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A Review of Cyclone Track Shifts Over the Great Lakes of North America: Implications for Storm Surges

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Abstract

Cyclone tracks over the Great Lakes of North America shift, both East-West as well as North-South. The reasons for the shifts are various small-scale as well as large scale processes associated with the general circulation of the atmosphere. The East-West shift has an approximate periodicity of 10 years, while the North-South shift occurs roughly with a periodicity of 20 years. The East-West shift is more important than the North-South shift. The amount of shift could be as much as a few hundred kilometers. The implication of these shifts for storm surges in the Great Lakes is considered.

Keywords: Storm surges; Cyclone tracks shift; Great Lakes of North America

1. Introduction

Figure 1 shows a map of the five Great Lakes of North America.

This paper considers tracks of extra-tropical cyclones (ETC) travelling generally from the west, as well as tropical cyclones (TC) from the Atlantic Ocean and the Gulf of Mexico, that get somewhat modified when they reach the Great lakes.

NAV Canada (2017) identified the following lows (low pressure systems) that influence the Great Lakes in winter (Figure 2): Mackenzie, Alberta, Colorado, Gulf, Hatteras, Great Lakes. A careful examination of their diagram reveals the deduction shown in Table 1.

Table 1: Names of the lakes affected by lows in winter.

Name of Low	Names of Lakes Affected
Mackenzie	Superior
Colorado	Erie, Ontario
Alberta Low	Michigan, Huron

Nav Canada (2017) identified the following lows that could affect the Great Lakes in summer (Figure 3): Mackenzie, Alberta, Colorado, Pacific, Hatteras, Great Lakes, Hudson Bay. A critical study of their map yields the results in Table 2.

Table 2: Names of the lakes influenced by lows in summer.

Name of Low	Names of Lakes Affected
Colorado	Michigan, Huron
Great Lakes	Erie, Ontario

2. Shift in the Cyclone Tracks

Two types of shifts have been identified by various authors (Danard, et al, 2004), Lewis (1987), Wood et al (1995), Sellinger and Quinn (1999). N.O.A.A. (1996) gave cyclone track maps for 1955-1964, 1965-1974, 1975-1984 and 1985-1994. Table 3 shows the North-south shift deduced from these maps.

Table 3: North-South shift in cyclone tracks.

Period	Shift
1955-1964	Shifted North
1965-1974	Shifted South
1975-1984	Shifted further South
1985-1994	Shifted North

Thus, the North-South shift shows an approximate periodicity of 20 years. Table 4 provides some information on the East-West shift.

Table 4: East-West shift in cyclone tracks.

Period	Shift
1959-1969	Tracks were West of Lake Michigan
1969-1979	Shifted Eastward (East of Lake Ontario)
1979-1989	Shifted Westward
1989-1995	Shifted Eastward

Thus, the East-West shift shows an approximate periodicity of 10 years. Wood. et al. (1995), using data going back to 1887, detected a northward shift of the tracks. This northward shift during 1980-1995 was as much as 100 km for Lake Michigan. Sellinger (1999) suggested that the East-West shift is more pronounced than the North-South shift.

3. Computation of Storm Surges

Linear storm surge prediction equations (Murty, 1984) are given below.

$$\frac{\partial M}{\partial t} - fN = -gD\frac{\partial h}{\partial x} - \frac{D}{\rho_o}\frac{\partial P_a}{\partial x} + \frac{1}{\rho_o}(\tau_{S_x} - \tau_{B_x}) \qquad (1)$$

$$\frac{\partial N}{\partial t} - fM = -gD\frac{\partial h}{\partial y} - \frac{D}{\rho_o}\frac{\partial P_a}{\partial y} + \frac{1}{\rho_o}(\tau_{S_y} - \tau_{B_y}) \qquad (2)$$

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \qquad (3)$$

For convenience, hereafter, the subscript on the density field will be omitted.

In these linear storm surge prediction equations, the dependent variables are the transport components M and N and the water level h. The forcing functions are the atmospheric pressure gradients given by $\frac{\partial P_a}{\partial x}$ and $\frac{\partial P_a}{\partial y}$ and the wind stress components τ_{S_x} *and* τ_{S_y}. The retarding force is the bottom stress. At this stage, there are more unknowns than the available equations. To get a closed system of equations, the bottom stress must be expressed in terms of the known parameters, such as the volume transports.

Bottom Stress

Here, parameterization of the bottom stress, based on Simons (1973), will be discussed. Let $\boldsymbol{V_B}$ denote the velocity vector near the bottom. Then, the bottom stress τ_B can be expressed as

$$\tau_B = \rho k |V_B| V_B \qquad (4)$$

Where k is a nondimensional coefficient referred to as skin friction; the value of k is about 2.5 x 10^{-3}. If one assumes a uniform velocity distribution in the vertical, and noting that the horizontal transport vector M is given by

$$M = (M, N) = \int_{-D}^{h} V_B \, dz = \int_{-D}^{h} (u, v) \, dz \qquad (5)$$

One obtains

$$\frac{\tau_B}{\rho} = BM \text{ where } B = \frac{k|M|}{(D+h)^2} \qquad (6)$$

In most storm surge studies, either for obtaining analytical solutions or for economizing on computer time in numerical models, the bottom stress relation (4) is linearized by assuming typical values either for the average velocities or the transport components. For a model of Lake Ontario, Simons (1973) assumed average velocities of the order of 10 $cm \cdot s^{-1}$ in the shallow waters and about 1 $cm \cdot s^{-1}$ in the deep waters of the lake. Thus, B varies from $0.0025/D$ to

0.025/D in C.G.S. units. Rao and Murty (1970) used a value of 0.01/D for B in their model for Lake Ontario.

Instead of the average velocity field, one can examine the mass transport, which varies more smoothly. For Lake Ontario, Simons (1973) gave a value of 2 x 10^4 to 4 x 10^4 $cm^2 \cdot s^{-1}$ in shallow as well as deep water, and this leads to $B = 50/D^2$ to $100/D^2$ in C.G.S. units. Another approach for prescribing the bottom stress is to specify the vertical turbulent diffusion of momentum by a constant eddy viscosity v. Platzman (1963) deduced a bottom friction coefficient as a function of the Ekman number, $D\sqrt{f/2v}$, in such a way that $B \rightarrow 0$ for great depths and $B = 2.5v/D^2$ for shallow water. For Lake Erie, Platzman took $v = 40 cm^2 \cdot s^{-1}$, which gives $B = 100/D^2$ in C.G.S. units.

Thus, the alternatives for the bottom friction can be summarized:

$$\text{Linear form } B = \frac{a}{D} \qquad a \sim 0.01 cm \cdot s^{-1}$$

$$\text{Quasilinear form } B = \frac{b}{D^2} \qquad b \sim 100 cm^2 \cdot s^{-1} \qquad (7)$$

$$\text{Nonlinear form } B = \frac{k|V|}{D^2} \qquad k \sim 0.0025$$

In most early storm surge studies, the linear form has been used. Fischer (1959) used the quasilinear form, whereas Hansen (1956) and Ueno (1964) used the nonlinear forms.

