Climatic Change (2021) 164:22
https://doi.org/10.1007/s10584-021-02995-4

Storm surge proxies in a data-poor landscape: a practical monitoring method for under-surveyed and -studied communities vulnerable to climate change

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Received: 10 January 2020 / Accepted: 6 January 2021/Published online: 26 January 2021

Abstract
The central problem we investigate is how coastal communities in the Arctic can plan for future storms in the absence of continuous, long-term data and/or instrumentation to monitor climatic events. The native village of Shaktoolik, Alaska recognizes these limitations and seeks increased monitoring of life-threatening storms affecting their village in their adaptation planning documents. To address this situation, and with the consent of the Tribal Council, we establish a baseline to monitor storm intensity in this data-poor region by dating and mapping storm surges in the Shaktoolik area. A storm surge is a proxy of storm intensity. We use driftwood in two ways to reconstruct past storm surges. First, we plot GPS points of driftwood lines on remote sensing imagery and digital elevation model data to map the maximum extent of storm surge for the November 2011 and 2013, and August 2019 storms. Second, in order to demonstrate that a particular log could have been deposited by those storms, dendrochronological analysis of individual logs within those deposits provides an estimate of when those trees died and could have entered the water as driftwood. These techniques, however, cannot determine the date of when those logs were deposited on a given beach. To narrow the date of the driftwood deposits from past storms, that is, to determine when the driftwood landed on the beach, local knowledge and observations are coupled with newspaper accounts. From these three lines of evidence, we show that the maximum storm surge the village can withstand without inundation is equivalent to the 2011 and 2019 storms. Those storms can be used as baseline indicators for future storms. This method of monitoring storm surges can be scaled up to other locations that also have minimal storm monitoring infrastructure.

Keywords Climate change · Storms · Storm surge · Driftwood · Shaktoolik

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1 Introduction

In the scientific literature, as assessed by the Intergovernmental Panel on Climate Change (IPCC), the consensus is that it is *likely* that climate change increased the frequency and intensity of extratropical storms in the north Pacific since the 1950s (IPCC 2007), but there is *low confidence* in this understanding (IPCC 2012). And, while it is *likely* that extratropical storms have shifted northward in the last 50 years, the evidence linking climate change to increased storm intensity and storminess is not robust "over the last century due to inconsistencies between studies or lack of long-term data" (IPCC 2014: 220). Observational studies continue to differ on whether Arctic storminess has increased or decreased (Day and Hodges 2018).

Hunters, fishers, and gatherers in Shaktoolik, AL (Fig. 1) possess local and traditional ecological knowledge (TEK) about climate change-induced biophysical change in their regions that largely corroborates the scientific observations and understanding of climate change in the Arctic (Ignatowski and Rosales 2013). An area of divergence, however, pertains to the level of confidence in the increased intensity of storms in the region. TEK holders in Shaktoolik state that storms are now stronger and more dangerous than 30 years ago (Ignatowski and Rosales 2013) and that these observations are particularly obvious in their native village evidenced with successive driftwood deposits in front of their homes marking storm events (Rosales and Chapman 2015) (see Fig. 3).

Shaktoolik is one of the most vulnerable villages in Alaska to storm surge, coastal flooding, and erosion (GAO 2009; State of Alaska 2016). Today, Shaktoolik is a largely indigenous village with a mixed Inupiat and Yupik ethnic heritage (Johnson and Gray 2014). Residents of Shaktoolik, among other things, hunt seals and caribou, and gather wild rhubarb and onions (Ignatowski and Rosales 2013). Subsistence activities and commercial fishing routinely expose residents of Shaktoolik to environmental conditions, including storms, producing a deep and continuous base of experience that informs their evaluation of storm history.

Along with the Yukon-Kuskokwim Delta to the south and the Seward Peninsula to the north, the Norton Sound area where Shaktoolik resides is known as the stormiest in Alaska, particularly in the fall when storms track north and northeast (Wise et al. 1981; Johnson and Kowalik 1986). Villages in this region receive storms regularly (Erikson et al. 2015). Shaktoolik resides on a narrow gravel bar no more than 13.1–16.3 m height above ellipsoid (HAE), the metric used for GPS measurements (roughly 4–7 m above mean lower low water (MLLW)), and surrounded by marshland (Glenn Gray and Associates 2012). While the region near Shaktoolik has been inhabited for thousands of years (Giddings 1964; Tremayne et al. 2018), residents moved to the coast from inland settlements in 1934 to a site three miles south of the current village location (Thomas 1982), referred to as the "old site." Shaktoolik started to move to its current location in 1974 after a series of strong storms flooded the "old site" in 1960 and 1965 when 0.5 m of water inundated the village (USACE 2011). A very large storm hit the Norton Sound in November 1974 with driftwood lines reaching 4–5 m above observed sea levels (Sallenger 1983).

