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Location and Areal Extent of Polynyas in the Bering and Chukchi Seas

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ABSTRACT. AVHRR imagery has been used to document the sites of 22 polynyas in the Bering and Chukchi seas. Two principal classes of polynyas have been identified that tend to be negatively correlated: 1) persistent polynyas, which are present much of the time and form off south- and west-facing coasts, and 2) north coast polynyas, which are only occasionally open and form off north-facing coasts. Median extent values characterizing 17 of these polynyas for six years have been compiled for the winter and spring months, and the results of attempts to correlate these values with synoptic meteorological measurements are reported. These attempts were not very successful, suggesting that more sophisticated approaches to the problem are required. Other factors, such as currents, may play a principal role in determining actual polynya extent.

Key words: polynya, sea ice, Chukchi Sea, Bering Sea, AVHRR imagery, statistics, location, area, wind, temperature

RÉSUMÉ. Des images prises au radiomètre perfectionné à très haute résolution ont fourni de l'information sur l'emplacement de 22 polynias dans la mer de Béring et la mer des Tchouktches. On a identifié deux classes principales de polynias, qui tendent à avoir une corrélation négative: 1) les polynias persistantes qui sont présentes la plupart du temps et se forment à partir des côtes orientées vers le sud et vers l'ouest, et 2) les polynias de la côte Nord, qui ne s'ouvrent qu'occasionnellement et se forment à partir des côtes orientées vers le nord. On a compilé les valeurs médianes de l'étendue caractérisant 17 de ces polynias pendant les mois d'hiver et de printemps sur une période de six ans. On rapporte les résultats d'essais de corrélation entre ces valeurs et les mesures obtenues en météorologie synoptique. Les essais n'ont pas été très concluants, ce qui donne à penser qu'il faudrait aborder le problème de façon plus complexe. D'autres facteurs, comme les courants, pourraient jouer un rôle majeur dans la délimitation de l'étendue réelle des polynias.

Mots clés: polynia, glace de mer, mer des Tchouktches, mer de Béring, images prises au radiomètre perfectionné à très haute résolution, statistiques, emplacement, superficie, vent, température

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INTRODUCTION

Polynyas are mesoscale areas of open water or thin ice that are found at predictable, recurrent locations in sea ice-covered regions at times and under climatic conditions where one would expect the water to be ice covered. There are generally considered to be two types of polynyas (Smith *et al.*, 1990): latent heat polynyas (also referred to as mechanically generated or wind-driven polynyas) and sensible heat polynyas. Latent heat polynyas occur in regions where sea water is at the freezing point. Heat loss to the atmosphere leads to ice formation rather than to additional cooling of the water column. Therefore, in order for a polynya to form, the ice that forms must be physically removed from the region by some combination of winds and currents — hence the terms "mechanically generated" and "wind-driven" polynyas. Sensible heat polynyas occur where sea water is above the freezing point and sufficient oceanic heat is available to the water surface to prevent ice from forming. The upward heat transfer can occur through vertical mixing of heat from deeper water or through upward advection of heat by upwelling (Smith *et al.*, 1990). Smith *et al.* (1990) note that these two mechanisms are not mutually exclusive and both can contribute to the maintenance of a polynya. Smith *et al.* (1990) identify those polynyas that form off the south-facing coastlines in the Bering and Chukchi seas as latent heat polynyas.

Transfer of heat and water vapor to the atmosphere from the open water surface of polynyas can lead to local climatological modifications (Martin and Cavalieri, 1989; Smith *et al.*, 1990). The study of these phenomena has been stated to be complimentary to and to contribute to present and planned international programs addressing global change and climatic interaction (IAP^2, 1989). Polynya formation affects the salt balance of the sea water and contributes to the formation of distinctive water masses in the Arctic Ocean (Martin and Cavalieri, 1989). These processes are sometimes accompanied by a conveyer-belt-like generation of sea ice (McNutt, 1981; Schumacher *et al.*, 1983). Polynya formation can be a phase in the pattern of breakup or meltback of the ice edge (Stringer and Groves, 1985; Paquette and Bourke, 1981). The open water of the polynyas is important habitat for migratory waterfowl and marine mammals (Stirling and Cleator, 1981). They are also suspected as being sites of relatively high primary productivity (IAP^2, 1989). The location and timing of polynya formation can be important for shipping and other economic activities, such as petroleum extraction operations.

Earlier work on polynyas suggested the feasibility of using AVHRR (advanced very high resolution radiometer) imagery to document the date of appearance and disappearance of polynyas for the Bering and Chukchi seas, as well as to quantitatively determine polynya areas and relate these areas to climatological data.

Dey *et al.* (1979) describe the use of AVHRR imagery for monitoring and mapping sea ice freeze-up and breakup and a method of rectifying AVHRR images. Dey (1980) describes the use of thermal infrared images for monitoring North Water, a polynya located in northern Baffin Bay, for the months of November through January. These studies concluded that AVHRR thermal infrared images are admirably suited for generalized statistical analysis of sea ice and that boundaries between first- and multi-year ice and open water can be mapped more reliably than boundaries between open water and thin ice.

