Reprinted from the Conference on Coastal Oceanic and Atmospheric Prediction, 28 January-2 February 1996, Atlanta, Georgia. Published by the American Meteorological Society, Boston, Mass.

10.4

OBSERVATIONAL AND NUMERICAL MODELING INVESTIGATIONS OF THREE BERING SEA STORMS AND THEIR ASSOCIATED STORM SURGES IN THE REGION OF NOME, ALASKA

Warren Blier*[1], Stanley Keefe[2], Wilson A. Shaffer[3], and Sung C. Kim[4]
[1]*Department of Atmospheric Sciences, UCLA*
[2]*National Weather Service, Alaska Region*
[3]*National Weather Service, Office of Systems Development*
[4]*Research and Data Systems, Greenbelt, MD*

1. INTRODUCTION

The Bering Sea coast of Alaska has experienced a number of coastal flooding events resulting from storm surges associated with extratropical cyclones. These "storm surges" are abnormally high water levels produced by the meteorological influences of cyclones; the storm surge is defined as the algebraic difference between the measured tide and the predicted astronomical tide. As many of the communities in western Alaska are situated on low-lying coastal land, they are vulnerable to such flooding. This is particularly true for villages built on sand spits, barrier islands, and river deltas.

Two regions along the Bering Sea coast that appear to be especially susceptible to large variations in water level are Norton Sound and Bristol Bay. Amplification of storm-induced changes in sea level is particularly notable in the former, with its west-facing opening and shallow average depth (approximately 20 m). Repeated destructive flooding events have occurred in the coastal city of Nome (situated on the northwest shore of Norton Sound as indicated in Fig. 1), the largest city in western Alaska, where water levels have risen as much as 4 m.

In the present century there have been at least 14 occurrences of flooding in Nome; all except two occurred in the fall (Wise et al. 1981). During the great storm of early October 1913, for example, ocean waves broke over the top of the city; many of the buildings along Front Street (situated along the waterfront, the main business street of the town) were torn from their foundations and thrown across the street into other structures. By the end of the storm, the central business district and the east end of the city had been completely destroyed, while a native village (and other houses) on a nearby sandspit had entirely disappeared (Cole 1984).

After a number of subsequent destructive storm surges, construction of a granite sea wall was initiated to protect the town; the wall was completed in 1951. However, on 11 and 12 November 1974, Nome was struck by one of the most powerful storms in its history. Despite the presence of the sea wall, Nome was severely damaged, with damage to the city estimated at $12-15 million dollars. Significant coastal flooding also occurred along many other stretches of the coast of western Alaska. The meteorological aspects of this surge event are documented by Fathauer (1975); he indicates that at the time of maximum water level in Nome, the actual water level was 4.0 m (13.2 ft) above mean low low water (MLLW), with 3.8 m (12.5 ft) of this rise attributed to the storm surge [the remaining 0.2 m (0.7 ft) resulted from tidal influences, which are minimal in this region]. Water overflowed from the harbor and over the sea wall into the city and reached a depth of 1.5 m (5 ft) in the lower-lying west end of Nome.

Given the recurrent nature of coastal flooding in western Alaska and the damage it causes, the National Weather Service (NWS) has considered it a priority to provide timely warning of these events. In this regard a statistical model was developed to predict storm surges along the coast of Alaska, based on regression analyses in which various parameters from the comprehensive Alaskan storm surge climatology developed by Wise et al. (1981) were correlated with the surge height. However, the accuracy and thus the operational value of the guidance provided by this model have generally proven to be quite limited.

More accurate forecasting of storm surge events has awaited the development and implementation of a dynamic storm surge forecast model. Such a model has recently been developed for, and applied to, the west coast of Alaska by the Techniques Development Laboratory (TDL) of the NWS. Evaluation of the quality of the model guidance, as well as more general study of storm surge events in the vicinity of Nome, has been greatly facilitated by the installation of a permanent tide gauge in Nome harbor in June 1992. This represents the only permanent National Oceanic and Atmospheric Administration (NOAA) tide gauge in coastal western Alaska. As a result, a continuous quantitative measurement of water level is now available.

Fortuitously, the most significant coastal flooding episode after November 1974 occurred during 5-6 October 1992, soon after the installation of the tide gauge. This was the first (and thus far only) major coastal storm surge event to have occurred since the Nome tide gauge data have become available. An extensive database of meteorological data and analyses was compiled for this case, and examined in conjunction with the tide gauge data in order to better understand the nature of these coastal surge events. Given the magnitude of the event, and the wealth of data available, this case provided an ideal first test for the newly-developed dynamic storm surge model for coastal western Alaska.

**Corresponding Author address:* Warren Blier, Department of Atmospheric Sciences, University of California at Los Angeles, CA 90095-1565.

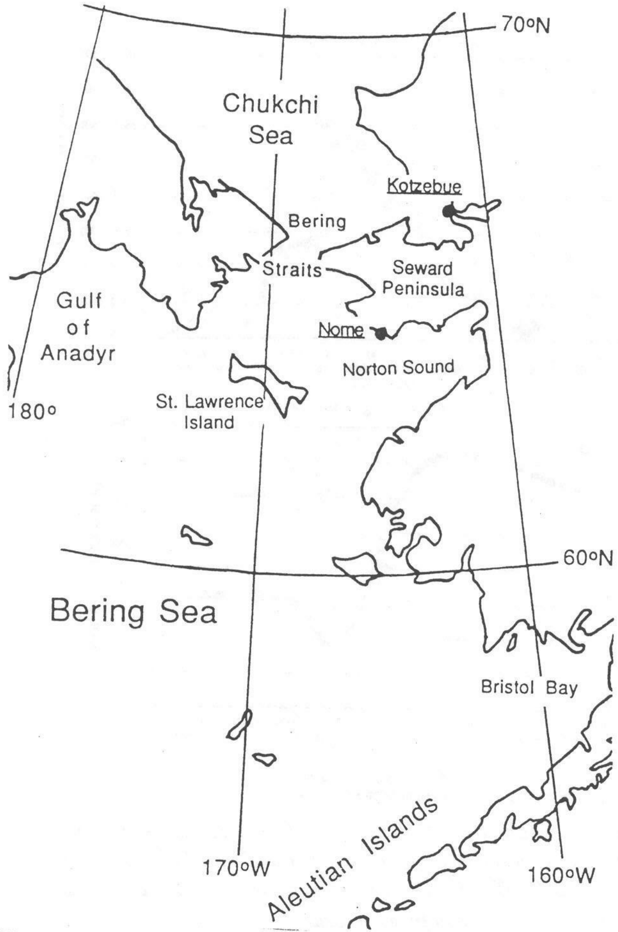

Figure 1. Map of the region of interest; key locations referred to in the text are indicated.

