MEASURING PHYSICAL-OCEANOGRAPHIC FEATURES RELEVANT TO THE MIGRATION OF FISHES

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ABSTRACT

Knowledge of the physical marine environment is a prerequisite to understanding migration of fishes. Variations in currents, drifts, tides, upwelling and other forms of motion in the ocean have direct and indirect effects upon the timing and paths of migration and upon reproductive strategies in general. This paper reviews some of the approaches for studying the marine environment that should be considered in developing projects concerning the migration and distribution of fish stocks. The three principal sources of physical oceanographic data are 1) publications and archives, 2) agency monitoring programs, and 3) field measurements. Physical data taken contemporaneously with fish observations have particular value. All three sources are frequently combined in a well-planned project. Remote sensing of the marine environment is an important new method that is now being used to influence the deployment of research and industry vessels.

INTRODUCTION

An important factor in the migration of fishes is the fields of motion in the ocean environment. Water motion, as it may influence fish stocks, occurs across a broad range of temporal and spatial scales. It can impinge directly upon fish in the form of long-term drift or strong, short-term advection by currents or tidal flow. It also can act in an indirect manner by creating or destroying food aggregations. Upward motion enriches the euphotic zone. Olfactory clues for migrating fish may be carried with the flow, and proper spawning habitats may depend on flow patterns. Fish may move with the drift or swim against it. These fields of motion may be used selectively by fish. Current systems often undergo cyclical changes in response to tidal or seasonal events, and they usually show even larger aperiodic fluctuations.

The published literature contains some excellent studies in which some part of the cycle of fish migration is associated with water motion or other events in the physical environment. There are other studies, however, which appear to have been handicapped by a failure in their design to give adequate attention to the vagaries of the ocean. There is a definite need to take physical-oceanographic measurements that might assist in explaining observed biological phenomena. The objective of this presentation is to review some approaches for studying the physical environment that should be considered in developing projects concerning the migration or distribution of fish stocks. It is not my intent to outline complex and expensive research into physical oceanography, but rather to consider some relevant measurements of the ocean that are affordable by a migration research group with a modest budget and which might indicate some physical order to biological distributions and might cue or direct migratory behavior.

EDDIES AND OCEAN FRONTS

Two major features in the ocean that form strong patterns in the distributions of physical characteristics are fronts and eddies. Fronts and eddies are regions where ocean dynamics are intensified. They are regions of horizontal shear, convergence and divergence, and vertical convection. Owen (1981), in a review of these classes of motion and their biological consequences, noted that diverse marine life forms, from the very small to the very large, alter their distributions in the presence of such flow patterns.

Eddies may be classified as free or stationary. Free eddies are formed from flow instabilities and atmospheric forcing. Examples include the warm-core and cold-core eddies that are formed when meanders are pinched off major current systems such as the Gulf Stream and the Kuroshio. These eddy "rings" transport large amounts of heat, salt and biota. The effect of such an eddy is the injection of a community of organisms and a body of water into a foreign water mass. However, free eddies are unlikely to provide a reliable mechanism for fish migration because of their episodic nature.

Stationary eddies, on the other hand, are topographically controlled and therefore persistent. Their circulation patterns are determined by banks, islands and the configuration of coastlines. They usually are semipermanent features but may have a large range of fluctuation. The Southern California Eddy (reviewed by Owen 1980) is an example of a stationary cyclonic eddy in which vertical convection produces an upward transfer of nutrients into the euphotic zone. A large number of studies has shown the Southern California Eddy to be a refuge for a variety of organisms including pelagic fishes. Smith (1978) found that the region about the Southern California Eddy, which comprises only 12% of the spawning area of the northern anchovy's (*Engraulis mordax*) central subpopulation, contained, on average over 24 years, 48% of the spawned larvae.

Ocean fronts may be classified into five major categories. Fronts are formed 1) at the boundary of intense currents, 2) in regions of convergent surface flow driven by wind stress, 3) as a result of coastal upwelling, 4) at boundaries of estuarine discharge plumes, and 5) as a result of restratification of water from tidal or wind stirring in regions of shallow topography. In the major oceans large-scale fronts lie in zonal bands in response to the time-integrated effect of large-scale wind stress.

