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Remote Sensing Techniques for Fisheries Oceanography: Examples from British Columbia

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Abstract

During the summer of 1981, an oceanographic study was conducted in conjunction with a major study of the British Columbia troll fishery for coho, pink and chinook salmon. This paper briefly describes the aircraft and satellite remote-sensing techniques used to define sea-surface temperature and water color, and the sea-surface measurements obtained in suport of the remote observations. A time-lapse radar-mounted camera provided continuous monitoring of the number and distribution of fishing vessels for comparison with remotely observed oceanographic features such as discontinuities. Examples of remote-sensing data and analyses are presented and briefly discussed in relation to the distribution of the fishing fleet and available oceanographic data. The difficulties and utility of the application of these techniques are also outlined.

Introduction

All fish have preferred environmental conditions under which they function best, i.e. conditions which keep them healthy, maximize their feeding success and allow them to successfully avoid predators. These preferences or requirements may at times exhibit themselves strongly enough to stop or alter movements in heterogeneous coastal conditions. Diversions or delays of migrating salmon can have important effects on their spawning success and can cause severe problems for fishery managers. Whereas some types of physio-chemical boundaries or fronts can have adverse effects, other types of fronts may lead to strong growth of phytoplankton and aggregations of zooplankton and small fish. In the ocean, as in other environments, aggregations of food organisms are important sources of food for foraging animals. Salmon and other fish often gather along such boundaries to feed, and knowing where such aggregations are likely to occur is important for fishery managers.

The study described here was part of a pilot project to investigate the relationship between the ocean environment and the distribution of pink salmon, *Oncorhyncus gorbuscha*, coho salmon, *O. kisutch*, and chinook salmon, *O. tshawytscha*, in the coastal zone off southern Vancouver Island, British Columbia, Canada. One object was to describe the near-surface oceanographic conditions as completely as possible, using several new techniques and avenues of obtaining data to reduce the cost involved. This report is presented as an example of a remote-sensing program with a fisheries application.

Components of the Monitoring Program

There were four principal components of the oceanography study in the area off Vancouver Island, as summarized in Table 1.

Satellite imagery

Satelite imagery of the study area, acquired by the U. S. NOAA-6, NOAA-7 and NIMBUS-7 satellites, was obtained for cloud-free days from Scripps Institute of Oceanography Remote Sensing Facility, La Jolla, California. The data were geometrically corrected and autoregistered to the Mercator projection. The infrared imagery thus obtained from the AVHRR (Advanced Very High Resolution Radiometer) aboard the NOAA satellites provided sea-surface temperature data accurate to approximately 0.5° C with a 1.1 km resolution (e.g. Fig. 1A).

The Coastal Zone Color Scanner (CZCS) aboard NIMBUS-7 was designed to measure phytoplankton chlorophyll concentrations using the upward flux of blue-green light from the sea, and the imagery is currently the subject of a great deal of work aimed at

TABLE 1. Summary of parameters measured and data sources for oceanographic study off British Columbia.

Parameters	Platform	Sensor and/or measurements	Coverage	Spatial resolution	Frequency
		Satellite Derived			
Water color in 5 spectral bands. Chlorophyll content and turbidity calculated	NIMBUS-7	Coastal Zone Color Scanner	Entire coastal zone from 955 km altitude	0.8 km	3 days of 5
Sea-surface temperature	NOAA-6 NOAA-7	Advanced Very High Resolution Radiometer	Entire coastal zone from 820 km altitude	1.1 km	4/day
		Aircraft Derived			
Water color at 2-nm intervals between 400 and 1,100 nm. Chlorophyll content and turbidity calculated	Britain Norman Islander aircraft	Inst. of Ocean Sciences Color Spectrometer	Zig-zag survey pattern to 50 km from coast at 90 m altitude	100 m	2 or 3 times during project
Sea-surface temperature	"	Barnes Precision Radiation Thermometer (PRT-5)	"	200 m	
Frontal boundaries, vessel number, position and type	"	Visual observations	"		
		Surface Vessels			
Surface temperature, salinity, chlorophyll concentrations, Secchi transparency and water color, vertical temperature profiles	Canadian Fisheries Patrol Vessels	Surface water samples, expendable bathythermographs	2 lines of 6 stations to a point 50 km offshore and back	stations 10 km apart	every 2 weeks
Surface temperature, chlorophyll concentration and water color; catch by number, species and size of fish; fish samples for ageing, stock identity, etc.	Trolling fishboats	Surface water samples, fish catch logbook records	Everywhere along the coast where fishing occurred		3/day, 15 May-31 Sep
		Land Based			
Distribution, number and movement of vessels within study area (for comparison with oceanographic and other data)	Coast Guard Vessel Traffic Radar	Time-lapse film of S-band radar screen	100 km radius from radar installation of 700 m mountain near the coast		Picture every 5 min May-Oct
Sea-surface temperature and salinity	Coast Light Houses	Surface water samples	6 stations at 40-60 km intervals		1/day
Sky condition, visibility wind speed and direction, sea swell	"	Weather observations	"		every 4 hr

