

Report of Investigations 2012-2  
Version 1.1

**COASTAL HAZARD FIELD INVESTIGATIONS  
IN RESPONSE TO THE NOVEMBER 2011  
BERING SEA STORM, NORTON SOUND, ALASKA**

by  
Nicole E.M. Kinsman and Meagan R. DeRaps



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## COASTAL HAZARD FIELD INVESTIGATIONS IN RESPONSE TO THE NOVEMBER 2011 BERING SEA STORM, NORTON SOUND, ALASKA

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N.E.M. Kinsman and M.R. DeRaps

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**COVER PHOTO:** *DGGS geologist Meagan DeRaps measures the crest elevation of a minor blowout in a rock revetment along the Nome–Council Road. The blowout occurred during the November 2011 Bering Sea Storm.*

This DGGS Report of Investigations is a final report of scientific research. It has received technical review and may be cited as an agency publication.



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## ABBREVIATIONS

AHAP	Alaska High-Altitude Photography
AKST	Alaska Standard Time (Coordinated Universal Time –9:00)
CERC	Coastal Engineering Research Center (United States Army Corps of Engineers [USACE])
CIAP	Coastal Impact Assistance Program (Bureau of Ocean Energy Management [BOEM])
CORS	Continuously Operating Reference Station
DCCED	Department of Commerce, Community & Economic Development (State of Alaska)
DEM	Digital Elevation Model
DGGS	Division of Geological & Geophysical Surveys (State of Alaska, Department of Natural Resources)
DOT&PF	Department of Transportation & Public Facilities (State of Alaska)
FAA	Federal Aviation Administration (United States Department of Transportation)
FEMA	Federal Emergency Management Agency (United States Department of Homeland Security)
GFS	Global Forecast System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
MLLW	local Mean Lower Low Water level
MODIS	Moderate Resolution Imaging Spectroradiometer
MSL	Mean Sea Level (local unless otherwise noted)
NASA	National Aeronautics and Space Administration
NGS	National Geodetic Survey (United States Department of Commerce, National Oceanic and Atmospheric Administration)
NOAA	National Oceanic and Atmospheric Administration (United States Department of Commerce)
NRCS	Natural Resources Conservation Service (United States Department of Agriculture)
NWS	National Weather Service (United States Department of Commerce, National Oceanic and Atmospheric Administration)
OPUS	Online Positioning User Service (United States Department of Commerce, National Oceanic and Atmospheric Administration; <a href="http://www.ngs.noaa.gov/OPUS/">http://www.ngs.noaa.gov/OPUS/</a> )
PPK	Post-processed kinematic
RTK	Real-time kinematic
TWL	Total Water Level (storm surge + astronomical tide + wave setup)
USACE	United States Army Corps of Engineers
USGAO	United States Government Accountability Office
USGS	United States Geological Survey (Department of the Interior)

## CONVERSION FACTORS & GEOGRAPHIC REFERENCE FRAMES

	<b>Multiply</b>	<b>by</b>	<b>To obtain</b>
<i>Length</i>	centimeter (cm)	0.3937	inch (in.)
	meter (m)	3.281	foot (ft)
	kilometer (km)	0.6214	mile (mi)
<i>Volume</i>	cubic meter (m <sup>3</sup> )	35.31	cubic foot (ft <sup>3</sup> )
<i>Rates</i>	knots	1.1508	miles per hour (mph)
	meters/second (m/s)	2.237	miles per hour (mph)

*Please note: All historic water level observations reported in feet in the original source material are presented in both feet and meters. All DGGs water level measurements were collected using metric units but some values are presented in both m/cm and feet at the request of Norton Sound community residents.*

### Datums

Horizontal coordinate information is referenced to the North American Datum of 1983, NAD\_83(2011)(EPOCH:2010).

Vertical coordinate information was converted from ellipsoid to orthometric heights, referenced to the North American Vertical Datum of 1988 (NAVD88), using GEOID09. Due to errors in the NGS GEOID09 for parts of Alaska, orthometric heights obtained using GEOID09 as opposed to local geodetic leveling may differ from true NAVD88 elevations.

The local transformations between geodetic and tidal datums used in this report are presented below. These values have been derived using 2010–2011 published orthometric heights of primary tidal benchmarks and local tidal station datum elevations from the 1983–2001 National Tidal Datum Epoch (NOAA, 2012).

### Tidal stations and benchmarks used to generate datum conversion values

Location	Tide Station	Tidal datum analysis period	Benchmark used for vertical control		NAVD88 orthometric height source
			Stamping	NGS Position ID (PID)	
Unalakleet	9468333	07/01/2011 – 08/31/2011	8333 H 2011	BBCK34	Published OPUS solution from July 2011
Shaktoolik	9468691	07/15/2010 – 08/23/2010	8691 A 2010	BBBZ37	Published OPUS solution from July 2010
Nome	9468756	09/01/2008 – 08/31/2010	8756 K 1992	DF3653	Published OPUS solution from July 2011

These conversions are presented as a convenience; they are subject to change and may vary in subsequent tidal epochs.

Subtract	from	To obtain
1.465 m	NAVD88(GEOID09)	Elevation above local MSL in Unalakleet
1.307 m	NAVD88(GEOID09)	Elevation above local MSL in Shaktoolik
1.101 m	NAVD88(GEOID09)	Elevation above local MSL in Nome
0.923 m	NAVD88(GEOID09)	Elevation above MLLW in Unalakleet
0.798 m	NAVD88(GEOID09)	Elevation above MLLW in Shaktoolik
0.851 m	NAVD88(GEOID09)	Elevation above MLLW in Nome

# COASTAL HAZARD FIELD INVESTIGATIONS IN RESPONSE TO THE NOVEMBER 2011 BERING SEA STORM, NORTON SOUND, ALASKA

by  
N.E.M. Kinsman<sup>1</sup> and M.R. DeRaps<sup>2</sup>

## Abstract

On November 8, 2011, an extra-tropical cyclone with a low pressure of 945 millibars developed over the Bering Sea and moved northeast across the western coast of Alaska. This large storm brought high winds (gusts of up to 85 mph) to the entire region and a storm surge of approximately 3 meters to parts of Norton Sound. In the week following the storm, a team of two DGGs scientists visited four communities in the Norton Sound region to document peak water levels, runup elevations, and inundation extents associated with the storm, and to revisit coastal profiles that were established in July 2011. This report is a summary of the reconnaissance fieldwork that was conducted in Unalakleet, Shaktoolik, Nome, and Golovin November 10–15, 2011.

## INTRODUCTION

Flooding is Alaska's most common natural disaster and accounts for the majority of average annual monetary damages in the state (Alaska Department of Military and Veterans Affairs [DMVA], 2010). Flooding and erosion affect 184 out of 213, or 86 percent, of Alaska Native villages, many of which are located along the coast (U.S. Government Accountability Office [USGAO], 2003). Coastal storm surge is a leading cause of both flooding and erosion in the Norton Sound region of Alaska (USGAO, 2009), and the potential negative consequences of storms may be increasing with changing climatic trends, including the timing and extent of arctic sea ice cover (Douglas, 2010). Improved documentation of event-specific changes can significantly enhance mitigation or adaptation efforts to minimize loss of life and property associated with future storm events.

Storm surges are elevated ocean levels that arise from a combination of onshore-directed wind stresses that generate both wind and wave setup, and reduced atmospheric pressure. These temporary and rapid rises in sea level can lead to extensive coastal flooding and erosion, especially when they occur in unison with peak astronomical tides and large wind waves. In western Alaska, recurrent extreme storm surge events with heights greater than 3 m have been documented in records dating back to 1898 (Wise and others, 1981) and by oral histories that extend further (Glenn Gray & Associates and others, 2012).

Norton Sound, on the west coast of Alaska, is particularly prone to severe storm surge for two primary reasons. First, the approximately 135 km mouth of this Sound is open to the west, exposing it to a long fetch across the Bering Sea. This orientation also makes the Sound positioned to 'trap' water along the path of extra-tropical cyclones that form in the mid-latitude Pacific Ocean and migrate northeast. Second, Norton Sound's shallow depths averaging 20 m (Johnson and Kowalik, 1986; Blier and others, 1997) allow for significant storm surge amplification across the gently sloping, semi-enclosed embayment. As a result of these conditions, many low-lying

coastal communities along the south- and west-facing coasts of Norton Sound have experienced periodic episodes of significant coastal flooding and erosion associated with the passage of large storms. Record storm surges in this part of Alaska have occurred primarily in the fall, from September through November. On average, three low-pressure systems with winds >15 meters/second move through the Norton Sound region each year (Johnson and Kowalik, 1986). Two of the most notable of the documented storm surges in Norton Sound occurred November 10–12, 1974 (4.1–6.4 m MSL in Nome; Wise and others, 1981; Fathauer, 1975), and October 2–4, 1960 (3.6 m MSL modeled in Shaktoolik; U.S. Army Corps of Engineers [USACE], 2011a). More recent storms with smaller resultant storm surge (3 m MSL in Nome) occurred in October 2004 (Hufford and Partain, 2004) and September 2005 (USACE, 2011b).

Throughout the arctic, sea-ice freeze-up is occurring later in the year; since the 1970s, the Chukchi Sea just north of Norton Sound has experienced a trend of 6.9 days/decade delay in freeze-up (Perovich and Richter-Menge, 2009). Over this same period, total sea-ice cover in the Bering Sea has declined 26 percent per decade (Perovich and Richter-Menge, 2009). Reductions in sea-ice coverage and duration have the potential to increase the frequency and amplitude of storm surge because less sea ice translates to larger open-ocean fetch for the development of waves, and delayed shore-fast ice formation removes the ability of ice to act as a protective buffer against ocean energy during the peak storm season (Forbes, 2011). The role that delayed sea-ice formation plays in intensifying the effects of coastal storm surge has been anecdotally reported in many Norton Sound communities (for example, Native Village and City of Shaktoolik and others, 2009; City of Unalakleet and others, 2008).

Documentation of coastal hazards is notoriously sparse in the Norton Sound region; the fragmented record that exists is largely composed of scattered damage reports with a very limited number of often conflicting measurements.

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Where efforts have been made to precisely document marine flooding, they have not always been sustained. For example, a flood-level marker on a utility pole in Golovin in the 1990s was not preserved when the utility system was relocated (USACE, 2011b). Baseline data are limited as well; the first permanent tidal gauge in Nome was not installed until 1992 (Blier and others, 1997) and it remains the only fixed water-level sensor in the region. Documentation of flood-water depths and aerial extents of inundation that have been historically absent from the records are crucial to efforts to improve storm forecast results (Wise and others, 1981). Numerous studies have also called for improved oceanic and atmospheric data collection in the region (for example, Johnson and Kowalik, 1986; Hufford and Partain, 2004). Quantification of event-specific erosion events is also necessary to improve estimates of long-term coastal retreat in the region (Sallenger and Dingler, 1978).

### **NOVEMBER 2011 BERING SEA STORM**

The National Weather Service (NWS) issued an initial public information statement at 7:15 am AKST on November 7, 2011, that warned of a developing Bering Sea storm that

would be similar to the Great Bering Sea Storm of 1974 (NWS, 2011). The NWS forecasted a peak storm surge of 10 ft (approximately 3 m) in parts of Norton Sound for the evening of November 8 to the morning of November 9, 2011. This statement cautioned that even though the peak surge was expected to be less than that of the 1974 storm (13.2 ft or 4.0 m at Nome), the protective ice cover that was along the northwest Alaska coastline in 1974 was absent, and that the 2011 storm would have “the potential to cause widespread damage.” Additional NWS Public Information and Special Weather Statements were regularly issued over the following days containing updated storm surge and peak wind forecasts as well as predictions of areas expected to receive “widespread major coastal flooding and severe beach erosion.”

The November 2011 storm, shown in the figure 1 satellite image, was typical of the large low-pressure storm systems that have generated significant surges in Norton Sound in the past. Winds associated with the storm system varied in direction and strength along the Norton Sound coastline. Nome experienced sustained onshore winds of nearly 40 knots and gusting winds in excess of 50 knots (figs. 2 and 3). Peak winds in Unalakleet and Shaktoolik were of a similar magnitude

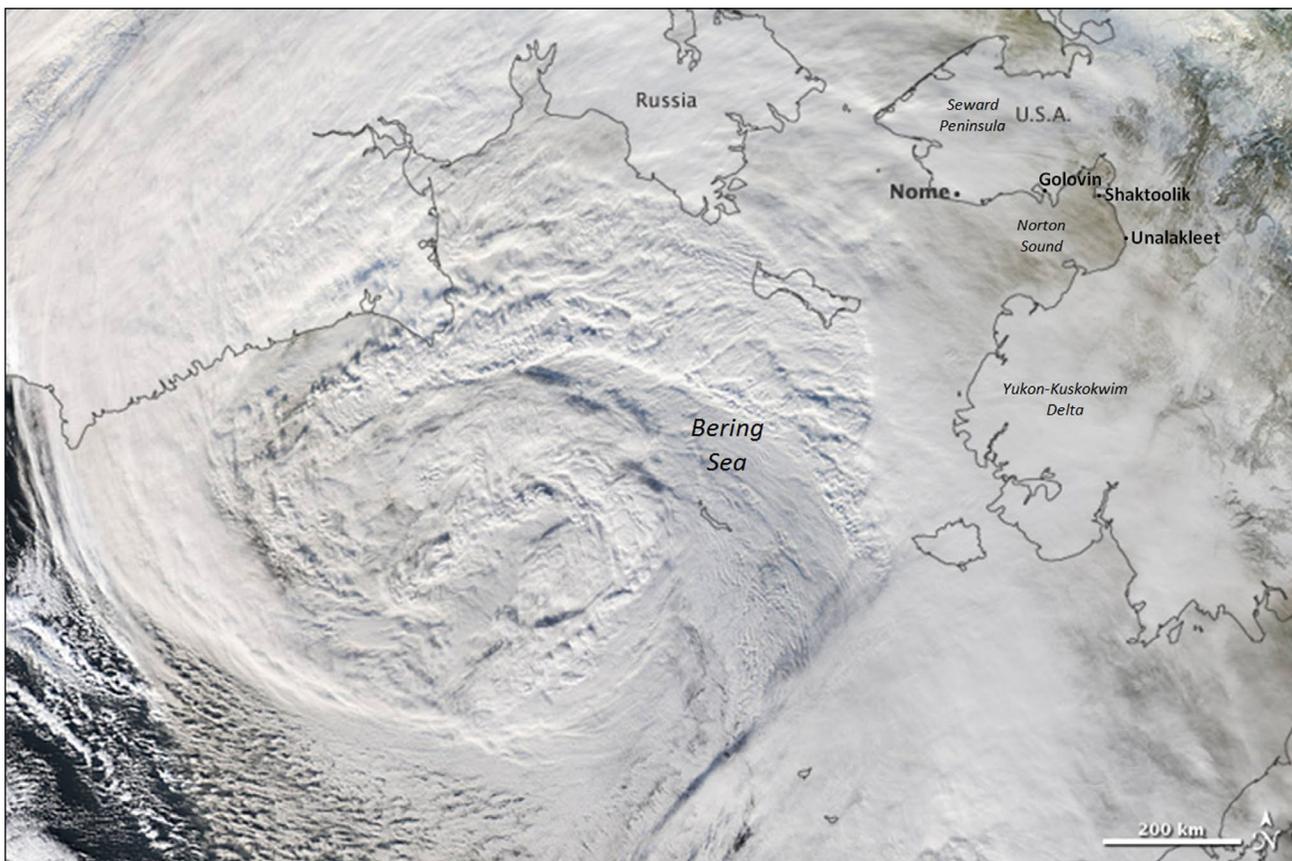


Figure 1. Satellite image (taken November 8, 2011, 2:45 pm AKST) of the extra-tropical cyclone described in this report as it tracks northeast across the Bering Sea. The locations of the four communities described in detail are shown in bold. (Modified from image by Jesse Allen; data obtained from NASA’s Land Atmosphere Near-real-time Capability for EOS, NASA Earth Observatory, Online.)

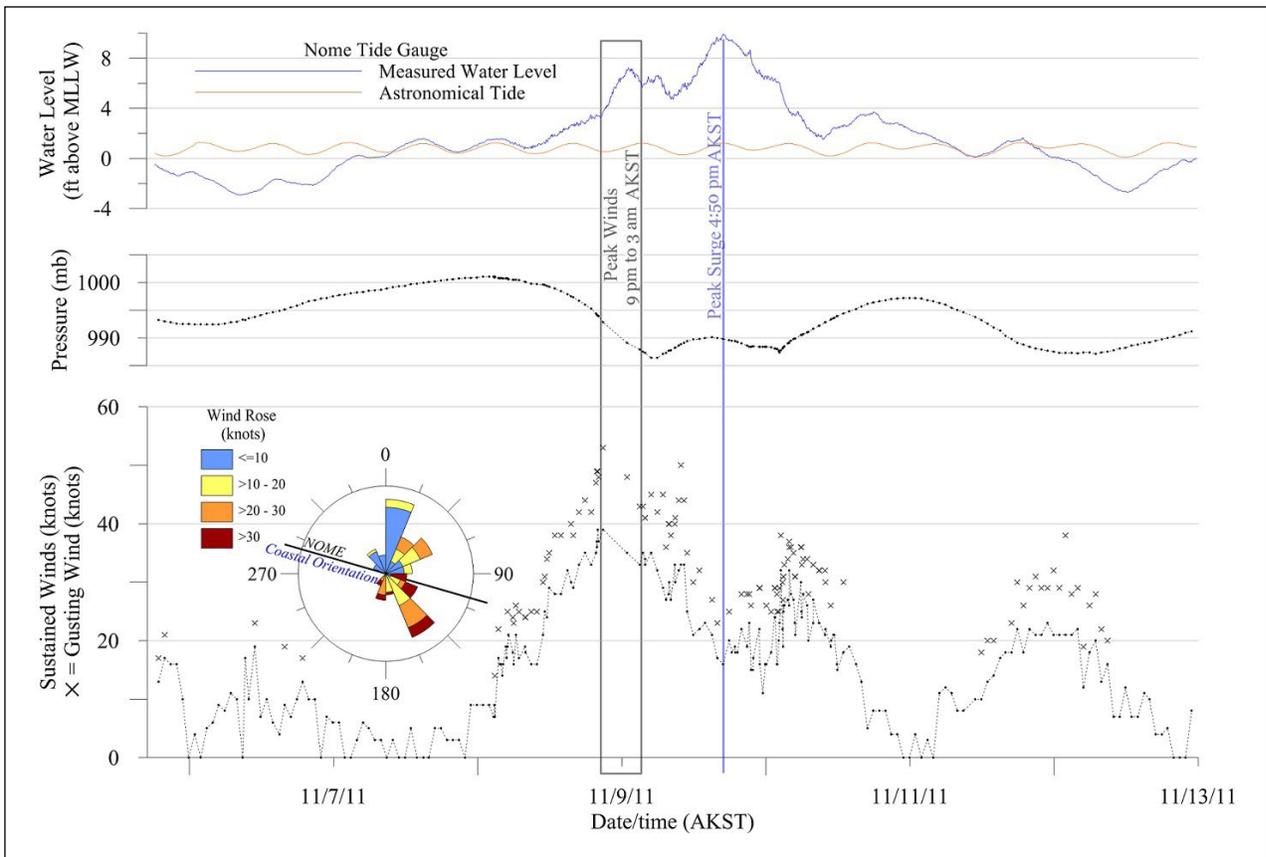


Figure 2. Summary of the atmospheric pressure, water level, and surface winds in Nome for the duration of the November 2011 Bering Sea storm. The wind rose diagram depicts the percentage of time between 11/6/11 and 11/13/11 that the winds were blowing from a particular direction. Plots were generated with data from the automated weather station at the Nome airport and the NOAA tide gauge at the mouth of the Snake River.

but in an offshore direction during the storm. Peak winds in Norton Sound arrived between midnight and 3 am AKST on November 9, 2011, and strong winds occurred again on November 10 and 12, associated with smaller storm systems (see Appendix A for additional information regarding atmospheric conditions in Unalakleet and Golovin).

The peak storm surge arrived between the hours of 3 and 5 pm AKST on November 9, 2011, at most locations in Norton Sound. With an approximately 12-hour lag between the peak winds and crest of the storm surge, the majority of severe flooding fell within a low wind 'window' throughout the region. Measurements of maximum water level during this storm were made by the tidal gauge in Nome, operated by NOAA (fig. 2; raw data available online at <http://tidesandcurrents.noaa.gov/geo.shtml?location=9468756>). The peak surge in Nome coincided with the astronomical high tide of 0.12 m MSL, increasing the overall water level. Notably, coastal flooding occurred during daylight hours during this event and water levels in the Norton Sound region crested just prior to local sunset.

On December 5, 2011, Alaska Governor Sean Parnell declared a State Disaster Emergency for the series of sea storms that struck the West Coast of Alaska from November 7, 2011,

through November 13, 2011 (Parnell, 2011). At the time of the declaration, damages in 37 cities and villages had been estimated at \$29.9 million. The majority of damages were caused by high winds and coastal flooding. Governor Parnell's action was followed by a Federal Alaska Disaster Declaration that was signed by President Barack Obama on December 22, 2011.

## DGGS FIELD RESPONSE

In 2009, the Alaska Division of Geological & Geophysical Surveys (DGGS) received federal funding from the U.S. Minerals Management Service (now Bureau of Ocean Energy Management) through the Coastal Impact Assistance Program (CIAP) to establish a new coastal community geohazards evaluation and geologic mapping program in support of local and regional planning. In summer 2011, field efforts were focused on the eastern Norton Sound coastline in the communities of Unalakleet and Shaktoolik. These activities consisted of collecting extensive baseline data pertaining to local geology, coastal and oceanic processes, and historic natural hazard events in and around the communities. Part of this work included the establishment of baseline profile measurements or 'elevation snapshots' of the coast.

