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Remote Sensing for Water Quality and Biological Measurements in Coastal Waters

Present applications are reviewed and potential areas for research are outlined.

ABSTRACT: *Results of experiments in the coastal zone indicate that pollution and oceanographic features may be detected by remote sensing from aircraft and satellite platforms. Wide-area synoptic and/or repetitive coverage by remote sensors provides information that is not readily available by conventional shipboard measurement techniques. Remotely sensed data may be used to determine concentrations and/or distributions of parameters such as particulates, chlorophyll* a, *temperature, salinity, and phytoplankton diversity.*

Our assessment of the state-of-the-art indicates that remote sensing can make a major contribution to research areas identified by national advisory groups as high priority problems. Suggested research areas also illustrate the potential for unique contributions from remote sensing techniques when carefully combined with conventional oceanographic research methods. These research areas include (1) estuarine and continental shelf sediment transport dynamics, (2) transport and fate of marine pollutants, (3) marine phytoplankton dynamics, and (4) ocean fronts. Measurements of particulates, temperature, salinity, chlorophyll, and other parameters by remote sensing may extend and aid in the interpretation of detailed shipboard investigations, thus providing more comprehensive research program results.

INTRODUCTION

REMOTE SENSING OBSERVATIONS from aircraft and spacecraft and their application in oceanography are relatively new research tools which have not been fully utilized by the ocean science community. The objective of this paper is to present a selective review of remote sensing measurement capabilities in relation to identified research and monitoring problems for coastal marine environments. Particular emphasis will be placed on the application of remote sensing measurements to water quality and biological problems since several comprehensive reviews have recently been published on physical and meteorological applications, Huh and Noble[1] and McClain.[2]

Recent experiments conducted in the United States' coastal zones indicate that certain biological and water quality parameters have distinctive spectral characteristics. Even these limited demonstration experiments make it clear that remote sensing measurements provide critical complementary information to conventional oceanographic measurements for regional and global studies. Remotely sensed wide-area synoptic coverage of surface ocean features pro-

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vides a perspective on problems such as river plume mixing and phytoplankton bloom development that is not available by shipboard measurements.

After briefly describing the primary platform and sensor options for remote sensing of marine environmental parameters, we will identify some current ocean research problems where these techniques could make a significant contribution.

Oceanographic Parameters by Remote Sensing

Data outputs from remote sensors, to date, include (1) high resolution measurements to determine concentrations and distributions of total suspended particulates, temperature, salinity, chlorophyll *a*, and phytoplankton color group associations from airborne and/or satellite platforms; and (2) low resolution measurements of total suspended solids, temperature, ocean color, and possibly chlorophyll from satellite platforms. Remote sensors are being developed and evaluated that will measure surface winds, surface roughness, and surface petroleum contaminants. A summary of these platforms, sensors, and parameters measured is given in Tables 1 and 2. The following paragraphs will briefly review selected results for each water quality or biological parameter.

Particulates

Particulates, or suspended solids, are readily observed in the coastal zone and inland waters using optical spectral range instruments from aircraft and satellite platforms. Aerial photographs have been analyzed by Scherz *et al.*[3] to locate and trace pollutant plumes and their dispersion. Klemas *et al.*[4] have analyzed Landsat and Skylab multispectral scanner imagery and photography to study sediment distributions, acid waste plume persistence, and other characteristics of coastal zone features. Yarger *et al.*,[5] Williamson and Grabau,[6] Klemas *et al.*,[7] Rogers *et al.*,[8] Bowker *et al.*,[9] and Johnson and others[10,11] applied classification or regression techniques to calibrate satellite (Landsat) and aircraft multispectral scanner data and to map distributions of water quality parameters in inland and estuarine systems. Subsequently, experiments were conducted to determine the applicability of aircraft and satellite remote sensing systems for studying ocean dumping in the United States coastal zone.[12-14] Maul and Gordon[15] applied computer enhancement techniques to Landsat data to assess its effectiveness for studying deep ocean currents. Presumably, particulates of biological origin were the cause of the relatively small radiance differences observed.