improving the calculations involved (Clark, 1981; Gordon, 1981; Sturm, 1981; Gordon *et al.*, 1980). The calculations have been greatly simplified in this study by applying sensor-gain corrections, an air-water transmission factor, and a variable empirical Rayleigh scattering function, so as to maximize the correlation between surface and spacecraft data. Agreement to within ±30% was obtained in situations where adequate sea-surface chlorophyll data were available over the full range of imaged concentrations (e.g. Fig. 1B). Where no sea-truth data were available, the CZCS data were used in a quantitative fashion only to map the most important water mass boundaries such as that separating the green coastal water from the relatively barren oceanic waters offshore.

Airborne surveys

Low altitude airborne surveys were also conducted. The Institute of Ocean Sciences (IOS) Colour Spectrometer (Walker *et al.*, 1975) and a Barnes PRT-5 Radiation Thermometer were used at 90 m altitude in a twin-engine Britain Norman Islander aircraft. These non-imaging devices provided quantitative measurements along the track of the aircraft. The IOS Spectrometer uses an array of silicon diodes to measure water color and *in vivo* fluorescence by which surface concentrations of the phytoplankton pigment chlorophyll *a* can be quantified (Gower, 1980). The PRT-5 uses infrared radiation from the sea surface to measure water temperature. Data from these sensors, while

