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ARTICLE

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Cumulative human impacts in the Bering Strait Region

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ABSTRACT

Introduction: Human impacts on Arctic marine ecosystems are increasing in extent and intensity as sea ice shrinks and utilization of marine resources expands. The effects of climate change are being felt across the arctic while stressors such as commercial fishing and shipping continue to grow as the Arctic becomes more accessible. Given these emerging changes, there is need for an assessment of the current cumulative impact of human activities to better anticipate and manage for a changing Arctic. Cumulative human impacts (CHI) assessments have been widely applied around the world in a variety of ecosystem types but have yet to incorporate temporal dynamics of individual stressors. Such dynamics are fundamental to Arctic ecosystems.

Outcomes: Here, we present the first CHI assessment of an Arctic ecosystem to incorporate sea ice as a habitat and assess impact seasonality, using the Bering Strait Region (BSR) as a case study. We find that cumulative impacts differ seasonally, with lower impacts in winter and higher impacts in summer months. Large portions of the BSR have significantly different impacts within each season when compared to a mean annual cumulative impact map. Cumulative impacts also have great spatial variability, with Russian waters between 2.38 and 3.63 times as impacted as US waters.

Conclusion: This assessment of seasonal and spatial cumulative impacts provides an understanding of the current reality in the BSR and can be used to support development and evaluation of future management scenarios that address expected impacts from climate change and increasing interest in the Arctic.

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Introduction

Human uses of the ocean and their collective pressure on marine ecosystems have been increasing (Halpern et al. 2015) and will likely continue to increase as global human population grows (Butchart et al. 2010; Hoegh-Guldberg and Bruno 2010). Highly sensitive ecosystems, such as the Arctic, are especially vulnerable to these changes. Indeed, the Arctic Ocean is already experiencing dramatic changes (Larsen et al. 2014). As Arctic sea ice continues to rapidly decline (Stroeve and Meier 2012), human impacts on the ecosystem are expected to intensify.

These changes have led to calls for international collaboration to monitor, plan for, and manage a changing Arctic (Berkman and Young 2009). A substantial gap exists in Arctic data and research (UNESCO 2009; Holland-Bartels and Pierce 2011; Gewin 2015), indicating a critical need for synthesis of existing data to create a current understanding that can help further guide and motivate efforts to monitor and manage Arctic ecosystems.

To better understand current impacts to an Arctic marine ecosystem, we apply the cumulative human

impacts (CHI) framework (Halpern et al. 2008) in an area already experiencing growth in human activity, the Bering Strait Region (BSR). Longer ice-free seasons (Comiso et al. 2008; Wendler, Chen, and Moore 2013) and improvements in technology have made the BSR more accessible for activities related to fishing, mining, commercial shipping, and tourism, among others. Effective management and decision making around this range of emerging and potential activity in the region will benefit greatly from synthesized information about current activities and impacts (Berkman, Vylegzhannin, and Young 2016).

Multiple methods exist to assess cumulative impacts of human activities on the environment including linkage frameworks (Knights, Koss, and Robinson 2013) and whole-ecosystem models (Griffith et al. 2012). The model used in this analysis is based on the framework published by Halpern et al. (2008), which utilizes available data to measure and map combined impacts of a range of stressors on each habitat type within the system. This framework is unique in that it normalizes and combines stressors of different units and spatial resolution in a manner that translates stressors into

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Supplemental data for this article can be accessed [here](#).

impact on ecosystems, allowing direct comparison among stressors and across locations.

Several underlying assumptions of the CHI methodology, however, may cause these assessments to deviate from reality (Halpern and Fujita 2013). In particular, the current methodology assumes that temporal dynamics of stressors (e.g., daily fluctuations, seasonality) do not matter, even though those dynamics may or may not align with the presence or vulnerability of species. This assumption is necessary because most locations do not have data for all stressor layers at high enough temporal and spatial resolution to allow for inclusion of temporal dynamics. With more data being collected at shorter time scales (e.g., daily, weekly, monthly), especially remote sensing and satellite imagery data, it is becoming increasingly possible to create discrete seasonal stressor layers defined by months or days that can be used to reveal temporal variability of cumulative impacts involving multiple stressors in a given region.

The method has been widely applied for assessing impacts on marine habitats at global (Halpern et al. 2008; Halpern et al. 2015) and regional scales (Halpern et al. 2009; Ban, Alidina, and Ardon 2010; Korpinen et al. 2012; Micheli et al. 2013; Batista et al. 2014; Holon et al. 2015) and has been adapted to assess cumulative impacts to species (Maxwell et al. 2013; Marcotte, Hung, and Caquard 2015). The approach is flexible in that it can be used to identify spatial patterns of low and high impact (Halpern et al. 2008; 2015), inform marine spatial planning (Longley and Lipsky 2013), examine impacts under future scenarios of development and climate change (Clarke Murray, Agbayani, and Ban 2015b), and compare impacts between protected and unprotected areas (Ban, Alidina, and Ardon 2010).

In fact, since the CHI framework was first published in 2008, there have been multiple regional applications and model advancements. A review of 40 cumulative impact assessments by Korpinen and Andersen (2016) found a majority of the assessments based off the global assessment (Halpern et al. 2008) maintain a similar overall framework with some model innovations. While a few assessments have looked at impacts over time (Marcotte, Hung, and Caquard 2015; Halpern et al. 2015), none of the assessments have examined seasonal impacts.

A recent CHI assessment by Andersen et al. (2017) began to correct for this assumption by evaluating different seasonal impacts to marine species in Greenland using temporally defined species ranges. The authors noted the lack of seasonal stressor data to be a limitation of their study. One of the defining characteristics of the BSR (Figure 1) is the role that sea ice plays in determining seasonal patterns of activities (Govorushko 2012), and therefore CHI. Thus, the BSR offers a compelling case study to explore seasonality of CHI because of (1) the seasonality of sea ice in the

region, (2) the importance of the region for access to the Arctic, and (3) its potential vulnerability to increasing pressures in the near future. This assessment incorporates temporal dynamics of stressors to provide an understanding of what current impacts exist and how they vary across (seasonal) time and space.

