

## Advances in Satellite Sea Surface Temperature Measurement and Oceanographic Applications

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Satellite techniques for measurement of sea surface temperature (SST) are reviewed briefly, and a discussion of satellite SST applications and recent research in oceanography is provided. These applications include the areas of climate, mesoscale oceanography, and fisheries. Examples given focus mainly on the Pacific and California Current regions. Satellite SST data are currently used operationally for fisheries applications and, in conjunction with in situ data, are providing new insights into mesoscale oceanographic phenomena. Requirements for sensor precision and calibration accuracy are more stringent in air-sea interaction studies and climate research, thus satellite data have gained only qualified acceptance for these applications. Improvements in future satellite instruments, more comprehensive in situ sensor deployments, and better data management procedures should eventually satisfy most oceanography and climate SST requirements.

### 1. INTRODUCTION

From the early days of satellite environmental remote sensing, efforts have been made to measure sea surface temperature (SST) from space with scientifically useful accuracy. The synoptic view from space allows SST to be mapped globally in regions where ships and in situ measuring devices are sparse or nonexistent. Furthermore, the coverage can be complete and frequent, enabling the motion of current eddies and meanders to be studied in detail. Nevertheless, it had to be demonstrated that the measurement accuracies and spatial and temporal resolutions available from satellites were adequate for the specific applications in which the data were to be used. Some generations of instruments later, the process of evaluating the scientific usefulness of satellite-derived SST's is still in progress. However, the satellite instruments and algorithms are now considerably improved, the scientific applications and requirements are much better understood, and the potential benefits of satellite observations have been widely recognized.

In this paper we present some of the major applications and requirements for satellite SST data, discuss how the satellite instruments have evolved to meet these requirements, and outline where improvements to SST data processing and assimilation procedures are needed. For convenience the applications have been separated into the broad areas of climate, mesoscale oceanography, and fisheries. Put together, these cover the full range of temporal and spatial resolutions for which satellite data are required and illustrate the accuracies needed for research and operational purposes. A more general review of applications of satellites to oceanography has been provided by *Brown and Cheney* [1983].

### 2. SATELLITE INSTRUMENTS

Early environmental satellites of the 1960's carried infrared radiometers primarily for mapping nighttime cloud cover and

estimating cloud heights. In the absence of clouds the infrared measurements provided useful estimates of the earth's surface temperature [*Rao et al.*, 1972]. With present-day infrared radiometers, highly accurate ( $\sim 0.5$  K) measurements of SST are possible if the atmosphere is clear, but the opacity of clouds is still a major obstacle to obtaining accurate SST measurements in overcast conditions. On the other hand, microwave measurements have been shown to be less affected by clouds, but they have other problems in accounting for variable ocean emissivity and obtaining a precise instrument calibration [*Njoku*, 1985]. For both types of sensor, satellite orbit configurations and instrument scanning geometries must be optimized to achieve the desired temporal and spatial resolution and coverage. Retrieval methods used to derive SST's from the measured radiances must be robust and flexible enough to account for environmental factors without being so complex as to render them useless for operational purposes. None of the satellite techniques currently used for measuring SST are entirely satisfactory on the above counts. However, some are particularly suited for specific applications, and there is promise that various combinations of satellite and in situ techniques may eventually satisfy all applications for which SST data are required.

The variety of satellite techniques presently available for SST measurement is illustrated by the four sensors primarily discussed in this issue. The advanced very high resolution radiometer (AVHRR) is a descendant of the early imaging visible and infrared sensors on polar-orbiting satellites that provides high spatial resolution and measures radiation in two visible and two or three infrared spectral bands [*McClain et al.*, this issue]. The high-resolution infrared sounder/microwave sounding unit (HIRS/MSU) is a polar-orbiting, sounding instrument that measures radiation at several infrared and microwave wavelengths, allowing better correction for atmospheric effects but with poorer spatial resolution [*Susskind and Reuter*, this issue]. The scanning multichannel microwave radiometer (SMMR) is a polar-orbiting, low-spatial-resolution sensor that is comparatively insensitive to clouds and other atmospheric effects [*Milman and Wilheit*, this issue]. The visible-infrared spin-scan radiometer atmospheric sounder (VAS) is a combination imaging/sounding instrument placed in geostationary orbit and has medium spatial resolution and a fixed-earth-disk field of view, but it can make measurements with high temporal frequency ( $\sim$  every 30 min) [*Bates and Smith*, this issue]. The characteristics of these instruments are summarized in Table 1. Instruments with capabilities similar to or approaching the above are also planned for satellites of

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TABLE 1. Characteristics of Satellite Sensors Used in Measurement of SST

Spacecraft	Orbit Type	Sensor	Spectral Channels <sup>  </sup>	Sensor Spatial Resolution, km	Spatial Resolution of Global SST Product, <sup>§</sup> km	Swath Width	Research/Operational Status of SST Product
NOAA 6-9	Polar, 98.8° inclination, 850-km altitude	AVHRR	Visible plus 3.7, 11, 12* $\mu\text{m}$ (infrared)	1	50-250	2500 km <sup>†</sup>	operational (several products)
NOAA 6-9	Polar, 98.8° inclination, 850-km altitude	HIRS/MSU	2.7-15 $\mu\text{m}$ (20 channels, infrared), 50.3-58.0 GHz (four channels, microwave)	20	60-250	2200 km	research
Nimbus 7	Polar, 99.3° inclination, 955-km altitude	SMMR <sup>‡</sup>	6.6, 10.7, 18, 21, 37 GHz (microwave)	150	150	800 km	research
GOES 4-6	Geosynchronous 0°N, 75°W latitude (GOES-East) 0°N, 135°W latitude (GOES-West) <sup>¶</sup>	VAS	Visible, plus 3.9, 11, 12.6 $\mu\text{m}$ (infrared)**	14	50-75	Earth disk <sup>†</sup>	research

\*This channel not included on NOAA 6 and 8.

<sup>†</sup>Useful area reduced by viewing angle constraints.

<sup>‡</sup>SMMR was also carried on the Seasat satellite.

<sup>¶</sup>Nominal positions (spacecraft failure may necessitate repositioning of remaining active satellite).

<sup>§</sup>Depending on method used to generate product.

<sup>||</sup>Not all channels used in SST determination.

\*\*Additional infrared channels available in dwell-sounding scan mode.

other countries, including those of the Soviet Union, Europe, Japan, and India.

### 2.1. Infrared Techniques

For a cloud-free atmosphere, infrared radiation emitted from the ocean surface can propagate relatively unattenuated through the atmosphere at wavelengths for which gaseous absorption is small. The variability in attenuation at a given wavelength is primarily due to water vapor. At these "window" frequencies ( $\sim 3.5\text{--}4\ \mu\text{m}$  and  $10\text{--}12\ \mu\text{m}$ ), atmospheric transmission can range from  $\sim 90\%$  for a dry atmosphere ( $\sim 1\ \text{cm}$  precipitable  $\text{H}_2\text{O}$ ) to only  $30\%$  for a humid atmosphere ( $\sim 5.5\ \text{cm}$  precipitable  $\text{H}_2\text{O}$ ). The transmittance depends on the vertical distribution of water vapor as well as the total water vapor amount. The total infrared radiance  $I(\lambda, \theta)$  measured by the sensor at wavelength  $\lambda$  and viewing angle  $\theta$  is the sum of components from the ocean surface, from the atmosphere itself, and from background solar radiation reflected at the ocean surface. This can be expressed by the equation

$$I(\lambda, \theta) = \varepsilon(\lambda, \theta)B(\lambda, T_s)\tau_0(\lambda, \theta) + I_a(\lambda, \theta) + \tau_0(\lambda, \theta) \iint_{2\pi} \gamma(\lambda, \theta; \theta') \cdot [I_d(\lambda, \theta') + \tau_0(\lambda, \theta')I_s(\lambda, \theta')] d\Omega' \quad (1)$$

where  $\varepsilon$  is surface emissivity,  $B$  is the Planck blackbody emission function,  $T_s$  is the ocean surface temperature,  $\tau_0$  is atmospheric transmittance,  $\gamma$  is the surface scattering coefficient,  $I_a$  is the upward component of atmospheric emission at the satellite,  $I_d$  is the downward component of atmospheric emission at the surface, and  $I_s$  is the extraterrestrial radiation (including solar radiation). Expressions for the dependence of  $\tau_0$ ,  $I_a$ , and  $I_d$  on atmospheric temperature, absorption, and scattering are provided in the literature [e.g., *Chahine et al.*, 1983].

