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Drift Velocities of Ice Floes in Alaska's Northern Chukchi Sea Flaw Zone: Determinants of Success by Spring Subsistence Whalers in 2000 and 2001

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ABSTRACT. By March each year, coast-influenced sea ice in Alaska's northern Chukchi Sea consists of the shorefast ice itself plus ice floes moving in a zone that extends from immediately beyond the shorefast ice to coherent pack ice, some 100 km farther offshore. Because westward-drifting polar pack ice encounters fewer landmasses (and less resistance from them) once it passes Point Barrow, a semipermanent polynya or flaw zone dominates coastal ice in this region. Iñupiat residents use open water in flaw leads to hunt migrating bowhead whales from mid-April to early June. Although Iñupiat hunters grasp the nature and importance of ice in motion beyond their horizon, the flaw zone has received less scientific attention than either shorefast ice or polar pack ice farther offshore. Synthetic aperture radar (SAR) satellite imagery is a form of remote sensing recently made available that allows us to address ice movement at a spatial scale familiar to traditional hunters. SAR-tracked ice movements differed between 2000 and 2001, illustrating contrasts between adverse and optimal conditions for spring whaling at Barrow. Case studies of ice-floe accelerations in the two contrasting seasons suggest that many variables influence ice motion. These include weather, seafloor topography, currents, sea-level changes, and events that occurred earlier during an annual accretion of ice. Adequate prediction of threats to ice integrity in the northern Chukchi Sea will require adjustments of our current concepts, including 1) recognizing the pervasive influence of the flaw zone; 2) replacing a focus on vessel safety in ice-dominated waters with an emphasis on ice integrity in high-energy environments; and 3) chronicling ice motions through coordinated ground observation and remote sensing of March-June events in future field studies.

Key words: Chukchi Sea, flaw zone, spring whaling, nearshore sea ice, ice motion

RÉSUMÉ. Quand arrive mars chaque année, la banquise soumise à l'influence de la côte dans la partie nord de la mer des Tchouktches de l'Alaska est formée de la glace côtière elle-même plus des floes en mouvement dans une zone qui s'étend de la lisière de la glace côtière au pack cohérent, à quelque 100 km plus au large. Vu que, une fois passée la pointe Barrow, le pack polaire dérivant vers l'ouest se heurte à moins de masses continentales (et donc moins de résistance), une polynie ou zone de séparation semi-permanente domine la banquise côtière dans cette région. Les résidents Iñupiat utilisent l'eau libre des zones de séparation pour chasser la baleine boréale sur sa route de migration de la mi-avril au début juin. Même si les chasseurs Iñupiat saisissent bien la nature et l'importance de la glace en mouvement au-delà de leur horizon, la zone de séparation a fait l'objet de beaucoup moins de recherches que la banquise côtière ou le pack polaire plus au large. L'imagerie satellitaire obtenue par radar à antenne synthétique (SAR) est une forme de télédétection toute récente qui nous permet d'étudier le déplacement de la glace à une échelle spatiale que connaissent bien les chasseurs traditionnels. Les déplacements de la glace suivis au SAR différaient en 2000 et 2001, illustrant le contraste entre des conditions défavorables et des conditions optimales pour la chasse printanière à la baleine faite à Barrow. Des études de cas de l'accélération des floes observée au cours de ces deux saisons où les conditions contrastaient, suggèrent qu'un grand nombre de variables influencent le déplacement de la glace. Celles-ci comprennent le climat, la topographie du fond marin, les courants, les changements du niveau de la mer et les événements qui ont eu lieu antérieurement durant une accrétion annuelle de glace. Pour prédire de façon satisfaisante les menaces à l'intégrité de la glace dans le nord de la mer des Tchouktches, il va nous falloir rectifier notre façon de penser actuelle, y compris: 1) reconnaître l'influence omniprésente de la zone de séparation; 2) changer l'accent de la sécurité des navires dans les eaux où domine la glace, à l'intégrité de la glace dans des milieux de haute énergie; et 3) enregistrer, lors de futures études sur le terrain, les déplacements de la glace en coordonnant les observations terrestres et la télédétection des événements ayant lieu de mars à juin.

Mots clés: mer des Tchouktches, zone de séparation, chasse printanière à la baleine, banquise côtière, déplacement de la glace

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INTRODUCTION

Arctic sea ice illustrates that the choice of a spatial scale over which to collect and analyze remote-sensing data is critical to the success of interpreting and predicting environmental processes. Before aircraft and satellites became available, an observer's distance to the visible horizon near Barrow, Alaska, was limited by the elevation of grounded pressure ridges in shorefast sea ice. Pythagorean logic shows that a hunter's eyes from atop the tallest known ice ridges (~13 m above sea level) cannot see surface features more than 15 km distant. Although hunters did return from misadventures on moving ice, and glimpsed distant ice motions through mirages and "ice blinks" reflected from clouds (cf. Pielou, 1995), these extensions of visibility were probably infrequent. Nevertheless, Iñupiat whalers along the northern Chukchi Sea coast of Alaska long ago developed descriptive terminology (cf. Nelson, 1969, 1982) for configurations and behaviour of sea ice in the flaw zone up to 100 km from land, that is, tens of kilometres beyond their normal horizon. A conceptual grasp of unseen events in distant moving ice must have been adaptive: hunters' success depended on occupying the narrow (~ 10 km) band of shorefast ice from which they staged late-winter activities, while at other times their survival depended on retreating to land when violent events threatened shorefast ice integrity (George et al., 2004, this volume).

Polar sea ice has become better understood since satellite imagery of high latitudes became available (cf. Shapiro and Burns, 1975; Burns et al., 1981). Remote-sensing data covering vast regions of the Arctic unknown to surface observers continue to reveal previously unknown features and processes (e.g., Bessonov and Newyear, 2002). Regional overviews of polar pack ice helped focus ship-based studies of pack ice during the Surface Heat and Energy Budget of the Arctic (SHEBA) project. One SHEBA study confirmed that stresses accumulating in the polar ice pack are proportional to the resistance to general ice motion by land features. To the west of Point Barrow, there is an abrupt interruption in landmasses resisting the westward motion of polar pack ice. Ice does not encounter resistance comparable to that offered by the Beaufort Sea coast until it meets Wrangel Island and the Siberian mainland (Richter-Menge et al., 2002). Paralleling Alaska's northern Chukchi Sea coastline lies a zone of divergence 100 km wide by 500 km long, in which the southern edge of westward-moving polar pack ice is released from stress upon passing Point Barrow (Fig. 1). This lee or divergence creates a semipermanent polynya or "flaw zone" (Martin et al., in press). In turn, the extensive open water in the alongshore flaw zone shaped both the spring migration route followed by bowhead whales (*Balaena mysticetus*) and indigenous peoples' development, by at least 2000 years ago, of ice-based hunting for bowheads in spring, as the whales pass Point Hope, Wainwright, and Barrow (Stoker and Krupnik, 1993). Dynamics of coastal sea ice

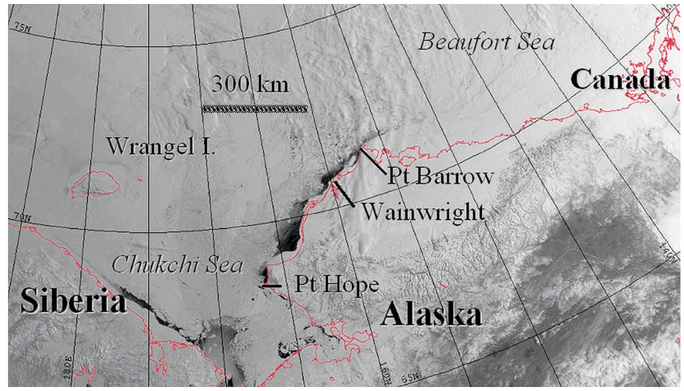

FIG. 1. Satellite Image (NOAA-AVHRR Channel 1, 15 May 2001 1717 hours GMT) showing Alaska's northern Chukchi Sea flaw zone as an extensive open-water (dark) area paralleling coast and shorefast ice, and extending approximately 500 km from northeast of Point Barrow to the southwest as far as Point Hope.

within 100 km of the Chukchi Sea shoreline thus furnish whalers with high-stakes opportunities each spring.

Concerns over risk-taking by modern Iñupiat whalers, who continue to hunt in flaw leads using skin-covered boats launched from shorefast sea ice (Brewster, 2004), led a team of investigators in 1999 to propose analyses of unusual past ice events within the recall of living coastal residents (Huntington et al., 2001, 2002; Norton, 2002; George et al., 2004, this volume). The project's rationale for reviewing and explaining the most dramatic (hence memorable to whalers) ice anomalies of recent decades was to refine concepts and tools for prediction of ice hazards, in the expectation that environmental change could increasingly destabilize coastal sea ice. To support this retrospective analysis of unusual events, the investigators arranged for access to several types and scales of archived satellite imagery.

The Human Dimensions of the Arctic System (HARC) initiative of the National Science Foundation's Office of Polar Programs supported the proposed analysis of six cases of anomalous ice events. In March 2000, however, during selection of specific case studies to be addressed at a sea-ice symposium six months later, the project adopted a more ambitious assignment. Russell Page of the National Weather Service (NWS), supported by whalers themselves, advocated substituting one real-time field study of coastal ice conditions for two retrospective case studies. Page is the one-person NWS Ice Forecast Desk, in Anchorage. He has worked tirelessly to extend NWS forecast capabilities from fishing- and shipping-based interests to those of Arctic subsistence whalers (Wohlforth, 2004). The advocacy of Page and the whalers persuaded collaborators that the approaching spring hunt for bowhead whales and the simultaneous counts of bowheads passing Barrow (~15 April to 1 June) should become a test of the predictive value of various environmental signals. Participants designed observations of spring sea ice to compare traditional (surface-based) with high-technology (remote-sensing) observations for monitoring conditions and predicting the safety of operations on coastal sea ice. In effect, the substitution of one real-time case study for two retrospective cases promoted the improvement of predictive understanding of coastal ice from an implicit to an explicit objective. The new objective in turn placed a premium on timely acquisition of satellite imagery, which had to be available at a sufficiently detailed scale to reveal ice features recognizable to subsistence hunters. Barrow whalers access their hunting sites by trails built over ice, outward from the beach, along a 50 km stretch of shoreline surrounding the community. They are placed as close to the outer edge of shorefast ice as is judged safe, at distances of some 3 – 15 km from shore. Our interest in following ice features of 0.1 km or less in diameter over distances of ~100 km matched the dimensions of subsistence hunters' familiarity, but these were novel dimensions for specialists in remote-sensing imagery for this region.

