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Sea-Ice Distribution in the Bering and Chukchi Seas: Information from Historical Whaleships' Logbooks and Journals

ANDREW R. MAHONEY,[1,2] JOHN R. BOCKSTOCE,[3] DANIEL B. BOTKIN,[4] HAJO EICKEN[1,5] and ROBERT A. NISBET[6]

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ABSTRACT. Satellite data have revealed dramatic losses of Northern Hemisphere sea ice since the end of the 1970s. To place these changes in a longer-term context, we draw on daily observations taken from logbooks and journals of whaling vessels cruising in the Bering and Chukchi seas to investigate sea-ice conditions in this region of the Arctic between 1850 and 1910. We compare these observations to sea-ice data from 1972 to 1982, which predate the majority of the recent changes and cover a period recognized as a relative maximum in recent Bering Sea ice extent. Records from May indicate that end-of-winter sea-ice extent in the Bering Sea during the mid 19th century closely resembled that in the 1972–82 data. However, the historical data reveal that sea ice was more extensive during summer, with the greatest difference occurring in July. This pattern indicates a later and more rapid seasonal retreat. These conclusions highlight the value of historical data, which we have far from exhausted in this study.

Key words: sea-ice extent, historical data, Arctic, Bering Sea, Chukchi Sea, Beaufort Sea

RÉSUMÉ. Des données satellitaires révèlent que l'hémisphère nord a enregistré des pertes dramatiques de glaces de mer depuis la fin des années 1970. Afin de mettre ces changements dans un plus long contexte, nous nous appuyons sur les observations quotidiennes tirées de journaux et de carnets de bord de baleiniers ayant parcouru la mer de Béring et la mer des Tchouktches dans le but d'étudier les glaces de mer de cette région de l'Arctique entre les années 1850 et 1910. Nous comparons ces observations aux données sur les glaces de mer recueillies de 1972 à 1982 – soit avant que la plupart des récents changements n'aient été enregistrés – ce qui couvre une période reconnue comme un maximum relatif en matière d'étendue récente des glaces dans la mer de Béring. Les données enregistrées en mai laissent entrevoir que l'étendue des glaces de mer en fin d'hiver dans la mer de Béring au milieu du XIX[e] siècle ressemblait beaucoup à l'étendue des glaces dont témoignent les données prélevées entre 1972 et 1982. Cependant, les données historiques révèlent que les glaces de mer étaient plus considérables au cours de l'été, la plus grande différence se manifestant au mois de juillet. Cette tendance indique donc un retrait saisonnier plus tardif et plus rapide. Les conclusions mettent en évidence l'importance des données historiques, que nous sommes loin d'avoir épuisées dans le cadre de cette étude.

Mots-clés : étendue des glaces de mer, données historiques, Arctique, mer de Béring, mer des Tchouktches, mer de Beaufort

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INTRODUCTION

Since 1979, satellite remote sensing of the Pacific Arctic has shown some of the largest changes in sea-ice coverage in the world, which have increased concerns about the effects of global climate change (e.g., Serreze et al., 2007; Stroeve et al., 2007; Parkinson and Cavalieri, 2008). These satellite observations have raised the question whether this decline is unique or has been characteristic of that same region in the past (Darby et al., 2006). Concerns about declines in Arctic ice extent have been increased by recent modeling studies that suggest the Arctic could be free or nearly free of sea ice in summertime within the next few decades (Holland et al., 2006; Eisenman and Wettlaufer, 2009; Wang and Overland, 2009; Overland and Wang, 2010).

Here we present results obtained from the analysis of more than 52 000 daily observations drawn from historical whaleships' logbooks. This unbroken 65-year record extends observations for the Bering, Chukchi, and Beaufort (B-C-B) seas back to the mid-19th century (though

[1] Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska 99775, USA
[2] Corresponding author: Mahoney@gi.alaska.edu
[3] New Bedford Whaling Museum, 18 Johnny Cake Hill, New Bedford, Massachusetts 02740-6317, USA; john_r_bockstoce@msn.com
[4] Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, California 93106, USA; danielbotkin@rcn.com
[5] Hajo.eicken@gi.alaska.edu
[6] 7126 Armstrong Road, Goleta, California 93117, USA; bob2@rnisbet.com

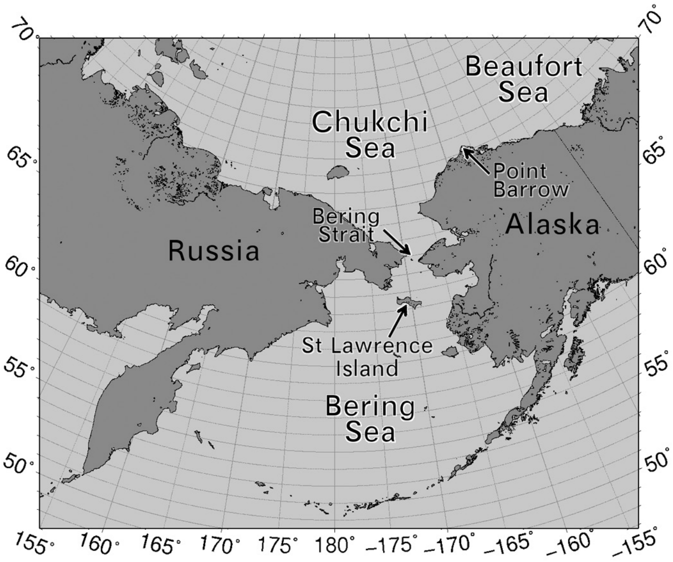

FIG. 1. Location of the Bering, Chukchi and Beaufort (B-C-B) seas.

most of the data were recorded in the Bering and Chukchi seas since the whaling fleet did not reach far into the Beaufort Sea until the 1880s). From these data, we have mapped observations of ice and ice-free conditions over time and compared them with recent climatological ice-edge data. We gain insight into the ability of the ships to penetrate the ice pack and how to reconcile ship-based and space-based data by comparing moderate and high-resolution satellite imagery with photographic data collected on a recent icebreaker cruise. The historical sea-ice records we present are useful in themselves for the history of Arctic sea-ice cover. But in addition, as one of the most detailed and extensive historical oceanic records of any kind, they provide a useful test of how such records can be of scientific value.