Smith and Rigby (1981) state that the timing of freeze-up and formation of polynyas, the size of polynyas at maximum ice cover and the pattern of ice breakup and disappearance are important factors for understanding ecological relationships. Using AVHRR visible and infrared imagery, Landsat imagery and weekly ice composition maps from the Ice Climatology

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and Applications Division of the Canadian Atmospheric Environment Service, they studied 16 polynyas occurring in the Canadian Archipelago between November and July for 1975, 1976 and 1977. They reported only broad dates for formation and disappearance of the polynyas and gave no quantitative measurements of the areas.

Carleton (1980) mapped the polynyas south of the Pt. Hope–Cape Thompson area (R, S, Fig. 1; Table 1) using Landsat imagery. Finding that he was able to differentiate between open water and thin ice on the polynyas' surfaces, he calculated areas for both the open water and thin ice regions and related their total size to wind and temperature measurements recorded at the synoptic weather station at Kotzebue, located 250 km southeast of the study site.

Stringer (1982) measured the width and persistence of the Chukchi polynyas (T, V, Fig. 1; Table 1) during late winter and spring for the years 1974-81 using Landsat and AVHRR imagery. The Chukchi polynyas can extend from Cape Lisburne to Pt. Barrow, generally extending seaward from just beyond the landfast ice. A qualitative correlation was noted between average ice motion away from the coast and the mean vector wind for all months except perhaps July. The winds here have a strong offshore component throughout most of the period studied.

Pease (1987) concluded that for the St. Lawrence Island (D) and Seward Peninsula (P) polynyas (Fig. 1; Table 1), air temperature appears to have a larger effect on polynya size than wind speed for winter conditions.

Using mesoscale meteorological networks and Defense Meteorological Satellite Program (DMSP) imagery, Kozo *et al.* (1990) successfully predicted the lengths of polynyas forming off the lee shores of St. Lawrence Island (D), Nunivak Island (G) and St. Matthew Island (A). These authors observed an apparent 24 hour time lag between the onset of a geostrophic wind and the appearance of windsock-shaped polynyas at these islands.

Certain statistical or modeling studies (e.g., Carleton, 1980; Pease, 1987; Kozo *et al.*, 1990) have addressed the short-term response of polynya size to meteorological variables such as wind or air temperature over a period of a few days. Other studies (Schumacher *et al.*, 1983; Martin and Cavalieri, 1989) have concentrated on the monthly or seasonal impact of polynya formation on the production of distinctive water masses. The International Arctic Polynya Program (IAP^2, 1989) considered polynya formation as a factor in global change.

By making numerous determinations of polynya size for the months of January through June over six years for most of the polynyas that could be identified in the Bering and Chukchi seas, we hoped to use the power of the central limit theorem to achieve two goals: 1) derive some quantitative and statistically valid measure of monthly polynya areal extent for each polynya, and 2) use this measure and synoptic meteorological variables readily available at the synoptic weather stations at St. Paul Island (approximately 600 km due south of St. Lawrence Island), Nome, Kotzebue and Barrow to establish a relationship between meteorological variables and polynya size for four polynyas, the St. Lawrence Island (D), the Norton Sound (K), the Kotzebue Sound (Q) and the Chukchi (T). Such a relationship would be useful not only for explanations of the present effect of polynyas on such processes as brine

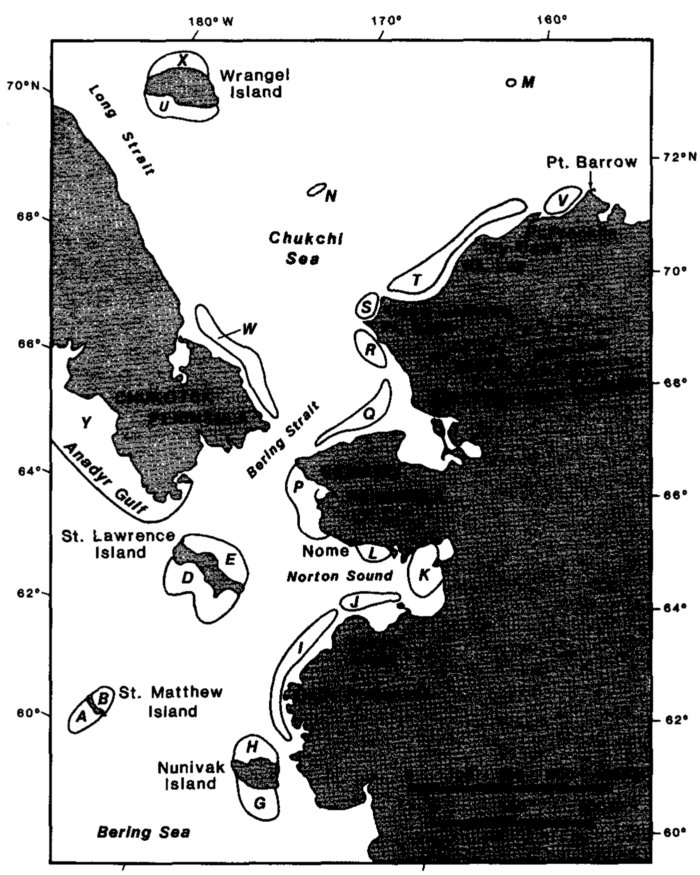

FIG. 1. Polynyas of the Chukchi and Bering seas. Table 1 identifies letter codes.

