradyi* is narrowly endemic in coastal upwelling along the Arabian Peninsula from the Gulf of Aden northeast to Oman. Although not reported off southwest India from the IIOE sampling, it shows up in SW monsoon samples off SW India (Madhupratap et al., 1992). It has no oceanic population at all. *Candacia tuberculata* is a coastal form whose range extends south along the Indian Peninsula from the Gulf of Oman to about Goa. It is not found elsewhere. *Candacia pachydactyla*, which is common across the equatorial belt becomes abundant in the Somalia Current and along the zone of the Findlater jet. However, it was present at only a few stations closer to the Arabian peninsula. On the other hand, *Paracandacia truncata*, which is common in tropical and subtropical waters worldwide, is common all over the Indian Ocean, including stock extensions nearly to the coast all around the Arabian Sea coast. Lawson's study of *Candacia* demonstrates that, as we find everywhere in every group of organisms, there are both habitat generalist and specialist species.

It can be expected that other copepod genera, when thoroughly studied will have both species endemic to the Arabian Sea and species with extended gaps in this region. For example, according to Rao et al. (1981), "The copepod *Gaussia sewelli* is endemic to the northern Indian Ocean particularly Arabian Sea and Bay of Bengal (Saraswathy, 1973)". Another copepod showing limited distribution in the Arabian Sea and Bay of Bengal is *Pleuromamma indica* (Saraswathy, unpublished data)." (see also Saraswathy and Krishnaiyer, 1986).

Rao et al. (1981) report other species of zooplankton (beside the *Candacia* species studied by Lawson) that are either endemic to the Arabian Sea or have exceptionally large stocks there:

> [A] preponderance of hydromedusae *Aglaura hemistoma* and *Solmundella bitentaculata* characterize the Arabian Sea water (Vannucci and Navas 1973). The cladoceran *Evadne spinifera* is found in the northeastern waters of the Arabian Sea (Della Croce and Venugopalan, 1973). Five out of the six species of the mysid belonging to the genera *Paralophogaster* are confined to the Red Sea and Arabian Sea while the species *Siriella ionesi* is limited to the Arabian Sea.

*Pseudeuphausia latifrons*, *Euphausia distinguenda* group, and *Euphausia diomediae* are the most abundant euphausiid species in the Arabian Sea (Brinton and Gopalakrishnan, 1973). *P. latifrons* is essentially a neritic species, with substantial populations found along the coasts of Somalia, Arabia, and India during the SW monsoon (Fig. 12). Densities exceeding 2500 per 1000 $m^3$ were found in and offshore of the coastal upwelling domain off Arabia in that season. This species also occurs along the Pakistan coast and in the Gulf of Oman (Weigmann, 1970). During the NE monsoon, *P. latifrons* populations along Somalia and Arabia were much lower; however, significant populations were observed along the coasts of Pakistan and India, and in the central Arabian Sea. The *E. distinguenda* group, comprised of two similar species, was abundant (>5000 per 1000 $m^3$) off Arabia during both the SW and NE monsoons. Abundance of *E. distinguenda* was highest around the margins of the Arabian Sea and lower in the central and southern Arabian Sea. *Euphausia diomediae* is abundant (>500 per 1000 $m^3$) throughout most of the Arabian Sea. This species was well represented off the coast of Arabia during both monsoon seasons, but especially during the SW monsoon.

*Southwest coast of India and coast of Pakistan*

The latitudinal, onshore-offshore, and to a lesser extent seasonal, distributions of species within a number of zooplankton taxa, including copepods (Haq et al., 1973; Stephen et al., 1976; Madhupratap et al., 1990; Madhupratap and Haridas, 1990), euphausiids (Mathew 1980, 1983, 1985, 1986; Silas and Mathew, 1986), appendicularians (Bückmann, 1972), chaetognaths (Srinivasan, 1981), and siphonophores (Rengarajan, 1975), along the west coast of India and coast of Pakistan are known. For the Indian Exclusive Economic zone and nearby waters, Mathew et al. (1990b) have summarized latitudinal and seasonal changes of abundance of total euphausiids

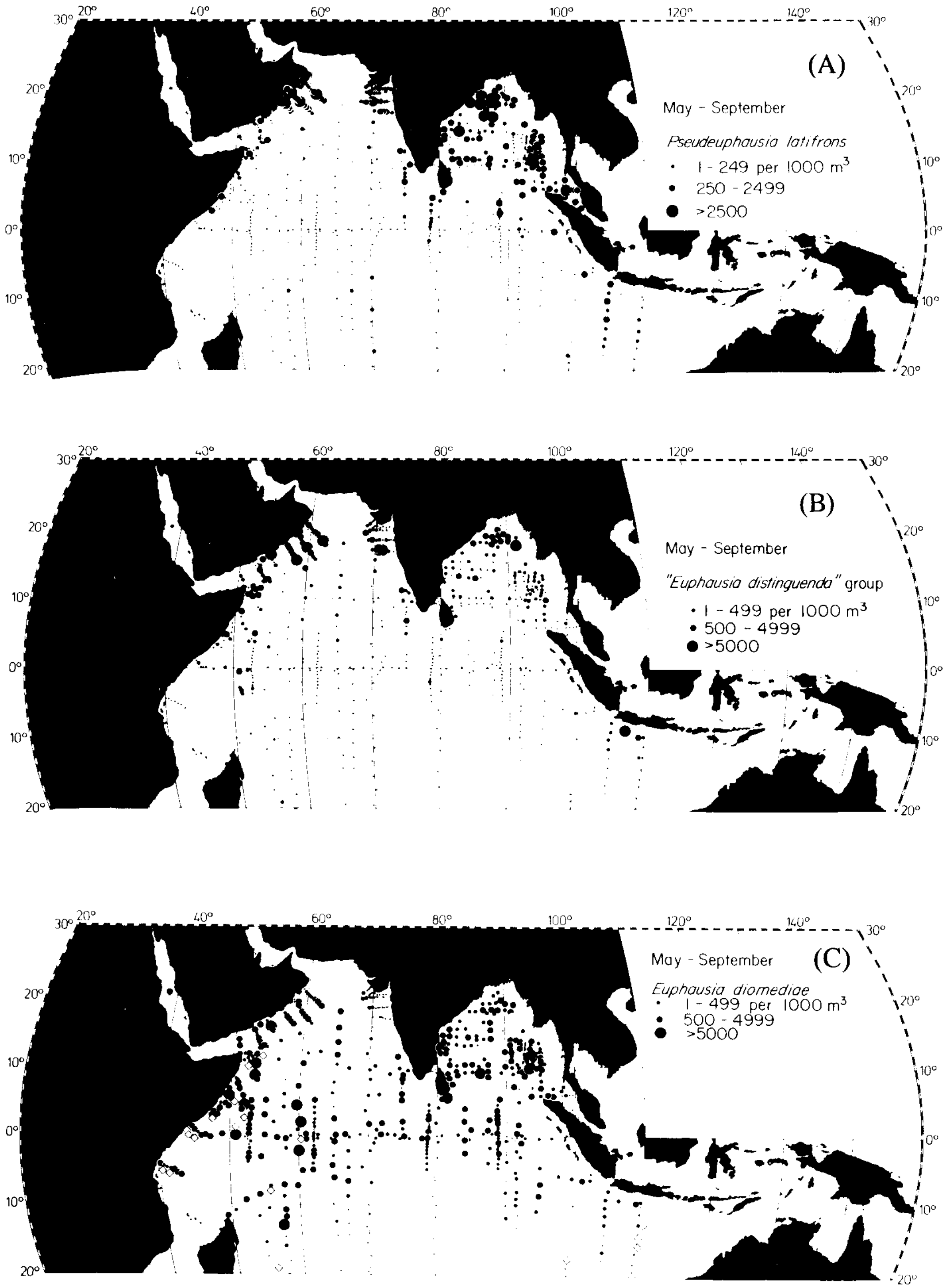



Figure 12. Euphausiid distributions and abundance in the Arabian Sea from IIOE sampling. *Pseudeuphausia latifrons* during (A) May to September (southwest monsoon) and (D) November to March (northeast monsoon); *Euphausia distinguenda* during (B) May to September and (E) November to March; *Euphausia diomediae* (filled circles) during (C) May to September and (F) November to March. (From Brinton and Gopalakrishnan, 1973).

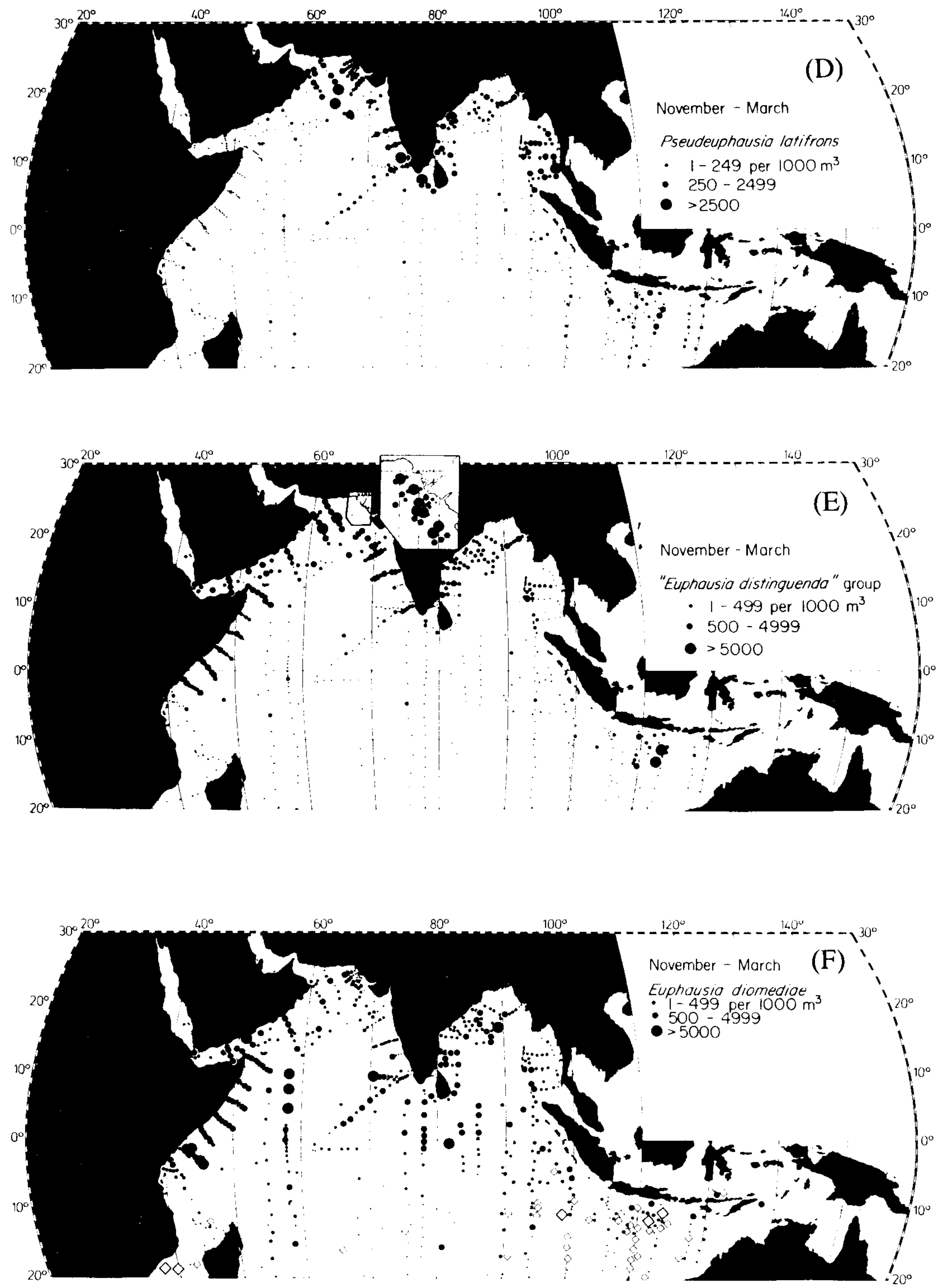



Fig.12. (continued)

(similarly, the somewhat less abundant mysids (Mathew et al., 1990c), and amphipods (Revikala et al., 1990). It should be noted that most zooplankton studies from coastal regions of India and Pakistan used nets with 300 µm or larger mesh; thus, the numerically dominant, small copepods common in tropical and subtropical regions have been inadequately sampled, as have the younger life stages of larger zooplankters.

During the summer coastal upwelling, zooplankton species composition differed markedly between upwelled waters and offshore waters. In upwelling areas the dominant copepods were species of *Eucalanus*, *Paracalanus*, *Clausocalanus*, *Temora*, and *Acrocalanus*. Note the absence from these observations of capable workers of *Calanoides carinatus*, the "indicator species" for upwelling in the tropical Indian and Atlantic Oceans. In offshore, non-upwelled waters, *Eucalanus attenuatus*, *Pleuromamma indica*, and *Pleuromamma abdominalis* were dominant.

There have been few studies in the northern and eastern coastal regions which go beyond descriptions of zooplankton composition, abundance, and distribution. The dynamics of zooplankton populations in the region are virtually unknown (see Banse, 1984). The most extensive studies of plankton dynamics of the waters off SW India are those of Mathew and coworkers on the euphausiids. Prominent euphausiid species along the Indian coast are *E. sibogae* (a species in the *E. distinguenda* group), *P. latifrons*, and *E. diomediae*, in agreement with observations of the dominant species in the Arabian Sea basin as a whole. Maximum euphausiid abundances (>4000 per 1000 $m^3$) along the southwest coast of India occurred during the August to October upwelling. This seasonal pattern was entirely caused by fluctuations of *E. sibogae*, which exceeded 4000 per 1000 $m^3$ in August and October, but during other seasons remained less than 100 per 1000 $m^3$. Conversely, populations of *P. latifrons* were greatest (200-500 per 1000 $m^3$) during winter (December to February), and low throughout the remainder of the year. Breeding seasons of these three species were identified by examination of the seasonal occurrence of post-naupliar larval stages. *Pseudeuphausia latifrons* and *E. diomediae* have wintertime (December to April) breeding seasons while *E. sibogae* breeds during August to December (Mathew, 1983).

*Somalia Region*

Off Somalia during the SW monsoon there are two offshore current jets, one associated with the parting of the Somali Current from the coast and the other with the Great Whirl (Brown et. al., 1980; Smith and Codispoti, 1980). Associated with the jets is upwelling of cooler, nutrient rich water which permits the development of blooms of diatoms like *Nitzschia delicatissima* (Smith and Codispoti, 1980). Chlorophyll concentrations exceeding 3 ug $L^{-1}$ have been reported in these upwelled waters (Smith, 1984). Adult females and copepodites of *Calanoides carinatus* and *Eucalanus* spp., which can readily ingest the diatoms, were markedly more abundant within upwelling areas along the Somalia coast during the SW monsoon (Smith, 1982). *Calanoides carinatus* was characteristically observed within the actively upwelling or recently upwelled waters during the SW monsoon season and was not found in areas where upwelling had not recently occurred during the SW monsoon nor anywhere along the Somalia coast during the NE monsoon when there is no coastal upwelling (Smith, 1982, 1984). Apart from *C. carinatus*, which was present only during the SW monsoon period, the other numerically dominant copepods, *Paracalanus* (3 species), *Clausocalanus* (5 species), *Acartia negligens*, and *Acrocalanus* spp., were observed during both the NE and SW monsoons and were nearly equally abundant within and outside areas of upwelling (Smith, 1982).

*Central Arabian Sea*

The dominant zooplankton taxa of the central Arabian Sea are not well identified because plankton investigations of the region are few in number, have inadequate seasonal and spatial coverage, and have poor or no vertical resolution. Furthermore, the samples which have been collected, especially from the IIOE, have not been fully analyzed and/or reported (although see the recent volume edited by Desai, 1992, and discussion above). This section summarizes the results reported to date.

Copepods comprised >80% of the zooplankton enumerated from oceanic regions of the Arabian Sea during the NE monsoon (Madhupratap and Haridas, 1986). The northernmost samples (ca. 9°N) of that study were within the permanently oligotrophic region of the southern Arabian Sea. No single species accounted for greater than 10% of total copepod number. Copepod species diversity was fairly high (>40 species at some stations) even though small calanoid and cyclopoid copepods were undersampled because of the coarse (300 µm) mesh of the net. Calanoid copepods were mostly typical subtropical (and small) copepods of the genera *Paracalanus*, *Acrocalanus*, and some *Eucalanus*. *Calanoides carinatus*, common in upwelling areas off South Africa (de Decker, 1973) and Somalia (Smith 1982, 1984), and observed off Oman (S. L. Smith, unpublished), was not observed in any oceanic samples during the NE monsoon season. Nor was *C. carinatus* mentioned by Sewell (1948) among the copepods of the John Murray Expedition of September 1933 to May 1934 in the Arabian Sea; however, this is not unexpected since they sampled off the Arabian peninsula during October to November, significantly after the SW monsoonal upwelling period.

Stephen (1984) reported on the distribution, abundance, and vertical distribution of copepods from the northern part of the Arabian sea (including Indian shelf and oceanic stations) in November. Dominant copepods in the surface layer at offshore stations (water depth >200 meters) were *Eucalanus pileatus*, *E. subtenuis*, *Undinula vulgaris*, and *Cosmocalanus darwini*. Below the mixed layer *E. attenuatus*, *Pleuromamma indica*, *Haloptilus longicornis*, and *Lucicutia flavicornis* were dominant.

Vinogradov and Voronina (1962b) obtained vertically stratified plankton collections from the surface to 500 m along a transect from Bombay to Cape Guardafui during the NE monsoon season in 1959-60. Among the more common zooplankton along that transect were *Euchaeta marina* (50-100 $m^{-2}$, 0-500m) and *Undinula darwini* (>100 $m^{-2}$) among the copepods, and the large ostracod *Pyrocypris* sp. (>1000 $m^{-2}$, 0-500m). The latter, a normally neritic species, was extremely abundant in the central Arabian Sea and relatively rare elsewhere in the western Indian Ocean.

## Low Oxygen Zone and Zooplankton Distributions

The reader is again referred to Peterson (1991, p. 105) for review materials not repeated here.