Methods

Study region

We use the same spatial boundaries of the BSR as described in Berkman, Vylegzhanin, and Young (2016) (Figure 1); the oceanic area between 62° and 68° N, covering 416,355 km². The total area is split almost equally between the waters under the jurisdiction of the USA (214,840 km²) and Russia (201,337 km²). The strait itself is a shallow (mean depth of 44 m) and narrow (~82 km) corridor connecting the Bering and Chukchi Seas and is the only access point between the Arctic and Pacific Oceans.

Stressors

Relevant stressors were identified in a workshop setting by science and policy experts with knowledge of the BSR (Berkman 2015). Data sources for all stressors, except for shipping, were found in peer-reviewed and gray literature discovered through the Google Scholar search engine with the following selection criteria: (1) collected in and representative of the BSR, (2) at relevant spatial and temporal scales, and (3) freely available. Vessel Automatic Identification System (AIS) data was provided by SpaceQuest Ltd. (<http://www.spacequest.com/>). A total of 12 stressors were identified for this assessment, with raw data resolution varying from 500 m² to 1 × 1 degrees (Table 1). The final pixel size for the cumulative impact model is 1 km². All analytical tasks were carried out using the R Statistical Language (R Core Team 2016) when possible, and ArcGIS (ESRI 2016) when necessary. All layers with coarser resolution were resampled to 1 km² using the nearest neighbor resampling algorithm from the raster package for R (Hijmans 2016). A 1 km² pixel size was chosen to increase detection of spatial patterns while remaining useful for policy and planning purposes, which typically occur at spatial scales between 1 km² and 100 km² (Halpern and Fujita 2013). Detailed methods for data processing of each layer are provided in the supplement.

Multiple criteria were used to determine if and how seasonality should be incorporated for every stressor: (1) do the data have fine enough temporal resolution to create seasonal layers? (2) does the presence of sea ice reduce the impact of the stressor?, and (3) are there temporal fluctuations in stressor

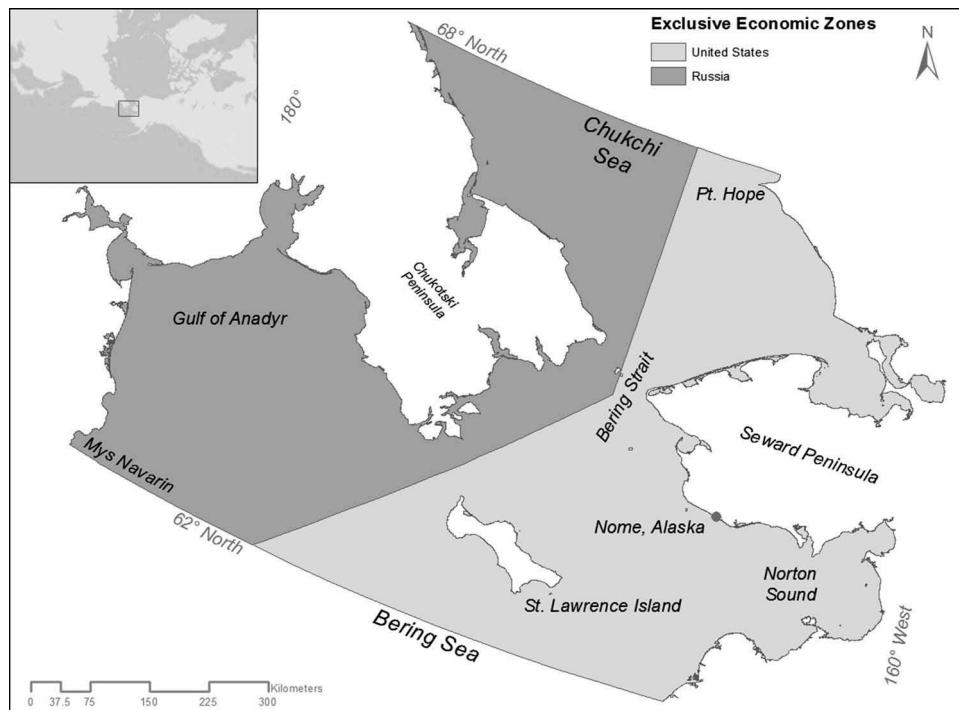


Figure 1. Bering Strait study region.

intensity that can be accounted for in other ways (in our case, here, land-based pollution that is affected by precipitation and runoff)? The answer to each of these questions influenced how the stressor was treated in regard to its temporal dynamics and is detailed below in the Methods section as well as in the supplemental information.

Ice mask

Long-term monthly observations of sea-ice coverage in the Bering Strait show generally ice-free seas in July, August, and September, and very little ice during October (Wendler, Chen, and Moore 2013). As a result, November through May are designated as the ice season (i.e., “winter”), and June through October as the ice-free season (i.e., “summer”). The “ice-free” season is used broadly here since there are regions of the Strait where sea ice is present in some or all of the summer months. We account for these seasons by developing both a summer and winter ice mask (Figure 2) that is applied to each normalized stressor layer known or expected to have seasonal dynamics correlated to the presence or absence of sea ice, but which are not accounted for in the raw data.

Seasonal ice masks were created using Multisensor Analyzed Sea Ice Extent (MASIE) sea data (National Ice Center (NIC) and NSIDC 2010). In the MASIE methodology, a 4 km^2 pixel (or cell) is considered ice covered for a particular day if more than 40% of it was covered with ice. Spatialized daily data were downloaded from MASIE and split into the winter and summer seasons according to the months defined above. For each

season, the total number of days across all years from 2006 to 2014 was summed and then the total proportion of days in that time frame in which a pixel was ice covered was calculated. The pixel value of each ice mask (Figure 2) represents the percentage of days within every winter or summer season that a pixel was ice covered.

