Reexamination of the 9–10 November 1975 "*Edmund Fitzgerald*" Storm Using Today's Technology

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The most severe marine conditions during the 9–10 November 1975 storm occurred for a short time over a relatively small area and were coincident with the time and location at which the ship *Edmund Fitzgerald* was lost.

An intense autumn storm moved through the upper Great Lakes region on 10 November 1975, producing extremely hazardous wind and wave conditions on Lake Superior. The storm is particularly memorable because it is forever linked with the loss of the ship *Edmund Fitzgerald* (U.S. Coast Guard 1977), which occurred at approximately 0015 UTC (7:15 P.M. EST) 11 November 1975. There are numerous theories about the specific cause for the loss of the *Edmund Fitzgerald,* and this article makes no attempt to further investigate possible causes, but rather focuses on determining the most likely weather conditions throughout the storm. Meteorological observations from the storm were combined with modern numerical weather prediction models to provide detailed hindcasts of conditions throughout the storm. These hindcasts indicate that although severe wind and wave conditions did occur during the storm, the most extreme conditions were confined to a 6-h period in the late afternoon and early evening of 10 November 1975, during which time the *Edmund Fitzgerald* sank.

Conditions on the Great Lakes can be extremely treacherous, and the enclosed nature of the lakes can produce very steep waves. Steep short-period waves can be particularly hazardous to large ships such as the *Edmund Fitzgerald,* especially when they exceed 5 m in height. The height of waves generated on the lakes is primarily a function of wind speed and the fetch or distance over which they are generated. Of secondary, yet substantial, importance is the degree of surface layer stability present over the lake. As described by Liu and Ross (1980), identical wind

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speeds and fetch distances can produce substantially different wave heights depending on the degree of atmospheric stability, leading to higher wave heights because of enhanced vertical transfer of momentum under unstable conditions. Lake Superior is the largest of the Great Lakes in surface area (82,100 km^2) and volume (12,100 km^3). It has the capacity to contain the water volume of the four other lakes plus three additional Lake Eries. Given its immense size, it is capable of sustaining waves in excess of 10 m, or the height of a four-story home.

Historically, the autumn season has produced many of the most intense storms on record in the Great Lakes region, with a substantial portion of these storms occurring during the month of November (Holden 1991). A few of the most noteworthy storms include the November 1913 storm (Brown 2004), the Armistice Day Storm of 1940 (Kean 2003), and the storm of November 1998 (Lombardy 2002; NOAA/NWS 2005). Nineteen ships were destroyed and more than 250 lives were lost on the Great Lakes during the 7–12 November 1913 storm. Sixty-six people died and five vessels were destroyed during the 11 November 1940 Armistice Day storm. Improvements in forecasting and access to weather information likely helped prevent any such disasters from occurring during the storm of 9–11 November 1998. Such significant and memorable storms are the reason that the term "November gale" (Hemming 1984) has become commonplace in the language of those around the Great Lakes to describe autumn storms that are particularly intense and potentially dangerous. So common is this term, in fact, that a variant of it (gales of November) is contained within the popular 1976 ballad "The Wreck of the Edmund Fitzgerald" by Gordon Lightfoot (Lightfoot 1976).

SHIPS CAUGHT IN THE STORM. During the early morning of 9 November 1975, a low pressure system began to take shape in the southern plains (Fig. 1a). This storm would move northeast and intensify considerably over the next 36 h as it moved across the Great Lakes region. As the storm moved northeast from Kansas, it intensified from 1000 hPa at 1200 UTC to 993 hPa at 0000 UTC 10 November 1975 (Fig. 1b) as it moved into Iowa. During this 12-h period, the *Edmund Fitzgerald* and another vessel, the *Arthur M. Anderson,* departed ports on western Lake Superior to begin their voyage east to the Sault Sainte Marie locks and eventually the lower Great Lakes. Details of this incident throughout this article, including specific information on the ships as well as their communications and actions during the storm, are taken from the National Transportation Safety Board Bureau of Accident Investigation (1978, hereafter NTSB78). The *Edmund Fitzgerald* was 222 m long and 23 m wide, weighed 13,632 tons, and had engines that produced 7,500 horsepower. At 1915 UTC it departed Superior, Wisconsin, en route to Detroit, Michigan, loaded with 26,116 tons of iron ore. The *Arthur M. Anderson* departed Two Harbors, Minnesota, with a similar cargo around 2130 UTC en route to Gary, Indiana. A gale warning was issued for Lake Superior at 1939 UTC, and Captain McSorley of the *Edmund Fitzgerald* acknowledged receipt of this warning while in communication with Captain Cooper of the *Arthur M. Anderson.* Because of the predicted weather conditions, the captains of the *Edmund Fitzgerald* and *Arthur M. Anderson* decided to take a more northerly track across Lake Superior (Fig. 2) in order to take advantage of the lee provided by the Canadian shore given the expected northerly gales. This practice was common among Great Lakes mariners to avoid the worst of adverse sea conditions during fall and winter storms when the wind direction makes this a favorable track.

Initially, the *Arthur M. Anderson* was traveling ahead of the *Edmund Fitzgerald,* but by 0800 UTC 10 November 1975 the *Edmund Fitzgerald* pulled ahead. A storm warning was issued for Lake Superior at 0700 UTC. Between 0000 and 1200 UTC, the surface low moved from Iowa to near Marquette, Michigan, and intensified by 11 hPa to 982 hPa (Fig. 1c). The 850-hPa chart at 1200 UTC (Fig. 3a) shows the 850-hPa low center nearly coincident with the surface low position, with a geopotential height of 1260 m. The position of the isotherms with respect to the geopotential height contours at this time indicated that warm air advection was present at 850 hPa over eastern Lake Superior. The 500-hPa analysis (Fig. 3b) shows a high-amplitude negatively tilted short-wave trough associated with the surface low, with the trough extending from south-central Canada through far eastern Illinois. This short-wave position, negatively tilted orientation, and high amplitude are favorable characteristics of extratropical cyclone intensification as discussed by Kocin and Uccellini (1990) and help to explain the rapid strengthening of the surface low that took place over the preceding 12 h. Conditions in the upper levels of the atmosphere, as shown by the 300-hPa chart in Fig. 3c, also suggest a favorable synoptic-scale environment for storm intensification. The same negatively tilted short-wave feature can be seen, along with the presence of two important upper-jet maxima. A departing 90 kt (45 m s^{-1}) jet maximum can be seen north of Lake Superior extend-