Oxygen concentration in the eastern half of the northern Arabian Sea can be as low as 0.1 ml $L^{-1}$. From studies in other low-oxygen environments (eastern tropical Pacific Ocean and elsewhere), most species avoid waters with oxygen contents below 0.1-0.2 ml $L^{-1}$ (Longhurst, 1967; Judkins, 1980; Sameoto, 1986; Sameoto et al., 1987). There are, however, species which tend to reach maximum concentrations within oxygen minima at least part of the time. These include copepods in the eastern Pacific (Judkins, 1980; Sameoto, 1986) and a host of microzooplankton in anoxic fjords (Fenchel et al., 1990). Vinogradov and Voronina (1962a) show that low oxygen levels can influence zooplankton biomass distributions and alter species compositions in the Arabian Sea (Figs. 13 and 14). In other low-oxygen environments, fish have been observed to penetrate into waters that are anoxic to the point of hydrogen sulfide production (Baird et al., 1973). While the primary response to the low oxygen layer is undoubtedly behavioral modification, i.e. avoidance, it is clear that some organisms have means for coping with low oxygen environments.

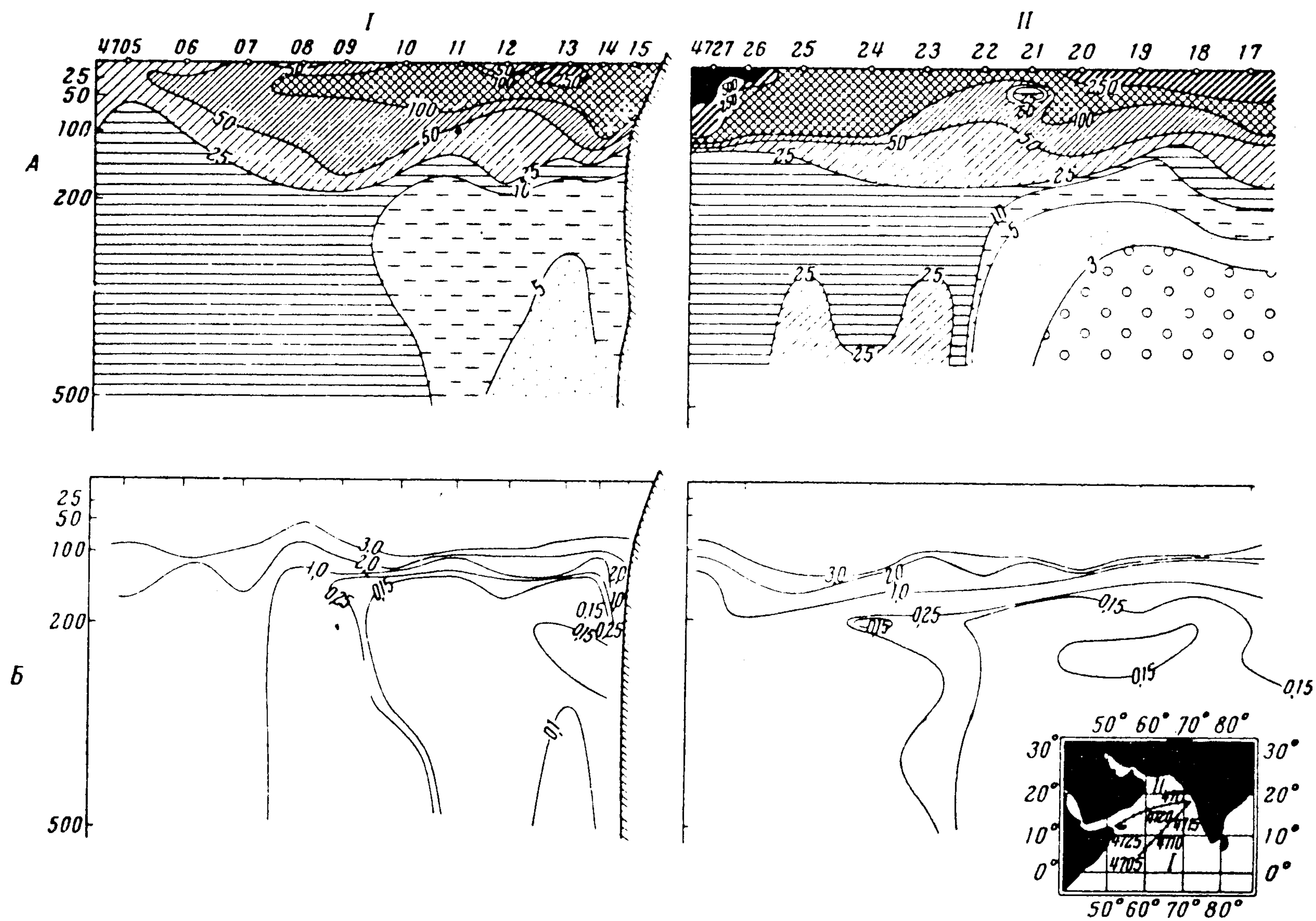



Figure 13. Distribution of (a) the amount of plankton ($cm^3$ per 1000 $m^3$) and (b) oxygen ($ml\ l^{-1}$) on sections from (I) the Seychelles to Bombay and (II) Bombay to Cape Guardafui. (From Vinogradov and Voronina, 1962a).

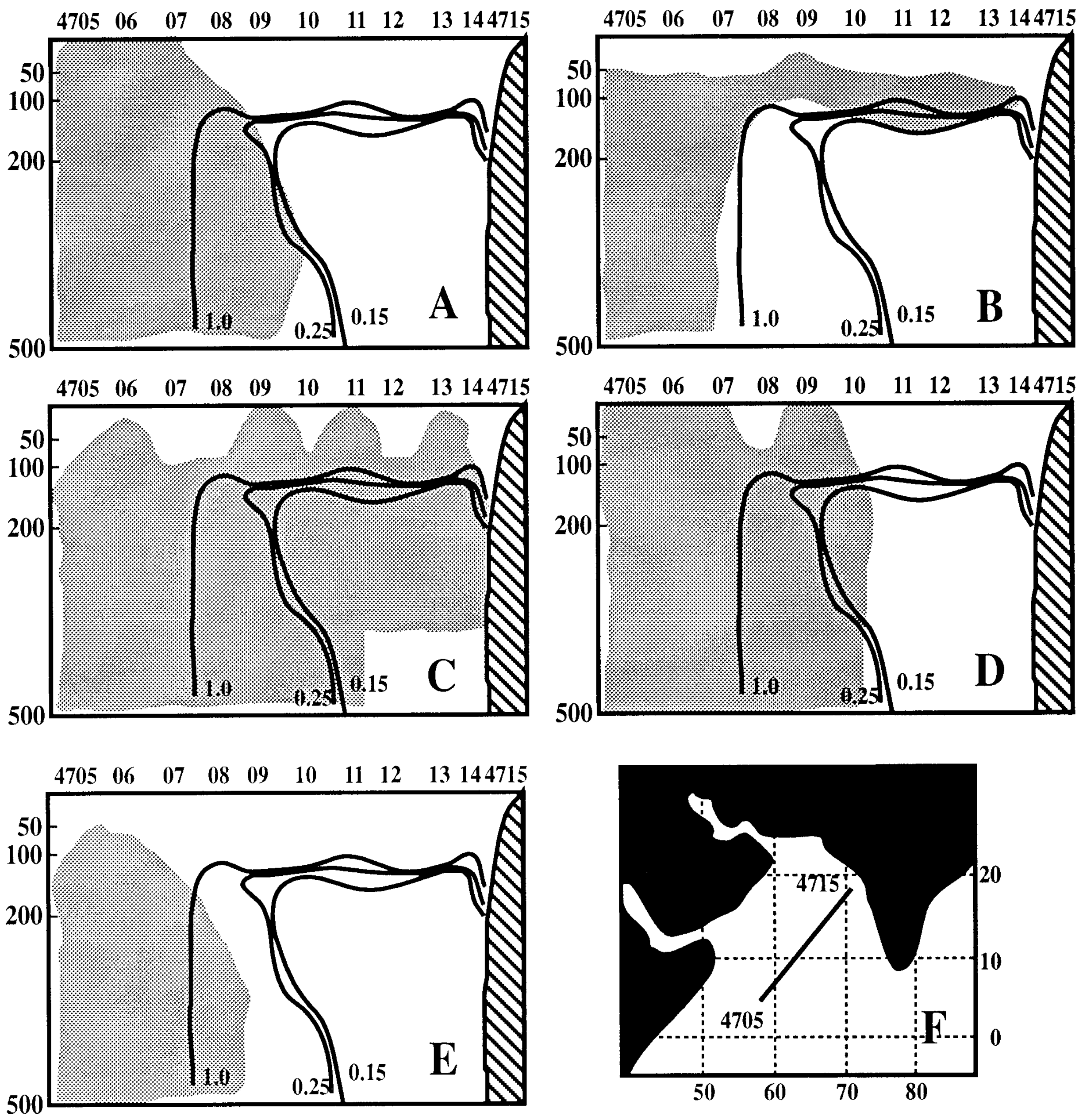



Figure 14. Distribution of certain forms of zooplankton on a section from the Seychelles to Bombay, (1) region of spread of *Neocalanus gracilis*, (2) *Haloptilus longicornis*, (3) *Pleuromamma indica*, (4) *Pleuromamma gracilis*, (5) *Pleuromamma xiphias*, and (6) isolines of oxygen concentration (ml $l^{-1}$). (From Vinogradov and Voronina, 1962a).

Interfaces of oxygen minimum zones may be regions of high biological activity and aggregation sites for the whole trophic web from bacteria through mesopelagic fish (Wishner, 1991). There is evidence for dietary shifts to bacteria as the dominant food resource in these low oxygen habitats. They may also be regions where zooplankton organisms show biochemical or metabolic changes that affect their ability to live or take advantage of these regions. It is to be expected (Childress 1975, 1977) that plankton (and nekton, too) living continuously or for part of each day in suboxic waters will have strong capacity for anaerobic metabolism. This will be expressed (and can be studied) as high activities of glycolytic (Krebs cycle) enzymes and possibly correlated with low activities of oxidative enzymes. New work (Thuesen and Childress, in progress) indeed shows exactly this metabolic set up in copepods inhabiting the oxygen minimum layer in the California Current region. Theusen and Childress have demonstrated wide taxonomic variation in metabolic poise within the Copepoda. The Arabian Sea is an ideal place to examine the distributional correlations of this variation in metabolic type. Thus new work should evaluate the upper and lower boundaries of the suboxic zone, and sampling should be directed by real time data on oxygen concentration, the challenge being to connect previous physiological work with demographic processes, e.g. site of egg laying, distribution of juveniles, and mortality. A central question may be: What are the relations of the life cycles (especially breeding seasons) and the recruitment of the dominant species (both fish and zooplankton) to the seasonality of the various physical domains, and how does the low-oxygen waters at depth modify this interaction?

**Problems of Sampling Zooplankton in Very Rough Seas**

Studies of the response of zooplankton populations to the southwest monsoon in the Arabian Sea could be a direct realization of the U.S. GLOBEC goal of studying secondary producers, recruitment processes, and the impacts of global climate variability. The attached maps (Fig. 10) show that the population responses of planktonic species to monsoonal upwelling are extremely strong. Large stocks of *Pseudeuphausia latifrons*, *Calanoides carinatus*, and probably other species develop along the coasts during this cooler, highly productive season. There may, or may not, be similar responses of more oceanic species to the upwelling and enhanced mixing resulting from the Findlater jet crossing the center of the Arabian Sea from SW to NE.

In both the coastal zone (Somalia, southern Arabian Peninsula) and central Arabian Sea there will be extreme problems for sampling and work at sea. Winds of 30 to 40 knots are standard for both the coastal jet and the Findlater jet. Waves are high. The scale of the rough weather sampling problem is probably quite severe. Heed this quote from A. deC. Baker who was on an IIOE cruise off the Arabian coast during the SW monsoon:

> "On that cruise none of us were specialists. I just came along because they needed an extra pair of hands. It was the most consistently bad weather I have ever experienced [Baker had substantial Antarctic experience for comparison]. We had a particular problem with our vertical net hauls because of the up-and-down movement of the ship. The net was equipped with an accumulator system to take up slack, but it would [still] close prematurely when the wire went slack. We had to rig up a block and each of us took turns standing on a platform and hauling in the slack on the net. We were fishing five depths, and we each pulled on that line half an hour at a time. We were like bell-ringers." (Behrman, 1981, p. 72-73)

Clearly, it was possible to stand outside and ring bells by hand for half an hour. Rough tropical seas are less difficult to work in than rough seas in near freezing conditions. Proposing investigators should keep this problem in mind. They should show plans for coping with this special sampling problem in their proposals.

So, to achieve any significant zooplankton study in the Arabian Sea, we must be able to work fairly consistently in rough weather. Solving the rough weather sampling problem (for both fish and zooplankton) seems central to a successful U.S. GLOBEC study in the Arabian Sea.

Essentially, it is necessary to equip a sizeable ship, that can move slowly in high winds and seas, to collect zooplankton samples with no personnel on deck. We need a crane or other mechanical arrangement for taking a ready sampler out of an interior, laboratory space, placing it overboard and lowering it to sample. It must then retrieve the sampler and return it to the laboratory for removal of the sample. For many kinds of work it will be necessary to be able to examine samples without too much wild rocking as the ship comes about in 40 foot waves. This may require one or more gimballed work stations including chair, working surface and microscope. Perhaps even a gyroscopically driven "gun table" would be justified; perhaps a small one could be obtained from the U.S. Navy. Each of these two requirements can be met by an engineering effort.

The Arabian Sea is stratified for several variables, with particular importance to zooplankton and fish attaching to the intense oxygen minimum layer from about 150 to 1500 m, particularly on the east side. Thus, characterization of the zooplankton community will require stratified sampling. Equipment for this that can be deployed and operated with no gear handlers on deck may be a difficult engineering problem. It is much simpler to deploy a single net for oblique or surface sampling from inside to outside, then over the side, down, and back. But that won't provide data on the vertical distribution of the fauna. For a multiple net sampler the most difficult part will be transfer of mesh fabric nets flopping wildly in a 50 kt wind back inside the ship. If we want to work effectively in this region, we must figure this out.

*Fish Stocks in the Arabian Sea*

If we take the main interest of U.S. GLOBEC to be secondary production and its transfer to higher trophic levels, then the Arabian Sea offers a first-class problem. The northern Arabian Sea is the habitat of large mid-water fish stocks (Gjøsæter, 1984). These stocks reside all along the outer edges of the coastal zone of the Arabian Peninsula, off Pakistan, and the Gulf of Oman. Doubtless there are also sizeable stocks off Somalia and northern India. Off the Arabian Peninsula and in the Gulf of Oman these stocks are dominated by myctophids, mostly by *Benthosema pterotum*, although *Benthosema fibulatum*, *Diaphus arabicus* (see Kinzer et al., 1993), *Myctophum spinosum*, and *Symbolophorus evermanni* are occasional large contributors. Possibly the *B. pterotum* population is the largest, localized fish stock in the world, amounting to 100 million tons! It has been suggested that this very large stock of the one species derives from the very small stocks of all other fish; for some reason *B. pterotum* and other myctophids are the competitive dominants. There are references in the literature to the importance of the oxygen minimum layers in this, but there is no suggestion of a specific mechanism.

A good deal is known about the biology of *B. pterotum*. Gjøsæter and Tilseth (1983) reported a stomach content study, which showed that copepods, and mesozooplankton generally (euphausiids, *Oikopleura*, etc.) are the diet. 94% of stomachs with food contained copepods. In a separate study, Delpadado and Gjøsæter (1988) showed that copepods make up 35 to 55% of the diet by weight, with the remainder varying among sampling sites and times (Fig. 15). The numerically dominant copepod prey were small species, *Corycaeus* sp. and *Oncaea* sp. Since these are believed to be associates of gelatinous zooplankton, it is possible that these myctophids take their meals at these "feeding stations." However, most of the stomach content mass was "larger calanoid species (prosome lengths 0.8 to 2.5 mm), of which the dominant species were: *Acartia danae, Candacia* sp., *Centropages furcatus, Clausocalanus* sp., *Eucalanus tenuis, Euchaeta marina*, ...." In an earlier study, Gjøsæter (1981) showed that feeding mostly occurs early in the night, slowing in the late night, and is minimal at depth in daytime. In a study in the Red Sea, Delpadado and Gjøsæter (1987) showed that mean copepod prey size increased with increasing length of *B. pterotum*. Kubota (1982) sampled this species in Suruga Bay and found that its principal diet is copepods (*Calanus*, *Oncaea*, many others) and euphausiids (*Euphausia* sp.), the latter especially important seasonally. Thus, this fish must be in the middle of a fairly short food chain: diatoms => copepods => *B. pterotum* => larger fish, squid, marine mammals. Outside of the upwelling season, and perhaps generally in the open sea, the food chain may well have an additional step: flagellate phytoplankton => protistan grazers => copepods, since the region has an unusually high coccolithophorid contribution to the production (Codispoti, 1991). We are now well prepared to study pelagic food webs of either type.