In practice, to obtain the radiation component emitted by the surface— $\varepsilon(\lambda, \theta)B(\lambda, T_s)$ —corrections must be made to the

measured radiance for the atmospheric and reflected solar contributions. Once the surface radiation is known, the surface temperature can be determined from knowledge of the surface emissivity and the form of the Planck function (as weighted by the spectral filter response of the receiver).

The simplest approach for atmospheric correction is to measure radiation from a given field of view at two or more window frequencies having different atmospheric absorptions. The SST can then be estimated as a linear combination of measured brightness temperatures at these frequencies:

$$\text{SST} = a_0 + \sum_{i=1}^N a_i T_i \quad (2)$$

where  $T_i$  is the brightness temperature at the  $i$ th frequency or channel, and  $N$  is the number of channels (usually two or three). The coefficients  $a_0$  and  $a_i$  are determined by regression, either theoretically, by using the model of (1), or empirically, by using satellite and in situ data. This type of algorithm has the advantage of simplicity and under ideal conditions performs surprisingly well. It forms the basis of the MCSST (multichannel sea surface temperature) approach used operationally by NOAA [*Strong and McClain*, 1984]. Its possible disadvantage is that two or three channels combined linearly may not be sufficient to account adequately for all the independent environmental variables, and the sources of errors observed when using the algorithm in a practical situation are difficult to determine. Small errors might be expected, for example, from any or all of the following: nonlinearity of the dependence of  $\tau_0$  on total water vapor content and on the vertical distribution of water vapor; dependence of surface emissivity on wavelength, angle, and roughness; residual cloud or aerosol absorption and scattering; reflected solar radiation; uncertainties in molecular absorption coefficients; and regression errors caused by theoretical model inaccuracies, in situ data errors, or incomplete statistical representation of the operating environment. Some of these errors may be negligible,

some can be rendered negligible by appropriate viewing or operating configurations, and others are very difficult to model physically in any case. Nevertheless, under the small but significant percentage of conditions when erroneous results are produced, it is not easy to determine why algorithm errors have occurred or how to remedy the situation.

An alternative approach to regression is to use an iterative method [e.g., *Susskind et al.*, 1984] in which initial estimates of ocean and atmosphere parameters are used to compute radiances at the instrument operating wavelengths according to (1). These initial parameters are then modified iteratively according to a chosen relaxation scheme until the computed radiances match the observed radiances to within a given tolerance. The attractiveness of this scheme is that the physics contained in (1) is maintained for each retrieval, since a separate iteration is carried out at each retrieval point rather than using a general set of prederived coefficients, as with the regression approach. This method, however, can be computationally more demanding, and there may be subtle reasons for nonconvergence, such as model errors or channel calibration biases. In principle it is easier to simulate the causes of errors produced by such physically based algorithms and hence more fully understand their operation. In practice, ad-hoc "tuning" of the procedures is often necessary to achieve adequate performance, in the process of which the user may lose some of the advantages of this method.

Variations of the above retrieval methods are used for most satellite infrared SST retrievals. Other differences between retrieval schemes lie in the methods used to account for clouds. These are basically cloud avoidance schemes, in which radiance measurements containing cloud emission are detected and rejected, or cloud correction schemes in which a correction is attempted for effects of clouds up to some upper threshold of cloudiness. Whatever the case, some clouds always remain undetected or imperfectly corrected, and SST accuracies degrade accordingly in persistently cloudy regions of the oceans. For examples of other development and applications of infrared SST algorithms, see *Bernstein* [1982], *Barton* [1983], and *Brown and Cheney* [1983].

## 2.2. Microwave Techniques

The emission of microwave radiation by the ocean and atmosphere can also be represented by (1). Atmospheric transmission in the microwave frequency range suitable for SST measurements ( $\sim 5\text{--}10$  GHz) is generally greater than  $\sim 98\%$  and, even in the presence of heavy clouds, does not fall below  $\sim 95\%$ . However, the microwave surface emissivity varies considerably as a function of wind speed on account of the generation of waves and foam (in contrast to infrared surface emissivity, which remains essentially constant  $\approx 1$ ). Thus additional channels must be introduced into a retrieval algorithm such as (2) in order to provide a correction for wind speed [*Wilheit and Chang*, 1980].

Similar comments apply to microwave retrievals as were discussed above for infrared methods; these comments concern the merits of regression and iterative retrieval algorithms. The major sources of error are different for microwave methods, however. Variability of surface roughness rather than atmospheric water vapor and aerosols is the principal uncertainty factor in determining SST, although clouds can cause erroneous retrievals also if they contain precipitation. For examples of other development and applications of microwave SST algorithms, see *Hofer and Njoku* [1981], *Wilheit et al.* [1984], and *Wentz* [1983].

## 2.3. Sensors and Systems

As shown in Table 1, satellite instruments currently exist that individually, or in combination, satisfy a variety of oceanographic requirements in terms of spatial resolution, temporal resolution, and global or regional coverage. What is required is a reliable mechanism for transforming or combining the satellite data into useful SST products and verifying the accuracy of these products. In most cases the accuracies need to be improved. As will be discussed in other papers in this issue, presently achievable SST accuracies are estimated to be in the range of  $0.5^{\circ}\text{--}1.5^{\circ}\text{C}$ , depending on the prevailing atmospheric and surface conditions, the amount of temporal and spatial averaging involved, and the method used for evaluation (which may involve sampling errors and in situ measurement errors).

The contributing error sources arise mainly from uncertainties in the physical radiation models and imperfections in the retrieval procedures. However, in some cases, instrument noise and calibration drifts may dominate the error budget and must be carefully monitored. In situations where high-resolution satellite imagery is required for detection of localized SST gradients, absolute calibration can be less important than ensuring that instrument rms noise is small in comparison to the desired signal. In other situations, such as for climate studies, absolute calibration accuracy is essential in order to observe small SST changes over long time periods and large spatial scales. Noise and calibration problems vary in severity with specific sensors. Thus, for example, excessive noise in the AVHRR  $3.7\text{-}\mu\text{m}$  channels has consistently occurred, and calibration drifts associated with instrument thermal cycles and component degradation have been observed in the SMMR channels. It is often difficult, if not impossible, for a user to get adequate information on how satellite instruments have been calibrated, usually resulting in a need for some kind of "end-calibration," i.e., adjustment of bias drifts in measured SST by periodic comparisons with XBT's, buoys, or other sensors of supposedly stable accuracy. This provides motivation for blended products in which data from two or more sensors are combined to produce an optimum SST field. The algorithms for performing such blending, and the sense in which the resultant fields are optimum, are areas of current research.

In the following sections the uses of satellite-derived SST's will be discussed for applications in mesoscale oceanography, fisheries, and climate. The requirement for high spatial resolution in determining temperature fronts for fisheries applications has dictated the use of primarily high-resolution ( $\sim 1$  km) AVHRR data to provide images of SST in coastal regions. Also for reasons of spatial resolution, mesoscale oceanography applications have used predominantly high-resolution AVHRR data for studying eddies and currents. Geostationary satellite data from infrared radiometers on the GOES and Meteosat satellites have also been used for this purpose. For climate applications, low-resolution sensors are useful, since these can be composited into well-calibrated weekly or monthly global fields of SST on appropriate grid scales, e.g.,  $2^{\circ}\text{--}5^{\circ}$  latitude and longitude. Thus the SMMR and HIRS/MSU, in addition to the AVHRR, are potentially well suited for this purpose.