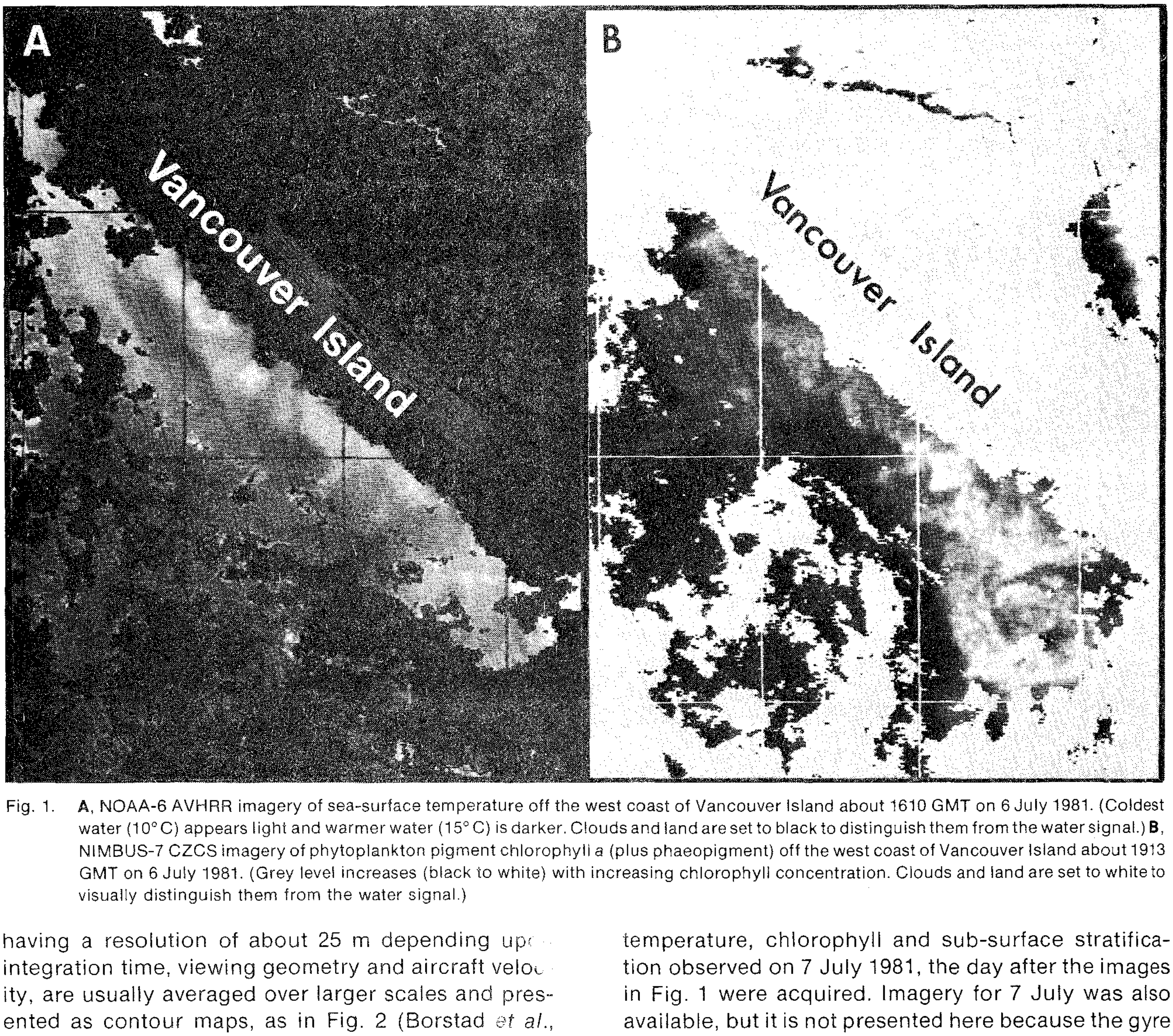

Fig. 1. **A**, NOAA-6 AVHRR imagery of sea-surface temperature off the west coast of Vancouver Island about 1610 GMT on 6 July 1981. (Coldest water (10° C) appears light and warmer water (15° C) is darker. Clouds and land are set to black to distinguish them from the water signal.) **B**, NIMBUS-7 CZCS imagery of phytoplankton pigment chlorophyll *a* (plus phaeopigment) off the west coast of Vancouver Island about 1913 GMT on 6 July 1981. (Grey level increases (black to white) with increasing chlorophyll concentration. Clouds and land are set to white to visually distinguish them from the water signal.)

having a resolution of about 25 m depending upon integration time, viewing geometry and aircraft velocity, are usually averaged over larger scales and presented as contour maps, as in Fig. 2 (Borstad *et al.*, 1980).

Sea-surface data

Sea-surface data, for comparison with and calibration of remotely-sensed data, were obtained from several vessels operating in the study area. At approximately 2-week intervals, a patrol vessel of the Canadian Department of Fisheries and Oceans made two 75-km transects to the edge of the continental shelf (Fig. 2). At 12 stations along these transects, surface temperature, salinity, chlorophyll concentration and Secchi disc transparency were measured. Water color was qualitativity described by comparing the apparent color of the Secchi disc at half its "disappearance depth" to a series of color standards available from Munsell Colour Company, Newburgh, New York, after the method of Austin (1980). Vertical temperature profiles were obtained by using expendable bathythermographs (XBT). Figure 3 illustrates the surface temperature, chlorophyll and sub-surface stratification observed on 7 July 1981, the day after the images in Fig. 1 were acquired. Imagery for 7 July was also available, but it is not presented here because the gyre at the mouth of Juan de Fuca Strait was partially obscured by cloud.

In addition to the repetitive observations made from the patrol vessels during the study period, approximately 1,200 measurements of water temperature and color were made by 12 fishery observers aboard trolling boats in conjunction with extensive notes and measurements of fish caught (species, size, age, stomach contents), thus allowing comparison of fishery statistics, such as catch-per-unit-effort, with oceanographic parameters. Oceanographic observations were made 3 or 4 times each day and fish records were accumulated for 4 to 6 hr periods. Secchi disc transparency and chlorophyll concentrations were measured less frequently from these small trolling vessels. The simple water color observations provide estimates of surface chlorophyll concentration with an accuracy of '50%.

