Deep-Sea Research II 94 (2013) 312–322

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

# The influence of wind and ice on spring walrus hunting success on St. Lawrence Island, Alaska

Henry P. Huntington [a,*], George Noongwook [b], Nicholas A. Bond [c], Bradley Benter [d], Jonathan A. Snyder [d], Jinlun Zhang [e]

[a] 23834 The Clearing Drive, Eagle River, AK 99577, USA
[b] Savoonga Whaling Captains Association, Native Village of Savoonga, P.O. Box 202, Savoonga, AK 99769, USA
[c] University of Washington/JISAO, Box 355672, 3737 Brooklyn Avenue NE, Seattle, WA 98105, USA
[d] U.S. Fish and Wildlife Service, Marine Mammals Management, 1011 East Tudor Road, Anchorage, AK 99508, USA
[e] Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98105, USA

ARTICLE INFO

Available online 14 March 2013

*Keywords:*
Pacific walrus (*Odobenus rosmarus divergens*)
Hunting
St. Lawrence Island
Bering Sea
Winds
Sea ice
Generalized additive model (GAM)

ABSTRACT

St. Lawrence Island Yupik hunters on St. Lawrence Island, Alaska, take hundreds of Pacific walrus (*Odobenus rosmarus divergens*) each year. The harvest and associated effort (hunting trips taken), however, are variable from year to year and also from day to day, influenced by physical environmental factors among other variables. We used data from 1996 to 2010 to construct generalized additive models (GAMs) to examine several relationships among the variables. Physical factors explained 18% of the variability in harvest in Savoonga and 25% of the variability in effort; the corresponding figures for Gambell were 24% and 32%. Effort alone explained 63% of the harvest in Savoonga and 59% in Gambell. Physical factors played a relatively smaller role in determining hunting efficiency (walrus taken per hunting trip), explaining 15% of the variability in efficiency in Savoonga and 22% in Gambell, suggesting that physical factors play a larger role in determining whether to hunt than in the outcome of the hunt once undertaken. Combining physical factors with effort explained 70% of the harvest variability in Savoonga and 66% in Gambell. Although these results indicate that other factors (e.g. fuel prices, socioeconomic conditions) collectively cause a greater share of variability in harvest and effort than ice and wind, at least as indicated by the measures used as predictors in the GAMs, they also suggest that environmental change is also likely to influence future harvest levels, and that climate models that yield appropriately scaled data on ice and wind around St. Lawrence Island may be of use in determining the magnitude and direction of those influences.


## 1. Introduction

Pacific walrus (*Odobenus rosmarus divergens*) hunting is vital to the well-being of the Yupik residents of St. Lawrence Island, Alaska (Fig. 1). In a 2009 subsistence harvest survey in Savoonga, the take of 962 walrus accounted for two-thirds of the weight of all the food harvested locally, and nearly three-quarters of the weight of the marine mammal harvest (Fall et al., 2013). Monitoring by the U.S. Fish and Wildlife Service (FWS), however, indicates that the number of walrus harvested each year in both Savoonga and Gambell, the two communities on the island, can vary by a factor of four or more (with 962 at the high end of the range). In interviews conducted as part of the local and traditional knowledge (LTK) component of the Bering Sea Project (Wiese et al., 2012), elders and hunters in Savoonga indicated that ice conditions are a major influence on spring hunting success. FWS walrus harvest monitors further identified weather as a crucial factor in determining the ability of hunters to travel by boat and successfully harvest walrus (Garlich-Miller et al., 2011).

Using these observations as a starting point, we quantify the extent to which readily available remote sensing measures of ice concentration, wind speed, and wind direction (physical factors) explain the daily variation in walrus harvest level (harvest) and the number of hunting trips taken (effort) at Savoonga and Gambell for the period from 1996 to 2010, the degree to which effort explains the variation in harvest, the degree to which the number of walrus taken per trip (efficiency) is influenced by physical factors, and the degree to which physical factors and effort together explain harvest.

In a highly variable physical environment, hunting communities would not likely persist if they lacked the flexibility to adjust to a range of conditions. At the same time, a host of societal

* Corresponding author. Tel.: +1 907 696 3564; fax: +1 907 696 3565.
*E-mail addresses:* hph@alaska.net (H.P. Huntington), gnunguk@hotmail.com (G. Noongwook), nab3met@u.washington.edu (N.A. Bond), brad_benter@fws.gov (B. Benter), jonathan_snyder@fws.gov (J.A. Snyder), zhang@apl.washington.edu (J. Zhang).

0967-0645/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.dsr2.2013.03.016

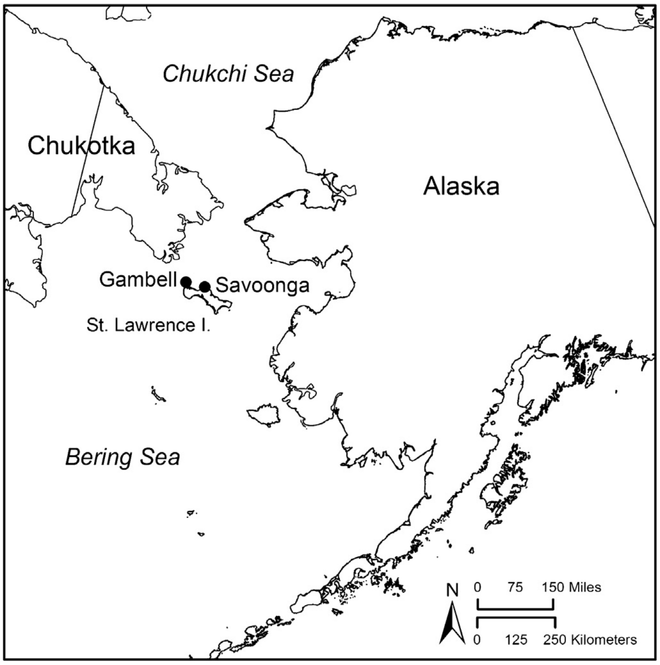


**Fig. 1.** Map of St. Lawrence Island and the eastern Bering Sea, showing the communities of Gambell and Savoonga.

factors also likely influence hunting success. Other physical conditions, such as fog, also hamper hunting, but are not readily reproduced in meteorological data or models. Finally, walrus hunting depends on the presence and abundance of walrus. Environmental conditions, therefore, establish a minimum threshold for hunting success. If hunters cannot travel upon the ocean, they cannot hunt. The ability to travel, however, means neither that hunters *will* go hunting, nor that they will succeed if they do. For these reasons, we did not expect to explain the majority of the interannual or daily variability in harvest levels. Instead, we sought only to identify the extent to which that variability can be attributed to ice and wind conditions, and then to further explore the relationship between effort and harvest.

Relatively few studies have quantitatively examined physical environmental factors as determinants of subsistence hunting success. Kapsch et al. (2010) examined the influence of ice concentration, wind speed and direction, visibility, and air temperature on spring walrus hunting success in the same communities, finding that the sea-ice concentration anomaly is a good predictor of the number of favorable hunting days. George et al. (2003) examined the influence of wind speed and direction on bowhead whale (*Balaena mysticetus*) harvests in Barrow, Alaska, finding that wind direction was the crucial variable in spring, largely because wind direction determined whether there was open water for whaling, whereas wind speed was most important in fall, when open water allowed waves to build up in high winds. Ashjian et al. (2010) confirmed that wind speed is crucial for fall whaling in Barrow, with 85% of whales harvested with wind speeds less than 6 m/s. These studies, however, primarily identified threshold environmental conditions. Our analysis goes a step further, describing functional relationships between harvests and environmental conditions taken, not one at a time, but as a suite of interacting factors.

The ability to assess correlations between harvest variability and physical environmental factors has the additional attraction of allowing an assessment of the likely impacts of changes in the physical environment. Climate change is having a marked impact on Arctic sea ice (e.g., Comiso et al., 2008; Hassol, 2004; Rothrock et al., 1999; Stroeve et al., 2008) and may also currently affect weather patterns including wind conditions (e.g., Overland et al., 2008; Wendler et al., 2010). Projections of the distribution and frequency of future physical conditions can therefore help assess the degree and direction that climate change is likely to affect practices such as walrus hunting. Such projections are beyond the scope of this paper, but our results indicate some variables of interest and the scales at which they are relevant, which may help define the scope of climate-model downscaling (e.g., Najac et al. (2011) among others) and similar efforts in order to be most useful to hunting communities.