## 3. MESOSCALE OCEANOGRAPHY APPLICATIONS

### 3.1. Introduction

The role of satellite sensors in mesoscale oceanographic studies can be examined on the basis of two questions: Does

this method of observing the ocean disclose new phenomena and processes, and do these observations contribute new ways of understanding mesoscale phenomena? In the case of sensors detecting SST, research during the past decade has answered the first question affirmatively. Qualitative descriptions using satellite images have altered mesoscale concepts and modified experimental approaches. The second question concerns the extraction of quantitative information and its effect on the representation of dynamics and processes. The answer here, though not as definite, is positive and reflects the present stage in which the development of methods and verification of measurements are taking place.

A general mesoscale characteristic length given by the Rossby radius of deformation is 100 km, and the associated wave period is approximately 60 days. Features on these scales include fronts and eddies that are the first-order expressions of oceanic turbulence. Investigations of mesoscale oceanographic phenomena in the last two decades have produced regional surveys as well as studies of specific features and processes. Satellite and surface observations have revealed a pervasive mesoscale presence as well as dynamic and structural elements of these features. Continued progress requires multiple-platform sampling schemes with increased spatial and temporal resolution and coverage. The simultaneous attainment of these requirements is difficult to achieve using surface platforms alone. The polar-orbiting and geostationary satellites listed in Table 1 that employ infrared sensors are particularly suited to this objective and can contribute quantitative as well as qualitative data pertaining to surface expressions and their evolutions. Infrared sensors are emphasized in this discussion, since microwave sensors for SST have not yet attained the necessary spatial resolution.

### 3.2. Mesoscale Studies

Satellite infrared imagery can provide information on distributions, relationships, structure, dynamics, and thermodynamics of the surface layer. As with all instruments and their observations, unique advantages and inherent limitations exist. The seasonal development of an isothermal surface layer tends to obliterate detectable temperature patterns in mid-latitudes. Depending on the strengths of initial temperature perturbations, this factor can inhibit use of AVHRR images during summer months. Obscuring clouds associated with storm systems tend to be seasonal also and can interrupt observations for periods of time that are critical in some mesoscale studies. However, the resolution and coverage of the AVHRR and VAS instrument systems aboard the recent NOAA satellites are examples of the significant capabilities now afforded researchers. Mesoscale analyses using satellite infrared imagery often require independent bulk temperature measurements, since infrared radiometers measure the temperature of the upper millimeter of the ocean surface only. Dynamic interpretations of satellite SST pattern evolution tend to focus on surface shear [Mueller and LaViolette, 1980] or baroclinic instabilities [Bernstein et al., 1977]. Analyses often require subsurface data to define vertical continuity and depth of the surface layer in order to estimate advective heat exchange [Brown et al., 1983]. While historical data can be used for this purpose, most studies of specific mesoscale features and processes depend on surface platforms for information coincident with the satellite observations. Vastano and Bernstein [1984a] have shown that combinations of satellite and XBT observations can yield synoptic understanding of front and eddy evolution in the Tohoku area of the northwest Pacific between the Kuroshio and Oyashio fronts.

Infrared SST data gathered over the world oceans by satellites have shown a variety of mesoscale features in regions near strong current systems and within adjacent gyres. Major surveys of such mesoscale SST features [e.g., Legeckis, 1978] illustrate that qualitative studies can confirm circulation features, provide initial detection, and support new hypotheses on the role of dynamic and thermodynamic balances. The seaward deflection of the Gulf Stream by topography off Charleston, South Carolina [Vukovitch and Crissman, 1980], upwelling along the northwest coast of Africa, and eddy production at the juncture of the Brazil and Falkland currents are examples.

Studies with infrared images have derived quantitative estimates that pertain to specific events. Information has been extracted about size, shape, translation, generation, and surface temperatures of mesoscale features. Brown et al. [1983] employed a sequence of 42 images in a study of a ring (81-D) in the Mid-Atlantic Bight. The translation of this ring and variations in its shape were correlated with Gulf Stream interactions. A time series of near-shore meanders and eddies off Vancouver Island contributed to the verification of a quasi-geostrophic numerical model [Ikeda et al., 1984]. In this case the AVHRR imagery provided evidence for the selection of model dynamic mechanisms and confirmed the production of predicted eddy features. Maul et al. [1978] studied time series of Gulf Stream positions observed with GOES infrared imagery. Observations over a 9-month interval were used to determine the spatial and temporal variability of meanders from the Yucatan Straits to Grand Banks.

Considerable effort has been made to develop algorithms that compute SST corrected for atmospheric water vapor and free of cloud contamination [e.g., McClain, 1981; Maul, 1981; Bernstein, 1982]. The production of synoptic, mesoscale-resolving SST maps is now possible with accuracies of less than 1°C. Vastano and Bernstein [1984b] presented a case study that compared satellite and XBT SST values for a complex mesoscale field in the Tohoku area. An rms scatter of 0.8°C was found about a mean bias of 0.6°C, with the satellite estimates warmer. SST maps of this nature can contribute to studies of mesoscale features as well as ocean environmental reports.

Progress has been made on the extraction of mesoscale flow maps and related information from infrared imaging. Vukovitch [1985] has obtained surface geostrophic flow vectors by starting with atmospherically corrected, cloud-free satellite SST values and associating salinity values from statistical temperature-salinity relations. Surface density distributions are calculated from an equation of state, and flow components on a uniform grid are derived from an integrated form of the thermal wind equation. Comparisons of satellite results with geostrophic currents derived from coincident hydrographic transects in the Gulf of Mexico show an average correlation coefficient for surface current magnitudes of 0.82. This utilization of temperatures from infrared observations is an extension of the standard Eulerian oceanographic procedure. Other methods are under study that utilize corrected as well as uncorrected image patterns and include a Lagrangian procedure for sea surface features that is related to cloud tracking developed by meteorologists. Submesoscale feature displacements in sequential satellite SST patterns can be interpreted in terms of advection by the general mesoscale motion. La Violette [1984] has estimated motion around the Alboran Sea gyre in this manner. Kelly [1983] has developed a procedure based on an analytical model that includes the thermal wind relation and conservation of temperature. The computations provide a