DATA AND METHODS

Whaling Ship Logbooks

We have analyzed sea-ice observations recorded in logbooks of ships engaged in whaling activities in the B-C-B fishery (Fig. 1) between 1849 and 1914. These whaling grounds were discovered in 1848, and in 1849 a whaling fleet began a hunt that continued until 1914. During this period, whaleships carried out 2712 annual cruises to the B-C-B seas. Complete records of 516 (19%) of the annual cruises were found in logbooks and journals in public and private collections throughout the United States, Canada, and Australia. These logbooks represent an unbroken record of the whale hunt in the B-C-B seas from 1849 to 1914. The data extraction was carried out at the New Bedford Whaling Museum (NBWM) from documents in its own collection, as well as from microfilm copies in the NBWM's International Marine Archive, which contains images of logbooks and journals in public and private collections worldwide.

As described by Bockstoce and Botkin (1983), the following information for each daily logbook entry was extracted and digitized: the date and geographical position of the vessel, wind direction and relative velocity, visibility, fauna encountered, and ice coverage. During the process of data extraction, when ice was reported, the extractors estimated the extent of the sea surface that was covered. The data format allowed only the use of numbers 0 through 9; consequently, these estimates were recorded in increments of eighths: for example, 0 for no ice, 1 for one-eighth coverage, and so on, 8 for total surface coverage, 9 for no report. For the most part, these estimates were subjective judgments based upon the description of sea ice contained in each entry. Below we present examples of the references to ice contained in the logbooks, but we have no way of confirming the accuracy of the extractors' estimates of ice coverage. Consequently we have limited our data reporting to whether ice was present (i.e., coverage of one-eighth or greater) or absent.

The resulting dataset (available at http://www.naturestudy.org/bowhead-sea-ice) contains 52 697 daily observations, within which are 23 842 reports of the presence of sea ice. Few ice reports were found in the logbooks for 1849, and after 1910 very few voyages were documented. We therefore confine our analysis to the six decades between 1850 and 1909. Daily records were available for most ships most of the time, but owing to occasional gaps in the record, there is an observation from each ship on average every 1.2 days.

Sea-Ice Observations in Logbooks

No standard protocol for ice observations had been established at the time of the B-C-B fishery, and references to sea ice in the ships' logbooks took many forms. Many logbook entries describe encounters with ice in vivid detail, such as this entry from the log of the *Wolga*, written on 23 May 1851 in the northern Bering Sea:

> These 24 hours begin with light winds from the NE and cold and rainy[.] Steering to the northward through the ice[.] The ice icresing [sic] every mile that we go[.] Huge masses 40 or 50 feet in length and so high above the water that there is danger of taking the boats off of the cranes[,] and the copper started in several places[.] The cutwater badly jammed and the ship completely covered with ice from the water edge to the royal truck...

The logbook record indicates that ships would routinely exploit openings in the ice edge to penetrate into the pack. Brief entrapments in the ice were common, but typically vessels were able to escape when a change in wind direction loosened the ice. The following excerpts, taken from the logbook of *Eagle* for 1868, describe the dynamic and changeable nature of the marginal ice zone:

> Wednesday May 6: In the night come on to blow from N. which packed the ice up again and we are again blocked up with everything furled … It is now breaking up and we are trying to work out with a light air from S.E. Cape Thadeus [Mys Fadeya] N.W. about 30 miles. 30 ships in sight.
>
> Thursday May 7: Drifting through the scattering ice with plenty snow and the ship grating hard upon the ice.
>
> Friday May 8: Blew very hard in the night we drifted into a patch of packed ice and furled everything ... Cape Navarin is N.N.E. 20 miles. 30 ships in sight.
>
> Saturday May 9: We have been all beating up through the scattering ice among 34 ships. Have now got up where the ice is packed.
>
> Saturday May 10: We have been cruising the ice all day…
>
> Sunday May 11: The ice comes S.W. fast in thick packed ridges…In the ice off Cape Bering
>
> Sunday May 17: In the night the ice closed up and at 12 we found our ship packed closely…
>
> Friday May 22: We are still packed closely in the ice…
>
> Saturday May 30: Ran down through an open place and now we are in very heavy ice
>
> Sunday May 31: The land is now in plain sight but the ice is very heavy and close packed and no clear water to be seen yet.

Excerpts such as those above are useful for understanding the ice conditions in which the whaling ships operated. Commonly, the entries describe a distinct edge to the pack ice. For example, the logbook from *Lagoda* on Monday 03 May 1869 reads, “At 1 AM made the ice…kept off along the edge of it to the Eastward.” However, many of the references to sea ice contained in the logbooks provide little information beyond its presence at the ship’s location. In such cases, it is impossible to know from a single entry where the ship was in relation to the ice edge or whether there was a well-defined edge. For the purposes of consistency in the analysis that follows, we simplify the record according to whether or not ice is noted in a logbook entry.

Studies of historical sea-ice conditions from whaleship logbooks have been a source of controversy in the past. De la Mare (1997) analyzed logbooks from Antarctic whaling vessels and concluded that Southern Hemisphere sea ice experienced an abrupt decline between the 1950s and 1970s, prior to the satellite record. Subsequent literature (Vaughan, 2000; Ackley et al., 2003; de la Mare, 2009) has discussed the validity of this conclusion, which is based

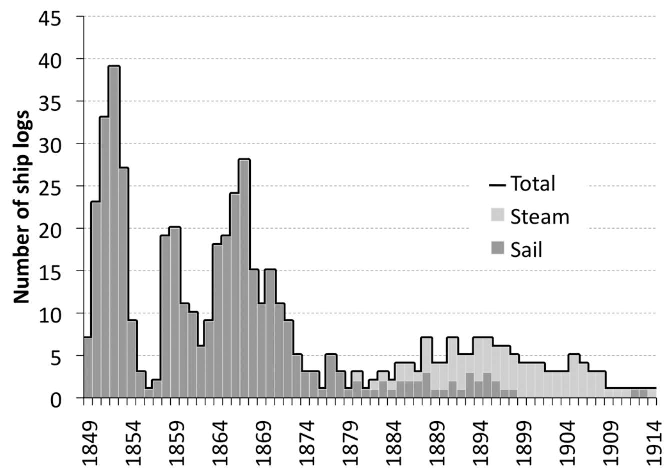

FIG. 2. The number of logbooks available from the Bering-Chukchi-Beaufort whaling fleet for each year from 1849 to 1914. Dark grey indicates purely sail-powered ships, while light grey shows those with auxiliary steam power.

largely on the premise that the southern limit of the Antarctic whaling fleet (and in particular, the locations of factory vessels) corresponded closely to the location of the sea-ice edge. It is clear from the logbooks of the B-C-B fishery that sea ice was not a constant limitation on navigation, and we therefore cannot assume that the northernmost position of the fleet was indicative of the location of the ice edge. Instead, our approach is to study the distribution of all ice and ice-free observations from the whole fleet.

