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Satellite observations of calcium carbonate precipitations in the Great Lakes[1]

Alan E. Strong
National Environmental Satellite Service, NOAA, Washington, D.C. 20233

Brian J. Eadie
Great Lakes Environmental Research Laboratory, NOAA, Ann Arbor, Michigan 48104

Abstract

Reflectance patterns apparently from calcium carbonate ($CaCO_3$) precipitation have been mapped in the Great Lakes using satellite multispectral imagery. The milky water phenomenon ("whiting") occurred regularly in summer and fall during the period studied, 1972–1975, in Lakes Ontario, Erie, and Michigan but not in Superior and Huron. In situ data provide nearly irrefutable evidence that these whitings are calcareous. They are attributed to supersaturation of $CaCO_3$ during periods of thermal stratification and are most intense in the warmer areas of the lakes. The whitings are maximal several meters below the surface and are undoubtedly significant with respect to light transmission, affecting the euphotic zone and thereby photosynthetic production. They may serve as lakewide markers in synoptic analysis of large-scale epilimnial horizontal motions.

Observers aboard research vessels in Great Lakes waters during the mid-1960s noticed the occasional appearance of green or milky water. These milky waters were most apparent in Lake Michigan during August 1966, when Secchi disk readings were reduced to only 2–4 m from the 6–14 m typical of midlake (Ayers et al. 1967). Researchers at the University of Michigan suspected that these attenuating conditions were the result of calcium carbonate ($CaCO_3$) precipitation in the surface waters.

The phenomenon of carbonate precipitation has been documented for small hard-water lakes (Wetzel 1966; White 1974) and in shallow carbonate marine environments (Broecker and Takahashi 1966) and has been called "whiting" (Bathurst 1971). Eadie and Robertson (1976) noted high levels of carbonate supersaturation in Lake Ontario during the period of stratification and a tendency toward undersaturation during winter. A simplified equilibrium model developed by Kramer (1967) also indicates supersaturation of carbonate in the lower Great Lakes.

An extensive study of transparency in Lake Michigan waters was made during 1971 and 1972 (Ladewski and Stoermer 1973). Drastic reductions in transparency began during July in both years and lasted for about 2 months. The reductions are most marked at the deeper water stations that are less affected by noncarbonate suspended particulate matter. During September minimum transparencies were observed at these midlake stations (>40-m depth). Average midlake Secchi depth readings in July were between 9 and 10 m, but were only 3 m by September. Furthermore, the midlake Secchi depths, which had been nearly 6 m deeper in July than the nearshore stations (<10 m), fell to within 1 m of the nearshore readings by September, only 2 months later. Ladewski and Stoermer found no increase in chlorophyll *a* and total algal cell concentrations for 1971 until late August and early September.

Analysis of multispectral data from NASA's Landsat satellite (formerly Earth Resources Technology Satellite—ERTS) shows that the whitings occur several meters below the surface in what was shown by NOAA satellite data to be relatively warm water (Strong et al. 1974). Vivid displays of whitings are frequently observed during or immediately following periods of upwelling (Strong et al. 1974) due to the contrast between the

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Table 1. NOAA (Very High Resolution Radiometer), Landsat (Multispectral Scanner Subsystem), and Skylab (Earth Terrain Camera) satellite statistics.

	NOAA-2,-3,-4 (VHRR)	Landsat-1,-2 (MSS)	Skylab (ETC)
Altitude	1,480 km	900 km	435 km
Equator crossing direction	0900 local time Southbound	0942 local time Southbound	Variable Both
Period	105 min	103 min	93 min
Ground resolution (nadir)	1,000 m	100 m	17–30 m
Data channels	Visible/IR	Visible/near-IR	Visible/near-IR
Wavelengths	0.6–0.7 μm 10.5–12.5 μm	0.5–0.6 μm; 0.6–0.7 μm 0.7–0.8 μm; 0.8–1.1 μm	0.4–0.7 μm color 0.5–0.7 μm B&W 0.5–0.88 μm color
Repeat cycle	12 h	18 days*	5 days
Data coverage swath	2,000 km	186 km	109 km
Launch dates	15 Oct 72—NOAA-2 6 Nov 73—NOAA-3 15 Nov 74—NOAA-4	25 Jul 72—Landsat-1 22 Jan 75—Landsat-2	May 73

* Landsat-2 orbited so that with both satellites a 9-day repeat cycle has been possible since January 1975.

clearer upwelling water and the adjacent epilimnetic water. The perspective obtained by remote sensing from space permits a valuable extension of the conventional data over the entire Great Lakes system.

Table 2. Landsat and Skylab data for Lakes Michigan, Erie, and Ontario. X—Not observed (clouds); N—no whiting; L—light; M—moderate; H—heavy; parentheses—Skylab. (Subscripts indicate date satellite observation was made.)