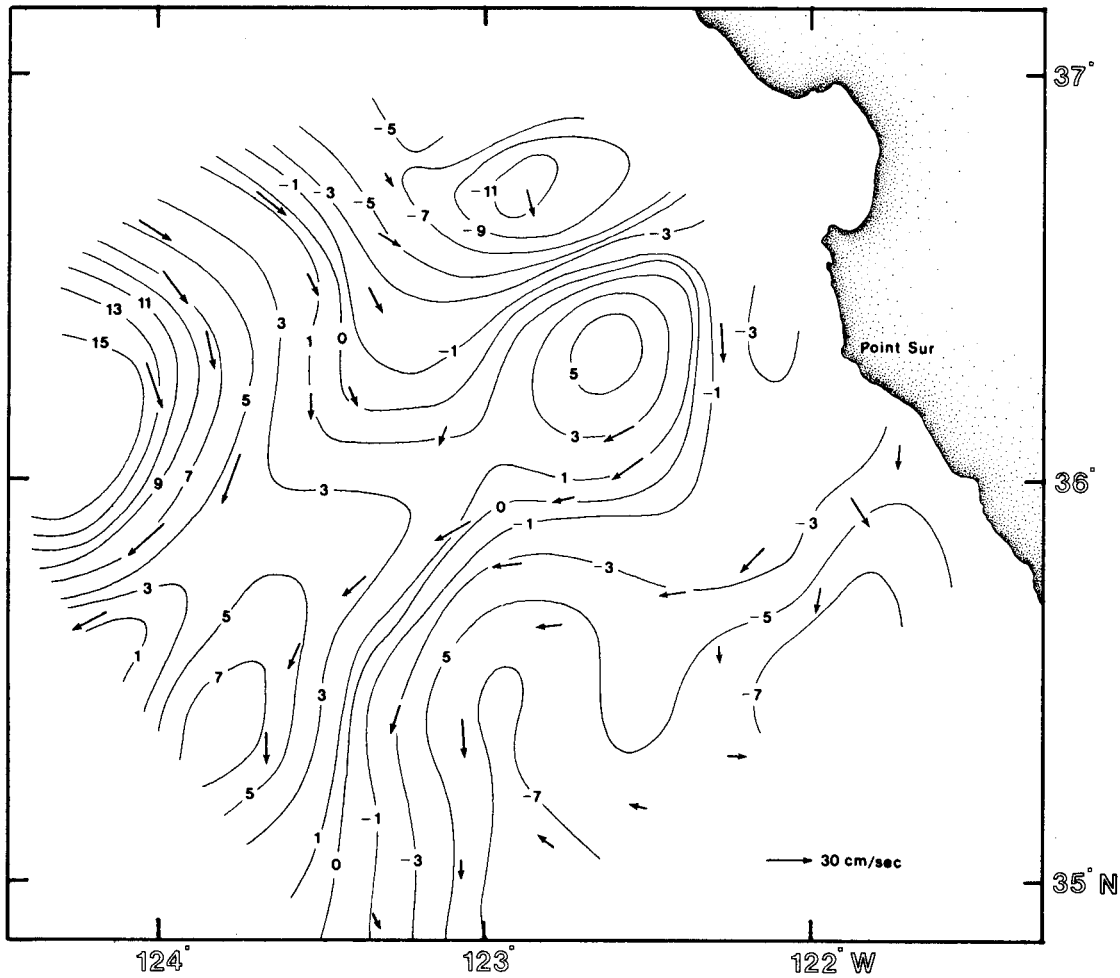


Fig. 1. Surface flow (cm/s) and topography (cm) derived from sequential AVHRR images for March 31 to April 1, 1982.

uniform distribution of along-isotherm and cross-isotherm flow components for an infrared image. Application to the California Current region showed good qualitative agreement with velocities obtained from coincident shipborne Doppler acoustic log velocities and surface drifter tracks. *Vastano and Borders* [1984] have used an interactive algorithm for flow that computes a nonuniform distribution of vectors by tracking submesoscale feature displacements in sequential imagery. This method can accommodate image patterns formed by discrete scalar values from infrared or visible observations and identifies small feature displacements in the direction of a scalar gradient. The flow vectors in Figure 1 were obtained with the interactive method from two sequential NOAA 7 infrared (channel 4, 11  $\mu\text{m}$ ) images of a California Current region taken during March 31 to April 1, 1984. The flow estimates are for portions of a warm core eddy (36°N, 124°W) and a cold water plume (35°30'N, 123°20'W) extending offshore from Point Sur.

Flow vector estimates obtained from infrared images can be used to find stream function representations for the flow fields. As an example, *Vastano and Reid* [1985] use a nonuniform distribution of vectors to derive coefficients of a two-

dimensional stream function expansion. By invoking a geostrophic approximation, the sea surface topography in Figure 1 was computed from the stream function. Although coincident hydrography or surface flow observations are not available, these satellite estimates of topography and the associated topographic gradients are in close agreement with similar estimates taken from historical CalCOFI (California Cooperative Oceanic Fisheries Investigation) dynamic topography maps given by *Hickey* [1979].

### 3.3. Discussion

The computation of dynamic and thermodynamic fields from infrared imagery is a major step in mesoscale studies. Research is required to improve their accuracy and range of applicability. A more thorough investigation of alternative SST techniques and accuracies has developed in comparison with the relatively new flow studies. The latter are currently derived with restrictive assumptions regarding the absence of external forcing and lateral flow. In the future these fields will form intermediate results in surface layer studies. For example, their analysis with XBT observations can be applied to research on surface layer heat content ( $Q$ ), the material or sub-

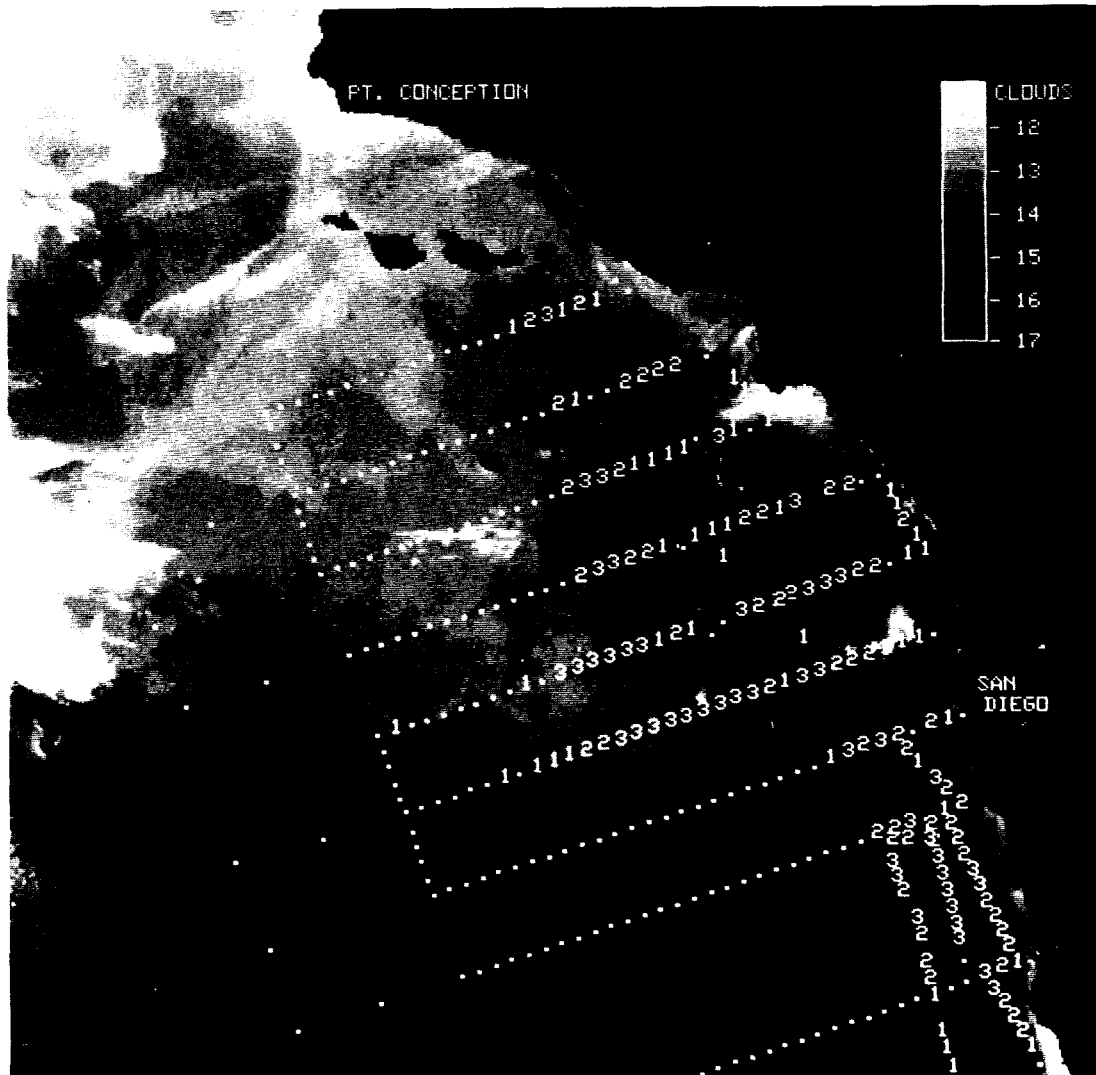


Fig. 2. Northern anchovy egg distribution based on plankton net hauls made during March 20 to April 10, 1980, and sea surface temperature from NOAA 6 AVHRR, channel 4, April 7, 1980. The number of eggs per  $0.05 \text{ m}^2$  are given, where  $\cdot = 0$ ,  $1 = 1-4$ ,  $2 = 5-17$ , and  $3 = 18-245$  eggs per  $0.05 \text{ m}^2$  [from Fiedler, 1983].

stantial derivative ( $dQ/dT$ ), and the local and advective components of  $dQ/dT$  at mesoscale resolution and coverage. Results from such studies will be pertinent to climatic research concerned with spatial and temporal variability of air/sea interactions.