Earlier storm surge numerical models used rectangular grids in a finite-difference (F-D) framework. Later irregular triangular grids in a finite-element (F-E) approach are used. Other approaches to model narrow connections between lakes are stretched coordinates and transformed grid systems.

Birchifield and Murty (1974) used a stretched coordinate system to model the combined system of Lake Michigan, straits of Mackinac and Lake Huron. The grid system is shown in Figure 4.

The transformed grid is shown in Figure 5.

The original equations (1) to (3) become as follows in the transformed coordinates.

$$\frac{\partial M}{\partial t} = gD\left(A_2\frac{\partial f_1}{\partial y} - A_1\frac{\partial f_1}{\partial x}\right)\frac{\partial h}{\partial \xi} + gD\left(A_2\frac{\partial f_2}{\partial y} - A_2\frac{\partial f_2}{\partial x}\right)\frac{\partial h}{\partial \eta} - C_1 M + C_2 N + B_1\tau_{s_x} - B_2\tau_{s_y}$$

(8)

$$\frac{\partial M}{\partial t} = gD\left(A_2\frac{\partial f_1}{\partial x} - A_1\frac{\partial f_1}{\partial y}\right)\frac{\partial h}{\partial \xi} + gD\left(A_2\frac{\partial f_2}{\partial x} - A_2\frac{\partial f_2}{\partial y}\right)\frac{\partial h}{\partial \eta} - C_2 M - C_1 N + B_1\tau_{s_y} - B_2\tau_{s_x}$$

(9)

$$\frac{\partial h}{\partial t} = -\frac{\partial f_1}{\partial x}\frac{\partial M}{\partial \xi} - \frac{\partial f_2}{\partial x}\frac{\partial M}{\partial \eta} - \frac{\partial f_1}{\partial y}\frac{\partial N}{\partial \xi} - \frac{\partial f_2}{\partial y}\frac{\partial N}{\partial \eta} \qquad (10)$$

Note that these equations are no more difficult than the original equations. Whereas in the original equations the coefficients depend only on the depth *D,* in these equations they depend also on the derivatives of the mapping function.

4. Storm Surges in the Great Lakes Due to Cyclones

Lake Superior, being the deepest of the five Great Lakes, does not give rise to significant storm surges. The biggest surges occur in Lake Erie, which is the shallowest of the five Great Lakes. Surges are generated, not only by the synoptic scale systems, such as cyclones, but also by meso-scale systems like squall lines and pressure-jump lines. This phenomenon is more observable in Lakes Erie, Ontario and the Southern part of Lake Michigan.

Murty and Polavarapu (1975) reconstructed some major storm surges due to storms that were extensive enough to affect all the Great lakes. Their study considered the period 1679 – 1940. The casualties due to high water levels (attributed to storm surges) in the Great lakes (both in Canada and the United States) during this period are listed in Table 5. The casualty toll resulted not only from people drowning near the coast but also from the sinking of ships battered by high waves. This table, at best, is only a partial list and several surges may have been missed. The fact that there is no entry for the eighteenth century is astonishing; it is inconceivable that there were no storm surges on the Great Lakes during a 100-yr duration.

An examination of Table 5 shows that all the major storm surges listed occurred during September to November. Irish and Platzman (1961) explained this as due to the convergence of two primary storm tracks from Alberta and Colorado lows in the Great Lakes region. This is due to the southward displacement of the polar front. Also, there is a contribution of cyclogenesis from the Great Lakes themselves.

Of the 10 entries in Table 5, the storm surges of 1913, 1916, 1940 were reconstructed by Murty and Polavarapu (1975). The tracks of these storms considered in this study are illustrated in Fig. 6. The notation used in the diagram represents day and time of storm. For example, 10 (1930) means that the center of the storm was at that location at 19:30 hours on the 10^{th} day of that month. The surface weather chart for 7:30 hours on November 12, 1940, is given in Fig. 7. The extensive size of weather system and the intensive atmosphere pressure gradients associated with this can be seen in this diagram. The locations of the water level stations used are shown in Fig. 8. The observed and computed maximum surges at various locations are listed in Table 6.

Table 5: Casualties due to high water levels in the Great Lakes. (Murty and Polavarapu, 1975)

Date	No. of casualties	Date	No. of casualties
Sept. 23, 1679	34	Nov. 9, 1913	251
Nov. 11, 1835	Several hundred	Oct. 20, 1916	55
Oct. 13, 1845	3	Nov. 24, 1918	76
Sept. 8, 1860	287	Nov. 24, 1919	40
Nov. 27-28, 1905	78	Nov. 12, 1940	67

Table 6: Recorded and computed water levels at Canadian stations on the Great Lakes. (Murty and Polavarapu, 1975).

Date of storm	Station	Observed maximum surge (m)	Calculated maximum surge (m)
November 1913	Port Colborne	1.36	1.40
	Fighting Island	0.48	0.52
	Kingston	0.33	0.27
	Isle aux Pêches	0.28	
	Port Dalhousie	0.20	
October 1916	Port Colborne	1.22	0.88
	Fighting Island	0.71	0.24
	Collingwood	1.64	0.46
	Isle aux Pêches	0.51	0.18
	Goderich	0.39	0.12
	Kingston	0.32	0.15
	Michipicoten	0.24	0.15
	Port Dalhousie	0.20	
	Port Arthur	0.14	
November 1940	Port Colborne	1.43	1.52
	La Salle	0.81	0.46
	Collingwood	0.77	0.73
	Point Edward	0.71	0.76
	Michipicoten	0.70	0.73
	Sault Ste. Marie	0.58	0.64
	Tecumseh	0.54	0.27
	Port Stanley	0.53	0.46
	Goderich	0.51	0.55
	Thessalon	0.39	0.37
	Port Lambton	0.29	
	Kingston	0.24	
	Toronto	0.24	
	Port Arthur	0.19	
	Port Dalhousie	0.18	

The effect of rate of growth of the storm on the subsequent surge is examined in Table 7 for the three storms studied here.

Table 7: Effect of the rate of storm growth on the subsequent surge. (Murty and Polavarapu, 1975).

Station	1913 Storm	1916 Storm	1940 Storm
Port Colborne (Lake Erie)	Faster growth; range of surge was >1.22m	Slower growth; range of surge was <0.91m	Faster growth; range of surge was <1.22m
Fighting Island (Detroit River)	Slower growth; positive surge was 0.48m	Faster growth; positive surge was 0.71m	Station did not exist
Isle aux Pêches	Slower growth; positive surge was 0.28m	Faster growth; positive surge was 0.51m	Station did not exist
Michipicoten	Station did not exist	Slower growth; positive surge was 0.24m	Faster growth; positive surge was 0.70m

Starting in the 1950s, the early warning systems and navigation techniques improved significantly, so that catastrophic disasters on the Great Lakes have become somewhat unlikely.