Quantitative distributions of particulates have been obtained from remote sensors on aircraft[10,11,13] and satellite platforms[9,14] to study relatively small scale phenomena such as river plumes and plumes resulting from ocean dumping of wastes. Figure 1 shows quantitative distribution of suspended solids in plumes resulting from dumping of sewage sludge in the New York Bight.[13]

Digital chromaticity analysis of Landsat computer compatible tapes is a rapid and convenient method for general application to water quality monitoring in coastal environments. Alfoldi and Munday[16] have applied the chromaticity concept to the problem of discriminating pure water, suspended solids, chlorophyll, bathymetry, dry versus wet sand, snow, ice, air pollution, haze, and clouds of variable thickness. These authors were particularly successful in obtaining quantitative data for suspended solids in the Bay of Fundy, Nova Scotia.

Qualitative investigations of oceanographic phenomena have been reported for nearshore[4,7] and deepwater[15] areas using visible spectral range Landsat data where suspended particulates served as a tracer. Results were related to tidal and ocean-current phenomena. Also, turbidity (particulate) phenomena have been observed by the National Oceanic and Atmospheric Administration (NOAA) Synchronous Meteorological Satellite/Geostationary Operational Environmental Satellite (SMS/GOES) and Television and Infrared Observation Satellite (TIROS-N is the most recent) satellites, but these have been of limited use to oceanographers due to the low resolution. Two recently launched satellite systems, AEM-A and Nimbus-7, with spatial resolutions of 500 and 800 m, respectively, provide additional potential for studying wide-area particulate distributions.

Chlorophyll *a*

Chlorophyll *a* has been recognized as a primary parameter for monitoring water quality and measuring productivity. Laboratory and deep ocean measurements[17,18] have indicated unique spectral characteristics of phytoplankton (chlorophyll containing particles) compared to other particles. Aircraft remote sensors have indicated the potential for discriminating spectral changes that could be correlated with chlorophyll *a* concentration changes; calibrated regression

TABLE 1. AIRCRAFT PLATFORMS, SENSORS, AND OCEANOGRAPHIC PARAMETERS

Aircraft and Sensor Characteristics						Oceanographic Parameter, Range (accuracy)				
							Chlorophyll *a*			
Fixed wing Aircraft (Typical)	Altitude, km (Typical)	Sensor	Spectral Range	Spatial Resolution (at Nadir) m	Swath Width, km	Suspended Solids, mg/*l*	Conc., mg/m³	Diversity	Temperature Degrees C	Salinity ppt
U-2	19.7	OCS	VIS, NIR	75	25	>5 (±5)	>2 (±2)	—	—	—
		Cameras	VIS, NIR	10	25	Qual.	Qual.	—	—	—
C-130	3.0	M2S	VIS, NIR	8	8.5	>5 (±5)	>2 (±2)	—	—	—
			TIR	8	8.5	—	—	—	0-35 (±2)	—
		Cameras	VIS, NIR	0.5	4.5	Qual.	Qual.	—	—	—
C-54	1.4	MWR	MW	500	500m (Line)	—	—	—	0-35 (±1)	>5 (±1)
Rotary wing										
Helicopter	0.03	ALOPE	VIS	50	50 m (Line)	—	>2 (2)	Yes	—	—

VIS–Visible; 0.3-0.7 μm (Typical)
NIR–Near IR; 0.7-1.1 μm (Typical)
TIR–Thermal IR: 10.5-12.5 μm (Typical)
MW–L and S bands (see ref. 25)
— No identified capability

TABLE 2. SATELLITE PLATFORMS, SENSORS, AND OCEANOGRAPHIC PARAMETERS

Satellite and Sensor Characteristics						Oceanographic Parameter, Range (accuracy)				
							Chlorophyll *a*			
Satellite	Coverage Frequency	Sensor	Spectral Range	Spatial Resolution (at Nadir), m	Swath Width, km	Suspended Solids, mg/*l*	Conc., mg/m³	Diversity	Temperature Degrees K	Salinity ppt
Landsat	18 Day	MSS	VIS,	70	185	>5 (±5)	"Bloom" (>10)	—	—	—
	(9 Day for 2)		TIR (*)	240	185	—	—	—	260-340 (±1.5)	—
AEM-A	5 Day	HCMR	VIS, NIR	500	700	Yes (**)	—	—	—	—
			TIR	500	700	—	—	—	Yes (**)	—
Nimbus-7	6 Day	CZCS	VIS, NIR	800	1200	Yes (**)	Yes (**)	—	—	—
			TIR	800	1200	—	—	—	Yes (**)	—
SMS/GOES	30 min	VISSR	VIS	1000	3500	Qual.	—	—	—	—
			TIR	8000	3500	—	—	—	180-315 (±2)	—
TIROS-N	0.5 Day	AVHRR	VIS, NIR	1000	2800	Qual.	—	—	—	—
			TIR	1000	2800	—	—	—	180-315 (±1)	—

