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Synoptic Thermal and Oceanographic Parameter Distributions in the New York Bight Apex

Concurrent surface water measurements were used to calibrate and interpret remotely sensed data collected from an aircraft platform.

Introduction

Experiments conducted in the United States coastal zones indicate that pollution and oceanographic features have distinctive spectral characteristics (Johnson and Harriss, 1980; Johnson and Ohlhorst, 1981; Klemas *et al.*, 1976). Remotely sensed wide area synoptic coverage provides information on these features that is not readily available by other means. Features of particular interest include plumes from rivers, bays, and other estuaries which distribute pollutants and nutrients over the highly productive continental shelf waters. Parameters that have been measured using remote-sensing techniques in plumes and receiving waters in the New York Bight include suspended matter, chlorophyll *a*, and temperature (Hall and Pearson, 1977; Polcyn and Sattinger, 1979). Information on distributions of these parameters in conjunction with other measurements (i.e., nutrient and contaminant concentrations and biological processes) could provide an increased understanding of the role of estuarine outwelling on continental shelf dynamics.

Abstract: *Concurrent surface water measurements made from a moving oceanographic research vessel were used to calibrate and interpret remotely sensed data collected over a plume in the New York Bight Apex on 23 June 1977. Multiple regression techniques were used to develop equations to map synoptic distributions of chlorophyll a and total suspended matter in the remotely sensed scene. Thermal (which did not have surface calibration values) and water quality parameter distributions indicated a cold mass of water in the Bight Apex with an overflowing nutrient-rich warm water plume that originated in the Sandy Hook Bay and flowed south near the New Jersey shoreline. Data analysis indicates that remotely sensed data may be particularly useful for studying physical and biological processes in the top several metres of surface water at plume boundaries.*

Aircraft and satellite remote-sensing systems have been used (1) to locate, identify, and map features without the requirement for concurrent surface measurements; and (2) to determine quantitative distributions of specific parameters

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by means of regression and other data analysis techniques, using concurrently collected surface measurements. Surface measurements in most of the experiments cited above were based on ship or helicopter sampling from a number of preselected sample locations on a preselected schedule that, in many cases, limited flexibility during the actual experiment. One means for more fully utilizing surface ships and providing experimental flexibility is to utilize continuous sampling techniques (e.g., fluorometry for chlorophyll *a*). In addition to the greater spatial coverage by the ship, communication between the aircraft and ship may be used to guide the ship to regions of potential interest.

It is the purpose of this paper to present results of a plume study from a coordinated aircraft-ship experiment conducted in the New York Bight on 23 June 1977. Concurrent surface water measurements made from a moving oceanographic research ship were used to calibrate and interpret remotely sensed data collected from an aircraft platform. Verbal communications were maintained during the experiment in order to coordinate remotely sensed and surface measurements. The experiment described here was conducted jointly by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA).

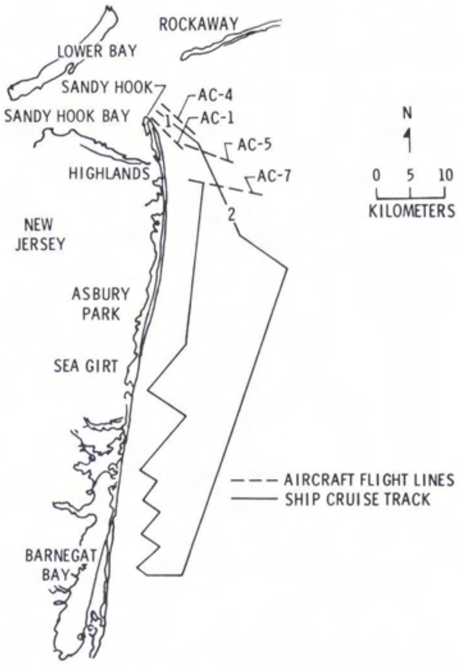

FIG. 1. Ship track and selected aircraft flight lines during NASA/NOAA experiment in the New York Bight Apex on 23 June 1977.

Experimental Method

Remotely sensed data were collected in conjunction with surface measurements made from a moving oceanographic research ship in the New York Bight Apex. During the experiment on 23 June 1977, data were collected in the New Jersey nearshore waters (Figure 1). One of the features monitored, and the focus of this paper, was the Hudson-Lower Bay estuarine plume which emanates from Sandy Hook Bay and flows southeast down the New Jersey shore. Results and interpretations of one part of the total experiment, specifically for data collected from about 0900 hours eastern daylight time (EDT) to 0940 hours EDT, are presented. The experimental locations are along ship tracks 1 and 2 and aircraft flight lines AC-1, AC-4, AC-5, and AC-7 (Figure 1).