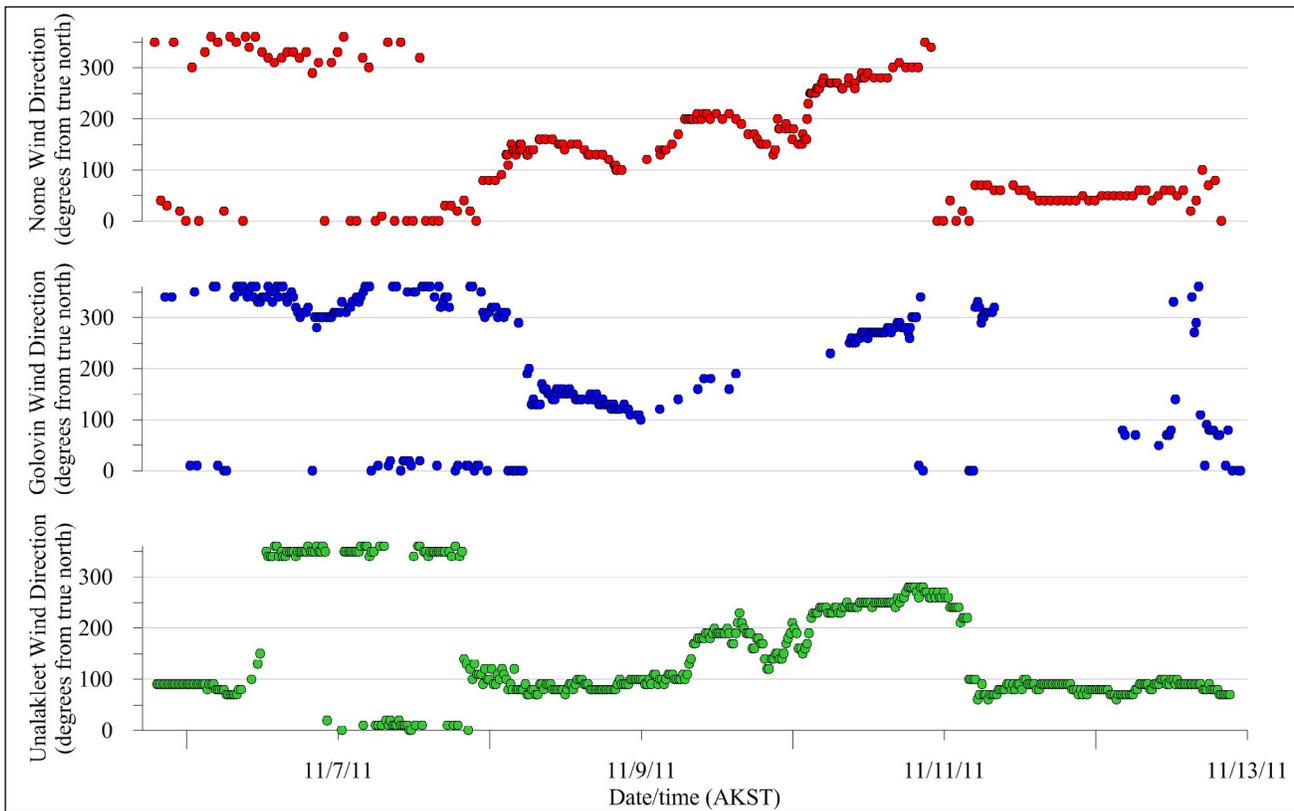


Figure 3. Summary of the direction of surface winds from 11/6/11 to 11/13/11 in Nome, Golovin, and Unalakleet. Wind directions are in degrees from true north so the minimum y-axis value of 0 is equivalent to the maximum value of 360. Plots were generated with data from the automated weather stations at the respective airports.

Immediately after the initial NWS public information statement that predicted landfall of a very large Bering Sea storm, a team of two DGGs coastal geologists began preparations for travel to Norton Sound in the wake of the storm to revisit areas mapped during the previous summer and to document the effects of the storm in these and other communities. By maintaining communications with observers on the ground in Unalakleet and Shaktoolik and at the Incident Command Center in Anchorage, the team conducted a safe, one-week series of community visits to four affected areas (fig. 4). The primary objectives of this trip were to:

1. Formally document the extent of coastal flooding (including local peak water level elevations)
2. Remeasure coastal profiles to quantify event-specific rates of erosion and profile modification
3. Collect photographs, video, and direct observations from residents

Several types of water levels are described in this report; these are summarized visually in figure 5. The storm tide level is the height of the storm surge superimposed upon the height of the astronomical tide (storm tide = storm surge + astronomical tide). Wave setup (or setdown if negative) is an additional factor that affects water levels in the nearshore

and is caused by a transfer of momentum in the surf zone. Total Water Level (TWL) is used to describe the storm tide level in combination with wave setup (TWL = storm surge + astronomical tide + nearshore wave setup). In sheltered areas where wave setup is negligible, the TWL is equal to the storm tide level. Additionally, wave runup is used to refer to the maximum height to which breaking waves can reach on a shoreface. Measurements of these individual or combined factors are required to calibrate improved storm surge models and to create inundation maps.

For the documentation of coastal flooding and water level elevations, a wide range of field methods were adopted by the DGGs team based on flood indicators and the available resources in each community. These included the measurement of debris lines, water and slush limits in the snow, and elevations of visibly overtopped or inundated areas. The team also employed methods that involved the use of the FAA Aviation Camera program network and photographs provided by residents to reconstruct inundation extents. Each measured flood indicator was assigned a qualitative confidence level to reflect the validity of inferring marine flood levels from the measurement. High confidence was applied to locations where evidence of a discrete water level was readily observed in the field (slush lines, for example). Medium confidence was applied to points that were measured at the

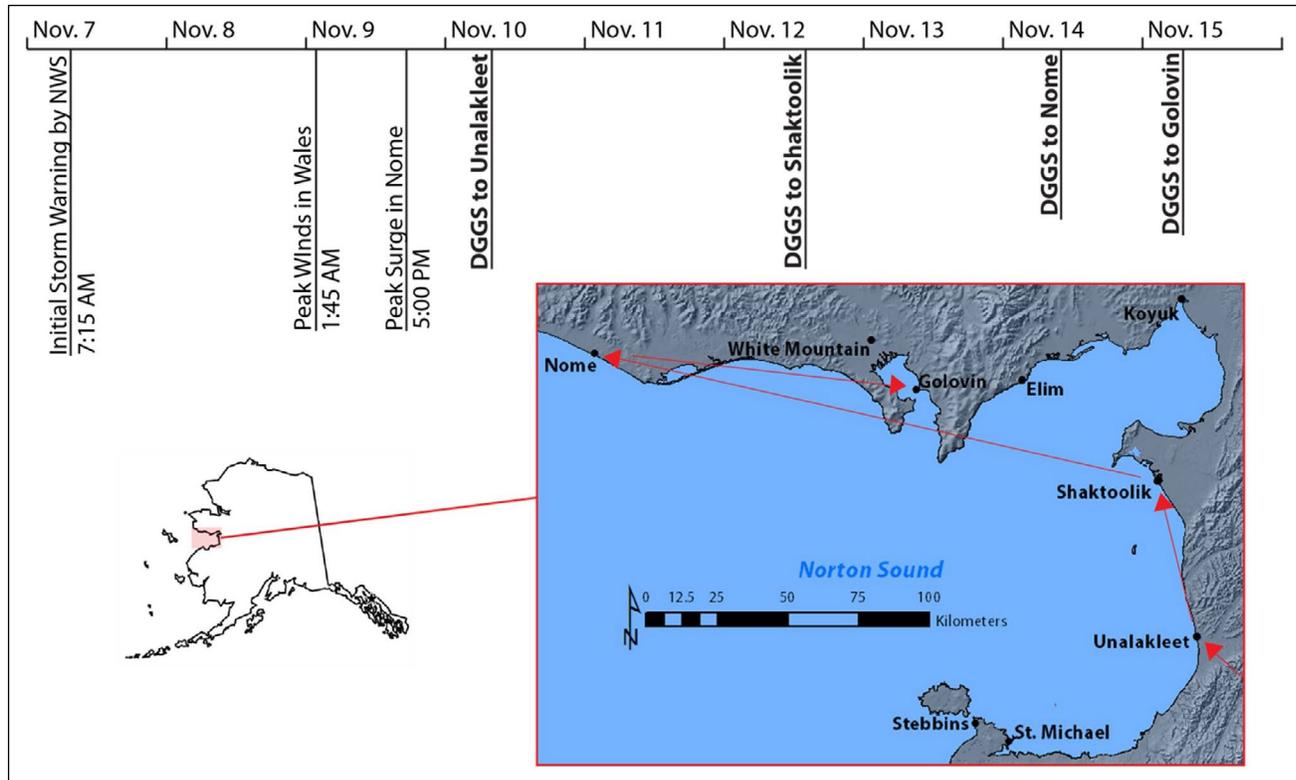


Figure 4. Timeline and map of DGGs rapid field response to the Norton Sound region following the November 9, 2011, Bering Sea storm. The DGGs team was on the ground within 24 hours of the peak storm surge in Unalakleet.

best approximation of the water position based on partially obscured or indiscrete evidence (tension cracks in snow or many of the photo-identified points, for example). Lowest confidence was applied to points where the role of floodwater in the creation of a flood indicator was ambiguous, where locations were identified solely from the memories of residents, or where clean-up activities had modified the site enough to conceal the exact location of the flood extent. These assigned confidence levels were used to weight vertical measurements in the determination of average inferred water level elevations for each community. We used the measurements of sheltered inundation limits/water levels to approximate the storm tide levels (surge + tide); inundation limits/standing water levels on exposed coasts were used to approximate TWL (surge + tide + nearshore wave setup), and water-limit measurements collected directly above the surf zone were used to infer the maximum elevation of wave runup (fig. 5).

The importance of a rapid response to document coastal storm damage has been widely recognized (for example, Doran and others, 2009) because of the swift nature with which coastal areas undergo modification and the prevalence of rapid clean-up efforts that remove useful flood indicators shortly after an event. This is especially true in rural Alaska, where high winds and snow can quickly obscure evidence of flooding. Because of these rapidly changing conditions, our team would not have been able to collect many of the measurements included in this report beyond the one-week

time span immediately following the storm. Additionally, we used the residents' photos from during the storm to reoccupy positions of inundation limits using 'landmarks' unlikely to remain in position through the spring, such as dry-docked boats and damaged fish drying racks.

For both the flood indicators and coastal profiles, precise horizontal and vertical measurements were collected with a survey-grade GPS system consisting of two dual frequency Topcon HiPer II GNSS receivers and a Topcon FC-250 field controller running TopSURV software. Due to varying time constraints in the field and limited benchmark access in some communities, we employed one of three different methods to obtain coordinates for each measured location: (1) In Unalakleet, we used RTK and PPK with local NGS-published geodetic control, (2) in Shaktoolik, we used PPK by establishing a local geodetic control, and (3) in Nome and Golovin, we used PPK without local geodetic control. These methods, and their associated error magnitudes, are summarized in table 1. Method 1 involved setting up the base receiver over a local benchmark (NGS PID DM4448, data-sheet last updated in 2010) with published coordinates. The team was able to use this method (preferred for high accuracy) in Unalakleet because we had adequate time in the field and had transportation to and from the benchmark location. When available, RTK allowed us to get real-time position corrections in the field, aiding in the reoccupation of the coastal profiles. In areas with no RTK signal, PPK locations were

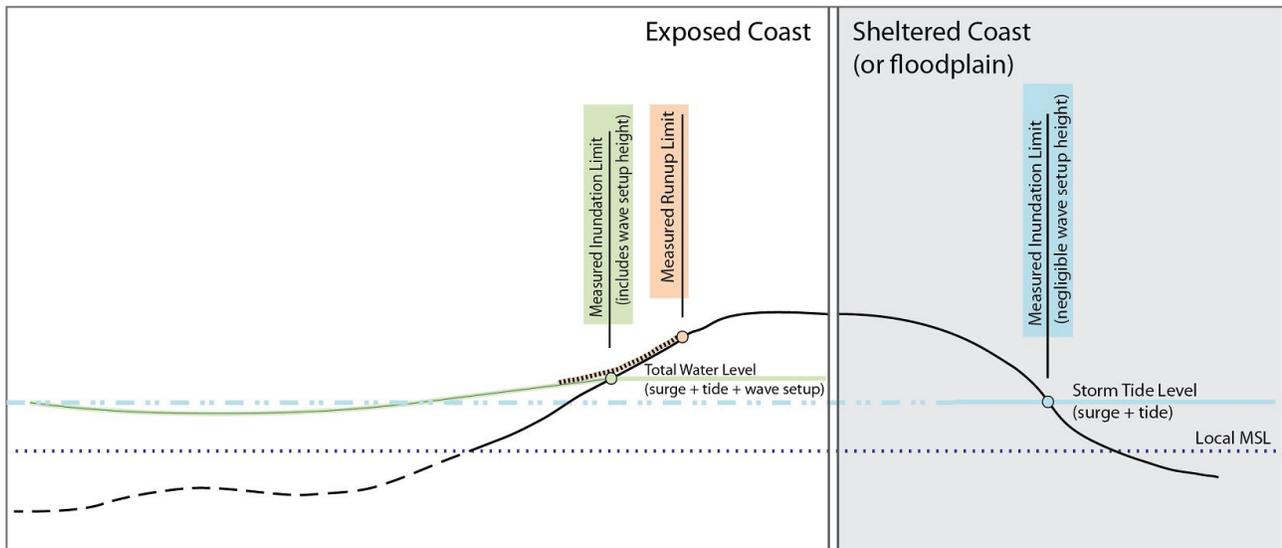


Figure 5. Definition drawing of the primary types of water levels referenced in this report: storm tide level (surge + tide; blue) measured along wave-sheltered coastlines, TWL (surge + tide + wave setup; green) measured along the open coast, and wave runup (orange if maximum observed in inhabited community and red if maximum observed in the broader community area).

later post-processed from the base receiver data. Method 2 involved setting up the base receiver over a location without published control and performing a 10-hour static occupation. The static occupation was then post-processed with data from NGS CORS and used as control for the PPK measurements. Method 3 yielded lower accuracies than methods 1 and 2 and was only used when the team lacked available time and resources to transport and set up the base receiver. For this method, only the roving receiver was used and the kinematic points collected were post-processed directly with the NGS CORS data. The four CORS stations that were used in the post-processing of the Method 2 and Method 3 data were AB11 (Nome), AB17 (Unalakleet), AC07 (Buckland), and AC31 (Bald Head).

The errors presented for each vertical measurement in this report encompass both coordinate precision and positional

accuracy. The precision value is the standard deviation of the post-processed data calculated using Topcon Tools software (see range of values presented by both method type and community in table 1). All vertical accuracies (summarized by community in table 1) were evaluated by comparison with known elevations such as a published benchmark or the water level at time of measurement. In Unalakleet, the occupation of a benchmark (NGS PID BBCK34) with a published elevation revealed a vertical accuracy of 2 cm, a value consistent with the GPS manufacturer’s reported specifications. In Shaktoolik, a comparison between the measured elevation of the roadway on Profile 20/21 and a July 2011 measurement of the roadway surface yielded a vertical accuracy of 4 cm. In Nome, vertical measurements of the calm water level at three profile locations were compared to the elevation of the water as recorded by the NOAA tidal gauge (Station

Table 1. A summary of the GPS processing options used to generate the coordinate measurements presented in this report. The experimental precision values are based on a 2011 controlled test of DGGS GNSS equipment, conducted in Unalakleet, Alaska, and do not include error associated with positional accuracy. The actual precision values were calculated with post-processing software and the accuracies were determined by comparison with an independently derived vertical NAVD88 elevation such as a benchmark or known water level.

	Experimental Horizontal Precision	Experimental Vertical Precision	Community	Actual values for reported positions (cm)			
				Horizontal Precision	Vertical Precision	Vertical Accuracy	Total Vertical Error
Method 1	0.6 cm (RTK)	1.1 cm (RTK)	Unalakleet	2.0 – 4.3	1.4 – 2.9	2	3 – 5
	2.4 cm (PPK)	3.0 cm (PPK)					
Method 2	2.1 cm	2.6 cm	Shaktoolik	1.7 – 16	2.2 – 23.5	4	6 – 28
Method 3	19 cm	29 cm	Nome	2.5 – 24	3.4 – 31.0	16	19 – 47
			Golovin	4.1 – 9.6	5.6 – 15.0	51	57 – 66

9468756) at the time of the measurements. The maximum observed variation between the measured elevations and the elevations recorded by the tidal gauge indicates a vertical accuracy of 16 cm for these values. In Golovin, vertical coordinates calculated using the CORS data were compared to a DEM surface published by DCCED (Alaska Department of Commerce, Community & Economic Development, 2004; NGVD29 to NAVD88 conversion completed with the use of DOT&PF airport benchmark 'COR2'). Variation between the measured elevations and the published DEM elevations yields an accuracy of 51 cm for the vertical measurements included on the Golovin map.

While high winds, short days, cold temperatures, and snow limited the team's ability to access some areas that could be reached in the summer months, the expertise and experience of local residents provided the DGGS team with critical information in the form of photographs and video that were used to compile a better understanding of how this storm affected each community that was visited. For example, observations of the patterns of slush and ice movement in the nearshore and how this contributed to the attenuation of wave energy highlighted differences in coastal flooding between this storm and previous storm events.

## SUMMARY OF OBSERVATIONS FOR EACH COMMUNITY

### *Unalakleet*

Unalakleet, located at the mouth of Unalakleet River and west of the Nulato Hills, has a population of 688 (U.S. Census Bureau, 2010). The community is situated on a sand and gravel barrier spit that is bounded to the west by Norton Sound, to the south by the river inlet, and to the east by Kouwegok Slough (fig. 6). The area experiences a mean tidal range of 97 cm (NOAA, 2012).

Extreme storm surges were recorded in Unalakleet in 1960 (20 ft or 6.1 m MSL; Wise and others, 1981), 1965 (18ft or 5.5 m MSL) and 1974 (15ft or 4.6 MSL) (USACE, 2011b). The 1960 event moved structures off of their foundations and put the power plant out of operation, whereas the 1965 event triggered an evacuation (Wise and others, 1981). Other notable coastal flooding events occurred in October and November 2004, when a gabion wall at the river mouth was damaged (City of Unalakleet and others, 2008), in 1963, resulting in \$100,000 in damages, and also in 1973, 1966 (Wise and others, 1981), and 1937 (unconfirmed, NRCS, 2003).

Engineering modifications to the Unalakleet coastal zone include an armor rock revetment with a crest elevation of 23 ft (7.0 m) above MLLW that extends around the southern perimeter of the spit (USACE, 2008). The current revetment project was completed in 2010 by the Army Corps of Engineers and included replacement of the seaward segment of a damaged gabion wall that was originally constructed in 2000 by the Natural Resources Conservation Service (fig. 7a). A sheet pile dock abuts the gabion wall on the inside of the inlet (fig. 7c). Beach Front Road, which runs along the seaward edge of the

spit, was elevated by 3 ft (0.9 m) in 2005 (fig. 8). In 2008, Alaska DOT&PF constructed a 'dynamically stable' beach project along the portion of coast that fronts the road to the airport and the southern end of Runway 33. The engineered beach had an initial crest width of 20 ft (6.1 m) and was designed to undergo gradual modification by marine energy to an equilibrium profile with a crest width of 10 ft (3.0 m; Smith and Carter, 2011).

November 2011 DGGS field investigations in Unalakleet consisted of two days of fieldwork during which our team was able to reoccupy nine of the coastal profiles established in summer 2011, measure 15 marine flood indicators, and collect photographs and video from residents (summarized in fig. 6). The results of measurements made to evaluate the peak water level elevations in Unalakleet are presented in table 2.

Inundation limits on the Kouwegok Slough side of the community are most indicative of a surge tide level because this area was protected from wind waves. Our team measured a water level elevation of 2.7 m (9 ft) MSL alongside Runway 26 (fig. 9) and at the crane on the sheet pile dock (fig. 6d); we interpret this to be the peak water level attributed to the storm surge and astronomical tide. On the seaward side of the community where wave setup resulted in an additional increase in water level, the floodwater levels reached 4.2 m (14 ft) MSL (fig. 10). We were able to document maximum wave runup elevations in the community of up to 5.8 m (19 ft) MSL along the raised Beach Front Road (fig. 11a) and at the airport (fig. 11b). Near the barge landing and farther to the north, where beach and surf zone are narrower and breaking waves dissipate less energy in the nearshore, we observed higher runup elevations of up to 6.1 m (20 ft) MSL.

Remeasured beach profiles in front of the community (profiles 15 and 16, fig. 6) revealed no modification other than the accretion of a ridge of ice at approximately 2.5 m MLLW. Profiles north of the community near the barge landing site indicate the removal of mid-beach gravel berms that were present in the summer. The removal of these berms by fall storms is typical of seasonal beach cycle modification and do not represent a permanent change to the beach morphology. Permanent and irreversible erosion of the back beach was observed at the northernmost profile (profile 5) that was remeasured. Numerous block failures at the edge of the low bluff along the road to Blueberry Creek were observed up and down the coast in the vicinity of this profile (fig. 12b). The plots in figure 12 illustrate the pre- and post-storm beach profiles at this location. The initial profile collected in July 2011 (green) has a mid-beach gravel berm at 3 m MLLW and a rounded, low bluff typical of terrestrial weathering processes (see fig. 12a). The post-storm profile reveals a sharp, vertical bluff at the backbeach, caused by basal marine erosion, and a bluff edge retreat of 2.3 m inland. A complete set of plotted profile change figures is included in Appendix B. A remeasured vegetation line on the Kouwegok Slough side of the community revealed no erosion or retreat in this area.