## 2. Methods

Our analysis draws upon many streams of data. We first describe each type of data and the methods by which it has been compiled, and then the statistical methods used to evaluate relationships among the quantitative data on walrus harvests, ice concentrations, and wind speed and direction. Most of our analyses examine 1996–2010 because that was the period for which data on all parameters was available. The analyses of harvest solely as a function of hunting effort and of hunting success (walrus taken per trip) considered the period 1992–2010 because hunting data were available for this longer period.

### 2.1. Local and traditional knowledge

Local and traditional knowledge (LTK) is defined by the North Pacific Research Board (2005: 144) as "an array of information, understanding, and wisdom accumulated over time based on experience and often shared within a group or community." The primary method used to document LTK in this study was the semi-directive interview (Huntington, 1998). In this method, interviews are conducted with individuals or groups, addressing a set list of general topics, but no fixed order or questionnaire to follow. Instead, the respondent or respondents discuss the topic in a manner that makes sense to them, perhaps making connections with other ecosystem components or describing trends over time. The interviewer can intervene to keep the discussion on topic, to ask for more detail on various points, or to guide the respondent(s) toward items of particular interest. Six elder hunters were interviewed as a group in Savoonga over the course of 5 days in July 2009. Two members of the interviewer team were also from Savoonga and contributed their own observations and knowledge.

The discussions about ice conditions and walrus harvests were only a small part of the interview sessions. A report on the interviews will be placed in the Bering Sea Project Data Archive (http://beringsea.eol.ucar.edu/) at the conclusion of the project in 2013. The interviews were the catalyst for examining relationships between physical conditions and walrus harvests.

### 2.2. Walrus Hunting data

Spring walrus harvest data have been collected in Gambell and Savoonga since the 1960s. We utilized data collected from 1992 onward by the Walrus Harvest Monitoring Program (WHMP) operated by the U.S. Fish and Wildlife Service (Service). From 1992 until 2004, the harvest was monitored from mid April through late May or early June. This time period allowed the WHMP to gather harvest information on the majority of the spring hunt, when the bulk of the walrus are harvested in these villages. From 2005 through the present year, the project has been shortened to a 2- to 4-week period attempting to encompass the peak of the harvest, with an emphasis on collection of biological samples used for walrus research and management.

Crews consisting of local monitors and Service biologists are responsible for keeping daily records of walrus hunting activity. An attempt to meet and interview each walrus hunting crew as they return is made in both communities. For each hunting crew, data are recorded on date of departure and return, distance traveled, number of walrus harvested, details about each walrus, and harvest location. If a boat stays out past midnight, harvest is recorded for the date the hunting trip started. Data on all walrus hunting trips are recorded, even if walrus are not harvested. With this information we are able to confidently know the days when hunting was attempted and when hunting was successful, when the WHMP was in operation. The data are stored in a database and error checked. Harvest statistics are mined from the database.

### 2.3. Ice concentration

Satellite ice concentration data were used to calculate daily mean sea ice coverage for ocean areas within 5, 10, 30, and 50 statute mile radii (8.05, 16.1, 48.3, and 80.5 km; miles were chosen as the unit because of the greater familiarity of Yupik hunters with miles) of Savoonga (63° 16′ 34″N, 171° 42′ 3″W) or Gambell (63° 16′ 34″N, 171° 42′ 3″W). The distances were chosen as simple increments of greater distance from the communities, but still within hunting distance. Daily passive microwave sea ice concentration data are from the National Snow and Ice Data Center (NSIDC; ftp site: ftp://n4ftl01u.ecs.nasa.gov/SAN/OTHR/). The daily NSIDC ice concentration data are first interpolated onto the BESTMAS (Bering Ecosystem STudy Ice–Ocean Modeling and Assimilation System; Zhang et al. (2010)) model grid and then used for the analysis. All the model grid cells with their centers within the 5, 10, 30, and 50-mile radii from Gambell or Savoonga were used to calculate the mean ice coverage for the respective distance. Although the interpolated data do not have finer resolution than the NSIDC data, the use of the finer grid derived from the BESTMAS interpolation makes it simpler to define the regions within the four radii and to calculate the mean values within those regions. The resulting ice concentration values do not depend on the interpolation procedure.

### 2.4. Wind speed and direction

The wind data used in our analysis are from the North American Regional Reanalysis (NARR) data set (Mesinger et al., 2006). This data set was produced using the Eta numerical weather prediction (NWP) model and a data assimilation system incorporating available surface, upper-air, and satellite-based observations. The grid spacing is nominally 32 km and the output is available at 3-h intervals. An alternative for the present study would have been to use the hourly winds observed at Savoonga and Gambell, Alaska. We expect that the NARR winds (which take into account the underlying surface characteristics including the presence of sea ice as estimated from satellite) are more representative of conditions over the northern Bering Sea than the land-based observations at Savoonga and Gambell, although the hunters of course are using their own observations from the shore to determine whether to go out on the water. It should be noted that the land-based observations were incorporated as part of the data assimilation procedure, and serve to constrain the NARR output. The correspondence between the two data sets for the winds was evaluated quantitatively using data for Savoonga from the spring of 2008. The daily variations in the zonal and meridional winds at 1800 and at 2100 UTC (Coordinated Universal Time, or Greenwich Mean Time) from the two sources tracked one another; Pearson's correlation coefficients between the wind components, and in the wind speed, are slightly above 0.6. The observed winds feature somewhat greater variability (e.g., higher peak speeds) than the NARR winds, as would be expected since the latter effectively includes some spatial smoothing. The validity of atmospheric reanalyses for characterizing the winds of the Bering Sea has been previously assessed. Using wind data from moored buoys that was not available for assimilation in the NCEP-NCAR Reanalysis, Ladd and Bond (2002) found that complex correlation coefficients between the measured and synthetic winds of about 0.9, with minimal systematic biases. It should be noted that the winds measured at the Savoonga and Gambel airports are subject to local (e.g., terrain) effects, and hence will not generally match the winds over the ocean. For the present study we considered the wind directions and speeds for the grid boxes over the ocean at Savoonga and Gambell at the times of 1800, 2100 and 0000 UTC (10 AM, 1 PM and 4 PM Alaska Daylight Time, respectively) for each day.

The weather station observations at Savoonga were used to evaluate the effects of fog on walrus hunting. These observations are at roughly 20 min intervals; the reported visibilities in miles from the reports closest in time to 1800 and 2100 UTC were used in analysis. As discussed in greater detail in Section 3, this variable was found to be a lesser environmental factor and therefore the present paper focuses on the ice and wind information.

### 2.5. Statistical analysis

A variety of approaches could be used to explore the relationships between physical environmental factors, namely ice concentrations and winds, and hunting effort, harvest, and hunting success. We chose to employ the generalized additive model (GAM) framework. This framework is akin to multiple linear regressions, but accounts for the potential of non-linear relationships between a predictand, in this case the number of walrus harvested, and each predictor. Examples of GAMs linking marine ecosystem variables to regional physical properties include Logerwell et al. (2003) and Brodeur et al. (2008), among others. The latter study, and in more detail, Hastie and Tibshirani (1990) and Wood (2004), summarize the characteristics of GAMs. A key point for the present study is that GAMs yield functional relationships between the predictand and predictors from the data itself, rather than from pre-conceived notions. The functions themselves range in complexity from linear to smooth cubic splines; the GAM is designed to seek as simple a set of relationships as possible that adequately fit the data. The R statistical software package (www.r-project.org) was used in the construction of the GAMs.

The first step in formulating the GAMs was to examine the relationships between harvest and effort and each physical factor individually. In general, in the GAM analysis the various ice concentrations and wind variables have statistically significant relationships with effort and harvest, but do not explain a large fraction of the variance in either. GAMs were then formulated using as predictors 3–4 variables expected to be complementary in terms of characterizing the ice and wind conditions each day. In particular, the GAMs were constructed with wind speeds and directions at only a single time of day because of the strong correspondence between the winds at one time with the other times during most days. The GAMs yield both functional relationships between each predictor and the effort or harvest, and information on model performance (percentage of explained variance, histograms of residuals or errors, etc.), as presented in the following section. We also used effort as a predictor of harvest, alone and in combination with the physical factors, and we used physical factors as a predictor of efficiency.