In order to further examine the capabilities of this surge model, two other surge events were also investigated. The first of these occurred in August 1993, and although in certain meteorological respects it at least superficially resembled the October 1992 event, the associated increases in water level were of much smaller magnitude and shorter duration. The other case occurred in September 1993. In this event the low-level winds in the vicinity of Nome were offshore rather than onshore and thus produced a reduction in water level. Such lowering of the water level can have significant adverse impacts on boats moored in harbor as well as on local fishing boats and maritime shipping traffic, especially given the shallow water depths in the coastal waters of the Bering Sea (including Norton Sound and the waters around Nome). Simulation of such a "reverse" event should also provide a useful test of the capabilities of the storm surge model.

2. THE EXTRATROPICAL STORM SURGE MODEL

The Extratropical Storm Surge (E-T Surge) model is based on the depth-integrated quasi-linear shallow water equations as in the dynamic surge forecast model developed by the National Weather Service for tropical cyclones: the Sea, Lake, and Overland Surges from

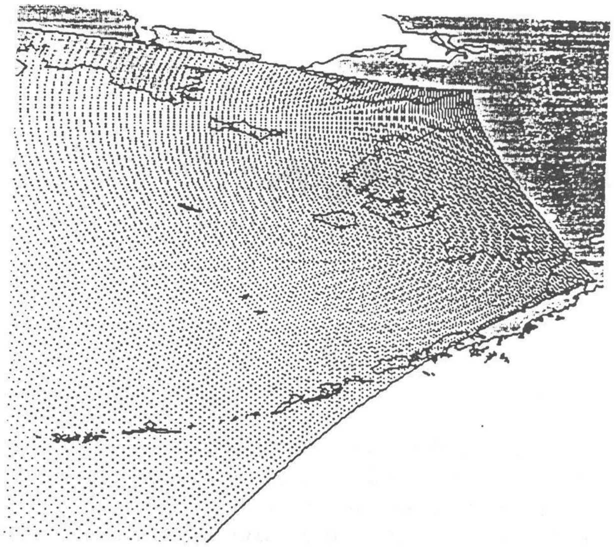

Figure 2. Domain over which surge model is implemented (grid continues to the west). Locations of grid points indicated.

Hurricanes (SLOSH) model (Jelesnianski et al. 1992). However, there are significant differences between surges associated with tropical and extratropical cyclones; thus the tropical model cannot be applied directly to the extratropical situation. In particular, extratropical storm surge models cannot rely on the sort of simple parameterized wind fields used in the tropical case. Each extratropical cyclone is associated with very different wind (and pressure) characteristics. Therefore, rather than obtaining the wind field from a simple parametric model as in the case of the hurricane, winds and pressures from one of the operational forecast models of the NWS are used to force the hydrodynamics of the surge model. An additional difference is that time and length scales characterizing extratropical cyclones are typically much larger than those associated with tropical cyclones. The attendant larger grid size and longer time of influence result in increased computational requirements.

A storm surge is primarily a barotropic response of coastal water to the atmospheric forcing, with the dynamics of the surge controlled by variations in the bathymetry of the ocean bottom and the geometry of the coastline. Successful surge forecasting will therefore be critically dependent upon the accuracy of both the bathymetry and the atmospheric forcing. Depth data were constructed from the National Oceanic and Atmospheric Administration (NOAA) ETOPOS global topographic-bathymetric data set (5-minute resolution) and interpolated onto the computational grid; the near-shore bathymetry was extracted manually from nautical charts. For the hindcasts of the three cases examined in the present study, values of atmospheric forcing (mean sea level pressure and lowest sigma-level winds) were obtained from the 12-hourly initializations of the NWS Aviation (AVN) model at a spatial resolution of 2.5° latitude x 2.5° longitude. Wind values were linearly interpolated in space and time to the model grid. Of

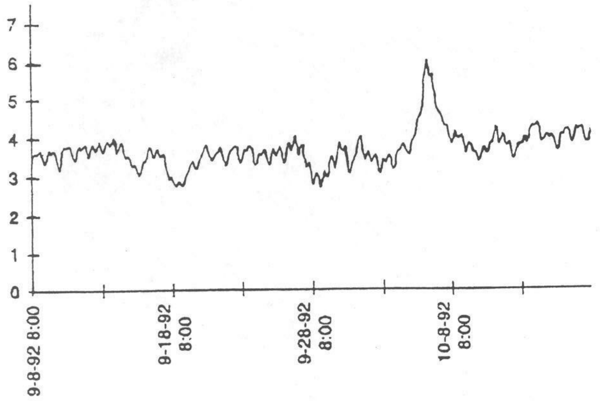

Figure 3. Trace from Nome tide gauge for the period 8 September to 18 October 1992. Water level (m) above the gauge reference is indicated along the ordinate while date and time (UTC) are indicated on the abscissa.

course, in operational application, predicted wind values from the appropriate AVN model forecast would be used after the initial time.

The domain over which the storm surge model was implemented is shown in Fig. 2. The elliptical/hyperbolic grid was generated following the grid transformation of Jelesnianski et al. (1992); high resolution spacing is maintained near the coast, while computational economy is achieved through the lower-resolution grid spacing farther offshore.

For further details on the mathematical formulation of the E-T surge model and the numerical schemes utilized, the reader is referred to Kim et al. (1996) elsewhere in this preprint volume.

3. THE OCTOBER 1992 STORM SURGE EVENT

The magnitude of the water rise produced by the October 1992 storm surge is indicated by the trace of tide gauge readings shown in Fig. 3. Immediately evident is the small range of the diurnal tidal fluctuations at Nome, with the difference in water level between low and high tide on the order of 0.5 m. This is much smaller than the approximately 2.5 m increase in water level associated with the early October storm. A magnified view of tide gauge output during the storm appears in Fig. 4. Highest water occurred just prior to 1100 UTC 6 October 1992, culminating a 30-hour period of increasing water levels. The height of the sea wall at the location of the tide gauge is 8.3 m, while that protecting the business district of the town is 7.9 m high (both values given on the scale of Fig. 4). Thus the peak water level remained 1.8 m below the top of the town sea wall. However, the tide gauge data do not include wave height. In the present case, significant flooding in Nome resulted from waves breaking over the sea wall. Superimposed on Fig. 4a are the hourly peak wind gusts from the NWS observing station in Nome. Good correlation is evident between the increase in wind speed and the rise in water level. In Fig. 4b, the sea level pressure curve is superimposed on the tide gauge trace. Lowest pressure and strongest wind gusts occurred at approximately the same time as the highest water.