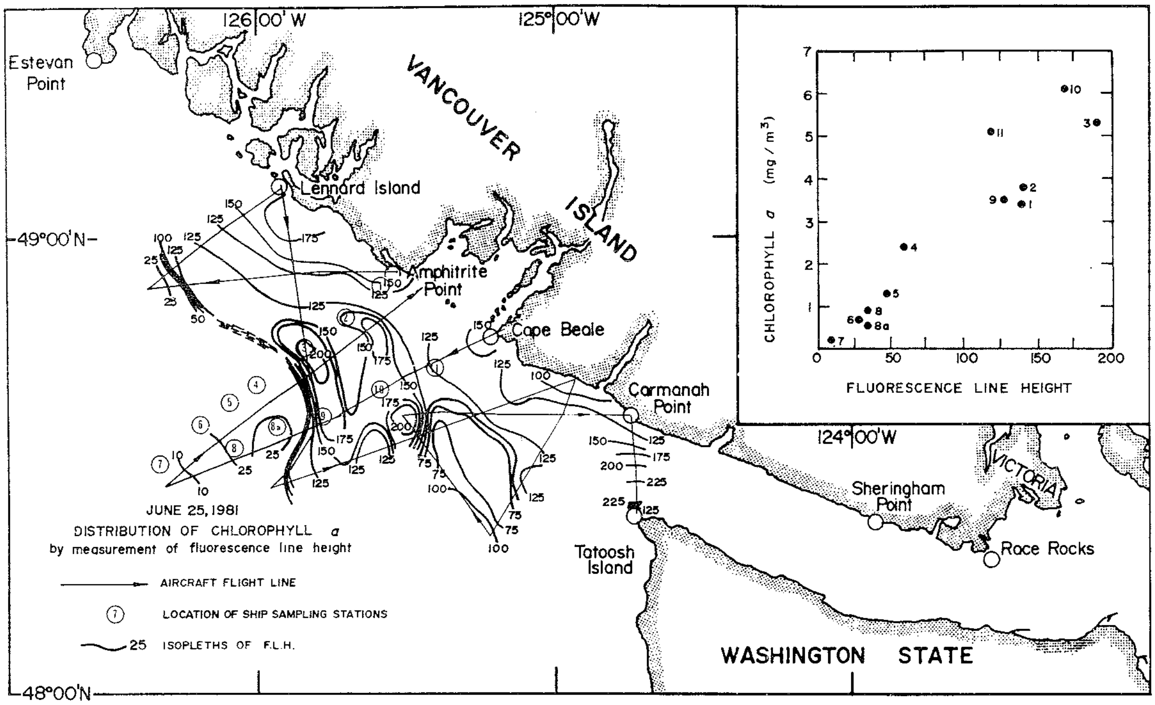

Fig. 2. Distribution of phytoplankton pigment chlorophyll *a* off the west coast of Vancouver Island on 25 June 1981 from airborne radiometer measurements of *in vivo* fluorescence. (The inset compares airborne measurements with chlorophyll *a* in surface samples taken on the same day.)

Land-based measurements

The distribution, number and movement of fishing vessels within the study area were recorded via a time-lapse motion picture of a radar screen covering the area off southwestern Vancouver Island from the Canadian Coast Guard Traffic Management installation near Amphitrite Point (see Fig. 4). Three or four consecutive images, taken at 5-min intervals, were projected onto map overlays and the positions of stationary and slow-moving, small vessels recorded. This allowed rejection of larger ocean-going ships and barges and provided continuous monitoring of vessel numbers, distribution and movements throughout the project. These data were compared with available satellite, aircraft and ship data in an attempt to relate fishing activity with oceanographic conditions such as frontal boundaries, water color and temperature as well as bottom topography. The data were also used to describe the behavior of the fishing fleet as it related to weather conditions and to fisheries management.