Date	Michigan	Erie	Ontario
Aug 72	N_5	X	N_{20} L_{21}
Sep	L_{14}	X	L_6
Oct	$M_{1,2}$ N_{19}	N_{15}	N_{13}
Nov	N_6	M_{20}	X
Jun 73	L_{10}	M-$L_{23,24,25}$	X
Jul	L_{16}	X	$H_{9,11}$ $M_{27,29}$
Aug	$H_{21,22}$ (H_5)	X	M_{15} H_{16}
Sep	H_9 (H_7, $M_{16,18}$)	L_3	M_3 N_{19}
Oct	L_{14}	X	L_{25}
Nov	X	M_{14}	X
Jan 74	X	X	X
Jul	L_{29}	L_6	L_6 M_{24}
Aug	L-M_{17}	X	X
Sep	$H_{3,4,21,22}$	M_{16}	N_{14} L_{16}
Oct	$L_{9,10}$ N_{27}	M_{22}	L_4 M_{22}
Nov	X	X	X
Jun 75	X	X	X
Jul	X	L_1 M_{28}	L_1 M_{28}
Aug	$L_{3,10}M_{11,28,30}$	X	X
Sep	$M_{7,17,26}$	M_{29}	L_{29}
Oct	$L_{4,13}$	X	X
Nov	X	X	X

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Methods

Three separate spacecraft systems are used in this study. The NASA Landsat satellites (Table 1) are used for the basic data set. We have used Landsat MSS (Multispectral Scanner Subsystem) data in the 0.5–0.6-μm band, since data taken in the green portion of the spectrum are needed to monitor the whitings accurately. Since the first Landsat launch in July 1972, imagery of select locations has been available on an 18-day revisit cycle. With the launch of the second Landsat, the repeat cycle was shortened to 9 days (using both satellies). All whiting observations by Landsat between 1972 and 1975 in Lakes Michigan, Erie, and Ontario are listed in Table 2.

The NOAA polar orbiting operational satellites that provide daily coverage of the Great Lakes unfortunately provide imagery in the visible portion of the spectrum only in the red wavelengths (0.6–0.7 μm) so that little water penetration is possible, and these data are not too useful in identifying whitings; furthermore, the spatial resolution of the measurements is an order of magnitude more coarse than

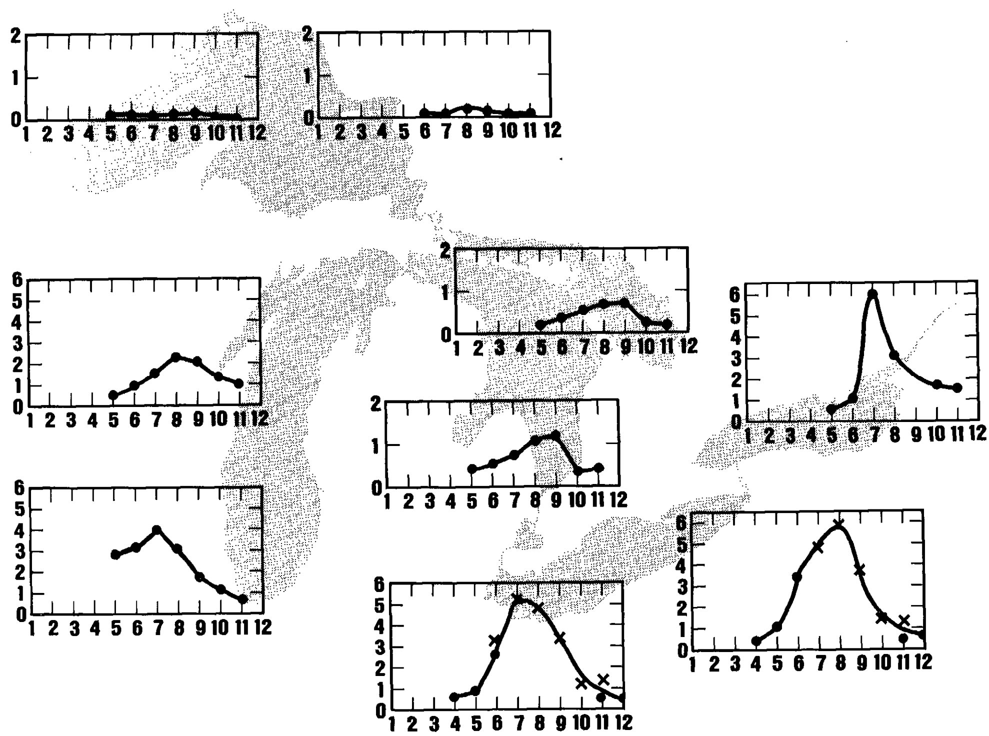

Fig. 1. Monthly ratios of (Ca^{2+}) (CO_3^{2-}) K'sp for selected regions of Great Lakes: E Superior—1968; W Superior—1969; N Michigan—1970; S Michigan—1975; N and S Huron—1966; E Erie—1965, ×, and 1967, ●; W Erie—1965, ×, and 1967, ●; Ontario—1971.

that for Landsat (1,000 vs. 100 m). The NOAA satellite imagery most useful in this work is that from the thermal-infrared sensor. For several cases we have been able to show the effects of active upwelling on the whiting distribution by the use of nearly coincident Landsat and NOAA imagery.