Remotely sensed data were collected by a Modular Multispectral Scanner (M2S) and a Zeiss mapping camera onboard a NASA Johnson Space Center (JSC) C-130 aircraft from an altitude of 3.0 km (10,000 ft). The M2S has 11 bands in the visible, near infrared, and thermal spectral ranges. Bandwidths and wavelengths of the remote sensors are shown in Table 1, along with spatial coverage information at the flight altitude. Data collections were accomplished by multiple overflights over the moving ship as it steamed approximately south-southeast along the New Jersey shore (Figure 1). Data flights at about 20-minute intervals were planned so that overlapping remotely sensed data could be used to synoptically map features in the experimental area. (Remotely sensed data were collected in 8500 m wide scans centered on the aircraft flight lines.

Surface measurements were made from the NOAA research ship *Albatross IV* moving at 11 knots. Data were continuously recorded to determine chlorophyll *a* and suspended matter con-

TABLE 1. SPECTRAL AND SPATIAL CHARACTERISTICS OF REMOTE SENSORS AT 3.0 KM ALTITUDE

Modular Multispectral Scanner (M2S) Band	Bandwidth (nm)
1	380–440
2	440–490
3	495–535
4	540–580
5	580–620
6	620–660
7	660–700
8	700–740
9	760–860
10	970–1060
11	8000–13,000
Scan width	8500 m
Resolution	9 m

Zeiss Mapping Camera

Spectral Range	*Film*	*Resolution (m)*	*Footprint (m)*
400–700 nm	Color	0.4	4550 × 4550

centrations at the sampling depth of about 2 m by using a Turner fluorometer and turbidimeter, respectively. The fluorometer was calibrated prior to the experiment using the spectrophotometric method for "corrected" chlorophyll *a* according to Lorenzen's (1967) equations given by Strickland and Parsons (1972), and employing actively growing cultures of *Skeletonema costantum.* While the experiment was in progress, discrete samples were removed from the fluorometer intake every 15 minutes to standardize the instrument.

Discrete samples also were removed from the turbidimeter intake at 15-minute intervals and analyzed according to the procedure in Standard Methods (APHA, 1975) to standardize the instrument. Filtration was accomplished using Whatman GF/F (nominal particulate retention 0.7 μm) glass fiber filters. Samples were filtered under low vacuum (approximately 55 mm Hg).

Concentrations of suspended matter and chlorophyll *a* along with corresponding radiances from the M2S at the same locations in the area selected for quantitative analyses are listed in Tables 2 and 3. These surface measurements were taken between 0924 and 0935 EDT. Radiance measurements were from the corresponding aircraft overflight (AC-7).

Representative radiance values in the remotely sensed scene were used for qualitative analysis (e.g., for temperature distributions where no corresponding surface measurements were made) and quantitative analyses (e.g., using concurrent surface measurements). For the analysis of temperature distributions, representative radiances were determined by averaging over a 10 by 10 pixel field, then multiplied by an instrument calibration to determine sea surface temperature. The field size was determined empirically as the appropriate area to compensate for uncontrollable spectral and spatial uncertainty. Representative radiance values for the quantitative analyses (e.g., chlorophyll *a* and total suspended matter) were determined by locating the sample location as accurately as possible, then taking the average of a 10 by 10 pixel field at that location to obtain the representative value as discussed above for the temperature distributions. Instrument calibration values were then used to determine average radiance values in each of the M2S bands.