Stressor seasonality

All stressors were normalized between 0 and 1 to allow direct comparison (Halpern et al. 2008). Decisions about how to normalize each data layer were primarily driven by the distribution of raw data. Three layers (shipping, organic pollution, and nutrient pollution), all with highly skewed distributions were first log-transformed; all other datasets were not transformed. Then, for all data, a reference point was used to set the maximum stressor value (i.e., 1.0) and rescale (normalize) all other values between 0 and 1 (see Table 1 for specific reference points).

Each stressor layer was assigned a specific method to account for the temporal dynamics of the stressor based on the layer’s temporal resolution, expected or known effect of sea ice, and seasonality of impacts (Table 2). Four of the 12 stressor layers had sub-annual temporal scales: sea surface temperature (SST) (weekly), ultraviolet radiation (UV) (daily), marine shipping (near-hourly), and ocean acidification (monthly) (Table 1). A winter and summer layer was created for each of these stressors by partitioning the data temporally based on the start and end of each season. The ice mask was applied to all five fishing stressors and three

Table 1. Stressors included in the assessment, their temporal dynamics, and source data information.

	Stressor	Data source	Spatial resolution	Description	Temporal resolution	Temporal method	Reference point
Climate	Ocean acidification	Feeley, Doney, and Cooley (2009)	1 x 1 degrees	Aragonite saturation state (Ω)	Monthly	1	Biological reference point
	Sea surface temperature	Casey et al. (2015)	4 km ²	Change in weekly SST anomalies	Weekly	2	>50% anomalous weeks
	Ultraviolet radiation	Thamminen and Arola (2013)	1 x 1 degrees	Change in UV-b irradiation anomalies	Daily	2	>50% anomalous weeks
Land-based	Sea level rise	Prandi et al. (2012)	0.125 x 0.125 degrees	Annual rate of sea level rise (mm/year)	Multiyear	3	99th quantile (pan-Arctic)
	Nutrient pollution	FAO	500 m ²	Annual average use of fertilizers (2002–2012)	Annual	4	99.99th quantile (pan-Arctic)
Fishing	Organic pollution	FAO	500 m ²	Annual average use of pesticides (2002–2012)	Annual	4	99.99th quantile (pan-Arctic)
	Demersal destructive bycatch	Watson (2017)	0.5 x 0.5 degrees	Catch (tons) per km ²	Annual	2	Maximum (BSR)
Demersal nondestructive low bycatch	Demersal nondestructive low bycatch	Watson (2017)	0.5 x 0.5 degrees	Catch (tons) per km ²	Annual	2	Maximum (BSR)
	Demersal nondestructive high bycatch	Watson (2017)	0.5 x 0.5 degrees	Catch (tons) per km ²	Annual	2	Maximum (BSR)
	Pelagic high bycatch fishing	Watson (2017)	1 km ²	Density of vessels	Sub-hourly	1	99.99th quantile (pan-Arctic)
See Table 2 details for temporal dynamics methods assignments. Reference Point is the value used to normalize each stressor between 0 and 1.							

climate stressors: SST, UVradiation, and sea level rise (SLR), since the raw data for each of these layers did not account for presence of sea ice. The mask was only applied after each layer was normalized.

The fishing stressor layers were derived from a database of annual global fish catch by gear type at a spatial resolution of half-degree cells from 1950 to 2014 (Watson 2017). The data do not include seasonal catch information; therefore, we used the ice mask to limit fishing effort (and its impact) during the winter season. Because the relationship of fishing effort to sea ice concentration is unknown, we assumed that when sea ice was present in a given pixel, there would be no fishing activity. The shipping layers did not require application of an ice mask as the raw data show presence and absence of shipping activity, which accounts for any effects from the presence of ice.

The shipping layers are derived from AIS data (SpaceQuest Ltd.), and impact scores were assigned only where ships are observed in the data. This layer acts as a proxy for all impacts of shipping activity including ship strikes on marine mammals, noise pollution, and bilge and sewage discharge.

The ice mask dampens or eliminates the impact of stressors in locations where ice is present. A given pixel, for example, may have ice present for 50% of the winter season and 10% of the summer season. A stressor with a pixel value of 1.0 would be reduced to 0.5 in winter and 0.9 during the summer. These stressor layers were normalized before the sea ice masks were applied.

Land-based pollution stressors are derived from nutrient and organic pollutant runoff from watersheds within the BSR using methods described in Halpern et al. (2008). In this approach, pollutants are introduced into the nearshore coastal environment through stream and river discharge. Input of pollutants to the marine environment is consequently related to streamflow, not sea ice. Both the nutrient input and organic pollution layers were split seasonally according to the percentage of annual stream discharge that occurred within each season.

Prior research has found that stream and river discharge within the Arctic is strongly seasonal, with most flow occurring during the warmer summer months (Su et al. 2005). To calculate the percentage of stream discharge during our defined seasons, discharge data were extracted from streams within the Arctic Circle in the Pan-Arctic River Discharge Data Project (<http://www.R-ArcticNET.sr.unh.edu>). Based on the data for all streams in the dataset for all years of available data, 84.7% of the total runoff for Arctic streams occurred during the summer months, while 15.3% took place during the winter. The annual land-based stressors were split into seasonal layers using these stream discharge values. Each pixel in the summer and winter seasonal layer was 84.7% and 15.3% of the annual stressor value, respectively.

Table 2. Temporal treatment of each stressor layer where; I = impact score, m = habitat, i = stressor, D = normalized stressor value, E = the presence of ecosystem, j , represented by a 1 (present) or 0 (absent), s = season (winter or summer), P = proportion of the season that the pixel had at least 40% ice cover (values range from 0 to 1), R = proportional runoff (0.847 in summer, 0.153 in winter; see methods), μ = vulnerability weight for stressor, i , and habitat, j .