During 1973, an active whiting year especially in Lakes Ontario and Michigan, we were able to use several outstanding images from NASA's Skylab mission which help fill in missing data between cloud-free observations from Landsat. In addition, some excellent natural color photographs of whitings were obtained.

In the calculation of $CaCO_3$ from Ca, pH, alkalinity, and temperature data, dissociation constants have been corrected for temperature and ionic strength, and activities were calculated using modified Debye-Hückel approximations (Stumm and Morgan 1970). Water samples (500 ml) were prepared for scanning electron microscopy by filtering through 0.45-μm Nuclepore pads, drying, and vacuum carbon coating.

Results

The speculation that $CaCO_3$ was the principal cause of whiting in the Great Lakes was investigated in several ways. Theoretically, one can calculate the equilibrium concentration of $CaCO_3$ from available data (pH, temperature, alkalinity, Ca^{2+}) and compare this to the value at saturation. At saturation the ionic product (*IP*) of calcium and carbonate equals the apparent solubility product (K'sp); for supersaturation the ratio IP:K'sp will be >1.

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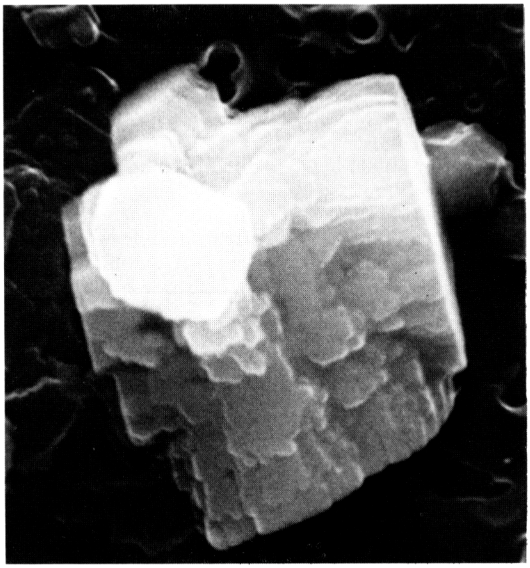

Fig. 2. $CaCO_3$ crystal (10,000× enlargement) on 0.4-μm Nuclepore filter. Surface sample collected 18 km off eastern shore in southern basin of Lake Michigan, July 1976.

Research Laboratory from 1965 through 1975 were analyzed for the $IP:K'$sp ratio (Fig. 1). Lakes Ontario, Erie, and Michigan exhibit extensive supersaturation during the warmer months, while Lakes Huron and Superior remain undersaturated throughout the year. This is in excellent agreement with the satellite observations of whitings. The equilibrium calculations do not indicate the actual precipitation of $CaCO_3$: the kinetics of precipitation above equilibrium concentrations are probably affected by organic coatings, the availability of nucleation sites, and biological activity. However evidence for precipitation does exist in the sediment, Lake Michigan's sediment containing a mean of about 5% carbonate (Torrey 1976) and Lake Ontario about 2% carbonate (Thomas et al. 1972).

The nature of the particulate matter causing the whitings was investigated through a series of scanning electron micrographs; a representative example collected on 29 July 1976 is shown in Fig. 2. X-ray fluorescence spectroscopy showed this particle to be almost pure calcium carbonate. The particle has the rhombohedral structure of the more stable calcite form, layered probably through the kinetics of slow accretion.

Other supporting data for our interpretation of the satellite observations include midlake calcium and transparency measurements taken during a 1970 midsummer cruise of Lakes Superior, Michigan, Huron, and Erie (Schelske and Roth 1973). These measurements are listed in Table 3, together with additional data from Weiler and Chawla (1968). Calcium and alkalinity levels are higher in Lakes Michigan, Erie, and Ontario than in Superior and Huron. Furthermore, a decrease in transparency is noted in these lakes during summer when $CaCO_3$ has been observed to be precipitating most actively.

1973 Whitings—Of all the Great Lakes whiting observations in the 1972–1975 period, no year showed more activity in the production of $CaCO_3$ than 1973. During the first Landsat cycle across the Great Lakes in July, Lake Ontario showed extensive whiting (Fig. 3). This 9 July observation coincides with strong upwelling along the Canadian shore from Toronto eastward to Point Petre where the milky water is directed offshore to-

Table 3. Comparative calcium and Secchi data for the Great Lakes (values from Schelske and Roth 1973, except those in parentheses from Weiler and Chawla 1968).

