SURFACE CIRCULATION IN THE GREAT LAKES AS OBSERVED BY LANDSAT-1 AUGUST 1972-DECEMBER 1973: SOUTHERN LAKE MICHIGAN

By Harry G. Stumpf and Alan E. Strong
National Environmental Satellite Service, NOAA, Suitland, Maryland

ABSTRACT

The surface current circulation patterns of southern Lake Michigan have been charted for all cardinal and subcardinal wind directions, employing LANDSAT-1 observations of the distribution of natural tracing material borne in the surface waters. These colorants consist chiefly of river discharges composed of suspended sediments, pollutants, and algae; extensive chemical precipitations proved valuable for areas farther from shore. Comparison of the satellite-derived surface current charts with previous theoretical and empirical studies shows good agreement.

INTRODUCTION

The LANDSAT-1 (formerly ERTS-1) system has added a new dimension to physical oceanography and limnology. Conditions permitting, scientists are now able to chart circulation patterns using natural tracing material borne in the surface waters. These colorants are chiefly turbidities from river discharges consisting chiefly of suspended sediments, pollutants, algae or natural dyes. Occasionally chemical precipitations are noted in the imagery (Figure 1); these, too, can be employed as circulation tracers, and they are particularly useful in areas farther from shore. Other sources of information are suspended sediment plumes originating from areas of shoreline erosion.

Synoptic oceanographic or limnologic investigations have always been difficult, if not impossible, from surface vessels. Circulation patterns are constantly being altered by changing meteorological conditions. The observation of naturally-occurring tracers from space, as a near-instantaneous "snap shot", provides circulation information that should relate to the meteorological influences at and immediately prior to the time of the satellite imagery.

METHOD OF ANALYSIS

Ayers (ref. 1,) has developed an empirical relationship that takes into account the large time lag between the onset of a given wind condition and the response of the surface circulation to this wind. A complete response of current to the wind requires many hours, or even several days. In Ayers' formula the resultant effective wind stress relationship is such that the forcing influence of the previous day is one-half that of the given day. In this Great Lakes investigation we have chosen to utilize three days of wind data prior to each LANDSAT-1 scene. In addition, to emphasize the 24-hour period immediately prior to the satellite data, we have represented the 6-hourly winds as a weighted resultant stress vector as follows:

$$\vec{W}_{(\text{day } 1)} = \frac{\vec{W}_{(-24)} + 2\vec{W}_{(-18)} + 3\vec{W}_{(-12)} + 4\vec{W}_{(-6)}}{10}$$

The subscript after each vector wind observation denotes observation time (hours) before noon of the day of the LANDSAT-1 observation.

A final vector resultant wind for the three-day period was obtained using the following formula:

$$\vec{W} = \frac{\vec{w}_{(day\ 3)} + 2\vec{w}_{(day\ 2)} + 4\vec{w}_{(day\ 1)}}{7}$$

For a more rigorous relationship one must take into account additional parameters such as atmospheric stability over the water, wave conditions, and current locations as a function of the distance to shore (ref. 2). Much of this fine-tuning, however, is not very realistic with the present paucity of wind data. In this study we have chosen to use the U.S. Coast Guard weather observations from shore installations rather than inland sites. Although these winds may suffer somewhat due to local anomalies in the wind field (e.g., lake breeze circulations), they are felt to be the most representative of true lake winds.

Circulation vectors have been extracted from each LANDSAT-1 scene using all natural or man-made tracers in the surface waters available to the analyst. As an illustrative example, the interested reader should compare the circulation derived for southern Lake Michigan under a northerly resultant wind (Figure 2) with the "whiting" image (Figure 1); the authors have discussed these extensive precipitations of calcium carbonate in detail elsewhere (refs. 3 and 4). Although complex, much of the analysis is straightforward in the hands of a trained interpreter.

Charts were prepared for all cardinal and subcardinal resultant wind directions (i.e., N, NE...NW). Some LANDSAT-1 observations of currents under a few wind directions were not available during the study period (August 1972 to December 1973). Whenever more than one LANDSAT-1 observation was used in a given area, the currents presented are composites. Although most of the current charts are based on only one LANDSAT-1 pass, if two scenes were available for a given resultant wind direction the observation under the stronger wind stress was generally used. It should be mentioned that circulation variations should be expected under weaker or stronger resultant wind stresses from the same direction. We have chosen to concentrate primarily on the direction of the wind vector rather than vector magnitude for this report.

Figure 3 shows the area covered by any given LANDSAT-1 pass.

The major difficulty encountered in the analysis of the LANDSAT-1 images was contamination by sunglint whenever the solar elevation exceeded 55° (ref. 4). Under these high sun angle conditions, current interpretations are subject to large errors. Future investigators should employ a sunglint-removal technique (e.g., MSS-6 minus MSS-5, (ref. 5) for more reliable results.

DISCUSSION

The locations of the wind information used in the preparation of the southern Lake Michigan current charts are shown in Figure 4. All locations referred to in the text are identified on this base chart. Only incomplete wind data were available from the Milwaukee and Muskegon Coast Guard facilities. Table I presents a summary of the LANDSAT-1 images that were analyzed in addition to the resultant wind directions calculated from the above formulae.

Northerly Winds

Figure 2 indicates the general surface circulation established by predominantly northerly light/moderate winds as derived from two cloud-free LANDSAT-1 passes (16 July

1973 and 21 August 1973). The latter pass (Figure 1) was particularly useful because that date marked the occurrence of an extensive $CaCO_3$ precipitation that was especially evident in MSS-4 (ref. 4). The major features established by this wind regime are several large gyres and distinct alongshore currents. An east shore southward current extends from Little Sable Point to Michigan City, where it becomes deflected to the northwest to become part of the eastern boundary of a large counterclockwise eddy off Chicago, first described by Ayers et al. (ref. 6) and confirmed by Bellaire (ref. 7). In this case, the eddy extends as far north as Waukegan. From Little Sable Point a branch of the east shore current flows southwestward and becomes incorporated in a second mid-lake counterclockwise gyre. This corresponds to the eddy noted by Bellaire (ref. 7) above the mid-lake sill between Milwaukee and Muskegon. A third eddy has a clockwise circulation and lies off Benton Harbor, Michigan, in the eastern part of the lake. This eddy has been previously observed (refs. 6 and 7), but here it is much smaller than reported previously. Along the Wisconsin shore at Milwaukee there may be a small nearshore clockwise eddy; it has been previously documented (ref. 6), but the evidence in the LANDSAT-1 images indicates only that there is a southward current some distance offshore.

