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Fisheries Applications of Satellite Data in the Eastern North Pacific

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ABSTRACT—Satellite sensors provide extensive and detailed images of sea surface temperature and color. Synoptic daily sampling by satellites gives a unique view of the ocean surface that can be extremely useful when used in conjunction with conventional shipboard data. Current and potential applications of satellite data off the U.S. Pacific coast and Alaska include interpretation of ship survey data, explanation of pelagic fisheries distributions, prediction of stock recruitment, spatial/temporal monitoring of the coastal zone and sea ice, studies of migration routes and timing, and production of charts to aid commercial fisheries.

Introduction

Remote sensing of the ocean is playing an increasingly important role in fishery research and fish harvesting along the Pacific coast of the United States and Canada. Satellite sensors make synoptic measurements of water temperature and color, winds, ice cover, wave height, and surface currents over large areas of the ocean surface. Variations in these ocean conditions play key roles in natural fluctuations of fish stocks and in their vulnerability to harvesting.

The promise of remote sensing techniques for fisheries research, management, and exploitation has been recognized since the early 1960's when the first visible and infrared images of the earth's surface were obtained from orbit. However, successful applications have only recently been realized with the advent of advanced and sensitive radiometers, high-speed data processing, and the availability of imagery to fishery scientists and fishermen.

Gower (1982) provides a useful overview of the different kinds of remote sensing data relevant to fisheries science and oceanography. Laurs and Brucks (In press) review living marine resources applications in the United States. Yamanaka (1982) gives examples of some uses of satellite data for fisheries applications off Japan. Other potential, ocean-related uses of remote sensing data were discussed by Montgomery (1981). This paper will review the satellite sensors currently measuring sea surface temperature and ocean color, data processing and availability, and several examples of recent and potential applications to eastern North Pacific fisheries.

Satellites provide a unique view of the ocean by covering large areas synoptically. Coverage of historically data-poor areas is particularly useful. However, satellite measurements are usually limited to the surface or near-surface layers in cloud-free areas. Therefore, satellite data complement conventional shipboard observations but cannot replace them. The best research approach often requires close coordination of the two sources of information. In this way, the evolving capabilities of satellite remote sensing are providing a powerful tool to enhance the efficient use of living marine resources.

Satellite Sensors

A variety of instruments measure radiance from the earth's surface in visible, thermal infrared (IR), and microwave wavelength bands (Table 1). The most readily available and useful data come from the Advanced Very High Resolution Radiometer (AVHRR) on meteorological satellites operated by the National Oceanic and Atmospheric Administration (NOAA) and the Coastal Zone Color Scanner (CZCS) on the experimental Nimbus-7 satellite operated by the National Aeronautics and Space Administration (NASA). These advanced sensors are characterized by high sensitivity in narrow wavelength bands, fine ground resolution, and extensive data archival.

Satellites receive electromagnetic radiation emitted from the sea surface (the IR temperature signal) and back scattered from below the surface (the visible ocean color signal). These signals are contaminated by reflection from the sea surface and clouds, and by absorption, emission, and scatter by atmospheric particulates and molecules. Some of these errors can be eliminated or minimized very simply. For example, sunglint and "limb darkening" (by long atmosphere paths at oblique viewing angles) are avoided by constraining the viewing geometry of the sensor. Corrections of some other errors, however, require advanced image processing methods.

Dense clouds may so completely absorb visible and IR radiation from the sea surface that no type of data

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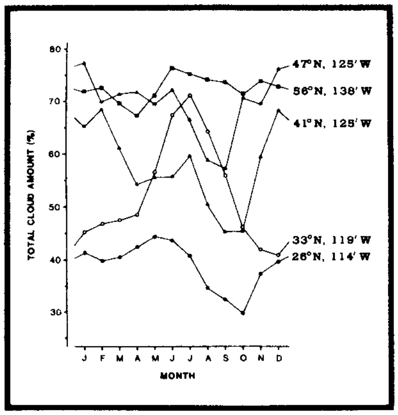


Figure 1.—Mean monthly total cloud amount over coastal waters, from surface marine weather observations, 1921-72 (Nelson and Husby, 1983): Baja California (27°N, 115°W), Southern California Bight (33°N, 119°W), Cape Mendocino (41°N, 125°W), Vancouver Island (48°N, 126°W). Gulf of Alaska data (56°N, 138°W) are from satellite observations, 1967-72 (Sadler et al., 1976), intercalibrated against data from Nelson and Husby (1983).

Table 1.—Some satellite sensors measuring visible, infrared, or microwave radiance for oceanographic measurements. Wavelengths are band midpoints. Ground resolution dimensions are directly beneath the satellite.

Sensor[1]	Satellite	Channel	Spectral band	Wavelength (μm)	Scan width (km)	Ground resolution (km)	Primary measurements
AVHRR	TIROS-N	1	Visible	0.63	3,000	1.1	Sea surface temperature, sea ice
	NOAA-6, 7, 8	2	Near-infrared	0.91			
		3	Infrared	3.74			
		4	Infrared	10.8			
		[2]5	Infrared	[2]12.0			
CZCS	Nimbus-7	1	Visible	0.44	1,566	0.825	Phytoplankton pigments, turbidity, sea surface temperature
		2	Visible	0.52			
		3	Visible	0.55			
		4	Visible	0.67			
		5	Near-infrared	0.75			
		6	Infrared	11.5			
MSS	LANDSAT	1	Visible	0.55	185	0.079	Water color, turbidity, sea ice
		2	Visible	0.65			
		3	Near-infrared	0.75			
		4	Near-infrared	0.95			
VISSR	GOES	1	Visible	0.62	Earth disk	7 × 3	Cloud cover, sea surface temperature
		2	Infrared	11.5			
SMMR	Nimbus-7	1	Microwave	4.54×10^4	600	20-100	Sea surface temperature, sea ice, near-surface winds
	SEASAT	2	Microwave	2.8×10^4			
		3	Microwave	1.66×10^4			
		4	Microwave	1.36×10^4			
		5	Microwave	0.81×10^4			

[1]Sensors: AVHRR = Advanced Very High Resolution Radiometer; CZCS = Coastal Zone Color Scanner; MSS = Multispectral Scanner; VISSR = Visible and Infrared Spin Scan Radiometer; SMMR = Scanning Multichannel Microwave Radiometer.
[2]Channel 5 on NOAA-7 and NOAA-8 satellites only.

processing can retrieve a useful signal. Clouds severely limit satellite coverage of the sea surface in some regions of the eastern North Pacific, particularly north of lat. 40°N (Fig. 1). South of lat. 27°N, off Baja California, mean monthly cloud cover is consistently less than 50 percent, due to persistent offshore flow of dry continental air. From lat. 30°N to 38°N, coastal waters are covered by a dense layer of low stratus clouds during the summer upwelling season (Nelson and Husby, 1983). The most favorable conditions for remote sensing at these latitudes are found from October through March or April, especially during occasional brief periods when Santa Ana winds blow warm, dry desert air offshore and produce cloud-free conditions up to 1,000 km from the coast.

