TECHNICAL PUBLICATION #89-2

August 1989

AVHRR SATELLITE MONITORING OF ALGAL BLOOMS AND TURBIDITY ON LAKE OKEECHOBEE, FLORIDA

Technical Publication #89-2

AVHRR SATELLITE MONITORING OF ALGAL BLOOMS AND TURBIDITY ON LAKE OKEECHOBEE, FLORIDA

by

Dewey Worth

August 1989

Environmental Sciences Division
Resource Planning Department
South Florida Water Management District
West Palm Beach, Florida

ABSTRACT

The occurrence of a major algal bloom on Lake Okeechobee in August 1986 intensified public debate over the long term environmental health of Florida's largest freshwater lake. Detecting and monitoring such events are difficult due to the large surface area of the lake (about 194,000 ha) and costly to monitor by conventional sampling techniques. Beginning in May 1987, an experimental program was initiated to measure surface chlorophyll a and turbidity on Lake Okeechobee using NOAA-9 and 10 weather satellites. Digital data from satellite sensors was compared with in-situ measures of chlorophyll a and turbidity. Results showed satellite-measured reflectance from NOAA satellites could be successfully used to detect algal blooms and turbidity on Lake Okeechobee.

EXECUTIVE SUMMARY

Occurrence of algal blooms (plankton chlorophyll concentrations > 40 mg/m^3) in Lake Okeechobee have caused increased public awareness and concern for the long term health of Florida's largest freshwater lake. Although blooms have been sporadically reported in the past few years, there is growing concern that the frequency and size of major bloom events are increasing, possibly signaling a decline in the trophic health of the lake.

Due to the large size of the lake, detecting and monitoring these bloom events is costly and time consuming using conventional sampling techniques. This study evaluated the potential use of Advanced Very High Resolution Radiometer (AVHRR) scanners on board National Oceanographic Atmospheric Administration (NOAA) weather satellites to detect and measure changes in lake algal chlorophyll levels and turbidity.

Beginning in May 1987, data from NOAA-9 and 10 weather satellites were acquired over Lake Okeechobee in conjunction with the Lake Watch algal monitoring program. Two daylight satellite scenes consisting of visible red, near_infrared and a calibrated thermal image were acquired twice each week. Several indices were then computed from the satellite data and compared with chlorophyll and turbidity measurements obtained from fixed sampling stations on the lake.

Cloud cover and other atmospheric affects (i.e. haze and smoke) reduced the effectiveness and application of AVHRR satellite data for detection of algal blooms in Lake Okeechobee. A high percentage of satellite scenes contained clouds over large areas of the study area. Morning satellite scenes acquired by the NOAA-10 satellite were more likely to be cloud free or contained a lower percentage of clouds over water compared with NOAA-9 images collected in the afternoon. From the available data sets, a total of six separate dates were selected for detailed analysis and comparison with in-situ water collections.

Statistically significant linear relationships ($P<0.05$) were found between measured satellite reflectance and water quality measures of surface chlorophyll and turbidity within the lake. Coefficients of determination (R^2) comparing ratios of near_IR/visible red albedo with chlorophyll ranged from .48 - .71. Extremely high chlorophyll levels (> 90 mg/m3) were not linearly related with satellite data and tended to be underestimated. Higher coefficients of determination for chlorophyll and turbidity were obtained with multiple regressions using red and near_IR reflectance as independent variables. The results compared favorably with observations reported in the Lake Watch Program. However, satellite results were better suited to relative detection of bloom conditions rather than quantifying chlorophyll amounts. Spatial patterns of turbidity were also important in identifying differences in the mixing of tributary inflows with ambient lake water.

ACKNOWLEDGEMENTS

Several members of the South Florida Water Management District staff were instrumental in this study. Chlorophyll collections and analyzes were provided by Brent Nicholas, Environmental Sciences Division, and Brad Jones, Water Quality Division. Water Quality Laboratory provided analysis of turbidity samples.

Access to the AVHRR data used in this study was provided through the assistance of Dr. Otis Brown and Dr. Robert Brown, University of Miami, Rosensteil School of Marine and Atmospheric Sciences (RSMAS). Dr. Mark Carle, formally with the University of Miami RSMAS staff, provided the software algorithms used to process the Miami AVHRR data.

Finally, I wish to thank Dr. Richard Stumpf, NOAA National Environmental Satellite, Data, and Information Service for his many helpful suggestions in use of AVHRR data and review of this manuscript. I would also like to thank Dr. Scot Smith, University of Florida, Department Civil Engineering and Mapping, Dr. Elijah Ramsey, University of South Carolina, Department of Geography, and Dr. Otis Brown, University of Miami, Department Meteorology and Physical Oceanography for their many helpful comments and editorial reviews.

LIST OF TABLES

1. AVHRR Spectral Band Characteristics 1

2 Incidence of Cloud Cover in AVHRR Satellite Data Acquired Over Lake Okeechobee, Florida. Cloud Free Data Include Images with 10% or Less Cloud Cover Occurring Over the Lake 5

3. Chlorophyll a (mg/m3) and Turbidity (NTU) Measured at Satellite Ground Truth Stations Together with Lake Hydrologic Conditions Present at Time of Collection 6

4. Correlation Coefficients (R) Comparing AVHRR Satellite Data with In-situ Chlorophyll a and Turbidity Measurements. All R values were Significant at P>.05 Unless Specified by NS = Not Significant 10

LIST OF FIGURES AND PLATES

FIGURE

1 Lake Okeechobee Sampling Stations Used in AVHRR Study 3

2 Scatter Plot of AVHRR Band 1 Albedo compared with Band 2 Albedo for Water Collection Sites. Values have been Corrected for Atmospheric Affects 8

3 AVHRR Band Ratio (B2/B1) Compared with Measured Values of Chlorophyll a (MG/M3) from Ground Truth Station 9

4 Combined Albedo of AVHRR Band 1 + Band 2 Compared with Surface Turbidity (NTU) from Ground Truth Stations 11

5 Lake Chlorophyll Values Measured at Ground Truth Stations Together with Bloom Locations 13

PLATE

1 Near Infrared AVHRR Image of South Florida 20

2 Digitally Enhanced Near Infrared Image of Lake Okeechobee Together with Prominent Geographic Features 21

3 Digitally Enhanced Visible Red and Near Infrared Image of Water Pixels for Lake Okeechobee 22

4 Spatial Distributions of Chlorophyll a Based on Regression Models 23

5 Spatial Distributions of Turbidity Based on Regression Models 24

6 TM Satellite Image of Lake Okeechobee on 2 September 1987 25

CONTENTS

Abstract i

Executive Summary ii

Acknowledgements iii

List of Figures v

List of Tables vi

Introduction 1

Methods and Materials 1

Results 5

- Weather Conditions and Lake Imagery 5
- Water Quality - Satellite Data Relationships 7
- Model Predictions of Spatial Patterns 12

Discussion 14

Conclusion 16

Recommendations 17

Literature Cited 18

INTRODUCTION

The occurrence of a major algal bloom on Lake Okeechobee in August 1986 intensified public debate over the long term environmental health of Florida's largest freshwater lake. Although blooms have been reported in the past (Marshall, 1977; Federico et al.,1981; Jones and Federico, 1984), there is growing concern that the frequency and surface area of the lake affected by these blooms has begun to increase, indicating a trend toward hypertrophic conditions. Detecting and monitoring such events are particularly difficult due to the large surface area of the lake (about 194,000 ha) and costly to monitor by conventional on-site techniques. Alternatively, modern satellite platforms have proven valuable in accurately measuring areal coverage and concentration of surface chlorophyll pigments and other water quality variables in a variety of aquatic and marine systems.

Several studies have successfully estimated water quality measures of chlorophyll a and suspended sediments using multispectral scanner data from the Landsat satellite high resolution Thematic Mapper (TM) and the coarser resolution Multispectral Scanner (MSS) (Uno et al.,1980; Carpenter and Carpenter, 1983; Verdin, 1985; Lathrop and Lillesand, 1986; Ritchie, et al., 1987). While these sensors provide detailed spatial information, the 16 day lag time between repeat observations and high frequency of cloud cover over south Florida reduces effectiveness of these satellite systems for early detection and monitoring of algal blooms. The Advanced Very High Resolution Radiometer (AVHRR) on board NOAA weather satellites provides an opportunity to collect daily data, but at a reduced spatial and spectral resolution, which may prove valuable in detecting and monitoring large algal blooms. Stumpf and Tyler (1988) successfully applied AVHRR satellite data to measure chlorophyll a in coastal estuaries. This study evaluates the potential use of AVHRR satellite data as a means of detecting and monitoring algal blooms and turbidity on Lake Okeechobee.

METHODS AND MATERIALS

Satellite Data Acquisition and Analysis

AVHRR scanner data from the NOAA TIROS (Television and Infrared Observation Satellite) number 9 and 10 satellite platforms provide two daylight passes over south Florida each day. Satellite orbits are sun-synchronous along a near polar track oriented north-south. Data is acquired over south Florida at local time of approximately 1400 hrs for NOAA 9 and 0800 hrs for NOAA 10. Each satellite contains five sensors sensitive to visible-red (channel 1), near_infrared (channel 2) and thermal (channels 3 - 5) wavelengths of reflected light (Table 1). Ground resolution is roughly 1.1 km square at nadir viewing angles.

