USE OF AIRBORNE RADIOMETERS FOR MONITORING SEA SURFACE TEMPERATURE AND CHLOROPHYLL IN A COASTAL FISHING ZONE

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ABSTRACT

The need for monitoring the rapidly changing coastal marine environment and using this information in the assessment of a coastal fishery such as the California anchovy is noted. Previous measurements of sea surface temperature and relative chlorophyll concentration suggest that these are two important biological parameters that can be rapidly obtained in a synoptic fashion from a suitably equipped aircraft. Experimental flights with a twin engine Beechcraft Travel Air aircraft equipped with a modified precision radiation thermometer (PRT-5) infrared radiometer and a dual channel differential radiometer (DCDR) for ocean color were made on several occasions in late 1974, and the results from the 4 and 9 October flights are briefly described. Analysis of these flight data suggest that by careful evaluation of the strip chart records, statistically significant relationships can be obtained between both remote sensors. While quantitative results depend upon reasonably frequent ground-truth observations for both radiometers, particularly the DCDR instrument, a rough conversion to mg chlorophyll/m^3 for the DCDR was made based on limited surface chlorophyll *a* measurements and published calibration curves. The results suggest that when the design constraints of the DCDR instrument are recognized and the instrument is used in conjunction with the PRT-5 radiometer the paired radiometers offer considerable potential for monitoring two biologically important parameters in a coastal fishing zone.

RESUMEN

Se indica que es necesario supervisar los cambios rápidos que se presentan en el ambiente marino costero y usar esta información en la pesca superficial, como es la pesca de la anchoveta californiana. Las medidas tomadas anteriormente de la temperatura superficial del may y, de la concentración relativa de clorofila indican que estos son dos parámetros biológicos importantes que pueden obtenerse rápidamente de una manera sinóptica desde un avión equipado convenientemente. A fines de 1974 se realizaron en varias ocaciones vuelos experimentales con un bimotor Beechcraft Travel Air, equipado con un radiómetro modificado infrarojo PRT-5 y un radiómetro diferencial de doble banda (Dual Channel Differential Radiometer [DCDR]) para obtener datos sobre el color del océano, y se describen brevemente los resultados de los vuelos realizados entre el 4 y 9 de Octubre. El análisis de los datos de estos vuelos indican que al evaluar cuidadosamente los registros del aparato de banda, se pueden obtener relaciones estadísticamente significativas entre los dos sensores remotos. Aunque los resultados cuantitativos dependen de las observaciones terrestres reales, obtenidas con frecuencia razonable de ambos radiómetros, especialmente del instrumento (DCDR), con respecto a este instrumento se hizo una conversión preliminar a mg de la clorofila/m^3 basadas en medidas limitadas de la clorofila *a* en la superficie y de publicaciones de las curvas de calibración. Los resultados indican que cuando se reconocen las limitaciones del trazado del instrumento DCDR y se usa éste junto con el radiómetro PRT-5, los dos radiómetros ofrecen un potencial considerable para la supervisión de los dos parámetros biológicamente importantes en una zona costera de pesca.

INTRODUCTION

Both coastal fisheries and pelagic fisheries respond to changes in the environment, but coastal conditions may frequently undergo greater changes than conditions in the open ocean. The famous anchovy (*Engraulis ringens*) fishery off Peru is located in a coastal upwelling regime where horizontal surface temperature gradients of 3°C/50 km may occur and give rise to fluctuations in the phytoplankton populations and corresponding surface chorophyll gradients of 3 mg/m^3 (Beers et al. 1971). Higher trophic levels such as the anchovy are in turn dependent upon the standing crop of the phytoplankton. An adequate understanding of the presence and variability of a regional coastal fishery, then, depends upon the scientists' ability to monitor the rapidly changing environment and to determine how coastal fish stocks respond to these changes in the environment.