In contrast, the most cloud-free conditions at lat. 40°-50°N are found in late summer, from August to October. Mean monthly cloud cover increases to the north and is consistently 70 percent or greater in the Gulf of Alaska, although March and April may be relatively clear. As a general rule, percent cloud cover increases by at least 10 percent from the coast to a distance on the order of 200 km offshore in the eastern North Pacific (Nelson and Husby, 1983).

The probability of cloud-free conditions in a region of interest during regular satellite passes is loosely reflected in these monthly cloud cover statistics. Cloud cover restricts the extent to which satellite data can be anticipated, or depended upon, to be available. Whereas it may be possible to obtain regular daily or weekly coverage of sea surface features in the south, such as in the Southern California Bight, in the north there are generally more frequent and longer data gaps. Satellite coverage of ocean features in the Alaska region is characteristically limited to occasional cloud-free scenes that, despite being infrequent, can be rich in information. Microwave radiometers can measure sea surface temperature through clouds, but with a lower sensitivity and much coarser resolution than IR radiometers.

Data Processing

The AVHRR measures thermal infrared radiant energy in three wavelength bands (Table 1). Temperature calibration data are obtained by scanning deep space and internal blackbody targets. Accurate sea surface temperatures are calculated from empirical regressions of ship and buoy temperatures on satellite temperatures in two or three bands. Such multispectral corrections are based on the different response of each band to the cold bias caused by atmospheric water vapor (McClain et al., 1983). Pixels (samples) containing clouds even smaller than the sensor's field of view are screened in daytime passes using the near-infrared albedo data from channel 2 (Bernstein, 1982).

The CZCS measures visible light in five narrow wavelength bands selected for estimating phytoplankton pigments, suspended sediments, and dissolved organic matter. Up to 90 percent of the visible radiance received at the satellite is skylight reflected and scattered within the atmosphere. Corrections are based on assumptions that the red light emitted by the ocean and measured by channel 4 is either negligible or can be accurately predicted from radiances in other bands. The atmospheric radiance measured by channel 4 can then be related to atmospheric radiances in other channels using known spectral properties of atmospheric scattering (Gordon et al., 1983). Corrected ratios of blue to yellow-green (channel 1/channel 3) or green to yellow-green (channel 2/channel 3) radiance are then used to calculate phytoplankton pigment concentration from empirical regression relationships (Smith and Baker, 1982).

Satellite data, properly corrected for the various errors described above, have been validated by sea truth data from ships to $\pm <1°C$ (Bernstein, 1982) and ± 0.4 log chlorophyll concentration (Smith and Baker, 1982). While important subsurface features such as chlorophyll maximum layers and some cold-core eddies or oceanic fronts may not be detected by satellites, the measured parameters are, in general, closely related to properties such as mixed-layer temperature and integrated chlorophyll or primary productivity in the euphotic zone (Smith, 1981).

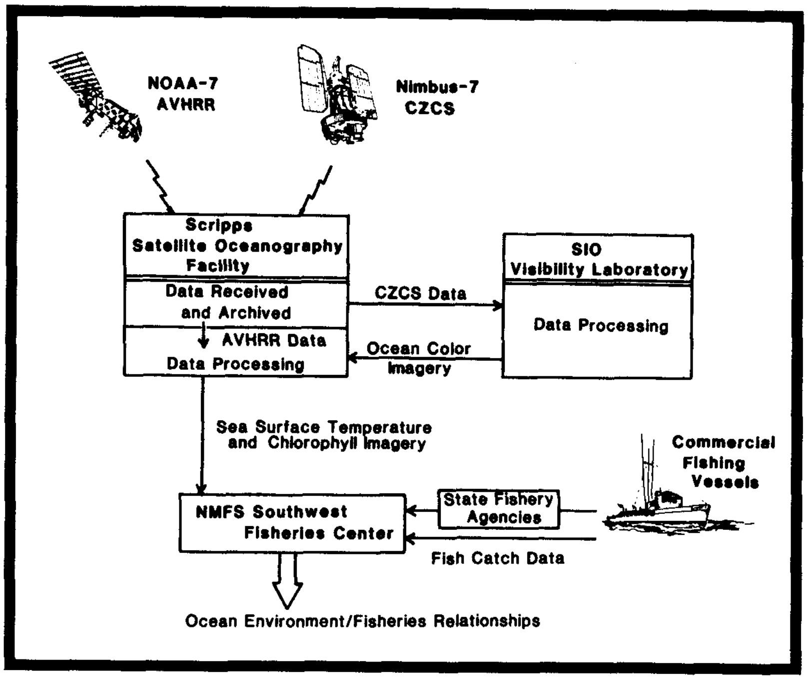


Figure 2.—Satellite data collection and processing network utilized by the National Marine Fisheries Service on the west coast.

Data Availability

Applications of satellite data are ultimately limited by their availability. Ideally, a user would have immediate access to data received directly from satellites and conveniently archived, with data processing facilities at his fingertips. This ideal has been approached by an arrangement at the Satellite Oceanography Facility of Scripps Institution of Oceanography in La Jolla, Calif., for most of the work reported here (Fig. 2). Similar arrangements, lacking direct data reception capabilities, have been established at the University of Miami and by the Northeast Area Remote Sensing System, which is a regional association of university, industry, and government organizations that was recently formed in the northeastern United States.

Global satellite data are archived by the Satellite Data Services Division of NOAA and are available to the public, although acquisition may require several months and a large backlog of CZCS data is unprocessed. AVHRR and CZCS data are available in various forms including photographic prints and negatives, digital data on magnetic tapes, and maps of derived sea surface temperature and ice cover. These products and a catalog of available CZCS data are available from the National Environmental Satellite Data and Information Service, Satellite Data Services Division, NOAA, Room 100, World Weather Building, Washington, DC 20233. Detailed procedures for obtaining environmental satellite data are given in Cornillon[1]. In general, photographic copies of raw data are of limited value and a user must have access to a computer-based, image processing system to extract useful information from satellite data on digital tapes (this situation may change in the future if products derived from satellite data are offered by commercial processing enterprises).