Most ice studies emphasize either the fine-scale (0.1 – 1000 m) mechanics of ice interactions with coasts and man-made structures (Weeks, 2001; Mahoney et al., in press), or regional and coarser scales (100 – 1000 km) for characteristics, motions, and deformations of polar pack ice (Kwok, 1998; Bessonov and Newyear, 2002; Richter-Menge et al., 2002). We focus here on a scale (1 – 100 km) intermediate between mechanical and regional emphases, and on motions of nearshore ice located seaward of the outer edge of shorefast ice in the northeastern Chukchi Sea.

Pioneering investigators in the 1970s laid groundwork for the present study, and covered part of the scale familiar to whalers, by tracking ice with 3 cm X-band marine radar from a 12 m tower on the Chukchi Sea coast near Barrow. They recorded ice motions year-round in prominent reflecting features or ice irregularities out to a distance of 5.5 km (3 nautical miles) offshore. The radar's CRT screen and a time-lapse 35-mm camera produced "motion pictures" that confirmed Iñupiat observers' accounts of the mobility of nearshore ice, both within and beyond the shifting outer edge of shorefast ice (Shapiro and Metzner, 1989; Shapiro and Barnes, 1991). Radar captured images through fog, severe storms, and winter darkness. By the mid-1990s, satellite-borne SAR (synthetic aperture radar) imagery extended weather- and daylight-independent views of ice out to hundreds of kilometres offshore, while preserving sufficient spatial resolution and frequent enough coverage to permit tracking of individual floes. Until the present investigation, however, this capacity of SAR imagery has not been used to measure ice velocities at locations, seasons, and scales familiar to subsistence hunters in northwestern Alaska.

Arctic coastal residents promptly adopt and master technologies ranging from internal combustion engines to global positioning system (GPS) satellite-assisted navigation. Recent developments have enhanced their access to remote-sensing information. Until recently, applications of satellite imagery were restricted to specialists with UNIX-based application programs for processing and viewing large digital image files. Now that use of the Internet has reached rural communities, members of whaling crews routinely acquire visual and thermal infrared images of sea ice and weather systems to share with captains and other crewmembers. Region-wide views of the Bering Sea and Arctic Ocean provide information about trends in the extent of pack ice and the orientation of its fractures and flaw zones near shorelines and shoals. Although the data on the Internet are of low resolution (1.1 km and 1.6 km pixel resolution), whalers find such region-wide overview images useful in planning their hunting activities from shorefast ice. The National Oceanic and Atmospheric Administration (NOAA) posts Advanced Very High Resolution Radiometer (AVHRR) imagery on the Internet both with and without interpretation. Ice-edge analysis from the Anchorage Forecast Office of the National Weather Service is refreshed on Mondays, Wednesdays, and Fridays. Annotated satellite analyses of sea ice are produced when clear skies and increasing daylight in spring allow these features to be observed (http://pafc.arh.noaa.gov/ice.php). Unannotated images of the Arctic Ocean and Alaska's other coasts are posted as frequently as viewable scenes are obtained. The lag between a NOAA satellite's acquisition of a view and its availability as a viewable Internet file can be less than 60 minutes.

For field verification of ice behaviour, however, we sought images with higher resolution than those available from NOAA, by obtaining SAR imagery of the northern Chukchi Sea, western Beaufort Sea, and adjacent perennial ice zone of the Arctic Ocean. SAR technology transmits pulsed microwave signals to the earth's surface and records patterns of reflected pulses. SAR images are independent of solar illumination and are not degraded by cloud cover. Unlike the thermal infrared bands of NOAA-AVHRR imagery, in which thermal distinctions between open water and ice diminish as ice warms in spring, SAR generally continues to distinguish water from ice surfaces. Although SAR's depictions of water, ice, and snow differ enough from reflectance in visible bands to confuse novices, the minute textural detail preserved in SAR images from surfaces of ice floes allows re-identification of individual floes in successive images even when they rotate or break, or when their outlines are reshaped by abrasion at their edges. Floes may be tracked for many months, depending on their location, size, and velocity, the scale and resolution (pixel size) of the images used, and the frequency of repeated satellite sensor passes (Kwok, 1998). The repeat cycle for RADARSAT imagery is 3 days for the Arctic region, typically 24 days for European Radar Satellite (ERS)-1, and 35 days for ERS-2 data. ERS-2 is situated 24 hours behind ERS-1, in the same orbit. Repeat local sampling, as with retrieval of any remote-sensing data, should be frequent enough to detect changes before they become catastrophic. Our analysis of late winter events took advantage of accelerated repetition of acquiring images near Barrow (from under one day to seven days, with a mean repeat interval of three days).

The objectives of this analysis are 1) to characterize the dominant regime(s), processes, and ice motions of the flaw zone in late winter between the outer edge of shorefast ice and the dense polar pack ice along Alaska's northern Chukchi Sea coast; 2) to describe departures from the dominant regime(s) and suggest causes for these excursions; 3) to relate ice events during the whaling season to the success of whaling and to risks taken or avoided by whaling crews; and 4) to identify prerequisites for effective ice prediction that would enhance public safety for subsistence hunters in the region who depend on stable late-winter conditions in coastal ice.

METHODS

A three-week closure of the alongshore lead in 2000, suspension of whaling from Barrow, and postponement of the bowhead count done every five years to the following spring caused us to repeat the shortened 2000 field test over a longer field season in 2001. This repetition allowed us to compare observations of ice dynamics in two successive whaling seasons.

SAR imagery covering each whaling period was acquired from the Alaska SAR Facility (ASF) at the Geophysical Institute of the University of Alaska Fairbanks. SAR images with 30 m and 100 m pixel resolution, respectively from ERS-2 and RADARSAT ScanSAR (Canadian Space Agency), were acquired through a data acquisition request processed by the ASF. The agreement permitted NSF-supported researchers to acquire two types of SAR imagery from polar orbiting satellite sensors. A near-real-time data acquisition request was also submitted to ASF in order to acquire promptly the Quicklook imagery of the Barrow study area captured by the Canadian Space Agency's RADARSAT sensor and the European Space Agency's European Remote Sensing satellites (ERS-1 and ERS-2). Near-real-time data acquisition was scheduled to coincide with the period when the maximum number of whalers and scientific observers would be on the ice hunting or counting bowhead whales (mid-March to mid-June.)

The digitized imagery was posted to an FTP server in Fairbanks and downloaded over the Internet in Barrow. Three hours usually elapsed between the capture of data by a SAR sensor and the posting of data to the FTP server by the ASF. The time to download the data from the FTP, depending upon access to a high-speed Internet connection in Barrow in 2000 and 2001, varied from 2 to 10 hours per image. Once an image was downloaded, it took 15 minutes to process it into a geo-referenced format for printing and export at lower resolution.

ERS has a spatial resolution of 30 m with a swath of 100 km. RADARSAT ScanSAR (wide) has a spatial resolution of 100 m with a swath of 500 km. The resulting data files posted to the FTP server vary in size from 64 to 258 MB. These large files require specialized software and powerful computers to process raw data into viewable imagery, so distributing them among sea-ice specialists is a challenge. We coped by reducing file sizes to what could be handled by Windows-based software such as Microsoft PowerPoint. The process included employing a generic binary import utility within ERDAS IMAGINE software, geo-referencing tools within ERDAS ArcView Image Analyst Extension, and the Environmental Systems Research Institute (ESRI) ArcView GIS 3.2. Researchers also participated in the Alaska SAR Demonstration project, which provided access to the SAR imagery via a Java-based Internet application known as the Web Image Processing Environment (WIPE). The interface required some training but proved to be a useful demonstration of near-real-time SAR applications. The SAR demonstration project was limited to accessing archived data and performing analysis with overlays of custom information. For this reason, it was still useful to obtain the raw data files from ASF to incorporate GPS-based ground validation information, bathymetry, shorelines, and whale migration data.

Analysis

The senior author analyzed ice-floe movements from georeferenced SAR images after their adjustment to suitable scales and orientations. Because ice floes disappeared from and then reappeared in the highest-resolution fields of view, it proved valuable to increase the sample size of resighted floes by working from a combination of 1:400 000 and 1:600 000 images. These scales span 80 km and 120 km, respectively, on the east-west axis of georeferenced views of the coastal ice. Full 500 km swath views (at a scale of 1:3 500 000) by RADARSAT ScanSAR were also inspected at 21- to 33-day intervals (February – June 2000 and March – June 2001) to compare velocities of ice features in polar pack ice with those of floes in the flaw zone. Identifications of second and further appearances of ice floes required many hundreds of hours to inspect and compare series of successive images.

Pattern recognition in resighting ice floes is challenging because radar reflectance ("brightness") can differ between sensors and as a function of a target's position relative to the satellite track's field of view on a given pass. The recognition of a displaced floe often required compensating for resolution and scale. Additionally, floes tended to rotate and fracture into smaller pieces, and their angular edges tended to become rounded through abrasion (cf. Norton, 2002). Attempts to use or adapt pattern-recognition software on moving ice floes were frustrated by these constraints. After all unambiguous repeat sightings of individual floes had been marked (and ambiguous repeats discarded), vectors were derived by plotting locations on an outline map of coastal features and bathymetry surrounding Barrow. A parallel ruler was used to transfer angular bearings from prominent coastal features in georeferenced SAR images of various scales to the same features on outline maps. From subsequent re-plotted floe positions and the resulting vectors, distances and compass directions of displacements were derived and then converted to 24-hour displacements ($km \cdot d^{-1}$) and hourly speeds ($km \cdot h^{-1}$).

