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2 **scientific ecological knowledge**

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24 **Abstract**

25 Humans who interact directly with local ecosystems possess traditional ecological knowledge
26 that enables them to detect and predict ecosystem changes. Humans who use scientific
27 ecological methods can use species such as mollusks that lay down annual growth rings to detect
28 past environmental variation and use correlative tools to make predictions about future change.
29 We evaluated local climate change in the coastal ecosystems of Kotzebue, Alaska, using
30 traditional ecological knowledge shared by local Iñupiaq, combined with growth histories of two
31 species of mollusks, each at a different trophic level. A combination of the Arctic Oscillation and
32 total Arctic ice coverage, and summer air temperature and summer precipitation explained 79-
33 80% of the interannual variability in growth of the suspension feeding Greenland cockle
34 (*Serripes groenlandicus*) and the predatory whelk (*Neptunea hero*) respectively, indicating these
35 mollusks are good biomonitors in coastal Alaska for both regional and local conditions. The
36 climate change experts within the community were the elders and the fishers, and they perceive a
37 fundamental change in the climate that could not be resolved from the rapid increase in mollusk
38 growth rates in the mid-1990s alone. We conclude that the coastal climate change of the last few
39 decades is different from the decadal oscillations that have happened before. Combining
40 traditional and scientific ecological knowledge provides greater insight than either approach

41 alone and offers a powerful way to document change in an area that otherwise lacks widespread
42 quantitative monitoring.

43 **Key words** climate change, scientific ecological knowledge, traditional ecological knowledge,
44 sclerochronology, knowledge networks, Arctic

45

46 **Introduction**

47

48 The average atmospheric temperature in the Arctic has increased twice as fast as the average
49 temperature for the rest of the world over the past 50 years, and is predicted to continue to
50 increase rapidly over the next 100 years (Arctic Climate Impact Assessment, 2005). The marine
51 and terrestrial ecosystem changes accompanying these rising temperatures have especially strong
52 impacts on the humans who depend on these ecosystems for their survival and quality of life
53 (Morison *et al.*, 2000; Huntington *et al.*, 2012). Not all species will be affected equally; rather
54 some species are more sensitive to rapid climate change than others (Wassmann *et al.*, 2011),
55 and within those sensitive species, some individuals are especially sensitive. While the emphasis
56 on sensitivity is typically focused on an organism's ability to withstand change, there is also a
57 component of sensitivity related to the ability to detect or record change. We assert that some
58 humans who interact with ecosystems are more attuned to observe changes than others, and are
59 therefore able to report more accurately on such changes (Davis and Wagner, 2003). Whereas
60 many studies of climate change only use key indicators that are physical in nature (e.g.,
61 atmospheric concentrations of carbon dioxide, sea surface temperature), we advocate here for
62 combining knowledge from key ecosystem components and key human observers in an
63 integrated approach to monitoring and assessing environmental change.

64

65 Traditional ecological knowledge (TEK) accumulates in individuals who regularly interact
66 with the natural environment, often via a subsistence lifestyle, making it possible to discern
67 changes occurring over several human generations. TEK can provide information on time scales
68 of 100 years or more (Davis and Wagner, 2003; Shackeroff *et al.*, 2011), and people with high
69 levels of TEK often successfully predict the behaviors of fish, mammals, and other higher
70 trophic level organisms by monitoring how natural resources respond to natural and
71 anthropogenic conditions, and tracking environmental change over time (Menzies and Butler,
72 2006; Griffith, 2006) (Fig. 1). TEK derived from subsistence and commercial resource extraction
73 activities is especially sensitive to environmental changes, as success in obtaining resources is
74 tied to an ability to predict and respond to changing conditions (Huntington, 2000). Further, TEK
75 can be studied using structured methodologies that afford the systematic documentation of
76 cultural beliefs about species, climate, food webs, and other dimensions of natural environments
77 (Boster and Johnson, 1989; García Quijano, 2007). This approach allows a comparison with, and
78 integration into, scientific ecological knowledge (SEK) models. Incorporating TEK into more
79 traditional SEK studies can improve the breadth of research findings while also providing
80 legitimacy to scientific findings for local communities, broadening the knowledge set that local
81 communities can draw on as they develop effective responses to changing ecosystems.

82

83 We used both TEK and SEK to understand coastal climate change in Kotzebue Sound,
84 Alaska. Our scientific knowledge of the system was based on the growth patterns of two

85 common mollusks. There is a close relationship between benthic and water column processes in
86 the Arctic (Grebmeier *et al.*, 1988; Ambrose and Renaud, 1995; Dunton *et al.*, 2005), making
87 long-lived, sessile, benthic organisms particularly good biomonitors of climate change on Arctic
88 shelves (Kortsch *et al.* 2012; Mann *et al.*, 2013). A wide range of marine climate conditions can
89 be reconstructed from the growth and shell chemistry of mollusks (Richardson, 2001;
90 Wanamaker *et al.*, 2011). In Kotzebue Sound, Alaska, we used the shell growth of the
91 suspension feeding Greenland cockle *Serripes gronelandicus* and the predatory whelk *Neptunea*
92 *hero* to provide a temporally consistent and uninterrupted record of change over decadal time
93 scales (Fig. 1).

94
95 Ducklow *et al.* (2009) maintain that attribution of longer-term changes in marine ecosystems
96 is best assessed with a minimum 50-year dataset, and they assert that documenting a regime shift
97 takes at least a decade of data. Mollusks shells can provide high-resolution seasonal records and
98 while at least one species is known to live in excess of 500 years (Butler *et al.*, 2013), most live
99 on the order of 50 years or less (Gröcke and Gillikin, 2008). The mollusks we examined lived 15
100 to 20 years, so use of TEK was necessary to distinguish climate change from a climate
101 oscillation in the mollusk growth data. We combined the derived growth patterns of mollusks
102 that reflected year-to-year changes in the environment with TEK shared by Iñupiaq experts, who
103 track changes over relatively longer time periods from upper trophic levels where subsistence
104 harvesting activities are concentrated. Combining these two forms of knowledge resulted in a
105 much more comprehensive assessment of local climate change than either type of knowledge
106 could alone.

107 **Material and Methods**

108 **Study Site and Organisms**

109
110 Kotzebue, Alaska (67° 00' N, 163° 00' W), is a town of approximately 3,500 people,
111 around 85% of whom are Iñupiaq the majority are enrolled in the Native Village of Kotzebue
112 (NVK), the federally recognized tribal government. Tribal organizations and corporations,
113 federal, state, tribal and city government, a hospital, school, and service and transportation
114 industries, provide the bulk of the employment in the community. Many Kotzebue households
115 are still dependent on caribou, seal, salmon, sheefish, berries, and other flora and fauna for food,
116 clothing, crafts manufacture, and cultural wellness. The town's population fluctuates seasonally,
117 with many families residing in hunting and fishing camps at various times of the year. Because
118 subsistence is so much a part of the local economy, most jobs provide paid subsistence leave.
119 This institutional support helps to allow hunting and fishing activities to remain central to the
120 Kotzebue population.

121
122
123
124 Kotzebue Sound is a shallow (average water depth 10-18 m) embayment in the southeast
125 Chukchi Sea. The area is characterized by long, severely cold winters and short, cool summers.
126 Sea ice is typically present from October to June, leaving the sound ice-free for a maximum
127 duration of four months. Sediments, poorly to very-poorly sorted, are primarily muddy sand to
128 sandy mud, with a minor portion of gravel (Feder *et al.*, 1991). The predominant currents are
129 counterclockwise, with clockwise circulation occasionally occurring at shallower depths (Kinder

130 *et al.*, 1977). During the period of sea ice formation, cold, high salinity bottom water flows out
131 of the Sound via the deepest (28 m) channel.

132
133 The shallow depth of the Sound, the influence of two major rivers (the Noatak and
134 Kobuk), and numerous connections to brackish lagoons result in large annual changes in both the
135 temperature and salinity of the Sound's near shore waters. A temperature and salinity logger we
136 moored in 3 meters of water near the town of Kotzebue recorded an annual water temperature
137 range of -0.8°C to 15°C and a salinity range of 0.1 ppt. to 35.09 ppt. The mollusks used in this
138 study were collected at ca. 10 m water depth near Cape Krusenstern (67° 04.9' N, 163° 41.5' W)
139 and Cape Blossom (66° 45.1' N, 162° 39.2' W). We measured water column properties at
140 collection sites at the time of sampling with a CTD. The mean bottom water temperature during
141 sampling for the years 2002, 2003, and 2004 was 5.5°C (range 4.8-7.3°C) at Cape Krusenstern
142 and 10.2°C (range 6.6-13.6°C) at Cape Blossom. Bottom salinity averaged 28.94 ppt. (range
143 27.34-29.92 ppt.) at Cape Krusenstern and 21.99 ppt. (range 18.15 to 27.9 ppt.) at Cape Blossom.

144
145 *S. groenlandicus* (hereafter *Serripes*) is a large suspension feeding cockle that has a
146 circumpolar distribution (Kafanov, 1980; Kozteyn *et al.*, 1990). Throughout the Arctic it is an
147 important food for walrus (Fisher and Stewart, 1997; Born *et al.*, 2007), bearded seals (Lowry
148 *et al.*, 1980; Finley and Evans, 1983) and bottom-feeding birds (Merkel *et al.*, 2007). *N. heros*
149 (hereafter *Neptunea*), is a large predatory whelk that is common in the Beaufort, Chukchi and
150 Bering Seas (Wagner, 1977; Feder *et al.*, 1991; Feder *et al.*, 2007). It preys on mollusks,
151 including *Serripes* and other infaunal taxa (WGA per. obs.). Although whelks are sometimes
152 found in the stomachs of marine mammals (Finley and Evans, 1983) they are not common prey
153 for marine mammals.

154 155 **Standard Growth Index for *Serripes* and *Neptunea***

156
157 *Serripes* were collected during July in 2002 ($N=16$ individuals), 2003 ($N=6$), and 2004
158 ($N=7$) using an otter trawl (2 m mouth) fitted with a tickler chain from approximately 10 m water
159 depth off Cape Krusenstern in 2002 and 2003 and off Cape Blossom in 2004. The trawl was
160 towed at 2 knots parallel to shore for 20-25 minutes. Only live cockles with undamaged shells
161 were used for analyses. *Neptunea* were collected by two means: 1) using the same trawl used to
162 collect *Serripes*, and 2) provided to us by local fishers from their crab traps. In 2003, *Neptunea*
163 ($N=27$) were trawled from the same areas off Cape Krusenstern and Cape Blossom as *Serripes*.
164 In 2006, all individuals ($N= 80$) were collected from crab traps placed 2-6 nautical miles off
165 Cape Krusenstern. A total of 29 *Serripes* and 103 *Neptunea* were used in our subsequent
166 analyses.

167
168 We only used the hard parts of the mollusks. Both species were removed from their shells
169 either immediately after collection or following freezing and thawing. Shells of both species
170 were measured and the opercula of *Neptunea* removed from the foot, washed, and dried.

171 *Serripes* deposit annual lines, which appear as thin dark lines deposited during the slow
172 growth periods in the winter, separated by thicker light bands on the external shell surface
173 representing the faster summer growth. These lines have been verified as annual in *Serripes* in
174 both the Chukchi Sea (Khim *et al.*, 2003) and in two fjords on Svalbard (Ambrose *et al.*, 2012).

175 The distances between the ventral edges of successive growth lines along the line of maximum
176 growth (shell height) were measured with a digital caliper to the nearest 0.01 mm. We excluded
177 growth beyond the last growth line in analyses because this represents an incomplete growth
178 year.

179
180 The articulated growth steps, or striate, on the internal face of the opercula of *Neptunea*
181 species and other genera of Buccinidae correspond to the summer growth season, and the
182 interrupting depressions to winter quiescence (Richardson, 2005). The forward edges of each
183 ridge are therefore annuli, representing the end of each year's growth. While we did not validate
184 the annual deposition of striate in *Neptunea heros* for Kotzebue Sound, we presume the same
185 pattern that occurs in other *Neptunea* species (Richardson, 2005). Annual growth of each
186 *Neptunea* was thus measured as the distance between each annulus. As described above for
187 *Serripes*, we used a digital caliper to measure the distance between each annulus to the nearest
188 0.01 mm and excluded growth beyond the last annulus.