Consistency and Reliability of Historical Records

To use these logbook records in a scientific analysis, it is important to consider their reliability and consistency. The logs were kept by the ships’ officers primarily as records of whaling activities, but also as legal documents to be used in insurance claims should vessels be damaged or lost. Therefore, the information they contain, particularly regarding the ship’s position, can be regarded as reasonably accurate. However, taking the record as a whole, the number of observations and their spatio-temporal distribution through the period are non-uniform. The number of ships (and therefore observations) was strongly linked to the success of the fishery, and the distribution of observations was heavily biased by the distribution of whales.

We discuss three matters relating to the reliability of these historical data for the analysis of sea-ice conditions, namely their use to represent temporal conditions, spatial conditions, and sea-ice extent.

1) Temporal Conditions: The Bering-Chukchi-Beaufort whaling fleet grew rapidly in the first four years, and the number of ships peaked in 1852, by which time one-third of the total estimated catch had been taken (Fig. 2). Some historical events affected the size of the B-C-B whaling fleet. The fleet largely deserted the region from 1855 through 1857 because of a newly discovered bowhead fishery in the Sea of Okhotsk; in 1865, the Confederate States’ raider *Shenandoah* burned 20 whaleships in the Bering Strait region, and the rest of the fleet scattered for safety; in 1871, 31 ships were lost to pack ice on the northwest coast of Arctic Alaska; and in 1876, 12 ships were lost in the ice north of Point Barrow (Bockstoce, 1986:93 – 128, 143 – 179, 2006). These events are reflected in the number of logbooks available to this study over the course of the fishery (Fig. 2).

2) Spatial Conditions: The commercial whale hunt was not a random search, but a rational economic attempt to acquire raw materials (whale oil and baleen) as cheaply (quickly) as possible. The whalemen used their best judgment about where to find bowheads, and they were constantly on the alert for them. They traveled only as far as necessary to reach their quarry. Purely exploratory cruises were rarely undertaken. The whalemen cruised on the whaling grounds only as long as it was necessary to fill their ships. In the early years of the fishery, ships occasionally became “full” and left the whaling grounds before the hunting season ended; in later years, this rarely occurred.

In the first two decades of the fishery, the fleet’s activities were widespread across the Bering and Chukchi seas. Nevertheless, over time the whales became harder to find, and whalers noted that their prey were learning to avoid them, often by fleeing into the protection of the pack ice (Bockstoce, 1986:101 – 102; Bockstoce and Burns, 1993; Bockstoce et al., 2005). Another significant change in the fishery occurred in 1880, when the first steam-auxiliary ships joined the fleet (Fig. 2). Being more maneuverable, these ships were able to sail deeper into the marginal ice zone, and eventually they largely replaced sailing ships. The introduction of steam auxiliaries led to the expansion of the whaling grounds into the eastern Beaufort Sea.

3) Sea-Ice Extent: As the bowhead population declined, the whalers recognized that they made their best catches near the ice edge. They found that they were most successful cruising among scattered floes at the margin of the pack ice, especially in May-June and August-September. In the eastern Beaufort Sea, east of approximately 140˚ W, the August-September hunt took place mostly in open water.

The following realities of the B-C-B fishery also constrained where and when whaleships may have encountered sea ice:

- The whalemen sought bowheads exclusively (because of their high yields of oil and baleen); if no bowheads were present, they would take any available alternative species, principally gray whales and walruses. The whalers quickly reduced the bowhead population. Out of an estimated total of 18 650 bowhead kills, one-third were achieved by 1852, one-half by 1863, and two-thirds by 1867.
- The ice coverage and weather conditions limited the whalemen’s hunting ability and the ships’ cruising range. In the spring and summer, the whalers could progress only as far as the retreating pack ice would allow. Throughout the cruise, fog and gales also hampered their ability to hunt.
- The bowheads quickly adapted to the hunting threat from the whaleships. By 1849, the year after the B-C-B fishery was discovered, the bowheads had apparently begun learning to avoid the whalers by diving or, most often, fleeing into the protection of the pack ice. Consequently, the whaleships were often close to the ice edge.
- In 1880, the first steam-auxiliary whaleship joined the fleet and proved its worth by being able to maneuver deeper into the marginal ice zone. From this date onward, we distinguish between sail-powered and auxiliary-powered whaleships because of their differences in mobility (Fig. 2).

In short, the sea-ice observations contained in these logbooks are not the result of a planned sampling strategy, and no single data point should be interpreted unless further context can be derived from a detailed reading of the logbook. However, by examining the data as a whole ensemble over decadal time scales, we can gain valuable insight into sea-ice conditions in the B-C-B seas during the 19th century.

Contemporary Analyses

This paper is not the first to study the reports of sea ice contained in the logbooks of the B-C-B whaleships. In a contemporary study for the U.S. Coast and Geodetic Survey, Dall (1882:303) studied “the remark-books of various whalers” and was able to determine “for each of six or seven years, from 1870 – 1878, the average southern limits of the pack in April and May, between the meridians of 169˚ and 190˚ west of Greenwich.” Eight years after Dall’s report was published, Simpson (1890:4) produced a map showing the northern limit of the ice edge in August and September for the years 1879 and 1885 – 89. To produce this map, Simpson drew on several sources including “the captains of five steam whalers and eleven sailing vessels.” We compare these contemporary analyses with our own later in the paper.

Modern Sea-Ice Observations

In order to place the historical sea-ice data in the context of modern conditions, we have taken mean sea-ice concentration contours from the Naval Oceanography Command (NOC) *Sea Ice Climatic Atlas* (NOC, 1986), which is a climatological summary of ice conditions compiled from gridded Joint Ice Center ice chart data. This atlas was chosen for its coverage of the B-C-B seas and the fact that it provides mean contours for different ice concentrations from 0% to 100% and therefore clearly delimits the region in which no ice was observed. Other commonly used modern-day ice edges, such as the National Snow and Ice Data Center Ice Index (Fetterer et al., 2002), are defined according to the 15% ice concentration contour.

The period of time spanned by the NOC atlas (1972 – 82) predates much of the sea-ice retreat that has taken place in recent years. In particular, during the first half of this period, ice extent in the Bering Sea was at a relative maximum compared to any other time during the past five to six decades (Niebauer, 1998). Hence, using the NOC atlas data allows us to examine changes in ice conditions preceding those documented in the satellite record (e.g., Stroeve et al., 2005; Serreze et al., 2007; Kwok et al., 2009) and therefore to place recent changes in a longer-term context.