Well-studied examples of ocean fronts are the subarctic and subtropic fronts of the North Pacific Ocean. The subarctic front lies about the 40°N parallel, except near its eastern terminus, where it curves southward to the vicinity of 35°N. The subtropic front lies near the 32°N parallel. In the 1970's the distribution of albacore (*Thunnus alalunga*) as they migrated toward the North American summer troll fishery was investigated in relation to these fronts (Laurs and Lynn 1977). In the late spring of 1972 and 1973 the fronts were well developed. The fronts had spatial continuity and strong gradients of temperature and salinity. Albacore catches were distributed along and between the fronts (Fig. 1). Such aggregation may have occurred in response to the availability of forage. The forage, in turn, was dependent on lower trophic levels and ultimately on the high productivity created by frontal dynamics. The changing patterns in the size composition of the albacore in these offshore catches over 7 weeks were repeated, after a delay, in the nearshore fishery, indicating that albacore were actively migrating through this area during the period of the study.

A repeat of the survey in the late spring of 1974 revealed significant differences (Fig. 1). The frontal structure was poorly developed and water-mass boundaries were less distinct. Albacore catches were made over a larger region and did not tend to persist in any local area as they had in the previous 2 years. There was, however, one pocket of high catches that was sustained over several days. A frontal meander of modest proportions nearly encompassed these catches. A sequence of catches--first within the meander, then coastward of the meander, followed by a recurrence of catches within the meander--suggested a funneling of the migrating albacore related to the feature. Thus, spring distribution and migration of albacore seem strongly influenced, whether directly or indirectly, by the presence of these large-scale fronts, the degree of development of

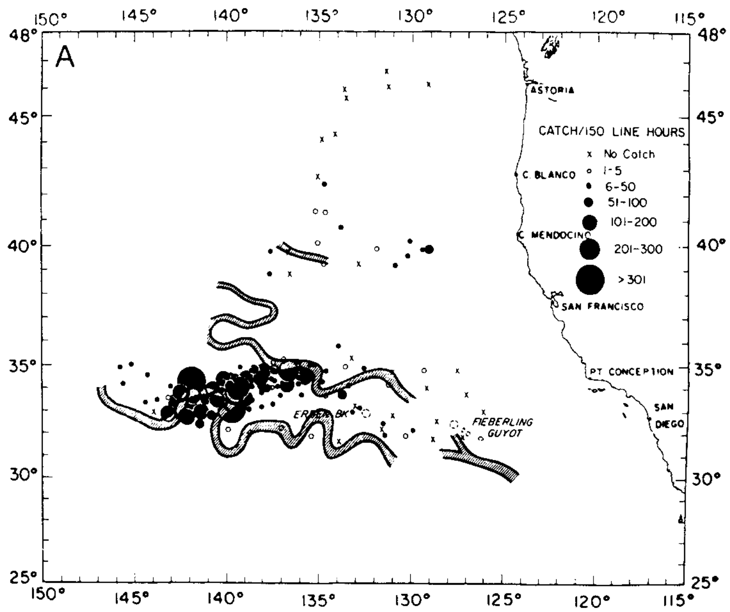

Figure 1. Albacore catch per 150 line-hours by 12 chartered fishing vessels during a preseason exploratory study and the subarctic (northern) and subtropic (southern) ocean fronts during (A) 1973 and (B) 1974 (from Laurs and Lynn 1977).

the fronts and the form of mesoscale features within the fronts.

OTHER CLASSES OF MOTION

Classes of motion which impact biological distributions, other than fronts and eddies, include coastal upwelling, current systems, long-term drift, turbulent mixing, tides, and river flow. In a comparative study of oceanographic regimes and spawning strategies within the California Current system, Parrish et al. (1981) described the seasonal cycle of upwelling, offshore transport and nearshore countercurrents. The reproductive strategies of pelagic fish in this highly productive region were shown to accommodate to these seasonal fluctuations in nearshore coastal dynamics. The strategies include seasonal timing, short planktonic stages and large numbers of spawn.