189
190 Annual mollusk growth declines with age, so it is necessary to standardize growth
191 increments within an individual and among individuals of different ages before growth can be
192 compared among years. Each growth increment can be assigned to a calendar year because we
193 collected all individuals live and lines are deposited annually. The same methods were applied to
194 *Serripes* and *Neptunea* data. We followed the methods of Ambrose *et al.* (2006) to remove the
195 ontogenetic change in growth rate. Briefly, we used the von Bertalanffy growth function and its
196 first derivative with respect to time to derive a predicted change in shell height for each age
197 based on all individuals in the population. Then we calculated the expected increase in shell
198 height for each individual for each calendar year of its life. Finally, we divided the measured
199 shell growth for each calendar year by the expected growth for that year to generate a
200 standardized growth index (SGI). This standardization process removes the ontogenetic changes
201 in growth and equalizes the variance for the entire series (Fritts 1976). Once annual changes in
202 shell or operculum growth were standardized, we calculated the mean SGI for each calendar year
203 from all individuals. The result is an annually-resolved growth record for the *Serripes*
204 population, reflecting relatively better and poorer growth years compared to the expected von
205 Bertalanffy fit of the data. An SGI greater than 1 indicates a better than average year for growth,
206 while a value less than 1 reflects a worse than average growth year.

207 208 **Climatological and Meteorological Data**

209
210 We examined two Arctic climate indices with potential influence on the region: the
211 Arctic Climate Regime Index (ACRI), and the Arctic Oscillation (AO). Recently, Proshutinsky
212 has refined and re-evaluated the ACRI, resulting in some slight changes to the originally
213 published ACRI values (Johnson *et al.*, 1999). Data for the AO were obtained from
214 http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html.
215 We also related growth patterns to three regional indices that influence North Pacific
216 ecosystems: the North Pacific Index NPI-Aleutian Low, reflecting the intensity of the mean
217 winter (November through March) Aleutian low pressure cell; the Siberian/Alaskan Index, the
218 difference between mean winter (December through March) pressure anomalies in eastern
219 Siberia and the Yukon (Alaska); and the Pacific Decadal Oscillation (PDO), a recurring pattern

220 of variability in climate with pan-Pacific effects on marine ecosystems (Overland and Wang
221 2005; Overland *et al.*, 2008). For the PDO, we examined the impact of the annual PDO and the
222 summer (June through September) and winter (December through March) indices. The North
223 Pacific Index-Aleutian Low, Siberian/Alaskan Index, and the PDO values were obtained from
224 <http://www.beringclimate.noaa.gov/data/>.

225
226 Meteorological data for the Kotzebue Airport were obtained from the Western Regional
227 Climate Center (<http://www.wrcc.dri.edu>). We used mean winter (December through March) and
228 summer (June through September) values for wind and mean summer, winter, and annual values
229 for air temperature and precipitation.

230
231 Local ice conditions were estimated from the data point nearest Kotzebue Sound
232 collected by the Nimbus-7 SMMR and DMSP SSM/I passive microwave satellite and obtained
233 from the National Snow and Ice Data Center (<http://nsidc.org/data/seaice/pm.html>). The spatial
234 resolution of the satellite imagery is 25×25 km, and the cell used for the ice analysis was
235 located at $67^{\circ} 5.4' N$, $163^{\circ} 41.5' W$. The temporal resolution is daily from 1990 to 2005. For our
236 analysis we used the Julian date of freeze-up and break-up defined as the day when ice
237 concentration first falls above or below, respectively, 50%. The threshold used to define ice-free
238 days was ice cover $< 25\%$.

239
240 Data on total Arctic-wide spatial extent (km^2) of pack ice are provided by the U.S.
241 National Snow and Ice Data Center (http://www.nsidc.com/data/seaice_index/). We used these
242 data to determine several measures of regional ice conditions: annual average extent of total ice
243 in the Arctic, maximum ice extent (typically in March), autumn ice (average October through
244 December ice coverage), ice coverage the previous 6 months (January through June of the year
245 preceding growth), and an ice anomaly index (percent difference between the average annual
246 total ice coverage and the average Arctic ice cover from 1980-2006).

247 248 **Mollusk Statistical Analysis**

249
250 To verify if averaging the growth rates of the individuals sampled was warranted, we
251 computed the Cronbach α measure of reliability (Bland and Altman, 1997) for the available
252 growth data on a common set of years (1990-2003). The reliability coefficient measures the
253 homogeneity of the mollusk growth rates. Cronbach α was 0.81 for *Serripes*; values of α above
254 0.7 are considered fairly reliable. The growth of individual *Neptunea* was remarkably
255 homogenous with a very high Cronbach α measure of reliability (0.94).

256
257 Once we established that the cockle and whelk samples were homogenous, we combined
258 the growth data into an annual mean value as a more reliable indicator of annual growth rates
259 than what was reflected by the individuals alone. We calculated Pearson correlation coefficients
260 in order to determine basic pairwise relationships between the SGIs of *Serripes* and *Neptunea*
261 and environmental and physical variables. Annual means were compared, and we also
262 investigated the time-dependence between data in consecutive years, leading us to incorporate
263 two data transformations: 2-year running means of environmental data to reduce the magnitude
264 of interannual variability of environmental data, and a 1-year lag to account for the time it may

265 take for physical processes to be reflected in shell growth. We calculated weighted correlation
266 coefficients, with the value for each year being weighted proportionally to the sample size for
267 that year.

268
269 We used linear mixed modeling (for example, Pinheiro and Bates, 2000), as implemented
270 in the R package nlme, to identify significant relationships between, in this case, individual
271 growth rates and all forms of the environmental variables. In these models the individuals define
272 the random effect, and an autoregressive lag-1 correlation is incorporated into the modeling at
273 the individual level.

274
275 Significance of the relationships with a single predictor (112 in all), were obtained as a
276 first overview. Since we are investigating many relationships, we used the step-down adjustment
277 of Benjamini and Hochberg (1995) to control the false positive rate, with an overall significance
278 level of 0.05 in the case of each species.

279
280 All subsets of two predictor variables were then investigated (over 6,000 models) as well
281 as all subsets of three predictors (over 200,000 models) in an attempt to detect optimum
282 combinations of variables. For the best subsets, interaction effects were also investigated.
283 Models were selected based on the AIC criterion, which penalizes the number of parameters in
284 the model. In order to measure the success of the model in recovering mean growth rates, the
285 predicted growth rates from the models were correlated with mean observed growth rates and
286 then squared to give an R^2 measure similar to that obtained in regression. Weighted correlation
287 coefficients were calculated as described above.

288 **Assessing Traditional Ecological Knowledge**

289
290
291 There were two phases of sampling for the TEK portion of the study (Johnson and
292 Weller, 2002). In Phase I, in-depth interviews were conducted with a non-probability sample of
293 Iñupiaq hunters and fishers in the region who were identified as being knowledgeable about the
294 Kotzebue Sound ecosystem, including hunters and fishers from the villages of Kotzebue and
295 Noatak). In Phase II, the sample consisted of the top 79 hunters and fishers as determined from
296 hunting and fishing records provided by the Native Village of Kotzebue (NVK). The interview
297 protocol for the study was approved by both the East Carolina University Institutional Review
298 Board and the NVK and written consent was obtained from all interviewees.

299
300 The Phase I open-ended interviews focused on individuals' uses of local natural resources
301 and the behavior of marine organisms, including their views about how natural resources
302 functioned and changed over time, yielding 25 ecological narratives. During these interviews,
303 respondents routinely spoke of the ways that various features of the natural environment had
304 either changed or not changed over their lifetimes.

305
306 The narratives were thematically coded and common themes and associated propositions
307 were compiled. The coded propositions were then converted to propositions in an agree/disagree
308 format (Johnson and Weller, 2002). For example, the original quote from the narratives "...we
309 look for clear ice, good ice that's not dirty...There's never ugruks on gray ice, dirty ice, what we

310 call dirty ice...” was written as “When hunting ugruk you need clear ice, good white ice that’s
311 not dirty, ugruks avoid gray ice or dirty ice.” We developed a list of 102 propositions, based on
312 highly shared themes in the 25 narratives, and subsequently asked the 79 Iñupiaq hunter-fishers
313 (Phase II sample) whether or not they agreed or disagreed with each of the propositions.

314
315 Lists of agree-disagree propositions are central to eliciting what is called “cultural
316 consensus”; or consensus among informants regarding specific domains of knowledge. It is
317 formally called the Cultural Consensus Model (CCM), and is a way to understand culture as a
318 matter of belief and knowledge agreement (Romney *et al.*, 1986). One important element of
319 culture is the idea of shared understanding and the CCM allows for an assessment of the extent
320 to which individuals within a culture have a shared understanding of a set of beliefs. Using
321 factor analysis on the transposed data matrix, where the variables are the respondents rather than
322 the propositions, the method reveals the extent to which respondents have a shared understanding
323 regarding an overall set of beliefs, where they do not, and which respondents are more
324 “culturally competent” regarding the consensus held by the group (i.e., which respondents more
325 consistently agree or disagree with the majority or culturally-shared understanding). For
326 respondents’ dichotomous responses (agree/disagree) to fit the model, the rule of thumb is the
327 ratio of the first to second eigenvalue in a minimum residual factor analysis should be greater
328 than 3, there should be no negative factor scores on the first factor, and the mean of the factor
329 scores should be > 0.5 . Table 1 provides the propositions for the change domain (a subset of the
330 102 propositions) and the culturally correct answers derived from a Bayesian weighting method
331 described by Romney *et al.* (1987). Also included for the first five propositions are the
332 responses reflecting the change index described below. Table 2 lists the 37 propositions (out of
333 the 102) used in the analysis of the ugruk knowledge domain for comparison.

334
335 We further derived a change index while investigating the relationship between expertise
336 and normative cultural ecosystem beliefs. The 35 change propositions (Table 1) were inter-
337 correlated and subjected to minimum residual factor analysis. The first factor contained five
338 propositions with high factor scores (Table 3 and the first five propositions of Table 1). These
339 five propositions were related to increases in water temperature, earlier salmon returns, increases
340 in flounder catches, trout leaving earlier, and increases in the Sound crab populations.
341 Responses to the 5 change propositions (1, 0) were summed across respondents to produce the
342 Climate Change Knowledge Index (CCKI). The higher the index score, the higher the belief in
343 ecosystem changes possibly due to unprecedented climate change.

344
345 During Phase II interviews, we also elicited information that allowed us to further define
346 the fishers’ and hunters’ knowledge networks. The fishers’ knowledge network was developed
347 by asking the 79 respondents to name the five individuals they thought were most knowledgeable
348 about fish and fishing in the Kotzebue Sound (Fig. 2A). The hunters’ knowledge network was
349 derived similarly (Fig. 2B). This resulted in two $n \times m$ matrices of respondents (rows) reports of
350 whom they perceived as knowledgeable about fishing/hunting (columns). Thus, the matrices
351 consisted of the responses of the 79 respondents who could nominate any of the 79 interviewees,
352 or hunters or fishers outside the 79, yielding two $n \times m$ matrices (not necessarily all the same
353 hunters/fishers in the rows as in the columns). These two-mode networks were transformed into
354 bipartite graphs and symmetrized. This yielded two $n \times n$ matrices where the i, j th entry is the

355 presence or absence of a knowledge relation between two respondents. Betweenness centrality
356 (Freeman, 1977) was used to determine knowledge experts in the network. The definition of
357 betweenness centrality is:

$$358 \quad b_j = \sum_{i,k} \frac{g_{ijk}}{g_{ik}}$$

359 where b_j is the betweenness centrality of node j and g_{ijk} is the number of geodesic paths (shortest
360 paths) connecting i and k through j and g_{ik} is the total number of geodesic paths connecting i and
361 k (Borgatti *et al.*, 2013). The measure, as used here, is normalized by dividing b_j by the
362 maximum possible betweenness thereby expressing the measure as a percentage. The more an
363 individual respondent connects respondents who are themselves not connected, the higher their
364 betweenness centrality. This generally reflects expertise and brokerage abilities in knowledge
365 and communication networks (Maiolo *et al.*, 1992). The two independent expertise variables
366 using betweenness centrality are “Fish Know Expert” and “Hunt Know Expert.”

