REMOTE SENSING DATA ACQUISITION, ANALYSIS, AND ARCHIVAL

by

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Final Report

Outer Continental Shelf Environmental Assessment Program
Research Unit 663

November 1988

ACKNOWLEDGMENTS

This study was funded in part by the Minerals Management Service, Department of the Interior, through an interagency agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Outer Continental Shelf Environmental Assessment Program.

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BACKGROUND

The current Alaskan OCS leasing schedule includes areas in the northern Bering Sea, and throughout the Chukchi and Beaufort seas. Sea ice in these areas not only poses a potential hazard to manmade structures and exploration activities such as drill ship operations, but is also a factor in pollutant transport and in the distribution and migration behavior of marine mammals. Remotely sensed imagery has been utilized in the Outer Continental Shelf Environmental Assessment Program for many purposes, but the most useful data to date have been those related to the forms, seasonal distribution and movement of sea ice. These data have also been used to estimate the concentration and distribution of suspended particulate matter, verify the presence of specific circulation features, and map the distribution of water temperature for use in other studies such as investigations of fish behavior. These data provide an excellent record of historical or baseline conditions which otherwise could not be available. Archival of satellite imagery has been considered a necessary part of providing a data base from which to assess specific environmental problems in view of outer continental shelf oil and gas development. The acquisition and archival of satellite imagery by this research unit provides convenient and economical access to this data base by OCSEAP investigations. While a decade ago satellite imagery was fairly inexpensive, a single 1:1,000,000 scale Landsat color image now costs $350, a single black and white Landsat print is $50, and a black and white AVHRR image is $44. Currently, the archive contains 20,000 AVHRR transparencies and various products (black and white single band prints and transparencies, color prints and transparencies, enlargements, etc., from 13,000 Landsat scenes, with a conservatively estimated replacement cost of around $3.5M for these photographic products alone, at current prices. In addition, the archive contains approximately 200 Landsat images in digital tape format and about the same amount of AVHRR digital tapes. These currently cost $660 and $80, respectively. Currently for AVHRR, the emphasis is on acquisition of digital tapes so that this particular part of the archive is showing the greatest relative growth. Furthermore, the archive contains images of both types not found in the national data base. This has resulted from a number of factors but chiefly because the institution maintaining the archive also acquires Landsat imagery directly from the satellite and deals directly with the Alaskan receiving station for AVHRR imagery. For this reason also, these data can be made available to OCSEAP users in a timely fashion. Thus this archive provides an extensive timely and economical access to these sources of data without the need to establish multiple channels of data flow from the sources of imagery.

In addition to acquisition and archive, the research unit maintains the equipment required to enhance the imagery and aid its analysis by OCSEAP investigators. Thus, color-coded ocean surface temperature maps have been generated and provided to OCSEAP investigators in the field within hours of their acquisition by the satellite, and retrospective data showing water surface temperature distributions from earlier years have been digitally enhanced and provided to OCSEAP management.

Finally, the research unit undertakes studies based on this extensive data set which have been identified by OCSEAP management as needed by other research units or as useful to OCSEAP/MMS for environmental assessment considerations. A number of such studies have been performed during this contract. Most were small, however, with one major study - on polynyi size, location.

OBJECTIVES

The stated objectives of this study were:

1. To acquire, analyze and archive remotely sensed imagery, including that based on infrared and microwave data, for the Alaska OCS areas, particularly those covered with seasonal sea ice. The Synthetic Aperture Radar (SAR) imagery shall be included as soon as it becomes available.

2. To provide imagery and special products to other OCSEAP investigators, and MMS and NOAA staffs.

3. Identify and describe sea ice distribution patterns and phenomena, such as building of ridges, movement of ice floes and islands, ice “breakout” through the Bering Strait, processes of freeze-up, and formation of leads and polynyi. The objective shall be accomplished in close cooperation with (or in support of) other OCSEAP investigations.

RESULTS

1. Acquisition and Archival of Remotely Sensed Imagery

A. AVHRR Imagery. In recent years, the value of this data set to OCSEAP studies has increased considerably. This is in part due to improvements in the quality of these data, partly due to advances in digital image processing and partly due to the types of studies conducted by OCSEAP. For the first two years of this three year contract period, we continued to acquire and archive AVHRR photographic positive transparencies of visible and thermal wavelength images on a daily basis. Some discretion was used taking into account the best data for the time of year.

During January of this year, NOAA closed its photographic laboratory at NOAA/NESDIS CDA Station (just outside Fairbanks), where photographic AVHRR products were being produced. At the same time, the host institution to RU 663 had developed a digital image capability so that much higher resolution multispectral AVHRR data products could be produced by RU 663 using AVHRR digital tapes. Therefore, it was determined to develop a new approach to archiving AVHRR data. First, a great quantity of facsimile AVHRR products were available from the weather service. While data from one or two of the six daily satellite passes had been archived previously, now data from all passes could be saved. While not the same quality as the previously archived transparencies, some useful information can be taken directly from them and, in addition, they can be used as a means of determining which digital tapes would be cloud-free in an investigator's area of interest. This is extremely important as the digital tapes are expensive. Therefore, the facsimiles were added to the archive and an additional archive of digital AVHRR tapes was initiated. This tape archive includes tapes identified by OCSEAP investigators as useful to their activities and tapes archived because they are largely cloud-free and represent good representations of conditions at various points in time. The archived tapes contain visual, near infrared and thermal infrared data and can be digitally analyzed and displayed in a multi-color format. In addition, products specific to a particular investigator can be produced. Tapes of AVHRR scenes found to be of interest to OCSEAP which have not been previously archived have been purchased by RU 663 from NOAA in Washington, D.C. and placed in the tape archive. Thus, AVHRR imagery has been obtained in three formats: positive photographic transparency, suitable for analysis or reproduction, positive paper facsimiles suitable for data selection (i.e. tape acquisition) and some analysis purposes, and magnetic tape. Appendix 1 describes lists of the positive transparencies, facsimile prints, and digital tapes acquired under the contract and submitted separately to NOAA/OCSEAP. Catalogue lists are necessary because choices were made and data were not archived for all dates.

B. Landsat Imagery. The host institution to this contract maintains a Landsat "Quick-Look" program under which Landsat imagery is acquired for scientific purposes. The image-producing equipment is located at the NOAA/NESDIS CDA Station where AVHRR imagery is acquired. Landsat has been purchased from the federal government by the EOSAT Corporation which is operating the satellite as a profit-making venture. We could not hope to maintain a useful archive by purchasing these images at their current prices. However, by special arrangement with EOSAT, the University of Alaska is permitted to acquire and archive these images for the purpose of scientific studies. The data is acquired through the cooperation of NOAA which operates the CDA Station and the University of Alaska, whose equipment and personnel transform the raw data into imagery. Although we have a number of Landsat images in digital tape format, only a few have been acquired through this contract. Almost all Landsat acquisitions under this contract have been in hard copy paper print and negative transparency format. We have two routes which can be used to perform digital image analysis on this imagery if we do not possess a digital tape: 1) we can purchase it at a rate of $660 per copy, or 2) we can digitize a hard copy print at a cost of around $50 (for time on an image scanner). This second route produces a somewhat lower quality image but in many instances - particularly where a number of images are to be analyzed - the value of the quantity available exceeds the loss of data quality. Appendix 2 describes Landsat images acquired and archived during this contract; a complete list was submitted separately to NOAA/OCSEAP.

C. **Side-Looking Airborne Radar.** We have maintained in our archive side-looking airborne radar imagery obtained by OCSEAP approximately ten years ago at the time that OCSEAP included a research unit for that purpose. In addition, we have added to this file a small quantity of side-looking airborne radar acquired by the Ice Centre Environment Canada as it is requested by investigators. We do not actively acquire these data because of their high cost relative to the demand for them. However, we can and have obtained these data from the Canadian archive as the need arises.

D. Aerial Photography. Our archive maintains file copies of the photographs obtained under the joint NASA/Alaska high altitude aerial photography program under which the entire state of Alaska was photographed at 1:125,000 scale in color infrared photography and selected portions of the state were re-photographed at 1:62,500 scale. Some areas such as the trans-Alaska pipeline corridor and the Beaufort Sea coast were photographed more than once during the life of the program. During this contract various copies of these photographs have been supplied to OCSEAP and MMS as they represent historical benchmarks in the development of the Alaskan coastal zone.

E. Passive Microwave Imagery. For several years NASA has operated the multi-channel passive microwave SMMR which provides low resolution (30 x 30 km) all-weather monitoring of ice in the polar ice caps. These data are available from NASA Goddard in raw format or gridded onto 10 km pixels. There have been no requests for these data by OCSEAP investigators. However, one of our students has acquired the data set for Alaska between 1983 and 1987. (Thus this data set contains 900 images of Alaska and the adjacent oceans on a two-day interval between 1983 and 1987.) These data are available for OCSEAP investigators, if the need arises. This instrument is aboard Nimbus 7, and all but one of the frequency bands have failed. Since the most useful data are derived form multi-frequency algorithms, the data set is essentially no longer being expanded.

Last year, a similar multi-channel microwave radiometer was launched aboard the most recent vehicle of the Defense Meteorological Satellite Program. These data are held for a period of months and then released to the World Data Center for Ice and Snow in Boulder, Colorado. We have been in contact with the data center and anticipate no problem in obtaining these data if they are desired by OCSEAP investigations.