Applications

We briefly review here examples of general applications of satellite data to fisheries research and management problems along the Pacific coast between California and Alaska. Some of these examples have been published elsewhere, but none of the applications has as yet been fully realized.

[1]Cornillon, P. 1982. A guide to environmental satellite data. Univ. R. I. Mar. Tech. Rep. 79, 469 p. Available for $20.00 from the University of Rhode Island, Marine Advisory Service, Publication Unit, Narragansett, RI 02882.

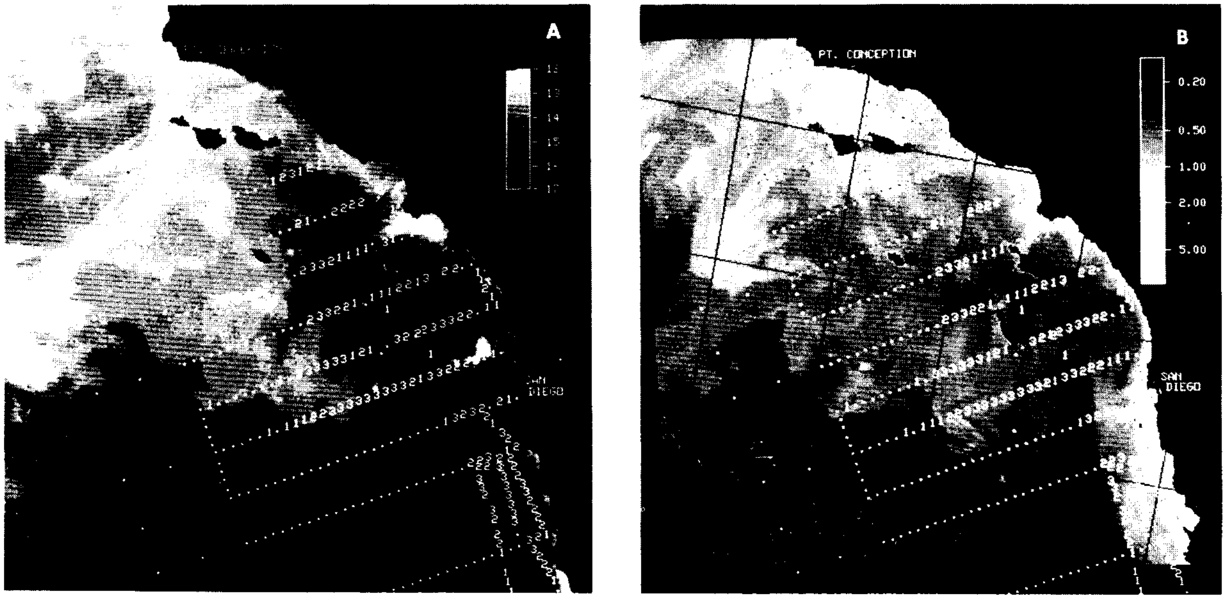


Figure 3.—Northern anchovy egg distribution, 20 March-10 April 1980; • = 0, 1 = 1-4, 2 = 5-17, 3 = 18-245 eggs/0.05 m². Top photo (A) is sea surface temperature (°C) from NOAA-6 AVHRR, 7 April 1980; Photo B is of phytoplankton pigments (mg m⁻³) from Nimbus-7 CZCS, 8 April 1980.

Interpretation of Ship Survey Data

A large stock of northern anchovy, *Engraulis mordax,* is found off southern California, where intensive egg surveys have been conducted since 1980 to estimate spawning biomass. Satellite images of sea surface temperature and phytoplankton pigment concentration, obtained during an egg survey in April 1980, depict environmental limits on the range of spawning anchovy (Fig. 3). North of San Diego, no eggs were found in water colder than 14°C. To the south, spawning northern anchovy were confined along the coast to a narrow band of water with high pigment concentrations. Similar distribution patterns were observed in 1981 and 1982 (Lasker et al., 1981; Fiedler, 1983).

The distribution of spawning adults may reflect the critical need by first-feeding larvae for aggregations of suitable food organisms in a stable water column. The environmental limits revealed by the satellite images would not have been revealed by the egg survey data alone, because phytoplankton pigments were not measured and spatial coverage was limited.

Satellites data may be used to interpret the large-scale patterns and possible causes of spatial/temporal variability in other types of ship survey data. Most measurements of fish eggs and larvae, plankton concentrations, chlorophyll, nutrients, temperature, and salinity are made at point locations at regular intervals along transects or in grid patterns. Remote sensing data collected concurrently, if available, may provide valuable information on factors contributing to patterns in the shipboard data and on conditions beyond the area surveyed. Besides the insight that usually results from a synoptic view, this information is important in evaluating the validity of interpolation and extrapolation of ship survey results.

Pelagic Fisheries Distribution

Albacore, *Thunnus alalunga*, is a migratory oceanic tuna that is an important target species for jigfishing, live bait, and recreational fishing along the U.S. Pacific coast from July to October. Fishermen search for aggregations of these fish in warm, blue oceanic waters near temperature or water color fronts at the offshore edge of productive coastal waters. Daily catch records during peak fishing in late summer 1981 were taken from logbooks submitted to west coast state fisheries agencies. Concentrations of fishing activity and large catches indicate sites of albacore aggregations.

Satellite images of sea surface temperature and phytoplankton pigment concentrations clearly show favorable sites for aggregations in pockets of warm, blue oceanic water intruding into the colder and more turbid coastal water mass (Fig. 4; Laurs et al., In press). Albacore are visual predators and may feed most efficiently in the clear water adjacent to coastal waters where prey densities are higher. Albacore fishermen, running several days out of port in small boats to reach offshore fishing grounds, can benefit from timely maps of sea surface temperature and ocean color gradients derived from satellite data. Potential benefits include decreased search time, lower fuel use, and increased catches.