Results and Discussion

One of the objectives of this project was to investigate the extent to which remotely-sensed data could be used to provide a continuous coherent description of surface oceanographic conditions over large areas

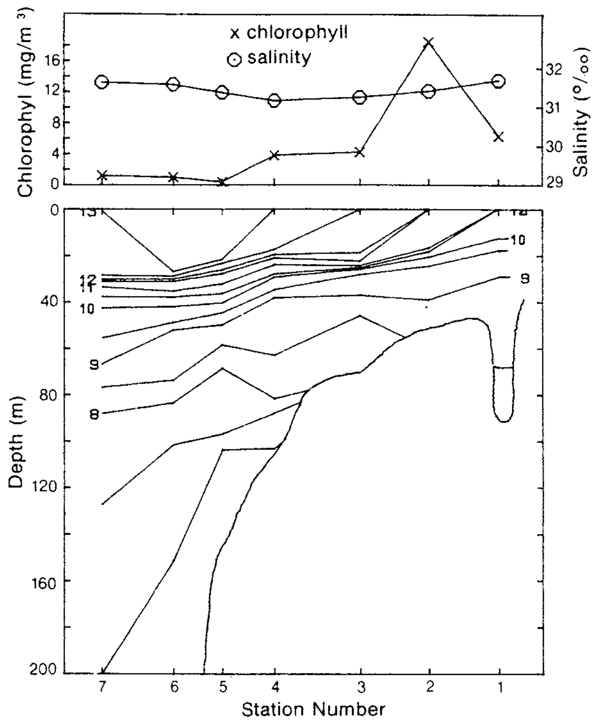

Fig. 3. Surface salinity, chlorophyll concentration and vertical temperature structure for a transect off Amphitrite Point, Vancouver Island, on 7 July 1981. (Note the uplifting of the isotherms over the continental shelf. Station positions are indicated in Fig. 2.)

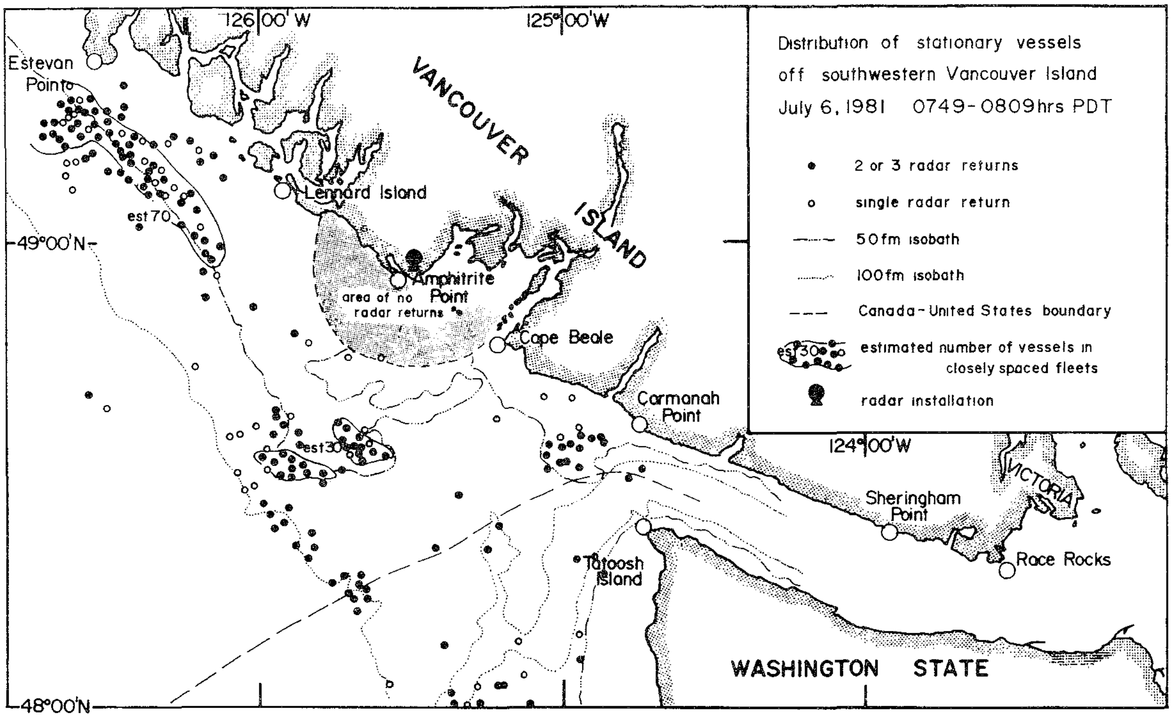

Fig. 4. Distribution of fishing vessels off southwestern Vancouver Island about 1500 GMT on 6 July 1981, derived from time-lapse photography of radar returns to the Coast Guard Vessel Traffic Management facility near Amphitrite Point. (This was the distribution of vessels near the time of the satellite images shown in Fig. 1.)

of the continental shelf off British Columbia. There was interest also in relating the distribution of fishing effort to oceanographic parameters such as water color (as a measure of phytoplankton concentration), temperature and water mass boundaries or discontinuities. Because of the large area and the very complicated distributions involved, spacecraft imagery was considered essential.