5. Storm Surges in the Great Lakes from Meso-Scale Weather Systems

On August 22, 1971 a squall line passed over Lake Huron and caused significant damage. The storm surge of August 22, 1971, in the southern part of Lake Huron was a combination of the effects of an intense and narrow squall line and a cyclonic circulation associated with a low pressure system (Freeman and Murty 1972; Murty and Freeman 1973). The simplified surface weather chart at 19:00 on August 22, 1971 (note that the peak surge occurred at 18:00), is shown in Fig 9. The track of the low-pressure system is also shown and the dots represent 6-h intervals. The storm moved from west-northwest across the southern portion of the lake with a speed of about $80.5 km \cdot h^{-1}$. With the center of the low to the east of the lake, a fairly steady wind from north-northeast blew along the longitudinal axis of the lake with a fetch almost two thirds of the lake and with an average speed of $32.2\ km \cdot h^{-1}$. Some time before 18:00, the deceleration of a portion of the rapidly advancing cold front produced a squall line with winds peaking to

112.6km·h^{-1}, which is much greater than the steady winds. The squall line, approximately 32 km long and 8 km wide, traveled over Lake Huron from the north-northeast to Sarnia and farther, cutting a 16-km-wide swath inland and causing significant damage onshore. Figure 9 shows the surface weather chart.

The meteorological and water level stations are shown in Figure 10.

Figure 11 shows the water level fluctuations at three locations.

Figure 12 shows the way the squall line was modeled in the numerical model by Murty and Freeman (1973)

6. Seiches, Edge Waves, Helmholtz Mode and Harbor Resonance

A seiche is a special case of a standing wave that is due to repeated reflections (assuming no dissipation) from the two sides of a closed basin (in the one-dimensional sense). Where anti-nodes exist, the period T_n of the n^{th} mode of oscillation in a rectangular basin of length L and uniform depth h is:

$$T_n = \frac{2L}{n\sqrt{gh}} \quad (11)$$

This is a generalization of the Merian formula and is valid for one-dimensional oscillation (no transverse motions). Note that at the nodes the motion is purely horizontal and at the antinodes it is purely vertical. The higher nodal (binodal, trinodal, etc.) seiches that may occur simultaneously with the fundamental mode (i.e. unimodal oscillation) are higher harmonics of the fundamental.

From equation 11:

$$\frac{T_n}{T_l} = 1, \frac{1}{2}, \frac{1}{3}, \dots, \frac{1}{n}, n = 1,2, \dots, n$$

However, for irregular water bodies with variable depth (unlike in the case of a narrow rectangular basin of uniform depth), such a simple relation as above need not exist. Another point worth remembering is that neither the use of an average depth $\hbar$ nor a better version of this, as done by du Boys (see Defant 1961) improves the Merian formula significantly.

$$T_n \sim \frac{2}{n} \int_0^L \frac{dx}{[gh(x)]^{1/2}} \qquad (12)$$

Wilson (1972) gave the periods (in minutes) of the fundamental mode in the Great lakes: Ontario (289), Erie (858), Michigan-Huron (2,700), Superior (480).

Next, consider the Helmholtz mode in the context of hydrodynamics (Miles (1971) used the term "Helmholtz mode," Platzman (1972) used "co-oscillating mode," and Lee and Raichlen (1972) referred to it as the "pumping mode"). Basically, Helmholtz resonance represents the balance between the kinetic energy of water flowing in through a narrow connecting channel and the potential energy from the rise in the mean water level within the harbor (Freeman et al. 1974). It is an additional gravitational mode of a substantially longer period than the fundamental free oscillation, as can be seen below.

To conceptualize the Helmholtz mode, Platzman (1972) presented the following argument. Suppose that at the mouth of a rectangular bay an adjustable barrier exists and that this barrier is gradually moved from the two sides of the bay to the center, completely closing off the bay. The open modes with periods initially of the form 2T/(2*n*-1), *n*=1,2,3,…, will be transformed continuously into the closed mode periods of T/*n*, *n*=0,1,2,… It is obvious that the fundamental mode for the open bay transforms into the zeroth mode for the closed basin, and as the barrier closes, this period approaches ∞. For small openings, the period of the Helmholtz mode is less than ∞ but greater than the period for a completely open bay. Plazman (1972) showed that earth's rotation changes the period of the Helmholtz mode by, at most, 3%.

Below, how the Helmholz mode in Goderich Harbor (Lake Huron) contributed to an amplified storm surge will be considered. The classic theory for the Helmholtz mode can be applied only to a single channel harbor. Freeman et al. (1974) extended this to a harbor (or basin) with multiple channels (or openings). The dissipative forces (due to the eddy viscosity of the fluid and to the energy radiated from the mouth) are ignored. These forces affect the amplification factor at resonance and will shift the resonant frequency slightly. The solution developed by Freeman et al. (1974) for the frequency ω_o is:

$$\omega_o = \sqrt{\frac{g}{A}}\sum_{i=1}^{n}(\frac{S_i}{L_i})^{1/2} rad \cdot s^{-1} \tag{13}$$

Where g is gravity, A is the surface area of the harbor, S_i is the cross-sectional area of the ith channel, and L_i is the length of the ith channel.

During March 17-18, 1973, a storm passed over Lake Huron and the resulting surge caused damage to several ships in Goderich Harbor. This harbor consists of a main berthing basin for commercial ships and a comparatively small basin called Snug Harbor for pleasure craft. Protection to the harbor against wave agitation is provided by two offshore breakwaters. The meteorological situation associated with this storm was studied by Lawford (1977) and the general water level problem in Goderich Harbor was studied by Shaw (1974).

Baird et al. (1976) studied the surge in Goderich Harbor associated with this storm. They showed that the wind waves and seiches were not the main causes of damage in this harbor and the surge was mainly caused by Helmholtz resonance. Recorded water levels in this harbor at a normal time (not during any storm) show clearly an average 14-min period Helmholtz mode. Actually, the period ranged from 13 to 15 min. Note that the independent theoretical calculation by Freeman et al. (1974) gives 14 min as the period of the Helmholtz mode in Goderich Harbor.

A reconstruction of the possible water level changes showed that the contributions to the total surge from wind waves, Helmholtz resonance, and static setup were 2 ft (0.6 m), 4 ft (1.2 m), and 1.2 ft (0.4 m), respectively. The fact that this surge is not an isolated event can be seen from the fact that a surge of 3.7 ft (1.1m) occurred on March 9, 1974, and the recorded water level for this surge also showed a period of 14 min, which is the Helmholtz period. Next, edge waves and their contribution to storm surges in the Great Lakes will be discussed.

