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Reconstruction of historic sea ice conditions in a sub-Arctic lagoon

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Highlights

- Sea ice conditions were reconstruction based on local temperature record.
- A statistical model of ice conditions is shown to be useful to determine seasonally aggregate ice conditions.
- The methods are transferable to other locations.

Abstract

Historical sea ice conditions were reconstructed for Izembek Lagoon, Bering Sea, Alaska. This lagoon is a crucial staging area during migration for numerous species of avian migrants and a major eelgrass (*Zostera marina*) area important to a variety of marine and terrestrial organisms, especially Pacific Flyway black brant geese (*Branta bernicla nigricans*). Ice cover is a common feature of the lagoon in winter, but appears to be declining, which has implications for eelgrass distribution and abundance, and its use by wildlife. We evaluated ice conditions from a model based on degree days, calibrated to satellite observations, to estimate distribution and long-term trends in ice conditions in Izembek Lagoon. Model results compared favorably with ground observations and 26 years of satellite data, allowing ice conditions to be reconstructed back to 1943. Specifically, periods of significant (limited access to eelgrass areas) and severe (almost complete ice coverage of the lagoon) ice conditions could be identified. The number of days of severe ice within a single season ranged from 0 (e.g., 2001) to ≥67 (e.g., 2000). We detected a slight long-term negative trend in ice conditions, superimposed on high inter-annual variability in seasonal aggregate ice conditions. Based on reconstructed ice conditions, the seasonally cumulative number of significant or severe ice days correlated linearly with mean air temperature from January until March. Further, air temperature at Izembek Lagoon was correlated with wind direction, suggesting that ice conditions in Izembek Lagoon were associated with synoptic-scale weather patterns. Methods employed in this analysis may be transferable to other coastal locations in the Arctic.

1 Introduction

In this study sea ice conditions in Izembek Lagoon were reconstructed to determine ice conditions in individual years and whether local ice conditions have changed during past decades. Izembek Lagoon is a crucial gateway for hundreds of thousands of migratory waterbirds travelling between breeding areas in Alaska, Russia, Canada and wintering areas in Asia, Oceania, and North and South America (Figure 1; Tibbitts et al., 1996; Alaska Shorebird Group, 2008). Each fall, virtually the entire eastern Pacific flyway population of black brant geese (*Branta bernicla nigricans*) stages in the lagoon to feed on eelgrass (*Zostera marina*) and build energy stores needed for migration and overwinter survival (Ward and Stehn 1989, Mason et al. 2006). In recent years a growing number of brant overwinter at Izembek Lagoon and adjacent estuaries, even though inter-annual variability is considerable (Ward et al. 2009). Reasons for variability and change are unknown but are likely a result of changing atmospheric circulation, air temperature, and ice conditions (Ward et al., 2009). While passive microwave data in recent years indicate a later onset of formation and earlier melt of pack ice in the Bering Sea (Markus et al., 2009), less is known about ice conditions in coastal lagoons. The scope of this work is therefore to obtain a historic record of ice conditions of Izembek Lagoon, based on a process model calibrated with satellite observations.

Izembek Lagoon is a 35,000 ha shallow water embayment situated on the north side of the Alaska Peninsula that is sheltered from the Bering Sea by barrier islands but allowing seawater exchange through three systems of deep channels (Ward et al. 1997; Figure 1). At latitude 55° N it is sufficiently far south to experience daylight year-round. While the tidal range in the lagoon is >1.5 m, water depth is of the order of 2 m, reaching 10 m in the channels. The ground cover in the lagoon can be separated into three types: shallow mud flats, intertidal eelgrass areas, and deep channels (Figure 1). The closest weather station is situated at the airport of the settlement of Cold Bay, 10 km South-East of Izembek Lagoon, recording first order climate data since the 1940s.

Izembek Lagoon is often ice-free in winter, with ice formation, melt, and break-up taking place repeatedly between December and April. We assessed ice conditions in Izembek Lagoon for recent years and sought proxies to relate observed ice conditions to long standing environmental records (e.g. wind and air temperature at Cold Bay, Alaska) that can be used to reconstruct historic ice conditions. A variety of potential data sources of ice conditions are available for the most recent decade. Recorded ground observations were taken into account, including field notes, aerial surveys, and bird cam imagery. While a good record of ground-based observations is available, particularly in 2009 and 2010, this period of time is not sufficiently long to identify proxies for ice conditions. We therefore supplemented this record with other data sources. The primary source for a long-term record stems from satellite remote sensing. Satellite imagery (Moderate-resolution Imaging Spectroradiometer (MODIS), Advanced Very High Resolution Radiometer (AVHRR), and SeaWinds/QuikScat) was analyzed for presence, absence and distribution of sea ice. The focus of this study is on results from MODIS and AVHRR data as they proved to be the most valuable resource with a compromise of spatial and temporal coverage and spatial resolution (Petrich and Tivy, 2011).

An empirical relationship between daily ice conditions and local air temperature was developed using cumulative degree days. We identified periods of significant ice conditions when access to eelgrass is limited, and severe ice conditions when ice coverage is nearly complete for the lagoon. Only time and air temperature enter degree day equations explicitly, and this simplicity combined with the general good agreement with observations makes them attractive. Freezing degree days and melting degree days are commonly employed as indicators for the state of sea ice growth and decay (e.g., Zubov 1945; Weeks and Lee, 1958; Petrich et al., 2012). For Izembek Lagoon in particular, the usability of a seasonal freezing degree day index and aggregate ice conditions has been suggested in earlier work (Ward et al., 2009). However, this appears to be the first study to consider over two decades of observational data to calibrate a process model. Reconstructed seasonal ice conditions were found to correlate with seasonal average temperatures, lending credibility to statistical approaches in assessing seasonal aggregate ice conditions.

2 Methods

In this study we define the ice season as extending until the end of June of a given year, starting in July the year prior, i.e., ice season 2003 refers to the winter from 2002 to 2003. High resolution MODIS ice observations were used from season 2001 to 2011 to fit parameters of an ice condition model and to assess the quality of the fit. In addition, model output was compared with lower resolution AVHRR observations since season 1986.