Northeasterly Winds

Only one LANDSAT-1 pass was available for northeasterly wind conditions (17 July 1973), and only the Milwaukee area was sufficiently cloud-free to allow mapping of the sediment distribution patterns (Figure 5). The outflow current begins along the Wisconsin shore at Sheboygan and flows southward. After several days of northeasterly winds, water is transported onto the west shore from Milwaukee to Gary and is piled up there; on the slope of this wind set-up, the water flows southward and northeastward (ref. 6).

Easterly Winds

On 11 March 1973, LANDSAT-1 passed over the southeast portion of Lake Michigan. It was evident from the sediment patterns observed (Figure 6) that the east shore current flowed southward from Holland to Michigan City and then westward to Chicago. Off Michigan City is an apparent small flattened counterclockwise eddy, previously described by Ayers et al. (ref. 6) under a similar easterly wind regime. North of Benton Harbor a branch from the east shore current flows southwestward toward the middle of the lake, presumably to become part of the large clockwise gyre located along the shore between Holland and Benton Harbor. This is the same clockwise gyre discussed under Northerly Winds and documented by Ayers et al. (ref. 6) and Bellaire (ref. 7).

Southwesterly Winds

The current diagram (Figure 7) is a composite analysis of two LANDSAT-1 passes (10 June 1973 and 14 October 1973). The major feature evident in the figure has already been discussed--the large clockwise gyre along the east shore between Benton Harbor and Holland. The southward current along the east shore is very narrow under these southwesterly winds and it was not observed to extend south beyond Benton Harbor, where it turns westward to become incorporated into the eddy. According to the sediment distribution patterns, water is flowing northeasterly directly offshore from Chicago to the center of the lake. This apparent major upwelling has not been previously documented; Ayers et al. (ref. 6) and Bellaire (ref. 7) have described fully-developed gyres at this location. Offshore currents are indicated all along the west shore from Chicago to Sheboygan, suggesting that extensive upwelling was occurring. There may be a small clockwise gyre along the west shore at Waukegan, as suggested by Ayers et al. (ref. 6), but the satellite data are inconclusive.

Westerly Winds

Three cloud-free LANDSAT-1 passes (24 November 1972, 13 December 1972, and 4 May 1973) were composited to obtain the current diagram (Figure 8). The clockwise eddy along the east shore discussed above and previously (refs. 6 and 7) apparently has enlarged considerably from its size under other wind regimes. It now extends from Benton Harbor north to Muskegon with a rather elongated shape. Between Gary and Michigan City lies a large counterclockwise gyre, which was discussed under Northerly Winds. In this case, however, the gyre has been displaced to the southeast as compared with other observations. Sediment distribution patterns suggest also the presence of a counterclockwise eddy above the mid-lake sill between Milwaukee and Muskegon; apparently a northwestward-flowing branch of the east shore southward current provides the driving force for this gyre. This was discussed under Northerly Winds. Alongshore currents converge in the Milwaukee - Racine area and then flow offshore, creating upwelling there and contributing to the circulation of the mid-lake eddy. A similar current convergence exists immediately north of Chicago in the Highland Park area; this offshore flow joins the east shore eddy system in the middle of the southern basin.

Northwesterly Winds

The diagram for northwesterly wind-generated currents (Figure 9) is based solely on one LANDSAT-1 pass (3 August 1973), which coincided with an extensive episode of calcium carbonate precipitation that turned the entire southern basin "milky" in MSS-4 (Figure 10). The east shore southward current is very narrow alongshore. Lakeward of that current is a long narrow band of upwelling from Benton Harbor to Muskegon; this was evident from the sunglint pattern on all four MSS bands. In the center of the lake is an elongated clockwise eddy that was discussed above and by Ayers et al. (ref. 6) and Bellaire (ref. 7); this wind regime has apparently displaced this gyre from the east shore toward the lake center. It extends from as far north as Milwaukee south to Benton Harbor. Between Milwaukee and Muskegon lies the mid-lake counterclockwise gyre discussed above; again it is driven by a westward branch of the east shore southward current that forms the northern boundary of the eddy. As discussed above, there is a flattened counterclockwise gyre from Gary to Benton Harbor driven by a branch current of the large central eddy and by the east shore southward current. Sediment patterns indicate a southward-flowing alongshore current at Chicago and suggest that a counterclockwise eddy exists there (refs. 6 and 7). Alongshore currents from Sheboygan to Highland Park are narrow and southward; at Racine and Highland Park they turn offshore (eastward), indicating upwelling at these locations.

CONCLUSIONS

The prevailing wind direction on Lake Michigan is southwesterly, although during winter northwesterly stresses are common. Along the western shore the current favors a northward direction, beginning with northeasterly to easterly winds, and probably (no LANDSAT-1 observations for easterly, southeasterly or southerly winds along this shore) continuing through southwesterly winds. Along the eastern shore a southward current appears dominant for all winds observed. South of Benton Harbor this flow reverses under southwesterly, westerly and northwesterly winds. The nearshore area between Michigan City, Indiana and Waukegan, Illinois contains an extremely complex circulation. Gyres in the central lake basin have been witnessed under southwesterly, westerly, northwesterly and northerly resultant wind regimes. Comparison with previously-observed, specific, localized circulations shows good agreement.

ACKNOWLEDGMENTS

The authors wish to express appreciation to NASA's Earth Resources Survey Program and their support through LANDSAT Contract S-70246-AG.

REFERENCES

1. Ayers, J.C. (1959a). Great Lakes waters, their circulation and physical and chemical characteristics. Paper presented to the Great Lakes Basin Symp., 29 December 1959, Chicago, Ill.

2. Jones, D.L. and F.R. Bellaire (1962). A numerical procedure for computing wind-driven currents on the Great Lakes. Proc. 5th Conf. on Great Lakes Res., Publ. #9, Great Lakes Res. Div., U. of Michigan, 93-102.

3. Strong, A.E., H.G. Stumpf, J.L. Hart and J.A. Pritchard (1974). Extensive summer upwelling on Lake Michigan during 1973 observed by NOAA-2 and ERTS-1 satellites. Proc. 9th Internat. Symp. on Rem. Sens. Environ., Environ. Res. Inst. of Michigan, Ann Arbor, 923-932.