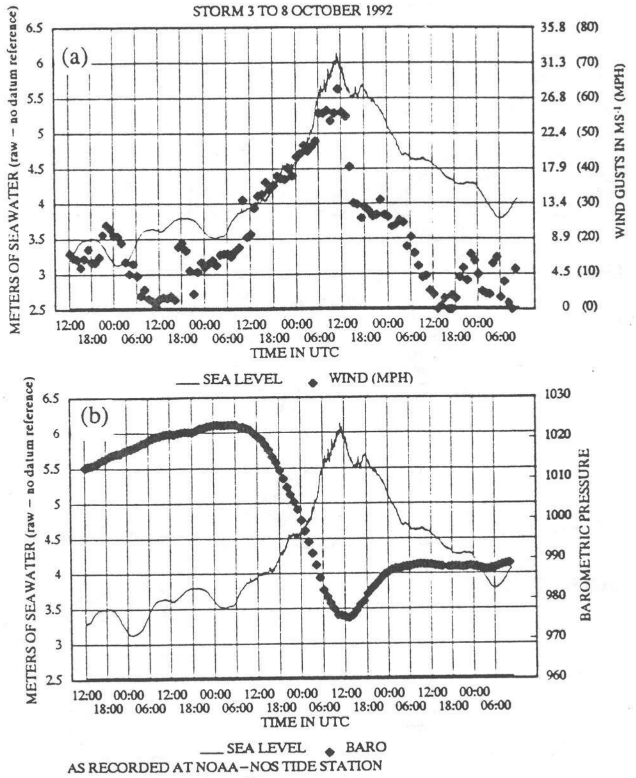

Figure 4. High-resolution Nome tide gauge data showing variation in sea level (m) for the period 0000 UTC 3 October 1992 to 1200 UTC 8 October 1992 along with (a) peak wind gust (ms^{-1}), and (b) sea level pressure (mb).

Hourly surface observations from Nome (not shown) are consistent with the wind speed and sea level pressure data shown in Fig. 4 and indicate that a frontal passage occurred at approximately 1400 UTC, or a few hours after the time of high water. Prior to this time, winds at Nome were out of the southeast and south-southeast, with winds shifting to the south-southwest behind the front. Polar orbiting (DMSP) infrared satellite imagery for 0630 UTC 6 October (Fig. 5) indicates that rear edge of the frontal band was still well to the west of Nome at that time. Similar timing of the high water with respect to the frontal passage was also seen in the November 1974 case (Fathauer 1975).

The 0000 UTC 6 October operational surface analysis from the Weather Service Forecast Office (WSFO) in Anchorage is shown in Fig. 6a. A 974 mb low center is analyzed over the eastern Gulf of Anadyr, with its associated occluded front extending to the southeast to a location just west of St. Lawrence Island, and then farther to the south. A developing surface frontal wave is depicted, with the associated low pressure center at 58°N, 175°W. A very strong west-east pressure gradient is evident over the entire portion of the Bering Sea to the east of the front, consistent with reports of strong winds from the south through southeast. Significant deepening occurred during the ensuing twelve hours; at 1200 UTC 6 October a single 962 mb low was

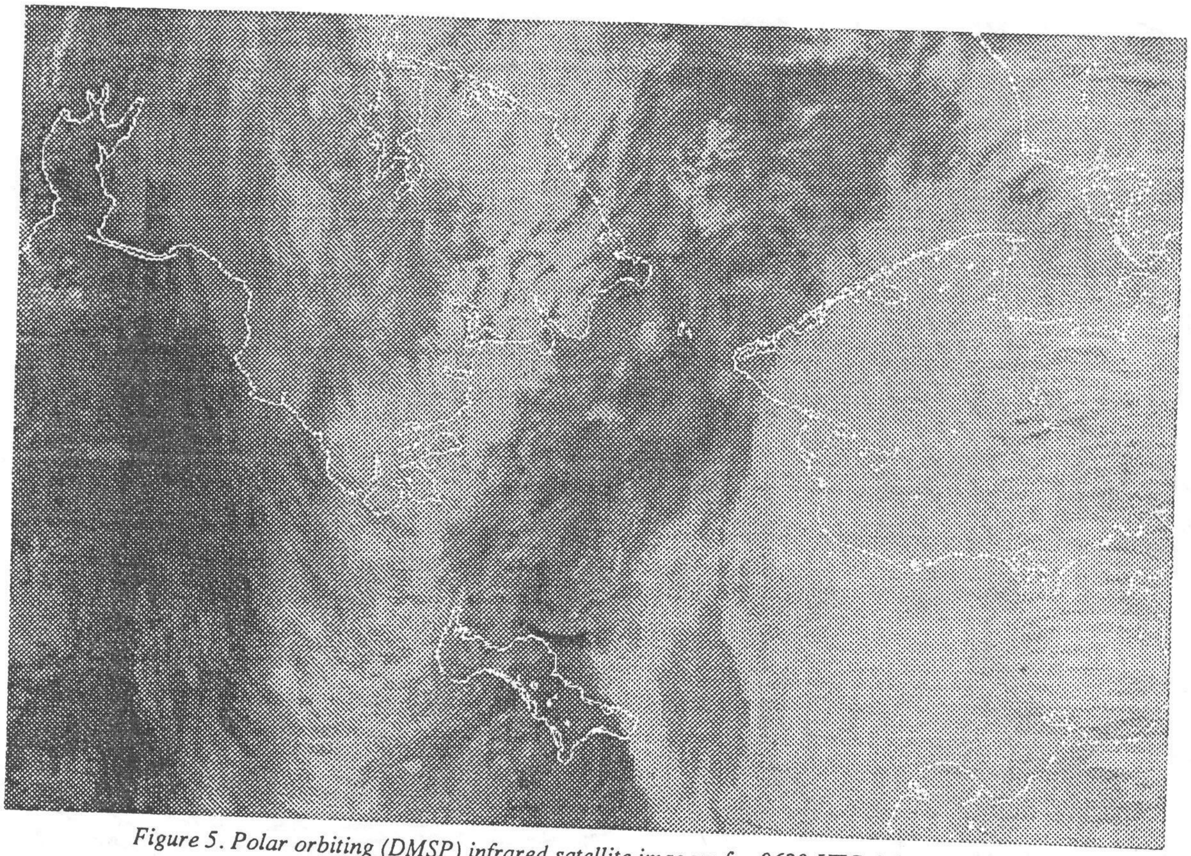

Figure 5. Polar orbiting (DMSP) infrared satellite imagery for 0630 UTC 6 October 1992.

analyzed over the far eastern tip of Russia, with the occluded front extending to the southeast from the low center and lying along the southwestern coast of the Seward Peninsula just to the west of Nome (Fig. 6b). With the further northeastward movement of the front and surface low, west-southwesterly winds now cover most of the Bering Sea, though Norton Sound (and Nome) is still experiencing the strong south-southeasterly winds ahead of the front. By 0000 UTC 7 October (not shown), the surface low has moved northward through the Chukchi Sea and begun to weaken, while west-southwest winds prevail throughout the Bering Sea and Norton Sound.