Table 2. Surface Measurements Along Ship's Track From 0924 to 0935 EDT

Observation No.	*Time EDT*	*Chlorophyll a (mg/m³)*	*Suspended Matter (mg/l)*
1	0924:00	53.5	33.5
2	0924:22.5	52.0	33.5
3	0924:45	53.5	33.5
4	0925:07.5	55.1	33.5
5	0925:30	50.0	33.5
6	0925:52.5	53.5	33.5
7	0926:15	57.0	33.5
8	0926:37.5	58.5	33.5
9	0927:00	60.2	33.5
10	0927:22.5	60.2	32.7
11	0927:45	66.8	32.7
12	0928:07.5	77.2	32.7
13	0928:30	85.0	33.5
14	0928:52.5	80.0	33.0
15	0929:15	80.0	32.0
16	0929:37.5	100.0	31.2
—	0930:00	OFF SCALE*	31.2*
—	0930:22.5	82*	34.2*
—	0930:45	60*	29.7*
—	0931:07.5	42*	29.6*
17	0931:30	38.1	28.1
18	0931:52.5	37.1	27.3
19	0932:15	34.0	27.3
20	0932:37.5	30.7	27.3
21	0933:00	30.7	26.6
22	0933:22.5	32.0	26.6
23	0933:45	32.6	26.6
24	0934:07.5	26.4	26.6
25	0934:30	27.5	26.3

* Plume interface (not used in regression analyses)

Qualitative Data Analysis and Results

Photographic products (from the Zeiss mapping camera) and M2S thermal band (Band 11) were used to locate features of primary interest in the remotely sensed scene. Evaluation of thermal data collected and instrument calibration indicated that a sea surface temperature difference of 0.25° C could be detected. Comparison of the remotely sensed thermal distributions with the color aerial photography indicated a cold mass of upwelled water in the Bight Apex with an overflowing warm water plume that originated in the Sandy Hook Bay and flowed southeast into the Bight waters (Figure 2).

Further comparisons of the thermal map, photography, optical spectral range data, and concurrent shipboard measurements indicated a significant gradient where the research ship crossed the plume boundary at about 0930 EDT. This area, indicated on the thermal mapping (Figure 2), was the focus of detailed quantitative analyses.

Quantitative Analyses and Results

Quantitative analyses were performed on the continuously recorded surface measurements of chlorophyll *a* and suspended matter and corresponding radiances. To minimize the time differences (between surface and remotely sensed measurements), observation locations were selected immediately behind and in front of the ship at the time of aircraft overflight and along the ship's track. Time differences between remotely sensed and surface measurements were within six minutes. Twenty-nine observations were taken from

TABLE 3. REMOTELY SENSED RADIANCE MEASUREMENTS ALONG SHIP'S TRACK FROM 0924 TO 0935 EDT

Observation No.	Radiance in M2S Bands, MW/CM²-STER-MICRON									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1	3.3427	2.5117	1.7419	1.4881	1.0684	0.9449	0.6784	0.4963	0.2583	0.0773
2	3.3622	2.5205	1.7371	1.5047	1.0716	0.9402	0.6895	0.5116	0.2644	0.0793
3	3.3409	2.5169	1.7299	1.4987	1.0716	0.9356	0.6895	0.5028	0.2649	0.0765
4	3.3685	2.5191	1.7383	1.5108	1.0763	0.9402	0.6979	0.5094	0.2705	0.0793
5	3.3442	2.5176	1.7287	1.5077	1.0716	0.9186	0.6923	0.5061	0.2603	0.0646
6	3.3442	2.5176	1.7287	1.5077	1.0716	0.9186	0.6923	0.5061	0.2603	0.0746
7	3.3611	2.5183	1.7239	1.4866	1.0700	0.9155	0.6895	0.5039	0.2620	0.0780
8	3.3839	2.5279	1.7251	1.5002	1.0826	0.9217	0.7007	0.5116	0.2656	0.0770
9	3.3984	2.5390	1.7359	1.5108	1.0888	0.9310	0.7104	0.5105	0.2689	0.0798
10	3.4022	2.5434	1.7299	1.5047	1.0904	0.9202	0.7049	0.5138	0.2665	0.0792
11	3.4309	2.5544	1.7363	1.5153	1.0967	0.9263	0.7076	0.5215	0.2738	0.0805
12	3.4141	2.5360	1.7143	1.4896	1.0794	0.9109	0.6909	0.4963	0.2603	0.0759
13	3.4141	2.5360	1.7143	1.4896	1.0794	0.9109	0.6909	0.4963	0.2603	0.0759
14	3.4403	2.5670	1.7407	1.5138	1.1061	0.9325	0.7174	0.5116	0.2705	0.0804
15	3.4788	2.5721	1.7407	1.5108	1.1046	0.9310	0.7104	0.5182	0.2730	0.0838
16	3.4433	2.5655	1.7275	1.5062	1.0936	0.9202	0.6943	0.5116	0.2677	0.0806
17	3.4948	2.6001	1.7743	1.5728	1.1250	0.9310	0.6951	0.5028	0.2705	0.0829
18	3.4909	2.6068	1.7790	1.5698	1.1250	0.9371	0.6951	0.5017	0.2656	0.0823
19	3.4683	2.6119	1.7922	1.5971	1.1423	0.9371	0.7174	0.5039	0.2681	0.0822
20	3.4986	2.6075	1.7850	1.5895	1.1454	0.9341	0.7090	0.5050	0.2689	0.0823
21	3.4900	2.6127	1.7838	1.5955	1.1423	0.9325	0.7049	0.5050	0.2714	0.0824
22	3.4990	2.6222	1.7994	1.6031	1.1407	0.9310	0.6895	0.4903	0.2640	0.0814
23	3.5348	2.6304	1.8066	1.6152	1.1423	0.9310	0.6923	0.4897	0.2656	0.0832
24	3.5285	2.6414	1.8198	1.6152	1.1485	0.9310	0.6951	0.4864	0.2673	0.0828
25	3.5333	2.6237	1.7994	1.5986	1.1344	0.9155	0.6770	0.4842	0.2558	0.0798