4. Strong, A.E. and H.G. Stumpf (1974). An evaluation of ERTS data for oceanographic uses through Great Lakes studies. Final Report NASA/GSFC, Greenbelt, Md.

5. Watanabe, K. (1974). Detection of several sea states around Japan from multispectral scanner imageries by ERTS-1. Proc. 9th Internat. Symp. on Rem. Sens. of Environ., Environ. Res. Inst. of Mich., Ann Arbor, 1353-1354.

6. Ayers, J.C., D.C. Chandler, G.H. Lauff, C.F. Powers and E.B. Henson (1958). Currents and Water Masses of Lake Michigan, Great Lakes Res. Inst., U. of Michigan, 169 pp.

7. Bellaire, F.R. (1964). A comparison of methods of current determinations. Proc. 7th Conf. on Great Lakes Res., Great Lakes Res. Div., U. of Michigan, 171-178.

8. Ayers, J.C. (1959b). The Currents of Lakes Michigan and Huron, Great Lakes Res. Inst., U. of Michigan, 51 pp.

TABLE I - LANDSAT-1 FRAMES USED FOR SURFACE CIRCULATION CHARTS OF SOUTHERN LAKE MICHIGAN

Resultant Wind Direction	Orbit #	Date	ID #	Sun Elevation
N	4991	16 Jul 73	1358-16040	58*
			1358-16042	58*
	5493	21 Aug 73	1394-16030	50
			1394-16033	51
			1394-16035	52
NE	5005	17 Jul 73	1359-16094	58*
E	3220	11 Mar 73	1231-15591	36
			1231-15593	37
SE	NONE	NONE	NONE	NONE
S	NONE	NONE	NONE	NONE
SW	4489	10 Jun 73	1322-16042	60*
			1322-16045	61*
	6246	14 Oct 73	1448-16021	34
			1448-16023	35
W	1728	24 Nov 72	1124-16043	23
			1124-16050	24
	1993	13 Dec 72	1143-16102	20
	3973	4 May 73	1285-15590	55*
			1258-15592	56*
NW	5242	3 Aug 73	1376-16034	55*
			1376-16041	55*

* - Solar elevation equal to or greater than 55°. (Possible sunglint contamination and confusion with sediment features used for circulation charting.)

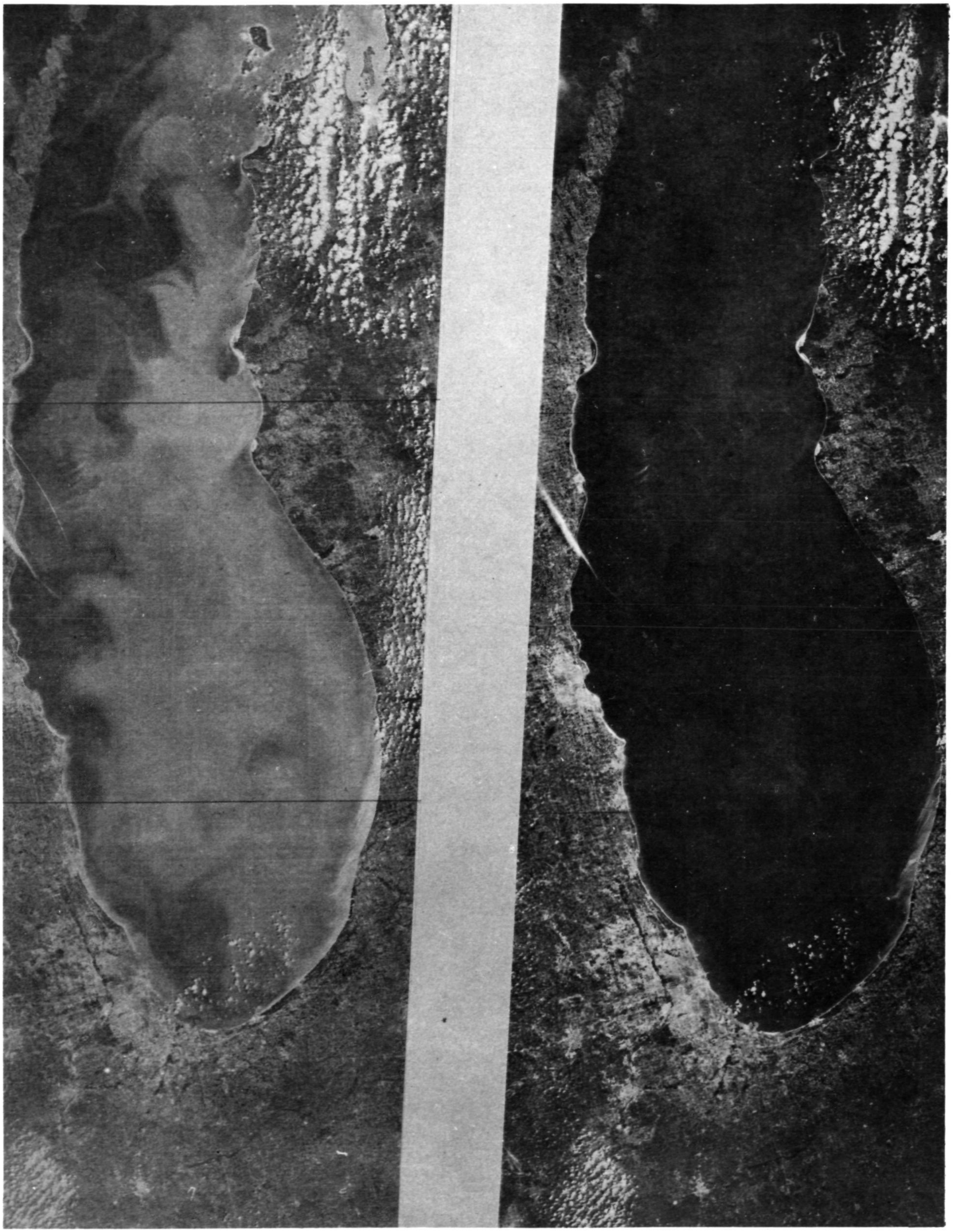

Figure 1. LANDSAT-1 images (MSS-4, left and MSS-5, right) obtained 21 August 1973, showing the extent of the calcium carbonate precipitation over southern Lake Michigan.