Satellite data may be applied to

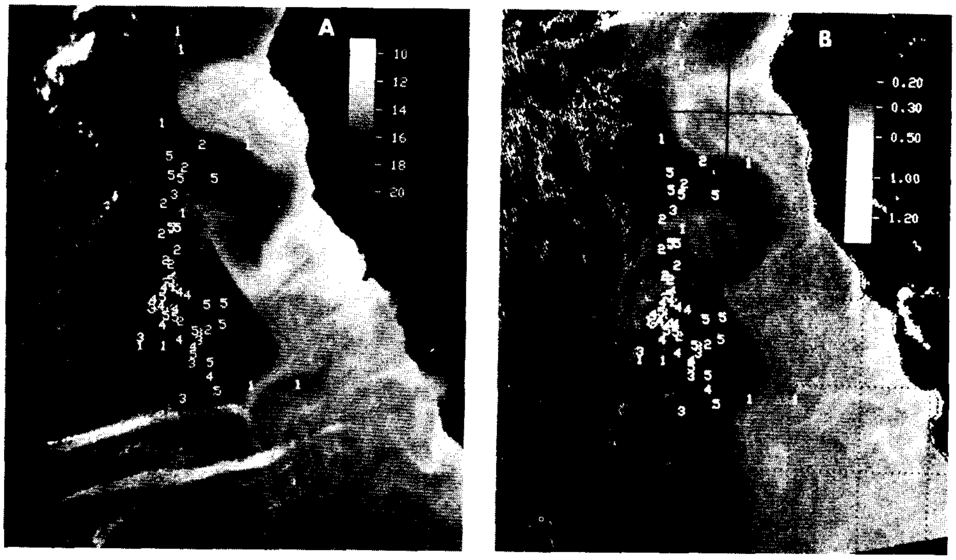


Figure 4.—Daily albacore catches off central California, 19-24 September 1981: 1 = 0-27, 2 = 33-63, 3 = 64-81, 4 = 87-140, 5 = 148-750 fish/boat. A is sea surface temperature (°C) from NOAA-7 AVHRR, 21 September 1981; B is phytoplankton pigments (mg m^{-3}) from Nimbus-7 CZCS, 22 September 1981.

other pelagic fisheries, both to direct fishing effort and for fisheries management. In the Pacific Northwest and off Alaska, five species of Pacific salmon—sockeye salmon, *Oncorhynchus nerka*; chum salmon, *O. keta;* pink salmon, *O. gorbuscha*; chinook salmon, *O. tshawytscha*; and coho salmon, *O. kisutch*—are important resources for a large fishing industry. During their oceanic life history phase, these salmon are caught by power or hand-trolling boats using methods similar to albacore fishing. The study described by Borstad et al. (1982) is an example of a use of remote sensing techniques to study relationships between salmon distributions, fishing, and oceanographic conditions. Other pelagic resources for which there may be analogous applications include Pacific herring, *Clupea harengus pallasi,* off Alaska; jack mackerel, *Trachurus symmetricus,* and Pacific mackerel, *Scomber japonicus,* off California; and bluefin tuna, *Thunnus thynnus orientalis,* off Baja California.

Stock Recruitment Predictions

An application of satellite data that merits investigation is the improved understanding and prediction of variations in recruitment to coastal fish stocks. In the eastern North Pacific, offshore transport and turbulent mixing may have important effects on the larval survival and subsequent recruitment of some species (Bakun and Parrish, 1982). Both processes are driven by surface wind stress. Offshore transport removes eggs and larvae from productive nearshore nursery grounds. This may be most important where strong seasonal upwelling occurs over a narrow continental shelf, as it does along the U.S. coast north of lat. 34°N. Turbulent mixing reduces stratification of the near-surface water column and disrupts aggregations of food organisms required for successful first feeding by newly hatched larvae (Lasker, 1981).

Variations in annual recruitment of Pacific whiting, *Merluccius productus,* have been related to monthly mean Ekman transport estimated from equatorward wind stress off central California (Bailey, 1981). Fiedler (1984) has used AVHRR imagery to document interannual changes in the sea surface temperature field related to variations in coastal upwelling off the U.S. Pacific coast. Satellite imagery has also revealed that offshore transport is a highly irregular process in both time and space, manifested as meandering jets and eddies of cold water (e.g. Fig. 5). Offshore transport could perhaps be quantified by measuring the areal extent of relatively cold water nearshore or the offshore displacement of frontal features between daily satellite passes. This application may be extended to other species for which there is evidence of similar environmental effects (e.g. Hayman and Tyler, 1980; Bakun and Parrish, 1982).

The seasonal timing and spatial location of northern anchovy spawning has been related to turbulent mixing, as indexed by the cube of mean surface wind speed in historical marine weather observations, by Husby and Nelson (1982). They suggested that strong year classes may depend upon the occurrence of "time-space windows" with sufficiently low turbulence to allow development of layers of food organisms.

The magnitude and direction of surface wind stress are directly

Figure 5.—Localized offshore transport of cold upwelled water (whiter shades) off northern California and southern Oregon. The three major coastal landforms, from top to bottom, are Cape Blanco, Cape Mendocino, and Point Arena. White features in the top left corner are clouds. Image from NOAA-7 AVHRR channel 4, 14 June 1982.

measurable by microwave sensors such as the scatterometer which flew on the short-lived SEASAT satellite in 1978. The U.S. government has not yet committed funds to orbit another such sensor, for which there are many potential scientific and commercial applications (NASA Satellite Wind Stress Working Group, 1982). Fisheries applications might include the real-time planning of fishing operations to avoid adverse sea state conditions, as well as the measurement of surface winds driving environmental processes affecting recruitment into coastal fish stocks. These benefits would be particularly significant in northern areas, such as the Pacific Northwest and Alaska regions, where present remote sensing coverage by visible and infrared sensors is usually limited by cloud cover.

Coastal Zone Monitoring

Mesoscale processes, such as upwelling and eddy formation, are very important components of the spatial and temporal variability of eastern North Pacific coastal waters, especially in the complex California Current System. Extensive and high-resolution satellite data are particularly valuable for studies of these processes (Bernstein et al., 1977). Anomalous ocean conditions along the U.S. Pacific coast were monitored during the 1982-83 El Niño event using AVHRR and CZCS data (Fiedler, 1984). Localized sea surface temperature anomalies up to +6°C were observed. Reduced coastal upwelling during the first half of the year was detected in patterns of cold, nearshore surface waters. CZCS images of the Southern California Bight indicated reduced phytoplankton productivity. This event affected many commercial and sport fisheries along the coast (Anonymous, 1984).

Monitoring coastal zone variability within a year or season with satellite data may be useful for developing better release strategies for hatchery-reared juvenile salmonids by enabling management decisions to be more adaptive and based on conditions in nearshore nursery areas. It might be possible to improve the growth and survival of hatchery-reared salmon by scheduling releases during periods of most favorable ocean conditions. AVHRR and CZCS imagery could be used as sources of information on sea surface temperature, river plume trajectory, upwelling intensity, primary production, and the oceanic frontal areas associated with each of these factors. Small improvements in the survival of juveniles released from hatcheries could result in substantial increases in the numbers of returning adults. If successful, this application would be particularly important in the Pacific Northwest and Alaska region, where hatchery operations are extensive and salmon resources have high value.