Satellite imagery

Satellite imagery has the advantage of providing instantaneous synoptic pictures of large areas not possible by other practical means. However, the availability of good quality imagery can pose a problem for seasonal or short-term studies, especially in cloudy areas such as the Canadian west coast.

The number of images obtained for this study was a function of several factors. For NOAA-6 and NOAA-7 satellites, both of which make two passes over the area every day, the limiting factors were fog or cloud coverage, the hours of operation of the Scripps Remote Sensing Facility (where data are not normally acquired on weekends unless specially requested), and the time required to search the Scripps data archives. This last problem is expected to be alleviated soon with the completion of a quick-look facility. In addition, the 2-hr-per-day on-board power limitation on NIMBUS-7 CZCS operation means that the sensor is turned off and on by NASA operators. As a result of these limitations, for the 99-day period from 1 May to 7 August 1981, the Scripps archives contained only 70 NOAA-6 images, 20 NOAA-7 images and 38 CZCS images of the study area. In a 36-hr period of operation on the Scripps Remote Sensing Facility computing system, data for 32 days (45 images) were viewed. From these data, only 12 good NOAA images and 7 CZCS scenes of the study area were obtained (2 days in May, 2 days in June, 5 days in July, and 3 days in early August.

This coverage is quite adequate to describe the evolution of large, long-lived features, such as a large cold-water plume extending offshore from the Juan de Fuca Strait between Vancouver Island and Washington State (Fig. 5). In 1981, this plume moved out of the Strait very quickly at the end of June and, impinging on a southerly flow near 126°W, it turned southward to form a cyclonic gyre, which remained visible during July and early August. Cyclonic circulation in this region has been described by others using conventional oceanographic techniques (Tully, 1942; H. J. Freeland, Institute of Ocean Sciences, Sidney, B. C., pers. comm.). A direct relationship between surface temperature and nutrient concentration in these waters was shown by Borstad et al. (1980). The fact that the cold nutrient-rich water exiting Juan de Fuca Strait is held close to the coast may be important to the fishery, because the high primary production resulting