				Erie		
	Superior	Michigan	Huron	West	East	Ontario
Ca, mg·liter^{-1}	14.5	37.4	26.2	32.1	37.8	—
	(13.2)		(28.1)		(37.4)	(40.3)
Alkalinity, mg $CaCO_3$·liter^{-1}	(41.3)	(113)	(78.6)		(92.4)	(92.8)
Secchi, m	12.6	4.8	7.9	2.0	4.4	—

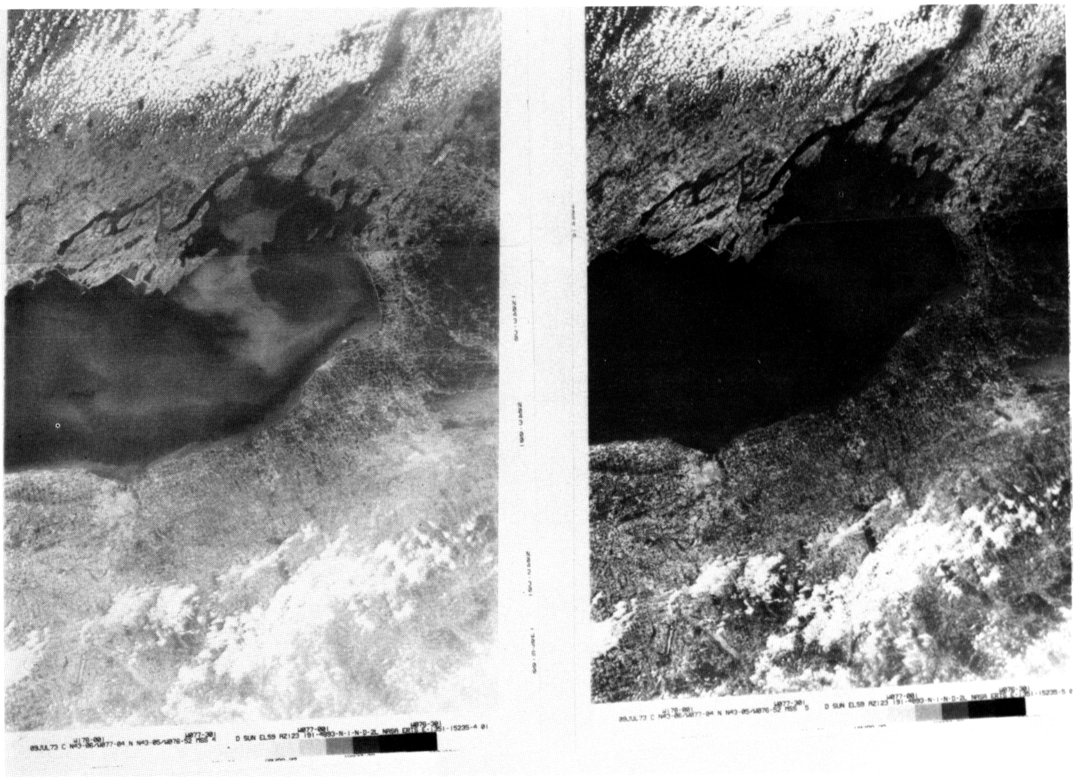

Fig. 3. Landsat-1 satellite images of eastern Lake Ontario taken on 9 July 1973. Bandwidth of left image swath is 0.5–0.6 μm (green, MSS-4); right is 0.6–0.7 μm (red, MSS-5).

ward the southeast. The NOAA-2 VHRR data confirmed this upwelling, as did an Airborne Radiation Thermometer Analysis by the Canadian Atmospheric Environment Service. The considerable milkiness in the surface waters visible in the 0.5–0.6-μm channel in Fig. 3 is barely apparent in the 0.6–0.7-μm channel data. Since the red channel is effective only for the upper few meters of the water, and the green channel is effective for observations to depths approaching 10 m, we conclude that the milky water is more pronounced somewhat deeper beneath the surface. In the case of suspended sediment from fluvial discharges, MSS-5 (red) data have been found most useful for monitoring turbidities (Stumpf and Strong 1975).

By 16 July Landsat had progressed westward to Lake Michigan, whose orientation permits nearly total coverage by a single day's data swath. Although the whiting was faint on this date (Fig. 4), it had intensified and expanded in extent since an earlier cloud-free Landsat observation in June. By the next Landsat cycle (18 days later) the $CaCO_3$ precipitation was much further developed. Although the atmosphere was hazy on 3 August, considerable detail in the whiting distribution may be observed through the haze. A most impressive display of near-surface $CaCO_3$ was seen during the subsequent Landsat transit of Lake Michigan on 21 August. Intense upwelling, introducing cooler, lower carbonate water, is responsible for the brightness gradient along the eastern shore. Thermal data from the NOAA-2 VHRR on 22 August (Fig. 5) delineate the extent and intensity of upwelling. (Identical upwelling activ-