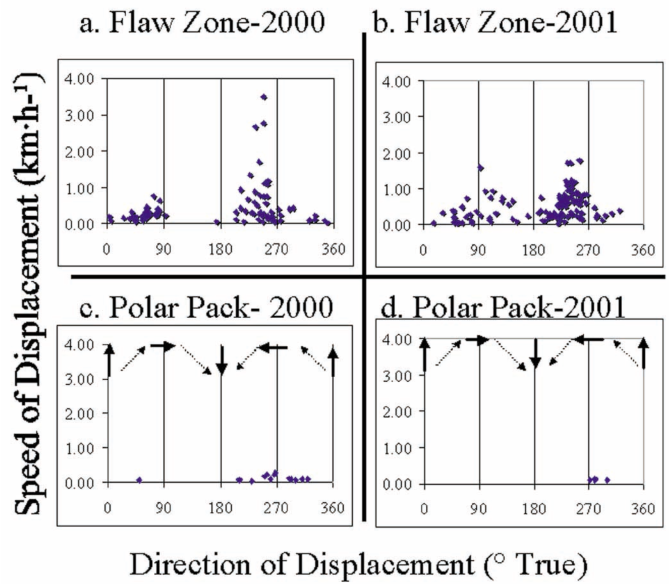

FIG. 2. Speeds and directions of resighted features in Chukchi flaw zone ice (a and b), and in polar pack ice farther than 100 km offshore (c and d) over two seasons of observations, 2000 and 2001. Solid and dashed arrows superimposed on c and d are not vectors, but visualisations of eight compass directions (N, NE, E, SE, S, SW, W, NW) corresponding to the compass bearings (degrees True) in a–d.

The velocity for each plotted floe displacement resulted from seven operations (four triangulations, drawing one line to connect points, and two measurements to calculate distance and direction of movement). Small accumulating errors of triangulation were estimated in relation to other sources of measurement and sampling errors (see Discussion).

After completing trajectories of moving ice floes for the two whaling seasons, we condensed the defining ice movements of those seasons into a chronology for each season. The seasonal chronologies were further distilled to a total of nine defining changes, or potential case studies of punctuations in the overall seasonal pattern, as Richter-Menge et al. (2002) distilled five months of ice movements within the polar pack. These defining punctuations were corroborated and interpreted by one or more of the following: surface observations from the ice near Barrow; National Weather Service Fairbanks Forecast Office's surface interpretive maps, archived at the Rasmuson Library, University of Alaska Fairbanks; NOAA Climate Prediction Center Reanalysis Project (http://wesley.ncep.noaa.gov/reanalysis.html) for reconstructed sea-level barometric pressures at six-hour intervals from 1950 to the present (cf. Norton, 2002); and visual and thermal infrared NOAA AVHRR satellite imagery, archived by the Alaska Data Visualization and Analysis Laboratory (ADVAL) at the Geophysical Institute, University of Alaska Fairbanks.

RESULTS

In 2000, SAR imagery within the flaw zone covered a span of 44 days (22 April to 4 June), during which 19 different floes yielded a total of 122 resightings. The most persistent moving floe was resighted 11 times over 25 days, during which time it reversed direction three times. Another floe first sighted on 22 April remained visible 44 days later because it had returned to the field of view from SW of Point Franklin and become incorporated into shorefast ice by 13 May. This floe was subsequently driven 15 km ENE into shallower water by a storm near Walakpaa, SW of Barrow, on 31 May and 1 June 2000. There was no complete break in the recorded tracks of individual floes (i.e., resighting of at least one ice floe threaded each SAR image to the preceding or next available image).

In 2001, SAR imagery spanned 100 days (18 March – 25 June), during which 56 ice floes were resighted a total of 129 times in the flaw zone. Because floes moved predominantly to the SW for much of the 2001 season, most passed only once through fields of view, so that persistence of individual floes was less than in 2000. The maximum persistence was a single floe's resighting seven times over 16 days. Four breaks in continuity of floe tracking occurred in 2001: between 21 and 24 March, 4 and 12 April, 15 and 20 April, and 22 May and 1 June.

Of 251 resightings of floes in the two years, 37 were of recognized floes that reappeared after being unidentifiable or drifting beyond any field of view for one or more satellite passes. A delayed resighting was treated as a newly sighted floe, useful only for subsequent velocity estimates when unambiguous resightings were made in the next available image. The remaining 214 displacements from two years of flaw-zone observations are compared to displacements of ice features resighted ($n = 17$) within dense pack ice (Fig. 2). Floe velocities in the northern Chukchi Sea flaw zone differ from those of polar pack ice. Floe motions in both regimes also differed between 2000 and 2001. In 2000, although floe motions to the ENE dominated, the highest speed attained by a floe was in the opposite direction (WSW). That floe moved 3.5 km·h^{-1} over a 14-hour interval between successive SAR images on 22 April 2000, or approximately 10 times faster than the polar pack ice moved (Fig. 2). In 2001, floes moved faster in brief episodes when their easterly direction was a reversal of the predominant WSW ice motion, and slower in the direction of that year's predominant motion. The directions in which floes moved fastest in the flaw zone are at approximately 70˚ and 250˚, close to those of axes of both the northern Chukchi Sea coastline and the Barrow Sea Canyon, whereas directions of polar pack ice motion cluster around true west (270˚), although these directions were more variable in 2000 than in 2001.

The tendency for either of two contrasting modes in velocities of ice moving in the flaw zone (Fig. 2) to persist may reflect constraints imposed by the similar axial orientations of the coast, the flaw zone, edge of shorefast ice, and the Barrow Sea Canyon. Occasional jumps between two nearly opposite states assume especial significance during the whaling season itself. Indeed, the

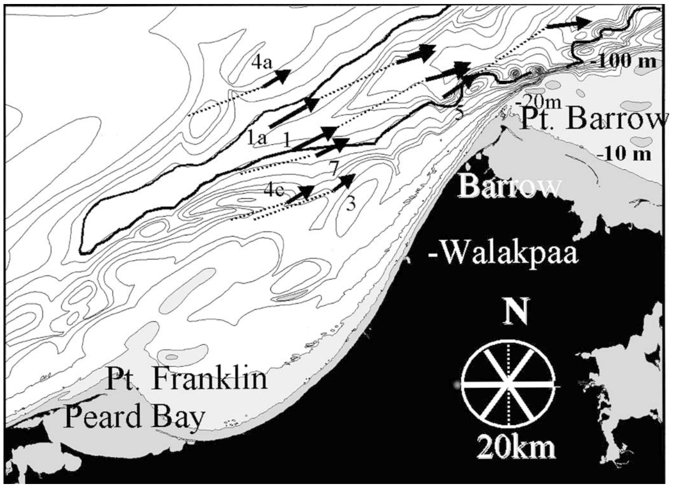

FIG. 3. 2000: Floe trajectories triangulated from SAR imagery during adverse conditions for whaling, when the alongshore lead was choked with ice. Vectors for ice floes tracked on 3–6 May and over part of a day on 13 May 2000. Numbers (1, 3, 4, 5, 7) are original parent floe designators. Lowercase letters (1a, 4a, 4c) denote fragments of larger floes with the same number. Solid arrows are vectors corrected to 24-hour displacements (km·day^{-1}), and dashed lines connect a floe's final position on 6 May with its initial position on 13 May. Thus floes 1, 1a, and 5 were tracked from 3 to 13 May; floes 3, 4a, 4c, and 7 were tracked from 6 to 13 May only. Scale of 20 km is shown as diameters at various angles within a circle for convenience in triangulating.

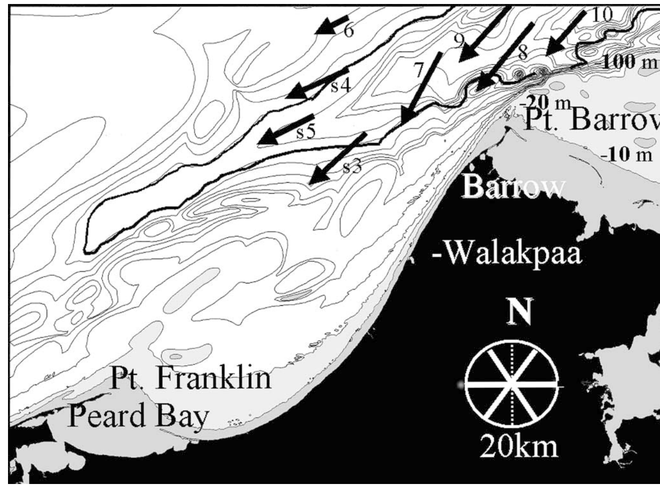

FIG. 4. 2001: Floe trajectories triangulated from SAR imagery during optimum whaling conditions, while the alongshore lead remained open. Vectors for ice floes resighted between 24 and 26 April 2001 are corrected to daily (km·day^{-1}) values. Numbers (6–10) are the original floe designators, as in Figure 3. Numbers with lower-case letter prefixes (s3-s5) designate tracked fragments of previously intact larger floes, 3–5.

highlights of a spring whaling season may be roughly captured as interplay between the opposing modes, as shown in the following two paragraphs that contrast ice motions in 2000 (Fig. 3) and 2001 (Fig. 4).

In 2000, a long period of generally NE wind and an open alongshore lead predominated from early March until 2–3 May. Then a SW wind regime set in for 21 days, closing the alongshore lead and depriving hunters of access to the peak passage of bowhead whales. The lead reopened on 24 May, but closed again when a violent storm brought SW winds to Barrow between 31 May and 3 June. Barrow crews landed only five whales in the abbreviated 2000 season. The persistent unfavourable ice movement for whalers is illustrated for the middle of this adverse period in 2000 (Fig. 3). Ice-floe trajectories from 3 to 13 May 2000 typify unsuitable whaling conditions, during which lead closure and movement of floes to the NE forced whalers to suspend on-ice activities for three weeks. Barometric pressures at sea level show 1) large, slow-moving low-pressure systems to the northwest of Barrow and 2) large, poorly defined high-pressure systems to the south. Winds and currents under this configuration of pressure tend to move in the same direction (i.e., from S and SW toward the NE).