VIS–Visible; 0.3-0.7 μm (Typical)
NIR–Near IR: 0.7-1.1 μm (Typical)
TIR–Thermal IR; 10.5-12.5 μm (Typical)
* Landsat C only; one of two detectors operational
** Recent Launch, data being evaluated
— No identified capability

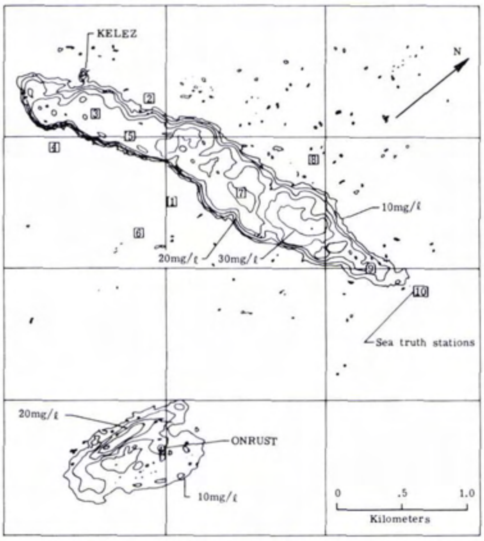

FIG. 1. Suspended solids concentrations (mg/l) in plumes resulting from dumping of sewage sludge in the New York Bight on September 22, 1975. Sea truth stations and monitoring ships are shown. (Taken from reference 13).

equations have been used to map distributions in the coastal zone.[19] Figure 2 is a mapping of chlorophyll *a* distribution in the New York Bight using the Ocean Color Scanner (OCS).

The Coastal Zone Color Scanner (CZCS) on the recently launched Nimbus-7 is a satellite remote sensor similar to the OCS.[20] Initial radiance measurements are being analyzed by the Nimbus-7 Experiment Team. Landsat satellite data also have indicated correlation with sea-truth measurements of chlorophyll *a* concentrations;[14] however, spectral discrimination in mixtures of particles appears to be a problem.

More recently, laboratory test results indicate an active laser system[21] may be used to determine chlorophyll *a* concentrations and phytoplankton diversity information (e.g., distribution among four major color groups: blue-green, golden brown, green, and red), thereby providing information on the community composition. Preliminary results from field tests using the system support the laboratory results.[22] Concurrent sea-truth measurements included attenuation coefficient for instrument calibration. An advantage of this line-scanning active system is its potential for all-weather monitoring.

TEMPERATURE

Temperature distributions of surface waters have been determined using information measured in the infrared (IR) and microwave spectral ranges. Thermal IR sensors have accuracies of 1 to 2°C and, on aircraft systems, have a spatial resolution of about 8 m when flown at an altitude of 3 km (e.g., the thermal band on the M2S scanner). The most widely used thermal scanners are on the SMS/GOES and TIROS-N satellites which have been used to map major ocean features such as the Gulf Stream and its eddies.[23] Frequent data collections (30 minute intervals on SMS/GOES) have provided information for detailed studies of these phenomena. The 8000 m spatial resolution is acceptable for large features; however, this low resolution has limited the application of these data in most coastal zone oceanographic experiments. As indicated previously, the improved resolution provided by the recently launched AEM-A and Nimbus-7 (spatial resolution of 500 and 800 m, respectively) may increase the utility of satellite sea-surface temperature measurements.