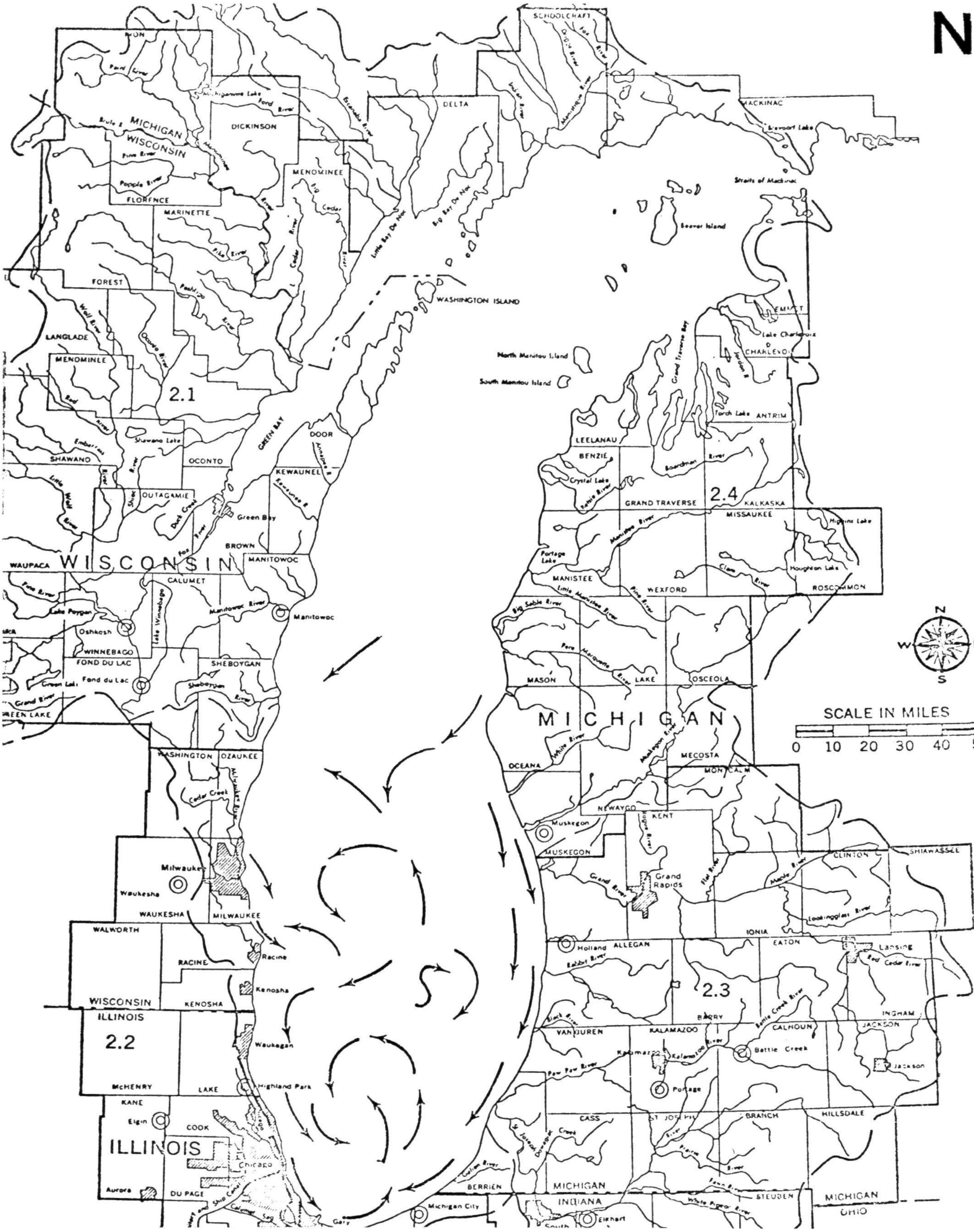

Figure 2. Surface current analysis as determined from turbidity patterns in LANDSAT-1 scenes. Weighted wind direction (Northerly) indicated in upper right-hand corner.