F. NOAA/Navy Ice Charts. These charts are produced weekly by the NOAA/Navy joint ice center, Suitland, Maryland. They contain comprehensive ice data including ice edge information based on passive microwave imagery. We have continued to obtain these charts as they become available. The charts cover the entire Alaskan study area and are filed in chronological order since 1972. We have found these charts to be useful for statistical studies of several ice edge location (but not highly detailed) studies of the nearshore environment.

G. SAR Imagery. These data are not yet available. The launch of ERS-1 carrying the first civilian synthetic aperture radar since Seasat (1978) is scheduled for October, 1990. It will be followed by a Japanese and a Canadian SAR later in that decade. The host institution to this contract will be the location of the Alaskan SAR receiving station. These data should provide cloud-free, year round images of sea ice and a measure of sea state in the Beaufort, Chukchi and Bering seas.

2. Provision **of Imagery and Special Products to Other OCSEAP Investigators, and MMS and NOAA Staffs**

During the last three years, we have responded to a number of data requests. These requests and our response to them follow this introduction. As will be seen, their requests range from provision of a representative satellite image from historical files to production of timely data sets consisting of products derived from satellite imagery using extensive interactive computer programs.

Our capability was considerably enhanced during the last part of this contract by the development of an interactive digital image analysis laboratory by the University of Alaska Fairbanks. This laboratory represents a total investment of approximately $800K. This facility has greatly expanded our capability to provide special products in fulfillment of our contractual obligations.

From January 1- March 31, 1986 we were engaged in three major activities: 1) a study of temporal changes in the Yukon Delta in response to a request from RU 660 (Martin, Envirosphere); 2) participation in the Chukchi Sea Update Meeting; and 3) provision of remote sensing imagery to OCSEAP management.

During the period April 1- June 30, 1986, the principal investigator participated in seal reconnaissance flights by RU 667 (Frost, Lowry, and Burns) out of Prudhoe Bay in mid-June. These flights were conducted at 300' altitude which made possible very detailed low altitude oblique photography. We were fortunate that clear sky conditions made Landsat imagery available from this period so that the photography obtained (approximately 450 photographs) can be used as "ground truth" for the Landsat imagery. Also during this period, we completed our Yukon Delta work for Martin (RU 087) and began preparation of the results in a format suitable for publication in an appropriate journal. John Brueggeman (RU 625) also contacted us concerning ice analysis using satellite imagery to support 1979 whale studies. Following the Chukchi Sea Update meeting in Anchorage this spring, Spaulding (RU 676) requested a copy of our digital Chukchi Sea ice edge data. This was provided with documentation.

During the period July 1- September 30, 1986, we completed preparation of the results of our Yukon Delta study with Martin (RU 087) for publication in an appropriate journal. We also performed analysis of ice conditions in conjunction with whale sightings in the Bering Sea for John Brueggeman (RU 625). For OCSEAP management, we provided satellite imagery to document sea surface conditions at the time of an oceanographic cruise in the Chukchi Sea. Data requested included both ocean temperature and sediment plume distributions.

During the period October 1- December 31, 1986, we continued to provide ice-related data which could be used in conjunction with Brueggeman's whale sightings in the Bering sea. This study occupied the bulk of our activities during this quarter. The whale sightings (about 3,000) have been coded in terms of latitude and longitude. The objective of our efforts was to provide data which could be used to determine whether a meaningful statistical relationship could be found between these sightings and ice parameters such as concentration, type (thickness) and ice edge location (including polynya boundaries). For OCSEAP management, we provided enhanced AVHRR imagery in the vicinity of Kotzebue Sound and in the Beaufort Sea.

From January 1 to March 31, 1987, we continued to provide assistance to RU 625 (J. Brueggeman). We created a program to distinguish whether a given station is within or outside a polynya from the digitized data. All 3,000 of Brueggeman's whale/no whale data were tested for correlation with polynyas.

During the period April 1- June 30, 1987, Everett Tomfelt of the Anchorage MMS Office requested a data search and copies of appropriately selected imagery, which was accomplished.

During the period July 1, 1987- September 30, 1987, Walter Johnson, Sathy Naidu and Jim Raymund (RU 690) conducted a cruise aboard the Surveyor in the Chukchi Sea between September 17 and October 8. This RU provided support to that effort by monitoring NOAA AVHRR satellite images as they became available during this time and producing high quality photographic prints of the scenes which may be of value to their study. A high-resolution SPOT image was also acquired showing suspended sediment in the vicinity of Kotzebue. Also during this quarter, we provided Dale Kinney of MMS with "Width and Persistence of the Chukchi Polynya," and Statistical Description of the Summertime Ice Edge in the Chukchi Sea." Mr. Dick Ragle wanted information regarding ice conditions and related hazards in Stephanson Sound and Prudhoe Bay.

During the period October 1- December 31, 1987, we attended and participated in the OCSEAP Arctic Information Transfer/Update Meetings held in Anchorage. We presented two papers - "Arctic Remote Sensing," which is a review of remote sensing techniques as they apply to the Alaskan OCSEAP needs; and "A Study of Possible Meteorological Influences of Polynya Size," which describes our research on polynyas. Following the presentation of the papers, there was a very helpful discussion with other OCSEAP investigators and OCSEAP and MMS staff. We have formulated our plans for further work based on these discussions.

From January 1- March 31, 1988 our activities were largely concentrated in two areas: data acquisition and data analysis. There were no requests for data assistance during this quarter.

During the period April 1- June 30, 1988, we responded to a request for image data showing the "West Dock" area of Prudhoe Bay at various stages of the West Dock Causeway. This request caused us to consider the" possibility of registering low resolution AVHRR imagery to higher resolution Landsat imagery in order to fix the location of features visible on the AVHRR imagery. This was done successfully and the resulting product forwarded to our contract monitor. We also received a verbal request for thermal imagery in support of fisheries studies later in the summer in the nearshore areas of the Beaufort Sea.

From July 1- September 30, 1988, the development of a digital image analysis capability made possible a number of projects providing assistance to OCSEAP investigators which included analysis of AVHRR images for use in fisheries study; response to a request from MMS to examine data to determine the relative feasibility of various routes of whale migration from Mackenzie Bay to Barrow; and responding to a request from Dale Kinney of MMS to produce images to provide data for studies . attempting to correlate the presence of ocean mammals with open-water areas in sea ice.

3. Performance of Studies Related to the Needs of the Outer Continental Shelf Environmental Assessment Program

A. Studies Resulting in Published Papers. Following a request for data assistance from RU 660 (Martin) (see section 2 above), we found that we had done a significant amount of research on the question of change in the vicinity of the mouth of the Yukon River. The material that had been produced was published as "Landsat Determined Geographic Change," in ***Photogrammetric Engineering and Remote Sensing.*** An abstract of this paper is included here as Appendix 3.

OCSEAP has long held an interest in ice motions through Bering Strait in terms of its influence on marine mammal migration and the possible transport of pollutants. We were able to work cooperatively with T. Kozo to produce "Mesoscale Nowcasting of Sea Ice Movement Through the Bering Strait with a Description of Major Driving Forces," submitted for publication in ***Monthly Weather Review.*** An abstract is included as Appendix 4.

One of the parameters often listed as important to models of pollutant transport in ice infested water is the distribution of sizes of ice floes. Earlier this year we submitted a manuscript entitled "Summertime Distribution of Floe Sizes in the Western Nearshore Beaufort Sea," to the ***Journal of Geophysical Research.*** It has been reviewed and is being revised according to suggestions, An abstract of the manuscript is included here as Appendix 5.

The flooding of rivers on Alaska's North Slope marks the beginning of the transition from winter to summer in the Beaufort Sea. The flood waters exit the river tributaries and spread upon the adjacent fast ice. The timing and extent of this springtime event have had a bearing on a number of regulatory decisions regarding petroleum development activities in this region. Over the past several years we have conducted a number of small studies related to springtime river flooding. Last year we assembled this material into a manuscript which has been submitted to ***Arctic and Alpine Research.*** An abstract is included here as Appendix 6.

B. Studies Resulting in Published Reports. Sea ice is seldom removed from the Chukchi Sea even in summertime. The ice edge in summer is usually located in the Northern part of the sea with its configuration controlled at least in part by bathymetrically steered currents. However, the ice edge location is variable both from year to year and within each year. This variability has a significant influence on the operation of drillships and other petroleum-related activities. We reported the results of a study of this ice edge behavior in the *Chukchi Sea Information Update,* published by OCSEAP in June 1987 (pp. 33-41).

Remote sensing is a particularly valuable tool to science in the Arctic because of the relative inaccessibility of the region. In the past few years there has been a significant increase in the quantity and quality of sensors available for arctic studies. Upon request, we performed a review of these sensors and their utility to OCSEAP studies. The results were presented at the November 1987 Arctic Information/Update meeting and published in the OCSEAP publication, ***Alaska OCS Region 1987 Arctic Information Transfer Meeting,*** June 1988 under the title, "Arctic Remote Sensing."

Because of the extensive shallow nearshore waters in the vicinity of Prudhoe Bay, causeways have been utilized for a variety of purposes including seawater intake facilities, docks, and drilling platforms. There has been considerable interest in the influence these structures exert on their physical and biological surroundings. Using satellite imagery we observed at least one occasion when a modification of the thermal regime was detectable. This was presented to OCSEAP and subsequently published as "The Causeway Effect: Modification of Nearshore Thermal Regime Resulting from Causeways," and published in ***Beaufort Sea Information Update,*** April 1988.