the surface measurement strip charts (Tables 2 and 3); however, as discussed later, only 25 observations were used in the quantitative analyses.

Multiple regression analyses were used to relate surface measurements of chlorophyll *a* and suspended matter (measured as turbidity) to normalized radiance measurements in the visible and near infrared spectral range (Bands 1 to 10) of the M2S. In the analysis, radiance spectra for plume water and background water were very nearly the same, making arithmetic enhancement of the data necessary in order to attain suitable correlations. Minimum and maximum values of radiance for background water were extracted from the full range of data collected in the experiment. For each sample point, the individual radiances were scaled in each channel according to the span between minimum and maximum values to yield normalized values. The average normalized value over all 10 channels was computed as a reference. The difference between the individual normalized value and the average normalized value was assigned to the particular channel as its enhanced radiance parameter for correlation and mapping. This was an extra step in the analysis beyond procedures as previously published (e.g., Johnson and Bahn, 1977; Johnson, 1978).

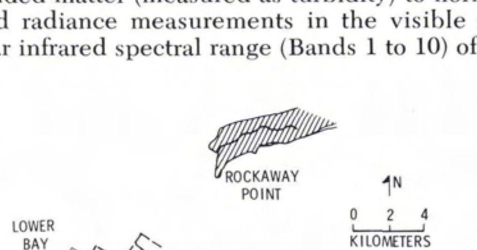

FIG. 2. Thermal distributions from aircraft measurements of *sea surface temperature* (°C) in a selected part of the experiment area (ship track from about 0847 to 0940 EDT) on 23 June 1977.

Regression equations for concentrations of chlorophyll *a* and suspended matter were

$$\text{Chlorophyll } a\text{, mg/m}^3 = 94.49 + 1419.6\, z_2 - 1499.5\, z_4$$

$$\text{Suspended matter, mg/l} = 33.19 - 166.65\, z_5$$

where the z_i are the normalized radiance differences for the M2S bands.

Statistical parameters for the regression analyses are given in Table 4.

Comparison of the remotely sensed and measured values of chlorophyll *a* concentrations are shown on Figure 3. Distributions are approximately random about the fitted line, indicating that the linear model is adequate for this set of data. Suspended matter analyses indicate similar charcteristics. A correlation coefficient of 0.719 indicates relatively low covariance between concentrations of chlorophyll *a* and suspended matter.

Thermal variations (from aircraft calibrated data) and concentrations of chlorophyll *a* and suspended matter (determined from the appropriate regression equations) are shown in Figure 4 along with surface observations for the selected part of the ship track. The estimated ship location at the time of aircraft overflight (AC-7) is also shown. The plume is readily distinguished from the surrounding coastal waters by the individual and/or combined measurements.

Both temperature and suspended matter concentrations are relatively flat in the plume and receiving coastal water (e.g., from 0924 to 0929 EDT in the plume and 0931 to 0935 EDT in the oceanic water) while the chlorophyll *a* concentrations increase rapidly and somewhat erratically as the ship approaches the plume boundary (from 0924 to 0929 EDT). There are spikes in both chlorophyll *a* and suspended matter concentrations as the ship moves through the boundary (at about 0930 EDT) to the more uniform coastal water. Four data points at the plume interface indicated different spectral characteristics and were not included in the final regression equations for chlorophyll *a* and suspended matter concentrations. These spectral anomalies are probably due to differences in remote sensing and surface measurement techniques as well as the probable sloping (nonvertical) interface at the plume boundary. (Note that the remotely sensed radiances are integrated values from the top several metres of the water column while the surface measurements are determined from continuous water sampling at a 2-metre depth.)