1980

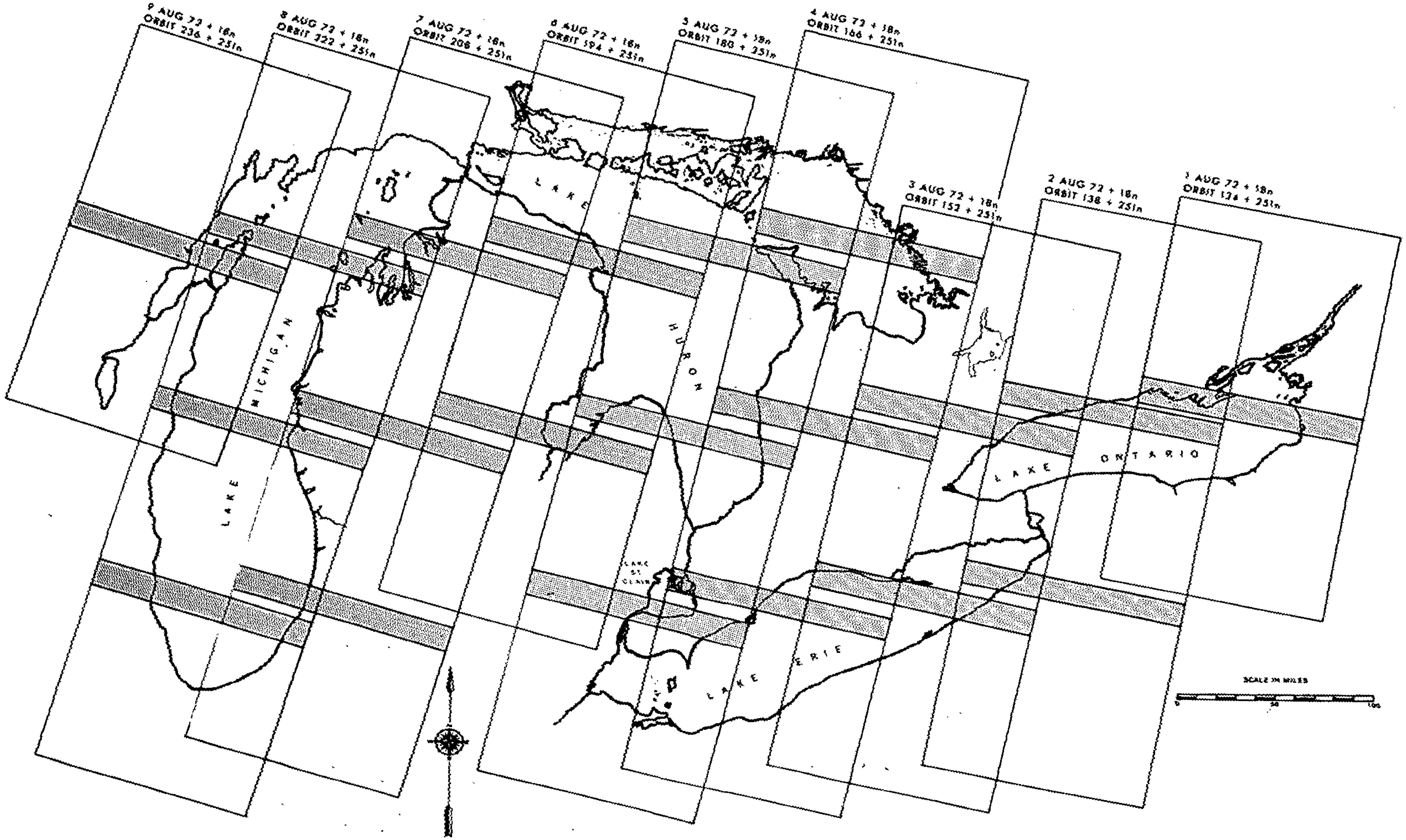

Figure 3. LANDSAT-1 coverage of the Great Lakes, excluding Lake Superior. Stippled areas indicate overlap.

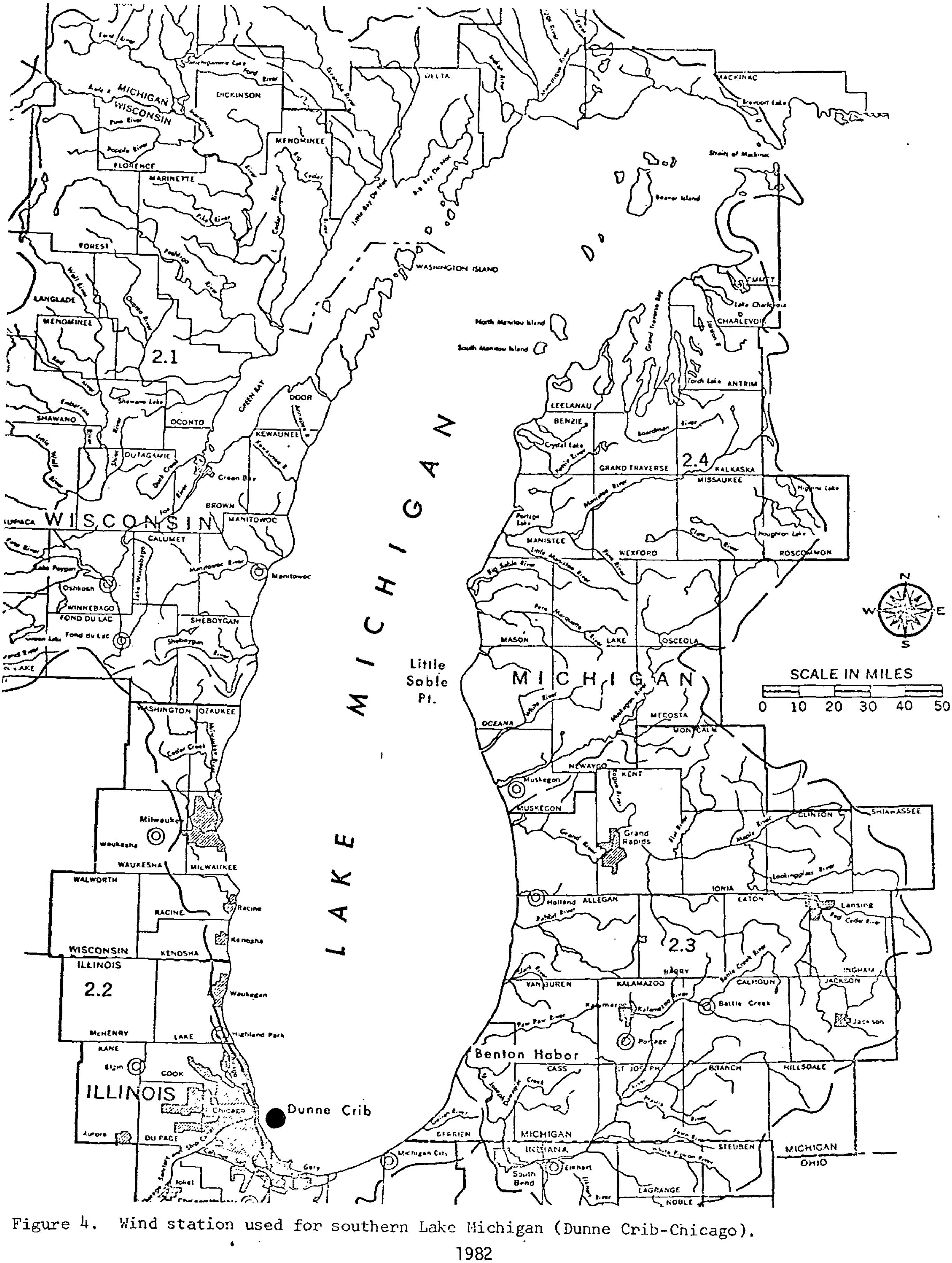

Figure 4. Wind station used for southern Lake Michigan (Dunne Crib-Chicago).