Several factors amplify storm surges, including low atmospheric pressure. strong winds. long and prolonged fetch. high tides, lack of sea ice cover. gently sloping sea floor. and low relief shoreline (Wise et al. 1981; Brower Jr et al. 1988). Shaktoolik has all these attributes. In addition, local knowledge holders maintain that storm surge is most severe when winds are from the SW (Ignatowski and Rosales 2013), and meteorologists concur (Wise et al. 1981).

Fig. 1 Study site. Shaktoolik resides in western Alaska on the eastern coast of the Norton Sound. The surrounding landscape is dominated by low-lying marsh that floods during storms

Winds from the SW are the strongest as modeled by Erikson et al. (2015) for nearby Unalakleet, AL.

In its fifth assessment report, the IPCC recognizes the importance of information for climate change adaptation (Noble et al. 2014). Lack of information limits adaptive capacity (Klein et al. 2014). There is very little quantitative storm data on native villages in western Alaska that are vulnerable to climate change, evidence that is needed to develop and secure funds for adaptation plans (Erikson et al. 2015) and emergency planning (Mesquita et al. 2009). Like for many localities in the Arctic, data on storm surge in Shaktoolik is absent, discontinuous, and inconsistent. There is one direct investigation of the 2011 storm in Shaktoolik (Kinsman and DeRaps 2012), one on pre-2011 storms in the village (USACE 2011), and several investigations on broader issues that include storms (Thomas 1982; Johnson and Kowalik 1986;

Brower Jr et al. 1988; Blier et al. 1997; Chapman et al. 2009; Glenn Gray and Associates 2012; Erikson et al. 2015). Efforts to automate data collection (AOOS 2016) in Shaktoolik failed with instruments lost and destroyed in subsequent storms. Alaska has only three permanent federal tidal gauges in the Bering Strait Region compared to 296 on the eastern seaboard of the USA (NOAA 2020). In a review of Arctic research since 2004, Walsh et al. (2011) conclude that there is not enough study done on storminess trends in the region, and an increase in storm intensity cannot be determined. The US federal government now acknowledges this lack of data and monitoring (NOAA 2020). The low scientific certainty of storm surge modeling or prediction at the regional scale affects local assessments of vulnerability.

Other types of information gathering efforts at the local level, such as our work here, are needed to clarify storm preparedness. In that way, communities can plan for climate change without their efforts being dismissed because of the broader uncertainty in the region. For example, the climate change adaptation plan developed for the village of Shaktoolik acknowledges the threat of increasingly large storms for the village, yet cannot state with certainty—based on climate science—that the storms are in fact intensifying (Johnson and Gray 2014). In turn, the lack of scientific certainty of storm intensity hampers regional adaptation efforts, making it harder to secure funding, to coordinate planning, and to justify political action. Yet, few studies have been conducted in this area and there is little documented information on storm surges in western Alaska (Terenzi et al. 2014). While modeling efforts continue, new hybrid approaches such as ours, especially using GIS technology, are needed (Mimura et al. 2014) to establish a baseline of how the storms actually are being experienced in these villages. As these evaluations are conducted, the villages will be better prepared for adaptation and emergency planning.

More broadly, member states of the United Nations Framework Conventions on Climate Change, acknowledge the need for better information, including the development of observation systems and incorporating indigenous knowledge, to assist developing countries adapt to climate change (UNFCCC 2006). Minority and disenfranchised groups in the USA are often overlooked with hazard assistance (Siders 2019) and recovery (Smith and Wenger 2007; Muñoz and Tate 2016), and monitoring Alaska's coastal zone for climate change adaptation is left out entirely in the USA over the next decade (NOAA 2020). With the absence of a national adaptation plan, indigenous villages in Alaska must rely on the state to coordinate their adaptation efforts.