TABLE 1. Polynyas of the Chukchi and Bering seas

Location of polynyas	Coded designation of Alaska base map
St. Matthew Island Polynya, South	A
St. Matthew Island Polynya, North	B
St. Lawrence Island Polynya, South	D
St. Lawrence Island Polynya, North	E
Nunivak Island Polynya, South	G
Nunivak Island Polynya, North	H
Cape Romanzof Polynya	I
Yukon Delta Polynya	J
Norton Sound Polynya	K
Nome Polynya	L
Hanna's Shoal Polynya	M
Herald Shoal Polynya	N
Seward Peninsula Polynya[3]	P
Kotzebue Sound Polynya	Q
Cape Thompson–Pt. Hope Polynya[1]	R
Cape Lisburne Polynya	S
Chukchi Polynya [2]	T
Peard Bay Polynya	V
Chukotsk Peninsula Polynya	W
Wrangel Island Polynya, South	U
Wrangel Island Polynya, North	X
Sireniki Polynya[4]	Y

[1]Carlton (1980).
[2]Chukchi Polynya (Stringer, 1982).
[3]Pease (1987).
[4]Bessonov *et al.* (1990).

rejection or climate change, but for monitoring of future hypothesized effects of polynyas on global change.

DATA

The Geophysical Institute GeoData Center, University of Alaska Fairbanks, includes a collection of photographic transparencies of AVHRR images from 1974 through 1987. This is a reasonably comprehensive archive, containing daily images acquired at the nearby NOAA/NESDIS CDA Station, a satellite receiving facility at Gilmore Creek. A computerized program has been developed at the Geophysical Institute that enables one to rectify AVHRR imagery to the USGS Alaska Map E and to calculate the areas of digitized features. Meteorological data were obtained from *Local Climatological Data* prepared for the synoptic weather stations at Barrow, Kotzebue, Nome and St. Paul by the U.S. Department of Commerce (NOAA) National Climatic Data Center. Geostrophic wind direction was obtained from surface pressure charts prepared for the Atmospheric Environment Service, Environment Canada, in Edmonton, Alberta.

METHODOLOGY

AVHRR visible and thermal infrared imagery were examined on a daily basis as available for the presence of polynyas for 180 days starting each 1 January for the years 1974, 1975, 1976, 1977, 1979 and 1983. Emphasis was placed on identification of polynyas within United States or international waters. Only the most conspicuous of the polynyas in Soviet waters were documented.

Twenty-two polynya sites were identified. The sites are displayed in Figure 1 and named in Table 1. An additional polynya site was recognized outside the study area in the Beaufort Sea 50-75 km east of Pt. Barrow. Extent determinations were made for 17 polynyas by a digitization process. This process involved the location and digitization of easily identified geographic sites, which then served as control points to register the image to a standard map projection by least squares fitting. Once the image was registered to standard map projection, extents were easily calculated after digitization of the perimeter of the polynyas. Replicate AVHRR area measurements for areas > 300 km^2 varied by ± 10% or less.

Comparisons of the extents derived from AVHRR imagery were made with those derived from Landsat MSS imagery (Carleton, 1980) for the Cape Thompson–Pt. Hope Polynya (R) as a check of the accuracy of the AVHRR determinations (Table 2). Landsat imagery has a spatial coverage of approximately 115 × 115 km and a spatial resolution of 80 m; AVHRR imagery has spatial coverage adequate to display most of Alaska and has a spatial resolution of 1 km. Because of the high spatial resolution, Landsat imagery is very useful for making highly accurate extent determinations of small polynyas like the Cape Lisburne (S) and Cape Thompson–Pt. Hope polynyas (R). Carleton used Landsat near-infrared imagery (0.8-1.1 μ) to distinguish water, land and ice boundaries and calculate polynya extents. For the AVHRR extent determinations, visible (0.6-0.7 μ), near-infrared (0.7-1.1 μ) and thermal infrared (10.3-11.5 μ) imagery were used. Table 2 reveals that, in general, extents determined from AVHRR imagery agree well with those determined from Landsat imagery. The discrepancies that do exist could arise from changes in polynya extent or nearby cloud cover that took place in the time interval between the AVHRR and Landsat satellite passes. The discrepancies in 7/8 April 1974 and the 3/5 June 1975 comparisons appear to arise for this reason. The discrepancy in the 15 June 1976 comparison appears to arise from a difference in interpretation of the images; the Cape Thompson–Pt. Hope Polynya (R) was seen as a discrete feature in the Landsat and was seen as joined to the Chukchi Polynya (T) on the AVHRR.