RESULTS

To account for differences in the number and types of vessels involved in the fishery and potential changes in the distribution of whales and ice, we subdivided the study period into the six decades that cover most of the logbook record, from the 1850s to the 1900s. Figures 3–5 show how the whaling fleet was dispersed at different times of year during these six decades. Blue dots correspond to locations where no ice was observed, while white dots indicate locations where ice was reported. The white dots are drawn over the blue, so that the figure highlights the southernmost occurrence of any and all ice observed.

We have chosen the months May, July, and September as representative of conditions at the end of the ice-growth season, in midsummer, and at the end of the ablation season, respectively. Although sea-ice extent in the Bering Sea is typically greatest during late March or early April, the ship data are sparse during these months. In recent years, ice has still been found well south of St. Lawrence Island in the Bering Sea in May, with full retreat from the Bering Sea typically complete by mid-June (Eicken et al., in press).

As noted previously, the addition of steam-powered whaleships in 1880 brought major changes to whaling in these northern seas. Figure 4 shows the distribution of the fishery relative to the ice before and after the arrival of steam-auxiliaries. The difference is most noticeable in September, when the fleet was most concentrated at the ice edge. Although the overall distribution of the fleet north of 70˚ N was similar in the two decades, a greater proportion of the ships was operating amid sea ice in the 1880s. The introduction of steam auxiliaries led to the expansion of the whaling grounds into the eastern Beaufort Sea and the concentration of whaling activity almost exclusively along the ice edge.

The differences in the distribution of the fleet over the course of the record, and particularly before and after 1870, are clearly evident in Figures 3 to 5. The trend towards further penetration of the fleet into ice-covered waters results in fewer observations of ice-free conditions, which makes it more difficult to determine the southern extent of sea ice. However, as noted above, two contemporary studies based partly on whaling records attempted to do so.

Dall (1882) published ice maps for April of specific years between 1870 and 1878. When his record is compared with the corresponding period of the whaleship record (Fig. 4a), there is reasonable agreement in the central Bering Sea (where data are most sparse), but in the western Bering Sea, the whaleship logs report many observations of ice south of the edges drawn by Dall. This discrepancy is even greater when Dall's ice edges are compared with whaleship data from earlier decades, when more logbook entries were available. Dall apparently relied on only a few "remark-books" in his analysis, so the discrepancy between Dall's maps and the whaleship records is likely due to the level of day-to-day and interannual variability in the location of the ice edge.

Simpson (1890) published similar ice edge records for the Chukchi Sea west of Point Barrow in August and September of 1879 and 1885–89. The southernmost and northernmost of these edges effectively show boundaries of the September ice observations in the whaleship logbooks for the 1880s. However, logs from earlier decades show a significant number of ice observations south of the southernmost of Simpson's ice edges.

Comparison with 1972–82 Ice Edge Climatology

The red lines in Figures 3–5 show the locations, taken from the NOC atlas, where the probability of encountering ice during the period 1972–82 was 0%. From here on, we refer to these as zero-ice lines. The first two decades of the whaling log record (1850–1869) contain the greatest number of historical observations and therefore offer the best opportunity for comparison with the 1972–82 NOC atlas data. The central Bering Sea data for May (Fig. 3a, b) show a clear boundary where the proportions of ice and ice-free observations change. This boundary approximately coincides with the 1972–82 zero-ice line, though there are still a number of scattered ice observations south of the line. There are also ice-free observations farther north, but these are generally close to the coast and are likely related to coastal polynya processes.

By contrast, the historical data for July during the 1850s and 1860s (Fig. 3c, d) show numerous observations of ice south of the zero-ice line. The NOC atlas data indicate very little ice outside of the Chukchi Sea, whereas the historical data show ice throughout the northern Bering Sea. The NOC atlas data for September show no ice in the southeastern Chukchi Sea, but between 1850 and 1869, the whaling ships observed ice throughout the Chukchi Sea and south of the Bering Strait (Fig. 3e, f). Nevertheless the concentration of ice observations south of the zero-ice line is not as great in September as in July. Overall, these data indicate that there was more summer sea ice in the western Arctic during 1850–69 than during 1972–82 and that the pattern of seasonal retreat—based on data binned into these three months—was different.

Because there were fewer ships in the fleet after 1870, there were also fewer ice observations, which makes it more difficult to determine the location of the ice edge. During May, when spatial coverage of the fleet was widespread throughout the record, the agreement between the distribution of ice and ice-free observations and the NOC zero-ice line continues into the 1900s (Figs. 3a, 4a, and 5a).