We carried out model tests for various sets of days. Our interest is in three types of days: all days with non-zero harvests, all days with non-zero effort, and all days during the periods of active hunting. The latter is defined as the stretch of days each season encompassing recorded trips, neglecting the periods of a week or more with only a trip or two that occurred in the early portions of some seasons. Most of our analyses used the latter set, which includes a mix of days with zero trips (and harvests), non-zero trips but zero harvests, and non-zero trips and harvests. The sets of days with non-zero trips are used to evaluate efficiency, defined as the ratio of the number of walrus harvested to the number of individual trips in that day. Their counterparts for the days of non-zero harvests formed the basis for experiments with log-normalized harvest as the predictand. Model runs were carried out using the data sets constructed for the hunting communities of both Savoonga and Gambell. These various experiments yielded similar results. The same sets of parameters tended to explain greater proportions of day-to-day variance in harvest, and the functional relationships from test to test resembled one another, with one exception noted below.

## 3. Results

### 3.1. Local and traditional knowledge

The LTK discussions about walrus and ice produced several insights regarding the relationships among walrus, wind, ice, and hunters' access, including:

- At a large scale, persistent northeast winds in winter create thin ice and open water (especially large polynyas in the lee of land such as St. Lawrence Island and parts of the mainland of Alaska and Chukotka), so in spring, the ice retreats quickly. This was the case in winter/spring 2008. Hunters know that winters with sustained northeast winds will result in rapid ice retreat the following spring when a south wind blows.
- In the winter of 2008–09, there was less northerly wind than during the previous winter and the sea ice stayed longer in spring, allowing for more marine mammal hunting.
- In more recent years, the ice is thinner than in the past and also softer so that it melts more quickly in spring. This may be a result of warmer winter weather, in which the ice does not freeze as hard and the brine is not forced out as much, leaving saltier, softer ice.
- At the local scale in Savoonga, when the north wind blows in spring, sea ice packs in against the north side of the island, preventing Savoonga hunters from getting out in their boats.

Note that north winds during winter tend to produce relatively thin ice that breaks up and melts more quickly during spring across the northern Bering Sea, resulting in a shorter duration of ideal ice conditions for hunting. At the same time, north winds (especially during spring) have the localized effect of pushing the ice against the shore at Savoonga, preventing hunters from launching their boats. Even after the shore ice has broken up, north winds will push pack ice against the shore, reducing open water near the community and making boat travel difficult. (In Gambell, north winds also push ice against the north shore of the community, and west winds do the same on the west side, but Gambell has ocean access in two directions in contrast to Savoonga's one [BB and JS, personal observations].)

### 3.2. Harvest, effort, ice concentration, and wind

The data in these four categories are daily figures for the walrus taken in Savoonga or Gambell, the number of hunting trips made, the average ice concentrations within various radii from the village in question, and wind speed and direction at three times during the day at or near each location. Space prohibits a presentation of all years of daily data (over 40 days per year per community), but an example period is provided in Table 1.

### 3.3. Statistical relationships

In Savoonga, 430 days were analyzed, including 247 days with at least one trip made and 175 days with at least one walrus harvested. In Gambell, 419 days were analyzed, including 258 days with at least one trip, and 172 days with at least one walrus harvested. For the years 1992–1995, ice concentration data were unavailable, so analyses that include physical factors were conducted on fewer total days (see Table 2). Excluded from the analysis were days outside the main hunting period (e.g., periods over 7 days without harvest, or days with low harvest separated by more than a week from days with more substantial harvests) and the few days in the record for which harvests were reported without trips having been made (likely a result of observers

**Table 1**
Sample of the data on harvest (number of walrus taken), effort (number of trips taken), and physical factors (ice concentration at four radii, and wind direction and speed (m/s) at three times per day) used in the analysis of environmental influences on walrus harvests in Gambell and Savoonga. This example is for Savoonga, from May 2006.

| Date | Harvest | Effort | 5 mile ice concentration | 10 mile ice concentration | 30 mile ice concentration | 50 mile ice concentration | 1800 UTC wind direction | 2100 UTC wind direction | 0000 UTC wind direction | 1800 UTC wind speed | 2100 UTC wind speed | 0000 UTC wind speed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12-May | 0 | 0 | 0.544 | 0.544 | 0.541 | 0.494 | 149.664 | 156.24 | 165.707 | 6.07 | 6.219 | 7.263 |
| 13-May | 0 | 0 | 0.533 | 0.533 | 0.533 | 0.471 | 176.097 | 171.264 | 176.979 | 6.771 | 6.531 | 5.792 |
| 14-May | 74 | 21 | 0.375 | 0.371 | 0.345 | 0.277 | 156.095 | 156.213 | 138.885 | 3.837 | 4.098 | 2.66 |
| 15-May | 0 | 0 | 0.291 | 0.286 | 0.244 | 0.181 | 148.118 | 132.472 | 108.184 | 4.293 | 4.649 | 4.073 |
| 16-May | 0 | 0 | 0.253 | 0.247 | 0.213 | 0.163 | 117.835 | 121.162 | 118.825 | 8.066 | 7.688 | 7.077 |
| 17-May | 0 | 0 | 0.238 | 0.237 | 0.227 | 0.188 | 105.256 | 112.721 | 110.891 | 5.962 | 6.211 | 4.921 |
| 18-May | 43 | 22 | 0.215 | 0.215 | 0.209 | 0.173 | 110.67 | 126.984 | 121.765 | 4.219 | 3.676 | 3.2 |
| 19-May | 0 | 9 | 0.26 | 0.258 | 0.229 | 0.179 | 132.851 | 128.273 | 83.589 | 3.77 | 2.506 | 2.87 |
| 20-May | 0 | 6 | 0.258 | 0.253 | 0.201 | 0.138 | 303.679 | 301.019 | 277.681 | 6.129 | 6.065 | 5.607 |
| 21-May | 104 | 28 | 0.251 | 0.246 | 0.199 | 0.15 | 239.511 | 216.419 | 193.904 | 2.752 | 2.133 | 2.559 |
| 22-May | 0 | 0 | 0.197 | 0.192 | 0.147 | 0.107 | 261.919 | 260.898 | 263.078 | 3.767 | 3.55 | 2.355 |
| 23-May | 101 | 26 | 0.202 | 0.198 | 0.163 | 0.124 | 261.458 | 252.883 | 239.279 | 2.25 | 2.727 | 0.989 |
| 24-May | 0 | 0 | 0.137 | 0.137 | 0.132 | 0.107 | 252.172 | 248.853 | 257.54 | 3.01 | 3.824 | 4.59 |
| 25-May | 5 | 2 | 0.152 | 0.149 | 0.12 | 0.085 | 249.888 | 248.286 | 252.604 | 4.682 | 4.496 | 6.87 |

**Table 2**
Summary of generalized additive model performance. All models are based on daily time series of harvest (number of walrus taken), effort (number of individual trips), and physical factors (ice at 5 nm scale, ice at 30 nm scale, wind speed and wind direction) except for the two entries indicating effort as the only predictor/independent variable. Efficiency is the number of walrus harvested per trip. The best predictor is the independent variable with the lowest p-value, taken in the context of the GAM. See text for details.

| Model | Explained variance | Number of days analyzed | Best single predictor |
|---|---|---|---|
| Harvest at Savoonga, from physical factors only | 0.18 | 348 | Wind speed |
| Effort at Savoonga from physical factors only | 0.25 | 348 | Wind speed |
| Harvest at Savoonga, from effort only | 0.63 | 430 | Effort |
| Efficiency at Savoonga, from physical factors only | 0.15 | 197 | Ice_5 |
| Harvest at Savoonga, from physical factors and effort | 0.70 | 348 | Effort |
| Harvest at Gambell, from physical factors only | 0.24 | 311 | Wind speed |
| Effort at Gambell, from physical factors only | 0.32 | 311 | Wind speed |
| Harvest at Gambell, from effort only | 0.59 | 419 | Effort |
| Efficiency at Gambell, from physical factors only | 0.22 | 201 | Ice_5 |
| Harvest at Gambell, from physical factors and effort | 0.66 | 311 | Effort |

