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on the

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SYMPOSIUM ON THE GREAT LAKES

THE ROYAL METEOROLOGICAL SOCIETY, CANADIAN BRANCH

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SYMPOSIUM ON THE GREAT LAKES

INTRODUCTION

By

JAMES P. BRUCE

There is little doubt that the Great Lakes exert a tremendous influence on the climate that affects the 5½ million people of Ontario. Among the more spectacular aspects of this influence are the Owen Sound snow belt and the temperate "peach climate" of the Niagara region.

Day-to-day weather features like fog and showers are influenced markedly by the Lakes - a fact to which all the Malton forecasters will doubtless attest.

There are, as well, some very interesting, but less obvious meteorological problems connected with the Great Lakes. The water balance of the Lakes themselves is an increasingly important problem, as it affects the water available for power production at the Niagara and St. Lawrence generating stations, and the depth of water for navigation.

The Lake surfaces themselves constitute a third of the total watershed area of the Great Lakes drainage basin. There is considerable suspicion that the precipitation falling on the Lakes themselves is substantially less than that which falls on surrounding land areas - perhaps as much as 20% less. This obviously affects the balance between precipitation and evaporation on the drainage basin.

Some imaginative research must be devoted to this particular problem. One hope is that photographs of the Malton weather radar scope, if handled on a climatological basis, may yield useful information on precipitation over Lake Ontario.

Synoptic studies of such photographs may help in assessing the effects of the Lakes on the rain production of major storms that pass over them. This is an important hydrometeorological problem. When considering the design capacity of spillways of high dams in southern Ontario, the question asked of the meteorologist is "Could a severe storm which produced 12.6" of rain in 6-hours in central Michigan, have occurred as readily over southwestern Ontario or would passage of the hot moist air mass that produced the storm over part of Lake Huron make such a storm impossible in southern Ontario?". To answer requires more detailed knowledge of the surface temperatures of the Lake water than we presently have, and of the water content and stability of air masses passing over them.

In view of such important problems as these, and the obvious economic value of the Great Lakes, there has been surprisingly little organized research on the Lakes. However, it should be noted that the Meteorological Branch has contributed notably to what Great Lakes research there is through the papers of F. Graham Millar on evaporation and Lake water temperatures.

One of the greatest hindrances to sizeable Great Lakes research programmes has always been the lack of an adequate research vessel. The cost of buying and operating a large enough ship to conduct research on the Lakes in fair weather and foul, in winter and summer, has always been prohibitive for any one agency concerned with a particular aspect of the Lakes.

Someone who recognized this fact early in his work is Dr. David V. Anderson. Dr. Anderson is a graduate in physics of the University of Toronto. For his M.A. work he specialized in electronics. His Ph.D thesis was in the fields of acoustics and seismology. He is a man of wide-ranging scientific interests.

Dr. Anderson has been, for the past 6 years, in charge of the Physics Section of the Ontario Department of Lands and Forests Research Division. In this capacity, he has insured that the physical approach has not been neglected in Lands and Forests research problems in forest fires, soils, forest regeneration, fisheries and other fields.

In connection with fisheries research, he stressed the importance of the environment of the fish, that is the Lakes themselves, in understanding fluctuating fish populations. Thus he became engaged in fresh water oceanography, or limnology, of Ontario's Lakes.

However, he soon found that the facilities available in the way of ships for research were adequate only for studies on the smaller Lakes up to about the size of Lake Simcoe. If any adequate limnological studies of the Great Lakes were to be conducted, a much larger ship was needed. It was obvious that it would be impossible to justify the large costs on the basis of fisheries research alone. It was equally obvious that the combined economic importance of lakes research applications in fisheries, shore erosion, meteorology, water supply and pollution, shipping and power production warranted a very sizeable research programme. The various U.S. agencies, each engaged in a particular facet of Great Lakes research, were in exactly the same position as were Dr. Anderson and the Department of Lands and Forests.

Instead of giving up the situation as being hopeless, however, Dr. Anderson decided something must be done to get the various organizations concerned together, to pool resources in a comprehensive Great Lakes research programme. He arranged with Dr. G.B. Langford, head of University of Toronto's Department of Geology, to call a conference on the Great Lakes in April 1957. More than 50 representatives of provincial, municipal and federal agencies, universities and industries were present. Out of this meeting was born the Great Lakes Geophysical Research Group, which Dr. Anderson discusses in the following pages.

Mr. Donald K.A. Gillies, our second author, is one of the small, but we hope, growing band of industrial meteorologists in Canada. He is employed by the Ontario Hydro-Electric Power Commission, and has made a number of notable contributions to the efficiency of that organization through the application of his meteorological knowledge.

As I understand Mr. Gillies' duties, he is involved operationally with several fields of applied meteorology such as hydrologic forecasting of reservoir storage, natural illumination forecasts and prediction of Lake Erie water levels as they affect the flow of the Niagara River. He has also become increasingly involved in economic planning problems some of which require climatological decisions.

However, Ontario Hydro could well afford to pay a meteorologist for many years to come for the method Mr. Gillies has developed for forecasting wind-induced fluctuations in Lake Erie levels, and his operational use of this method. It is of this matter he writes here.

The final section of this Symposium on the Great Lakes contains a bibliography of geophysical papers on the Great Lakes Basin of Ontario selected from the unpublished "Bibliography of Canadian Climate" by Morley K. Thomas, Deputy Chief of the Climatology Division, Meteorological Branch.

GEOPHYSICAL RESEARCH ON THE GREAT LAKES

By

D. V. Anderson

In the spring of 1959 a time of decision had been reached for judgement of a Canadian geophysical research programme on the Great Lakes. The programme had been under development for eight years, but in 1958 was greatly expanded in a trial way under the auspices of the Great Lakes Geophysical Research Group. The trial having been concluded, it now remained to be seen whether the work on the Lakes was to be continued and if so in what fashion. This paper gives a brief review of the growth and structure of the research programme on the Lakes, and of the considerations attending the actual practice of research. The paper is an outgrowth of an informal talk given to the Royal Meteorological Society, Canadian Branch, 25 February 1959, and of a brief on the Lakes prepared in 1958.

Since many of the underlying administrative and scientific problems of Lakes research have their counterparts in other fields of Canadian research endeavour, the results of the Great Lakes "experiment" may be instructive to those engaged in those other fields.

To begin with, it is best to explain the scope of work envisaged by the description "geophysical research on the Great Lakes". The geographical limits are for the most part the Great Lakes drainage area and St. Lawrence (to Montreal, say). The scientific subject matters are most conveniently grouped in: hydrometeorology of the Lakes' Basins - winds, precipitation, evaporation and runoff, over the land and on the Lakes themselves, and seasonal variation in all these elements; geology - structure of the Lake Basins, shoreline structure and sediments; and hydrodynamical description of the movements and temperature changes of the Lake waters, currents, surface and internal seiches, waves, turbulence and mixing. Many of these are closely inter-related, and their context is the general fabric of the earth sciences. In addition, model and other laboratory studies may be employed in other geophysical investigations.