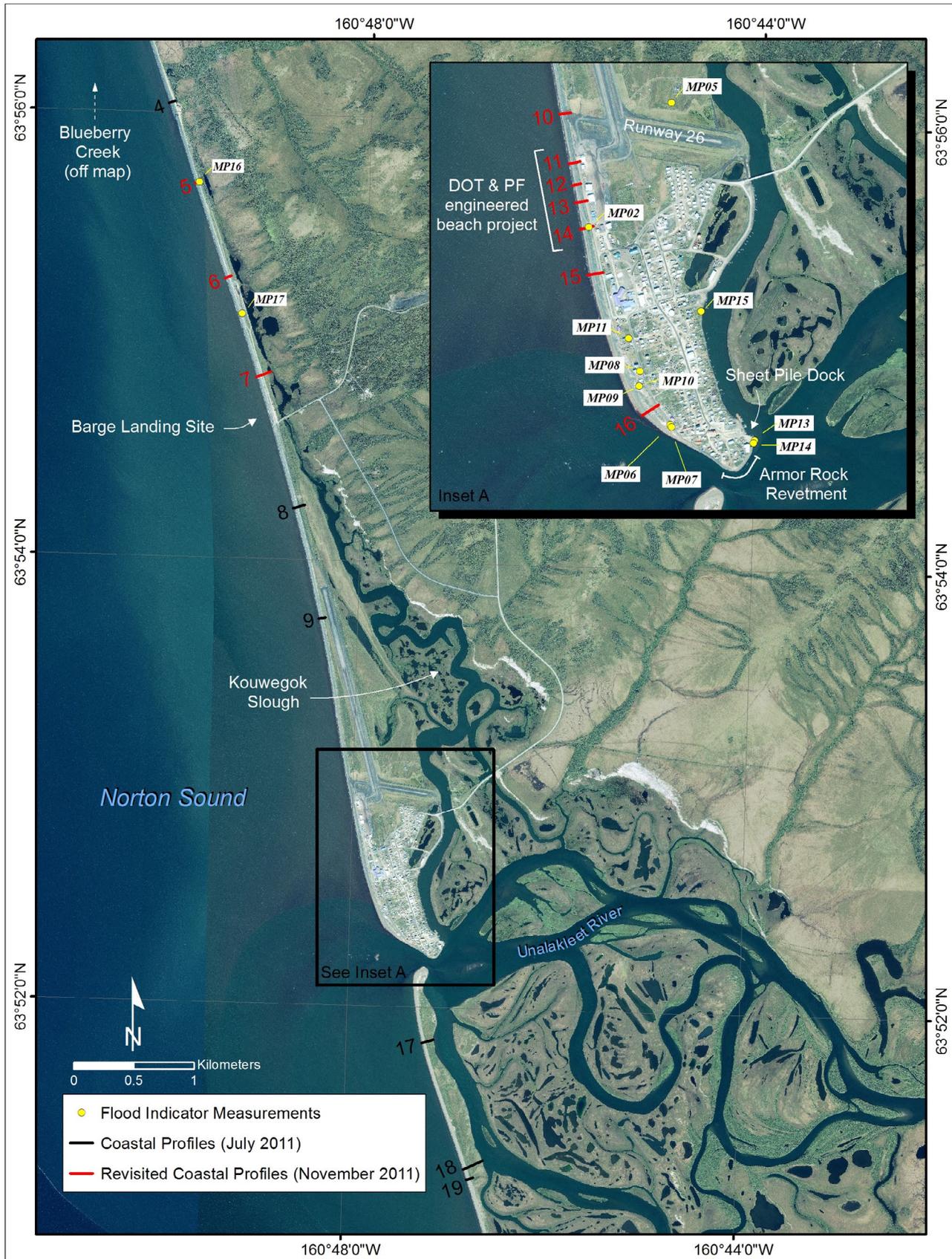


Figure 6. Summary map depicting the locations of coastal profiles and points where flood indicators were measured in the vicinity of Unalakleet, Alaska. The base map is a 2005 IKONOS satellite image.



Figure 7. Coastal modifications along the northern side of the Unalakleet River mouth including the armor rock revetment, gabion wall and sheet pile dock. The gabion wall is shown (a) in a pre-storm oblique aerial photo and (b) when a blowout was observed post-storm. The sheet pile dock is shown (c) pre-storm, (d) at the peak surge (photo by Maggie Halleran), and (e) again post-storm. MP14 in table 2 was collected at the crane site.



Figure 8. Beach Front Road in Unalakleet, which runs along the coast exposed to Norton Sound, was raised approximately 3 ft (0.9 m) in 2005. The western terminus of the armor rock revetment is visible in the photo and the arrow points to a location along the road where runup measurements MP06 and MP07 (table 2) were collected (photo by Steve Ivanoff).

Table 2. Elevations and descriptions of marine flood indicators that were measured in the vicinity of Unalakleet, Alaska on November 11, 2011. Point numbers not preceded by 'MP' were collected along coastal profiles (for example, 15\_02 was the second point collected on Profile 15). Measurements used to infer different types of water level elevations during the peak storm surge are highlighted: Storm tide (surge + tide; blue), TWL (surge + tide + wave setup; green), maximum wave runup within the inhabited community (orange) and maximum observed runup in the entire area (red).

Point Number	Measurement Type	Confidence Level	Elevation (m MSL)	Description
MP15	Inundated area	High	0.92 ± 0.05	Elevation of rafted river ice on bank of Kouwegok Slough
MP13	Inundated area	High	1.07 ± 0.05	Elevation of rafted ice chunks near sheet pile dock
MP05	Inundation limit	Medium	2.66 ± 0.06	Identified on FAA camera image, north of Runway 26
MP14	Peak flood level	High	2.66*± 0.04	Elevation of visible water line on side of dock crane
MP11	Inundated area	High	3.24 ± 0.04	Spillover point identifiable in photograph from storm
MP09	Inundated area	Medium	3.85 ± 0.04	Toe of scarped beach gravels on shoreface
MP08	Inundation limit	High	4.20 ± 0.05	Slush limit adjacent to a garage that was flooded
MP10	Above inundation	Lowest	4.32 ± 0.05	Top of scarped beach gravels on shoreface
MP07	Runup limit	Medium	4.82 ± 0.05	Slush line with driftwood, raised Beach Front Road, location confirmed by local resident (cleaned up)
MP17	Overtopped area	Medium	4.87 ± 0.05	Elevation of driftwood on roadway (cleaned up)
MP02	Overtopped area	Lowest	4.95 ± 0.05	Elevation of driftwood on roadway (cleaned up)
MP06	Runup limit	High	5.08 ± 0.05	Slush line with driftwood, raised Beach Front Road
15_02	Runup limit	High	5.75 ± 0.05	Slush line with driftwood on Profile 15, on raised Beach Front Road near the school
05_01	Runup limit	High	5.95 ± 0.05	Slush line atop road on Profile 05
MP16	Runup limit	High	6.13 ± 0.05	Slush line with driftwood on road beside low coastal bluff north of the barge landing

\*Elevation derived from measured elevation of crane base and flood height on crane as measured by a local resident

At the DOT&PF engineered beach (profiles 11–14, fig. 6) a steepening of the upper beach slope from approximately 15° to 23° occurred at profiles 11 and 13. The base of the upper scarp, near the crest of the constructed beach, retreated inland 0.7 m. At profile 12, a significant volume of material was transported seaward, translating into 4.5 m retreat at the crest and a loss of 12.5 m<sup>2</sup> from the upper cross-sectional area. There was no significant modification to the beach at profile 14. Minor overtopping of the profile crest and adjacent roadway was observed along the length of the constructed beach project (fig. 11b). Based on the slight steepening observed at two of the profiles, we anticipate that subsequent crest retreat will occur along some portions of the project as the beach profile re-equilibrates. In the last two years, human modifications to the engineered beach project involving the placement of finer-grained sediment to the upper face of the beach may have contributed to the overtopping that was observed. Wave runup heights can be reduced through the dissipation of energy over coarser-grained material (United States Department of the Army, Coastal Engineering Research Center [CERC], 1984); efforts to leave the coarser materials that were newly exposed at the surface by this event could reduce runup heights during future events.

The eyewitness accounts that our team received were in general agreement that the November 2011 event was the

most severe storm surge that has occurred since the 1970s. The consensus among residents was that the offset of the peak surge from the peak winds combined with the favorable (non-onshore) wind direction and the lower tides at the surge peak prevented more extensive flooding (see Appendix A for local plots of wind and atmospheric pressure). The new armor rock revetment appeared to minimize erosion and flooding at the mouth of Unalakleet River where flood inundation had been initiated in the past. Areas on either end of the revetment remained vulnerable: the most extreme runup elevation that was measured in the community was located at the western terminus of the new structure (fig. 8) and on the eastern end a large blowout occurred in the remaining segment of gabion wall (fig. 7b). Shifts in armor rock placement as well as any changes at the toe of the structure will need to be evaluated.

### Shaktoolik

Shaktoolik, located 50 km north of Unalakleet, has a population of 251 (U.S. Census, 2010). The community is situated on a sand and gravel barrier spit that is bounded to the east and north by Tagoomenik River and to the west by Norton Sound. Shaktoolik has been in its present location since 1974 following a relocation from 9 km to the south, which was initiated in response to escalating coastal hazard risks (Native Village and City of Shaktoolik and others,

2009). The area experiences a mean tidal range of 74 cm (NOAA, 2012).

According to resident accounts summarized in a 2011 report by the U.S. Army Corps of Engineers (USACE, 2011a), extreme coastal flooding events occurred at the old community site in 1960 and 1970 that resulted in the complete overtopping of the barrier spit near the former airstrip. Resident reports of an observed 1.5 ft (0.5 m) flood depth at the old community site (Wise and others, 1981) would correspond to a TWL of at least 6 m MSL based on the old site's elevation. Other notable storm surge events that preceded the community's relocation occurred in 1965, resulting in the loss of a dwelling and outhouses (USACE, 2011a); 1966; and the 1974 storm that resulted in \$20,000 in reported damages (Wise and others, 1981). Significant coastal storms at the present site occurred in 1978, and more recently in 2004, 2005, and 2009 (Glenn Gray & Associates and others, 2012).

November 2011 DGGs field investigations in Shaktoolik consisted of 1.5 days of fieldwork, during which our team was able to reoccupy five of the coastal profiles established in summer 2011, measure 23 marine flood indicators, and collect photographs and video (summarized in fig. 13). A water-level sensor that was deployed in Tagoomenik River during the summer of 2011 was still in place for the November storm; however, significant ice activity on the river displaced the sensor and it has not been located to date (August 2012). The results of measurements made to evaluate the elevations of the storm water levels in Shaktoolik are presented in table 3.

Inundation limits observed on the side of the community along Tagoomenik River are most indicative of a storm tide elevation because this area was protected from wind waves. An average storm tide level of 3.3 m (11 ft) MSL was interpreted from measurements of flood levels marked by residents and visible slush lines along the bank

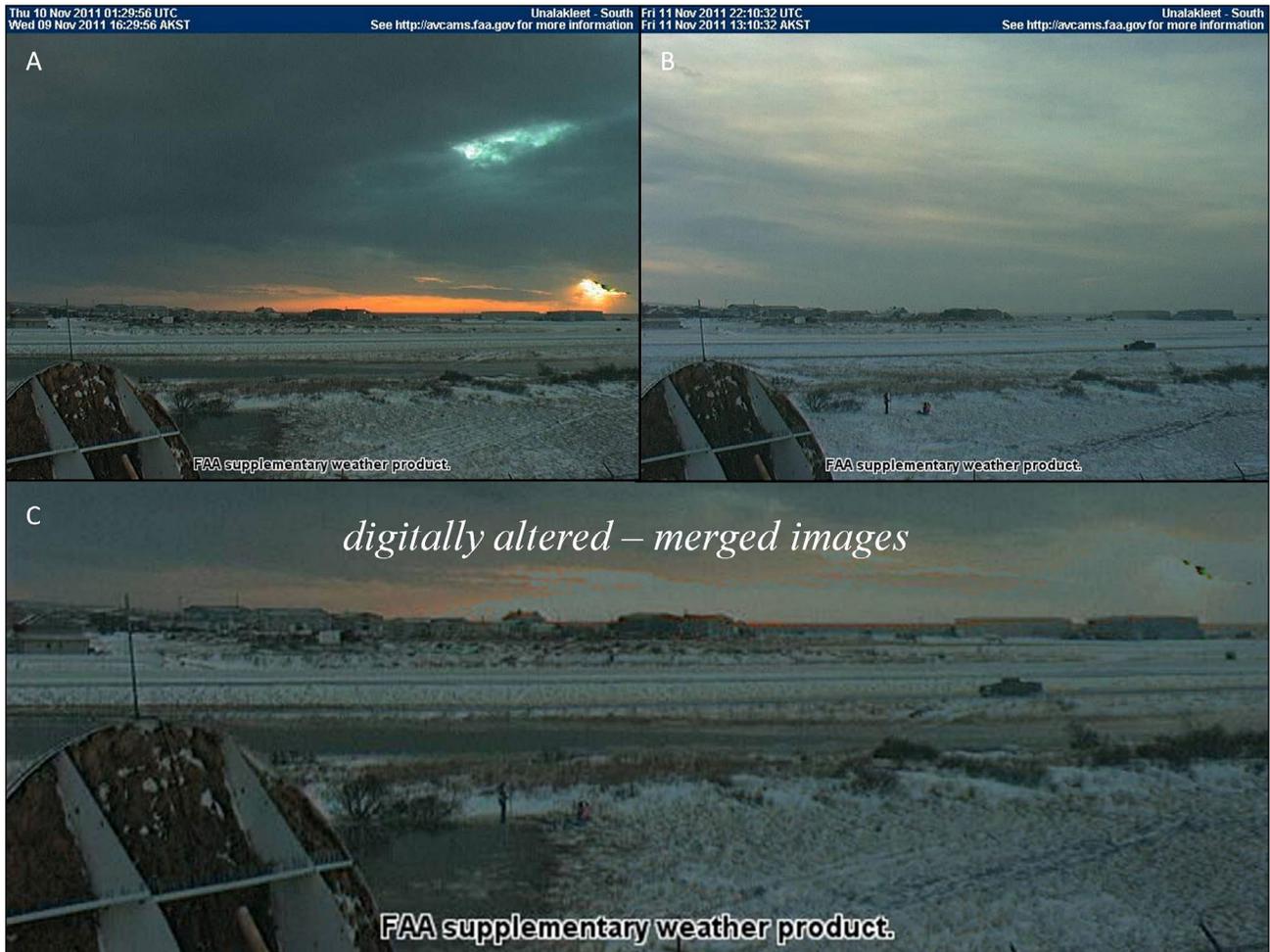


Figure 9. Collection of MP05 (table 2), a flood inundation limit on the eastern side of the Unalakleet airport, which was visible in an FAA webcam adjacent to Runway 26. (a) Image taken on the afternoon of November 9, 4:29 pm AKST, following the peak surge. (b) Image taken at 1:10 pm November 11 as DGGs workers collected an elevation measurement. (c) Digitally stitching images (a) and (b) together allows us to view the position of the workers relative to the inundation limit.



Figure 10. Photographs of flooded areas on open ocean side of Unalakleet provided an estimate of the TWL along the front of the community where the water surface was elevated above the storm tide level by nearshore wave setup. A spillover point photographed by Steve Ivanoff during the storm (a) was measured as MP11 in table 2 (b) and a slush limit adjacent to flooded garage provided the elevation for MP08 (c).



Figure 11. (a) Level of runup on side of raised Beach Front Road, Unalakleet, along Coastal Profile 15 near the school. (b) Runup level in driftwood where waves have overtopped the crest of the dynamically stable beach project on the road to the airport.

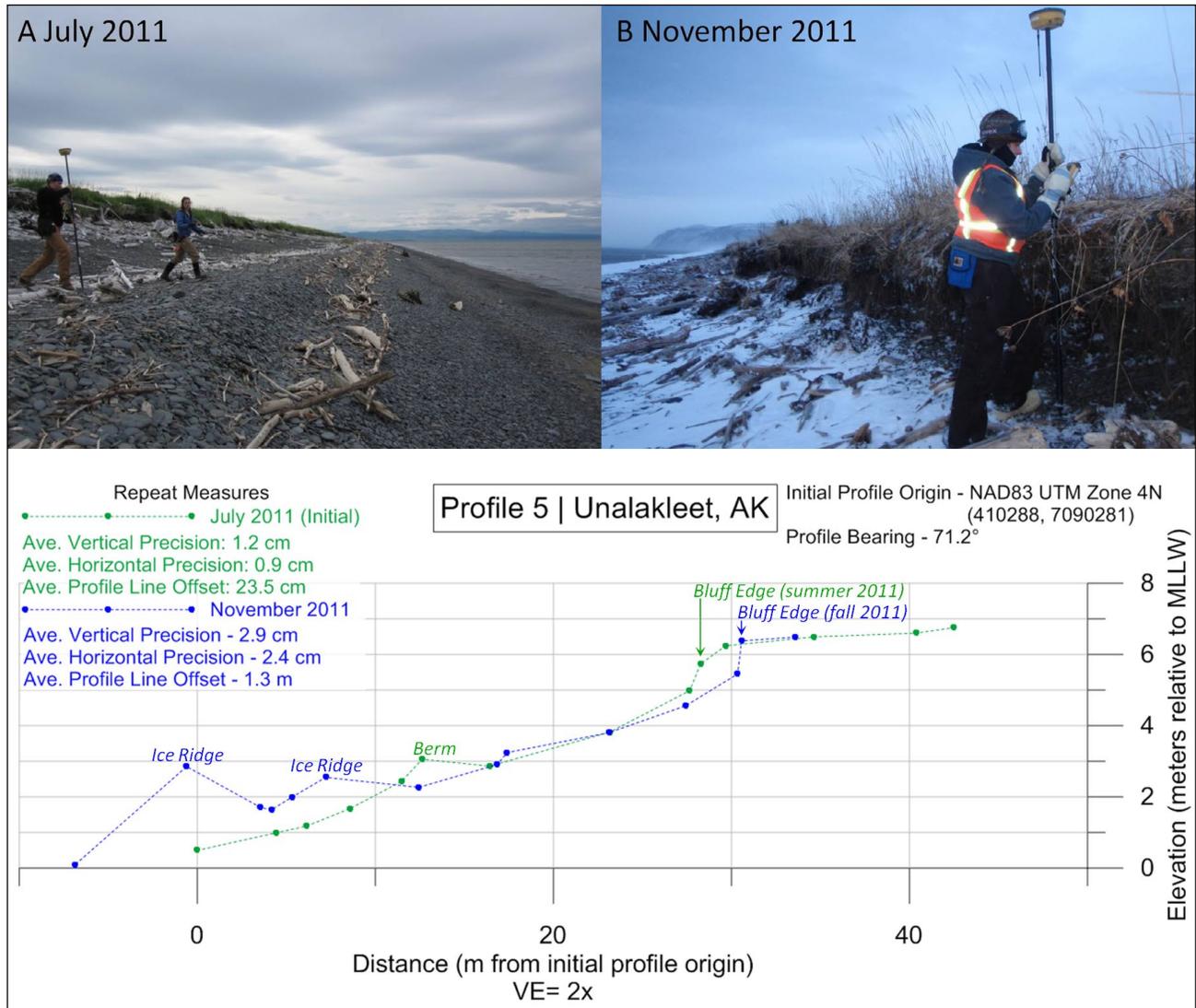


Figure 12. (a) Coastal Profile 05, north of the Unalakleet barge landing, showing a well-developed mid-beach berm and rounded low bluff, and (b) erosion of the bluff toe caused by waves during the November 2011 storm. The plots illustrate change in the morphology of the beach cross section at this location including the removal of the berm, erosion at the bluff, and the accretion of ice ridges on the lower beach.

of Tagoomenik River as well as floodwater levels that were identified with the aid of photographs taken by residents during the storm (fig. 14). An absence of sheltered flooded areas on the seaward side of the community precluded an estimate of the TWL independent of runup effects. Maximum runup elevations at the current community site were as high as 5.8 m (19 ft) MSL near the tank farm and Native Corporation building (fig. 15). At the old community site, where deeper nearshore water results in less dissipation of wave energy in the nearshore, we documented a maximum runup elevation of 7.8 m (25 ft) MSL and there was extensive wave overtopping of the low bluff indicated by slush deposits and driftwood. Floodwater capable of transporting large logs entirely overtopped the barrier spit at an elevation of 7.0 m (23 ft) MSL near the old site's runway (fig. 16).

Remeasured coastal profiles in the vicinity of Shaktoolik did not reveal any immediate, obvious changes to the coastal morphology as a result of the November 9 storm surge. However, we observed significant undercutting of the low bluff, up to 60 cm into the base of the bluffs, at the old community site (fig. 17). In many areas around the old community site, the protective talus toe had been removed and the bluff edge was being held aloft and in position by a combination of frozen ground, vegetation, and frozen slush that was deposited on the back beach as elevated water levels ebbed. When thawing occurs in the spring and summer, block failures in the bluffs along the front of the old community are expected to be prevalent. Overtopping of the wood debris deposit that extends along the coast fronting Norton Sound was isolated to only a few locations at the present community location.