In 2001, a favourable combination of conditions predominated from early April through 18 May, by which time Barrow whalers had reached their allotted quota of strikes and had landed 20 whales. Figure 4 illustrates the predominant local ice motions. Ice-floe trajectories from 24 to 26 April 2001 illustrate the middle of the period when the alongshore lead was steadily open, movement of floes to the SW, and other stable conditions conducive to whaling. Reconstructed barometric pressure maps at mean sea level for this period show 1) slow-moving or stationary high-pressure systems as a ridge that dominated the northern Chukchi Sea, Arctic Ocean, and western Beaufort Sea, and 2) low-pressure systems to the south, over the western Bering Sea, and over the Gulf of Alaska to the east. This relative position of anticyclonic and cyclonic systems produced steady NE winds in the northeastern Chukchi Sea, while the extensive high pressure may have suppressed any episodic surges of water northward through the Bering Strait arising from distant Bering Sea storms (cf. George et al., 2004, this volume). For a month after 21 May 2001, the motion of ice reversed from its whaler-friendly configuration so that ice moved to the NE, from the Chukchi into the Beaufort Sea. Because their whaling season had concluded early, however, this episode of adverse ice motion in 2001 was not of concern to Barrow's whalers.

Although outright reversals are striking, traditional subsistence hunters monitor less dramatic coastal ice accelerations, which are also detectible with high-resolution remote sensing (Norton, 2002). To follow the annual development of coastal ice, the whaling community begins tracking accelerations of ice floes in the fall preceding the spring hunt. Satellite imagery becomes useful for interpreting ice conditions to be faced by whalers no later than early March (6–7 weeks before the first whales arrive). Table 1 summarizes (in chronological order) nine episodes of ice acceleration, starting before and continuing through each of the two whaling seasons. The two ice seasons of 2000 and 2001 were to a great extent shaped by these changes (including the reversals noted above) in the movements of floes detected by SAR imagery in the flaw zone. Some accelerations (including decelerations and small angle changes in direction) were of short duration, but are included for their illustration of possible causal mechanisms.

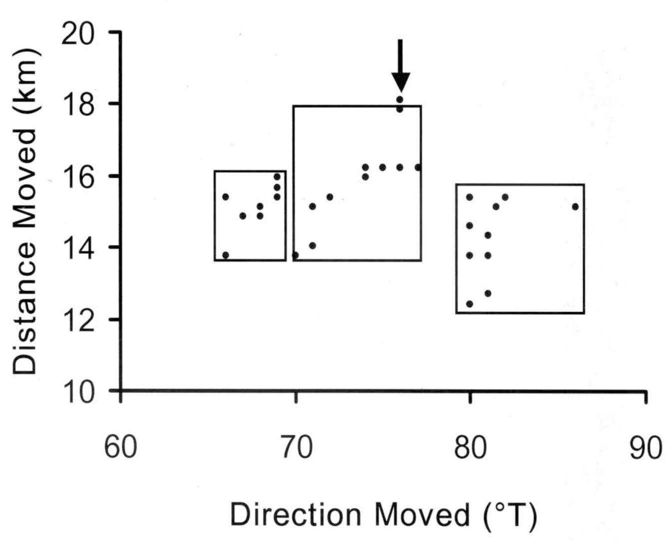

FIG. 5. Visual representation of errors accruing during triangulation of ice-floe locations. The displacements for three floes were measured and re-estimated 10 times. All but one of the 30 resulting points fall within non-overlapping sets, shown here within rectangles. Outlier (arrow) belongs within the rectangle to the left (see Table 1 for variance figures).

Two distinctions between 2000 and 2001 deserve notice because they are not represented as ice accelerations in Table 1. In 2000, the floes that passed Barrow were smaller than 12–15 km in their largest dimension, and passing floes rotated very little while in SAR views. In 2001, in contrast, floes exceeding 25–30 km in diameter were regularly observed from late March to mid-May, and these large floes tended to rotate clockwise as they moved to the SW along the Chukchi Sea coast past Barrow (Norton, 2002).

DISCUSSION

In the months of March through June, the variable trajectories of ice floes in the flaw zone of Alaska's northern Chukchi Sea distinguish this from other Arctic regions. The mobility of ice in the Chukchi flaw zone differs nearly as much from that of polar pack ice farther offshore as it does from the shorefast ice that forms the zone's variable landward boundary. Floes and pans accelerate dramatically in this flaw zone, especially if small and moving into open water, where impedance by other ice bodies is minimal. Impedance appears to increase the longer a wind regime persists. In both years of this study, the highest ice speeds were observed following reversals of direction. Thus, although floe displacement to the NE was dominant in 2000, highest speeds were achieved by floes moving in the opposite direction (SW) soon after their direction reversed. Similarly, ice motion toward the SW predominated in 2001, but whenever motion reversed, the result was relatively high-speed displacements toward the NE (Fig. 2a). Vigilance by whalers for any detectible changes in long-standing wind or current velocities at the outer edge of shorefast ice reflects generations of accumulated respect for the importance of such reversals.

Sources of Measurement Error

Because small errors accumulate in triangulating and transferring initial and final positions of a resighted floe from pairs of images to an outline map at a different scale, the reliability of velocity estimates reported here was assessed by repeating the operations ("bootstrap" strategy to a statistician). Positions of three ice floes that moved independently were triangulated from two successive SAR images onto outline maps, and the process was repeated 10 times to measure estimate variance.

The test for the degree to which errors in triangulation affect data in Figures 2–4 involved distance and bearing of motion by three ice floes that moved independently, in slightly different directions and distances, between 30 May and 4 June 2000 (Fig. 5). Of the 30 displacement estimates, 29 fall unambiguously within one of the three non-overlapping rectangles, each containing data from one ice floe. A single "outlier" velocity estimate (arrow in Fig. 5) could have been grouped incorrectly with the floe represented by the middle cluster of points (intermediate compass bearing) rather than that to the left (most northerly bearing). Table 2 summarizes the variance in distance and bearing estimates for these repeatedly sampled ice floes. Small, cumulative uncertainties arising from errors in mechanical operations used here to estimate ice-floe velocities from SAR imagery do not appear to undermine our conclusion that the Chukchi Sea flaw zone is extremely dynamic.

A larger source of error is that SAR-based vectors tend to underestimate maximum speeds attained by ice floes in the flaw zone. Some fast-moving floes almost certainly escaped re-identification by passing from a sensor's field of view before the next satellite pass. SAR imagery is well suited in spatial scale for documenting flaw-zone ice mobility, but the repeated SAR passes can be too infrequent to be ideal for detecting extreme ice velocities. Results from Richter-Menge et al. (2002) illustrate the problem of sampling frequency: the icebreaking ship supporting their SHEBA project moved a net distance of 575 km generally westward during the five months between 1 November 1997 and 1 April 1998. This value translates to 3.8 $km \cdot d^{-1}$ or 0.16 $km \cdot h^{-1}$. Because a given piece of ice (or the icebreaker itself) describes a course with numerous changes of velocity, the shorter the intervals into which that five-month period is divided, the greater the estimate of mean daily speed and the greater the maximum daily speed observed. When each of 151 daily icebreaker displacements is used to compute an overall mean speed, the resulting estimate is approximately double that of a single net displacement: 8 $km \cdot d^{-1}$ or 0.33 $km \cdot h^{-1}$ (Richter-Menge et al., 2002).

By analogy, had SAR ice images been available at six-hour intervals instead of at varying intervals with a mean of 72 hours, our maximum observed displacement speeds for ice floes in the flaw zone would be greater than the maximum of 3.5 $km \cdot h^{-1}$ recorded over a 14-hour interval between images on 22 April 2000 (Table 1). Floes less than

TABLE 1. Chronology of nearshore sea-ice events in 2000 and 2001, northern Chukchi Sea, grouped as nine punctuations (instances of accelerations or reversals in motion) exhibited by ice floes in the flaw zone.

Case #. Year: Inclusive hours and days (GMT)	SAR-supplied and other remote-sensing observations on ice-floe movements	Weather correlates from NWS surface condition maps and NOAA reconstructions	Surface or other remote-sensing data on the event
#1. 2000: 0400 h 20 April to 1800 h 22 April	Ice-floe velocities reach maximum of 3.5 $km \cdot h^{-1}$ at a WSW heading of 240˚ T	Persistent low over Gulf of Alaska, with stationary high NW of Barrow; strong NNE winds	Alongshore lead opens, floes not impeded
#2. 2000: 0000 h to 2000 h 25 April	Floes moving SW from Beaufort Sea meet floes heading NE in the Chukchi Sea; alongshore lead fills with floes off Barrow	Weak winds at Barrow, but low drifting E over Kamchatka and high-pressure ridge over Aleutians produce strong S winds at Bering Strait.	First of several floe reversals; lead closes, later opened again until 3–4 May 2000
#3. 2000: 0000 h 2 May to 1200 h 3 May	Sudden reversal of floes, from heading SW to heading NE	Two low-pressure systems influencing S winds at Bering Strait; High pressure NE of Barrow breaks down	Alongshore lead closes for three weeks; whaling suspended until last days of May
#4. 2000: 0400 h 30 May to 1200 h 2 June	Open alongshore lead closes violently, causing grounded ice to move up to 18 km ENE and into shallower water (shoreward)	Deep low in northern Bering Sea and another that develops NW of Barrow 31 May to 1 June bring peak winds moving through from SW to NW	Recently opened lead closes again and shorefast ice shears along crack after whalers retreat to land
#5. 2001: 1800 h 20 March to 2200 h 22 March	Reversal of floe direction, lead closes briefly, first add-on to floating shorefast ice	Stationary moderate high-pressure system E of Barrow produces steady SSE wind along Chukchi Sea coastline; floes move ENE and stick to fast ice	First add-on to persist through whaling season; small floes involved in add-on
#6. 2001: 0400 h 31 March to 0400 h 4 April	Another reversal of floe direction; second add-on to shorefast ice completed in this interval	Erratic low N of Wrangel Island stalls, weakens, W winds drop by 2 April; Strong low moves from SW Bering to NE, bringing SE winds by 4 April; falling water strands add-on	Second add-on is multi-year ice, consistent with W winds that separate ice floes from pack ice; again small floes grafted
#7. 2001: 0400 h 8 May to 0400 h 11 May	Brief partial reversal of floe direction in SW sector (near Peard Bay) from SW to NE; Peard Bay floe seen pivoting from shore N of Point Franklin	Combined weak high pressure N of Wrangel Island and weak low over mainland Alaska produce E winds at Barrow, gradually shifting to SE, producing short reversal	AVHRR images show large floes breaking loose in the Beaufort Sea between 8 and 11 May; mostly sitting idle
#8. 2001: 0300 h 15 May to 2200 h 17 May	General change in floe displacement direction from NW to SW	Weak E wind regime slowly shifts to stronger NE wind regime with low-pressure system to SW of Barrow and high pressure to NE.	Cyclonic motion of sea ice over Barrow Canyon by end of 17 May
#9. 2001: 0000 h 21 May to 0400 h 22 May	Peard Bay floe breaks free; Contradictory ice-floe movements: at Point Franklin moving NE, but across Canyon moving SE (converge on Canyon)	Low-pressure cell over the central Alaska Beaufort Sea draws W, S wind flow, then weakens; Chukchi ice motion into Beaufort persists for several more days	Visual Band AVHRR shows local wind field and shift; large floes keep moving into the Beaufort Sea