It must be emphasized that application of knowledge of results of laboratory physics (if they are available) is not enough to gain understanding of the processes of nature "on the land". There are often too many factors involved, and many complexities connected with the size of the system. Thus in the case of the Lakes it is true that many phenomena already studied on smaller lakes or in the oceans give helpful clues or even solutions to particular problems. Generally speaking, however, the uniqueness of the Lakes and of their climatic regimes prescribe a thorough experimental programme of observation to see how they actually behave, and coupled closely with analysis, to try to understand and forecast their behaviour. The practical aim of this process is to explain to users of a Lake what happens in it, to forecast for their benefit what will happen in various contingencies, and to prescribe procedures for manipulating it.

Conversely, it must not be expected that observations on a large lake will always clarify basic ideas of complicated physical phenomena, such as turbulence, in which close experimental control is a prerequisite.

Performing experimental or observational work on a Lake, and proceeding further to application (i.e. solution of particular problems) is different from most geophysical work. The distinction is that in most respects the Lake must be regarded as a whole (or as the elephant of Aesop's fable). It is just this attribute of the Lakes that has been the source of most of the difficulty in promoting work on them. Work on the Lakes is inextricably interconnected in respect to:

1. the applications or various uses of the Lakes.
2. various scientific disciplines involved.
3. the mechanics of doing the work.

The principal applications referred to are: water supplies, sewage disposal, navigation, harbour design, shore erosion, fisheries, hydro-electric and steam-electric power, and weather forecasting. The accompanying Table shows the interconnections.

Insofar as the uses are concerned, the Lakes should be regarded more as large ponds than as small oceans. Not only may they be managed or regulated by man to some degree (e.g. regulation of discharges) but their constitution is markedly affected by pollutants. (The oceans and the atmosphere on the other hand are virtually unaffected by man except locally). By the same token some uses are in partial conflict with others. The idea of "multiple use" by priority of public importance that is growing in watershed management will undoubtedly become the criterion for the Lakes as the population on their borders increases. Indeed there are plenty of examples already to illustrate the existence of conflict in interest, viz. the Chicago diversion versus down-lake hydro use, offshore gas drilling vs. fisheries, sewage disposal vs. water supplies, hydro power vs. shore erosion. On the other hand some uses may go well with one another, e.g. navigation and water power (as in the St. Lawrence Seaway).

It is the simple and obvious but cardinal principle of resource management that a resource such as the Lakes which is pressed for use will be best used - the most obtained from it at the least cost - if adequate scientific knowledge of its attributes is available. Assuredly this applies only when the demands upon a resource increase to a point that troubles arise. Fifty years ago one could not have argued for a then-present need for research on the Lakes. Unfortunately many of the problems on the Lakes require many years of observation and other effort, and it is often too late to solve a problem when the problem is at last recognized.

TABLE OF BRANCHES OF RESEARCH VERSUS APPLICATIONS

RESEARCH / APPLICATIONS	WATER SUPPLIES	Water quality	Intake Location	SEWAGE DISPOSAL	Movements of pollutants	Assimilation of pollutants	NAVIGATION	HARBOURS	SHORE EROSION	Erosion of shore	Deposition	Protection devices	WATER POWER	FISHERIES	METEOROLOGICAL	Weather forecasting	Climatic effects	Flood forecasting	Atmospheric pollution
PHYSICAL LIMNOLOGY																			
Lake Temperatures		x	x		x	x				x	x	x	x	x		x	x	x	x
Currents		x	x		x	x	x	x		x	x	x	x	x		x	x	x	x
Water Levels																			
Long term change							x	x		x	x	x	x	x					
Short term change		x	x		x		x	x					x						
Internal seiches		x	x		x		x	x						x					
Water chemistry		x	x		x	x													
Meteorological interaction																			
Wind and waves					x		x	x					x	x					
Heat budget													x			x	x	x	x
Rainfall and evaporation							x			x			x					x	
GEOLOGY																			
Bottom sediments			x				x	x		x	x	x		x					
Erosion and deposition Processes			x				x	x		x	x	x		x					
HYDROBIOLOGY																			
Plankton		x	x			x								x					
Bacteriology		x	x			x								x					
Biochemistry of water		x	x			x								x					
Biochemistry of sediments		x				x								x					
Bottom organisms		x				x								x					

Assuredly the lack of complete information is no reason and would not be accepted as a cause for not taking needed action. But the Lakes are a resource worth billions of dollars, and their various uses involve expenditures of hundreds of millions annually. Research thus has only to result in savings or increase in national product of a small fraction of a per cent to justify itself.

The main stem of research in the Lakes and the common basis or unifying element for most research projects is research on the waters themselves, i.e., hydrometeorological study of the temperature structure, circulation, and meteorological interaction with the air above. Understanding of Lake processes is required for evaluation of what goes on at one spot or locality. For example, forecast of wave characteristics at one spot to devise shore protection will require not only study of waves at that spot, but studies over the whole Lake of wind patterns and seasonal variation in them, of seasonal stability of air over the lake, refraction effects and lakewide seiches. In geology and meteorology study of bottom sediments gives information on bottom water circulation, and the effect of the weather on the Lakes is obverse to the effect of the Lakes on local climate.

There is the further link in Lakes research and common with oceanography. The making of observations on the Lakes requires transportation, usually by boat. Thus observations which on land can be made easily and unilaterally, must be made from a boat, often at the same time. The cost of making observations on the water is high, and consequently coordinate observations are essential. Thus, scientists who on the land might go entirely separate ways, are thrown together by the need to share facilities.

Although valuable preliminary work had been done previous to 1958 with chartered and borrowed boats, the Canadian programme was limited to a low level of observational activity by lack of a research vessel. Thus the programme has been greatly enhanced by the loan from the Royal Canadian Navy of a 400 ton, 125 foot research vessel, the PORTE DAUPHINE. She is large and seaworthy enough that observations can be made year round in all weather, and limnological, meteorological and geological work can be conducted from her with great facility. While a research vessel can be regarded merely as a transportation facility, she is also an actual connecting link between the various phases of lakes research, all of which require regular or occasional lake observations but which singly could not justify the expense of the ship's operation.

All these considerations led to the formation of the Great Lakes Geophysical Research Group which has proved a temporary means for scientists and technical men interested in the Lakes to cooperate in projects of mutual concern.

The Great Lakes Geophysical Research Group is a rather tenuous association of individuals in Canadian agencies interested in the Lakes. Its only formal structure is a Steering Committee composed of representatives of the Federal and Provincial governments, Universities, private industries, and public utilities. This Committee is composed of scientists who have met from time to time to discuss methods of conducting research on the Lakes, raising money, and co-ordinating research. The Committee was intended from the start to be only an interim mechanism until a more formal "home" could be found for its activities. It is similar to the Joint Committee on Oceanography but differs from it in its membership. (The J.C.O. is composed only of Federal government officials).

The Group has been an effective device and under the chairmanship of Dr. G.B. Langford of the University of Toronto has performed a function not open to individual agencies or other bodies. Without it the work on the Lakes would undoubtedly have stopped.

