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This bulletin, which was prepared by Mr. Lawrence D. Burroughs of the Environmental Modeling Center of the National Centers for Environmental Prediction (NCEP) and Mr. J. Paul Dallavalle of the Techniques Development Laboratory, describes the Great Lakes automated storm surge guidance. Forecasts are generated for Toledo, Ohio, and Buffalo, New York, on Lake Erie and for Essexville and Lakeport, Michigan on Lake Huron. The Lake Erie storm surge forecast system is a dynamical system which uses wind input from the Great Lakes wind forecast system. The Lake Huron storm surge forecast system uses sea level pressure forecasts from the Regional Analysis and Forecast System (RAFS).

Prior to withdrawal of the Limited-area Fine-mesh model (LFM) from the NCEP operational job stream, the Lake Erie storm surge system was changed to use the new Great Lakes wind forecasts and the Lake Huron storm surge system was changed to use RAFS output. These changes were implemented in March 1993.

In November 1993, the titles of the forecast bulletin were changed to indicate that the product was NGM (Nested Grid Model - the model used in the RAFS) BASED. Finally, in March 1994, the World Meteorological Organization (WMO) bulletin header for these guidance products was changed from FZUS1 KWBC to FQUS20 KWBC.

This bulletin describes these Great Lakes storm surge guidance products, discusses the major changes in the system since 1979, and supersedes Technical Procedures Bulletin No. 275 (NWS, 1979), which is now operationally obsolete.

U.S. DEPARTMENT OF COMMERCE **National Oceanic and Atmospheric Administration**

GREAT LAKES STORM SURGE GUIDANCE[1]

by L. D. Burroughs[2] and J. P. Dallavalle[3]

1. INTRODUCTION

Abnormal water levels can cause serious problems on the Great Lakes particularly Lakes Erie and Huron. Lake levels above normal cause flooding, while below normal lake levels cause navigational problems. In 1969, at the request of the National Weather Service (NWS) Eastern Region, the Techniques Development Laboratory (TDL) developed an automated, statistical storm surge forecast guidance system for Buffalo and Toledo on Lake Erie (Richardson and Pore 1969), and in 1977 a similar system was developed for Essexville and Lakeport on Lake Huron (NWS 1977). The locations of these four cities are shown in Fig. 1.

In 1979, the system for Lake Erie was changed from a statistical to a dynamical system (Schwab 1978 and Richardson and Schwab 1979). In 1983, the Lake Erie guidance was extended from the 36-h out to the 48-h projection.

Richardson and Schwab (1979) determined that the use of multiple equation sets caused the statistical storm surge forecasts to have spurious oscillations. They remedied the problem by computing the water level fluctuations for each 6-h interval between 01- and 48-h and determining which interval had the largest difference (highest or lowest) They recomputed the water levels by using the equation set that produced the greatest difference, applying it with forecast values of pressure from the numerical model to get forecast water levels at 6-h intervals, and interpolating between the 6-h water levels to get the hourly water levels during the 01-h to 48-h forecast period. In early 1981, a similar procedure was implemented for the Lake Huron storm surge forecasts.

Before June 1987, the Lake Huron storm surge forecasts were transmitted only when the absolute value of a surge height was $\geq$ 1.0 ft during a 48-h forecast period. For 48-h forecast periods, when the absolute value of the peak storm surge height was less than 1.0 ft, only the maximum and minimum storm surge heights were transmitted. In June 1987, the program was changed so that all the Lake Huron storm surge forecasts were transmitted regardless of their value.

Prior to withdrawal of the Limited-area Fine-mesh model (LFM) (Newell and Deaven 1981) from the NCEP operational job stream, the Lake Erie storm surge system was changed to use the new Great Lakes wind forecasts (Burroughs and Dallavalle 1995), and the Lake Huron storm surge system was changed to use Regional Analysis and Forecast System (RAFS) output (NWS 1985). These changes were implemented in March 1993.

In November 1993, the titles of the forecast bulletin were changed to denote that the product was NGM BASED. Finally, in March 1994, the World Meteorological Organization (WMO) bulletin header for these guidance products was changed from FZUS1 KWBC to FQUS20 KWBC.

2. METHODS

Completely separate methods are used to forecast storm surges on the two lakes. An impulse response function method (Schwab 1978), developed by the Great Lakes Environmental Research Laboratory, is used to make storm surge forecasts for Toledo, Ohio, and Buffalo, New York. In contrast, the forecast approach for Lake Huron is statistical and is in the form of single station regression equations, *i.e.*, separate equations were derived for each location.