2.1.1 MODIS

Ice conditions in Izembek Lagoon were evaluated by visual inspection of visible and near-infrared satellite images. Daily data are available from the MODIS onboard satellite Terra since early 2000, recorded during overpasses around local noon. The MODIS instrument records data in 36 spectral bands covering wavelengths from 400 nm (visible, blue) to 14 µm (thermal emission). Seven bands are general purpose reflective bands in the visible and near-infrared range at a nominal resolution of 250 m or 500 m.

In order to assess sea ice conditions, true-color and false-color images were visually evaluated. While true-color images (bands 1-4-3) give an intuitive impression of the surface condition, a distinction between snow and ice on the one hand and clouds on the other hand can be made in the near infrared as snow and ice appear markedly darker. Hence, in addition to true-color images we analyzed false-color images of band combinations 7-2-1 (ice seasons 2008–2011, processed by MODIS Rapid Response System to 250 m resolution), and 3-6-7 (ice seasons 2001–2007, processed from Level 1B MODIS data to 500 m resolution). While the combination 3-6-7 is preferred as it provides a particularly strong contrast, processed MODIS images in the combination of 7-2-1 were readily available since the ice season 2008.

An aggregate ice condition index was created to characterize the state of Izembek Lagoon, based on visual assessment of satellite images (Table 1). States were defined as: ice-free conditions in which no signs of ice were visible (category 0), traces of ice near the shores and possibly grounded (category 1), light ice conditions with notable ice cover yet eelgrass areas accessible in particular in the North and South of the lagoon (category 3), significant ice conditions with all eelgrass areas and some mud flats covered (category 5), severe ice conditions with the entire lagoon covered with the exception of the deepest parts of the channels (category 7), and a complete ice cover (category 8). Examples of category 1 conditions, i.e. slush ice along the shore, and category 7 conditions, i.e. a complete ice cover with the exception of the channels near the barrier islands, are shown in Figure 2.

2.1.2 AVHRR

Visual assessments of daily outputs of AVHRR imagery for ice seasons 1986 to 2000 were used to calibrate a degree-day model (described below). AVHRR imagery is available at the 1 km nominal resolution since the end of 1985. The comparatively low resolution of the imagery with respect to the size of the lagoon often made it difficult to determine accurately the presence of ice or its distribution, but data still allowed us to discriminate between insignificant (categories 0 to 3) and significant/severe (categories 5 to 8) ice conditions.

2.2 Ice Condition Model

A freezing degree- day (FDD) equation, based on air temperature data and day-of-year, was used to numerically categorize the severity of the ice conditions in Izembek Lagoon. After identifying two threshold values for significant (FDD_5) and severe (FDD_7) ice conditions, daily ice conditions were predicted as insignificant, significant, or severe.

Freezing degree days are a measure of the cumulative heat withdrawn from the water due to low air temperatures (cf. Petrich and Eicken, 2010). Freezing degree-days with respect to a base temperature T_{base} are defined as

$$\mathrm{FDD}(t) = \int_{\mathrm{July}}^{t} \begin{cases} \left[T_a(\tau) - T_{base}(\tau)\right] \mathrm{d}\tau & \text{while FDD} < 0 \ \text{ or } \ T_a < T_{base}(\tau) \\ \left[0\ ^\circ\mathrm{C}\right] \mathrm{d}\tau & \text{else} \end{cases}, \qquad (1)$$

where T_a is the air temperature (°C) at time τ (day of year). FDD are customarily expressed in units of °C days. The integration of FDD to a specific point in time, t, started in early November, prior to the onset of ice formation. Note that FDD defined in Equation (1) decreases during cold spells and increases during warm spells, never exceeding 0. Since ocean heat content and solar radiation change throughout the year we allowed for the possibility that T_{base} depends on day of year. We used two different values for winter and spring

$$T_{base}(\tau) = \begin{cases} T_{\mathrm{spring}} & \tau_x \le \tau < \mathrm{July} \\ T_{\mathrm{winter}} & \mathrm{else} \end{cases}, \qquad (2)$$

where τ_x is the day-of-year of transition from T_{winter} to T_{spring}. Two empirical FDD threshold values, FDD_5 and FDD_7, were fitted to identify significant (category 5) and severe (categories 7 and 8) ice conditions, respectively. The parameters of the model fitted to the observations were: FDD_5, FDD_7, T_{winter}, T_{spring}, and τ_x, allowing predictions of insignificant (FDD>FDD5), significant (FDD7≤FDD≤FDD5), or severe

(FDD<FDD7) ice conditions. Attempts to use one value of T_{base} for the entire ice season did not yield satisfactory results due to systematic rather than random errors in predicted ice conditions: either ice-free days in April had severe ice conditions, or ice conditions were systematically underpredicted throughout winter.

Parameters were optimized by maximizing the goodness-of-fit with the downhill simplex algorithm. The goodness-of-fit was a linear function of the number of days with mispredicted ice conditions, based on observations of MODIS imagery for ice seasons 2001–2011. Since the goodness-of-fit is a discontinuous function of initial parameters, i.e., a small change in parameters can lead to a jump in goodness-of-fit, the parameter space was searched based on both systematically and randomly generated initial guesses.

3 Results

3.1 Observations

Ice conditions were identifiable for a subset of satellite imagery gathered. The number of days that allowed an assessment of ice conditions from MODIS images ranged from 18 to 43 days between November and May each ice season. MODIS images tended to be spread throughout the ice season, resulting in observations during 12 to 24 weeks.

An example of Cold Bay weather and ice condition (IC) model output is shown in Figure 3 for the ice season 2008. From the IC model we expect Izembek Lagoon to have been significantly ice covered ($FDD<FDD_5$) during three periods, i.e., in mid January, mid February to early March, and in late March, with severe ice cover ($FDD<FDD_7$) observed during each of these periods. Observations were generally consistent with model expectations, ranging from category 0 to 7. However, a notable exception was observed on 6 and 7 February. Not shown in the figure, the northern half of Izembek Lagoon was ice

free on 4 February (the southern half was obstructed by clouds). On 6 February, following a particularly cold and relatively calm day with temperatures falling to –10 °C and winds below 5 m/s, ice conditions were significant with extended areas of open water around mud flats and channels. By 7 February, the lagoon was ice covered except in the channels. The ice cover appeared dark gray, indicating thin ice. This rapid freeze-up of the lagoon was not captured by the IC model and is the only documented example of a rapid freeze-up in ice seasons 2001 through 2011.