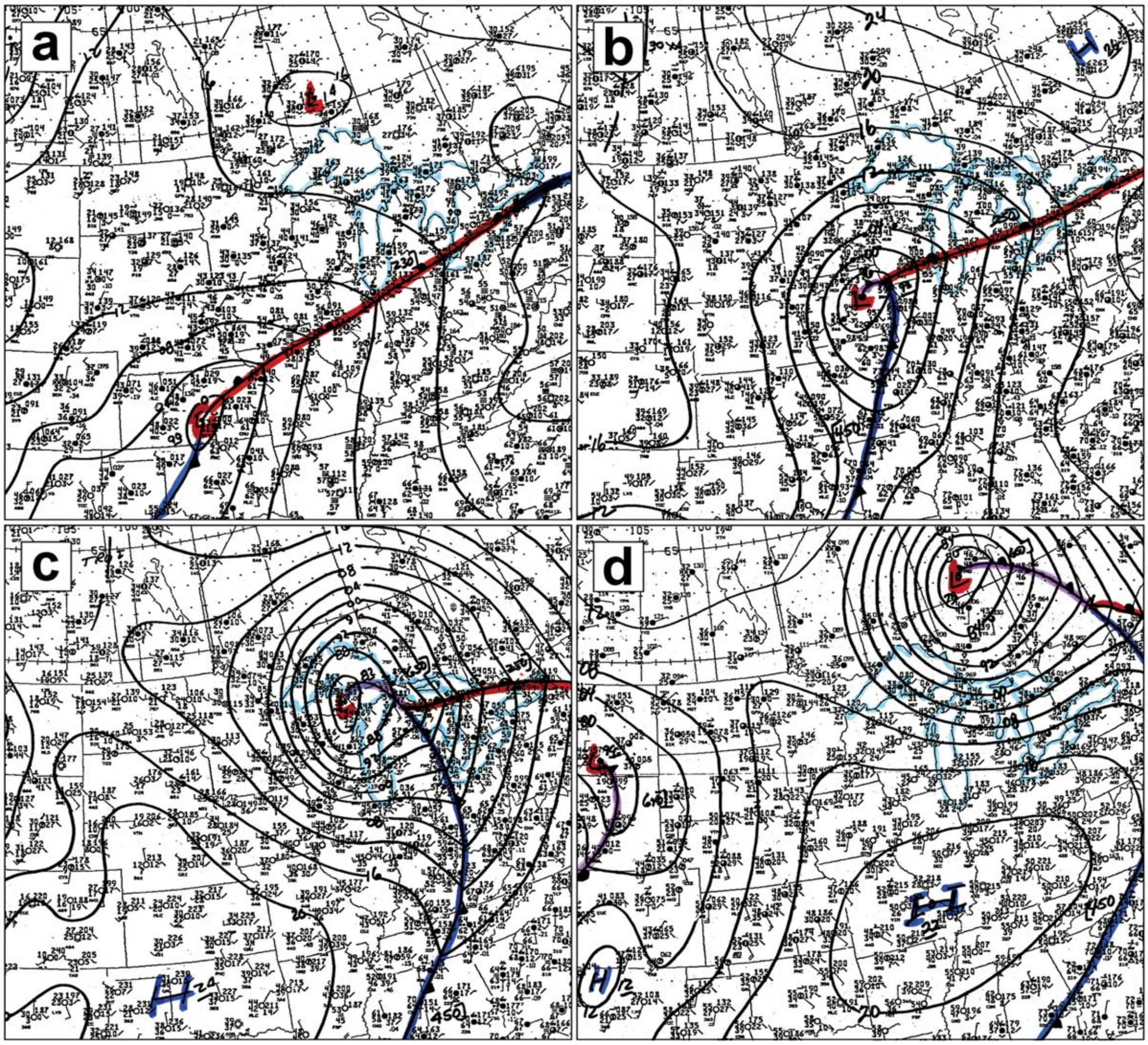

Fig. 1. Conventional station model plots and surface analyses for (a) 9 Nov 1975 at 1200 UTC; 10 Nov 1975 at (b) 0000 and (c) 1200 UTC; and (d) 11 Nov 1975 at 0000 UTC. Cold frontal boundaries are in blue, warm frontal boundaries are in red, and occluded frontal boundaries are in purple. Isobars are shown every 4 hPa.

ing northeast across Hudson Bay, with another 90-kt (45 m s^{-1}) jet maximum over lower Michigan. In addition to the diffluence apparent in the 300-hPa geopotential height contours downstream of the trough axis, one can postulate that this coupled jet structure would produce a substantial amount of divergence in the upper levels of the atmosphere as described by Uccellini and Kocin (1987), further representing a favorable environment for the intensification of the low-level cyclone.

The *Edmund Fitzgerald* and *Arthur M. Anderson* changed to a southeast course toward Michipicoten Island around 1800 UTC (Fig. 2). At this time, the *Edmund Fitzgerald* was approximately 13 km ahead and slightly east of the *Arthur M. Anderson.* At 2030 UTC, the *Edmund Fitzgerald* was located northeast of Caribou Island and reported to the *Arthur M. Anderson* that a fence rail was down, a couple of vents were lost, and it had developed a list. At this time, Captain McSorley of the *Edmund Fitzgerald* also indicated that he would slow down to allow the *Arthur M. Anderson* to close the distance between the vessels. Captain Cooper of the *Arthur M. Anderson* inquired as to whether the *Edmund Fitzgerald*'s pumps were running, and Captain McSorley indicated that both were operating. Conditions aboard the *Edmund Fitzgerald* worsened by 2110 UTC, when it reported to the *Arthur M. Anderson* that both of its radars were inoperative and that it would need the *Arthur M. Anderson* to provide navigational assistance. During this time, between 1800 UTC 10 November 1975 and 0000 UTC 11 November 1975, the surface low moved

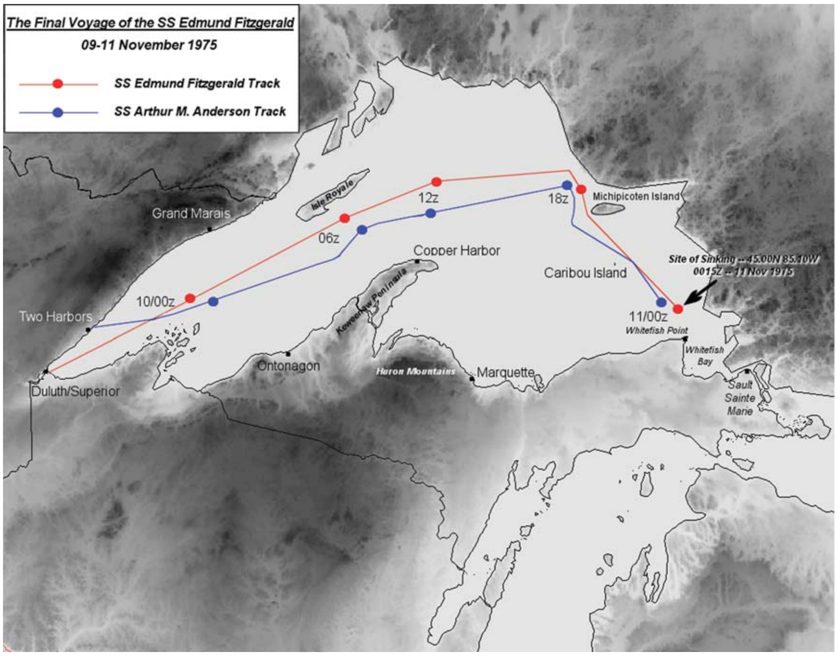

Fig. 2. The most probable tracks and positions of the *Edmund Fitzgerald* (red) and *Arthur M. Anderson* (blue) based upon reports of their position and information contained in the NTSB78. Final position of the *Edmund Fitzgerald* is 46.99°N, 85.11°W.

northeast to near James Bay and strengthened to 978 hPa (Fig. 1d). The pressure gradient tightened over Lake Superior during this time and northwest winds intensified.

At 2139 UTC 10 November 1975, the U.S. Coast Guard Station in Grand Marais, Michigan, advised the *Edmund Fitzgerald* that the radio beacon at Whitefish Point was not functioning. The *Edmund Fitzgerald* communicated with the *Arthur M. Anderson* at 2238 UTC to help it set the proper heading, toward a position approximately 4 km east of Whitefish Point. Between 2200 and 2230 UTC, Captain McSorley communicated with the pilot on the northbound Swedish vessel *Avafors.* During their communication, the master of the *Edmund Fitzgerald* indicated to the *Avafors* that the ship was listing badly, had lost both radars, and was taking heavy seas over the deck in one of the worst seas he had ever encountered.

The *Arthur M. Anderson* continued to follow the *Edmund Fitzgerald* and provide navigational assistance as the ships headed toward Whitefish Bay during the early evening hours of 10 November 1975. At 0000 UTC 11 November 1975, the *Arthur M. Anderson* advised the *Edmund Fitzgerald* that it was 16 km ahead and about 2 km east of the *Arthur M. Anderson*. The *Arthur M. Anderson* informed the *Edmund Fitzgerald* of northbound traffic approximately 14 km ahead of the *Edmund Fitzgerald* at 0010 UTC. It was at this time that Captain McSorley, when asked about the ship's problems, indicated "We are holding our own." This marked the final radiotelephone conversation between the two ships, and there was no radar contact with the *Edmund Fitzgerald* when the *Arthur M. Anderson*'s radar was checked again at 0020 UTC. Visibility increased at that time between snow squalls such that lights on shore more than 32 km away were visible as were the lights of a northbound vessel 30 km away, but the *Edmund Fitzgerald,* which should have been approximately 16 km away, was not there. The *Arthur M. Anderson* attempted to contact the *Edmund Fitzgerald* several times between 0020 and 0130 UTC, but all attempts were unsuccessful. At 0132 UTC, the *Arthur M. Anderson* informed the U.S. Coast Guard that the *Edmund Fitzgerald* may have suffered a casualty.

The *Edmund Fitzgerald* rests on the bottom of Lake Superior, fractured in two large pieces at 46.99°N, 85.11°W in 162 m of water, just north of the international boundary in Canadian waters. All 29 crew members aboard the *Edmund Fitzgerald* were lost with the ship. Captain McSorley and the chief mate aboard the *Edmund Fitzgerald* were experienced Great Lakes mariners, having been licensed since 1938 and 1941, respectively. Captain McSorley was a ship captain since 1951, and was master of the *Edmund Fitzgerald* since 1972. The 200-lb bronze bell from the *Edmund Fitzgerald* was recovered in 1995 at the request of surviving family members and is on display at the Great Lakes Shipwreck Museum in Whitefish Point, Michigan, as a memorial to its lost crew.

FILLING THE GAPS. During the storm, there were a total of 31 surface weather observations taken by ships on Lake Superior. Given the fact that the surface of Lake Superior covers 82,100 km^2 and that these 31 observations occurred over a period of 42 h, this amounts to fewer than one observation per hour for an area roughly the size of South Carolina. More importantly, only one observation was available over Lake Superior in the vicinity of the *Edmund Fitzgerald* when it sank. This lack of observed data, both in space and time, makes it difficult to assess the severity of conditions on Lake Superior throughout the storm, and how those conditions varied. Numerous studies (Uccellini et al. 1987; Whitaker et al. 1988; Martin 1998a; Mann et al. 2002; Roebber et al. 2002; Poulos et al. 2002; Meyers et al. 2003) have shown the utility of using numerical weather prediction models to better diagnose the specific conditions of the atmosphere throughout an event. It was therefore determined that high-resolution numerical simulations could be used to help attain a more complete picture of the wind and wave conditions during the storm.

