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MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

Volume 90, Number 2 Washington, D.C. FEBRUARY 1962

AN INVESTIGATION OF THE METEOROLOGICAL CONDITIONS ASSOCIATED WITH EXTREME WIND TIDES ON LAKE ERIE

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[Manuscript received August 11, 1961; revised November 6, 1961]

ABSTRACT

The dates of incidence of extreme wind tide on Lake Erie have been determined for the 20-year period 1940 through 1959, for all cases in which the difference in lake level between Buffalo and Toledo exceeded 6 feet. A frequency-intensity analysis shows that a set-up in excess of 10 feet may be expected once every 2 years. Extreme wind tides occur mainly in the 6-month period October through March; more than 70 percent of the cases fall in the three months November, December, and January. November is the month of most frequent incidence, having more than one-third of the total number of cases in the period studied.

The observed seasonal variation of extreme set-up frequency is interpreted as a reflection of the seasonal variation of storm frequency and of storm-track location. Secondary, but important factors are: seasonal variation of storm intensity and seasonal variation of thermal stability of the atmospheric boundary layer. The tendency for marked temperature stratification to be present in the Lake during the summer probably inhibits set-up to a significant degree during that season.

Storms which produce extreme set-up follow very similar paths during the 24 hours preceding the time of maximum set-up. However, no clear-cut relation was found between source region and set-up intensity, apart from a tendency for Alberta Lows to yield slightly smaller set-up. Brief descriptions are given of the storms of March 22, 1955, and November 17, 1955.

Finally, the writers report that no relation was found between frontal speed and set-up intensity, and infer that resonant coupling with the Lake does not contribute significantly to set-up magnitude.

It should be noted that storms accompanied by strong easterly winds, which produce high water on the western end of the Lake, have not been studied in this investigation.

1. INTRODUCTION

Each year severe storms on the Great Lakes are produced by several of the numerous cyclones that move across central North America on paths which converge in the Great Lakes region. The effects of the southwesterly gales which accompany some of these storms are particularly prominent on Lake Erie, where orientation (west-southwest to east-northeast) and depth (average: 60–65 feet) favor excitation of the fundamental seiche mode. Indeed, the most severe storms have produced a difference in lake level in excess of 13 feet between Buffalo at the eastern extremity and Toledo at the western extremity of the Lake.

The purpose of the present report is to establish some of the characteristic features of meteorological conditions associated with extreme wind tides on Lake Erie. This subject was first considered in detail many years ago in admirable studies by Henry [7] and by Garriott [2]. The latest discussion, together with much useful climatological data pertaining to the Great Lakes, is given by the U.S. Weather Bureau [18]. Other investigations have placed somewhat greater emphasis upon the hydrographic aspects of the problem; among these are the early work of Hayford [5], and more recently should be mentioned those of Hellström [6], Keulegan [11], Harris [14], Gillies [3], Hunt [9], and Verber [19].

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*This investigation was supported by funds provided by the U.S. Weather Bureau (contract Cwb-9768, Technical Report 4, May 1961).

2. CASE SELECTION

Rather arbitrarily, we have selected for this investigation the 20-year period January 1940 through December 1959; for convenience in the sequel, we refer to this as the *prime period.*

The U.S. Lake Survey and the Canadian Hydrographic Service maintain stage recorders on the Great Lakes which produce continuous autographic records of lake level. On Lake Erie the gages having records which span the entire prime period of our investigation are located at: Toledo and Cleveland, Ohio; Buffalo, N.Y.; Port Colborne and Port Stanley, Ontario (see fig. 1). The customary procedure for reducing and compiling autographic gage records leads to tabulations of "hourly scaled values" for each hour of the day (starting at 0100), each "scaled" value being the instantaneous water level (relative to mean tide at New York) expressed in feet, to the nearest hundredth foot. In figure 2 we show a sample of the U.S. Lake Survey tabulation of hourly scaled values for the month of March 1955 at Toledo, Ohio.

Hourly scaled values are ideally suited for studies of seasonal variations of lake level and of variations over periods of several years. For surges of lake level produced by mesoscale atmospheric disturbances (such as squall lines), one must have recourse to the original continuous record because the time scale of such surges often is substantially less than one hour (Platzman [16]). In the present study we are concerned with fluctuations of lake level associated with *large*-scale atmospheric disturbances (namely, the migratory middle-latitude cyclones). These fluctuations—which we shall refer to generally as "wind tides"—are characterized by time scales of at least several hours (on the Great Lakes); for this reason, we have adopted the working assumption that hourly scaled values are suitable for the investigation of wind tides on Lake Erie. This assumption is, of course, open to question in special circumstances.

TABLE 1.—*The date, hour, and set-up for each incidence of extreme wind tide which produced a Buffalo-minus-Toledo set-up in excess of 6 feet during the 20-year period 1940–59 (based upon hourly scaled values)*

Date	Hour (EST)	Set-up (ft.)
1940 Nov. 12	16	7.70
1941 Jan. 4	15	6.77
Sept. 25	16	9.92
Nov. 1	20	6.28
7	18	9.06
Dec. 5	24	6.75
1942 Jan. 2	10	13.42
Mar. 9	10	8.75
Nov. 10	18	6.76
26	14	6.84
Dec. 2	19	12.43
1943 Jan. 19	12	6.84
Feb. 7	01	6.45
Dec. 12	04	7.07
1944 Mar. 7	04	6.38
1945 Jan. 2	02	8.87
Apr. 4	24	6.77
Nov. 22	06	8.48
1946 Jan. 12	24	6.60
Feb. 14	10	8.94
Nov. 22	10	9.19
Dec. 17	10	7.56
29	17	6.38
1947 Jan. 21	16	8.23
Mar. 25	10	10.22
Nov. 8	01	6.78
24	18	6.70
Dec. 5	13	6.06
17	24	6.53
1948 Nov. 17	08	8.10
1949 Jan. 19	08	8.56
28	14	6.75
Dec. 27	19	6.53
1950 Jan. 10	24	7.53
14	10	10.99
Nov. 16	22	7.36
Dec. 7	22	6.22
1951 Mar. 24	08	9.20
Oct. 7	19	8.70
24	19	6.29
Nov. 4	10	8.92
26	05	6.90
Dec. 21	18	9.51
1952 Jan. 22	24	8.09
Nov. 26	18	8.75
1953 Jan. 18	04	6.43
Feb. 21	12	10.79
Mar. 4	06	6.24
Dec. 10	05	6.77
1954 Mar. 3	18	9.70
Sept. 21	19	9.38
Oct. 16	01	6.59
Nov. 29	09	7.71
Dec. 30	06	6.46
1955 Jan. 15	20	6.89
27	02	6.10
Mar. 22	18	12.90
Nov. 3	10	8.11
17	08	12.92
28	22	6.08
Dec. 4	24	6.75
1956 Mar. 8	17	9.23
11	13	6.94
Nov. 16	10	8.93
21	15	11.08
1957 Nov. 9	05	8.24
19	11	8.96
1958 Jan. 1	07	7.63
Apr. 24	18	6.23
Oct. 10	16	6.64
Nov. 6	01	7.32
19	04	6.20
29	18	7.27
1959 Jan. 22	05	7.11
Mar. 6	21	6.59
Nov. 30	06	6.66