National Meteorological Center (NMC) 500 mb analyses bracketing the time of maximum water level in Nome are shown in Fig. 7. At 0000 UTC 6 October (Fig. 7a), there was strong southwesterly flow aloft into western Alaska, with the 500 mb ridge axis centered over Alaska. Similar to the November 1974 storm surge event, the 500 mb ridge initially developed over the west coast of Alaska (not shown); Fathauer (1975) notes that the presence of a strong ridge aloft in this area is a very reliable precursor of stormy weather along the western Alaska coast. An intense short-wave trough is evident to the south of the Gulf of Anadyr (Fig. 7a) and just to the west of the wave on the surface front noted in Fig. 6a. This upper-level short-wave moves rapidly to the northeast during the ensuing 24 hours, to a location just southwest of Nome and the Seward Peninsula at 1200 UTC 6 October (not shown), and then moves north of Alaska and over the Arctic Ocean as it weakens (Fig. 7c). Very strong southerly winds aloft preceded this trough as it approached the Seward Peninsula; the plotted 500 mb wind report from the 1200 UTC Kotzebue sounding (not shown) was approximately 40 ms^{-1}. By 0000 UTC 7 October, the upper-level ridge has moved eastward to the region of the Alaska-Yukon Territory border, with the flow over the northern Bering Sea now more westerly and significantly weaker.

The storm surge hindcast for this case was begun at 0000 UTC 3 October 1992 [approximately 84 hours prior to the time of high water (1100 UTC 6 October)], and run for 120 hours. Lowest sigma-level winds (representative of winds at an elevation of approximately 30 m) and sea level pressure from the 12-hour AVN model analyses from 1200 UTC 5 October through 0000 UTC 7 October are shown in Fig. 8. As the surface low center approaches from the region of the Kamchatka Peninsula (Fig. 8a), increasing south-southeasterly winds develop over the Bering Sea. By 0000 UTC 6 October (Fig. 8b), a large swath of very strong south-southeasterly winds extends from the Aleutian Islands to the Chukchi Sea north of the Bering Straits. Under the combined influence of this surface flow and the bathymetry and bottom stresses, the surge model produces significant net transport of water into Norton Sound, with highest water levels along the southwestern coast of the Seward Peninsula, downwind of the longest fetch of strong surface winds across the Sound itself (not shown). Nome tide gauge data (Fig. 3) indicate that the water level has risen significantly by this time. The highest water level

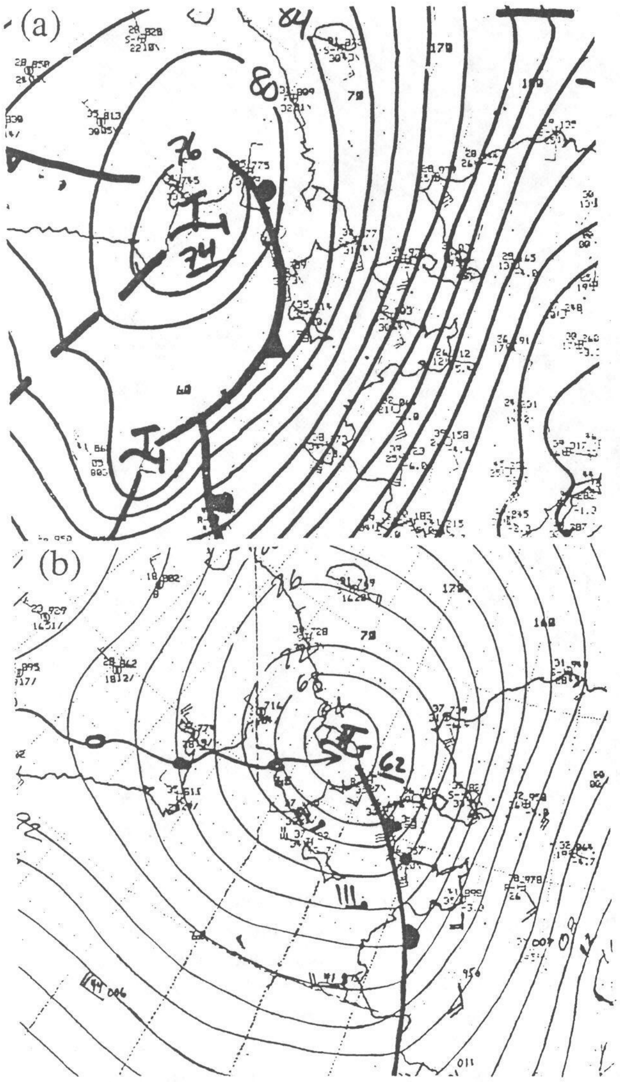

Figure 6. NWS WSFO-Anchorage operational surface analyses for (a) 0000 UTC 6 October 1992, and (b) 1200 UTC 6 October 1992. Isobaric interval is 4 mb.