Comparison of the thermal and concentration graidents along the ship's track suggest several interesting possibilities. First, the thermal distribution indicates relatively mild and uniform rates of mixing between the plume and coastal water in the top metre of surface water; second, the erratic and rapid increase of chlorophyll *a* near the plume boundary and the spikes of chlorophyll *a* and suspended matter concentrations suggest small scale patchiness near the edge of the plume; third, on the oceanic water side of the plume there is a short mixing zone as evidenced by the gradual decrease beyond the spikes; and finally, the spatial displacement between the remotely sensed and shipboard measurements in the plume boundary indicates a sloping interface with depth between the plume and adjacent oceanic waters. Similar characteristics at plume/front interfaces in the Delaware Bay have been identified and reported by Klemas and Polis (1977). It appears that more detailed studies of the optical and thermal remotely sensed data in conjunction with the

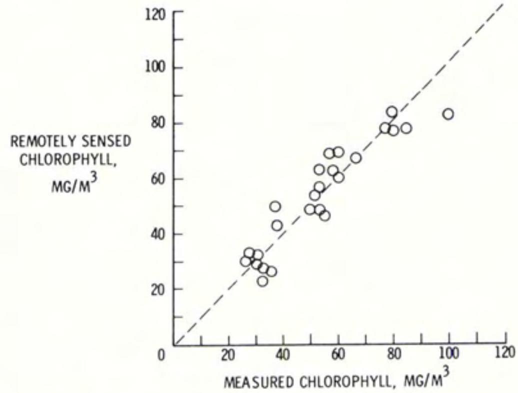

FIG. 3. Comparison of remotely sensed and surface measured values of chlorophyll *a* from 0924 to 0934 EDT

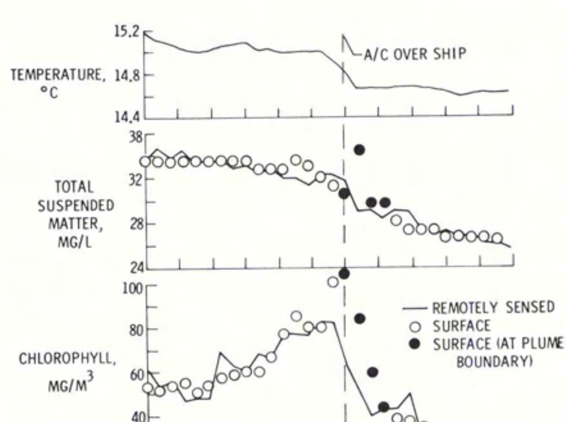

FIG. 4. Comparison of sea surface temperature (°C) and concentrations of total suspended matter and chlorophyll *a* along part of the ship's track. (Open circles are) surface measurements used in regression analyses. (Solid circles are): surface measurements not used in regression analyses. Solid lines determined from regression analyses (except temperature which used aircraft calibration values).

TABLE 4. STATISTICAL PARAMETERS FOR THE REGRESSION ANALYSES

Parameter	M2S Bands	Correlation Coefficient, *R*	Standard Error of Estimate	Range of Surface Measurements
Chlorophyll *a* (mg/m^3)	2, 4	0.936	7.4	26–100
Suspended matter (mg/l)	5	0.965	0.8	24–34

shipboard measurements may provide additional information on the oceanographic processes at the plume interfaces; however, they are beyond the scope of the present analysis.

Chlorophyll *a* distributions were determined using the earlier regression equation over a portion of the area shown in Figure 2, specifically for the area covered by AC-7. (As noted earlier, this was for the period when the ship moved across the plume boundary.) This chlorophyll *a* distribution is shown on Figure 5. As may be seen, the essential outline of the plume is indicated by chlorophyll *a* concentrations (Figure 5) as well as a thermal boundary (Figure 2) at the same location. Thus, the plume is characterized by having warm temperatures and high chlorophyll *a* concentrations. Outside of the plume, water had generally low chlorophyll *a* concentrations. However, we also may differentiate water southeast of the plume into two different temperature regions (see Figure 2) which have similar chlorophyll *a* concentrations. The cooler water (15° C and less) may be related to local upwelling and the warmer water (greater than 15° C) is part of the normal surface water.