A convenient index of Lake Erie wind tides is the difference in level between Buffalo and Toledo, a quantity which we shall call the "Buffalo-minus-Toledo *set-up*". Where no ambiguity can arise, we refer to this quantity as *the* set-up.

As a first step, hourly scaled values at Buffalo and at Toledo were examined for the entire prime period in order to select all cases of extreme wind tide that occurred during this period. All cases were noted for which the hourly scaled value at either Buffalo or Toledo differed from the station's monthly mean by 3 or more feet in magnitude. From this selection we obtained a total of 76 cases during the prime period, in which the set-up exceeded 6 feet; these are listed in table 1. For all entries of table 1 the set-up is positive: Buffalo stage higher than Toledo stage. There were in addition three cases of negative set-up during this period: Buffalo stage lower than Toledo stage by 6 feet or more. These occurred on April 9, 1942 (6.40 feet); January 30, 1947 (7.09 feet); and January 1, 1948 (7.95 feet). They are the result of rather exceptional conditions and are not included in the compilations which follow.*

3. SET-UP STATISTICS

In table 2 we show the set-up frequency distribution by months at 1-foot intervals, for the 76 cases listed in table

TABLE 2.—*Frequency distribution, by months and intensity, of the 76 cases in which Buffalo-minus-Toledo set-up exceeded 6 feet during the 20-year period 1940–59 (based upon hourly scaled values)*

Month*	Set-up (in ft.)								Total
	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	
September	0	0	0	2	0	0	0	0	2
October	3	0	1	0	0	0	0	0	4
November	9	5	7	3	0	1	1	0	26
December	9	2	0	1	0	0	1	0	13
January	7	3	4	0	1	0	0	1	16
February	1	0	1	0	1	0	0	0	3
March	4	0	1	3	1	0	1	0	10
April	2	0	0	0	0	0	0	0	2
Total	35	10	14	9	3	1	3	1	76
Cumulative totals	76	41	31	17	8	5	4	1	------

*There were no cases in the months May, June, July, August.

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*One of our reviewers has pointed out that although rare, these "easterly" storms may produce more extensive flood damage than "westerly" storms because of differences of land configuration at the western and eastern ends of the Lake.