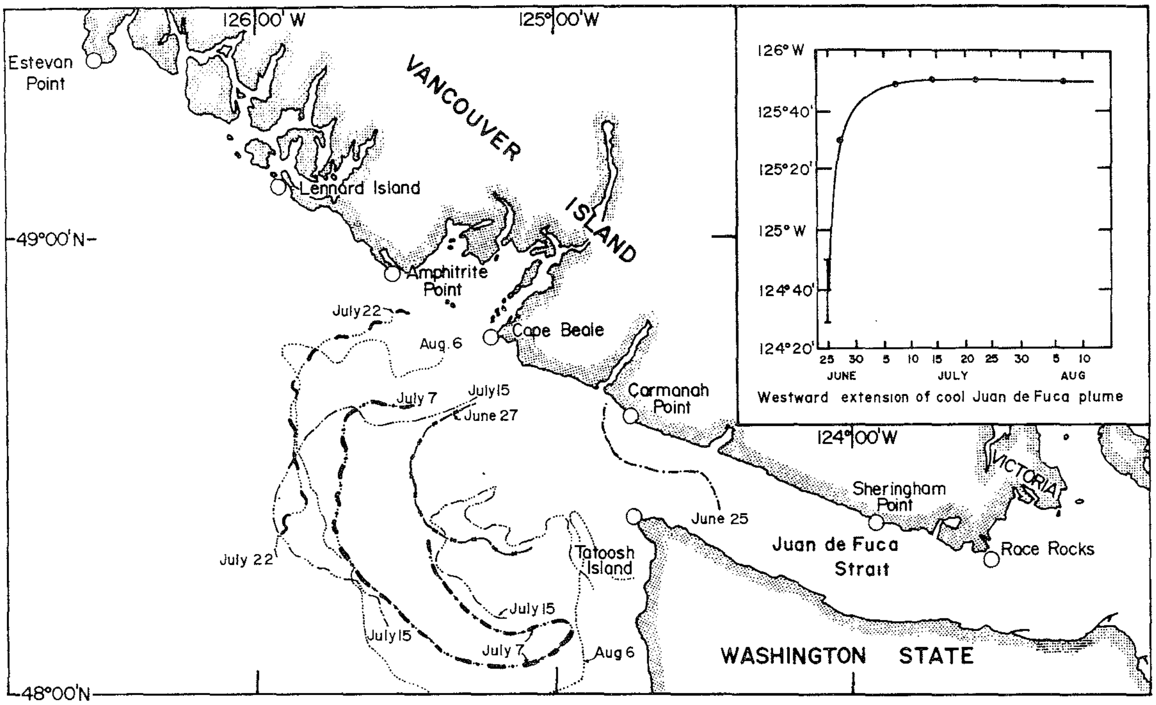

Fig. 5. Westward extension during the summer of cool water exiting Juan de Fuca Strait near the end of June 1981, as indicated by a series of NOAA-6 AVHRR and NIMBUS-7 CZCS imagery.

from stratification of the water should ultimately provide abundant food at higher trophic levels. Note the large chlorophyll concentrations in this area in Fig. 1B. The cold-water plume outlined in Fig. 5 is partially obscured in Fig. 1A (6 July) because of cloud, but a narrow east-west band of colder (light) water coincides with the low chlorophyll (dark) band in Fig. 1B which curls westward and then south. This is cold nutrient-rich water which has not yet stabilized.

Where imagery is available for consecutive days, it is possible to examine the movement and deformation of water mass boundaries such as those in the vicinity of 49° N, 126° W (Fig. 6) and relate those to the distribution of vessels in Fig. 4. This comparison is for a 24-hr separation, but it is also possible for 6-hr separations using the NOAA-6 and NOAA-7 satellites.

Aircraft surveys

Aircraft can be used to survey coastal areas, but the data are rather different from photograph-like satellite products. The aircraft surveys, although being non-imaging and limiting in coverage by the endurance of the aircraft and its occupants, do compare favorably with satellite imagery for several reasons. Firstly, the aircraft surveys can usually be conducted under overcast or cloudy conditions, such as commonly exist along the Pacific coast. Consequently, large field experiments involving airborne sensors will not be affected by poor weather as often as those depending solely on satellites. Secondly, the aircraft

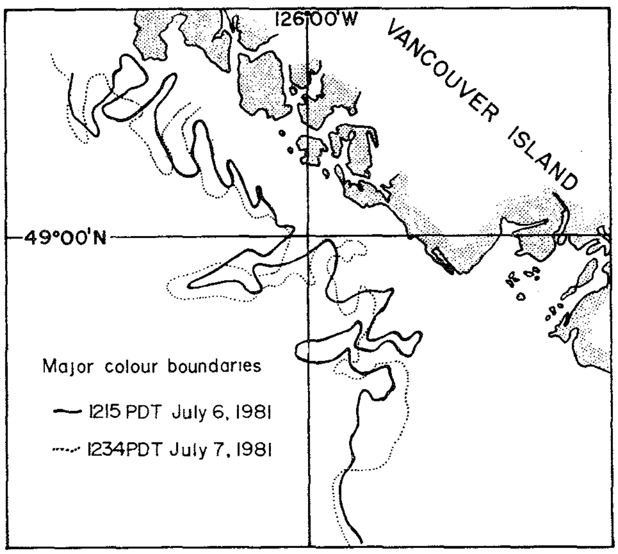

Fig. 6. Position of the major water color boundary off western Vancouver Island on 6 and 7 July 1981, as observed from consecutive CZCS images.

provides a platform from which visual observations may be made of parameters other than those measured by sensors: number, type and activity of fishing vessels; concentrations of flotsam and jetsam along frontal boundaries; sea state including estimates of wave height and direction; concentrations of birds, mammals and large medusae. A third positive feature of aircraft surveys is that they are more flexible than those utilizing satellites. Since the aircraft is under the control of the local project scientist, it is easier to obtain coincident comparative 'sea-truth' data. It is also possible to direct surface vessels from the aircraft and give the ship scientist an invaluable perspective of the position of temperature and water color boundaries.