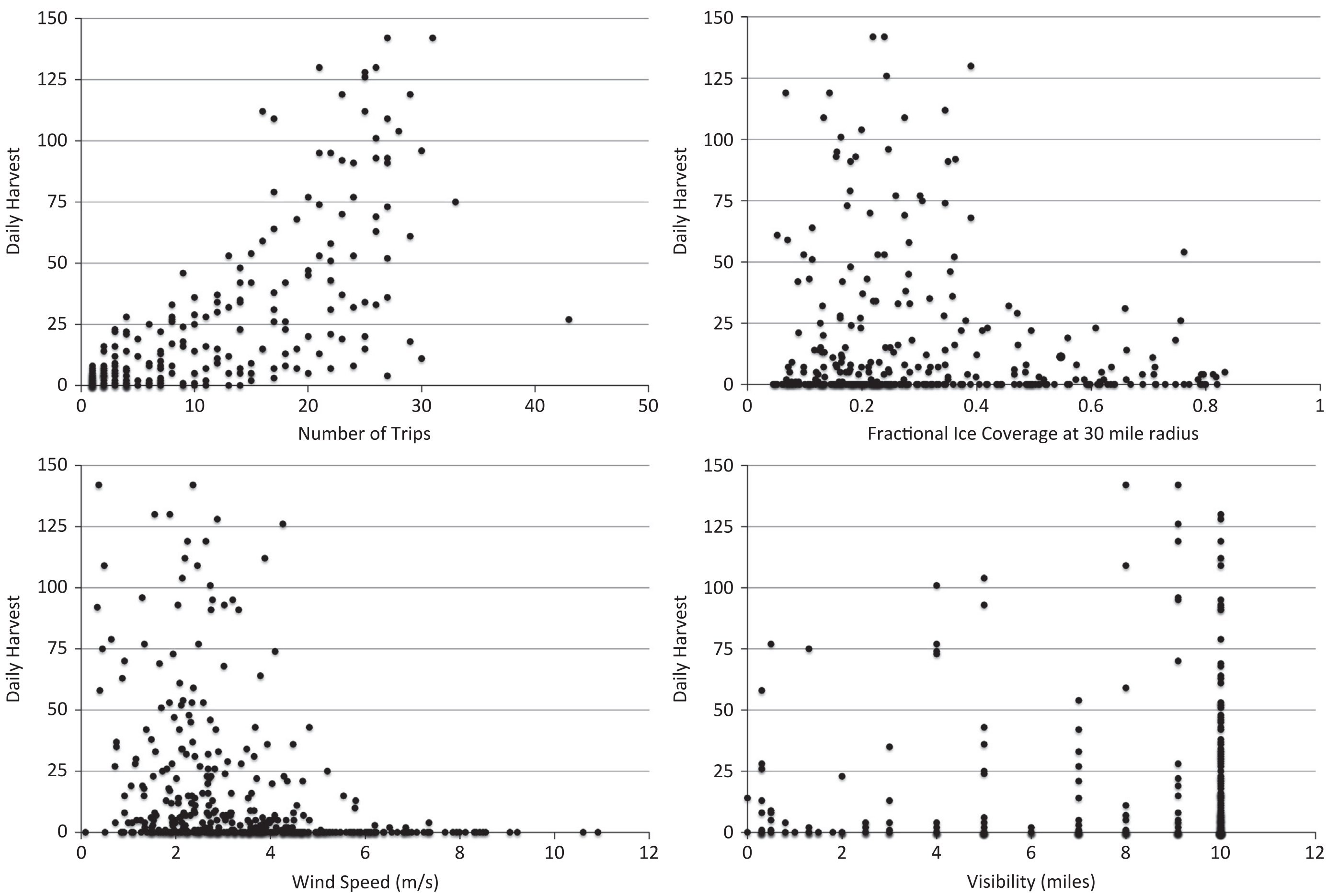


**Fig. 2.** Scatter plots of daily data showing walrus harvest vs. effort (upper left), ice concentration at the 30-mile radius (upper right), wind speed (lower left), and visibility (lower right) at Savoonga.

allocating overnight hunting trips to 1 day and the resulting harvest to another).

The first step in the GAM analysis was to examine individual relationships among the variables. Four examples are shown in Fig. 2, illustrating the types of data and the relationships among them that were incorporated into the GAMs. The correlation between harvest and effort is evident, as is a clear threshold effect at a wind speed of about 4.5 m/s. Ice concentration at the 30-mile radius suggests a threshold with some exceptions, but visibility indicates only a modest effect on highest harvests, though the number of days with harvests in good visibility is clearly higher.

The results from our evaluations of GAMs relating harvest and effort to ice concentrations and winds are summarized here. A variety of combinations of predictor variables, namely different scales for the ice concentrations and different times for the winds, were incorporated in GAM predictions of the Savoonga and Gambell harvests. From the perspective of the robustness of the results, an important outcome from these multiple tests is the consistency in the functional relationships identified by the GAMs. For the sake of brevity, we present below representative results from single combinations of variables for Savoonga and Gambell, and log-transformed harvests for Savoonga. A variety of GAM experiments were carried out; a measure of model skill (explained variance) for each of these experiments is itemized in Table 2.

The GAM prediction of harvest at Savoonga considered all days during the active and reported periods of the hunting seasons. This formulation incorporates ice concentrations on the scales of 5 miles and 30 miles, and the wind speed and direction at 2100 UTC. There is a positive relationship between observed and predicted harvest values, but the physical factors only account for 18% of the observed variation in harvest. The same exercise was conducted for Gambell, with the difference that the 1800 UTC wind speed and direction were used because they yielded a slightly better fit than the 2100 UTC data. For Gambell, physical factors accounted for 24% of the observed variation in harvest.

Next, we predicted effort based on the same physical factors. The GAM explained 25% of the variability in effort in Savoonga and 32% in Gambell, an improvement over the ability to predict harvest, but still unable to account for a majority of the variability. A scatter plot of the observed (ordinate) versus modeled (abscissa) effort and a histogram of residuals of model errors and at Savoonga are shown in Fig. 3.

We then examined the relationship between effort and harvest, since they are neither independent of one another nor equivalent. The correlation between effort as the independent variable and harvest as the depended variable was 63% in Savoonga and 59% in Gambell. This result raised the question of the influence of physical variables on efficiency, and the degree to which physical variables plus effort might together explain harvest variability.

The GAM experiment for the influence of physical variables on efficiency (walrus per trip) explained 15% of the variability in Savoonga and 22% in Gambell. These relatively low figures suggest that physical factors are most important in the decision to hunt or not to hunt, but that once a hunting trip is undertaken, physical factors are not a major influence on outcome.

We next considered harvest as a function of physical factors plus effort. The explanatory variables accounted for 70% of the variance in the daily harvest in Savoonga and 66% in Gambell. Fig. 4 shows a scatter plot of observed versus predicted harvests

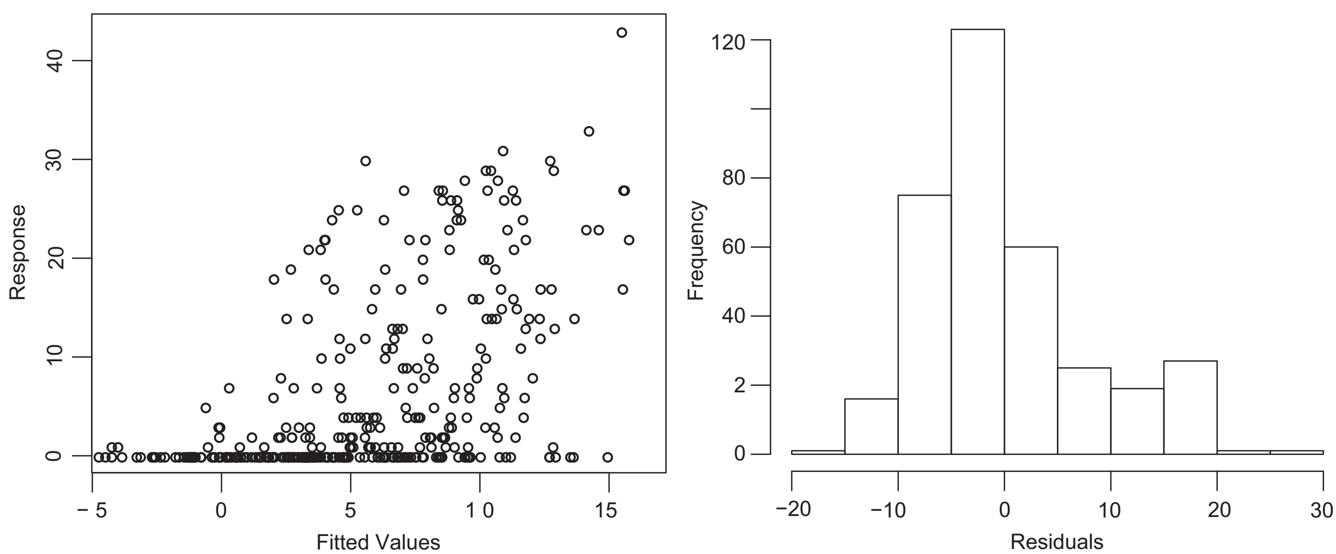


**Fig. 3.** Overall performance of basic GAM for Savoonga, predicting effort as a function of physical factors. Plot at left reflects distribution of observed (ordinate) versus modeled (abscissa) harvest totals for all non-zero harvest days. Histogram at right indicates the number of days with errors (observed-modeled) binned in multiples of 20 for the errors.