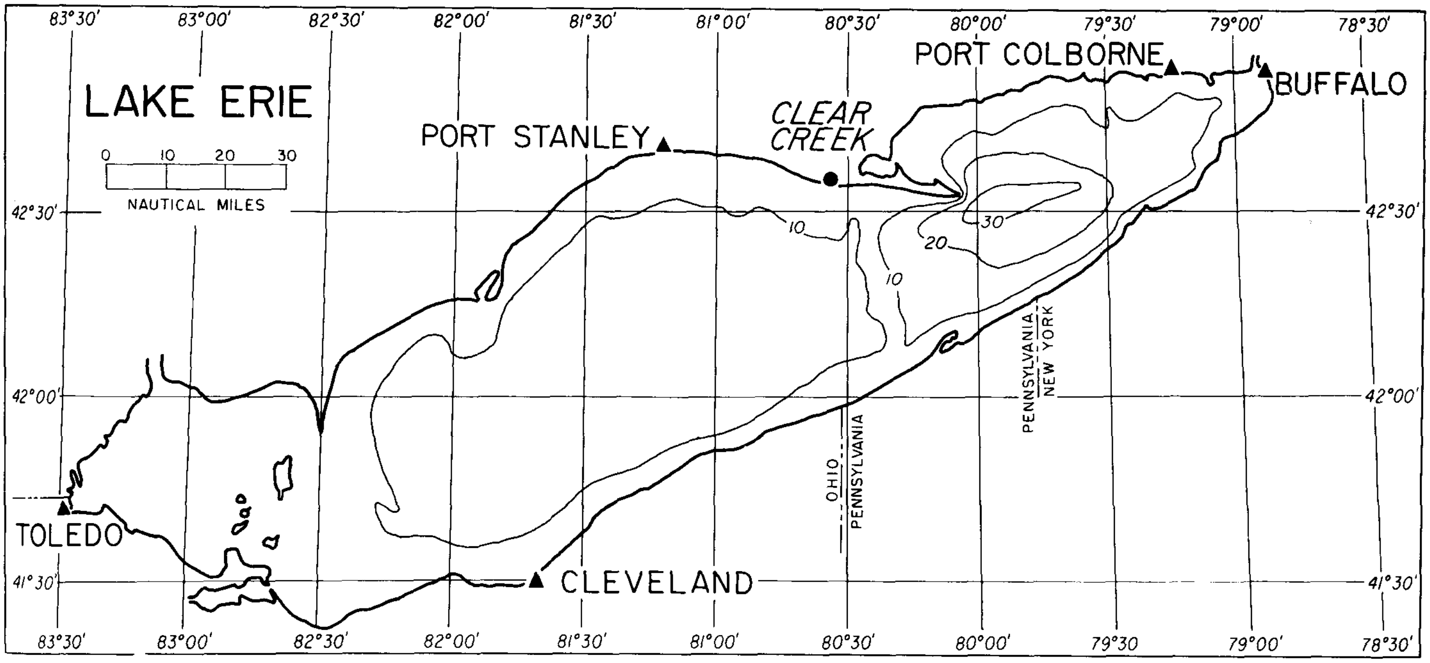
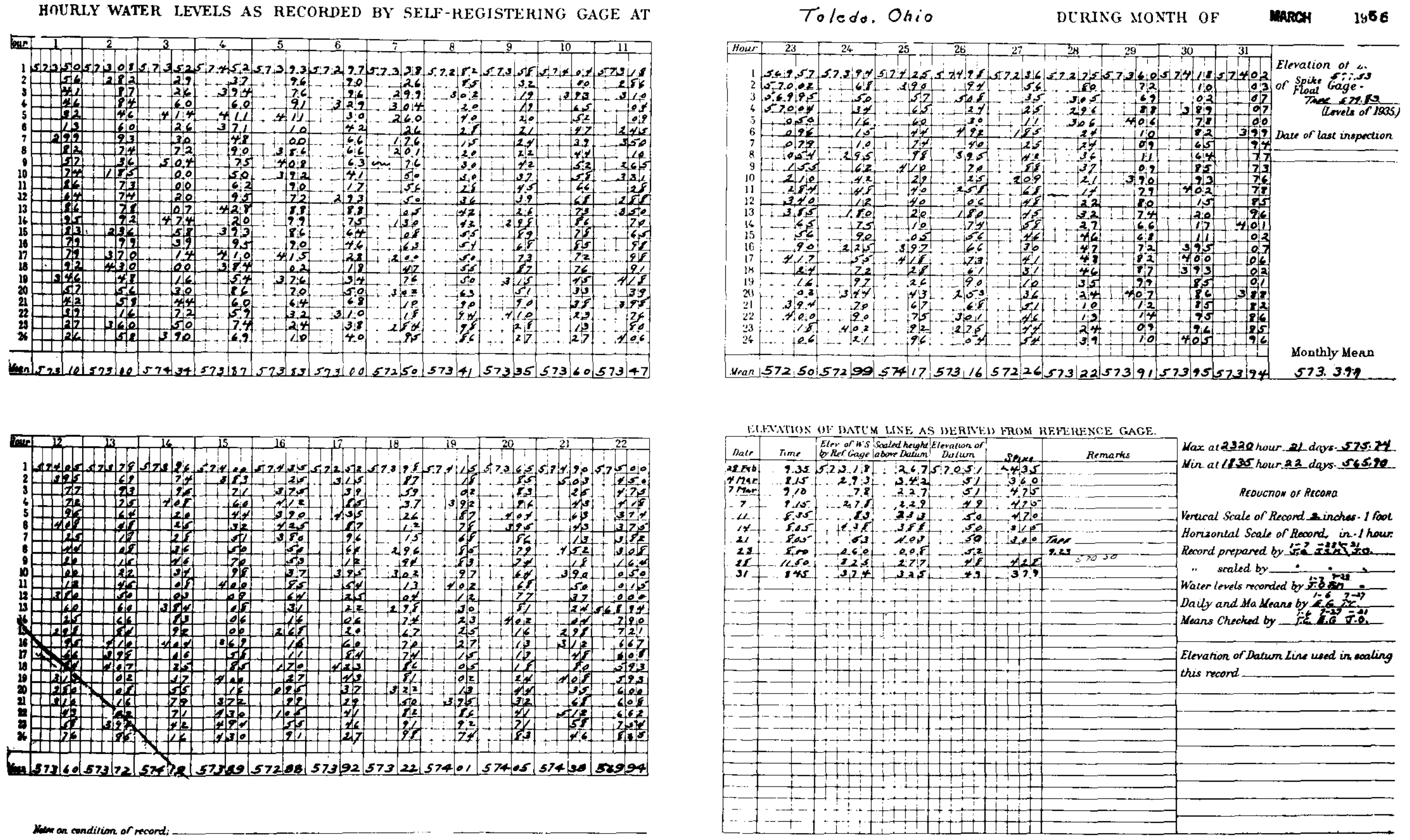


FIGURE 1.—Locations (▲) of the five stage recorders for which continuous records of lake level are available throughout the "prime" period (1940–59). Depth contours are shown at 10-fathom intervals (1 fathom=6 feet).



HOURLY WATER LEVELS AS RECORDED BY SELF-REGISTERING GAGE AT *Toledo, Ohio* DURING MONTH OF MARCH 1956

Hour	1	2	3	4	5	6	7	8	9	10	11
Mean	573 10	573 80	574 34	573 87	573 83	573 00	572 50	573 41	573 35	573 60	573 47

Hour	12	13	14	15	16	17	18	19	20	21	22
Mean	573 60	573 72	574 72	573 89	572 88	573 92	573 22	574 01	574 05	574 38	573 94

Hour	23	24	25	26	27	28	29	30	31
Mean	572 50	572 99	574 17	573 16	572 26	573 22	573 91	573 95	573 94

Monthly Mean 573. 399

Elevation of Spike Float Gage 577.53 *Tape* 577.83 (Levels of 1935)

Date of last inspection

ELEVATION OF DATUM LINE AS DERIVED FROM REFERENCE GAGE.

Date	Time	Elev of W.S. by Ref. Gage	Scaled height above Datum	Elevation of Datum	Spike	Remarks
28 Feb	9.35	573.18	2.67	570.51	4.35	
4 Mar	8.15	2.93	3.42	51	3.60	
7 Mar	9.10	78	2.27	51	4.75	
7	9.15	2.78	2.29	49	4.75	
11	8.35	83	3.33	50	4.70	
14	8.05	4.38	3.88	50	3.15	
21	8.05	63	1.03	50	3.00	Tape
23	8.00	2.60	0.08	52		9.23 570 50
28	11.50	3.25	2.77	48	4.28	
31	8.45	3.74	3.25	49	3.79	

Max at 2320 hour 21 days 575.74
Min. at 1835 hour 22 days 565.90

REDUCTION OF RECORD

Vertical Scale of Record 2 inches - 1 foot
Horizontal Scale of Record, in.-1 hour
Record prepared by
" scaled by
Water levels recorded by
Daily and Mo. Means by
Means Checked by

Elevation of Datum Line used in scaling this record

Notes on condition of record:

FIGURE 2.—Sample of "hourly scaled values" of lake level at Toledo for the month March 1955, as tabulated by the U.S. Lake Survey from continuous record of stage recorder.