367
368 We used a general linear model to investigate the relationship between perceived change
369 (CCKI) and expertise while controlling for a number of demographic independent variables
370 including: Age, Education (number of years of formal schooling), Store Bought (percent of food
371 purchased from store), Kotzebue resident (dummy variable, where 1=Kotzebue residence, 0
372 otherwise), Wage Labor (dummy variable, where 1=engaged in wage labor, 0 otherwise), and
373 Percent Marine Food (percent of food that is marine subsistence including mammals) (Table 4).
374 Intercorrelations among the independent variables were conducted in order to limit any potential
375 problems with multicollinearity. Finally, the two expertise variables were simply the normalized
376 betweenness centrality measures in both the hunting and fishing knowledge networks as
377 calculated in UCINET (Borgatti *et al.*, 2002).

378 379 **Results**

380 381 Scientific Ecological Knowledge.

382
383 The growth patterns of individual cockles and of individual whelks were homogenous,
384 meaning that individuals of the same species were responding similarly to environmental
385 conditions (i.e. high signal to noise) and individual SGIs could be reliably averaged. The mean
386 standard growth index (SGI) for each calendar year for both species of mollusks varied
387 considerably over the 22 years of the data set (Figs. 3 and 4), and patterns for both species
388 exhibit two distinct phases. Before 1996 (for *Serripes*) and 1995 (for *Neptunea*) SGIs are
389 consistently below 1.0, representing relatively slow growth, and with little interannual
390 variability. Subsequently, SGIs are near or above 1.0 for both species, with a high degree of
391 interannual variability for *Serripes*. The growth of both species declines after 2001 (*Neptunea*)
392 and 2002 (*Serripes*), with this decline continuing to the end of the chronology in 2005 for
393 *Neptunea*.

394
395 The SGI of both species was strongly negatively correlated with regional climate indices;
396 *Serripes* most strongly with the two-year running mean of the annual and winter Arctic
397 Oscillation (AO) index and *Neptunea* most strongly with the annual and summer Pacific Decadal

398 Oscillation (PDO) and the annual AO (Table 5). The growth of both species was also negatively
 399 correlated with the North Pacific Index-Aleutian low. Correlations were generally stronger with
 400 the running means and/or the lagged running means of the environmental parameter than with
 401 current year conditions.

402
 403 Growth of both species was also negatively correlated with large scale patterns of ice
 404 coverage with the strength and significance of the correlations generally improving with running
 405 means and an annual lag of the ice parameters. Measures of total Arctic ice coverage were more
 406 frequently correlated with growth than local measures of ice coverage, though there were modest
 407 positive correlations between growth and the day of Kotzebue Sound freeze up for both species,
 408 indicating that a longer ice-free period results in greater growth.

409
 410 Other local environmental parameters did not correlate as strongly with growth as
 411 regional parameters. Annual and winter air temperatures were positively correlated with *Serripes*
 412 growth, but there was no relationship between growth during the expected growing season,
 413 summer, and temperature. *Neptunea* growth was actually negatively correlated with summer
 414 temperature. *Neptunea* growth was also negatively related to wind and winter precipitation,
 415 presumably a proxy for spring runoff.

416
 417 The best linear mixed model for *Serripes* includes two regional parameters and their
 418 interaction:

$$\begin{aligned}
 419 \quad \text{SGI} &= 10.486 - 41.859 \text{ AOsummer}_{m2} && p=0.004 \\
 420 & - 0.7896 \text{ TotalArcticIce}_{-1} && p<0.0001 \\
 421 & + 3.4427 \text{ AOsummer}_{m2} \times \text{TotalArcticIce}_{-1} && p=0.005 \\
 422 & &&
 \end{aligned}$$

423
 424 where the subscript m2 represents the two year running mean of the variable and -1 a one year
 425 lag.

426
 427 This model explains 80.3% of the variability in mean growth. The interaction term means
 428 that the negative effect of Total Arctic Ice (lagged one year) is less as the two year running mean
 429 of the AO in summer increases.

430
 431 The best mixed model for *Neptunea* includes a mixture of regional and local parameters
 432 and is more complicated than for *Serripes* because it contains three terms and an interaction
 433 term:

$$\begin{aligned}
 434 & \\
 435 \quad \text{SGI} &= 79.6786 - 6.8780 \text{ AirTempSummer}_{m2} && p<0.0001 \\
 436 & - 5.8282 \text{ TotalArcticIce PreWinter}_{m2,-1} && p<0.0001 \\
 437 & + 0.00476 \text{ PrecipSummer}_{m2,-1} && p<0.0001 \\
 438 & + 0.5027 \text{ AirTempSummer}_{m2} \times \text{TAIPreWinter}_{m2,-1} && p<0.0001
 \end{aligned}$$

439 Subscripts are as above for *Serripes* and m2₋₁ is a one year lag of the two year running mean.

440

441 This model explains 79.3% of the variability in *Neptunea* growth and uses the two year
442 running mean for all parameters. The interaction between summer air temperature and total
443 Arctic ice the previous winter (two year running mean lagged one year) means that the negative
444 effect on SGI of the previous winter total Arctic ice extent is minimized with increasing summer
445 air temperature.

446 447 Traditional Ecological Knowledge

448
449 TEK, integrating over longer time scales than the mollusks we examined, can further
450 elucidate the apparent shift in the coastal ecosystem that began in the mid-1990s. Of the 35
451 separate agree/disagree propositions concerning coastal ecosystems, 20 addressed
452 change/variability, and 16 specifically addressed marine fish or invertebrates (with 7 of the 16
453 fish/invertebrate propositions related to change) (Table 1). These propositions derived from in-
454 depth interviews with Iñupiaq hunter-fishers will allow for the systematic modeling of cultural
455 ecosystem beliefs and their variation across individuals and groups. In the factor analysis of the
456 inter-correlations among respondents' answers, (i.e., factor analysis of the people rather than the
457 propositions), the ratio of the first to second eigenvalue for coastal ecosystem knowledge was
458 3.19 and all the factor scores were positive, indicating cultural consensus among the respondents
459 for propositions in this domain (Romney *et al.*, 1987). It is not, however, nearly as strong as the
460 consensus found for bearded seal (ugruk) knowledge (ratio of 7.78, Table 6, with questions
461 presented in Table 2). In fact, the coastal ecosystem knowledge is approaching the classification
462 of 'proto-cultural' (Caulkins, 2004) (knowledge just entering the cultural system) due to higher
463 levels of intra-cultural variability within the shared understanding. A comparison among the
464 various cultural and TEK knowledge domains assessed indicates that cultural knowledge
465 competency in one domain does not necessarily translate to such competency in others for the
466 Kotzebue community (Table 7). It is important to note that our overall study addressed several
467 topics, and included both hunting and fishing experts.

468
469 Further break-down of the 35 coastal ecosystem propositions resulted in the previously
470 mentioned climate change knowledge index (CCKI) a subset of 5 statements that dealt explicitly
471 with change. Table 1A compares the culturally correct answers for the 5 statements as
472 determined by the CCM with the responses for the change index. There is general agreement
473 between the two that the water is getting warmer and that the salmon are returning earlier.
474 However, the index reflects more change, particularly with respect to changes in the behavior of
475 some fish and in increasing numbers of some species being observed in the Sound. The CCKI
476 showed that respondents who perceived more change were often at odds with the overall
477 normative ecological beliefs, particularly for the fish/climate domain (Table 7, $r = -0.526$, $P =$
478 0.0001). We subsequently used the knowledge network information to further characterize the
479 hunters/fishers who believe the ecosystem is changing.

480
481 The size of the nodes in the networks for both the hunters and the fishers (Figure 2) is
482 proportional to their betweenness centrality and is used as index of expertise in each of the
483 domains as described in the Material and Methods section. The two networks are similar in
484 structure, but vary slightly in terms of the distribution of centrality values. Whereas both have a
485 core periphery structure, the fish knowledge network core is more dominated by a single fisher in

486 the core (including a number of fishers with moderate centrality), while the hunt knowledge
487 network has a more uniform distribution of centrality among core members. In both cases,
488 however, the hunters and fishers with higher centrality are in the core of the network linking to
489 other actors in the periphery of the network. The extent to which hunters and fishers are central,
490 in terms of betweenness centrality, in the two networks reflects domain expertise in that they
491 receive knowledge nominations from a broader range of hunters and fishers who are themselves
492 not connected in the network. In addition, hunters and fishers in these central positions in the
493 knowledge network would have access to a wider range of shared ecological knowledge as well
494 as more novel ecological information.

495
496 We compared expertise, as determined by normalized betweenness centrality in the
497 knowledge networks, and the change index (CCKI) while controlling for a set of other possible
498 independent variables including age, education, residence, engagement in wage labor, percent of
499 total food purchased at stores, and percent of food from marine subsistence. Interestingly, the
500 two expert subsets of the population (hunters and fishers) had different perspectives on coastal
501 ecosystem change. In a regression of factors that may be driving the increased perceptions of
502 change, both age and fish expertise (Fish Know Expert) were positively related to the change
503 index (CCKI), while involvement in wage labor, education, age and hunting expertise (Hunt
504 Know Expert) were negatively related (Table 4). This suggests that the fish experts were more
505 likely than others, particularly the hunting experts, to perceive increased coastal change that was
506 outside the range of the normative ecological beliefs as reflected in the consensus analysis of the
507 change statements. Hunters and fishers are aware of the natural variability in the climate over
508 time and as such these normative ecological beliefs already incorporate the normal range of
509 variation that might result from such things as the Arctic Oscillation. For example, in response to
510 the statement on variation in ice conditions from one year to the next (Table 1B), the culturally
511 correct answer clearly pointed to recognition of annual variability. What may be difficult to
512 tease out perceptually are the differences between changes due to decadal and interannual
513 variation from a shift in climate. These results, however, indicate that the perceived changes in
514 climate and subsequently in the coastal ecosystem are outside the range of natural variation and
515 are best understood by the older, more experienced fishers, who are less involved in wage labor,
516 and these change perceptions appear to represent the beginnings of the diffusion of new cultural
517 beliefs related to climate and ecosystem change. We expect that these perceptions will diffuse
518 from these fish experts to other hunters and fishers over time.

519 520 **Discussion**

521
522 Local knowledge of ecosystems has become increasingly valued and used in ecosystem
523 and resource management over the past three decades (Johannes, 1981, 1984; Berkes *et al.*,
524 2000; Le Fur *et al.*, 2010). When combined with SEK, this often yields a more holistic view of
525 ecosystems than either knowledge base alone (Huntington *et al.*, 2011; Ferguson *et al.*, 2012).
526 Combining TEK and SEK could be especially useful in the Arctic where long-term historical
527 data are lacking (Wassmann *et al.*, 2011), and indigenous peoples have accumulated
528 environmental information for many generations (Huntington, 2011). Despite the
529 acknowledgement that TEK can inform SEK and lead to an enhanced environmental
530 understanding in the Arctic (Huntington *et al.*, 2004; Nicholas *et al.*, 2004; Laidler, 2006), few

531 studies have successfully combined the two ways of knowing in Arctic systems (Mahoney *et al.*,
532 2009; Weatherhead *et al.*, 2010; Carter and Nielson, 2011; Huntington *et al.*, 2011; Riseth *et al.*,
533 2011). We demonstrate that Iñupiaq fishers are especially attuned to perceiving changes in
534 coastal climate and they provide the longer time frame needed to interpret the high-resolution
535 changes we see in the growth rate of mollusks. This provides a better understanding of climate
536 change in Kotzebue than if we had relied on either TEK or mollusk growth alone as a climate
537 proxy.