Two of the more important parameters used to monitor the marine environment are surface temperature (may indicate relative intensity and duration of upwelling) and chlorophyll (estimates standing crop of phytoplankton). In principle it would be desirable to make weekly, if not daily, ship surveys of the coastal zone to monitor these and other important parameters. In most instances, however, ship time is expensive and, therefore, limits such surveys to several-day cruises. A method that can rapidly scan a long coastal zone and provide environmental data of reasonable accuracy would represent an optimum method of obtaining the needed environmental information in order to make indirect assessment of some fish stocks of the coastal waters. Stevenson and Miller (1974) have correlated tuna fish catch with sea surface temperature in a region 1800 km west of California, although cloud cover was a problem. Intervening clouds may be more of a problem in coastal zones, and in those regions a low-flying aircraft using remote sensors may be ideally suited for the job.

Airborne survey flights to assess apparent fish abundance have been made commercially for a number of years. Squire reports (1972) that it is feasible to estimate fish school tonnage from commercial spotter aircraft flights over the coastal zone of California from the Los Angeles Bight south to the Mexican border. Squire's study is based on more than 17,000 flight hours made during 1962-69. More recently Squire has made survey flights to monitor sea surface temperature patterns for correlation with change in catch and catch rates for several coastal species. Sea surface temperatures were determined with a Barnes' PRT-5 radiometer from an aircraft. Arvesen et al. (1973) have developed an extremely compact instrument for detecting changes in ocean color, the dual channel differential radiometer (DCDR). He has flown the DCDR and PRT-5 radiometer off the California coast where, during an offshore transect, he obtained an inverse pattern between sea surface temperature and chlorophyll concentration.

During September-October 1974, a visit was made by Professor Ikeda to the Inter-American Tropical Tuna Commission (IATTC) headquarters, at the National Marine Fisheries Service (NMFS) Laboratory in La Jolla, to investigate methods of using airborne and spacecraft data in the field of fishery oceanography. After some discussions by the first two authors with Ikeda, several instructional/experimental flights using the NMFS PRT-5 radiometer were made off the southern coast of California. It then came to our attention that Dr. Arvesen's DCDR ocean color radiometer was on loan to Mr. Booth of the Institute of Marine Resources (IMR), and we invited Mr. Booth to participate in joint flights where both the DCDR and PRT-5 instruments might be flown together.

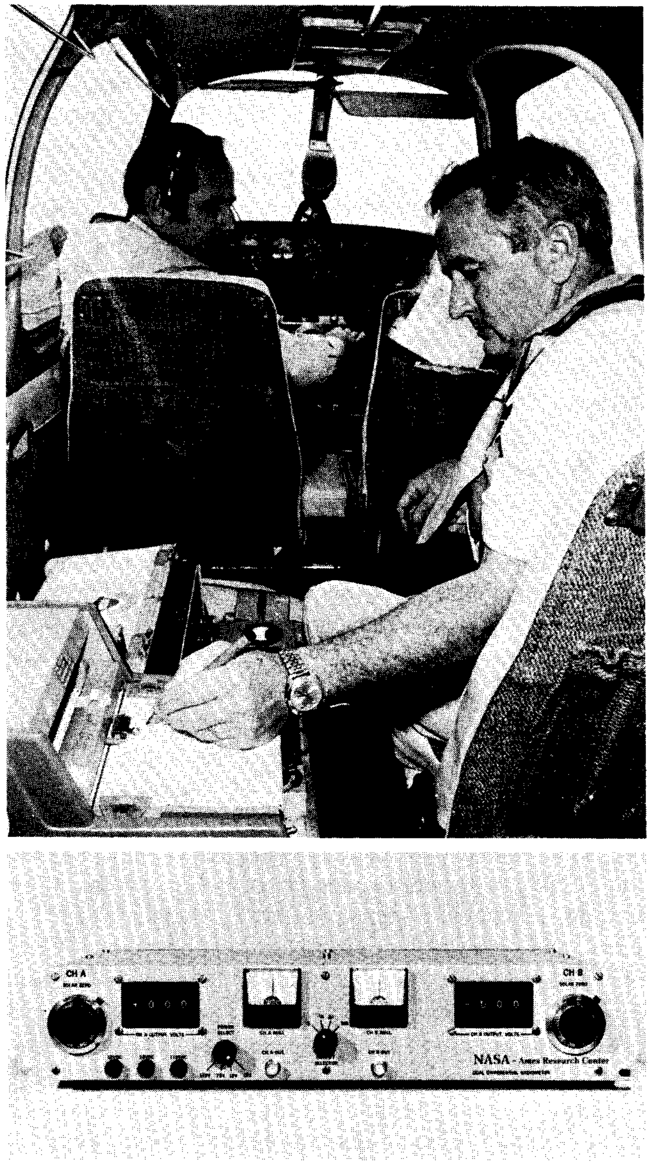

Figure 1. (Upper) Modified precision radiation thermometer (PRT-5) mounted in aircraft. Scientific observer sits in opposite seat to make time and position annotations on charts produced by the PRT-5, and the (lower) dual channel differential radiometer (DCDR).

