LIMITATIONS OF GIS AND REMOTE SENSING FOR CONSIDERING SPATIAL AND TEMPORAL CHANGE IN STUDIES OF HABITAT USE BY POLAR BEARS

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ABSTRACT

To investigate the feasibility of using satellite-based remote sensing to study habitat use of polar bears (*Ursus maritimus*), we compared distributions of satellite locations of radio-collared adult female bears to sea ice concentration (percent ice coverage of 25 x 25 km grid cells) in the Bering and Chukchi Seas at intervals of 10-14 days from April 1990 through February 1991. Ice concentrations were calculated from daily images of surface brightness temperatures detected by satellite-based passive microwave imaging (Special Sensor Microwave/Imager [SSM/I]). Limited precision of the satellite imagery and radio-tracking data prevented us from investigating use of ice concentrations <1%, which bears commonly used during late summer. Furthermore, lack of surface-truth data to support the ice classifications and the possibility of geolocation errors in the SSM/I data indicate that our results must be considered with caution. However, our data suggested that habitat use by female polar bears varied during the year. Most bears remained on the ice pack all year, and were widely distributed during winter and spring, when seasonal ice covered much of the Bering and Chukchi Seas. During summer, bears were found most often in areas with <50% coverage of sea ice, and were rarely found in areas with >75% ice cover or in the interior of the permanent ice pack. This pattern was reversed during winter, when bears never were found in areas with <50% ice coverage. The data-gathering and management capabilities of remote sensing and GIS technologies present the opportunity to include spatial and temporal changes as components of habitat studies, although limitations in accuracy and precision of remotely-sensed habitat data must be addressed. Furthermore, current methods of analyzing data on use and availability of habitats do not allow for changes in habitat type or availability.

INTRODUCTION

Polar bears range throughout much of the Arctic, and, although sometimes found on land, they spend most of their time on sea ice. The sea ice is an unusually dynamic habitat, showing dramatic spatial and temporal differences in form and extent. For example, the ice in some areas may be relatively smooth, unbroken, and covered by snow. In other areas, the action of wind and ocean currents may break the ice and push neighboring floes together, forcing large blocks up to form ridges. Elsewhere, polynyas may exist, which are areas of open water created and maintained by circulating winds or currents that continually break the ice apart and prevent new ice from forming. Charactertistics of the ice at any particular location can change rapidly. Kozo et al. (1987) illustrated how ocean currents and differences in atmospheric pressure can cause ice floes to move up to 78 km per day through the Bering Strait. The structure of the ice pack is likely to influence polar bears in several ways (Lentfer 1972). For example, the seals that constitute much of the bears' diet are found most often along open or newly refrozen leads (Burns 1970; Stirling and Archibald 1977). Also, ridges formed by upthrust blocks of ice may provide concealment for hunting bears or shelter from strong winds.

Polar bears found along the west coast of Alaska move throughout a large area (Fig. 1), extending from near St. Mathew Island in the Bering Sea north to approximately 80°N latitude, west into the East Siberian Sea, and east to at least Point Barrow, Alaska (Garner and Knick 1991). Individual radiocollared bears from this population traveled an average of 6,022 km during the year beginning March 1990 (Garner et al. in press). The large distances traveled by polar bears and the dynamic nature of their habitat have inhibited studies of polar bear habitat selection in this population using traditional techniques, although studies using direct observation of bears (Martin and Jonkel 1983) and aerial surveys of bears and tracks (Stirling et al. 1993) have been conducted in northern Canada. Since 1972, satellite-based remote sensing has provided data on distribution and concentration of sea ice over much of the Arctic. However, problems with using these data remain, due to limitations of satellite technology and lack of appropriate methods for data analysis. In this paper, we will illustrate some of these problems by comparing remotely sensed data on sea ice concentrations with movements of polar bears, and present an initial attempt to develop a method to analyze data on habitat selection when availability changes between samples.

METHODS

From 2 March-2 April 1990, 31 adult female polar bears were captured using tranquilizer darts fired from low-flying helicopters. Nine females were captured off the west coast of Alaska, and were alone or accompanied by yearling or 2-year-old cubs. The other 22 females, captured on Wrangel Island, Russia, had recently left maternal dens and were alone or accompanied by cubs of the year. Adult females were equipped with radio collars, which operated on a 3-day cycle (on for 7 hours, then off until the next cycle). Transmitters were tracked by satellites through the Service Argos system and each location was assigned a quality code of 1-3 representing a level of precision (standard error of repeated measurements) ranging from 1,000-150 m, which was estimated using stationary transmitters (Service Argos, unpublished data cited by Harris et al. 1990). Within each 7-hour transmitting period, up to 14 locations of a bear were recorded. From these, we selected 1 location per bear per day based on the quality code and the distance from the previous location. Locations with the highest quality were selected first, and if >1 location per day were of the same quality then we selected the one closest to the previous location. In this way we deleted the locations most likely to be errors.

Sea ice concentration was determined from data provided by the National Snow and Ice Data Center, Boulder, Colorado. These data were obtained by the satellite-based Special Sensor Microwave/Imager (SSM/I), a passive microwave sensor using polarized 19 and 37 GHz bands. This system provided daily images of surface brightness and thermal temperatures binned onto a grid with cells of 25 x 25 km (National Snow and Ice Data Center 1992). These data were converted to values representing percent of each cell covered by ice using algorithms originally developed for the Scanning Multichannel Microwave Radiometer (SMMR; Comiso 1986) and subsequently modified for use with SSM/I (National Snow and Ice Data Center 1992).