*Benthosema pterotum* is associated with the continental slope all around the northern Indian Ocean and in the western Pacific as far north as Japan. There are populations in the Gulf of Panama of the very close relative *Benthosema panamense*. Thus, it has a tropical-subtropical, Indo-Pacific distribution, but it is not found over oceanic depths. The exact effects of topography in determining its distribution are not fully understood. Probably there are strong ecological analogies with the large midwater fish biomass of the Benguela upwelling system (Prosch 1991; Armstrong and Prosch 1991). It is readily collected by large trawls (or even small trawls) so that diet, growth rates, biochemical composition, and many other aspects of its biology can be studied readily. It is an excellent sonar target, so stock size can be estimated by sonar survey. It is a strong diel migrator, inhabiting surface layers at night, and only descending to 150-350 m during the day. Gjøsæter (1981, 1984) showed with sonar that the population in daytime is divided into two layers, one at 150-200 m, the other at 250-325 m, with a distinct gap between (Fig. 16). Samples from these separate groups were not distinct in size, reproductive state, sex ratio, or anything else that Gjøsæter could examine. Gjøsæter suggests that its distribution is related to and controlled by the shallow oxygen minimum layer of the Arabian Sea; the fish apparently are driven

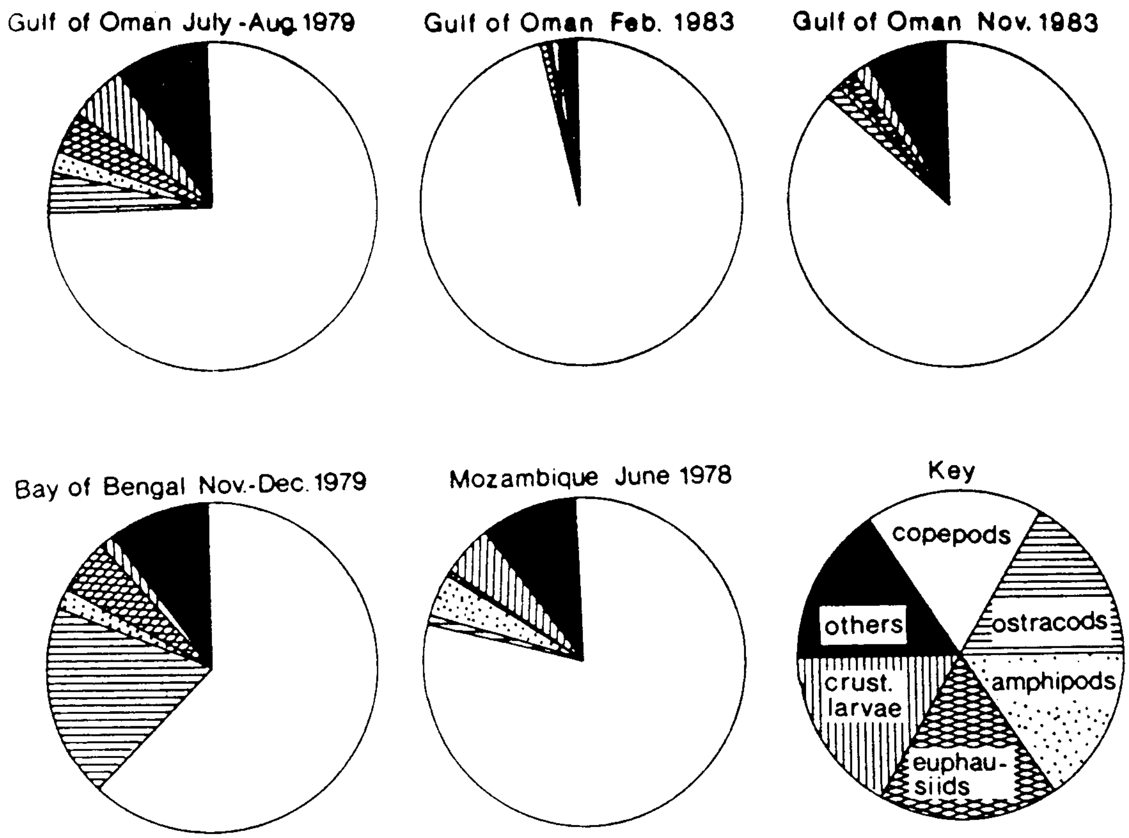



Figure 15. Composition of gut contents from *Benthosema pterotum* at various sites on various occasions in terms of numbers of prey items. (From Delpadado and Gjøsæter, 1988).

inshore by intensification or elevation of the minimum. The vertical gap in daytime distribution in the Gulf of Oman coincides with a local $O_2$ minimum (ca. 1 ml $L^{-1}$) there.

*Benthosema pterotum* has an annual life history with reproduction at age approximately 7 months (Gjøsæter, 1984). Egg production is observed in females ranging from 27 mm (300 eggs) to 52 mm (3,000 eggs) (Delpadado 1988, Hussain and Ali Khan 1987) with very little variation among sites (Fig. 17). Despite the wide range of size at reproduction, Delpadado (1988) thinks that there may be only one round of egg production with death ensuing, since apparently-spent females are found across the same size range. The presence of three size classes of eggs in ovaries of all sizes of fish (Hussain and Ali Khan 1987), however, makes a single reproductive burst seem unlikely. At any rate, the life span is surely no more than a year, which implies that the entire 100 million tons is produced every year! This is a staggering sum, implying a primary productivity around the arc of continental slope from Cape Guardafi to India on the order of 1 billion tons carbon. Measured primary productivity in this area is indeed high, often running 2 gC $m^{-2}$ $d^{-1}$, and sometimes reaching 6 gC $m^{-2}$ $d^{-1}$ (Codispoti, 1991), but these high figures do not prevail during the entire year. GLOBEC work in the region can benefit from association with U.S. JGOFS, drawing insight from proposed U.S. JGOFS primary production studies.

Gjøsæter and Tilseth (1988) have shown that *B. pterotum* in the Gulf of Oman spawns at depths of 100 to 300 m early in the night. The slightly buoyant eggs hatch within 12 hours before they reach the surface. The larvae are well described (Tsokur 1982). Some further work on vertical distribution and diet of larval phases would be informative. Nellen (1973) states that larvae of *B. pterotum* overwhelmingly dominate collections along the coast of Pakistan, and later data (Ali Khan 1976) confirm that for areas off the edge of the shelf. Over the shelf off Karachi *Sardinella sinensis* is more abundant. There have been no larval surveys along the Arabian coast, but since adult *B. pterotum* are abundant, and larvae are abundant both in the Gulf of Aden and off Pakistan, it certainly is the dominant among larval fish all around the north rim of the Arabian Sea. No seasonality in larval stocks has been reported, although there are hints in the literature of greater larval abundance in the NE monsoon. Sanders and Bouhiel (1982, seen in abstract) considered recruitment to the fishable stock to be confined to the two monsoon transition seasons. The basis for this statement is not given in the available abstract. Venema (1984) shows some seasonality in total pelagic and demersal fish stocks in various coastal sectors of the northern Arabian Sea, and this must certainly derive mostly from variations in pelagic species. Stocks are high in the NE monsoon, lower in the SW monsoon. The data are sketchy, with a glaring hole in the middle of the SW monsoon. Delpadado (1988) found mature and spawning fish in all seasons, and found no definite evidence of any seasonality in population processes. It is, however, very likely that the life history of *B. pterotum* is in some fashion in phase with the monsoon cycle. This aspect of coupling between the animal and its habitat could be a research topic.

*Benthosema pterotum* is a good subject for a direct study of larval recruitment and year-to-year variation in stock size and success, although spawning is not seasonally focussed enough for characterization of years by simple one-shot surveys. U.S. GLOBEC workers should be able to couple observations from primary productivity through tertiary productivity about as well as for any region - taking this dominant fish as a key study subject, an upwelling system component suitable for detailed population quantification. The main drawback to this species as a focus is that it tastes terrible. According to Kubota (1982), fishermen in Suruga Bay who eat large quantities of *Diaphus* spp. sort out and discard *B. pterotum* as inedible. That does not mean that this huge production is useless; fish oil and protein have other uses than direct human consumption. Studies in India (Gopakumar et al. 1983; Nair et al. 1983) show that meal and hydrolysate from *B. pterotum* are excellent protein supplements in fish and poultry feeds. These myctophids are readily fished; Norwegian results reached 100 tons $hr^{-1}$ with a sonar-guided, 750 $m^2$ (15 X 50 m) double warp trawl (which is a seriously large piece of gear).

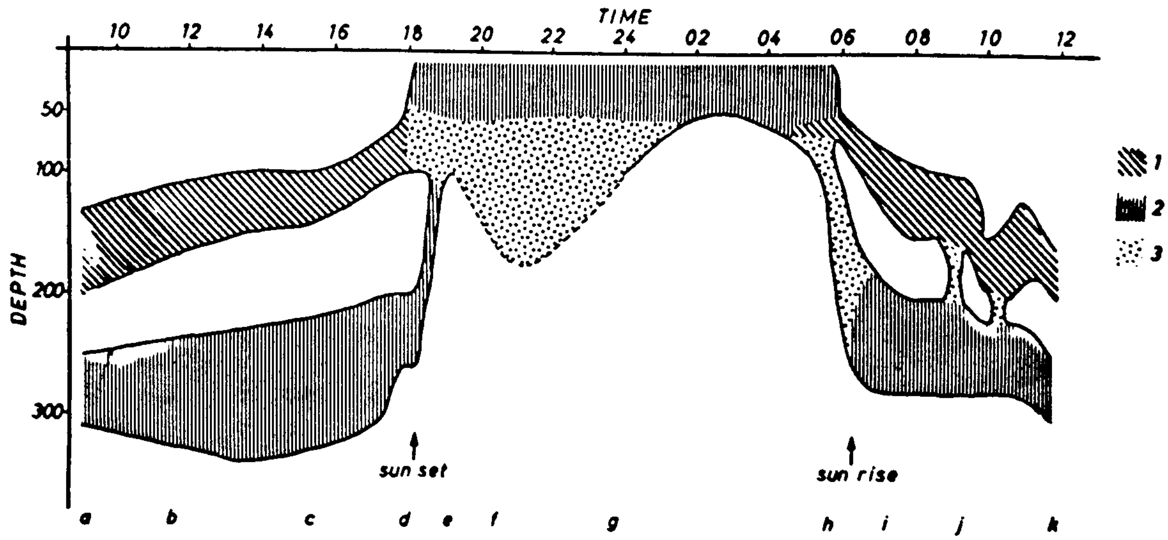



Figure 16. Daytime division and nightime coalescence of scattering from *Benthosema pterotum* in the Gulf of Oman in March 1976. Different levels of hatching indicate (1) schools and very dense aggregations, (2) dense recordings, and (3) scattered recordings. (From Gjøsæter, 1981).

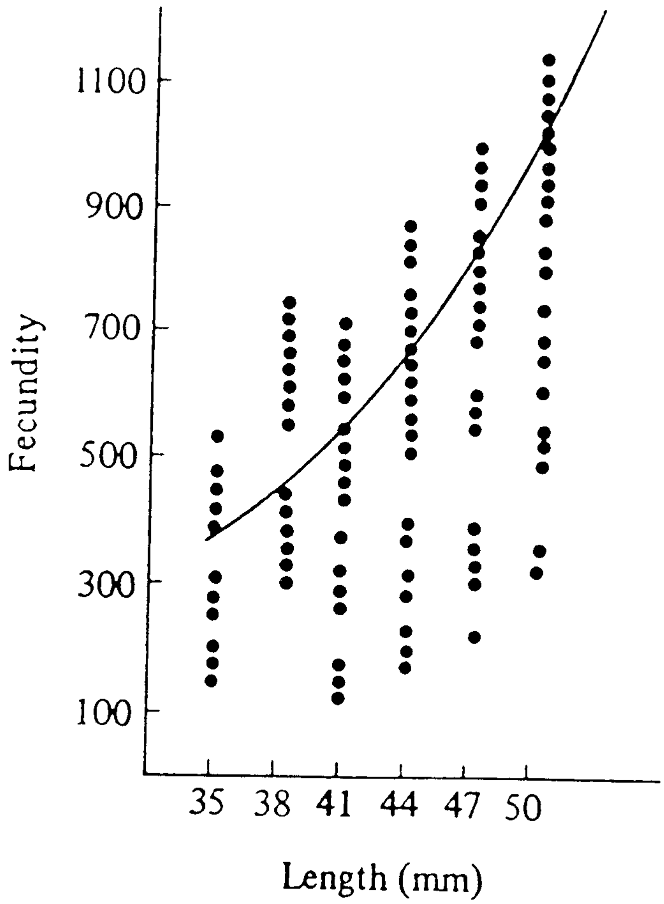



Figure 17. Fecundity versus length curve for *Benthosema pterotum* from the northern Arabian Sea. Data are counts of fully ripe eggs. (From Hussain and Ali Khan, 1987).

## *IMPLEMENTATION PLANS*

Two levels of plan are developed here. The first is scaled to the very modest funds believed to be committed (as intimated by program managers at NSF and NOAA) to U.S. GLOBEC's participation in Arabian Sea studies. We chose a working number of $1.5M, sufficient to support participation by only three, possibly four, principal investigators over a three year period. The second is a more ambitious program designed to answer some of the exciting questions presented by the pelagic ecology of the Arabian Sea. It proposes deployment of a vessel equipped for modern study of fish stocks, together with supporting studies of zooplankton populations. The plans for at least the fish stocks are couched in terms of hypotheses about processes in the region. Given the level of available information about zooplankton, plans must be developed around more general hypotheses (See Appendices). Both the limited and full plans seek *dynamical* understanding of population processes for both fish and zooplankton that will lead to evaluation of the impact of global climatic change on the Arabian Sea ecosystem.

### *Implementation Plan for a U.S. GLOBEC Add-On to Anticipated Studies in the Arabian Sea*

The implementation committee proposes that U.S. GLOBEC sponsor a study of modest scale that will take advantage of the ships and other logistics expected in the Arabian Sea region in 1994-1996. These include field programs of U.S. JGOFS, WOCE, ONR, and NOAA and imply the presence of three research vessels. The plan has been scaled so as to require very modest resources. Its returns will not necessarily be correspondingly modest, given the leveraging of resources that association with the other programs will provide.

While the problems of myctophid biology in the Arabian Sea are perhaps its most attractive feature for U.S. GLOBEC work (see below and Appendices A-C), they are not particularly suitable for attack as a modestly priced enrichment of the U.S. JGOFS Arabian Sea Study. The logistic requirements for a detailed study of myctophid biology and distribution may be too different from those of U.S. JGOFS to be accomodated by a UNOLS vessel (however, for an alternative view see Appendix E). Of equal interest to U.S. GLOBEC is the extraordinary time and space variation of physical forcing (monsoonal reversals, coastal and open-ocean upwelling) and its potential effects on the pelagic ecosystem, including the zooplankton. A planktological study of great sophistication and detail can readily be mounted from a large UNOLS vessel. This can include net and specialized sampling to determine relationships among distribution and hydrographic features, field determinations of feeding rates, physiological and enzymatic experimentation, and more. A very rich body of information can be developed by a small number of U.S.-based investigators, particularly if cooperative programs develop with European, Omani, Pakistani, and Indian oceanographers.

The U.S. JGOFS Implementation Schedule (U.S. JGOFS Arabian Sea Process Study, Implementation Plan, May 1992, page 14) shows "cruises" aboard a large, otherwise U.S. JGOFS-specific, UNOLS vessel that are essentially intended as place holders for ONR/ARI and U.S. GLOBEC work for the following periods:

| | |
|---|---|
| October 1994 | July 1995 |
| January 1995 | October 1995 |

The U.S. GLOBEC Steering Committee should request assignment of those cruises or additional ship-time for a U.S. GLOBEC study of the Arabian Sea. In order to maximize intercomparability of U.S. GLOBEC with U.S. JGOFS data, U.S. GLOBEC should carry out zooplankton and fish observations along the U.S. JGOFS station line (U.S. JGOFS Implementation Plan, page 5) which extends from the Omani coast at Cape Madraka (Ras al Madraka) to 8°N, 65°E (Figure 18). This would allow a U.S. GLOBEC observation set in the coastal upwelling regime off the Arabian

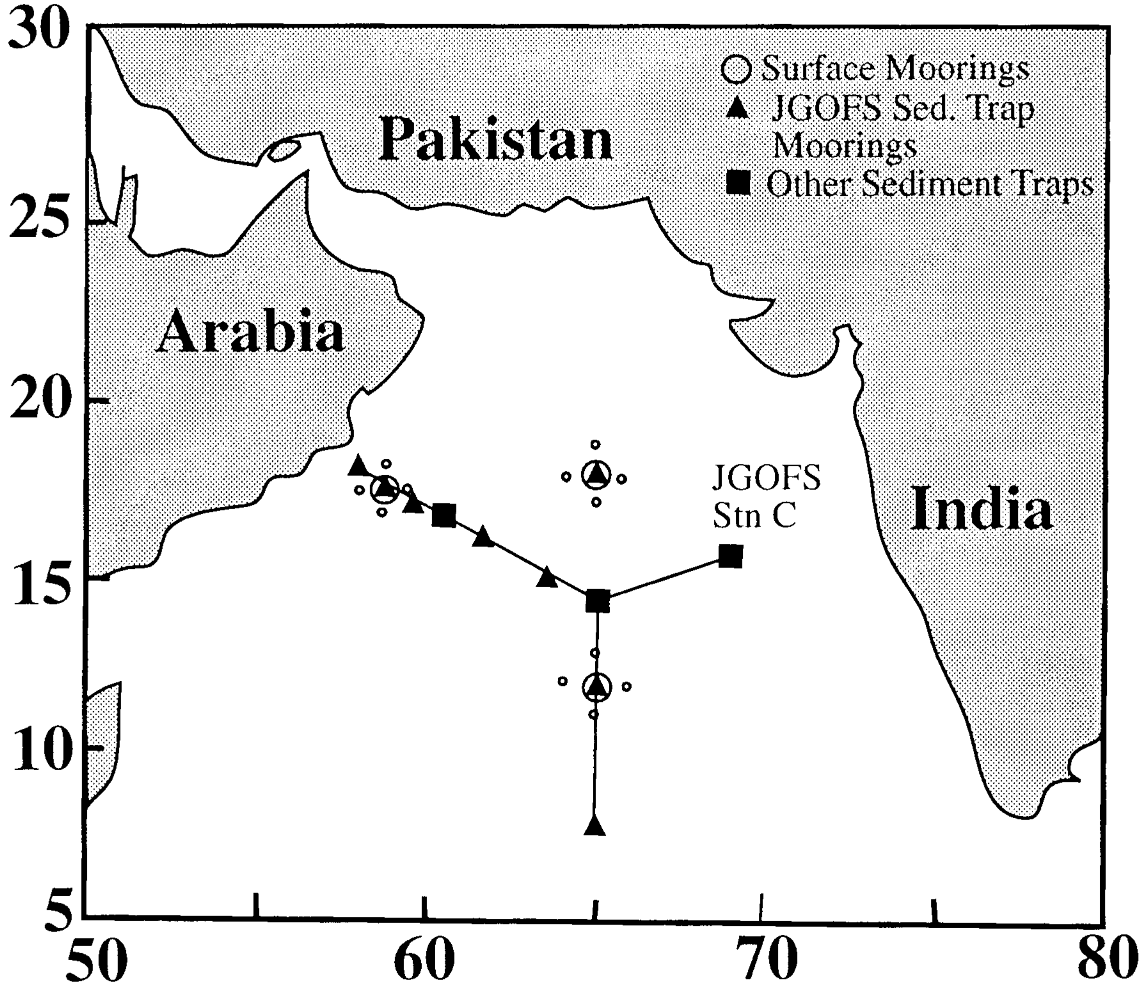



Figure 18. Tentative locations of U.S. JGOFS and ONR moorings planned for the Arabian Sea in 1994-1996 (from Arabian Sea presentation made by S. Smith at December 1992 AGU meeting in San Francisco). The main research transects for U.S. JGOFS cruises are line A, which crosses the coastal and mid-ocean upwelling regions; line B, which extends towards the region of minimum subsurface oxygen concentration; and line C, which extends south into the region of permanent oligotrophy.