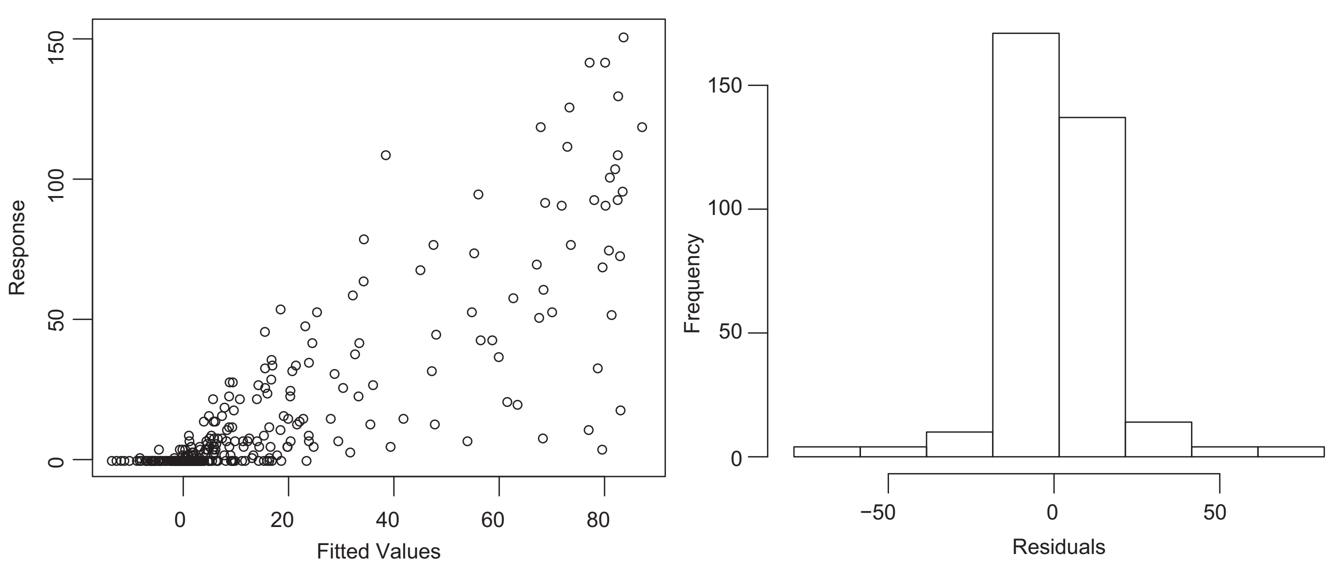


**Fig. 4.** As in Fig. 3, but for the GAM for Savoonga with effort and physical factors as the predictors and harvest as the predictand.

and the histogram of residuals of model errors for Savoonga, and Fig. 5 does the same for Gambell. Note the similarity in the character of the model residuals, and the systematic under-prediction of the higher harvest values.

The under-prediction of the magnitude of harvest on the most successful days led to a final GAM experiment. The highest predictions from the GAM are about 85 while the observations include a number of days with harvests exceeding 100 animals, and a peak of 151. The inability of the GAM to fit the extreme events is not surprising, but does beg the question of whether there is a more meaningful test of the relationship between harvest and physical variables plus effort. We attempted such a test using a GAM with the logarithm of the harvest values as the predictand, and only for the days with non-zero harvests. The log-transform effectively serves to lessen the influence of the days of extremely high harvest in the fitting of the model, relative to the model run with non-transformed harvest values. Such a transformation is often used, for example, in the formulation of stock-recruitment relationships for fisheries due to the occasional occurrence of very large year classes (e.g., Shelton, 1992). This GAM better replicated the harvests on the best days, but was slightly less skillful with both trips and physical factors used as predictors (61% for Savoonga vs. 70% for the non-transformed GAM, and 65% vs. 66% for Gambell).

It is worthwhile to examine the relationships that the GAM yields between predictors, i.e., number of trips, ice concentrations and winds, and predicted daily harvest values. Fig. 6 illustrates these relationships from the basic GAM for Savoonga. (Note that the relationships are determined by the GAM as a whole, and thus do not represent individual relationships between predictor and predictand.) There is a strong positive correspondence between daily harvests and number of trips (Fig. 6A), as would be expected. There was a roll-off in the predicted harvest for high values of trips, and greater uncertainty (Fig. 6A). It is unknown why, but the days with a large number of trips may include a high proportion of less skilled hunters, or more trips of shorter duration, and hence not necessarily more total time devoted to hunting. For whatever reason(s), a similar functional form was found in the equivalent GAM experiment for Gambell. Adding ice and wind variables as predictors resulted in 7% of additional explained variance for both Savoonga and Gambell. This value is not a true measure of the importance of environmental information to harvests, in that this information is not independent of the daily number of trips.

We now turn our attention to the functional forms of the environmental variables. As anticipated, ice concentrations on the 30-mile scale are inversely related to harvests (Fig. 6B) with a steeper drop-off in expected harvest at higher concentrations. A result that was unanticipated is that ice concentrations on the 5-mile scale are actually positively related to the harvest (Fig. 6C). Our interpretation of this result is that enhanced ice concentrations locally may help by reducing wave heights near shore, as long as there is enough open water on larger scales to minimize the prospect of getting trapped. It should be noted that the signal for the ice on the 5-mile scale is somewhat lower than that for the ice on the 30-mile scale; both have $p$-values less than 0.01.

The functional relationships for the wind direction and speed at 2100 UTC are illustrated in Fig. 6D and E, respectively. The GAM found that winds from the north to northeast, i.e., directions between near 0° and 50°, tended to be counter-productive in terms of harvests. The signal here is modest (note the difference in the scale on the ordinate versus its counterparts with respect to ice concentrations). The result for wind speed indicates that low wind speeds are highly favorable, and that higher wind speeds are unfavorable in an overall sense, but with large uncertainty. This large uncertainty is an artifact of the type of test that was carried out, at least in part. There were 40 days in the record for Savoonga during which the winds at 2100 UTC exceeded 6 m/s, and ice concentration values were available for use in the model. Trips were made on only five of these days. The average wind speed was 2.7 m/s for all the days with one or more trips out of Savoonga, and 4.5 m/s for those without, a divergence similar to that found by Kapsch et al. (2010), who also found that 69% of Savoonga's walrus were taken in winds 1–5 m/s. (Note that Kapsch used a different data set for winds, which reported higher wind speeds than the data we used; the pattern of wind and harvest in both cases is similar.)

The concept that strong winds are unfavorable is supported by the GAM for Gambell. In particular, the GAM yields a similar negative relationship between harvest and wind speed (Fig. 7A). There is a slightly greater tendency to hunt out of Gambell than out of Savoonga on days with higher wind speeds, but the success rate is still low. (This result is consistent with the fact that Gambell has access to the sea to the north and to the west, whereas Savoonga only has access to the north, providing no alternatives if the waves and/or ice are coming from that direction.) The GAM's fitting with respect to wind direction at Gambell is shown in Fig. 7B.