Recently there has been increased interest in the role of polynyas on the behavior of marine mammals. As a result of this interest, this research unit has conducted an extensive analysis of polynyas in the Alaskan nearshore region. Some preliminary results thought to be of particular interest at the time were presented as "A Study of Possible Meteorological Influences on Polynya Size," and published in ***Alaska OCS Region 1987 Arctic Information Transfer Meeting,*** June 1988.

C. Studies Reported **in This Final Report.** We have been conducting a major study of polynyas in the seas adjacent to Alaska. In particular, we have measured the areal extent of these polynyas versus time for six study years. Following that, we have calculated correlation statistics between the polynya extent and regional winds. These results are reported in Appendix 7.

APPENDIX 1

Description of NOAA/AVHRR Positive Transparencies, Facsimile Prints, and Digital Tapes Acquired and Archived Under the Contract

NOAA/AVHRR transparencies for the period January 1986 through January 20, 1988 are listed by date and orbit number and categorized according to presence or absence of clouds in four regions: the Beaufort Sea, the Chukchi Sea, the Bering Sea, and the Gulf of Alaska. This imagery is predominantly thermal infrared band from the last week in October through mid-March and visible band imagery for the remainder of the year. No transparencies were available from Gilmore Tracking Station after January 20, 1988.

NOAA facsimile prints are listed for the period January 1986 through February 1989. They are listed by date and orbit number and categorized according to presence or absence of clouds in nine regions: USSR, Beaufort Sea, Chukchi Sea, Bering Sea, Interior Alaska, Gulf of Alaska, Cook Inlet, Southeast, and Canada. After January 20, 1988, the facsimile prints are a replacement for transparencies.

NOAA digital tapes are listed for the period September 1974 through February 1989. This is not daily acquisition. Approximately 175 tapes are archived from numerous sources. All are listed by date, satellite number, and orbit number. Additional information varies depending on the source of the imagery. It may contain qualitative descriptions of cloud-free areas on the imagery or information useful if the imagery is to be used on the ADVAL image analysis system.

There is some overlap in the listings between the record kept at the Geodata Center and that kept by ADVAL.

All of the image products are archived at the Geophysical Institute's Geodata Center.

APPENDIX 2

Description of Landsat Images Acquired and Archived Under the Contract

Between January 8, 1986 and March 3, 1989, we archived 1,103 Landsat scenes of Alaska. They are sorted by Grid, Path, Row, and Date. Additional information is given on percent cloud cover and bands, and for some scenes quality of the image is recorded.

Most Landsat imagery has been obtained from the University of Alaska Quick Look program and is archived as photographic prints at the Geodata Center.

APPENDIX 3

Landsat-Determined Geographic Change

by

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ABSTRACT

Geomorphic changes in the Yukon River Delta occurring over a 35-year span have been detected through comparison of a recent Landsat image with earlier maps compiled from aerial photography. Island formation or growth and channel migration were found to have taken place with a calculated location precision of around 200 m. Geographic control of the Landsat image was established through digitization of surveyed control points used for control of aerial photography for mapping. Tide stage considerations were found to be useful in these low-lying areas, even though the astronomical tide range here is relatively small.

(Submitted to ***Photogrammetric Engineering and Remote Sensing.)***

APPENDIX 4

Mesoscale Nowcasting of Sea Ice Movement Through the Bering Strait with a Description of Major Driving Forces

by

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ABSTRACT

Surface atmospheric pressure data from a triangular station network surrounding the Bering Strait are used to calculate hypothetical geostrophic wind velocities. Net daily Strait sea ice movement is derived from visible and infrared NOAA satellite imagery for November through May, 1974 to 1984. These historical ice-motion data and network wind-velocity data are used to develop an empirical 12-hr advance forecast (nowcast) sea ice movement model with all-weather capabilities. A necessary outgrowth of this study has been the identification and classification of three modes of ice movement and two modes of ice immobilization according to their major driving forces. The flit ice-movement mode is from the Chukchi Sea to the Bering Sea requiring a minimum northeasterly geostrophic wind of 12 m s^{-1}. The second and third modes represent ice movement from the Bering Sea to the Chukchi Sea. Mode 2 is driven by a preexisting north-flowing ocean current that offsets weak winds from the northeast. Mode three is large movement due to a combination of southwesterly winds and north-flowing ocean current. The first immobilization mode (maximum duration one week) is an apparent balance between northerly wind stress, current stress from the south, and internal ice stresses. The second immobilization mode (least common) is due to double, solid sea ice arches forming across the Strait. These arches remained intact under strong northeasterly geostrophic winds (20–26 m s^{-1}) and can last up to 4 weeks.

(Submitted to ***Monthly Weather Review.)***

APPENDIX 5

Summertime Distribution of Floe Sizes in the Western Nearshore Beaufort Sea

by

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ABSTRACT

The areal extent of ice floes has been measured from Landsat imagery of the summertime Beaufort Sea, spanning the five months between break-up and freeze-up. In general, the distribution of floe areas was found to obey a power law: $N(S) = N_1 S^{\lambda}$, where the counted number of floes per unit floe size interval, ISI(S), is related to the number of floes in the particular distribution at unit floe size, (N_1), the floe size, (S), and λ, a parameter found hereto range between -1.33 and -2.06. The value of λ decreased from -1.33 in May to -2.06 in August and then increased to nearly -1.47 in September. An exponential relationship with A was found among the values of N_1 from the various distribution $N_1(\lambda) = N_O e^{-14.4\lambda}$. This relationship appears to hold regardless of the seasonal variation of A. Thus, floe size distributions were found to obey $N(S) = N_O(e^{-14.4}S)^{\lambda}$, with a value $N_O = 1.23 \times 10^{-6}$, where N_O is the projected number of floes per unit floe size at unit floe size for A = 0.

Although not observed, a value of A = -1 was found by theoretical considerations to produce a floe size distribution in which the apparent distribution of floe size is the same regardless of the scale at which it is viewed. Based on the observed variation of λ with season, it is hypothesized that such a distribution might appear earlier in the year than the observing period reported here.

(Submitted to ***Journal of Geophysical Research.)***

APPENDIX 6

The Timing of Snowmelt Flooding of Alaska's Major North Slope Rivers--An Anomalous Occurrence

by

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ABSTRACT

Six milestones associated with snowmelt flooding of a major Alaskan North Slope river during breakup have been identified and their dates of occurrence established for a 14-year period using satellite imagery. The most reliably measured milestone is over-ice flooding, which occurs when river snowmelt floodwaters spread out upon oceanic fast ice at the river's mouth. On the average, for the Sagavanirktok River, this occurs on May 25 with a standard deviation of 8 days. However, the pattern of dates for this event suggests bimodality, with the primary mode having an average date of May 27 and a standard deviation of only 3 days, and the secondary mode occurring nearly a month earlier. Time series analysis yields a trend toward earlier dates of over-ice flooding in agreement with the concept of a climatic warming. However, the statistical reliability of this result is low.

(Submitted to ***Arctic and Alpine Research.)***

APPENDIX 7

A Study of Possible Meteorological Influences on Polynya Size

This report describes in outline form the results of a comprehensive study of polynyi, areas of open water occurring in the otherwise ice-covered wintertime Bering and Chukchi Seas. The data used were images obtained by the Advanced Very High Resolution Radiometer aboard the NOAA series satellites. Polynya boundaries were traced directly from satellite imagery using a digitizing table. A computer program was used to rectify the image distortion and calculate the extent of each polynya. This yielded tables of polynya extent for all cloud-free days for six one-year study periods.

The first objective was to document the locations of recurring polynyi in the U.S. portions of the Outer Continental Shelf. This was accomplished and the results appear in this report in map format. The second objective was to develop a statistical picture of the extent of these polynyi over a number of years. This was accomplished also and the results appear here in summary form and more completely in a comprehensive report on file with OCSEAP management in Anchorage, Alaska. The third objective was to attempt to relate polynya extent with environmental parameters whose measured values were readily available. These results are quite extensive but unfortunately, largely ambiguous. For this reason they are only described here in general terms while the complete results are detailed in the file report. The remainder of this summary describes the rationale for the various statistical approaches taken in our approach to this third objective, and an assessment of the results.

If one examines wintertime satellite images of the Bering and Chukchi Seas, the most prominent class of features related to sea ice to be seen is the scattering of polynyi generally located along coasts. If a sequence of images is viewed, these polynyi can be seen to expand and contract over periods of several days to weeks. Often groups of polynyi appear to open in phase giving the impression that some general regional forcing is responsible for their formation. There are two large scale regional forcing agents that are external to the ice, winds and ocean currents, and one, ice stress, that is internal to the ice. Clearly ice stress is ultimately related to winds and currents but the force can be transmitted distances sufficiently large that locally it may be the only apparent force acting on the ice. Furthermore, the application of these forces is modified by Coriolis acceleration.