INSTRUMENTS AND METHODS

Two radiometers were used from the aircraft normally chartered by NMFS for its sea surface temperature survey flights, etc. (Figure 1). The NMFS instrument, a modified PRT-5 radiometer equipped with a 10.5-12.5 micron filter, together with a strip chart recorder and power supply, were mounted to a miniature instrument rack. The rack was attached to the positioning frame of a passenger seat in the rear of the plane after the seat had been removed from the aircraft. The access port for instruments was located directly behind the rear cabin bulkhead and was reached by removal of the bulkhead prior to the flights.

The DCDR instrument was developed by Dr. John Arvesen of the NASA/AMES Center and was available through his courtesy for field experiments. Because a detailed description of the system's specifications is found in Arvesen et al (1973), only a brief explanation is given here. The DCDR is a rack-mounted, all solid-state instrument and requires a conventional strip chart recorder for output. The color sensor consists of a wide-angle field of view lens cemented to one end of a fiber optics cable. The fiber optics bundle is split at the other end into four smaller bundles. Each of these is arranged so that the emerging light passes through a narrow band interference filter and strikes a silicon diode detector. The chlorophyll sensing is accomplished by use of two of these detector-filter combinations. One combination uses a 525-μm band-pass filter for the reference signal as this is the wavelength region of minimum attenuation due to chlorophyll. The other detector-filter combination has a 443-μm band-pass filter which is an absorption maximum for chlorophyll *a*. The ratio of the light from the fiber optic bundle striking these detector-filter combinations is calculated by the instrument and displayed on a strip chart recorder. During an experiment the probe is pointed downward at an angle (approximately 15°) to minimize the reflected glitter on the ocean surface. The probe is occasionally pointed at or toward an unobstructed view of the sun during each flight, and the DCDR instrument's gain is normalized at that time. For the experiments described in this paper, the PRT-5 instrument rack was modified to accommodate the DCDR instrument and a Hewlett Packard Mosley strip chart recorder. The power for both PRT-5 and DCDR instruments was obtained from the aircraft's electrical generators. For simultaneous operation of the two radiometers, a cylindrical flange was made and attached to the circumference of the access port so that the narrow beam PRT-5 sensor head was axially aligned through the port. Special slots were cut into the flange to accommodate the DCDR probe. While the two probes were not exactly coaxially aligned, the wide-angle field of view of the DCDR probe assured adequate overlap of the viewing targets of the two radiometers.

The principal problem with the DCDR is its dependence on constant solar illumination of the sea surface. This problem has two parts. First, atmospheric conditions must be uniform over the flight path so that the spectral composition and intensity of the light incident on the sea surface remains constant. This drawback may be compensated for by repetitive standardization by viewing the sun with the probe. This limits flights to days with uniform clearness. The second problem arises when the airplane changes headings, thus changing the probe viewing angle relative to the angle of the sun and resulting change in the amount of back reflection or "glitter" from the sea surface. Efforts to compensate for this effect by changing the position of the probe are never wholly satisfactory. This effect tends to bias the signal to the null position, which corresponds to 1 mg/m^3 chlorophyll *a*. It is very difficult to correct for this effect on the present instrument, although we hope to make certain modifications in the future to reduce the instrument's sensitivity to glitter.

Calibration for the PRT-5 was provided by flying over the Naval Electronics Laboratory (NEL) tower located about 3 km offshore from San Diego. In previous flights with the NMFS PRT-5 instrument, Squire found the corrected airborne temperature data to be within 0.1-0.2°C of temperatures measured from the NEL tower. The calibration of the DCDR instrument was accomplished in a similar fashion. The DCDR does not provide readout directly in units of chlorophyll but rather in volts. To convert the volts into mg chlorophyl *a*/m^3, one or more surface water samples are collected beneath the flight path and chemically analyzed for chlorophyll *a* concentration, and the DCDR data are then converted from volts into chlorophyll units.