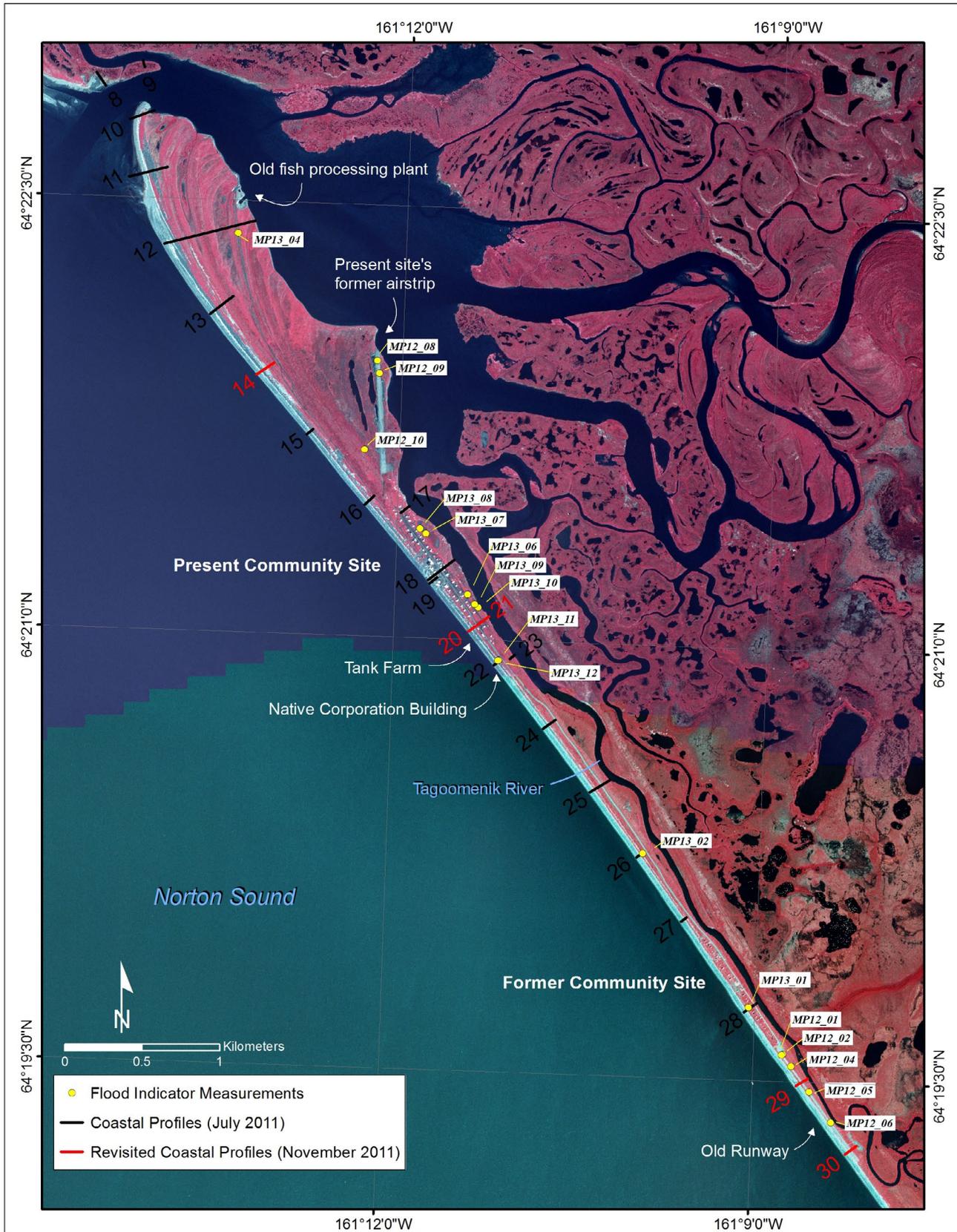


Figure 13. Summary map depicting the locations of coastal profiles and points where flood indicators were measured in the vicinity of Shaktolik, Alaska. The base layer is composed of orthorectified 1981 Alaska High-Altitude Photography (AHAP) imagery.

The coastal profile collected at the airport suggests that new wood debris was deposited above previous levels north of the present community. A complete set of plotted profile change figures is included in Appendix B.

Because the community of Shaktoolik has relocated within the last 30 years, observations of historic storms have been made from a different vantage point. This makes it more difficult for residents to provide objective comparisons regarding the relative severity of pre- and post-1974 events. Disagreement regarding the severity of recent events exists as well: many residents with whom our team spoke perceived the November 2011 event to be the largest storm surge since the relocation while others felt that the 2009 storm was of a

greater magnitude. Some residents voiced fear and concern about overtopping at the old site that could impede or block the route of evacuation along the barrier spit from the present community site to inland areas; this has been a concern prior to this event as well (Glenn Gray & Associates and others, 2012). Eyewitness accounts, from both during and after the storm, emphasized the elevated water level along the banks of Tagoomenik River as being unique to this storm. Homeowners on the eastern side of the barrier spit reported that, for the first time, they felt more at risk for flooding than those with homes on the open-ocean side of the community. Wave runup was apparently lessened along this section of open-ocean coast by a wide area of slush that dampened the

Table 3. Elevations and descriptions of marine flood indicators that were measured in the vicinity of Shaktoolik, Alaska, November 12–13, 2011. Point numbers not preceded by 'MP' were collected along coastal profiles. Measurements used to infer different types of water levels during the peak storm surge are highlighted: Storm tide (surge + tide; blue), maximum wave runup within the inhabited community (orange) and maximum observed runup in the entire area (red).

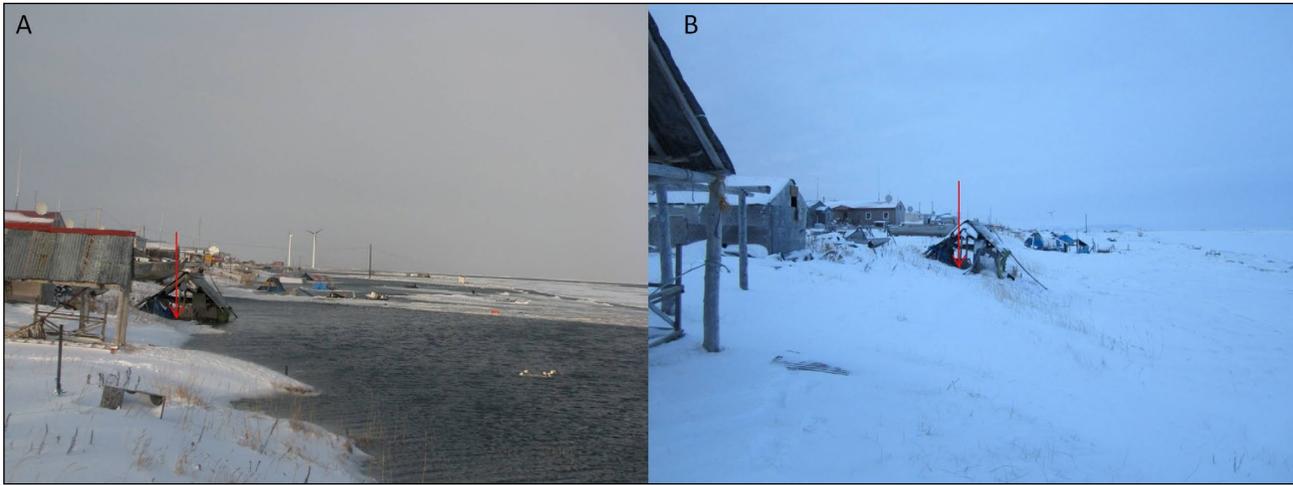
Point Number	Measurement Type	Confidence Level	Elevation (m MSL)	Description
21_14	Inundated area	High	2.16 ± 0.07	Elevation of slush on bank of Tagoomenik River, Profile 21, no visible extent (drifted snow present)
MP13_08	Inundation limit	Medium	2.58 ± 0.06	Photo-located on bank of Tagoomenik River (not at peak)
MP13_10	Inundation limit	Lowest	2.59 ± 0.06	Slush limit and calving snow line on Tagoomenik River
MP12_08	Inundated area	Medium	2.71 ± 0.14	Elevation of ice jam at the present site's old airstrip
MP12_09	Inundated area	High	3.17 ± 0.14	Elevation of rafted ice atop present site's old airstrip
MP13_07	Peak flood level	Medium	3.22 ± 0.07	Photo-located elevation on fish drying rack along Tagoomenik River
MP12_10	Inundation limit	Lowest	3.24 ± 0.14	Slush limit in low area on the Tagoomenik River side of active airport, near windmills (snow present)
MP13_09	Inundation limit	Medium	3.32 ± 0.06	Photo-located on fish drying rack along Tagoomenik River
MP13_06	Inundation limit	High	3.42 ± 0.06	Marked with stake by local resident, on Tagoomenik River
MP13_04	Inundation limit	Lowest	3.48 ± 0.07	Slush limit on surface of road to old fish plant next to the Tagoomenik River (snow covered)
14_01	Below runup	High	4.89 ± 0.07	In slush with unclear extent, airport Profile 14
14_02	Overtopped area	High	5.48 ± 0.06	Elevation of slush-capped wood debris on Profile 14
MP13_11	Runup limit	High	5.52 ± 0.06	Slush and debris line in front of Native corporation building
20_07	Runup limit	High	5.85 ± 0.06	Slush line on front face of driftwood debris pile (not overtopped) on Profile 20 near the tank farm
30_01	Runup limit	Lowest	6.00 ± 0.06	Slush line atop coastal bluff (snow covered)
MP12_05	Runup limit	High	6.29 ± 0.17	Large driftwood deposited on old site's runway
MP13_12	Overtopped area	Medium	6.39 ± 0.07	Maximum elevation of slush deposited atop driftwood debris pile in front of Native corporation building
MP12_04	Runup limit	High	6.83 ± 0.06	Large driftwood deposit on old site's runway
MP12_02	Overtopped area	Medium	6.83 ± 0.06	Elevation of slush-capped driftwood pile at old site
MP12_06	Inundated area	High	6.98 ± 0.06	Washover location at old site's runway, driftwood
MP13_02	Below runup	Medium	7.01 ± 0.06	Driftwood, gravel, and slush deposited atop willows near a washed-out portion of bluff edge
MP13_01	Runup limit	Medium	7.66 ± 0.28	Slush line with driftwood atop bluff at old site
MP12_01	Runup limit	High	7.77 ± 0.14	Slush line with driftwood atop bluff at old site

amplitude of the incoming waves and reduced wave energy prior to landfall. Slush accumulation was also reported at the mouth of Tagoomenik River and this, combined with ice jams near the mouth of the river, may have slowed outflow from the river as the storm subsided, and contributed to elevated water levels along the river.

**Nome**

Nome, situated on the southern edge of the Seward Peninsula (fig. 18) has a population of 3,500 (Hufford and

Partain, 2004) and is the largest city in the Norton Sound region. The city is located on a coastal plain south of the Kigluaik Mountains and is home to a seaport at the mouth of Snake River. The area experiences a well-established mean tidal range of just 31 cm (NOAA, 2012). The Nome–Council Road runs east from the city along a low, bluffed coastline to Cape Nome. Just east of Cape Nome, a barrier island and spit system fronts Safety Sound, a shallow lagoon that drains Flambeau, Eldorado, and Bonanza rivers. In contrast to the



*Figure 14. (a) Location of elevated water level on the bank of Tagoomenik River as photographed by Elmer Bekoalok on November 9, 2011, and (b) the measured point MP13\_09 (table 3) as determined by the position of the water relative to the upright support on the fish drying rack highlighted by the red arrow in both photos.*



*Figure 15. Inland limit of a runup deposit (highlighted by white dashed line) that overtopped the driftwood debris pile in front of the Native corporation building (MP13\_11 and MP13\_12, table 3).*

coarse gravels of eastern Norton Sound, the beaches in Nome are composed of sand. In past events, the coastal morphology has exhibited a complex response to storm events including both net erosion and accretion, as well as episodic and localized bluff retreat (Sallenger and Dingler, 1978).

The record of damages in the Nome area caused by coastal flooding is extensive and dates back to 1898 (Wise and others, 1981). In 1900, a September 12 storm led to \$750,000 in damages and the loss of life. Just a few years later, in 1913, a storm destroyed half of the developed city and caused \$1 million in damages (City of Nome and others, 2008). The extreme storm surge event of 1960 caused \$100,000 in damages along the road due to erosion, and an event in 1974 (12 ft or 3.7 m MSL, City of Nome and others, 2008; 13.2 ft or 4.0 m MSL flood of record, USACE 2011b; 20 ft or 6.1 m MSL, Wise and others 1981) overtopped the seawall and caused \$12–\$30 million in damages (Wise and others, 1981; Sallenger and Dingler, 1978). In 1978, a 10 ft (3.0 m) MSL surge led to more than \$1 million in damages both inside the city limits and along the Nome–Council Road (Wise and others, 1981). Other notable flooding and erosion events occurred in 1902, 1937, 1942, 1946, 1967, and 1972 (City of Nome and others, 2008). Emplacement of extensive coastal defense structures beginning with port jetties in 1940 and a seawall in 1951 (FEMA, 2010), have mitigated damages from large storms that have impacted other communities in more recent years, but they do not offer complete protection. In 1992, Nome sustained more than \$6 million in damages fol-

lowing a large storm event (Blair and others, 1997). In 2004, a 3 m MSL storm surge resulted in more than \$5 million in damages (Hufford and Partain, 2004), and in 2005 a similar storm resulted in extensive damages to local infrastructure.

Unlike in Unalakleet and Shaktoolik, staff from the DGGs Coastal Hazards Program had not previously conducted work or established coastal profiles in the Nome area. November 2011 DGGs field investigations consisted of one day of fieldwork, during which our team was able to establish three coastal profiles along the Nome–Council Road and measure 14 marine flood indicators (summarized in fig. 18). Significant clearing of the road and clean-up that was already underway limited the total number of flood indicators that could be measured. The results of measurements made to evaluate the inundation and runup elevations in Nome are presented in table 4.

Inundation limits measured along the edge of Safety Sound, on the inland side of the barrier spit, can be inferred to be most indicative of a storm tide elevation. Our measurements in this area indicate a storm tide level elevation of 3.3 m (11 ft) MSL. On the seaward side of the Nome–Council Road, where wave setup resulted in an additional increase in water level, the TWL reached 4.2 m (14 ft) MSL (fig. 19c). Maximum wave runup elevations along the observed portion of coast were as high as 6.4 m (21 ft) MSL (fig. 19b) atop the coastal bluffs between Nome River and Cape Nome. Large pieces of ice and driftwood were deposited by waves atop 3–4 m bluffs throughout this area.



Figure 16. Photograph, looking to the south, of an area on the runway at the old Shaktoolik community site, where the barrier spit was overtopped and water flowed from Norton Sound into Tagoomenik River, visible on the left side of the photograph (MP12\_06, table 3).



Figure 17. (a) Basal notching 60 cm into the low coastal bluff at the old community site was observed in areas that had a vegetated talus toe prior to the November 2011 storm (inset photo b).

Our team observed extensive damage to the roadway and rubble mound revetments along much of the Nome–Council Road that we visited. One day prior to our arrival, portions of the road were still closed to vehicle access and clean-up efforts were in progress as we were collecting measurements. Just west of Nome River, a breach in the armored revetment exposed the road to undermining (fig. 20a). Additional breaches to revetments along the road were also observed, particularly along the coast adjacent to Safety Sound. Near Mile 17 on the Nome–Council Road, large pieces of riprap were washed across the road during the storm and deposited both atop the spit and in the Sound (fig. 20b). The three coastal profiles that were established in Nome are not presented in this report but will be included in a future DGGs publication once more profiles have been established.

### **Golovin**

Golovin, a community of 156 residents (U.S. Census, 2010), is located on a peninsula between Golovnin Bay and Golovnin Lagoon on the northern edge of Norton Sound (fig. 21; for variations on the use of ‘Golovnin’, see Orth, 1971). A majority of the facilities and infrastructure in the

community, including the school, City and Native corporation building, health clinic, power plant, and communication services buildings are built upon low-lying coastal deposits (see map sheet 1 for additional detail). More recent development including the new airport, the Economic Development Administration building, and recently constructed residences are built on an elevated (>12 m) bedrock surface to the east. The area experiences a mean tidal range of less than 55 cm (based on 2005 spring tidal range for nearby Carolyn Island; NOAA, 2012).

Golovin’s sheltered position in Norton Sound protects it from some of the peak winds observed elsewhere during strong storms, yet extensive coastal flooding in the lower-lying areas of the community has been a recurrent issue. During large storms, coastal flooding typically encroaches on the community from the northern, or lagoon, side. The earliest documented storm surges in the community date to 1900 and the most severe event on record took place in 1913 (City of Golovin and others, 2008). The record of storm damages specific to the City of Golovin is sparse but includes the loss of a building in 1945 (City of Golovin and others, 2008) and flooding of the old airport in 1977 (Wise and others, 1981).

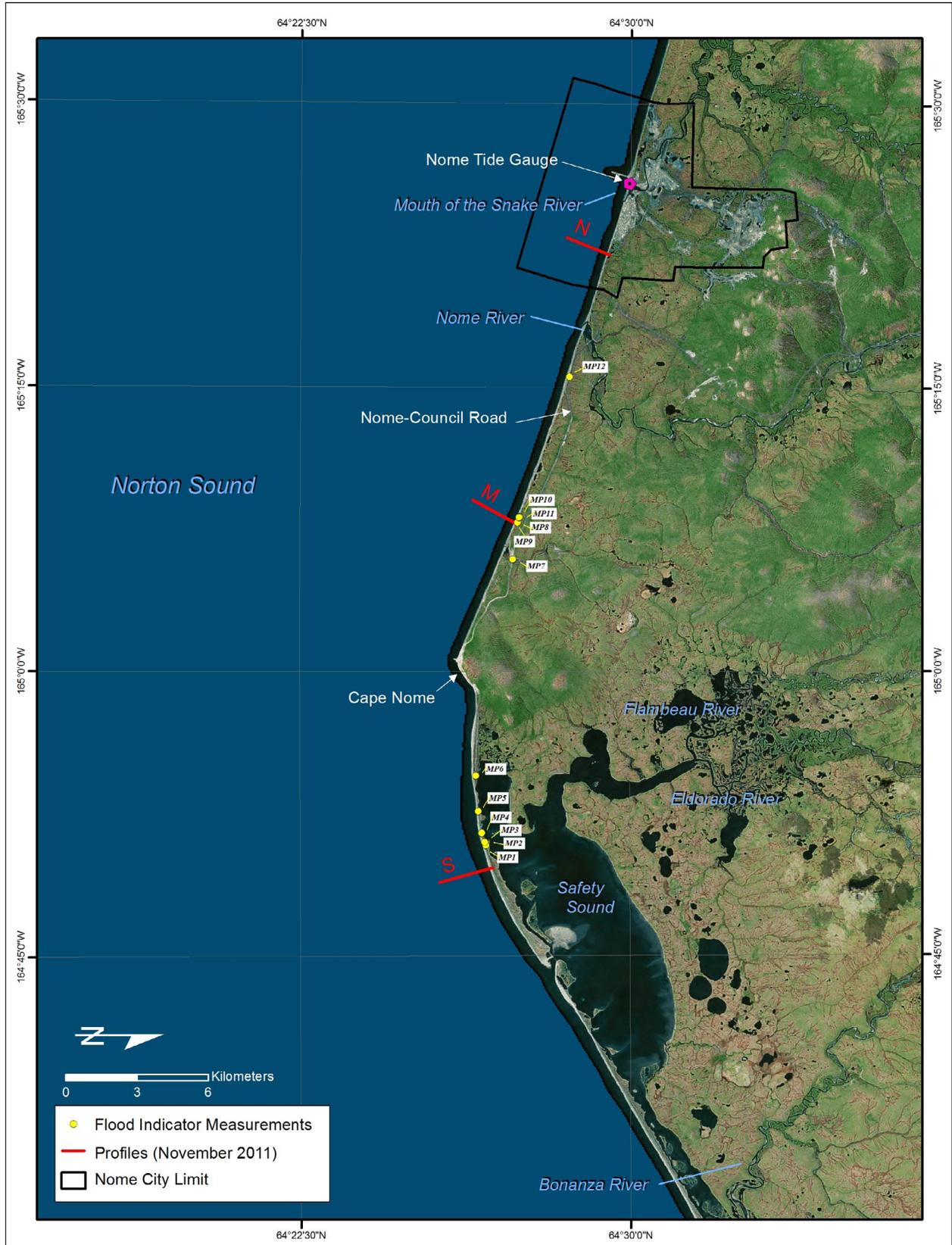


Figure 18. Summary map depicting the locations of coastal profiles and points where flood indicators were measured along the Nome-Council Road east of Nome, Alaska (note direction of north arrow). The base layer is a 2000 LANDSAT satellite image.

Table 4. Elevations and descriptions of marine flood indicators measured along the Nome–Council Road on November 14, 2011. Point numbers not preceded by ‘MP’ were collected along coastal profiles. Measurements used to infer different types of water levels during the peak storm surge are highlighted: Storm tide (surge + tide; blue), TWL (surge + tide + wave setup; green), and maximum observed runup in the entire area (red).

Point Number	Measurement Type	Confidence Level	Elevation (m MSL)	Description
MP02	Inundated area	High	2.26 ±0.47	Maximum elevation of flow into the lagoon at Mile 18
MP01	Inundated area	Medium	2.73 ±0.45	Low point on inland side of road (snow covered)
MP06	Inundation limit	High	3.26 ±0.22	Slush limit against roadway, inland side of barrier spit
MP04	Inundation limit	Lowest	3.41 ±0.22	Waterline on lagoon side of road, area not overtopped
MP03	Overtopped area	Medium	3.71 ±0.21	Maximum elevation of a wide overflow on roadway
MP05	Overtopped area	Medium	3.94 ±0.21	Maximum elevation of breached portion of revetment
MP12	Inundation limit	Medium	4.20 ±0.22	Slush line against base of roadway open-ocean side
S_03	Runup limit	High	4.23 ±0.23	Driftwood and slush line atop dune grass along Profile S, undisturbed grass from this point inland
MP07	Above flooding	Medium	4.84 ±0.19	Elevation of Hastings Creek bridge, not overtopped
MP08	Runup limit	High	5.19 ±0.20	Driftwood and slush line atop coastal bluff
MP09	Runup limit	High	5.91 ±0.22	Driftwood, ice chunks and slush line atop bluff
M_02	Runup limit	High	6.02 ±0.19	Driftwood, ice chunks and slush line atop coastal bluff along Profile M
MP11	Overtopped area	Lowest	6.28 ±0.21	Wave-tossed driftwood and ice chunks atop bluff
MP10	Runup limit	High	6.43 ±0.20	Driftwood and slush line atop protruding bluff

The previous flood of record for the City occurred in 1992 and the current flood of record was in 2005 (USACE, 2011b). In recent years, Golovin has experienced severe flooding and erosion that have resulted in damages to city infrastructure in 2004, 2005, 2008, and 2009 (City of Golovin and others, 2008). Rafted debris transported during previous storms, such as a large fuel tank, can be seen stranded around the edges of Golovnin Lagoon.

As in Nome, DGGs Coastal Hazards Program staff had not conducted field investigations in Golovin prior to November 2011. Investigations following the storm consisted of one day of fieldwork, during which our team was able to measure 32 marine flood indicators and collect personal accounts, photos, and video from residents. The results of measurements made to evaluate the inundation and runup elevations in Golovin are presented in table 5 and on map sheet 1. The team lead also made a site visit to an area near the head of Golovnin Lagoon at the mouth of Kachauik River where the November 9 storm surge triggered an ice override event (or ivu) that caused extensive damage to the community’s permanent summer fish camp.