#### 4. FISHERIES APPLICATIONS

##### 4.1. Introduction

The use of satellite remote sensing to provide synoptic measurements of the ocean is becoming increasingly important in fisheries research and fishing operations. Variations in ocean conditions play key roles in natural fluctuations of fish stocks and in their vulnerability to harvesting. Information on the changing ocean, rather than on average ocean conditions, is necessary to understand and to eventually predict the effects

of the ocean environment on fish populations. The evolving capabilities of satellite sensors and data-processing technology, combined with conventional data collection techniques, provide a powerful tool toward ensuring the wise use of living marine resources.

Satellite remote sensing applications in fisheries have concentrated on the measurement of ocean temperature and color and computation of ocean transport based on satellite-measured wind stress. Laurs and Brucks [1985] review fisheries applications of satellite oceanic remote sensing in the U.S. Examples of recent and potential uses of satellite imagery in eastern North Pacific fisheries are given in Fiedler *et al.* [1985]. Yamanaka [1982] describes the utilization of satellite imagery in Japanese fisheries. Gower [1982] gives an overview of the different kinds of remote sensing data relevant to fisheries science and oceanography, and Montgomery [1981] dis-

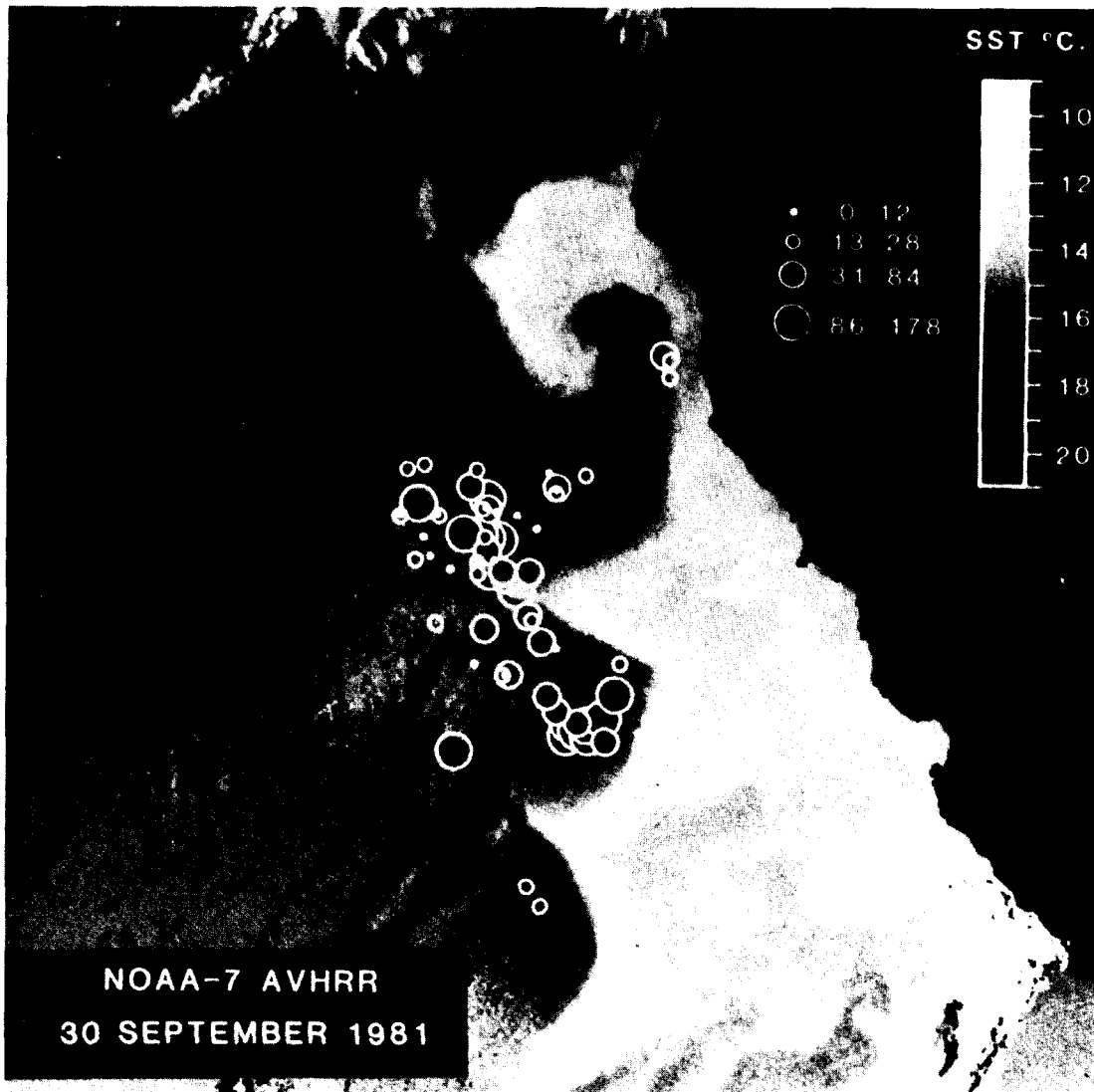


Fig. 3. Central California daily albacore tuna catches, September 27 to October 2, 1981, and sea surface temperature from NOAA 7 AVHRR, channels 4 and 5, September 30, 1981 [from Laurs *et al.*, 1984].

cusses the utility of satellite imagery to ocean industries, including fisheries. This section will concentrate on fisheries applications of satellite sea surface temperature measurements.

#### 4.2. Measurement of Environmental Conditions Affecting Fishery Resources

Variations in environmental conditions affect the recruitment, distribution, abundance, and availability of fishery resources. It is not possible to measure remotely from satellites the entire spectrum of information needed to assess changes in the marine environment. However, information about important oceanographic conditions and processes affecting fish populations, such as surface temperature isotherms, oceanic frontal boundaries, current and circulation patterns, and coastal upwelling, may often be deduced by using ocean surface temperature measurements made by satellite.

Ocean temperature measurements made by satellite remote sensing can be extremely useful in defining the distribution of marine fish habitat conditions. *Lasker et al.* [1981] and *Fiedler* [1983] have demonstrated that the northern boundary of northern anchovy spawning habitat in the Southern California Bight may be delimited by using AVHRR imagery from NOAA polar-orbiting satellites (Figure 2). In general the northern extent of spawning in the bight and the offshore extent of spawning north of Santa Catalina Island are limited by cold, upwelled waters advected south of Point Conception. The cold waters are readily evident in satellite infrared imagery of the region. The southern limit of the anchovy spawning corresponds to low chlorophyll concentrations apparent in ocean color imagery from the coastal zone color scanner (CZCS) aboard *Nimbus 7* [Fiedler, 1983].