538
539 Annual growth patterns of both *Neptunea* and *Serripes* reflect variations in large-scale
540 climate drivers in the Kotzebue Sound/ Chukchi Sea system and local manifestations of these
541 drivers (Table 5, Figures 3 and 4). The relationships we document between *Serripes* growth and
542 large scale climate oscillations, primarily the North Pacific Index-Aleutian low, the PDO, and the
543 AO (the latter two indices are closely related, Sun and Wang, 2006), are consistent with studies
544 of *Serripes* growth in the European Arctic where this relationship is well established (Ambrose *et*
545 *al.*, 2006; Carroll *et al.*, 2009, 2011a). In our study, *Neptunea* growth was also negatively
546 correlated with the AO (Table 5). No study has linked growth of a buccinid to climate
547 oscillations, but the deposition of annual lines in the operculum and statolith and the longevity of
548 some taxa (Richardson, 2005) make members of this genus a good candidate for climate studies.
549 Even similar species in the same production regime can have opposite responses to a regime shift
550 (Benson and Trites, 2002), so it is remarkable that species at two trophic levels exhibited
551 relatively simultaneous and significant shifts in annual growth patterns. Only one other study has
552 documented an effect of the AO on two trophic levels simultaneously (Aanes *et al.*, 2002). The
553 AO index shifted from a strong positive to a negative or neutral phase after 1995 (Thompson and
554 Wallace, 1998; Overland and Wang, 2005) concurrent with the PDO switching from a warm to a
555 cool phase (Matua and Hare, 2002) and an increase in the growth of *Serripes* and *Neptunea*
556 (Figures 3 and 4). A major restructuring of the ecosystem in the northern Bering Sea has been
557 hypothesized to have occurred around 1996 and is attributed to a reduction in the strong positive
558 phase of the Arctic Oscillation resulting in stronger southerly winds, less ice and warmer
559 temperatures over the northern Bering Sea and eastern Siberia (Grebmeier *et al.*, 2006a). The
560 change in ecosystem structure and function in the northern Bering Sea from an Arctic system
561 dominated by tight pelagic-benthic coupling to a sub-Arctic one dominated by pelagic processes
562 representative of the southern Bering Sea could potentially affect the Pacific-influenced portion
563 of the Arctic Ocean (Grebmeier *et al.*, 2006a). If so, we would expect to record evidence of a
564 coincident regime shift north of Bering Strait in the Chukchi Sea, which is heavily influenced by
565 input from the Pacific Ocean (Weingartner *et al.*, 2005; Grebmeier *et al.*, 2006b), and also
566 because of tight pelagic-benthic coupling on Arctic shelves (Grebmeier and Barry, 1991,
567 Ambrose and Renaud, 1995).

568
569 There is not always a direct relationship between a climate index and local conditions
570 (Stenseth *et al.*, 2003), but ultimately the growth of organisms is determined by the manifestation
571 of climate oscillations on the local environment (Ambrose *et al.* 2006). *Serripes* growth is best
572 explained by large scale patterns of ice extent (Table 5). Interestingly, it is the Arctic-wide ice
573 pattern (total Arctic ice) that is better predictor of growth than the local ice conditions (freeze up,
574 ice free days) in the mixed-effects model. The local conditions are based on conditions in a 25
575 km x 25 km area which may not be as robust as predicting larger scale conditions in Kotzebue

576 Sound as Arctic-wide metrics. Food and temperature are the most important determinants of
577 growth in suspension feeding bivalves (Beukema *et al.*, 1985; Lewis and Cerrato, 1997;
578 Witbaard *et al.*, 1999; Dekker and Beukema, 1999) and annual phytoplankton production in the
579 Arctic is directly proportional to the length of the open water period (Rysgaard *et al.*, 1999).
580 While *Serripes* can utilize ice algae as food (McMahon *et al.*, 2006), ice generally limits
581 phytoplankton productivity and therefore likely limits *Serripes* growth. Temperature is not a
582 predictor in the mixed model and there is no apparent relationship between *Serripes* growth and
583 temperature during the summer (Table 5) when *Serripes* appear to put on most of its growth
584 (Ambrose *et al.*, 2012). *Serripes* growth appears to be determined largely by factors directly or
585 indirectly affecting its food.

586
587 The growth of *Neptunea* was explained more by local factors than by the larger scale
588 atmospheric patterns that presumably determine local conditions (Table 5) and both regional and
589 local factors enter the multiple regression. As with *Serripes*, *Neptunea* growth is also negatively
590 affected by a large scale measure of ice cover, total Arctic ice the previous winter. Unlike
591 *Serripes*, however, local parameters are also important predictors of *Neptunea* growth. Whelks
592 feed primarily on bivalves (including *Serripes*, personal observation WGA) and polychaetes
593 (Shimek, 1984) and benthic biomass on Arctic shelves is inversely related to ice cover (Ambrose
594 and Renaud, 1995), so ice cover the preceding years might affect the abundance of *Neptunea*
595 prey and the predator's growth. A similar explanation could explain the importance of summer
596 precipitation in determining *Neptunea* growth. Higher precipitation would deliver more
597 terrestrial carbon to Kotzebue Sound where it is an important contributor to the benthic and
598 pelagic food web (McMahon, Ambrose and Clough unpublished data). Rivers might also deliver
599 nutrients to local waters increasing primary productivity. Both these effects would increase the
600 abundance and biomass of *Neptunea* prey. The negative relationship between *Neptunea* growth
601 and the running mean of summer temperature is harder to explain. The growth rate of mollusks
602 in general and a *Neptunea* congeneric, *Neptunea arthritica* in particular, increase with increasing
603 temperature (Fujinaga, 1987; Miranda, 2009). If the increased metabolism associated with an
604 increase in temperature is not compensated for with an increase in food consumption, however,
605 growth rates may decline as has been seen in an Arctic scallop (Bilcher *et al.*, 2010). The
606 significant interaction between ice cover and summer temperature indicates that higher
607 temperatures do reduce the negative effect of ice.

608
609 Summer wind is one of the few parameters that had a stronger impact on *Neptunea*
610 growth in the present year than incorporating the previous year as a running mean or with a time
611 lag (Table 5). It might be reasonable to expect the behavior of predator and/or prey to be
612 negatively affected by wind increasing water and sediment movement in the shallow waters of
613 Kotzebue Sound. Experimental evidence, however, indicates water flow does not interfere with a
614 whelk's ability to detect prey (Ferner and Weissburg, 2005) or its predation rate on bivalves
615 (Powers and Kittinger, 2002). It is possible that the wind-induced bottom currents in Kotzebue
616 Sound are higher than the speeds used in experiments or have different effects on bottom
617 sediments, but we have no evidence of the impact of wind induced waves on the Kotzebue
618 Sounds benthos. We can only speculate that prey burrowing behavior may be modified by wind
619 induced bottom currents, with prey burrowing deeper and therefore becoming less accessible to
620 *Neptunea* predation when wind impacts bottom sediments.

621
622 Growth of the mollusks was usually best explained by local and regional parameters
623 when parameters were lagged a year relative to growth or when a two year running mean of the
624 parameter was used to incorporate the previous year's conditions. Lagged response to climate
625 oscillations are common in marine systems (Overland *et al.*, 2010) and can typically span many
626 trophic levels (Post, 2004) from benthic infauna (Tunberg and Nelson, 1998), including bivalves
627 (Witbaard *et al.*, 2003; Ambrose *et al.*, 2006, Carroll *et al.*, 2011b), to zooplankton (Pershing *et al.*,
628 *et al.*, 2004), fish (Ottersen *et al.*, 2004) and birds (Thompson and Ollason, 2001). This lagged
629 response is well explained by the double integration hypothesis where atmospheric forcing
630 affects large scale environmental factors (e.g. sea surface temperature, ocean circulation) which
631 in turn affect population dynamics (Bestelmeyer *et al.*, 2011; di Lorenzo and Ohman, 2013;
632 Doney and Sailley, 2013). The growth of relatively long-lived mollusks is likely best modeled
633 using lags of atmospheric processes and even local conditions because growth is not continuous
634 throughout the year and at some times of the year energy is diverted from growth to reproduction
635 (Peterson and Fegley, 1986; Bayne, 2004).

636
637 Mollusks are frequently touted as excellent biomonitors for reconstructing environmental
638 conditions (Wanamaker *et al.*, 2011), especially in the Arctic (Mann *et al.*, 2013; Carroll *et al.*,
639 2014). Without a much longer dataset, though, it is unclear from SEK alone whether the shifts
640 we see in growth are a result of a decadal oscillation, as the relationships between growth and
641 regional climate indices would suggest, or, in contrast, is related to a more sustained climatic
642 change.

643
644 Accordingly, our TEK results indicate that the Kotzebue Sound ecosystem has been
645 undergoing changes on a broader time scale than would be evident from natural oscillations
646 alone. In support of this assertion, Moerlein and Carothers (2012) collected TEK via
647 ethnographic methods in the Northwest Alaska communities of Noatak and Selawik, and
648 concluded that the changes in Northwest Alaska over the last 20-30 years are “without precedent
649 and outside of the normal range of variation.” Many of the more observable changes are
650 occurring within the Sound ecosystem as reflected in the clam growth analysis. It is therefore not
651 surprising to find that the older, more experienced fish experts were the first to observe such
652 changes, which includes reported changes in the behavior and increased presence of several
653 marine species. Furthermore, the fact that experts are seeing these changes before other marine
654 mammal hunters and fishers points to the beginnings of the diffusion of new cultural ecological
655 knowledge and understandings. Over time this incipient knowledge will eventually gain a
656 broader cultural consensus, eventually representing a new ecological normative understanding.

657
658 One possible hypothesis is that it is the experts who would be the most likely to see these
659 changes before anyone else. After all, they are the ones who are more experienced and
660 knowledgeable about the ecological and environmental factors, such as air and water
661 temperature, that are essential for being successful as a hunter or fisher. In addition, they are
662 more committed to the subsistence way of life in that they are older, have less formal Western
663 education, and do not tend to engage in forms of wage labor. They have spent most of their lives
664 on the water and ice fishing. Therefore, it is the fish experts who have intimate knowledge of
665 spawning behaviors and marine species assemblages that are seeing unprecedented increases in

666 some species, particularly benthic species such as crabs. Although we interviewed hunters and
667 fishers at a single point in time, we argue here that the difference in beliefs between fish experts
668 and the traditional cultural beliefs reflects the beginnings of the diffusion of new cultural
669 knowledge.

670
671 This is not to say that it is only the fish experts reporting ecosystem change that may be
672 due to a shift in climate. There was clearly agreement that the ice is breaking up earlier and
673 freezing later, the west summer winds are becoming less frequent, and the air temperatures are
674 getting warmer across the seasons (Table 1B). Further, as is evident from a comparison of
675 responses to the change statements in Table 1A, there is overall cultural agreement among
676 hunters and fishers that the water in the Sound is getting warmer and the salmon are returning
677 earlier. It is the fish experts, however, more than any other group, who recognize the connection
678 between the warming of the water and the increasing numbers of crabs entering the Sound (Table
679 1A). In addition, they also are observing increases in flounder numbers and changes in trout
680 behavior, changes that have yet to be noticed by others, in particular, the hunting experts. The
681 hunting experts tend to concentrate more on marine mammals, such as ugruk, who interface with
682 hunters on the surface of the water or on the ice. In the consensus analysis there was general
683 agreement that the ugruk population numbers have been relatively stable over the last 15 years
684 and that the fat content of the ugruk has stayed relatively the same (Table 1B). Whereas some
685 have claimed there has been increased movement north of beaver populations, such movements,
686 if true, appear not to have affected the spawning abilities of species such as whitefish
687 (*Coregonus* spp., Table 1B). What this suggests is that ecosystem changes due to a shift in
688 climate may be more readily observed in the marine ecosystem, particularly the benthos, as
689 opposed to the terrestrial system. It also seems to be the case that it also had less effect on
690 marine mammal populations and behavior, at least at the time of our study. Recent scientific
691 research has suggested that the pace of a shifting climate may be more pronounced in the ocean
692 than on land at similar latitudes (Burrows et al. 2011). If this is the case, then the fact that the
693 fish experts are noticing ecosystem change before others certainly follows.