An atmospheric simulation of the event was performed utilizing the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992), version 4.4. The model run started at 0000 UTC 9 November 1975 and ran through 0600 UTC 11 November 1975. The *Edmund Fitzgerald* sank shortly after 0000 UTC 11 November 1975, approximately 48 h into the model simulation. The model was run in a nested configuration so that a horizontal grid spacing of 5 km was achieved over a nest that covered the western Great Lakes, as shown in Fig. 4. Initial and lateral boundary conditions for the simulation were provided by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Global Reanalysis Dataset (Kalnay et al. 1996). A simulation of wave conditions was performed using the Great Lakes Environmental Research Laboratory (GLERL) Wind-Wave Model (Schwab et al. 1984). This simulation employed 10-km horizontal grid spacing, was driven by wind and temperature output from the atmospheric simulation, and covered the same time

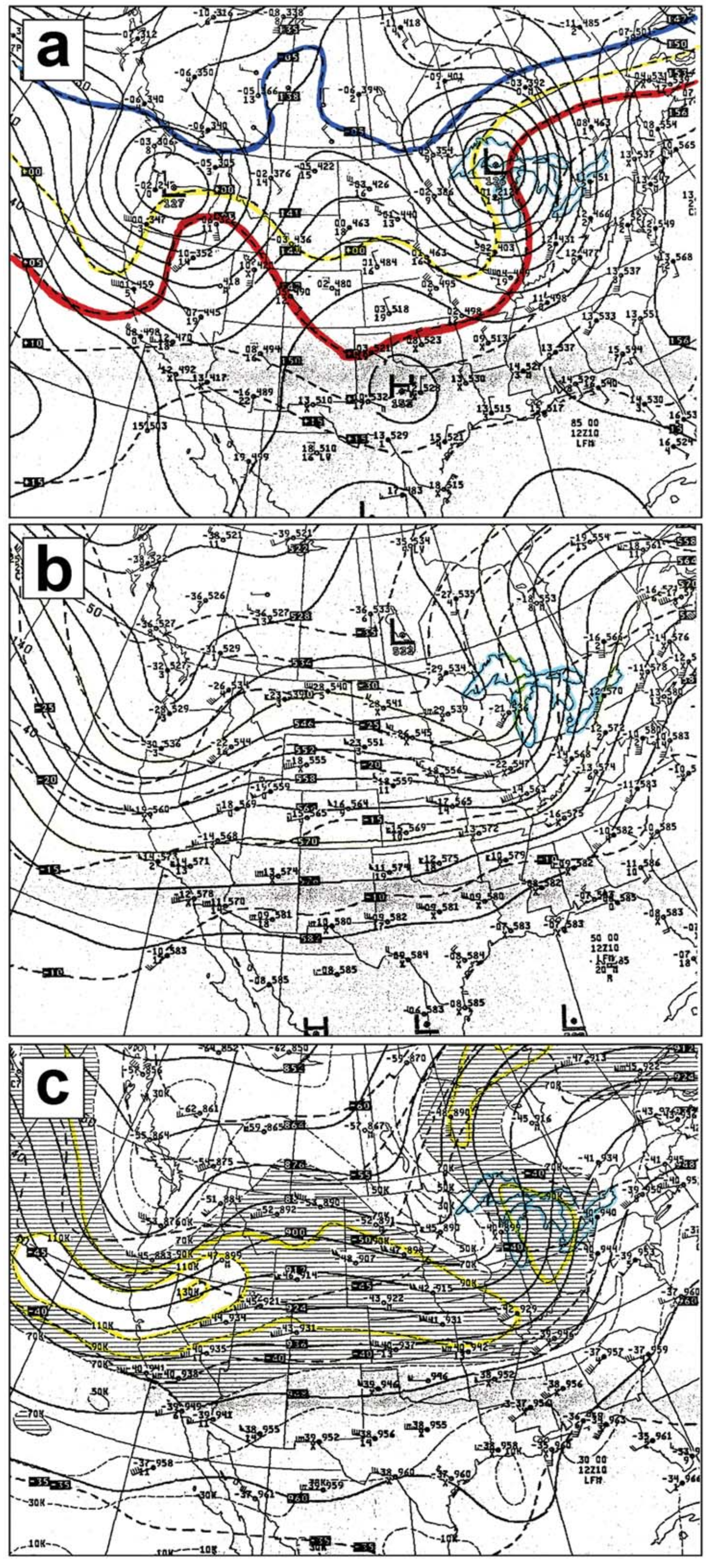

Fig. 3. Conventional station model plots and upper-air analyses valid at 1200 UTC 10 Nov 1975 for (a) 850, (b) 500, and (c) 300 hPa. Geopotential heights are drawn in solid contours in 30-m intervals at 850 hPa, 60-m intervals at 500 hPa, and 120-m intervals at 300 hPa. Isotherms are long dashed contours in 5°C intervals, and isotachs (on 300 hPa) are short dashed contours. The –5°, 0°, and 5°C contours at 850 hPa are highlighted in blue, yellow, and red, respectively. Isotachs of 90 kt (45 m s^{-1}) and greater at 300 hPa are highlighted in yellow.

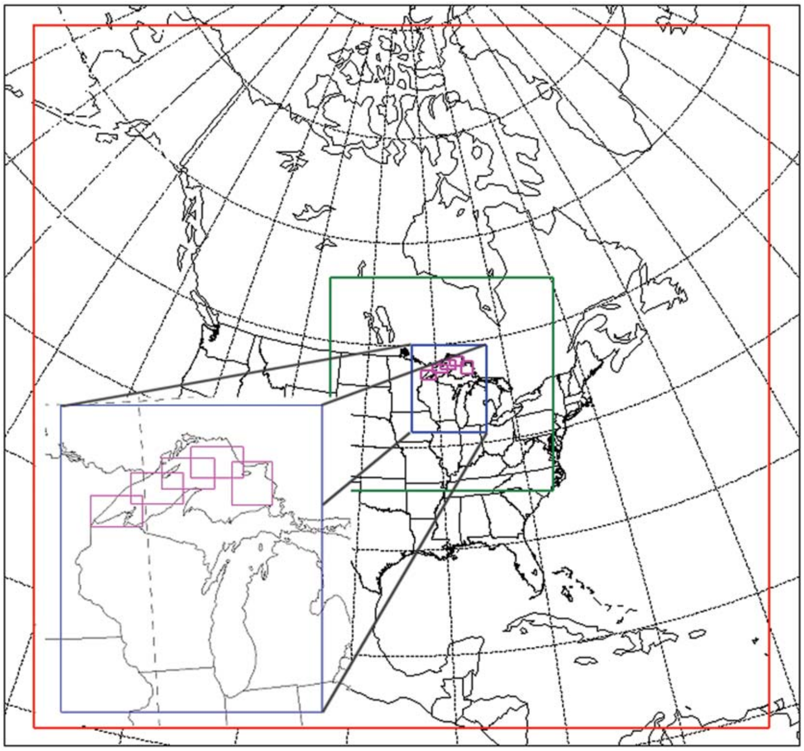

Fig. 4. Computational domain and associated nests for the RAMS model simulation. Outer grid (red) was at 80-km grid spacing with 31 vertical levels, nest 1 (green) was at 20-km grid spacing with 61 vertical levels, nest 2 (blue) was at 5-km grid spacing with 61 vertical levels, and nests 3–7 (magenta) were at 1-km grid spacing with 61 vertical levels. Nests 3–7 were run in succession for a period of 6 h each, running from 1800 UTC 9 Nov 1975 through 0000 UTC 11 Nov 1975.

period. Details on the configuration of these models can be found in the appendix.

In order to consider output from the model simulations to be representative of conditions on Lake Superior during the storm, some comparison between model output and larger-scale atmospheric conditions is necessary. Previous studies that included successful model simulations of events (Martin 1998b; Roebber et al. 2002; Poulos et al. 2002; Meyers et al. 2003) utilized high-resolution output from the simulations to help diagnose conditions in greater detail than would be possible through observational data alone. Following along these lines, we believe that if the atmospheric simulation successfully resolves synoptic-scale conditions, it also offers a reasonable estimate of mesoscale details over Lake Superior throughout the storm. Given an accurate estimate of atmospheric conditions, the resulting wave simulation results can also be considered accurate in time and space, since wave heights on the Great Lakes are essentially the result of winds and stability over the given lake (Liu et al. 1984). This allows one to have a detailed description of how conditions on Lake Superior likely evolved during the storm, and more specifically can help to determine the probable wind and wave conditions in the vicinity of the *Edmund Fitzgerald* when it sank.

SIMULATION VERSUS REALITY. The storm was undergoing rapid intensification by 1200 UTC 10 November 1975 as the surface low moved across the upper peninsula of Michigan (Fig. 1c). A comparison of mid- and upper-atmospheric output from the simulation with analyses of observed data indicates that the model simulation accurately depicts synoptic-scale features at this time. At 850 hPa (Fig. 5a), features correspond well between the simulation and analysis (Fig. 3a). The 850-hPa low center has identical geopotential height values of 1260 m in nearly the same location in both the simulation and observed data. Temperatures at 850 hPa are also remarkably similar, with the −5°, 0°, and 5°C contours transecting the same locations in the upper Great Lakes and eastern Canada. The 500-hPa geopotential height and temperature output shown in Fig. 5b also match observational data (Fig. 3b) quite closely, with nearly the identical position and intensity of the midtropospheric shortwave. The 500-hPa temperatures from the simulation also correlate well with those that were observed. Finally, Fig. 5c shows a high-amplitude negatively tilted upper trough at 300 hPa approaching the upper Great Lakes, with an upper-jet max of over 90 kt (45 m s^{-1}) downstream of the trough axis over southeast Michigan. These features also compare favorably with those depicted in the analysis at this time in Fig. 3c.