As part of emergency planning in its Strategic Management Plan (SMP), the village of Shaktoolik identifies four areas of "proactive" measures to monitor "mitigate against, prepare for, respond to, and recover from disasters" (State of Alaska 2016: 45). This plan identifies four monitoring programs needed to address the village's critical need of mitigating the threats of storms to monitor erosion in front of the village and at First Bend where its drinking water source is located, and to monitor storm surge levels during storms and afterward by the driftwood and debris lines left by the storms. The SMP also calls for collaboration to conduct this work. The method and evaluation that we report here was prompted by the desire of the governing bodies in Shaktoolik to monitor storms in their village. In a meeting with the Tribal Council of Shaktoolik in 2016, we agreed to monitor storm intensity as called for in the village's SMP and returned in 2017 to do fieldwork for this study.

The lack of data at the local, and even regional, scale makes it difficult to corroborate local accounts of storm intensity and contributes to the disparity in evaluations of trends in storm intensity between the scientific literature and local accounts. In its fifth assessment report, the IPCC identify criteria for establishing effective indicators to support climate change adaptation efforts. According to IPCC, any metric used should be valid, purposeful, and accurate; it should be valuable, targeting relevant needs; and it should generate continuous data (Noble et al. 2014: 855). With these data requirements in mind, we develop a feasible method to monitor storm surge in under-studied villages.

2 Methodology

We employ three lines of evidence to reconstruct the surge from past storms affecting Shaktoolik. We combine the GPS readings of driftwood deposits with local accounts of storm activity, newspaper accounts, and verify log age with tree-ring analysis to produce storm surge maps.

We use driftwood log deposits and associated debris lines when visible (i.e., smaller material left by storm surges) to measure storm surge extent of past storms (Harper et al. 1988; Zhang et al. 2008; Hatzikyriakou and Lin 2017). Debris lines remain as they mix in the swash area of storm surge are better indicators of storm surge than larger, denser driftwood piles in areas that tend to accumulate driftwood (Terenzi et al. 2014). Blier et al. (1997) reaffirm Sallenger (1983) that the combined effects of sea level rise from wind setup, atmospheric pressure, wave effects, both run-up and setup, and tides are seen in driftwood lines. Driftwood lines from major storm surges form highly visible deposits on the landscape, in the case of Shaktoolik visible on a daily basis from inhabitant's homes (see Fig. 3 below) and represent a valuable subsistence fuel and building source. Driftwood deposits incorporate a mix of newly deposited logs with older debris (Sallenger 1983; Blier et al. 1997; Alix 2005). Increased storminess additionally mixes driftwood logs as subsequent storms may wash away and redistribute older driftwood deposits.

In 2017, we collected forty-eight cross-sectional samples of drift logs, 44 white spruce (*Picea glauca*), and four hardwood, most likely cottonwood (*Populus balsamifera*), from four driftwood deposits near Shaktoolik (Fig. 2). Samples were taken from the entire extent of the large driftwood line in sample areas 1 and 2, and then more selectively from sample areas 3 and 4 which were less accessible and whose deposits were not as large. We did not gather samples in these areas where the driftwood was moved by the residents of Shaktoolik who may use the wood for fuel, building supplies, or, as in front of the village, as part of the protective berm built in 2015.

Samples were analyzed for their last year of growth, or last measured growth ring, of individual logs within a storm line can provide an earliest possible date for the age of delivery on the beach, assuming a tree dies, enters the water, and is deposited by a storm in the same year. While dendrochronology techniques can determine the age of the logs and provide the earliest possible date of a driftwood deposit, they cannot establish the precise date of when the logs were deposited by a storm. Under certain conditions, a spruce log may remain in the water for 18 months before sinking (Häggblom 1982), depending on the condition of the tree when it falls in the water, or get stranded on the beach and potentially redeposited if picked up again during another storm (Alix 2005).

In addition, we use the last measured ring (LMR) of a number of logs for several reasons. Since there are multiple driftwood lines in a given area, we had to determine which of the driftwood lines that lied the furthest inland, i.e., the largest storm surge, was left by the 2011 or 2013 storms. We therefore had to determine if the age of the logs predate those storms