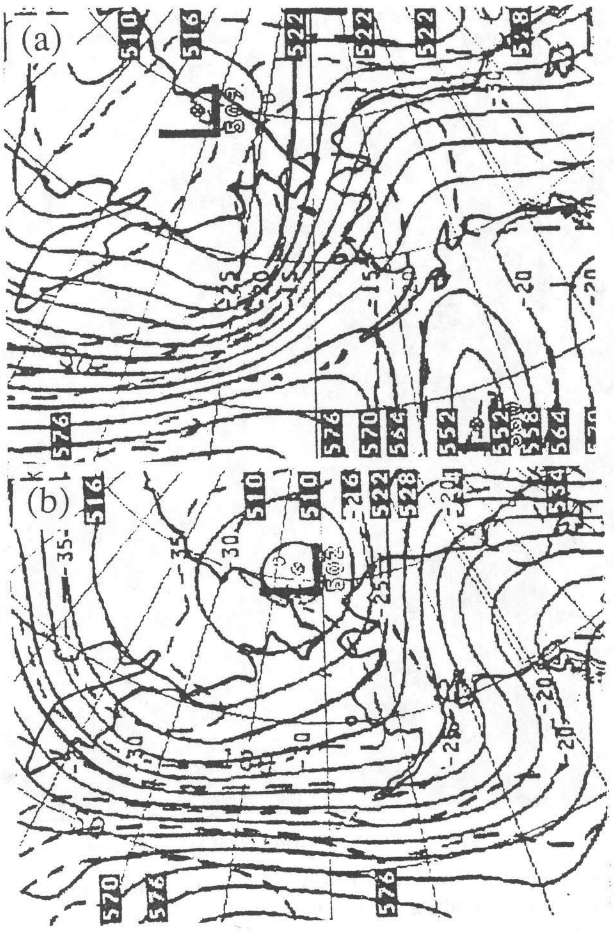

Figure 7. NMC Final 500 mb analyses for (a) 0000 UTC 6 October 1992, and (b) 0000 UTC 7 October 1992. Contour interval is 60; isothermal interval is 5°C.

observed in Nome occurred approximately one hour prior to the time of Fig. 8c (1200 UTC 6 October). At 1200 UTC 6 October, west-southwesterly surface flow covers most of the Bering Sea, as the northwest-southeast oriented surface frontal trough is situated just to the southwest of Nome. Surface winds by the entrance to Norton Sound are now out of the southwest, while southeasterly flow remains over the eastern end of the Sound. The surge model indicates a migration of maximum water levels eastward along the north shore of Norton Sound during the preceding 12 hours, with highest water levels at 1200 UTC in the vicinity of Nome (not shown). The surge model indicates a continuation of this eastward migration of maximum water levels within the Sound during the subsequent 12 hours in conjunction with the eastward propogation of the westerly surface flow. By 0000 UTC 7 October (Fig. 8d), southwesterly flow behind the front extends over the entire Sound, with the model indicating receding water levels in the vicinity of Nome as local (albeit lower) maxima in water level propagate to the far eastern part of the Sound.

The model-simulated time-evolution of water level at Nome is shown in Fig. 9, along with the same Nome tide gauge trace shown in Fig. 4. In comparing the model simulation with the tide gauge measurements, it is important to note that the surge model does not include the astronomical tide. Proper comparison of the model output with the tide gauge measurements thus requires superposition of astronomical tide levels. In Fig. 9, the corresponding adjusted model-predicted water level (i.e., with the astronomical tide also taken into account) is indicated just at 1200 UTC 6 October, the approximate time of highest water level (which happened to occur at about the time of high tide). The surge model thus does an impressive job of capturing the storm surge that occurred in Nome. The timing of the increase (and subsequent decrease) in water level is almost perfectly replicated; the model fails to capture only the last 0.8 meter of water rise at the peak of the event. This error is likely a consequence of several factors: the low spatial and temporal resolution of the wind and pressure data input from the AVN model analyses (2.5° latitude by

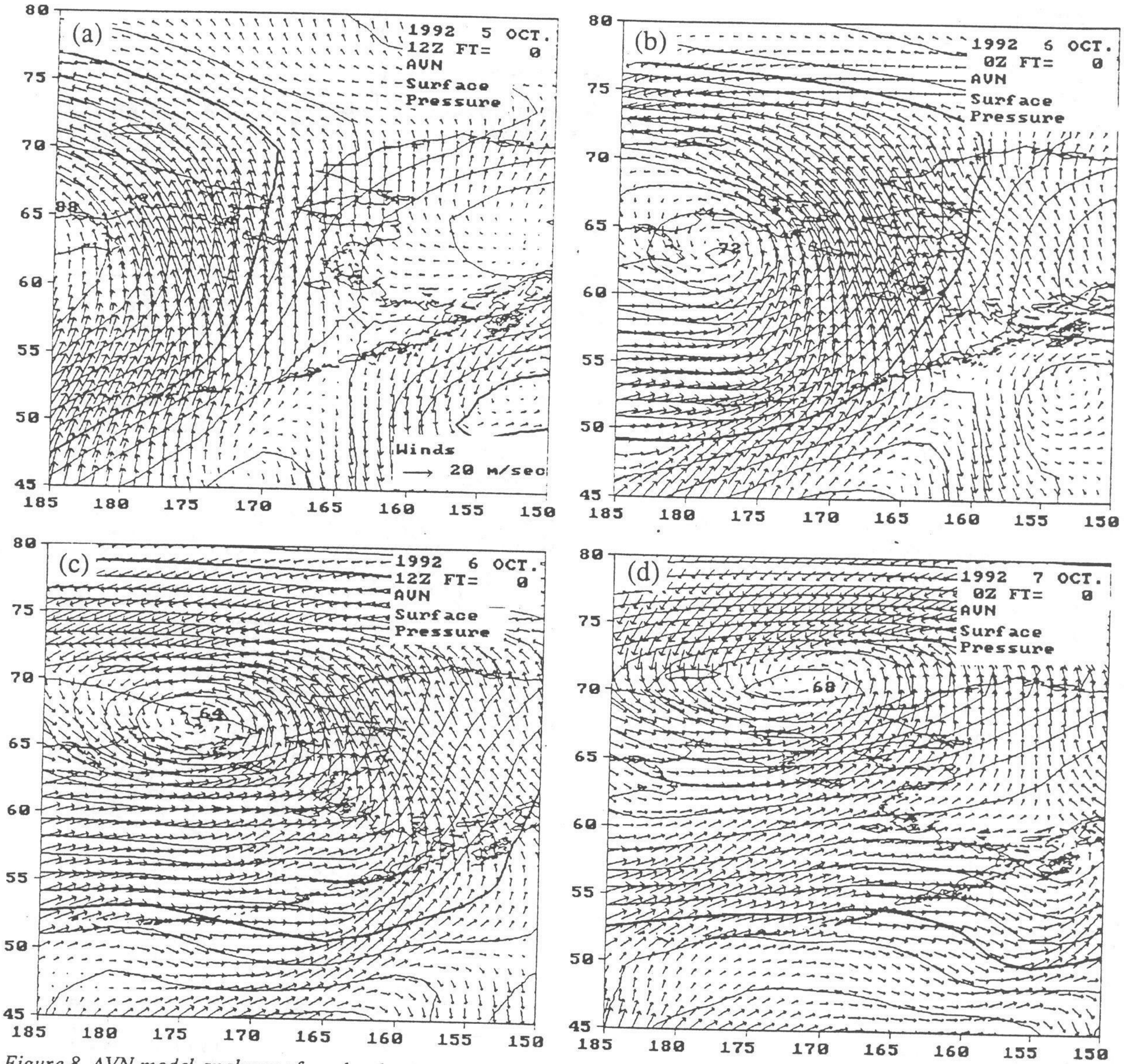

Figure 8. AVN model analyses of sea level pressure and lowest sigma level wind for (a) 1200 UTC 5 October, (b) 0000 UTC 6 October, (c) 1200 UTC 6 October, and (d) 0000 UTC 7 October 1992. Interval between isobars is 4 mb; the 1012 mb isobar is darkened. Scaling for surface wind vectors is indicated in the inset.