Salmon enhancement programs on the Columbia River, the largest river on the Pacific Coast of North America, provide an example of the potential. The National Marine Fisheries Service funds 22 salmon hatcheries and 7 rearing ponds on the Columbia River at an annual cost exceeding $4.5 million. Each year, these facilities culture and release 80-100 million salmon smolts in late April and early May. The present release schedule is decided largely on the basis of administrative criteria, tradition, and attempts to emulate nature. However, survival rates for these hatchery-reared salmon are relatively low, only about 3.7 percent (range, 0.23 to 12.35 percent) for coho salmon in their first year (Mathews, 1980).

There is increasing evidence that juvenile salmon survival, and subsequent adult returns, are critically influenced by conditions in the ocean environment within the first 6 months after hatchery release (Hartt, 1980; Wahle and Zaugg, 1982). Important factors may be food availability and the extent that food limitations occur in the nursery habitats as a result of crowding. On the Columbia River, although hatchery-reared salmon pass downstream and through the lower river and estuary relatively rapidly, significant losses occur in each of these migratory stages and areas. After reaching the ocean, juvenile salmon typically migrate along a relatively narrow coastal belt (Hartt, 1980). In purse seine studies off the Columbia River, juvenile salmonids (<50 cm) have been found to be distributed mainly within 28 km of shore; chinook salmon and steelhead, *Salmo gairdneri*, were distributed almost entirely in the river plume (Miller et al., 1983). Upwelling and its effects on food production have been related to juvenile survival and adult salmon production (Gunsolus[2]). A better understanding of these environmental relationships is a goal of current research.

Figure 6 shows three satellite images of sea surface temperatures along

[2]Gunsolus, R. T. 1978. The status of Oregon coho and recommendations for managing the production, harvest, and escapement of wild and hatchery-reared stocks. Oreg. Dep. Fish Wildl., Columbia Reg. Off., 17330 S.E. Evelyn St., Clackamas, OR 97015. Unpubl. manuscr., 59 p.

the Pacific Northwest coast during summer 1982, illustrating changes in coastal conditions that can occur over relatively short (2-3 week) time intervals. On 5 July, coastal upwelling was very weak, although signs of intensification were developing at Cape Mendocino. By 23 July, upwelling had intensified considerably, especially to the north. By 18 August, however, upwelling was again weaker. Changes in the mesoscale pattern of cold-water jets and meanders can be seen. In the latter two images, the Columbia River plume is indicated by a dark, warm-water break in the band of cold, upwelled water along the coast.

Figure 6.—Variations in the intensity and pattern of coastal upwelling off the Pacific Northwest between lat. 39°00'N and 48°30'N, July-August 1982. Sea surface temperature (°C) from NOAA-7 AVHRR channels 4 and 5. Clouds (white) screened with channel 2 data.

Monitoring Sea Ice

Sea ice is an important seasonal feature of the Alaskan environment that can be monitored by satellite coverage (Weeks, 1981; McNutt, 1981). Ice affects commercial fishing activities by threatening vessel safety, limiting navigation and access, and damaging fishing gear. Yet sometimes waters near the edge of pack ice can offer shelter or rich fishing grounds. Ice is also important because of its significance in the ecology of, and as a habitat for, northern marine mammals.

In the eastern North Pacific, winter ice cover occurs in inlets along the coasts of southeastern Alaska, the Gulf of Alaska, and the Aleutian Islands. Its formation is often associated with freshwater runoff, such as in Cook Inlet (Poole and Hufford, 1982). Freshwater ice forms on stream and river deltas, then sea ice forms in lower parts of the embayments. However, much greater ice cover occurs in the extended area to the north. Ice covers the Chukchi Sea, Bering Strait, and nearly the entire northeast half of the eastern Bering Sea during winter and spring. Movements of pack ice in the Bering Sea are influenced by winds and water currents, and are highly dynamic.

Ice off the North Slope, along the southern coast of Alaska, and in the Bering Sea, is monitored routinely by the National Weather Service. When cloud cover permits, ice and open water can be discriminated with a 1 km resolution using AVHRR visible and infrared data (Fig. 7). Combined with data from the Nimbus-7 Scanning Multichannel Microwave Radiometer, which are not influenced by clouds but have a resolution of 60 km, large-scale maps of ice coverage or concentration are produced. Some information about ice type (age and thickness) can be gleaned from satellite data, but the analysis is supplemented by aerial reconnaissance and reports from ships and shore stations. Ice analysis maps are distributed to users in the fishing and oil industries three times a week by radio facsimile and once a week by mail.

Winter fisheries affected by ice cover in the eastern Bering Sea include: Foreign groundfish fisheries, involving 200-300 vessels per year and an annual catch of about 1.3 million metric tons (Bakkala et al., 1979); highly-valued U.S. fisheries for king crab, *Paralithodes* spp., and snow (Tanner) crab, *Chionoecetes* spp. (Otto, 1981); and U.S. fisheries for Pacific herring that take place along the north shore of Bristol Bay. Vessels operating in these fisheries often need to work around sea ice, can have stability problems, and are sometimes trapped in shifting pack ice and lost.

Ice is an important part of the habitat of 25 species of marine mammals that occur in the Bering Sea (Fay, 1974; Burns et al., 1981). It may serve as a substrate, barrier, or to force migrations. Species that regularly come in contact with ice include the following: Polar bear, *Ursus maritimus;* walrus, *Odobenus rosmarus;* harbor seal, *Phoca vitulina;* ringed seal, *P. hispida;* ribbon seal, *P. fasciata;* bearded seal, *Erignathus barbatus;* narwhal, *Monodon monoceros;* beluga whale, *Delphinapterus leucas;* and bowhead whale, *Balaena mysticetus.* For these and other species, the wide views of ice

Figure 7. – Ice cover in the eastern Bering Sea, 18 February 1983, NOAA-7 AVHRR channel 4. Ice, clouds, and snow-covered land all appear whiter (colder) than open water. Pack ice extends from the Bering Strait, in the top left corner, past St. Matthew and Nunivak Islands, but does not reach the Alaska Peninsula to the southeast. Photograph courtesy of G. L. Hufford, NOAA/NESDIS, Satellite Field Services Station, Anchorage, Alaska.

characteristics that can be obtained from satellite imagery provide unique information for use in conservation and management.

Migration Routes and Timing

Satellite imagery can provide useful information on environmental conditions related to the routes and timing of long-distance migrations by marine mammals and fish. In the eastern North Pacific and in waters off Alaska, many important species occupy large habitat areas and make extensive seasonal migrations. These large activity areas are often in remote and data-poor regions. Satellite coverage, because of its wide areal views and long-term repeated observations, provides data with time and space characteristics that are appropriate for interpreting large-scale migratory phenomena. Applications include planning research, experimental design, and evaluating strategies for population enumeration.