Stokes (1847) obtained solutions for wave motion over a sloping beach, these solutions being different from the traditional wave pattern on beaches. In these new solutions, the crests are perpendicular to the coast, but they travel in a direction parallel to the coast and their amplitudes decrease drastically from the shore seaward, and at a distance of one wavelength from the beach, their amplitudes are negligible. Lamb (1945) called them edge waves. Ursell (1952) showed that the Stokes solution is the gravest of an infinity number of possible modes of edge waves. For the *n*th mode (which has *n* extrema in elevation between the coast and the sea), the velocity *c* and the length L are given by

$$c = \frac{gT sin(2n+1)}{2\pi} \qquad (14)$$

$$L = \frac{gT^2 sin(2n+1)}{2\pi} \qquad (15)$$

On June 26, 1954, a squall line passed over the southern part of Lake Michigan and caused a surge on the Chicago water front. Several people were killed. This was explained by resonant coupling between the squall line and the resulting gravity waves generated in the lake (Donn and Ewing 1956). A resurgence (i.e. reflection of the waves from the eastern shore of the lake) explains its unexpected arrival at Chicago some 2h after the squall line had passed.

On July 6-7, 1954, another squall line crossed Lake Michigan from north to south with an average speed of 50 $mi \cdot h^{-1}$ ($80.5 km \cdot h^{-1}$). Long-period waves were recorded at several locations following this squall line. Donn and Ewing (1956) invoked edge waves to account for these water level disturbances. The computed period of the edge waves is 103 minutes, which agrees well with the observed period of 109 minutes.

7. Conclusions

The Great Lakes are influenced by extra-tropical cyclones (ETC) as well as tropical cyclones from the Atlantic Ocean and the Gulf of Mexico, that get modified somewhat when they arrive at the Great Lakes region. The storm surges in the Great Lakes are generated by synoptic scale cyclones, and also by meso-scale weather systems, such as squall lines and pressure-jump lines. Invocation of edge waves and Helmholtz resonance is needed to account for some of the water level oscillations.

An approximate periodicity of ten years for an East-West shift and a rough periodicity of twenty years for a North-South shift, has a great influence on where the surges will occur.

Please note, in this paper, most of the literature on storm surge on the Great Lakes looks dated because, even if decades ago, storm surge was a threat to the Great Lakes, presently, it is much less, thanks to improved techniques for timely prediction, existence of much better coastal defences and availability of highly improved navigational techniques. As a consequence, active research on Great Lakes storm surges is much less now than earlier.

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References

1. Baird, W. F., N. G. Freeman, and T. S. Murty. 1976. Reconstruction of the high water levels in Goderich Harbour during march 17-18, 1973. Report prepared by Environment Canada to the Department of Justice, Ottawa, Ont. 6 p.
2. Birchfield, G. E., and T.S. Murty. 1974. A numerical model for wind-driven circulation in Lakes Michigan and Huron. Mon. Weather Rev. 102(2): 157-165.
3. Danard. M. B, S. K. Dube, G. Gonnert, A. Munroe, T. S. Murty, P. Chittibabu, A. D. Rao and P. C. Sinha (2004) Storm surges from extra-tropical cyclones, Natural Hazards, vol 32, 177-190.
4. Defant, 1961. Physical oceanography. Vol. 2. Pergamon Press, Inc., New York, NY. 598 p.
5. Donn, W. L., and M. Ewing. 1956. Stokes' edge waves in Lake Michigan. Science (Washington, DC) 124(3234): 1238-1242.
6. Fischer, G. 1959. Ein numerisches Verfahren zur Er-rechnung von Windstau und Gezeiten in Randmeeren. Tellus 11: 60-76.

7. Freeman, N. G., and T. S. Murty. 1972. A study of a storm surge on Lake Huron, p. 565-582. Proc. 15th Conf. Great Lakes Res.

8. Freeman, N. G., P. F. Hamblin, and T. S. Murty. 1974. Helmholtz resonance in harbours of the Great Lakes, p. 399-411. Proc. 17th Conf. Great Lakes Res. Int. Assoc. Great Lakes Res. Proc. 15: 766 p.

9. Hansen, W. 1956. Theorie zur Errechnung des Wasserstandes und de Stromungen in Tandmeeren nebst Anwendungen. Tellus 8: 287-300.

10. Irish, S. M., and G. W. Platzman. 1961. An investigation of the meteorological conditions associated with extreme wind tides on Lake Erie. U.S. Weather Bur. Tech. Rep. No. 4. Department of Meteorology, University of Chicago, May 1961. 35 p.

11. Lawford, R. G. 1977. A study of meteorological events which occurred on March 17th and 18th, 1973, in the vicinity of Goderich, Ontario. Int. Rep. SSU-77-6. Ontario Region of Atmospheric Environment Service. 19 p.

12. Lee, J. J., and F. Raichlen. 1972. Oscillations in harbors with connected basins. J. Waterways Harbors Coastal Eng. Div. Proc. ASCE Issue WWZ, Aug. 1972. Vol. 98: 311-332.

13. Lamb, H. 1945. Hydrodynamics. Dover, New York. 738 p.

14. Lewis. P. J.. (1987) Severe storms over the great lakes: a catalogue summary for the period 1957 to 1985, Canadian climate center, report No. 87-13, Atmospheric environment service, Downsview, Ontario, Canada, no pagination

15. Murty, T. S., and N. G. Freeman. 1973. Applications of the concepts of edge waves and numerical modelling to storm surge studies on Lake Huron. Proc. 16th Conf. Great Lakes Res. Int. Assoc. Great Lakes. Res. 16: 533-548.

16. Murty, T. S., and R. J. Polavarapu. 1975. Reconstruction of some of the early storm surges on the Great lakes. J. Great Lakes Res. 1(1): 116-129.

17. NAV Canada, 2017, Personal communication.

18. N. O. A. A. (1996) Internal report of the national weather service, national oceanic and atmospheric administration, Washington, D.C. no report number or pagination.

19. Platzman, G. W. 1963. The dynamic prediction of wind tides on Lake Erie. Meteorol. Mongr. 4(26): 44 p.

20. Platzman, G. W. 1972. Two-dimensional free oscillations in natural basins. J. Phys. Oceanogr. 2(2): 117-138.

21. Sellinger. C. E. and F. H. Quinn (1999) Proceedings of the Great Lakes paleo-levels workshop, the last 4000 years, Great Lakes environmental research laboratory, N.O.A.A, Annarbor, Michigan, USA, 43 pages.

22. Shaw, V. K. 1974. Surge study, Goderich Harbour, Ontario. Marine Engineering Design and Construction Branch, Department of Public Works, Ottawa, Ont. 25 p.

23. Simons, T. J. 1973a. Development of three-dimensional numerical models of the Great Lakes. Sci. Ser. No. 12. Inland Waters Directorate, Canada Center for Inland Waters, Burlington, Ont. 26 p.1973b. Comparison of observed and computed currents in Lake Ontario during Hurricane Agnes, June 1972, p. 831-844. *In* Proceedings of the 16th Conference on Great Lakes Research. Proc. Int. Assoc. Great Lakes Reg. 16: 1068 p.