3. DEVELOPMENT AND DEFINITIONS

a. Storm Surge Heights (Predictand)

Hourly storm surge heights were calculated by subtracting the monthly mean of the lake level from hourly lake levels which

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[1]OPC Contribution No. 105

[2]National Centers for Environmental Prediction, NWS, Washington, D.C. 20233

[3]Techniques Development Laboratory, NWS, SSMC2, Silver Spring, MD 20910

were measured by the U.S. Lake Survey gages at the four locations. The storm surge height is the meteorologically-generated lake level fluctuation which does not include long-range fluctuations due to precipitation.

On the average, Buffalo and Toledo experience about five storm surges a year where the magnitude of the surge is $\geq$ 3 ft (Pore *et al.* 1975). On the Saginaw Bay at Essexville, surges of these magnitudes occur about once every 2 years. Lakeport experiences much smaller surges than those on Saginaw Bay or on Lake Erie. A storm surge with a magnitude of > 2 ft occurs about once every 2 years at Lakeport. Storm surges are especially pronounced on Lake Erie because of its shallow depth and geographical orientation.

b. Predictors

Wind forecasts for Lake Erie (Burroughs and Dallavalle 1995) and uninflated wind forecasts for Buffalo and Toledo (Miller 1993) are the predictors in the Lake Erie response function method. The storm surge predictors for Essexville and Lakeport are RAFS sea-level pressure forecasts at RAFS Grid-B points (mesh length of 190 km) surrounding Lake Huron.

c. Equation Development

1) Dynamical

The dynamical method uses impulse response functions to calculate the storm surge height. The surge at a given time is calculated as a weighted sum of forcing terms during some period before the specified time, *i.e.*,

$$h_k = \sum_{i=1}^{m}\sum_{j=1}^{n} \vec{g}_{ij} \cdot \vec{\tau}_{il} \qquad \textbf{(1)}$$

Here the surge height at time k is h_k, $\vec{g}_{ij}$ is the water level response at time j due to an impulse from forcing station i, $\vec{\tau}_{ik-j}$ is the forcing function at station i and time k-j, m is the number of forcing stations, and n is the length of the response function. The forcing function is calculated as

$$\vec{\tau}_{ij} = c|\vec{V}_{ij}|\vec{V}_{ij} , \qquad \textbf{(2)}$$

where $\vec{V}_{ij}$ is the wind vector at station i and time j, and c is a dimensionless constant, $4\text{x}10^{-6}$.

The response functions $\vec{g}_{ij}$ were calculated by means of a linear finite difference numerical model of Lake Erie described by Schwab (1978). To take into account hourly changes in the forcing function, the response functions are recorded as hourly values. Richardson and Schwab (1979) determined that a 36-h response function was sufficient for Lake Erie Storm surges. Water level responses at Buffalo and Toledo were computed by using forcing at four wind forecast points: two over lake points and the Buffalo and Toledo airports. Forcing functions for storm surge forecasts are calculated according to (2) with hourly winds interpolated from the 6-h forecasts over Lake Erie (Burroughs and Dallavalle 1995) and the 6-h uninflated surface wind forecasts at Buffalo and Toledo (Miller 1993). This method gives more accurate storm surge forecasts than the statistical method which was formerly used on Lake Erie (Richardson and Schwab 1979).

2) Statistical

This method was developed by Richardson and Pore (1969), and its applications on Lake Huron were implemented in 1977 (NWS 1977). It was modified according to the method developed in Richardson and Schwab (1979) and implemented in 1981. Hourly water level deviations from the monthly mean at Essexville and Lakeport (storm surges) were correlated with 6-h mean sea level pressure analyses interpolated to a set of LFM grid point positions surrounding Lake Huron. A screening correlation program (Miller 1958) was used to find the best predictors of storm surges. The regression equations have the form