TABLE 1. AVHRR Spectral Band Characteristics

Channel #	Characteristics
1	visible red sensitive (.58-.68 μm)
2	near_infrared (.72-1.0 μm)
3	thermal Infrared (3.5-3.9 μm)
4	thermal Infrared (10.5-11.3 μm)
5	thermal Infrared (11.5-12.5 μm)

Real-time satellite data were acquired through the University of Miami Rosensteil School of Marine and Atmospheric Science via a modem computer link over commercial telephone lines. Beginning in May 1987, two daylight scenes consisting of channels 1, 2 and a calibrated thermal channel were transmitted three times each week (Monday, Wednesday, and Friday) to the District image processing system. Prior to receiving the data, the University provided corrections for sensor gain and offset calibrations, positional navigation errors, and finally converted data to an 8 bit format compatible with the District display device (retaining the nominal least significant bits). Frequency of satellite data collections were later reduced in June to twice weekly, coinciding with in-situ chlorophyll and turbidity sampling.

Water Quality and Satellite Comparisons

A total of 20 water collection stations were established throughout Lake Okeechobee (Figure 1) and sampled by helicopter each Monday from June 8 to October 16, 1987. Sites were located away from shallow water areas (< 1.5 m or where secchi depths were < 1.5 m) and vegetated shorelines. These restrictions were imposed to minimize problems with mixed pixel data caused by reflectance from bottom substrates or emergent vegetation. LORAN-C coordinates were recorded for each site and used to relocate stations on subsequent collection trips.

Samples for chlorophyll and turbidity analysis were collected from the water surface generally within two hours of the morning satellite pass. Samples were immediately iced in the field and kept in the dark while being transported. Chlorophyll a estimates were later determined in the laboratory following Strickland and Parsons (1968). Turbidity (NTU) measurements were made according to Standard Methods (1985). Additional in-situ chlorophyll and turbidity data were available through an on-going water quality monitoring program that included nearshore and a few open water sites obtained by boat each Wednesday or Thursday, depending on weather conditions. However, results from boat collections were used only for qualitative checking of spatial patterns obtained from satellite data due to their close proximity to shorelines.

To equate field collections with satellite data, LORAN-C navigation coordinates were first converted to latitude-longitude. Satellite scene row and column coordinates were next geometrically transformed to UTM coordinates and corresponding latitude and longitude. Multidate scenes were further geometrically registered to a common single reference date with a root mean square error (RMS) of +.4 pixels. Pixel locations for each sample site were then identified within each scene. Corresponding values for visible and near_IR wave bands were then extracted from a 3x3 pixel window using each collection site as the center, averaged and statistically compared with in- situ measurements using least-squares regression.

Principles of Application

Dissolved and suspended constituents in water selectively alters the amount and type of incident light reflected or absorbed by the water volume. Prior studies using Landsat (MSS and TM) and other multispectral scanners showed chlorophyll and turbidity in water could be estimated by exploiting unique spectral characteristics associated with reflected red and near infrared (near_IR) wavelengths (Uno et al.,1980; Carpenter and Carpenter, 1983; Verdin, 1985; Lathrop and Lillesand, 1986; Ritchie, et al., 1987). More recently, Stumpf and

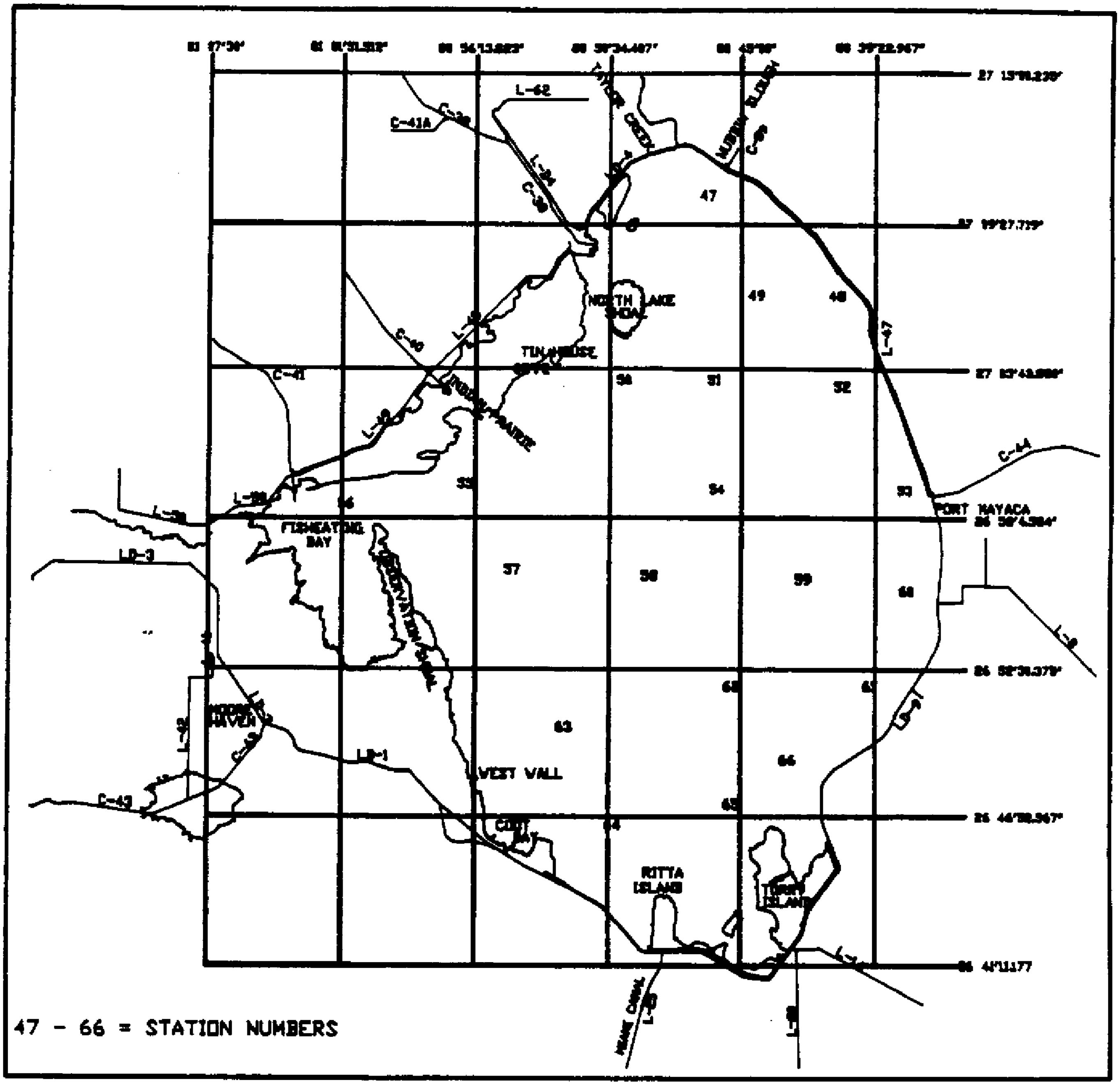


FIGURE 1.' LAKE OKEECHOBEE SAMPLING STATIONS USED IN AVHRR SATELLITE STUDY.

Tyler (1988) successfully used linear combinations and ratios of visible red (Band 1) and near_IR (Band 2) frequencies from AVHRR satellites to estimate chlorophyll and turbidity in estuaries.

Spectral properties of algal chlorophyll a are well known, producing a minimum absorbance (maximum reflectance) within a range of .5 - .6 um. Band 1 of the AVHRR satellite has a similar range of sensitivity (.58 - .68 um) and responds to presence of chlorophyll a. As concentration of chlorophyll a in the surface water increases, the amount of reflected red light will increase with respect to the background. High concentrations of chlorophyll a may also produce increased absorption of red light (Stumpf and Tyler, 1988). In contrast, suspended sediments and dissolved solids increase scattering causing spectral properties of water to shift, increasing the reflectance of longer wavelengths in the near_IR. Band 2 of the AVHRR satellite is responsive to a relatively broad range of near_IR frequencies, while not particularly sensitive to changes in chlorophyll concentration. Similar spectral comparisons between AVHRR red and near_IR wavelengths were used in this study. However, cloud cover and aerosol content in the atmosphere distorts and attenuates light reflectance within these wavelengths, thus limiting the usefulness of these satellite bands.

Data Processing

Several satellite data sets were generated for each observation date. These included raw digital data, atmospherically corrected data sets, and transformations into physical measurements of radiance (Price, 1987; 1988) and reflectance (Stumpf, 1987). To compensate for differences in scene brightness caused by differences in sun elevation angles, all pixel values were adjusted to a common solar zenith angle of 45 degrees. Corrections for atmospheric scattering were approximated using a modified dark pixel subtraction technique as described by Ritchie, et al., (1987). Accordingly, minimum pixel values for cloud shadows near the the lake were identified in each scene for bands 1 and 2 separately. The resulting minimum pixel values minus one were then subtracted from all water pixels to approximate atmospheric conditions and sensor noise. When cloud shadows were not present, coastal offshore water pixels were substituted as reference pixels to approximate minimum reflectance. Band ratios of near_IR/visible-red were then calculated and compared with measures of chlorophyll_a (Stumpf, 1987; Stumpf and Tyler, 1988). Spatial patterns in turbidity were analyzed by linearly combining information from both the red (band 1) and near_IR (band 2) wavelengths and comparing these results with in-situ measurements.