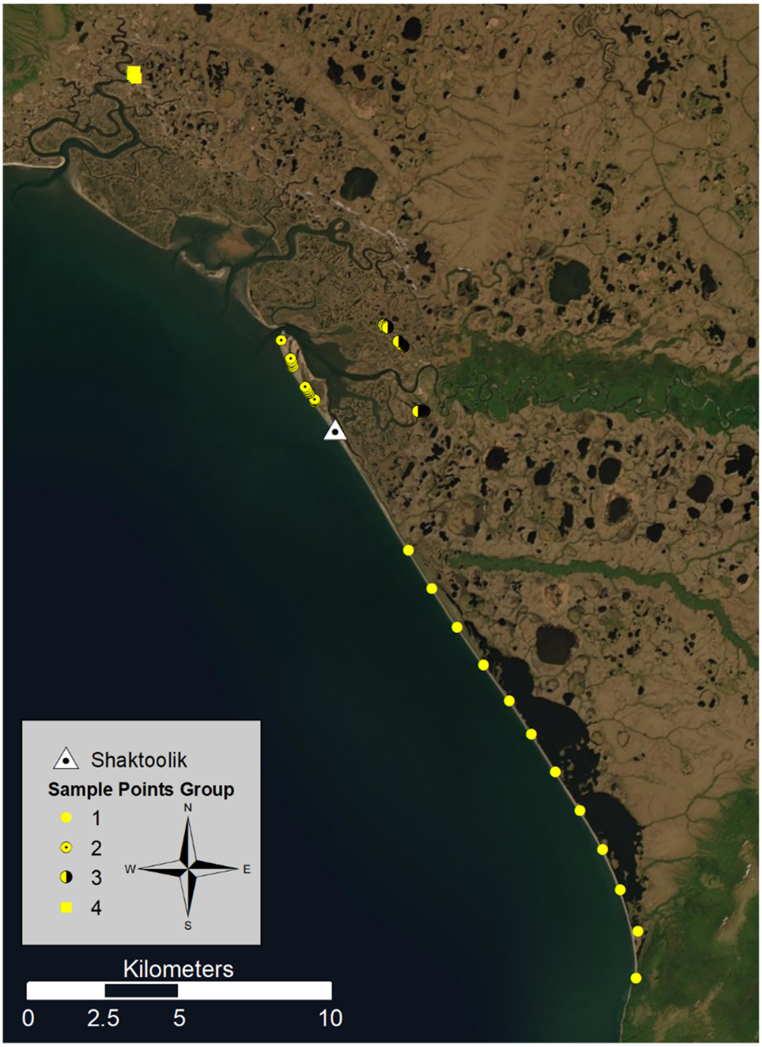

Fig. 2 Sample sites. Sample areas varied in accessibility and amount of driftwood left by storms. Twelve samples taken from location 1, 13 from location 2, 12 from location 3, and 12 from location 4. Twenty-three analyzed with dendrochronology

establishing that it was possible for a particular log to be in a driftwood deposit left by a 2011 or 2013 storm.

We combined the dating data to other sources to get a more accurate account of when particular driftwood may have been deposited on a beach. Similar to Fang et al. (2018), we use qualitative sources to fill in data gaps of storm dates in the Bering Strait Region. We use a combination of local knowledge (Ignatowski and Rosales 2013; Rosales and Chapman 2015) and updating previous work done by Mason et al. (1996) on newspaper accounts from the Nome Nugget on Norton Sound or Bering Strait storms (Rosales forthcoming) (Table 1). We use Nome Nugget newspaper articles on storms for the period after the LMR to the present, paying particular attention to articles on storms that coincide with storm dates given to us by local knowledge holders in Shaktoolik.

Newspaper accounts and local knowledge holders do not differentiate multiple driftwood lines when they appear in the same area; we therefore rely on the dendrochronology evidence to demonstrate that the logs we sampled could have been deposited by those storms.

Finally, GPS coordinates of the maximum extent of debris lines are plotted and overlaid on to remote sensing elevation data to show possible storm surge extent (for a detailed description sampling methods, tree-ring analysis, and local storm date accounts, see supplemental material.)

3 Results

Out of the 48 collected disks, 23 could be cross-dated with accuracy (Table 2). We might have missed some rings due to the degraded conditions of the log. In the four driftwood deposits sampled, no tree LMR predates 1972, and the results show a range of dates mostly between 1985 and 2009 representing a 24-year period. Half of the dated logs arrived in the area within 9 years prior to 2009. The variability of LMR indicates how much potential mixing of logs occurs in the process of drifting from place of growth to place of deposit (Alix 2005). A documented example of this process is represented by mixing of wood when the driftwood line of 1913 was washed away during the 1974 storm at the Nome, AK (Fathauer 1975).