CONVENTIONAL OCEAN MEASUREMENTS

Methods of ocean measurement must be chosen with consideration for the characteristics of the species of fish studied as well as the availability of financial and manpower resources. The objective of

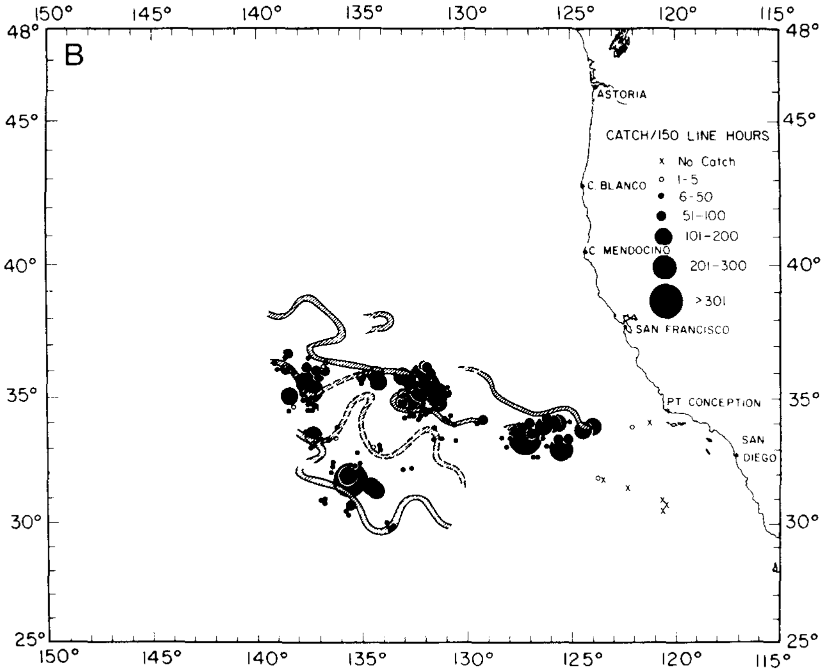

Figure 1 continued.

such measurements of ocean currents is to estimate the effective fields of motion over spatial and temporal time scales that are pertinent to the migrations of a particular population of fish. Often there is no obvious method to achieve the desired results directly. Moored current meters can provide relatively dense coverage in time. However, if one is to achieve reasonable coherence among current meters, a modest deployment can cover only a small part of the migratory domain. That still might represent a large investment in time, effort and money. Thus current meters are most effective in confined regions such as channels, embayments and continental shelves. In the open ocean current meters usually involve logistics of such proportions that they would dominate, in an operational sense, a modest project on fish migration.

Other direct methods of current measurement used in larger-scale regions are drogued drifters, ship's drift and, in coastal zones, drift cards. Recently, acoustic doppler logs and expendable temperature/velocity probes have been used successfully to measure velocity profiles from a moving vessel.

More commonly, we observe fields of motion indirectly by sampling the density (temperature and salinity) field in hydrographic Conductivity/Temperature/Depth (CTD) surveys from which geostrophic velocities can be computed and water masses and fronts located. Other variables such as water clarity, productivity and oxygen content can also be measured. Distributions of these variables may strongly influence the distribution and movement of fish. This method has limitations which arise from the assumption of synopticity, and it produces only one slice in time of a varying state. Repeated surveys (a costly endeavor), which are often done on monthly intervals, can be seriously biased. When data are too sparse to examine events within a season, an accumulation of measurements may permit calculation of long-term mean seasonal changes that may relate to mean seasonal distributions of fish. Other indirect methods include using Ekman drift to estimate time-varying aspects of surface currents over periods of weeks to months and using records of tide level to follow changes in coastal currents.

Sources of Ocean Data

The sources of data for marine environmental studies may be divided into three principal categories.

1. One source is historical files in the form of data archives, scientific literature, and summary publications including atlases.

2. A second source is ongoing ocean monitoring programs. These programs, often found in government agencies and universities, may provide ocean data in the planning stages or during the operations of a study project. Examples include maritime reports of weather and sea-surface temperature, remote-sensed satellite imagery, and sea level.

3. The third major source is field measurements conducted during fisheries studies. These data have particular value in being contemporaneous with observations of fish. They may come from measurements aboard a research vessel or gathered by arrangements aboard commercial fishing vessels or other ships-of-opportunity.

Perhaps a fourth source is model simulations of ocean dynamics. Most or all of these sources usually are brought to bear upon a problem.