Stressors (i)	Temporal dynamics method	Equation
Ocean acidification	1	$I_s = \frac{1}{m} \sum_{j=1}^m D_{i_s} * E_j * \mu_{i,j}$
Shipping	2	$I_s = \frac{1}{m} \sum_{j=1}^m D_{i_s} * E_j * P_s * \mu_{i,j}$
Sea surface temperature		
Ultraviolet radiation		
Demersal destructive fishing		
Demersal non destructive high bycatch fishing		
Demersal nondestructive low bycatch fishing		
Pelagic low bycatch fishing		
Pelagic high bycatch fishing		
Sea level rise	3	$I_s = \frac{1}{m} \sum_{j=1}^m D_i * E_j * P_s * \mu_{i,j}$
Organic pollution	4	$I_s = \frac{1}{m} \sum_{j=1}^m D_i * E_j * R_s * \mu_{i,j}$
Nutrient pollution		

The final impact score per pixel is the mean impact of stressor (i) across all habitats (m). Temporal dynamics method indicates how each stressor layer was either seasonally or annually created; 1 = seasonal layers were created using temporal information from data source. No ice mask was applied since data source accounted for presence of sea ice; 2 = seasonal layers were created using temporal information from data source and a seasonal ice mask was applied; 3 = data does not have temporal information so seasonal layers were created by multiplying the normalized data by the seasonal ice masks; 4 = seasonal layers were created according to the percentage of annual stream discharge that occurs within each season.

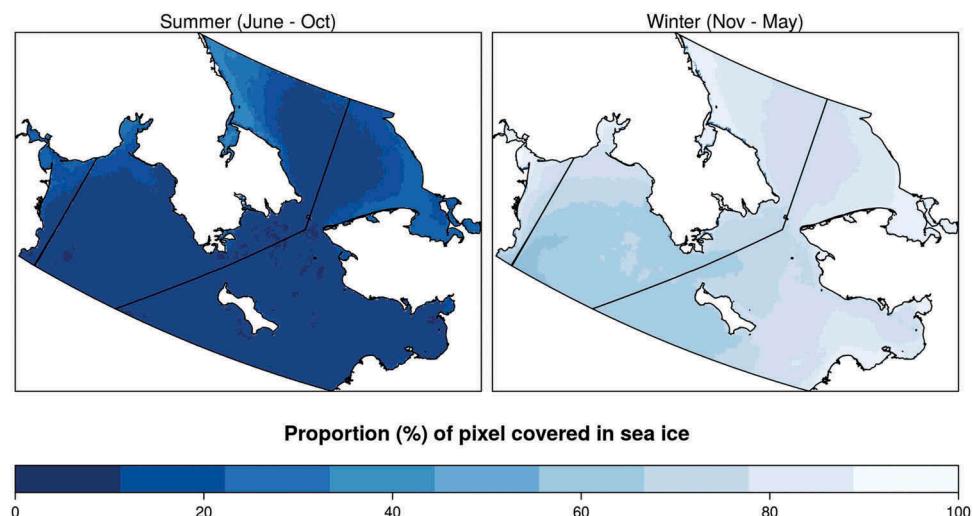


Figure 2. Ice masks used for the summer and winter seasons. Values shown indicate the proportional time the pixel is covered in sea ice.

Habitats

Habitats were defined in broad categories, as was done previously for global and regional assessments (e.g., Halpern et al. 2008; Halpern et al. 2009; Halpern et al. 2015). Ten of the 17 habitats in the global assessment (Halpern et al. 2008) are present in the BSR (Table 3). All habitats had more recent and/or higher resolution data for at least some of the region compared to what is available globally. The coastal habitat layers for intertidal mud, beach, salt marsh, and rocky intertidal were created using data from the Alaska ShoreZone Project (<http://www.shorezone.org/>) and Environmental Sensitivity Index (ESI) data from NOAA's Office of Response and Restoration (<http://response.restoration.noaa.gov>). Hard and soft bottom benthic habitat data came from Audubon's Arctic Marine Synthesis (Smith 2010). Where data were lacking for coastal, hard and soft bottom habitats within Russian waters, we used habitat data from the original global assessment (Halpern et al. 2008).

Sea ice has not previously been included as a habitat in global or regional CHI assessments; however, given the importance of sea ice in this region as a habitat, it is included here. All other habitats are represented in the model as a single raster layer with a binary distinction of present/absent (1 or 0) regardless of season. Due to the ephemeral nature of sea ice throughout the year, two sea ice habitat layers were derived from the MASIE data, one for each season. Both of these layers were scaled from 0 to 1 according to the total proportion of the season that ice is present. This decision was made to more accurately account for impacts to sea ice only when it is present. Otherwise, the persistence and spatial coverage of sea ice and the subsequent impacts would be overrepresented. For example, if a single pixel has sea ice present for 60% of the winter season, the stressors present in that pixel are multiplied by 0.6 rather than 1 to scale the resulting impact to be proportional to the amount of time the sea ice is present.

Table 3. Habitats included in the cumulative impact analysis for the Bering Strait Region (BSR).