The extensive tabulation of polynya extent we had compiled invited an attempt to correlate polynya extent with these forcing agents. However, of the three, only winds are measured with regularity and on anything like a comprehensive basis. Thus, winds were the only data set available for correlation studies. Even these data are not ideally suited for correlation with polynyi since none of the observing stations are adjacent to the polynya sites, and in many locations orographic configurations cause wind measurements to be only locally valid. On the other hand, this region is known for large storms generally associated with ice motions. It was thought that even scalar winds might be a measure of general ice forcing events related to polynya openings, and although strong correlations might not be found, some relationship might be found. As will be seen, this was not the case. Generally speaking, the correlations found were weak and the confidence levels low. Initial failures at farther straightforward correlations led to attempts to find more and more exotic relationships involving thresholding, running average, delayed correlations, and even application of less rigorous correlation techniques such as ranking.

INTRODUCTION

A polynya is rigorously defined as an irregularly shaped opening enclosed by ice which may contain brash ice or uniform ice markedly thinner than the surrounding ice [Stringer, Barnett, and Godin, 1984). Polynyi are frequently described in the literature as non-linear open water areas surrounded by sea ice without mention of whether an attempt was made to clearly differentiate the open water from thin ice or if such a distinction was possible. Polynyi are important for the understanding of climatic, oceanographic, and biological phenomena in the Arctic.

Dey, Moore, and Gregory (1979) describe the use of AVHRR thermal infrared imagery for monitoring and mapping sea ice freeze-up and break-up 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-January. They concluded that AVHRR thermal infrared images are admirably suited for generalized statistical analysis of sea ice and that boundaries between first-and multiyear 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 polynyi, the size of polynyi at maximum ice cover, and the pattern of sea ice break-up 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 and Applications Division of the Canadian Atmospheric Environment Service, they studied 16 polynyi in the Canadian Archipelago from July to November, 1975-1977, and they reported broad dates for formation and disappearance of the polynyi.

Stringer (1982) measured the width and persistence of the Chukchi Polynya using Landsat and AVHRR imagery. A qualitative correlation was found between average ice motion away from the coast and the mean vector wind for all months except perhaps July. Carleton (1980) mapped the recurring polynyi south of the Pt. Hope/Cape Thompson area using Landsat imagery. He was able to differentiate between open water and thin ice. He calculated areas for both the open water and thin ice regions and related their total size to the climatic factors of wind and temperature.

Smith and Rigby suggest that polynyi are formed by the effects of wind and temperature, or from the effects of upwelling, currents and tides. Treating a similar and somewhat related subject, Rogers (1978) correlated the distance of the summertime ice edge from Barrow with thawing degree days and components of the geostrophic wind. This report describes the results of a study performed to determine whether polynya area could be correlated with meteorological conditions in a manner similar to the relationships found between these factors and the location of the ice edge.

DATA AND ANALYSIS

The Geophysical Institute Geodata Center includes a collection of AVHRR images from 1974 to the present. Thus, it appeared feasible to document the dates of appearance and disappearance of polynyi for the Bering and Chukchi Seas as well as to quantitatively determine the polynya areas and relate these areas to climatological data.

Nineteen polynyi locations were originally identified and named. A twentieth, the Anadyr Gulf polynya was added to the years of 1975, 1979, and 1983 for the months January through April and January 1986. The names and locations of the polynyi are given in Figure 1 and Table 1. At the conclusion of this study, it became obvious that a few of the original nineteen polynyi sites ought to be revised. The revisions are given in Figure 2 and Table 2.

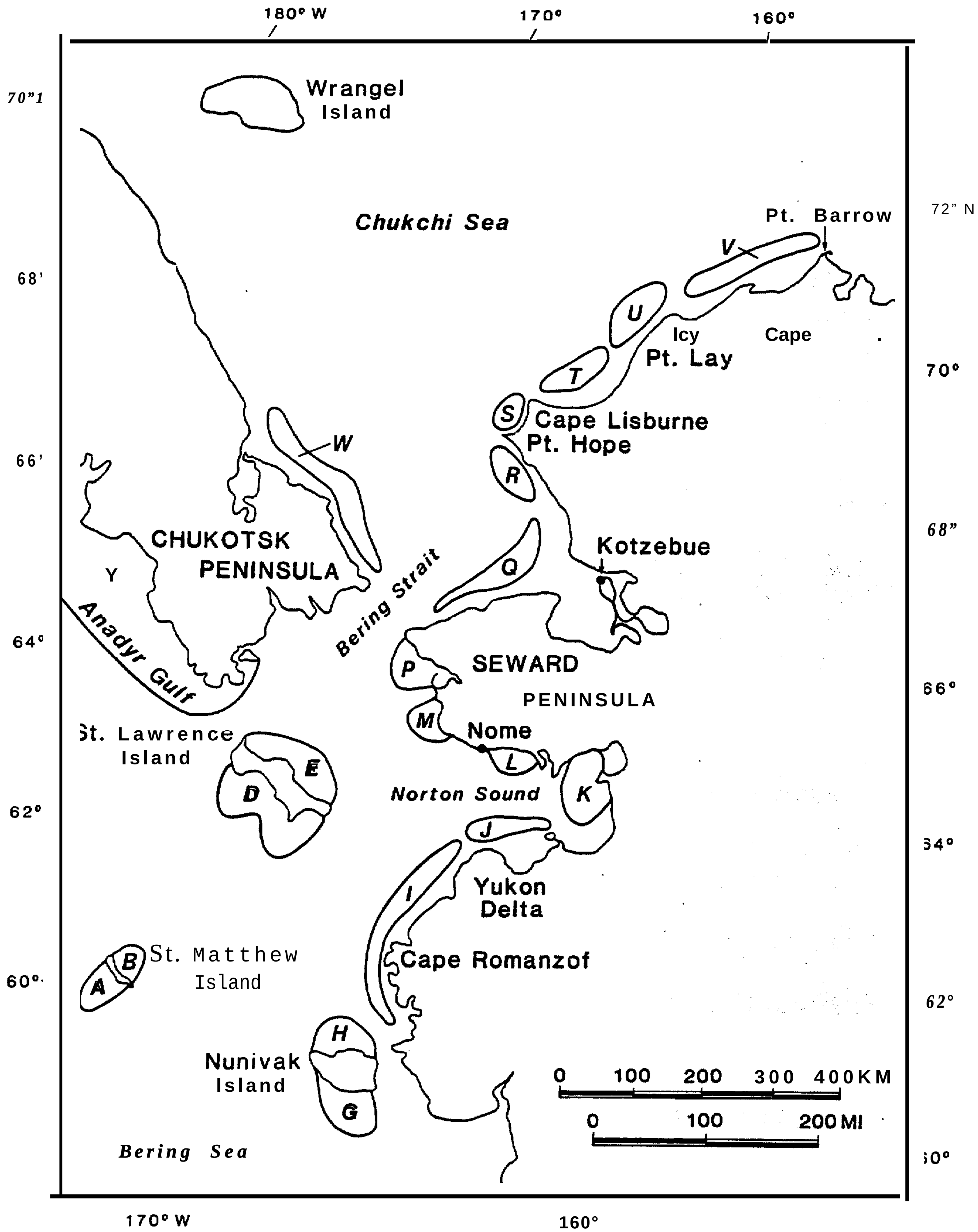

Figure 1. Preliminary Identification of Polynyi for Statistical Studies.

Table Ia. Preliminary Identification of Polynyi for Statistical Studies.

Location of Polynyi	Coded Designation on Alaska Base Map	Median Size (km^2) by Month Averaged Over Six Years						
		Jan.	Feb.	Mar.	Apr.	May	Jun	Jul
St. Matthew Island Polynya, South	A	OPEN	402	1050	1920	OPEN	OPEN	OPEN
St. Matthew Island Polynya, North	B	o	0	0	0	OPEN	OPEN	OPEN
St. Lawrence Island Polynya, South	D	3280	1940	2740	5050	OPEN	OPEN	OPEN
St. Lawrence island Polynya, North	E	o	0	0	0	OPEN	OPEN	OPEN
Nunivak Island Polynya, South	G	3000	1160	2440	23400	OPEN	OPEN	OPEN
Nunivak Island Polynya, North	H	0	0	126	39200	OPEN	OPEN	OPEN
Cape Romanzof Polynya	I	796	883	1880	27800	OPEN	OPEN	OPEN
Yukon Delta Polynya	J	o	0	0	225	OPEN	OPEN	OPEN
Norton Sound Polynya	K	1290	1070	2080	6140	15400	OPEN	OPEN
Nome Polynya	L	322	164	1400	5070	15400	OPEN	OPEN
Seward Peninsula Polynya, South	M	1670	613	1720	1260	7880	OPEN	OPEN
Seward Peninsula Polynya, North	P	1620	833	1740	1270	7600	OPEN	OPEN
Kotzebue Sound Polynya	Q	2720	0	0	194	0	OPEN	OPEN
Cape Thompson-Pt. Hope Polynya*	R	218	140	510	216	60	250	OPEN
Pt. Hope-Cape Lisburne Polynya	s	80	0	18	55	247	5630	OPEN
Cape Lisburne to Pt. Lay Polynya**	T	283	0	515	590	5470	8820	OPEN
Pt. Lay to Icy Cape Polynya**	u	o	0	188	530	7040	8980	OPEN
Icy Cape to Pt. Barrow Polynya**	v	417	0	0	153	5290	53	488
Chukotsk Peninsula Polynya	w	o	0	0	0	0	OPEN	
Anadyr Gulf Polynya	Y	4950	3140	4490	6180			

• Carleton (1 980)
** Chukchi Polynya (Stringer, 1982)

Table 1 b. Preliminary Identification of Polynyi for Statistical Studies.