The seasonal distribution of ice observations from 2001 to 2011 is revealed in Figure 4. While observations are spread throughout the seasons, there are periods of the order of weeks without observations.

3.2 Model results

Minimizing the discrepancy between model predictions and observations (data of Figure 4), we found an optimal base temperature $T_{\mathrm{winter}} = -3.8\ ^{\circ}\mathrm{C}$ for the winter months. This optimum value was robust, i.e. it emerged regardless of initial conditions and variations in the choice of goodness-of-fit function. The best fit threshold values for FDD are FDD_5=−14 °C days and FDD_7=−35 °C days for significant (category 5) and severe (categories 7 and 8) ice conditions, respectively. These threshold values are also robust. Assuming $T_{\mathrm{spring}} = T_{\mathrm{winter}}$, we found that the amount of ice present in April is overestimated. However, the best date τ_x to change the base temperature, and the value of T_{spring} were not well confined by the data set. In particular, τ_x and T_{spring} were not independent of each other. Optimal parameter pairs ranged from τ_x=60 with T_{spring} of 0.5 to 1 °C below T_{winter}, to τ_x=75 with T_{spring} of 1 to 1.5 °C below T_{winter}. As a compromise, all model calculations (back to 1943) were performed with T_{spring}=−4.8 °C and starting day-of-year τ_x=65.

Figure 4 is a graphical comparison of ice classification from MODIS data with model predictions, indicating that the model generally captures ice conditions of Izembek Lagoon well.

A matrix summarizing classification errors is given in Table 2. In addition to counting the actual number of days of disagreement between observations and model predictions, all days were counted between observations as mispredicted if ice conditions were unambiguous (e.g. all days between observations of significant ice conditions were counted as mispredicted and if temperatures were above T_{base} and ice conditions were predicted to be severe). Inferences like this were made in three ice seasons (2006, 2009, 2011). Table 2 shows that the model never confused severe ice conditions (classes 7 and 8) with insignificant or absent ice (classes 0, 1 and 3). Throughout the 11-year record, significant ice conditions were misclassified as insignificant/absent on 5 days and as severe on 8 days. Severe ice conditions were misclassified as significant on 5 days, and insignificant/absent ice was misclassified as significant on 2 days. The longest continuous period of misclassification was in 2009 when 4 consecutive days of significant ice conditions were misclassified as severe. Given that there are usually between zero and 2 severe ice periods each season, that most errors are likely to occur either at the beginning or at the end of an ice period, and that there are compensating effects in nearly every season due to both under-classification and over-classification errors, the seasonal total estimate of either severe or combined severe and significant ice days is accurate to ±5 days. Lower errors can be expected for generally warm years. The largest seasonal error observed in the 11 year MODIS record was a 3 day net overestimate of significant ice conditions in 2009.

Comparison of AVHRR images with IC model predictions for ice seasons 1986 to 2000 confirmed model assessments of ice conditions (Figure 4). In particular, observations of significant ice cover tended to coincide with periods of modeled significant or severe ice conditions (i.e., $FDD \leq FDD_5$), while observations of insignificant ice conditions coincided with modeled $FDD > FDD_5$. In some instances observed ice conditions were ambiguous as they qualified neither as clearly insignificant nor as clearly significant. The FDDs reached values as low as –155 °C days in ice season 2000, establishing the lower verified bound of the model as FDD=–155 °C days.

3.3 Historical data

The IC model was used to determine expected ice conditions in years without observations. Since the lowest FDD value reached during an ice season with observations was −155 °C days in the ice season of 2000, we flagged all ice seasons with FDD values below this number as potentially mispredicting ice conditions. Figure 5 shows the seasonal distribution of predicted ice conditions since 1943. Significant ice cover existed as early as the end of November and as late as mid April (possibly early May). Severe ice conditions never occurred more than three times per ice season. The cumulative number of significant and severe ice days is summarized in Figure 6, highlighting the inter-annual variability of ice conditions. Significant or severe ice conditions were observed between 0 days (e.g., 2001) and ≥67 days (e.g., 2000) in a single ice season. Periods of generally severe ice conditions may have existed in the early 1970s, from 2006 to 2010, and possibly in the mid-1950s. Based on a linear trend from 1943 until 2011 (excluding the year of missing data, 1955), the number of days with significant or severe ice conditions decreased by 0.3 per season. The presence of a trend is statistically significant with 90% confidence (i.e., the two-sided p-value for a hypothesis test whose null hypothesis is that the slope is zero is p=0.09).

4 Discussion

4.1 Errors

Errors in ice assessment can be the result of errors in the interpretation of satellite images, and errors based on the simplicity of the IC model. Interpretation errors can be the result of mistaking snow for grounded ice on the shore, clouds for ice in visible imagery, and turbid water or low water levels for thin ice in near-infrared imagery. Further, uncertainty in ice conditions was increased due to atmospheric haze and when Izembek Lagoon was captured at the edge of the satellite swath rather than close to the center. In order to guard against misinterpretation of clouds and turbid water, both visible and near-infrared images were evaluated. Errors in the interpretation of ice or snow at the shore would at most result in confusion of categories 0 and 1, a distinction beyond the capabilities of the IC model and not part of this study. Errors due to image quality from haze and pixelation could have swayed the assessment of ice conditions that are at the edge of two categories in either direction. These errors are likely random and appear during both freeze-up and break-up, and therefore introduce no systematic bias during fitting of the model parameters.

The IC model is simple, using only air temperature and day-of-year as input parameters. Freezing degree days indicate the amount of energy removed from the water to the atmosphere. Physically, this energy is related to the mass of ice formed, and it can be related to area and distribution only empirically assuming that growth conditions (e.g., winds, ice drift, ocean heat flux) do not vary. As exemplified above, this assumption seems to be violated during relatively calm periods with particularly low temperatures.

Model parameters T_{winter} and T_{spring} are within the range of threshold temperatures used before, i.e. the freezing point of seawater, -1.8 °C (Weeks and Lee, 1958), and -5 °C (Karelin, quoted by Armstrong (1955)). The transition time τ_x is in spring, consistent with a general increase in solar irradiance. Threshold values FDD_5 and FDD_7 are likely to be specific to the wind and ice drift conditions particular to Izembek Lagoon.