Case Studies

For example, let us look at a project in progress involving albacore tuna; it uses all three principal data sources. A phase of the complex migration of North Pacific albacore is the movement following the seasonal decline of the United States-Canadian surface fishery in the fall to the subsurface longline fishery conducted in winter by Japan, South Korea and Taiwan. This is a southward and westward movement from a region offshore of the US west coast to a broad zone across much of the North Pacific. Catch records of the

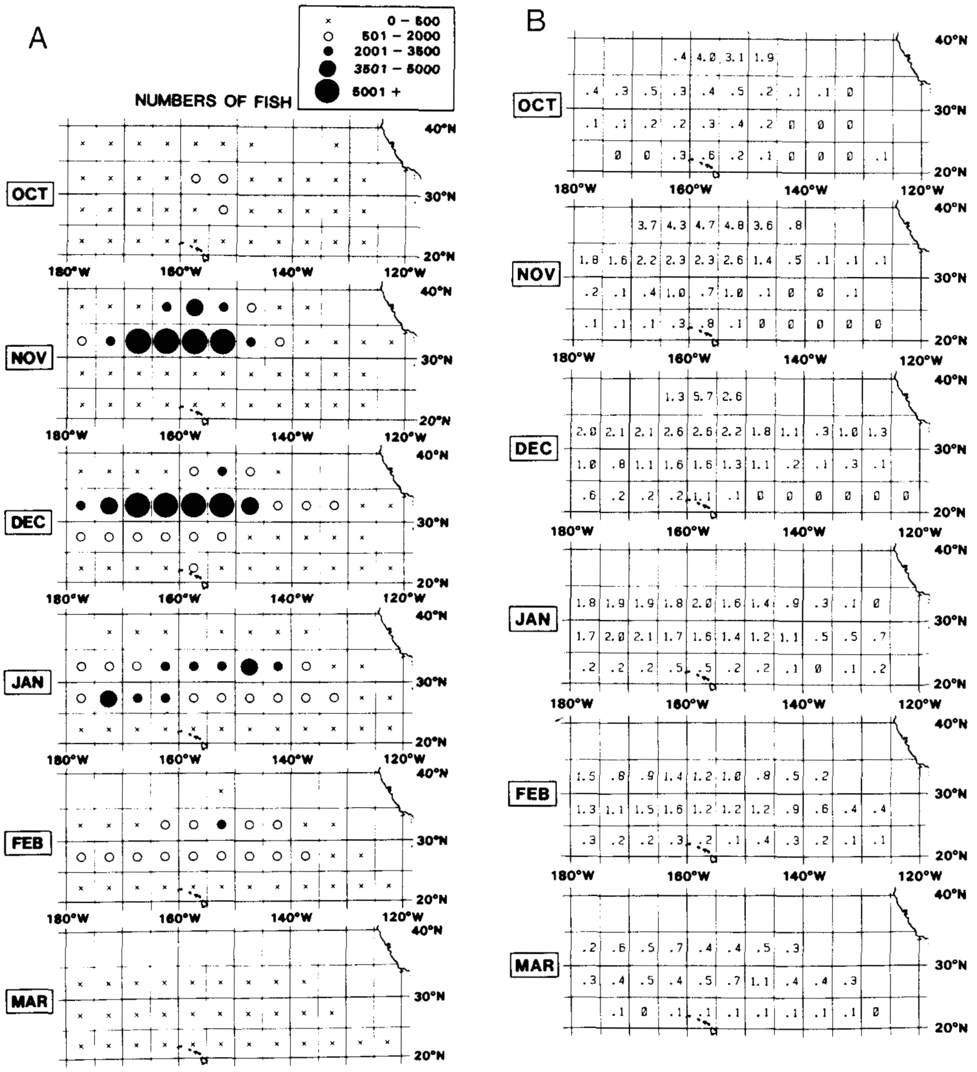

Figure 2. (A) Japanese longline albacore catches in the eastern north Pacific for October through March averaged for 1969-1979 (from Lynn and Bliss 1982). (B) The same data as catch per 100 hooks.