Location of Polynyi	Coded Designation on Alaska Base Map	Average Size (km2) by Month Averaged Over Six Years						
		Jan.	Feb.	Mar.	Apr.	May	Jun	Jul
St. Matthew Island Polynya, South	A	975	467	2310	2200	OPEN	OPEN	OPEN
St. Matthew Island Polynya, North	B	o	0	94	123	OPEN	OPEN	OPEN
St. Lawrence Island Polynya, South	D	4250	1900	4320	13900	24700	OPEN	OPEN
St. Lawrence Island Polynya, North	E	o	297	2790	260	797	OPEN	OPEN
Nunivak Island Polynya, South	G	2870	1830	2800	26100	OPEN	OPEN	OPEN
Nunivak Island Polynya, North	H	38	520	2040	11000	OPEN	OPEN	OPEN
Cape Romanzof Polynya	I	1250	2750	4600	8640	OPEN	OPEN	OPEN
Yukon Delta Polynya	J	280	1810	1230	4380	OPEN	OPEN	OPEN
Norton Sound Polynya	K	1820	3160	4500	7730	13200	OPEN	OPEN
Nome Polynya	L	800	1820	3810	5280	10600	OPEN	OPEN
Seward Peninsula Polynya, South	M	3510	2000	2370	2880	7680	OPEN	OPEN
Seward Peninsula Polynya, North	P	3200	2140	2120	2940	6260	OPEN	OPEN
Kotzebue Sound Polynya	Q	1630	2690	932	607	267	166	OPEN
Cape Thompson%. Hope Polynya*	R	1700	2320	1550	1030	569	5080	OPEN
Pt. Hope-Cape Lisburne Polynya	s	360	1880	182	159	4480	11600	OPEN
Cape Lisburne to Pt. Lay Polynya**	T	1700	3320	1150	2420	11500	12500	OPEN
Pt. Lay to Icy Cape Polynya **	u	1970	2920	1330	2240	10800	12200	OPEN
Icy Cape to Pt. Barrow Polynya **	V	2160	2290	1310	2150	9480	7770	1340
Chukotsk Peninsula Polynya	w	964	471	511	0	145	OPEN	
Anadyr Gulf Polynya	Y	7540	3340	5950	11600			

• Carleton (1980)
** Chukchi Polynya (Stringer, 1982)

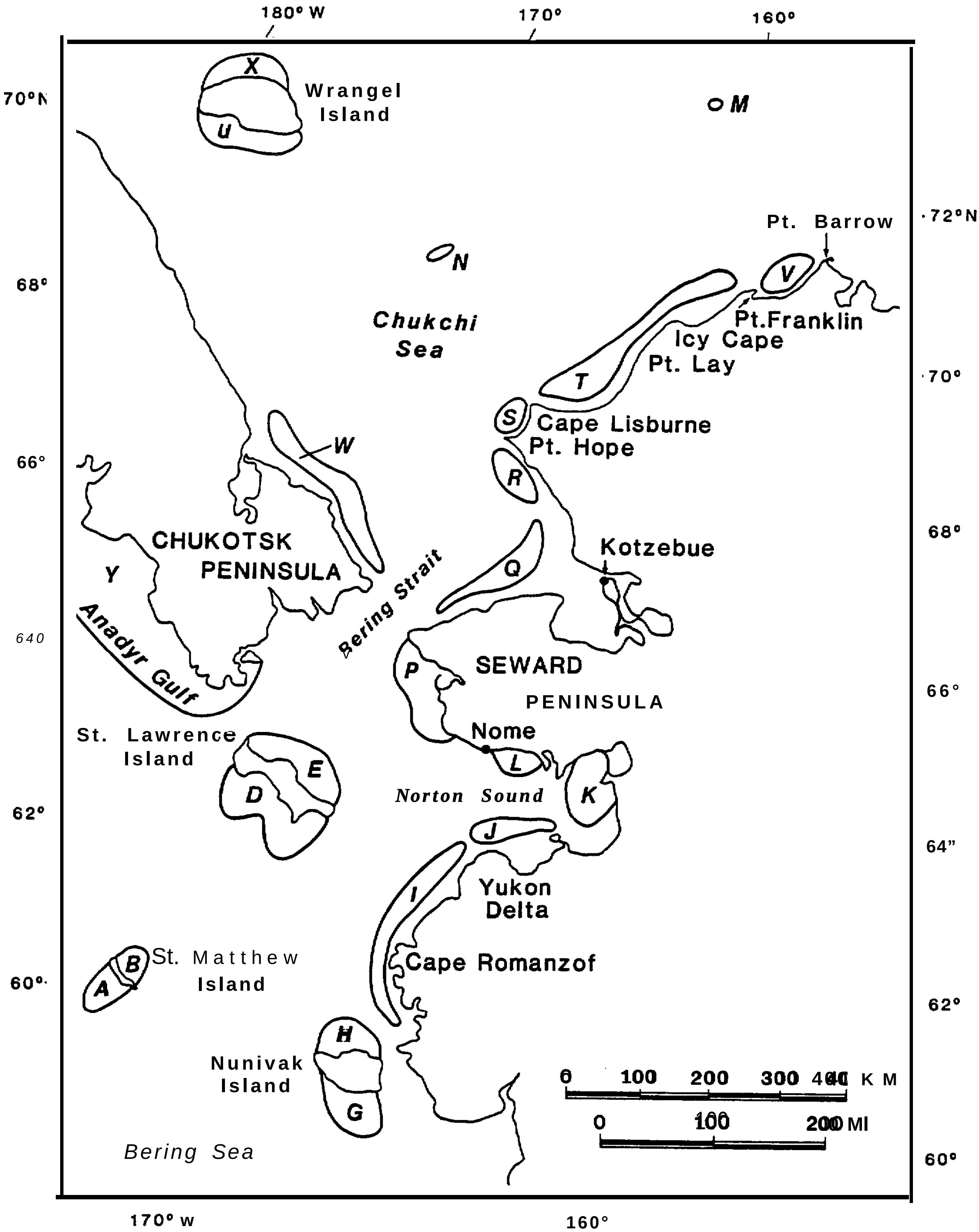

Figure 2. Final catalog of Recurrent Polynyi in the Chukchi and Bering Seas.

Table 2a. Final Catalog of Recurrent Polynyi in the Chukchi and Bering Seas

Location of Polynyi	Coded Designation on Alaska Base Map	Median Size (km2) by Month Averaged Over Six Years						
		Jan.	Feb.	Mar.	Apr.	May	Jun	Jul
St. Matthew Island Polynya, South	A	OPEN	402	1050	1920	OPEN	OPEN	OPEN
St. Matthew Island Polynya, North	B	0	0	0	0	OPEN	OPEN	OPEN
St. Lawrence Island Polynya, South	D	3280	1940	2740	5050	OPEN	OPEN	OPEN
St. Lawrence Island Polynya, North	E	0	0	0	0	OPEN	OPEN	OPEN
Nunivak Island Polynya, South	G	3000	1160	2440	23400	OPEN	OPEN	OPEN
Nunivak Island Polynya, North	H	0	0	126	39200	OPEN	OPEN	OPEN
Cape Romanzof Polynya	I	796	883	1880	27800	OPEN	OPEN	OPEN
Yukon Delta Polynya	J	0	0	0	225	OPEN	OPEN	OPEN
Norton Sound Polynya	K	1290	1070	2080	6140	15400	OPEN	OPEN
Nome Polynya	L	322	164	1400	5070	15400	OPEN	OPEN
Katie's Polynya	M							
Herald Shoal Polynya	N							
Seward Peninsula Polynya	P							
Kotzebue Sound Polynya	Q	2720	0	0	194	0	OPEN	OPEN
Cape Thompson-f% Hope Polynya*	R	218	140	510	216	60	250	OPEN
Pt. Hope-Cape Lisburne Polynya	S	80	0	18	55	247	5630	OPEN
Cape Lisburne to Pt. Franklin Polynya**	T							OPEN
Pt. Franklin to Pt. Barrow Polynya**	V							OPEN
Chukotsk Peninsula Polynya	W	0	0	0	0	0	OPEN	
Wrangel Island Polynya, South	U							
Wrangel Island Polynya, North	X							
Anadyr Gulf Polynya	Y	4950	3140	4490	6180			

* Carleton (1980)
** Chukchi Polynya (Stringer, 1982)