The median was chosen as the measurement of central tendency to characterize polynya extent rather than the mean because of problems related to defining large polynya sizes. At some times polynyas open to the extent that they join to the open ocean or fuse with neighboring polynyas for short periods; this leads to the inclusion of very large or undefinable areas, which is a departure from the concept of a polynya as a feature confined to well-defined borders. We must also recognize that AVHRR imagery does not permit measurements during periods of extensive cloud cover; the measurements were therefore biased in favor of polynya extent during periods of cold, clear weather.

Two definitions were created for separate calculation of median areal extent values. Each summarized monthly polynya areal extent. In the first, *all* extent determinations are included. Thus, the median *size* approximates the contribution a process, such as brine rejection, might have over a defined region during the monthly period. In the second, all values were excluded for those cases when the polynya was completely frozen over or when the polynya joined the open ocean. Thus, the median *area* allows one to estimate the anticipated extent of a polynya that forms infrequently — such as a north-coast polynya. Median *size* and median *area* determinations are given in Tables 3 and 4. Ninety percent confidence intervals for the medians were calculated using the large

TABLE 2. Comparison of daily area of the Pt. Hope Polynya (R in Fig. 1) calculated from AVHRR imagery with polynya area calculated on the same day from Landsat imagery

		Area (km^2)	
Year	Image date	Landsat (Carleton, 1980)	AVHRR (this study)
1974	1 March	63[1]	clouds
	20 March	2280	2100
	7/8 April	4125	2500 ± 150[2]
	13 May	1450[1]	1000 ± 50
	17 June	4500	5200 ± 150[3]
1975	12 April	560[1]	800 ± 100
	16 May	1290[1]	1100 ± 50
	3/5 June[4]	1650	600[3]
1976	10 February	1800	2000 ± 20
	17 March	4235	4400 ± 146
	22 April	475	350 ± 60
	10 May	1850	1500 ± 100
	15 June	2660	7800[3]

[1]Carleton believes Landsat area was underestimated.
[2]AVHRR area underestimated because of cloud cover.
[3]Pt. Hope Polynya (R) appears to be fused with the Chukchi Polynya (T) on the AVHRR imagery.
[4]Area may be underestimated on both types of imagery.

TABLE 3. Median size[1] (km²) of polynyas in the Chukchi and Bering seas

Location of polynyas	Map code	January	February	March	April	May	June	July
St. Matthew Island Polynya, South	A	Open	549<660<1260	1520<1560<3380	1950<2700<11700	Open	Open	Open
St. Matthew Island Polynya, North	B	Open	0<0<0	0<0<0	0<0<0	Open	Open	Open
St. Lawrence Island Polynya, South	D	2020<2260<2440	872<1440<1950	1810<2370<2920	3090<4620<5500	Open	Open	Open
St. Lawrence Island Polynya, North	E	0<0<0	0<0<0	0<0<0	0<0<0	Open	Open	Open
Nunivak Island Polynya, South	G	1440<1880<3110	665<972<1140	1330<2370<2710	1360<Open<Open	Open	Open	Open
Nunivak Island Polynya, North	H	0<0<0	0<0<0	0<0<0	2010<48000<Open	Open	Open	Open
Cape Romanzof Polynya	I	694<1380<1840	345<810<1640	664<1260<2000	1270<2510<Open	Open	Open	Open
Yukon Delta Polynya	J	0<0<0	0<0<0	0<0<0	0<362<1210	Open	Open	Open
Norton Sound Polynya	K	886<1500<1630	788<1150<1430	1640<2420<3590	3190<5590<8190	Open	Open	Open
Nome Polynya	L	227<411<534	62<218<390	542<1440<3030	2580<5830<8460	14500<19400<25400	Open	Open
Seward Peninsula Polynya	P	656<1410<1880	562<884<1230	1100<1520<1680	1410<1780<2170	9640<21000<34900	Open	Open
Kotzebue Sound Polynya	Q	0<0<517	0<0<560	0<0<0	0<0<0	0<0<64	1150<Open<Open	Open
Cape Thompson–Pt. Hope Polynya	R	93<545<1340	0<544<684	232<571<1000	0<96<265	132<218<322	383<1290<183	Open
Cape Lisburne Polynya	S	21<112<202	0<0<322	0<0<341	26<104<132	239<352<560	4570<10800<14500	Open
Chukchi Polynya	T	0<582<965	0<1020<1730	0<528<776	245<514<962	6420<8260<10400	7380<10200<11300	Open
Peard Bay Polynya	V	0<610<1200	0<0<0	0<0<0	0<0<0	2780<7260<9630	0<62<324	Open
Chukotsk Peninsula Polynya	W	0<0<0	0<0<0	0<0<0	0<0<0	0<0<0	Open	
Sireniki Polynya	Y	2640<4470<5080	2050<3040<4440	3180<3640<4240	4960<6190<10000			

[1]Median of all possible area determinations of the polynya. It includes those where the polynya was frozen over (area = 0) and those where the polynya has become part of the open ocean. Confidence intervals (90%) are given for medians calculated for 20 or more observations.