1982

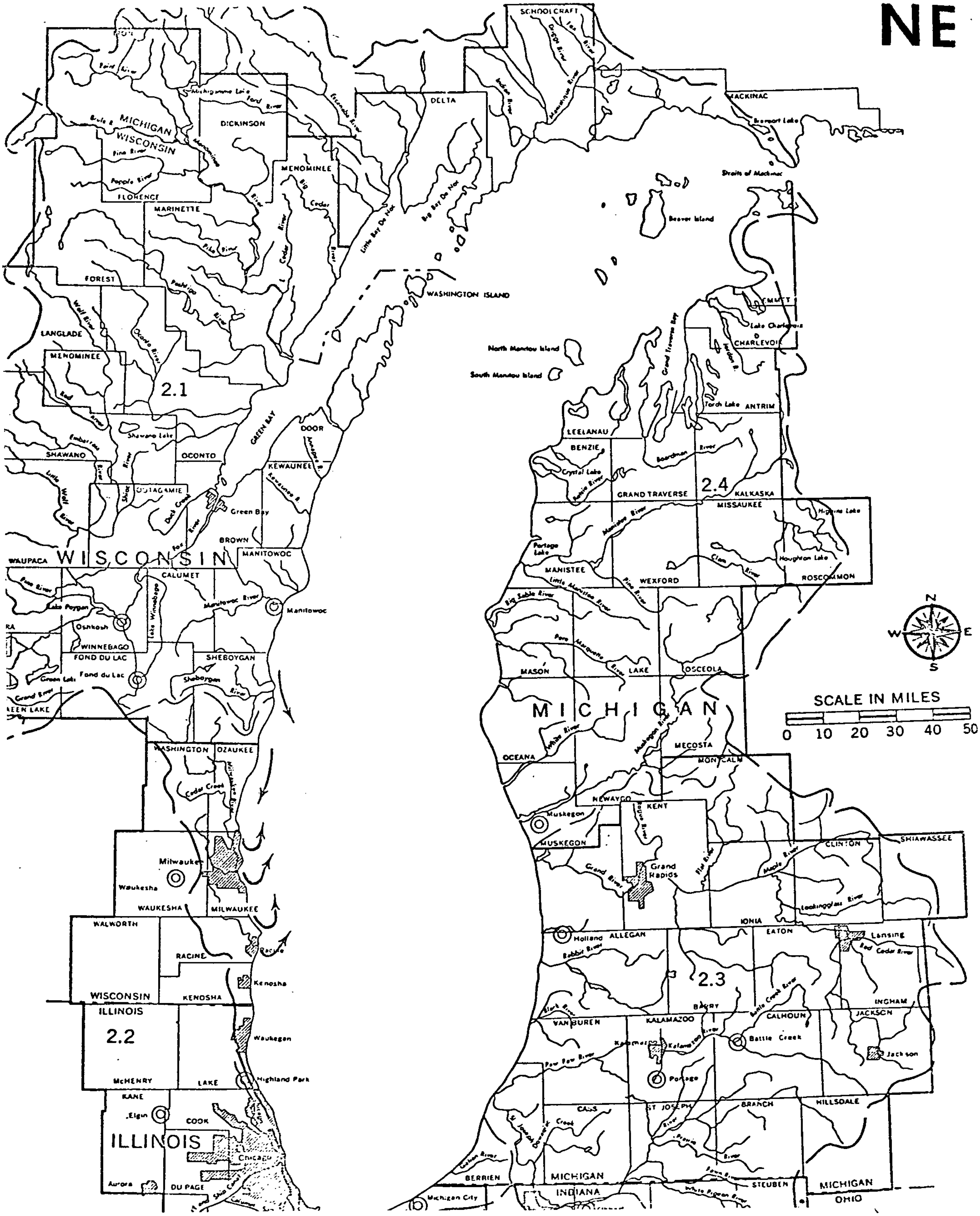

Figure 5. Surface current analysis as determined from turbidity patterns in LANDSAT-1 scenes. Weighted wind direction (Northeasterly) indicated in upper right-hand corner.

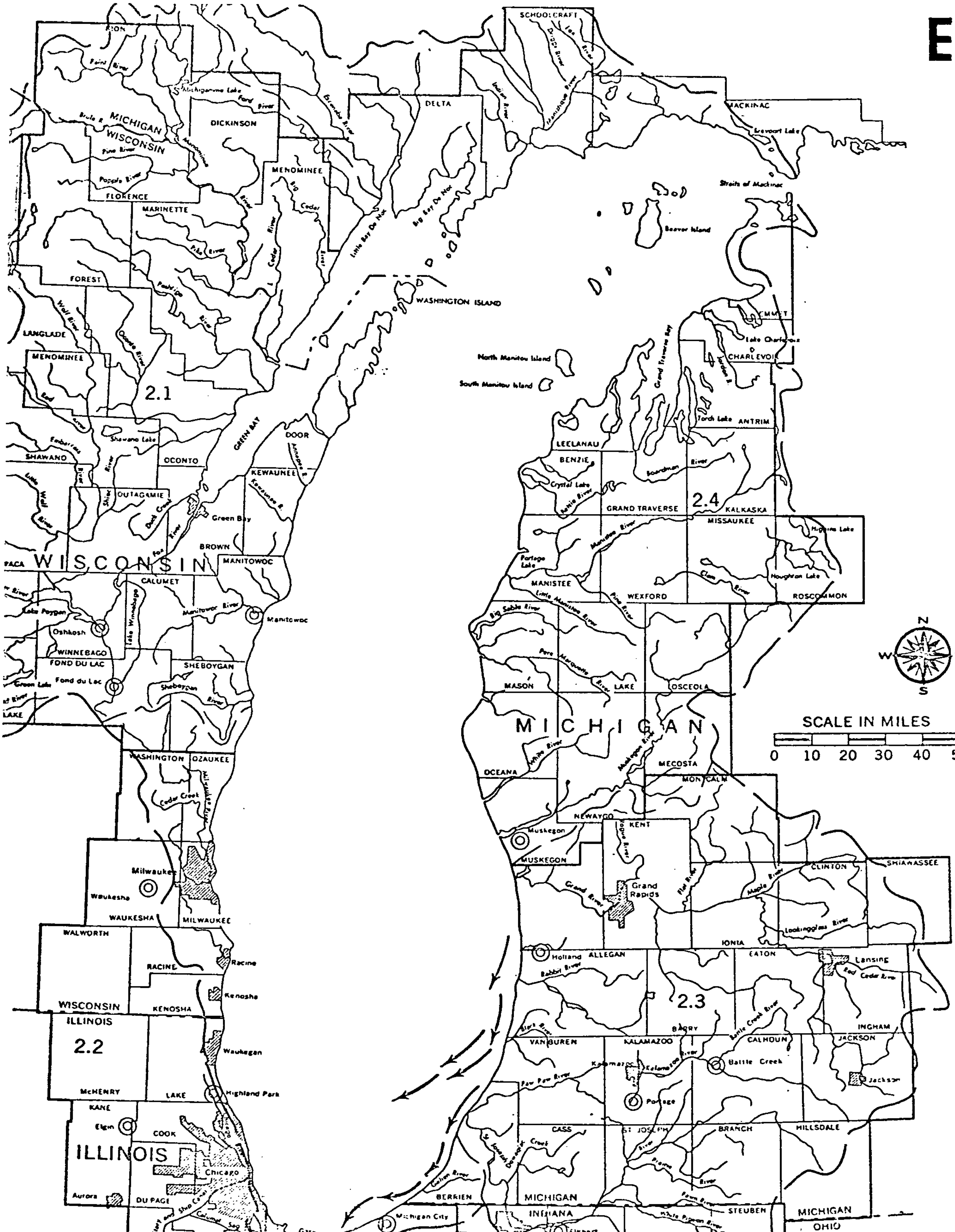

Figure 6. Surface current analysis as determined from turbidity patterns in LANDSAT-1 scenes. Weighted wind direction (Easterly) indicated in upper right-hand corner.