2.5° longitude, and 12 hours, respectively); and errors in the AVN model analyses, not at all unlikely given the data sparse nature of the region. Although the AVN sea level pressure fields in Figs. 8b and c generally compare well with the corresponding NWS WSFO-Anchorage subjectively-analyzed sea level pressure fields in Figs. 6a and b, some significant differences do appear. Most significant among these, perhaps, is the absence of any indication in the 0000 UTC 6 October AVN sea level pressure field of the frontal wave and associated low pressure center depicted on the subjective analysis for the same time. Given these limitations and sources of error, the performance of the surge model appears to be quite impressive.

4. THE AUGUST 1993 STORM SURGE EVENT

A trace of Nome tide gauge output for a three-month period beginning 1 July 1993 is shown in Fig. 10. Several significant departures from the usual diurnal tidal variation are apparent. The present discussion will focus on the elevated sea level event of 20 August 1993 while the subsequent section will consider the reduction in water level that occurred on 20-21 September 1993.

On 20 August 1993, a storm surge resulted in a brief elevation of the water level in Nome of 1.2 m (peak water level occurred at 1500 UTC 20 August). Comparison of this event with the much more significant and longer-duration storm surge of October 1992 reveals that magnitude of the surge is very dependent on the track followed by the surface cyclone. In the October 1992 case, the surface cyclone and associated front approached the Bering Straits from the west-southwest; ahead of it a wide swath of strong south-southeasterly surface flow covered the entire meridional extent of the

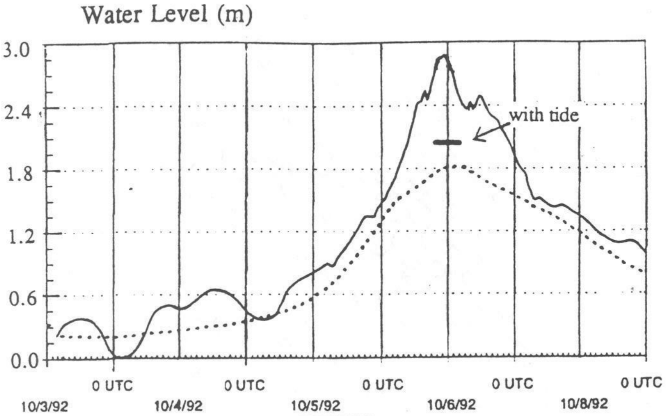

Figure 9. Hindcast surge model sea level heights and Nome tide gauge measurements (as in Fig. 3). Solid and dashed lines represent the observed and model-simulated water levels, respectively. See text for further details.

Bering Sea (Fig. 8). In the August 1993 event, however, the surface cyclone approached the Bering Straits from the south-southeast (Fig. 11). At 0000 UTC 19 August, the surface low was centered over the western portion of Bristol Bay (not shown). During the ensuing 12 hours, the low moved to the northeast, to a position approximately 200 km to the southeast of St. Lawrence Island at 1200 UTC 19 August (Fig. 11a). As Norton Sound was then in the northeast quadrant of the low, surface winds over the Sound were out of the east-southeast. Continued movement of the low to the northeast resulted in a wind flow more conducive to increased water levels in Nome (and along the north shore of Norton Sound) by 0000 UTC 20 August (Fig. 11b). This favorable wind flow was short-lived, however, as the low weakened significantly during the next 12 hours (8 mb increase in central pressure), as did the pressure gradient around it. At 1200 UTC 20 August (not shown), predominantly westerly flow covers most of the Bering Sea south of St. Lawrence Island, while winds over Norton Sound have backed to southeasterly ahead of the surface trough approaching from the south. These AVN surface analyses compare favorably with the corresponding WSFO-Anchorage subjective surface analyses.

Comparison of Fig. 11b (15 hours prior to highest water in Nome in the August 1993 event) with Fig. 9b (11 hours prior to highest water in Nome in the October 1992 event) shows not dissimilar locations and central pressures of the two surface lows. Pressures are much higher over the interior of Alaska in the October case, however, resulting in a comparatively stronger pressure gradient over a wider region to the east of the low. (That sea level pressures are significantly higher over the interior of Alaska in an October event than in an August event is unsurprising given the climatological cooling that occurs between these months.) In addition, the shape of the low and the somewhat more easterly position of its center are both more conducive to south-southeasterly flow over a much larger region of the central and eastern Bering Sea. The difference in paths,

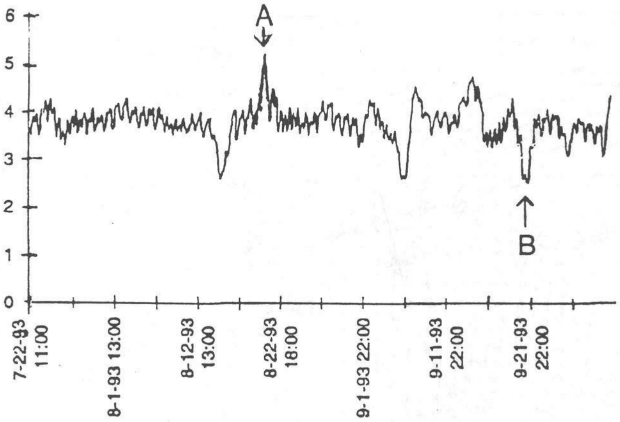

Figure 10. Trace from Nome tide gauge for the period 22 July through 1 October 1993. Arrows A and B indicate the 20 August 1993 and 20-21 September 1993 events, respectively. Other conventions as in Fig. 3.