Peninsula, through the upwelling hiatus landward of the Findlater jet, then through the oceanic upwelling regime, and finally out into persistently oligotrophic waters in the central Arabian Sea. Each expedition should be completed by occupation of a station in the NE Arabian Sea, in the location of U.S. JGOFS Station C (18°N 65°E; Fig. 18). This will allow detailed investigation of zooplankton and fish distribution and physiology in the region of most strongly developed, sharply defined suboxia at depth.

No substantive refitting of ships or basic scientific gear will be required for this work, over and above that required by U.S. JGOFS workers (CTD and rosette). However, individual proposing investigators will need to obtain sampling gear and move it to Oman for use in the U.S. GLOBEC cruises. Specific gear should be proposed by individual investigators. We recommend the following problems to the attention of the U.S. GLOBEC Steering Committee and to proposing investigators:

1) Detailed population analysis based on seasonal sampling for a suite of target zooplankton species. This should be accompanied by the most comprehensive measurements of functional ecodynamics for these species that the time available and timing of cruises permits. We recommend as target organisms:

*Calanoides carinatus*, a large, nearly circumtropical copepod species likely to be abundant in the coastal upwelling regime.

a group of Arabian Sea euphausiids, including *Pseudeuphausia latifrons*, an euphausiid abundant in coastal waters throughout the northern Indian Ocean, and *Euphausia distinguenda* and *Euphausia diomedia*, which are more widely distributed in the Arabian Sea.

*Thalia democratica*, a salp repeatedly reported as present in high abundance in the Gulf of Oman, along the Omani and Pakistan shelf and occasionally from more oceanic sites.

Each of these choices is justified in a separate essay below. By functional ecodynamics we mean that investigations should be carried out on feeding rates, growth rates, fecundity, population age structure at different seasons, diel and seasonal vertical migration, respiration rates, enzymology (particularly metabolic poise with respect to aerobic and anaerobic respiration), and genetical differentiation among subpopulations for each of these target species. In addition, proposing groups seeking support to carry out this work should offer contingency plans for their work in the event that these species prove less important than their appointment here as target species might suggest.

2) A planktological reconnaissance of the Arabian Sea. This has been done, of course, by the John Murray Expedition of 1933, by the IIOE of the 1960's, and by the Soviets. However, by and large, a coherent, process-oriented view of the monsoonal Arabian Sea ecosystem has not emerged. Moreover, what is really lacking from prior investigations, including the Soviet literature, and what is particularly relevant to U.S. GLOBEC, is that the juveniles have not been studied, so that such basic issues as generation time, production, and seasonality related to the monsoon cycle cannot be addressed. In the opinion of the implementation committee, we haven't much idea which species of animals dominate the plankton in this region either as a whole or in specific sites at specific seasons. It is regrettable that we must recommend a study at this level after all the work in hand, but a basic study is needed.

3) Study of seasonality and general biology of midwater myctophids and ichthyoplankton of all types in the northern Arabian Sea. To what extent are larvae of *Benthosema pterotum* and other species variable in abundance and age structure with season? How fast do they grow and at what ages do they metamorphose into vertically migrating juveniles? At what depths do they live?

What do they eat? Because of the traditional separation of ichthyological and general planktological expertise, actual study of fish larvae probably cannot be done by the same people working on the study of holoplanktonic target species described in (1). However, the same sampling techniques are required, and the samples can be cooperatively exploited by appropriate experts. Study of larval stages of the abundant Arabian Sea myctophids will set the stage for more extensive U.S. GLOBEC work (see FULL-SCALE Plan on p. 56) on their biology when the opportunity arises. The fish working group at the Denver workshop recommended (see Appendix C) that a dedicated trawler vessel be requested for a comprehensive study of the distribution and ecology of midwater myctophids. Logistically, such a study cannot be conducted within the $1.5M constraint. Subsequently, the implementation committee has been convinced (see Appendix E) that much can be learned about the biology and distribution of adult myctophids using smaller, research-scale gear (1-10 $m^2$ MOCNESS or equivalent) and acoustics from UNOLS vessels. We recommend that such studies be done, remembering that weather conditions may often prevent large-gear deployment.

### Justification of Target Zooplankton Species

After extended review of the literature on Arabian Sea zooplankton, the implementation committee agrees that great uncertainty exists about the dominant species and basic seasonal succession of the zooplankton of the northern Arabian Sea. This makes designation of suitable target species difficult. However, we recommend that an attack on metazooan zooplankton in the region be planned around three target groups clearly present and possibly dominant. Here we review the biology of each as an aid to proposal development.

*Calanoides carinatus* - This species was described by Krøyer in 1849. It is a 1.6 to 2.5 mm calanoid copepod distributed from the tropical Indo-Pacific as far east as New Zealand (Vervoort 1946, citing Farran 1929) westward to the coastal waters of Brazil and the Caribbean. In the Atlantic it is most abundant to the east, but it does occur all across the tropical zone (e.g., Björnberg 1972). It is not reported from the eastern Pacific. As stated by Smith (1982) who worked in the Somalia Current during the SW monsoon upwelling, there is a "remarkable association of *C. carinatus* with upwelling...." This is true throughout its range, and Vives (1974) has suggested that in the vicinity of Cap Blanc (21$^{o}$N, NW Africa) its presence is explicit evidence of upwelling (see also Weikert 1982). Extensive work in the Gulf of Guinea (Binet and Suisse de Sainte Claire 1975, Binet 1979, Mensah 1974a,b, Petit and Courties 1976, Petit 1978, 1982) and off South Africa (Borchers and Hutchings 1986, Peterson et al. 1990) shows the same thing all along the West African Coast. There is evidence that *C. carinatus* is associated with patches of upwelling that occur near islands and coastal features throughout the Malay Archipelago, off Taiwan, in the Tasman Sea, and elsewhere (Tranter 1977, Tranter et al. 1983). Occurrences of the species are associated with upwelling sites in the western Atlantic as well, particularly at Cabo Frio, Brazil (Valentin et al. 1987).

The seasonal phenology of *C. carinatus* is the same throughout its range. Intervals between upwelling seasons are spent in a fifth copepodite resting stage deep in the water column, well offshore. At the onset of upwelling, regardless of the local physical dynamics, the resting phase individuals are carried shoreward in the deep feeder flows to the upwelling. They arouse from their diapause and go through a number of rapid life cycles at intervals as short as 16 days, then return to depth and the diapause phase at the end of the upwelling season. No aspect of the environmental control or signalling involved in this alternation between active and resting life phases is known. Angel (1984) has suggested that perhaps "*C. carinatus* can only build up really large populations where there exists a quasi-stable eddy system" directly offshore of the upwelling zone. Smith (1982, pages 1350-1351) has calculated some of the parameters of population movement in just such a deep gyre in the NW Indian Ocean during the season spent submerged.

Some of the data of Binet are sufficient to support an estimate of secondary production attributable to *C. carinatus* off the Ivory Coast, but the calculations have never been made. It is certain, however, that huge production of biomass is attributable to this species over the African continental shelves, and it may be responsible for a major fraction of global copepod production. It is certainly an important component in nutrition of midwater fishes across the equatorial belt, although quantitative studies of is resting stock and transfer to fish remain to be made. In addition, there must be tropical pilchards and other coastal fish that feed on the growing stocks of *C. carinatus*, but those details also remain for study.

Several rearing studies have been done with *C. carinatus*, providing estimates of development time as a function of temperature and food availability. Hirche (1980) worked with the population in the upwelling region off northwest Africa (ca. 30°N); Tomasini and Petit (1977) succeeded with pre-feeding stages off Zaire; Borchers and Hutchings (1986) and Peterson and Painting (1990) reared individuals from the Benguela stock. Thus, it has been demonstrated that *C. carinatus* is readily amenable to experimental work. Moreover, the whole life history could be carried through several times in the space of a single oceanographic cruise.

Feeding rate studies have been done by Smith (1984) and Schnack (1982). Smith used the phytoplankton available in the ambient water; Schnack used cultures developed from local phytoplankton. Schnack's results were more extended and consistent. Smith's results showed a little less feeding, but were also reasonably consistent. Filtering rates were typically 325 ml female$^{-1}$ day$^{-1}$, a rate not unlike those for temperate calanids as determined by Gauld, Frost, Dagg, and a hundred others. *Calanoides carinatus* eats big diatoms and dinoflagellates readily in feeding experiments, and they were found by Schnack to have gut contents of small diatoms (*Cyclotella* sp., 15 X 5 µm). Smith (1984, Table 4, p. 962) has produced a remarkable table for the Somali current, comparing *C. carinatus* stock size, and by implication feeding rates, with primary production. Where the copepod is abundant, right in the upwelling centers and upwelling-fed flow streams, it can eat half(!) of the primary production, which far exceeds any other system examined. Abundances in the Gulf of Guinea, where it constitutes >90% of mesozooplankton stock during the upwelling season, are higher than Smith's estimates for the Somali Current, so it may be even more important there.

It is not fully established that *C. carinatus* is an abundant and recurring component of the copepod community during the upwelling season along the coast of the Arabian peninsula. However, we believe that it is because the previous sampling results (IIOE in particular) are so radically underreported (see however the large occurrences off Oman recorded from IIOE collections in a restricted area off Oman and, in lower abundance, off Pakistan (Stephen et al., 1992)). Also recent sampling (Sharon Smith, personal communication) has shown this species in substantial abundance at three stations off Oman during the SW monsoon. Continuity (Fig. 10) during the SW monsoon of the region of very high plankton biomass between the Somali coastal zone, where *C. carinatus* is known to be dominant, and the Arabian coast across the Gulf of Aden, suggests that the species is the upwelling season dominant at least as far east as the Gulf of Oman. The life cycle in the Arabian Sea must be tied somehow to the physics of the Arabian upwelling, since the species can be regarded as definitively absent from the long-lasting coastal upwelling off southwest India (cf. Madhupratap and Haridas, 1986; Madhupratap et al., 1992).

Arabian Sea Euphausia - The Arabian Sea has three species of euphausiid that appear to be particularly abundant there: *Pseudeuphausia latifrons*, *Euphausia distinguenda*, and *Euphausia diomediae*. All three are also found in the Bay of Bengal. *E. distinguenda* (or a close relative) has a disjunct population in the eastern tropical Pacific, and *E. diomediae* is an Indo-Pacific tropical species with recurring high numbers in the Arabian Sea. We propose these species as a target group. *Pseudeuphausia latifrons* appears to be a very abundant species, but virtually all that we know of its biology comes from the distributional study of Brinton and Gopalakrishnan (1973).

Repeating the information given above, it is essentially a neritic species, with substantial populations along the coasts of Somalia, Arabia and India during the SW monsoon. Although no samples are available, this species probably also occurs along the Pakistan coast and in the Gulf of Oman during the SW monsoon. During the NE monsoon, *P. latifrons* populations along Somalia and Arabia were much lower (although sampling off Arabia was sparse); however, significant populations were observed in the Persian Gulf, Gulf of Oman, along the coasts of Pakistan and India, and in the central Arabian Sea North of 15°N. No significant biological information whatever has been located about this species.

Distributions of the two *Euphausia* species (Brinton and Gopalakrishnan 1973) also extend to the shore, but they are more widely distributed across the Arabian Sea. They are on average more abundant than *P. latifrons*, and because they will be reliably available for study, they are excellent candidates for study of distributional shifts and life history adaptations in response to the seasonal variations of the monsoon. Their large body size and likely extended vertical migrations make them excellent candidates for study of metabolic adaptation of large zooplankton to suboxic conditions. Again, while we are certain that these species are consistently present and often abundant, we know essentially nothing of their detailed biology. Therefore, we propose that U.S. GLOBEC develop ecological and life-history information about these euphausiids.

*Thalia democratica* - Data on abundance of pelagic tunicates from the Arabian Sea are spotty in space and time, but several workers have reported very high densities of salps at several times of year (Sewell, 1953, Godeaux, 1972, Gjøsæter, 1984). Although several species are listed as common, *Thalia democratica* seems to be the most consistently abundant. Thousands of individuals were collected in the Gulf of Oman and northwestern Arabian Sea by the John Murray Expedition (Sewell, 1953), and *Thalia* occurred in 70% of the samples collected in the same region by *Commandant Robert Giraud* (Godeaux, 1972). The species is known to produce swarm concentrations associated with regions of upwelling world-wide (Berner, 1967, Heron, 1972, De Decker, 1973, Paffenhöfer and Lee, 1987) and therefore should be well represented in the plankton of the productive inshore regions of the Arabian Sea. *Thalia democratica* are filter feeders capable of very high rates of ingestion and growth (Alldredge and Madin, 1982; Mullin, 1983, Heron and Benham, 1984) which enables them to respond rapidly to favorable environmental conditions (Paffenhöfer and Lee, 1987). Preliminary biomass data from the Arabian Sea indicates that *T. democratica* may play a significant role in the seasonally varying zooplankton community of the mixed layer, but their role as grazers of primary production and competitors with crustacean consumers has not been evaluated. Because salps, and especially *T. democratica*, respond rapidly to changes in their environment, the implementation plan committee proposes that U.S. GLOBEC develop a better understanding of their population structure and dynamics in the seasonal upwelling regions of the Arabian Sea.

## Ichthyoplankton and Fish Studies

We address the massive myctophid stocks of the Arabian Sea in our development of an implementation plan for a "full-scale" U.S. GLOBEC study of the Arabian Sea. Appropriate considerations can be borrowed from there for development of proposals for study of ichthyoplankton and adult myctophid biology to be included in U.S. GLOBEC work ancillary to the U.S. JGOFS Arabian Sea Process Study and ONR/ARI investigations. Clearly the stocks of key importance are *Benthosema pterotum*, *Benthosema fibulatum*, and *Diaphus arabicus*. Establishing the status of description of developmental stages (with distinguishing characters) for these species, design of sampling strategies, and specific details of possible and desirable studies are all left to proposing investigators. Possibly, research-scale gear (1-10 $m^2$ MOCNESS) can be used to collect juvenile and adult myctophids for examination of vertical distribution and migration, metabolism, diet, and population genetics (see Appendix E).

## Approaches

Hypotheses around which to organize research on these target species are left as an open issue for proposing investigators. Only very broad general hypotheses can be stated at this time (potential scientific questions are detailed in the working group reports, Appendices A-C). For example, it can be postulated that species composition, growth, and feeding biology will vary among the four general parts of the monsoon cycle. Based on its behavior elsewhere, *Calanoides carinatus* can be expected to appear and prosper in the coastal upwelling zone during the SW monsoon. It should be essentially absent from the coastal zone during the rest of the year, when, based on studies in other upwelling regions, it should be found at depth offshore in diapause. Surely the suboxic layer of the northern Arabian Sea will modify the location of its diapause habitat, possibly causing it to move as deep as 1500 m. Thus, net sampling for this species, and to reveal the general response of zooplankton to suboxic conditions should extend at least to 2000 m, possibly somewhat deeper.

Zooplankton and fish sampling in the Arabian Sea during the height of especially the SW monsoon will require work in extreme sea states, certainly in sea state 6. This will require investigators to develop new, very rugged equipment, and it will probably preclude the use of classical, exposed nets altogether. For zooplankton, several solutions to this requirement can be imagined, including self-contained pumping-filtering systems in deployment packages resembling CTD-rosette systems. Development and deployment of such instrumentation is in line with U.S. GLOBEC's general goal of supporting improved technology for studies of pelagic ecology.

In addition to sampling with a newly developed, weather-hardened system, the zooplankton team should plan and propose a net-based sampling system for use in good weather and capable of filtering the large volumes required for capture and study of larval (and perhaps adult) fish. The system can be based on moderately coarse mesh (500 μm) and can be built in a very rugged format for use in extreme sea conditions. The goal will be large samples of large plankton suitable for estimating stock numbers, size-frequency distributions, and biological characteristics of myctophid larvae. Since traditionally studies of ichthyoplankton and mesozooplankton are carried out by people with different interests and training, the zooplankton work should probably be divided among several investigators. However, cooperation in use of samples will be required, and it should be explicitly proposed by investigators.

The implementation committee leaves all details of approach and methodology to proposing investigators. The Arabian Sea provides an excellent ecological system for application of several of the new technologies for which U.S. GLOBEC has been providing support. Sonar methodology will have special applications for accurate estimation and spatial integration of the abundance of abundant myctophid fish. Specialized, high frequency sonar methods suitable for zooplankton studies may be ideal or certainly suitable for study of the target plankton species. All of the species populations are likely to be subject to subregional differentiation, and they will make good subjects for studies by modern, molecular methods in population genetics.

Some matters left to proposing investigators will eventually require negotiation and compromise among the successful candidates. These include station-spacing along the basic U.S. JGOFS line and duration and schedule of activities at each site. Possible plans include stations of several days duration at a series of locations. For example, on each cruise experimental and observation stations might be 1) over the shelf in the coastal upwelling, 2) in the gap between coastal and oceanic upwelling zones, 3) at the core of the Findlater jet (both when it is active and in other seasons), 4) offshore of the jet, 5) farther offshore in tropical oligotrophic waters, and 6) northeast of the main transect line in the most intensely suboxic region of the Arabian Sea. Intercalary sampling sites might be briefly visited during transit between these principal stations. Each main station could be occupied for 3-4 days on cruises of reasonable duration that fit within the overall U.S. JGOFS schedule for the ship. Consult Appendices A-D for additional information on potential approaches and logistical considerations.

## Conclusion

The implementation committee recommends that U.S. GLOBEC funding suitable in scale for a program ancillary to the U.S. JGOFS Arabian Sea Process Study be spent on:

1) a study of population structure and population dynamics (broadly defined) of three target groups of mesozooplankton (*Calanoides carinatus*, Arabian Sea euphausiids, and *Thalia democratica*);

2) a general planktological reconnaissance of the northern Arabian Sea, including the open-ocean and coastal upwelling regimes; and

3) a study of the biology, ecology, distribution, and systematics of the larvae and adults of the dominant species constituting the massive myctophid stocks of the region.