Japanese longline fishery for albacore east of the international dateline (Lynn and Bliss 1982) show that the major catches in the eastern North Pacific are taken between 30°N and 35°N during the months of November through February (Fig. 2a). In the early part of this period there are also some modest catches north of 35°N and between 145°W and 165°W. The interesting aspect is that the catch rates north of 35°N are high (Fig. 2b). Based upon a resolution of monthly catch totals for 5° blocks of latitude and longitude, the catch rates are close to five albacore per 100 hooks compared to no more than two to three per 100 hooks elsewhere. We know from earlier work that the subarctic front lies within the zone of 35°N to 40°N. November is a period of cooling and deepening of the shallow, seasonal, mixed layer. Beneath this layer there is the deeper frontal structure remaining from the previous winter. Oceanographic atlases (e.g. Robinson 1976) show that in November the 16 C to 18 C isotherms from the surface to 60 m fall in this zone (Fig. 3) and are thus coincident with the mean position of the subarctic front. This range of ocean temperature is characteristic of albacore fisheries. These conditions suggest that in the early phases of the longline fishery, as albacore and surface layer isotherms retreat from northerly latitudes, the albacore are once again aggregated by events about the subarctic front, thus producing the circumstances that result in high catch rates. By mid or late December temperatures about the front are lower than those apparently preferred by albacore and catches decrease accordingly.

This background information influenced the strategy developed for recent exploratory longline surveys (Laurs et al. 1981, 1982). In these surveys US fishing vessels experimented with gear and methods in a project conducted by the American Fishermen's Research Foundation and carried out in cooperation with the National Marine Fisheries Service, under the scientific leadership of R.M. Laurs. Five fishing vessels are participating in the recent survey. Prior

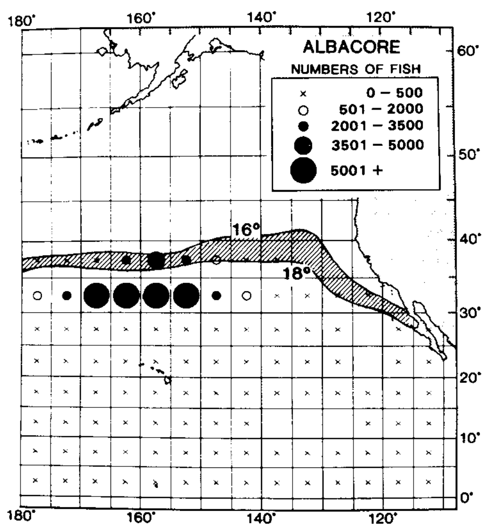

Figure 3. The albacore longline catch for November from Figure 2A and the monthly mean 16 C and 18 C isotherms.

to sailing, up-to-date expendable bathythermograph (XBT) data were obtained from the US Navy's Fleet Numerical Oceanographic Center. Plots of isotherm depth in the upper 150 m of the survey region revealed a zone of abrupt changes identifying a strong front. Thus, an ocean monitoring program provided input for tactics in deploying the vessels. Each of the five vessels was instructed to record twice-daily weather and sea conditions and sea-surface temperature. Also, each vessel made daily XBT casts. This measure of thermal structure, taken concurrently with fishing operations, will be combined with the background information to address the question of the association of migration with ocean fronts.

The 1972-74 albacore surveys (Laurs and Lynn 1977) in which the spring migration into the North American surface fishery was investigated, offer an example of a more comprehensible level of operations using physical oceanography in conjunction with fisheries research. The surveys combined the use of the R/V DAVID STARR JORDAN and chartered commercial-fishing vessels. The JORDAN conducted oceanographic observations on a planned grid. Traditional observations were made: CTD profiles; XBT and water bottle casts; continuous recording of surface temperature, salinity and chlorophyll concentration; and analysis of water bottle samples for O_2 and chlorophyll concentrations. Nutrient chemistry was desired but proved to be beyond our resources. Micronekton tows, to obtain potential forage organisms for albacore, were made using an Isaacs-Kidd midwater trawl. The JORDAN also trolled for albacore as time permitted. The catches made by the JORDAN, while not comparable in effort to those of the chartered fishing vessels, did provide confirmation that areas well beyond the regions of fronts were less productive or unproductive. The chartered fishing vessels recorded weather and sea conditions and made XBT casts. These additional physical observations extended our interpretation of the ocean conditions beyond the grid covered by the JORDAN.

An added factor in these surveys was the cooperation of unchartered fishing vessels. Daily broadcasts of findings from the JORDAN and chartered fishing vessels were given on radio frequencies used by fishermen. Many of the fishermen responded in kind by reporting their daily catches, thus assisting in the success of the operations, and many also voluntarily completed catch logs as part of an interstate and federal program (Laurs et al. 1975). This project combined a number of activities directed toward describing and understanding the migration of albacore of which the study of the physical environment was an integral part.