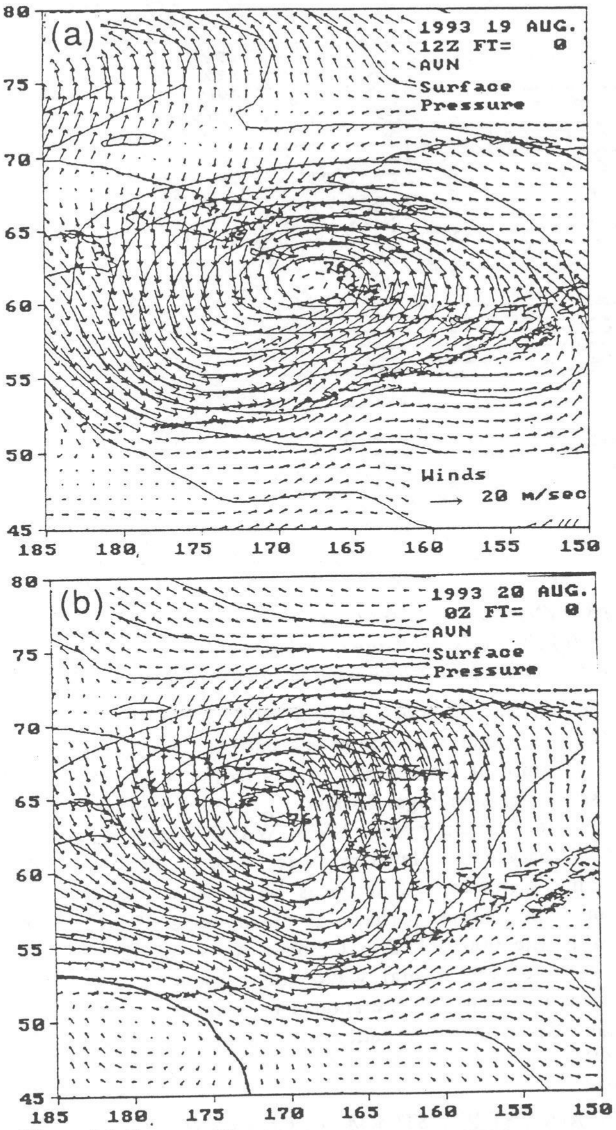

Figure 11. Same as Fig. 8 except for (a) 1200 UTC 19 August, and (b) 0000 UTC 20 August 1993.

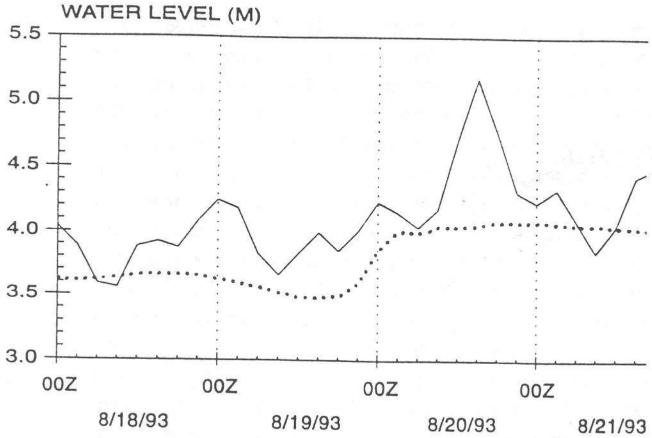

Figure 12. Hindcast surge model sea level heights and Nome tide gauge measurements. Solid and dashed lines represent the observed and model-simulated water levels, respectively.

however, appears to be the most significant influence on the difference in the magnitudes of the storm surges experienced in Nome. In the August 1993 case, favorable winds for elevated water levels in Norton Sound were comparatively short-lived and only occurred over the far eastern part of the Bering Sea. The large fetch of southerly-southeasterly flow that developed over much of the central and eastern Bering Sea in the October 1992 case never occurred in the August 1993 case. (Interestingly, the surge model did predict a much more significant rise in water level along the northeastern shore of Bristol Bay, which appeared to experience a more favorable wind flow for a longer duration of time. Unfortunately, no observational data are available to verify the surge model prediction in that area.)

The E-T surge model did not accurately simulate the 20 August 1993 surge event in Nome. Figure 12 shows a comparison of the surge model output with the tide gauge data. The relatively brief duration of the event appears to have been the most significant factor limiting the accuracy of the model output -- given the 12-hour interval between times of input of surface pressures and winds from the AVN model analyses (and thus 12-hour long periods through which these fields must be determined from linear interpolation in time). The operationally implemented version of the model will use a 3-hour interval and thus may better capture these shorter-duration, weaker events.

5. THE SEPTEMBER 1993 STORM SURGE EVENT

On 20-21 September 1993, strong north-northeasterly flow developed over the Seward Peninsula and Norton Sound. As a result, water was transported out of Norton Sound, as evidenced by the reduction in water level indicated in Fig. 10. This offshore flow developed in response to a deepening surface low that moved northeastward from latitude 175°W over the Aleutian Island chain at 1200 UTC 19 September (not shown) to just south of the eastern end of Norton Sound at 0000 UTC 21 September (Fig. 13). After this time, the low weakened as it continued to move to the northeast over the interior of Alaska.

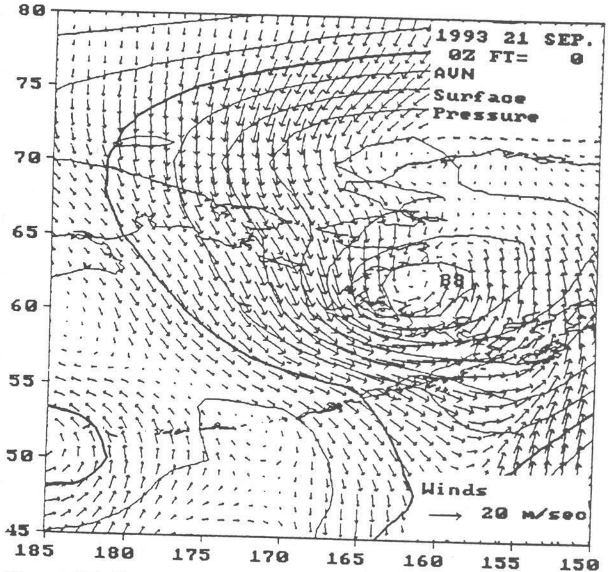

Figure 13. Same as Fig. 8 except for 0000 UTC 21 September 1993.

Throughout this event, surface winds at Nome were out of the north-northwest and thus approximately 180° out of phase with those in the October 1992 positive surge event. Also, as the time scale for this case is more comparable to the longer time scale of the October 1992 surge (Figs. 3 and 4) than the very short time scale of the August 1992 surge (Figs. 10 and 12), it should provide a good test of the robustness of the surge model, *viz.* its ability to also simulate wind-driven outflow of water from Norton Sound. In fact, the model hindcast for this event was remarkably good. Comparison of the model prediction with the tide gauge values (Fig. 14), shows excellent agreement in both phase (timing) and amplitude. As noted previously, astronomical tides are not included in the model; low tide occurred at about 0000 UTC 21 September which is approximately the time of the first of the two minima in water level that occurred during this event (the other occurred 12 hours later). The variation between this low tide and the preceding high tide, however, is less than 0.5 m.