694
695 There is cultural consensus that the air and water temperatures of the Kotzebue area are
696 warming, the elders and fishers perceive behavioral and population abundance changes in
697 ecologically important marine species, and the changing growth of two mollusk species in
698 response to regional and local environmental conditions suggest continued change for Kotzebue
699 Sound. The fish experts are seeing changes in animal behavior such as the timing of salmon runs
700 and the abundance of crabs and flounder. The recent decreases in ice cover will increase the
701 growth rates of both *Serripes* and *Neptunea*. These changes are likely to have profound impacts
702 on the structure of the marine community, especially the benthos, and on subsistence hunting.
703 There will be a longer fishing season due to less ice, more crabs to fish, and faster growing clams
704 (*Serripes*) will provide more food for bearded seals (ugruk). On the other hand, the reported
705 changes in ice conditions do not bode well for traditional, ice-based ugruk hunting and new
706 immigrant marine species may reduce the abundances of clams. While speculative, we feel our
707 predictions, based on a combination of TEK and SEK, are robust, and should be useful for future
708 local (town), regional (borough), and statewide planning, as well as for scientific modeling of
709 ecosystem responses to climate change.

710

711 It is challenging to determine whether a deviation in environmental conditions at a given
712 time is due to a shift to a new climate regime or to natural cycling. The 15-20 years of mollusk
713 growth data clearly indicate a change in growth conditions in the middle of the 1990s (Figures 3
714 and 4). The SEK data set alone cannot discern if this change is part of a decadal climate
715 oscillation, a fundamental change in climate affecting the near-shore ecosystem, or a
716 combination of the two. The TEK shared by the Iñupiaq ecomonitors provide insight into
717 ecosystem change not revealed by mollusks. The experts' knowledge of the ecosystem is
718 typically very local, integrative, and is longer in duration than the time frame provided by the
719 mollusks we studied. Together these two approaches provide more insight than either would
720 alone; the mollusks indicate precisely when change occurred and the Iñupiaq tell us the change is
721 not only a decadal oscillation. Recently the United States Arctic Research Commission
722 recommended the incorporation of traditional ecological knowledge into long-term monitoring of
723 Arctic climate change (United States Arctic Research Commission, 2013). We have
724 demonstrated that such a combination of scientific and traditional ecological knowledge provides
725 a much more holistic view of local climate change in one Arctic location than by relying solely
726 on either approach. Application of this method across the Arctic would provide an assessment of
727 the extent to which local ecosystems are affected by the changing Arctic climate even in the
728 absence of continuous environmental monitoring with scientific instruments.

729

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742

743 **References**

744

745 Aanes, R, Sæther, B-E, Smith, F.M., Cooper, E.J., Wookery, P.A., and Øritsland, N.A. (2002).
746 the Arctic Oscillation predicts effects of climate change in two trophic levels in a high-
747 Arctic ecosystem. *Ecol. Lett.* 5, 445-453.

748

749 Ambrose, W. G. Jr., Renaud, P. E. (1995). Benthic response to water column productivity:
750 evidence for benthic pelagic coupling in the Northeast Water Polynya. *J. Geophys. Res.*
751 100, 4411-4421.

752 Ambrose , Jr. W.G., Carroll, M. L., , M., Thorrold S. R., and McMahon, K. (2006). Variation in
753 bivalve growth in a Norwegian high-Arctic fjord: Evidence for local- and large-scale
754 climatic forcing. *Global Chg. Bio.* 12, 1595-1607.

- 755 Ambrose, Jr. W. G., Renaud, P. E., Locke, W. L., V, Cottier, F. R., Berge, J. R., Carroll, M. L.,
756 Levin, B., and Ryan, S. (2012). Growth line deposition and variability in growth of two
757 circumpolar bivalves (*Serripes groenlandicus* and *Clinocardium ciliatum*). *Polar Biol.*
758 35, 345-354.
- 759 Arctic Climate Impact Assessment (2005). *Impacts of a Warming Arctic: Arctic Climate Impact*
760 *Assessment*. (Cambridge Univ. Press).
- 761 Bayne, B.L. (2004). Phenotypic flexibility and physiological tradeoff in the feeding and growth
762 of marine bivalve molluscs. *Integr. Comp. Biol.* 44, 425-432.
- 763 Benjamini, Y. and Hochberg, Y. (1998). Controlling the false discovery rate: a practical and
764 powerful approach to multiple testing. *J. Royal Stat. Soc., Series B*, 57, 289-300.
- 765 Benson, A. J., and Trites, A. W. (2002). Ecological effects of regime shifts in the Bering Sea and
766 eastern Pacific Ocean. *Fish Fisheries* 3, 95-113.
- 767 Bilcher, M.E., Rysgaard, S., and Sejr, M.K. (2010). Seasonal growth variation in *Chlamys*
768 *islandica* (Bivalvia) from sub-Arctic Greenland is linked to food availability and
769 temperature. *Mar. Ecol. Prog. Ser.* 407, 71-86.
- 770 Berkes, F., Colding, J., and Folke, C. (2000). Rediscovery of traditional ecological knowledge
771 as adaptive management. *Ecol. App.* 10, 1251-1261.
- 772 Beukema, J. J., Knoll, E., and Cadée, G. C. (1985). Effects of temperature on the length of the
773 annual growing season of the Tellinid bivalve *Macoma balthica* (L.) living on tidal flats
774 in the Dutch Wadden Sea. *J. Exper. Mar. Biol. Ecol.* 90, 129-144.
- 775 Butler, P.G., Wanamaker, A.D. J.r, Scourse, J.D. et al. (2013). Variability of marine climate on
776 the North Icelandic Shelf in a 1,357-year crossdated *Arctica islandica* chronology.
777 *Palaeoceanogr., Palaeoclimatol., Palaeoecol.* 373, 141-151.
- 778 Bland, J. M., and Altman, D. G. (1997). Cronbach's alpha. *British Medical Journal*, 314, 572.
- 779 Born, E.W., Rysgaard, S., Ehlme, G., Sejr, M., Acquarone, M., and Levermann, N. (2003).
780 Underwater observations of foraging free-living Atlantic walrus (*Odobenus rosmarus*
781 *rosmarus*) and estimates of their food consumption. *Polar Biol.* 26, 348-357.
- 782 Borgatti, S.P., Everett, M.G., and Freeman, L.C. (2002). Ucinet 6 for Windows: Software for
783 Social Network Analysis. Harvard, MA; Analytic Technologies.
- 784 Borgatti, S., Everett, M., and Johnson, J. (2013). *Analyzing Social Networks*. (Sage, London).
- 785 Boster, J. S., Johnson, J. (1989) Form or function: A comparison of expert and novice judgments
786 of similarity among fish. *Amer. Anthro.* 91, 866-899.
- 787 Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M.,
788 Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V.,
789 Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B.,

- 790 Sydeman, W.J., and Richardson, A.J. (2011). The Pace of Shifting Climate in Marine and
791 Terrestrial Ecosystems. *Science* 334, 652-655.
- 792 Carroll, M.L., Johnson, B., Henkes, G.A., McMahon, K.W., Voronkov, A., Ambrose, W.G., Jr.,
793 and Denisenko, S.G. (2009). Bivalves as indicators of environmental variation and
794 potential anthropogenic impacts in the southern Barents Sea. *Mar. Poll. Bull.* 59:193-206.
- 795 Carroll, M.L., Ambrose, W.G., Jr., Levin, B.S., Locke, W.L., Henkes, G.A., Hop H., and
796 Renaud, P.E. (2011a). Pan-Svalbard growth rate variability and environmental regulation
797 in the Arctic bivalve *Serripes groenlandicus*. *J. Mar. Syst.* 88,239-251.
- 798 Carroll, M.L., Ambrose, W.G., Jr., Levin, B., Ratner, A., Ryan, S., and Henkes, G.A. (2011b).
799 Climatic regulation of *Clinocardium ciliatum* (bivalvia) growth in the northwestern
800 Barents Sea. *Palaeogeog. Palaeoclimatol Palaeoecol.* 302, 10-20.
- 801 Carroll, M.L., Ambrose, W.G., Jr., Locke, W.L., Ryan, S.K., and Johnson, B.J. (2014). Bivalve
802 growth rate and isotopic variability across the Barents Sea Polar Front. *J. Mar. Syst.* 130,
803 167-180.
- 804 Carter, B.T.G, and Nielson, E.A. (2011). Exploring ecological changes in Cook Inlet beluga
805 whale habitat through traditional and local ecological knowledge of contributing factors
806 for population decline. *Mar. Policy* 35, 299-308.
- 807 Caulkins, D. (2004). Identifying Culture as a Threshold of Shared Knowledge: A Consensus
808 Analysis Method. *Inter. J. Cross Cultural Manag.* 4, 317-333.
- 809 Coan, E. V., P. Valentich & F. R. Bernard. (2000). *Bivalve seashells of western North America*.
810 Santa Barbara Museum of Natural History. Monograph 2, Studies in Biodiversity 2.
811 Santa Barbara, CA, USA. 764 pp.
- 812 Davis, A., and Wagner, J. R. (2003). Who knows? On the importance of identifying “experts”
813 when researching local ecological knowledge. *Human Ecol.* 31, 463-489.
- 814 Dekker, R., and Beukema, J. (1999). Relations of summer and wintertemperatures with
815 dynamics and growth of two bivalves, *Tellina tenuis* and *Abra tenuis*, on the northern
816 edge of their intertidal distribution. *J. Sea Res.* 42, 207-220.
- 817 Di Lorenzo, E. and Mark D. Ohman, M.D. (2013). A double-integration hypothesis to explain
818 ocean ecosystem response to climate forcing. *Proc. Nat. Acad. Sci.* 110, 2496-2499.
- 819 Doney, S.C. and Sailley, S.F. (2013). When an ecological regime shift is really just stochastic
820 noise. *Proc. Nat. Acad. Sci.* 110, 2438-2439.
- 821 Ducklow, H. W., Doney, S. C., and Steinberg, D. K. (2009). Contributions of long-term research
822 and time-series observations to marine ecology and biogeochemistry. *Ann. Rev. Mar. Sci.*
823 1, 279-302.

- 824 Dunton, K. H., Goodall, J. L., Schonberg, S. V., Grebmeier, J. M., and Maidment, D. R. (2005).
825 Multi-decadal synthesis of benthic pelagic coupling in the western Arctic: Role of cross-
826 shelf advective processes. *Deep-Sea Res. II* 52, 3462-3477.
- 827 Feder, H. M., Naidu, A. S., Baskaran, M., Frost, K., Hameedi, M. J, Jewett, S. C., Johnson, W.
828 R., Raymond, J., and Schell, D. (1991). Bering Strait-Hope Basin: habitat utilization and
829 ecological characterization. Institute of Marine Science technical report 92-2, University
830 of Alaska, Fairbanks.
- 831 Feder, H.M., Jewett, S.C., and Blanchard, A. (2005). Southeastern Chukchi Sea (Alaska)
832 epibenthos . *Polar Biol.* 28, 402-421.
- 833 Finley, K.J., and Evans, C.R. (1983). Summer diet of the bearded seal (*Erignathus barbatus*) in
834 the Canadian high Arctic. *Arctic* 36, 82-89
- 835 Fisher, K. I., and Stewart, R.E.A. (1997). Summer foods of Atlantic walrus, *Odobenus rosmarus*
836 *rosmarus*, in northern Foxe Basin, North West Territories. *Can. J. Zool.* 75, 1166–1175.
- 837 Freeman, L. C. (1977). A set of measures of centrality based on betweenness. *Sociometry* 40,
838 35–41.
- 839 Fritts, H. C. (1976). *Tree Rings and Climate*. Academic Press, New York.
- 840 García Quijano, C. (2007). Fishers’ knowledge of marine species assemblages: bridging
841 scientific and local ecological knowledge in southeastern Puerto Rico. *Amer. Anthro.* 109,
842 529-536.
- 843 Griffith, D. (2006). “Local knowledge, multiple livelihoods, and the use of natural and social
844 resources in coastal North Carolina,” in *Traditional Ecological Knowledge and Natural*
845 *Resource Management*, ed. C. Menzies (University of Nebraska Press), 153-174.
- 846 Grebmeier, J.M., McRoy, C.P., and Feder, H.M., (1988). Pelagic-benthic coupling on the shelf of
847 the northern Bering and Chukchi Seas. I. Food supply source and benthic biomass. *Mar.*
848 *Ecol. Prog. Ser.* 48, 57–67.
- 849 Grebmeier, J.M., Overland, J. E., Moore, S. E., Farley, E. V., Carmack, E. C. , Cooper, L. W.,
850 Frey, K. E., Helle, J. H., McLaughlin, F. A., and McNutt, S. L. (2006a). A major
851 ecosystem shift in the Northern Bering Sea. *Science* 311, 1461-1464.
- 852 Grebmeier, J.M., Cooper, L.W., Feder, H.M., and Sirenko, B.I. (2006b). Ecosystem dynamics of
853 the Pacific-influenced Northern Bering and Chukchi Seas in the Amerasian Arctic. *Prog.*
854 *Ocean.* 71,331-361.
- 855 Grebmeier, J.M, and Barry, J.P. (1991). The influence of oceanographic processes on pelagic-
856 benthic coupling in polar regions: A benthic perspective. *J. Mar. Syst.* 2, 495-518.
- 857 Gröcke, D. R., and Gillikin D. P. (2008). Advances in mollusk sclerochronology and
858 sclerochemistry: tools for understanding climate and environment. *Geo-Marine Letters*
859 28, 265-268.