RESULTS

Weather Conditions and Lake Imagery

Quality of satellite data varied with atmospheric conditions, ranging from mild distortions in image clarity (blurred pixels) to total cloud cover, completely obscuring the lake. A large percentage of the afternoon satellite passes over Lake Okeechobee contained clouds (Table 2). Morning satellite passes were more likely to provide cloud free data for correlation with water quality collections. Plate 1 is a typical near_IR image of the south Florida peninsular under relatively cloud free conditions. Lake Okeechobee and other smaller lake bodies were easily distinguished with this band due to the high absorbance of near_infrared wavelengths by water at this band frequency. This high contrast between land and water features make it possible to discern several prominent geographic features within the lake on enlarged and digitally enhanced images (Plate 2).

TABLE 2. Incidence of cloud cover in AVHRR satellite data acquired over Lake Okeechobee. Cloud free data include images with 10% or less cloud cover occuring over the lake.

Month	Number of Morning Scenes*		Number of Afternoon Scenes	
	Cloud Free	With Clouds	Cloud Free	With Clouds
May	7	8	1	14
June	3	4	0	9
July	5	4	7	1
August	3	5	0	8
September	12	9	6	12
October	10	19	7	21

* Note the total number of scenes obtained each month is not consistent. See text for explanation.

From the available data, a total of six satellite scenes were selected for detailed analysis and comparison with in-situ water collections. Lake conditions included a wide range of lake stages, chlorophyll and turbidity concentrations (Table 3). Plate 3 is an enhanced image showing relative brightness patterns for red and near_IR bands observed over Lake Okeechobee. In this scene, brightness values for both red and near_IR bands were lowest at the north end of the lake with higher values in the vicinity of Kreamer and Torry Islands.

TABLE 3. Chlorophyll a and Turbidity Measured at Satellite Ground Truth Stations Together with Lake Hydrologic Conditions Present at Time of Collection.

	Collection Date					
	6-15-87	7-20-87	7-27-87	8-17-87	9-14-87	9-21-87
Hydrology:						
Lake Stage (NGVD)	14.34	13.95	13.89	13.85	13.61	13.53
Inflows (cfs)						
Kissimmee R. (S-65E,84,154)	0	280	328	124	606	35
Taylor Creek Nubbin Slough	43	162	0	53	0	0
	Chlorophyll (C) MgM^3 - Turbidity (T) NTU					
	C/T	C/T	C/T	C/T	C/T	C/T
Station #						
47	50/16	29/7	33/7	40/7	35/8	43/5
48	53/20	27/10	29/11	25/12	36/14	42/11
49	28/37	21/10	24/13	22/12	17/10	25/10
50	62/18	33/30	29/13	21/8	31/11	31/7
51	34/32	51/29	23/17	13/9	40/14	16/11
52	43/20	30/15	19/14	24/13	30/16	22/12
53	87/15	40/16	19/11	24/16	21/20	16/14
54	17/34	18/29	23/18	16/13	32/20	17/12
55	37/11	31/10	19/6	13/4	17/4	15/5
56	18/3	4/18	10/2	3/1	5/2	14/1
57	13/15	8/11	7/4	7/7	4/4	8/3
58	27/20	31/32	16/18	28/14	32/18	24/12
59	39/22	53/30	14/14	23/17	20/17	27/21
60	134/18	17/16	17/10	26/17	23/19	15/13
61	51/9	23/19	19/11	26/10	18/19	16/12
62	15/20	21/28	19/13	37/10	17/20	21/15
63	10/12	8/9	6/3	20/5	5/2	2/1
64	27/10	20/10	23/5	12/6	11/2	6/1
65	6/5	13/15	16/8	-/4	10/7	2/2
66	26/12	31/18	21/11	9/8	13/14	4/7
MEAN	40/17	25/13	18/10	20/10	21/12	18/9
S.D.	30/9	13/8	7/5	10/5	11/7	12/6

Water Quality - Satellite Data Relationships

Scatter plots of bands 1 and 2 showed red and near_IR albedo for water pixels were linearly related throughout most of the lake (Figure 2). Exceptions occurred in areas adjacent to vegetated shorelines and where shallow water depths produced mixed pixels (pixels representing water and other sources of reflectance) due to bottom reflectance from the lake bed or submerged vegetation. Pixel values extracted from a sampling station at Fish Eating Bay (site 56), for example, were consistently higher in near_IR reflectance than expected compared to open water pixels. Site 56 is located in a shallow embayment that supports dense mats of Hydrilla verticillata which may have contributed to the higher near_IR albedo. This site and other stations influenced by local atmospheric conditions such as cloud shadows, smoke or haze were isolated within each image date and excluded from evaluations.

Of the data set combinations that were tested, atmospherically corrected ratios of near_IR/red albedo (ratio 2) provided the best fit with measured chlorophyll a (Figure 3). With the exception of July 27, linear trends were evident between increasing chlorophyll a concentration and an increasing ratio of near_IR/red albedo measured by the satellite for each date. Regression analysis yielded coefficients of determination (r^2) ranging from .48 to .82 ($P<0.05$; Table 4). At chlorophyll values greater than 90 mg/m3, relationships between computed ratios and algal pigment concentration were non-linear. Comparisons among other data sets, including transformations and linear combinations of variables, did not measurably improve coefficients of determination. However, higher coefficients of determination could be obtained through multiple regressions using red and near_IR albedo as independent variables (Table 4).

Indicies computed without correcting for atmospheric affects (ratio 1) generally yielded lower coefficients of determination. Linearly combining the red and near_IR albedo for the 27 July date significantly improved the predictability between chlorophyll a and satellite data (actually depicted in Figure 3). Attempts to combine red and near_IR bands for other dates produced lower coefficients of determination compared to ratios of these variables.

Multiple regressions with turbidity as an additional independent variable generally did not improve regression fits between satellite data and chlorophyll measurements. Including turbidity in the 21 September data set, however, accounted for an additional 20 percent of the variability in chlorophyll and significantly increased the coefficient of determination from .55 to .75 (Table 4). Correlation analysis showed variations of in-situ chlorophyll and turbidity concentrations among the remaining dates were only weakly correlated (highest $R=.35$; $P<.05$). Partitioning the data sets did indicate high turbidity often coincided with moderate to low concentrations of chlorophyll suggesting that high turbidity may suppress chlorophyll activity.

With the exception of 17 August, linear relationships ($P<0.05$) were evident between turbidity and the combined reflectance from both visible red and near_IR wave bands (Figure 4). Coeffficients of determination ranged from .55 to .87 for turbidity and the combined red and near_IR albedo. Higher coefficients of determination were again obtained with multiple regressions treating the red and near_IR albedo as independent variables (Table 4).