Interpreting and Using Ocean Measurements

The CTD, XBT and water-sample casts provide the basis for identifying water masses and fronts (Fig. 4) and for calculating the dynamics of stability, mixing and geostrophic currents. Meanders or

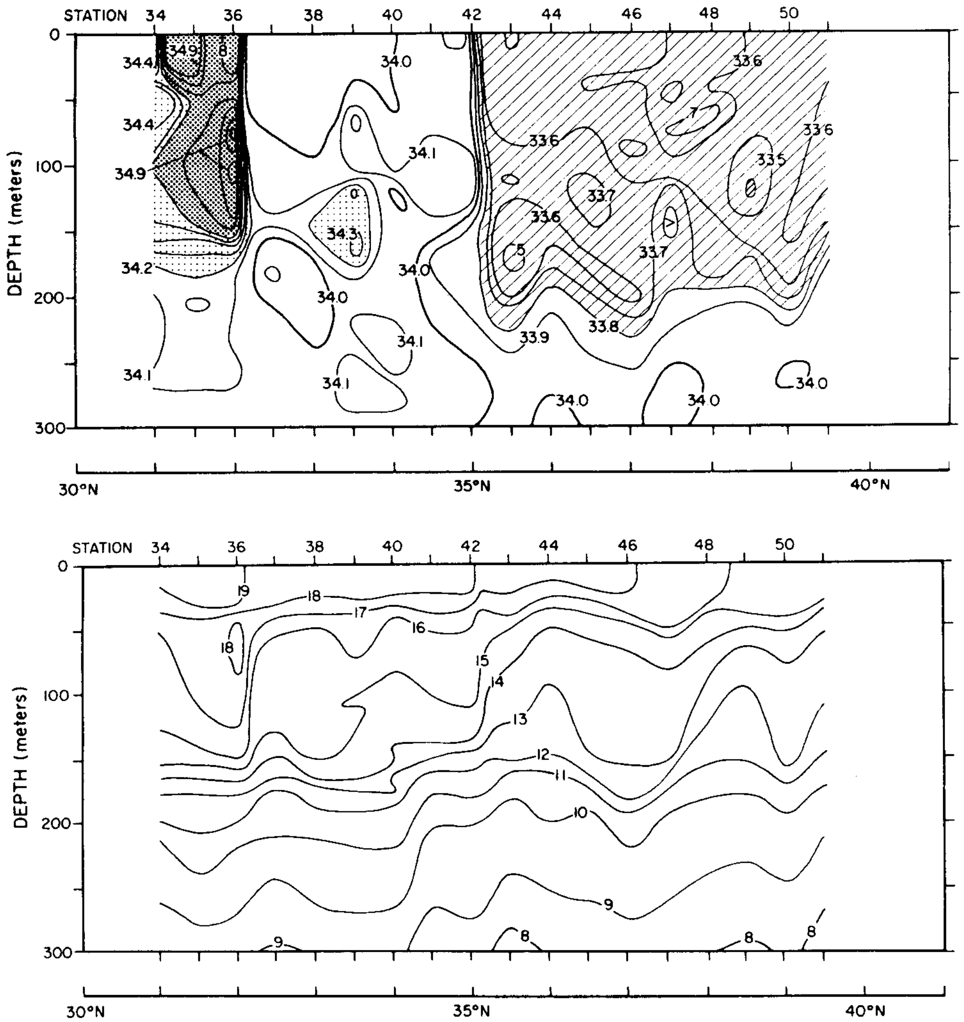

Figure 4. Vertical section of salinity (upper panel) and temperature (lower panel) along 137.5°W for June 1973. The subtropic front is seen at 32°N and the subarctic at 35°N. Hatching indicates salinities < 33.8 °/oo; light stippling indicates salinities between 34.2 and 34.6 °/oo and heavy stippling indicates salinities > 34.6 °/oo.

eddies spun off the fronts can be described. The nutrient chemistry, chlorophyll determinations and micronekton hauls provide the links between the physical and biological regimes. The thermosalinograph, which provides a continuous underway recording of surface layer temperature and salinity, reveals the presence of surface frontal gradients as they are crossed (Fig. 5). Thus, opportunity arises for