Microwave spectral range remote sensors flown on aircraft platforms may be used to determine temperature distributions to about 1°C accuracy for essentially all-weather conditions.[24] A system under development at the NASA Langley Research Center (LaRC) uses dual L and S bands (1.43 and 2.65 Gigahertz (GHz)) to concurrently determine temperature and salinity distributions.[25]

SALINITY

Salinity distribution may be determined by a microwave radiometer as indicated in the previous section. Dual inversion of microwave brightness measurements in two bands (L and S) provides both temperature and salinity values.[25] Salinity may be mea-

FIG. 2. Chlorophyll *a* concentrations (mg/m³) in the New York Bight on April 13, 1975. Sea truth stations are indicated in the OCS scan line. (Taken from reference 19).

sured with a mean deviation of 1 ppt (for salinity greater than 5 ppt). Microwave radiometer measurements are essentially all weather; however, local calibrations for sea-surface roughness effects are required.

SURFACE WINDS, SURFACE ROUGHNESS, AND SURFACE POLLUTION

Surface winds, surface roughness, and surface pollution measurements may be evaluated by several microwave spectral range instruments.[24] Results from aircraft tests on the surface wind measurement instrument, Radscat, are presented by Jones *et al.*[26] Design information on the Radscat and other Seasat-A instruments is presented in Dunne.[27]

POTENTIAL RESEARCH APPLICATIONS FOR REMOTE SENSING IN COASTAL WATERS

A recent comprehensive bibliography on remote sensing of oceanographic parameters lists hundreds of items.[28] A content analysis of a representative selection of the literature on remote sensing of coastal marine environment parameters indicates that the dominant themes to date on this subject have been instrument development and demonstration, and qualitative observations of acute pollution features. However, our assessment of the state-of-the-art for making unique, wide-area qualitative and quantitative measurements of important water quality and biological parameters in coastal waters suggests that remote sensing can now begin to make a major contribution to regional and global ocean studies. In the following paragraphs, we briefly review four research areas identified by national science advisor groups as high priority problems.[29-31] These research needs were also selected to illustrate the unique contribution which could result from a set of remote sensing measurements carefully integrated with conventional oceanographic research methods.

ESTUARINE AND CONTINENTAL SHELF SEDIMENT TRANSPORT DYNAMICS

Estuarine and continental shelf sediment transport dynamics is a research area which requires a broadly based, coordinated multidisciplinary scientific investigation of the physical, geological, chemical, and biological factors involved in the movement of particulate materials from continents to oceanic continental shelves. Specific problems and objectives for future research in sediment dynamics have been detailed in a recent report sponsored by the United States National Science Foundation, *Continental Shelf Sediment Dynamics: A National Overview*.[29] Remote sensing techniques can contribute to sediment transport and deposition studies with at least two general classes of measurements: (1) Repetitive, qualitative wide-area synoptic mapping of suspended particulates in major estuarine discharge to the oceans, when interpreted in the framework of known physical forcing parameters (e.g., weather variables), can provide unique information on temporal and spatial variability in patterns of sedimentation. Such information can be obtained with the use of an integrated set of high altitude airborne photographic mapping missions in combination with satellite imagery. For qualitative mapping very little coordinated sea-surface data are required. Platforms and sensors particularly useful for this task include the U-2 with cameras and/or OCS, Landsat, Nimbus-7, and AEM-A. Quantitative mapping of suspended particulates requires a carefully coordinated remote sensing and sea-surface measurement program. Previous work in the New York Bight[13] and Great Lakes[32] suggests that logistical and data analysis considerations will probably focus quantitative studies on local and regional scales characteristic of individual river and estuarine sediment plumes. The platforms and sensors most suitable for quantitative remote sensing of suspended particulates include fixed wing aircraft with multispectral scanners and possibly Landsat and Nimbus-7 optical sensors.