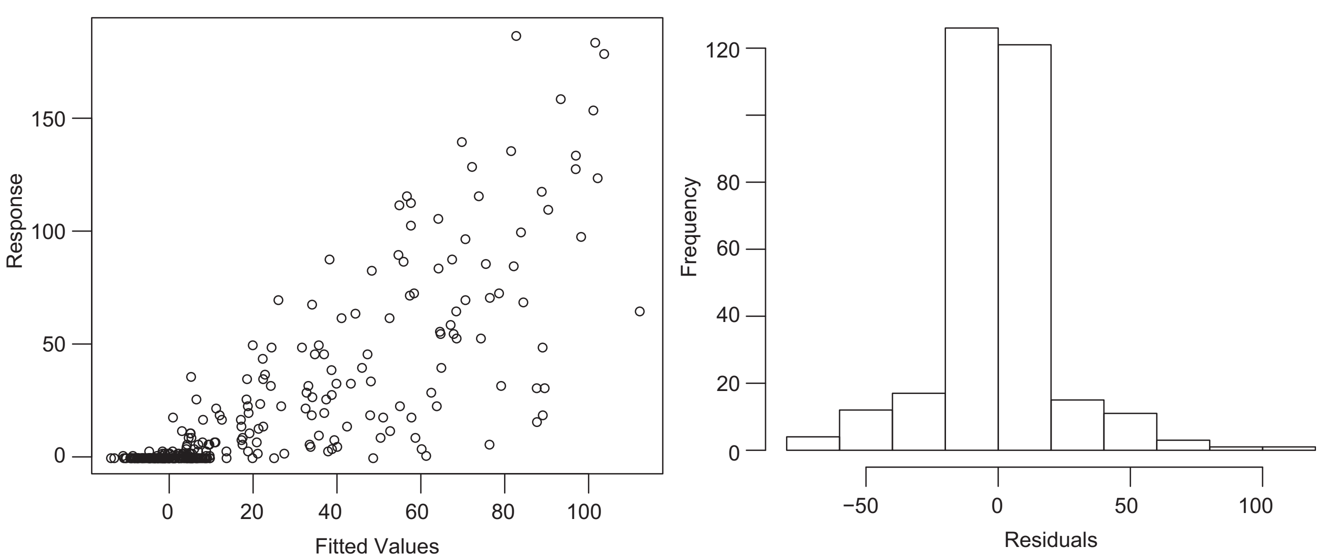


**Fig. 5.** As in Fig. 4, but for Gambell.

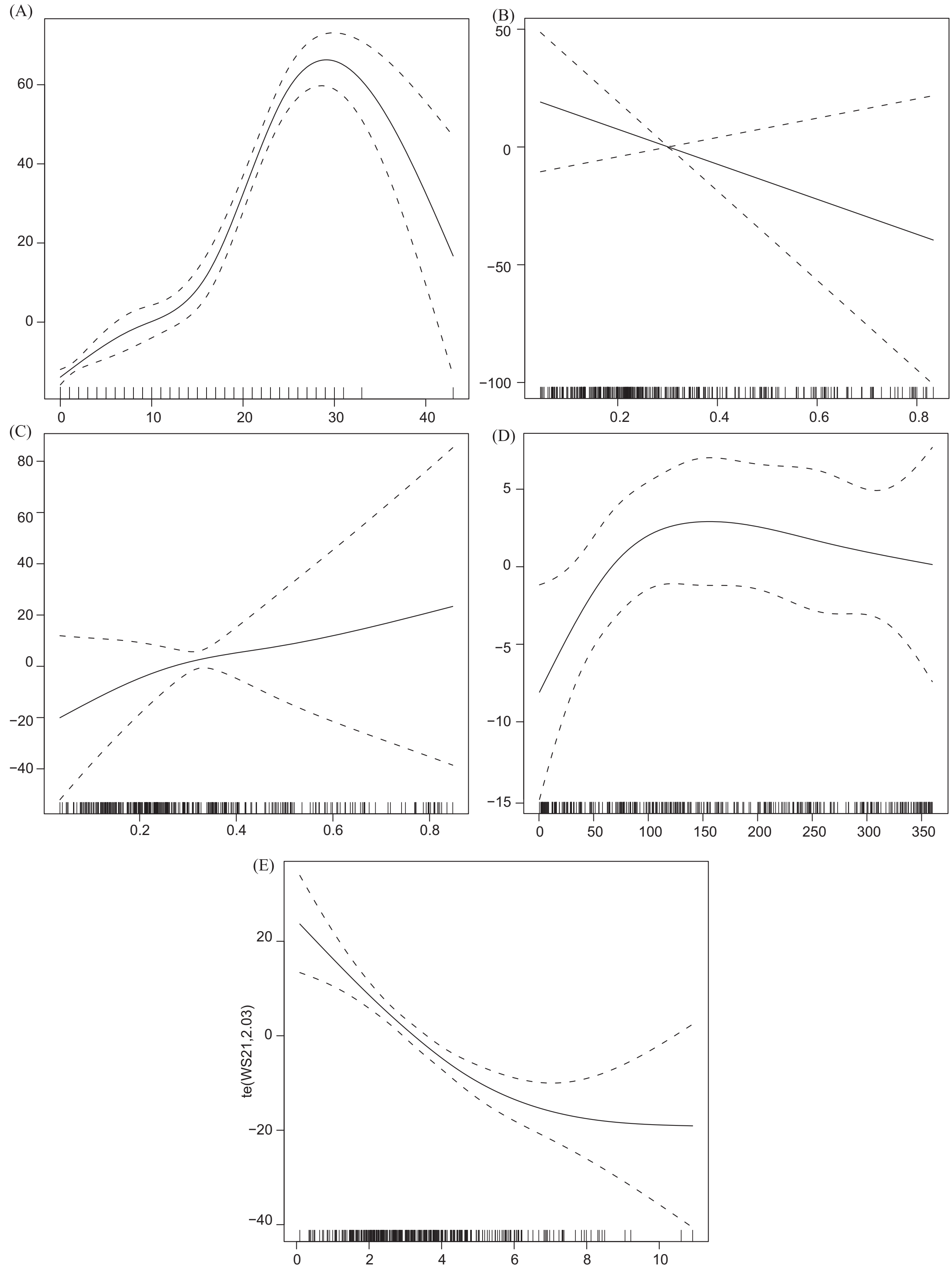


**Fig. 6.** (A) Fitted relationship on the effect of effort (abscissa) and harvest (ordinate, mean removed) from basic GAM for Savoonga. The solid line represents the model fit; the dashed lines encompass roughly 95% of the modeled values and hence are a representation of the confidence level in the model fit to this parameter. The individual values of the predictor are indicated along the bottom. (B) Fitted relationship between ice concentration on the 30-mile scale (abscissa) and harvest (ordinate, mean removed) from basic GAM for Savoonga. (C) Fitted relationship between ice concentration on the 5-mile scale (abscissa) and harvest (ordinate, mean removed) from basic GAM for Savoonga. (D) Fitted relationship between wind direction (abscissa) and harvest (ordinate, mean removed) from basic GAM for Savoonga. (E) Fitted relationship between wind speed (abscissa) and harvest (ordinate, mean removed) from basic GAM for Savoonga.

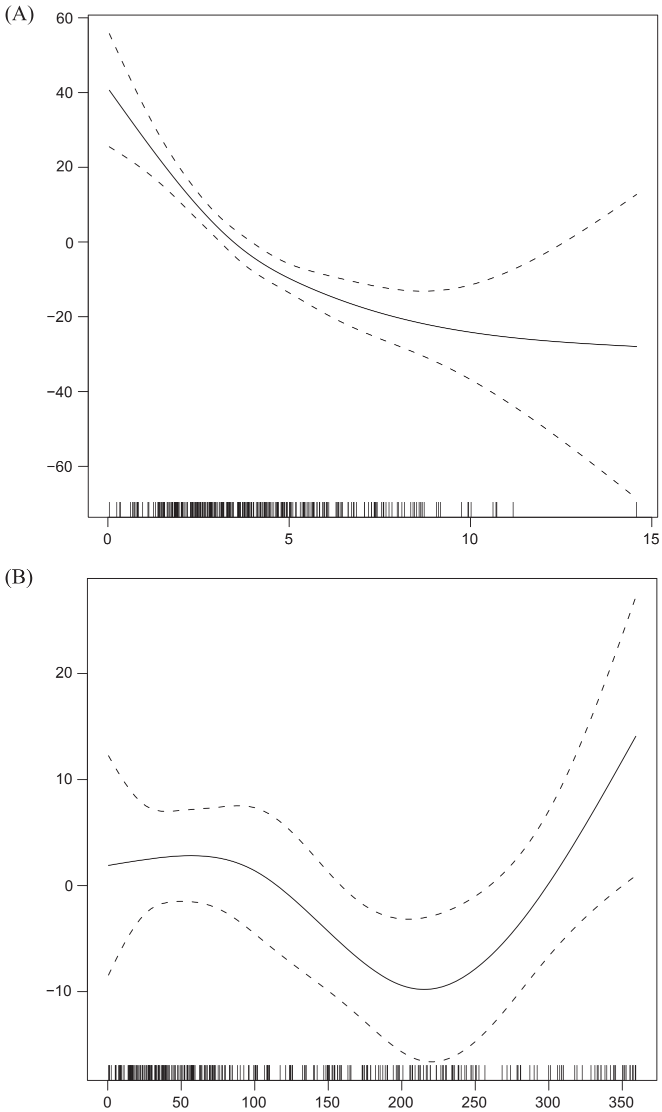


**Fig. 7.** (A) Fitted relationship between wind speed (abscissa) and harvest (ordinate) from basic GAM for Gambell. (B) Fitted relationship between wind direction (abscissa) and harvest (ordinate, mean removed) from basic GAM for Gambell.