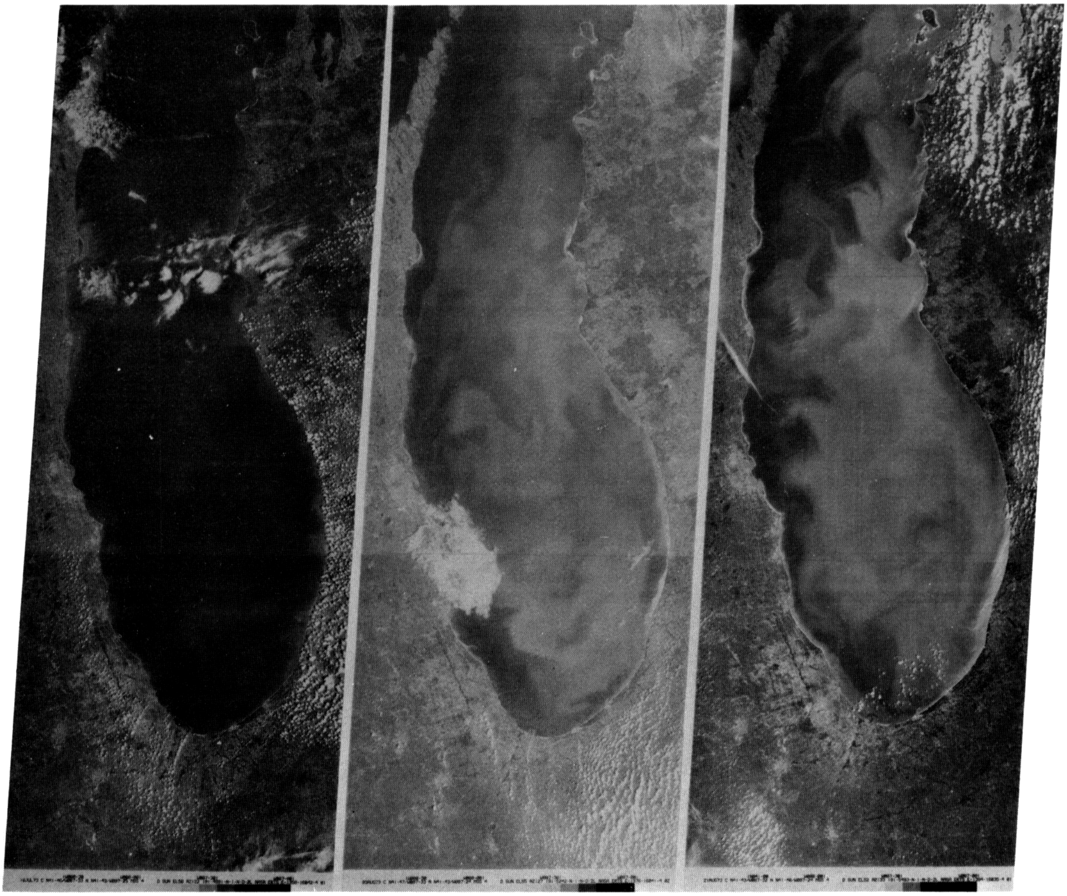

Fig. 4. Three selected 1973 Landsat-1 image swaths of Lake Michigan. All data are 0.5–0.6-μm bandwidth (MSS-4). Left to right: 16 July, 3 August, 21 August.

ity was noted on 21 August but was distorted near the edge of the imagery.) Near-coincident Landsat imagery of the westernmost portion of Lake Michigan on 22 August (not shown) provided a "picture" of the whiting distribution virtually identical to that on 21 August. More detail about this August 1973 whiting event is given by Strong et al. (1974).

On 3 September 1973 Landsat provided imagery of both western Lake Ontario and eastern Lake Erie (Fig. 6). $CaCO_3$ is still abundant in the near-surface waters of Lake Ontario; however, we interpret the darker "tongue" of Niagara River–Lake Erie water extending to nearly midlake as containing little $CaCO_3$. A cyclonic gyre may be faintly seen in Lake Erie near midlake toward the left edge of the image, probably revealed by the variable horizontal whiting distribution. Nevertheless, the $CaCO_3$ levels in Lake Erie appear generally lower than those in Lake Ontario.

On 7 September, the astronauts in Skylab (SL-3) gathered information on the Lake Michigan whiting with the satellite's Earth Resources Experimental Package (EREP). The black and white photographs in Fig. 7 were made using the ETC 0.5–0.7-μm band (Table 1). The original photographs yield surface resolutions of 21 m. The photographs from the Skylab pass over northern Lakes