It has been a very cheering experience to be able to work cooperatively with many agencies to a common end. There has been, however, by no means unanimous support of the programme, which has nearly foundered several times in the past five years. For one thing, this is a programme promoted largely by civil servant scientists. The general public does not clamour for it since the Great Lakes affect the public only indirectly in most instances. There have, however, been a few statements of public support such as the following Editorial in the Toronto Globe and Mail, 24 December 1958:

"What the people of Canada know about the Great Lakes is but a small fraction of what is yet to be learned about this truly wonderful system of fresh water basins and their connecting rivers. This summer will be the beginning of a 20-year program of study by a Great Lakes Geophysical Research group. A Canadian naval vessel is on loan to it as a base for a team of scientists drawn from Ontario Government departments, the Hydro-Electric Commission, private industry and universities.

"Detailed studies will be made of the general direction and periodic shifts of currents, and their effect on erosion and silting; of the rate of natural dissipation of pollution and methods of control, the habits of fish and the effects of pollution on their breeding, migrations and health. The siting of industrial areas on the shores, and the direction of storm paths across the surface, are to be charted. In addition, the lake bottoms will be drilled to discover their composition, their anomalies of structure and the extent of their contribution to the behavior of water resting upon them.

"Such problems are intriguing, but probably not as important as the wealth of other information to be gleaned from an exhaustive, multiphased examination of every feature and characteristic of the Great Lakes.

Obviously the data to be accumulated will have tremendous economic importance to Ontario and the Dominion. No part of the projected program should be skimped or allowed to languish for lack of funds. Every specialized team within the research group should be provided with all the equipment and personnel required to make its work as complete as possible. Each will contribute something of value to the economic development of Canada; and the sum of all their efforts will make a continuing contribution to the national economy for centuries to come."

Many of the government administrators and legislators concerned are not personally aware of the problems and have many interests to serve. Moreover, the subject matter of specific research programmes cuts across related provincial, federal and private realms of administrative responsibility. But research in the national interest is demonstrably difficult to establish within a framework of activities of one agency which is restricted in money and work by the application it is responsible for. Nor has there been unanimity by both scientists and administrators regarding the need for "research on the Lakes in the national interest", or for the close inter-relationships of scientific activities by different agencies. Moreover, it is difficult to convince a man who is supporting the programme on the basis of his interest in the fisheries (say) that study of bottom sediments or of winds will help solve fisheries problems.

Canadian oceanographers face similar problems, but the Lakes are comparatively so small that cooperation in Lakes research is imperative. Moreover, the scale of reasonable expenditure would not allow setting up a research team of all the specialists (physicists, chemists, meteorologists, geologists, hydrologists, and instrument engineers and so on) necessary for a complete team. Indeed this is only now becoming possible in Canadian oceanographic circles. By drawing upon part-time or occasional services of specialists in various agencies, a well-rounded programme has proven feasible. The main stimulus has come from the physics section, Division of Research, Department of Lands and Forests, and the Department of Geological Sciences, University of Toronto, but colleagues in the Meteorological Branch, Ontario Hydro, Canadian Hydrographic Service, Royal Canadian Navy, Defence Research Board, National Research Council and other Universities and government agencies have been essential elements in the catenated mechanism of Great Lakes research.

There are other ways, and perhaps better ways, of promoting new work of this sort. For example, a number of physicists in the Canadian Association of Physicists (C.A.P.) have worked for some years on a proposal to establish a high energy laboratory for studies in particle physics. The proposal, involving many millions of dollars, has just recently been turned down but was forcefully presented by the C.A.P. to the Federal government and considered by it. In the Lakes research programme, the protocol of communication from scientific echelons (low on an administrative scale) to senior administrative levels has inhibited effective consideration of many proposals.

The C.A.P. is now considering making an assessment of "research that can be undertaken in Canada and perhaps nowhere else because of favourable geographic conditions", and study of the Great Lakes system assuredly qualifies on grounds of location. The fact that a quarter to a third of the populations of both Canada and the United States live in the area of influence of the Great Lakes gives a principal motive for work on them not only because of their importance to these peoples, but because of their being the near-by example of what they are paying for, with similar motives, in oceanographic research.

The Lakes programme is benefitting too from current expansion in Federal oceanographic research by the Department of Mines and Technical Surveys and the Fisheries Research Board, for the techniques are very similar. (It is hoped that there may be converse benefits to the oceanographic programme from the Great Lakes endeavours).

Research activities in the United States confer benefit to Canada. While there is no single research programme in the Lakes of corresponding diversity in the U.S.A., there has been steady growth of staff and increased production of research in various State and Federal agencies. Canadian and American geophysical research activities have been conducted largely independently although close liaison is maintained.

Not enough work has been done to show full well the stated interconnections of research and application but the following two illustrations will serve to show the trends of the argument for the Lake parameters, bottom sediments and temperatures.

1. The study of bottom sediments requires the taking of cores or of samples from surface layers, and the heavy coring equipment needs a large vessel and heavy winches. Analysis of the inorganic and organic components of the sediments will allow reconstruction of the history of the Lake and of the present state of the bottom circulation and of biochemical processes. Thus shore erosion, fisheries and pollution interests are served directly by such studies, and they supply data for studies of the circulation of the Lake.

2. The study of temperature fluctuations of a Lake are a major component of physical studies of its circulation. In addition to immediate application of temperature studies to design of water intakes for steam-electric plants and weather forecasting, they are an essential element in heat budget determinations, which permit an independent assessment of evaporation. This in turn can lead to improved forecasts of the long term levels of the Lakes, which impose well known strictures on water power, navigation and shore erosion. Year-round, Lake-wide and continuous observations are of course imperative in temperature studies.

These and other studies are being carried out in a skeletal fashion principally in Lake Ontario until the fate of the whole programme is settled. There, 6000 miles of cruises from July to November 1958 permitted preliminary examination of Lake climate, circulation in the West basin and bottom sediments.

A potentially powerful and useful research team has been developed in the process. It remains to be seen whether financial and administrative arrangements can be worked out to allow it to continue to contribute to Canadian science or whether it will have to be dispersed* .

*Ed. note: At time of publication a tentative agreement has been reached between the Federal and Ontario governments and the University of Toronto for continuing the Great Lakes work on a more formal and sound basis. The work will be organized as a section of the Department of Geological Sciences, the funds for scientific staff and equipment will come from the Ontario government through the Department of Lands and Forests, and the money for operating the ship will be channelled by the Federal government through the Department of Mines and Technical Surveys.

WINDS AND WATER LEVELS ON LAKE ERIE

By

D. K. A. Gillies

INTRODUCTION

Prior to 1956 the flow of water from Lake Erie into the Niagara River was sufficient to provide virtually uninterrupted power production for both Canadian and American plants. As well, sufficient water flowed over Niagara Falls to meet the regulations of the International Board set up by the United States and Canada under the terms of the 1950 Niagara River Treaty (1). However, with the construction of the new 1.2 million kw plant by Ontario Hydro at Queenston which requires, for power production, about 60,000 cfs out of a total long-term average river flow of about 210,000 cfs, it became apparent that hourly and daily variations in Niagara River flow cause problems to the scheduling of power production. Figure 1 shows the variations in hourly river flow from 162,000 to 330,000 cubic feet per second during the week December 4-11, 1927.