TRANSPORT AND FATE OF MARINE POLLUTANTS

The transport and fate of marine pollutants can be studied using approaches very similar to those described above for sediment dynamics research. While there are few, if any, hazardous pollutants which can be assessed directly by remote sensing at low levels typical of chronic marine pollution, many of the heavy metal and chlorinated hydrocarbon pollutants are highly insoluble in seawater and are transported in particulate form. For example, recent studies on the chemistry of lead, a high priority potential pollutant, in the coastal waters of Long Island Sound demonstrated that virtually all lead transport and fate is associated with suspended sediment dynamics.[33] The role of remote sensing is particularly critical to marine pollution studies due to the relatively large proportion of the total pollution burden which is derived from non-point sources. Again, for example, greater than 50 percent of the anthropogenic lead flux to the

Southern California coastal zone originates as nonpoint source storm water runoff or as washout from the atmosphere.[34] A recent report by the Office of Science and Technology Policy (OSTP) to the President's Policy Committee for the Water Resources Policy Study identified nonpoint source pollution as a top priority issue for future research.[35] To obtain quantitative data on the transport and deposition of nonpoint source pollutants in coastal waters, a coordinated program of remote sensing and sea-surface measurements must first define the total particulate fluxes as described in the previous section of sediment dynamics. The total flux measurements are then combined with either direct measurements or literature data on the pollutant concentrations per unit of particulate material to obtain a total pollutant flux for any area of interest. A combination of remote sensing and conventional sea-surface measurements provides a capability that makes a scientifically comprehensive regional geochemical flux program feasible, possibly for the first time.

MARINE PHYTOPLANKTON DYNAMICS

Marine phytoplankton dynamics are the primary determinants of chlorophyll concentrations and distribution in coastal waters. While there have been successful experiments on direct remote sensing of marine fish,[36] it is clear that the major thrust in remote sensing of marine biological parameters has been directed to the discrimination and measurement of indicators of marine plant biomass (e.g., chlorophyll *a*). Although both the optical and active laser sensors described in an earlier section of this paper have definite limitations, it seems likely that extensive field applications are both feasible and important to the further understanding of large area marine productivity dynamics. Two specific approaches to the application of remote sensing to the study of marine productivity are particularly promising at present. These are (1) Qualitative, large area synoptic mapping of indicators of marine phytoplankton biomass with the CZCS on the Nimbus-7 satellite and the U-2 OCS can provide very important data on the temporal and spatial character of seasonal variations in phytoplankton productivity. Areas of particular interest for these qualitative studies include major fishery regions (e.g., Georges Bank, upwelling areas off Peru and West Africa, etc.). A carefully coordinated program of sea surface and remote sensing should also be directed to the study of ocean/atmosphere coupling that drives variability in mesoscale productivity. Testable hypotheses and theories on causal linkages between weather, ocean circulation, and fluctuations in basic productivity now exist.[30] (2) Quantitative mapping of chlorophyll *a* with low level airborne multispectral scanners and active laser sensor systems is now feasible under certain limited conditions. The techniques can make a significant contribution to research on coastal eutrophication and episodic phytoplankton bloom dynamics (e.g., Red Tides, blooms related to storm induced upwelling, etc.). These studies will require extensive sea-surface data for the development of empirical algorithms to analyze the remotely sensed signals. In addition, it is not yet possible to obtain an accurate measurement of chlorophyll in waters with equal or greater amounts of inorganic particulates, limiting quantitative remote sensing of biomass to coastal waters relatively distant from high turbidity river discharge. This is probably not a serious limitation since high turbidity inhibits phytoplankton growth, making these areas relatively unimportant for primary productivity assessments.

OCEAN FRONTS

Ocean fronts are important in understanding many physical, biological, geological, and chemical aspects of ocean dynamics since they are regions where exchanges between different water masses are intense. Large-scale fronts also have important effects on the weather and climate. Remote sensing has recently been demonstrated to be an extremely valuable research tool for mapping the sea-surface thermal structure associated with major ocean fronts.[23] Satellite thermal sensors will continue to be the primary methods for investigating the temporal and spatial variability of dynamic frontal structures such as the Gulf Stream boundaries and associated features. High resolution thermal mapping of coastal fronts with airborne sensors will be a critical component of the sediment dynamics, pollution transport, and productivity studies described above.

CONCLUDING REMARKS

Results of experiments in the coastal zone indicate that pollution and oceanographic features may be detected by remote sensing from aircraft and satellite platforms. Wide-area synoptic and/or repetitive coverage by remote sensors provides information that is not readily available by conventional shipboard measurement techniques. Remotely sensed data may be used to determine concentrations and/or distributions of parameters such as particulates, chlorophyll *a*, temperature, salinity, and phytoplankton diversity.

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