24. Stokes, G. G. 1847. On the theory of oscillatory waves. Trans. Cambridge Philos. Soc. 8: 441.

25. Ueno, T. 1964. Nonlinear numerical studies on tides and surges in the central part of Seto Inland Sea. Oceanogr. Mag. 16: 53-124.

26. Ursell, F. 1952. Edge waves on a sloping beach. Proc. R. Soc. London Ser. A 214: 79-97.

27. Wood. W. L, R. W. Wood and G. A. Meadows (1995) The climatology of cyclones over the great lakes in relation to lake level change and wave climate, programs, and abstracts of the 38 conferences on Great Lakes research, page 22.

28. Wikimedia Commons contributors (2014). File:Great Lakes 1.PNG', Wikimedia Commons, the free media repository. 6 December 2014, 23:12 UTC, https://commons.wikimedia.org/w/index.php?title=File:Great_Lakes_1.PNG&oldid=141673992. (accessed 22 July 2018).

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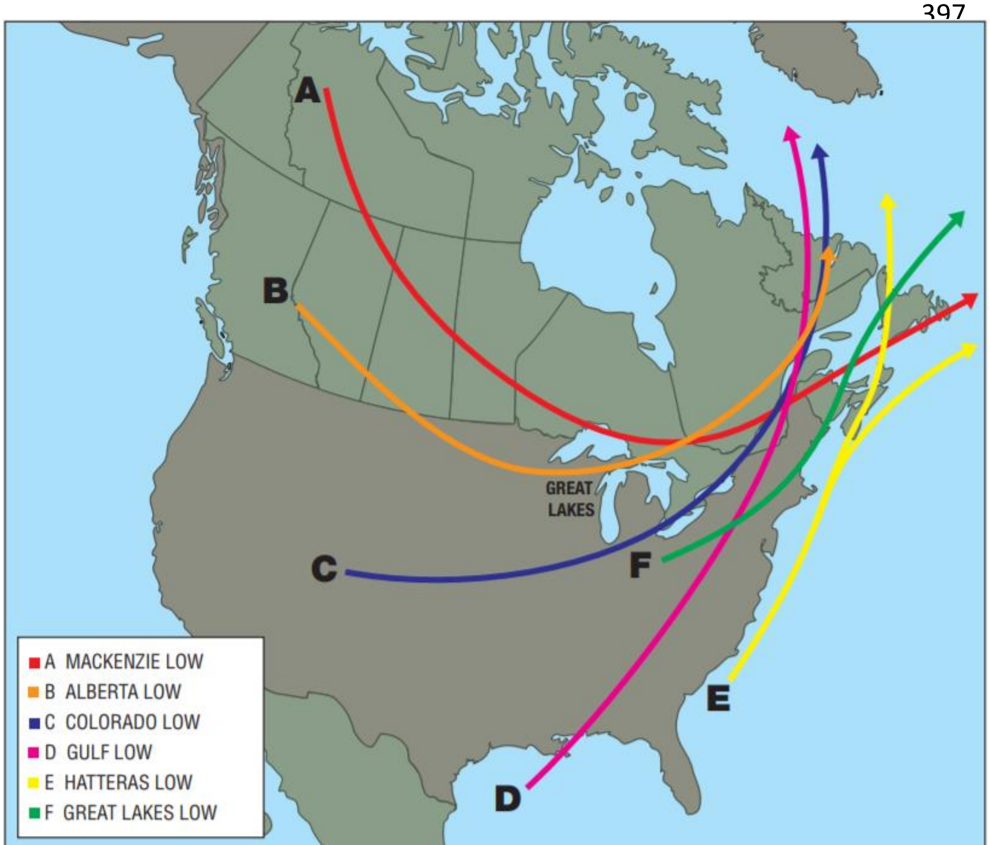

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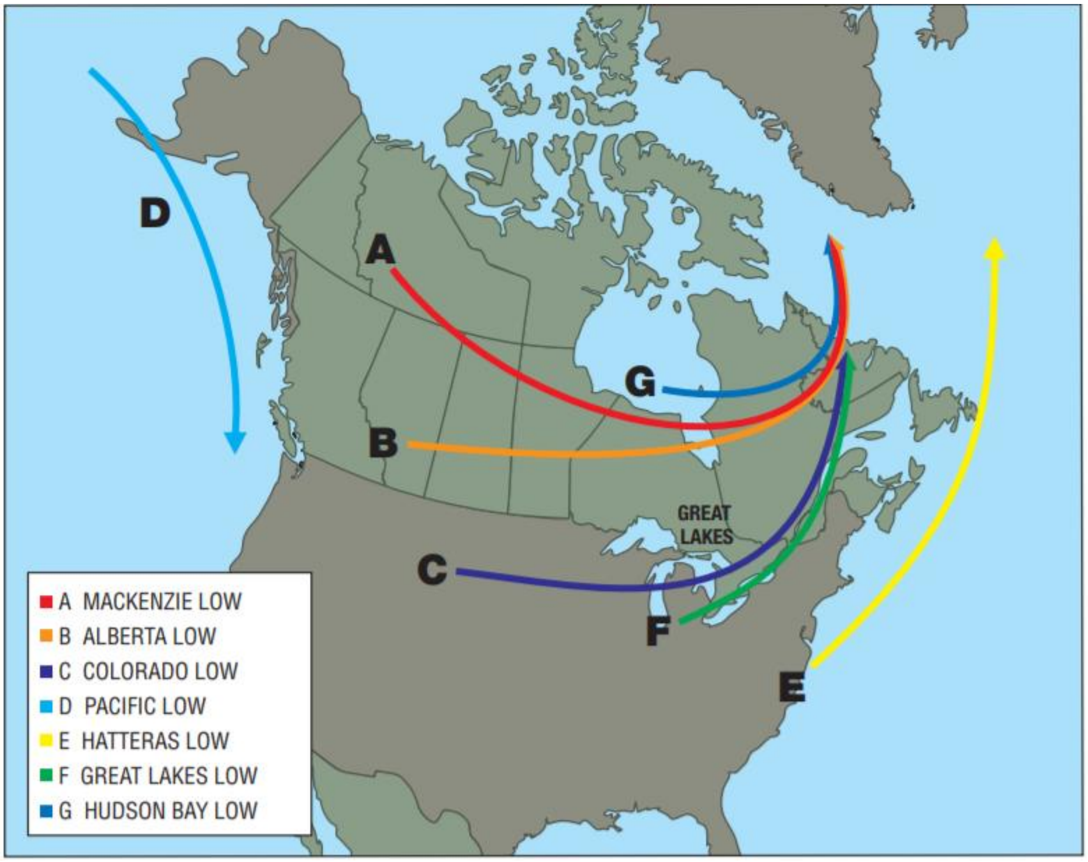