Since the thrust of this study was to determine the most probable wind conditions near the surface of Lake Superior (and resultant wave conditions) throughout the storm, it is also important to assess how well the simulation mirrored reality in terms of the low-level pressure gradient, which drives the wind field. Figure 6 includes a series of three images depicting the surface features from the simulation at 0000 and 1200 UTC 10 November 1975 and 0000 UTC

11 November 1975. A comparison of this output with the observational analyses in Fig. 1 shows a very close match of features in time, space, and intensity. At 0000 UTC 10 November 1975, the simulation indicates a 995-hPa low centered over eastern Iowa, quite similar to the 993-hPa low apparent in the observational data. By 1200 UTC 10 November 1975, the low in the simulation moves to far south-central Lake Superior, just northeast of Marquette, and intensifies to 982 hPa. This corresponds very well with the observed low over Marquette and its pressure of 983 hPa. Finally, by 0000 UTC 11 November 1975, the simulation indicates a 978-hPa low centered just southwest of James Bay. This is nearly identical to the intensity and position of the observed low at the time.

The comparison of both surface and upper-air features from the model simulation to observed features demonstrates that the simulation captures the synoptic-scale conditions associated with the storm very well. Therefore, the high-resolution simulated output can serve as a close approximation of observational data on Lake Superior throughout the storm and can be used to drive the wave model simulation, producing a representative picture of marine conditions during the period of 9–10 November 1975. The discussion that follows will focus on the 5 (10)-km grid spacing wind (wave) output from 1800 UTC 9 November 1975 through 0600 UTC 11 November 1975, encompassing the entire period during which the *Edmund Fitzgerald* traveled across Lake Superior.

A TEMPEST ON LAKE SUPERIOR.

The high-resolution wind output shown represents winds at approximately 50 m AGL (second model sigma layer) over Lake Superior. Winds at this level compared most favorably with observations, and therefore were felt to be most representative of likely conditions throughout the event. Observations used for comparison were primarily from ships, whose anemometer heights were approximately 30 m above lake level. Increasingly colder air moved into the area during the height of the event as the surface low moved northeast of Lake Superior. The arrival of colder air substantially increased the temperature difference between the lake, where water temperatures average around 7°C in early November, and the overlying air (Fig. 7). It is likely that vigorous mixing

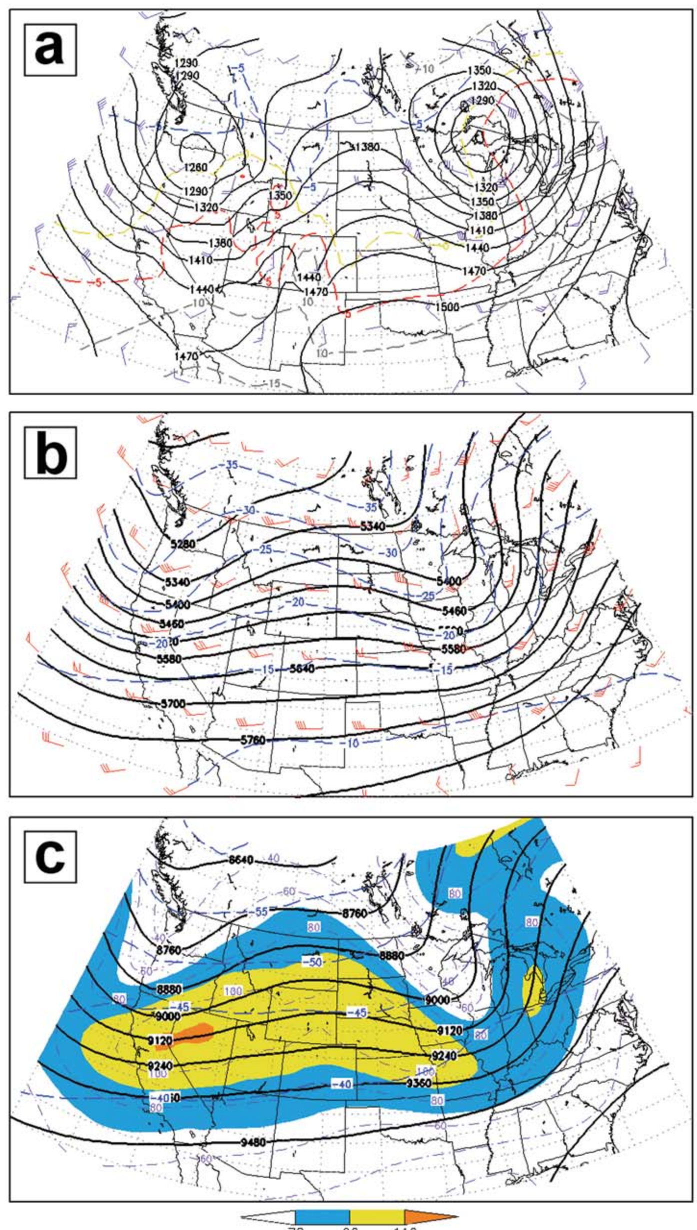

Fig. 5. Upper-air analyses from model simulation valid at 1200 UTC 10 Nov 1975 for (a) 850, (b) 500, and (c) 300 hPa. Geopotential heights are drawn in solid black contours in 30-m intervals at 850 hPa, 60-m intervals at 500 hPa, and 120-m intervals at 300 hPa. Isotherms are long dashed contours in 5°C intervals. The –5°, 0°, and 5°C contours at 850 hPa are highlighted in blue, yellow, and red, respectively. Isotachs at 300 hPa are long dashed purple contours, with values of 70–89 kt (35–44.5 m s^{-1}) shaded in blue, 90–109 kt (45–54.5 m s^{-1}) shaded in yellow, and values of 110 kt (55 m s^{-1}) and greater shaded in orange. Wind barbs in kt are indicated in purple at 850 hPa and red at 500 hPa.

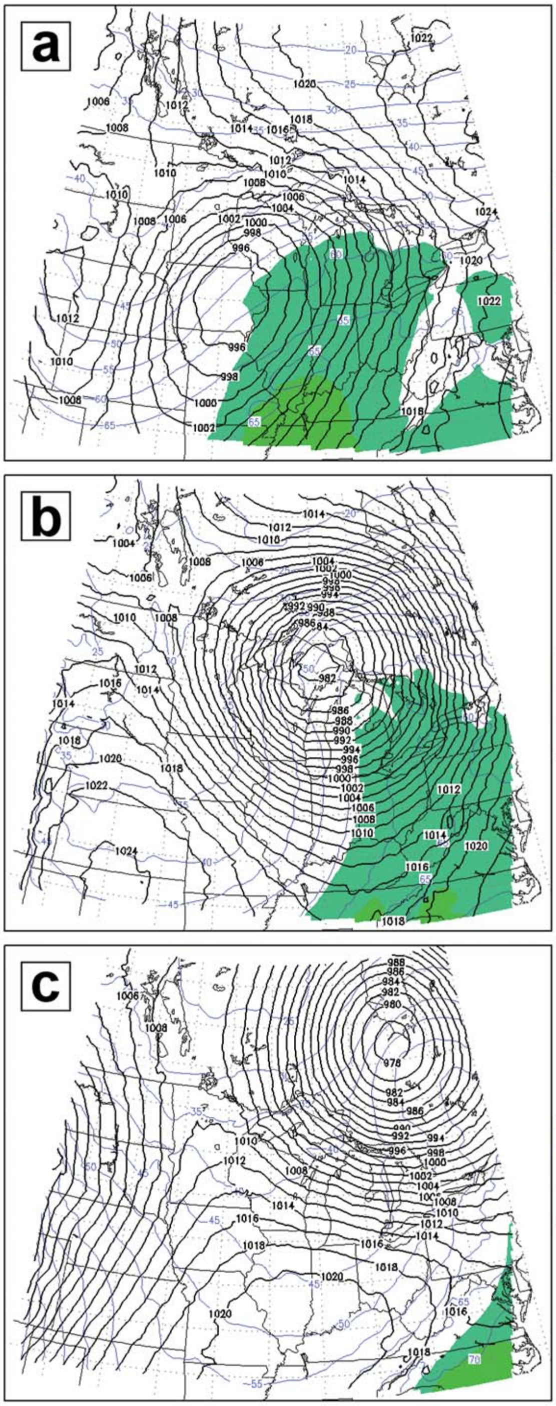

FIG. 6. Mean sea level pressure analyses from model simulation for 10 Nov 1975 at (a) 0000 and (b) 1200 UTC, and (c) 11 Nov 1975 at 0000 UTC. Isobars are depicted in solid black contours with a 2-hPa interval. Isotherms are in solid blue contours with a 5°F interval. Dewpoint temperatures at and above 55°F are shaded.