Map sheet 1 shows the extent of the November 9, 2011, flood in Golovin based on the position of measured flood indicators, the 2004 DCCED digital elevation model (DEM; DCCED and Kawerak, Inc., 2004), and the locations of floodwater as visible in residents’ photographs from the event. The 2004 DEM was used to develop a static model of horizontal inundation extents at different water elevations for comparison with actual observations. This model, combined with the timestamps on the residents’ photographs, was used to reconstruct the timing and direction of flow as the flood crested. A preliminary version of this map, including a set

of questions that was designed to resolve gaps in observed inundation extents and discrepancies between 2004 and 2011 elevations, was sent to the community of Golovin for review in March 2012. This map was circulated among members of the Golovin Native Corporation, the City of Golovin (including equipment operators involved in clean-up activities), and the Chinik Eskimo Community. It was also placed in a central location in Golovin for general review by any other interested parties (fig. 22). In April 2012, feedback from this community review process was incorporated into the final version of the inundation map included with this report.

The final map of the flood extent in Golovin includes the peak flood inundation line and all of our measured flood indicators. Flooding in the vicinity of the old airport progressed in a chambered fashion; the topography of the peninsula caused the flooding to start at the southwestern end of the old runway, yet the elevated runway surface prevented overtopping from occurring in this area and water flowed along the runway, finally overtopping at a lower elevation on the northeast end. This meandering flow through the low-lying areas protected the part of the community housing the tank farm and water holding tank from heightened setup and runup effects by dissipating the wave energy. The elevated grading of Antone Street also restricted the primary floodwater path into the main part of town to the intersection just south of the small craft harbor. During the November 9 surge, the flood crossed this intersection sometime between 11 am and noon. In the early afternoon, the floodwaters progressed along the south side of Antone Street, past the communication towers, spilling over Punguk Street into the low-lying area on the eastern edge of town between 1 and 2 pm, and eventually almost entirely surrounding the school. The flooding crested

and began to ebb a little after 4 pm on November 9, 2011. The low-lying area on the east side of town often collects water from surface runoff in the warmer months but the sandy soils quickly drain when the ground is not frozen. At the time of our visit, iced-over floodwaters were still present in many of the low-lying areas around town.

Based on the measured flood inundation limits that we collected from around the community and on a direct water level measured on the fill pile near the end of Antone Street (point GLV\_16), the measured elevation of the peak water level including astronomical tide (storm tide level) in Golovin was  $4.3 \pm 0.6$  m NAVD88. A tidal datum has not been estab-



Figure 19. Examples of measured flood indicators along the Nome–Council Road from east to west: (a) Inland limit of flooding along Profile S (S\_03, table 4); (b), slush line (MP09, table 4) atop a coastal bluff near Profile M; and (c) inundation limit on open-ocean coast behind beach cabins (MP12, table 4).



*Figure 20. Significant modification to coastal engineering structures and damages along the Nome–Council Road included (a) undermining of the paved road and (b) the removal/transport of armor rock from the revetment near Mile 17. For scale, the rock highlighted by the red arrow in (b) was approximately 0.6 m in diameter.*

lished near Golovin so this elevation cannot be accurately reported relative to local MSL. A direct water-level measurement that was collected on the face of the cliffs adjacent to the community (fig. 23, point GLV\_32;  $5.59 \pm 0.6$  m) was higher than other measured flood indicators. This location was exposed to flowing water and waves in Golovnin Lagoon and may have been elevated by nearshore setup effects. If this area was affected by wave setup, then the measurement suggests a nearshore setup height of approximately 1.3 m (peak observed TWL minus storm tide level) on the lagoon side of the community where the primary encroachment of floodwaters was initiated. Due to the morphology of the Golovin coastline, which shelters the community from direct wave attack, the paucity of runup limit indicators and the short amount of time available in the field, measurements of the elevation of wave runup on the Golovnin Bay side of the community could not be made. However, reported accounts from several residents indicated that a protective band of slush helped to reduce the incident wave energy on the southern side of the community. Our observations supported these accounts because there was no evidence of waves overtopping the crest of the ice ridge along the Golovnin Bay

coast, except at the very southwestern tip of the peninsula near the old airport (GLV\_06).

Eyewitness accounts that our team received were in general agreement that flooding from the November 2011 storm was not as severe as other storms that have occurred during the last decade, such as in 2005. Many people reported that Antone Street, which was elevated in 2006, helped to reduce the amount of flooding within the town and around the school. Although Golovin received little media coverage during the storm, at least nine structures were reported to be fully surrounded by water during the peak of the marine flooding, cell phone communications were lost when electronic equipment at the towers was damaged by floodwater and some of the fuel was contaminated by water. Further, flooding may have contributed to the freeze-up of the primary underground water transmission line (written commun., Anungazuk, 2012). Residents expressed relief that peak flooding occurred during daylight hours and that it did not last for as long as it has during past events. Concern was voiced over the location of the flooding relative to the power transformer and about the damage caused by the ivu at the fish camp.

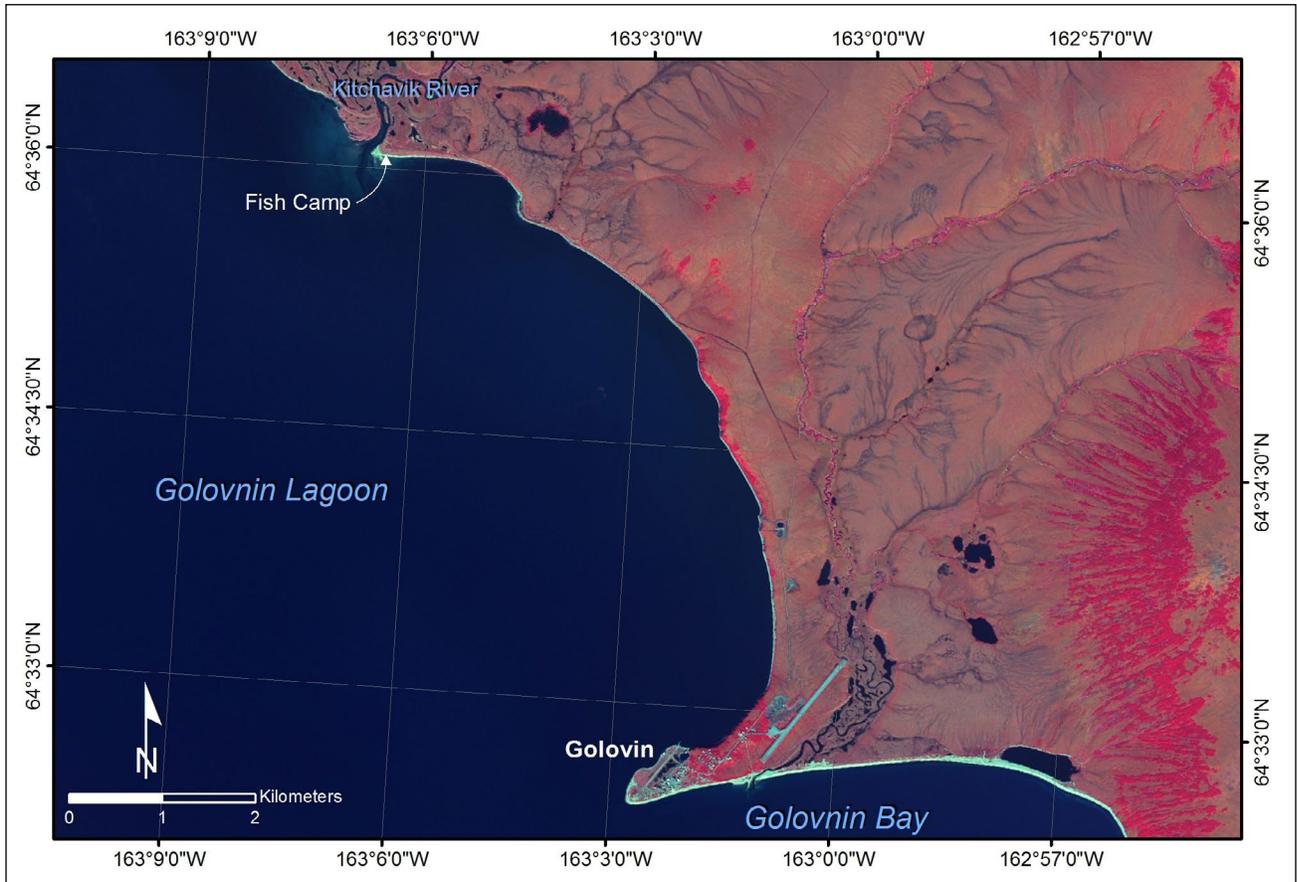


Figure 21. Summary map of Golovin, Alaska, area including the location of fish camp shown relative to the position of the community. The base layer is a 2009 SPOT5 infrared satellite image (vegetation appears red).



Figure 22. Dora Davis, a Chinik Eskimo Community grant writer, displays a preliminary version of the flood inundation map that was circulated by Golovin residents for collaborative feedback and edits prior to publication in this report (photo by Carol Oliver).

Table 5. Elevations and descriptions of marine flood indicators measured in Golovin, Alaska, on November 15, 2011. Measurements used to infer different types of water levels during the peak storm surge are highlighted: Storm tide (surge + tide; blue), and TWL (surge + tide + wave setup; green).

Point Number	Measurement Type	Confidence Level	Elevation (m NAVD88)	Description
GLV_14	Inundation limit	Lowest	3.18 ±0.58	Slush line near the corner of the school (modified)
GLV_18	Inundation limit	Lowest	3.27 ±0.58	Elevation of tension cracking in snow surface near road
GLV_15	Inundation limit	High	3.58 ±0.60	Truncated snow and slush line along raised Antone Street
GLV_13	Inundation limit	High	3.66 ±0.59	Slush line visible on dike surrounding tank farm
GLV_17	Inundated area	High	3.78 ±0.59	Location of overflow across the road to low-lying area
GLV_04	Inundation limit	High	3.93 ±0.66	Slush line near sewer drain field (minor snow cover)
GLV_02	Inundation limit	Lowest	4.02 ±0.58	Transition in slush surface near the old runway
GLV_05	Inundated area	Medium	4.07 ±0.59	Slush-covered area near sewer drain field
GLV_09	Inundation limit	Medium	4.10 ±0.58	Slush line along a berm that was raised up in 2008
GLV_26	Inundated area	High	4.02 ±0.66	Area by homes that were surrounded with water
GLV_01	Inundation limit	Medium	4.12 ±0.58	Slush line along road near generators; ice present
GLV_11	Inundated area	Medium	4.11 ±0.61	Slush-covered area by water holding tank (modified)
GLV_23	Inundated area	Medium	4.16 ±0.57	Low-lying portion of road that was flooded (modified)
GLV_27	Inundation limit	Lowest	4.19 ±0.57	Slush line along the road near Dexter Roadhouse
GLV_20	Inundation limit	Lowest	4.20 ±0.57	Slush line along hillside edge of a low-lying area
GLV_12	Inundation limit	Medium	4.22 ±0.58	Slush line between the school and the tank farm
GLV_24	Inundation limit	Lowest	4.27 ±0.58	Elevation of tension cracking in snow surface along road edge, exact slush extent obscured by road clearing
GLV_19	Inundated area	Medium	4.32 ±0.58	Location of overflow across road into low-lying area
GLV_16	Peak flood level	High	4.32 ±0.60	Water level as preserved on the sides of a soil fill pile between Antone Street and the small craft harbor fence
GLV_28	Inundation limit	Medium	4.42 ±0.58	Slush line on a mound near road at Dexter Roadhouse
GLV_07	Inundation limit	Medium	4.46 ±0.58	Slush line on side of earth foundation below hangar
GLV_08	Inundation limit	High	4.44 ±0.60	Elevation of tension cracking in snow surface
GLV_21	Inundation limit	Medium	4.49 ±0.57	Slush line along hillside edge of a low-lying area
GLV_03	Inundation limit	Lowest	4.56 ±0.58	Transition in slush surface near the old runway
GLV_22	Inundated area	Lowest	4.66 ±0.60	Location of overflow forming a pool across the road
GLV_30	Inundation limit	Lowest	4.80 ±0.58	Extent of floodwater on road in front of school, as determined by an <i>in situ</i> consensus of residents
GLV_10	Inundation limit	High	4.83 ±0.58	Slush line between the washeteria and the power plant
GLV_31	Inundation limit	Lowest	4.99 ±0.58	Extent of floodwater on road in front of school, as determined by an <i>in situ</i> consensus of residents
GLV_29	Inundated area	Lowest	5.30 ±0.58	Slush-covered area on road by church (modified)
GLV_06	Overtopped area	High	5.29 ±0.60	Crest elevation of ice ridge overtopped by waves (frozen puddle behind) at south tip of community
GLV_32	Peak flood level	High	5.59 ±0.59	Water level as observed in a truncated snowdrift on the cliffs on the north side of community

The Kitchavik fish camp is 7.5 km northwest of Golovin on Native Corporation land. Approximately eight cabins and numerous fish drying racks on Native allotments are used in the summers as a base of operations for subsistence activities along Kitchavik River. The cabins that were standing at this site had been built atop stilts to prevent damage from occasional flooding in the area. Many of the cabins had been in place for many years; one structure owned by an elder resident dates to the 1950s. Photographs from a visit to the site of the ivu are shown in figure 24. Ice was piled up at the site to a height of 5 m and the ice pile wrapped around the entire fish camp and berry-picking site. All of the cabins at this site were extensively damaged by the November 2011 storm, and most had been moved from their original foundations by up to 40 m. One cabin was rafted by floodwaters approximately 0.5 km to the northeast from its starting location (figs. 24c and 25). As the ice melted in the spring, large volumes of ice-rafted sediment were deposited at the ivu site, making the affected area very apparent from both the ground and the air (fig. 25).

## DISCUSSION AND CONCLUSIONS

Our reconnaissance measurements in four coastal areas following the November 9, 2011, storm (table 6) present a picture of how the peak storm water levels and inundation extents varied in Norton Sound. In general, the amplitude of the total sea surface was greatest at the eastern edge of the Sound, with Shaktoolik experiencing the largest overall increase in water level during the peak surge. Due to the limited tidal instrumentation in Norton Sound, the absolute contribution of the astronomical tide to water levels is unknown outside of Nome. Where observed, nearshore setup values on open ocean segments of the coast contributed to an additional 0.9–1.6 m rise in the ocean surface. These setup values are consistent with a theoretical maximum setup value of 1.5 m based on the open ocean wave conditions and existing empirical relationships (Appendix C; Holman and Sallenger, 1985). At isolated locations, wave runup was capable of carrying slush, water, and debris approximately 2–4 m higher than the peak elevation of the storm surge. As would be expected, maximum runup elevations were



Figure 23. Total floodwater level as preserved in a truncated snowdrift on the sedimentary cliffs to the north of town, along the Golovnin Lagoon shoreline. The peak water line is highlighted by the orange arrow; the elevation of the line was measured at the location shown with the person in the red ellipse (GLV\_32, table 5).

observed in coastal areas exposed to heightened wave energy, for example, areas subject to refractive wave focusing (convex coastal bluff edges in Nome) and areas with deeper nearshore depths (old community site in Shaktoolik).

We used inundation limits on sheltered portions of coastline (in lagoons, rivers, etc.) to approximate the storm tide levels presented in table 6; however, these areas are not fully sheltered from the effects of wind and wave setup or runup so they represent an upper limit approximation. In Nome, our measured storm tide elevation (3.3 m above MSL; table 6) is approximately 50 cm greater than the peak water elevation documented by the NOAA tide gauge at the mouth of Snake River (2.8 m MSL at 16:54 AKST). A discrepancy of this magnitude between surge heights measured in the field and tide gauge records is typical because of the differences in the methods of measurements (National Weather Service, 2010; oral commun., Sallenger, 2012), and we can infer that the true storm tide elevation may be slightly lower than the elevation that is measured using field techniques. Additional factors may also contribute to this discrepancy: for example, floating ice and debris on top of the water surface is capable of pushing slush farther onshore. In Shaktoolik,

‘whale-sized’ pieces of ice were reportedly transported in the swiftly moving current of Tagoomenik River during the storm, and the accumulation of ice and slush at the inlet may have dammed the ebb of the surge and increased sheltered water level measurements above pure storm tide levels. This would be consistent with observations of ice and slush at the river mouth as well as reportedly higher water along Tagoomenik River than in previous storms of similar magnitude. Conversely, in places such as Unalakleet, the observed storm tide elevation may be much closer to the true storm tide level because the coastal geometry presented more opportunities to measure inundation limits in sheltered locations.

Due to the limited number of well-documented storms in this part of Alaska, the recurrence interval for a storm of this magnitude is somewhat subjective. In 1981, Wise and others produced a statewide set of empirical storm surge frequency curves based on the relationship between historic surge elevations with associated atmospheric conditions and regional frequencies of various wind speeds. According to this early study, the November 9, 2011, surge in Nome corresponded to a 40-year event. The surge in Unalakleet would be considered a 20-year event, and in Shaktoolik the observed



Figure 24. Photos documenting the ivu that occurred at the mouth of Kachauik River: (a) Looking southwest across the fish camp at the forward edge of the ivu that damaged all of the cabins on the site; (b) Toby Anungazuk, a cabin owner, stands beside a building that was transported by the ivu; and (c) a photo taken from the fish camp shows a cabin in the distance (red inset) that floodwater rafted approximately 0.5 km to the northeast.



Figure 25. Oblique aerial image of the fish camp at the mouth of Kachauik River taken July 2012, eight months after the storm. The approximate transport distances of two cabins from their pre-storm foundation locations are depicted by red arrows and the deposition of ice-rafted sediment up to 150 m inland is apparent.

Table 6. A side-by-side comparison of Norton Sound tidal ranges and November 9, 2011, peak storm water levels as interpreted from various types of flood indicators that the DGGs team measured in the field. Colors correspond to those in tables 2 thru 5; ‘–’ signifies that the water level type was not measured.

Water Level Type	Vertical Datum	Unalakleet	Shaktoolik	Nome	Golovin
Storm Tide Level (surge + tide)	Local MSL	2.7 m	3.3 m	3.3 m	no tidal datum
	NAVD88 (GEOID09)	4.1 m	4.7 m	4.4 m	4.3 ±0.6 m
TWL, Total Water Level (surge + tide + setup)	Local MSL	4.2 m	–	4.2 m	no tidal datum
	NAVD88 (GEOID09)	5.7 m	–	5.3 m	5.6 ±0.6 m
<b>Water Level Component</b>					
Mean Tidal Range		0.97 m	0.74 m	0.31 m	<0.55 m
Storm Surge Height (Storm tide level – predicted tide)		–	–	3.2 m	–
Wave Setup Height (Storm tide level – TWL)		+1.6 m	–	+0.9 m	+1.3 m
Maximum Runup in Community (height above storm tide level)		+3.1 m	+2.3 m	–	–
Maximum Runup (height above storm tide level)		+3.5 m	+4.4 m	+3.1 m	–

surge height corresponded to a nearly 100-year event on the calculated curve for eastern Norton Sound. The report by Wise and others (1981) suggests that the surge magnitudes in northern Norton Sound are greater in size compared to those in eastern Norton Sound. Our measurements suggest more similar surge heights during the 2011 storm. Following the 1974 event, Sallenger (1983) reported coastal water elevations to be greatest along the eastern edge of Norton Sound, ranging from 3 to 4.75 m MSL (including runup). The regional variability of surge heights within eastern Norton Sound and the relative height inconsistencies that are based on in situ observations suggest that the report by Wise and others (1981) presents an over-simplification of recurrence intervals for eastern Norton Sound and should no longer be used as a reliable estimate of surge elevations for this region (Sector 9; Wise and others, 1981).

A 2009 study conducted by Chapman and others at the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory used storm hindcasting, a hydrodynamic circulation model, and a detailed bathymetric grid of Norton Sound to develop frequency-of-occurrence relationships for storm-surge water levels. The results of this modeling study indicate that the November 9, 2011, surge corresponds to a 10- to 15-year event for Unalakleet, a 15- to 25-year event for Shaktoolik, and a 100-year event for Nome (or a 50-year event based on the tide gauge values). The current Flood Insurance Study for the City of Nome (FEMA, 2010) presents flood elevation recurrence intervals that reflect the combined effects of astronomical tide, storm surge, wave setup, and runup; the November 9, 2011, water level was a 50-year event by this calculation.

The National Weather Service’s Meteorological Development Laboratory generates storm surge predictions as part

of their Extratropical Water Level Forecast program. These surge predictions are generated every 6 hours and are driven by the Global Forecast System (GFS) atmospheric model. A comparison of the measured surge heights (measured water level minus predicted astronomical tide) in Nome to the forecasted surge heights modeled by NWS during the storm is presented in figure 26. The magnitudes of the modeled storm surge heights encompass the peak observed storm tide levels in the four communities that we visited. As was demonstrated in the October 18–20, 2004, storm (Hufford and Partain, 2004), the NWS model was able to accurately predict the track, intensity, and timing of this storm with enough precision to produce site-specific surge predictions that could be used for emergency planning purposes.

Remeasured coastal profiles exhibited morphology typical of seasonal change, such as the removal of midbeach berms. Coastal retreat was only observed at a few locations; however, we observed notching at the base of bluffs, bluff or upper scarp steepening and the removal of vegetation, talus toes or protective debris at many of the revisited profiles. We anticipate the types of profile modifications we observed in the field at some locations will result in up to 1 m of coastal retreat of the bluff edge when thawing and re-equilibration occurs over the next year. Many of our post-storm coastal profiles also included one or more ice ridges or berms, some in excess of 1 m tall, on the lower shoreface. While these accreted ice features obscured the beach surface, they preserve a record of secondary surge elevations because they are deposited just above a peak water level. In Unalakleet a very consistent ice berm with a crest elevation of 3 m MLLW was observed in nearly all of the profiles. Unlike observations following the 1974 storm (Sallenger and Dingler, 1978; oral commun., Sallenger, 2012), the shoreface was not swept

clear of log-sized driftwood in most locations as a result of this storm and no new debris berms were observed at any of the revisited sites.