TABLE 4. Median area[1] (km²) of polynyas in the Chukchi and Bering seas

Location of polynyas	Map code	January	February	March	April	May	June	July
St. Matthew Island Polynya, South	A	1460	388<550<648	498<844<1520	788<1200<1940	1300	Open	Open
St. Matthew Island Polynya, North	B	**	**	1140	1330	Open	Open	Open
St. Lawrence Is. Polynya, South	D	1940<2190<2440	1640<2000<2480	2290<2680<3550	3450<4660<5270	15900	Open	Open
St. Lawrence Is. Polynya, North	E	**	4640	3085	1240<2220<2360	5950	Open	Open
Nunivak Island Polynya, South	G	1370<1610<1820	1090<1230<1490	1540<2360<2700	3240<4440<4860	4420	Open	Open
Nunivak Island Polynya, North	H	**	4190	2370<3410<4630	1600<2440<3250	1830	Open	Open
Cape Romanzof Polynya	I	1310<1600<2110	1640<2670<3590	1800<3760<5190	980<1290<1600	6300	Open	Open
Yukon Delta Polynya	J	1150	2560	1390<1900<3550	2180<4140<7920	12600	Open	Open
Norton Sound Polynya	K	1500<1630<1990	1010<1340<2110	2720<4500<5920	3190<5180<8090	6650<9710<13900	17500	Open
Nome Polynya	L	468<697<1010	451<867<1620	1780<3760<6370	5920<8460<9730	9600<13800<16800	17500	Open
Seward Peninsula Polynya	P	1490<1900<3340	1180<1680<2310	1650<1770<2030	1720<2060<2270	2570<3800<4540	17500	
Kotzebue Sound Polynya	Q	1400<2330<4270	1080<2970<4500	1480<2810<3320	574<819<1340	284<898<1070	445	Open
Cape Thompson–Pt. Hope Polynya	R	1500<2220<2270	1410<1760<2200	1160<1900<2200	690<1950<2420	405<693<888	1380	Open
Cape Lisburne Polynya	S	206<376<507	720<1660<2180	218<263<374	165<200<268	518<704<833	6420	Open
Chukchi Polynya	T	1270<2340<2940	2180<3050<3430	1300<1570<3030	1200<1470<1730	6860<8620<10800	8420	
Peard Bay Polynya	V	1270<2490<2880	2180<4180<9630	2030<3100<3760	1210<2260<3190	8260<11600<13400	3940	
Chukotsk Peninsula Polynya	W	2570	942	1840	**	1420	4340	
Sireniki Polynya	Y	2920<4740<5080	2340<3180<4450	3540<4100<5170	6010<9030<11300			

[1]Median of area determinations excluding those cases where polynya was frozen over (area = 0) as well as those where the polynya has become part of the open ocean. Confidence intervals (90%) are given for medians calculated for 20 or more observations.

**Polynyas not observed open.

sample approximation based on the central limit theorem. Confidence intervals are given for sample sizes of 20 or more.

Extensive statistical analyses were performed in an attempt to relate synoptic meteorological data to polynya areal extent using daily areal extent as well as the monthly medians defined above (Stringer and Groves, 1988). The statistical analyses performed included parametric and non-parametric models and time series. Daily temperature and wind data were selected from synoptic meteorological data recorded at the National Weather Service stations at Barrow, Kotzebue, Nome and St. Paul Island (at 57°N, 170°W, just off the bottom of Fig. 1) for pairing with polynya extent observed for the Chukchi (T), Kotzebue Sound (Q), Norton Sound (K) and St. Lawrence Island (D) polynyas. Wind data were converted to vector form; for example, the daily component of the wind from the northeast was calculated for use in time series analysis. Monthly relationships between the extent of the four polynyas and monthly estimates of air temperature, freezing-degree days and wind vectors were investigated using linear (Pearson) and non-parametric (Kendall's tau) correlations. Daily relationships between extent of the four polynyas and daily records of air temperature and vector winds were investigated using cross-correlation techniques.

RESULTS

A catalog of 22 polynyas in the Bering and Chukchi seas was compiled (Fig. 1; Table 1). In addition to the generally persistent polynyas that form off south-facing coasts, a special class, "north-coast polynyas," was identified. These polynyas form off the north-facing coasts of St. Matthew (B), St. Lawrence (E) and Nunivak islands (H) and off the Yukon Delta (J), Seward Peninsula (Q) and Chukotsk Peninsula (W). They occur less frequently than the more typical persistent polynyas adjacent to coasts facing south. When the north-coast polynyas are present, the more typical polynya sites are often closed or diminished in extent (Fig. 2).