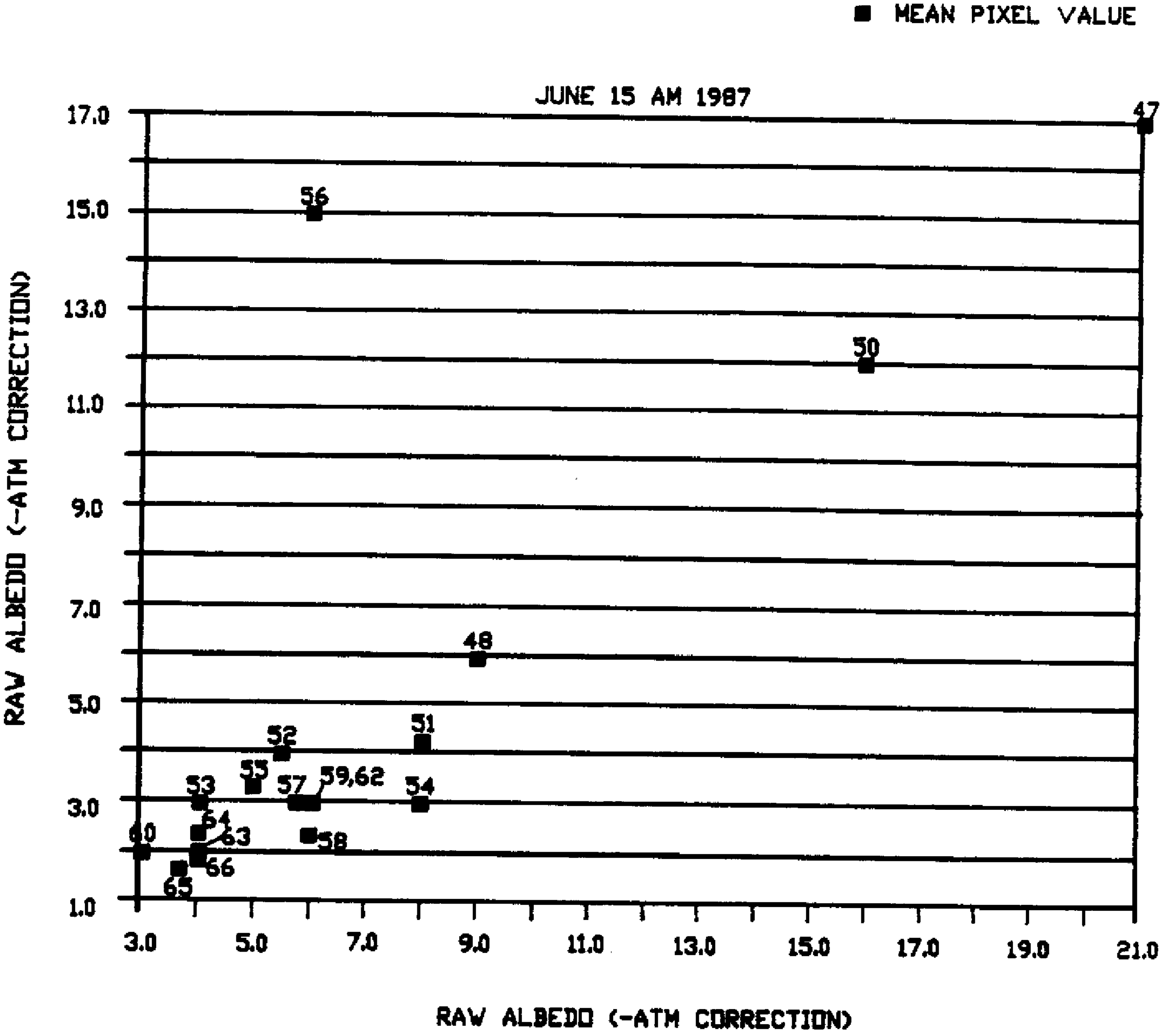
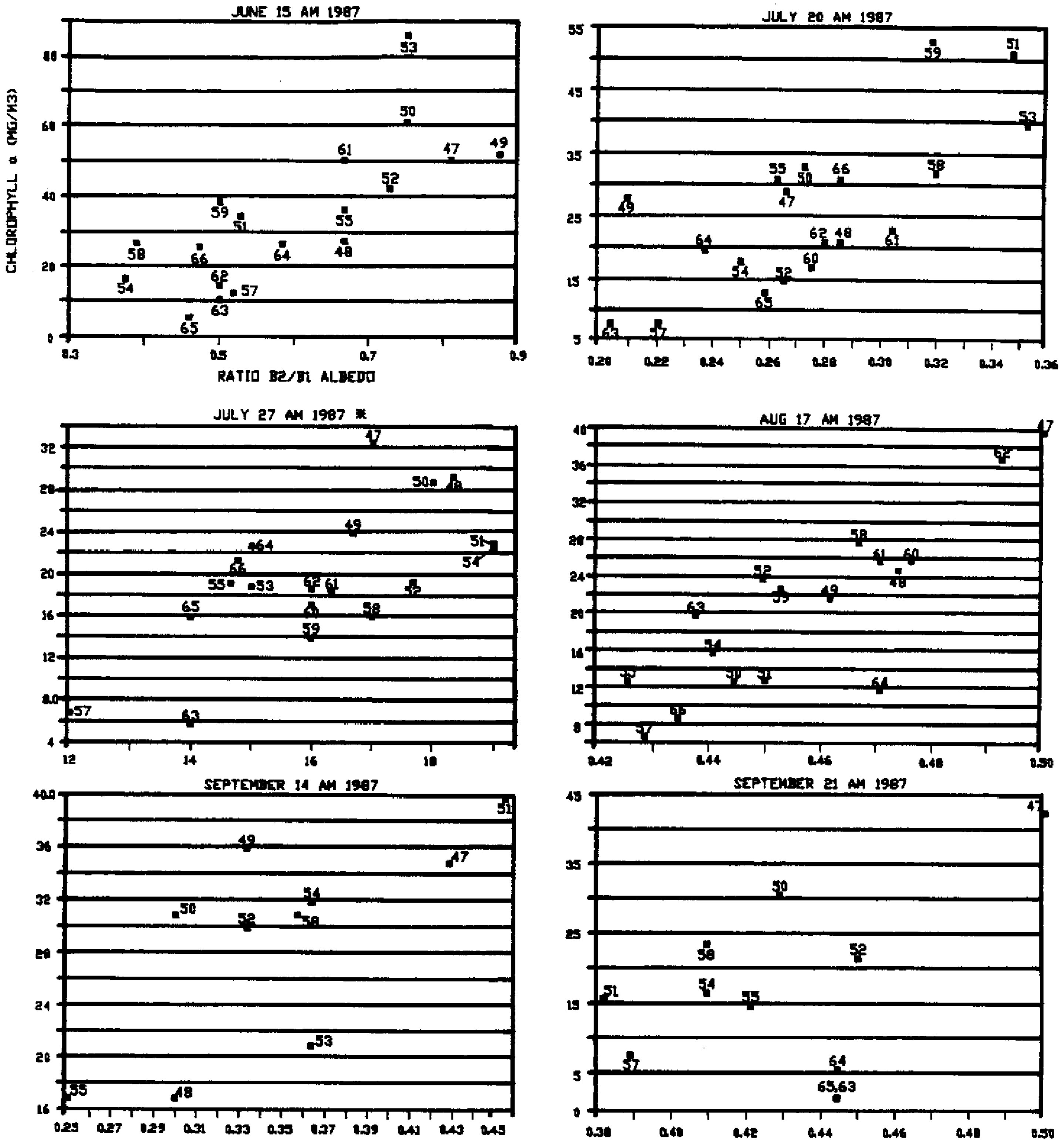


FIGURE 2. SCATTER PLOT OF AVHRR BAND 1 ALBEDO COMPARED WITH BAND 2 ALBEDO. ALBEDO VALUES HAVE BEEN CORRECTED FOR ATMOSPHERIC AFFECTS.

NOTE: AXIS LABELS ARE IDENTICAL FOR EACH GRAPH, EXCEPT WHERE NOTED BY AN ASTERISK (*).

■ — MEAN PIXEL VALUE AT STATION LOCATION


JUNE 15 AM 1987

JULY 20 AM 1987

JULY 27 AM 1987 *

AUG 17 AM 1987

SEPTEMBER 14 AM 1987

SEPTEMBER 21 AM 1987

* CHL a vs B1 + B2 LINEARLY COMBINED

FIGURE 3. AVHRR BAND RATIO (B2/B1) COMPARED WITH MEASURED VALUES OF CHLOROPHYLL a (MG/M3) FROM GROUND TRUTH STATIONS.

TABLE 4. Coefficients of Determination (R^2) Comparing AVHRR Satellite data with In-situ Chlorophyll a and Turbidity Measurements. All R^2 values were significant at $P<.05$ unless specified by NS = Not Significant. Columns containing more than one variable separated by a comma (,) denote multiple independent variables used in multiple regression analysis.

Chl a

	Ratio 2	B1,B2	Ratio 1	Ratio 2, B2	Ratio 2, LOGe Turb
JUNE 15	0.56	0.38	0.37	0.57	0.58
JULY 20	0.48	0.63	0.10 ns	0.50	0.43
JULY 27	0.10 +	0.44	0.43	0.44	0.20
AUG 17	0.82	0.75	0.67	0.85	0.84
SEP 14	0.57	0.57	0.32	0.58	0.58
SEP 21	0.55	0.66	0.06 ns	0.67	0.75

TURBIDITY

	B1+B2	Ratio 2	B1,B2	B1,B2* Raw B2	Raw B1
JUNE 15	0.87	0.01 ns	0.91	0.81	0.92
JULY 20	0.63	0.39	0.64	0.69	0.69
JULY 27	0.66	0.20	0.71	0.64	0.64
AUG 17	0.08 ns	0.21	0.13	0.27 ns	0.12 ns
SEP 14	0.61	0.20 ns	0.63	0.64	0.64
SEP 21	0.55	0.01 ns	0.56	0.45	0.81

+ $r^2 = .31$ when Band 1 (B1) and Band 2 (B2) albedo combined

* = Turbidity converted to Log format prior to analysis

Ratio 1 = uncorrected raw data, Band 2/Band 1
Ratio 2 = atmospherically corrected data, Band 2/Band 1
B1 = atmospherically corrected data from Band 1
B2 = atmospherically corrected data from Band 2
Raw B1 = uncorrected raw data from Band 1
Raw B2 = uncorrected raw data from Band 2
B1 + B2 = addition of corrected data from Band 1 and Band 2