4.2 Statistical model

Figure 7 relates the cumulative number of ice days of significant or severe ice cover in a particular ice season to the respective average air temperature of 31 December through day-of-year 90 (i.e., 31 March, except in leap years). The time frame was chosen to minimize the residual of a linear best fit for ice seasons 1986–2011, i.e., the time frame with satellite observations. The best fit line follows N_{ice}= 5.6 – 14.3 T_{air}, where N_{ice} is the number of significant or severe ice days, and T_{air} (in °C) is the mean air temperature at Cold Bay from 31 December until day-of-year 90. There is a statistically significant association between mean air temperature and modeled significant or severe ice days (R^2=0.7), and this correlation extends to ice seasons without satellite observations (R^2=0.8 for all ice seasons 1943 to 2011 except 1943, 1956, 1962, 1971, 1972, and 2000. Best fit line N_{ice}= 6.7 – 14.3 T_{air} not shown). The number of significant or severe ice days in three ice-heavy ice seasons 1943, 1962, and 2000 was notably higher than expected because severe ice formation started mid December or earlier, i.e. before the period over that air temperatures were averaged. The modeled number of significant or severe ice days is higher than expected from extrapolating the linear trend for ice seasons in which the verified range of the IC model was exceeded, i.e., 1943, 1956, 1971, and 1972. This indicates either that the IC model should not be used outside its verified range or that the correlation between average temperature and aggregate ice days is in fact non-linear. Scatter around the linear best fit for 1986–2011 falls within a range of ±20 days (except 2000) with a standard deviation of 10 days. While ice conditions are modeled rather than directly observed, model output for ice seasons 2001–2011 and as far back as 1986 is confirmed by satellite observations. In summary, the average air temperature from January through March is a suitable indicator for the number of days of significant or severe ice cover in Izembek Lagoon. However, ice conditions may be underestimated in years of severe ice conditions as early as December.

Ice conditions in Izembek Lagoon change in response to prolonged spells of cold and warm temperatures. Average warm (cold) temperature in winters should be interpreted as indicator rather than cause of light (heavy) ice conditions at Izembek Lagoon as the ice cover actually evolves in response to episodic weather events rather than mean conditions. In particular, sustained periods of cold weather are required for a significant ice cover to develop.

4.3 Inter-annual variability

Ice conditions at Izembek Lagoon appear to be linked to synoptic pressure systems. Since we found that a model based on freezing degree days of air temperature can be used to predict ice conditions, a relationship between ice conditions and air temperatures at Cold Bay exists. In Figure 8 the relationship is illustrated between local air temperatures and local winds. Due to topographic steering, winds observed at Cold Bay are approximately bimodal throughout the year, with a distinct NW–SE component. We regressed daily average temperatures with daily mean wind speed and direction (1943–2011) and found winds and air temperatures to be correlated. The highest correlation in winter (December through the end of March) was found with the North–South component of the winds (R^2=0.46), with northerly winds indicating lower temperatures than southerly winds (Figure 8). This observation is plausible as northerly winds would not only transport cold air from the sea ice cover of the Bering Sea toward Izembek Lagoon, but also push the sea ice edge southward toward Izembek Lagoon (Pease et al., 1982).

Ice conditions in Izembek Lagoon appear to be linked to regional climate. Figure 9 shows the standardized Jan-Feb-Mar-Apr (JFMA) average ice extent in the Bering Sea and the standardized, modeled Izembek Lagoon ice cover for 1979-2010. Monthly time-series of sea ice extent in the Bering Sea is publicly available from the National Snow and Ice Data Centre and is based on ice concentration estimates derived from satellite passive microwave data using the bootstrap algorithm (Stroeve, 2003).

The correlation between the two time-series is 0.65 ($p<0.01$) suggesting that a little over 40% of the inter-annual variability in the Izembek time-series co-varies with ice extent in the Bering Sea. Both monthly and seasonal averaged ice extent and ice area were tested and the strongest correlation was found with JFMA ice extent. If ice extent is limited to the eastern Bering Sea (54-64° N, 175-155° W) the correlation increases to 0.7 ($p<0.01$). There is a good agreement between extreme ice years, i.e., standardized anomaly greater than 1, in the Izembek Lagoon and Bering Sea time-series (Figure 9). Of the 6 extreme ice seasons in each time-series, 4 are common between the two (1971, 1972, 2008 and 2009). In general, sea ice in the Bering Sea is advected south by northerly winds and the ice edge is limited by warm ocean temperature to the south (Pease et al. 1982). Year to year variations in ice extent in the Bering Sea have been linked to the strength and position of the Aleutian Low (e.g. Pease et al., 1982; Niebauer, 1998; Rodionov et al., 2007). Significant correlations between ice cover in Izembek Lagoon, local meridional winds, and ice extent in the Bering Sea suggests that inter-annual variability in the ice cover at Izembek Lagoon may also be influenced by inter-annual variability of the strength and position of the Aleutian Low.

5 Conclusion

Ice conditions in Izembek Lagoon were reconstructed successfully with an ice condition model based on degree days. Model data were compared with categorized ice conditions based on satellite observations from 1986 to 2011. Daily ice conditions were inferred back to 1943 based on the local weather record. Daily satellite imagery was suitable to calibrate an ice model even though the region is known to experience cloud cover frequently. While the model was able to capture ice conditions accurately, a source of systematic errors was identified in one instance: ice coverage on a moderately cold but calm day was underpredicted. This serves to illustrate that simple models based on degree days are limited by the implicit assumption of systematic (stationary) environmental conditions.

It was possible to relate reconstructed ice conditions statistically to seasonal average temperatures even though formation of a significant ice cover requires persistent low temperatures, which is not directly captured by temperature averages. This observation may be transferable to other coastal regions, providing a comparatively simple method for estimating aggregate ice conditions in years without observations.