The distribution and availability of albacore tuna off the

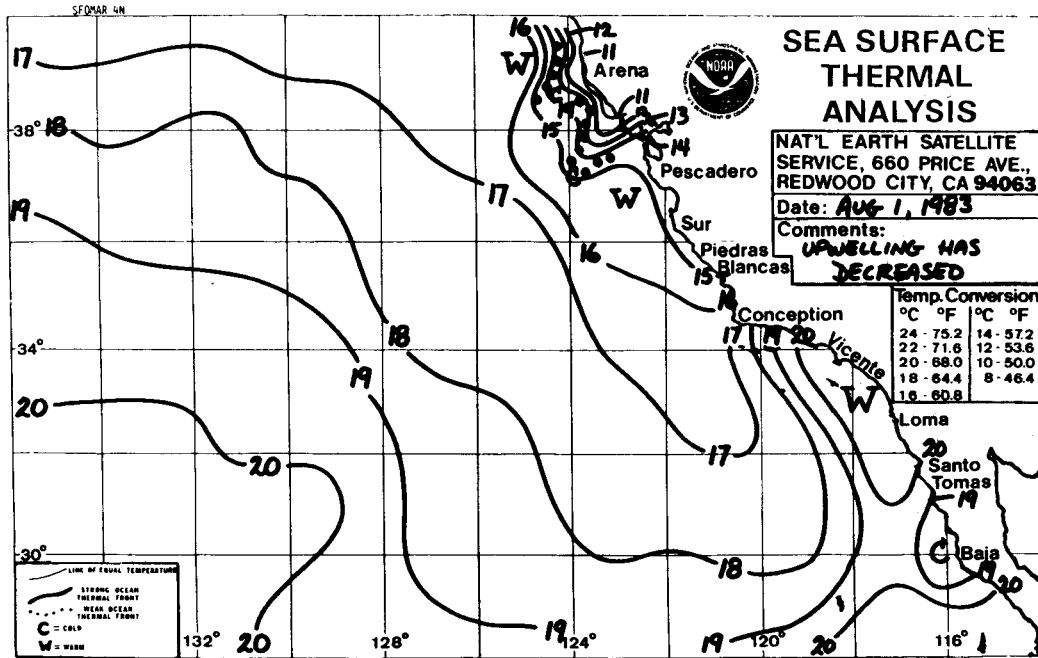
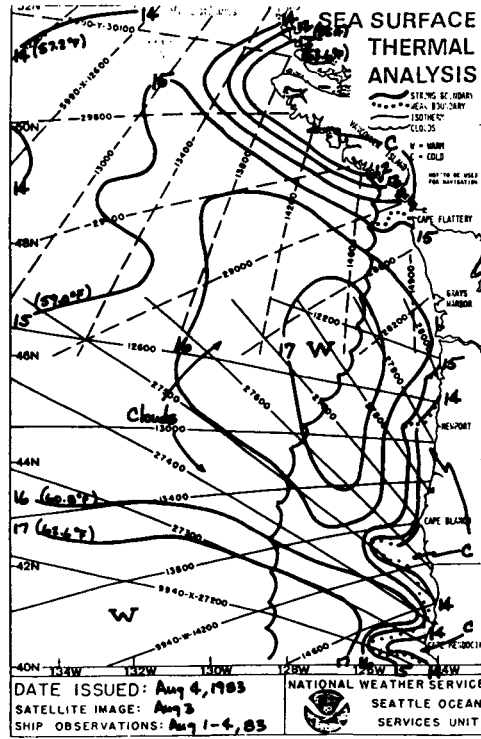


Fig. 4. Examples of fishery advisory charts showing sea surface thermal analysis for waters off the West Coast. Upwelling during this period was nonexistent along the Washington coast and strong along the central and southern Oregon coast.



TABLE 2. Data Requirements for Satellite Sea Surface Temperature Measurements for Fisheries Applications [adapted from Sherman, 1980]

	Accuracy, °C	Precision, °C	Spatial Resolution, km	Temporal Resolution, days	Acceptable Time Delay, days	Areal Coverage
Research	0.5	0.15	2-10	0.1-1	0.5-5	selected coastal and mid-ocean
Fishing operations	0.5	0.15	2-10	1	0.5	selected coastal and mid-ocean

west coast of the United States have been related to oceanic fronts seen in AVHRR infrared and color imagery [Lauritsen *et al.*, 1984] (Figure 3). Infrared thermal and visible color data from satellites can define environmental limits on the spatial distribution of fishable aggregations of albacore and can do so more effectively than ship or aircraft data used in the past. Commercially fishable aggregations of albacore are found in warm, blue oceanic waters near temperature and color fronts on the seaward edge of coastal water masses. These oceanic boundary features, which are believed to result primarily from coastal upwelling, are clearly observable in satellite imagery collected along the U.S. Pacific coast. The distribution of albacore during winter in regions hundreds of miles off the coast has also been related to sea surface temperature fronts observed in AVHRR imagery from the NOAA 7 polar-orbiting satellite [Lauritsen *et al.* 1981]. These fronts are believed to mark the outer boundary of the California Current.

Satellite infrared measurements have also been used to trace the development and duration of the various bluefin tuna fisheries along the east coast of the United States [Roffer *et al.*, 1982]. These fisheries follow the movement of seasonal warming of near-surface waters; this movement is monitored by observing the northerly progression of the 19°–20°C isotherms in satellite infrared imagery. Limited success has been achieved in relating the winter distribution of tuna longline fishing in the Gulf of Mexico with the position of the Loop Current deduced from temperature frontal patterns observed in GOES infrared imagery [Maul *et al.*, 1984]. In summer months, after seasonal warming, it is not possible to resolve temperature frontal structure in the GOES infrared imagery from the Gulf of Mexico.

Satellite remote sensing played an especially important role during the recent El Niño for monitoring anomalous ocean temperatures along the U.S. Pacific coast [Fiedler, 1984a]. The satellite imagery contains invaluable information for use in assessing the effects of the El Niño conditions on West Coast fisheries. Virtually all of the fisheries were affected in varying degrees: some fisheries benefited from the El Niño, and others were harmed substantially. Many fish populations experienced changes in their latitudinal and onshore-offshore distribution. For example, shifts in the distribution of anchovy spawning could be delineated by using NOAA 7 AVHRR infrared satellite imagery [Fiedler, 1984b].

#### 4.3. Use of Satellites in Collection and Interpretation of Ship Data

Satellite ocean temperature data can save time and money in the planning and the execution of fishery research field studies involving vessel operations. This important application of satellite remote sensing usually requires direct reception and processing of satellite data in real time. The cost savings can be significant, since a single satellite image from data

received and processed in a matter of a few hours can save days of expensive ship time by locating significant environmental features and permitting optimum allocation of sampling effort [Fiedler *et al.* 1985]. In addition, satellite data collected concurrently with field studies at sea can be especially valuable. It can be used to validate the interpolation and extrapolation of shipboard measurements and as a basis for interpretation of mesoscale patterns and possible mechanisms responsible for spatial and temporal variability observed in shipboard observations [Lasker *et al.*, 1981].

#### 4.4. Fisheries-Aid Products for Fishermen

Several projects and programs have used or are using satellite-derived ocean temperature data in fisheries-aid products distributed to fishermen by radio facsimile transmission, voice broadcast, U.S. mail, and telephone telecopier. The first utilization of satellite data in fisheries-aid products was in the early 1970's when visual and infrared imagery received by automatic picture transmission (APT) were employed in the preparation of advisory charts transmitted to tuna purse seine fishermen operating in the eastern tropical Pacific [Lauritsen, 1971]. A prime motivation leading to the expanded use of satellite observations in fisheries-aid products was provided by the Seasat Commercial Demonstration Program sponsored by NASA/JPL. This program led to the development of an operational satellite data distribution system to distribute oceanographic products to users [Montgomery, 1981].

Charts showing the locations of oceanic thermal boundaries are derived from AVHRR infrared imagery and are provided to commercial and recreational fishermen for use in locating potentially productive fishing grounds along the Pacific coast from central Baja California to British Columbia and Canada [Breaker, 1981]. Fishermen use these charts (example shown in Figure 4) to save time in searching for productive fishing areas associated with oceanic frontal features [Short, 1979; Breaker, 1981]. Lower-resolution infrared images from the GOES satellites and ship reports are used to prepare charts for waters off the Atlantic coast that are distributed to fishermen and other interested users [Chamberlain, 1981]. Of particular interest to fishermen, these charts show (1) the outer limit of the shelf water mass in which many fishery resource species are concentrated, and (2) the numbers, sizes, and persistence of warm-core Gulf Stream rings, which can markedly alter conditions on the fishing grounds. These charts have been particularly useful to lobster fishermen in reducing loss of fishing pots caused by strong currents of the Gulf Stream warm-core eddies. Charts based on GOES infrared imagery are also prepared to show the path of the Loop Current in the Gulf of Mexico and are used notably by recreational fishermen [Lowry and Leaky, 1982]. The multichannel sea surface temperature (MCSST) charts [Strong and McClain, 1984], improved versions of the former global operational sea surface

temperature computation (GOSSTCOMP) charts, are also used by fishermen in locations around the world where both historically and operationally there is little information on the distribution of sea surface temperature because of low ship traffic.