We established the limits of our study area to include all locations of radio-collared bears monitored between 1986 and 1992. This area extended from longitude 140°W to 150°E and from latitude 82°N southward to the edge of the ice pack, which we defined as the southern limit of contiguous grid cells with $\geq$1% ice cover (Fig. 1). We assumed that all bears monitored during this study were capable of traveling to any part of this area, and therefore all parts of the area were available for selection.

We selected images for 25 dates at intervals of 10-14 days from late April 1990-February 1991 (Table 1). Days were selected to maximize the number of concurrent bear locations. Because transmitters operated on only one of every 3 days and because individual bears were located on different days, we defined concurrent locations as those that were obtained within $\pm$1 day of an image. We used this time interval because monthly averages of distance moved by bears in a 24-hr period (range = 7.6-26.4; annual $\bar{x}$ = 14.8 km/day) exceeded the cell size of the ice images only during November, when the mean rate was 26.4 km/day (Garner et al. in press). Although errors might have occurred because of a 1-day separation between bear locations and ice images, we believe that bears rarely moved far enough in a day to move into a different habitat type.

Using Arc/Info, sections covering our study area were split from the original circumpolar images. These were converted from the original polar stereographic projection to an Albers projection and the areas occupied by various categories of ice concentration were determined. Ice concentration was calculated to the nearest one percent (National Snow and Ice Data Center 1992). However, we combined concentration values into the arbitrary categories 1-25, 26-50, 51-75, and 76-100% ice cover to obtain adequate numbers of bear locations to determine percent use of each category. Bear locations were then overlaid onto the ice images, and we determined the category of ice concentration present at each point. We only used one location per bear for each comparison and we excluded bears that may have been denning during December-February.

For each date, we compared use of ice types with availability using the selection index proposed by Manly (1974). This was calculated by dividing the proportion of bear locations in a habitat type by the proportion of the total area composed of that type on that date. This ratio was then divided by the sum of the ratios for all habitat types on that date. The resulting index may range from 0-1, and represents the probability that a habitat type would be selected if all types were equally available (Chesson 1983; Manly et al. 1993). We then grouped sample dates into five seasons and determined mean values of the index for all habitat types within each season. Season dates were based on bear movements and ice characteristics and were: post-denning, from 13 April to 10 May; receding ice, from 25 May to 28 July; minimum ice extent, from 10 August to 7 October; advancing ice, from 20 October to 21 December; and maximum ice extent, from 7 January to 23 February. We did not consider data from March or early April to avoid including any unusual movements of bears immediately following their capture. To calculate the selection index, we excluded bears that evidently were stranded on land when the ice pack retreated and bears that were in areas with <1% ice coverage. Areas with <1% ice could not be distinguished from open water, so we could not determine their availability.

Although the selection index should be approximately normally distributed (Chesson 1983; Manly 1974), combining data from several bears requires the assumption that all bears exhibit similar patterns of habitat selection. We could not test this assumption, so we made no statistical comparisons of the mean seasonal index values.

RESULTS

The extent and characteristics of the ice coverage varied greatly during the year (Table 2). During the post-denning season, ice extended well into the Bering Sea and the ice near Wrangel Island was nearly continuous, except for temporary leads formed at cracks in the ice pack (Fig. 2). During the period of receding ice, the edge of the pack retreated rapidly north through the Bering Strait, and the proportion of low (≤50%) ice concentration increased (Fig. 3). Bears were widely distributed during this period. During July, August, and September, bears frequently were found in areas with <1% ice (Table 1, Fig. 4). Frequency of use of this type reached a maximum of 52.4% on 10 August, and averaged 35.8% from 10 August-7 October. When ice was at its minimum extent between late August and early October, the proportion of low ice concentration decreased, to form narrow bands along the edge of the ice pack (Fig. 5). Most bears were found in these areas of lower ice concentration during this period, and they did not go north into the interior of the ice pack. This pattern may have been exaggerated during 1990, because the ice pack retreated much farther north than in most years.

During the period of advancing ice, the ice pack extended rapidly southward and the new ice consolidated quickly as it formed so that availability of low ice concentrations decreased slightly. During this period bears also moved southward (Fig. 6). During the period of maximum ice extent, much of the Bering Sea and all of the Chukchi Sea were covered by high (>50%) concentrations of ice (Fig. 7). Although areas of low ice concentration were available along the southern edge of the ice pack, radio-collared bears did not move that far south, and did not use this type of ice.

Mean values of the selection index indicated that the pattern of habitat selection by bears varied among seasons (Table 2). During the minimum ice period, lower ice concentrations were used more than higher concentrations, and bears were always found in areas near the edge of the ice pack. During the period of maximum ice extent, the pattern was reversed, and bears only used higher ice concentrations. During periods of advancing and receding ice, bears used intermediate (25-75%) ice concentrations more than very high or low concentrations. The selection pattern during the post-denning period was most similar to that during the period of maximum ice extent, and it may be appropriate to consider these as a single period.

DISCUSSION

Our study illustrates some major limitations of satellite-based remote sensing for studies of habitat use by polar bears. Although SSM/I data show little effect due to cloud cover, which is an important consideration in Arctic regions, the usefulness of these images is limited by the lack of surface-truth data to support the classification of ice types and by the coarseness of the resolution. Comiso et al. (1984) and Comiso and Sullivan (1986) compared surface-truth data to ice classifications from SMMR images, but few details of the methods used were provided and the results were inconclusive. Cavalieri (1992) reviewed several studies comparing SMM/I data to Advanced Very High Resolution Radiometer (AVHRR), Landsat, and radar images and concluded that, although differences between calculated ice concentrations generally were <10%, additional work is necessary to improve and verify the classification algorithms.