Despite the cloudiness that accompanies these polynyas, examination of daily polynya occurrences revealed that on 102 occasions when one north-coast polynya was observed, at least one more (and on some occasions as many as four more) north-coast polynyas were also seen. Because the north-coast polynyas tend to open when the persistent polynyas are not opening, we hypothesized that the north-coast polynyas arose from a regional reversal of driving forces. In particular, we suspected winds changing to southerly from northerly or northeasterly, the predominant wind directions in winter over that part of the Bering Sea north of St. Matthew Island (Brower *et al.*, 1988; Overland, 1981; Wilson *et al.*, 1984). As these southerly winds may be warmer than the ambient air encountered at the higher latitudes and may have traversed an extensive region of ice-free water in the southern Bering Sea, they may also be responsible for the extensive regional cloud cover observed when these polynyas form.

Geostrophic wind direction obtained from inspection of Canadian Atmospheric Environment Service synoptic surface pressure charts is displayed in Figure 2. Three extended periods of wind from the south are present that appear to be associated with north-coast polynyas. They are 24 January through 7 February, 4 through 11 March and 3 through 5 April. For the period 24 January through 7 February, extensive regional

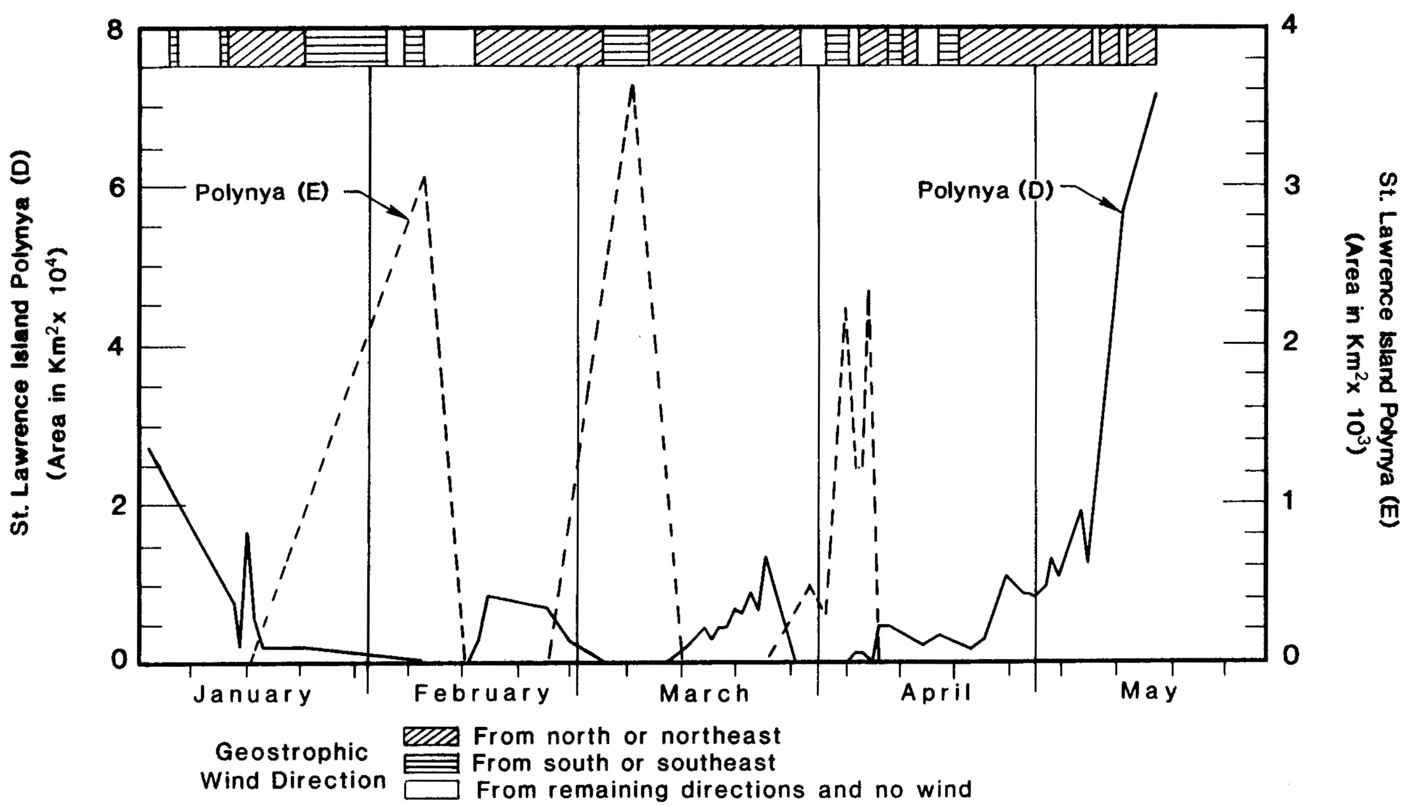

FIG. 2. Daily area variation of the St. Lawrence Island polynyas (D and E) in 1975 showing the tendency of the north-coast polynya (E) to form when the south-coast-facing polynya (D) is closed and vice versa. Geostrophic wind direction at St. Lawrence Island was determined from surface synoptic meteorological charts prepared by the Atmospheric Environment Service, Environment Canada, at Edmonton, Alberta.