The ways in which this particular storm affected each community was shaped by both natural and man-made factors. The timing and direction of winds led to the development of protective bands of nearshore slush, particularly in front of Shaktoolik, which reduced the open-ocean wave energy in most of the communities we visited. The lag between the peak winds and peak surge also lessened the effects of the storm because maximum wind waves did not coincide with the peak surge. Engineering structures in the coastal zone, such as the revetment at the mouth of Unalakleet River and the newly elevated Antone Street on the lagoon side of Golovin, protected areas where floodwaters have spilled into communities in the past. Additionally, the advance warning from the National Weather Service and implementation of local emergency plans (Hufford and Partain, 2004) were instrumental in reducing damages including the loss of life and property.

As recognized by others, a timely field-response is critical to quantitatively document the extent of storm-related coastal flooding before features are obscured and cleanup occurs (NWS, 2010). Most documented rapid field responses to coastal flooding have been conducted following hurricanes or other warm-weather storms. The remote nature and harsh weather of northwestern Alaska present some unique difficulties to mounting a rapid response. Obstacles that the DGGs crew encountered included high winds, limited availability of daylight for field activities, difficulty accessing frozen or buried benchmarks, electronic issues in the equipment caused

by condensation in fluctuating temperatures, and drifting snow that quickly covered evidence of the recent flood in some areas (fig. 27).

While harsh weather inhibited some components of field operations, the cold also allowed for unique flood indicators that would not have been present in warmer climates. For example, tension cracks on the surface of the snow along the limit of inundation and truncated snowdrifts preserved the location of flood limits in areas where they would not have otherwise been visible. Furthermore, the deposition of slush-filled seawater at peak surge changed the character of the snow and ice at the surface so that in areas where snow had obscured the storm inundation extent we could traverse across the surface of the snow and could feel the extent of flooding in the behavior of the ice below our feet. In many cases, low-lying areas that were inundated during the peak surge were not able to drain due to frozen ground, and the water was frozen in place. Also, the abundance of large driftwood (and ice) in Norton Sound produced numerous debris lines that could be used to measure the extent of flood inundation.

By traveling to affected areas immediately after the storm we were able to collect photos, video, and eyewitness accounts that improved our final interpretations. In the summer, when most of our coastal hazards mapping field activities occur, local residents are often too busy with subsistence activities to locate old photos of storm events. We found that the active involvement of community members was a critical component of completing this rapid response work, particularly in the smaller communities. The prevalence of subsistence activities in some Alaskan villages poses additional challenges to coastal hazard evaluation and response

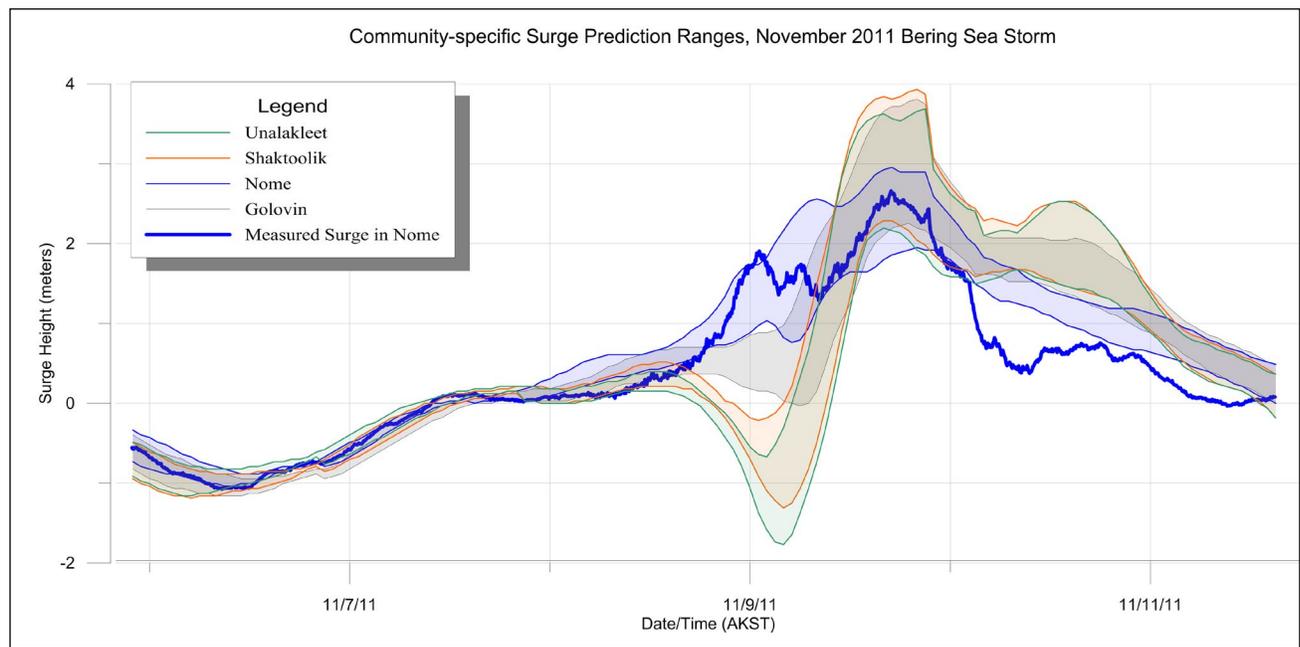


Figure 26. Plots of the total range of peak storm surge predictions made for each visited community as a function of time based on output from 20 individual National Weather Service model runs that were executed every six hours from November 6 to November 11, 2011.

because it changes the value emphasis on some community resources that are not present in much of the United States. For example, “fish camps provide an important winter food source, especially to low-income families” and damages to these types of temporary dwelling structures are not eligible for repair or replacement under federally declared disasters (written commun., Anungazuk, 2012).

Based on our team’s experiences in the field we would make the following recommendations to improve future rapid response work or to assist researchers working in similar conditions:

- If possible, install temporary water-level gauges in advance of storm events
- Attempt to identify benchmarks with published vertical positions that can be easily accessed in winter conditions for improved vertical control on measurements
- Maintain regular communication with emergency coordinators to ensure that field activities do not interfere with necessary emergency procedures
- Encourage residents to set timestamps on their personal cameras prior to a large storm event or note exact times of photograph collection
- Encourage residents to place stakes or other visible markers along water lines in the event that flood indicators have been lost by the time a field crew arrives
- In cold weather climates, revisiting coastal profiles both immediately after an event and post-thaw is necessary to fully document event-related change
- A continued expansion of the tide-gauge network in northwestern Alaska would improve local tidal datum corrections and improve site-specific predictions

During the summer of 2012, our team will continue CIAP-funded coastal hazard investigations in Golovin, along the Nome–Council Road and in other parts of western Alaska. This work will involve new baseline coastal profiles and

remeasurement of the three profiles that were established in Nome during the course of this reconnaissance trip. Additional work in Golovin in 2012 will examine rates of erosion along the bay side of the community and also investigate in more detail the site of the ivu. We will use the post-storm observations to improve our interpretation of coastal landforms and the evolution of coastal morphology in this region to enhance coastal hazard assessments. If conditions permit, the DGGs Coastal Hazards Program will conduct additional post-storm field activities of this type in the future.

## ACKNOWLEDGMENTS

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Bryan Fisher and the entire staff of the November 2011 Incident Command Center in Anchorage provided our DGGs team with timely information regarding on-the-ground conditions throughout the affected area, allowing us to time our arrival as soon after the storm as possible without interfering in emergency activities. Archived Global Forecast System surge predictions and National Weather Service statements from November 2011 were obtained with the assistance of John Lingaas at NOAA. We would like to thank Walter Combs and John Truitt at the FAA Aviation Cameras Program for retrieving FAA webcam captures before deletion. George Plumley (DCCED) and Alexa Green (DOT&PF) provided us with critical elevation data that allowed us to constrain the vertical control in Golovin. Julie Prusky and Dave Doyle at NOAA/NGS gave guidance for adjustment to

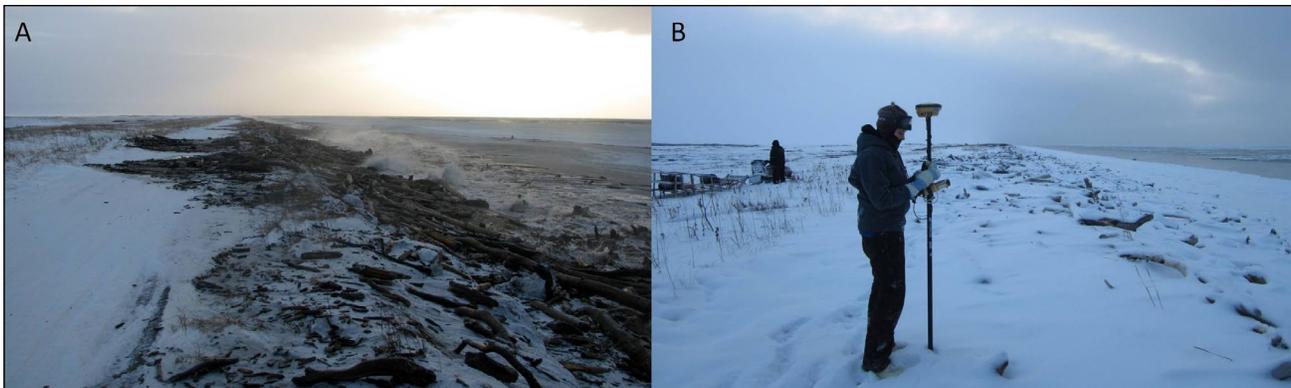


Figure 27. These two photos taken near the runway at the old community site south of Shaktoolik illustrate the importance of a rapid response to collect useful measurements of storm surge elevations. The slush and debris lines clearly visible (a) within a day of the storm (photo by Elmer Bekoalok) were already being obscured by snow (b) less than four days after the event.

the tidal datum in Nome. We would also like to thank Abby Sallenger for taking the time to discuss his post-1974 storm observations from the region with us. Ann Gibbs (USGS), Bruce Richmond (USGS), Ruth Carter (DOT&PF) and Toby Anungazuk (Chinik Eskimo Community, Golovin) provided insightful reviews and recommendations that have greatly improved the final manuscript.

We would like to extend our deepest gratitude to all of the community residents who took the time to share their videos, photographs, and observations with us and to those who provided us with feedback that improved this report. We would not have been able to collect many of the measurements contained in this report without the logistical support, transportation, and lodging to which we were generously given access so soon after the storm occurred. In particular we would like to thank the following people for their exceptional assistance in support of this work: Steve Ivanoff, Harry Johnson, and Maggie Halleran of Unalakleet; Eugene Asicksik, Myron Saveitilik, Elmer Bekoalok, Harvey Sookiyayak, and the Paniptchuk family of Shaktoolik; as well as Chon Peterson, Don and Carol Oliver, and Jack Fagerstrom of Golovin.

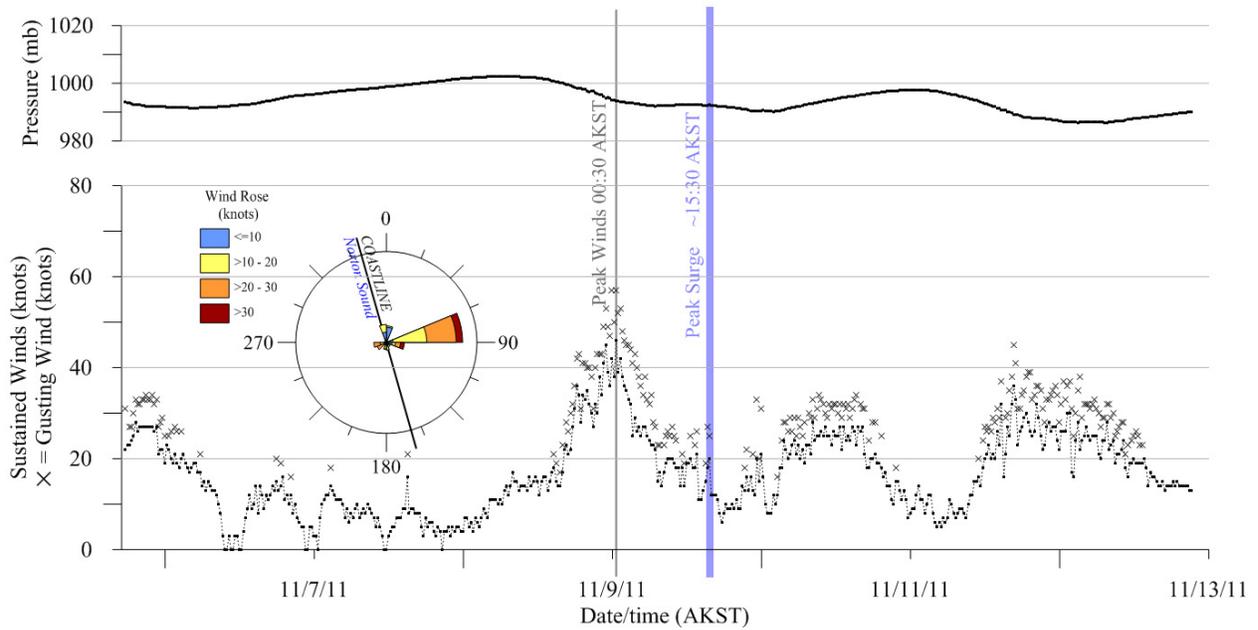
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## Appendix A

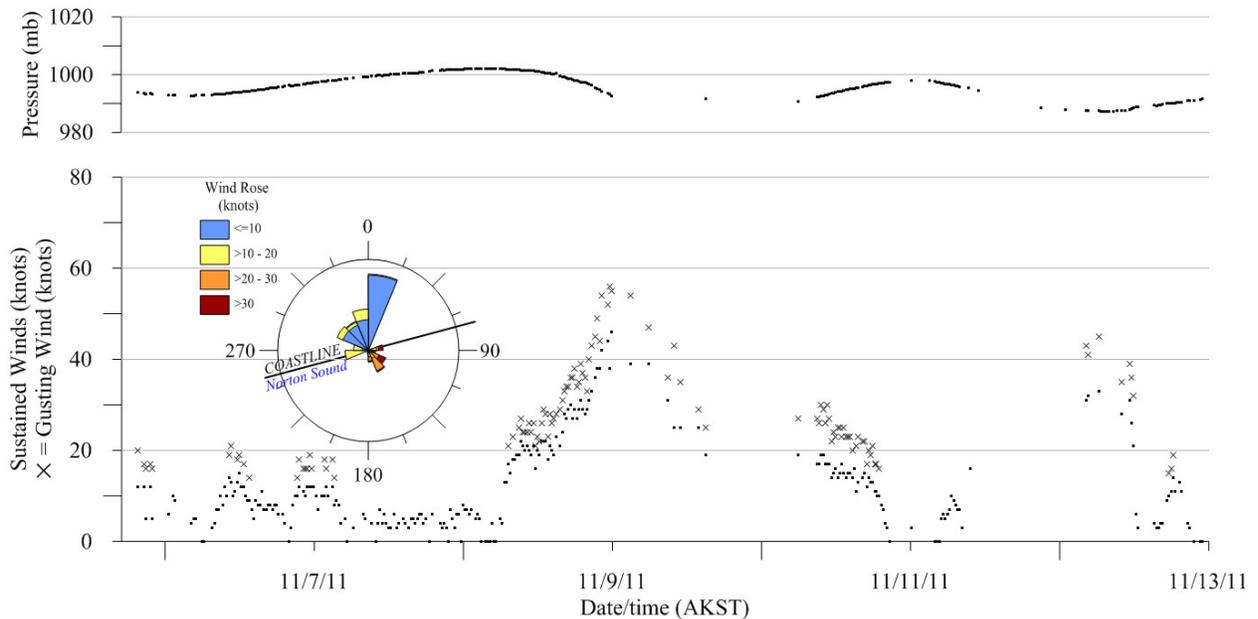
### Atmospheric Conditions, Unalakleet Airport Automated Weather Station, Nov. 5–12, 2011



Note: Estimated time of peak surge in Unalakleet is based on FAA webcam images.

### Atmospheric Conditions, Golovin Airport Automated Weather Station, Nov. 5–12, 2011

Note: Gaps in data due to weather station outages

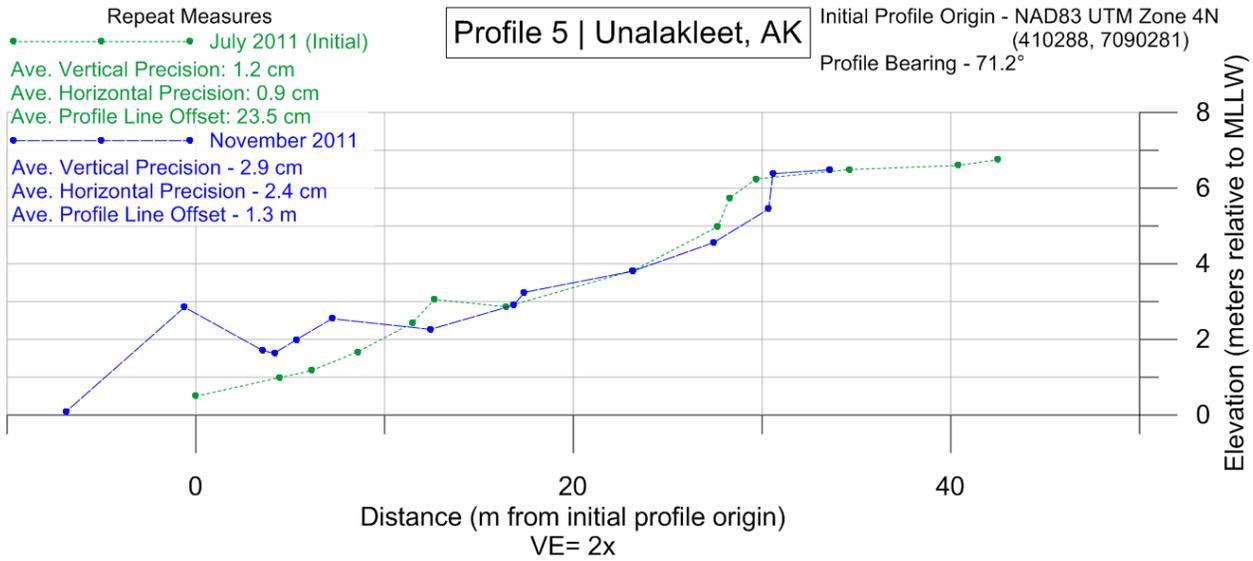




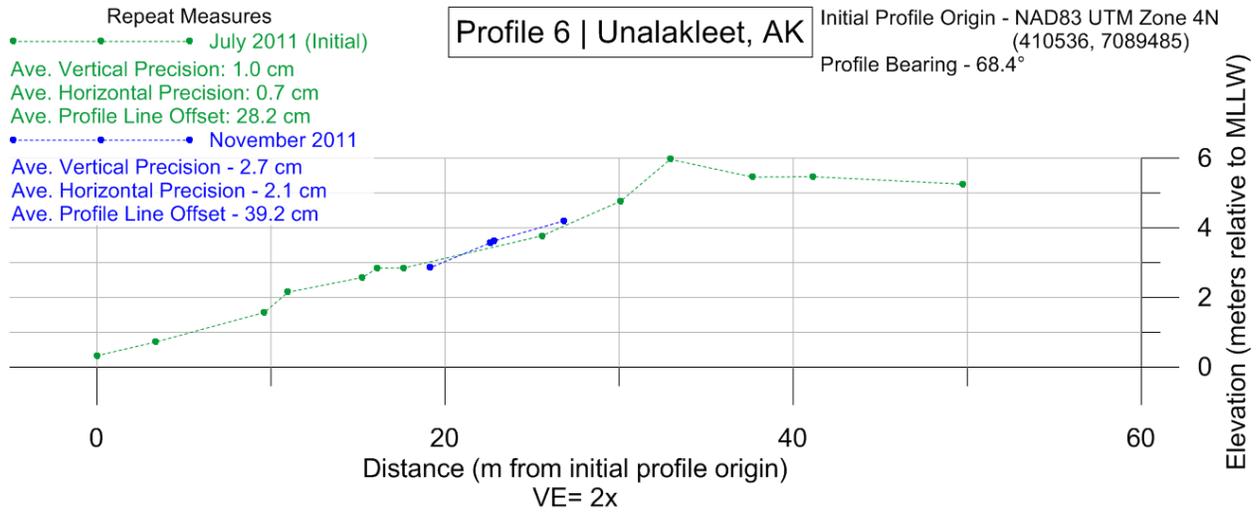
## Appendix B

Fifteen coastal profiles that were established by DGGs in July 2011 were revisited following the November 2011 Bering Sea Storm. The following pages include detailed information regarding each of the resurveyed profiles listed in the table below. For each location we present a vertical plot of July and November 2011 profiles, a short summary of key features observed, and representative photographs. The average precision values presented for each profile are the standard deviation of the post-processed data and are not representative of total GPS error (coordinate precision + positional accuracy). GPS accuracy was best during the summer surveys; accuracies were better than 4 cm in both the horizontal and vertical directions for all of the presented data. More detailed profile information may be available in location-specific DGGs reports.