THE PROBLEM-VARIABLE LAKE ERIE WATER LEVELS AND NIAGARA RIVER FLOWS

These short-term variations in water levels are not a new discovery. As early as 1899, Hayford (2) reported his observations which indicated that, during intense storms, wind and pressure were the main factors in causing the short-term changes in elevation up to 9 feet at Buffalo. Figure 2 illustrates the variations of the daily mean Niagara River flow about the monthly mean of 219,000 cfs. Since power production depends on Niagara River flow, the stage discharge relationship developed for the gauge at Buffalo by the United States Lake Survey is used to convert Lake level to river flow. This relationship indicates that a 1 foot change in elevation at Buffalo changes the flow in the Niagara River by about 20,000 cfs (approximately 10 per cent of the average river flow). Recent variations of 100 per cent are shown in Figure 2 where hourly flows varied from 162,000 to 330,000 during December 1927. From this relation it may easily be calculated that a 3 foot drop in level of Lake Erie at Buffalo means that the discharge down the Niagara River is reduced by 60,000 cfs. This variation of river flow when converted to an equivalent electrical energy represents a loss in generation of 1,200 mw which is approximately the electrical load of the whole Toronto Region. The use of a pumped storage reservoir helps to fill in these gaps of "low river flow" but should flow be reduced for long periods the pumped storage becomes depleted. One further critical factor affecting the value of water at

Niagara is the construction of an equally large hydro plant at Lewiston, N.Y., whose requirement for water is also about 60,000 cfs.

Of course at the same time that the level of Lake Erie rises at Buffalo the level at Toledo falls by an amount usually less than at Buffalo. These changes in elevation at the western end of the lake often cause problems to shipping in the Detroit River area.

CAUSES OF CHANGES IN LAKE ERIE ELEVATION

The main factors affecting the water surface elevations of Lake Erie are (3) :

1. The depth and shape of Lake Erie.
2. The wind speed and direction.
3. The seiche period and the state of the Lake at the beginning of the storm.
4. The atmospheric pressure.
5. The actual speed of cold fronts crossing the Lake from west to east.
6. The relationship between water and air temperatures.

Each of the above factors produces a positive or negative change on the level of the Lake surface.

1. Depth and Shape of the Lake (see Figure 3) - The shallow depth of Lake Erie, which averages 70 feet, when compared to its length of 240 miles, makes it comparable to a very large saucer containing a thin layer of water. Wind velocities cause much larger deviations in water level on Lake Erie than on deep lakes such as Lake Ontario or Lake Superior. This, of course, is borne out in the equation relating total difference in elevation between the two ends of the Lake (4) called "set-up", and the wind stress as follows:

$$\text{Set-up} = S = \frac{T_s F}{\rho g H}$$

where
- T_s = surface stress caused by wind friction on water
- F = fetch in miles
- ρ = density of water
- g = acceleration due to gravity
- H = undisturbed water depth (ft.)

This formula shows that the smaller the depth (H), the greater becomes (S). Furthermore, in a shallow lake there is less ability for the water, driven to one end of a lake by the wind, to return as an underwater current. (3).

The funnel shape of the east end of Lake Erie as compared to the rather broad end at Toledo probably accounts for the larger changes which usually occur in elevations at Buffalo rather than at Toledo during any particular storm.

2. Wind Speed and Direction - The wind speed is related to the wind stress mentioned above by the following (4) :

$$T_s = K \rho_a V^2 \quad \text{where } T_s = \text{wind stress}$$

K = coeff. of wind stress

ρ_a = density of air

V^2 = component of the wind down the lake axis.

To obtain the wind stress acting on Lake Erie, we have used an average of four wind stresses calculated from wind readings at Buffalo, Erie, Cleveland and Toledo. Although Keulegan (3) has suggested that a weighted mean should be used in assessing this average wind stress and although there have been occasions in our study where this weighted average would have fitted our data better, no conclusive proof was available to produce a completely acceptable weighting. Our observations show that the occasions when this weighting is desirable occur with frontal systems or wind shift lines located somewhere across the Lake.

From the hourly meteorological reports, the wind speed and direction are tabulated, the separate and average stresses are calculated according to the above formula and compared to the corresponding hourly lake level. The wind stresses at Buffalo and the hourly levels of Lake Erie at Buffalo and Toledo are shown in Figure 4.

Using a suggestion by Keulegan (3) the average wind stress is calculated for 6 hours preceding the hour in which the maximum change in lake level occurred. This averaged wind stress then should bear some relation to the deviation of the lake level from its state of rest or its position before the wind increased its velocity or changed its direction. This relation will be discussed later.

3. Seiches and Seiche Period - The surface of a lake is never at rest. Winds blowing along a lake surface produce a rhythmic short-term oscillation of the lake level - such oscillations are called seiches, so named by the Swiss who first noted these oscillations on Lake Geneva. (For examples of seiches on Lake Erie, see Figure 5). The period of the seiche caused by the winds on Lake Erie is easily obtained from the records to be between 14 and 15 hours for the primary oscillation. However, it is equally easy to see from the records that the lake does not always oscillate with this 14-15 hour periodicity. Hayford noted periods of 4 and 13 hr and Keulegan (3) mentioned only a 4 hour seiche period. There are several

explanations for the 4 hour seiche, which has more nearly a 3-4 hour period. One is that it is the first harmonic of oscillation of the primary seiche, the second is that it is a separate seiche occurring in the region of the lake between Buffalo and Long Point Bay, or it may be a complex combination of these. Another possible explanation has recently been advanced by Donn (5) who suggests that edge waves may produce these abnormally high water levels at Buffalo. In analyzing past data and also during those times when our forecast was not as correct as we wished, it could be noted that the secondary seiche with a period of 3-4 hours was often present. Although with easterly and south-easterly winds over Lake Erie, a seiche between Long Point Bay and Buffalo is possible, no direct proof of its occurrence is available. A water level recorder recently installed at Port Dover in Long Point Bay may help to clarify this problem of secondary seiches.

4. Seiche Decay Rate - Another useful fact which has been gleaned from the records involves the rate of decay of seiches on Lake Erie. When forecasting the levels of a lake surface, displaced from its place of rest, the effect of the inertial force of this displaced lake must be considered first before we consider the effect due to wind and/or pressure.

By choosing data from an oscillating lake under little or no wind stress an average value of .65 as a decay ratio between adjacent displacements from the "calm level" of the rest of the lake has been obtained. As the name implies, "calm level" of the lake is the level which the lake would assume if no forces were acting on it. If the wind suddenly stopped blowing when the lake was 6 feet above its "calm level" it would be expected to drop 3.9 feet below normal in 7 hours ($\frac{1}{2}$ seiche period) and rise to about $2\frac{1}{2}$ feet above normal in 14 hours.

5. Cold Fronts Crossing Lake Erie - During those hours when a cold front moves eastward with a speed of about 35 miles per hour, there is an unexpectedly large increase in the level of Lake Erie at Buffalo. This is probably due to the superposition of the wind and seiche effects which are in phase as they move down the lake. This resonant coupling has been impossible to assess for use in forecasting, but, the presence of a higher water level at Buffalo than would normally be expected with the velocities present during the storm suggests this super-position relationship. Others (5,6) have suggested some of these effects may be caused by edge waves.

6. Water-Air Temperature Relationships - Sailing boat enthusiasts appreciate the effect of cool lake water on very warm summer air which tends to produce much lower wind speeds over water than would normally be expected from the pressure gradient on a weather map. Conversely when cold air blows over warmer water, wind speeds at the water's surface are greater than a forecaster might forecast from his weather map.