The North Pacific albacore, *Thunnus alalunga,* performs transpacific migrations and supports important commercial fisheries in the western, central, and eastern North Pacific. Seasonal migration into North American coastal waters is associated with the Transition Zone between Pacific central and subarctic water masses (Laurs and Lynn, 1977). The frontal structure of these waters may affect both the timing and location of the arrival of albacore into the summer fishery along the coast. Figure 8 illustrates CZCS color frontal patterns in the central Pacific that could influence the course of the migration.

The potential for using both color and infrared temperature imagery in

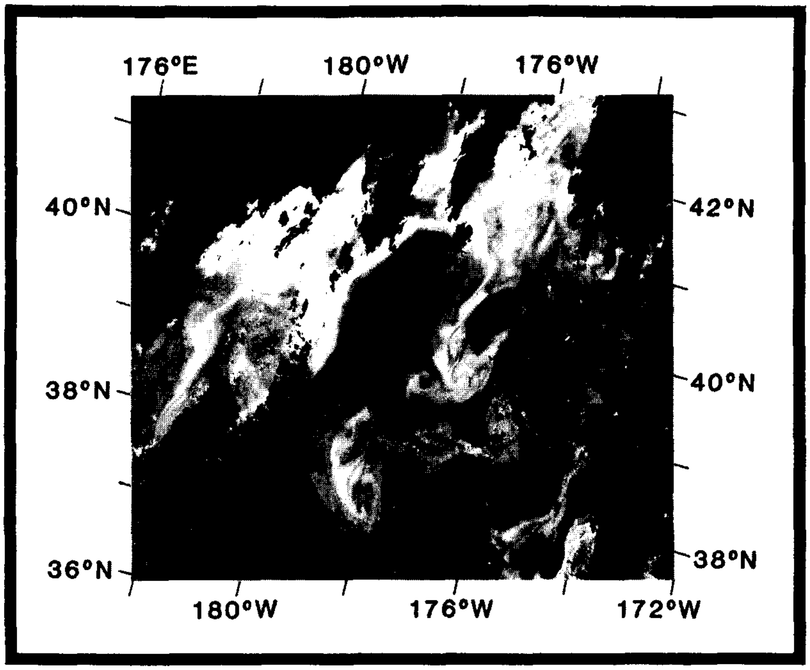


Figure 8. — Phytoplankton pigment concentration in a 600 × 600 km area of the central North Pacific, measured by the Coastal Zone Color Scanner, 30 June 1980. Black = clouds, darkest gray = 0.08 mg m^{-3}, white = 5.7 mg m^{-3}.

fishery operations in these waters has been explored on a limited basis with promising results. Although cloud cover allows only infrequent views of the sea surface, the surface patterns seem to be less dynamic than in coastal waters. Color boundaries are detectable from satellites during all seasons, but pronounced sea surface temperature fronts are not present during summer-autumn due to seasonal warming. However, infrared satellite imagery has been used to locate the subtropical front during winter (Van Woert, 1982) and spring months[3].

In Arctic and subarctic areas, such as the Beaufort Sea and northern Bering Sea, the movements and distribution of sea ice have important influences on the movements of marine mammals. Bowhead and beluga whales make regular seasonal migrations through the shear zones and lead systems that develop in the Arctic pack ice (Braham et al., 1980). In the case of the bowhead whale, the prediction and evaluation of migration paths is important because it is an endangered species and the western Arctic population requires careful annual censusing. Satellite imagery showing ice cover and open-water corridors is used to spot check the sampling design for summer whale counts.

There is potential for similar applications of satellite data in other oceanic and coastal areas, although the relationships between environmental characteristics and marine mammal migrations are not as obvious. For example, the eastern Pacific stock of gray whale, *Eschrichtius robustus,* undergos regular annual migration between summer feeding grounds in the Chukchi Sea and winter breeding grounds in Mexico (Pike, 1962). Satellite coverage of the onset of winter ice cover in the Bering Strait may help explain the environmental signals that initiate the southern migration. Other marine mammals that are important in the region, and that undergo long-distance movements, include: Northern fur seal, *Callorhinus ursinus,* migrating between summer breeding grounds on the Pribilof Islands in the eastern Bering Sea (and on other islands around the Northern Pacific rim) and wintering areas in the Gulf of Alaska and off the U.S. Pacific coast (Fiscus, 1978); humpback whale, *Megaptera novaeangliae,* an endangered species of which the eastern Pacific stock migrates between breeding and calving areas in the Hawaiian Islands and summer feeding grounds in the inland waters of southeastern Alaska (Wolman, 1978); and a number of species of dolphins and porpoise.

Allocation of Sampling Effort

Annual egg and larva surveys of northern anchovy are a regular activity of the California Cooperative Oceanic Fisheries Investigations (CalCOFI). Each survey requires 4-5 weeks of ship time to make vertical net tows at 800-900 stations. The accuracy of the estimate of spawning biomass derived from each survey depends on complete coverage of the geographic range of the spawning stock. Without a priori knowledge of this distribution, many extra stations beyond the range limits must be sampled to ensure adequate coverage. We are now investigating the use of satellite imagery to plan egg surveys based on environmental limits characterizing the spawning habitat and detectable from satellites, as described above.

The 1983 survey plan was modified during the cruise using information from satellites. When the cruise began north of Point Conception in February, eggs were found much farther north and offshore than in recent years. Upon examination of AVHRR temperature imagery, we realize that this extension of the spawning range was due to the 1982-83 El Niño event. The cold-water boundary which normally limits

[3]R. Lynn. 1984. Southwest Fisheries Center, National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, Ca 92038. Pers. commun.