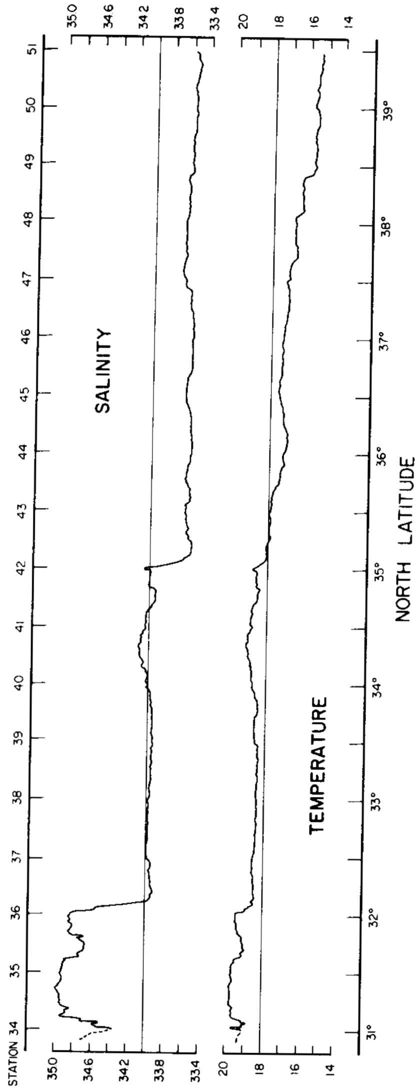

Figure 5. Surface temperature and salinity recorded by thermosalinograph along the same track as in Figure 4.

a tactical response in sampling procedures and fishing operations. The temperate zone frontal system of the eastern North Pacific Ocean often exhibits a temperature change on the order of only 0.7-1.0 C in 4-20 km. It is the abruptness of change in an otherwise flat signal that identifies these features. The salinity change at the front, 0.5-1.0 $^{o}/oo$, is even greater relative to its ambient fluctuations in the surface layer.

APPLICATIONS OF REMOTE SENSING

Remotely sensed measurements from aircraft and satellites have been employed in directing commercial-fisheries and fisheries-research operations and in analysis of the results of biological- and physical-oceanographic projects. This powerful tool is growing in acceptance and importance in the fishery sciences and industries. The applications of satellite remote sensing in fisheries, including the use of thermal infrared radiometry, the Coastal Zone Color Scanner (CZCS), and the SEASAT-A microwave scatterometer, has recently been reviewed by Laurs and Brucks (in press).

For many ocean scientists the initial exposure a decade ago to thermal-infrared images from satellites raised questions as to relevance of the images to subsurface features. Experience has demonstrated that, for the most part, the observed plumes, fronts, eddies, wakes and the like are features rooted in the mixed layer or deeper. In a time sequence of satellite images some are found to evolve slowly in form; others show a strong response to major wind events in a short time. This imagery reveals expressions of the advection and exchange processes at the surface and potentially reflects related patterns in the biological distributions.

The major, western, boundary-current systems are monitored by satellite. Contemporary multidisciplinary studies of the warm- and cold-core rings in the North Atlantic rely upon remotely sensed data. Satellite imagery is equally useful in small-scale studies and in the lesser-gradient features found in eastern boundary currents. Using images from the NOAA-5 satellite, Simpson and Pingree (1978) confirmed the occurrence of convergent tidal fronts in the Celtic Sea. These shallow sea fronts divide regions of tidally mixed and well-stratified waters. They stimulate local primary productivity and concentrate zooplankton. At the National Marine Fisheries Service Southwest Fisheries Center (NMFS/SWFC) we have used imagery to direct effort in a detailed survey of an upwelling plume. Also the SWFC participated in a joint venture of industry, university and government to supply salmon and albacore fishermen on the US west coast with timely maps of gradient features (Montgomery 1981). Recently the development of processing techniques for data from the CZCS aboard the Nimbus 7 has added a new instrument to our arsenal. R.M. Laurs and colleagues are studying an application of the CZCS to the west coast albacore fishery, which has altered our perception as to the mechanism of response of these fish to upwelling fronts. Albacore, which are visual feeders, are now suspected to be responding to strong changes in turbidity which are seen as color fronts associated with upwelled waters rather than to the temperature fronts (R.M. Laurs personal communication).