Table 2b. Final Catalog of Recurrent Polynyi in the Chukchi and Bering Sea

Location of Polynyi	Coded Designation on Alaska Base Map	Average Size (km^2) by Month Averaged Over Six Years						
		Jan.	Feb.	Mar.	Apr.	May	Jun	Jul
St. Matthew Island Polynya, South	A	975	467	2310	2200	OPEN	OPEN	OPEN
St. Matthew Island Polynya, North	B	0	0	94	123	OPEN	OPEN	OPEN
St. Lawrence Island Polynya, South	D	4250	1900	4320	13900	24700	OPEN	OPEN
St. Lawrence Island Polynya, North	E	0	297	2790	260	797	OPEN	OPEN
Nunivak island Polynya, South	G	2870	1830	2800	26100	OPEN	OPEN	OPEN
Nunivak Island Polynya, North	H	38	520	2040	11000	OPEN	OPEN	OPEN
Cape Romanzof Polynya	I	1250	2750	4600	8640	OPEN	OPEN	OPEN
Yukon Delta Polynya	J	280	1810	1230	4380	OPEN	OPEN	OPEN
Norton Sound Polynya	K	1820	3160	4500	7730	13200	OPEN	OPEN
Nome Polynya	L	800	1820	3810	5280	10600	OPEN	OPEN
Katie's Polynya	M							
Herald Shoal Polynya	N							
Seward Peninsula Polynya	P							
Kotzebue Sound Polynya	Q	1630	2690	932	607	267	166	OPEN
Cape Thompson-Pt. Hope Polynya*	R	1700	2320	1550	1030	569	5080	OPEN
Pt. Hope-Cape Lisburne Polynya	s	360	1880	182	159	4480	11600	OPEN
Cape Lisburne to Pt. Franklin Polynya●*	T							
Pt. Franklin to Pt. Barrow Polynya**	v							
Chukotsk Peninsula Polynya	w	964	471	511	0	145	OPEN	
Wrangel Island Polynya, South	u							
Wrangel Island Polynya, North	x							
Anadyr Gulf Polynya	Y	7540	3340	5950	11600			

● Carleton (1 980)
●* Chukchi Polynya (Stringer, 1982)

Six polynyi were collectively identified as North Coast Polynyi because they form off the north facing coasts of St. Matthew, St. Lawrence, and Nunivak Islands and off the Yukon Delta, Seward Peninsula, and Chukotsk Peninsula. They occur less frequently than polynyi adjacent to coasts facing south. They appear to arise from a reversal of winds from the North or Northeast, the predominant wind directions in winter over that part of the Bering Sea north of St. Matthews Island (Brewer et al., 1977; Overland, 1981; Wilson et al., 1984). Many polynyi form on the north, south, and eastern coast of the Chukotsk Peninsula. However, as the emphasis in this report was on polynyi occurring in Alaskan waters, only two polynyi were identified here.

The original intention was to digitize polynya areal extent from as many years' AVHRR data as possible. The images were processed from January through May on a daily basis. Tables were prepared which display these measurements. In those cases where an area could not be measured, each polynya was designated as frozen (0), obscured by cloud cover (C), not available (N), fused with the main body of open water (0), or observable, but not capable of being digitized (P).

The numerical areal data contained in the tables were used to calculate monthly summary statistics for all 20 polynyi for all six years. In these calculations the numerical data were used in combination with the non-numerical "presence" designation to produce monthly time series plots for all 20 polynyi for all six years. The "presence" observations were converted to quantitative measurements by interpolating between digitized area determinations.

Each polynya boundary was digitized at least twice. This was to serve two purposes: first, it was desirable to learn how accurately one could reproducibly determine the area of a given polynya under both optimal conditions and under marginal conditions. Second, it allows one to differentiate between genuine daily area fluctuations and variability due to the digitizing method.

Throughout this study, only correlations whose confidence level were 95% or greater were considered significant.

RESULTS

Description of the Data Base and the Organization Plan for Analysis:

Four polynyi were selected for special scrutiny from the twenty studied for all years. These are the St. Lawrence (South) Polynya, the Norton Sound Polynya, the Kotzebue Polynya, and the Chukchi Polynya. The reasons for selecting these polynyi are as follows:

The St. Lawrence (South) Polynya (D; Table 1, Figure 1) is located in the central Bering Sea. It has been studied in connection with the effect polynya formation has on the salt balance of seawater and on the generation of sea ice (McNutt, 1981; Schumacher, Aagaard, Pease, and Trip, 1983). Recently, it has been of interest as whale habitat(Brueggeman, 1982).

The Norton Sound Polynya (K; Table 1, Figure 1) is often a prominent wintertime feature of Norton Sound. Its size is more constrained than that of the other polynyi, because Norton Sound has a well defined area of 36700 km^2. It frequently assumes a characteristic shape determined in part by the configuration of the Sound. A conspicuous feature of this polynya is that the pattern of ice cover remaining within Norton Sound appears to duplicate the shape of the summer sediment plume from the Yukon River described by Dean (Dean, McRoy, Ahlnas, and George, 1987). It is possible that the shape of the Norton Sound Polynya may therefore be influenced in part by outflow from the Yukon River.

The Kotzebue Sound Polynya (Q; Table 1, Figure 1) is located in theChukchi Sea immediately north of the Seward Peninsula. It is a North Coast Polynya. Like all North Coast Polynyi (and unlike all typical polynyi which one may expect to view daily), this polynya is present only occasionally and for short periods. Its occurrence is a potential indicator for the unusual meteorological conditions which create North Coast Polynyi.

The Chukchi Polynya forms off the Chukchi Sea coast of Alaska from Cape Lisburne to Pt. Barrow. The polynya is often present as a series of small individual polynyi, rather than a single continuous feature. Therefore, thispolynya was divided into three roughly equal segments in the hope that one might discern some pattern in their formation (T, U, and V; Table 1, Figure 1).

In theory, using available AVHRR imagery, one should beable to document changes in polynya area over periods as short as only a few hours as more than one orbit passes over Alaska in a day, and during some periods, there have been more than one NOAA satellite in orbit. In practice, only one acceptable image is available per day. In those rare cases where more than one image was available per day, evidence exists that polynya area can increase markedly in the course of only a few hours. However, there is insufficient imagery to document how unusual or common these events are.

Median monthly values of polynya areas were determined. This is because median values are not unduly influenced by a few arbitrarily large values at one end of the data set - for instance, if the polynya opens into the ice-free ocean - and tend to de-emphasize the influence of continuous strings of data (provided they are short compared to the entire data set). As part of the analysis procedure tables were compiled which list median values and the maximum polynya area observed on a monthly basis for each of the years investigated.

Total open water sums were calculated for the Chukchi and Bering Seas for the months January through April for all six years, because it seemed worthwhile to consider the polynyi not only individually, but also in terms of their total contribution to the open water area of the Bering and Chukchi Seas. These calculations are reported both in absolute terms and as percentages of the areas of the Bering and Chukchi Seas. Individual polynya areas, median polynya areas, and the summed polynya area totals are discussed on a monthly basis in the section: Statistical Analysis of Monthly Changes in Polynya Area. Tables were compiled recording monthly summary statistics for all twenty polynyi for each month of the six years.

Daily time series plots comparing daily polynya area variation with the climatic variables; temperature, wind component from the North, Northeast and East, and barometric pressure difference between Barrow and Nome are discussed in the section: Statistical Analysis of Daily Changes in Polynya Area. Daily time series plots were made for all six years and for January 1986 for the Chukchi Polynya group (T, U, and V and the sum T + U + V) which compared daily polynya areas with temperature and wind components at Barrow and the barometric pressure difference between Barrow and Nome. Daily time series plots were compiled for all six years and January 1986 for the polynyi of Kotzebue Sound (Q and R) which compared daily polynya areas with temperature and wind components at Kotzebue. Daily time series plots were compiled for all six years and January 1986 for the Norton Sound Polynya (K) and for all six years for the Yukon Delta Polynya (J) which compared daily polynya area and temperature at Nome and barometric pressure difference between Barrow and Nome. Daily time series plots were made comparing the timing of the presence of St. Lawrence Island Polynya, South (D) with that of St. Lawrence Island Polynya, North (E) for all six years.

A descriptive analysis of climatic events during 1975 which might be responsible for unusual polynya formation in that year is given in section: Descriptive Analysis of Polynya Formation in 1975.

Use of Thermal Infrared Analysis of the temperature structure of the Chukchi Polynya is described in the section: Thermal Infrared Analysis of the Chukchi Polynya.

Finally, using the information gained during the statistical analyses, a revised catalog of sites of recurrent polynyi formation is given in the section: A Catalog of Recurrent Polynya Formation observed in the Bering and Chukchi Seas.

STATISTICAL ANALYSIS OF MONTHLY CHANGES IN POLYNYA AREA

Discussion of the Statistical Analysis of the Monthly Data Base

Any attempt to relate polynya size to climatic conditions is limited by the scarcity of recording weather stations in the study area. Four synoptic weather stations exist in the Bering-Chukchi region; Barrow, Kotzebue, Nome and St. Paul. Weather records are kept on a less rigorous schedule at Cape Lisburne, Wales, Cape Romanzof and Unalakleet. The first attempt to relate polynya size to climatic conditions involved the correlation of the polynya median areas with climatic variables obtained at the four synoptic weather stations. The polynyi and the synoptic weather stations were paired as follows: Chukchi Polynya (T)-Barrow; Kotzebue Polynya (Q)-Kotzebue; Norton Sound (K)-Nome; St. Lawrence Island Polynya South (D)-St. Paul. The relationship between the Chukchi Polynya and the Barrow climatic variables were studied especially intensively.

Potential temperature effects were investigated using average temperature, median temperature and heating degree days. Heating degree days were used as a measure of temperature integrated over time. They are a compiled climatological statistic and therefore readily available. Potential wind effects were investigated using average wind speed, resultant wind speed, and wind component are in miles per hour. Resultant wind speed is the vector sum of the wind directions and speed divided by the number of observations. The wind component was calculated from wind resultant direction and resultant speed.

Linear correlation coefficients (Pearson) were obtained to determine if linear relationships existed between average monthly temperature, degree days, resultant wind speed, average wind speed, and wind component with median polynya size and median polynya area. Relationships were tested by month, by year and among all the area measurements taken together.