This theory was borne out in fact in our March records as 50-60°F temperatures south of Lake Erie blown along by a 20-30 mph south wind appeared at Clear Creek as a foggy, nearly calm day after passing over water at 32°F. Hunt (7) has produced a useful relationship which combines water and air temperatures, land and water winds.

EMPIRICAL RELATIONSHIP BETWEEN WIND STRESS AND LAKE LEVELS

A plot of the 6 hourly-average-wind-stress and the deviation of the lake from its "calm" level is shown in Figure 6. It indicates a useful relationship between these two variables. Although there is considerable scattering of points about the least squares line the relationship is used as a guide in estimating future elevations and Niagara River flows.

METHOD OF FORECASTING LAKE LEVELS

Let us assume that the levels of Lake Erie at Buffalo for the next 14 hours are requested. In order to proceed, the following information is obtained:

a. The "calm" level of the lake, which is defined as the elevation of the lake if no external forces are acting on it, is obtained. This is obtained by keeping an up-to-date graph of daily mean elevations. By paying most attention to mean levels with little or no wind present, a satisfactory calm level can be chosen. Seasonal variations in lake level make it necessary to keep an up-to-date "calm level".

b. The hourly elevations at Buffalo for the immediate past 14 hours are plotted. This plot allows one to assess what effect, due to seiche action, should be used to determine future elevations. From the seiche-decay relationship of .65 mentioned earlier we know that the lake level, if already above its calm level and falling, will go below the calm level if there is no wind stress to prevent it.

c. A forecast of the 6 hourly average wind stress over the lake for the forecast period is made. These stresses are calculated by taking the wind direction and speed as forecast by the Toronto Malton Dominion Public Weather Office and adjusting it to produce average conditions over the whole lake. Since the weather office tries to forecast maximum winds, at water level, their forecasts are usually much greater than average winds over the whole lake as measured at land stations and used in our relationship. We have found in general that the forecast wind stresses are about twice as strong as the actual wind stresses calculated from the winds at shore stations. This difference varies by season and Hunt (7) produced a table showing variations in effective wind stresses according to differences in air and water temperatures.

SHORTCOMINGS

Although this method gives a satisfactory guide as to how high or low the hourly lake elevations will reach up to 36 hours in advance, there are times when the forecast becomes completely out of phase with reality, and the explanation for these conditions is not apparent in all cases.

One of the main problems is the inaccuracy of the lake level change - wind stress relationship developed from winds at elevated land stations. More knowledge is required of the actual winds at water level over the Great Lakes for a given pressure gradient under all humidity, temperature and seasonal conditions. Hunt has brought some knowledge in this field - it remains now to see if it is a workable relationship.

As mentioned earlier, the seiche period, whether 14 hours, 7 hours or some combination of these, is a difficult factor to assess consistently.

CONCLUSION

With reasonably accurate forecasts from a weather office and the relationships I have mentioned, it is possible to produce an operationally useful forecast of lake levels at Buffalo and Toledo. These forecasts have been very useful to Ontario Hydro in the hourly and daily scheduling of our hydraulic and steam generating requirements for the past 3 years. It is hoped that a mathematical model which treats the lake as an oscillating pendulum moving in a viscous medium can be satisfactorily programmed on our computer to give regular lake level forecasts (8). The most critical and one of the least known variables to be used in this model is the wind stress actually acting on the lake. Harbour Authorities and shipping interests at the west end of Lake Erie might be interested in such a simple system to help solve their problems of varying lake levels under high westerly wind conditions. Perhaps actual forecasts of winds on Lake Erie from weather offices could be accompanied by an indication of the changes in the lake elevation to be experienced by such winds. As well, it is not improbable that a notice could be written on navigation maps stating, for example, that when winds are westerly 30 miles per hour the level at Toledo harbour may drop 4 feet to 5 feet.

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HOURLY DISCHARGES-NIAGARA RIVER