Finally, sea ice forecast charts derived from Nimbus 7 scanning multichannel microwave radiometer (SMMR) and AVHRR imagery are prepared for regions off Alaska and are transmitted by radio facsimile to fishermen and other marine users.

#### 4.5. Data Requirements, Sources, and Limitations

*Data requirements.* The data requirements for satellite sea surface temperature measurements for fisheries applications have been specified in several satellite program documents [e.g., Sherman, 1980] and are summarized in Table 2.

While the requirements of satellite sensor measurements for fisheries applications have been treated extensively, specification of requirements for ground processing and data delivery systems have been neglected and require further development. There are pressing needs to increase the availability of ocean temperature measurements made by satellite for use in fisheries applications. In some cases, direct reception and processing of the satellite data are required. In others the routine distribution of earth-located and geographically rectified charts of level 3 data will suffice.

*Data sources.* Virtually all fisheries studies employing satellite ocean temperature measurements have utilized data from thermal infrared sensors. The advanced infrared sensors, notably the advanced very high resolution radiometer (AVHRR) aboard the NOAA polar-orbiting meteorological satellites, are characterized by high sensitivity in narrow frequency bands, fine ground resolution, and extensive data archiving [Fiedler et al., 1985]. These sensors yield high-quality data but do have some limitations.

There have been a very few attempts to apply ocean temperature measurements made from microwave instruments aboard satellites to fisheries studies. These attempts have been only marginally successful, mostly because of the large footprint of the measurements and the contamination of the data in the vicinity of land. However, the utility of satellite microwave ocean temperature measurements in fisheries problems has yet to be adequately evaluated. Efforts to do so have been severely hampered by difficulties in obtaining high-quality microwave temperature data and lack of high-speed data-processing capabilities.

*Data limitations.* The major inadequacy of satellite infrared technology is that it can measure sea surface temperature only through a cloud-free atmosphere. This has hampered its utilization and acceptance for fisheries research and fish-harvesting applications because many important fisheries are in areas that have dense cloud cover much of the time. Fiedler et al. [1985] examined the seasonal and areal distribution of cloud conditions over the eastern North Pacific and discussed the probabilities of conditions suitable for satellite coverage. They found that (1) south of latitude 27°N, mean cloud cover is consistently less than 50%; (2) from latitude 30°N to 38°N the most favorable conditions for remote sensing are between October through April, whereas a dense layer of low stratus clouds covers the coastal waters during the summer upwelling season; (3) from latitude 40°N to 50°N the best conditions for remote sensing occur from August to October; and (4) north of latitude 50°N, mean cloud cover increases and is consistently 70% or greater in the Gulf of Alaska, although March and April may be relatively clear.

Another drawback to satellite ocean temperature measurements is their restriction to the uppermost skin of the ocean surface. Although AVHRR measurements in some situations can be representative of general temperature conditions in the upper mixed layer [Bernstein et al., 1977; Maul et al., 1984], many important species live below the thermocline or on the bottom, where temperature patterns are not necessarily apparent at the surface. Another shortcoming of infrared imagery is that its use to detect fronts in open ocean areas may be limited to periods prior to the onset of seasonal warming. The use of ocean color imagery from the coastal zone color scanner (CZCS) on the Nimbus 7 satellite can help circumvent this problem [Laurs et al., 1984].

In spite of the limitations noted, data from advanced infrared sensors on satellites meet the general needs for many fisheries applications. However, the development of reliable microwave radiometers that can measure sea surface temperature with high resolution through clouds is required in addition to infrared to make full utilization in fisheries of ocean temperatures measured from space.

### 5. CLIMATOLOGICAL USES OF SATELLITE SST DATA

This section broadly outlines ways in which satellite-derived SST products can be used to study both regional and global-scale climate phenomena. A brief summary is then given of some of the instrumental problems that appear serious for climatic studies.

#### 5.1. Regional Climate Studies

Contrary to popular belief, many climate studies deal with areas a few thousand kilometers in dimension, not the entire global domain. An example of how satellite SST fields can assist in this type of study occurs off the coast of western South America. It is here that the largest El Niño signals are observed, exhibiting SST anomalies of order 6°C. How these anomalies first appear and evolve is a problem that appears soluble only by incorporation of remote sensing data. Ships and drifting buoys have provided the limited knowledge that we now have regarding evolution of the SST anomalies off South America, but most would agree this description is far from adequate. Without an adequate description it is difficult to test the various theories that now exist for SST variability in this oceanographically complicated area.

By contrast there are some areas where the satellite products may not be adequate in their current state for the study of regional climate variations. Good examples of such areas are the North Atlantic Ocean and western equatorial Pacific, where the rms variability away from the boundaries is only of order 0.3°C. Without some type of calibration to an in situ data field it is unlikely that current satellite products will be capable of achieving this accuracy on a consistent basis.

#### 5.2. Global Studies

Satellites offer perhaps the only hope of obtaining a truly global view of changes in the sea surface temperature field. This is because ships do not adequately sample all of the world's oceans. However the combination of ship and satellite data together offers exciting possibilities. For instance, Weare [1982] has used the existing data base to study what appears to be the propagation of sea surface temperature anomalies from the region of Australia to the coast of western South America across the entire south Pacific Ocean. He suggests that the ability to track these anomalies may allow the possibility of long lead-time forecasts for El Niño events. Weare also notes that the data available to support his studies were

meager at best. A good coherent set of satellite SST fields would permit further analyses to be performed in a more complete manner.

Monitoring changes in global SST will become particularly important in the future as the research community searches for an expected CO<sub>2</sub>-induced increase in the planet's atmosphere and, presumably, ocean temperature. It is clear that the only hope of obtaining such a globally averaged number lies in the application of satellite technology. Here again, the instrumental problems noted below can be critical and may lead to misguided conclusions, unless they are adequately addressed.

### 5.3. Modeling Studies

Meteorologists interested in constructing numerical models for climate studies often state that the information needed about the oceans is the sea surface temperature. This information is used to initialize the models for subsequent prognostic runs. Inserting observed or simulated SST patterns as initial conditions in general circulation models (GCM's) has led to a number of interesting results. Examples of this type of research are simulations of the effects of El Niño on the general circulation of the atmosphere [e.g., Blackmon *et al.*, 1983; Lau, 1985]. For such initializations, temperature anomalies are not the critical item. The quantity required is the absolute temperature of the ocean. Given the strong relation between surface temperature and atmospheric water vapor content, this specification of temperature becomes critical in the tropical regions, particularly the western equatorial Pacific and eastern Indian oceans. Indeed, errors as small as 0.5°C could lead to rather large differences in model responses to initial SST fields. Ironically, it is in these regions of the oceans that some satellite SST sensors are most prone to error because of high water content of the atmosphere and the resulting large, uncertain numerical corrections to estimated SST's. It is these ocean areas that seem to be of fundamental importance in determining changes in global climate. Thus attempts to achieve the highest accuracy and reliability of SST products, using remotely sensed data, should be focused on this part of the world, as appears to be demanded by the physics of the climate system.

### 5.4. Data Problems

There are at least three classes of instrumentation problems that must be addressed if one is to use satellite-derived SST's to study climatic problems. The first has to do with biases introduced into the satellite-estimated SST's. Such biases make it difficult to mate the satellite-derived SST products with the much longer historical data set derived from ship weather observations [e.g., Barnett *et al.*, 1979]. Fortunately, the bias problem seems to be partially resolved by the newer satellite sensors and algorithms.