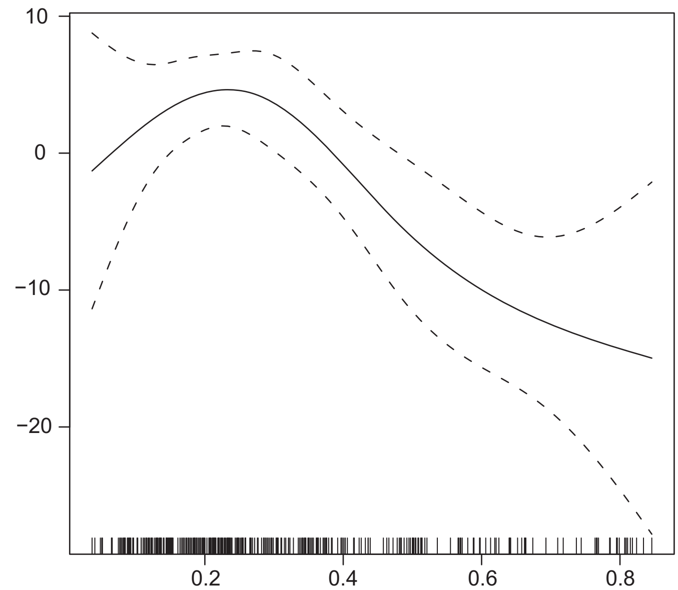


**Fig. 8.** Fitted relationship between ice concentration on the 10-mile scale (abscissa) and harvest (ordinate) from basic GAM for Savoonga.

The differences with its counterpart for Savoonga (Fig. 6C) are intriguing. In particular, wind directions from between about 160° and 260°, i.e., out of the south and southwest, tend to be unfavorable for Gambell while winds out of the north tend to be unfavorable for Savoonga. We suspect that this distinction can be attributed to contrasts in the nature and orientation of the coastlines at the two locations, and hence the direction of winds that would tend to close the leads in the ice near shore required for passage. Based on the various configurations of the GAM that were tested (not all of which are presented here), it seems to be the most consistent difference between the model results for the two communities, a difference also noted by Kapsch et al. (2010).

It is interesting to further consider GAM results regarding sea ice. In particular, the functional relationship between ice concentrations on the 10-mile scale and daily harvests at Savoonga (Fig. 8) indicates that moderate concentrations (~0.3) tend to yield the best conditions. This result may reflect elements of the relationships found for the ice on 5- and 30-mile scales, specifically that greater concentrations at the 5-mile scale and lower concentrations at the 30-mile scale tend to be associated with higher harvests, leaving the 10-mile scale in between. Our results are again similar to Kapsch et al.'s (2010) finding that 88% of walrus harvests occurred in ice concentrations less than 30% in a 75 × 75 km grid off each community, though our results offer additional insight into the form of the relationship between harvest and ice concentration at different radii from the community.

We also investigated the effects of visibility on walrus hunting out of Savoonga. The results from a series of GAM experiments yielded surprisingly little additional predictive skill (~1–2%) with respect to the number of trips or harvests. This can be explained in part by the lack of independence between the winds (especially direction) and visibilities, but in general, wind direction was a better predictor. In more quantitative terms, the GAM experiments yielded $p$-values of typically 0.1–0.3 for wind direction and about 0.5 for visibility, indicating that the statistical robustness of visibility as a predictor is minimal. The model runs did indicate that fewer trips, and smaller harvests, tend to be associated with lower visibilities, as expected. Kapsch et al. (2010) found that less than 5% or less of the walrus harvest took place on days with visibility less than 6 km, noting that fog is a major impediment to hunting (as also reported by St. Lawrence Island hunters). Our result likely indicates either that low visibility is not particularly prevalent (visibility is below Kapsch et al.'s threshold less than 18% of the time during the hunting season) and thus affects relatively few days, or that low visibility is correlated with wind direction and thus by itself adds little new information to the GAM, or both.

We recognize that other methods, e.g., regression trees, could be employed with our data sets. An evaluation of the relative benefits and drawbacks of different methods is outside the scope of this study. Given the consistency in the results from the tests that were carried out using a GAM, we expect that alternative approaches would yield similar results regarding the strength and nature of the relationships between hunting success and physical conditions.

## 4. Discussion

Establishing a quantitative relationship between human use of an ecosystem (walrus hunting) and physical conditions in that ecosystem (ice and winds) offers insights regarding both traditional hunting practices and the ways in which those practices may be affected by climate and other environmental change. It is important to note, however, that many important variables are not included in this analysis. In particular, the distribution and abundance of walrus are also critical to a successful hunt. Although there is no particular reason to think that either has varied greatly enough (independent of ice concentrations) over the past two decades of spring hunting to have a major impact on hunting success (Chad Jay, personal communication, October 2011), changes in the walrus population or its migratory movements could clearly have an enormous impact on hunting success in the future. Local distribution patterns also affect hunting effort and outcomes. Reports of walrus close to the community, for example, can lead to hunters heading out even in marginal weather conditions or on a workday for those with regular employment.

Likewise, we have made no attempt to account for societal variables that might affect spring walrus hunting success, although it is highly likely that changes in equipment, employment, gasoline prices, and the like influence hunter decisions. Local rules are also a factor. Both Gambell and Savoonga have tribal ordinances limiting the take of walrus to four animals per hunting trip, though hunters can make multiple trips in a day if walrus are close (GN, personal observation). While such a rule might keep the actual harvest below the potential harvest, Gambell has taken up to 187 walrus in a single day and Savoonga up to 151, suggesting that hunters are capable to taking full advantage of optimal conditions when they occur, including making multiple trips when walrus are nearby.

With these qualifications in mind, we are still able to account for 25–32% of the daily variability in effort and 18–24% of the daily variability in harvest by considering three straightforward physical parameters: ice concentration, wind direction, and wind speed, readily available from remote sensing or reanalyses. Kapsch et al. (2010) took a different approach, identifying thresholds in ice concentration, winds, temperature, and visibility to determine optimal walrus hunting conditions for St. Lawrence Island. The findings of both studies are broadly consistent, that high ice concentrations and high wind speeds yield little effort or harvest, but our approach offers also a functional relationship between physical conditions and hunting. In other words, the GAM analysis allows a prediction of expected harvest under any combination of ice and wind conditions, whereas Kapsch et al.'s thresholds only indicate favorable or unfavorable conditions for single variables, without further differentiation and without combinations of variables. One difference between the studies is that our results suggest that low visibility, while it may restrict hunting, is not a major independent influence on either effort or harvest. Use of the GAMs allowed us to evaluate the combined influences of different factors in effort and harvest success, rather than being limited to separate analyses of each variable. Kapsch et al. also consider trends in suitable hunting conditions, a topic that is outside the scope of our analysis.

Although the strongest individual correspondence we found is between effort and harvest, the influence of physical factors on effort, harvest, and efficiency are not negligible. Perhaps more importantly, this result suggests an ability to say something meaningful about future walrus hunting by projecting changes in ice and winds in the northern Bering Sea. To date, most assessments of impacts on traditional hunting have been qualitative (e.g., Ford et al., 2006; Wenzel, 2009), often relying on past adaptations to evaluate a general degree of adaptability in Arctic communities. These evaluations, while useful in identifying potential problems, are often unable to identify or predict specific adaptations and adjustments by hunters, for example the development of a fall whaling season in Savoonga in response to a delayed freeze-up (Noongwook et al., 2007).

By contrast, the identification of statistical relationships that connect readily available remote sensing and reanalysis data on ice and wind conditions with spring walrus hunting success offers specific and plausible targets for downscaling of global and regional climate models to project parameters that are now known to influence human behavior or human outcomes. Our evaluation is based on quantitative data (informed by qualitative insights into anticipated relationships between ice, wind, and hunting). The ability to predict physical conditions, however, does not necessarily equate to the ability to predict how hunters will be affected by those changes, nor how they might take advantage of new opportunities such as fall whaling in Savoonga. Nonetheless, the step from qualitative to quantitative relationships offers a way to connect numerical models with hunters' experiences and expectations.

That said, the example of walrus hunting in Gambell and Savoonga is an exceptional case. Few other harvest data sets include daily data over the course of two decades. Even for other communities in Alaska where walrus harvests are monitored by the U.S. Fish and Wildlife Service, the records were not long enough or the number of animals taken was too low to allow a similar analysis. Thus, our analysis offers a glimpse of what could be, but cannot be easily replicated for other species or other locations.