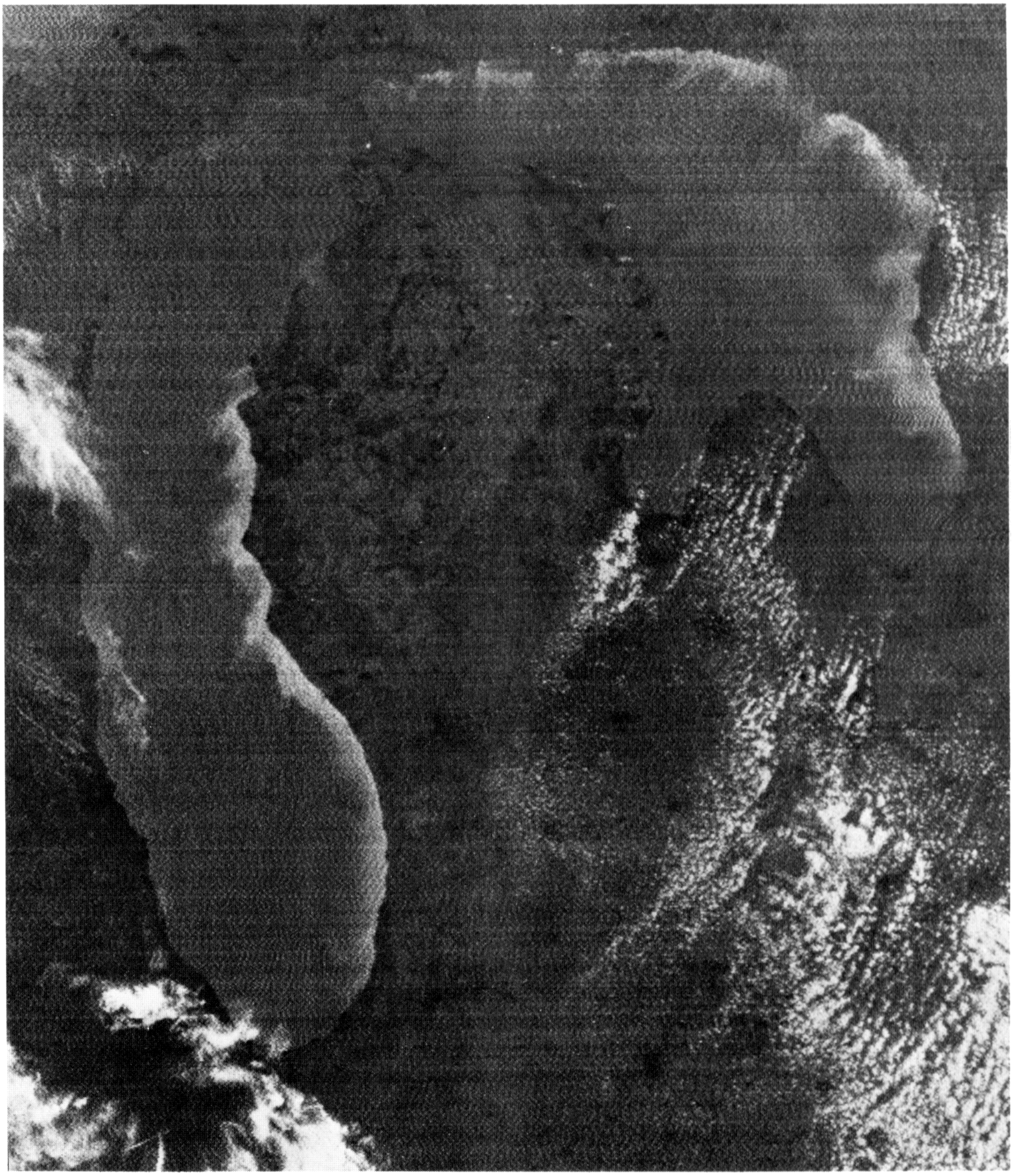

Fig. 5. Thermal-infrared image from NOAA-2 satellite for 22 August 1973 depicting upwelling (lighter tones) along eastern shoreline (right) of Lake Michigan.

Michigan and Huron show the apparent dissolving effects of Lake Huron water (Table 2). As those $CaCO_3$-rich waters move eastward and southward along the Lake Huron shoreline the milky water gradually disappears. Ladewski and Stoermer (1973) reported that on a September cruise in 1972 through the Strait of Mackinac, Secchi transparencies decreased from 10 m to 3–5 m as they passed from Lake Huron into Lake Michigan and the water became milky.

Fig. 6. Landsat-1 image of western Lake Ontario (above) and eastern Lake Erie (below) on 3 September 1973, 0.5–0.6-μm bandwidth.

Eleven days later, 18 September, Skylab passed over the southern portion of Lake Michigan. The photomosaics in Fig. 8 should be compared with Fig. 7. Suspended sediment gives a much different reddish hue (in the original color photographs) when viewed from above and can be observed at most river mouths in Lake Michigan. Polluted (dark) water from Indiana Harbor is being carried eastward in Lake Michigan under northwesterly winds.

By October both Lakes Michigan and Ontario had returned to more normal levels of $CaCO_3$ production. At this time of year the lakes are cooling and displayed little apparent horizontal color contrast (brightness).

1972, 1974, and 1975 whiting activity in Lake Michigan—1972 was a disappointing year for Landsat observations of summer whiting in the Great Lakes. Most of the chemical precipitation may have occurred later in the year (Ladewski and Stoermer 1973). In 1974, as in 1973, vivid displays of whiting were seen in Lake Michigan waters. Although the Landsat coverage cycle unfortunately tended to coincide with cloudy conditions over the lakes during the summer, a good observation (not shown) was made on 4 September of the western half of the lake.

During a research aircraft flight on 10 September 1975 across Lake Michigan between Ludington (Michigan) and Manitowoc (Wisconsin), we saw very green milky water of nearly homogeneous reflectance during the entire flight. During this period water samples were taken off Ludington which, under scanning electron micrograph analysis, gave us the first identification of calcite crystals. These surface samples revealed no significant differences in pH, alkalinity, and temperature. This was our first effort to collect simultaneous data.