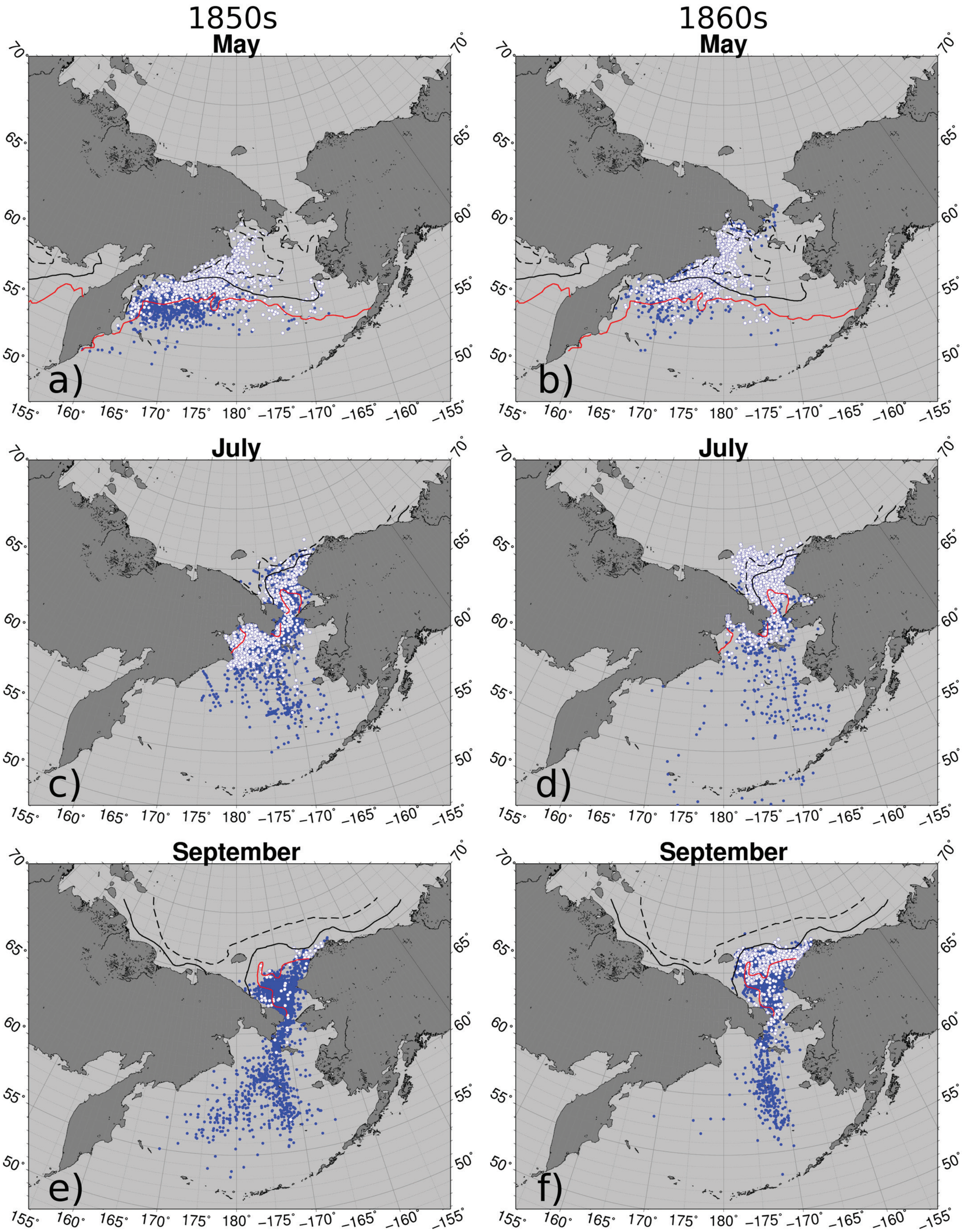

FIG. 3. Locations of ice observations made from whaling ships during May (a, b), July (c, d), and September (e, f) in the 1850s and 1860s. White dots show locations where ice was reported, and blue dots, those where no ice was reported. Red lines show the southernmost extent of ice reported in the NOC atlas for the period 1972–82. Black solid and dashed lines are the 20% and 40% mean ice concentration contours, respectively, for 1972–82.

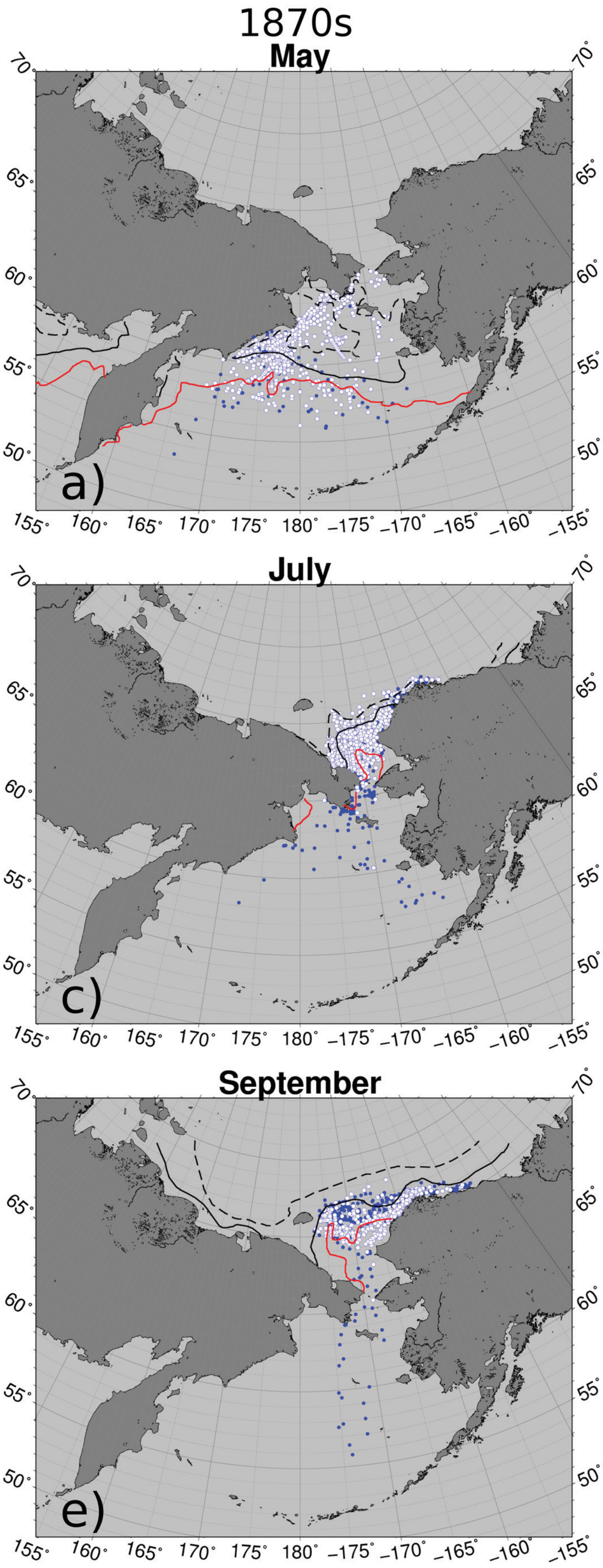

FIG. 4. Locations of ship-based ice observations during the 1870s and 1880s (details as in Fig. 3).