1984

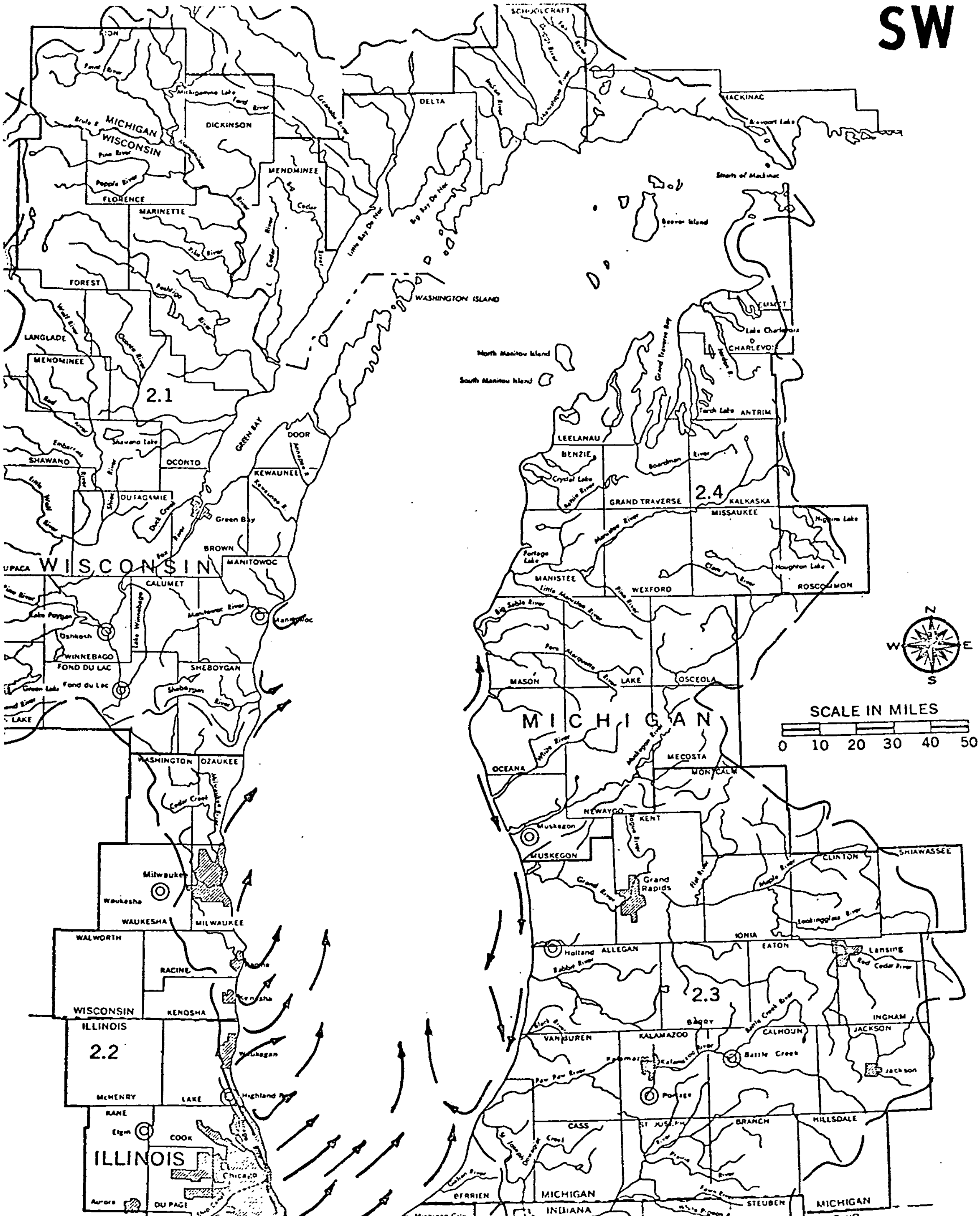

Figure 7. Surface current analysis as determined from turbidity patterns in LANDSAT-1 scenes. Weighted wind direction (Southwesterly) indicated in upper right-hand corner.