- 860 Huntington, H. P. (2000). Using traditional ecological knowledge in science: methods and
861 applications. *Ecol. App.* 10, 1270-1274.
- 862 Huntington, H.P., Callaghan, T.V., Fox Gearheard, S., and Krupnik, I. (2004) Matching
863 traditional and scientific observations to detect environmental change: a discussion on
864 Arctic Terrestrial Ecosystems. *Ambio* 33, 18–23.
- 865 Huntington, H.P., Gearhead, S., Mahoney, A.R., and Salomon, A.E. (2011). Integrating
866 Traditional and Scientific Knowledge through Collaborative Natural Science Field
867 Research: Identifying Elements for Success. *Arctic* 64:437-445.
- 868 Huntington, H. P., Goodstein E, and Duskiuchen E. (2012). Towards a tipping point in
869 responding to climate change. *Ambio* 41, 66-74.
- 870 Johannes, R.E. (1981). Working with fishermen to improve coastaltropical fisheries and resource
871 management. *Bull. Mar. Sci.* 31(3): 673–680.
- 872 Johannes, R.E. (1984). Marine conservation in relation to traditional lifestyles of tropical
873 artisanal fishermen. *Environmentalist*, 4(Suppl. 7):30–35. doi:10.1007/BF01907290.
- 874 Johnson, J. C., Weller, S. (2002). in Gubrium. J. F, and Holstein, J. A., (eds.) *Handbook of*
875 *Interview Research*, J.F Gubrium and J.A. Holstein eds.(Sage, Newbury Park), 491-514.
- 876 Johnson, M. A., Proshutinsky, A. Y., and Polyakov, I. V. (1999). Atmospheric patterns forcing
877 two regimes of Arctic circulation: A return to anticyclonic conditions? *Geophys. Res.*
878 *Lett.* 26, 1621-1624.
- 879 Kafanov, A. (1980). Systematics of the subfamily Clinocardiinae Kafanov, 1975 (Bivalvia,
880 Cardiidae). *Malacologia* 19, 297–328.
- 881 Khim, B-K, Kranz, D. E., Cooper, L. W., and Grebmeier, J. M. (2003). Seasonal discharge to
882 the western Chukchi Sea shelf identified in stable isotope profiles of mollusk shells *J.*
883 *Geophys. Res.* 108, doi:10.1029/2003JC001816.
- 884 Kinder, T. H., Schumacher, J. D., Tripp, T. B., and Pashinski, D. (1977). The physical
885 oceanography of Kotzebue Sound, Alaska, during late summer, 1976. Technical report
886 M77-99, University of Washington, Seattle.
- 887 Koszteyn, J., Kwasniewski, Różycki, O, and Węslawski, J.M. (1990). *Atlas of the Marine Fauna*
888 *of Southern Spitzbergen*. Institute of Oceanology, Poland.
- 889 Kortsch, S., Primicerio, R., Beuchel, F., Renaud, P. E. Rodrigues, J., Lønne, O. J., and
890 Gulliksen, B. (2012). Climate-driven shifts in Arctic marine benthos. *Proc. Nat. Acad.*
891 *Sci.* 109, 14052-14057.
- 892 Laidler, G.J. (2006). Inuit and scientific perspectives on the relationship between sea ice and
893 climate change: the ideal complement? *Climatic Chg.* 78, 407–444.

- 894 Le Fur, J., Guilavogui, A. and Teitelbaum, A. (2011). Contribution of local fishermen to
 895 improving knowledge of the marine ecosystem and resources in the Republic of Guinea,
 896 West Africa. *Can. J. Fish. Aquat. Sci.* 68, 54–1469
- 897 Lewis, D. E., and Cerrato, R. M. (1997). Growth uncoupling and the relationship between shell
 898 growth and metabolism in the soft shell clam *Mya arenaria*. *Mar. Ecol. Prog. Ser.* 158,
 899 177–189.
- 900 Mahoney, A., Gearheard, S., Oshima, T., and Qillaq, T. (2009). Sea ice thickness measurement
 901 from a community-based observing network. *Amer. Bulletin Meteorological Sci.* 90,
 902 371-377.
- 903 Maiolo, J., Johnson, J. C., and Griffith, D. C. (1992). Applications of social science theory to
 904 fisheries management: three examples. *Soc. Nat. Res.* 5, 391-407.
- 905 Mann, R., Munroe, D.M., Powell, E.N., Hofmann, E.E. and Klinck, J.M. (2013). “Bivalve
 906 mollusks: Barometers of climate change in Arctic marine systems”, in *Responses of*
 907 *Arctic Marine Ecosystems to Climate Change*, eds. F.J. Mueter, D.M.S. Dickson, H.P.
 908 Huntington, J.R. Irvine, E.A. Logerwell, S. A. MacLean, L.T. Quakenbush, and C. Rosa
 909 (Alaska Sea Grant, University of Alaska Fairbanks) doi:104027/ramecc.2013.4, 61-82.
- 910 Matua, N. J., and Hare, S. R. (2002) The pacific decadal oscillation. *J. Ocean.* 58, 35-44.
- 911 McMahan, K. W., Ambrose, W. G. Jr, Johnson, B. J., Sun, M. Yi., Lopez, G. R., Clough, L. M.,
 912 and Carroll, M .L. (2006). Benthic community response to ice algae and phytoplankton in
 913 NyÅlesund, Svalbard. *Mar. Ecol. Prog. Ser.* 310, 1–14.
- 914 Menzies, C, and Butler, C. (2006). “Understanding Ecological Knowledge,” in *Traditional*
 915 *Ecological Knowledge and Natural Resource Management*, ed. C. Menzies (University
 916 Nebraska Press), 1-17.
- 917 Merkel, F.R., Jamieson, S.E., Falk, K. and Mosbech, A. (2007). The diet of common eiders
 918 winter in Nuuk, Southwest Greenland. *Polar Biol.* 390, 227-234.
- 919 Moerlein, K. J., and Carothers, C. (2012). Total Environment of Change: Impacts of Climate
 920 Change and Social Transitions on Subsistence Fisheries in Northwest Alaska *Ecol. Soc.*
 921 17, 10-19.
- 922 Morison, J., Aagaard, K., and Steele, M (2000). Recent environmental changes in the Arctic: A
 923 review. *Arctic* 53, 359–371.
- 924 Nicholas, Berkes, F., Jolly, D., Snow, N.B., and the community of Sachs Harbour (2004).
 925 Climate Change and Sea Ice: Local Observations from the Canadian Western Arctic.
 926 *Arctic* 57,68-79.
- 927 Overland, J., and Wang, M. (2005). The Arctic climate paradox: the recent decrease of the Arctic
 928 Oscillation. *Geophys. Res. Lett.* 32, doi:10.1029/2004GL021752 .

- 929 Overland, J. Rodionov, S., Minobe S., and Bond, N. (2008). North Pacific regime shifts:
930 Definitions, issues and recent transitions. *Prog. Ocean.* 77, 92-102.
- 931 Overland, J.E., Alheit, J., Bakun, A., Hurrell, J.W., Mackas, D.L. and Miller, A.J. (2010).
932 Climate controls on marine ecosystems and fish populations. *J. Mar. Syst.* 79, 305-315.
- 933 Peterson, C.H. and Fegley, R. S. (1986). Seasonal allocation of resources to growth of shell
934 soma, and gonads in *Mercenaria mercenaria*. *Biol. Bull.* 171, 597-610.
- 935 Pinheiro, J.C., and Bates, D.M. (2000). *Mixed-Effects Models in S and S-PLUS*, Springer, New
936 York.
- 937 Richardson, C.A., Saurel, C., Barroso, C.M., and Thain, J. (2005). Evaluation of the age of the
938 red welk *Neptunea antique* using statoliths, opercula and element ratios in the shell *J.*
939 *Exper. Mar. Biol. Ecol.* 325, 55-64.
- 940 Richardson, C. A (2001). Molluscs as archives of environmental change. *Ocean. Mar. Biol. Ann.*
941 *Rev.* 39, 103-164.
- 942 Riseth, J. Å and 11 authors (2011). Sámi traditional ecological knowledge as a guide to science:
943 snow, ice and reindeer pasture facing climate change. *Polar Rec.* 47, 202-217.
- 944 Romney, A. K., Weller, S., and Batchelder, W. (1986). Culture as consensus: A theory of
945 culture and informant accuracy. *Amer. Anthro.* 88, 13-338.
- 946 Romney, A. K., Batchelder, W., and Weller, S. (1987). Recent applications of cultural consensus
947 theory. *Amer. Beh. Sci.* 31,163-177.
- 948 Rysgaard, S., Nielsen, T., and Hansen, B. W. (1999). Seasonal variation innutrients, pelagic
949 primary production and grazing in a high-Arctic marine ecosystem, Young Sound,
950 Northeast Greenland. *Mar. Ecol. Prog. Ser.* 179, 13–25.
- 951 Shackeroff, J. M., Campbell, L. M., and Crowder, L. B., (2011). Social-ecological guilds: putting
952 people into marine historical ecology. *Ecol. Soc.* 16, 1-20.
- 953 Shimek, R. L. (1984). The diet of Alaskan *Neptunea*. *Veliger* 26, 274-281.
- 954 Stenseth, N. C., Ottersen, G., Hurrell, J. W., Mysterud, A., Lima, M., Chan, K-S., Yoccoz, N.,
955 G., and Ådlansvik, O. (2003). Studying climate effects on ecology through the use of
956 climate indices: the North Atlantic Oscillation, El Niño Southern Oscillation, and beyond.
957 *Proc. Royal Soc. Lond.* 270, 2087-2096.
- 958 Sum, J. and Wang, H. (2006). Relationship between Arctic Oscillation and Pacific Decadal
959 Oscillation on decadal timescale. *Chinese Sci. Bull.* 51, 75-79.
- 960 Thompson, D.W.J, and Wallace, J.M. (1998). The Arctic Oscillation signature in the wintertime
961 geopotential height and temperature fields. *Geophys. Res. Lett.* 25, 1297-1300

- 962 United States Arctic Research Commission (2013). Report on the Goals and Objective for Arctic
963 Research 2013-2014 for the U.S. Arctic Research Program Plan. (U.S. Arctic Research
964 Commission, Washington, D.C.).
- 965 Wagner, F.J.E. (1977). Recent mollusk distribution patterns and palaeobathymetry, southeastern
966 Beaufort Sea. *Can. J. Earth Sci.* 14, 2013-2028.
- 967 Wanamaker, A. D. Jr., Hetzinger, S., Halfar, J. (2011). Reconstructing mid- to high-latitude
968 marine climate and ocean variability using bivalves, coralline algae, and marine sediment
969 cores from the Northern Hemisphere. *Paleogeogr. Paleoclimatol. Paleoecol.* 302, 1-9.
- 970 Wassmann, P., Duarte, C. M, Agustí, S., and Sejr, M. K. (2011). Footprints of climate change in
971 the Arctic marine ecosystem *Global Chg. Biol.* 17, 1235-1249.
- 972 Weatherhead, E., Gearheard, S., and R.G. Barry, R.G. (2010). Changes in weather persistence:
973 Insight from Inuit knowledge. *Global Environ. Chg.* 20, 523-528.
- 974 Weingartner, T., Aagaard, K., Woodgate, R., Danielson, S., Sasaki, Y., Cavalieri, D. (2005).
975 Circulation on the north central Chukchi Sea shelf. *Deep-Sea Res. II* 52, 3150–3174.
- 976 Witbaard, R., Duineveld, G. C. A., and de Wilde P. A. W. J. (1999). Geographical differences in
977 growth rates of *Arctica islandica* (Mollusca: Bivalvia) from the North Sea and adjacent
978 waters. *J. Mar. Biol. Assoc. U. K.* 79, 907–915.