Accuracy of satellite data also may be reduced by geolocation errors. For the SSM/I data, geolocation errors were reported to be usually ≤8 km (Gooderbelt and Swift 1992), much less than the image resolution. However, occasional errors of 50 to several hundred kilometers have been reported (National Snow and Ice Data Center 1992).

Because of the limited resolution of the ice images, we could investigate habitat use only on a broad geographic scale and we could not examine selection of ice concentrations <1%, even though this type was commonly used during summer. It is unlikely that bears ever were located while in the water, because salt water interferes with radio transmissions. Thus, bears located in areas with <1% ice probably were on ice floes too small to be detected with a cell size of 625 km^2. Polar bears are capable of swimming long distances and thus would have no difficulty using small floes some distance from the ice pack. The apparent use of areas with <1% ice might also have been due to the unknown level of accuracy and precision of the ice concentration algorithms, movement of bears or changes in ice concentration within the 1-day interval, or locational errors in the ice or radiotracking data. Although we could not calculate a selection index for ice concentrations <1%, the frequency of use of this type during summer suggests this is an important habitat.

Unlike many other measures of habitat selection, relative values of Manly's (1974) selection index are not affected by the decision to include or exclude other possible habitat types (Manly et al. 1993); thus, the comparisons among the four habitat types we examined are valid, despite our exclusion of areas with <1% ice cover. However, because we could not distinguish these areas from open water, our analysis was limited to areas with more ice that seemed to be relatively less important to bears during mid-summer. Furthermore, much of the data on bear movements during the minimum ice period could not be used because the bears were in areas with <1% ice.

Other types of imagery currently available have greater resolution than SSM/I, but these systems have other limitations. For example, data from AVHRR are available with a resolution of approximately 1 km (Kidwell 1991), but these images are useful only for cloud-free areas, which often may not coincide with bear locations. Techniques are being developed to classify ice concentrations using radar images, but currently these images are not available for the large areas necessary for studying polar bears. Furthermore, although using images with greater resolution would help in distinguishing small ice floes from open water and small leads from the surrounding ice, this also would increase the importance of location errors inherent in satellite telemetry. Currently, the only available data concerning accuracy of satellite telemetry has come from studies using stationary transmitters on land, and the relationship between these data and conditions encountered in radiotracking polar bears on sea ice is unknown.

Our analysis was complicated by the fact that availability of habitat types changed continually, so traditional methods of analysis could not be used. This problem might arise in other studies where habitat conditions are variable, such as studies of seasonal wetlands or of snow cover that changes depth and consistency during winter. Previously published techniques of evaluating habitat selection have assumed availability of habitats was constant, at least during defined periods (e.g., Neu et al. 1974; Johnson 1980; Alldredge and Ratti 1986, 1992, Manly et al. 1993). However, studying the responses of animals to habitat changes may suggest species-habitat affinities (e.g., O'Connor 1986). Thus, a method is needed to consider changing habitat conditions in studies of habitat selection. Although Manly's (1974) selection index can be used to compare repeated samples of use and availability, independent samples of animals should be obtained for each sample date. Using repeated samples of a small group of animals may confound the results if individuals show different patterns of selection.

Despite these limitations, we found that selection of ice concentration types by female polar bears seemed to differ among seasons. Whether this was because habitat requirements of bears changed, distribution of prey changed, or for some other reason is unknown, but these differences suggest areas for future research.

The increasing availability of remotely-sensed data and improved data-handling capabilities of GIS software should facilitate studies of habitat selection by polar bears. However, concerns regarding accuracy and precision of ice classifications derived from satellite data must be addressed before these data can be used for a more detailed analysis. In addition, new statistical techniques are needed to account for the constantly changing habitat conditions.

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Table 1. Dates and numbers of locations used to investigate polar bear habitat use in the Bering and Chukchi Seas, April 1990 through February 1991.

	Number of bear locations			Percent of non-land
Date	Land[a]	<1% ice[a]	≥1% ice	locations with <1% ice
13 Apr	1	0	30	
25 Apr	0	0	29	
10 May	0	0	30	
25 May	0	0	29	
4 Jun	0	0	30	
18 Jun	0	0	29	
2 Jul	0	0	29	
16 Jul	0	11	14	44.0
28 Jul	1	9	12	42.9
10 Aug	1	11	10	52.4
23 Aug	0	6	9	40.0
2 Sep	0	7	13	35.0
16 Sep	2	8	9	47.1
27 Sep	2	4	14	22.2
7 Oct	2	3	15	16.7
20 Oct	2	0	18	
5 Nov	0	1	10	5.6
19 Nov	0	0	18	
1 Dec	1	0	17	
21 Dec	1	0	11	
7 Jan	1	0	12	
22 Jan	2	0	9	
1 Feb	2	0	9	
12 Feb	2	0	8	
23 Feb	3	0	8	

[a]Locations on land or in areas with <1% ice were not used in analysis of habitat use.

Table 2. Mean area available (%) and mean use (% of bear locations) of ice concentration categories in the Bering and Chukchi Seas, 1990-1991.