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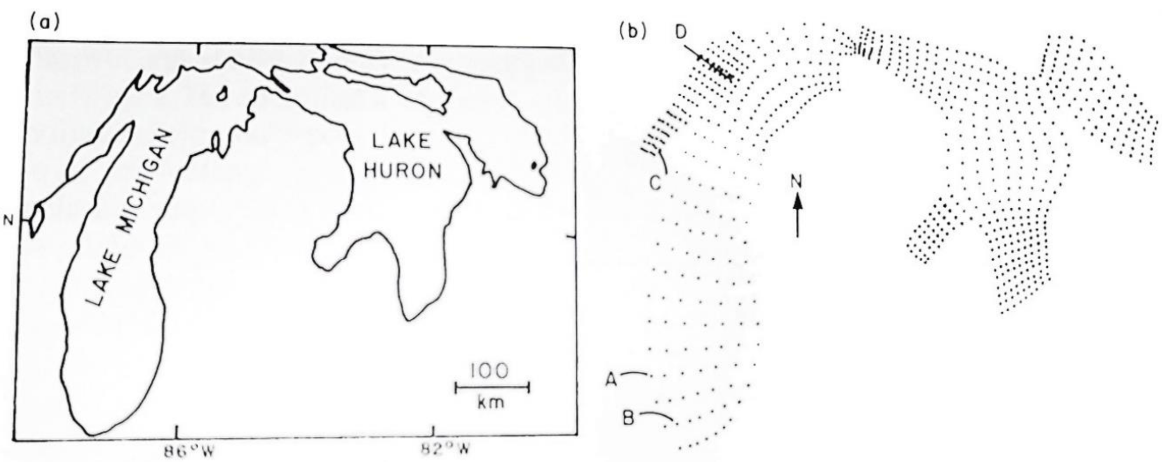

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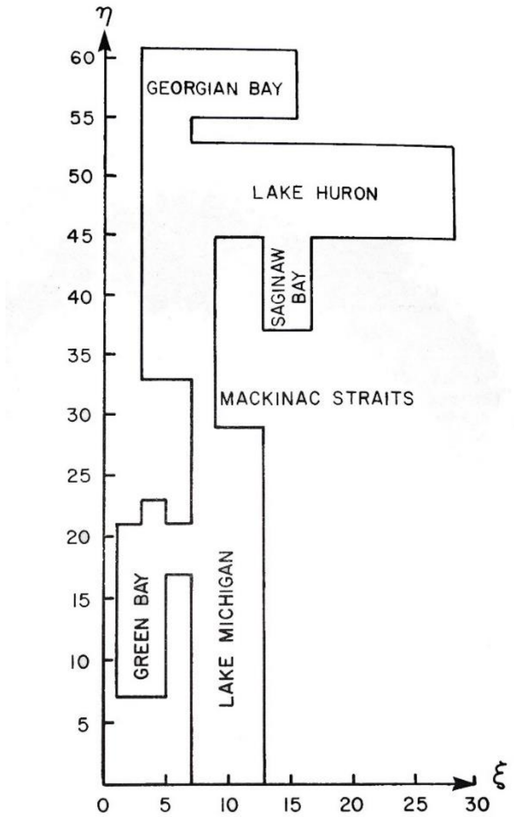

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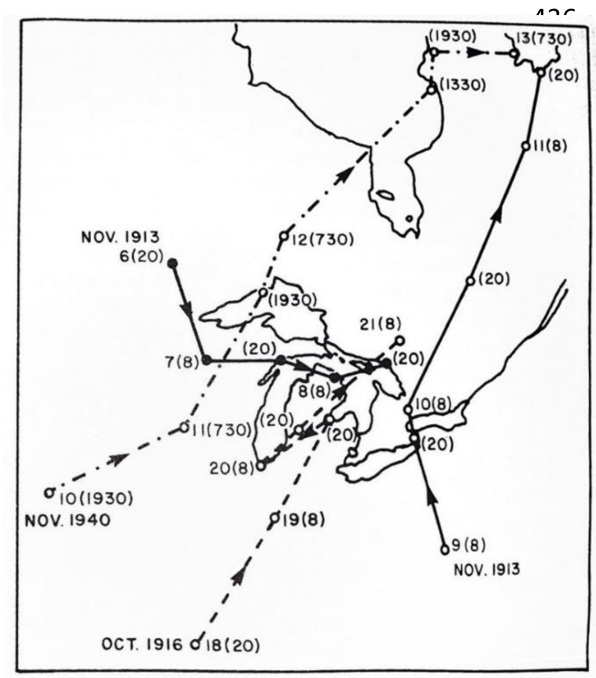

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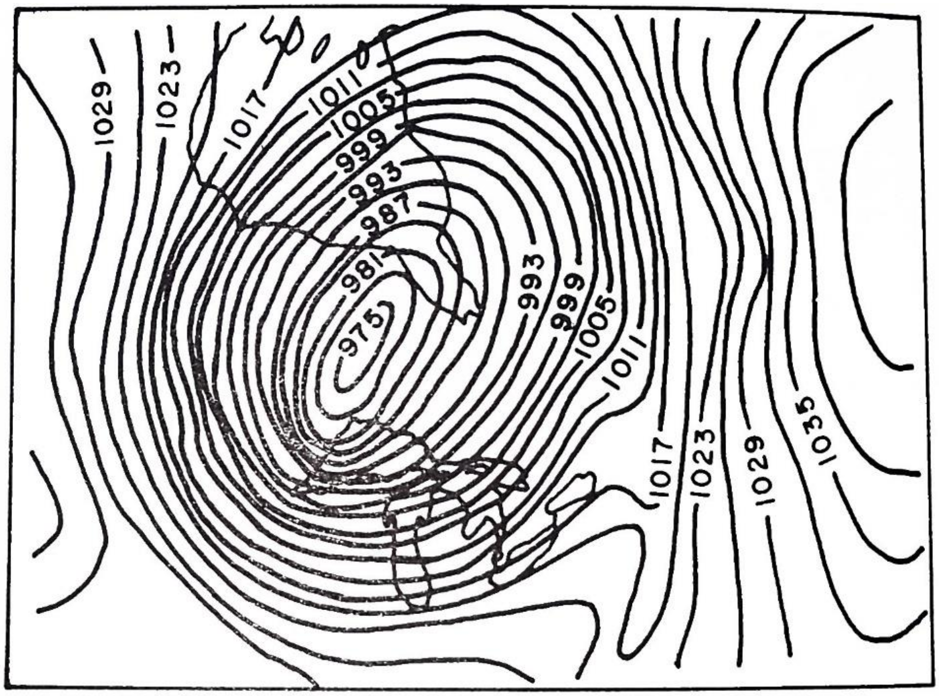