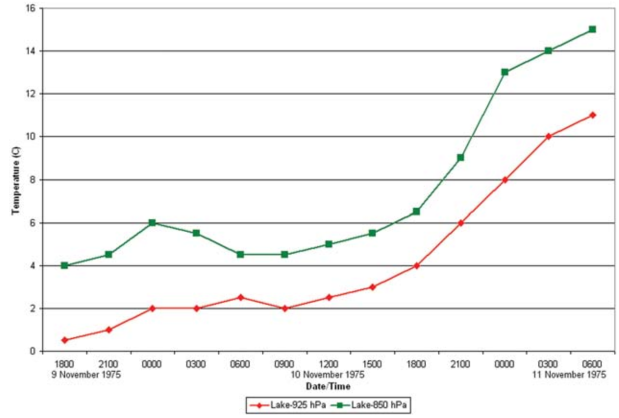

FIG. 7. Difference between Lake Superior climatological water temperature (°C) and overlying air temperature at 925 (red) and 850 hPa (green) from model simulation near location of *Edmund Fitzgerald* between 1800 UTC 9 Nov 1975 and 0600 UTC 11 Nov 1975.

allowed winds from 50 m AGL to reach the surface over Lake Superior with minimal reduction in speed, particularly during the afternoon and evening of 10 November 1975. Wave heights shown (as in Fig. 8) represent significant wave height, which is traditionally defined as the average height of the upper tercile of waves (Glickman 2000). Simulated wind and wave conditions are discussed as if they represent actual conditions, with references to ship observations included when possible.

At 1800 UTC 9 November 1975, approximately 75 minutes before the *Edmund Fitzgerald* departed Superior, Wisconsin, winds over Lake Superior (Fig. 8a) were generally east at 10–15 kt (5–7.5 m s^{-1}). Wave heights over western Lake Superior were 0.5 m or less at this time (Fig. 8b). Ship observations on western Lake Superior at the time indicated northeast winds of around 15 kt (7.5 m s^{-1}). By 2100 UTC, winds increased to over 20 kt (10 m s^{-1}) over western Lake Superior and presented a northeast headwind to the *Edmund Fitzgerald* (Fig. 9). Winds strengthened further by 0000 UTC 10 November 1975 as the surface low moved into eastern Iowa (Fig. 6a), with winds in excess of 25 kt (12.5 m s^{-1}) over portions of western and eastern Lake Superior (Fig. 10). Ship observations over western Lake Superior at 0000 UTC indicated northeast winds between 24 kt (12 m s^{-1}) and 28 kt (14 m s^{-1}).

At 0600 UTC, winds of 30–35 kt (15–17.5 m s^{-1}) were present over western and central Lake Superior in the vicinity of the *Edmund Fitzgerald* (Fig. 11a). However, it should be noted that at this time, the observation from the *Edmund Fitzgerald* indicated a northeast wind of 52 kt (26 m s^{-1}). This observation is the only noteworthy departure between observational data and output from the model simulations during the storm, and the difference may be due to observational error. It is possible that error was introduced into the wind speed observation during the process of converting ship-relative winds to ground-relative winds, particularly since the ship was traveling northeast into a northeast wind. This is a credible possibility since the simulated wave heights at 0600 UTC were approximately 3.1 m (Fig. 11b), which closely matches the reported wave height of 3 m from the *Edmund Fitzgerald*. Since wave heights are a derivative of wind speed, this suggests that the simulated wind speeds are accurate and that the reported 50-kt (25 m s^{-1}) wind may have been due to an error in the observation. Two other ships located on western Lake Superior at 0600 UTC reported northeast winds of 32 kt (16 m s^{-1}) and 38 kt (19 m s^{-1}), respectively, which more closely match the simulated wind speeds. If the observation was not in error, then the difference could be the result of locally enhanced winds due to coastal convergence south of Isle Royale, which was not adequately simulated.

During the early morning of 10 November 1975, conditions calmed on Lake Superior as the surface low center moved over the east half of the lake (Fig. 6b).

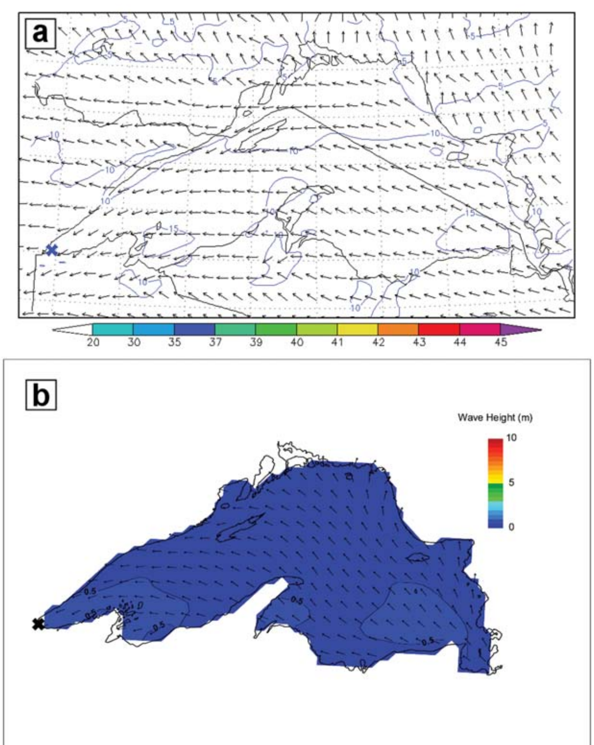

Fig. 8. Output from model simulations valid at 1800 UTC 9 Nov 1975 indicating (a) wind speed (kt, shaded) and direction (vectors), and (b) significant wave height (m, shaded) and direction (vectors). The U.S./Canadian border is shown in (a) as a solid black line. Approximate position of the *Edmund Fitzgerald* is indicated by a blue X in (a) and by a black X in (b).

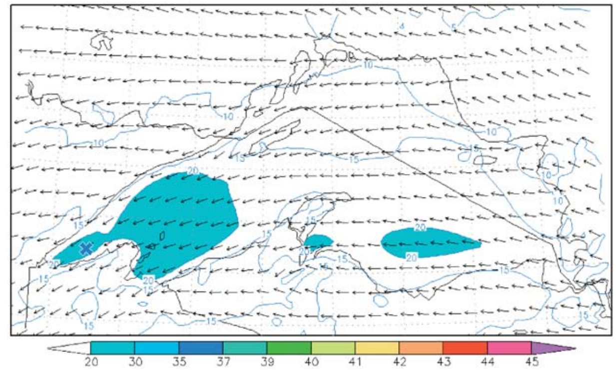

Fig. 9. Same as in Fig. 8a, except for 2100 UTC 9 Nov 1975.

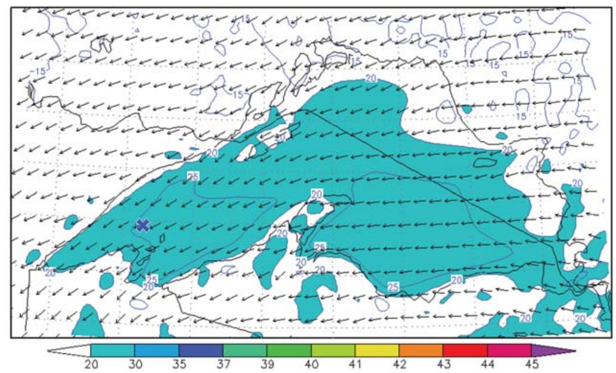

Fig. 10. Same as in Fig. 8a, except for 0000 UTC 10 Nov 1975.

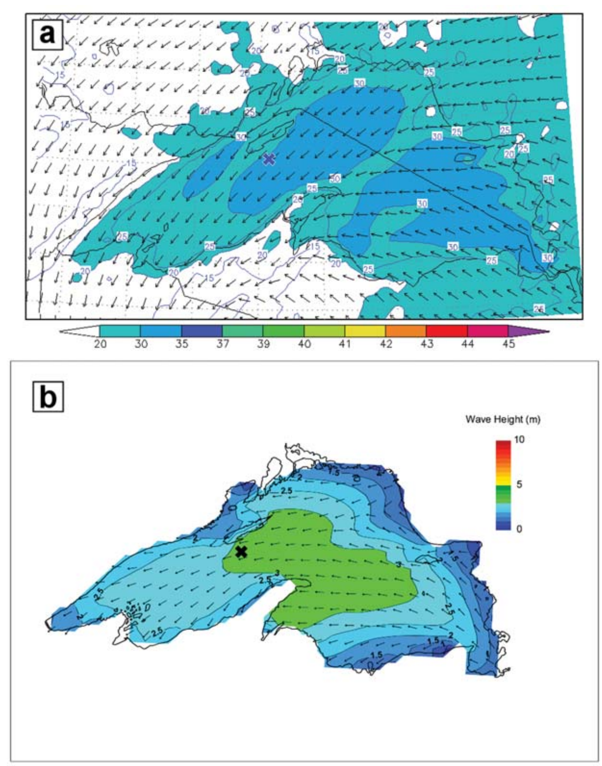

Fig. 11. Same as in Fig. 8, except for 0600 UTC 10 Nov 1975.

Winds at 1200 UTC were variable in direction with the center of the low's circulation near the tip of the Keweenaw Peninsula. Wind speeds were generally between 15 kt (7.5 m s^{-1}) and 25 kt (12.5 m s^{-1}), with the strongest winds being from the southeast at 30 kt (15 m s^{-1}) to 35 kt (17.5 m s^{-1}) over southeast Lake Superior (Fig. 12a). Ship observations over central and eastern Lake Superior around this time indicated winds of 23 kt (11.5 m s^{-1}) to 37 kt (18.5 m s^{-1}), with the *Edmund Fitzgerald* reporting a northeast wind of 35 kt (17.5 m s^{-1}) and wave heights of 3 m. Simulated wave heights in the vicinity of the *Edmund Fitzgerald* matched the observation closely, indicating waves just above 3 m at 1200 UTC (Fig. 12b).