*Implementation Plan for a Full-Scale U.S. GLOBEC Study of Pelagic Populations and Ecosystem Dynamics in the Arabian Sea*

Arabian Sea processes are attractive for U.S. GLOBEC studies in two respects:

• The Arabian Sea provides a comparison between two different types of upwelling systems in close geographic proximity. These are a coastal upwelling regime along the Somali and Arabian Peninsula shores and an oceanic upwelling regime under the Findlater jet. It is obvious that the ecological requirements of these two upwelling regimes for mesozooplankton will be different, but the responses of planktonic species are not known. In addition, the monsoon climate offers alternating seasons in a tropical-subtropical setting, which it can be anticipated will offer some of the advantages for study of population processes usually found only in high latitudes.

• The Arabian Sea is peculiarly rich in myctophid fishes, home to one of the largest, single species stocks in the world. Production of this fish, *Benthosema pterotum*, amounts to 100 million tons per year. Its population processes must be coupled to the extremely high production of the region which is based on nutrients supplied by monsoonal upwelling. This coupling seems to be unique but is not understood, and a U.S. GLOBEC program could elucidate the mechanisms.

The implementation plan offered below seeks to pursue these attractive features of the ecology of the Arabian Sea. Proposed studies of both mesozooplankton and fish stocks will be greatly enhanced by the prolonged operation of a dedicated, fishery research vessel in the northern Arabian Sea. An appropriate vessel is described in the section below on fish research. Zooplankton work is flexible enough to fit on this vessel or any other general oceanographic ship.

## Fish Stocks

Hypotheses and Tests of Hypotheses:

Study of the unusual fish stocks of the Arabian Sea can be based on some general and specific hypotheses. The latter are really questions. In many respects the population processes are not well enough understood for formulation of *testable* hypotheses.

General Hypothesis: The large stocks of myctophid fish and their high growth rates in the Arabian Sea are a function of regional physical conditions, including the dual coastal/oceanic upwelling system and the large region of suboxia below 150 m.

Specific Hypotheses:

• These myctophids are protected from daytime predation at depth by descent into dysoxic waters.

• Rapid growth is promoted by the unusually high productivity associated with both coastal and open sea upwelling.

• Variations in myctophid abundance are related to topography.

• Much myctophid production goes to non-predatory mortality, with the decomposing biomass ending up contributing to benthic nutrition.

A Modified General Hypothesis: It was suggested at the Denver workshop that possibly the dominance of myctophids in the Arabian Sea upwelling regimes contrasts with the dominance of clupeids in the Peru and California ecosystems for a different reason. In those latter systems, forcing winds for upwelling are episodic, they have an event scale (shorter than the seasonal scale) on which the winds lapse, then resume. During the lapses the mixed layer stabilizes and particulate foods can aggregate above a threshold for larval feeding. In the Arabian Sea both coastal and oceanic upwelling are prolonged and without lapses. The wind blows night and day for up to 3.5 months (but see the essay above on monsoonal variations). In the coastal regime there may be no mechanism for returning developing zooplankton stocks to the coast, probably a function served by lapses in upwelling off Oregon (Peterson et al. 1979) and Peru. In the oceanic upwelling region of the Arabian Sea, where much of the primary production may be by coccolithophorids, the food chain may be longer, less efficient, and less capable of supporting large stocks of clupeids, than in upwelling regions elsewhere. Myctophids in the Arabian Sea, then, essentially are filling a niche left open by the failure of clupeids.

Tests of these hypotheses will require varied sampling efforts, both in the water column and of the sediments. First, the levels of stock abundance and the growth rates that have been reported must be confirmed. There is reason for doubt about the accuracy of the earlier Norwegian sonar surveys, although they cannot be wrong in showing the stocks to be enormous. For this purpose we require a recurring, geographically dispersed stock estimation program using both carefully calibrated, echo-integrating sonar and large, preferably sonar-guided trawls. The trawls will provide secondary, immediate calibration checks for sonar results as well as large quantities of fish for direct study (species composition, size-frequency, condition factors, gut contents, reproductive status, enzymology and proximate analysis). Second, plankton sampling studies are required for study of food selection by comparison to gut contents and for study of the timing of larval development and geographic differences in larval distribution and success. Third, sites should be sought for evaluation of sediment accumulation of scales and otoliths so that temporal changes in myctophid stocks can be examined. Since it is a region of extensive suboxic, and on the seabed occasionally anoxic, conditions, it is possible that, as in the California, Peru and Benguela Current areas (Soutar and Isaacs 1974; Shackleton, 1987), sites can be found with very slight degradation and very detailed temporal records of fish remains.

An ambitious program of study can focus its seasonal comparisons along a single, onshore-offshore transect line, and the line out of Oman proposed for U.S. JGOFS work is an excellent choice. To provide a range of physical conditions and to investigate myctophids in both the coastal and oceanic upwellings, one station should be located on the shelf, 2-3 over the slope, and 2-3 along the line offshore. It should not be necessary to proceed beyond the limit of eutrophic conditions established by the SW monsoon beneath the Findlater jet. In addition, it will be necessary for studies to be dispersed alongshore, certainly at least from Cape Guardafi east to the southeastern limit of Pakistan. A tour of this perimeter on a seasonal basis would produce useful information on the response of the stocks to the variations of the monsoon regime.

Evaluations of our specific "hypotheses" may be developed as follows:

• Sonar and trawl studies will evaluate the diel migratory behavior of *B. pterotum* and other myctophids, examining the relationship of these movements to suboxic conditions at the bottom of the epipelagic zone (ca. 150 to 1500 m) and to the distributions of potential predators. Gut contents of larger fishes and squid captured by the trawls will be examined for myctophid remains. The hypothesis predicts (1) that myctophids will spend the daylight period in the suboxic layer, and (2) that larger fish and squid predators will be greatly reduced or absent in that layer. Some evaluation of the impact of very large predators, like tunas, can be obtained by cooperation with the fisheries for them, obtaining distributional and gut content data. The hypothesis also predicts (3) that *B. pterotum*, *D. arabicus*, and possibly other species are metabolically well suited for prolonged occupation of suboxic waters. They will be anaerobically poised with high activities of lactate dehydrogenase and other glycolytic enzymes. This can be examined with the copious materials we anticipate from our trawling program.

• Growth rates can be determined by classic ichthyological techniques: study of otolith growth rings (useful rings are likely to represent daily or lunar intervals); study of seasonal cohorts developing roughly in phase; experimental rearing (although success with rearing myctophids is very limited). Differences in growth between subregions with different production regimes should shed light on the basis for rapid growth in *B. pterotum* and other myctophids.

• Variations in abundance with topography is a straightforward sampling problem. It will be greatly assisted by deployment of echo-integrating sonar along transects of varying bathymetry.

• Examination of sediments may provide clues to the fate of the high primary and myctophid production, although some of the best preserved remains of fish may appear in sediments after their death by predation. Direct evaluation of the fate of 100 million tons of myctophids per year will take some further thought. Because macrourids, hagfish, and amphipods will quickly remove directly deposited bodies, we do not expect to find "windrows" of dead *Benthosema* lying on the bottom. It is also possible that most of the removal is by predation by scombrids, carangids, mackerels, and any number of pelagic predators.

• The alternate hypothesis concerning the relative importance of clupeid and myctophid populations in differing upwelling regimes can only be "tested" by continuing development of pelagic ecosystem theory, by advance of our general understanding of how these ecosystems work. The proposed study will help by expanding and clarifying the myctophid side of the comparison.

Equipment and Approach

A fully implemented U.S. GLOBEC study of myctophid stocks in the Arabian Sea will require a dedicated vessel specially equipped for fishery studies. This need not be a particularly large ship, but it should have the following capabilities:

• It should be suitable for operation in marginal working conditions, including scientific work off the Arabian coast and under the Findlater jet during the SW monsoon (sea state 6: winds at 22-47 knots, significant wave heights of 6-9 m/mean 7.5, wave period 14 sec).

• Accommodations are required for 12-15 scientists

• Equipment must include state-of-the-art, low-frequency (38 kHz) acoustic sampling devices; double-warp trawling capability and power to tow and haul 500 $m^2$ (or larger) trawls; processing capacity for handling catches made by such trawls (commercial-scale processing facilities below decks and winches and booms for deploying smaller oceanographic gear, including CTD and plankton samplers; and a full suite of communications and meteorological instrumentation. Higher frequency (>200 kHz) acoustics (ADCP, dual or split-beam systems) would be useful in providing distributions of zooplankton prey to complement acoustic estimates of fish distributions and abundance.

Ships suitable for this service exist. For example, a Bering Sea-type trawler-processor (135-150 ft. LOA) could be chartered for costs comparable to research vessel costs. For tropical service, air conditioning equipment would have to be added. Suitable trawler-processors also operate off South Africa, including one operating for the South African Sea Fisheries Service. Possibly one of those could be obtained for charter.

The organizational design for the scientific work would involve teams with the following designations and duties:

- An Acoustic Survey Team - to gather, collate and interpret geographically and temporally extensive estimates of fish stock biomass by state-of-the-art acoustic methods. The array of possible equipment is now extensive, including 38 kHz acoustic integration systems (Norwegian designs primarily), higher-frequency dual-beam systems, multi-frequency systems, and modified ASW sonar systems now becoming available in the civilian sector. One of the goals of initial work under the aegis of U.S. GLOBEC has been improvement of acoustic technology for fishery and plankton work. The Arabian Sea should be an ideal milieu for this technology to show its value.

- A Trawl Survey Team - to capture large samples of midwater fish populations, then produce and interpret the data recommended above.

- An Ichthyoplankton Survey Team - to evaluate myctophid spawning regions and seasons using egg and larval survey techniques.

- A Zooplankton Population Biology Team - to evaluate the general population and production biology of mesozooplankton upon which the myctophid stocks prey. This work should include studies of gelatinous forms (salps, appendicularians, ctenophores), given the evidence in hand that common foods for myctophids are plankters associated with them. This team should come equipped to sample during persistent sea state 6 conditions, which certainly preclude diving.

- An Ecophysiology Team - to work on detailed physiology of both myctophid fish and mesozooplankton, particularly those aspects enabling and precluding life in suboxic conditions (cf. Waller, 1989). These include study of aerobic vs. anaerobic metabolic poise, capacity for oxygen exchange at low and extremely low oxygen tension, and determinations of swimming capability and endurance of myctophids under a range of temperature and oxygen conditions. Given the differences between work on fish and zooplankton resulting from differences in size and behavior, separate subgroups should probably address these different groups.

### Mesozooplankton

We recommend that the principal focus for an extended Arabian Sea U.S. GLOBEC study be to develop understanding of the prodigious myctophid stocks of the region. Zooplankton studies should be proposed that will supplement and extend this central study of fish. Therefore, the necessary zooplankton studies can be adequately outlined in very brief space. Much is left to the specific interests and creative ability of the proposing investigators.

Investigators proposing Arabian Sea work under the extended plan, as under the minimal plan, should develop their plans around studies of Arabian Sea euphausiids, *Calanoides carinatus*, and *Thalia democratica.* Reiterating, these species are certain to be present, likely to be ecologically important, and possibly are significant in the biology of regional fish stocks. Both the euphausiid and copepod species should be amenable to seasonal sampling studies of their population responses to monsoonal variations in upwelling and production. Both species will be suitable for dynamical experimentation, including studies of feeding, fecundity, growth and molting rates, respiration, enzyme rate functions, and adaptation to suboxic conditions.

A topic not addressed in the minimal plan that requires thorough examination in the extended plan, is the dominance of cyclopoid copepods as prey of *B. pterotum* and *D. arabicus* (see Kinzer et al., 1993). The importance of the small, numerous cyclopoid copepods to the general economy of the Northern Arabian Sea has been badly neglected to date (although R. Böttger-Schnack is currently investigating the systematics and vertical distribution of cyclopoids in the Northern Arabian Sea using nets with 50 and 100 µm mesh; Kinzer, pers. comm.).

## Approach

As for the minimal plan, the implementation committee leaves the specific hypotheses around which the research is to be organized to proposing investigators. We only offer the hypotheses above as a general organizing theme. Further, like the minimal plan, all of the specific sampling and experimental methods, station plans, and logistic details are left to proposing investigators. Again like the minimal plan, the Arabian Sea offers an excellent milieu for application of new, U.S. GLOBEC-supported technology in sonar, molecular biology, and other areas. We commend their use to proposing investigators, but the problems proposed for study and the hypotheses proposed for test should determine methods and approach, not U.S. GLOBEC's prior commitment to specific techniques.

## Conclusion

Given the system prevalent in U.S. GLOBEC for developing specific research programs, we see no need to specify what should be done beyond this point. That system is for principal investigators to respond to a general implementation plan with specific proposals. Then program managers and review panels assemble the final scientific program and investigator team by selection among proposals and (presumably) by negotiations with and among the proposing workers. If a full U.S. GLOBEC study program is ever to address problems in the Arabian Sea, a program can be developed in that fashion based on the simple outline above. Doubtless, considerable additional biological detail will be considered by proposers, managers, and reviewers as development proceeds. Thus the proposing investigators should expect a shifting target. However, the committee writing this open plan have no doubt that Arabian Sea myctophid fishes, particularly *Benthosema pterotum*, are among the most exciting target species available in the world for research in pelagic biology. Ancillary studies of zooplankton will generate understanding of how the myctophids fit in the Arabian Sea pelagic ecosystem, and they will make a valuable contribution to planktology in their own right. We recommend this plan (and continued, detailed planning) to the oceanographic community with strong enthusiasm.

*INTERACTION WITH OTHER PROGRAMS IN THE REGION*

During the past three years, several national and international programs have been planning oceanographic studies for 1994-1996 in the Arabian Sea. Coordination and cooperation among the various U.S. planning efforts (U.S. JGOFS, WOCE, ONR, and U.S. GLOBEC) and international plans has been extensive. The region selected for the U.S. JGOFS study includes the upwelling zones (both coastal and offshore) off Oman, a central, oligotrophic region, and a domain off central India. The U.S. JGOFS strategy for studying the Arabian Sea includes interdisciplinary process-study cruises; long-term deployment of surface and subsurface moorings with instruments to measure chemical, biological, optical, and physical properties; intensive satellite data acquisition; and numerical modelling. Their focus is a better understanding of the unique biogeochemical characteristics of the region (for additional information on the U.S. JGOFS Arabian Sea program see U.S. JGOFS Planning Report No. 13 (1991) and U.S. JGOFS Arabian Sea Process Study Implementation Plan (1992)). The U.S. WOCE program plans a hydrographic section in the Arabian Sea and plans to deploy moorings and conduct additional studies off both Oman and Somalia. The Office of Naval Research (ONR) has announced plans for an Accelerated Research Initiative (ARI) on Forced Upper Ocean Dynamics of the Arabian Sea. The program, to study the response of the physics and biology of the upper ocean of the Arabian Sea to atmospheric forcing of the region, is scheduled to occur in 1994-1995 at the same time as the U.S. JGOFS Arabian Sea process studies.

Formal meetings to plan international JGOFS Arabian Sea studies began in January 1991 in Goa, India. Subsequent meetings took place in Bermuda (October 1991) and onboard the RV *Tyro* (May 1992). The international planning committee of JGOFS has representatives from Germany (presently, chair), Britain, France, Canada, the Netherlands, United States, Kenya, Oman, Pakistan and India. One goal of the international planning committee is to actively encourage countries bordering the Indian Ocean to participate within the JGOFS Arabian Sea study and, importantly, to encourage regional scientists to continue observations in the Arabian Sea after the concerted JGOFS expeditions of 1994-96 are concluded.

Expeditions to the Arabian Sea have already begun. The Netherlands has been conducting a JGOFS-type investigation of the upwelling off northern Somalia since June 1992. A collaboration with Kenya, India and the U.S., this program includes many of the recommended core JGOFS measurements. Pakistan has begun the North Arabian Environmental and Ecosystem Research (NASEER) program of quarterly cruises making U.S. JGOFS, U.S. GLOBEC and WOCE type observations of hydrography, chemistry, production and biomass in the northern Arabian Sea (see Fig. 19). The NASEER program is scheduled to continue through 1994. Sediment traps have been deployed in the open Arabian Sea since 1986 by a consortium of India, Germany and the U.S. These traps will continue to be deployed throughout the period that JGOFS investigates the Arabian Sea.

Future international JGOFS collaborations will include British and German research vessels. The British vessel RV *Discovery* plans to conduct JGOFS studies at three sites in May and August 1994. The German vessel RV *Meteor* plans to participate in Arabian Sea JGOFS studies in May and August 1995. Additional studies by India, using the RV *Sagar Kanya*, have not yet been finalized. U.S. plans call for two research vessels, the RV *T. G. Thompson* and the RV *M. Baldridge*, to participate in combined U.S. GLOBEC, U.S. JGOFS, and ONR investigations in the Arabian Sea in 1995. The *Thompson* will begin operations in October 1994 and finish in January 1996 according to the present schedule (for details see U.S. JGOFS Arabian Sea Process Study Implementation Plan (1992)). The *Baldridge* will have cruises in the Arabian Sea in March, July and August 1995 (Fig. 19). Investigations aboard the *Baldridge* will focus on biological processes in the upper water column (above the suboxic zone) and thus are relevant to both U.S. GLOBEC and U.S. JGOFS investigations.

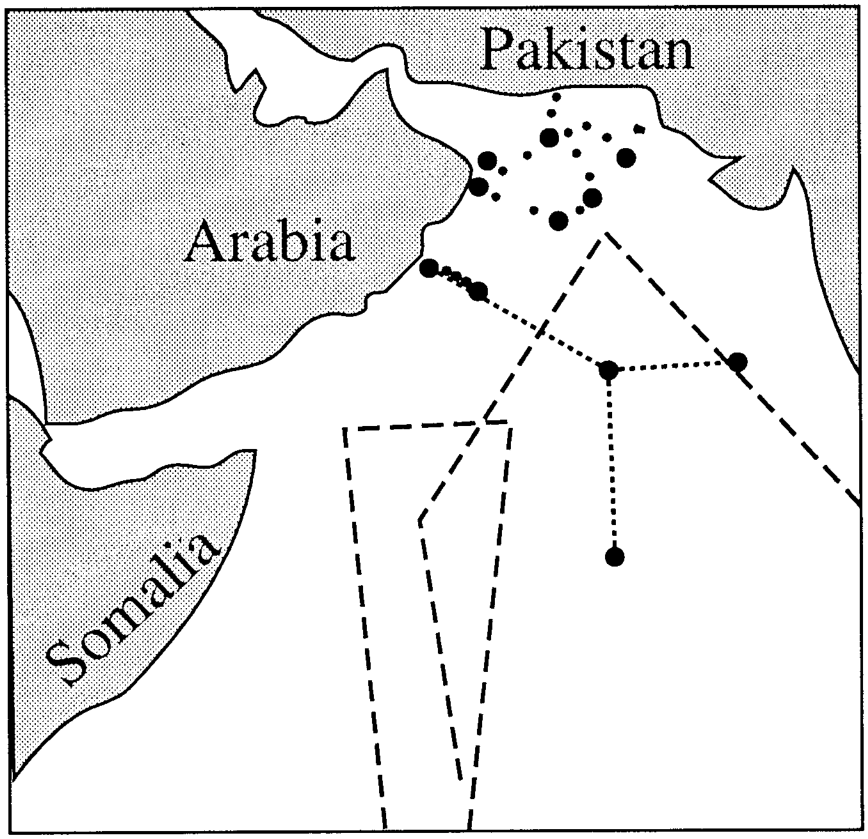



Figure 19. Locations of various studies being conducted in the Arabian Sea during 1992-1996 (modified from the International JGOFS Implementation Plan). Large solid circles indicate locations of intensive or time-series stations. The group of stations off Pakistan are the NASEER program; the stations off Somalia are the Netherlands Indian Ocean Program. The dashed lines indicate proposed cruise tracks of the RV Baldridge (USA-NOAA). The lines of stations extending off Oman indicate the U.S. JGOFS study. This chart does not include the WOCE sampling lines in the region (Figure 20) or the locations of moorings (Figure 18).