Sea-surface measurements

If data from satellite or airborne sensors are to be used in a quantitative sense, surface measurements are required for several locations within the area of coverage. Both types of remote measurements suffer from atmospheric contamination of the signals. However, simple empirical corrections based on theory and sea-surface measurements allow estimation of chlorophyll pigment concentrations from CZCS data. Good accuracy can be obtained from aircraft surveys by flying at low altitudes to reduce atmospheric effects.

In airborne experiments (Gower, 1980; Borstad *et al.*, 1980), water color measurements under most conditions were found to relate closely to chlorophyll concentration in the 1-2 m surface layer. For this reason, the shipboard measurements for this project were reduced to surface samples and XBT, which could be obtained from a moving vessel. Simplifying the shipboard data-collection procedures permitted the use of unspecialized vessels, such as fisheries patrol vessels, and thus increased the number of transects possible. Therefore, the time series of surface sampling, which is not often possible because of the difficulty in obtaining adequate time on research vessels, permitted a description of an upwelling event which was observed by satellite in early July 1981 along the west coast of Vancouver Island (Fig. 1A). The transects perpendicular to the coast provided more satisfactory sea-truth data than earlier attempts to collect surface data for this purpose by using ships-of-opportunity moving parallel to the coast (Borstad *et al.*, MS 1980). In the latter case, the ships did not often encounter a wide range of chlorophyll concentrations.

It is now considered that fisheries observers provided only fair quality data for associating fish catch statistics with water temperature and color because of extreme spatial heterogeneity in the study area. It was not always possible to use this information for calibration of satellite imagery. Not all observers were at sea at one time, and, if one or two observers were at sea on the day when a satellite image was acquired, they were sometimes outside the study area, outside the imaged area, under localized cloud, or located close together in water of the same color or temperature.

Land-based radar

The time-lapse camera was mounted on a small, seldom-used maintenance display screen so as not to disturb the normal operations of the Coast Guard Vessel Traffic Management staff. The microprocessor controller and the 16-mm Bolex camera functioned very well and provided good quality images after determining optimum exposure and aperture parameters. However, since the time-lapse camera on the maintenance display screen was unmanned, problems encountered in this part of the study related mostly to variability associated with fluctuations in the power supply and with alterations of signal strength, repetition rate and pulse length by Coast Guard operators. For some combinations of operating and environmental conditions, rain and sea clutter were extensive. Because of these difficulties, data were not always available for all parts of the study area, and statistical analysis at regular short-term intervals was not possible. Comparison of radar-derived vessel distribution maps, such as Fig. 4, with visual counts on the same day by military surveillance aircraft indicated that the radar-derived vessel counts were only 30–70% of those recorded by airborne observers. This accuracy could be substantially improved by having a technician at the radar installation to insure optimal adjustment of the radar display unit. However, even with optimal image adjustment and wide-pulse radar beam, it is likely that the fleet size would still be underestimated by as much as 50%. This problem is partly related to the size and construction of the fishing vessels, some being small wooden boats with no radar reflectors. If these vessels are assumed to be randomly distributed within the study area, airborne counts can be used to calculate the radar imagery.

Despite the problems with the time-lapse radar photography, the available information indicates large fluctuations in the amount and distribution of fishing effort within the study area during the summer. Radar-derived distribution maps, such as Fig. 4, indicate frequent concentration of vessels at particular locations, apparently related to the bottom topography, on the shallow banks or along the bank slopes. In addition to these concentrations at "favorite spots", there were other aggregations of vessels which appear to be associated with color or temperature boundaries, such as the large fleet along the 50-fath (90 m) isobath between Estevan Point and Lennard Island on 6 July 1981 (Fig. 4). These correlations and previous airborne observations confirm that some fishing effort does occur near such discontinuities. Studies are now required to see if this relationship can be found over larger areas using satellite imagery and radar-derived data. The oceanography of the "favorite spots" should also be investigated in some detail.

All of the data for this project were analyzed over periods of days to months after collection. This is usually sufficient for research purposes, but real-time operations will be required for in-season fisheries management dependent on remote-sensing techniques. However, such management of Canadian fisheries will have to await readily accessible receiving stations. More importantly, use of remote-sensing technology by fisheries scientists and oceanographers presupposes the continued existence of appropriate statellite sensors, but expensive space programs in many countries are in danger of being reduced due to budgetary restraints.

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