<b>Community</b>	<b>Remeasured Profile Number</b>
Unalakleet	Profile 05 Profile 06 Profile 07 Profile 10 Profile 11 Profile 12 Profile 13 Profile 14 Profile 15 Profile 16
Shaktoolik	Profile 14 Profile 20/21 Profile 29 Profile 30



<p><b>Profile Setting:</b>                  Located 5.4 km north of the Unalakleet airport. Profile extends from Norton Sound to the road (across the road in July profile) that leads north to Powers Creek. The backbeach is characterized by a low coastal bluff capped by grassy vegetation.</p>	
<p><b>July 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Coarse sand lens present in the intertidal zone</li> <li>• Moderately-well-developed gravel horns/beach cusps on lower shoreface</li> <li>• Well-developed berm on the mid shoreface</li> <li>• Woody debris concentrated in mid shoreface runnel and at the toe of low backbeach bluff</li> <li>• Scarped portion of bluff composed of interbedded sands and gravels with organic cap</li> <li>• Talus toe present at base of coastal bluffs</li> <li>• Woody debris observed atop shoulder of bluffs</li> </ul>	
<p><b>November 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Block failures and bluff face steepening due to marine erosion at the base of the bluffs</li> <li>• Woody debris and slush was tossed up and over the bluff edge onto the edge of the road by waves</li> <li>• Wave notching/undercutting observed at bluff toe</li> <li>• Upper shoreface is not covered by thick layer of ice, the shoreface is exposed</li> <li>• Two gravel-rich ice ridges have formed on the lower shoreface</li> </ul>	
<p><b>Other Notes:</b>                  This resurveyed profile is discussed in more detail in the report.</p>	



**Profile Setting:**

Located 4.5 km north of the Unalakleet airport, just north of the barge landing site. Profile extends from Norton Sound across the road that leads north to Powers Creek. The backbeach is characterized by a tall driftwood debris deposit.

**July 2011 Notes:**

- Poorly-developed gravel horns/beach cusps on lower shoreface
- Low and poorly-developed gravel berm on the mid shoreface
- Large, woody debris across the entire upper half of the shoreface
- Patch of beach peas and grass on upper shoreface fronting tall line of woody debris at backbeach



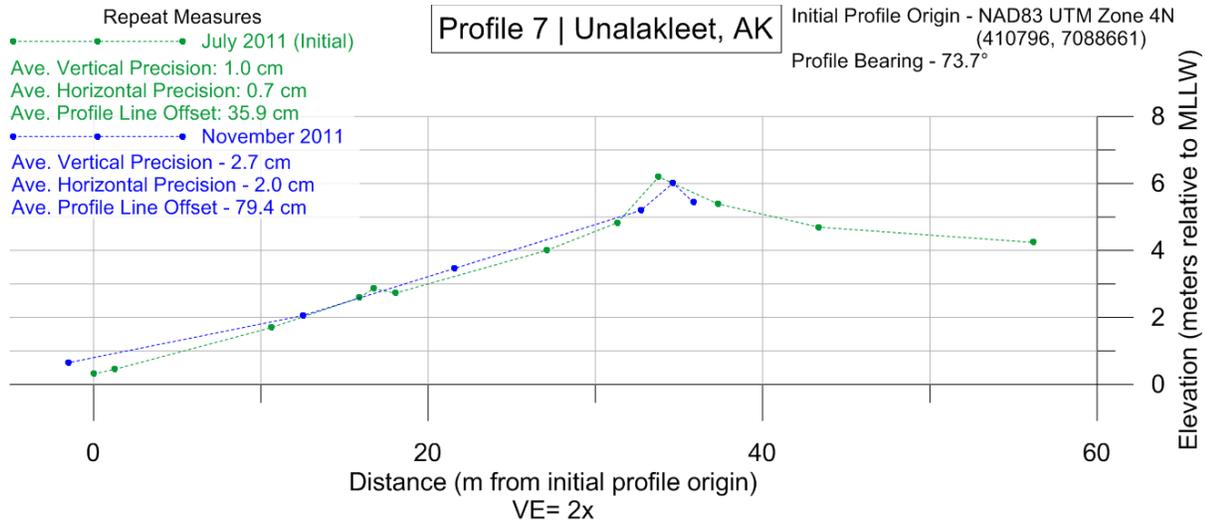
**November 2011 Notes:**

- Limited/no overtopping or beaching of the backbeach woody debris line occurred
- Woody debris and rounded ice chunks limited to upper shoreface only
- One ice ridge is present on the lower mid shoreface
- Wide bands of accreted slush in the intertidal region

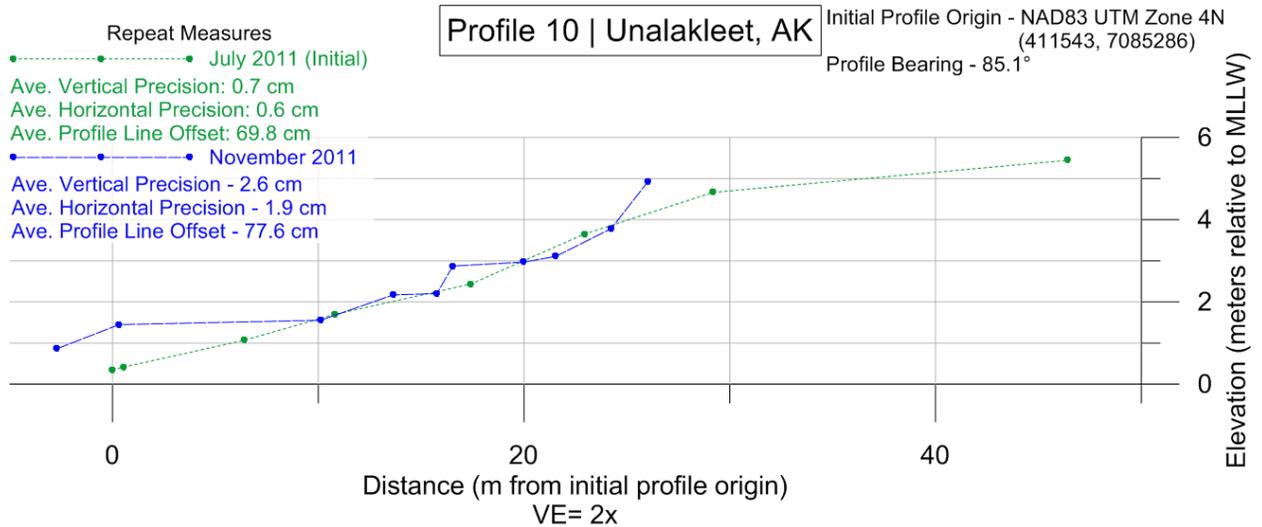


**Other Notes:**

The November profile is incomplete; the number of measured locations along profile 6 is small because of a processing failure at several points along the profile, likely due to an inadequate satellite lock between the rover and base receivers.



<p><b>Profile Setting:</b>                  Located 3.6 km north of the Unalakleet airport, north of the bridge across Kouwegok Slough. Profile extends from Norton Sound to/across the road that leads north to the barge site and Powers Creek. The backbeach is characterized by a low, woody debris deposit atop a vegetated gravel ridge.</p>	
<p><b>July 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Sand lens present atop gravel on the lower shoreface along the ATV trail</li> <li>• Low and poorly-developed gravel berm on the mid shoreface</li> <li>• Woody debris across the entire upper half of the shoreface to vegetation line</li> <li>• Dense/wide patch of beach peas and grass on upper shoreface fronting low, woody debris line</li> </ul>	
<p><b>November 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Low, woody debris line at backbeach was overtopped and partially breached during storm</li> <li>• Woody debris moved upslope in the storm, extending from mid shoreface to base of low, woody debris line on backbeach ridge</li> <li>• Low, cusped ice ridge just above accreted bands of slush in the intertidal</li> </ul>	
<p><b>Other Notes:</b>                  None</p>	



**Profile Setting:**

Located at the seaward end of Runway 26 in front of an armor rock revetment north of the dynamically stable engineered beach project. Profile extends from Norton Sound to the paved runway threshold. The airport fence is discontinuous at this location.

**July 2011 Notes:**

- Locally quarried rip rap forms a revetment at the end of the runway
- Fine-grained sediment has been pushed up and placed on top of low half of revetment by a bulldozer
- Some large, woody debris is strewn at the base of the revetment
- Sand lenses are present on the lower shoreface along the ATV trail



Photo by Harvey Smith, DOT&PF

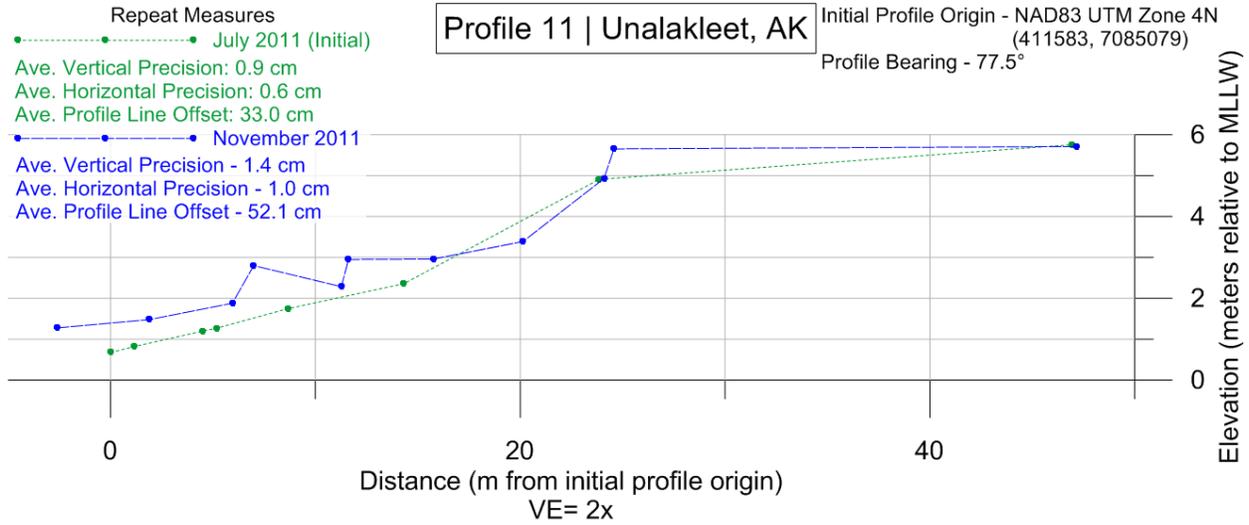
**November 2011 Notes:**

- Log-sized woody debris was deposited on paved runway threshold during storm
- Convex profile of armor rock suggests some slumping of the revetment occurred
- Large ice ridge present at the base of the revetment
- Ice blocks and logs on the lower shoreface are pushed up against the ice ridge
- Cuspate bands of accreted slush in the intertidal region



**Other Notes:**

Additional armor rock was emplaced at this location on top of the finer-grained fill prior to Fall 2011. The effects of this addition are visible in the measured profiles and in the appearance of the revetment. Some debris had been cleared from the paved runway surface and pushed onto the revetment by work crews prior to the post-storm measurements. The complete summer profile includes offshore bathymetry at this location.



**Profile Setting:**

Located next to the main building at the DOT&PF-engineered beach project. Profile extends from Norton Sound to the parking area next to the airport building. Concrete barriers atop the revetment mark the outer edge of the parking area.

**July 2011 Notes:**

- Dynamically stable beach (engineered by DOT&PF)
- Parking area extends onto crest of engineered portion of beach
- Fine-grained material has been added to the face of the engineered beach project by a bulldozer
- Some minor woody debris is strewn at the base of the revetment
- Sand lenses are present on the lower shoreface along the ATV trail



Photo by Ruth Carter, DOT&PF

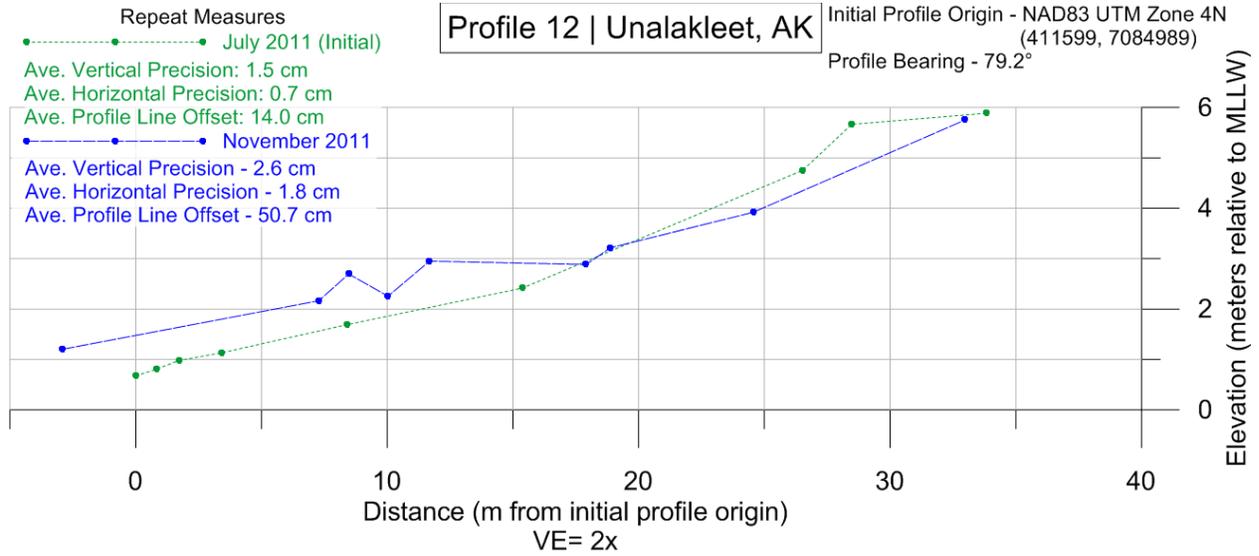
**November 2011 Notes:**

- Steepening and minor undercutting below the concrete barriers has occurred at the crest of the dynamically stable beach
- No overtopping of the crest by water or debris was observed at this profile location
- Two large ice ridges have developed on the lower shoreface
- Woody debris is all oriented parallel to shore in front of and between the ice ridges
- Linearly accreted bands of slush are present in the intertidal zone



**Other Notes:**

The dynamically stable beach was extended seaward of the recommended design template at this location. This resurveyed profile is discussed in more detail in the report.



**Profile Setting:**

Located next to the ATS building at the dynamically stable engineered beach project. Profile extends from Norton Sound to the edge of the DOTPF road.

**July 2011 Notes:**

- Dynamically stable beach (engineered by DOT&PF)
- Fine-grained material has been added to the face of the engineered beach project by a bulldozer
- Some minor woody debris is present on the face of the engineered beach
- Sand lenses are present on the lower shoreface along the ATV trail



*Photo by Harvey Smith, DOT&PF*

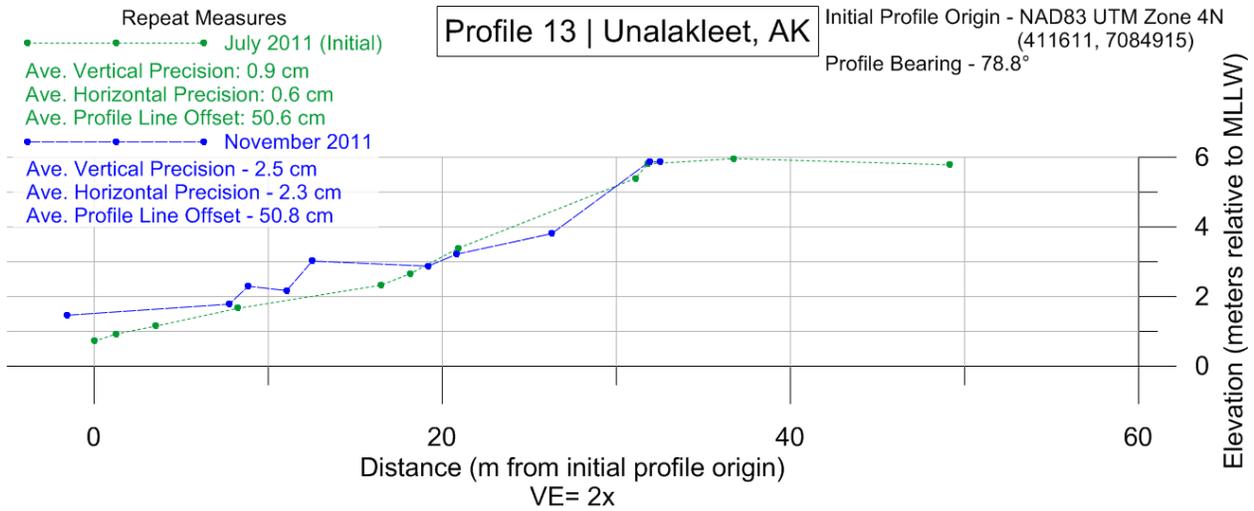
**November 2011 Notes:**

- Woody debris from overtopping was observed at the crest of engineered beach
- Woody debris and ice chunks are evenly strewn across the mid shoreface
- Two ice ridges present on the lower shoreface
- Woody debris is all oriented parallel to shore in front of and between the ice ridges
- Linearly accreted bands of slush are present in the intertidal area

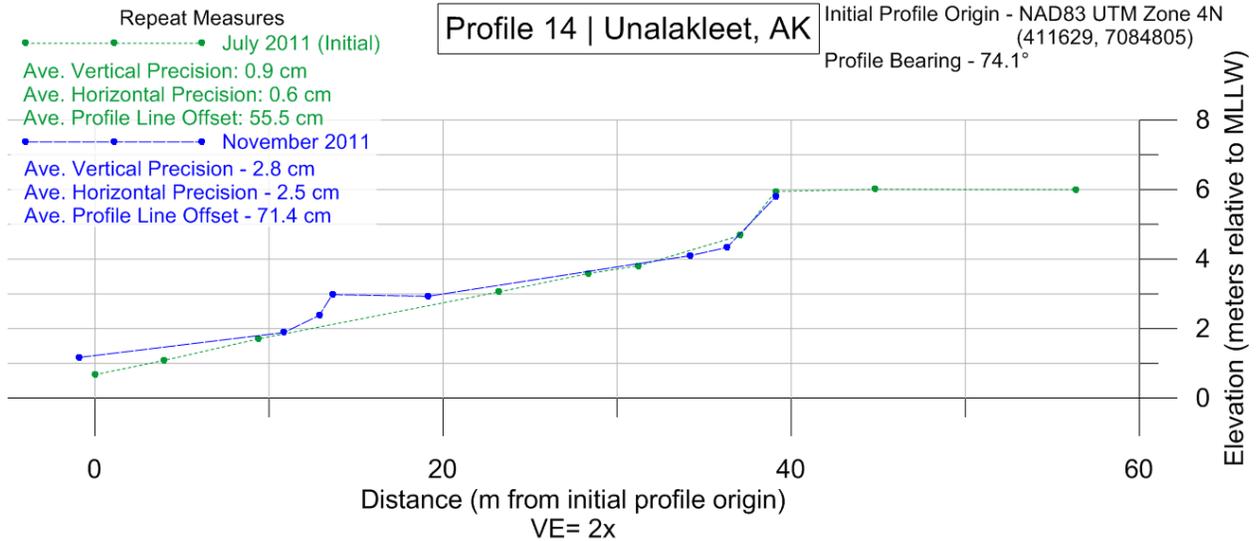


**Other Notes:**

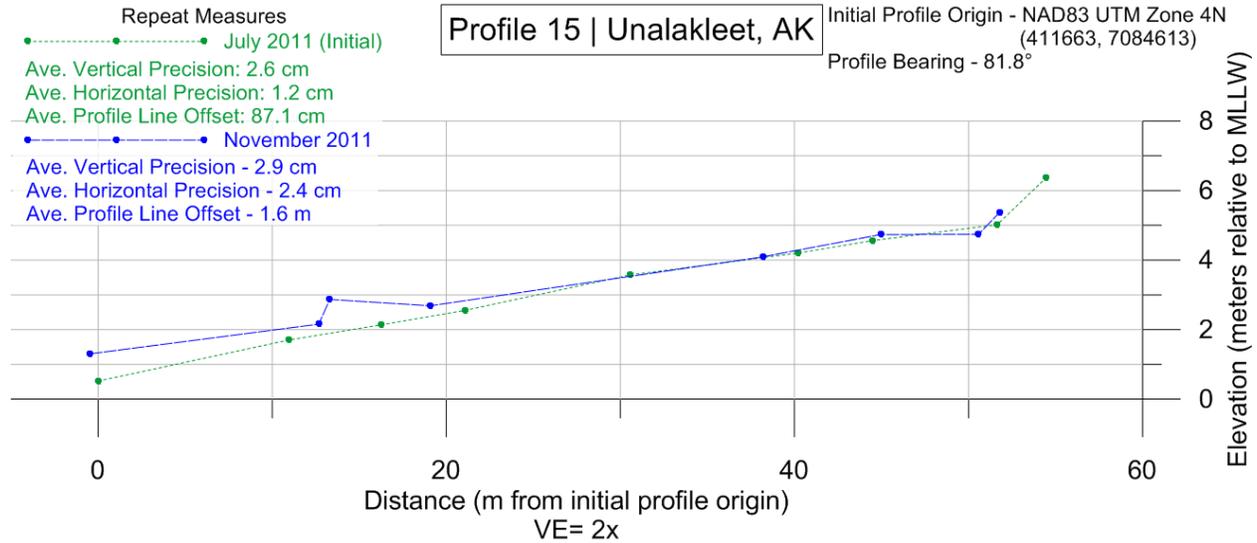
This resurveyed profile is discussed in more detail in the report.



<p><b>Profile Setting:</b> Located next to the BSSD Hanger at the dynamically stable engineered beach project. Profile extends from Norton Sound to the inland edge of the DOT&amp;PF road.</p>	
<p><b>July 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Dynamically stable beach (engineered by DOT&amp;PF)</li> <li>• Fine-grained material has been added to the face of the engineered beach project by a bulldozer, in some areas obscuring coarse clasts entirely</li> <li>• Some minor woody debris is present on top of the fill material on the face of the engineered beach</li> <li>• Sand lenses are present on the lower shoreface along the ATV trail</li> </ul>	<p><i>Photo by Harvey Smith, DOT&amp;PF</i></p>
<p><b>November 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Abundant woody debris from overtopping was observed at the crest of engineered beach, some was reportedly cleared away already</li> <li>• Engineered beach slope was visibly scarped near the base and frozen blocks of finer-grained material had been deposited at the toe</li> <li>• Two ice ridges present on the lower shoreface</li> <li>• Woody debris is all oriented parallel to shore in front of and between the ice ridges</li> <li>• Linearly accreted bands of slush are present in the intertidal</li> </ul>	
<p><b>Other Notes:</b> This resurveyed profile is discussed in more detail in the report.</p>	



<p><b>Profile Setting:</b>                  Located between the old DOT&amp;PF garage and the FAA building at the dynamically stable engineered beach project. Profile extends from Norton Sound to the inland edge of the DOT&amp;PF road and crosses an ATV access trail to the beach.</p>	
<p><b>July 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Dynamically stable beach (engineered by DOT&amp;PF)</li> <li>• Boulders are present in fine gravel at the base of the engineered portion of the beach</li> <li>• Woody debris has been cleared from this area</li> <li>• Some beach peas have grown next to the upper ATV trail (fine gravel)</li> <li>• Sand lenses are present on the lower shoreface along the lower ATV trail</li> </ul>	
<p><b>November 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Abundant storm-deposited driftwood debris was observed at the crest of engineered beach, some was reportedly cleared away before our observation</li> <li>• Large blocks of ice and some woody debris deposited near toe of engineered beach slope</li> <li>• Two ice ridges present on the lower shoreface</li> <li>• Linearly accreted bands of slush are present in the intertidal region</li> </ul>	
<p><b>Other Notes:</b>                  This resurveyed profile is discussed in more detail in the report.</p>	



**Profile Setting:**

Located next to the BSSD garage. Profile extends from Norton Sound to the seaward edge of Beach West Road.