Habitat	Source	Spatial Resolution	Brief Description
Rocky reef	Audobon (Smith 2010), Halpern et al. (2008)	1 km ²	Gravelly substrates (Smith 2010) and hard bottom habitat at 0–60 m (Halpern et al. 2008)
Hard shelf	Audobon (Smith 2010), Halpern et al. (2008)	1 km ²	Gravelly substrates (Smith 2010) and hard benthic habitat at 60–200 m depth (Halpern et al. 2008)
Subtidal soft bottom	Audobon (Smith 2010), Halpern et al. (2008)	1 km ²	Silt, mud, and sandy substrates (Smith 2010) and soft bottom habitat at 0–60 m (Halpern et al. 2008)
Soft shelf	Audobon (Smith 2010), Halpern et al. (2008)	1 km ²	Silt, mud, and sandy substrates (Smith 2010) and soft benthic habitat at 60–200 m depth (Halpern et al. 2008)
Surface waters	Halpern et al. (2008)	1 km ²	Top 60 m of ocean in areas deeper than 60 m total depth
Deep waters	Halpern et al. (2008)	1 km ²	Water column from 60 m depth to benthos
Beach	Alaska ShoreZone, NOAA ESI, Halpern et al. (2008)	1 km ²	Fine or coarse sand and/or gravelly beaches
Salt marsh	Alaska ShoreZone, NOAA ESI, Halpern et al. (2008)	1 km ²	Salt to brackish marsh
Rocky intertidal	Alaska ShoreZone, NOAA ESI, Halpern et al. (2008)	1 km ²	Sheltered or exposed rocky shores
Intertidal mud	Alaska ShoreZone, NOAA ESI, Halpern et al. (2008)	1 km ²	Sheltered or exposed tidal flats
Sea ice	National Ice Center (NIC) and NSIDC. (2010)	4 km ²	MASIE Daily sea ice concentration (2006–2014)

Habitat vulnerability weights

The vulnerability of a habitat to a given stressor is represented as a weight between 0 and 3.8 (Table S1). Vulnerability weights for each stressor-habitat pair, aside from sea ice, were kept the same as two other regional CHI assessments from the US West Coast (Teck et al. 2010) and British Columbia (Clarke Murray et al. 2015a). The weight matrix applied in Teck et al. (2010) was developed through eliciting expert knowledge from scientists with expertise on marine ecosystems in the California Current. The majority of stressors and habitats present in the BSR was included in this weight matrix, and the same weight matrix has subsequently been used in Clarke Murray et al. (2015a) to study cumulative impacts in British Columbia. Since sea ice was not included in these assessments, the vulnerability weights for the sea ice habitat layer came from Halpern et al. (2007).

Calculating cumulative impact scores

Annual impact scores were calculated for each 1 km² pixel using the modified CHI model presented in Halpern et al. (2009). The modified model computes the mean impact of each stressor per pixel rather than summing across all habitats that fall within a single pixel. Seasonal cumulative impact maps were calculated by aggregating seasonal stressor impact layers together and summing values across all pixels:

$$I_s = \sum_{i=1}^m I_{s_i}$$

where the cumulative impact score, I , for season s (winter or summer), is calculated by summing all seasonal stressor layers (I_{s_i}) for each seasonal stressor, ($m = 12$).

An annual cumulative impact map was created for comparison with the seasonal maps. Rather than simply aggregate the seasonal layers into a single annual layer, we developed annual versions for each

of the 12 stressors, i.e., the same input data but without separating the data seasonally. Mean annual stressor values were calculated and then normalized between 0 and 1 using the same reference point as listed in Table 1. A mean annual sea ice layer was derived from the daily sea ice data for years 2006–2014. Each pixel value was equal to the proportion of days in a year the pixel has at least 40% ice coverage. The ice mask was applied to all five fishing layers and three climate change layers: UV, SST, and SLR. The final impact map was calculated by summing pixel values across each stressor's impact:

$$I_a = \sum_{i=1}^k I_i + \sum_{j=1}^n I_j$$

where the annual cumulative impact per pixel (I_a) is the sum of impact scores per pixel for each stressor affected by presence of sea ice (I_i ; where $k = 7$), and impact scores for stressors not multiplied by the ice mask (I_j ; where $n = 5$). For each layer that is multiplied by the ice mask, impact scores (I_i) are calculated by multiplying the normalized stressor value (D) by the presence or absence (E) of habitat j , the mean annual proportion that the pixel had at least 40% ice cover (P , values range from 0 to 1), and the vulnerability weight, μ , for the habitat (j) and stressor (i) pair. The final impact score per pixel is equal to the mean impact across all habitats (m).

$$I_i = \frac{1}{m} \sum_{j=1}^m D_j * E_j * P * \mu_{i,j}$$

Results

Cumulative impact scores in the BSR exhibit both temporal and spatial variability, with mean impact scores of 0.13 in the winter (range = 0–1.74; $sd = 0.15$) and 0.18 in the summer (range = 0–2.04, $sd = 0.26$; Figure 3). Seasonal cumulative impact scores are significantly different from annual scores in both seasons primarily within the Gulf of Anadyr and along both coasts (Figure 4). When accounting for

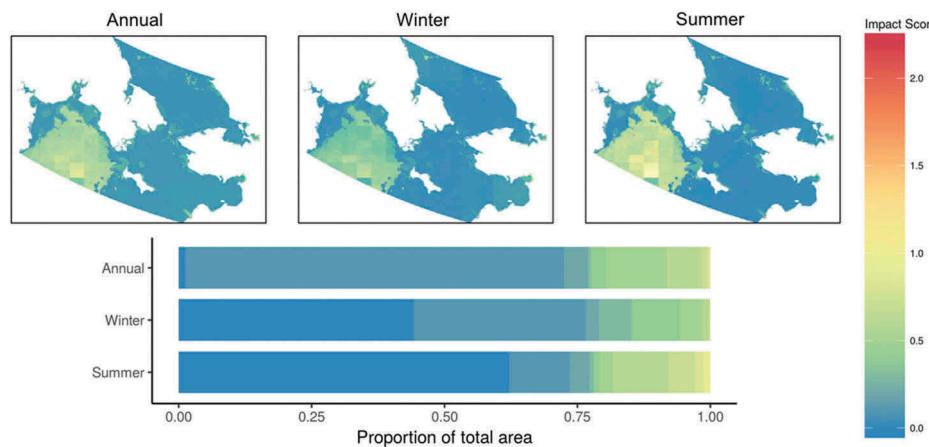


Figure 3. Annual and seasonal cumulative impact maps for the Bering Strait Region (BSR) and total proportional area receiving an impact score between 0 and 2.20.