cloud cover was present in both the Bering and Chukchi seas. All the north-coast polynyas were observed at least once, and for those few cases where they could be observed well enough for polynya extent to be calculated, the extent was quite large. For the period 4 through 11 March, on 4 March north-coast polynyas E, H, J, Q and W were observed simultaneously; land-based meteorological stations recorded a 15 $m \cdot s^{-1}$ wind from the south at the Bering Strait and a 13 $m \cdot s^{-1}$ wind from the south at Cape Lisburne on the 4th. For the 3 through 5 April period, north-coast polynyas E, H, J and Q were observed at least once. On 4 April, a 15 $m \cdot s^{-1}$ wind from the southeast at the Bering Strait and a 13 $m \cdot s^{-1}$ wind from the southwest at Cape Lisburne were recorded. Inspection of the Canadian Atmospheric Environment Service synoptic pressure charts for the three periods cited above reveal that the southerly winds tend to be associated with a high pressure region centered over the state of Alaska. Periods where the wind is from the northeast tend to be associated with a low pressure region centered in the Gulf of Alaska.

Polynya median size and median area are given in Tables 3 and 4. Although the median and not the mean was chosen as a measure of central tendency, one can ask how many observations per month would be needed to ensure that the population mean was within 0.5 standard deviation of the sample mean at the 90 and 95% confidence levels. Using the sample size estimation technique inherent in the central limit theorem, we determined each polynya site would have to be observed 11-14 times a month respectively to achieve those two confidence levels. In this study each polynya site was observed at least 11 times a month nearly 75% of the time. The standard deviation from the mean, calculated by either definition used for the median and restricted to those months where the polynya was not joined to the open ocean, was equal to the mean value or greater. Our areal extent sampling frequency was sufficient to justify our means to ±50% at the 90% confidence level. Thus, the standard deviation of the observed extent represents the natural variation in monthly polynya extent, not measurement error. Therefore it is not really possible to assign a truly meaningful "typical" monthly extent to these polynyas because the above observations indicate that there is a large natural variation in polynya extent, and the variations we observed were not simply due to the sampling population.

The natural variation of polynya extent is very large. This sizable variation is largely due to the propensity of polynyas to change status from ice-covered to extensive open water area or the reverse over a 24 hour period; in some cases major open water area changes can be observed over the period of a few hours. Groves and Stringer (1991 – this issue) document the difficulties of using World Meteorological Organization (WMO, 1970) ice thickness estimates based on visual gray scales. The use of digital data for thermal infrared analysis and improved detection of thin ice and open water boundaries in preference to photographic transparencies would remove a small portion of this variance.

Our statistical analyses provided evidence that at times both the vector wind and temperature influence polynya areal extent, but the results were not definitive and despite the effort represented, we do not think it useful to report the results. Often the results were not statistically significant, and even in those cases where the results were statistically significant, the correlation coefficient was not very large (Stringer and Groves, 1988). One major difficulty in performing our statistical analysis was the great distances between the land-based synoptic recording stations and the polynya sites. Two refinements in the use of meteorological data would likely improve statistical significance of the analyses. Kozo *et al.*'s (1990) paper demonstrates that geostrophic winds calculated from mesoscale meteorological networks are superior to winds calculated from synoptic networks for predicting polynya length. Thus our earlier attempt to relate polynya extent to synoptic winds (Stringer and Groves, 1988) may have been too much of an over-simplification, because orographic effects present at coastal weather stations produce wind records that are not representative of the wind regime at the polynya site (Kozo, 1988). Pease (1987) states that after the spring equinox, input from solar radiation is the dominant factor influencing polynya extent. After the spring equinox estimation of polynya extent will have to reflect both wind and solar radiation effects.

A study of Chukchi Sea ice movement conducted by Pritchard and Hanzlick (1988) determined that winds explained 2-77% of the ice velocity variance, whereas currents explained 44-93%. The authors concluded that currents explained a larger proportion of the variance than the wind but acknowledge that there were cases where wind influences predominated and also cases where neither current nor wind explained the variance. Thus, it may well be that polynyas are opened by a variety of influences, including currents, and that winds are the major factor only occasionally.

However, qualitative statements regarding the influence of temperature and wind direction on polynya areal extent can be made from inspection of Tables 3 and 4. A general trend exists for polynyas to increase in size as the season progresses from winter through spring. This explains the general correlation found between polynya extent and temperature over long time scales. Exceptions are noted for the most southerly of the polynyas (A, D and G), when the ice edge may not have extended that far south in all years in January, and for the north-coast polynyas.