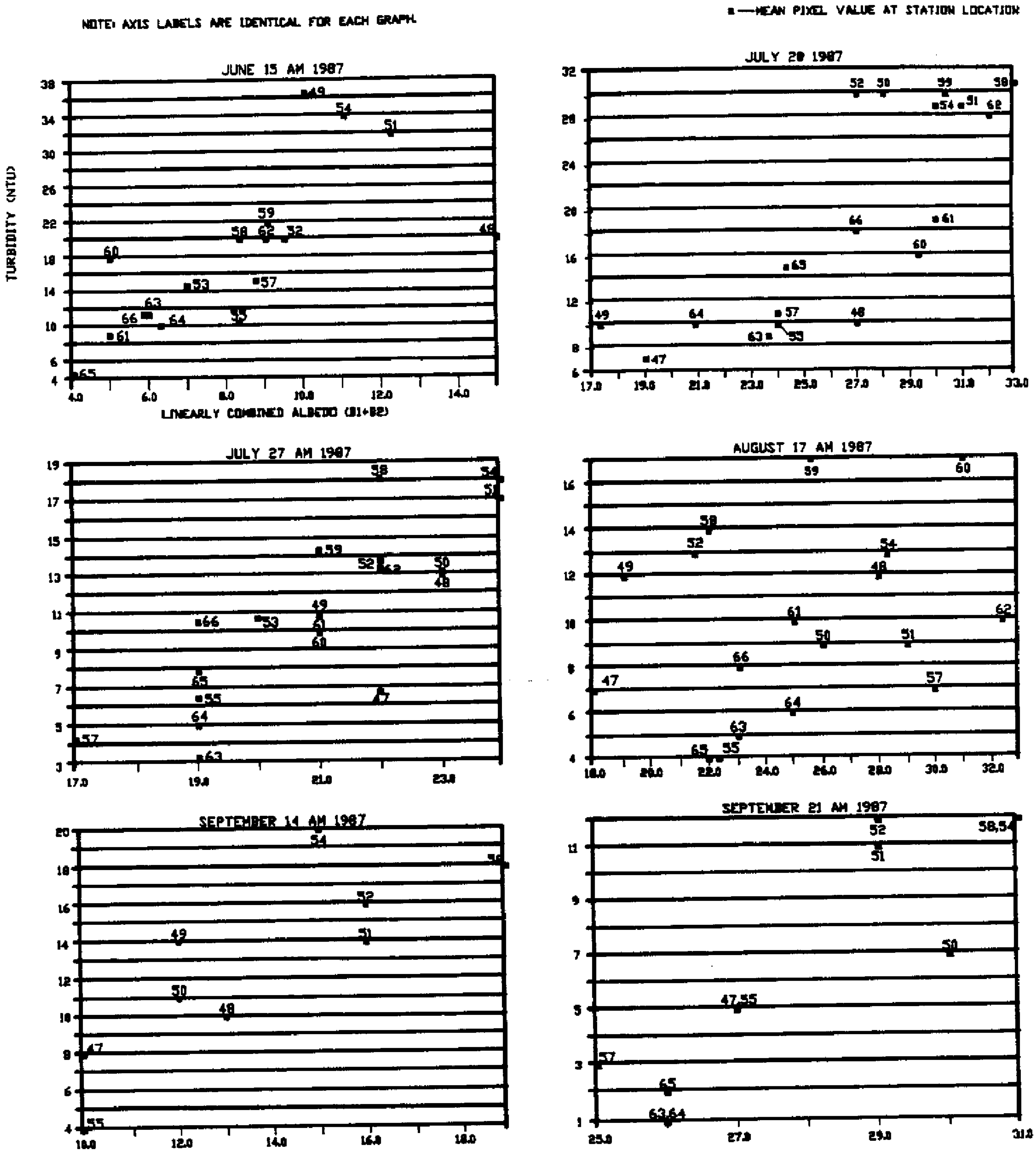


FIGURE 4. COMBINED ALBEDO OF AVHRR BAND 1 + BAND 2 COMPARED WITH SURFACE TURBIDITY (NTU) FROM GROUND TRUTH STATIONS.

Factors contributing to the particularly poor fit on 17 August are not clear. Abnormally low albedo values in both red and near_IR bands were observed in the middle northeast and center region of the lake affecting stations 49, 52, 58 and 59. Both turbidity and chlorophyll concentrations were moderate. Assuming satellite data from these sites contained an additional atmospheric component, excluding these stations from the data set improved the linear fit with the data and produced a significant coefficient of determination ($r^2 = .68$).

Predictions of Spatial Patterns

Based on the prior regression results, spatial distributions of chlorophyll and turbidity were predicted throughout the lake for each date by applying simple linear regressions using the red-visible and near_IR ratio and a linear combination of these wavelengths, respectively, as independent variables. In general, the pattern and distribution of chlorophyll depicted using these models compared favorably with Lake Watch Maps (Plate 4 and Figure 5). For example, on 15 June, high chlorophyll values (>40 mg/m3) were measured near North Lake Shoal along the northwest and east shorelines and extending in a continuous band south to the West Palm Beach Canal. Chlorophyll values in the center region of the lake were generally below 30 mg/m3. Satellite interpretation of the bloom position and background concentrations estimated in the center of the lake closely matches the in-situ measurements and observed spatial pattern of the bloom. Model predictions also suggest elevated chlorophyll levels were present along the edges of Kraemer and Torry Islands in the southern portion of the lake. Comparisons with field data indicate chlorophyll levels were overestimated in this area of the lake and may have been influenced by the vegetated shorelines or background reflectance from the shallow lake bottom.

Spatial predictions for the remaining dates show lower background levels of chlorophyll throughout the lake with smaller and fewer blooms present (Plate 4). Small size blooms occurred in the center of the lake on 20 July, at the north end on 27 July, at the mouth of the Kissimmee River on 17 August, and in the vicinity of Taylor Creek on 14 September and again on 21 September. With the exception of 17 August, the presence and location of these blooms and background concentrations of lake chlorophyll values were correctly identified in the model output. Chlorophyll distributions on 17 August were underestimated in the center of the lake and overestimated in the south end of the lake. However, the lack of model sensitivity on this date could be expected due to the low coefficients of determination between in-situ measurements and satellite data.

Model results were also effective in describing changing spatial and temporal patterns of lake turbidity (Plate 5). Results showed consistently higher NTU values present in the center of the lake, particularly on 15 June and 20 July, compared with predominately lower values occurring just offshore of Observation Shoal. Further inspection of results showed water of low turbidity, compared to background lake levels, flowing from the C-38 canal in the north end of the lake on 20 and 27 July. Kissimmee river discharges were relatively low totaling about 280 and 328 cfs, respectively on these dates. A similar but larger area of low turbidity also occurred on 14 September. Low turbidity water on that date extended from the north end of the lake to the southwest along the marsh shoreline and coincided

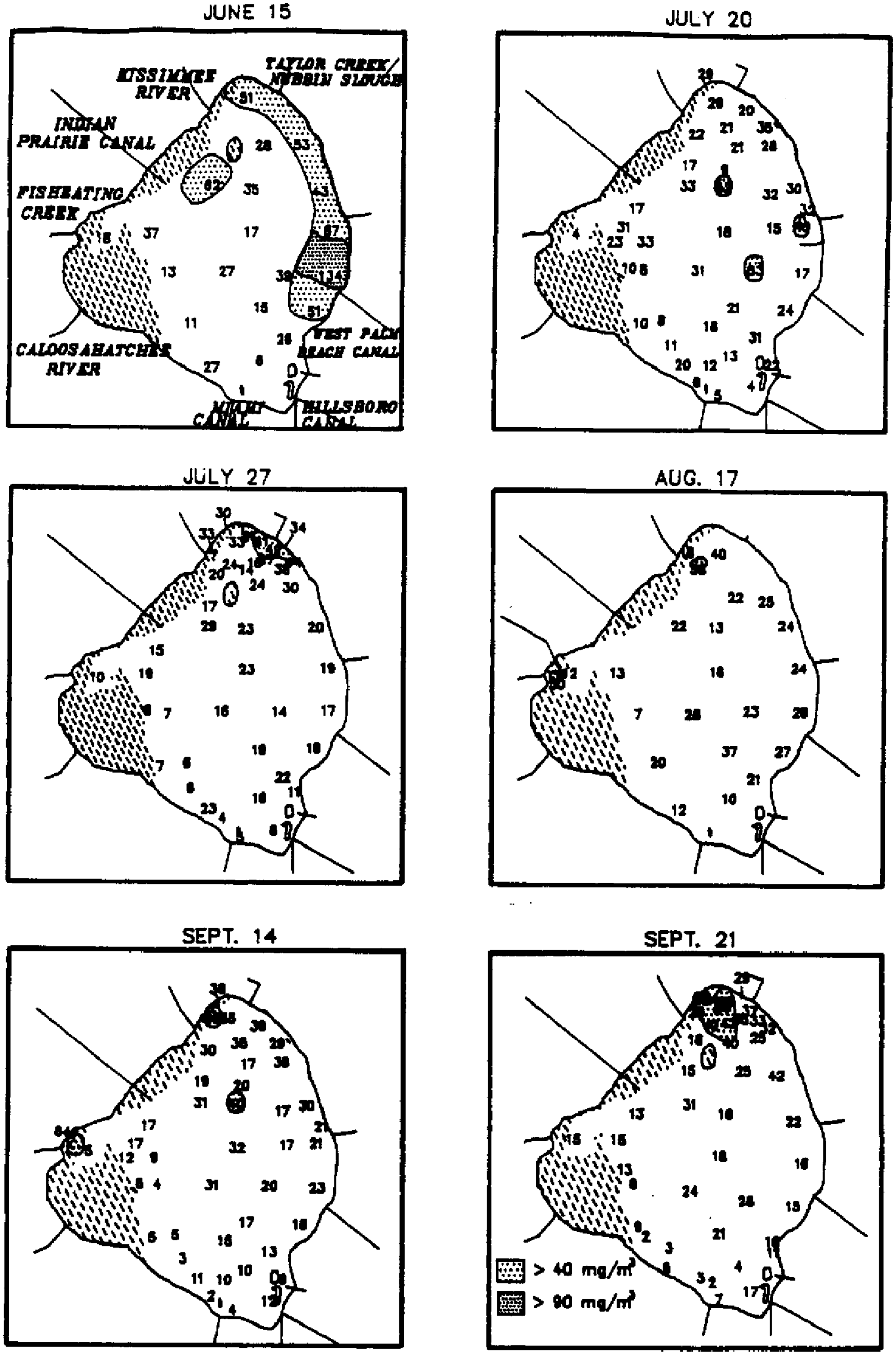


FIGURE 5. LAKE CHLOROPHYLL MEASURED AT GROUND TRUTH STATIONS TOGETHER WITH BLOOM LOCATIONS.

with a larger volume discharge of 600 cfs from the C-38 canal.