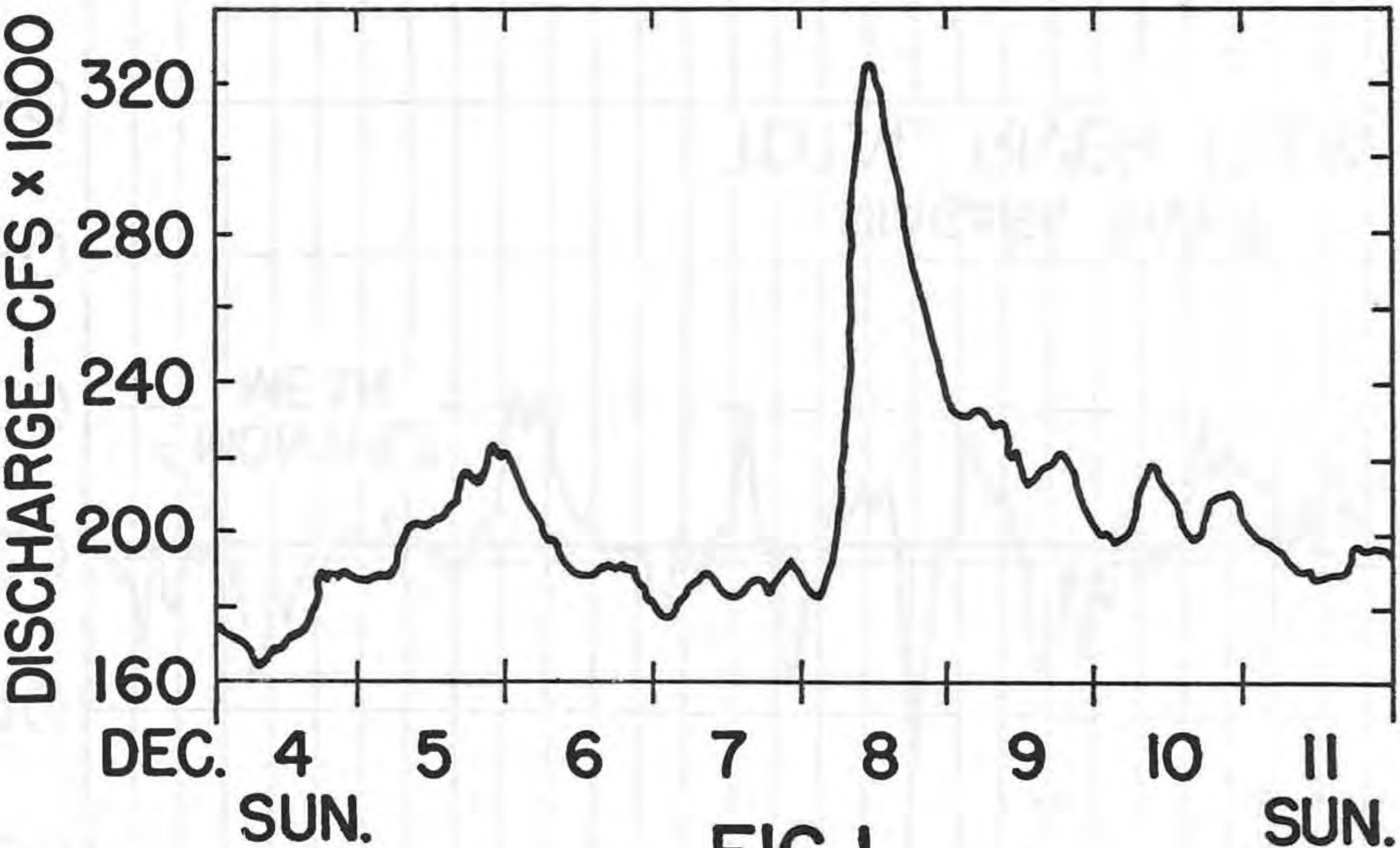
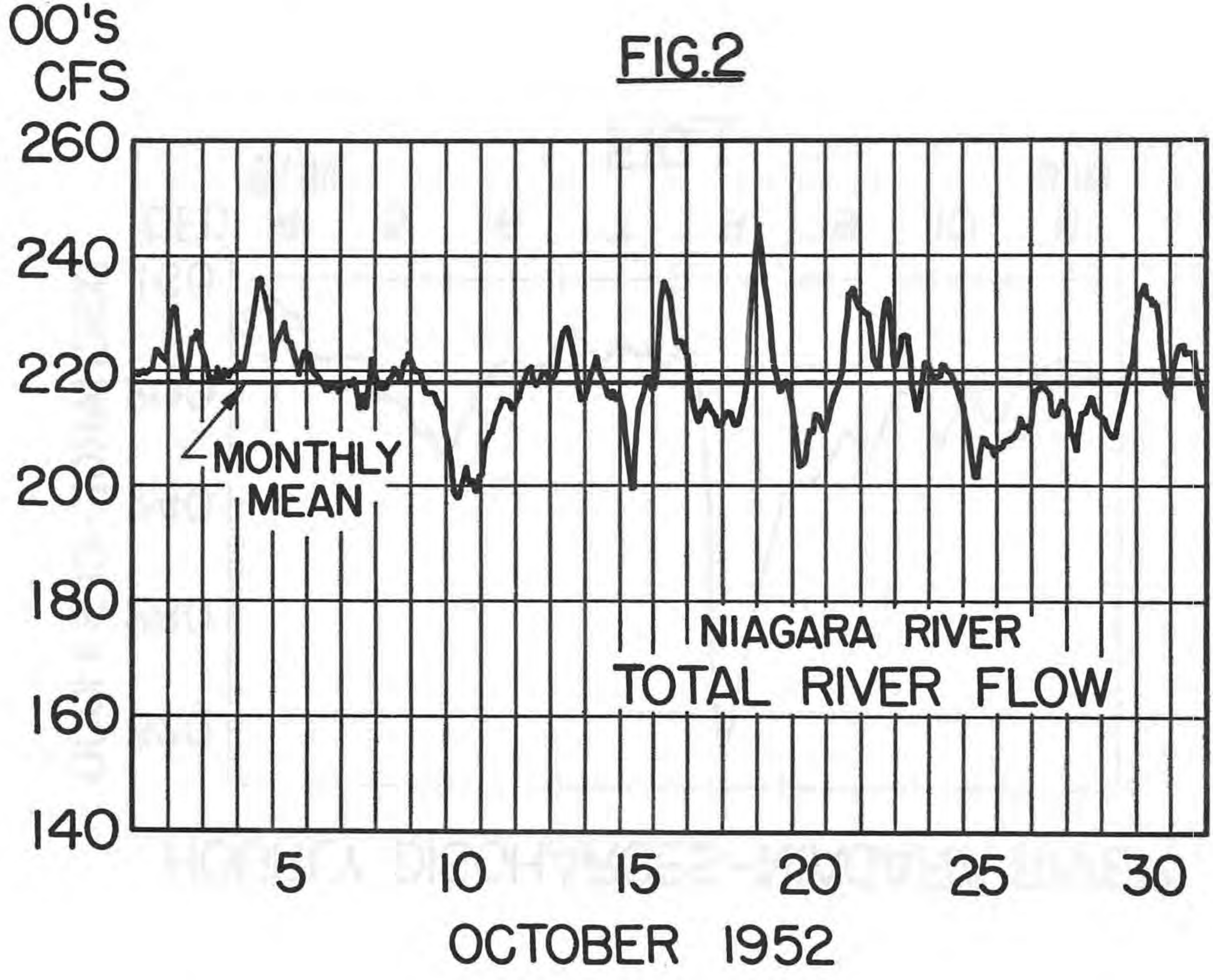