Monthly polynya extent can be used to estimate the contribution from polynyas to open water within the ice-covered regions of the Bering and Chukchi seas (Table 5). The monthly percentages were calculated by summing the median *sizes* (Table 3) and *areas* (Table 4) of each polynya site within the Bering and Chukchi seas and dividing that quantity by the area of the pertinent sea. Hood (1981) reports an area of 2.3×10^6 km^2 for the Bering Sea, which is defined as bounded on the east by Alaska, the west by the U.S.S.R. and the south by the Aleutian Islands. The extreme limit of the ice extent in the Bering Sea closely coincides with the edge of the continental shelf as defined by depths less than 200 m; the shelf occupies about half the area of the Bering Sea. Stringer and Groves (1985) report an area of 6×10^5 km^2 for the Chukchi Sea, which is defined as bounded on the east by the northwest coast of Alaska, on the west by Long Strait and Wrangel Island and on the north, approximately, by the 72nd parallel. The percentages represent median estimates likely to be observed each month. Strictly defined statistical limits cannot be assigned to these percentages. Median *size* percentages are smaller than median *area* percentages for January through March because this calculation is sensitive to the condition that polynya sites are often frozen or closed prior to April. In April polynya sites often join to the open ocean and the relationship between median *size* and *area* percentages reverses. The observation

TABLE 5. Monthly median percentage of open water surface contained within polynyas in the Bering and Chukchi seas

	Bering Sea[1]		Chukchi Sea[2]	
	Median size	Median area	Median size	Median area
January	0.58	0.96	0.30	2.0
February	0.40	1.1	0.26	2.4
March	0.56	1.4	0.18	1.9
April	3.1	2.0	1.9	1.1

[1]Calculated using the median *sizes* and *areas* of the Bering polynyas (A, B, D, E, G, H, I, J, K, L, P and Y).
[2]Calculated using the median *sizes* and *areas* of the Chukchi polynyas (Q, R, S, T, V and W).

that median *size* percentage is relatively constant for January through March and increases dramatically in April might imply that wind influences predominate in determining polynya extent for January through March and that in April solar radiation input predominates or acts in combination with wind influences.

An unusual meteorological event occurred in February 1975 that resulted in a polynya present as a continuous feature from Nunivak Island to Norton Sound and from the Bering Strait to Barrow. Between 24 January and 7 February the prevailing wind was from the south at St. Lawrence Island (Fig. 2) and from the east along the Chukchi coast. Winds were recorded from the south at 15 $m \cdot s^{-1}$ at the Bering Strait and from the east at 10 $m \cdot s^{-1}$ off the Chukchi coast. Using summed daily polynya extent observed during this period, upper limits of open water percentage of 2.0% for the Bering Sea and 5.7% for the Chukchi Sea were calculated for this unusual event.

Polynyas M and N (Hanna's Shoal and Herald Shoal) are frequent, conspicuous, but small features that do not form off coastlines. A seamount located at 71.94°N, 161.48°W (Hanna's Shoal) rises to within 20 m of the surface. The ice that grounds on Hanna's Shoal is referred to as Katie's Floeberg (Barrett and Stringer, 1978). This grounded ice is the fixed obstruction from which winds or currents move ice and create the polynya. The Herald Shoal Polynya (N) forms by a like mechanism west of Herald Shoal, which rises to 10 m of the surface at 70.37°N, 170.85°W. The depth reported for Hanna's Shoal was obtained from a provisional bathymetric chart published by the National Oceanic and Atmospheric Administration (NOAA); the grounding of ice at this site suggests the chart may be inaccurate.

CONCLUSIONS

1) Twenty-two polynya sites in the Bering and Chukchi seas were identified (Fig. 1; Table 1).

2) Representative monthly areal extent values that can be related to oceanic processes or frequency of appearance were tabulated for 17 polynyas (Tables 3, 4). Ninety percent confidence intervals are provided as a measure of the monthly variability of polynya extent.

3) Two distinct classes of polynya were recognized in this region: the generally recognized persistent polynyas that form off south-facing coasts and the less-frequently occurring north-coast polynyas that form off north-facing coasts.

4) The north-coast polynyas tend to form simultaneously and when the persistent polynyas are at least not growing. The north-coast polynyas tend to be associated with winds from the south, which, in turn, appear to arise from the presence of a high pressure region centered over Alaska.

5) Extensive statistical analyses attempting to relate local measured meteorological variables with polynya extent were largely inconclusive, leading to the suggestion that the driving forces responsible for polynyas are much more complex than simple local wind forcing and may involve regional forcing mechanisms, including oceanic currents.

6) Of all the meteorological variables, temperature correlation yielded the most promising results, showing a positive correlation between polynya extent and temperature. The most noticeable manifestation of this correlation was on a seasonal time scale. This relationship was most noticeable after the spring equinox at a time when solar heating begins being a significant factor at these latitudes.

7) Monthly estimates of total open water extent contributed by polynyas to the Bering and Chukchi seas were made (Table 5).

8) Shoal polynyas that form off grounded islands of ice located semi-permanently on shoals in the Chukchi Sea are described.

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