DISCUSSION

Cloud cover and other atmospheric affects (i.e. haze and smoke) reduced the effectiveness and application of AVHRR satellite data for detection of algal blooms in Lake Okeechobee. Thermal convective patterns around the lake cause rapid formation of dense clouds that frequently drift out over the lake by early afternoon. As a result, images captured by the NOAA 9 AVHRR satellite (approximately 1300 hrs local time), were frequently unusable. While NOAA 10 images acquired during early morning (approximately 0800 hrs local time) provided more frequent opportunities to view the lake, these images were also frequently difficult to use due to atmospheric haze and high clouds, which resulted in attenuation of the satellite signal.

Under favorable weather conditions, reasonably accurate estimates of chlorophyll levels and detection of major blooms were possible using AVHRR satellite data. However, the utility of AVHRR satellite data may be better suited to relative measures of chlorophyll, in terms of presence or absence of "blooms", than as a means of remotely quantifying chlorophyll content. Standard errors for regression coefficients were generally large resulting in wide confidence intervals for estimates of chlorophyll (20 - 50 percent of the mean predicted concentration). Additional study would facilitate development of a generalized regression model to predict chlorophyll a on dates when concurrent in-situ samples were not available. Patchiness of algal blooms and the limited resolution of the AVHRR satellite (1 km^2) also made it difficult to accurately measure or detect small algal blooms (blooms covering 2-4 km^2 or less).

Spatial comparisons were further complicated by limitations inherent with the point sample collections and the visual methods used to monitor presence of algal blooms. Under the Lake Watch program, estimates of bloom location and areal coverage were based an observer's ability to visually delineate presence of algal blooms against the ambient background color of the lake, a difficult and subjective task when water conditions were turbid. Sample results from station locations were later used to refine visual estimates of bloom presence and location, but due to the spacing of collection sites, continuity in the interpretations of bloom(s) position and lake coverage could be misleading. Other objective techniques such as in-situ fluorometric measurements of chlorophyll would provide a more precise assessment of the areal coverage of blooms. Areal measurements verified in this manner (i.e. towing the sensor in transects to precisely identify areal extents of algal blooms) may yield better spatial relationships between ground truth measurements and satellite data.

The relatively low spectral sensitivity of the NOAA 10 AVHRR satellite and low sun angle illumination may additionally reduce the accuracy of lake chlorophyll estimates. Recent studies show the spectral sensitivity of NOAA 10 is slightly lower compared to that of the NOAA 9 satellite (Gallo and Eidenshink, 1988). The dynamic range of the sensor is further reduced by low sun angles coinciding with the time of satellite pass. Differences in illumination angles between dates in this study were partially compensated by adjusting the digital counts to a common solar zenith angle. However, the range in digital counts for near_IR reflectance remained narrow, frequently less than 3-5 counts over the entire lake surface. Atmospheric scattering additionally reduces spectral sensitivity of the visible and near_IR sensors. A major portion of the spectral signal (>75%) reflected from water can be attributed to atmospheric scattering. Although attempts were made to estimate and correct these affects in this study, a more rigorous model that estimates aerosol and particle scattering may improve the accuracy of chlorophyll estimates.

AVHRR results were slightly more consistent in identifying spatial differences in lake turbidity. Extreme spatial variations in low and high turbidity were readily detected. Of particular interest were areas of low turbidity measured by the satellite along the southwestern shore of the lake. Differences in the spatial distribution of this low turbidity water were apparent in several scenes suggesting wind direction, tributary discharges or other factors influence the presence and movement of this water mass. In contrast, high turbidity in the center of the lake showed less spatial variation. Higher turbidity values in the lake center have been attributed to resuspension of fine muds originating from the lake bottom (Federico, et al., 1981).

Spectral differences between the AVHRR bands also provided insights into the chemical characteristics and mixing of tributary inflows from C-38 and Taylor Creek-Nubbin Slough. Throughout the summer, visible red albedo values in the north end of the lake were low compared to other areas. High concentrations of chlorophyll and dissolved organic matter readily absorb incident red light which may produce low reflectance in the visible red wavelength (Stumpf, 1987). Comparisons with in-situ measurements on several dates clearly showed chlorophyll values below normal bloom thresholds in this region, suggesting lowered red albedo values were not related to high densities of chlorophyll. Other dissolved constituents carried in the C-38 and Taylor Creek/Nubbin Slough discharges may have contributed to lower red reflectance. Both tributaries are sources of dissolved organic nitrogen derived from dairy waste and contain high concentrations of tannin (Federico, et al., 1981). The contrast in mixing of tributary discharges with ambient lake water could be readily distinguished in a Landsat TM satellite image acquired on September 2 (Plate 6). Enhancements of this scene showed a dark plume of water discharging from C-38 into the lake and drifting in a northeast direction.

Use of higher resolution satellites such as the Landsat TM and SPOT (French satellite) could provide more refined spatial and spectral information of interest for water quality monitoring. Enhanced spatial and spectral resolution capabilities of these sensors and the potential for more accurate measurement of lake chlorophyll levels could be useful in estimating the trophic status of the Lake Okeechobee and other Florida lakes. A combination of satellite data such as the AVHRR and TM or SPOT collected over a period of time could provide useful information concerning temporal trends in lake trophic status.

CONCLUSION

AVHRR satellite data were successfully used to estimate presence of algal blooms and turbidity on Lake Okeechobee. However, the utility of AVHRR satellite data were better suited to the detection of blooms rather than as a technique to quantify algal biomass. Spatial patterns in chlorophyll and turbidity also closely matched in-situ observations. Atmospheric conditions, particularly cloud cover, significantly limit and reduce the frequency of usable satellite scenes. Continued acquisition of satellite data coupled with information from existing lake studies would be valuable in understanding algal bloom dynamics of Lake Okeechobee.

RECOMMENDATIONS

A significant potential exists to further expand our understanding of Lake Okeechobee using satellite remote sensing. Applications using AVHRR satellite data, in particular, could provide a cost effective tool for long term monitoring and further improve understanding the interrelationships between turbidity and algal bloom dynamics of the lake. Further research is recommended to improve techniques using AVHRR and other satellite data to remotely measure turbidity and chlorophyll concentrations. Additional study would facilitate development of a generalized regression model to predict chlorophyll a without independent verification from concurrent lake sampling. Atmospheric scattering is a major source of error when attempting to predict results using these regression techniques. Efforts to quantify and reduce the atmospheric components inherent in satellite data could significantly improve techniques for estimating spatial trends and concentrations of chlorophyll a and turbidity on Lake Okeechobee.

LITERATURE CITED

Carpenter, D. S., and Carpenter, S. M., 1983. Modeling inland water quality using landsat data. Remote Sens. Environ. 13(4): 345-352.

Federico, A. C., Dickson, K. G., Kratzer, C. R., and Davis, F. E. 1981. Lake Okeechobee water quality studies and eutrophication assessment. Tech. Pub. 81-2, South Florida Water Management, West Palm Beach, Fl.

Gallo, K. P. and Eidenshink, J. C. 1988. Differences in visible and near_IR responses, and derived vegetation indices, for the NOAA-9 and NOAA-10 AVHRRs: a case study. Photogrammetric Engineering and Remote Sensing 54(4): 485-490.

Jones, B. L. and Federico, A. C. 1984. Phytoplankton, Chlorophyll a, and Primary production in Lake Okeechobee. Tech. Pub. 84-4, South Florida Water Management District, West Palm Beach, Fl.

Lathrop, R.G,JR., and Lillesand, T.M., 1986. Use of thematic mapper data to assess water quality in Green Bay and central Lake Michigan. Photogrammetric Engineering and Remote Sensing 52(5): 671-680.

Marshall, M. L. 1977. Phytoplankton and primary productivity studies in Lake Okeechobee during 1974. Tech. Pub. 77-2, South Florida Water Management District, West Palm Beach, Fl.

Price, J. C. 1987. Calibration of satellite radiometers and the comparison of vegetation indices. Remote Sens. Environ. 21: 15-27.

Price, J. C. 1988. An update on visible and near infrared calibration of satellite instruments. Remote Sens. Environ. 24: 419-422.

Ritchie, J. C., Cooper, C. M., and Yongqing, J. 1987. Using landsat multispectral scanner data to estimate suspended sediments in Moon Lake, Mississippi. Remote Sens. Environ. 23: 65-81.