Dendrochronology analysis shows that the LMR for samples taken from sample area 1 south of Shaktoolik range from 1992 to 2005 (Table 2). LMR from samples taken from areas 2–4 range from 1972 to 2009. These oldest LMR dates show us that the storms that deposited the sampled driftwood near Shaktoolik could not have occurred before 1972 from sample areas 2–4 and 1992 from sample area 1. Local knowledge holders note that large storms hit Shaktoolik in 2003, 2004, 2005, 2009 (also documented in Native Village and City of Shaktoolik 2009), and 2011 and 2013 (Rosales and Chapman 2015), leaving the majority of the driftwood and debris lines. We know from local informants that driftwood in sample area 1 was deposited in 2011 and in 2013 for the rest of the sample areas, excluding three samples from an older, low-lying deposit in area 2. There are several older driftwood deposits surrounding Shaktoolik that may have been deposited during the 1974 storm, but the date of

Table 1 Major storm events in Shaktoolik, AK (1900-)

Year	Day	Description
1900	2 August	The “Great Storm,” 75 mph winds in Nome, AK; boats lost
1913	Early October	60 mph wind, 40 ft. waves, most of Nome destroyed
1946	25 October	9 ft. storm surge, buildings leveled, led to construction of seawall in Nome
Shaktoolik moved to current location		
1974	9–11 November	“Great Bering Sea Storm,” 12 ft. storm surge above MLLW in Nome
2004	18–21 October	$17 million damage to western Alaska
2005	22–25 September	High winds, tidal surges, flooding. Most severe north of Shaktoolik
2011	9–10 November	All of SW Alaska, Yukon delta, and Norton Sound affected
2013	5–14 November	Yukon delta on up Norton Sound affected, FEMA disaster declaration
2019	31 July–2 August	40 mph winds, 2.47 in. of rain, berm damaged

Sources: Nome Nugget newspaper; Chapman and Walsh 2007; Wise et al. 1981; Terenzi et al. 2014; USGS 2015; City of Nome 2017

Table 2 From the 48 cross-sectional samples taken from around Shaktoolik, 23 were cross-dated, to identify the year of the last measured ring (LMR). The other samples were either too weathered (punky) or their growth patterns do not correlate with dendrochronology master chronologies. Storm years were documented from local knowledge holders (LK) and storm dates from the regional newspaper. Note: the LMR has to predate the LK and newspaper storm dates for the log to be part of that driftwood deposit (i.e., the tree would have had to die or be cut down before it could be a piece of driftwood)

Sample ID (location/no.)	LMR	LK storm year	Nome Nugget storm date(s)
1.1	2005	2011	8–13 November 2011
1.2	2005	2011	8–13 November 2011
1.4	2000	2011	8–13 November 2011
1.6	2003	2011	8–13 November 2011
1.9	2002	2011	8–13 November 2011
1.11	1992	2011	8–13 November 2011
1.12	2001	2011	8–13 November 2011
2.4	2008	Unknown	
2.6	1999	Unknown	
2.7	1994	2013	5–14 November 2013
2.8	2002	2013	5–14 November 2013
2.10	2006	Unknown	
3.1	1972	2013	5–14 November 2013
3.2	1991	2013	5–14 November 2013
3.4	1997	2013	5–14 November 2013
3.10	1993	2013	5–14 November 2013
4.3	1998	2013	5–14 November 2013
4.4	2006	2013	5–14 November 2013
4.5	2003	2013	5–14 November 2013
4.6	1988	2013	5–14 November 2013
4.10	1995	2013	5–14 November 2013
4.11	1985	2013	5–14 November 2013
4.12	2009	2013	5–14 November 2013

those deposits is unknown to local knowledge holders and most of the wood is too decayed to sample. The LMR of the logs analyzed predate the 2011 and 2013 storm dates indicating that those trees *could have* been deposited during those storms, or any other storm post-LMR. In other words, our LMR analysis indicates if a particular tree died before the 2011 and 2013 storm dates making that log a potential part of the driftwood deposit left by those storms (see Table 2). Our results show that all LMR dates predate local knowledge (LK) and newspaper accounts, and LK and newspaper accounts coincide.

Storm surge from the 2013 storm drove driftwood further inland in area four, but not higher than the 2011 and 2019 storms. Maximum run-up for the 2013 storm was 13.1 m height above ellipsoid (HAE). Residents of Shaktoolik tell us that the wind direction from the 2011 storm was perpendicular to the beach at the height of the storm, at high tide, with winds from the SW (roughly 230°), the direction with the greatest possible fetch. Wind direction measurements at the peak of the storm taken at nearby Unalakleet, AL weather station 56 km to the south show a more westerly (265°) direction (Kinsman and DeRaps 2012).