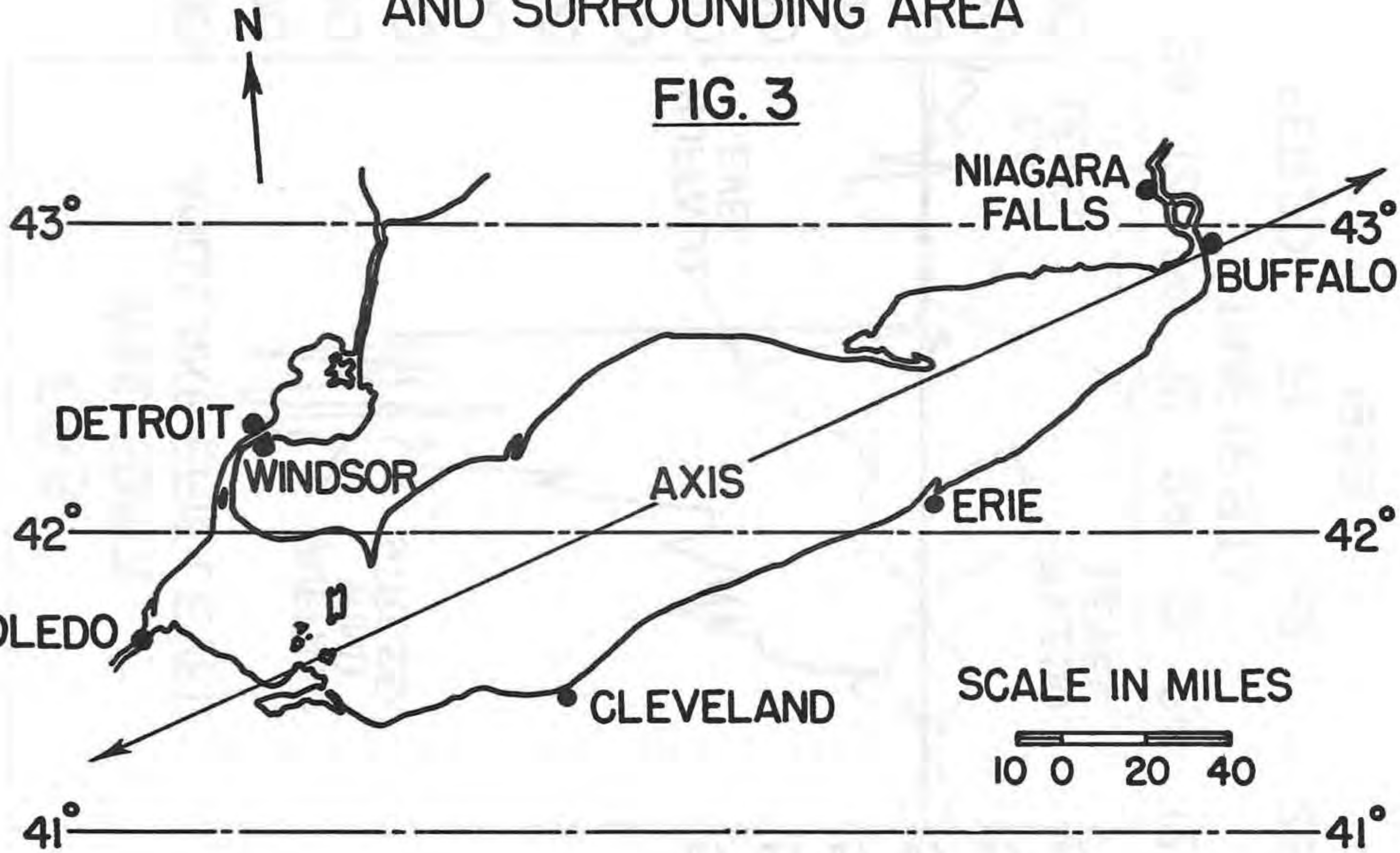
FIG. 1

FIG.2


00's
CFS
260
240
220
200
180
160
140
MONTHLY
MEAN
NIAGARA RIVER
TOTAL RIVER FLOW
5
10
15
20
25
30
OCTOBER 1952

MAP OF LAKE ERIE
AND SURROUNDING AREA

FIG. 3



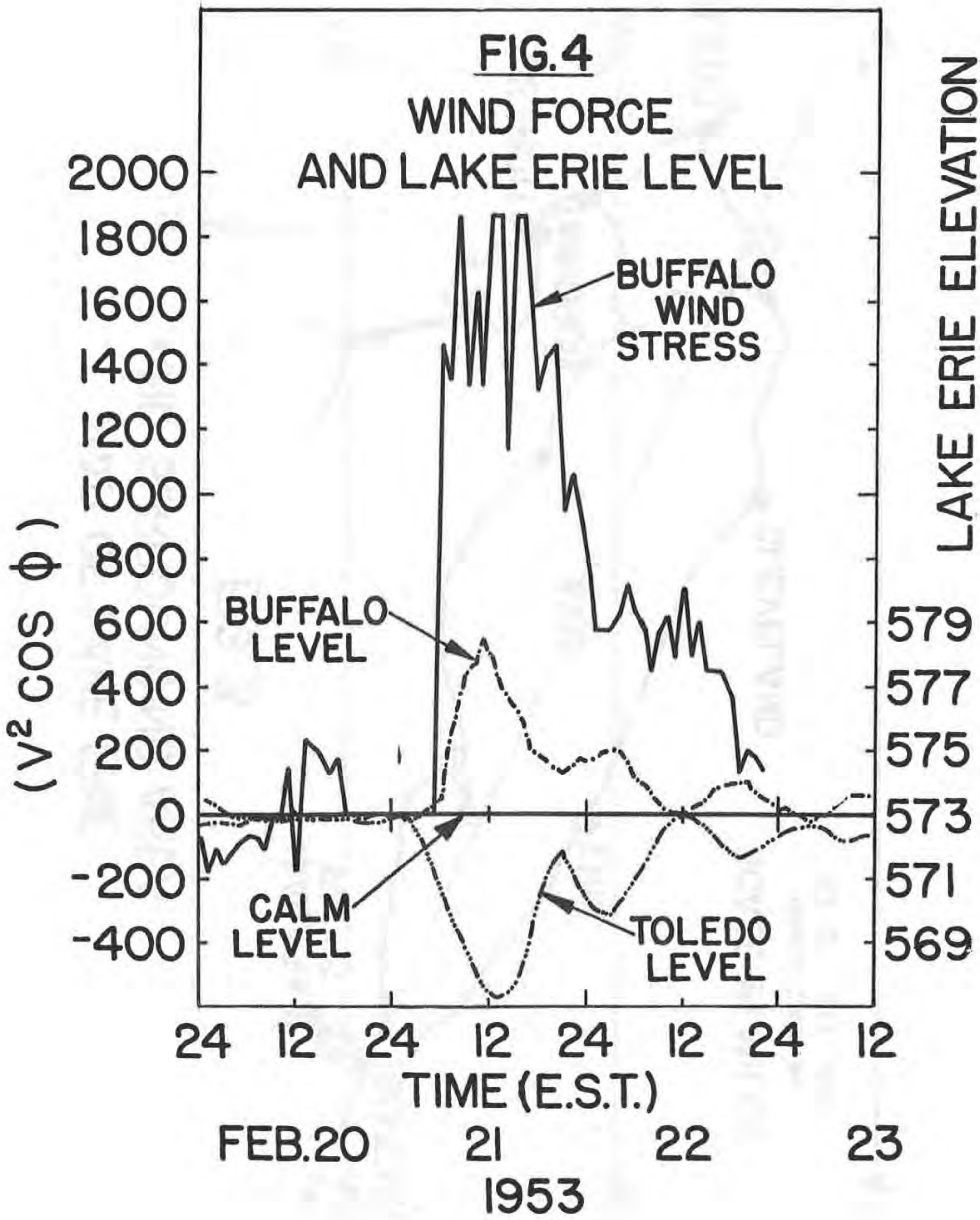


FIG. 4
WIND FORCE
AND LAKE ERIE LEVEL
BUFFALO
WIND
STRESS
BUFFALO
LEVEL
CALM
LEVEL
TOLEDO
LEVEL
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
(V^2 COS ϕ)
LAKE ERIE ELEVATION
579
577
575
573
571
569
24
12
24
12
24
12
24
12
TIME (E.S.T.)
FEB. 20
21
22
23
1953