A nonparametric measure of correlation based on ranks, Kendalls Tau, was calculated to determine if large polynya areas were paired with high temperatures or low degree days or if analogous pairing occurred with any of the wind related variable. Kendall's Tau was calculated for the above climatic variables and median polynya size and area combining all years, on a yearly basis, and on a monthly basis.

The Student's *t* probability distribution was utilized to test whether the correlation coefficients were significantly different from zero. Both the linear and rank correlation coefficients were considered significant if the significance levels were equal to or exceeded the 95% confidence level.

The Chukchi Polynya (T) and Barrow Climatic Variables

Graphs were prepared displaying the monthly variation of heating degree days, average temperature, and wind component with polynya extent for the six years investigated. Wind component is much more variable than the temperature variables These charts have not been reproduced here because of their extensive number. However, no obvious consistent relationships were found, although occasional direct correlations were to be seen.

Linear and rank correlations found by combining data from all six years suggest that largepolynyi are associated with high temperatures and low heating degree days. These linear correlations have an absolute value of approximately 0.6 and the rank correlations have values of approximately 0.5. However, no significant correlations were observed among the wind related variables.

Linear and rank correlations found by combining the data by year were compiled. These correlations also suggest that large polynyi are associated with warmer temperatures. Some years had linear and rank correlations as high as 0.9. No significant linear or rank correlations were found with any of the wind related variables.

Linear and rank correlations found by combining the data by month were also compiled. These correlations support the conclusion that large polynya area is associated with warmer temperatures or low heating degree days. Some months had no linear or rank correlation betweenpolynya extent and temperature or heating degree days. No conclusive relationship was found between polynya area and any of the wind-related variables on a monthly basis.

The above results suggest that the apparent high correlation between the temperature vari ablesandpolynyi observed for individual years improbably dueto the fact that the temperature becomes warmer and more open water appears as the seasons change from winter to summer. If temperature and open water in polynyi were more significantly related, one would have expected a high correlation using the combined data set. It also suggests that other factors in addition to temperature influence polynya size.

Such an additional factor could be the Alaska Current which travels northward along the Bering and Chukchi Coasts in the summer. It has been shown to have a major effect on the timing and pattern ofmeltback of the ice edge in the Chukchi Sea (Paquette and Bourke, 1981, Stringer and Groves, 1985). Coachman and Aagaard (1981) describe bottom current flow reversals off Cape Lisburne for the winter of 1976-77. From December through March, frequent current reversals from north to south were observed. Coachman and Aagaard advance this as evidence that the current regime is different in the winter than it is in the summer. It is possible that this reversing current pattern could have as profound an effect on the presence of open water in polynyi in winter as the movement of the Alaska Current has on meltback of the ice edge in summer. However, adequate current measurements do not exist to test this hypothesis.

The Kotzebue Polynya (Q) and Kotzebue Climatic Variables

Figures were prepared displaying the monthly variation of average temperature and wind component from the Northeast with polynya extent for the six year and bimonthly wind component from the Northeast during that time. No obvious consistent relationships were evident.

Linear and rank correlation coefficients were determined for the climatic variables and polynya area obtained by combining all six years. Linear and rank correlation coefficients were obtained for both temperature and wind related variables. The linear and rank correlationcoefficients had an absolute value of 0.6.

Linear and rank correlations were obtained between the climatic variables and median polynya area and size combing the data byyear. The temperature related variables do not appear to have much influence on thispolynya. In the cases where a relationship can be detected, it suggests large polynya area is associated with warmer temperatures. The effect of the wind related variables on thispolynya is not clear.

Linear and rank correlations were **obtained for average temperature, median** temperature and wind component **combining twelve two week periods for all the** years. Fewer significant correlations were found than were found combining monthly periods for all the years. Thus, refining temporal resolution does not improve correlations.

The Norton Sound Polynya (K) and the Nome Climatic Variables

Figures were prepared showing the monthly variation of average temperature wind component from the Northeast, and wind component from the East with polynya extent for six years. These were examined for evidence of obvious consistent causal relationships. None were obvious.

Linear and Kendall rank correlations were obtained by combining the data for all six years for median polynya area and size and correlating these against the climatic variables: average temperature, degree days, wind component (calculated as wind from the Northeast and East), average wind speed, and resultant wind speed. These correlations implied a large polynya was associated with warmer temperatures. The linear and rank correlation coefficients had an absolute value of approximately 0.7. The wind components had essentially identical negative correlations with polynya area. These linear and rank correlations ranged from -0.3 to -0.4.

Rank and linear correlations were determined between climatic variables and median polynya area and size by year. The size of the Norton SoundPolynya was much more strongly correlated with temperature using the combined data set than was the case in individual years. Few linear and no rank correlations were found between the wind components and polynya area.

Kozo (1987) performed an analysis of 1964-1968 surface winds, pressures and temperatures at three weather stations around Norton Sound. He states that surface wind histograms at Nome and Unalakleet do not show the true large scale wind distribution which would be the major factor in surface pollutant and ice movement in Norton Sound. He offers this as evidence that time series data of winds from Nome should not be used in offshore oil spill trajectory models. This may explain why the correlation coefficients (both linear and ranked) did not show a more pronounced relationship with polynya size.

The St. Lawrence Island Polynya, South (D) and St. Paul Island Climatic Variables

Figures were prepared showing the monthly variation of average temperature and wind component from the northeast polynya extent for six years.

Linear and Kendall rank correlations were calculated for polynya area and the climatic variables: average temperature, degree days, wind component (calculated as wind from the Northeast), average wind speed, and resultant wind speed by combining data for all six years. A wind from the Northeast might be expected to open a polynya on the south side of St. Lawrence Island.

No linear correlations were found for either of the temperature variables. Negative linear correlations (-0.6 to -0.8) were found for average wind speed and wind component and polynya area. This would suggest that winds were more likely to be responsible for freezing polynyi than opening them. Rank correlations were found for the temperature variables and polynya area which suggest large polynyi are associated with warmer temperatures. The rank correlations had an absolute value of approximately 0.45.

There was not sufficient data to warrant calculating correlations by year for the St. Lawrence Island Polynya.

Investigation of Possible Anomalous Polynya Formation in 1975

1975 was an unusual year among the six studied in that unusually large polynyi were formed early in that year. In order to determine whether 1975 meteorological data were anomalous, contingency analyses were run to compare the temperature and wind component distributions by month among the six years. No significant differences were found among the years.

The conclusions which must be drawn from the above observations (if 1975 casual relationships were actually significantly different in some manner from the other five years) are: 1) the weather data recorded at the three synoptic weather stations either did not contain the appropriate variable to demonstrate this difference or the format in which the data was reported by the synoptic stations did not exhibit correlation; 2) another manipulation of the synoptic data such as pressure differences between two different synoptic stations might yield relationships; 3) more meaningful weather data might be obtained at sites other than the four synoptic stations.

1975 was selected for a descriptive analysis in the subsection: Descriptive Analysis of Polynya Formation in 1975.

The Chukchi Polynya Group (T, U, and V) and the Barrow Climatic Variables

One hundred and forty time series plots were made comparing variation in daily polynya area for the individual polynyi, Cape Lisburne to Pt. Lay Polynya (T), Pt. Lay to Icy CapePolynya (U), and Icy Cape to Pt. BarrowPolynya (V) and their sum (T + U + V) known as the Chukchi Polynya and the climatic variables, temperature, wind component from the North, wind component from the Northeast and wind component from the East at Barrow and barometric pressure difference between Barrow and Nome. This barometric pressure difference was selected as a possible indicator of storm conditions and of current flow in the Chukchi Sea in the region where the Chukchi Polynya forms.

Each plot was individually inspected to see if a sufficient relationship existed between polynya area and climatic variable to justify across-correlation analysis or if an especially dramatic change in a climatic variable signaled a dramatic change in polynya area.

The only apparent relationship observed was between temperature and polynya area. As daily temperatures increased, daily polynya area tended to increase. This tendency was indicated earlier with the correlation studies of the monthly data.

Seven and thirteen day moving average plots of the wind components were prepared for comparison with polynya area to determine if polynya area was influenced by sustained winds. Some of the thirteen day moving average plots suggested that there might be a relationship for this period of sustained wind, but it was not prominent.

Seven and thirteen day moving average plots of the barometric pressure difference between Nome and Barrow were also compared with daily polynya area plots. No relationship was detectable for either average.

None of the moving average plots suggested cross-correlations would be instructive.

Histograms were made from the six years of daily climatic data recorded as wind components and barometric pressure difference and the 99th and 95th percentiles determined in an effort to identify extreme conditions.

Suitable time series plots of polynya area were selected. These were then examined individually to determine if any extreme wind component or barometric pressure difference was associated with a significanpolynya formation event or if any threshold wind velocity existed. Whether considering the Chukchi Polynya

System as a whole or in its constituent parts, there appears to be no consistent relationship between extreme winds and polynya area for wind component from the East or the Northeast. Likewise, no relationship was found for barometric pressure difference.

The best conclusion that can be drawn on a qualitative basis is that the Chukchi Polynya system is generally related to winds. The two years, 1975 and 1976, which had the most extreme winds had the largest polynya area. It is also suggested that sustained winds over a one week or two week period have more effect on polynya size than an extreme wind of one or two days duration.