The present reconstruction revealed fundamental features of ice conditions in Izembek Lagoon. While there were clusters of years of notably heavy ice (e.g. early 1970s and 2006 to 2010), the high inter-annual variability in ice conditions likely dampened the strength of the long-term negative trend in seasonal aggregate ice conditions. Statistical correlations show that ice conditions were stronger in colder seasons, and that air temperature is associated with wind direction. Significant correlations with January through April ice extent in the Bering Sea suggest that the position and strength of the Aleutian Low influences not only variability in the Bering Sea ice extent but also inter-annual variability of the severity of the ice season in Izembek Lagoon.

Following an investigation of location-specific ice conditions, the methodology employed for Izembek Lagoon in this study should be transferable to other coastal areas, opening opportunities to assess the day-to-day and inter-annual variability of wildlife over a wider area in relation to ice conditions.

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6 Tables

Table 1. Classification of aggregate ice conditions in Izembek Lagoon

Category	Ice cover	Description
0	ice-free	No ice detectable.
1	traces	Any amount of ice from remnants possibly grounded on-shore to small amounts of ice floating along the mainland coasts.
3	light	More extensive ice cover East and North of Round Island, extending or almost extending from the mainland to the barrier islands. Some eelgrass areas are likely accessible.
5	significant	Mainland coast is completely ice-covered, typically two ice bridges extending between mainland and barrier islands. A narrow ice-free channel may still exist along the barrier islands, however. All eelgrass areas are likely covered by ice.
7	severe	Eelgrass areas and mud planes are ice covered. Channels are largely ice-covered except at the gates between the barrier islands. A larger area of the channel North of the barrier islands may be ice-free.
8	complete	Izembek Lagoon is completely ice-covered, including the gates between the islands.

Table 2. Classification error matrix between observations and model predictions (days) for ice seasons 2001 to 2011

Observed \ **Predicted**	**insignificant/absent** FDD > FDD_5	**significant** $FDD_5 \leq FDD \leq FDD_7$	**severe** FDD < FDD_7
categories 0, 1, 3 **“insignificant/absent”**	—	2011: 2	0
category 5 **“significant”**	2010: 1 2009: 1 2008: 3	—	2009: 4 2007: 1 2006: 3
categories 7, 8 **“severe”**	0	2009: 1 2008: 1 2006: 2 2004: 1	—

Figures

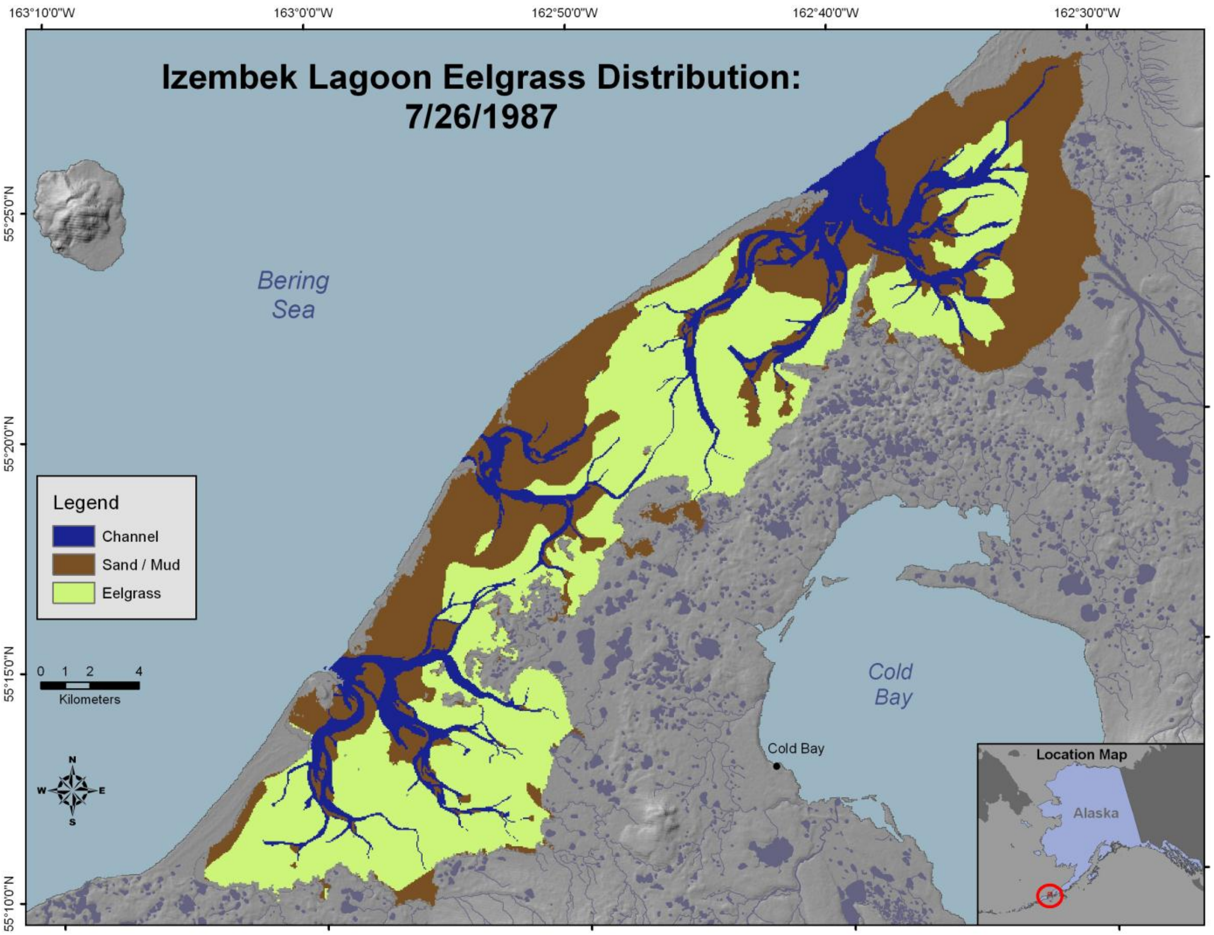

Figure 1. Distribution of channels (blue), eelgrass (light green), and sand/mud (brown) in Izembek Lagoon (Ward et al., 1997). The circle in the inset shows the approximate location of the main map.