10 km in diameter might reach speeds as great as 5 $km \cdot h^{-1}$ in strong winds. In the 1970s, shore-based radar tracked ice floes (of unrecorded diameter, but probably < 0.1 km) that attained maximum speeds of 8.3 $km \cdot h^{-1}$ during an episode of high winds that peaked at 130 $km \cdot h^{-1}$ for about three hours (L.H. Shapiro, pers. comm. 2003).

A Revised Perception of Alaska's Northern Chukchi Sea Flaw Zone

Whalers describe shorefast ice as part of the three-dimensional coastal ice system that accumulates and records the effects of various events throughout each ice season (Huntington et al., 2001; Norton, 2002). They regard the nearshore ice system as having a "memory" in the sense that the integrity of a given section of shorefast ice reflects the accumulated effects of various processes. Thus variations in ice thickness, strength, roughness, brittleness (tendency to shatter), and extent of grounding on the seafloor are results of processes that may have occurred at any time since the beginning of the ice-growth season the preceding October. This concern for the integrity of shorefast ice should not obscure whalers' appreciation of the flaw zone. In contrast to the Beaufort Sea east of Point

TABLE 2. Variance in measurements of ice-floe displacements (km, ˚True) for three grounded floes that were floated and shoved ENE by the storm of 31 May to 3 June 2000. The figures given are the results of 10 repetitions of vector estimations (see also Fig. 5).

Value	Distance 1	Distance 2	Distance 3	Bearing 1	Bearing 2	Bearing 3
Minimum	13.78	13.78	12.43	66	70	80
Mean	15.49	15.70	14.27	68.7	73.6	81.3
Maximum	18.11	17.84	15.41	76	77	86
SD	1.10	1.18	1.08	2.83	2.46	1.83

Barrow, small ice floes in the Chukchi flaw zone occupy a zone beyond shorefast ice that is 50–100 km or more wide. The Iñupiaq term *sarri* ('ice pack') may be precisely stated in English as "moving ice beyond shorefast ice." Reimnitz et al. (1978) introduced the widely adopted graphic representation of continental shelf ice (= shorefast ice + pack ice) in Alaska's Beaufort Sea (cf. Norton and Weller, 1984). Our findings make it appropriate to regard nearshore ice regimes in the Chukchi Sea as substantially different from those in the Beaufort.

We offer a diagrammatic conceptual revision of the coastal ice (= shorefast ice + highly mobile ice in the flaw zone) specific to late winter–early spring in Alaska's northern Chukchi Sea (Fig. 6). The alongshore flaw lead is represented in its two dominant, opposing configurations. These views acknowledge the width of the semipermanent flaw zone, the northern boundary's proximity to Point Barrow, the shelf break, the Barrow Canyon, the adjacent Beaufort Sea, and the local interruption to unrestricted ice movement by Hanna Shoal (Barrett and Stringer, 1978). Our intent with the two-part schematic concept of Chukchi Sea coastal ice is to suggest the spatial scale over which further inquiry into forecasting configurations of flaw-zone ice will be most productive.

In addition to differences illustrated by the two views of ice configuration in this zone (Fig. 6), flaw-zone ice differs qualitatively in motility from the relatively coherent motions of pack ice beyond 100 km to the west and north of Barrow (i.e., clearly beyond the dynamic flaw zone). Units or sectors of ice within the polar pack, or perennial ice zone, have been followed for more than a year. The gradual distortion of an initially rectilinear grid denoting an extent of polar pack ice in the Western Arctic during 14 months of drift resembles a sheet of cloth being rotated, slowly rumpling and stretching as it makes a quarter turn in the polar gyre's clockwise movement (Kwok, 1998). SAR images of polar pack ice north and west of Barrow in 2000 and 2001 likewise contained many features resighted between March and June, but their motions were so coherent that calculating more vectors within this 100-day period adds little scatter of points to the variability shown in Figures 2c and 2d. By contrast with pack ice, ice floes in the Chukchi Sea flaw zone move independently. Consistently clockwise rotations by large (> 25 km) floes moving to the SW past Barrow in 2001 illustrate this independence of movement. These rotations further suggest that forces acting on the nearshore edges of large floes behave differently from those acting on offshore edges. Offshore edges may be resisted by more continuous and slower-moving ice and by shallower depths on the far side of the Barrow Canyon. Nearshore edges of rotating floes may be moved faster by stronger currents flowing through the deepest part of Barrow Canyon.

Ice-Forecasting Challenges Illustrated

Even when causes behind ice motions become better understood than they are today, predicting sea-ice behaviour in northern Alaska will inevitably continue to run the paired risks that all forecasters face: failing to detect and predict hazardous conditions on the one hand, and spreading unwarranted alarm on the other. Having demonstrated here two seasons' extreme dynamism and variability by ice motion in the Chukchi Sea flaw zone, we are more impressed than ever by the challenge of forecasting ice safety in this region. Essential ingredients for successful prediction will undoubtedly include 1) understanding the end-users' (whalers') needs for information, advisories and warnings; 2) picking the "right" signals; and 3) following the signals over the appropriate spatial scales.

Safe spring whaling depends on shorefast ice that by late winter has grown thick, and through collisions with moving ice, has been deformed, overridden, rafted, piled, and ridged sufficiently to anchor the fast ice to the seafloor in places. Shorefast ice ideally should not contain too much brittle multiyear ice, lest it shatter when struck by moving ice. Whalers' dependence on the stability of grounded and floating ice means that their information needs differ fundamentally from those of commercial fishers, shippers, and offshore petroleum operators, all of whom regard most floating ice as ranging between a nuisance and a hazard to operations. Any ice forecasts addressed to whalers will necessarily emphasize different concerns and parameters from those issued to vessels. It is essential for future ice forecasters to appreciate the preferences of whalers, as Russell Page, NWS ice-forecasting pioneer, has shown (Wohlforth, 2004). If whaling crews could script the annual ice cycle, for example, they would schedule all violent high-energy meteorological and oceanographic events in the months before whales return from the Bering Sea (October to April). From mid-April to June, however, whalers would permit only benign conditions to prevail—NE winds, uninterrupted by reversals or surges in winds, currents, or ice motion—to keep the alongshore flaw zone accessible to boats (Fig. 6a).