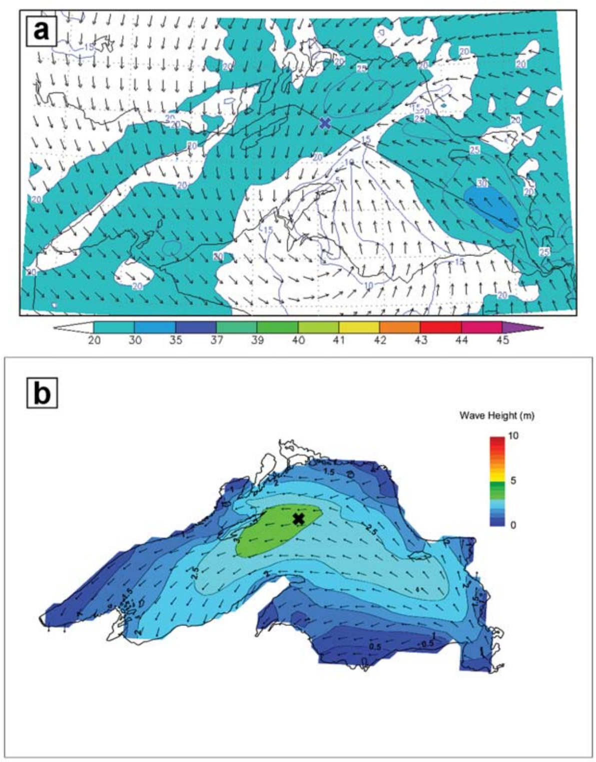

Fig. 12. Same as in Fig. 8, except for 1200 UTC 10 Nov 1975.

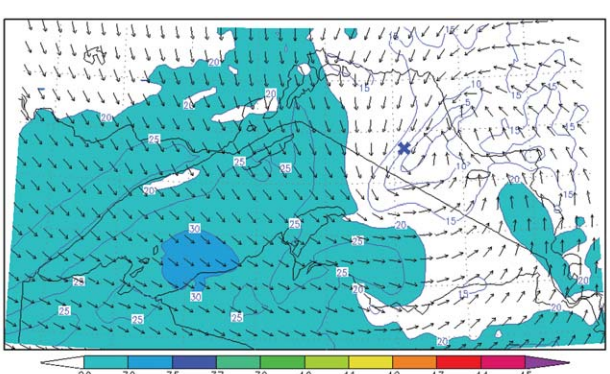

Fig. 13. Same as in Fig. 8a, except for 1500 UTC 10 Nov 1975.

By 1500 UTC, the low center was in the vicinity of the *Edmund Fitzgerald* as it made its turn toward the southeast. Wind speeds in this area were around 10 kt (5 m s^{-1}), although it should be noted that winds were already increasing over western Lake Superior where northwest winds in excess of 30 kt (15 m s^{-1}) were developing (Fig. 13). The surface low moved northeast of Lake Superior by 1800 UTC, and northwest winds continued to intensify over the lake (Fig. 14a). Of particular note is the core of wind speeds in excess of 40 kt (20 m s^{-1}) that developed over south-central Lake Superior, likely enhanced due to acceleration of the flow north of the high terrain of the Huron Mountains (Fig. 2) owing to coastal convergence. At this time, the *Edmund Fitzgerald* was located just to the north-northwest of Michipicoten Island, where winds were northwest between 25 kt (12.5 m s^{-1}) and 30 kt (15 m s^{-1}). Although an observation from the *Edmund Fitzgerald* was not available at 1800 UTC, ship observations over the eastern half of Lake Superior indicated that winds were between 20 kt (10 m s^{-1}) and 40 kt (20 m s^{-1}). Wave heights were beginning to build by 1800 UTC (Fig. 14b) and were

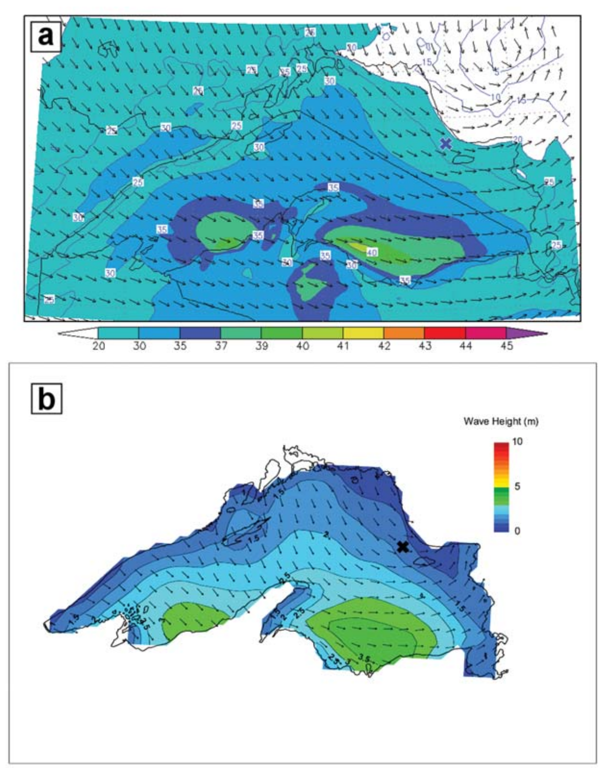

Fig. 14. Same as in Fig. 8, except for 1800 UTC 10 Nov 1975.

approaching 4 m over portions of south-central and southeast Lake Superior. At 2100 UTC, two cores of higher wind speed are evident (Fig. 15a)—one area in excess of 45 kt (22.5 m s^{-1}) originating north of the Huron Mountains, and a second in excess of 40 kt (20 m s^{-1}) originating north of the high terrain at the tip of the Keweenaw Peninsula. Stronger winds developing in these areas were spreading east and appearing to coalesce over southeastern Lake Superior, spreading into the area toward which the *Edmund Fitzgerald* was heading. Wave heights continued to increase, and at this time were approaching 6 m over much of southeast Lake Superior (Fig. 15b).

By 0000 UTC 11 November 1975, west–northwest winds in excess of 45 kt (22.5 m s^{-1}) were present over most of southeast Lake Superior, with gale-force winds in excess of 35 kt (17.5 m s^{-1}) extending into western Lake Superior (Fig. 16a). The *Edmund Fitzgerald* was located in a precarious position at this time, at the eastern edge of the zone of highest winds, where the maximized fetch distance would produce the highest wind waves. Significant wave heights in this area continued to increase, from over 7 m at 0000 UTC (Fig. 16b) to in excess of 7.5 m at 0100 UTC (Fig. 16c), with a maximum height of 7.8 m noted in the raw model output at 0100 UTC. In addition, note that the waves were essentially propagating from west to east, which could result in a hazardous rolling motion for southward-moving vessels. Around this time, the *Arthur M. Anderson* reported northwest winds of 50 kt (25 m s^{-1}). Simulated winds in the vicinity of the *Arthur M. Anderson* correlated well with this observation, indicating northwest winds of around 47 kt (23.5 m s^{-1}). Shortly after this time, at around 0015 UTC, the *Edmund Fitzgerald* was lost with all hands. The captain of the *Arthur M. Anderson* later indicated that as it moved into the area where the *Edmund Fitzgerald* was lost (Fig. 2) waves were between 5.5 and 7.5 m and winds gusted between 70 kt (35 m s^{-1}) and 75 kt (37.5 m s^{-1}). A high-resolution

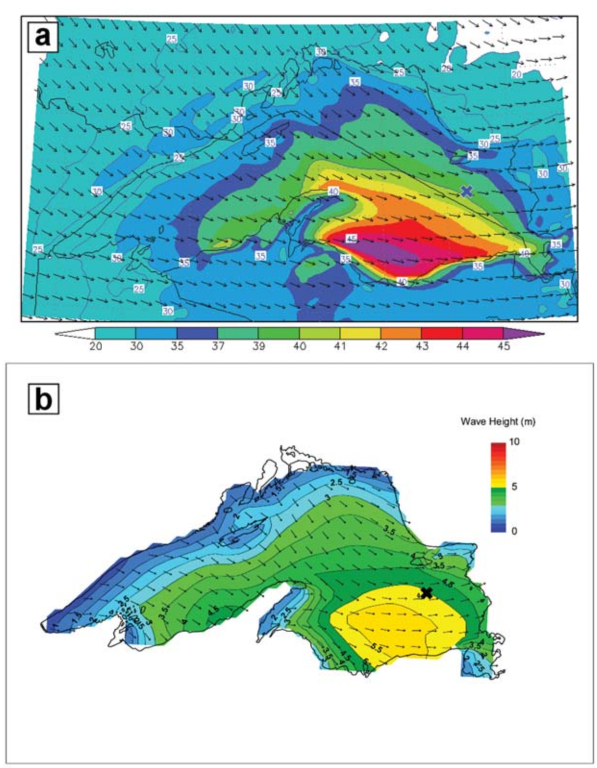

Fig. 15. Same as in Fig. 8, except for 2100 UTC 10 Nov 1975.