FIELD EXPERIMENTS

Because the time available to make the cooperative flights fell within the time frame of the NMFS sea-surface temperature survey flights, we decided to use the NMFS flight track to make simultaneous measurements with both radiometers. One observer sat in the starboard rear seat in order to operate the radiometer recorders mounted on the port side; a second observer sat in the copilot's seat and assisted with general flight operations. Flights using both PRT-5 and DCDR instruments were made on 4 and 9 October 1974. The same general flight plan was followed each time. Since the flight observations were also similar, only the October 4 flight will be discussed. The aircraft flew from a local San Diego airport over the coastal water at 150 m altitude starting at 1150 PDT, and the flight track was terminated at 1330 PDT after which the aircraft returned to the same airfield. During the flight the aircraft flew over the NEL tower twice to obtain sea surface calibration temperatures for the PRT-5 data. The DCDR uses a solar reference, and during cloud-free conditions, when properly normalized, provides a reasonably stable output signal. During the flight a calibration of the DCDR was conducted by twice passing over a boat where surface water sample was collected for chlorophyll *a* analysis. The boat was located about 1.5 km off the Scripps pier.

RESULTS

After the 3.5-hour flight, the strip chart records were checked for proper time and position annotations, and the charts were then manually digitized. PRT-5 data

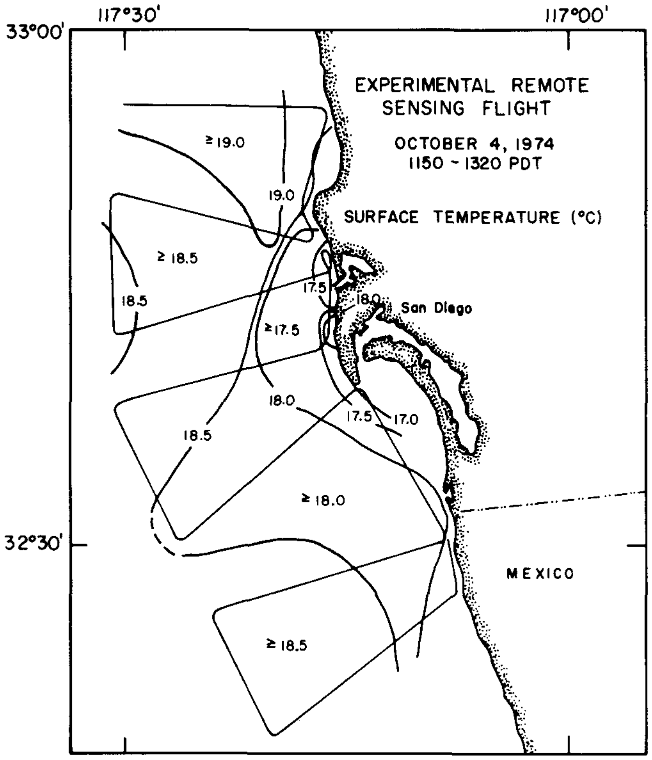

Figure 2. Sea surface temperature map for 4 October 1974, based on Barnes PRT-5 radiometer data. Blackbody thermal radiation is measured continuously as the aircraft moves along its flight path.