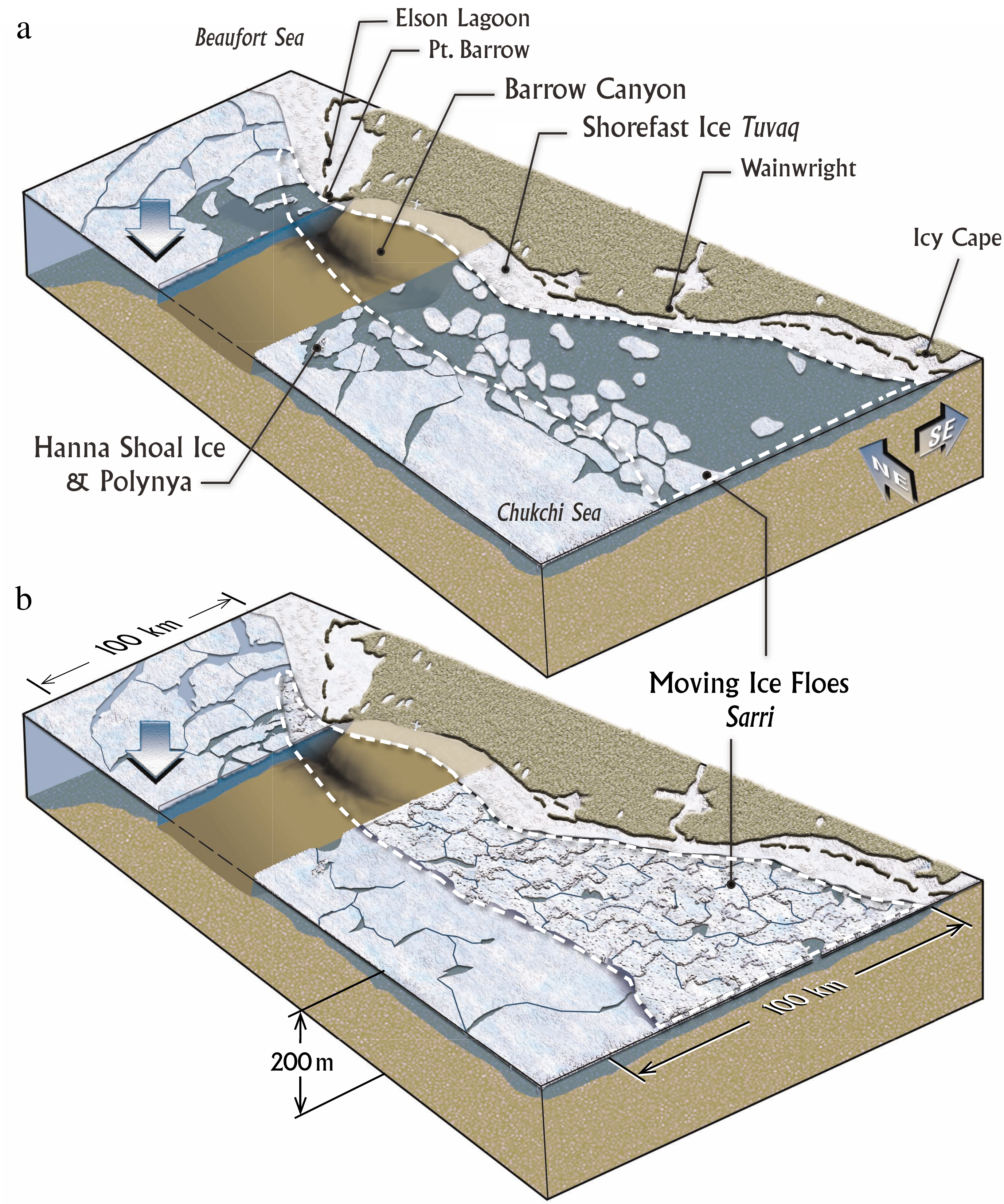

FIG. 6. Diagrammatic representations of the two dominant ice regimes experienced by spring subsistence whalers in Alaska's northern Chukchi Sea flaw zone from Icy Cape to the western edge of the Beaufort Sea northeast of Point Barrow. A dashed white line indicates the northern half of this flaw zone, and the de-watered cutaway is intended to emphasize the shape and orientation of the Barrow (subsea) Canyon. Note: vertical scale is exaggerated 100 × horizontal scale. a) Optimal conditions: Ice floes move southwestward (after leaving the influence of the westward motion of polar pack ice in the Beaufort Sea depicted by the arrow in the upper left corner). The alongshore lead(s) remain passable to whalers' small boats, a state that persisted through most of the 2001 spring season; b) Adverse conditions: Ice floes move northeastward, congesting alongshore leads and denying whalers boat access. These conditions persisted for 22 days at Barrow in the middle of the 2000 spring whale migration.

Once they occupy the ice, spring whalers particularly dread two types of high-energy events. These are destructive override (Iñupiaq = *ivu*) and breakoffs (*uisauniq*) of shorefast ice. Huntington et al. (2001) and George et al. (2004, this volume) suggest that both hazards can follow rapid changes in sea level. Rises in sea level are sometimes credited to distant S and SW winds that push a surge of water northward through the Bering Strait. Such surges near Barrow may be strongest when unopposed by high barometric pressure to the north of Barrow. Override may take place during a surge, whereas a drop in sea level may trigger breakoff events—the whalers' *katak* ('to fall') explanation—especially if a drop follows a rise in level. Breakoffs and override have occurred without warning, under locally benign weather conditions. To protect whalers from these events, forecasts may have to be generated from an expanded region of observations during spring whaling, so that weather patterns causing changes in sea level can be linked predictively from the Bering Sea to the Beaufort Sea, as well as verified with ground observations for a number of years.

In neither 2000 nor 2001 did extreme ice events take place under locally benign conditions. Events in Table 1 are all accelerations in ice motion. Several accelerations in each of the two field seasons were outright reversals in pre-existing ice motions, meteorological conditions, or both. Whalers' reactions to reversals (ranging from heightened alertness to full retreat from landfast ice) suggest that ice forecasts should emphasize reversals and their magnitude. Three cases drawn from Table 1 are treated below as potential ice forecast alert situations, to illustrate the range of reactive strategies that can be taken by whalers and the challenges inherent in predicting ice motions in this region.

Potential Alert Situation 1: Ice forecasts issued by Russell Page, regional weather forecasts issued by Fairbanks and Barrow NWS offices, and local surface observers agreed sufficiently to persuade all whaling and scientific crews to retreat from the ice on the last day of May 2000 (Case 4, Table 1; cf. Norton, 2002). The Ice Forecast Desk's concerns were first communicated to the Alaska Eskimo Whaling Commission in Barrow as an advisory on 26 May and revised over subsequent days. A long crack appeared in shorefast ice near Barrow on 28 May, running parallel to shore along the 30 m isobath. Over the next two days, whenever they ventured seaward of that crack, whalers and biologists left radio-equipped observers behind to watch for changes in crack width where their trail crossed it. Meat from the last whale landed was sledded ashore across the crack without mishap by early 31 May. As predicted by the Weather Service, peak 45 $km \cdot h^{-1}$ WSW winds accompanied a storm that lasted from 31 May through 2 June. During the storm, a surge probably lifted grounded pressure ridges, after which violent onshore motion by drifting ice shattered a band of shorefast ice by driving some of its outer features 13–18 km to the ENE and closer to shore (Fig. 7). Destruction of shorefast ice by shearing—lateral displacement of outer shorefast ice along the crack paralleling the shore—combines characteristics of both *ivu* (override) and *uisauniq* (breakoff). This high-energy destruction would have threatened the lives of any crews attempting to weather the storm on shorefast ice beyond the 30 m isobath. At best, crews would have had trouble finding safe routes back to shore across a 200 m wide band of floating rubble (ice ground into fragments too small to float beneath the mass of a person or a snow machine).

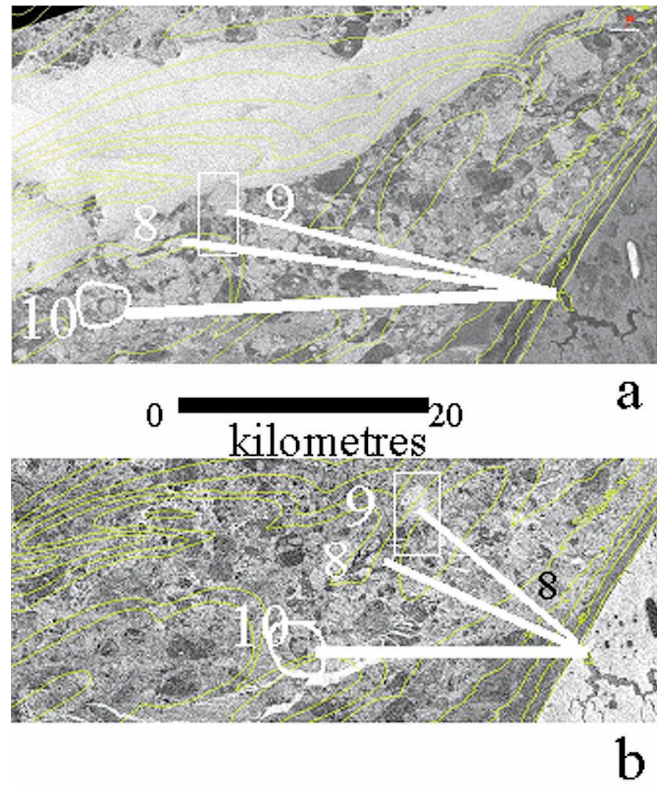

FIG. 7. Ice Alert Situation #1 (see also Table 1, Case 4) during which whalers and scientists retreated to land when both ice and weather forecasts predicted unsafe conditions: a) Three immobile, probably grounded, ice floes (8, 9, 10) within shorefast ice as they appeared in SAR imagery on 30 May 2000 (ERS2 Scene E2_26714_STD_179, © ESA, 2000); b) The same three floes on 3 June 2000, after the violent storm of 31 May to 2 June had floated and shoved outer shorefast ice 13–18 km east-north-eastward into shallower water creating a shear zone of destruction in shorefast ice at about the 30 m isobath (RADARSAT Scene R1_23904_SWB_185, © Canadian Space Agency, 2000). These images and floes were used in bootstrap estimations of variance and sources of error arising during triangulation to estimate floe velocities; see Fig. 5 and Table 2.

In this case, the National Weather Service addressed safety warnings specifically to the whaling community well in advance. Ground observations of the weakened sheet of shorefast ice reinforced remote-sensing indicators, and everyone on the ice returned to land as soon as the predicted storm began to be felt.