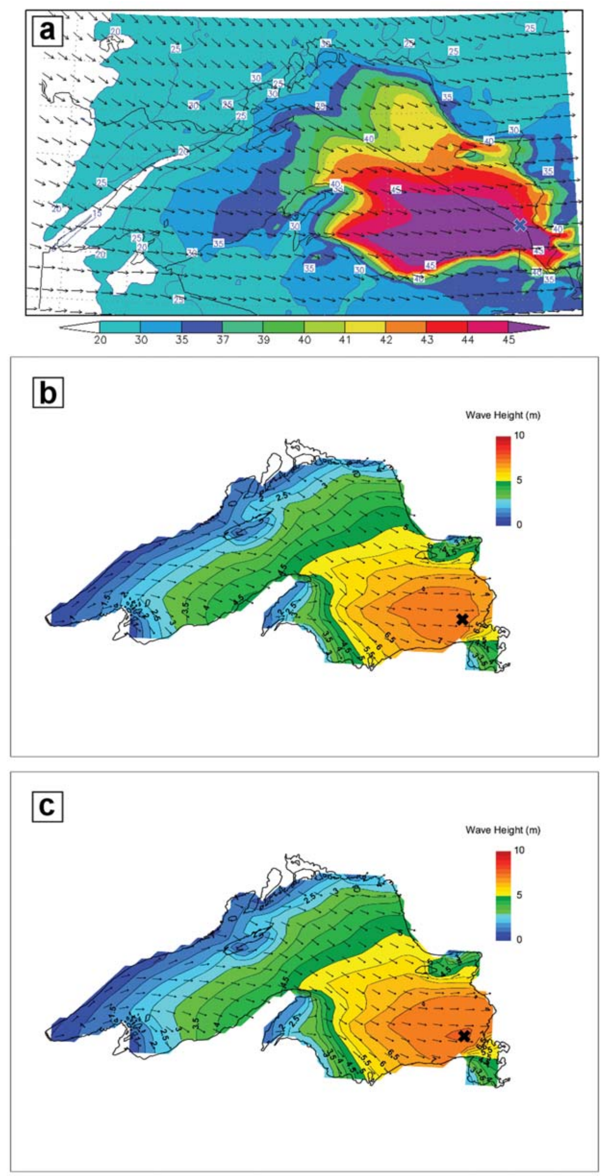

Fig. 16. Same as in Fig. 8, except for 11 Nov 1975 at (a), (b) 0000 and (c) 0100 UTC.

model nest over southeast Lake Superior (Fig. 4) at 0000 UTC depicts a very complex wind field (Fig. 17). This high-resolution nest, at 1-km horizontal grid spacing, may be resolving lake-effect horizontal roll convection as described by Kelly (1984) and Niziol et al. (1995), resulting from the increasingly cold air moving across the relatively warm water of Lake Superior (Fig. 7). However, it is also possible that the banding and squally nature of the winds are an artifact of computational noise manifesting itself at scales 2 or 4 times the model's horizontal grid spacing. Wind speeds of 50 kt (25 m s^{-1}) to 60 kt (30 m s^{-1}) are evident within many of the bands (Fig. 17), and raw model output indicated a maximum sustained wind of 65 kt (32.5 m s^{-1}). Wave heights of individual waves generally follow a Rayleigh distribution (Lonquet-Higgins 1952) so that the maximum wave height in 7-m seas, although rare and unlikely, could be as high as 14 m. It is particularly noteworthy that the most severe conditions in the simulations occurred between 0000 and 0100 UTC, coincident in time and location with the loss of the *Edmund Fitzgerald*.

Just three hours later, at 0300 UTC, winds decreased to under 45 kt (22.5 m s^{-1}) over southeast Lake Superior, with gale-force winds confined to only eastern Lake Superior (Fig. 18). By 0600 UTC, which marked the end of the model simulations, only gale force winds of 35 kt (17.5 m s^{-1}) to 40 kt (20 m s^{-1}) could be found over southeast Lake Superior (Fig. 19a), and wave heights diminished to 6 m over far southeast Lake Superior, with waves of 5 m or less over most of eastern Lake Superior (Fig. 19b). A ship observation at 0600 UTC over central Lake Superior correlated well with the simulated conditions, indicating winds of 28 kt (14 m s^{-1}), while a ship over eastern Lake Superior indicated winds of 30 kt (15 m s^{-1}). Wave height observations from these ships were 2.0 and 4.5 m, respectively.

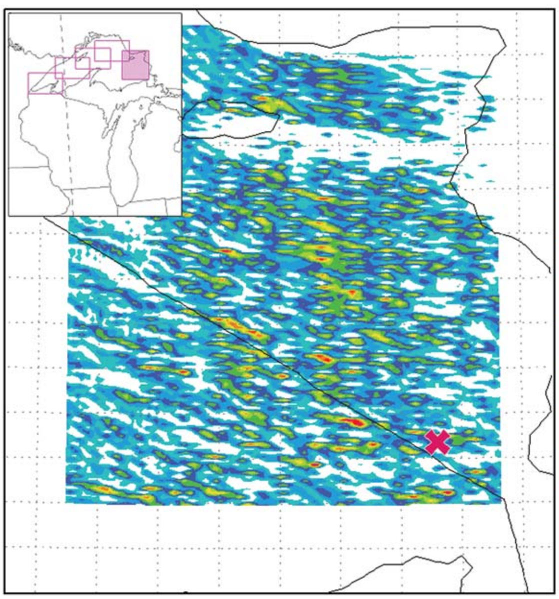

Fig. 17. Output from RAMS simulation valid at 0000 UTC 11 Nov 1975 for nest 7 (at 1-km grid spacing) over southeast Lake Superior. Shaded box on inset shows geographic area covered by nest 7. Wind speed values in kt are shown, with values of 42 kt (21 m s^{-1}) or greater shaded. The dotted grid lines depict 16 km × 16 km grid boxes. The approximate position of the *Edmund Fitzgerald* is indicated by the red X.

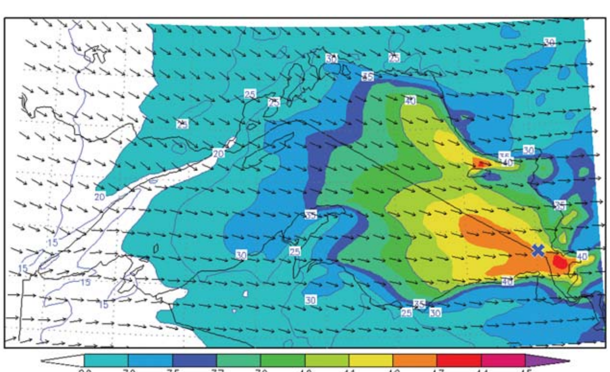

Fig. 18. Same as in Fig. 8a, except for 0300 UTC 11 Nov 1975.

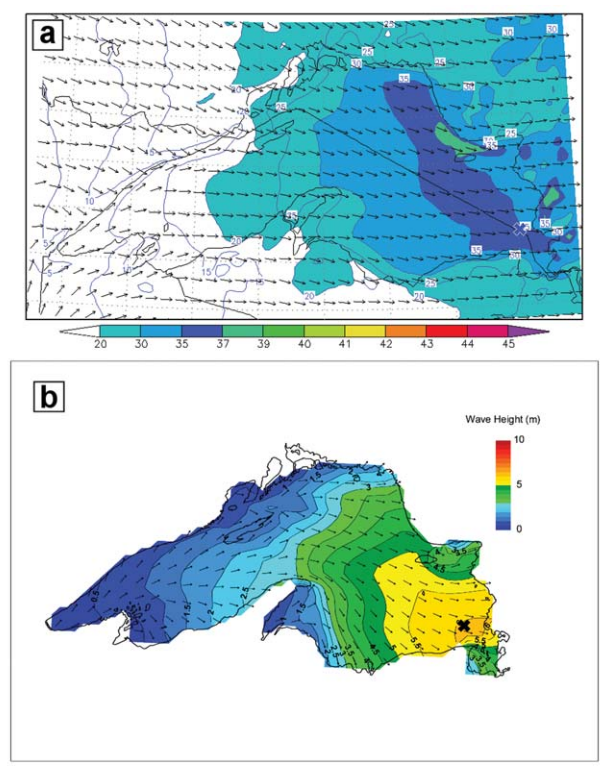

Fig. 19. Same as in Fig. 8, except for 0600 UTC 11 Nov 1975.

HOW UNUSUAL WAS THIS EVENT? To understand the climatological significance of this deadly storm, a short climate summary for eastern Lake Superior is presented. The National Oceanic and Atmospheric Administration (NOAA) weather buoy network on Lake Superior has been operational since 1979. This period is too short to obtain a complete climatology of wind and waves on the lake, and therefore it is difficult to assess the rarity of this event based on that data alone. Also, buoys on the Great Lakes are normally removed during the winter and early spring months (generally November through April) to avoid equipment damage from drifting ice. Therefore, to understand the climatological rarity of the conditions on eastern Lake Superior during the 9–10 November 1975 storm, data from the U.S. Army Corp of Engineers, Waterways Experiment Station (WES) Wind and Wave Hindcast Model (Hubertz 1989) were used as a climate reference. This dataset covers the period of 1956–87. Eid et al. (1991) used the WES hindcast dataset and developed the *Wind and Wave Climate Atlas,* which includes statistics for eastern Lake Superior.