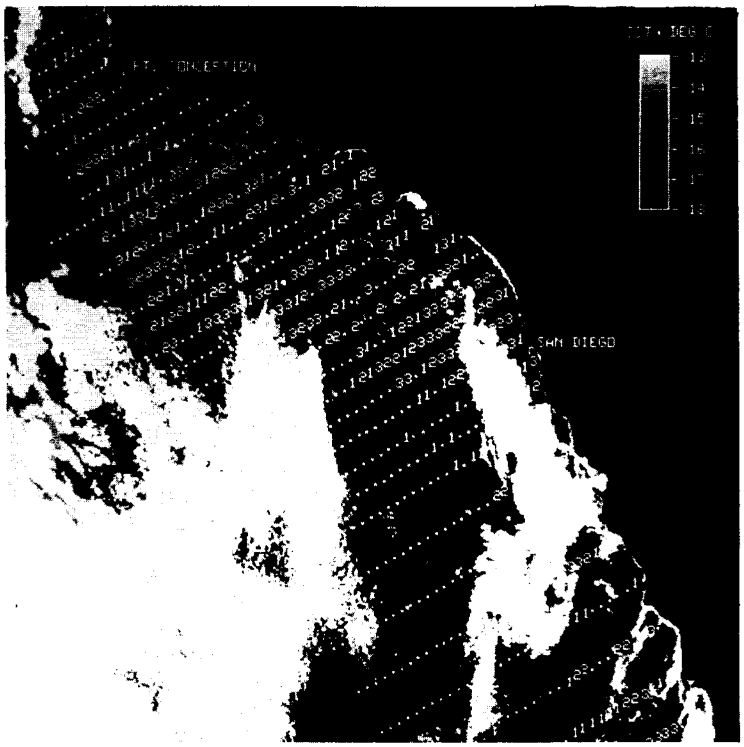


Figure 9.—Northern anchovy egg distribution, 9 February-29 March 1983: • = 0, 1 = 1-3, 2 = 4-12, 3 = 13-229 eggs/0.05 m². Sea surface temperature (°C) from NOAA-7 AVHRR, 10 February 1983.

spawning to the southeast of Point Conception had shifted to the north and offshore (Fig. 9, compare with Fig. 3). As a result, the lines of sampling stations were extended farther offshore than originally planned, to ensure coverage of the entire spawning stock.

In another study conducted in June 1980 on the feeding biology of larval jack mackerel, satellite data were used to locate an intensive sampling grid on a temperature front. The front was observed southwest of San Diego in a NOAA-6 AVHRR image obtained over 1 week prior to the cruise, and it persisted during the sampling period (Fig. 10). The front was subsequently found to be related to an important gradient in food availability[4].

These two examples demonstrate how a single satellite image, from data received and processed in a matter of hours, can save days of ship time by locating significant environmental features and permitting efficient allocation of sampling effort. The potential cost savings are obvious, but the real-time use of satellite data requires facilities for direct reception and processing.

Fisheries Aid Charts

Operational applications of satellite data to commercial fishing activities

[4]R. Hewitt. 1983. Southwest Fisheries Center, National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038. Pers. commun.

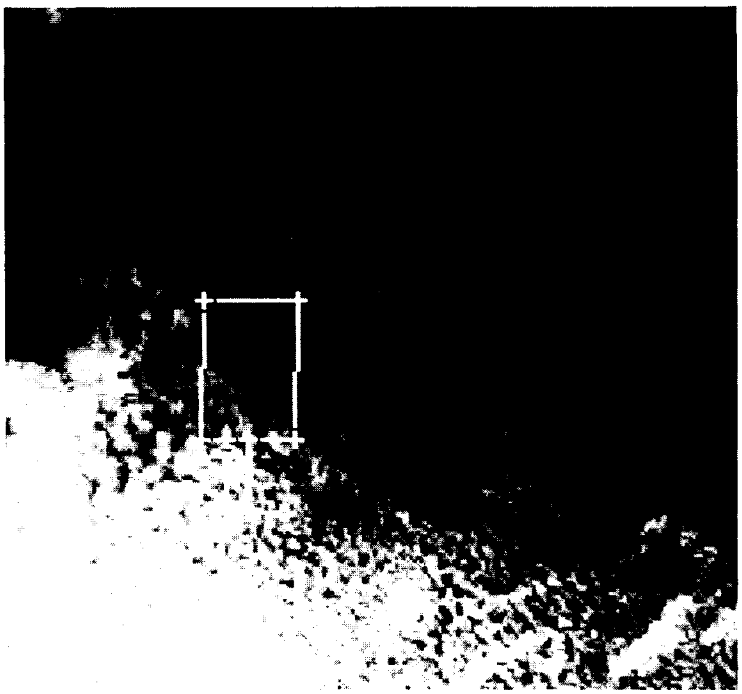
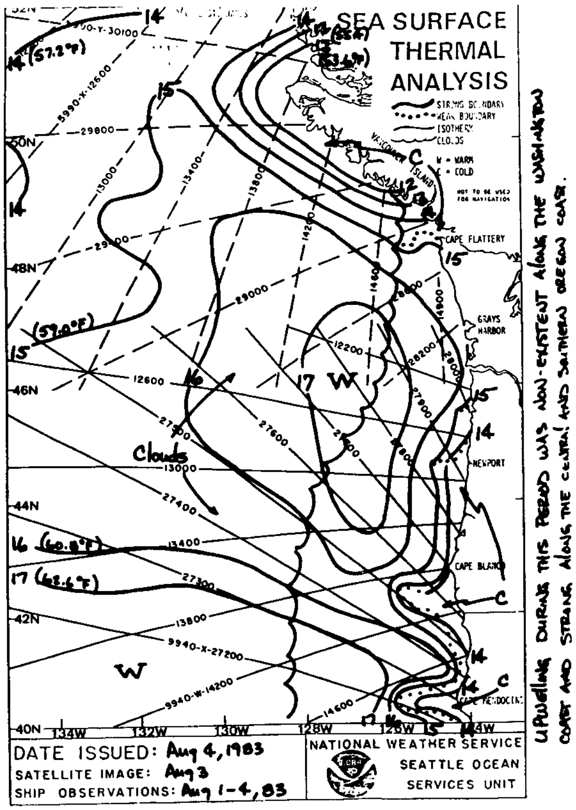
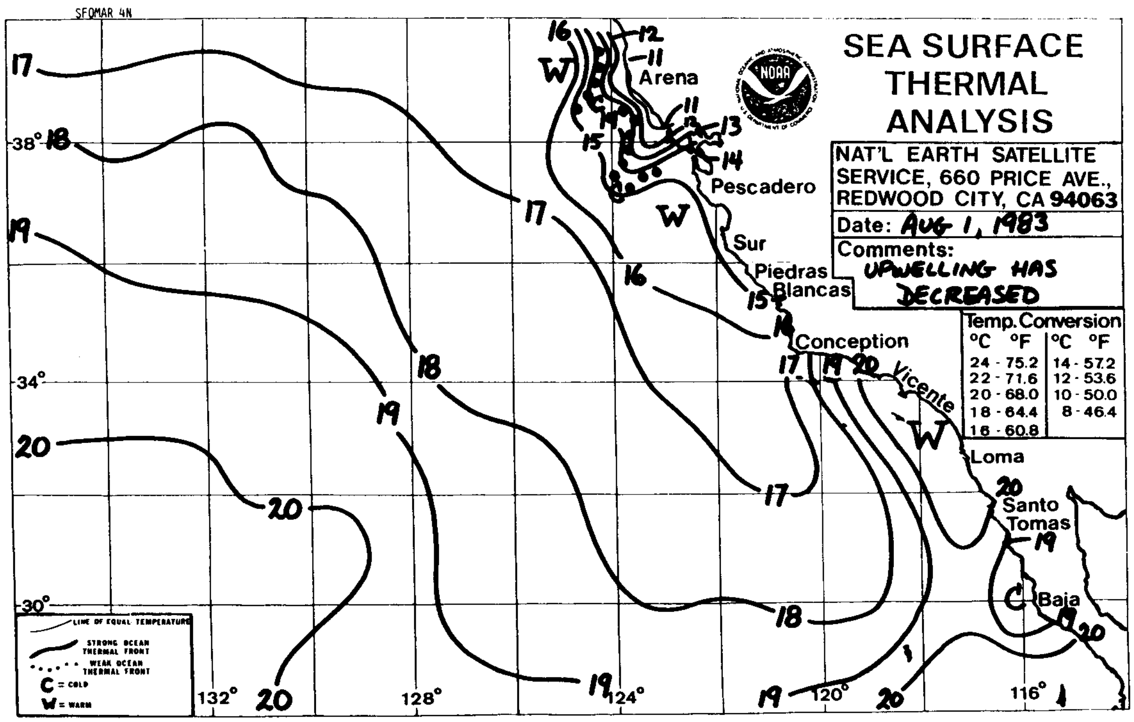