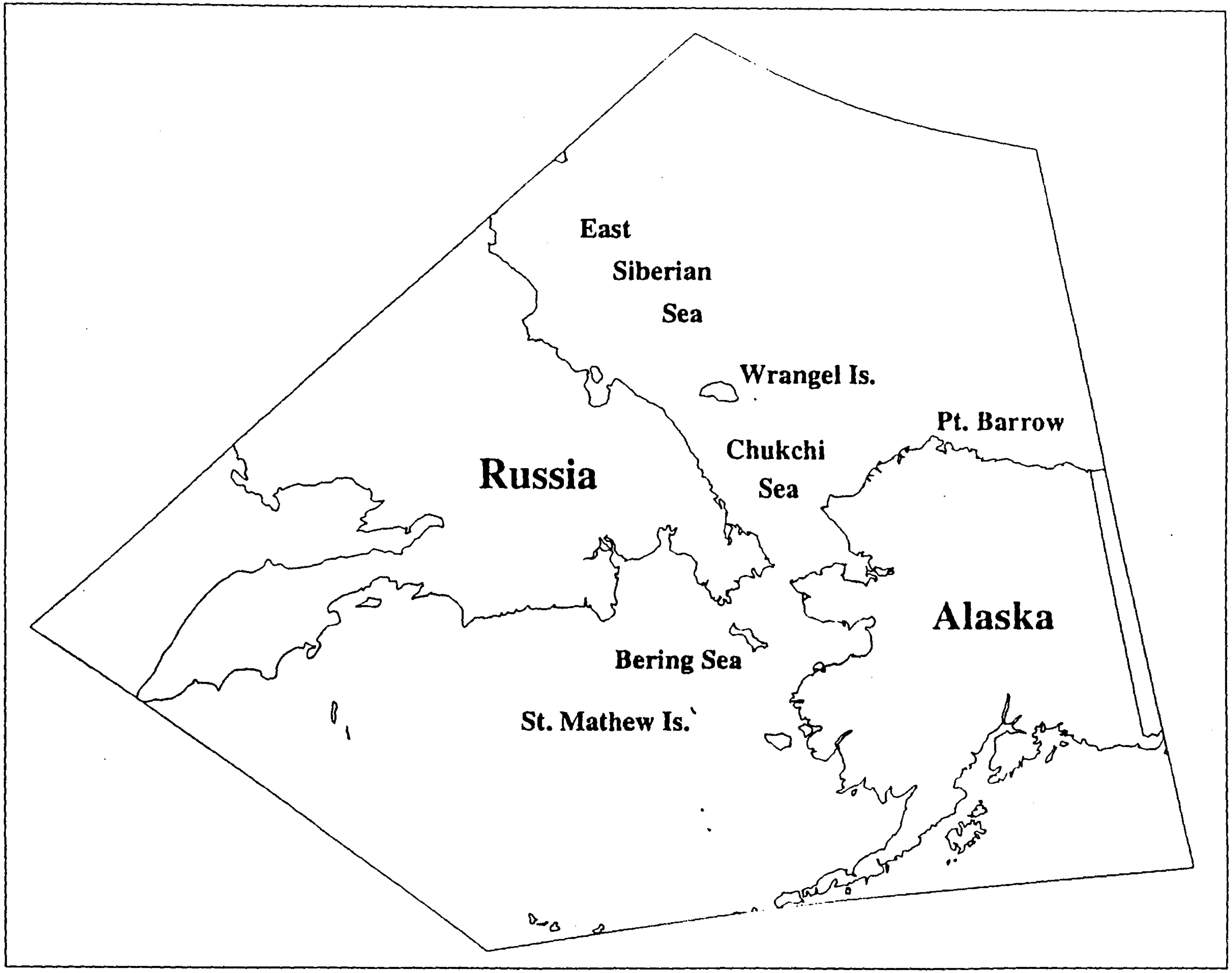
			Percent cover by sea ice											
			1-25			26-50			51-75			76-100		
Season	Days[1]	Bears[2]	Area	Use	Index[3]	Area	Use	Index[3]	Area	Use	Index[3]	Area	Use	Index[3]
13 Apr-10 May	3	29-30	2.8	1.1	0.008	3.8	2.2	0.107	16.7	26.0	0.494	76.7	70.7	0.322
25 May-28 Jul	6	12-30	7.3	12.2	0.232	9.4	22.3	0.380	35.8	46.3	0.318	47.5	19.3	0.007
10 Aug-7 Oct	6	9-15	4.5	33.5	0.458	5.2	30.3	0.399	24.1	29.0	0.137	66.2	7.3	0.006
20 Oct-21 Dec	5	11-18	1.7	4.8	0.124	2.8	9.4	0.199	9.7	48.5	0.624	85.8	37.4	0.005
7 Jan-23 Feb	5	8-12	1.4	0.0	0.000	2.7	0.0	0.000	8.4	10.8	0.388	87.6	89.2	0.612

[1]Number of days on which habitat use and availability were determined during the season.

[2]Minimum and maximum numbers of bears located per day.

[3]Mean values of Manly's (1974) selection index, calculated for each date as: x_i / Σx_i, where x_i = percent use of habitat *i* divided by percent availability of habitat *i*. For four habitat types, a value of 0.25 indicates use was in proportion to availability; values greater or less than 0.25, respectively, indicate the type was used relatively more or less than it was available.