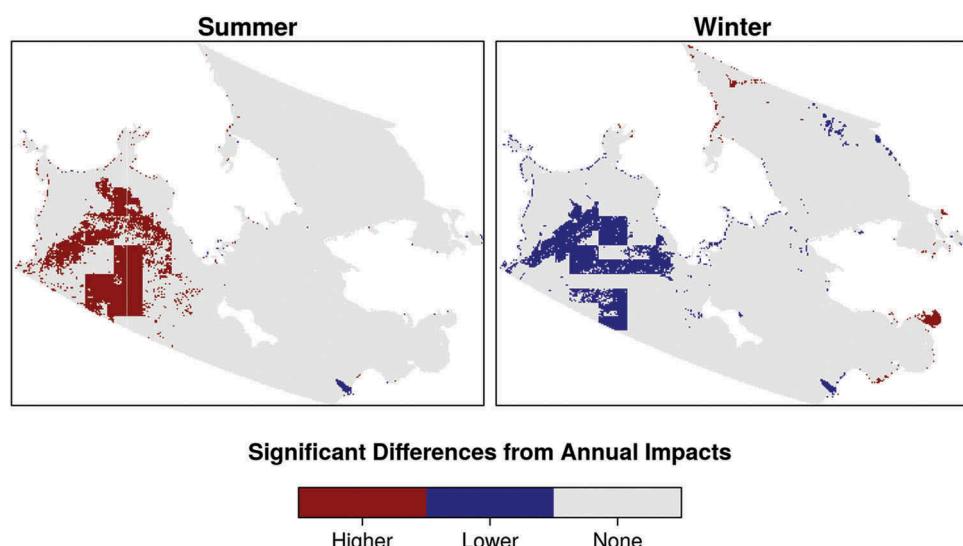


Figure 4. Significant differences in seasonal cumulative impact scores when compared to annual impacts. Red pixels indicate areas of significantly higher impact, pixels in blue indicate areas of significantly lower impact in comparison to the annual map (see Figure 3). Differences were calculated using the SDMTools R package (VanDerWal et al. 2014) and significance levels were set at 0.05.

seasonality, summer impact scores are higher in the Gulf of Anadyr and along the coast of the Chukotka Peninsula when compared to the annual cumulative impact map. Winter impact scores are more patchy, with areas of both lower (along both coasts) and higher (coast of northern Chukotka peninsula, areas of the Gulf of Anadyr, and a portion of Norton Bay within Norton Sound) impact compared to the annual map. The ocean acidification stressor layer largely drives these higher impact scores, where these two regions have undersaturated waters (Fig. S3).

A Monte Carlo simulation was used to test the sensitivity of the model to vulnerability weights. We ran 1000 simulations on randomly shuffled weight matrices that maintained the mode and distribution of the matrix values. The mean annual cumulative impact score and standard deviation were calculated for each simulation, and the 95% confidence interval was 0.14–0.27. Our calculated annual cumulative

impact map using the modified expert weights has a mean of 0.19, which falls within the confidence interval for the simulations. The same held true for both summer (mean = 0.18, 95% confidence interval = 0.16–0.30) and winter (mean = 0.13, 95% confidence interval = 0.12–0.25) seasons.

Russian territorial waters experience higher impacts in both seasons (Figure 5; summer; mean = 0.29, $sd = 0.30$, winter; mean = 0.19, $sd = 0.17$) compared to the United States (summer; mean = 0.08, $sd = 0.14$, winter; mean = 0.08, $sd = 0.11$), although the highest single-pixel score (2.04) is located near the mouth of the Yukon River in US waters during the summer. The combination of sensitive habitats and higher land-based pollution near the mouth of the Yukon River results in these high cumulative impact scores.

Ocean acidification has the highest mean impacts across the Bering Strait in both seasons, although

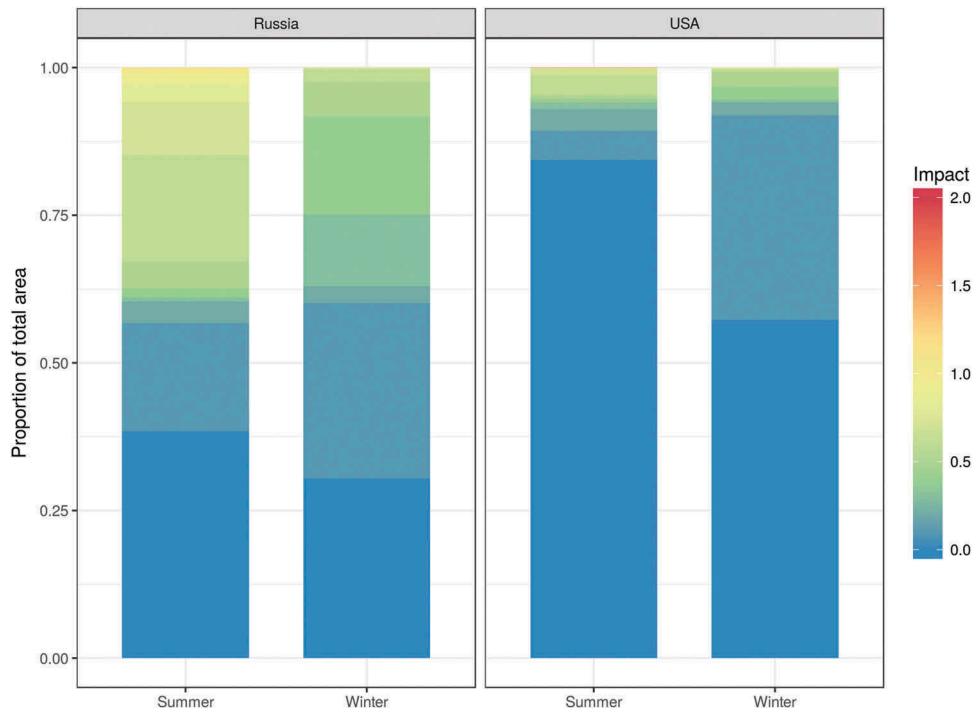


Figure 5. Spatial distribution of seasonal cumulative impact scores in Russian and US territorial waters of the BSR.