Residents of Shaktoolik tell us that driftwood from the 2011 storm directly in front of the village was pulled back into the ocean during the 2013 storm and redeposited further west on to the tundra to sample areas 2, 3, and 4. They also tell us that the driftwood in sample area 1 from the 2011 storm remained in place during the 2013 storm. Residents also tell us that the wind direction of the 2013 storm was from the SSW (roughly 200°), more angled to the beach than the 2011 storm, and did not disturb the driftwood in sample area 1 where it was sheltered by the foothills to the south (see Fig. 1). The winds blew the driftwood toward the mouth of the Sineak River, and from there driven on to the tundra.

With the near disasters of the 2011 and 2013 storms, and the absence of state and federal assistance to build an evacuation road and center, the village decided to build a protective berm in 2015. A village-wide effort commenced to move gravel from a deposit 3 mi from the village. The berm was completed in 2018 and stood roughly 2 m higher than the top of the gravel bar running the length of the village. The August 2019 storm was the largest storm to test the berm, eroding roughly half of its girth (Fig. 3).

Mapping GPS points of the extent of how far the driftwood was driven on to the land on to newly available DEM data (Polar Geospatial Center 2019) gives us an estimate of storm surges from the 2011, 2013, and 2019 storms (Fig. 4). The 2019 storm was also mapped with GPS and remote sensing and represents the first event documented by our method after establishing the baseline maps from the 2011 and 2013 storms. Our results show that the 2011 and 2019 storm surges in Shaktoolik rose to the height of land at grade with the houses of the village, and associated debris line struck the Native Corporation store on the south side of town. Measurements of the 2011 storm taken by the State of Alaska in a post-storm survey found storm run-up in the center of the village of 5.8 m above MLLW (Kinsman and DeRaps 2012), or roughly 15.5 m HAE. Driftwood in sample area 1 from this storm rose 16.3 m HAE. The surge from the 2019 storm rose to roughly the same height but the surge was impeded by the protective berm completed in 2016. Should the protective berm fail, we conclude that the 2011 and 2019 storms represent a maximum safe storm run-up for the village. Storms with greater

Fig. 3 Photo taken before high tide of the November 2011 storm by Elmer Bekoalak, a resident of Shaktoolik, AL (upper left panel). Photo used with permission. Photo taken in July of 2012 by Jon Rosales 8 months after the 2011 storm (upper right panel). Berm construction in the summer of 2014 (lower panels)

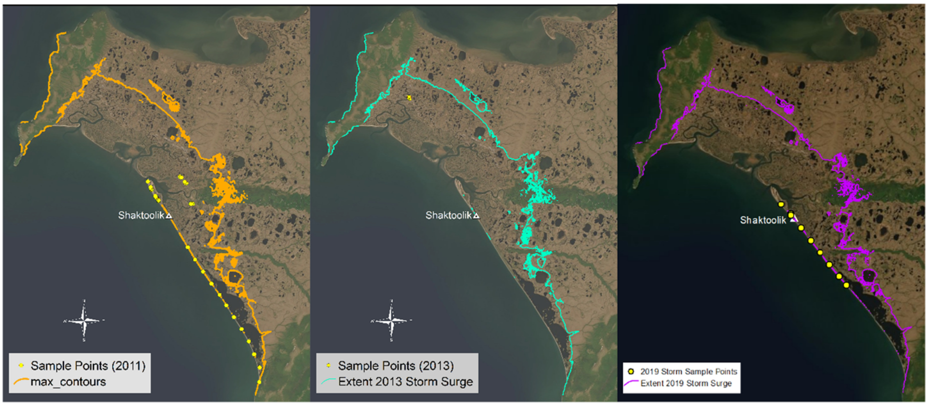

Fig. 4 Maximum storm heights measured by on the ground GPS readings of driftwood and debris lines then portrayed across the landscape for November 2011 (left panel), November 2013 (middle panel), August 2019 (right panel)

storm surge may damage the village with erosion and large driftwood striking village structures.

4 Discussion

This work is situated within the broader context of climate adaptation planning under uncertainty. Even though it is well established that climate change is expected to increase storm intensity and frequency in the Arctic (ACIA 2005; Manson and Solomon 2007; Simmonds et al. 2008; Barnhart et al. 2014; Terenzi et al. 2014; Day and Hodges 2018), including the Bering Strait Region (Graham and Diaz 2001), adaptation planning is still hampered by the remaining uncertainty of these expectations. There is evidence that Pacific low pressure systems are taking a more northerly track (Chapman and Walsh 2007) and there has been a general poleward shift in storm tracks (Bengtsson et al. 2006). Some individual events, such as the August 2012 storm in the Arctic, are now more intense and persistent (Simmonds and Rudeva 2012; Aizawa and Tanaka 2016). Storms are likely to increase in frequency and intensity given the physical changes seen in the Arctic. Strong temperature gradients between sea ice and the ocean, and a strong Tropopause Polar Vortex in the Arctic intensify storms in that area (Tao et al. 2017), and warming is evidenced throughout the troposphere above the Arctic (Komatsu et al. 2018). The impact of Arctic warming at the surface, where the region has warmed twice (AMAP 2017; Overland et al. 2018) to six times as fast as the rest of the globe in some hotspots (Huang et al. 2017), is most evident on sea ice.