Standard Methods for the Examination of Waste Water and Sewage (16th ed.) 1985. American Public Health Association, New York. 1268pp.

Strickland, J. D. H. and Parsons, T. R. 1968. A practical handbook of seawater analysis. Fisheries Research Board of Canada, Ottawa. Bull. No. 167.

Stumpf, R. P. 1987. Application of AVHRR satellite data to the study of sediment and chlorophyll in turbid coastal water. NOAA Tech. Memo NESDIS AISC 7, Marine Environmental Assessment Division Assessment and Information Services Center, Washington, D. C.

Stumpf, R. P. and Tyler, Mary A. 1988. Satellite detection of bloom and pigment distributions in estuaries. Remote Sens. Environ. 24: 385-404.

Uno, S., Sugahara, Y., and Hayahawa, 1980. Remote Sensing of Chlorophyll Found in Bodies of Water. Proceedings, Fourteenth International Symposium of Remote Sensing of Environment. Ann Arbor, Michigan, pp. 1147-1157.

Verdin, J.P., 1985. Monitoring water quality conditions in a large western reservoir with landsat imagery. Photogrammetric Engineering and Remote Sensing 51(3): 343-353.

Plate 1 LOCATION MAP OF LAKE OKEECHOBEE, FLORIDA. IMAGE PRODUCED FROM THE NEAR-INFRARED (BAND 2) OF AVHRR SATELLITE DATA.

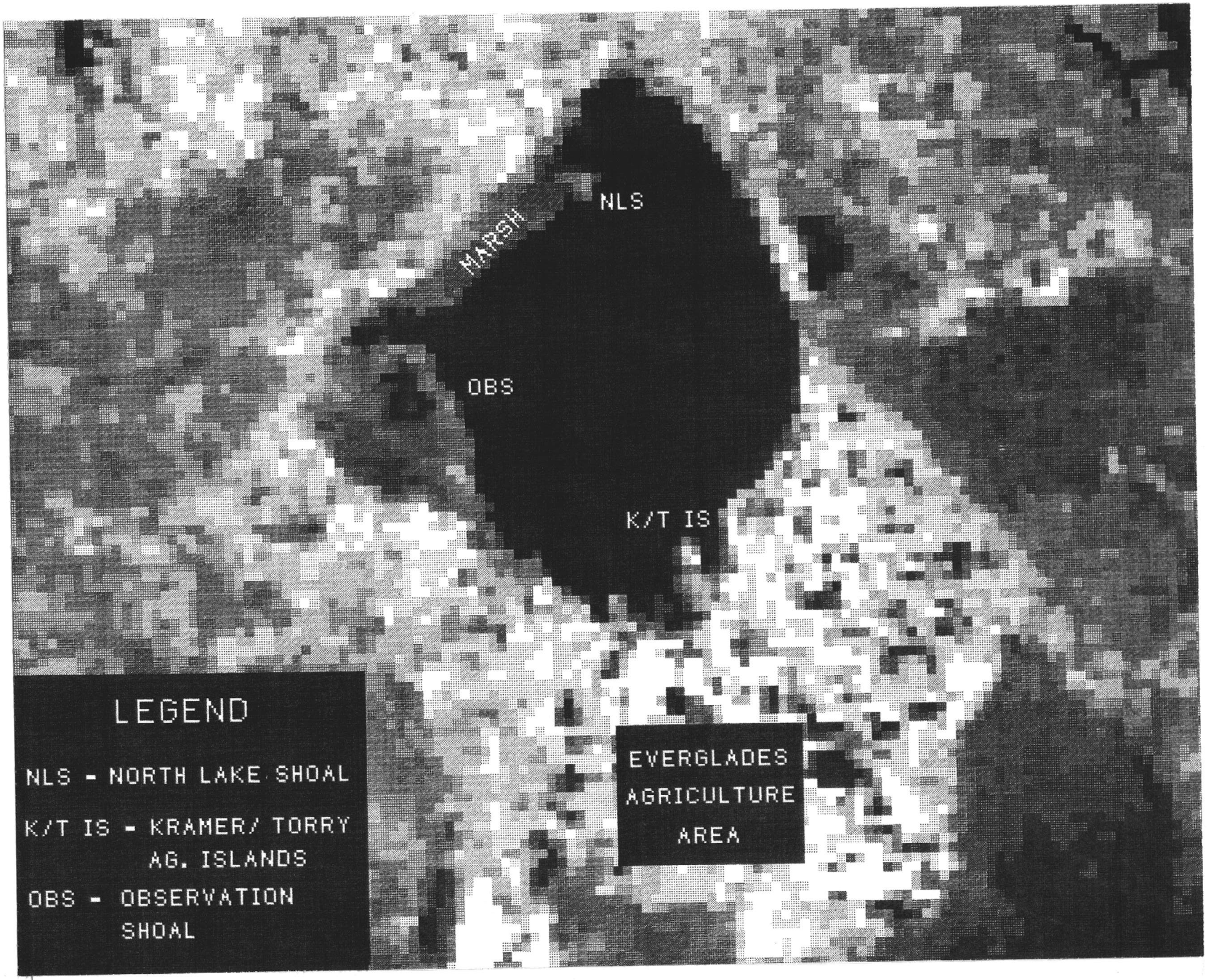
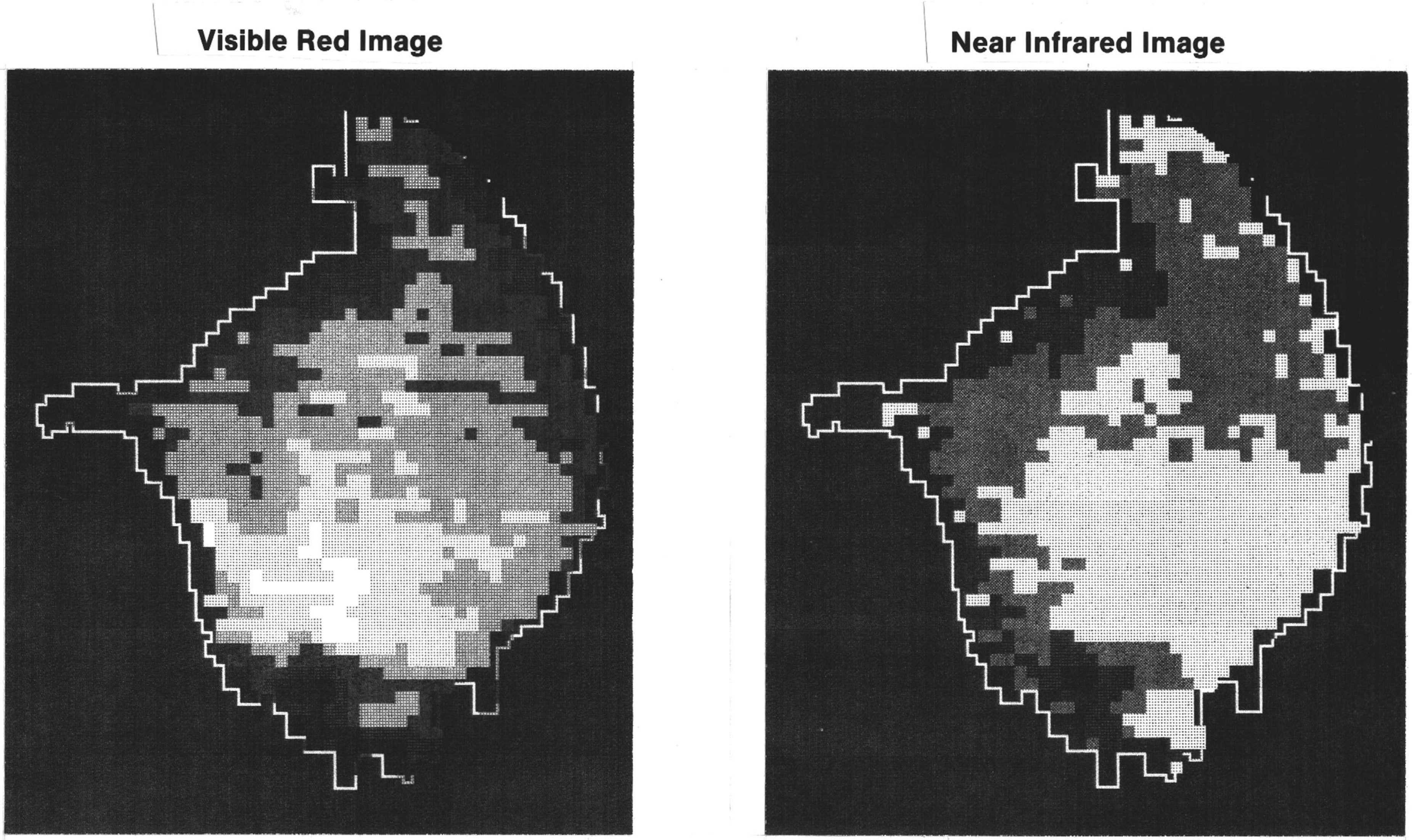


Plate 2 DIGITALLY ENHANCED NEAR-INFRARED IMAGE OF LAKE OKEECHOBEE TOGETHER WITH PROMINENT GEOGRAHIC FEATURES.