A problem comparable to the bias can be introduced if the rms variability seen by the satellite sensor is substantially different from that associated with the historical SST fields. Any attempts to standardize the data or otherwise normalize it will again lead to a discontinuity in the historical record that could have misleading consequences.

Another type of instrumentation problem that has not been adequately addressed has to do with the problem of sensor drift. A satellite sensor may gradually degrade in orbit while faithfully returning numbers to interested scientists on earth. Without an external calibration, scientists could be led to the conclusion of a long-term trend in SST. If, for example, this was an increasing trend, it might be inferred that the first sign

of a CO<sub>2</sub> warming had been detected. It seems that the only reliable way to avoid the instrument drift problem is to continually check the satellite SST products against in situ standards.

A final class of problem has to do with changes in the sensors and algorithms. If one wishes to study the behavior of SST over, say, 20 years, with satellite-borne devices, then it is fair to expect that improvements will be made in both the sensors and the algorithms over that period of time. Without care, however, each improvement could result in a "jump" in the SST time history associated with each satellite launch. Clearly, this problem can be overcome by allowing the sensor deployments to overlap. Alternatively, tying the satellite product to a consistent in situ data set also would avoid the problem.

### 5.5. Recommendations

The preceding text seems to justify one recommendation above most others. This has to do with finding methods to optimally blend satellite and in situ information into an estimate of a global SST field. Use of the ship and buoy data in such a product will alleviate the instrument problems alluded to earlier as well as allow a blend between the improved, mixed product and the historical SST fields that are currently available from ships alone. The satellite data will, of course, provide the data coverage and homogeneity of observing technique that the ship observations cannot provide.

The best methods for use in developing an optimal blend of satellite and in situ data are not known. However, recent work on this problem has produced promising results [Reynolds and Gemmill, 1984]. Still it appears that less resources are available to solve this problem than are required. A program needs to be established to optimally blend various types of satellite and in situ information into an SST product that will benefit a wide range of the scientific community as well as be a practical input to numerical weather and climate forecasts.

## 6. DISCUSSION

The preceding discussions have shown that satellite-derived SST measurements are being increasingly utilized for a variety of oceanographic applications. In some cases, however, particularly for climate research, satellite data will not be widely accepted unless data availability, precision, and calibration accuracy can be maintained continuously for several years, even decades. Thus one must look to the future to plan specific sensors and data-processing capabilities required to provide the desired SST products.

Table 3 shows satellite sensors planned for launch during the next decade that will be useful for SST measurements. The NOAA satellite series G through J provides a continuation of the present operational capabilities with the AVHRR and HIRS/MSU sensors essentially unchanged from their present configurations. Starting from the early 1990's, the next satellites in the NOAA series, designated K through M, will carry a modified AVHRR with the addition of a 1.6- $\mu$ m channel and will replace the MSU with a new instrument, the advanced microwave sounding unit (AMSU). The 1.6- $\mu$ m AVHRR channel may improve the capability of the AVHRR to correct for aerosol contamination in the SST retrievals. The AMSU will have 20 microwave channels in the range 23–183 GHz and is primarily intended for atmospheric sounding. However, it should enhance the capabilities of the HIRS/(A)MSU combination for SST measurement.

Three more satellites in the present GOES series are planned, with no changes to the VAS instruments on board.

TABLE 3. Future Satellite Sensors for SST Measurement

Spacecraft	Time Frame	Sensors	Sensor Characteristics or Modifications	Projected Improvements Over Present SST Capability
NOAA G-J (U.S.)	1985-1990	AVHRR HIRS/ MSU	Same instruments as present (NOAA G is last four-channel AVHRR) (HIRS on NOAA H-J will have two modified channels)	
GOES 7-9 (U.S.)	1985-1991	VAS	Same instrument as present	
MOS-1 (Japan)	1987	VTIR	Infrared (6.3, 11, 12 $\mu\text{m}$ ) plus visible; polar-orbiting, 1-km resolution, 500-km swath, limited on-board recording	
ERS-1 (Europe)	1989	ATSR*	Infrared (3.7, 11, 12 $\mu\text{m}$ ), microwave (24, 36 GHz); polar-orbiting, dual-look, 1-km resolution, 500-km swath	improved water vapor and aerosol corrections
N-ROSS (U.S. Navy)	1989	LFMR/ SSMI	Microwave (5.2, 10.4 GHz)/(19.3, 22.2, 37, 85 GHz); polar-orbiting, 25-km resolution, 1400-km swath	ability to derive SST in cloud-covered areas
NOAA "Next" (K-M) (U.S.)	1990	AVHRR HIRS/ AMSU	AVHRR: additional 1.6- $\mu\text{m}$ channel, switchable with 3.7 $\mu\text{m}$ , AMSU: 20 microwave channels (23-183 GHz), 50-km resolution	AVHRR: better correction for aerosols; HIRS/AMSU: better humidity and cloud correction, operational product (?)
GOES "Next" (U.S.)	1991	VAS	Added 3.7- $\mu\text{m}$ channel, modified 11- and 12.6- $\mu\text{m}$ channels; sounder independent of imager	correction for reflected solar radiation, improved split-window retrieval rms; increased data availability, operational product (?)
Radarsat (Canada)	1991	AVHRR†	Same instrument as on NOAA K-M, polar-orbiting	
MOS-2 (Japan)	1992	OCTS†	3.7, 11, 12 $\mu\text{m}$ plus five other visible/infrared channels.	
ERS-2 (Europe)	1992/3	TBD‡	TBD	
EOS/Polar Platform† (U.S.)	1993(?)	MODIS  HMMR	Several visible and narrow-band infrared channels (3-5 $\mu\text{m}$ , 8-14 $\mu\text{m}$ ), 1-km resolution; several microwave channels (1.4-183 GHz), three subsystems	improved spatial resolution, cloud filtering, and atmospheric corrections
Meteosat "Next" (Europe)	1994	VAS type† IR imager† MW sounder†	Geostationary Instruments in conceptual stage	improved SST from geostationary orbit, global coverage (with GOES and GMS). see Meteosat
GMS "Next" (Japan)	199?	VAS type†	Geostationary	

\*Possibly also a 1.6  $\mu\text{m}$  channel switchable with the 3.7  $\mu\text{m}$  as in the AVHRR (NOAA K-M).

†Proposed.

‡To be determined.

The GOES "Next" satellites will carry a modified VAS, with an additional 3.7- $\mu\text{m}$  channel and slightly shifted 11- and 12.6- $\mu\text{m}$  channels. These changes should improve the SST measurement capability. There is a possibility that NOAA may produce an operational geostationary SST product when this new VAS instrument becomes available.

Two new instruments will also become available in the 1990's. The European satellite ERS-1 will carry an along-track scanning radiometer (ATSR), which will have infrared channels similar to the AVHRR but with two viewing angles: one at nadir and one at a forward incidence angle of 55°. This will provide an additional capability for correcting path attenuation through the atmosphere in deriving SST. The U.S. Navy Research Oceanographic Satellite System (NROSS) will carry a low frequency microwave radiometer (LFMR) as well as a special sensor microwave imager (SSMI) of a type scheduled for prior launch on an Air Force satellite (DMSP) in 1985. These two instruments, in conjunction, should provide an improvement over the SST-sensing capabilities of the SMMR.

In addition to the above, several other sensors that may be

useful for SST measurement are planned for the 1990-1995 time frame. Most of these are presently in the proposal stage.

The increased data volume provided by these sensors will require superior capabilities for archiving, retrieval, and validation to those that are currently available to most researchers. Various scientific committees are now addressing these issues as part of the larger problem of satellite data management. Clearly, much work lies ahead in coordinating satellite SST data sets for specific research and operational programs and in determining optimum methods for producing validated SST products.

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