List of Figures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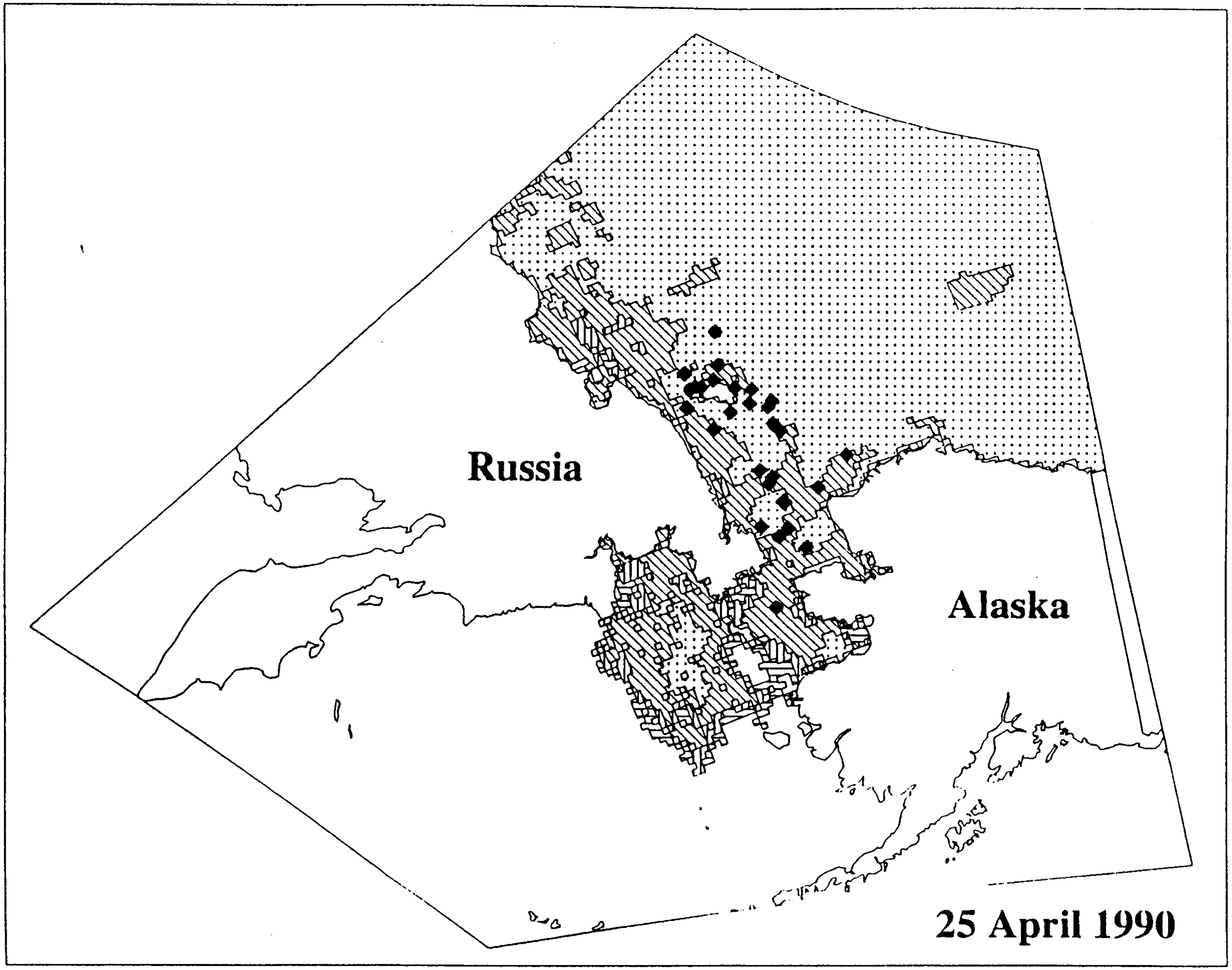
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