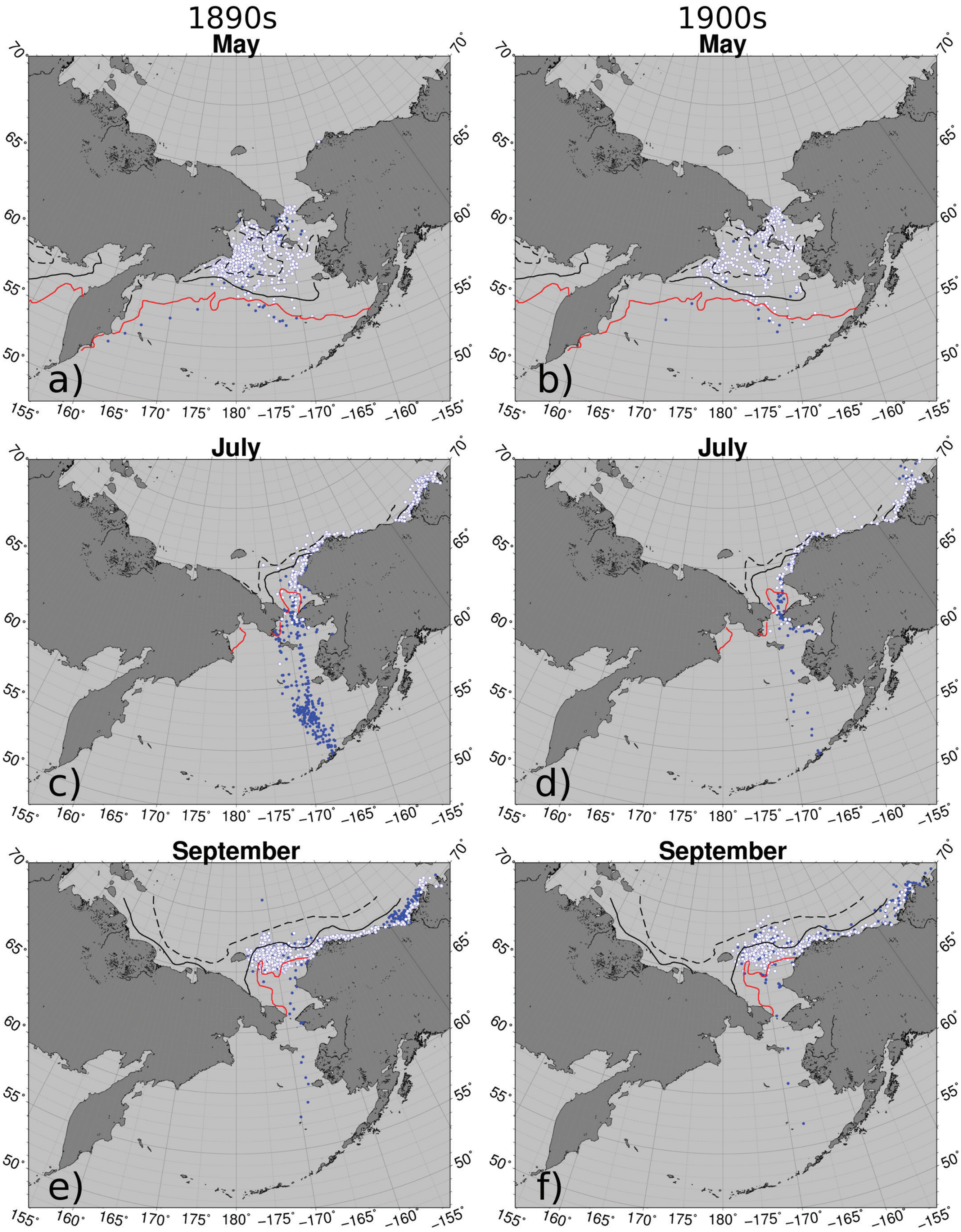

FIG. 5. Locations of ship-based ice observations during the 1890s and 1900s (details as in Fig. 3).

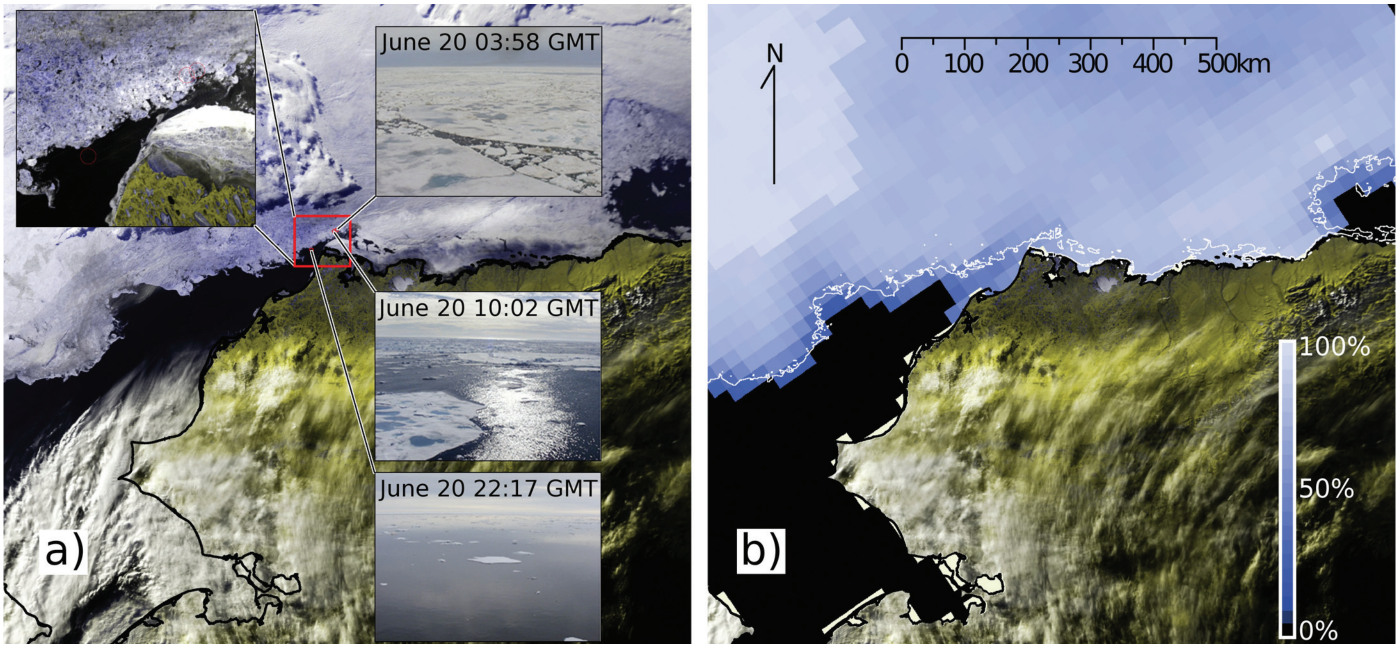

FIG. 6. a) False color Moderate Resolution Imaging Spectrometer (MODIS) image from 20 June 2004 showing the sea-ice edge in the Chukchi Sea. The inset at top left shows the area inside the red box in more detail. The three photographs were taken from the USCGC *Healy* at the locations and times indicated. b) A 25 km resolution sea-ice concentration grid for the same date derived from passive microwave data. For visual reference, the white line shows a threshold-derived ice edge from the MODIS imagery that is shown in panel a).

However, the number of ice observations south of the line decreases, suggesting some retreat of the ice edge later in the fishery. In July and September, the difference in the spatial distribution of the data before and after 1870 is much greater than in May. Whaling activity was concentrated in the Chukchi and Beaufort seas after 1870, and data from the Bering Sea are much more sparse (Figs. 4c, e and 5c, e). However, the available ship observations indicate a retreat of ice in the northern Bering Sea in the latter part of the record, which is most noticeable in July. During the period 1890–1909, there were few ship observations of ice-free conditions south of the 1972–82 zero-ice line except during July in the 1890s, when an unusually large number of vessels traveled between the whaling grounds in the Beaufort Sea and Dutch Harbor in the Aleutian Islands. This pattern was common in the 1850s, when ships would become full partway through the season. In the 1890s, however, it reflected the increasing scarcity of whales, which led some ships to give up on hunting during the spring season, while others headed south to search for right whales in the southeastern Bering Sea.