The Netherlands' vessel RV *Tyro* may return to the Arabian Sea in June 1996. Preliminary planning for this has begun and has been strongly encouraged for two reasons. First, if that happens, then the international JGOFS program will have collected JGOFS observations during three successive southwest monsoons. Since the strength of the southwest monsoon varies interannually (as discussed above), coverage of the region during multiple southwest monsoons is essential. Second, if the *Tyro* returns in 1996, it could retrieve moorings in October 1996. This would permit sediment traps and moorings to be deployed through two southwest monsoons. Furthermore, the preliminary plan for 1996 *Tyro* investigations includes studies of the distribution and activity of *Calanoides carinatus* in the post-upwelling season (September-November inclusive) off Oman, Sri Lanka and Java. Such studies are certainly of interest to U.S. GLOBEC.

The Arabian Sea was first suggested as a region of interest to U.S. GLOBEC by Don Olson. Subsequently, Sharon Smith and Don Olson presented to the U.S. GLOBEC Scientific Steering Committee (SSC) the rationale for conducting studies in the Arabian Sea. In March 1992 the U.S. GLOBEC SSC agreed to sponsor a planning meeting to discuss U.S. GLOBEC relevant scientific research in the Arabian Sea. That meeting was held in Denver in June 1992. Its results and recommendations are included within this report (Appendices A-D).

Planning for Arabian Sea studies by other U.S. national programs (U.S. JGOFS and the ONR/ARI) began earlier (as early as July 1987 for U.S. JGOFS) than did U.S. GLOBEC planning. The ONR-ARI and U.S. JGOFS Arabian Sea programs have both entered their implementation phases; both are actively soliciting proposals and they continue to develop cooperatively. At a recent meeting a consensus was reached regarding the locations and types of moorings to be deployed in the Arabian Sea by U.S. JGOFS and ONR (Figure 18).

The World Ocean Circulation Experiment (WOCE) World Hydrographic Program (WHP) plans to survey the Indian Ocean in FY 1995. The northern portion of WHP line I7 transects the Arabian Sea region of interest identified by U.S. JGOFS (Fig. 20). As presently conceived, WOCE plans to occupy line I7 during the southwest monsoon of 1995. Hydrographic observations along line I7 by U.S. JGOFS and/or U.S. GLOBEC cruises in the northern Arabian Sea will enable WOCE to achieve their goal of repeated hydrographic observations in the Arabian Sea. WOCE line I1 provided the southern boundary for bulk calculations of transport and properties which will useful for calculating U.S. JGOFS carbon and particulate budgets. Hydrographic and meteorological data collected along WOCE line I1 may be of value to U.S. GLOBEC investigations of the Arabian Sea as well.

During the planning activities for Arabian Sea research that have taken place from March 1990 to present, Sharon Smith has acted as liaison among the U.S. JGOFS, international JGOFS, U.S. WOCE, ONR, NOAA, Pakistan's NASEER, the Netherlands', and the U.S. GLOBEC programs. Smith has been only one contact between the various programs; there are others as well. This liaison has permitted timely exchange of information among the various programs so that Arabian Sea studies planned for the mid-1990's are coordinated and integrated both nationally and internationally. The results of this effort are best examplified by examining Figure 19, which shows a chart of the cruise tracks anticipated or ongoing within the Arabian Sea, and Figure 21, which shows the seasonal cruise coverage anticipated during 1994-1996.

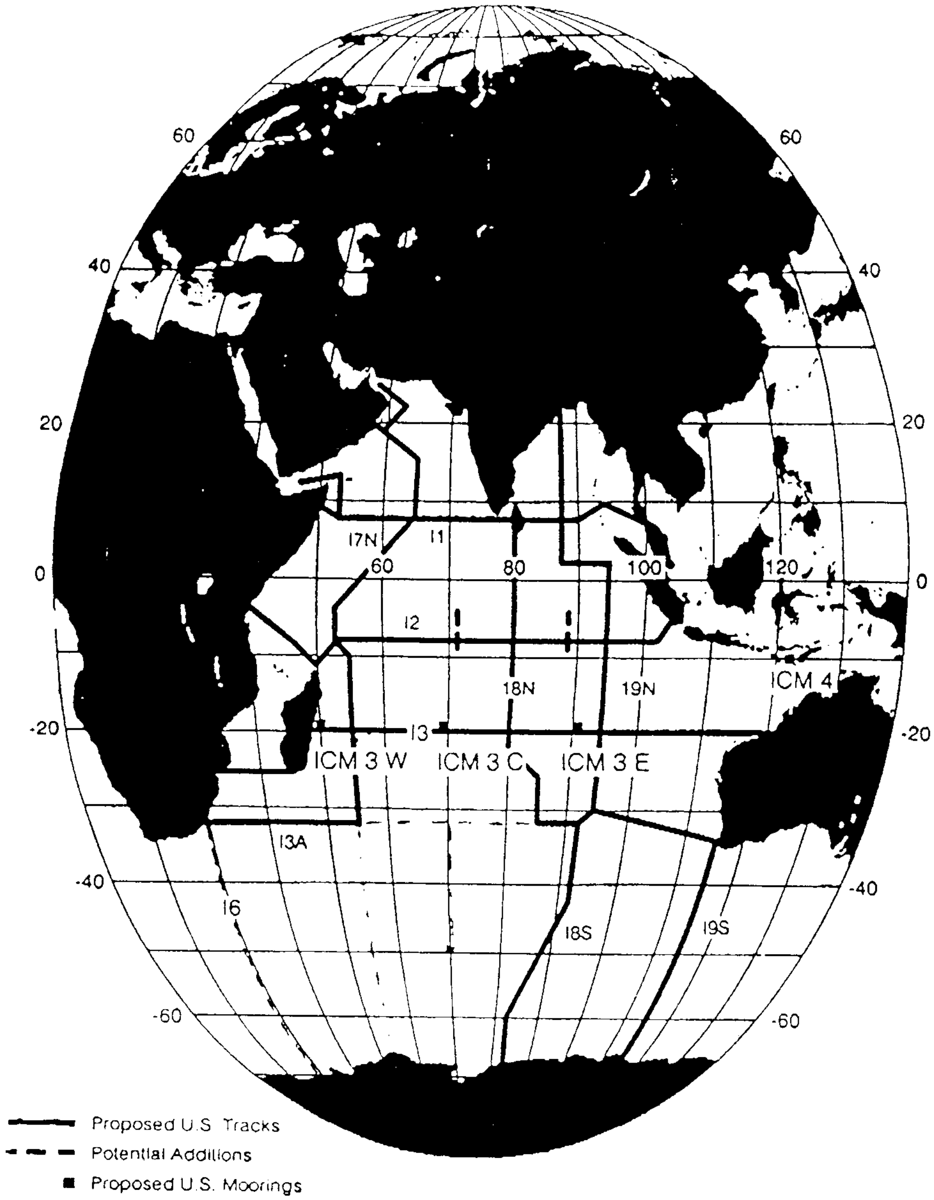



Figure 20. Proposed WOCE cruise tracks in the Indian Ocean.

| | 1994 | | 1995 | | | | 1996 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SHIP | May | SW | I | NE | I | May | SW | I | NE | I |
| *Discovery* | ********** | | | | | | | | | |
| *Vodyanitsky* | | | | ? | ? | ? | ? | ? | | |
| *Meteor* | | | | | ************ | | | | | |
| *Thompson* | | ****************************************** | | | | | | | | |
| *Sagar Kanya* | | | | ? | ? | ? | ? | ? | | |
| NASEER | ***************** | | | | ? | ? | ? | ? | | |
| *Tyro* | | | | | | | | | ***** | |
| *Baldridge* | | | | ********************* | | | | | | |
| *Sonne* | | ****** | | | | | ******* | | | |

Request of RV *Thompson* has been made to UNOLS; total of 16 months for U.S. JGOFS and ONR combined.

Figure 21. List of ships presently under discussion for participation in Arabian Sea research during 1994 to 1996. SW indicates the southwest monsoon; I indicates Intermonsoons (in text called transitions); NE indicates northeast monsoon. *Meteor* and *Sonne* are German vessels; *Discovery* is British; *Tyro* is from the Netherlands; *Sagar Kanya* is from India; *Thompson* and *Baldridge* are from the U.S.; NASEER is the Pakistani program conducted from various chartered vessels; and *Vodyanitsky* is a vessel from the Ukraine.

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## *APPENDICES*

### Appendix A. Workshop Summary

Eighteen scientists from universities and federal laboratories (Appendix F) with research interests in zooplankton and fish ecology met in Denver during 16-17 June 1992 to outline the scientific issues and formulate a research plan for a U.S. GLOBEC program in the Arabian Sea. The charge to the group was to define the scientifically interesting questions, relative to zooplankton and fish ecology, posed by the unique conditions of the circulation of the northern Arabian Sea. The seasonally reversing monsoon winds cause massive changes in the physical and biological phenomena of the region. The group was also charged with producing a series of hypotheses about and a plan of research on the upper trophic levels of the Arabian Sea. Following background presentations on the physical circulation (Don Olson) and numerical modelling of the physics (Mark Luther) of the Arabian Sea, three working groups were formed to address questions associated with zooplankton, fish and technology. Reports of the working groups follow this summary.

Working group discussions centered around the question of how structure and dynamics of the pelagic biota differ between the coastal Arabian Peninsula and the central Arabian Sea upwelling regions. Structure includes species composition, distribution, abundance and genetics, and dynamics includes population dynamics, individual vital rates and trophic interactions. The two upwelling regions differ dramatically in scale as well as in the physical mechanism responsible for the upwelling.

Major questions to emerge from the workshop discussions were: What are the trophodynamic links between the high and sustained primary productivity of the southwest monsoon and the large populations and biomasses of midwater myctophids, especially *Benthosema pterotum*, in the Arabian Sea? What is the fate of the enhanced primary production associated with the southwest monsoon in the central Arabian Sea?

The zooplankton working group also considered these questions (Appendix B): What is the response of the zooplankton populations to the strongly seasonal physical forcing? How does the strong seasonality affect species composition and abundance and trophodynamic linkages among the higher trophic levels? How do the population dynamics (vital rates) of the zooplankton respond to changes in the physical environment associated with the southwest monsoon, northeast monsoon and transitional periods?

The fish working group focused on the large standing stocks of myctophids, especially of *Benthosema pterotum*, in the slope-water regions of the northern Arabian Sea (Appendix C). The group proposed as a general hypothesis that the large stocks of myctophid fish and their high growth rates in the north Arabian Sea are a function of regional physical conditions. Several specific hypotheses were formulated. Among them: Myctophids are protected from daytime predation at depth by descent into dysoxic waters. Rapid growth is promoted by the unusually high productivity associated with both coastal and open sea upwelling. Variations in myctophid abundance are related to topography.

Both the zooplankton and the fish working groups discussed preliminary sampling plans. Central to their discussion was an onshore-offshore transect across the northern Arabian Sea, with sampling sites within the Oman coastal upwelling domain, the offshore upwelling domain and the permanently oligotrophic, downwelling domain further to the southeast.

Discussion in the technology issues working group (Appendix D) focused on methods for rapid and quantitative description of the distribution and abundance of zooplankton and fish. Among the topics discussed were multiple frequency acoustics, optical imaging, conventional nets, pump samplers and molecular systematics.  The group also discussed the measurement of population dynamical rates, such as consumption, birth and growth.

Appendix B. Zooplankton Working Group Report

Chair: Karl Banse
Rapporteur: Hal Batchelder

Participants: Ann Bucklin, Dave Checkley, Tim Cowles, Bill Peterson, Karen Wishner

*Introduction*

The western Arabian Sea offers a unique opportunity to study pelagic ecosystems subject to very strong seasonality in physical forcing by the reversing monsoons, with considerable interannual fluctuation correlated with ENSO signals, and a known paleontological record of past climate and climatic effects. The geographic domain of particular interest lies offshore from the Arabian Peninsula and stretches toward the Indus delta. During the summer, southwest monsoon, the Findlater (East African) jet leads to open-sea upwelling and ensuing phytoplankton production under rather steady, very strong winds. During this period, the approximately 500km wide open-ocean upwelling domain is, toward Arabia, adjoined/bordered by a coastal domain with strong seasonal upwelling, and on the seaward side by a central Arabian Sea downwelling domain, which intergrades into the persistently oligotrophic domain of the eastern and southern Arabian Sea. North of 20 °N lies a fourth domain which has two phytoplankton blooms per year, one wind-driven and concurrent with the blooms in the upwelling domains, and another caused by nutrient injection during winter surface cooling and convective overturn.

We expect that the major goals of U.S. GLOBEC, to study biological processes (e.g. growth, production, mortality) of dominant species and the causes of fluctuations of their abundance in relation to the physical regime, can most profitably and uniquely be investigated in such regimes of physical contrast but which are, at least in part, inhabited by the same species of zooplankton and mesopelagic fish. We believe that adaptations of such planktonic and nektonic populations to strongly physically forced habitats should be investigated to understand the Present, as well as to anticipate the effects of future climate change here and in other areas of the sea where climate change might lead to conditions similar to those found in the four domains of the Arabian Sea. Such a study would best be done in coordination with other programs (U.S. JGOFS, ONR/ARI, WOCE) working in the same area, or even at the same stations. In fact, we suggest that U.S. JGOFS, which focusses on the primary production of organic matter and vertical fluxes from the euphotic zone, but does not consider in any substantive way the higher trophic levels, would benefit greatly from a U.S. GLOBEC oriented investigation of growth processes and population dynamics of mesozooplankton and mesopelagic fishes.

The zooplankton working group developed the following primary questions: How do the structure and dynamics of ecosystems in coastal and open-sea upwelling domains in the Arabian Sea differ? To what extent are the domains biologically distinct, i.e., containing genetically distinct populations among the abundant species occurring in two or more domains? What are the determinants of community composition, e.g. physiological adaptation, fecundity, growth, mortality, and genetic isolation. Note that these questions are not restricted to zooplankton populations; they are valid questions for mesopelagic fish populations as well. That was intentional. General and specific scientific questions which were discussed by the working group are detailed below and posed as questions rather than as hypotheses.

*General Themes and Specific Scientific Questions*

Discussion focused on two general themes. The first focused exclusively on the plankton dynamics and structure of the open-ocean upwelling domain, the second on a comparison of plankton structure and dynamics among the various physical domains of the north Arabian Sea.

General Theme: To describe and understand the higher trophic level structure and dynamics of the physically-unique, open-ocean upwelling system in the Arabian Sea.

Specific Questions:

- Are there large suspension-feeding mesozooplankton in the central north Arabian Sea that are capable of taking advantage of the strongly seasonal pulses of food? If so, what are they? What are their vital (development, growth, reproduction, mortality) rates? If such grazers, typical of coastal upwelling systems, are not a dominant feature in the central Arabian upwelling region, why not? And by what are they replaced?

- What are the trophodynamic links between the high and sustained primary productivity during the several months of the SW monsoon and the enormous populations and biomass of midwater fish, especially myctophids, in the Arabian Sea?

- What is the fate of the enhanced primary production associated with the SW monsoon in the central Arabian Sea? Is it grazed? Does it ultimately enhance fish production in the central Arabian Sea? Does it end up on the bottom to enhance benthic production? This would appear to be a principal question of U.S. JGOFS studies in the Arabian Sea.

- To what extent does the oxygen minimum zone (at ca. 150-1500 meters) in the central and eastern Arabian Sea restrict the vertical distribution and vertical migration of zooplankton? Is the oxygen minimum in some way responsible for the apparently low species diversity of the mesopelagic animal groups (fish, euphausiids, copepods) in the northern Arabian Sea?

- What is the response of the zooplankton (and higher trophic levels) populations to the strongly seasonal physical forcing? How does the strong seasonality affect species composition and abundance and trophodynamic linkages among the higher trophic levels? How do the population dynamics (vital rates) of the zooplankton vary among the SW monsoon, NE monsoon, and transitional periods?

General Theme: How do the upper trophic level structure and dynamics in the open-ocean upwelling domain compare to those in adjacent physical domains of the Arabian Sea: the Arabian Peninsula coastal upwelling domain, the permanently oligotrophic region of the southeastern Arabian Sea, and the Arabian Sea north of 20 °N.

- Are there substantial differences in the pelagic biota (net zooplankton and fish fauna) species composition and food web dynamics between the coastal Arabian Peninsula (Oman) upwelling region and the central Arabian Sea upwelling region?

- Unlike the central Arabian Sea, the area north of 20°N exhibits two phytoplankton blooms, one during each of the SW and NE monsoons. The physical dynamics responsible for the two blooms differs markedly. The primary productivity during the SW monsoon is driven by wind-induced upwelling of deeper waters, whereas the NE monsoon bloom occurs as a response to convective overturn due to winter cooling. How do the plankton structure and dynamics of the two regions differ?

- How does the zooplankton composition and dynamics in oceanic regions of the eastern Arabian Sea, which are permanently oligotrophic, differ from regions where upwelling occurs?

- What are the physical and biological linkages between the open-ocean upwelling domain of the Arabian Sea and the adjacent physical domains?