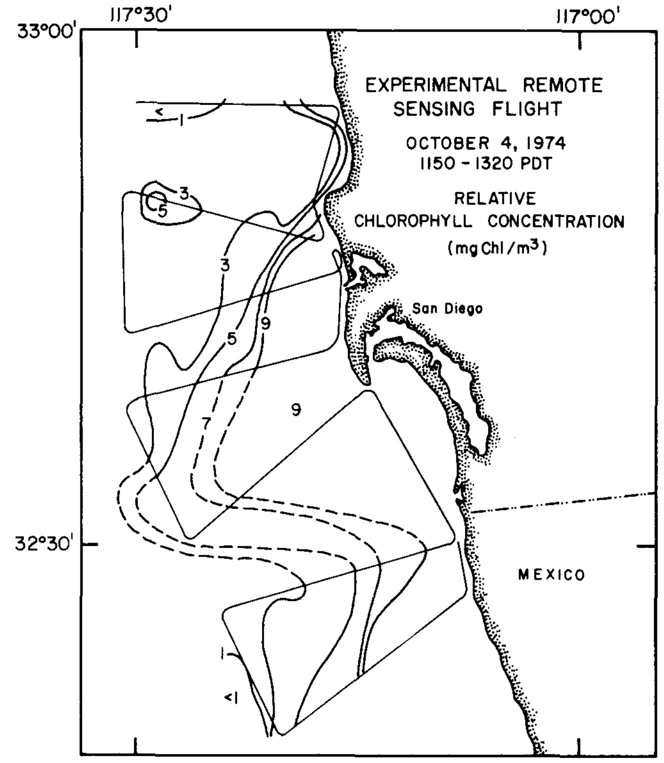

Figure 3. Relative chlorophyll concentration map for 4 October 1974, based on the DCDR ocean color instrument data. The intensity measurements of 443 μm ocean color, which change in response to chlorophyll concentration are referenced to 525 μm radiation, which undergoes minimal change due to the presence of chlorophyll.

were calibrated with the NEL tower temperature data, and the calibrated temperatures were used to construct a contoured map of the surface temperature shown in Figure 2. Ocean color data from the DCDR instrument was similarly digitized and calibrated with the surface chlorophyll measurements off Scripps Pier, and the data were used to construct the surface chlorophyll map shown in Figure 3.

For statistical purposes, the analog records were read at 1-minute intervals to form data pairs. A comparison of the PRT-5-derived surface temperatures and DCDR-derived Chlorophyll Index data (CI) obtains a correlation coefficient for the 4 and 9 October experiment of $r = -0.49$ and -0.60 ($P = 1\%$ level), respectively, and the following relationships:

$$\mathrm{CI} = -0.58T + 21 \text{ and}$$
$$\mathrm{CI} = -0.55T + 12.8$$

respectively, where the slopes are the conversion constants from Chlorophyll Index (volts) to surface water temperature. Analysis of the individual strip charts shows considerable "small structure," appreciable gradients in temperature that extend over distances of several hundreds of meters. Because one surface measurement of chlorophyll was made on 4 October, it was only possible to roughly calibrate the DCDR data. The result of the calibration is based on data from Arvesen et al. (1973) and for $0 < \mathrm{CI} < 3$ volts is

$$\text{chl } a = 0.58(\mathrm{CI} - 7.6)^2 + 1.2,$$

where 0.58 is the conversion rate from volts to 1.2-6.5 mg chl a/m^3 and 7.6 and 1.2 are voltage and recorder curve offsets. For lower concentration levels, i.e. $0.1 <$ chl $a < 1$ mg/m³, an approximate conversion is

$$\text{chl } a = 0.027\,(\mathrm{CI} - 1.4)^2 + 0.092.$$

It should be recognized that the conversion from Chlorophyll Index to chl *a* is only approximate unless the conversion can include the effects of non-chlorophyll suspended sediment and more calibration points.

Due to a lack of fish school sightings during the flights, it was not possible to compare locations of fish schools with thermal and chlorophyll fronts. Squire, however, has noted (manuscript 1975) that when albacore concentrations are present and observed off central California, they are often found on the seaward (warm) side of thermal fronts. Other studies, e.g. Stevenson and Miller (1974), have shown that tropical and subtropical tunas are frequently found along edges of pronounced thermal gradients or fronts. Because anchovy, at least in their early life, feed first upon phytoplankton and later upon zooplankton which in turn feed upon phytoplankton, it is important to make comparisons of apparent abundance of anchovy schools relative to concentrations of chlorophyll (phytoplankton). Aircraft surveys similar to those described in this paper may determine whether or not distribution of anchovy larvae and adult schools off southern California and Baja California is related to measurements made with infrared radiometry and airborne ocean color radiometer without the measurements of the intermediate zooplankton trophic level. Thus far no researchers have shown the feasibility of directly monitoring zooplankton by remote sensor. The question to be answered is whether or not information on zooplankton abundance must also be available or whether sufficient information about the presence of the anchovy can be obtained from aerial infrared and multispectral radiometry. Future airborne survey flights are needed to address this question.

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