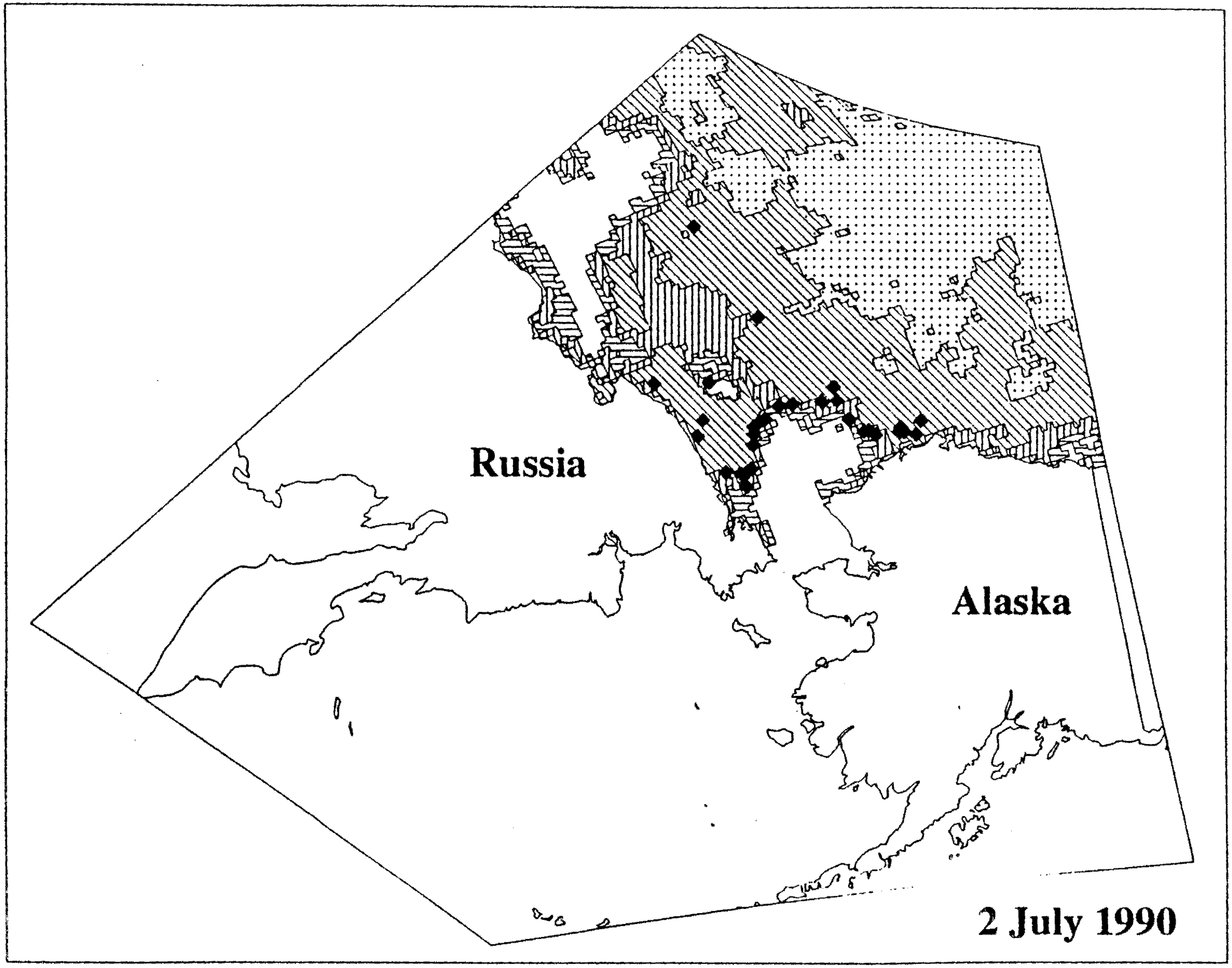
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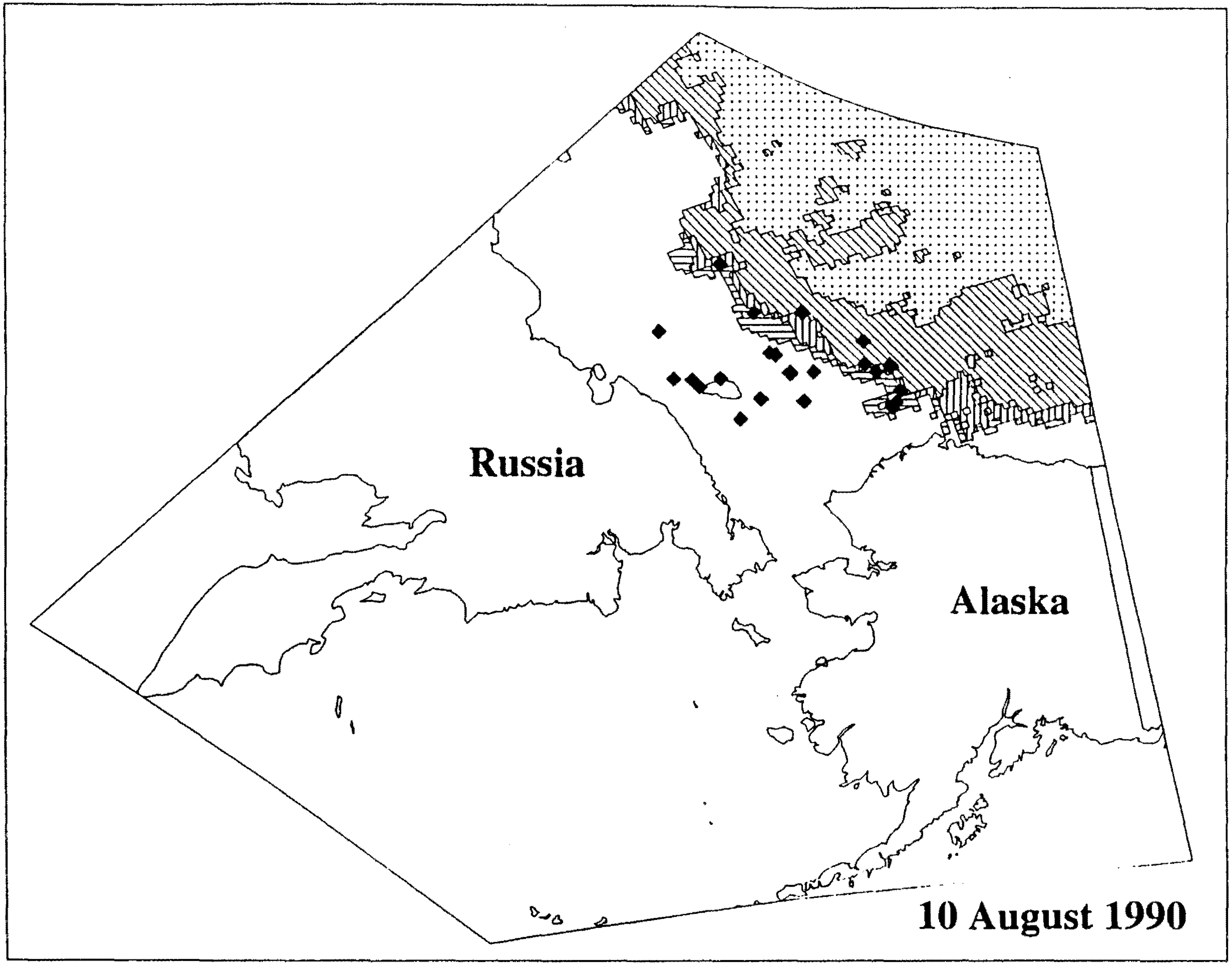
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