R. Lasker and colleagues at the SWFC are applying satellite imagery to studies of northern anchovy spawning in the Southern California Bight. Anchovy eggs and larvae were sampled during March and April 1980 in a closely spaced grid of stations covering most of the Bight. The first-day larvae were well represented in net tows in some areas and absent from others. There was remarkable coincidence in the larval distribution's southern boundary with a strong gradient of chlorophyll concentration as measured by the blue-green ratio in a CZCS image taken in early April, 1980. Spawning appears to have occurred within the plankton-rich areas and was absent from the clear blue, and more sterile, waters offshore and to the south. The northern limit of egg distribution was coincident with the 14-C surface isotherm as determined by direct measurements and thermal IR satellite imagery. Temperatures less than 14 C, while not physiologically unsuitable for anchovy spawning, indicate recently upwelled waters. The 14-C isotherm may denote a zone of change in the succession of planktonic-community composition or in the vertical stratification of the water column, both of which are important factors in spawning (Lasker 1978). A repeated set of data for February 1981 did not confirm the correspondence with the surface-chlorophyll gradient. More observations are scheduled.

PRESENT DAY DEVELOPMENTS AND FUTURE EXPECTATIONS

I expect application of remote-sensing techniques to continue to advance our understanding of the oceans and to expand in usefulness in marine biology. There are several recent improvements in remote sensing, and more are anticipated. The present application of thermal IR imagery is to utilize the relative temperature-gradient patterns for interpretation of events. Until recently the accuracy of estimates of sea temperature from single channel IR data was no better than 4-5 C (or 2-3 C if sea surface measurements were available). Algorithms have now been developed for multichannel IR data, limiting error to 0.6-0.9 C (Bernstein 1982; McClain et al. 1983).

Overcast and atmospheric moisture continue to be the major problems in collecting useful IR and visual imagery. Bernstein (1982) has devised a routine which retrieves sea-surface temperatures even from small scattered openings in clouds. Using image-screening techniques the routine eliminates all but the best data. Applying the routine to a series of images collected over days to weeks produces a field of data not unlike that from maritime ship reports. The satellite data have a smaller bias than do maritime ship reports, however, and are not constrained to shipping lanes. This routine might be used to improve the present program for monitoring sea-surface temperature that relies on maritime reports and would likely improve the spatial resolution. It also could be applied regionally.

One experimental sensor that is unaffected by clouds is the microwave scatterometer used aboard the ill-fated SEASAT-A. It provides the basis for estimates of wind stress. Bakun and Parrish (1980) have found a spatial alternation in the pattern of wind-curl stress along the California and Baja California coastal zone. A lobe of positive curl between regions of negative curl appears to block the seasonal development of the countercurrent, resulting in two semi-indepedent gyres. These gyres correspond to separate subpopulations of pelagic fish. The wind stress was derived from a composite of many years of data. The wind-stress curl could not have been resolved by the methods available for synoptic sampling. Bakun and Parrish suggested that the design resolution of 50 km for the microwave scatterometer would allow synoptic viewing of wind-stress features on a size scale relevant to fish stocks.

Within the past decade we have seen substantial technological advances in computers and in data handling systems. These improvements have facilitated the archiving and use of voluminous time series of environmental data. Numerous resulting studies and papers have examined interactions between the oceans and atmosphere on scales from regional to global. The benefits to fisheries research, which are yet to be fully realized, should include the development of environmental indices and simulation models which have potential for interfacing with fisheries data sets and migration models.

CONCLUSION

The linkage between the distribution and movement of fish and fields of motion and related ocean features is complex and involves multiple trophic levels. It may not be possible to demonstrate a direct causal relationship, but evidence and intuition point toward such linkages. Both physical and biological data sets tend to be deficient because the number of samples is usually small, the medium is highly variable, and most data sets require considerable interpolation. Despite these deficiencies, evidence is overwhelming for the influence of spatial and temporal variations in the marine environment upon fish. Hypotheses so raised can lead to improved experiments and alternate approaches to confirm or dispel the ideas.

The technological advances also provide for rapid data retrieval and sophisticated graphic display of data from oceanographic archives--quite the equivalent of an electronic atlas. As these developments become available they improve our capabilities for accessing marine environmental data for development of project plans and in analysis. However, the advances in remote sensing and data technologies do not supplant the need for field measurements but rather supplement them. There is still the need for lowering instruments over the side to take the measure of the ocean environment concurrently with sampling fish.

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