Reconciling Ship and Satellite Observations

A remarkable aspect of the ship data is their revelation of how far into the pack ice ships were sailing. The black solid and dashed lines in Figures 3–5 are the 20% and 40% mean ice concentration contours, respectively, taken from the NOC atlas. If the distribution of ice beyond the zero-ice line was similar during the time of the B-C-B fishery, then these whaling vessels, especially those with auxiliary power, could maneuver in ice concentrations of perhaps as much as 40%. Clearly, the bowhead whale was a prized resource at that time, and the distribution of whale sightings was closely related to the distribution of ice.

The degree of penetration by whaling vessels into the ice pack raises the broader question of how to interpret the location of present-day 0%, 20%, and 40% ice concentration contours shown in Figures 3–5 in relation to information contained in ship logs on the position of the ice edge or the presence of ice. Whereas the term "ice edge" refers to the demarcation between the open ocean and sea ice of any kind (WMO, 1970), it is often more appropriate to refer to the "marginal ice zone" as a transitional region, typically up to tens of kilometers wide, between the open ocean and the ice pack. Wadhams (2000) defines the marginal ice zone as the region over which penetration of ocean waves governs the size and geometry of ice floes. However, in the Chukchi and Beaufort seas, where limited fetch results in comparatively little generation of ocean swell, the width of the marginal ice zone is mostly governed by the impacts of winds, surface currents, and melt on the ice pack.

Here, we discuss the nature of the ice edge or marginal ice zone in the Chukchi and western Beaufort seas in the context of the historical logbooks and journals, using an example of the 2004 ice edge in the early and advanced melt season (Figs. 6 and 7).

The summer of 2004 was characterized by ice conditions representative of the 1990s and early 2000s in the Pacific Arctic sector (Shirasawa et al., 2009) and thus provides some insight into the nature of the ice edge and how to interpret ice conditions both from the perspective of ship-based observations and maritime navigation and from satellite remote sensing. Here, we rely on shipboard

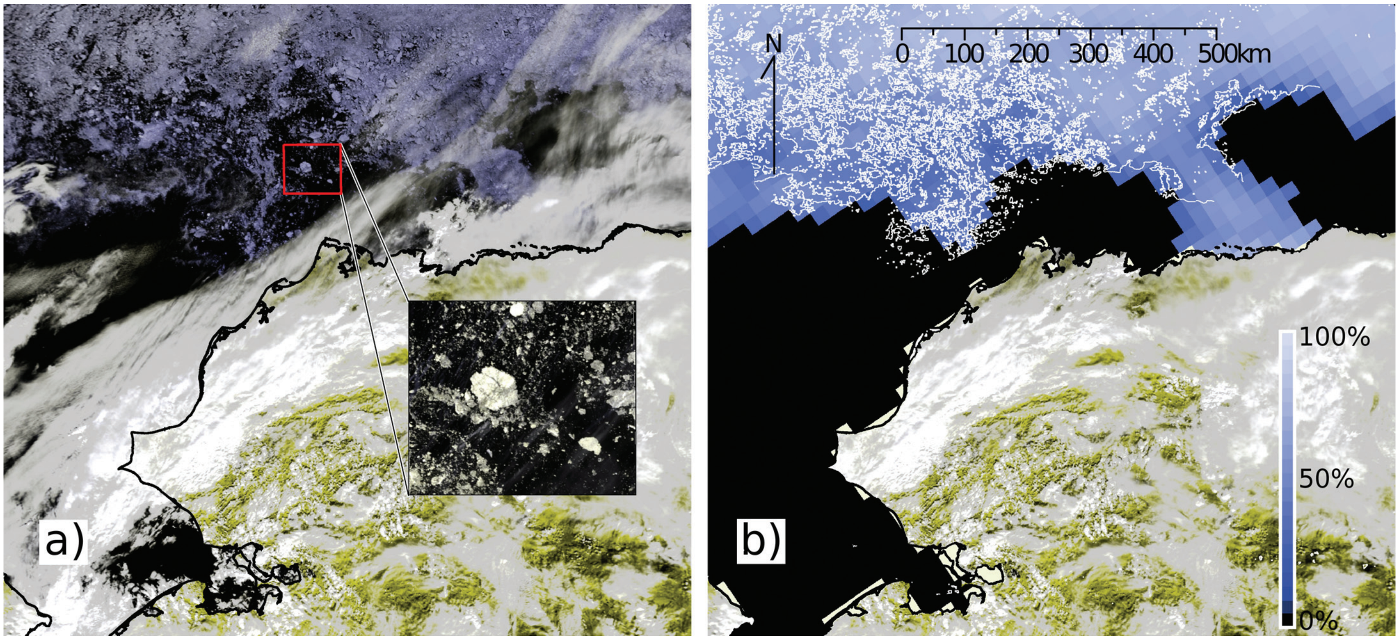

FIG. 7. a) False color Moderate Resolution Imaging Spectrometer (MODIS) image from 27 July 2004 showing the sea-ice edge in the Chukchi Sea. The inset shows the area inside the red box in more detail. b) A 25-km resolution sea-ice concentration grid for the same date derived from passive microwave data. For visual reference, the white lines show threshold-derived ice floe edges from the MODIS imagery shown in a). Clouds have been masked manually from the edge.

observations of ice conditions made during a scientific cruise of the USCGC *Healy* into the region, as detailed by Shirasawa et al. (2009). Figure 6a shows a typical example of a compact ice edge (20 June 2004), with a sharp transition from ice-free open water to very close (> 9/10) pack ice that ranges in width from a few kilometers to a few tens of kilometers. Conditions on this day were characterized by on-ice winds, comparatively slow rates of melt-related ice retreat, and moderate surface ocean currents responsible for minor fraying of the ice edge. Under such conditions, if positioning errors and other factors governing the accuracy of historical observations are taken into account, then the 0%, 20%, and 40% concentration contours coincide.

The passive microwave–derived ice concentration data shown in Figure 6b (data from Comiso, 1999) confirm this tight packing of the marginal ice zone, showing no ice present in concentrations lower than 30%. However, they also illustrate that because of the size of grid cells in such datasets (25 km), the 15% concentration contour (typically taken as the ice edge in studies of present-day ice climatology) can lie outside of the ice edge proper. For visual reference, the white lines in Figure 6b show an estimate of the ice edge location derived by arbitrarily thresholding the uncalibrated brightness values in the MODIS data shown in Figure 6a. Furthermore, "mixed pixels" comprising both ocean and land surface are often misclassified as ice, which explains the artifact of high ice concentrations south of the box highlighted in red.