Potential Alert Situation 2: Shorefast ice integrity was never threatened as seriously in 2001 as it was by the storm that sheared ice and terminated the whaling season in 2000. On the other hand, violent events preceding 2001 spring whaling did enhance shorefast ice and did affect the whaling season. A sequence of events recorded in SAR and AVHRR imagery between 19 March and 4 April 2001

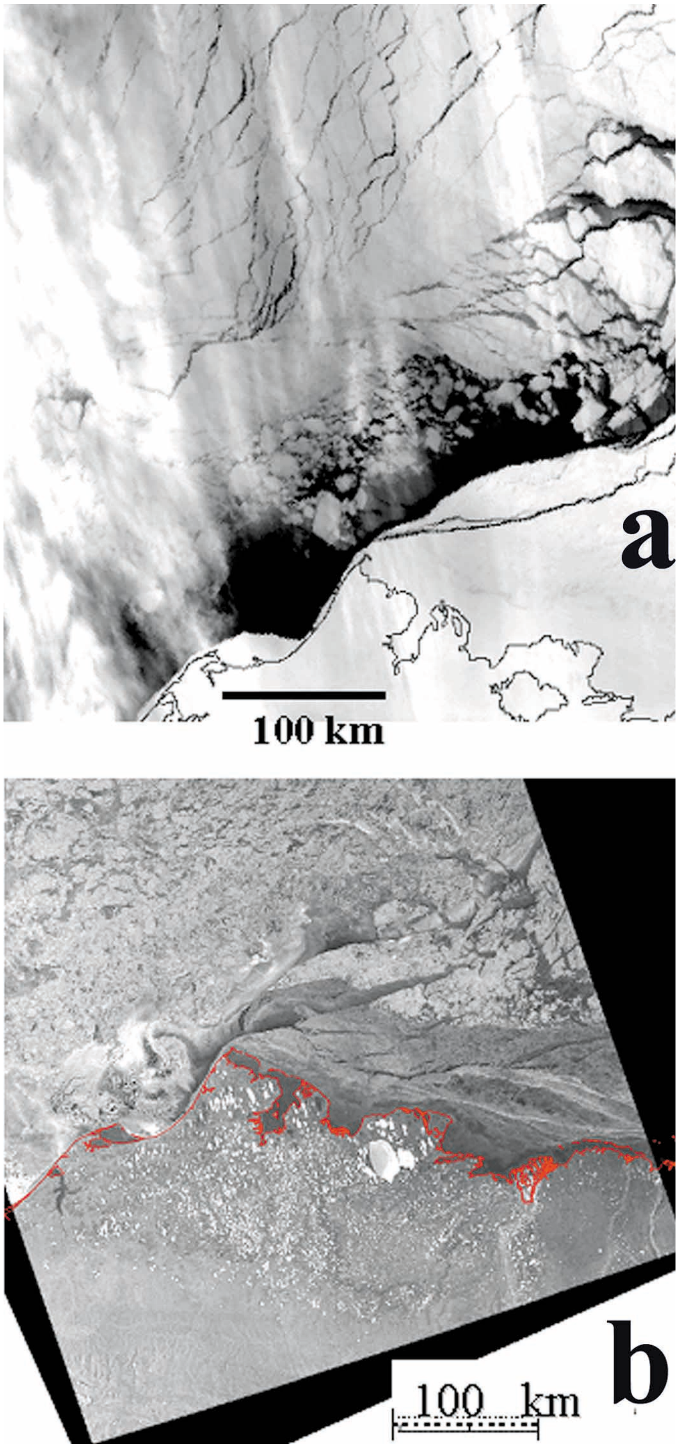

FIG. 8. Ice Alert Situation # 2 violent preliminaries (see also Table 1, Cases 5 and 6). a) 2001, 19 March, 0029 hours GMT, NOAA AVHRR Thermal IR Band image: an especially extensive (150 km long) breakoff of shorefast ice in the Beaufort Sea northeast of Point Barrow is in progress, coincident with an unusually large proportion of open water in the same region. b) 2001, 21 March 0335 hours GMT, RADARSAT Scene R1_28063_SWB_180 (full swath), © Canadian Space Agency, 2001: A surge of Chukchi Sea water appears to be headed northeast toward the Beaufort Sea near Point Barrow. Upon meeting opposing current west of Barrow, this surge becomes a counterclockwise swirl marked by many small (~1 km) floes and fragments of ice. Note that the long sections of Beaufort Sea ice seen cracking in Fig. 8a have continued to move offshore, and will later appear as large floes in the Chukchi Sea flaw zone.

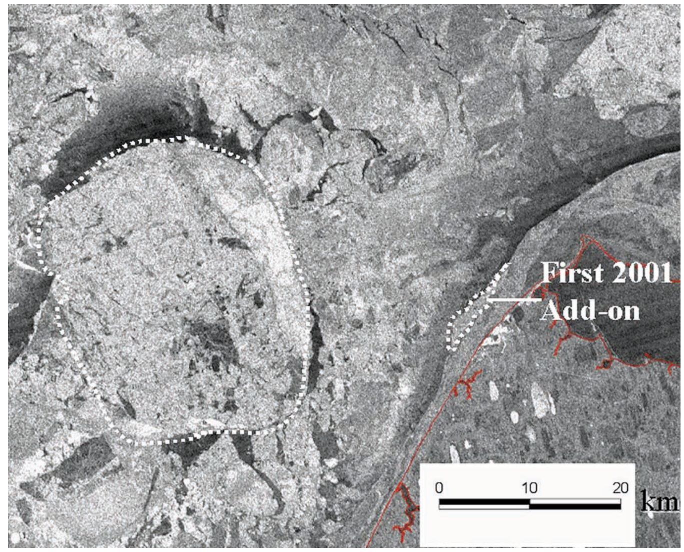

FIG. 9. Ice Alert Situation # 2 continued. 2001, 31 March 0342 GMT, RADARSAT Scene R1_28206_SWB_181, © Canadian Space Agency, 2001: The year's first add-on (*iiguaq*) to shorefast ice is outlined with a dashed line as a 10 km long sliver opposite the community of Barrow. Also highlighted with a dashed line is a large floe (25 × 35 km) moving southwestward, while rotating clockwise—note the open water being left to the north of this floe as it spins. This large floe did not contribute the add-on, because imagery from 28 March shows this floe still NE of Point Barrow with the add-on already in place (Norton, 2002).

bracket two episodes (Cases 5 and 6, Table 1) of moving ice being grafted to the outer edge of shorefast ice near Barrow. A period of strong E winds at Barrow ended when a high-pressure system weakened offshore of the Mackenzie River delta, and a deep low-pressure system moved northward over the Sea of Okhotsk on 18 March. By early 19 March, winds at Barrow were blowing from the SSE. NOAA-AVHRR thermal infrared imagery shows that the alongshore flaw lead became unusually wide and long, extending more than 100 km to the NE into the Beaufort Sea (Fig. 8a). The 19 March image also shows a crack that had developed in Beaufort Sea shorefast ice, extending from just N of Point Barrow to more than 150 km ENE of it. About 48 hours later, a surge of water from the SW had entered the alongshore lead. A 21 March ScanSAR image viewed full swath (Fig. 8b) shows this surge as a counterclockwise eddy marked by numerous small ice floes NW of Barrow. This image also shows that long strips of Beaufort Sea shorefast ice had continued to break and move away from land along a series of easterly running fractures. The first *iiguaq* (floating add-on) or *ivuñiq* (grounded pressure ridge) added to shorefast ice in 2001, which was in place by 24 March, appears to have resulted from the surge shown in Figure 8b, when the Chukchi flaw lead completely filled with small ice floes. The cause of the surge itself is unknown, but handwriting on the archived Fairbanks Forecast Office weather map (20 March 2000 surface analysis) specifically remarked, "Wshift 1830 Z" at Wainwright some nine hours before the surge was detected by the SAR image. For the following 30 hours, winds at Barrow remained ESE "10 knots,"

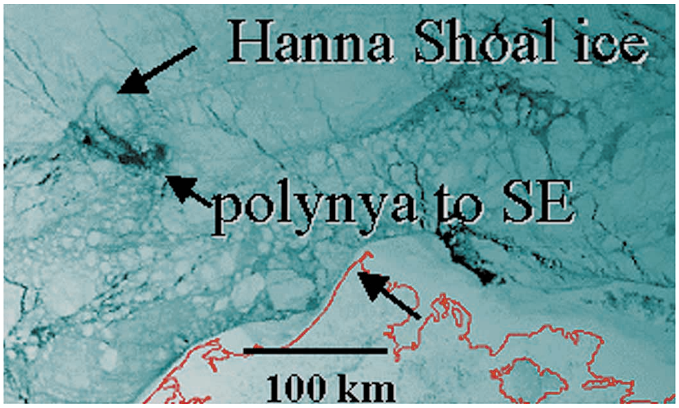

FIG. 10. Ice Alert Situation # 2 continued. 2001, 3 April 0125 hr GMT, NOAA-AVHRR Thermal IR image: An unusual direction of ice motion toward the southeast is indicated by the open water showing to the southeast of the Hanna Shoal ice pileup. The unlabeled arrow points to the first add-on seen in Fig. 9. A swarm of floes smaller than AVHRR resolution limits (1.6 km) lies between this shorefast ice and the Hanna Shoal polynya.

while Wainwright surface winds continued from the W at similar speeds.

The next noteworthy SAR image in this sequence, from 31 March, shows the location of the first 2001 add-on (Fig. 9). Immediately to the W of this add-on is a rounded ice floe 25–35 km in diameter that is rotating clockwise as it moves toward the SW. SAR images from 24 March and 28 March both show this floe still north of Point Barrow at a time when the first add-on was in place (Norton, 2002). Without those images, the large rotating floe could be suspected of having collided with shorefast ice and leaving the ice that remained as *iiguaq*. Instead, it appears more likely that the first add-on involved collisions of small (< 1 km diameter) floes with the shorefast ice. Smaller fragments of ice, which accelerate more rapidly when winds and currents change direction, may be the primary shapers of shorefast ice in late winter. As further evidence that small pans were involved in 2001, clear weather permitted a sharp NOAA-AVHRR image from early on 3 April (Fig. 10). The unusual position of the Hanna Shoal polynya to the SE of the shoal itself suggests that ice motion toward the SE was taking place at the time of the second 2001 add-on, during a period when only small (< 1 km) ice floes were in a position to impinge on shorefast ice. NOAA satellite imagery, however, lacks the resolution necessary to identify the small floes that we suspect were grafted to shorefast ice by 4 April (Fig. 11).