Table 1. A) The five propositions comprising the Climate Change Knowledge Index (CCKI) as derived from a factor analysis of all 35 propositions, the classification of the statement as either change related or system related, the statement topic, the culturally correct answer (as determined by the cultural consensus model using Bayesian modeling), and the answer for the index. B) The remaining thirty agree/disagree propositions, the classification of the statement as either change related or system related, the statement topic, and the culturally correct answer (as determined by the cultural consensus model using Bayesian modeling).

A.

Statement	Change/ System	Topic	Culturally Correct Answer	Change Index Answer
The temperature of the water is a lot warmer than ten years ago.	Change	Climate	Agree	Agree
The first salmon are arriving earlier than they used to.	Change	Fish/Invertebrates	Agree	Agree
The increase in water temperature in the Sounds is bringing in more crabs to the area.	Change	Fish/Invertebrates	Disagree	Agree
People are getting more flounders in their nets today than in the past.	Change	Fish/Invertebrates	Disagree	Agree

The trout are going out earlier than usual.	Change	Fish/Invertebrates	Disagree	Agree
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B.

Statement	Change/ System	Topic	Culturally Correct Answer
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Over the past few years, freeze-up has been longer and break-up a little bit earlier.	Change	Climate	Agree
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The west winds in the summer are not coming as much as they used to.	Change	Climate	Agree
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The temperatures on the whole are warmer throughout the year.	Change	Climate	Agree
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People are beginning to get more pink salmon in the Sounds.	Change	Fish/Invertebrates	Disagree
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The last three or four years there have been less trout.	Change	Fish/Invertebrates	Disagree
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There has been an increase in dirty ice.	Change	Ice	Agree
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The ice has been staying	Change	Ice	Disagree
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longer in the spring than it used to.

There is very little difference in ice conditions from one year to the next.	Change	Ice	Disagree
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The ugruks and the seals aren't any skinnier or fatter, but are about the same as always.	Change	Marine mammals	Agree
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Over the last fifteen years the ugruk population in the Sounds has stayed about the same.	Change	Marine mammals	Agree
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Some years there's so many boats out there that the ugruk won't stay up on the ice.	Change	Marine mammals	Agree
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There is less beluga today because of all the outboard noise and exhaust.	Change	Marine mammals	Agree
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More porpoise have been showing up in recent years.	Change	Marine mammals	Agree
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Beaver moving into this country are blocking the ability of the whitefish to spawn.	Change	Terrestrial and Fish/Invertebrates	Disagree
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People have begun taking more animals than they can use.	Change	Terrestrial and Marine mammals	Agree
Mussels and clams come up along the beach whenever you get a good west wind or storm.	System	Fish/Invertebrates	Agree
Herring come in right when the Kobuk ice starts breaking up.	System	Fish/Invertebrates	Agree
Break-up is a good time to get sheefish.	System	Fish/Invertebrates	Disagree
Sheefish are the first fish that come out from the rivers under the ice.	System	Fish/Invertebrates	Agree
Sheefish very seldom are taken in the oceanfront along Sisaulik.	System	Fish/Invertebrates	Agree
The adult tomcods come out with the freshwater flush of the Noatak in springtime.	System	Fish/Invertebrates	Disagree
The tomcods lay their eggs in the waters just in front of Kotzebue in December and	System	Fish/Invertebrates	Disagree

January.

When ice fishing in front of Kotzebue for tomcod the best time is when the tide is going out.	System	Fish/Invertebrates	Agree
As the ice first breaks up trout migrate right along the coast of Krusenstern and Sisaulik.	System	Fish/Invertebrates	Agree
The less snow covering in the winter, the thicker the ice.	System	Ice	Agree
When there are a lot of heavy east winds in the spring the ice leaves the Sounds quickly.	System	Ice	Agree
It is difficult to read the ice after a fresh snow.	System	Ice	Agree
When there is less rain, there are fewer berries.	System	Terrestrial	Agree
The wind affects our tidal changes here in the Kotzebue Sounds more than anything else.	System	Weather	Agree
A lot of east wind in the winter can lead to thinner ice in the spring.	System	Weather	Agree

Table 2. The 37 agree/disagree propositions comprising the data used to construct the cultural consensus model for ugruk.

1. We try to catch the ugruks as they're migrating up north.
2. The ugruk and the spotted seal are gone for the winter, except for the few seals that stay in the area.
3. We don't really know where the ugruks go for the winter.
4. Beluga and ugruk show up in the Sound at different times of year.
5. Most of the time, it's good, clear weather we look for when hunting ugruk.
6. Ugruk don't mind cloudy or raining weather to get up on top of the ice.
7. Ugruks avoid gray ice or dirty ice.
8. In the evenings the ugruk spend more of their time in the water than on the ice.
9. When there is a lot of east wind early in November, December, and January the Sound toward Deering doesn't freeze as think as it normally should.
10. Even in nice, clear weather when hunting ugruk you've got to know which way the current is going so you can get out before the ice closes in.
11. On the good white ice, that clear thick ice, you can hunt ugruk wherever you want.
12. When the wind is blowing hard in the open ice pack you need to find some ice for shelter and protection from the shifting ice and rolling seas.
13. Usually during break-up the pack ice sits out by Sealing Point where the shelf drops and the ice piles up there keeping the ice in and protecting you from the ocean waves.
14. You'll find ugruk on thick clean white ice.
15. If the ice moves out early and quickly you can still find ugruk close to town.
16. With strong east or west winds in the spring the ice by Deering can get closed over and unable to move, while the rest of the Sound is free of ice.
17. The young ugruk (ugrutchiaq) head into the rivers where they feed on fish.

18. The young ugruk (ugrutchiaq) are skinny in the fall.
19. As an ugruk grows into an adult they can eat less fish and eat more crabs and shrimp.
20. In the fall you can get young ugruk (ugrutchiaq) in the open water and once it freezes, they disappear.
21. The larger adult ugruk leave with the ice as it moves north after break up.
22. You find mostly the younger, smaller ugruk (ugrutchiaq) if the ice piles up around Deering in the spring.
23. The brown rotten ice is safe to travel on.
24. In normal years when the ice breaks up you have enough time to hunt ugruk all the way into early July.
25. You have to wait for the wind to blow the ice along and smash it up before it is safe to go out ugruk hunting in the spring.
26. Different conditions out there dictate where you go ugruk hunting in the spring.
27. It is best to wait until the ice is broken up enough before hunting ugruk, because if you go too early, then you get a chance of getting jammed in and stuck in the ice for a few days.
28. During break-up the last place the ice is going to really rot is along the sandbars.
29. Young ugruk (ugrutchiaq) can only be found in Kotzebue Sound and avoid going up the rivers.
30. In the fall you see the young bearded seal (ugrutchiaq) but not the adults.
31. Beluga and bearded seal can be difficult to find in the spring when there are killer whales in the upper and lower Kotzebue Sound.
32. Ugruk go down to the bottom and dig up shrimp and crabs to feed on.
33. In February or March you may find some ugruk or natchiq along the leads in the Sound.
34. Seals can be seen on top of the ice some times as early as January when the sun starts to come up.
35. A black faced ringed seal (natchiq) is a bull male, and is stink to eat.
36. When seal hunting in February and March the ice is not stable, and it will open one day and freeze up the next.

37. When you go out on snow machines seal hunting in February/March you go on the leads and shoot the females.

Table 3. Factor loadings from a minimum residual factor analysis for the top five propositions used in the Climate Change Knowledge Index (CCKI).

1st Factor

Loadings	Propositions
0.601	The temperature of the water is a lot warmer than ten years ago.
0.540	The first salmon are arriving earlier than in the past.
0.508	The trout are going out earlier than usual.
0.481	People are getting more flounders in their nets today than in the past.
0.463	The increase in water temperature in the Sound is bringing in more crabs to the area.

Table 4. Multiple regression for Climate Change Knowledge Index (CCKI) as dependent variable with models using demographic and non-network independent variables (Model 1; $R^2 = 0.279$) and a model including network independent variables (Model 2; $R^2 = 0.421$). [Age = age of respondent, Store Bought (%) = percentage of diet from store food, Kotzebue Resident (dummy variable: 1, 0), Education = years of education, Wage Labor (dummy variable: 1, 0), Marine Subsistence (%) = percentage of food from marine systems, Hunt Know Expert and Fish Know Expert = the normalized betweenness centralities in the knowledge networks of hunter and fishers respectively]. Significant relationships are in bold. The levels of significance are: * $P < 0.05$, ** $P < 0.01$.

Effect	t	t
Constant	2.816	2.631
Age	2.593**	2.909**
Store Bought (%)	-1.016	-1.436
Kotzebue Resident (dummy)	-0.187	-0.016
Education	-1.662	-2.074*
Wage Labor (dummy)	-2.212*	-2.401**
Marine Subsistence (%)	0.253	0.095
Hunt Know Expert		-2.627**
Fish Know Expert		2.480**

Table 5. Pearson correlations relating the mean standardized growth index (SGI) of *S. groelandicus* and *N. heros* to various environmental variables in the periods 1990-2003 and 1983-2005 respectively. The first set of columns of coefficients for each species is from annual and 2-year running means of the annual data. The second set of columns is from the environmental data being set back (lagged) by one year with respect to the growth data, relating growth to the previous year's environmental data. Significant correlations, shown in bold, are subject to the step-down adjustment of Benjamini and Hachberg (1995) for multiple comparisons. The levels of significance are: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Environmental Variable	<i>Serripes</i>				<i>Neptunea</i>			
	Present Year not Lagged		1 Year Lagged		Present Year not Lagged		1 Year Lagged	
	Annual	Running Mean 2 yr.	Annual	Running Mean 2 yr.	Annual	Running Mean 2 yr.	Annual	Running Mean 2 yr.
Temperature Air (Annual)	0.346	0.588**	0.359*	0.063	0.266	0.260	0.102	0.126
Temperature Air (Summer)	0.065	0.179	0.153	-0.158	-0.300**	-0.419***	-0.299**	-0.298***
Temperature Air (Winter)	0.378*	0.477**	0.268	0.267	0.303*	0.320**	0.167	0.114
Precipitation (Winter)	-0.238	-0.337	-0.262	-0.227	-0.320**	-0.395**	-0.229	-0.410**
Precipitation (Summer)	0.247	0.256	0.074	0.101	0.245	0.413***	0.298	0.428**
Wind (annual)	-0.199	-0.189	-0.105	-0.077	-0.473*	-0.608***	-0.519**	-0.584***
Wind (Summer)	-0.324	-0.237	-0.064	-0.087	-0.585***	-0.501***	-0.267	-0.300
Freeze up (Julian Days)	-0.042	0.257	0.283*	-0.111	0.131	0.347***	0.214**	0.206