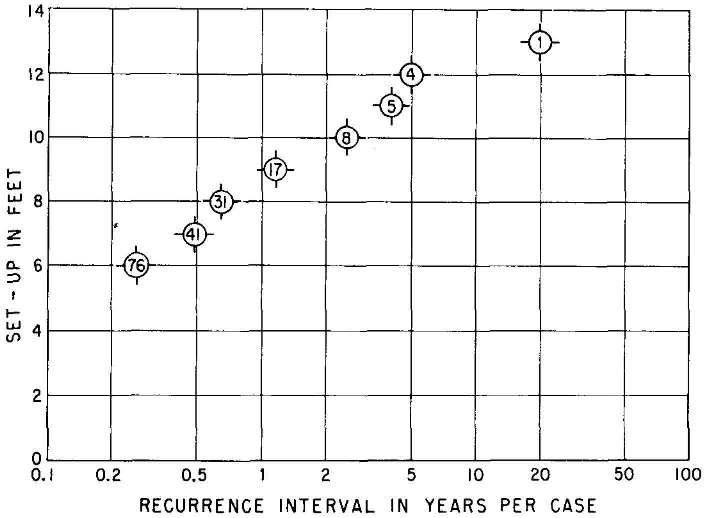


FIGURE 3.—Recurrence interval for which Buffalo-minus-Toledo set-up exceeded specified amounts. The circled numbers give the number of cases for which set-up exceeded 6, 7, 8, 9, 10, 11, 12, 13 feet during the 20-year period 1940–59.

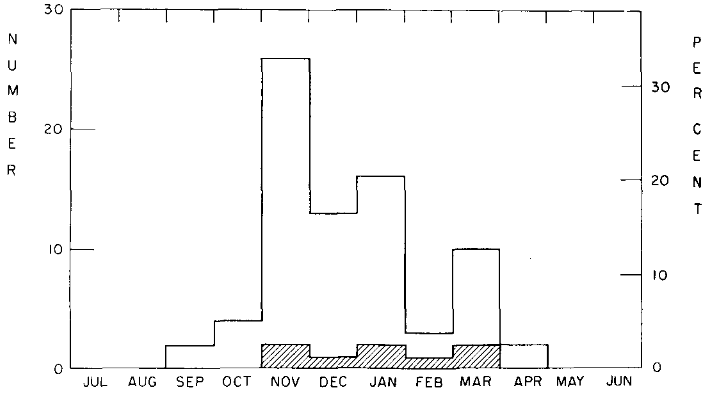


FIGURE 4.—Monthly distribution of 76 cases in which Buffalo-minus-Toledo set-up exceeded 6 feet during the 20-year period 1940–59. Hatching shows distribution of 8 cases in which set-up exceeded 10 feet.

1. These data are arranged in figure 3 to show the frequency-intensity relation. Here the circled numbers are the numbers of cases (in the 20-year prime period) in which the set-up exceeded the amount shown on the ordinate. The abscissa gives the corresponding recurrence interval, equal to the ratio of 20 years to the number of cases. According to figure 3, one may expect on the average a set-up in excess of 10 feet once every 2 years, and a set-up in excess of 12 feet once every 5 or 6 years.

The monthly distribution of set-up frequency, from table 2, is shown as a histogram in figure 4. Evidently, a set-up in excess of 6 feet will occur on Lake Erie most frequently during the month of November: about 34 percent of the cases fall in that month. We shall discuss briefly the climatological interpretation of figure 4.

Garriott [2] studied all "the more important storms of the Great Lakes that have been described in the Monthly Weather Review during the 25-year period 1876 to 1900, inclusive." The selection criteria are not explicitly given by him, *but probably do not involve water-level fluctuations;* he states: "The standard of intensity observed in selecting the storms varies with the seasons; the object has been simply to present typical lake storms of the various months that have been of sufficient strength to endanger shipping,"

In figure 5 the broken curve shows the monthly frequency distribution of the 238 cases which Garriott selected in his 25-year period. The solid curve in this figure is the frequency distribution of the 76 cases in our 20-year prime period—the distribution presented in figure 4 as a histogram. The similarity of the two curves means that the main features of the seasonal frequency distribution of extreme set-up are a result of seasonal variations of *storm* frequency. The fact that November is the month of greatest storm frequency on the Great Lakes was noted by Garriott and all others subsequently who studied the problem. As stated by Klein [12]: "Another notable feature of November is the convergence of two primary storm tracks, composed of Alberta and Colorado Lows, into a center of maximum cyclone frequency around the Great Lakes. This occurs every month from November through April and was noted as early as 1903 by Garriott. . . ."

It is interesting to note also that Namias [14] has found month-to-month persistence of temperature and precipitation as well as 700-mb. pattern to be at a minimum for the transition October to November, reflecting a dislocation of circulation more pronounced than occurs between any other two consecutive months.

An explanation of the November maximum frequency of Great Lakes storms undoubtedly is to be sought in the southward displacement of the mean position of the polar front. The influence of the Great Lakes themselves should not, however, be overlooked. In a recent study, for example, Petterssen and Calabrese [15] showed quantitatively that the Great Lakes region, acting as a heat source in winter, may contribute appreciably to the deepening of storms which pass through this region.