**July 2011 Notes:**

- A mid-beach line of coarse gravel is present but a berm has not formed
- The mid-upper shoreface is sparsely vegetated by beach peas and grass
- A woody debris line, mixed with minor vegetation, is present along the base of the graded road



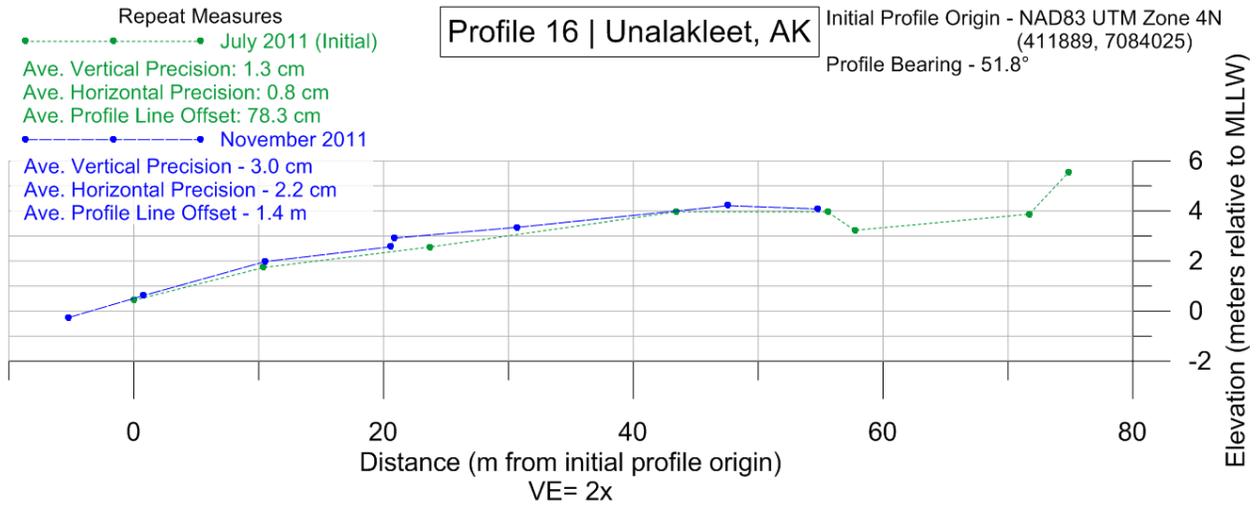
**November 2011 Notes:**

- Slush and small, woody debris deposited by runup on slope of the graded road surface
- Large, woody debris line present along base of roadway
- At location of profile, a woody debris line was breached and large volumes of coarse sand and slush were deposited on the upper shoreface
- Ice ridge present on lower shoreface
- Woody debris is all oriented parallel to shore in front of the ice ridge
- Linearly accreted bands of slush are present in the intertidal zone

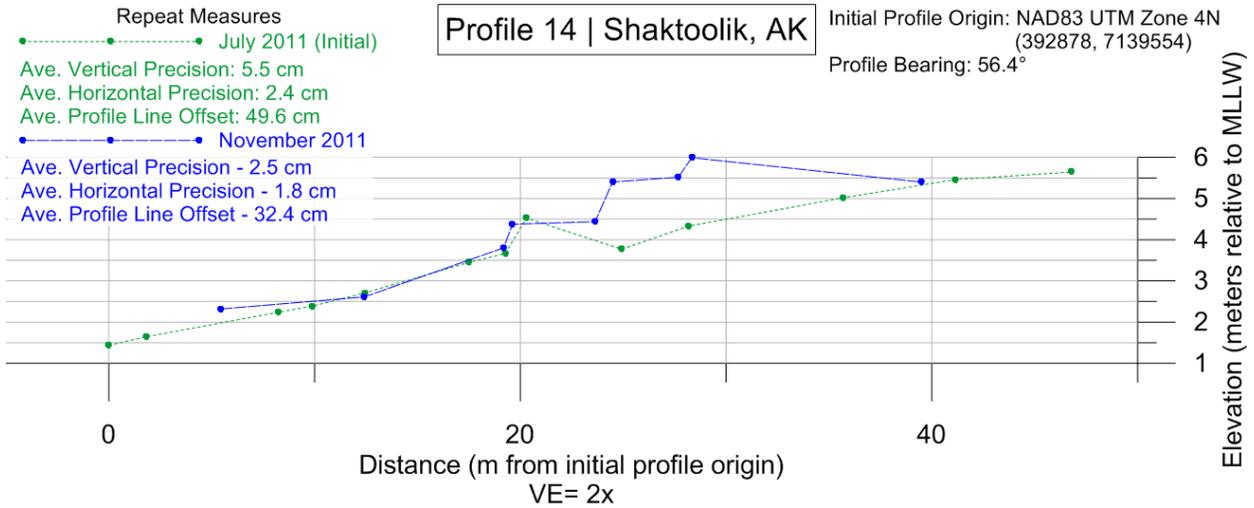


**Other Notes:**

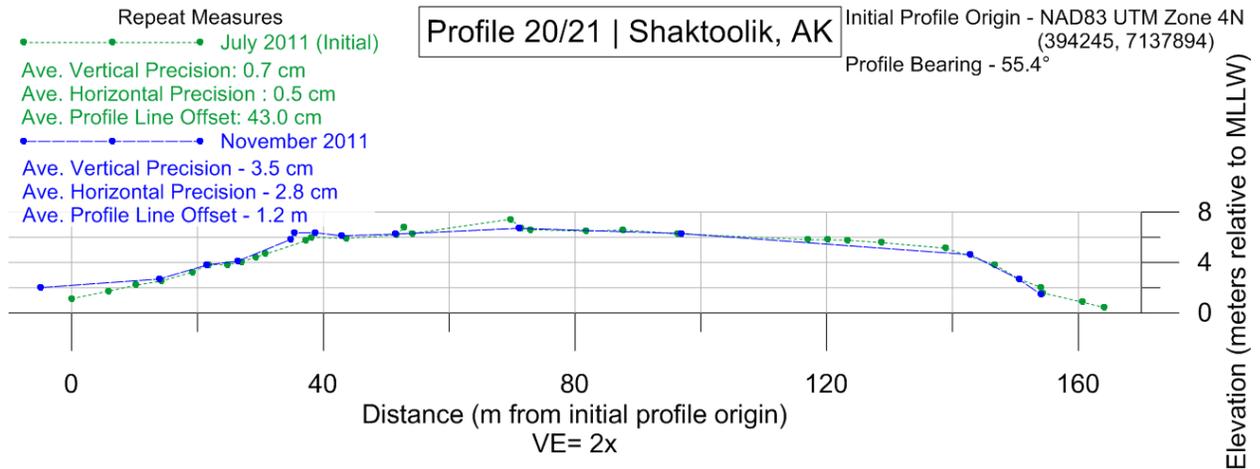
See Figure 9a in report for example of a runup line collected along this profile on the road grade.



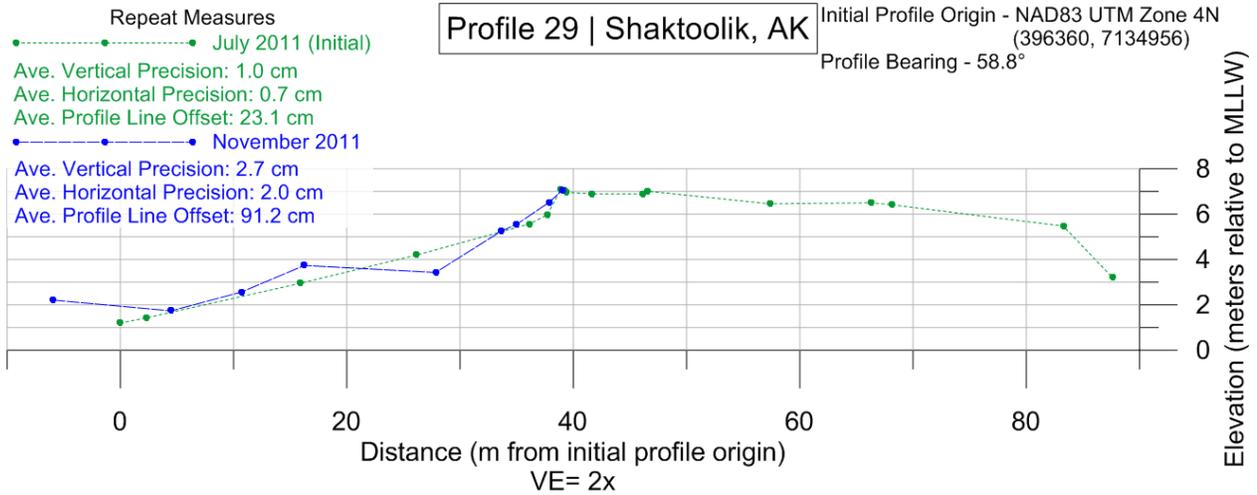
<p><b>Profile Setting:</b>                  Located near the inlet mouth, 100 m north from the end of the U.S. Army Corps of Engineers (USACE) revetment. Profile extends from Norton Sound to the seaward edge of the raised Beach Road.</p>	
<p><b>July 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>Wide, low-angle beach composed primarily of coarse sand</li> <li>Woody debris present on the lower shoreface just above the intertidal zone</li> <li>Low area adjacent to the raised road is filled with beach grasses and log-sized woody debris</li> </ul>	
<p><b>November 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>Stable vegetation inland of remeasured portion of profile, adjacent to the raised road</li> <li>Fish-drying racks in area were not damaged even though they were inundated at the base</li> <li>Abundant jumbled ice and woody debris present across entire remeasured profile</li> <li>Minor ice ridge present on the mid shoreface</li> </ul>	
<p><b>Other Notes:</b> None</p>	



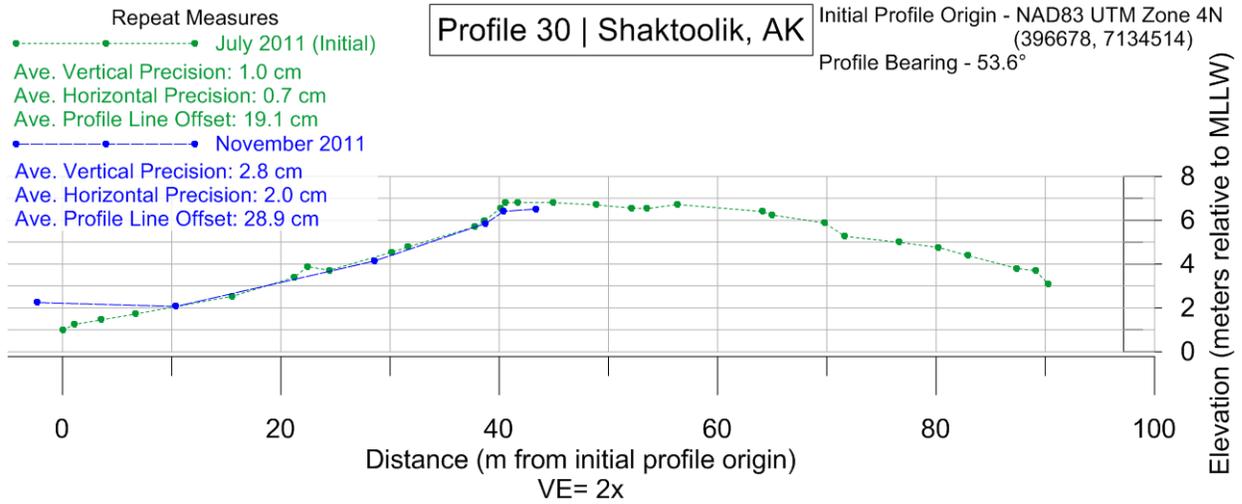
<p><b>Profile Setting:</b>                  Located next to the runway and apron near the airport building. Profile extends from Norton Sound to the inland extent of woody debris observed on the berm adjacent to the runway surface.</p>	
<p><b>July 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Mid-profile berm is capped by a large amount of log-sized woody debris</li> <li>• Woody debris present from crest of lower berm to area below the runway surface</li> <li>• Sparse vegetation (grasses) present in area inland from lower berm</li> </ul>	
<p><b>November 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Large quantities of slush were washed up and frozen atop pre-existing woody debris</li> <li>• Area between lower berm and edge of runway surface is filled with drifted snow and ice</li> <li>• Multiple generations of steep ice and slush ridges present across the profile</li> </ul>	
<p><b>Other Notes:</b>                  Complete summer profile includes more measured elevations farther inland.</p>	



<p><b>Profile Setting:</b></p> <p>Located next to the tank farm and adjacent to the community. Profile extends from Norton Sound across the barrier spit to the bank of Tagoomenik River.</p>	
<p><b>July 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>Sand lenses present on the lower shoreface along the lower ATV trail</li> <li>Two lines of woody debris on the upper shoreface; one sits atop a lower berm and one caps the upper berm directly in front of the tank farm</li> <li>Beach peas and grasses present between the woody debris lines</li> <li>Tank farm is surrounded by a low levee of sandbags and geotextile material</li> <li>Edge of Tagoomenik River is well vegetated by grasses, with a narrow, sandy beach at the base of a &lt;1 m scarp in the riverbank</li> </ul>	
<p><b>November 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>Low ice and frozen slush ridge with a stepped surface present at front edge of upper woody debris line</li> <li>Lower woody debris line is no longer present</li> <li>Waves did not overtop the upper woody debris line at this location; runoff of slush is visible below snow cover</li> <li>Shoulder of Tagoomenik River bank is heavily drifted over by snow that has an icy crust that is difficult to penetrate</li> <li>Tagoomenik River is slushy and covered with large floating pieces of ice</li> </ul>	
<p><b>Other Notes:</b></p> <p>The engineered berm surrounding the tank farm was not remeasured in November 2011. This resurveyed profile is discussed in more detail in the report.</p>	



<p><b>Profile Setting:</b>                  Located next the old runway at the former community site. Profile extends from Norton Sound to the bank of Tagoomenik River.</p>	
<p><b>July 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Well-developed gravel horns and beach cusps</li> <li>• Abundant large, woody debris on entire upper half of shoreface</li> <li>• Debris toe with sparse vegetation at base of low, eroding gravel bluff</li> <li>• Woody debris had been deposited atop low bluff and across old runway</li> <li>• Bank of Tagoomenik River is steep and densely covered by low willows</li> </ul>	
<p><b>November 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Extensive slush and woody debris overwash 2 m north of profile location</li> <li>• Wood debris and frozen slush pushed up against the low bluff at the backbeach</li> <li>• Less woody debris on the upper shoreface than was seen at this location in the summer</li> <li>• Low ice ridge containing lots of gravel on the mid shoreface</li> <li>• Slush ridges containing logs are present in the intertidal zone</li> </ul>	
<p><b>Other Notes:</b>                  Complete summer profile includes offshore bathymetry.</p>	



<p><b>Profile Setting:</b>                  Located next the old runway at the former community site and near an ATV access trail to the beach. Profile extends from Norton Sound to a low floodplain adjacent to Tagoomenik River.</p>	
<p><b>July 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Well-developed gravel horns and beach cusps</li> <li>• Low gravel berm present at the mid shoreface</li> <li>• Abundant large, woody debris on entire upper half of shoreface</li> <li>• Debris toe with sparse vegetation at base of low, eroding gravel bluff</li> <li>• Woody debris observed on inland side of old runway</li> <li>• Floodplain is grassy with patches of shrubby willow and birch</li> </ul>	
<p><b>November 2011 Notes:</b></p> <ul style="list-style-type: none"> <li>• Additional woody debris has been deposited atop the old runway surface</li> <li>• No horizontal retreat of the low bluff observed</li> <li>• Less woody debris on the upper shoreface than was seen at this location in the summer</li> <li>• Slush and ice ridges are present in the intertidal area</li> </ul>	
<p><b>Other Notes:</b>                  Snow cover obscured the full extent of woody debris deposited atop the old runway during the November 2011 storm.</p>	



## Appendix C

### Archived data from National Data Buoy Center Station 46035 – BERING SEA 310 NM North of Adak, AK

Available online at: [http://www.ndbc.noaa.gov/station\\_page.php?station=46035](http://www.ndbc.noaa.gov/station_page.php?station=46035)

Buoy location: 57.067°N 177.750°W or 57°40"N 177°45"W

#YY	MM	DD	hh	mm	WDIR	WSPD	GST	WVHT	DPD	APD	MWD	PRES	ATMP	WTMP	DEWP	VIS	TIDE
yr	mo	dy	hr	mn	degT	m/s	m/s	m	sec	sec	degT	hPa	degC	degC	degC	mi	ft
2011	11	08	19	50	166	24.1	32.7	7.43	11.43	8.38	999	970.1	999.0	999.0	999.0	99.0	99.00
2011	11	08	20	50	175	25.1	32.3	9.69	12.12	9.32	999	966.6	999.0	999.0	999.0	99.0	99.00
2011	11	08	21	50	188	23.9	29.4	10.95	13.79	10.26	999	965.3	999.0	999.0	999.0	99.0	99.00
2011	11	08	22	50	207	25.8	32.0	11.72	13.79	10.71	999	965.5	999.0	999.0	999.0	99.0	99.00
2011	11	08	23	50	212	28.5	37.1	10.67	13.79	10.02	999	970.6	999.0	999.0	999.0	99.0	99.00
2011	11	09	00	50	222	27.6	35.9	12.07	13.79	10.69	999	972.9	999.0	999.0	999.0	99.0	99.00
2011	11	09	01	50	219	26.1	33.3	11.09	13.79	10.30	999	976.9	999.0	999.0	999.0	99.0	99.00
2011	11	09	02	50	217	25.1	31.9	12.14	14.81	11.29	999	980.2	999.0	999.0	999.0	99.0	99.00
2011	11	09	03	50	215	23.9	30.4	10.68	13.79	10.82	999	983.0	999.0	999.0	999.0	99.0	99.00
2011	11	09	04	50	221	22.7	29.9	11.84	16.00	11.59	999	985.4	999.0	999.0	999.0	99.0	99.00
2011	11	09	05	50	218	20.8	26.9	10.63	16.00	10.83	999	987.5	999.0	999.0	999.0	99.0	99.00
2011	11	09	06	50	218	20.1	26.4	10.25	14.81	11.11	999	989.7	999.0	999.0	999.0	99.0	99.00
2011	11	09	07	50	218	18.7	23.3	10.92	14.81	10.98	999	991.0	999.0	999.0	999.0	99.0	99.00
2011	11	09	08	50	218	16.4	20.6	10.39	12.90	10.75	999	991.5	999.0	999.0	999.0	99.0	99.00
2011	11	09	09	50	212	17.2	21.5	8.46	13.79	9.87	999	991.3	999.0	999.0	999.0	99.0	99.00
2011	11	09	10	50	225	18.7	22.5	9.11	13.79	10.01	999	991.4	999.0	999.0	999.0	99.0	99.00
2011	11	09	11	50	228	16.6	19.8	9.33	13.79	9.83	999	991.2	999.0	999.0	999.0	99.0	99.00
2011	11	09	12	50	228	19.7	25.1	8.74	12.90	9.51	999	991.0	999.0	999.0	999.0	99.0	99.00
2011	11	09	13	50	216	18.3	23.0	8.10	12.12	9.17	999	990.6	999.0	999.0	999.0	99.0	99.00
2011	11	09	14	50	208	15.7	18.8	7.19	12.12	8.83	999	989.4	999.0	999.0	999.0	99.0	99.00

Relevant NOAA measurement descriptions:

WVHT: “Significant wave height (meters) is calculated as the average of the highest one-third of all of the wave heights during the 20-minute sampling period.”

DPD: “Dominant wave period (seconds) is the period with the maximum wave energy.”

Estimate of maximum wave setup conditions based on open ocean storm conditions:

Calculation of deep-water wave length ( $L_\infty$ ) using standard linear airy-wave theory equations for deep-water waves:

$$L_\infty = \frac{gT^2}{2\pi} \quad \text{where wave period (T) = 14.81 seconds} \quad L_\infty = 342 \text{ m}$$

Based on an observed typical Norton Sound region beach slope (S) of 5:100, the dimensionless deep-water Iribarren number ( $\xi_\infty$ ) under the above conditions would be:

$$\xi_\infty = \frac{S}{\sqrt{H_\infty/L_\infty}} \quad \text{where } H_\infty = 12.14 \text{ m} \quad \xi_\infty = 0.27$$

Using the empirical relationship between deep-water significant wave height, the Iribarren number, and the maximum setup height at the shoreline ( $\bar{\eta}_{max}$ ) identified by Holman and Sallenger (1985)<sup>1</sup>, we can estimate an expected value for these storm conditions:

$$\bar{\eta}_{max} = 0.45\xi_\infty H_\infty \quad \bar{\eta}_{max} = 1.5 \text{ m}$$

<sup>1</sup> Holman, R.A., and Sallenger, A.H., 1985, Set-up and swash on a natural beach: *Journal of Geophysical Research*, v. 90, no. C1, p. 945–953.