Visible Red Image

Near Infrared Image

Plate 3 ALBEDO DISTRIBUTIONS IN LAKE OKEECHOBEE FOR VISIBLE RED AND NEAR-INFRARED BANDS. WHITE PIXELS DENOTE AREAS OF HIGH REFLECTANCE WHILE DARK PIXELS DENOTE AREAS OF HIGH ABSORBANCE. LAND AND MARSH AREAS HAVE BEEN MASKED IN BLACK.

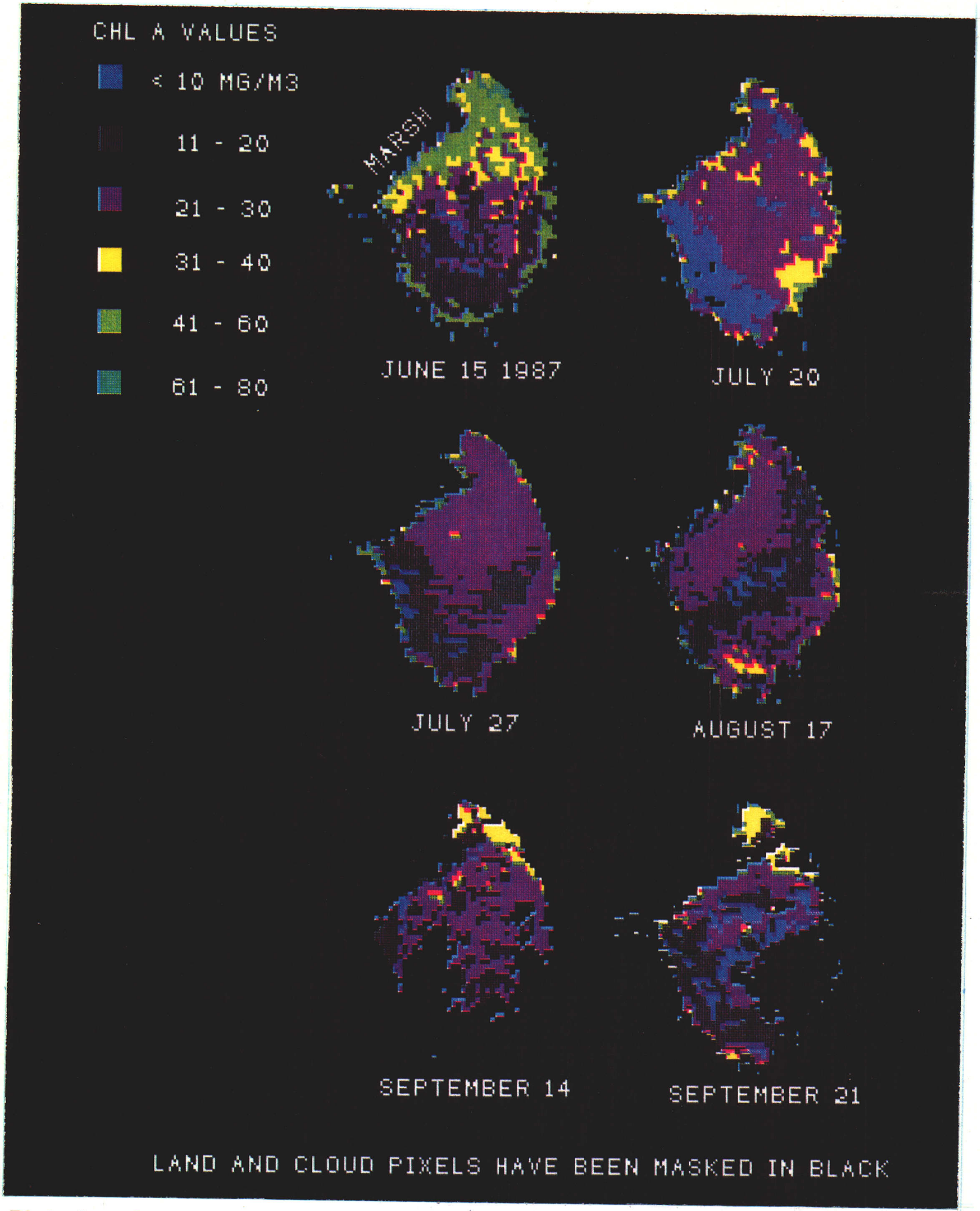


Plate 4 **SPATIAL DISTRIBUTIONS OF CHLOROPHYLL *a* BASED ON REGRESSION MODELS. LAND AND WATER PIXELS HAVE BEEN MASKED IN BLACK.**

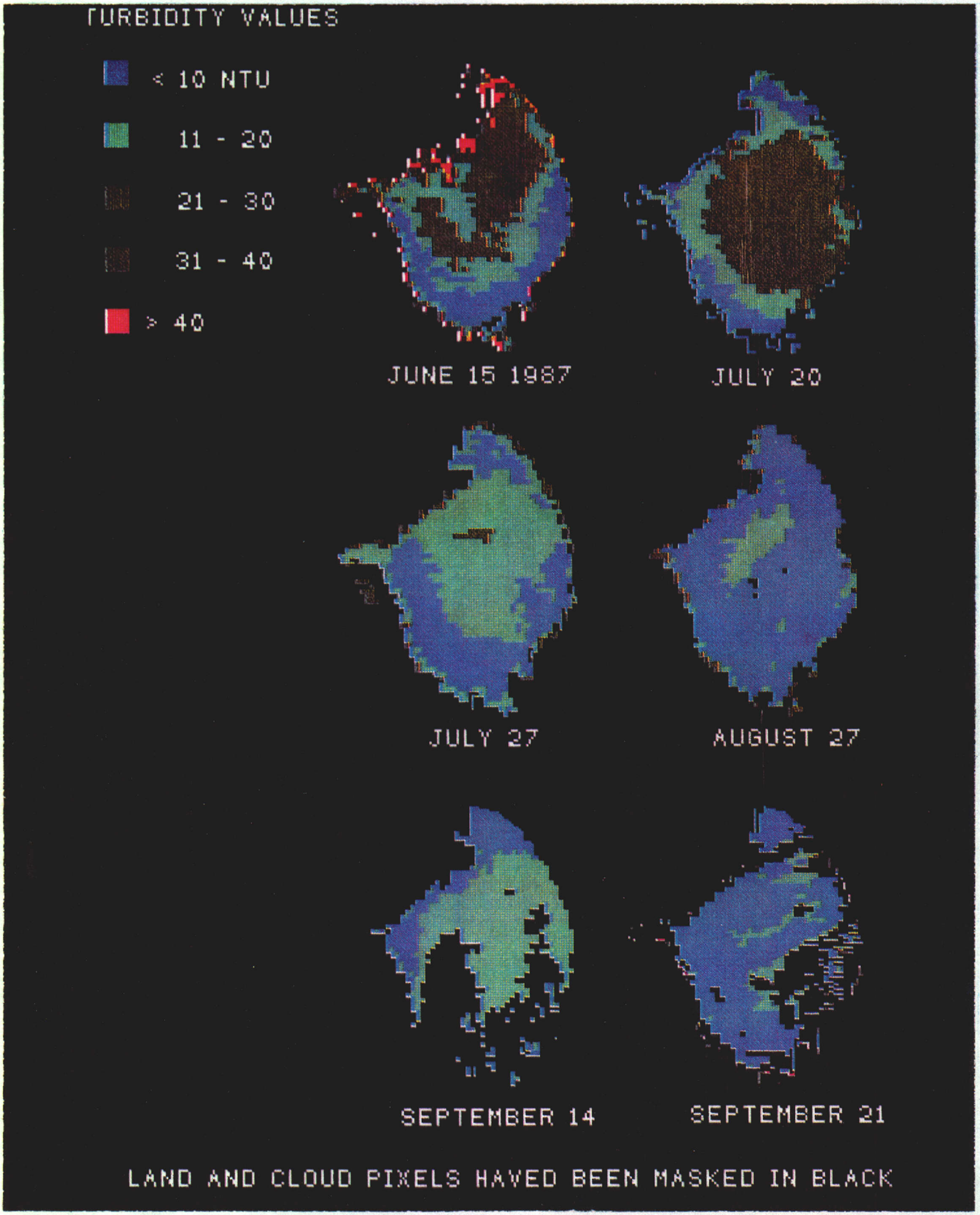


Plate 5 SPATIAL DISTRIBUTIONS OF TURBIDITY BASED ON REGRESSION MODELS. LAND AND CLOUD PIXELS HAVE BEEN MASKED IN BLACK.

Plate 6 TM SATELLITE IMAGE OF LAKE OKEECHOBEE ON 2 SEPTEMBER 1987. IMAGE IS ENHANCED TO SHOW MIXING OF TRIBUTARY DISCHARGES WITH AMBIENT LAKE WATER. THE DARK PLUME OF WATER FLOWING FROM THE C-38 (KISSIMMEE RIVER) IS EASILY DISTINGUISHED IN THE UPPER NORTHWEST CORNER OF THE LAKE. SIMILAR PLUMES WERE IDENTIFIED IN THE AVHRR SATELLITE DATA.