4.1 Sea ice and storms

Loss of arctic sea ice is also well established (Perovich and Richter-Menge 2009; AMAP 2017; Osborne et al. 2018), including in the Bering Sea where it has declined by 26% per decade since the 1970s (Erikson et al. 2015). Sea ice coverage and storm intensity are related as storms interact with the planet's surface and atmosphere. Less sea ice allows more energy transfer from ocean to atmosphere and leads to larger storms in the Arctic (Simmonds and

Keay 2009), and greater wind/sea-surface drag (Erikson et al. 2015). Conversely, sea ice dampens waves and wind-driven currents (Wise et al. 1981) and shore fast ice controls wave action and concomitant erosion and sedimentation, and fetch controls water levels and wave field development (Barnhart et al. 2014) and larger waves (Fang et al. 2018). Sea ice protects communities from erosion (Osborne et al. 2018). Sandy beaches and barrier islands, like in Shaktoolik, are more susceptible to wave and storm surge erosion than flooding (Barnhart et al. 2014). These changes prompt Barnhart et al. (2014: 1778) to state that, "The changes in the duration of Arctic sea-ice cover exert a first-order control on the physical vulnerability of the Arctic coastline." In addition, the loss of sea ice causes social and ecological impacts (Perovich and Richter-Menge 2009).

These sea ice-storm effects are most pronounced in the fall when the loss of sea ice most affects atmospheric heat budget (Walsh et al. 2011). With warming, ice-free conditions extending longer in to the fall coincide with fall storms (Fang et al. 2018). Open-water season became 1.5–3.0 times longer in the Arctic from 1979 to 2012 (Barnhart et al. 2014). In villages in Alaska, loss of shore fast ice leads to increased flooding, erosion, exposure, damages, waves, higher and more frequent storm surges, and increased fetch (Fang et al. 2018). The potential fetch for Shaktoolik from the SW is 1000 s of kilometers of open water toward Japan, only limited by the size of the storm. Barnhart et al. (2014) find no limit to the positive contribution fetch makes toward storm surge and wave height; their modeled storm fetch for storms between 1981 and 2013 for Unalakleet, AL, roughly 60 km to the SE of Shaktoolik, ran up to 250 km. More broadly and going forward, modeled sea ice for the Bering Sea shows nearly ice-free September, increasingly ice-free conditions in December, and a sea ice extent reduction of 58% in the spring (March to May) by 2050 (Wang et al. 2012). However, the prospects for realization of these results and the broad range of outcomes make the value of their direct application for planning purposes uncertain.

4.2 Modeling studies

According to the IPCC assessment report on extreme weather (IPCC 2012), the lack of model accuracy and certainty of the causes of increased storm intensity in the high latitudes stems from the complex nature of the changing temperature gradient between the poles and the tropics, combined with changes in precipitation patterns. In addition, variations in precipitation patterns affect the latent heat releases in the atmosphere and cause changes to the jet stream, which in turn influences storm tracks. These changes currently are too complex to model, and paleoclimate studies cannot predict them accurately (IPCC 2012). As a result, there remains an element of uncertainty in current understanding of a trend in "storminess" in this region (IPCC 2014: 113). More recently, Fang et al. (2018) similarly do not detect a change in storminess in their study of Kivalina, to the north of Shaktoolik. Models are unable to predict present day Arctic storminess contributing to uncertainty of longer-term forecasts (Day and Hodges 2018). Still, other modeling investigations show storms increasing in intensity (Crawford and Serreze 2017; Day et al. 2018).