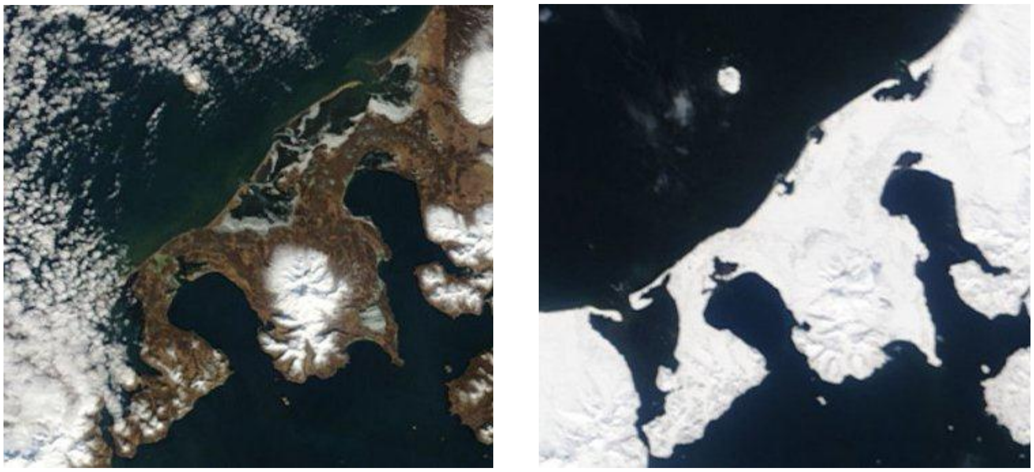

Figure 2. Example true-color MODIS images of category 1 ice conditions with slush ice mostly near the shore (left hand side, 4 March 2011) and category 7 ice conditions with ice cover throughout Izembek Lagoon with the exception of the gates between barrier islands (right hand side, 5 April 2010). Images provided by the MODIS Rapid Response System at 250 m pixel resolution.

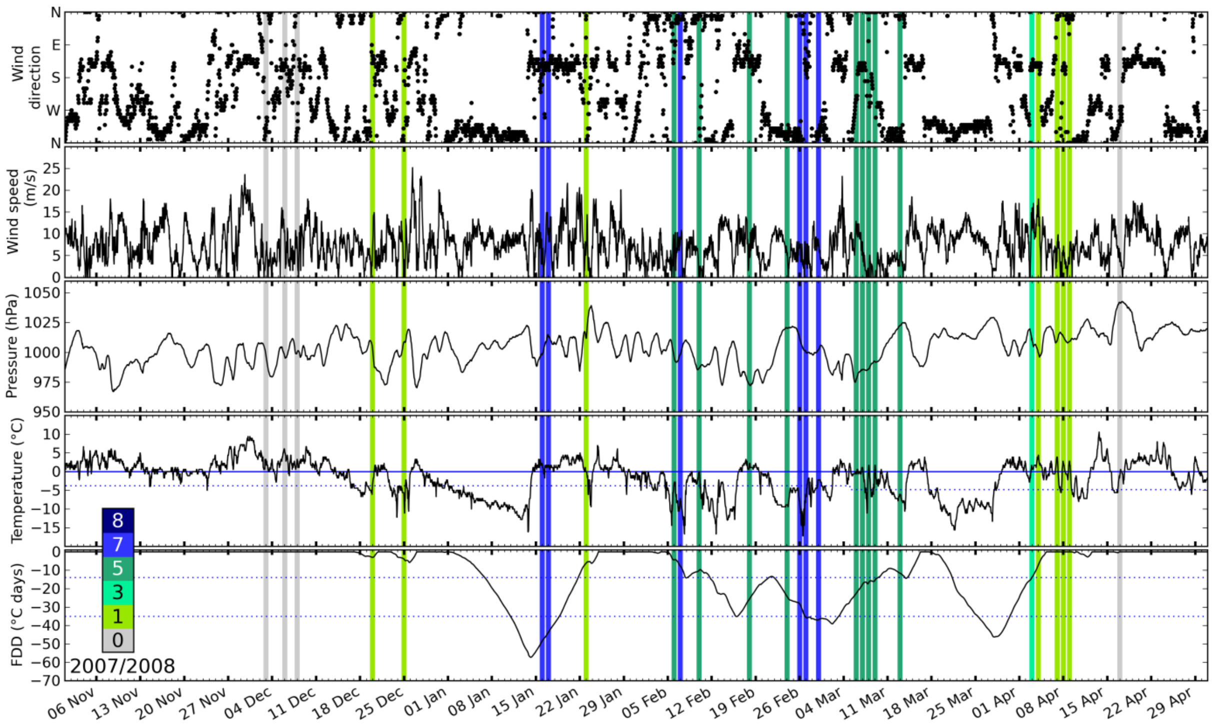

Figure 3. Cold Bay weather data (wind direction, speed, sea level pressure p, air temperature T), calculated FDD values, and MODIS ice observations at Izembek Lagoon in ice season 2008. The horizontal dotted line in the temperature plot is drawn at T=–3.8 °C and –4.8 °C before and after day-of-year 65 (i.e., 5 March 2008), respectively. The dotted lines in the FDD plot are at the threshold of significant and severe ice conditions FDD_5=–14 °C days and FDD_7=–35 °C days, respectively.