Even in such a compact ice edge regime, vessels may have penetrated somewhat into the pack, taking advantage of bights (such as several features visible in the western part of the image), polynyas, or other openings in the ice that provided unimpeded passage for tens of kilometers into the pack (such as those apparent in the insert in the upper left of the satellite image). Bockstoce (1986:46–53) described how the whaling fleet took advantage of shore leads along the Russian or Alaskan coast, depending upon prevailing wind directions. Such features may explain log entries of "open water" (in particular under conditions of poor visibility that would not allow detection of ice several kilometers away) to the north of areas where sea ice was present.

Judging by the shipboard observations, it is highly doubtful that whaling vessels would have penetrated into the actual ice pack to locations such as that corresponding to the photo taken at 10:02 a.m., shown in Figure 6a. Logbook entries, shipboard experience on icebreakers, and operation of a small craft in ice-covered waters by one of us (J.R. Bockstoce) suggest that whaling vessels, in particular steam-powered vessels, may have penetrated to the 20% ice concentration contour and possibly to 30% or 40% ice concentration. The logbooks indicate that vessels often found themselves in denser pack ice, but this situation typically resulted from local ice convergence rather than from the efforts of the crew to move into the pack. Ships would generally avoid such heavy ice conditions because they would not only risk becoming ice-bound, but also find it difficult or impossible to carry out the hunt from the smaller whaleboats.

A much less compact ice edge, characteristic of a broader marginal ice zone, is shown for 27 July 2004 in Figure 7. As a result of ice retreat driven by melt and by the action of surface currents and winds, the ice is herded into bands or zones of higher (50% or more) and lower (well below 50%) ice concentration. Note, however, that the high-resolution insert shown in Figure 7a and the passive microwave satellite data shown in Figure 7b indicate that even within these lower-concentration zones, average ice concentrations often exceed 30%. Whaling vessels may have ventured some distance into such openings and reported open-water conditions within the ice pack (see, e.g., the mix of ice and open-water records for the Chukchi Sea apparent in Figure 3e, f). For the example shown in Figure 7, the width of this intermediate zone is around 100–200 km. However, given the distribution of ice within this zone, at least for the case shown here, whaling vessels may have penetrated only a few tens of kilometers under comparable conditions because of their limited navigability in ice concentrations above 20%.

The case studies discussed above suggest that even in cases of a diffuse ice edge, the ice concentration contours defining the ice edge from the perspective of historical whaling vessels still coincide with ice edges derived from present-day passive microwave data, which lends additional credence to the records analyzed in this study. While the apparent juxtaposition of open water and ice areas apparent in Figures 3 to 5 is largely due to combining observations from different years and days of the month into single diagrams, it can also be explained in part by the convoluted nature of the ice edge, which would have allowed whalers to penetrate some distance into the pack.

DISCUSSION AND SUMMARY

Between 1849 and 1914, the whaling ships of the Bering-Chukchi-Beaufort fishery collected a wealth of ice data, data which have become especially valuable in recent times as we try to understand more about sea-ice variation in the past. Observations from the 1850s and 1860s were most abundant. These data show that at that time, the winter maximum sea-ice extent was similar to that during 1972–82, but in summer the sea ice extended farther south than it does today. Comparison of the zero-ice line for the 1970s and early 1980s (Figs. 3–5) likely underestimates the amount of centennial-scale change in ice extent because whaling vessels were able to penetrate into the pack beyond the 20% to 30% ice concentration contour.

The difference between historical and modern ice conditions is greater in July than in September, which indicates a slower start to the melt season in the 1850s and 1860s. Earlier seasonal retreat has been linked to thinner ice in the Bering Sea (Clement et al., 2004), which may suggest that ice was thicker in the Bering Sea during the mid 19th century than during the 1970s and early 1980s, a period of above-normal ice extent for the 20th century (Niebauer, 1998).

There is some indication in the logbook record that ice conditions in the 1850s and 1860s were more severe than those in the latter part of the record, which more closely resemble the 1972–82 conditions shown in the NOC atlas. Contemporary analyses during the latter part of the fishery (Dall, 1882; Simpson, 1890) show ice edges in the 1870s and 1880s that were farther north than many ice observations in the 1850s and 1860s. This pattern agrees with observations of an Iñupiaq expert reported by Rochfort Maguire near Point Barrow in the early 1850s (Bockstoce, 1988:255, 413–419; see also Eicken et al., in press), which suggest that ice conditions were more severe before the mid-19th century.

After 1870, however, the whaling fleet had fewer ships, and whaling activity was concentrated at the ice edge. As a result, it is difficult to draw firm conclusions about interdecadal variability during the time of the B-C-B fishery. A more detailed examination of the contents of the logbooks, combined with more sophisticated data mining and statistical methods (e.g., Nisbet et al., 2009), would be necessary to confirm the pattern of variability during the fishery.

Although the nature of the whaleship record makes it difficult to ascertain changes in sea-ice conditions over the course of the fishery, we would expect that record to capture the occurrence of any year marked by a significant lack of ice. Scoresby (1820) noted that the abnormally extensive retreat of sea ice in 1817 had a significant impact on the success of the North Atlantic whale fishery. However, the logbook record of the B-C-B fishery gives no indication that any sea-ice retreat similar to that of 2007 occurred between 1850 and 1909.

Further research, including advanced spatial and temporal statistical analyses, will have to reconcile and synthesize these different findings. However, the present work does suggest that there is promise in a more detailed examination of spatial and temporal patterns of seasonal ice retreat within the study region. Thus, the fact that the largest differences in ice-edge positions appear to occur during the month of July mirrors findings from a small study examining May–June ice retreat in the Bering Strait region (Eicken et al., in press), which found earlier and more rapid seasonal ice retreat in the 2000s compared to the early 20th century.

We have far from exhausted the limits of the historical data. Should the logbook record be digitally transcribed in the future, we expect it would be possible to assess decadal-scale changes in sea ice that took place in the 19th century. As noted above, the logbooks also include relevant weather conditions, so that more detailed follow-up studies might therefore be able to link the potential for off-ice winds to promote a diffuse ice edge and at the same time affect the advance of sailing vessels into the ice. Further exploration of the whaling vessel records may also yield information on the distribution of open water and the state of the ice pack that will provide more insight into the changes we discuss here.

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