Terenzi et al. (2014) and Erikson et al. (2015) address this lack of scientific consensus for areas south of Shaktoolik. Using a mixed approach with modeling, aerial imagery, and field evaluations, Terenzi et al. (2014) conclude that the largest storm surge events between 1913 and 2011 happened when fall storms coincided with high tides and SW winds. Erikson et al. (2015) develop a storm surge model based on historical tide, wave run-up, and atmospheric and sea ice data for Unalakleet, AL, a village roughly 60 km south of Shaktoolik, and rank the

30 strongest storms from 1981 to 2012. They find no increase in storm height or frequency, however, over that period. Additionally, some general circulation model simulations show decrease in sea-level pressure and extreme cyclones in the Bering Sea area (Vavrus 2013). Globally, Bengtsson et al. (2006) find no indication of increased storm intensity in their model, albeit a poleward shift in storm paths. As with sea ice, storm models are currently limited in their ability to assist villages adapt to life-threatening storms at present.

We therefore developed this more localized approach to reconstruct the history of and monitor storms for the village of Shaktoolik. Previous studies on storms in Shaktoolik and the region have been done by request after a large storm to assess the threat (USACE 2011) and those studies develop storm models (e.g., Chapman and Walsh 2007; USGS 2015). The methodology we employ here does not match the accuracy and fidelity of measured beach profiles as those studies using SBEACH models (USACE 2011), but represents a low- or no-cost method to monitor storm surge with existing infrastructure and instrumentation, a benefit for communities vulnerable to storm surge with limited financial resources. Maps can be developed immediately after a storm with this method with cell phones and partnership with a GIS lab.

The limitations of this approach include the available accuracy of GPS coordinates and remote sensing datasets. The fidelity of our approach is 2 m (Polar Geospatial Center 2019); by comparison, the fidelity of the study by the Army Corps of Engineers requires beach profile measured and modeled to the nearest hundredth of a foot (USACE 2011). An additional limitation of our approach is that it requires establishing partnerships with the affected villages. Partnerships require trust- and relationship-building and continued communication. Of upmost importance is to establish a partnership between a resident of the village and an institution with a GIS lab. Until more robust monitoring systems are implemented in the Arctic, the approach developed here can commence immediately with some coordination between villages and research institutions.

5 Conclusion

The IPCC recognizes that local scale interaction between researchers and community are useful, especially when efforts are direct and pointed toward a particular need (Noble et al. 2014). Shaktoolik's SMP also recognizes this imperative where partners are identified at each step to assist the village (State of Alaska 2016). Our methodology here requires a university-village partnership to continue monitoring storm surge. Of critical importance is the role of a Village Coordinator, a pivotal, local contact who manages communication and logistics between the village and researcher. Working with the Village Coordinator, an agreement can be arranged for a village resident (currently Sophia Katchatag) to continue monitoring storms. This person would agree to take GPS readings on their cell phones after storm events and send them to St. Lawrence University GIS staff to develop successive maps to monitor change in storm intensity. This university-village partnership serves as a foundation to systematically analyze driftwood in this village going forward.

The storm surge maps we develop uphold data criteria developed by the IPCC for adaptation efforts (Noble et al. 2014: 855). The maps are non-ambiguous and purposeful in targeting the imminent threat Shaktoolik faces and can be quality checked and replicated by other investigators; the outcome is comprehensible and relevant to the residents of Shaktoolik and policy makers; the methodology is periodic, can be disaggregated for further study, and is participatory allowing for residents to document future storm surge with GPS technology on their phones when the storms occur; and the elevation data is publically available and homogenous for the Arctic.

Additionally, the area maps developed here (Fig. 4) enable residents and community leaders in Shaktoolik to contextualize the storm surge and run-up of previous large storms on the landscape. Such maps enable them to identify where potential surges drive the furthest inland and can help identify sites to avoid building structures and potential sites for evacuation and retreat. Shaktoolik and villages across the region can use such maps when discussing emergency management and planning, evacuation routes, and road building. Village scale maps (Fig. 5) also assist emergency planning and to identify structures prone to flooding. Of particular importance in Shaktoolik is illustrating which households would require evacuation assistance first and which households with the furthest walking distance to the school in the center of town that is used as the evacuation center during storms.

Fig. 5 Reconstructed storm surge contours for Shaktoolik, AL from the driftwood deposits for the November 2011 and 2013 storms. Storm surge measured directly after the 2019 storm contour

Importantly, the maps are generated at an appropriate scale for the village with existing technology and at no additional cost. These maps address the current safety needs that may go unmet by existing state and federal infrastructure. The methodology outlined here offers a low-cost, immediate, and practical approach to storm monitoring in Alaska. Additionally, this methodology is conducive to scaling up as coordinated efforts in the Arctic of long-term monitoring are needed (Larsen et al. 2014). Other villages in the Arctic that are vulnerable to storms may be interested in monitoring storms in a similar manner.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-021-02995-4.

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