The gradient from the coastal upwelling domain off Arabia (Oman) to the broadscale Findlater Jet driven offshore upwelling domain to the permanently oligotrophic domain in the eastern Arabian Sea is the region of interest to U.S. JGOFS. Detailed process studies and intercomparisons of the dynamics and structure of the upper trophic levels in these different domains by U.S. GLOBEC should be of immense value to, and nicely complement, the studies planned by U.S. JGOFS.

*Logistics Recommendations*

• Examine the extant literature on zooplankton species composition, community structure and dynamics in the Arabian Sea. Unlike many other regions of the world's oceans, the information on the zooplankton of the Indian Ocean, including the Arabian Sea, is sparse. The data that have been worked up are scattered, often in foreign languages. It was the belief of the zooplankton working group that one such resource is the substantial information on the abundance and distribution of zooplankton and mesopelagic fishes in the Arabian Sea generated by Soviet research cruises. We recommend that one or several U.S. investigators collaborate with Russian oceanographers in the Sevastopol and Moscow institutes, with the goal of writing and publishing reviews (in English) of the accumulated results of Russian (formerly Soviet Union) investigations of the zooplankton and fish ecology of the Arabian Sea and Indian Ocean generally. These reviews should also include data from regional countries near the Arabian Sea, eg. India and Pakistan, to the extent that such inclusion is possible.

• As an aid in defining the distribution of mesopelagic fishes and zooplankton biomass, acoustic data on scattering layers (DSL) in the open Arabian Sea should be collated and examined.

• The working group felt that initial survey cruises, using Seasoar (or similar) techniques to define the biological, optical, acoustic, and physical properties of the various oceanographic domains, and to define the scales of variability of these parameters would be valuable as part of U.S. GLOBEC studies of upper trophic level structure and dynamics. Such survey cruises should be conducted prior to each major oceanographic process cruise sponsored by U.S. GLOBEC.

• A consensus was established that to "piggyback" a large U.S. GLOBEC scientific effort on U.S. JGOFS cruises, or to be restricted to ship time when other programs were idle, was not the preferred method for conducting a viable USGLOBEC study of the upper-trophic levels of the Arabian Sea. Rather, the group felt that U.S. GLOBEC should request a moderate-to-large, modern, well equipped UNOLS vessel that would be dedicated to U.S. GLOBEC investigations. Moreover, it was felt that with two UNOLS vessels (one for U.S. GLOBEC, one for U.S. JGOFS) in the Arabian Sea during the proposed study period, there would be enhanced opportunity for exchange of scientists between the two programs, as well as potentially better seasonal coverage of the dynamic oceanographic conditions of the Arabian Sea.

*Survey Mode and Measurement Recommendations*

The principal goal of the survey operations is to define the gradient in property fields in the coastal upwelling domain, the offshore upwelling domain, and the oligotrophic domain of the northern Arabian Sea. Surveying should be done using an underway, towed undulating body instrumented with sensors for biology, physics, chemistry, optics, and bioluminescence. Multiple frequency acoustics should be used on towed bodies, or vessel mounted to provide detailed information on the distribution of biomass and size frequency of zooplankton. Vessels conducting the oceanographic surveys should be equipped with acoustic doppler current profilers for underway measurement and two dimensional mapping of current velocities and acoustic backscatter (an analog for zooplankton/micronekton biomass). Survey vessels should be equipped with modern meteorological sensing packages, capable of continuous, frequent observations and should be equipped with serial ASCII interface loop (SAIL) systems, and shipboard instruments (automatic size counters, fluorometers, thermistors, etc.) for routine underway measurement of near-surface optical, biological, bioluminescent, and physical properties.

In addition to underway measurements, we recommend that short-stay stations be done. The purpose of the short-stay survey station measurements is to provide additional ancillary data, or extended depth range data, that cannot be obtained directly using towed undulating sensors. An example of the former is the use of nets and or pumps to provide samples for the evaluation of zooplankton biomass and species composition and for collection of specimens for molecular/biochemical studies. An example of the latter, is hydrographic profiles to greater depths, esp. within the oxygen minimum zone, than can be sampled by towed packages (200-300m). In addition, the survey station measurements will provide the data needed for sea-truthing remote sensing devices (fluorometers, acoustics, etc.). The working group suggested that possibly 1-2 of these sea-truthing stations per physical domain (coastal upwelling, offshore upwelling, oligotrophic) might be sufficient. However, more frequent sampling might be required in regions having large gradients.

*Extended Station Mode and Measurement Recommendations*

The primary goal of the extended station measurements is to obtain an understanding of the population dynamics and structure of the upper trophic levels (zooplankton and fish) of the Arabian Sea. Toward that end, the zooplankton working group strongly recommends that U.S. GLOBEC consider extended stays at fewer stations, one or more in each of the three different physical domains. The structure (abundance, distribution, species composition, and genetics) of zooplankton populations should be measured using direct (nets, pumps) and indirect (acoustical and optical) means. Sampling should be vertically stratified to reflect the strong vertical gradients (especially oxygen concentration) that may control (or restrict) animal distribution and determine physiological condition. Moreover, measurements should be done throughout the diel cycle. Zooplankton dynamics (rates) that should be studied include trophic interactions, population dynamics, and individual processes. Trophic interactions (e.g. consumption, mortality) should be investigated in each of the physical domains as a function of depth and the diel cycle. Population dynamics (e.g. vital rates of birth, development, and mortality rates) should be examined in the dominant zooplankton species, whatever they may be. Individual processes (e.g. feeding, metabolism, growth, defecation, and behavior) should be investigated in the dominant plankton. The dynamics of the zooplankton should be investigated by a combination of shipboard experiments, *in situ* observations, and if possible *in situ* experiments.

## Appendix C. Fish Working Group Report

Chair: George Boehlert
Rapporteur: Charlie Miller

Participants: Johannes Kinzer, Don Olson, David Stein, Bernie Zahuranec

The group dealing with fish discussed the general lack of information available on pertinent species at higher trophic levels in the Arabian Sea. It is imperative that all literature and unpublished studies be drawn together to better refine any proposed research. Questions were raised about the source of prey, distribution and abundance, and ultimate fate of the most important species (assumed here to be *Benthosema pterotum* and *Diaphus* spp.).

### *General Themes and Specific Scientific Questions*

Specific hypotheses were posed to serve as a focus of discussion, as follows:

General Hypothesis: The large stocks of myctophid fish and their high growth rates in the Arabian Sea are a function of regional physical conditions.

Specific Hypotheses:

- Myctophids are protected from daytime predation at depth by descent into dysoxic waters.

- High growth is promoted by the unusually high productivity associated with both coastal and open sea upwelling.

- Much myctophid production goes to non-predatory mortality. It should end up on the bottom.

- Myctophid abundance is related to topography.

Tests of these hypotheses will require sampling both the water column and the benthos using a variety of sampling gear. Water column sampling should be done with acoustics for biomass estimation, discrete depth midwater trawling for specimen collection and identification, and larval fish and plankton sampling. Bottom cores should be collected to examine present and historical myctophid abundance as reflected in otolith and/or scale deposits. To examine a wide range of physical conditions, stations should be located on the shelf, slope and in offshore waters. Sampling should be conducted monthly for at least one full year.

Several questions should be answered, including:

- What is the geographic distribution and biomass of *Benthosema pterotum* (and other important midwater fish species), particularly in the offshore dimension? It seems likely that *B. pterotum* is largely replaced by *Diaphus arabicus* beyond the continental slope. *Benthosema fibulatum* and several other species may be important in the total stock in particular places and seasons. Several ecological analogies may be drawn with the large midwater fish biomass in the Benguela upwelling system (Prosch, 1991; Armstrong and Prosch, 1991).

- What are the mechanisms through which high biomass midwater fish populations are maintained? The genus *Benthosema* is typically associated with continental slopes or other topography (Reid et al., 1991). Analogous populations of *Maurolicus muelleri* and

*Lampanyctodes hectoris* exist in the Benguela upwelling system and are proposed to be maintained by interactions of vertical migration with Ekman transport (Hulley and Prosch, 1987), similar to the mechanism proposed by Peterson et al. (1979) for copepods off Oregon. *Benthosema pterotum* (along with other midwater fishes) may be maintained around offshore banks such as the Murray Ridge through a variety of mechanisms including topographically influenced anticyclonic circulation (Boehlert and Genin, 1987; Loder et al., 1988). Such midwater fish populations may be the principal source of energy to benthic fish populations, as seen on seamounts farther to the south in the Indian Ocean (Parin and Prutko, 1985).

• What is the diel pattern of vertical migration relative to the oxygen minimum layer? Gjøsæter (1984) suggests that only a portion of the *B. pterotum* population undertakes a diel vertical migration each night, so the frequency of this migration should be carefully examined.

• How does the distribution relate to physical factors, including oxygen? How does the distribution (including variation in biological factors like fecundity, body condition) relate to topography? This latter includes position relative to the continental slope and effects of offshore ridges.

• What are the vital rates (growth rate, reproduction, mortality) of the dominant fish species?

• What is the fate of the annual fish production? If the midwater fish production ends up on the bottom, then a signal of enriched organic matter, as well as otoliths and fish scales, should be evident in the sediments. If varved sediments are available, historical patterns of fish abundance following the techniques of Soutar and Isaacs (1974) or Shackleton (1987) should be conducted. Benthic studies should be coordinated with U.S. JGOFS benthic investigations.

• What role does seasonal predation by larger nekton (squid, tunas) play in removals of some portion of the midwater fish population? An initial effort at determining the regional abundance of these larger nektonic predators should be made from regional fisheries data and any available fisheries surveys (see Stequert and Marsac, 1989; Mohri et al., 1991; and also data reports of the FAO Indo-Pacific Tuna Programme). Should they be abundant seasonally, the extent of larger nekton feeding on mesopelagic fishes (including estimates of total removals) should be determined.

• Why are clupeoids and demersal slope fishes such as gadoids, so common in most productive upwelling areas, apparently at low levels in the Arabian Sea?

*Equipment and Approach Recommendations*

The working group discussed how to approach and undertake an extensive and thorough study of the midwater myctophids of the Arabian Sea. We agreed that more than one sampling technique should be applied to the estimation of stock size. For acquisition of specimens and data for the micronekton component, we recommend the following gear:

• An RMT net or equivalent, 25 $m^2$ if possible, although 8 $m^2$ would probably be satisfactory. This would be used to obtain detailed vertical structure of the populations and its relation to the oxygen-depleted layers.

• A medium sized trawl (of order 100 $m^2$) is needed for bulk collections, and checking of acoustic density estimates. It should have a divided catching apparatus at the cod end.

• Acoustics (more below) should be state-of-the-art at the time of the study. The equivalent of a SIMRAD EK-500 now used for research and commercial purposes. The unit should have full recording and integrating capability.

The ideal platform for deployment of these varied gear is a specially equipped dragger/processor ship, possibly chartered from the commercial fishing industry. Suitable ships are not fast, but have high power. In the U.S. suitable ships are mostly in service in the Bering Sea fishery.

The sampling schedule should include the following:

• Monthly or more frequent onshore-offshore surveys on a transect line off Oman, covering a shelf station and 2-3 stations each over the slope and offshore. Each station should include a full 24-hour day of fishing and acoustic work.

• Detailed 48 hour studies for migration and feeding timing and gut content studies at several locations.

• Seasonal geographic surveys to quantify *Benthosema* and general myctophid populations over the region as a whole. Data shown at the meeting (by Don Olson, from a report by Gjøsæter) suggests a fairly strong seasonal variability in stocks along the south Arabian coast. Perhaps two extended geographic surveys would be sufficient, if coupled to much more dense seasonal coverage along a single transect (probably off Oman). The principal tool for the geographic surveys should be hydroacoustics.

A central goal of ichthyological studies in the Arabian Sea U.S. GLOBEC work is full understanding of myctophid biology and basic ecology. To this end U.S. GLOBEC should support a number of biological studies. We recommend the following minimum list of program components:

• A detailed gut content study coordinated with zooplankton collections. The species of food items should be studied and compared to the zooplankton fauna. At the tropical temperatures immediate preservation of myctophid catches is important to this work. Immumulogical studies of gut contents should be considered depending upon the adequacy of traditional methods. Evacuation rates and daily ration should be determined.

• Fecundity and gonad cycling should be studied in detail to determine the seasonality and nature of spawning. This should be done in histological detail detail with quantification of spawning frequency and batch fecundity (see Hunter and Goldberg, 1979). A similar study dealing with midwater fish was conducted by Melo and Armstrong (1991). Sampling and special preservation of materials for this work should be done on the seasonal, diel and 48 hour sampling schedules of the trawl sampling. Depth distribution of egg release should be determined.

• Respiration may well be specially organized in Arabian Sea myctophids, since the daylight period is spent in dysoxic waters. Oxygen debt may build to substantial levels and be tolerated. Special enzymatic mechanisms may exist for extracting oxygen from low concentration waters, for rapid relief of oxygen debt upon return to high oxygen waters, and for tolerating occasional sulfide toxicity. One or more respiratory physiologists should be included in the program.

• Establishing the growth and development timing is essential to advancing the life history analysis of Arabian Sea myctophids. To this end we need detailed calibration of the otolith increments in *B. pterotum* and other species. Alternative ageing methods (including length-frequency analysis) should be undertaken to confirm otolith estimates as well as to confirm growth rates and individual longevity.

• A study of bioluminescence in myctophids might also be a focus of U.S. GLOBEC studies. Ventral photophores are a prominent feature of myctophid morphology. An investigation of their function in Arabian Sea species could provide some special insights. Does luminescence persist in dysoxic waters at depth during daytime, or is it suppressed by low oxygen levels?

The working group discussed the possibility that all expeditions to the Arabian Sea in the mid-1990's could be equipped with a sophisticated, recording echo integrator system for low frequency (ca. 38 kHz) records of fish abundance. Possibly data could be gathered in a nearly automated fashion and analyzed by U.S. GLOBEC fish program investigators. The WOCE representative present at the meeting emphasized the "not to interfere" basis that would be enforced by investigators from other programs. It was also suggested that calibrated ADCP instruments might make useful records. In general the frequency of these is too high to be useful for evaluation of fish abundance and distribution, but the records of zooplankton abundance would be useful for the overall U.S. GLOBEC research program.

*Recommendations*

We recommend that a dedicated ship be requested by U.S. GLOBEC for nekton and plankton research. A dedicated ship is needed in order to ensure adequate sampling (e.g., number, duration and location of stations). A Bering Sea type trawler-processor (135-150 ft) could be chartered for reasonable costs for 6-12 months to enable seasonal sampling along an inshore-offshore transect and geographic surveys. Such a vessel would be capable of working in high wind, rough sea states typical of the region for much of the year. It would be able to accommodate 12-15 scientists and provide ample laboratory space. The ship would include state-of-the-art acoustics and it would have the ability to tow large midwater trawls double warp. It would include a deck crane suitable for moving and deploying small gear, and it would be fitted with a third wire or an acoustic net monitor.

Modifications to the vessel would be installation of a hydrowinch (and A-Frame?), an echo integrator, and a running sea water system. Meteorological deck sensors, modern communications and satellite downlinks, and SAIL systems would be desirable. It would have to be airconditioned.

Appendix D. Technology Working Group Report

Chair: Peter Ortner

Participants: Ann Bucklin, Tim Cowles, Gus Paffenhöfer

*Introduction*

From our perspective U.S. GLOBEC is an effort to understand the relationship between physical forcing processes and the dynamics of marine animal populations. The northern Arabian Sea would be an especially appropriate study site because it is dominated by regular but highly dynamic physical processes (monsoonal wind reversals and oceanic upwelling). These are closely correlated with a dramatic biological signal (enhanced plant pigment in CZCS images). The amplitude of this signal exceeds that in any other oceanic regime. One cannot but suppose that population variability at higher trophic levels must be, at least in part, regulated by this periodicity. Moreover the Arabian Sea/Indian Ocean is scheduled to be the site of extensive study under the aegis of the U.S. JGOFS, WOCE and ONR/ARI programs. This represents an enormous practical opportunity. At absolutely no cost to U.S. GLOBEC, the physical variability and primary production cycle in the Arabian Sea will be characterized. Moreover these same programs will support extensive modelling efforts aimed at elucidating the dynamics of the Arabian Sea/Indian Ocean. The level of detailed understanding anticipated greatly exceeds that available to date for any other major oceanographic system.

The zooplankton and fish working groups have posed a set of interrelated biological-physical questions that might be addressed by an U.S. GLOBEC program in the Arabian Sea. The primary charge of the technology working group was to consider how these questions can best be answered, what tradeoffs would be involved and what priorities we would assign to specific technical alternatives. There are a number of practical considerations. First, to be co-extensive with U.S. JGOFS and WOCE means U.S. GLOBEC will be in the Arabian Sea as soon as the winter of 1994/95. This implies the use of currently available technology, or that already being field tested, in preference to technologies requiring considerable further development followed by field testing. Second, during the SW monsoon, winds are routinely in excess of 35 kt and the sea state is correspondingly high. This implies ruggedness and sea-state independence are important considerations in selecting sampling gear and experimental methods. Third, at some seasons the Arabian Sea varies between near eutrophy and extreme oligotrophy over relatively short distances. This implies that a wide dynamic range in instrumentation sensitivity is an important consideration. Last, fieldwork already planned in U.S. JGOFS and WOCE seemingly offers U.S. GLOBEC practical cost-effective sampling opportunities. However, inherent constraints associated with these include predetermined tracklines and mooring locations as well as limited wiretime and bunkspace. These opportunities have to be closely scrutinized in light of specific U.S. GLOBEC scientific objectives.

*Mesopelagic Fish Sampling Issues and Recommendations*

Given the lack of basic knowledge about both abundance and distribution and basic biology (reproduction, growth, feeding, and mortality) in the Arabian Sea, there is absolutely no question that purely indirect sampling methods, e.g., acoustics, will be insufficient for U.S. GLOBEC. Net sampling will be required since individual organisms will need to be collected. It is possible no single sampling device will suffice. Vertical distribution studies will certainly require some sort of multiple net sampler like an 8 square meter (or larger) RMT net. To be sure that avoidance is not a significant problem, a larger net, perhaps a 100 $m^2$ line rope trawl with multiple cod ends, may be desirable. Another alternative might be a larger 25 $m^2$ RMT. While the RMT nets can be deployed from a properly equipped oceanographic vessel, a trawl is almost certain to require a commercial dragger.