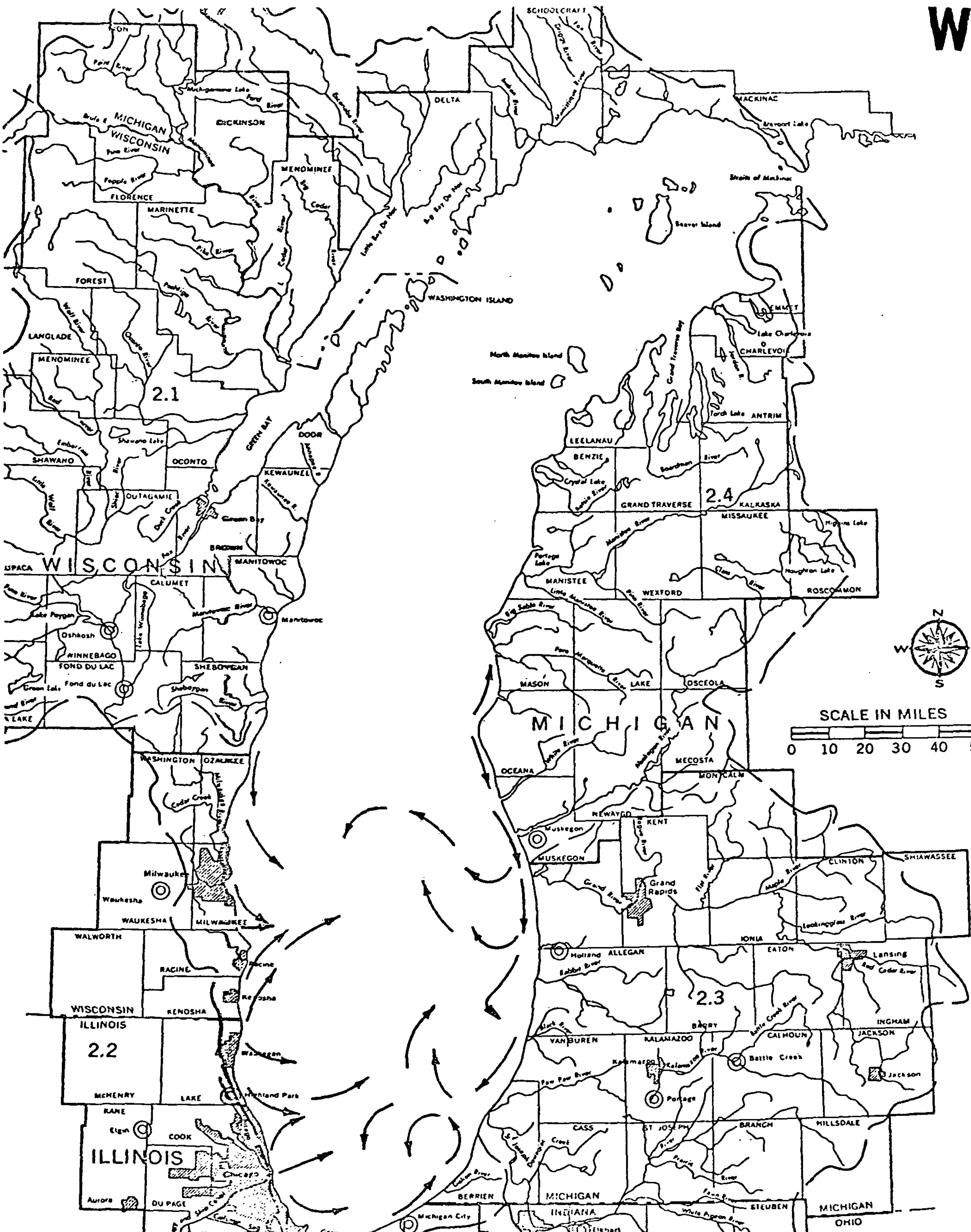

Figure 8. Surface current analysis as determined from turbidity patterns in LANDSAT-1 scenes. Weighted wind direction (Westerly) indicated in upper right-hand corner.

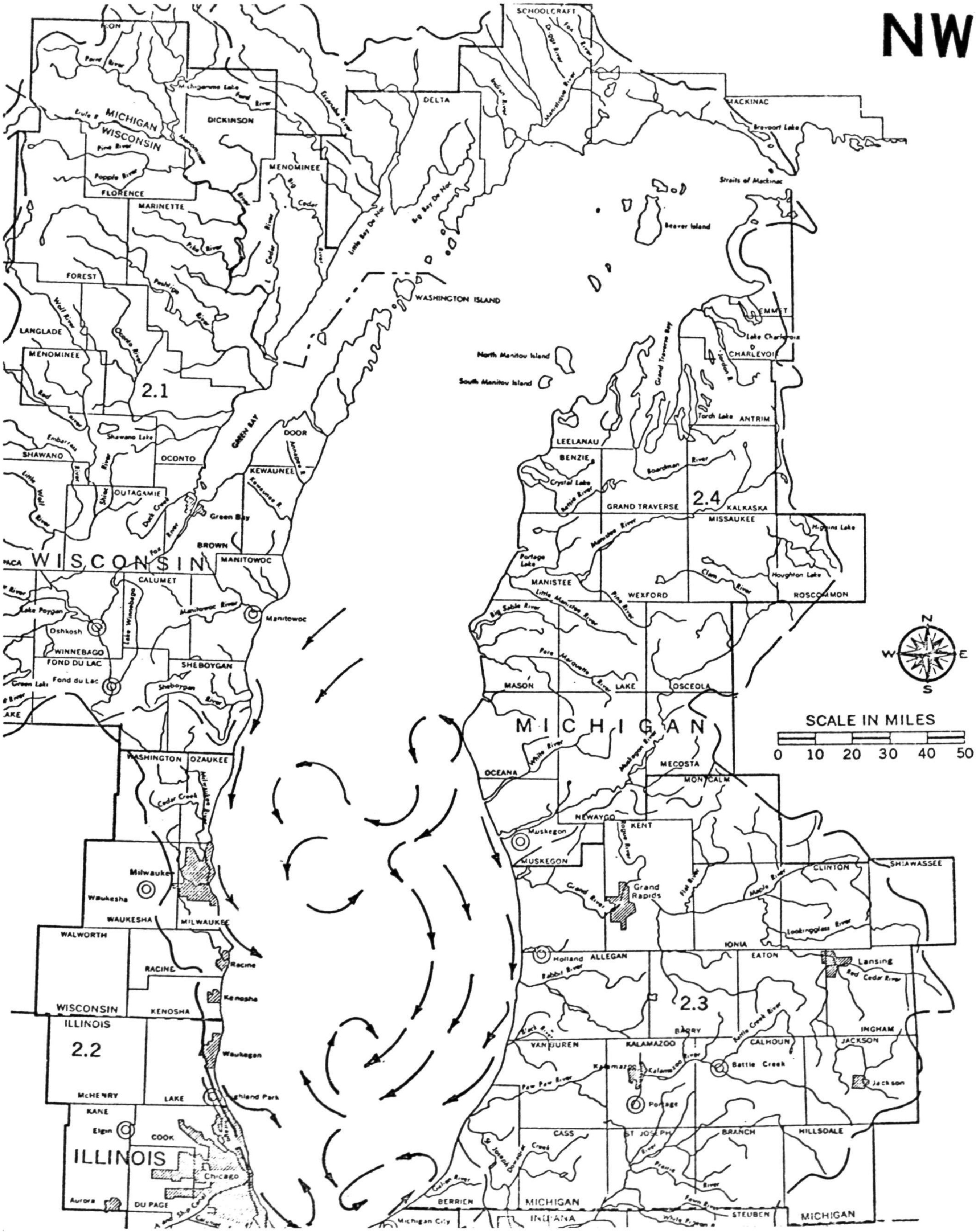

Figure 9. Surface current analysis as determined from turbidity patterns in LANDSAT-1 scenes. Weighted wind direction (Northwesterly) indicated in upper right-hand corner.

Figure 10. LANDSAT-1 images (MSS-4, left and MSS-5, right) obtained 3 August 1973, showing the extent of the calcium carbonate precipitation over southern Lake Michigan.