6. SUMMARY AND CONCLUDING REMARKS

Three storm surge events in the region of Nome, Alaska, have been examined meteorologically and simulated with the E-T surge model. The October 1992 high surge event was associated with large and persistent area of strong south-southeasterly surface flow that developed to the east of a deep surface low moving northeastward over the western portion of the Bering Sea. The surface development was associated with a short-wave trough embedded in strong southwesterly flow at 500 mb ahead of an amplifying upper-level ridge. The surge model performed well at Nome, though it failed to capture the entire increase in water level. The hindcast for the September 1993 negative surge event, which occurred as a surface cyclone centered to the southeast of Nome produced strong north-northwesterly flow, was also

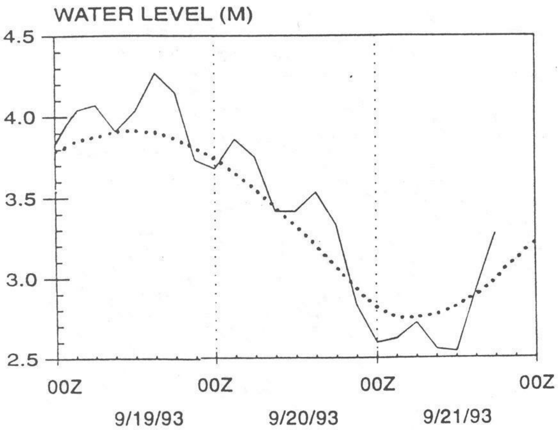

Figure 14. Hindcast surge model sea level heights and Nome tide gauge measurements. Solid and dashed lines represent the observed and model-simulated water levels, respectively.

very impressive. The significantly shorter-duration August 1993 surge event, however, was not well-simulated. The low spatial and temporal resolution of the wind data input from the AVN model likely limited the ability of the model to accurately replicate the observed brief increase in water level. Previous applications of the surge model to the U.S. East Coast indicate that use of similarly low-resolution data resulted in degraded predictions for short-duration events associated with fast-moving systems.

In this regard, the recently-implemented operational version of this surge model in Alaska utilizes 1° latitude by 1° longitude wind and sea level pressure values from the AVN model output at 3-hour intervals (rather than the 2.5° by 2.5° data output at 12-hour intervals as in the present study). It is expected that the higher resolution input from the AVN model will lead to better predictions by the surge model. One possible mitigating factor must also be considered, however. As the operational surge model generates forecasts, it will require input of forecast surface wind and pressure fields from the AVN model; for the hindcasts presented here, AVN-model analyses could be used instead -- and verified by comparison with detailed surface observations and analyses. Thus the accuracy of the operational surge model forecasts will depend on the quality of the input forecast information from the AVN model. This surge model has generally worked well on the U.S. East Coast, however, and thus we are optimistic that it will provide valuable guidance to the operational forecaster in Alaska in issuing timely and accurate storm surge warnings. In the future, input of higher-resolution and more accurate forecast surface winds and pressures from, for example, the National Center for Atmospheric Research Mesoscale Model Version 5 (MM5), may lead to further improvements in the surge model forecasts.

In addition, further consideration is needed of the potential influence of sea ice. For all of the cases considered in the present study, the Bering Sea and Norton Sound were ice-free. However, some of the most significant storm surge events have occurred with sea ice present (e.g., the storm surge events of November 1974 and November 1978). The possible consequences of the presence of sea ice are potentially significant, and complex. In the November 1978 case, for example, the shore fast ice extending several hundred meters offshore from the beach before the storm began was broken up during the event; Fischer (1978) speculates, however, that the broken ice dampened the wave action and therefore resulted in less water coming over the sea wall. In contrast, in the November 1974 storm, floating blocks of sea ice aggravated the flood damage to communities in eastern Norton Sound (Fathauer 1978). Johnson and Kowalik (1986) have investigated the influence of the inclusion of shore fast ice on storm surge modeling in Norton Sound and have found that it can produce measurable differences in the results.

Finally, improved verification of the surge model forecasts in western Alaska will necessitate the availability of tide gauge data from locations other than Nome.

7. REFERENCES

Cole, T. (ed.), 1984: Nome: City of the golden beaches. *Alaska Geographic*, **7**, 183 pp.

Fathauer, T.F., 1975: The great Bering Sea storms of 9-12 November 1974. *Weatherwise*, **28**, 76-83.

Fathauer, T.F., 1978: A forecast procedure for coastal floods in Alaska. *NOAA Tech. Mem. NWS AR-23*, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 27 pp.

Fischer, R.E., 1978: Major Bering Sea storm of November 7-10, 1978 and associated coastal flooding at Nome, Alaska. Final Report (unpublished). Available from the National Weather Service Forecast Office in Fairbanks.

Jelesnianski, C.P., J. Chen, and W.A. Shaffer, 1992: SLOSH: Sea, lake, and overland surges from hurricanes. *NOAA Tech. Rep. NWS 48*, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 71 pp.

Johnson, W.R., and Z. Kowalik, 1986: Modeling of storm surges in the Bering Sea and Norton Sound. *J. Geophys. Res.*, **91**, 5119-5128.

Kim, S.C., J. Chen, and W.A. Shaffer, 1996: An operational forecast model for extratropical storm surges along the U.S. East Coast. Preprints, Conference on Oceanic and Atmospheric Prediction, Atlanta, Georgia. American Meteorological Society, Boston, Massachusetts.

Wise, J.L., A.L. Comiskey, and D. Becker, Jr., 1981: *Storm Surge Climatology and Forecasting*. Arctic Environmental Information and Data Center, University of Alaska, Anchorage, 32 pp.

Acknowledgements. This research was supported in part by COMET grant UCAR S9357 and NOAA's Coastal Oceans Program. Many individuals contributed to the success of this project; we gratefully acknowledge assistance provided by Fabrice Cuq, James Murakami, and John Oleska at UCLA, Brian Bezenek, Dennis Dickson, Jerry Steiger, John Stepentin, and Robert Tschantz at the NWS WSO in Nome; Ted Fathauer and Kraig Gilkey at the NWS WSFO in Fairbanks; Ray Moore and Per Pedersen with PRC Corporation in Anchorage; and Nancy McGuire, publisher of the *Nome Nugget*.