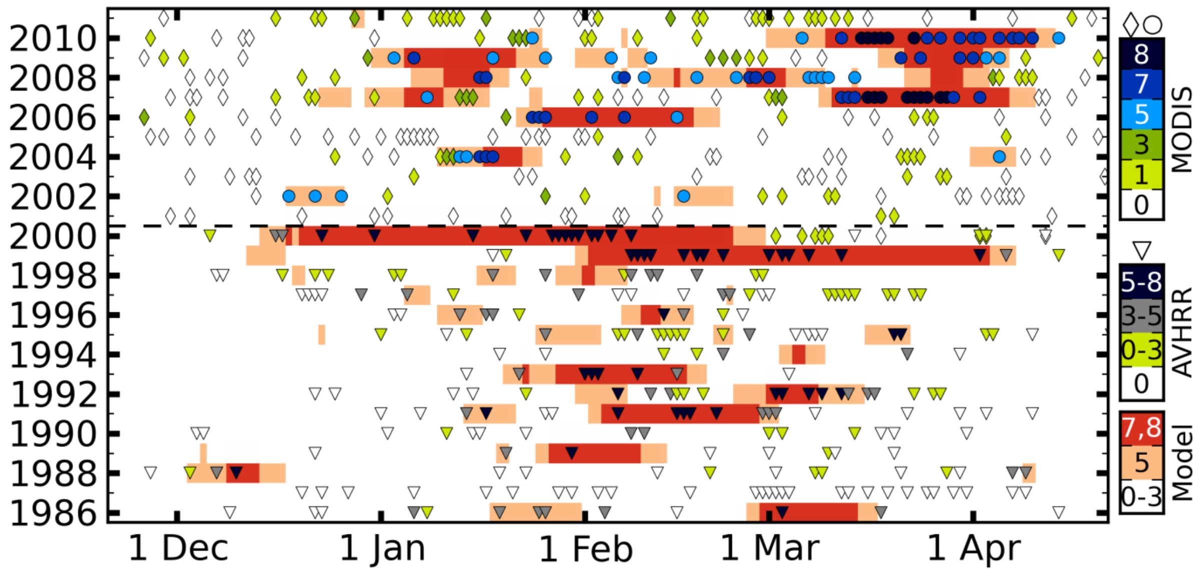

Figure 4. Comparison of classified model output (background shades, light red for category 5, dark red for categories 7 and 8) with MODIS (white or green-shaded diamonds for categories 0 to 3, blue-shaded circles for categories 5 to 8) and AVHRR (shaded triangles) ice observations. The color code for ice categories is indicated at the right hand side of the figure. Not all ice categories could be resolved in AVHRR observations and model simulations, leading to grouping of categories. Calibration of the IC model is based on observations since season 2001 (data above the dashed line).

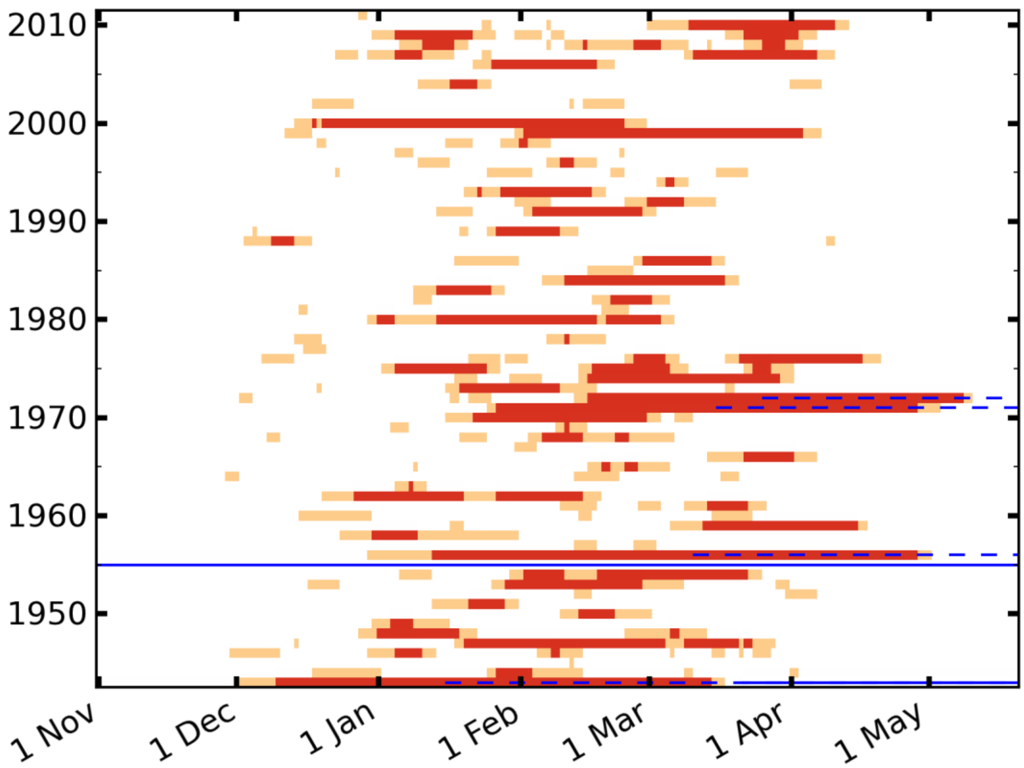

Figure 5. Seasonal distribution of modeled ice conditions in Izembek Lagoon from 1943 to 2011. Light and dark shades indicate significant ($FDD_7 \leq FDD < FDD_5$) and severe ($FDD < FDD_7$) ice conditions, respectively. Solid lines mask times of missing temperature data, dashed lines indicate where ice conditions may have been misestimated because FDD exceeded the verified range.

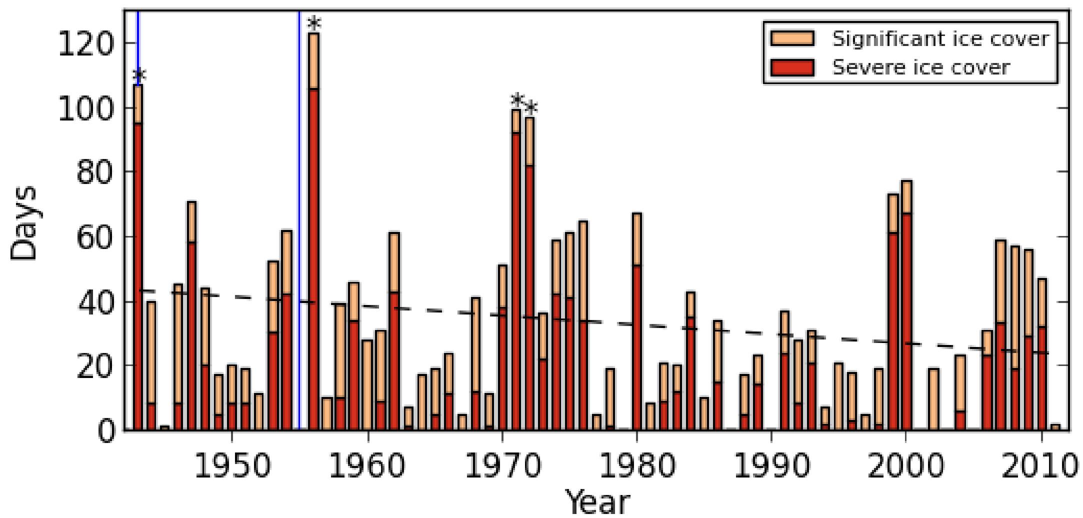

Figure 6. Modeled number of days with significant (light shade) and severe (dark shade) ice conditions. Vertical lines indicate years of incomplete temperature record, i.e. number of ice days shown are lower estimates (1943 and 1955). A star above a bar indicates that the number of ice covered days may be overestimated because FDD exceeded the verified range (1943, '56, '71, and '72). The dashed line follows the linear trend of number of days with either significant or severe ice cover. The trend (-0.3 days/year) is statistically significant at the 0.1 level.