Discussion

Our results have shown the extent of probable carbonate precipitation but have not dealt with its cause. Both the increase in pH due to photosynthesis, resulting in higher CO_3^{2-} activities, and the seasonal warming, resulting in lower $CaCO_3$ solubility, are significant although their relative importance is yet to be determined.

The effects on the biota in the euphotic zone when this milky cloud is present in the upper layers are poorly known. One result of $CaCO_3$ crystal formation is the reduction of light available for photosyn-

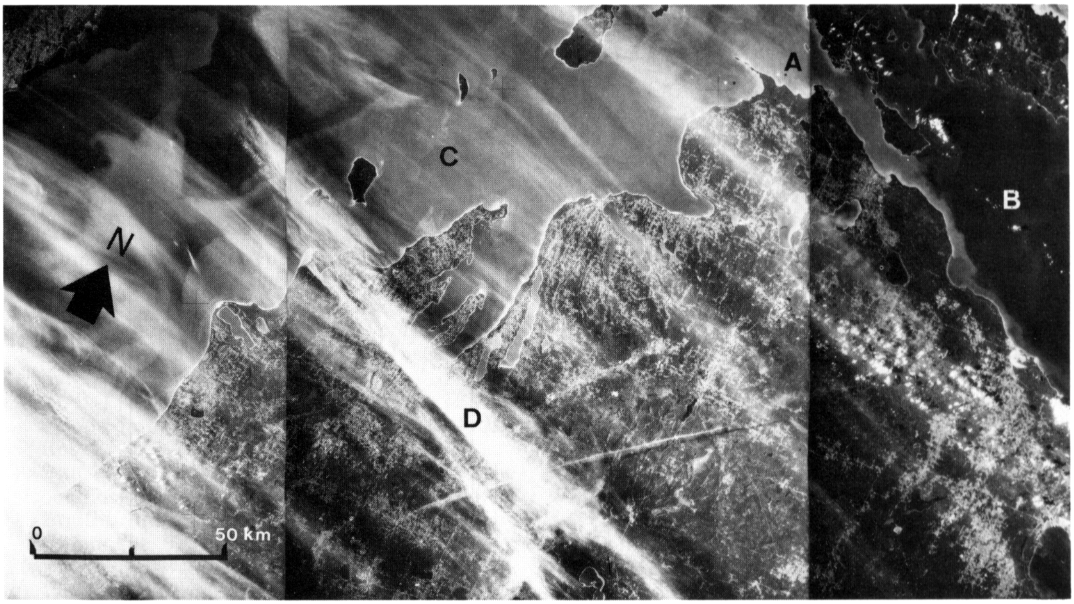

Fig. 7. Black and white mosaic of 0.5–0.7-μm band Skylab photographs of northern Lakes Michigan and Huron. Photos taken on 7 September 1973. Traverse City and most of Lake Michigan to south partially obscured by cloud. A—Straits of Mackinac; B—Lake Huron; C—Lake Michigan; D—cloud streak.