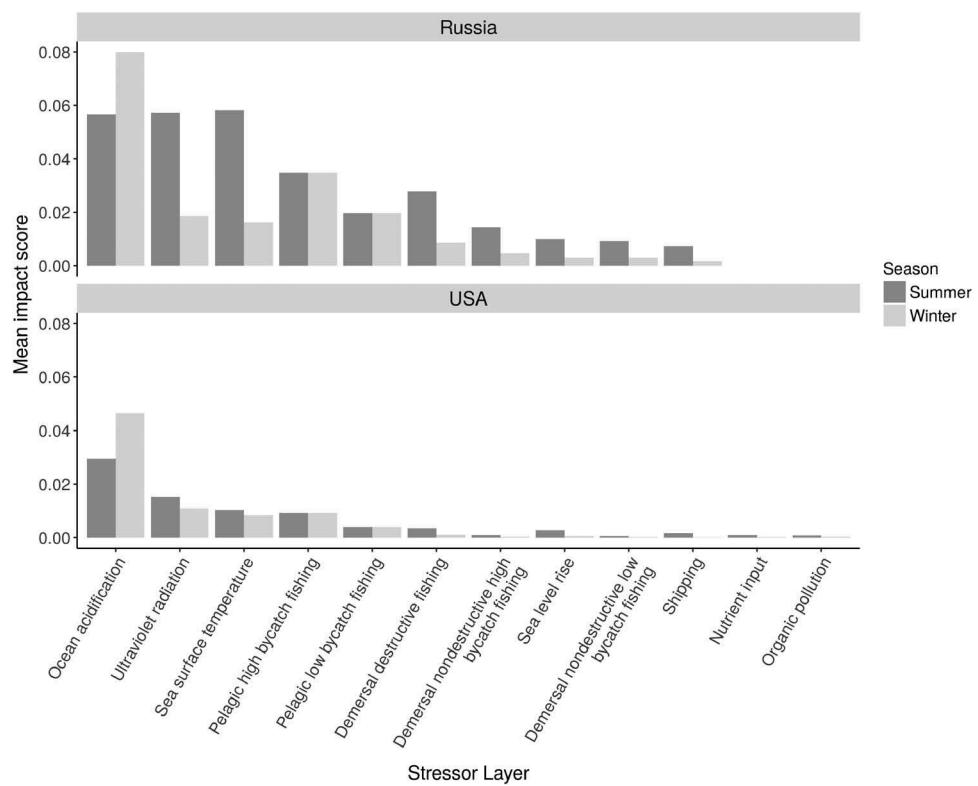


Figure 6. Mean cumulative impact scores for each stressor in the winter and summer seasons within Russian and US territorial waters.

impacts are higher in the winter (Figure 6). Climate and fishing stressors follow ocean acidification in mean impacts, with the summer months exhibiting higher impacts than winter. Russian territorial waters are more heavily impacted than US territorial waters across all 12 stressors. Aside from ocean acidification, the commercial fishing stressors

primarily drive high cumulative impacts in Russian waters in both seasons (Figs. S5–S7). Highest impacts in US waters are found along the coast and are primarily driven by climate stressors. The highest impacts from shipping are in areas of high ship density in the Gulf of Anadyr and off the coast of Nome, Alaska (Fig. S5).

Discussion

CHI in the BSR are spatially and temporally variable. Not surprisingly, impacts are highest during the ice-free summer months when human activity is greater. Areas of higher impact are concentrated in Russian waters where scores are, on average, 3.63 times higher than the United States in the summer and 2.38 times higher in the winter seasons. That two areas of similar size within the same region are experiencing such dramatically different impacts can largely be attributed to (a) a higher number, and larger spatial extent, of habitats with high vulnerability to climate stressors in Russian waters, and (b) the differences in commercial fishing activity between the two countries. Due to the shallow nature of the Strait on the US side (mean depth of 33 m), soft shelf, deep and surface water habitats are found in less than 8% of US waters, but each of these habitats exists in over 50% of Russian waters (Fig. S7). These habitats are particularly vulnerable to climate stressors (Table S1), increasing the cumulative impact scores in areas where they exist. Improved habitat data in the region could help refine these results, especially for those habitats for which we used the global data layers from Halpern et al. (2008).

Comparisons between the annual and seasonal cumulative impacts map show important differences in how the outcome varies when including temporal dynamics within the CHI model. The annual impact map provides a snapshot of what is happening in the BSR, but if used to manage seasonal stressors it would underestimate impacts in the Gulf of Anadyr and overestimate impacts along parts of the Alaskan coast. Perhaps most importantly, the summer seasonal maps give an indication of what the future will be like as the BSR becomes ice-free year round.

Commercial fishing impacts (e.g., removal of biomass from a stock, impacts to habitats by fishing gear) have some of the highest impacts in both winter and summer seasons, especially within Russian waters. The significant spatial differences in commercial fishing between the United States and Russia are largely due to different management regimes of these two countries. While Russia fishes its waters extensively, the United States has banned most fishing in its half of the BSR.

Impacts from marine operations and shipping activity are low compared to climate and fishing stressors, even in the summer season when ship traffic is highest. Halpern and Fujita (2013) claim that stressors and human activities are often conflated in cumulative impact assessments, which could be argued here. Assessment of impacts due to shipping could be improved by modeling the individual components of marine operation impacts, including ship strikes on marine mammals, noise pollution, and bilge and sewage discharge. Currently, data do

not exist to allow such disaggregation of shipping stressors and their associated impacts. In other words, regional shipping activity is tracked while associated stressors are not. Since management and mitigation of impacts is done through regulation of human activities rather than individual stressors, including a shipping stressor layer is no doubt better than excluding it. If and when regional data on shipping-associated stressors become available, this framework can easily be adapted to include that information.