Break up (Julian Days)	-0.139	-0.168	-0.137	-0.106	0.025	0.076	0.094	0.085	
Ice Free days (50%)	0.092	0.269	0.281*	0.127	0.041	0.010	-0.019	-0.061	
Ice Free days (25%)	0.079	0.243	0.273	0.060	0.122	0.068	-0.015	-0.098	
Total Arctic Ice Annual	-0.041	-0.469	-	0.670***	-0.570*	-0.195	-0.248	-0.268	-0.317
Total Arctic Ice (Max. March)	-0.012	-0.206	-0.274	-0.649**	-0.045*	-0.168	-0.261	-0.477*	
Total Arctic Ice Winter (Avg. Oct-June)	-0.379	-0.538*	-0.550	-0.598*	-0.199	-0.233	-0.245	-0.391	
Total Arctic Ice Autumn (Avg. Oct-Dec.)	-0.410	-0.595**	-	0.691***	-0.545*	-0.458**	-0.483***	-0.422**	-0.425
Total Arctic Ice (pre. 6 mo.)	-0.043	-0.376	-0.540*	-0.625**	-0.013*	-0.054*	-0.100	-0.222	
Ice Anomaly	-0.341**	-0.144	0.151	0.062	0.135	0.274*	0.306**	0.405***	
NP Index-Aleutian Low	-0.526**	-0.643***	-0.258	-0.053	-0.299*	-0.405**	-0.240	-0.280	
AO Index (Annual)	-0.593*	-0.769***	-0.592*	-0.550	-0.280	-0.444*	-0.442**	-0.577***	
AO Index (Winter)	-0.739***	-0.794***	-0.250	-0.483	-0.329*	-0.427*	-0.282	-0.410**	
Arctic Climate Regime Index	-0.407	-0.418	-0.236	0.010	-0.257	-0.248	-0.136	-0.257	
PDO Index (Annual)	-0.073	0.079	0.203	-0.032	-0.347*	-0.372**	-0.272	-0.280**	
PDO Index (Summer)	-0.221	-0.005	0.207*	-0.067	-0.418**	-0.491***	-0.345*	-0.354**	

PDO Index (Winter)	0.363**	0.203	-0.105	-0.037	-0.011	-0.045	-0.053	-0.087
Siberian/Alaskan Index	-0.362*	-0.258	-0.029	-0.078	0.072	0.133	0.123	0.167

Table 6. Comparison of the cultural consensus tests between two domains. Both fit the model but the ugruk domain shows higher consensus in comparison to the change/fish domain.

Cultural domain	1st to 2nd Eigenvalue Ratio	Mean Competence	Range
Change/Fish	3.192	0.409	0-0.75
Ugruk (bearded seal)	7.778	0.632	0.14-0.89

Table 7. Relationships among cultural ecological knowledge domains. Pearson correlation coefficients relating various knowledge domains and the Change Index. Significant correlations are in bold. The levels of significance are: * $P < 0.05$, *** $P < 0.001$.

	Ugruk Knowledge	Food Web Knowledge	Change Knowledge Fish/Climate	Fall Seal Knowledge	Change Index
Ugruk Knowledge	1.000				
Food Web Knowledge	-0.141	1.000			
Change Knowledge	-0.013	0.180	1.000		
Fall Seal Knowledge	-0.040	0.061	0.460*	1.000	
Change Index	0.379*	-0.196	-0.526***	-0.327*	1.000

Figure Legends

Figure 1. Conceptual model for integrating traditional ecological knowledge (TEK) and scientific ecological knowledge (SEK) of ecosystem change. Experts and Mollusks represent members of the human population and ecosystem (represented by the circles) respectively who accurately monitor environmental conditions. Experts generally rely on information gathered at mid-high trophic levels (and are themselves usually at these trophic positions) while mollusks reflect conditions at low-mid trophic levels. The length of the cylinders represents the time scale covered by each source of environmental information. Our use of the combined information represents an area of overlap.

Figure 2. Graphs of the fish (A) and hunt (B) knowledge networks with the size of the nodes (corresponding to hunters and fishers) proportional to normalized betweenness centrality.

Figure 3. Observed and fitted mean growth rate (± 2 standard errors) for *Serripes*, based on the linear mixed modeling, for predictors the two year running mean of the summer Arctic Oscillation, and total Arctic ice lagged a year and including an interaction between these two terms. A SGI greater than 1.0 indicates greater than average growth while one less than 1.0 lower than average. Number of individuals = 29, number of individual-years = 228. Serial correlation = 0.363, as estimated in the model. R^2 based on weighted correlation = 0.803.

Figure 4. Observed and fitted mean growth rate (± 2 standard errors,) for *Neptunea*, based on the linear mixed modeling, for predictors two year running mean of summer air temperature, two year running mean lagged year of total Arctic ice the previous winter, the two year running mean of summer precipitation lagged a year and including an interaction of the first two terms. A SGI greater than 1.0 indicates greater than average growth while one less than 1.0 lower than average. Number of individuals = 107, number of individual-years = 1484. Serial correlation = 0.384, as estimated in the model. R^2 based on weighted correlation = 0.793.

Figure 1.JPEG

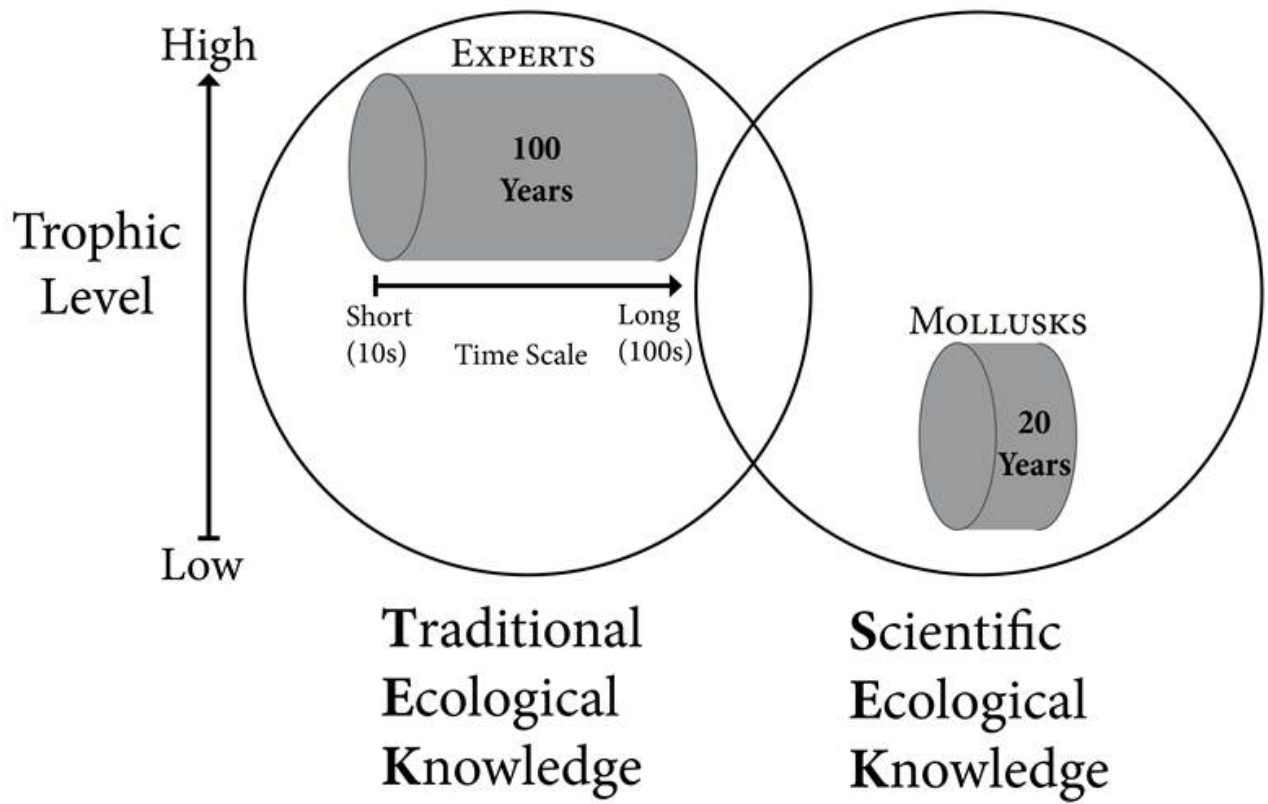


Figure 2.JPEG

A



B

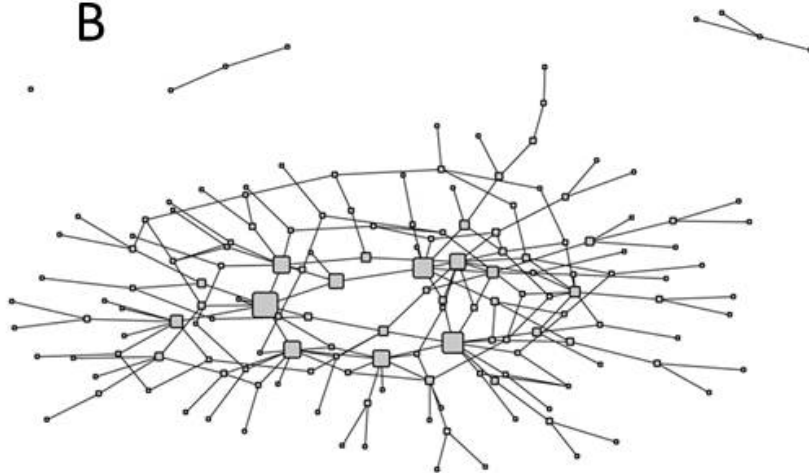


Figure 3.JPEG

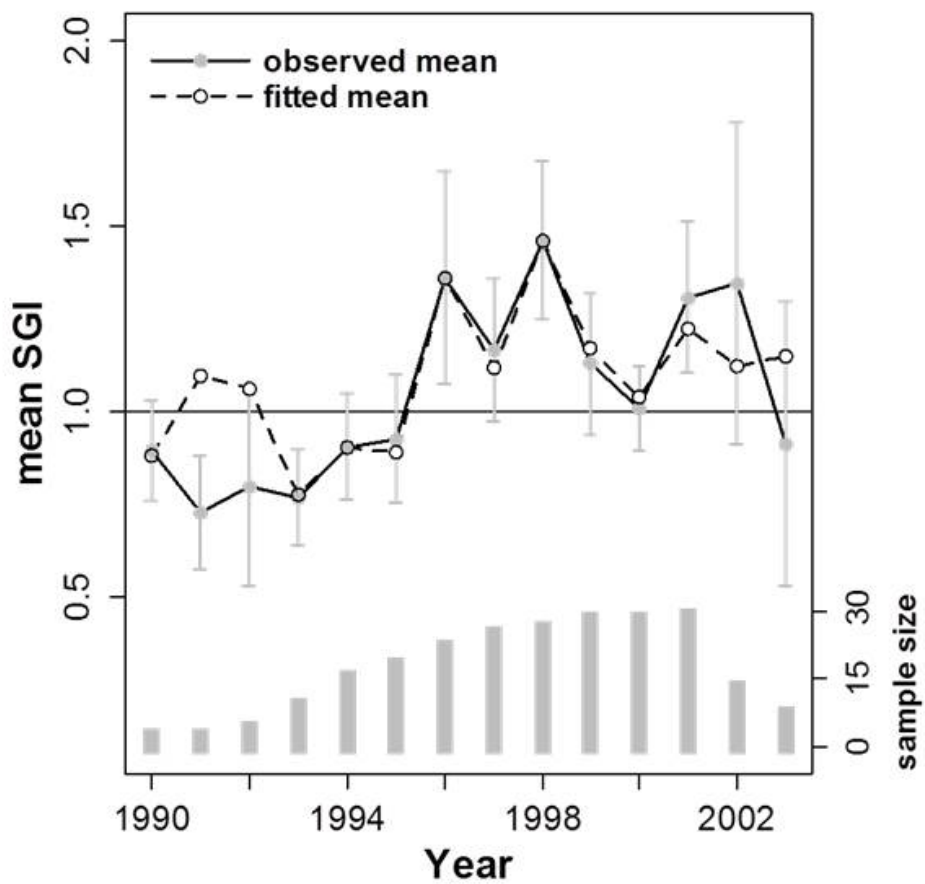


Figure 4.JPEG