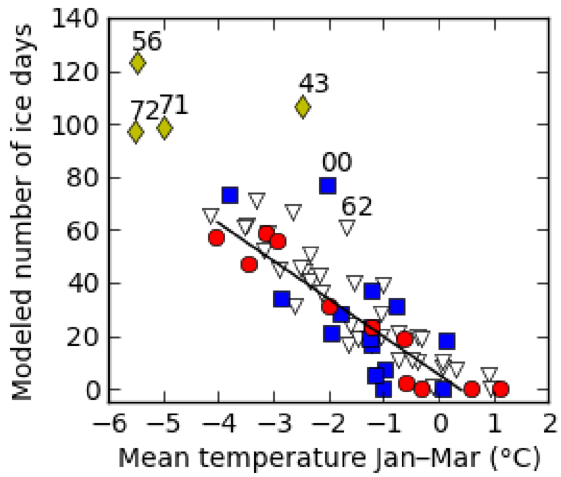

Figure 7. Modeled number of significant or severe ice days ($FDD<FDD_5$) compared with mean air temperature from 31 December until 31 March for years with MODIS observations 2001–2011 (circles), AVHRR observations 1986–2000 (squares), years outside the IC model range 1943, 1956, 1971, 1972 (diamonds), and all other years with data 1943–1985 (triangles). The line is a least square fit to data 1986–2011. 1943, 1962, and 2000 were heavy ice years with severe ice formation starting prior to January.

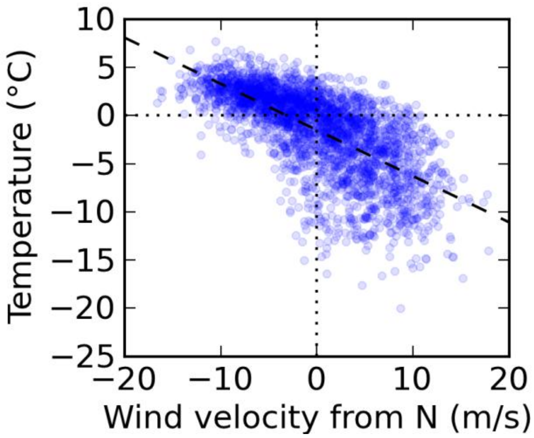

Figure 8. Relationship between daily mean temperature and North-South component of winds observed at Cold Bay from December to March. Negative velocity components represent winds from the South. The linear best fit line is shown dashed.

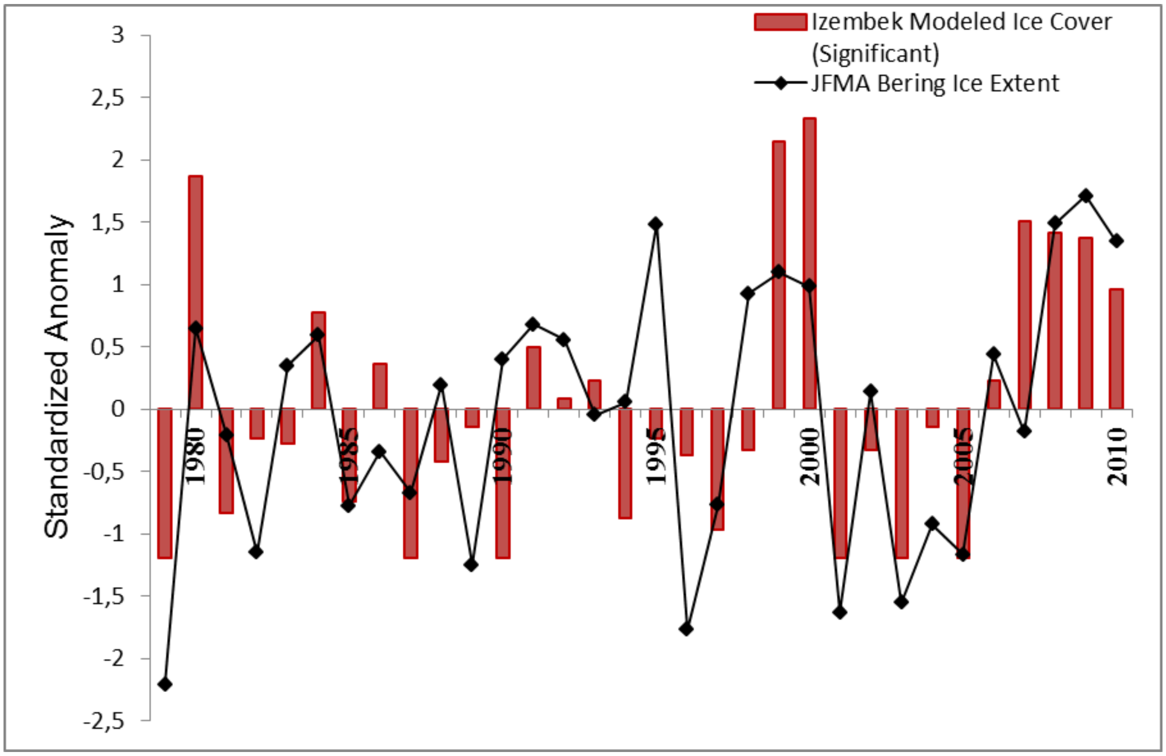

Figure 9. Standardized anomaly of cumulative significant ice cover in Izembek Lagoon (bars) and Bering Sea ice extent from January through April (lines) from 1979 until 2010.