While seasonal variation of storm frequency is the main factor which determined the distribution in figure 3, several other possible influences should be mentioned. Extreme set-up is, of course, highly dependent upon storm *intensity,* and here again November is a favored month for the Great Lakes region. This is illustrated by the arrows plotted in figure 5, which show the monthly normal mean hourly wind speed and prevailing direction at Clear Creek, a well-exposed station on the northern shore of Lake Erie (see fig. 1). The peak value in November is clearly present in these data, as well as the secondary maximum in March which appears also in the set-up frequency data as well as in Garriott's storm-frequency data. (The secondary peak set-up frequency in January

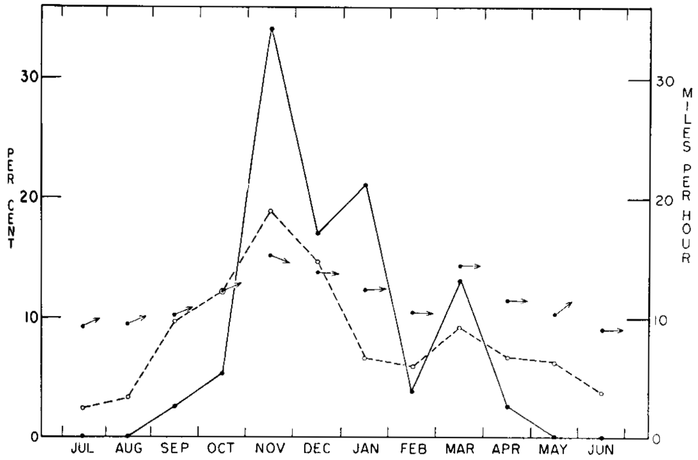


Figure 5.—Broken curve: monthly frequency distribution of severe storms on the Great Lakes, given by Garriott [2]; solid curve: monthly frequency distribution from the histogram of figure 4; arrows: monthly normal mean hourly wind speed and prevailing direction at Clear Creek, Ontario.

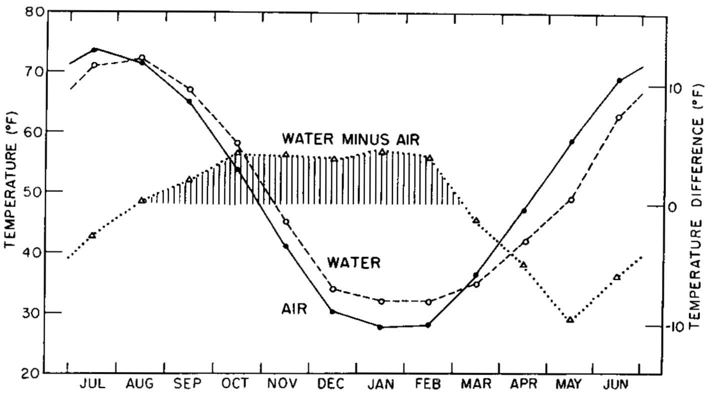


Figure 6.—Solid curve: average of normal monthly air temperatures at Detroit, Toledo, Sandusky, Cleveland; broken curve: mean monthly temperature of surface water of Lake Erie given by Hunt [9]; dotted curve: water temperature minus air temperature, with positive values indicated by hatching.

may be attributed to small sample size, since it does not appear in the other data.)

Surface wind stress depends not only upon wind speed but also upon thermal stability of the atmospheric boundary layer, a factor which has been studied in detail by Hunt [8]. In figure 6 the solid curve gives the course of normal monthly air temperatures for the southwestern shore of Lake Erie, obtained as an average of the normal monthly air temperatures at Detroit, Toledo, Sandusky, and Cleveland. The broken curve in figure 6 shows mean monthly surface-water temperatures as given by Hunt [8]; the latter are intended to represent average temperatures of the entire Lake surface, and therefore are subject to corresponding uncertainties. To assess atmospheric thermal stability we show water temperature minus air temperature (dotted curve), with the period of least stability indicated by hatching. During the 7-month period from mid-August to mid-March, Lake Erie surface-water temperatures are higher on the average than are temperatures of the ambient air. Throughout the 5-month period from mid-October through mid-March the surface water is about 4° F. warmer than the air. Further, as pointed out by Hunt [8], destabilization of the atmospheric surface layer is especially pronounced following passage of the cold front normally associated with storms producing extreme set-up. As a further interpretation of the monthly distribution of set-up frequency (fig. 5), it seems reasonable therefore to say that the predominance of frequencies in November, December, and January is partly a consequence of wind-stress intensification through thermal instability of the lower atmosphere.

Finally, we touch briefly on the question of influence of thermal stability of the Lake itself. In principle, fluctuations of lake level in response to wind stress may be inhibited appreciably if a well-developed temperature stratification exists in the Lake, since much of the energy transmitted to the Lake by wind stress may be absorbed through internal motions and adjustments of the mass field (see, for example, Mortimer [13]). Before discussing Lake Erie temperature data, it is necessary to observe that the bottom configuration lends itself to a broad division of the Lake into a small, shallow western section (one-eighth of the total area) with maximum depth about 40 feet; a large, shallow central section (two-thirds of the total area) with maximum depth about 70 feet; and a small, deep eastern section (the Deep Hole) with maximum depth about 210 feet; see figure 1.

The available temperature data (U.S. Fish and Wildlife Service [17]) indicate that the temperature of the bottom water in the Deep Hole fluctuates only very slightly throughout the year. In summer there is a well-developed thermocline over the Deep Hole; while over the central Great Plain, the thermocline probably is weaker and transient in character, sometimes disappearing completely. In winter, all portions of the Lake approach very nearly a state of temperature homogeneity. If this appraisal is approximately valid, one may infer that seasonal variation of thermal stability of the Lake would tend to inhibit water-level fluctuations in summer but not in winter. It is possible that one may in this way account in part for the absence of any set-up values in excess of 6 feet during the months May, June, July, August (in our prime period).