Whalers and biologists rarely camp overnight on shorefast ice before bowhead whales start moving past Barrow. Alaska's Ice Forecast Desk is fully engaged in helping Bering Sea commercial fishing vessels avoid ice hazards in March and April, so that the NWS has not attempted anticipating conditions that graft moving ice onto shorefast ice. These add-ons are nevertheless important to whalers. Remote sensing (at SAR resolution) and surface observations of grafting processes could furnish information of especial value to ice forecasting in general. The two ice add-ons in this example were heavily used and

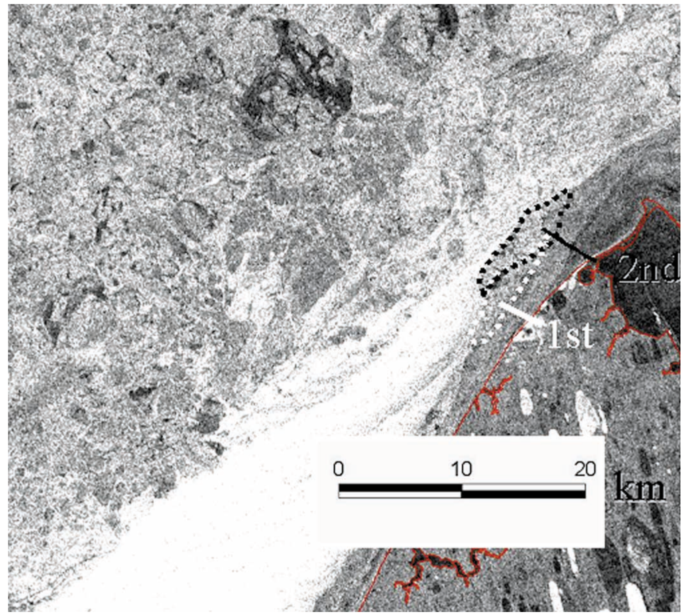

FIG. 11. Ice Alert Situation # 2 concluded. 2001, 4 April 0325 hr GMT, RADARSAT Scene R1_28263_SWB_181, © Canadian Space Agency, 2001: The second add-on of the 2001 whaling season is now in place in this view, and it will remain in this position until at least early June.

occupied during the whaling of 2001. Camps for several whaling crews, a "perch" for counting whales visually, and most of the year's array of passive acoustic sensors used to detect and locate vocalizing whales passing Barrow were positioned on these adjacent *iiguaq* (add-ons).

Potential Alert Situation 3: On 11 May 2001, the NWS Forecast Office detected in NOAA-AVHRR imagery (NWS Forecast Offices lack routine access to SAR imagery) a 30 km × 15 km piece of ice in early stages of detaching from shorefast ice just offshore of Peard Bay (cf. Fig. 1). As soon as the Anchorage office shared its concerns about this large ice pan with Barrow whalers, we accelerated the schedule for downloading SAR imagery in Barrow to monitor motion of the Peard Bay floe. Whaling camps near Barrow seemed to be threatened. Superimposing georeferenced SAR images on bathymetry, however, soon made it clear that the shallows under the southwestern quarter of this pan (Fig. 12) held the ice, so that its other (ungrounded) end only swung offshore and onshore like a hinge. Eventually, on 19–20 May, most of the floe broke free of the shoal, after which it moved slowly alongshore toward Barrow. By 23 May, the floe had broken into several smaller fragments, as it ceased to be recognizable in SAR or NOAA imagery. No significant collisions with occupied shorefast ice were recorded.

Once the limited mobility of this large ice floe became apparent, several days before whaling concluded (on 18 May), whalers' concern over it dissipated. Because this large piece of ice in shallow water gained little momentum, the calving of shorefast ice from shallow water to the SW of Barrow seems to be an improbable source for threats to Barrow whalers' camps on shorefast ice. Like the add-on events above, this event suggests that floes large enough to be

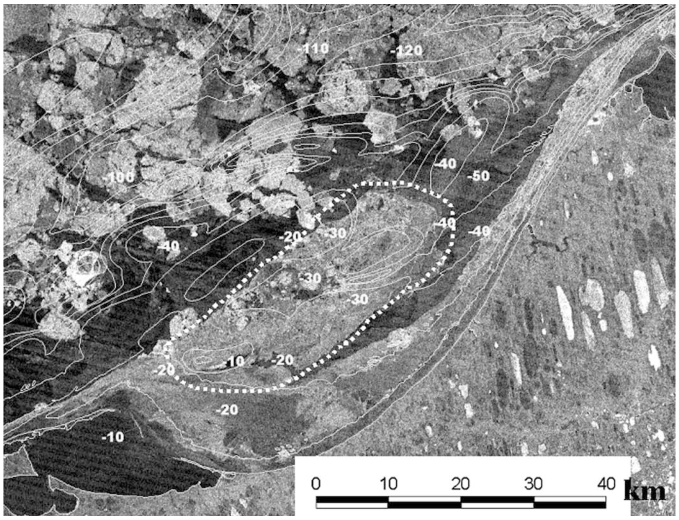

FIG. 12. Ice Alert Situation # 3 (see also Table 1, Cases #7–9). Highlighted is the ice floe measuring 15 × 38 km that partially detached from shorefast ice north of Peard Bay. It was first detected on 11 May by the National Weather Service's Alaska Forecast Office on NOAA-AVHRR imagery (see Fig. 1). The floe is here shown a week later (18 May, 1719 GMT, RADARSAT Scene R1_28900_SWB_266, © Canadian Space Agency, 2001) at about the time Barrow whalers reached their seasonal quota of whales struck. For 10 days this floe failed to break free from shoals reaching to within 10 m of the surface at its southwestern end. It finally detached on 21–22 May and began moving NE, but disintegrated before reaching the locations of Barrow whalers' ice camps.

individually recognizable in NOAA-AVHRR satellite imagery do not contribute as much to destructive and accretive processes in coastal ice as smaller pieces of ice do.

CONCLUSIONS

Precisely because the dynamism of drifting ice makes nearshore systems from Point Hope to Point Barrow so daunting to surface observers, the flaw zone in Alaska's northern Chukchi Sea deserves increased scientific attention. Its dimensions (500 × 100 km) qualify the zone as one of the major polynya systems in the Arctic. Science, however, has left observation and interpretation of this system's late-winter ice regime largely to Iñupiat whalers and other coastal residents (Harritt, 1995). Trans-cultural collaboration and interpretation of Arctic phenomena are otherwise common in this region. Collaboration began locally during Lieutenant P. H. Ray's Expedition to Barrow for the first International Polar Year, 1881–83 (Ray, 1885). Since the Ray Expedition, whenever researchers have exchanged concepts with Iñupiat observers, rewards have been levels of synergistic understanding that enhance confidence in the results by both participating communities (Albert, 2001; Kassam and the Wainwright Traditional Council, 2001; Norton, 2002; Brewster, 2004; Wohlforth, 2004). An early and momentous outcome of this synergism was the Pacific Steam Whaling Company's decision to establish a station at Barrow in the 1880s to facilitate hunting bowhead whales from shore and shorefast ice in the manner of Iñupiat whalers (Bockstoce, 1986). In this context of wide-ranging collaboration with Arctic residents, the absence of scientific focus on ice in the flaw zone is conspicuous. Ice researchers have long found it more feasible to investigate distant polar pack ice than the moving ice floes closer to research support facilities such as the Naval Arctic Research Laboratory and the community of Barrow. Beginning with Nansen's transpolar drift in the ice-strengthened vessel, *Fram*, in the 1890s (Weeks, 2001), motions by polar pack ice have attracted increasingly sophisticated scientific inquiry, so that the gap between scientific familiarity with polar pack ice and that with ice in flaw zones has steadily widened.

Whalers regard balancing risks against opportunities as the key to hunting successfully and safely from the ice, but now perceive that ongoing secular changes in environmental conditions have eroded the confidence with which they anticipate risks to nearshore ice integrity (Norton, 2002). Recent advances in instrumentation and remote-sensing technology have improved the prospects for successfully tracking oceanographic, meteorological, and ice development events despite hazardous conditions of the Chukchi flaw zone. Until now, scientific neglect of an intriguing subject could be excused as avoidance of the genuine risks of losing instruments, vessels, and observers.

During this project, we expected to assess the predictive value of water column data provided to surface observers by two pressure sensors ("tide gauges" used in 2000 and 2001) and one current meter installed on the seafloor through shorefast ice (2001). Our optimism proved to be naive: changes in sea level recorded by the pressure sensors could not be linked unambiguously to the single loss of shorefast ice integrity experienced in two whaling seasons, and the mechanical current meter loaned to the project failed to record under-ice currents reliably. Even if all instruments had worked, only a longer series of observations (e.g., over a minimum of five whaling seasons) might have persuaded us of the value of one or another oceanographic parameter to ice forecasting.

Gradually it became evident that a more fundamental revision in thinking about coastal sea ice was needed before quantitative evaluation of oceanographic or other predictors would make sense. In 2001, in the middle of our second field season, while attempting to reconstruct the direction that ice moved during the destructive storm of 31 May to 2 June 2000 (Potential Alert Situation #1, above), we first noticed that archived SAR images of the event could reveal drift velocities of ice floes in the flaw zone. That lesson was soon reinforced by using SAR images to track the Peard Bay floe detected by the NWS Forecast Office on 11 May 2001, which might have threatened whalers' ice camps near Barrow (Potential Alert Situation #3, above). Not until we had reconstructed the entire sequence of ice motions in both whaling seasons, however, did the importance of ice drift become obvious. Even then, evidence that ice floes so often reversed directions at first strained credulity. Whalers, however, confirmed that reversals in ice drift were common, and reminded us of their depictions of ice floes rotating and moving "like a hinge" against or away from shorefast ice. Repeated boardings of the derelict Canadian supply ship *Baychimo*, over the first three years after her abandonment in ice off Peard Bay in the autumn of 1931 (Greist and Cook, 2002), also confirm that floating objects have been known to drift back and forth many times through much of this flaw zone. The last reported sighting of this "ghost ship of the Arctic" off Alaska in 1969 (http://www.theoutlaws.com/unexplained8.htm, 21 April 2004) signifies that some floating objects are not incorporated into the Transpolar Drift of polar pack ice. Therefore they can have long residence times in the region of the Chukchi Flaw Zone.

We hope that by distinguishing Alaska's northern Chukchi Sea flaw zone fundamentally and semiqualitatively from other coastal ice regimes, such as that of the Alaskan Beaufort Sea, this analysis of drift velocities contributes the sort of scientific clarification that Akasofu (2001:174) articulated in connection with his contribution to aurora studies as scientifically a "…new development [that] is, by definition, qualitative." Ideally, our analysis will stimulate others to pursue the goal of extending regional ice-forecasting capabilities.

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