With more than half of the Bering Strait receiving an impact score of less than 0.054 in both seasons, less than 3% of the regional maximum, the BSR is not currently a severely impacted area. This is not surprising since the biogeographical characteristics of the region limit the amount of human activity feasible in the area. Although impacts are generally low, Russian waters are experiencing much higher impacts from fishing and shipping activities. Impacts from climate stressors are less spatially and temporally discriminant with both US and Russian waters containing areas of high impact. Ocean acidification contributed to higher impacts in the winter, especially in Norton Sound and along the northern Chukotka Peninsula (Fig. S3) where the seawater is undersaturated in aragonite (Ω_{arag}).

Each of these stressors presents challenges and opportunities in management. Climate stressors have the highest impacts across the Bering Strait. Mitigating the impacts of these stressors will no doubt require a significant effort at the global scale before seeing any regional improvements. Recent findings show the Arctic is warming at a rate twice as fast as the rest of the world (Richter-Menge, Overland, and Mathis 2016), which could further increase the cumulative impacts within the BSR. Although little can be done at the regional scale to directly address these climate impacts, steps can be taken to address more local stressors by focusing management and policy decisions on activities such as fishing and shipping.

Commercial fishing has largely been scaled back by the United States and any further mitigation of impacts from fishing will require heavy involvement of the Russian government. Marine operations and shipping activities may currently be low, but as longer ice-free seasons become more common, the Northern Sea Route and the Northwest Passage will be more feasible options for commercial shipping routes (Smith and Stephenson 2013) and the Bering Strait will be the only access point to these routes. The number of ships traveling through the Bering Strait has more than doubled in recent years (Berkman, Vylegzhannin, and Young 2016); future increases in shipping will depend on current and emerging economic, safety and environmental factors (Pollock 2009; Brigham 2010b). The risks and impacts associated with increased ship traffic, such as collisions

with small fishing vessels or displacement of marine species (Huntington et al. 2015), should be considered in addition to this cumulative impact assessment to further inform regulatory measures surrounding commercial ship traffic in the BSR. These challenges present an opportunity for collaborative governance between Russia and the United States. International agreements such as the International Maritime Organization's Polar Code can play a large role in protecting this ecologically sensitive region by acting as proactive regulation to help manage for an unknown future.

Commercial fishing is expected to increase in the region as the open water season lengthens and as sub-temperate species begin to shift their range into northern waters (Cheung et al. 2009; García Molinos et al. 2015), although fisheries management may limit expansion of the sector. Local observations are already confirming these shifts in the location of fish stocks (Wassmann et al. 2011). General trends indicate increased biomass from both native and non-native marine species, but the ecological impacts on local food chains and fisheries remain uncertain. These changes could further exacerbate the spatial variability in impacts from commercial fishing between Russia and the United States, making the need for shared knowledge and management even more immediate, especially with transboundary marine species.

There are pressing management concerns about increasing human activities in the region (Berkman, Vylegzhannin, and Young 2016) and their interactions with existing uses and each other. In particular, the Arctic, and BSR specifically, have seen increasing global interest in shipping (Kerr 2002; Brigham 2010a; Hong 2012), energy development (Johnston 2010; Clement, Bengtson, and Kelly 2013), military activity (Kraska and Baker 2014), and fishing (Hollowed, Planque, and Loeng 2013). With longer ice-free seasons (Comiso et al. 2008; Wood et al. 2015) and technological advances (Michel and Noble 2008), growth in commercial activity in the region is expected to continue (AMSA 2009). The cumulative impact of these activities will have on the marine environment is largely unknown.

Even as the Bering Strait continues to be recognized as a region of global importance, there remain significant gaps in available data for the region. These gaps are a known limitation to this study and with higher resolution data, especially commercial fishing activity and habitat data, the model could certainly be improved. Since marine biophysical processes and species do not abide by international boundaries, it is essential that efforts to collect and share data are broadly consistent throughout the region to better understand and monitor impacts.

As presented here, improvements to the CHI model can be adapted and applied elsewhere in the Arctic or Antarctic, where temporal sea ice dynamics are at play. This same approach could also be applied in other regions where temporal dynamics play key roles in

ecosystem functioning, such as dynamic habitats (e.g., kelp, seagrass beds), seasonal species movements (e.g., spawning aggregations, seasonal migrations), and areas heavily driven by large-scale oscillating climate regimes (e.g., El Niño-Southern Oscillation events).

Conclusion

Although the habitats of the BSR are not heavily impacted by human activity, our analysis indicates greater impacts during the ice-free months. A warming environment with longer ice-free seasons will likely lead to greater total CHI throughout the region.

Incorporating seasonal dynamics of stressors allowed us to discern temporal variability that is often ignored when evaluating mean annual impacts. Calculating average annual impacts in the BSR provides a less accurate representation of the human impacts at any given time throughout the year. This could have implications for managing human activity and mitigating the impact of stressors. In some cases, human impacts can be reduced with simple shifts in the timing of activities. For example, shipping routes could potentially be adjusted seasonally to reduce spatial overlap of stressors that occur in different seasons or different times within seasons. Our analysis of seasonal spatial patterns provides a current understanding of CHI to start informing management decisions about when, instead of just where, activities can occur. An obvious next step would be to apply this model under future scenarios of climate change and growth in human activity to best predict what areas of the Arctic will be most vulnerable and how impacts are expected to change compared to current status quo. By evaluating seasonality of CHI, we also improve upon the CHI framework by moving closer to a more realistic understanding of how humans are impacting the ecosystem through both time and space. With higher resolution data, this methodology could be further enhanced at smaller time scales to better illustrate the ebb and flow of human activity and impact in the Bering Strait.

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