4. STORM TRACKS

An attempt was made to classify the storms associated with extreme wind tides on the basis of source region,

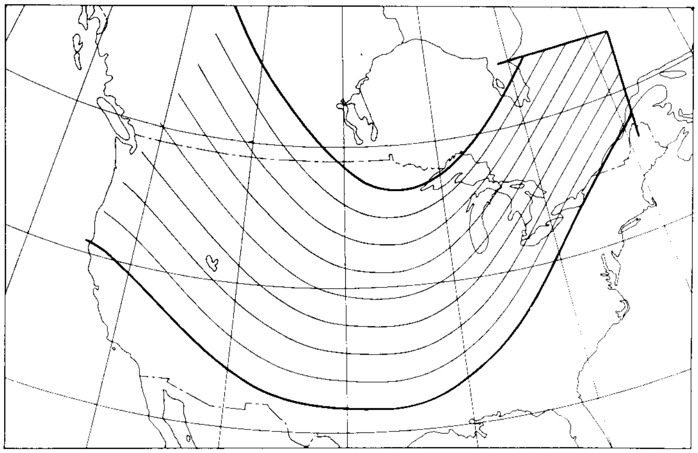


FIGURE 7.—Envelope of tracks of low centers in 27 cases (out of a total of 31) in which Buffalo-minus-Toledo set-up exceeded 8 feet during the period 1940–59.

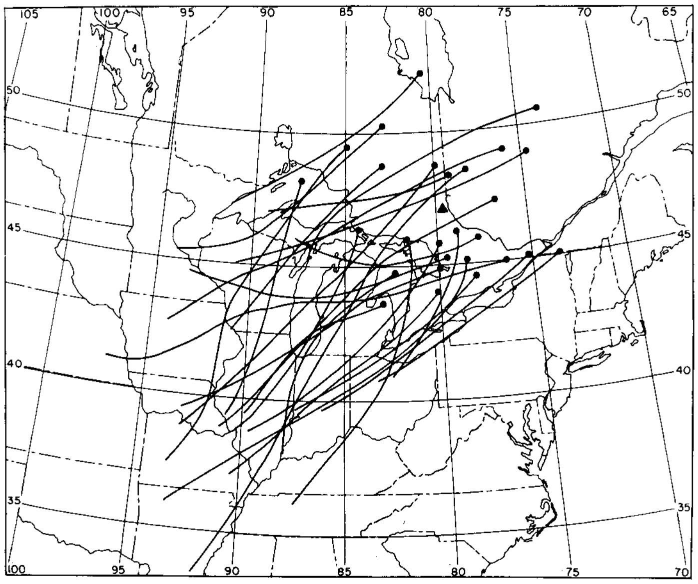


FIGURE 8.—Locations of low centers (heavy dots) at time of maximum set-up (for the same cases as in fig. 7), and tracks of centers during preceding 24 hours. The small triangle marks location of mean position of centers.

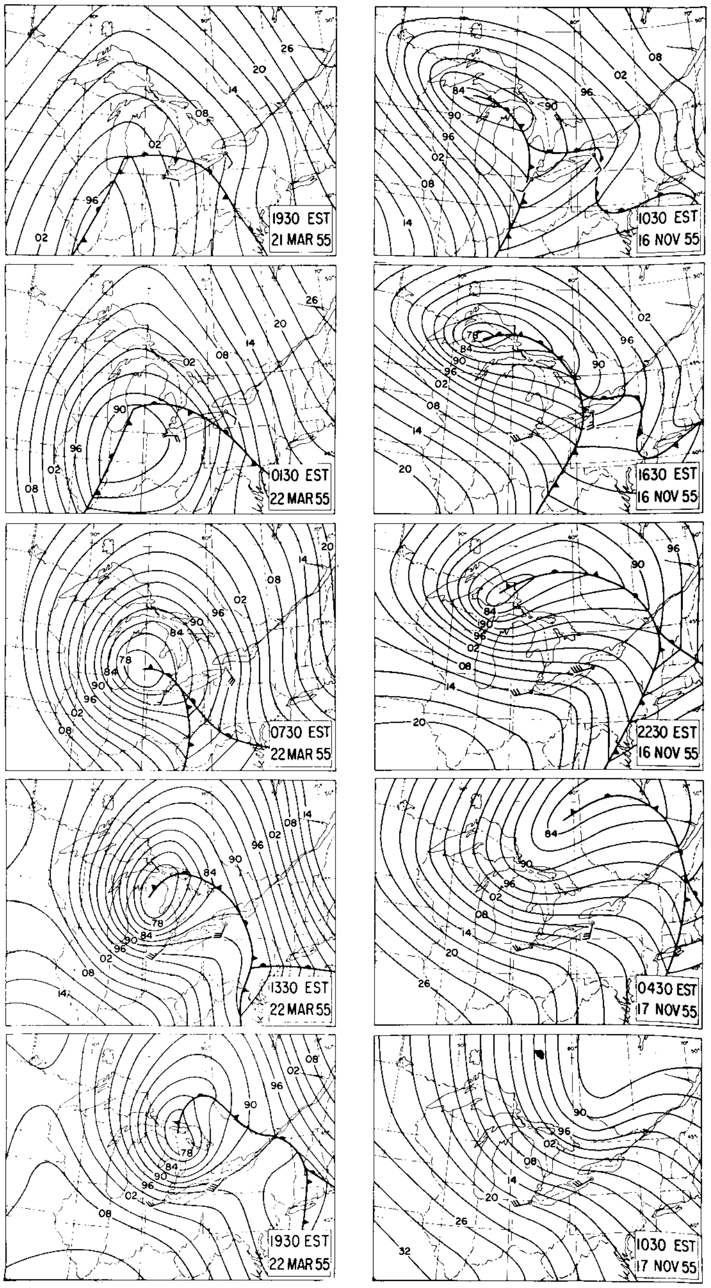


FIGURE 9.—Six-hourly positions of fronts and sea level isobars (based upon Weather Bureau analysis) for the 24-hour period preceding maximum set-up in two cases in which set-up exceeded 12 feet. Left panel: case of 12.90-ft. set-up, 1800 EST, March 22, 1955. Right panel: case of 12.92-ft. set-up, 0800 EST, November 17, 1955. Also shown are surface winds at Toledo and at Buffalo.

using the source regions adopted, for example, by Bowie and Weightman [1]. The results of this attempt were, on the whole, unsatisfactory: the data do not lend themselves to a classification which is both unambiguous and useful, mainly because the source regions of many storms cannot be clearly defined.