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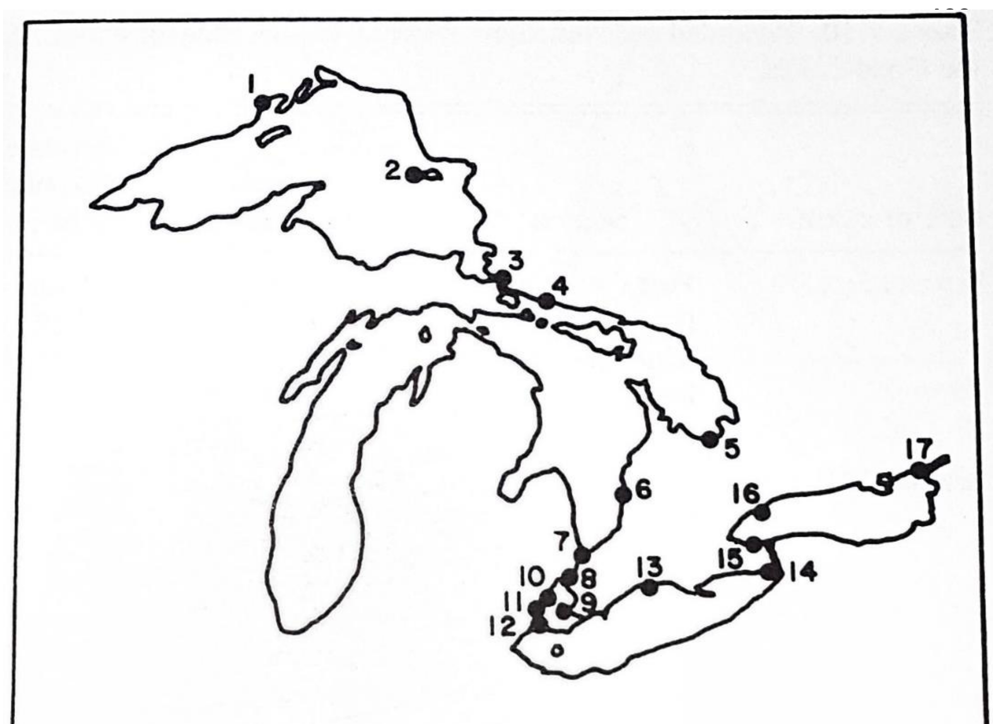

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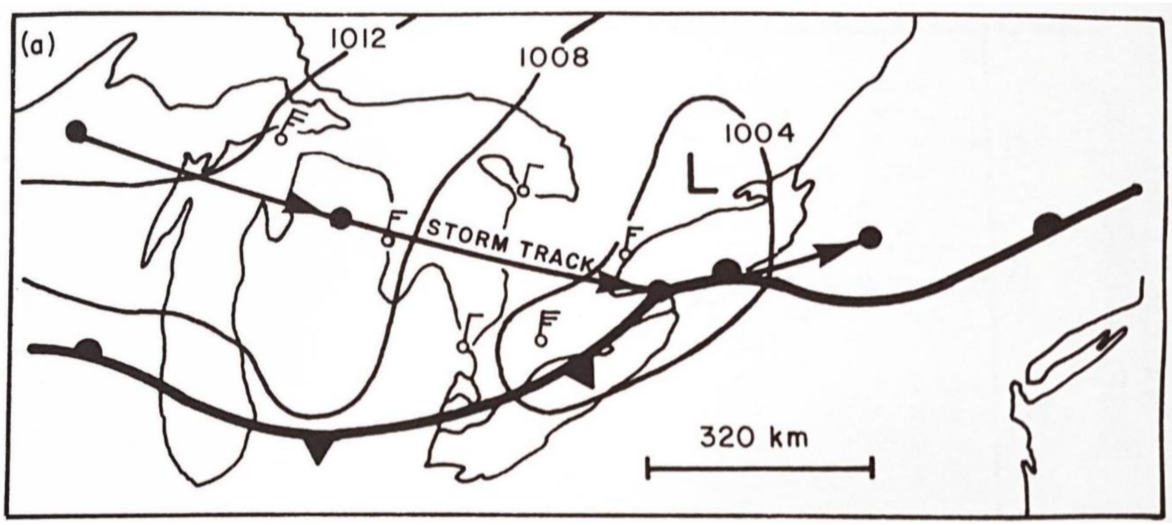

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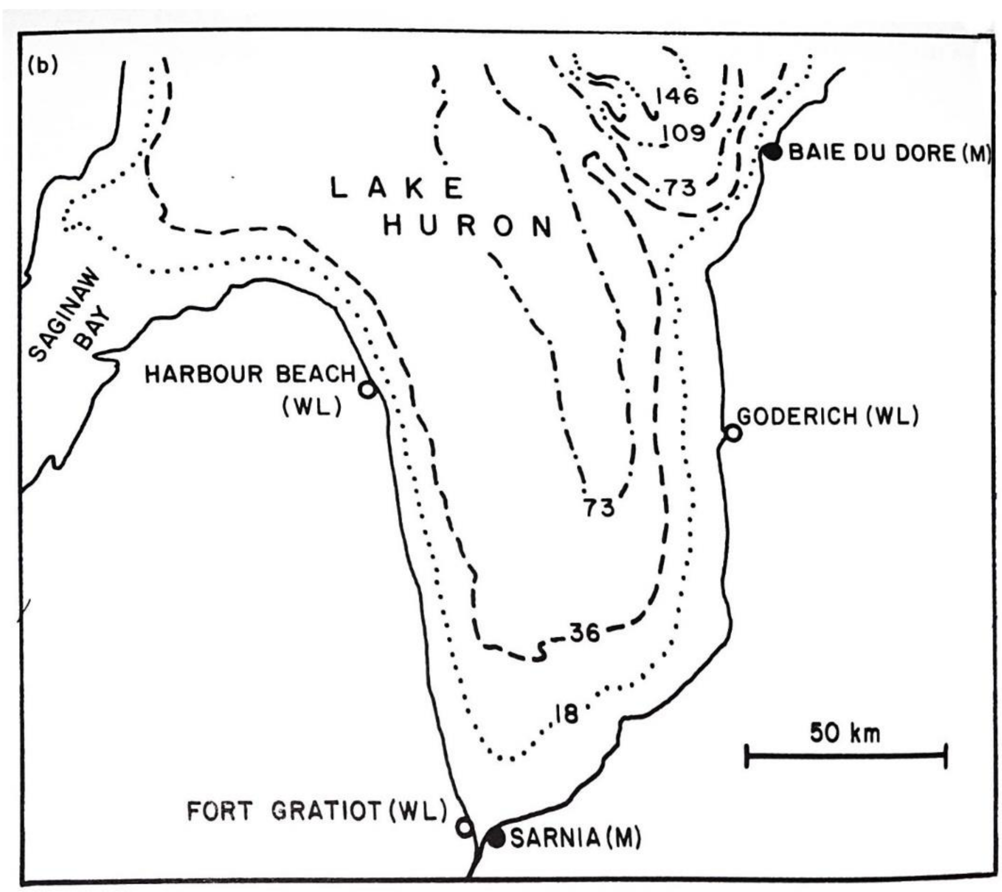