$$h_{kl} = A_{ol} + \sum_{j=1}^{n} A_{jl} P_{jl} , \qquad \textbf{(3)}$$

where h_{kl} is the storm surge height at time k and projection l, A_{ol} is a constant for each l, A_{jl} are regression coefficients for each predictor j and projection l, P_{jl} are sea level pressures at selected LFM grid points for projections tau and tau-1, k is 0, 1, 2, 3, 4, or 5 hours before the tau or tau-1 being used or the lag time of a given water level equation, and n is the number of predictors in each equation. A set of 12 water level forecast equations (six for projection tau and six for projection tau-1) were derived for Essexville and another set for Lakeport. The first subset of six equations uses pressures for projection tau. The second subset of six equations uses pressures that are lagged 6-h at tau-1. They are applied with RAFS output at each 6-h projection from 6- to 48-h and give hourly water level values from -05- to 48-h. Then the equation pair that predicts the greatest water level fluctuation (positive or negative) between projections tau and tau-1 during the 48-h forecast period is used to recompute all the water level values. For example, suppose $h_{k=3,l=24}$ - $h_{k=3,l=18}$ gives the largest water level fluctuation. The difference is divided by 6 and added successively to $h_{k=3,l=18}$ to give water level values at the intervening hours between l = 18 and l = 24. This is done for each tau from 6- to 48-h and removes any spurious oscillations that may occur when using all six pairs of water level equations for each tau.

4. MESSAGES AND SCHEDULES

The Great Lakes storm surge forecasts are transmitted as the FQUS20 bulletin on the Domestic Data Service of the Family of Services and as the NMCMRPESS product on AFOS. An example is shown in Fig. 2. The bulletin is available at approximately 0500 and 1700 UTC daily and may be obtained on AFOS by typing: **NMCMRPESS**

The bulletin contains hourly storm surge forecasts from 01- to 48-h for Buffalo, Toledo, Essexville, and Lakeport. The bulletin is divided into two parts: LAKE ERIE NGM BASED STORM SURGE FORECAST and LAKE HURON NGM BASED STORM SURGE FORECAST. Each part also gives the maximum (max) and minimum (min) of the forecasted storm surges for each city.

5. OPERATIONAL CONSIDERATIONS

The effects of ice cover on Great Lakes storm surges were not considered in the development of either of the forecast methods. Hence, there may be times when strong winds over Lake Erie, Lake Huron, and Saginaw Bay suggest large storm surges, but if the lake surfaces are frozen, the surges may not occur. Therefore, the forecaster who uses these techniques as guidance may have to modify the forecasts during times when Lake Erie, Saginaw Bay, or the southwestern portion of Lake Huron is frozen.

a. Lake Erie Forecasts

In the developmental sample, the storm surges at Buffalo tended to be higher than normal. Thus, when the prediction method was tuned by choosing appropriate drag coefficients, the peak surges were suppressed somewhat. As a consequence, the peak positive surges at Buffalo tend to be under forecast (Richardson and Schwab 1979). The accuracy of the method is also directly affected by the accuracy of the wind forecasts. Forecasters may have to modify the storm surge guidance when the wind forecasts are in doubt.

b. Lake Huron Forecasts

The regression equations used to make the forecasts are dependent on the behavior of the NGM output. When the forecaster has reason to believe that the NGM is not performing properly for a given situation, the automated guidance should be modified accordingly. For example, if a trough or front has intensified or accelerated more than predicted by the model, corresponding changes to the guidance should be considered. Specific localized conditions and mesoscale features detected by real-time, ground-based or satellite observations also should be taken into account.

6. REFERENCES

Burroughs, L. D. and J. P. Dallavalle, 1995: Great Lakes wind and wave guidance. *Technical Procedures Bulletin No. ???*, National Weather Service, NOAA, U.S. Department of Commerce, 11 pp. [Available from Office of Meteorology, NWS, SSMC2, Silver Spring, MD 20910]

Miller, D. T., 1993: NGM-based MOS wind guidance for the contiguous United States. *Technical Procedures Bulletin No. 399*, National Weather Service, NOAA, U.S. Department of Commerce, 19 pp. [Available from Office of Meteorology, NWS, SSMC2, Silver Spring, MD 20910]

Miller, R. G., 1958: The screening procedure. A statistical procedure for screening predictors in multiple regression, Part II. *Studies in Statistical Weather Prediction*, Contract No. AF19 (604) - 1590, Travellers Weather Research Center, Hartford, Conn., edited by B. Shorr, 86-95.

National Weather Service, 1977: Storm surge forecasts for Essexville and Lakeport, Michigan. *Technical Procedures Bulletin No. 186,* NOAA, U.S. Dept. of Commerce, 6 pp. [Obsolete]

_____, 1979: Storm surge forecasts for Lake Erie and Lake Huron. *Technical Procedures Bulletin No. 275*, NOAA, U.S.

Department of Commerce, 6 pp. [Obsolete]

_____, 1985: The Regional Analysis and Forecast System (RAFS). *Technical Procedures Bulletin No. 345*, NOAA, U.S. Department of Commerce, 7 pp. [Available from Office of Meteorology, NWS, SSMC2, Silver Spring, MD 20910]