Figure 10.—Uncalibrated NOAA-6 AVHRR channel 4 image off southern California, 5 June 1980. Lighter shades represent cold sea surface temperatures, clouds appear white. Box encloses a 30 × 67 km grid of 41 stations centered at lat. 31° N, long. 120°30′ W.



began along the Pacific coast in 1975 (Breaker, 1981) and have now been extended to Alaska. Charts showing sea surface temperature fronts and sea ice visible in satellite AVHRR images, and surface isotherms mapped from satellite and ship data, are produced routinely by NOAA (Fig. 11). The Northwest Ocean Services Center in Seattle produces a chart covering northern California, Oregon, Washington, and southern British Columbia, from lat. 40°N to lat. 52°N. The Satellite Field Services Station in Redwood City, Calif., produces a chart covering central and southern California and northern Baja California, from lat. 28°N to lat. 40°N. Coverage of both charts extends offshore to long. 135°W. They are produced once or twice weekly year-round and are distributed primarily by radio facsimile from the U.S. Coast Guard

Figure 11.—Sea surface temperature charts produced by the National Weather Service.



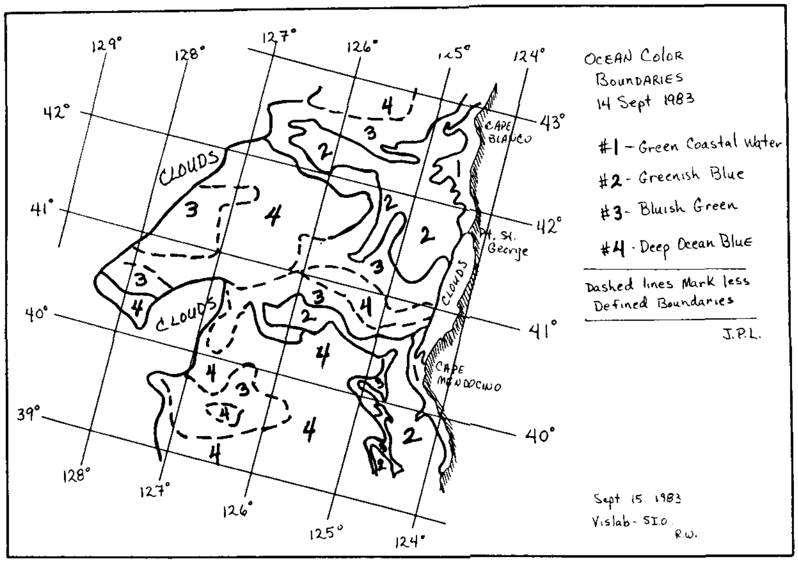


Figure 12.—Ocean color boundary chart off northern California and Oregon (R. Wittenberg, Scripps Visibility Laboratory).

radio station at Point Reyes, Calif. Fishermen use these charts to save time in searching for productive fishing areas associated with frontal features.

The Alaska Ocean Services Unit, located in Anchorage, produces charts covering British Columbia, the Gulf of Alaska, Aleutian Islands, eastern Bering Sea, Chukchi Sea, and Beaufort Sea, from lat. 48°N to lat. 75°N. Charts showing sea surface temperature and sea ice are distributed three times a week; these are intended to aid the safety and efficiency of fishing. Other charts showing 3-and 5-day sea ice forecasts are also distributed daily in winter. Both types of charts are issued by radio facsimile from the U.S. Coast Guard Station at Kodiak, Alaska.

Ocean color boundary charts have been produced experimentally from CZCS data since 1981 in a NASA/Jet Propulsion Laboratory program (Montgomery, 1981). The charts delineate strong gradients in the blue/green color ratio (channel 1/channel 3 radiance). In 1983, charts were produced at almost weekly intervals from May to October (18 charts total), covering coastal areas up to 700,000 km^2 between Vancouver Island, B.C., and Guadalupe Island, Mex. (Fig. 12). A chart was produced only when a large, cloud-free area was located in a Nimbus-7 pass. The chart was then broadcast on the same or following day to fishing boats by radio facsimile from Point Reyes and La Jolla, Calif. Color photographs of the satellite images were distributed by express mail to various fishing ports and to Sea Grant marine advisors in daily contact with fishermen. The color boundary charts and photographs are used by albacore and salmon fishermen. These fish are sometimes found aggregated along color fronts which do not correspond to temperature fronts.

Conclusions

Satellites have altered our perceptions of the ocean environment through the extensive spatial coverage, temporal continuity, and high resolution of the data they provide. Limited, but useful, applications to several types of problems in fisheries research and operations have been demonstrated. Continued development of these and other applications will depend on inexpensive and convenient access to data and data-processing facilities. Recent trends in the federal budget have not been encouraging. For instance, there are no current prospects for a new ocean color scanner to replace the aging CZCS on Nimbus-7. The commercial utility of satellite data depends largely on near real-time availability to fishermen and other maritime users. In the future, this demand may be met by processed satellite data products tailored more to particular user needs.

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