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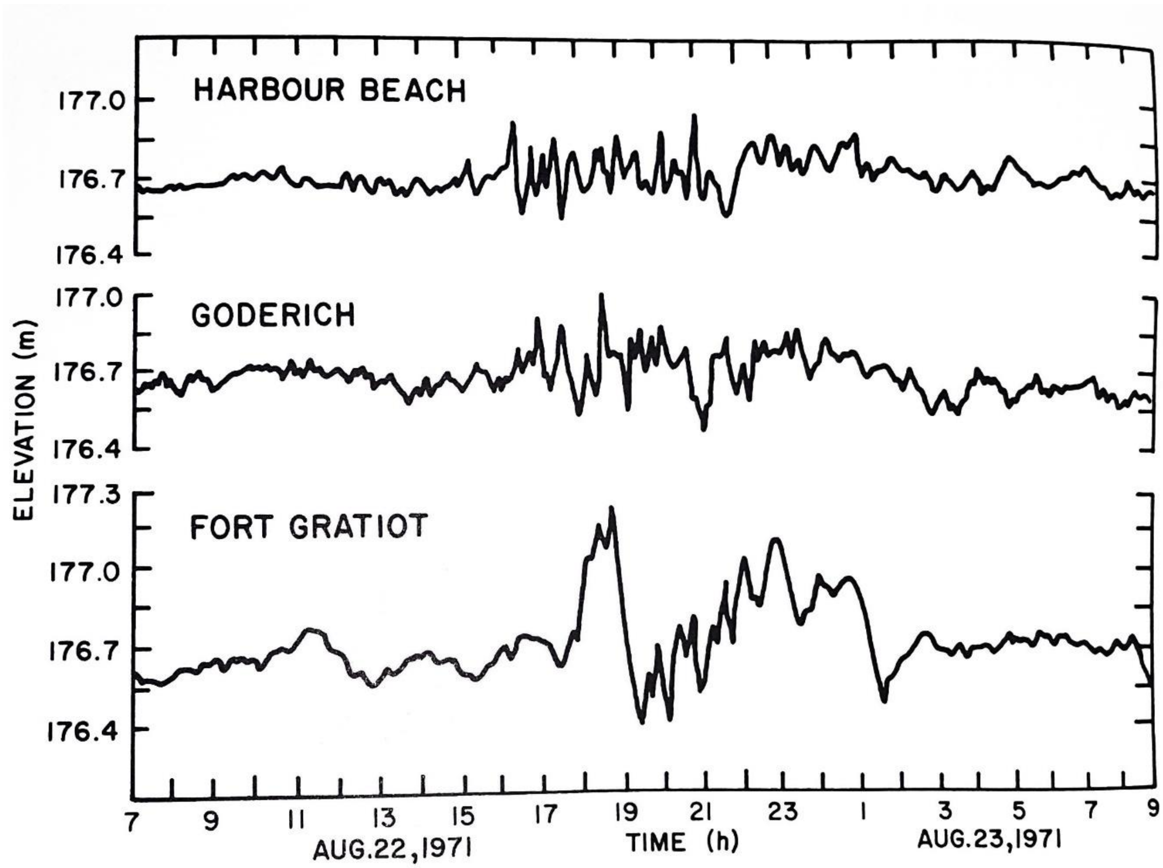

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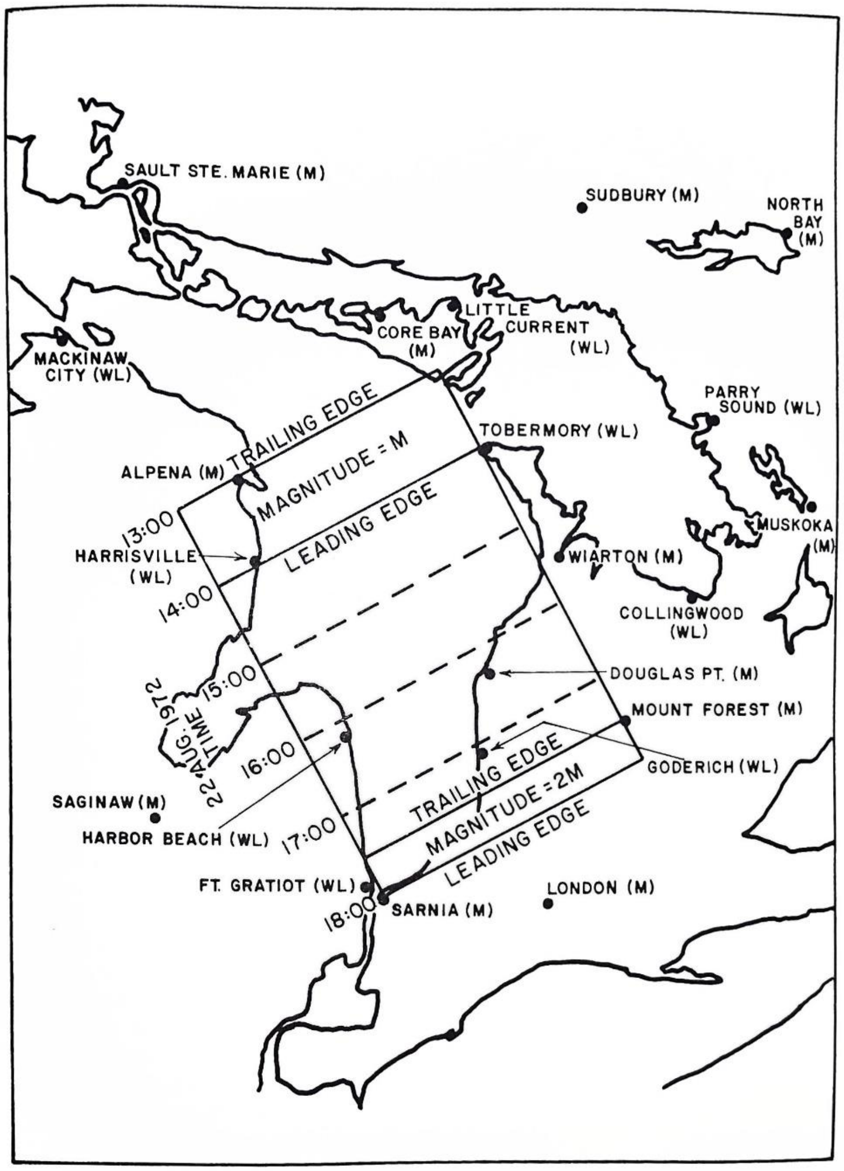

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