The data in the *Wind and Wave Climate Atlas* suggest that the return period for significant waves with a height in excess of 7 m over eastern Lake Superior is around 2 yr, with a return period of 6–7 yr for significant waves in excess of 8 m in height. The atlas also indicates that the percentage frequency of significant waves in excess of 7 m in height is 0.1%, with the majority of these waves generally traveling from north to south. When averaged over eastern Lake Superior, virtually no waves with heights greater than 7 m were found to be moving from west to east (Table 1), which likely occurred the night of 10 November 1975. Since west- to east-moving waves in excess of 7 m in height are very rare on eastern Lake Superior, it is unlikely Captain McSorley had ever seen a sea state similar to that which occurred during the afternoon and evening of 10 November 1975. This may help to explain why the master of the *Edmund Fitzgerald* indicated to the ship *Avafors* that the seas were the worst he had ever encountered (NTSB78). It should be noted that the highest significant wave height recorded at NOAA buoy 45004, located 105 km east of Copper Harbor, Michigan, was 6.9 m at 1900 UTC 18 October 1981 (National Data Buoy Center 2005). This is the only buoy on eastern Lake Superior that records wave height, and it is not likely to experience the worst possible conditions on eastern Lake Superior, since it is not located at the end of the available fetch in a west or northwest wind scenario. The period of record for this buoy is from April 1980 to present.

Table 1. Percentage frequency of significant wave height by direction for eastern Lake Superior (adopted from Eid et al. 1991). Note that significant wave heights of 7.0+ m occur approximately 0.1% of the time, with the majority of those waves having a direction out of the north. Significant waves in excess of 7.0 m are very infrequent.

Wave height	Direction—Coming from								Total
	N	NE	E	SE	S	SW	W	NW	
0.0 to < 0.5 m	2.5	2.3	1.1	1.2	3.0	2.3	1.6	2.1	16.1
0.5 to < 1.0 m	7.0	5.8	3.0	2.8	6.3	5.3	5	5.9	41.2
1.0 to < 1.5 m	3.4	2.1	0.4	0.3	3.2	2.9	2.5	3.8	18.8
1.5 to < 2.0 m	2.0	0.8	0.2	0.2	1.3	1.4	1.2	2.2	9.3
2.0 to < 2.5 m	1.3	0.4	0.1	0.0	0.2	1.2	0.8	1.3	5.3
2.5 to < 3.0 m	1.1	0.3	0.0	0.0	0.0	0.4	0.4	1	3.3
3.0 to < 3.5 m	0.9	0.3	0.0	—	0.0	0.1	0.1	0.8	2.2
3.5 to < 4.0 m	0.7	0.2	—	—	—	0.0	0.0	0.5	1.5
4.0 to < 4.5 m	0.6	0.1	—	—	—	0.0	0.0	0.3	1
4.5 to < 5.0 m	0.4	0.1	—	—	—	0.0	0.0	0.2	0.8
5.0 to < 5.5 m	0.3	0.0	—	—	—	—	0.0	0.1	0.4
5.5 to < 6.0 m	0.2	0.0	—	—	—	—	—	0	0.2
6.0 to < 6.5 m	0.1	0.0	—	—	—	—	—	0.0	0.1
6.5 to < 7.0 m	0.1	0.0	—	—	—	—	—	0.0	0.1
7.0+ m	0.1	0.0	—	—	—	—	—	0.0	0.1

Similar statistics were also noted when examining wind climatology on eastern Lake Superior. The *Wind and Wave Climate Atlas* suggests that the return period for sustained wind speeds of 50 kt (25 m s^{-1}) or greater is approximately 2 yr, while the return period for wind speeds in excess of 65 kt (32.5 m s^{-1}) is approximately 20 yr. This would imply that although the winds experienced on the evening of 10 November 1975 were not typical, they were also not "rare," suggesting that this was not a climatologically extreme wind event on eastern Lake Superior. However, although the conditions are not climatologically rare, it is likely rare for ships to encounter such conditions given the size of the lake, the fairly low number of ships, and the infrequent nature of such events.

SUMMARY. During 9–10 November 1975, the upper Great Lakes were impacted by an intense storm that produced winds in excess of storm force on Lake Superior, with observed wind gusts in excess of hurricane force. It was during this storm that the ship *Edmund Fitzgerald* sank in southeast Lake Superior. All crew members aboard the ship, 29 in total, were lost. Several theories exist to explain what ultimately led to the loss of the ship, with extreme weather and sea conditions being a common ingredient in each theory. High-resolution numerical simulations were conducted to better assess the most likely wind and wave conditions that were present on Lake Superior throughout the storm. The results from these simulations not only help fill gaps in the available observational data, but also illustrate how quickly conditions can worsen and become life threatening on the Great Lakes.

Conditions on Lake Superior deteriorated rapidly during the afternoon of 10 November 1975, as the *Edmund Fitzgerald* made its southward journey toward the shelter of Whitefish Bay. By that evening, sustained winds near 50 kt (25 m s^{-1}) encompassed most of southeast Lake Superior, with more localized sustained winds in excess of 60 kt (30 m s^{-1}). These winds generated waves in excess of 7.5 m, which moved from west to east across southeast Lake Superior, nearly perpendicular to the documented track of the *Edmund Fitzgerald.* At around 0015 UTC 11 November 1975, the *Edmund Fitzgerald* was lost with all hands, coincident in both time and location with the most severe simulated and observed conditions on Lake Superior during the storm. A ship following a similar course to the *Edmund Fitzgerald,* but six hours earlier or later, would have avoided the worst conditions associated with the storm.

Strong storms impact the Great Lakes each year, and storms that produce conditions on eastern Lake Superior similar in magnitude to the 9–10 November 1975 storm occur every two to six years on average. Ships of all sizes, including 300-m freighters, continue to travel the Great Lakes for commercial and recreational purposes, and are therefore at risk of encountering such conditions in the future. Modernized observation and forecast systems have helped to substantially improve forecasts for the Great Lakes over the past 30 years, allowing for greater advance notice of storms, which allows most ships to avoid such severe conditions rather than simply endure them. But, the tragic events of 10 November 1975 should continue to serve as a reminder of the hazards one can encounter when traveling on the Great Lakes.

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APPENDIX: ATMOSPHERIC MODELING APPROACH AND WAVE MODELING APPROACH.

Atmospheric modeling approach.

- Model: Regional Atmospheric Modeling System (RAMS), version 4.4 (Pielke et al. 1992; Walko and Tremback 2005)
- Initial/boundary conditions: NCEP–NCAR reanalysis
  - 6-h temporal resolution
  - 2.5° × 2.5° degree horizontal resolution
  - 17 vertical levels
- Nest information (Fig. 4): Two-way interaction
  - Outer grid
    - Horizontal grid spacing: 80 km
    - Vertical levels: 31
  - Nest 1
    - Horizontal grid spacing: 20 km
    - Vertical levels: 61
  - Nest 2
    - Horizontal grid spacing: 5 km
    - Vertical levels: 61

    - Nests 3–7
        - Horizontal grid spacing: 1 km
        - Vertical levels: 61
        - Nests activated individually in succession for 6-h periods beginning at 1800 UTC 9 November 1975
- Lateral boundary conditions: Klemp–Wilhemson
- Longwave and shortwave radiation: Harrington two-stream parameterization
- Convective scheme: Kuo (outer grid, nest 1, nest 2), explicit (nests 3–7)
- Land surface model: RAMS Land Ecosystem Atmosphere Feedback model 2 (LEAF2)
- Horizontal/vertical diffusion: Mellor and Yamada (outer grid, nest 1, nest 2), Hill and Lilly isotropic deformation (nests 3–7)
- Microphysics: 6 class bulk microphysics

Wave modeling approach. Winds from approximately 50 m AGL from the RAMS simulation were used as input to the GLERL–Donelan Wind-Wave Model (Schwab et al. 1984), implemented on a 10-km grid on Lake Superior. The RAMS 2-m temperature output was also used in the calculation of over-water stability, which was used to help extrapolate winds to the water surface. The wave model adjusts wind speed to account for decreased drag during unstable conditions. The adjustment is calculated for a 10-m anemometer height, but in this study it was applied directly to the 50-m AGL winds from the RAMS simulation, since these winds were found to be most representative of over-lake conditions. The GLERL–Donelan model is parametric and is based on the conservation of momentum applied to deep water waves. It assumes a Joint North Sea Wave Project (JONSWAP) distribution of wave heights as a function of wave period. The parameters predicted by the model are 1) variance of the water surface (from which significant wave height is derived), 2) peak wave period, and 3) mean wave direction. Swell is not included in the version of the model currently in use for the Great Lakes. This model has been shown to produce results comparable to results from much more complex wave models with much less computational demand (Schwab et al. 1991). This model is currently used operationally by National Weather Service offices on the Great Lakes for routine wave forecasting and is also part of a prototype coastal forecasting system for the Great Lakes (Schwab and Bedford 1999).

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