Newell, J. E., and D. G. Deaven, 1981: The LFM-II Model--1980. *NOAA Technical Memorandum NWS NMC-66*, NOAA, U.S. Department of Commerce, 20 pp. [Available from Environmental Modeling Center, NCEP, NOAA Science Center, Temple Hills, MD 20748]

Pore, N. A., H. P. Perrotti, and W. S. Richardson, 1975: Climatology of Lake Erie storm surges at Buffalo and Toledo. *NOAA Technical Memorandum NWS TDL-54*, NOAA, U.S. Department of Commerce, 27 pp. [Available from Techniques Development Laboratory, NWS, SSMC2, Silver Spring, MD 20910]

Richardson, W. S. and N. A. Pore, 1969: A Lake Erie storm surge forecasting technique. *ESSA Technical Memorandum WBTM TDL 24*, ESSA, U.S. Department of Commerce, 23 pp.

Richardson, W. S. and D. J. Schwab, 1979: Comparison and verification of dynamical and statistical Lake Erie storm surge forecasts. *NOAA Technical Memorandum NWS TDL-69*, NOAA, U.S. Department of Commerce, 19 pp. [Available from Techniques Development Laboratory, NWS, SSMC2, Silver Spring, MD 20910]

Schwab, D. J., 1978: Simulation and forecasting of Lake Erie storm surges. *Mon. Wea. Rev.*, **106**, 1476-1487.