Garriott [2], in the study mentioned previously, used "Southwest," "Middle-West," and "Northwest," as source regions for classification of severe Great Lakes storms. He states that "The most destructive storms of the Great Lakes come from the Southwest," while storms of Middle-West origin are next in order of severity, and Northwest storms least severe. His Southwest region corresponds roughly to the Texas region of Bowie and Weightman's classification; his Middle-West Lows are the Colorado and Northern Rocky Mountain Lows of Bowie and Weightman, and his Northwest region includes Pacific-coast as well as Alberta Lows.

The writers examined the track of each of the Lows associated with the 31 cases in our prime period in which

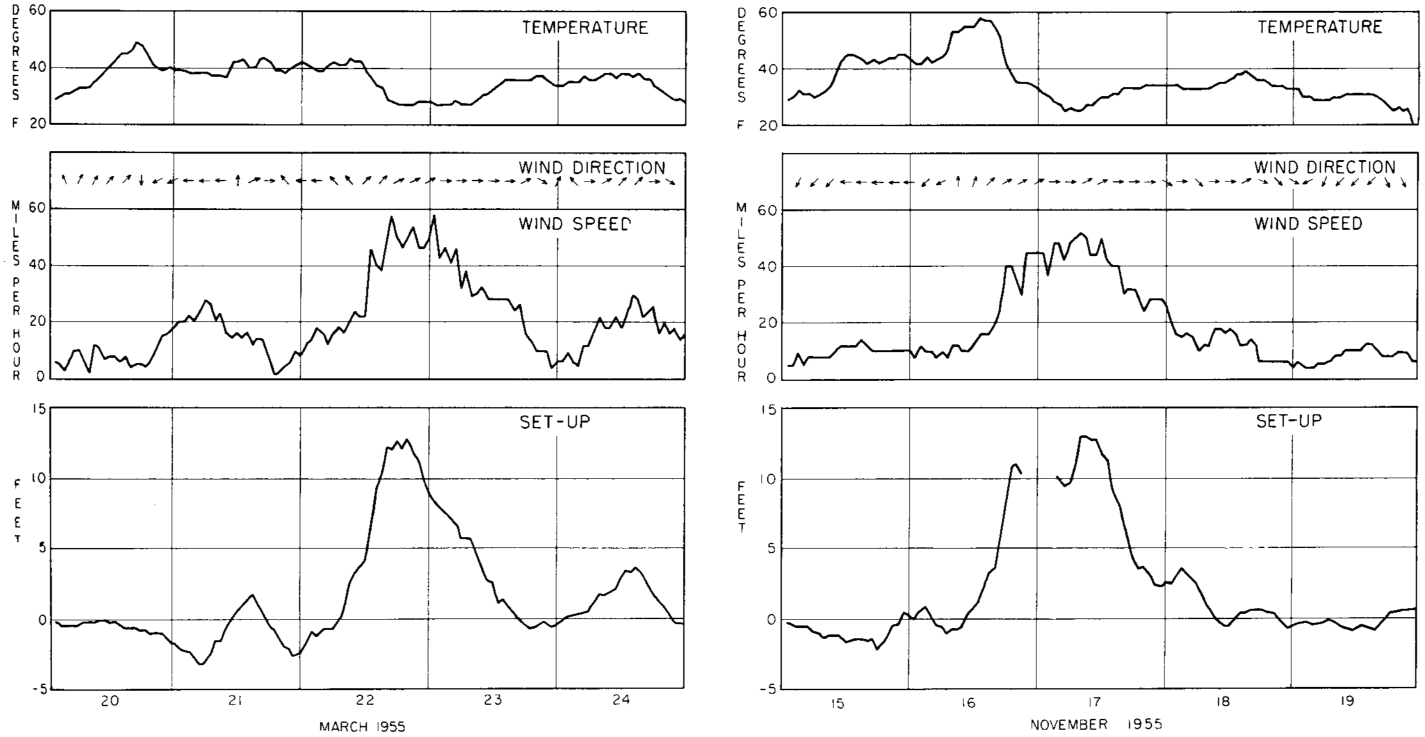


Figure 10.—Hourly air temperature, wind direction, wind speed at Clear Creek, Ontario; and hourly Buffalo-minus-Toledo set-up. Left panel: March 20–24, 1955; right panel: November 15–19, 1955.

Buffalo-minus-Toledo set-up exceeded 8 feet on Lake Erie. One of these Lows was a tropical storm (September 25, 1941), one was an East Gulf storm (January 21, 1947), and two crossed to the lee of the Appalachian Mountains before the time of maximum set-up (December 2, 1942 and January 2, 1945). The remaining 27 cases are storms which originated west of the Mississippi River. (The envelope of the tracks in these 27 cases is shown in fig. 7.) However, in these cases the principal deepening of the Low took place east of the Mississippi River, as the storm advanced in a northeasterly direction in its migration toward the Icelandic center of action.

On the whole there was no well-defined relation between set-up magnitude on the one hand, and complete storm track or source region on the other—apart from a tendency for Alberta Lows to be associated with slightly smaller set-up. There is, however, rather well-marked similarity of the *critical* portion of the storm tracks, defined as that segment of the track covered by the Low during the 24 hours preceding the time of maximum set-up. In figure 8 are shown critical segments for the 27 cases mentioned above; locations of the Lows at the time of maximum set-up are marked in this figure by the heavy dots.

We should also mention in this connection that a study was made of frontal speeds in an attempt to establish a relation between set-up magnitude and propagation speed of the front in its passage across the Lake. This was motivated by the fact that the propagation speed of free long waves on Lake Erie, corresponding to the mean depth of the Lake, is about 25 to 30 knots, so that resonant coupling with a frontal system might be conjectured. Careful estimates of frontal speeds were made, for the period of transit of the front across the Lake, in more than 20 cases in which set-up ranged from 6 to 13 feet. The data did not, however, exhibit any relation which would support the idea that resonant coupling is a significant factor in determining set-up magnitude. The result was corroborated by an independent analysis of the response of a one-dimensional lake to a moving stress band of finite width. The latter analysis (to be presented elsewhere) confirmed that resonance is almost completely suppressed when the stress-band width is greater than the length of the lake, as would be the case for Lake Erie, the major axis of which is about 350 km. in length.