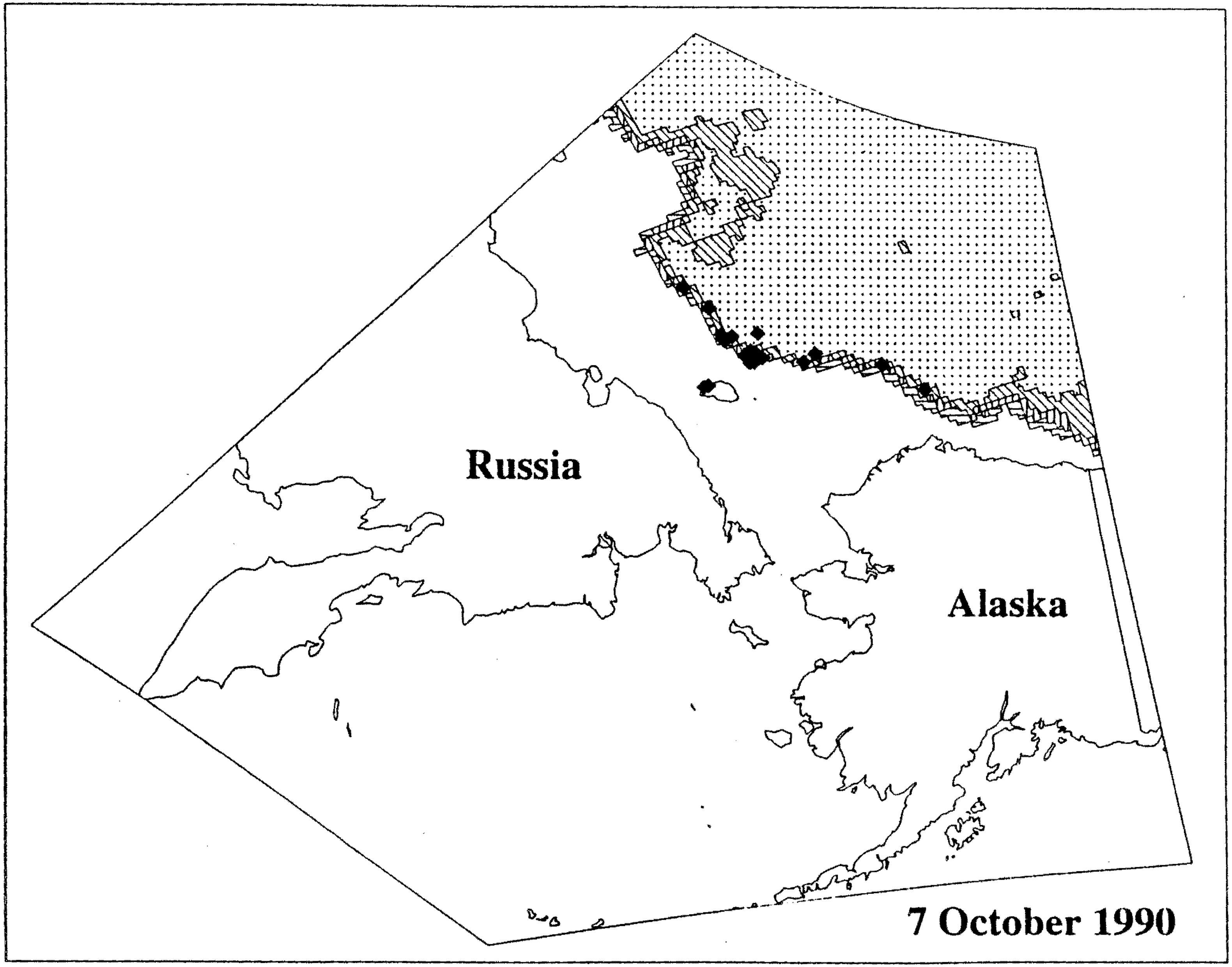
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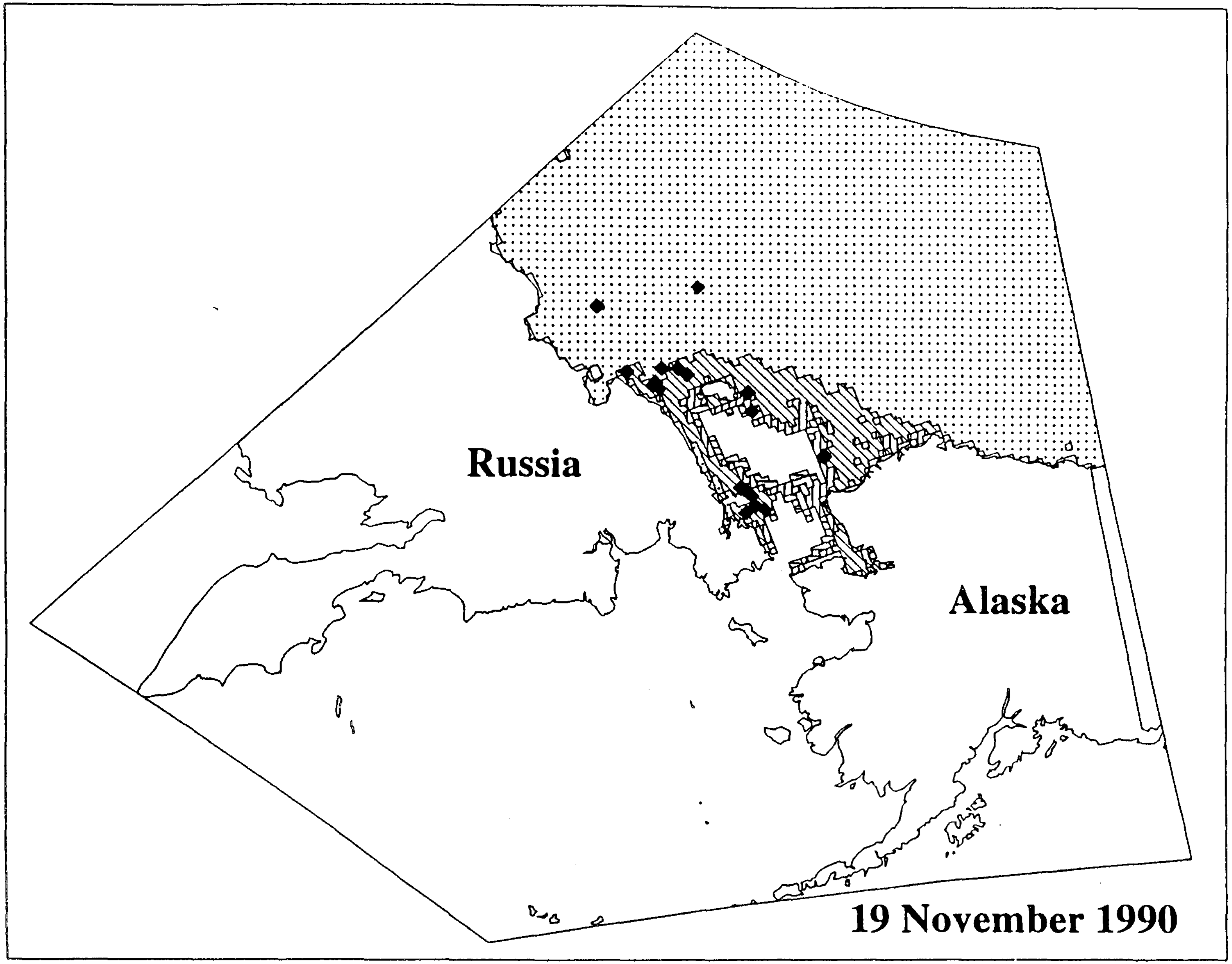