Concluding Remarks

Results of a joint NASA/NOAA experiment conducted in the New York Bight Apex on 23 June 1977 indicate that a single aircraft/single oceanographic research ship combination can be used effectively to locate and map oceanographic features in near-shore coastal zones. Combined thermal and water parameter distributions were used to locate and map the distribution of a cold mass of upwelled water in the Bight Apex and an overflowing nutrient-rich warm water plume that emanated from Sandy Hook Bay and flowed southeast near the New Jersey shoreline.

During the experiment, communication between the aircraft and ship directed the ship to features of interest. Remotely sensed data were collected on multiple overflights of the ship by a multispectral scanner and camera onboard an aircraft platform at 3.0 km altitude. Surface measurements by the moving ship were made using continuously recording instruments to determine concentrations of chlorophyll *a* and total suspended matter. Multiple regression techniques were used to develop regression equations to determine distributions of these parameters in the plume and at the boundaries. Thermal and oceanographic parameter mapping of the plume indicated general agreement. Finally, it appears that remotely sensed data may provide information for additional studies of physical and biological processes in the top several metres of the water at plume boundaries.

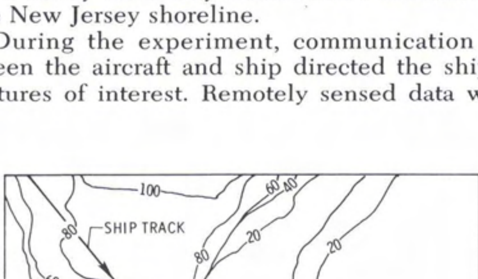

FIG. 5. Quantitative chlorophyll *a* concentrations in mg/m^3 from remotely sensed data along flight line AC-7 (map is compressed spatially along flight line—see Figure 2). Ship track and position at 0930 are shown.

References

APHA (American Public Health Association), 1975. *Standard Methods for the Examination of Water and Wastewater*. 14th ed., p. 1193.

Hall, J. B., Jr., and A. O. Pearson, (Compilers), 1977. *Results from the Remote Sensing Experiments in the New York Bight, April 7-17, 1975*. NASA TM X-74032.

Johnson, R. W., 1978. Mapping of Chlorophyll *a* Distributions in Coastal Zones *Photogrammetric Engineering and Remote Sensing*, Vol. 44:pp. 617-624.

Johnson, R. W., and G. S. Bahn, 1977. *Quantitative Analysis of Aircraft Multispectral Scanner Data and Mapping of Water Quality Parameters in the James River in Virginia*. NASA TP 1021, 31 p.

Johnson, R. W., and R. C. Harriss, 1980. Applications of Remote Sensing of Water Quality and Biological Measurements in Coastal Waters. *Photogrammetric Engineering and Remote Sensing*, Vol. 46, pp. 77-85.

Johnson, R. W., and C. W. Ohlhorst, 1981. Application of Remote Sensing to Monitoring and Studying Dispersion in Ocean Dumping. In *Ocean Dumping of Ocean Wastes*, eds. B. H. Ketchum, D. R. Kester, and P. K. Park. Plenum Press, New York and London, pp. 175-191.

Klemas, V., and D. F. Polis, 1977. A Study of Density Fronts and Their Effects on Coastal Pollutants. *Remote Sensing of Environment*, Vol. 6, pp. 95-126.

Klemas, V., D. Bartlett, W. Philpott, R. Rogers, and L. Reed, 1976. *Skylab/EREP Applications to Ecological, Geological, and Oceanographic Investigations of Delaware Bay*. Final Report, Contract NAS1-12304, NASA CR-144910.

Lorenzen, C. F., 1967. Determination of Chlorophyll and Phaeopigments: Spectrophotometric Equations. *Limnol. Oceanogr.*, Vol. 12, pp. 343-346.

Polcyn, F. C., and I. J. Sattinger, 1979. *Marine Ecosystem Analysis Program: A Summary of Remote Sensing Investigations in the New York Bight*. ERIM Report 131200-1-F, Ann Arbor, Michigan.

Strickland, J. D. H., and T. R. Parsons, 1972. *A Practical Handbook of Seawater Analysis*. Fisheries Res. Bd. of Canada, Ottawa.

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