Whatever net sampler is selected we strongly recommend the use of a self-contained CTD with an oxygen probe on every tow. These data are commonly collected in conjunction with plankton sampling but rarely with mesopelagic fish sampling. In the U.S. GLOBEC context these data are critical. Moreover, the net sampling needs to be guided by state-of-the-art fish sonar (mapping) and echo sounder (integrator) records. All ships used as sampling platforms will have to be suitably equipped.

Use of U.S. JGOFS or WOCE platforms is likely to be limited in regard to mesopelagic fish studies. Assuming ADCP units are calibrated (see zooplankton section below) their backscatter intensity may yield some scattering layer information (large-scale patterns). At the likely frequencies (>= 150 kHz), a substantial part of the ADCP return will be associated with zooplankton rather than larval or adult fish. Moreover, at these relatively high frequencies, no data will be obtained at the lower part of the oxygen minimum, nor below it. Yet some of the most significant biological questions posed by the zooplankton and fish working groups relate to the dysoxic zone. We recommend that every effort be made to equip all research vessels in the study area, including those used by U.S. JGOFS and WOCE, with a calibrated acoustical sensor suite with the appropriate frequencies. These data will greatly extend the generality of inferences to be made from specifically U.S. GLOBEC sampling efforts.

If a dragger is leased it too will need similar acoustic capability. It could then be used for acoustic surveys in the interstices between regular trawl sampling cruises. This may be essential to ground-truth the acoustic data. Moreover, for the data to be quantitative renewed efforts will have to be made to measure, or more accurately estimate, target strength at the chosen frequency for the dominant mesopelagic species found in the trawls. Whatever acoustical system is selected must have the capacity for digital data storage rather than yielding a simple hardcopy record.

An option worth consideration is acoustical instrumentation on U.S. JGOFS surface moorings or using Lagrangian drifter packages. The former will be deployed for extended periods throughout the annual cycle, i.e., between whatever U.S. GLOBEC process cruises are taken, and will be regularly serviced. A formidable constraint would appear to be data transmission of moored and drifting instruments. Considerable thought and testing would be required given the distance from the coast of planned mooring sites. Current satellite data links are not adequate for most acoustic data given its relatively high density, but the situation could change over the next several years. Quite likely only expendable Lagrangian devices would be practical and it is not yet evident that these will be affordable.

Last, there has been discussion of direct visualization of feeding and/or *in situ* physiological measurements using ROVs or submersibles. While these alternatives are feasible they are very expensive. Given the remote study site, logistical costs would be considerable. Prior use of such devices has required either a devoted tender vessel or a considerable number of days of multipurpose research vessel shiptime. The latter is likely to be incompatible with other sampling requirements for U.S. GLOBEC cruises. Moreover, ROV or submersible deployment and retrieval may be hampered by severe weather; a likely condition in the Arabian Sea, at least during the SW monsoon.

*Plankton Sampling Issues and Recommendations*

As with the mesopelagic fish, indirect sampling will, by itself, be insufficient to meet U.S. GLOBEC objectives. Conventional net-sampling will be required to obtain animals for determination of reproduction, growth, feeding, and physiology, as well as to provide definitive taxonomic identification. It is expected that microzooplankton as well as juvenile and adult stages of the dominant mesozooplankton will have to be collected, identified and enumerated. This implies the use of more than one net sampler and perhaps bottle samples as well. As with mesopelagic fish all such conventional sampling gear will have to be fully instrumented (temperature, salinity, depth, fluorescence, oxygen). Deployment should be guided where possible by real-time feedback of these environmental parameters as well as of zooplankton biomass distribution. The latter can be obtained with available high frequency acoustics.

ADCP biomass estimation must be made a routine aspect of all U.S. JGOFS, WOCE and U.S. GLOBEC cruises. This requires a complex system calibration and the choice of appropriate software options from the manufacturers applications package. It can be accomplished with minimal interference with other aspects of the U.S. JGOFS or WOCE cruises. Given our present lack of knowledge of overall zooplankton biomass distribution patterns and their relationship to Arabian Sea hydrography, a considerable effort should be devoted to quantifying general patterns along proposed transects. The ADCP approach and any other that can obtain data underway will be invaluable in mapping efforts as well as subsequent hypothesis testing.

We believe it will be necessary to employ the latest developments in acoustical and optical zooplankton distribution assessment. As discussed in U.S. GLOBEC Report 4 from the Workshop on Acoustical Technology and the Integration of Acoustic and Optical Sampling Methods, these are often most efficiently deployed in conjunction. Specifically, optical approaches can be used to identify acoustic targets. Since U.S. GLOBEC is interested in populations, not simply biomass distribution or particle size, this capability is essential. An alternate approach is to use optical particle counting and sizing in conjunction with image visualization. Both approaches have already been used in the field. With imaging video the major remaining technical difficulty is efficient data processing (automated image analysis). In its present state, however, the technology is thought to be closer to satisfying the target identification objective than functioning as a routine primary sampler. Prototypes have a suitable wide dynamic range and have, in some cases, already been integrated with the recommended suite of U.S. GLOBEC environmental sensors. Suitable tow vehicles would have to be adapted for U.S. GLOBEC that permit long-term virtually unmonitored deployment and tow-yo cycling in relatively high sea states, but such vehicles are now commercially available, e.g., Batfish, Seasoar, Aquashuttle, etc. The patterns indirectly observed and mapped will be ground-truthed by systematic use of conventional samplers for U.S. GLOBEC process studies. Indirect and direct (or traditional) sampling are not alternatives but rather mutually essential complements. With the former rigorous relationships to physical parameters and extensive data sets may be efficiently collected at high spatial and/or temporal resolution. With the latter species identification may be validated and specimens collected.

In addition to the survey sampling discussed above the questions raised imply the desirability of obtaining a more extended series of observations within the various hydrographic domains within the northern Arabian Sea, e.g., an open ocean upwelling site, an oligotrophic downwelling site, and a coastal upwelling site. Time-series data is essential to fulfilling some of the U.S. GLOBEC objectives. There are basically three non-exclusive alternatives. Each has advantages and disadvantages. Ship-based studies could be made at fixed location near one of the U.S. JGOFS moorings, acoustical or optical sensors could be incorporated into these or other moorings, or Lagrangian drifters could be constructed specifically for U.S. GLOBEC. As discussed above, the realistic constraints are likely to be data transmission and "recoverability", rather than equipment sensitivity, ruggedness, etc. Prototype acoustical and optical systems have already been tested in the field, but have not been used in sites so remote for long periods.

A range of techniques are available to evaluate physiology, growth, reproduction and feeding rates of micro- and mesozooplankton. While *in situ* methods have been discussed it is unlikely these will be ready for routine use by 1994/95. Indeed they may never be suitable for use in the demanding conditions anticipated. The measurements must be usable despite extreme sea states, high ambient animal densities, and high ambient temperatures (> 25°C). This may require considerable adaptation of existing techniques (e.g., consider the adaptability of large volume incubation methods). These problems require addressing before any proposed field study. These practical considerations also suggest that if they can be made sufficiently specific and rigorous, biochemical and molecular approaches may be a critical component of an Arabian Sea U.S. GLOBEC since they can be performed on appropriately preserved specimens. We encourage sample preservation and curation sufficient to permit subsequent molecular systematic analysis.

The optimum platform for zooplankton work is likely to be a UNOLS research vessel. Unfortunately, the work requires extensive shiptime and would in its entirety be incompatible with U.S. JGOFS and WOCE field plans. Beneficial use might be made of ships-of-opportunity. For example, equipping the U.S. JGOFS CTD system with a simple (2-4 frequency) acoustic sensor would appear to be a cost-effective way to obtain better data coverage. The same would apply to WOCE efforts within the northern Arabian Sea, but not to WOCE cruises considerably further south in the Indian Ocean.

U.S. JGOFS apparently plans to fund limited zooplankton studies. Rather than pursuing a token effort, we recommend an integrative exhaustive study that can satisfy U.S. JGOFS basic requirements and as well the more extensive demands of U.S. GLOBEC. While this implies somewhat more of an imposition (bunks, wiretime) upon U.S. JGOFS cruises it likely represents a more efficient overall utilization of limited NSF Global Climate Change Program resources. Conversely, a U.S. GLOBEC vessel should certainly be equipped with continuous sensing capability (chlorophyll, irradiance, meteorological parameters, etc.) what will assist U.S. JGOFS (and possible WOCE) to address their scientific objectives.

*Molecular and Biochemical Approaches to Arabian Sea Studies*

Molecular approaches may be appropriate for use in the study of a variety of biological phenomena, including physiological rates and conditions, feeding rates and dietary components, the genetic basis of phenotypic variation, genetic exchange across species distributions, recruitment processes, and taxonomic identification of species (see U.S. GLOBEC Report Number 3, U.S. GLOBEC Workshop on Biotechnology Applications to Field Studies of Zooplankton, 1991).

The questions posed by the zooplankton and fish working groups of the Arabian Sea workshop provide the opportunity to apply molecular-based techniques in a fruitful way. Only molecular methodologies and approaches that will be ready for implementation (i.e., already field-tested) by fall 1994 should be considered for inclusion in the program. However, we must prepare ahead so that zooplankton and fish sample collection, preservation, and curation are done appropriately so that molecular and biochemical methods can be used later.

Fundamental information is needed to continue the transfer of biotechnology to the ocean sciences. Examples are DNA base sequencing of targeted regions of the genome and careful determination of levels of intra- and inter-specific variation. This need is particularly critical for marine invertebrates, for which very little molecular information is available. Once DNA sequence data are available, appropriate strategies may be developed to address physiological, ecological, and evolutionary questions.

Although automated taxonomic identification of plankton may not be achieved in the near future, molecular characteristics may be helpful in identifying zooplankton or fish species that are difficult or impossible to distinguish using morphological characters and in resolving systematic questions regarding the limits of a species. The U.S. GLOBEC Arabian Sea program offers an opportunity to study an ecologically important, but little-known, fauna. The zooplankton samples in particular should be collected and curated carefully to allow analysis of molecular diversity within and between species.

Molecular approaches to discriminating conspecific populations of fish and zooplankton will be useful for the U.S. GLOBEC Arabian Sea program. Prior U.S. GLOBEC workshops have identified a need for basic information on the amount of molecular genetic variation within and between populations of marine organisms. This information will lay the groundwork for studies of the effects of global climate change on marine populations and for analysis of the genetic basis of phenotypic variation. In the Arabian Sea, it is essential to determine whether Arabian Sea populations of widespread species (such as the myctophid fishes) are isolated from populations outside the region. For endemic species, analysis of population genetic structure will address questions of recruitment patterns and dispersal.

We expect that molecular analysis of nutritional status and metabolism will be possible as part of the U.S. GLOBEC Arabian Sea program. Molecular studies are ongoing to quantify the level of expression of physiologically significant genes in zooplankton, and RNA/DNA ratios are now used in field studies of growth and condition in ichthyoplankton. These and related condition factors can address questions of how plankters and fish respond to physical forcing and cope with seasonal variation in their environment.

There are molecular approaches which offer promise for the analysis of dietary components. Taxon-specific probes for identification of gut contents are feasible, and will discriminate herbivores and carnivores. However, potential difficulties with this approach indicate that implementation in 1994/95 is unlikely. Biochemical approaches, such as immunological and pigment-based identification of prey species and isotopic analysis to determine trophic level, are better developed and may provide indications of trophic relationships in the Arabian Sea ecosystem. Additionally, priority should be given to the development of molecular and/or biochemical analysis of feeding rates in field populations.

Population genetic approaches can be used to address significant questions in the marine environment: recruitment variation, ontogenetic shifts in gene frequency, geographic structure of the ecosystem at different scales, etc. Protein and nucleic acid polymorphisms are powerful markers of population structure. U.S. GLOBEC should encourage molecular studies of oceanic life processes; a specific goal should be the sequencing of DNA for targeted regions of the genome of marine, especially invertebrate, species.

U.S. GLOBEC is also an opportunity to institute changes in the way that biological samples are collected and preserved on oceanographic cruises. Formalin preservation, the norm, is not appropriate for molecular analyses. Biochemical analyses require frozen tissue, which can also by used for molecular studies. Alcohol preservation is suitable for many studies as well. Splitting of collections and preservation by a variety of means is highly desirable. At the minimum, 1/8 to 1/4 of all samples should be preserved in alcohol to allow a variety of molecular and genetic techniques to be used for future study. U.S. GLOBEC should emphasize the importance of existing sample archives and plan for molecular and biochemical analyses of future collections. As new techniques are developed, appropriately archived samples may become useful and important in ways not envisioned now. Time-series collections of plankton from around the world may prove essential for unraveling questions about global climate change.

Appendix E. Alternative Viewpoint for Near-Term U.S. GLOBEC Myctophid Studies in the Arabian Sea

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As detailed in the Fish Working Group report and scientific review of fish biology sections, myctophids are very important in the Arabian Sea ecosystem. Their densities in the northern part of the Sea are higher than any observed elsewhere (Gjøsæter, 1984). They undergo diel migration down into the oxygen minimum zone, potentially accelerating vertical fluxes. Their biomass peaks in winter and spring, possibly in response to monsoon effects. The significance of the fish populations to U.S. JGOFS objectives seems clear: "If these (very high) fish biomass numbers are accurate, then any attempt to balance a carbon budget cannot fail to include a high level of effort at determining the biomass of mesopelagic fishes, their daily rations, and their impact on zooplankton" (Peterson, 1991 p. 105). The population dynamics of these organisms, and their likely responses to monsoonal forcing of production cycles make their biology equally central to any proposed U.S. GLOBEC efforts. The question is how best to sample the fish, and whether that sampling method is affordable and logistically compatible with other goals of U.S. GLOBEC or U.S. JGOFS.

We agree with the desirability of the sampling equipment and approach recommended by the Fish Working Group. However, if use of chartered fishing vessels is not an economic possibility, we believe that information on midwater fish and macrozooplankton populations crucial to U.S. GLOBEC and U.S. JGOFS goals can be obtained using smaller and more manageable MOCNESS trawl and acoustic systems during process-oriented research cruises aboard a UNOLS vessel. We presume there will be coordination of planning and overlap of investigators between the U.S. JGOFS and U.S. GLOBEC efforts, and we want to argue for the importance and feasibility, in both programs, of sampling midwater fish and macrozooplankton with research-scale gear.

- Larger nets do not necessarily provide better estimates of population size. Potter et al. (1990) compared catches of 3-5 cm young cod collected with a 10 $m^2$ MOCNESS (3 mm mesh, 2 kt tow speed) and the 104 $m^2$ International Young Gadoid Pelagic Trawl (105-5 mm graded mesh, 3.5 kt tow speed). They found that abundance estimates were at least as high with the MOCNESS as with the IYGPT, with very little difference in size distribution of the fish caught.

- The results of Potter et al. were a primary reason why the 10 $m^2$ MOCNESS was chosen as the best gear to sample juvenile cod and haddock in the U.S. GLOBEC Georges Bank/Northwest Atlantic Field Program. These trawls have been proposed for use in both broad scale surveys and process-oriented sampling.

- Myctophids are in general less active fish (Barham, 1971; Craddock, pers. obs.) than the cod fished by Potter et al. (1990), and probably less able to avoid capture in nets. MOCNESS trawls have been and are now being used to sample midwater fish in parts of the Atlantic that are far more oligotrophic than the Arabian Sea.

- Different size trawls were also used in collections of myctophids of the Benguela region (Hulley, 1986). Catch rates from three nets, an RMT-2 (2 $m^2$), RMT-8 (8 $m^2$) and MT-1600 (ca. 300 $m^2$), were <u>inversely</u> proportional to net size, decreasing from 0.2474 to 0.0565 fish per 1000 $m^3$. Stock estimates based on catches of the three nets were very similar, except for the mean size of the fish caught. There was little overlap in sizes caught by the smallest and largest nets, so that stock estimates based on their catches probably represent different parts of the population.

• The commercial trawls used by Gjøsæter (1984) in the Arabian Sea caught far more fish than researchers could handle. The 250 $m^2$ net had mean catch rates of 200 kg $h^{-1}$ in 1979 and 1000 kg $h^{-1}$ in 1981. The 750 $m^2$ trawl used in 1983 had a mean catch rate of 4700 kg $h^{-1}$. We don't need (or want) that many fish. A first-order scaling of the mouth areas back to the 20 $m^2$ MOCNESS ("MOC-20") we propose using (12.5 and 37.5 times smaller mouth area) indicates it might catch between 16 and 125 kg $h^{-1}$. For research purposes, commercial gear is not only unnecessary, it is undesirable.

• Kinzer et al. (in press) used three much smaller nets, an 8 $m^2$ IKMT, a 4 $m^2$ Jungfisch-Trawl, and a 1 $m^2$ BIOMOC, to sample myctophids in the eastern Arabian Sea. The IKMT caught tens to hundreds of the commoner species per haul, sufficient to estimate vertical distribution and abundance, as well as provide material for stomach analysis.

• Commercial trawls are open nets that cannot provide accurate data on depth distribution. In contrast, the MOC-20 can fish 6 discrete depths down to 2000 m, and provide continuous environmental data (CTD, O2, etc.) in real time. The 3.0 mm mesh means the MOC-20 will sample post-larval fish better, providing better size data to model population dynamics and growth rates.

• An important sampling goal will be to catch fish in good condition shipboard studies of metabolism, diet, and bioluminescence. We expect the MOC-20 to catch fish in better condition, both for identification and experimental use, because of the relatively soft mesh and the smaller number of fish in the cod end. We also anticipate fitting thermally-protecting cod ends to the nets.

These observations lead us to conclude that a 20 $m^2$ MOCNESS should be at least as accurate as a commercial trawl for estimating myctophid abundances, and much more effective for sampling vertical distribution and migration, and retrieving experimental specimens. The MOC-20 can be easily fished from a UNOLS vessel, along with other sampling work. It is towed from the stern, but launched and recovered over the side, so that the net frame is stabilized against the hull of the ship as it enters and leaves the water. Despite its size, the trawl is well suited to work in rough weather.

The frequent and intensive sampling schedule recommended by the Working Group is clearly desirable for midwater fish (as it would be for zooplankton). But if it is not fiscally possible, we suggest that accurate, depth specific sampling with the MOC-20 and acoustic equipment should be carried out along with other pelagic process-oriented work aboard the UNOLS ship.

We hope that U.S. GLOBEC will not dismiss or defer the study of myctophids in the Arabian Sea for simple logistic reasons. If the scientific questions surrounding the population biology and ecology of these fishes are of sufficient interest and importance -- as we agree they are -- then technology and expertise are currently available to sample these organisms in a quantitative and cost-effective manner.

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