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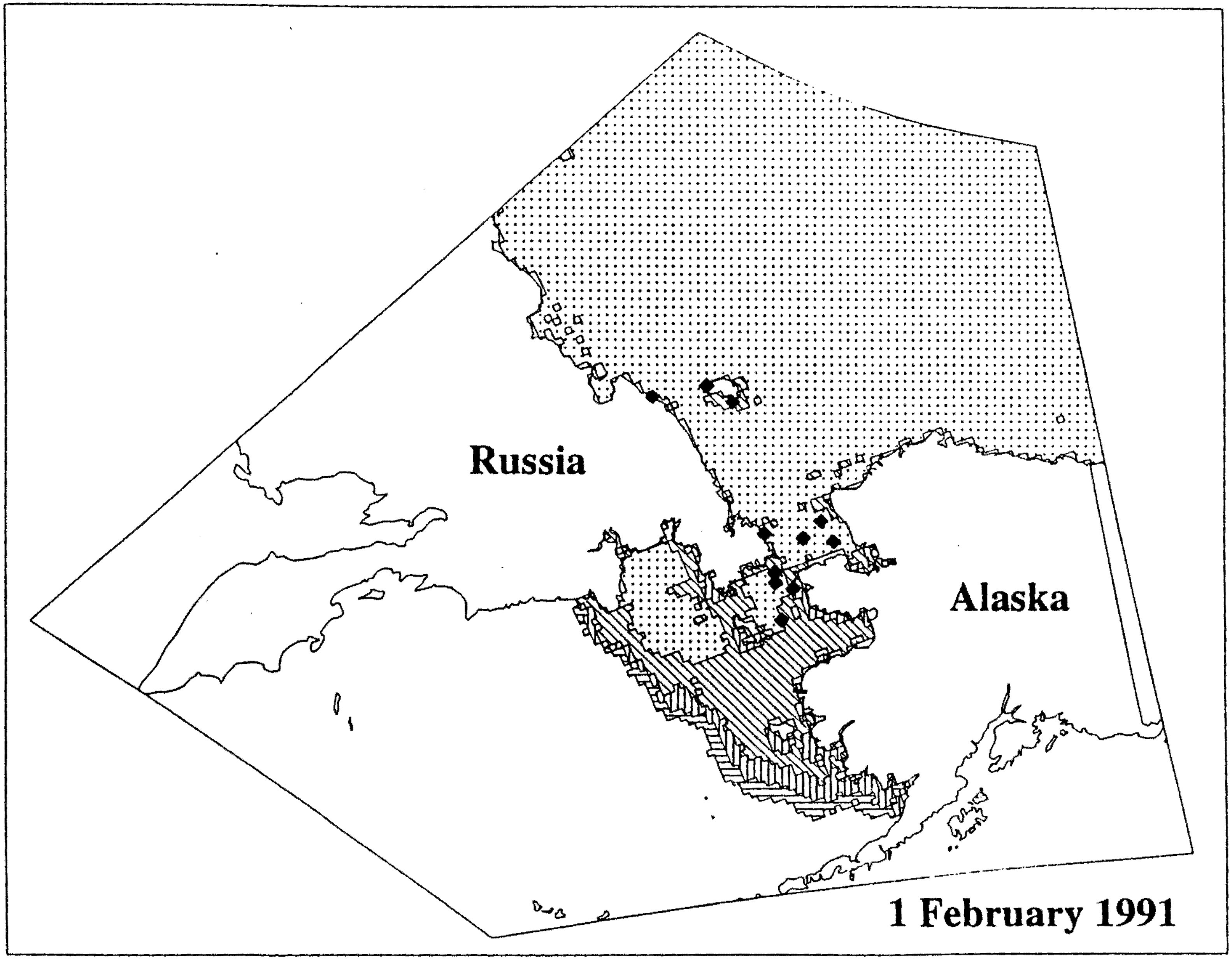
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