The fact that wind and ice only explain a certain portion of the variability in harvest indicates that many key variables are missing from the analysis. It is impossible to estimate how much additional variation is due to other environmental factors (e.g., walrus populations and distribution) and to societal factors (e.g., employment patterns, fuel prices, success of the spring bowhead whale hunt). Nonetheless, the persistence of human settlement on St. Lawrence Island, and the continued importance of walrus to sustaining those communities, indicates a high degree of reliability in walrus hunting. Despite environmental variability, hunters have been able to provide for their families year after year for a very long time. If key determinants of access such as wind and ice vary greatly from year to year but only account for a relatively small proportion of hunting variability, it seems reasonable to conclude that the skill and experience and adaptability of St. Lawrence Island hunters is a major contributor to their ability to thrive across a wide range of conditions.

## Acknowledgments

This paper began with the insights of elders and hunters from Savoonga, Alaska, who patiently and generously shared their understanding of the Bering Sea ecosystem. We are grateful to Larry Kava, Raymond Toolie, Clarence Waghiyi, Chester Noongwook, Henry Noongwook, and Morris Toolie Sr. for their participation. We are also grateful to Sylvia Toolie, Preston Noongwook, and others in the community who helped guide the project and assist the visiting researchers during their time in Savoonga. We also thank the St. Lawrence Island hunters who have provided valuable harvest data for so many years and the local harvest monitors who collected the harvest data while spending endless hours on the beach awaiting the hunters' safe return. We are grateful to Tom Van Pelt, Chad Jay, Bruce Marcot, Quinn Smith, and the late Caleb Pungowiyi for joining the interviewing team. Winslow Hansen and James MacCracken provided constructive comments on an earlier draft, for which we thank them. Danielle Dickson made the map in Fig. 1, for which we are grateful.

We thank the North Pacific Research Board for funding our work, and the leaders and researchers of BEST-BSIERP for their encouragement and support. We thank the BSIERP LTK Regional Advisory Board and its members for providing guidance and ideas for our project. J.Z. also thanks the National Science Foundation, whose grant ARC0611967 supports his work.

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

This is NPRB Publication No. 394. This project was part of the Bering Ecosystem Study—Bering Sea Integrated Ecosystem Research Program, and this paper is BEST-BSIERP Publication No. 79.

## References

Ashjian, C.J., Braund, S.R., Campbell, R.G., George, J.C. Craig, Kruse, J., Maslowski, W., Moore, S.E., Nicolson, C.R., Okkonen, S.R., Sherr, B.F., Sherr, E.B., Spitz, Y.H., 2010. Climate variability, oceanography, bowhead whale distribution, and Iñupiat subsistence whaling near Barrow. Alaska. Arctic. 63, 179–194.

Brodeur, R.D., Decker, M.B., Ciannelli, L., Purcell, J.E., Bond, N.A., Stabeno, P.J., Acuna, E., Hunt Jr., G.L., 2008. Rise and fall of jellyfish in the eastern Bering Sea in relation to climate regime shifts. Prog. Oceanogr. 77, 103–111.

Comiso, J.C., Parkinson, C.L., Gersten, R., Sock, L., 2008. Accelerated decline in the Arctic sea ice cover. Geophys. Res. Lett. 35, L01703, http://dx.doi.org/10.1029/2007GL031972.

Fall, J., et al., 2013. Subsistence harvests in the BSIERP communities 94, 274–291.

Ford, J.D., Smit, B., Wandel, J., 2006. Vulnerability to climate change in the Arctic: a case study from Arctic Bay. Can. Glob. Environ. Chang. 16, 145–160, http://dx.doi.org/10.1016/j.gloenvcha.2005.11.007.

Garlich-Miller, J., MacCracken, J.G., Snyder, J., Meehan, R., Myers, M., Wilder, J.M., Lance, E., Matz, A., 2011. Status review of the Pacific walrus (*Odobenus rosmarus divergens*). U.S. Fish and Wildlife Service, Anchorage, Alaska 〈http://alaska.fws.gov/fisheries/mmm/walrus/pdf/review_2011.pdf〉.

George, J.C., Braund, S., Brower Jr., H., Nicolson, C., O'Hara, T., 2003. Some observations on the influence of environmental conditions on the success of hunting bowhead whales off Barrow, Alaska. In: McCartney, A.P. (Ed.), Indigenous Ways to the Present: Native Whaling in the Western Arctic. Canadian Circumpolar Institute and University of Utah Press, Edmonton and Salt Lake City, pp. 255–275.

Hassol, S.J., 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Cambridge University Press, New York.

Hastie, T., Tibshirani, R., 1990. Generalized Additive Models. Chapman and Hall, London.

Huntington, H.P., 1998. Observations on the utility of the semi-directive interview for documenting traditional ecological knowledge. Arctic 51, 237–242.

Kapsch, M.-L., Eicken, H., Robards, M., 2010. Sea ice distribution and ice use by indigenous walrus hunters on St. Lawrence Island, Alaska. In: Krupnik, I., Aporta, C., Gearheard, S., Kielsen Holm, L., Laidler, G. (Eds.), SIKU—Arctic Residents Document Sea Ice and Climate Change. Springer, Berlin, pp. 115–144.

Ladd, C., Bond, N.A., 2002. Evaluation of the NCEP–NCAR Reanalysis in the northeast Pacific and the Bering Sea. J. Geophys. Res. 107 (3158), http://dx.doi.org/10.1029/2001JC001157.

Logerwell, E.A., Mantua, N., Lawson, P.W., Francis, R.C., Agostini, V.N., 2003. Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (*Oncorhynchus kisutch*) marine survival. Fish. Oceanogr. 12, 554–568.

Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P.C., Ebisuzaki, W., Jovič, D., Woollen, J., Rogers, E., Berbery, E.H., Ek, M.B., Fan, Y., Grumbine, R., Higgins, W., Li, H., Lin, Y., Manikin, G., Parrish, D., Shi, W., 2006. North American regional reanalysis. Bull. Am. Meteor. Soc. 87, 343–360.

Najac, J., Lac, C., Terray, L., 2011. Impact of climate change on surface winds in France using a statistical–dynamical downscaling method with mesoscale modelling. Int. J. Climatol. 31, 415–430, http://dx.doi.org/10.1002/joc.2075.

Noongwook, G., the Native Village of Savoonga, the Native Village of Gambell, Huntington, H.P., George, J.C., 2007. Traditional knowledge of the bowhead whale (*Balaena mysticetus*) around St. Lawrence Island. Alaska. Arctic 60, 47–54.

North Pacific Research Board, 2005. North Pacific Research Board Science Plan. North Pacific Research Board, Anchorage.

Overland, J., Turner, J., Francis, J., Gillett, N., Marshall, G., Tjernstrom, M., 2008. The Arctic and Antarctic: two faces of climate change. EOS 89, 19.

Rothrock, D.A., Yu, Y., Maykut, G.A., 1999. Thinning of the arctic sea-ice cover. Geophys. Res. Lett. 26 (23), 3469–3472.

Shelton, P., 1992. The shape of recruitment distributions. Can. J. Fish. Aquat. Sci. 49, 1754–1761.

Stroeve, J., Serreze, M., Drobot, S., Gearhead, S., Holland, M., Maslanik, J., Meier, W., Scambo, T.S., 2008. Arctic sea ice extent plummets in 2007. EOS 89, 13.

Wendler, G., Shulski, M., Moore, B., 2010. Changes in the climate of the Alaskan North Slope and the ice concentration of the adjacent Beaufort Sea. Theo. Appl. Climatol. 99, 67–74.

Wenzel, G.W., 2009. Canadian Inuit subsistence and ecological instability—if the climate changes, must the Inuit? Polar Res. 28, 89–99, http://dx.doi.org/10.1111/j.1751-8369.2009.00098.x.

Wiese, F.K., Wiseman, W.J., Van Pelt, T.I., 2012. Bering Sea linkages. Deep-Sea Res. II 65-70, 2–5.

Wood, S.N., 2004. Stable and efficient multiple smoothing parameter estimation for generalized additive models. J. Am. Stat. Assoc. 99, 637–686.

Zhang, J., Woodgate, R., Moritz, R., 2010. Sea ice response to atmospheric and oceanic forcing in the Bering Sea. J. Phys. Oceanogr. 40, 1729–1747, http://dx.doi.org/10.1175/2010JPO4323.1 2010.