5. CASE STUDIES

Analyses will now be presented of meteorological and hydrological data in two cases of extreme wind tide.

A set-up of 12.90 feet was produced at about 1800 EST, March 22, 1955 by an intense cyclone which first began deepening in eastern Texas early in the morning of the preceding day. In figure 9 (left) are weather maps adapted from the available Weather Bureau analyses, for the 24-hour period preceding the time of maximum set-up.

This Low deepened rapidly as it moved up the Mississippi Valley, and by 0730 EST, March 22, it had reached Lower Michigan with a central pressure of 975 mb. The low-pressure center continued northeastward across Lake Huron and northern Ontario into Quebec while the associated warm air pushed rapidly eastward.

The fronts, which moved across the Lake with a speed of about 42 knots, were preceded by gusty south to southeast winds with rain or rainshowers, and followed by strong southwest winds with gusts up to 74 m.p.h. reported. They occluded while moving over the Lake, and with their passage, rain changed to snow and temperatures fell from the fifties to the mid-twenties. The occluded front passed Buffalo at about 1230 EST, March 22; approximately 6 hours later the lake level at Buffalo reached a peak of about 6 feet above normal, while at Toledo the stage was then about 7 feet below normal, giving a peak set-up of about 13 feet. Strong southwest winds continued until early March 23, then gradually abated as the low-pressure center moved northeastward into Quebec.

In figure 10 (left) are shown hourly data for the 5-day period March 20–24, 1955; included are Buffalo-minus-Toledo set-up, and temperature and wind at Clear Creek (fig. 1).

The other example which we present is the storm which produced a set-up of 12.92 feet at about 0800 EST, November 17, 1955. The low-pressure center first began to intensify in northwestern Nevada early in the morning of November 14, and moved rapidly eastward to Nebraska, then northeastward. At 1030 EST, November 16, the low center was located in Upper Michigan with a pressure of 987 mb. (see fig. 9, right panel); at this time, Lake Erie was covered by warm air with temperatures near 60° F. The warm air advanced eastward as the low pressure moved northward to Hudson Bay. Strong, gusty southwesterlies replaced southerly winds and temperatures began to fall with the cold-front passage: snow flurries were common in the cold air. In this case the peak set-up occurred at 0800 EST, November 17 (see right panel of fig. 10), about 15 hours after the cold front passed Buffalo. Strong winds persisted over Lake Erie until noon on the 17th.

6. SUMMARY AND CONCLUSIONS

The writers have discussed some climatological aspects of extreme wind tides produced on Lake Erie by strong southwesterly winds associated with severe cyclonic storms. In the 20-year period 1940 through 1959 there were 76 storms that produced a set-up in which Buffalo lake level exceeded Toledo lake level by 6 feet or more. In the same period, only three storms produced an "easterly" set-up in which Toledo level exceeded Buffalo level by 6 feet or more; in none of the latter cases did the set-up exceed 8 feet.

The frequency-intensity distribution of the 76 cases shows that one may expect on the average a set-up in excess of 10 feet once every 2 years, and a set-up in excess of 12 feet once every 5 or 6 years. The monthly frequency distribution of these data shows that about one-third of the total number of cases falls in the month of November and the remainder of the cases in the other seven months excluding May, June, July, August; no cases of extreme wind tide occurred in the four latter months during the 20-year period examined. The November maximum frequency of extreme set-up on Lake Erie probably reflects mainly the November maximum frequency and intensity of Great Lakes storms, which in turn is associated principally with southward displacement of the mean position of the polar front, and to some extent also with the autumnal enhancement of thermal instability of the atmospheric boundary layer. Thermal stability of the Lake itself may tend to inhibit wind tides during summer months, thereby exaggerating the winter maximum.

An examination of storm tracks failed to reveal any simple relation between magnitude of set-up and source region or path followed by the associated low centers. During the 24 hours preceding the time of peak set-up, however, all centers move approximately from southwest to northeast along tracks that lie in a band bounded by one southwest-northeast line along the longitudinal axis of the Lake and another line parallel to this lying about 600 miles to the northwest. The mean position of low centers at the time of peak set-up is located about 350 miles due north and slightly east of the center of the Lake, the individual positions having a dispersion approximately 225 miles from the mean.

Frontal speeds also were examined, with a view to establishing a relation between set-up magnitude and propagation speed of the front in its passage across the Lake, as would be expected if there is resonant coupling involved in the energy transfer from atmosphere to Lake. The data did not, however, exhibit any relation which would support the idea that resonant coupling is significant in determining set-up magnitude. This result has been corroborated by an independent theoretical analysis of the response of a one-dimensional lake to a moving stress band of finite width, which confirmed that resonance is suppressed almost completely when the stress-band width is greater than the width of the lake. This is certainly the case for Lake Erie, the major axis of which is only about 350 km. in length—much less than the scale of cyclonic systems.

The study presented in this paper was begun as an initial phase of a program for dynamical prediction of wind tides (which will be reported elsewhere), and was continued as an independent investigation of the climatological aspects of the problem. This explains in part why the writers have not entered here into the practical questions of forecasting extreme wind tides, which may be of interest to some readers. One of our reviewers, for example, suggests that an antecedent regime of easterly winds followed by a sudden reversal to westerlies (as in fig. 10) might in many cases be responsible for augmenting the wind-tide amplitude. The writers did, in fact, make a cursory scrutiny of the cases in hand with this point in view, but found no clear-cut evidence to support that hypothesis. However, we have not studied our data from the standpoint of subjective or empirical forecasting, and would welcome any future contributions in that field.

ACKNOWLEDGMENTS

Lake-level data at Toledo and Buffalo were provided by the U.S. Lake Survey; the writers gratefully acknowledge the assistance of Mr. W. T. Laidly and of Mr. L. D. Kirshner in this connection. Much useful advice was obtained also from Mr. D. Lee Harris of the U.S. Weather Bureau.

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