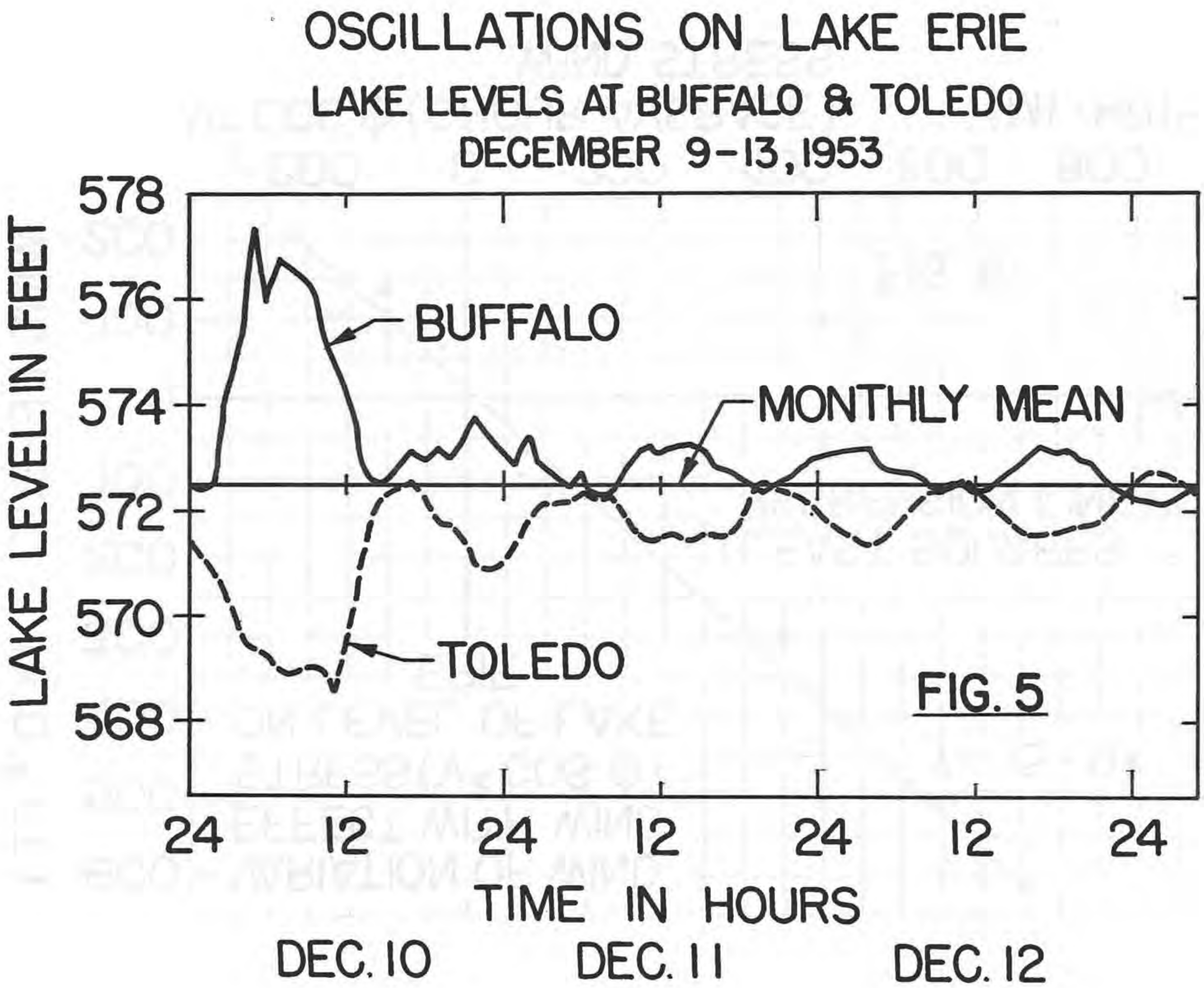
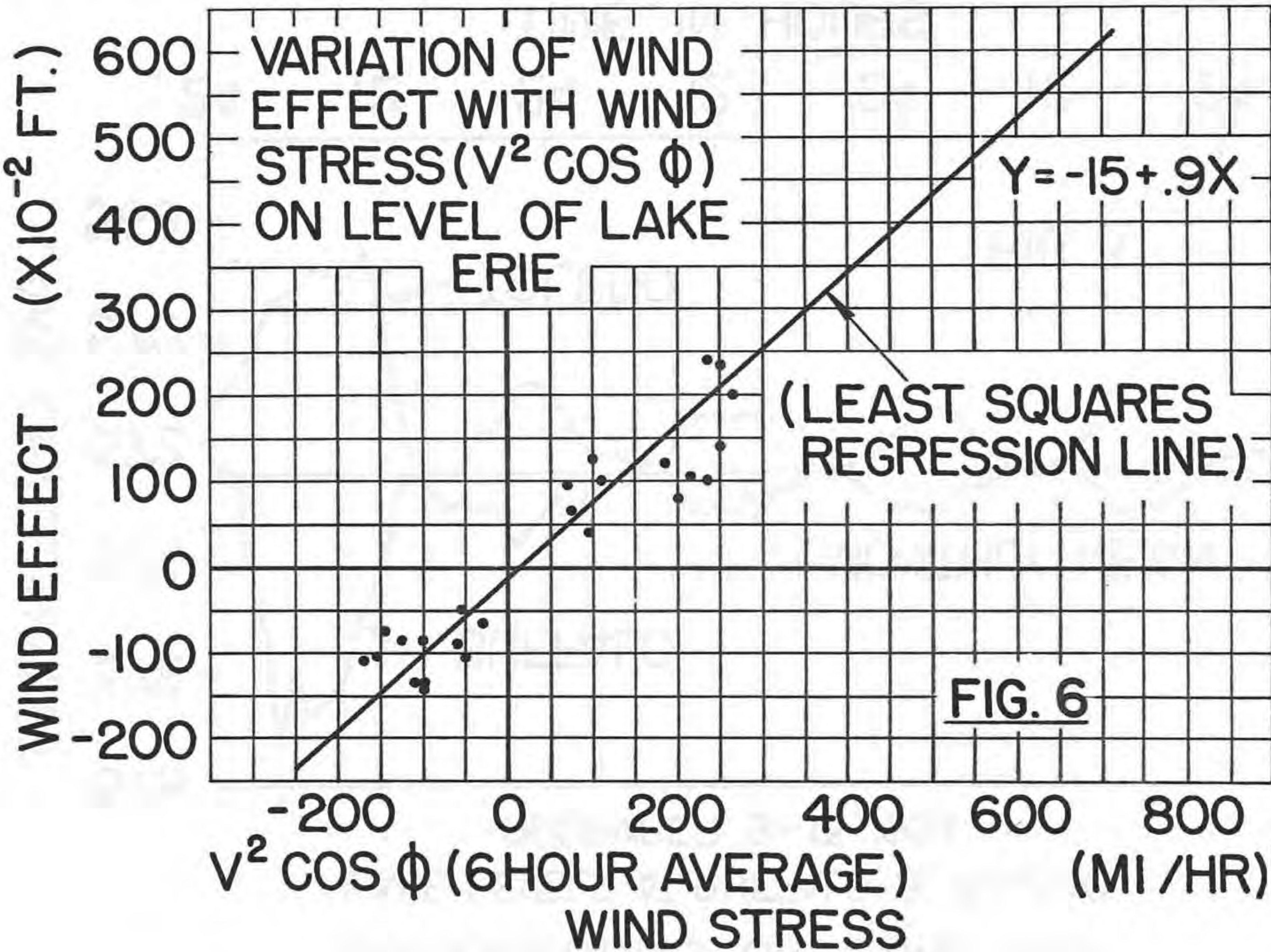

OSCILLATIONS ON LAKE ERIE
LAKE LEVELS AT BUFFALO & TOLEDO
DECEMBER 9-13, 1953
578
576
574
572
570
568
LAKE LEVEL IN FEET
BUFFALO
MONTHLY MEAN
TOLEDO
24
12
24
12
24
12
24
TIME IN HOURS
DEC. 10
DEC. 11
DEC. 12

FIG. 5


VARIATION OF WIND EFFECT WITH WIND STRESS (V^2 COS Φ) ON LEVEL OF LAKE ERIE
Y = -15 + .9X
(LEAST SQUARES REGRESSION LINE)
WIND EFFECT (X10^{-2} FT.)
600
500
400
300
200
100
0
-100
-200
-200
0
200
400
600
800
V^2 COS Φ (6 HOUR AVERAGE) (MI/HR)^2
WIND STRESS
FIG. 6

A SELECTED BIBLIOGRAPHY ON THE CLIMATE

OF

THE GREAT LAKES BASIN OF ONTARIO

BY

M. K. Thomas

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