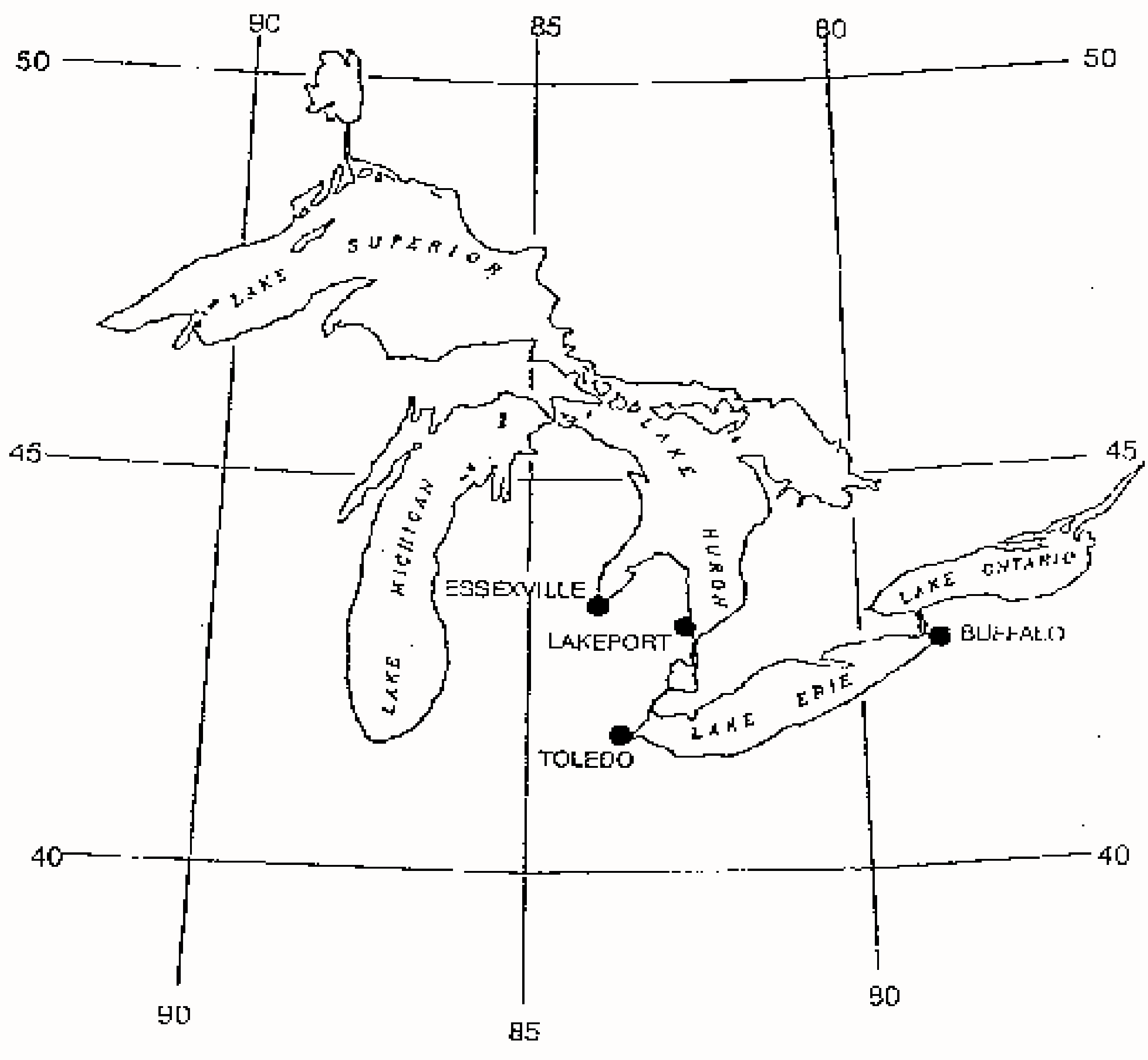

Figure 1 - Locations of Sites for FOUS Bulletins

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FOUS20 KWBC 150000
LAKE ERIE NGM BASED STORM SURGE FORECAST(FEET)
BUF MAX  0.6 MIN -0.4 TOL MAX  0.5 MIN -0.8
GMT BUF  TOL GMT BUF  TOL GMT BUF  TOL
01  0.5 -0.8 17  0.1 -0.0 09 -0.4  0.5
02  0.4 -0.7 18  0.1  0.0 10 -0.4  0.5
03  0.4 -0.6 19  0.2  0.1 11 -0.3  0.5
04  0.4 -0.5 20  0.2  0.0 12 -0.3  0.5
05  0.4 -0.4 21  0.2 -0.0 13 -0.3  0.4
06  0.4 -0.4 22  0.3 -0.1 14 -0.3  0.4
07  0.5 -0.5 23  0.2 -0.2 15 -0.3  0.4
08  0.5 -0.5 00  0.2 -0.2 16 -0.3  0.4
09  0.6 -0.6 01  0.1 -0.1 17 -0.2  0.4
10  0.6 -0.7 02  0.0 -0.1 18 -0.2  0.4
11  0.6 -0.7 03 -0.1  0.1 19 -0.2  0.3
12  0.5 -0.7 04 -0.2  0.2 20 -0.1  0.3
13  0.3 -0.6 05 -0.2  0.3 21 -0.1  0.3
14  0.2 -0.5 06 -0.3  0.4 22 -0.1  0.2
15  0.2 -0.3 07 -0.3  0.4 23 -0.2  0.2
16  0.1 -0.1 08 -0.4  0.5 00 -0.2  0.3
LAKE HURON NGM BASED STORM SURGE FORECAST(FEET)
ESSEXVILLE MAX  0.2  MIN -0.5
GMT SURGE GMT SURGE GMT SURGE GMT SURGE
01  -0.5  13  -0.3  01   0.1  13   0.1
02  -0.5  14  -0.3  02   0.1  14   0.1
03  -0.5  15  -0.3  03   0.1  15   0.1
04  -0.5  16  -0.3  04   0.1  16   0.1
05  -0.5  17  -0.3  05   0.1  17   0.1
06  -0.5  18  -0.3  06   0.0  18   0.1
07  -0.4  19  -0.3  07   0.0  19   0.1
08  -0.4  20  -0.2  08   0.0  20   0.1
09  -0.4  21  -0.1  09   0.1  21   0.1
10  -0.4  22  -0.1  10   0.1  22   0.2
11  -0.3  23  -0.0  11   0.1  23   0.2
12  -0.3  00   0.0  12   0.1  00   0.2
LAKEPORT    MAX  0.2  MIN -0.4
GMT SURGE GMT SURGE GMT SURGE GMT SURGE
01  -0.4  13  -0.2  01   0.0  13  -0.1
02  -0.2  14  -0.1  02   0.1  14  -0.1
03  -0.3  15  -0.1  03   0.1  15  -0.1
04  -0.3  16  -0.1  04   0.1  16  -0.1
05  -0.4  17  -0.1  05   0.2  17  -0.1
06  -0.4  18  -0.1  06   0.1  18  -0.1
07  -0.3  19  -0.1  07   0.1  19  -0.1
08  -0.3  20  -0.1  08   0.0  20  -0.1
09  -0.3  21  -0.1  09  -0.0  21  -0.1
10  -0.2  22  -0.1  10  -0.1  22  -0.2
11  -0.2  23  -0.0  11  -0.2  23  -0.2
12  -0.2  00  -0.0  12  -0.1  00  -0.2
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Figure 2 Sample FOUS20 KWBC bulletin. See text for details.