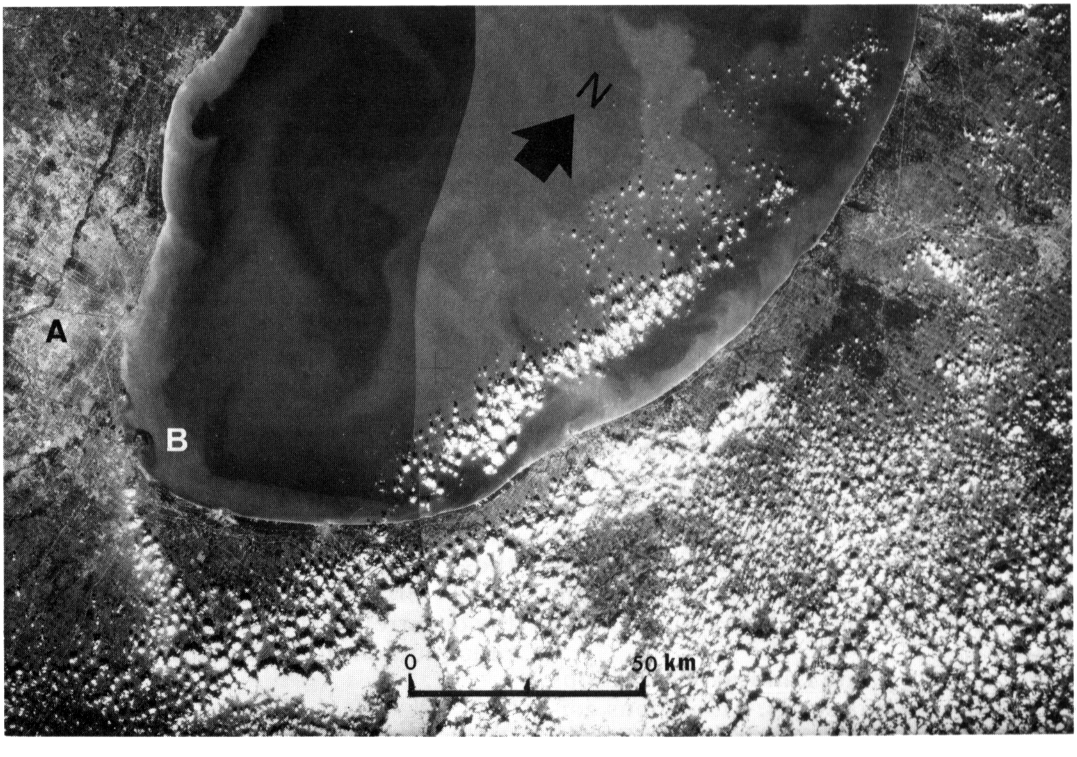

Fig. 8. Black and white mosaic of Skylab photographs of southern Lake Michigan. Photos taken on 18 September 1973. A—Chicago; B—Indiana Harbor.

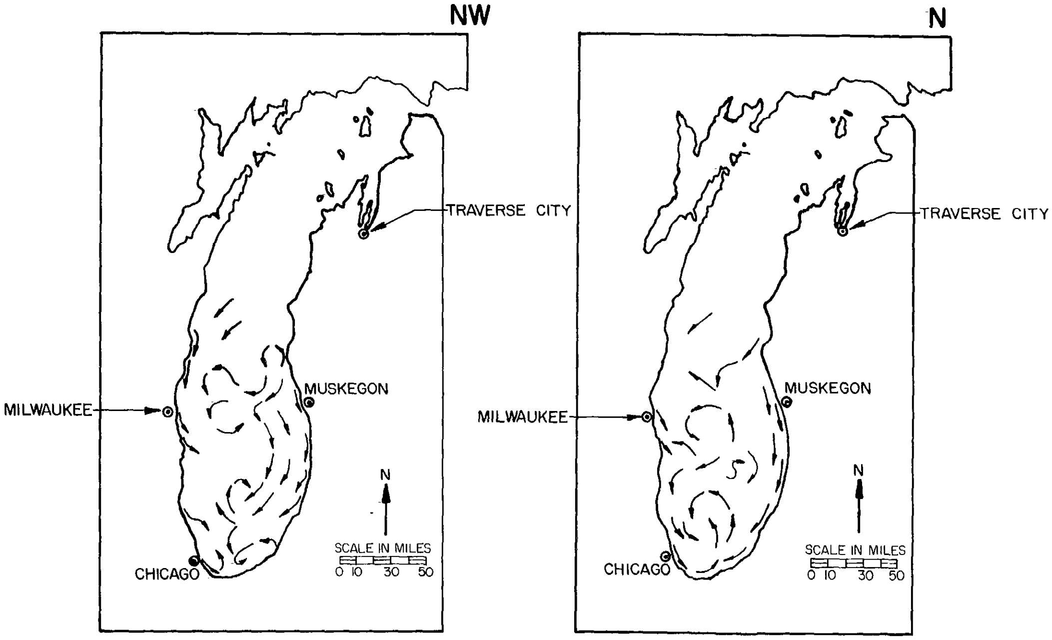

Fig. 9. Surface current patterns as deduced from Landsat imagery during periods of northwesterly and northerly resultant wind stress.

thesis. A possible second effect is the complexation of nutrients, vitamins, and trace metals on the organic coatings which seem to form on these particles (White 1974; Chave 1970).

We have been able to use these extensive natural markers for charting near-surface current patterns in the lakes (Stumpf and Strong 1975), in good agreement with previous drogue measurements under similar wind conditions (Ayers et al. 1958). From the Landsat imagery of 3 August 1973 and that of 16 July 1973 and 21 August 1973 (Fig. 4), currents associated with northwesterly and northerly winds were identified. Composite current charts such as those shown in Fig. 9 would be restricted exclusively to nearshore areas (river plumes, etc.) were it not for the whiting phenomenon that provides a tracer in midlake waters.

We need to relate Landsat observations to in situ measurements. An obvious correlation would be expected with Secchi disk measurements of water transparencies. We are working to relate $CaCO_3$ concentration horizontally and with depth to satellite observations. Furthermore, the green (0.5–0.6 μm) channel on Landsat may not be optimal for quantitative measurements of $CaCO_3$ precipitation by remote sensing. Data from the Coastal Zone Color Scanner (CZCS), to be launched in 1978 on the Nimbus-G satellite, will undoubtedly provide more definitive data for studies in the Great Lakes and other coastal areas. The CZCS will provide higher spectral resolutions and more frequent coverage than Landsat. With synoptic coverage made possible by earth satellites and a specific ground program, the causes and effects of these extensive whitings should soon be much better understood. Meanwhile, these Landsat observations have provided the first substantial documentation of the occurrence and distribution of $CaCO_3$ precipitation in the Great Lakes.

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