The Polynyi of Kotzebue Sound (Q) and (R) and the Kotzebue Climatic Variables

Fifty six time series plots were made comparing daily polynya area for Kotzebue Sound Polynya (Q) and Cape Thompson-Pt. Hope Polynya (R) with daily temperature and wind components from the East, Northeast and North.

Each plot was individually inspected to see if a sufficient apparent relationship existed between polynya area and climatic variable to justify a cross-correlation analysis or if an especially dramatic change in a climatic variable signaled a dramatic change in polynya area. These are instantaneous relationships because they relate one day's wind or temperature on that day's polynya area.

No relationships were found between any of the climatic variables and polynya area except a possible qualitative one between temperature (positive) and the wind components from the East (positive) and North (negative) for the area of the Kotzebue Sound Polynya (Q) in 1976.

Seven and thirteen day moving average plots of the wind components were prepared for comparison with polynya area to determine if polynya areas were influenced by sustained winds. No relationship was obvious between East or Northeast wind components and polynya area. A possible relationship was detected between wind component from the North at both seven and thirteen days and polynya area for both Kotzebue Sound Polynyi.

Cross-correlations were performed for the seven and thirteen day moving average plots of wind component from the North and Polynya area for 1975 and 1976 for the Kotzebue Sound Polynya (Q). The 1976 wind component analysis showed a positive relationship between wind from the South and polynya area. The most significant lag was for -1 or 2 days for a moving average of seven days. The cross-correlation coefficient was 0.48. The 1975 cross-correlations were not significant. The 1976 finding suggests that a sustained wind from the South for a week may be more influential in the formation of the Kotzebue Sound Polynya than instantaneous winds or sustained wind over two weeks.

Histograms were made from the six years of daily climatic data recorded as wind components in an effort to determine extreme conditions. The 95th and 99th percentiles were recorded in a table. Analysis of this table showed that no generalizations could be made about the association of extreme wind from any direction and polynya size.

The Kotzebue Sound Polynya (Q) and the Cape Thompson-Point Hope Polynya (R) constitute a North and South Coast Polynyi pair in that they are located on opposite (north-south) sides of Kotzebue Sound. If polynya extent is related to forcings directed along that axis, these polynyi should exhibit a tendency toward an anti-correlation. Figure 3 shows the daily variation of the extent of these two polynyi during 1976. The extent of the Kotzebue SoundPolynya is shown as a dotted line while the Pt. Hope-Cape Lisburnepolynya is shown as a dotted line while the Pt. Hope-Cape Lisburne polynya is shown as a solid line. During this time the major openings and closing of these two polynyi can be seen to be anti-correlated.

The Norton Sound Polynyi (J, K and L) and the Nome Climatic Variables

Sixty-five time series plots were made comparing dailypolynya area for the Norton Sound Polynya (K) and the Yukon Delta Polynya (J) with daily temperatures, wind components from the East, Northeast, and North and barometric pressure difference between Barrow andNome.

Seven and thirteen day moving average plots of the wind components were made for comparison withpolynya area to determine ifpolynya area were influenced by sustained winds.

Histograms were made from the six years of daily climatic data recorded as wind components in an effort to determine extreme conditions. The 95th and 99th percentiles were recorded in a table. Likewise these extreme values were examined with the appropriate time series plot to determine if any extreme wind component values were associated with a significant polynya event or if any threshold velocity existed.

The Norton Sound Polynya (K)

Each daily plot was individually inspected to see if a sufficient relationship existed between polynya area and climatic variable to justify a cross-correlation analysis or if an especially dramatic change in a climatic variable signaled a

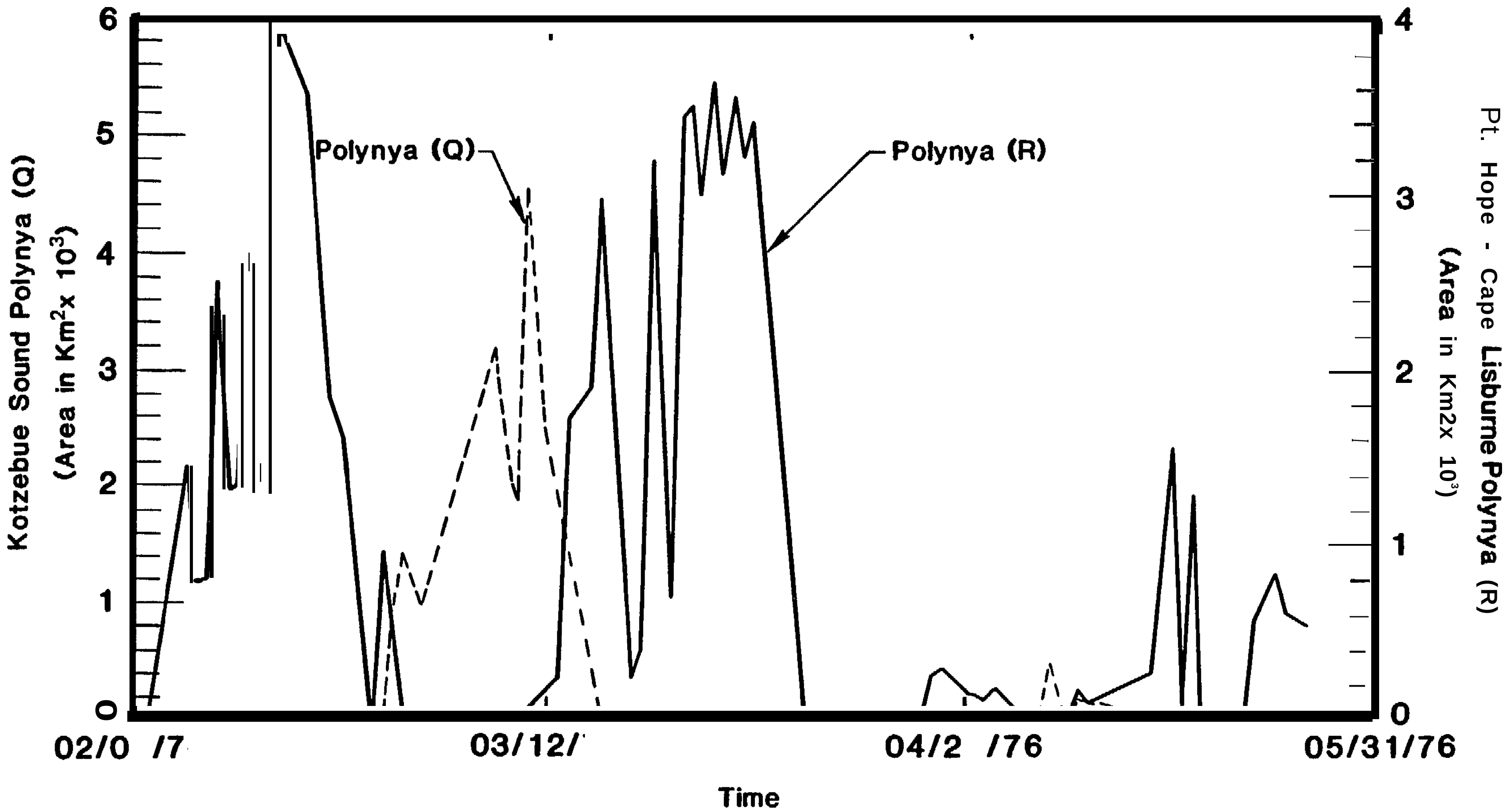

Figure 3. Daily area variation of the Kotzebue Sound Polynya (Q) and the Pt. Hope – Cape Lisburne Polynya (R) in 1976 showing the tendency of the North Coast Polynya (Q) to form when the south coast facing Polynya (R) is closed and vice versa.

dramatic change-in polynya area. Fouryears' data revealed a relationship between temperature and polynya area where higher temperatures were associated with larger polynya area. There appears to be no significant relationship with the other variables

Inspection of the seven andthirteenth daymovingaverage plots revealed some apparent direct relationships between temperature andpolynya area at both the seven and thirteen day moving averages. Apparent direct relationships between wind components and polynya area were foundat both the seven and thirteen day averages.

Cross-correlations were performed between polynya area and temperature. The coefficients varied between 0.7 for a one day lag to 0.50 for a nine to thirteen day lag.

The only consistent conclusion one can derive is that the Norton Sound Polynya (K) tends to be large during warmer temperatures. There also may be some correlation between large polynya area and wind component from the East, North, or Northeast both in the sustained situation and at threshold values.

The Yukon Delta Polynya (J)

The Yukon Delta Polynya is a North Coast Polynya. It was selected with the other Norton Sound polynyi for a cross-correlation study because, like the other Norton Sound polynyi, it has a well-defined site and there was a long run of continuous area measurements available in 1976.

Each daily plot was individually inspected to determine whether a sufficiently strong relationship existed between polynya area and climatic variable to justify a cross-correlation analysis or if an especially dramatic change in a climatic variable signaled a dramatic change in polynya area. It is difficult to draw conclusions from these daily plots as the Yukon Delta Polynya forms much less frequently than other polynyi. Nevertheless, some associations were seen for both the sustained and the threshold effects.

The data suggest that the Yukon Delta Polynya is associated with extreme wind components from the South or Southwest. A one to two day lag with a cross correlation coefficient of approximately 0.5 behind the observation of peak polynya area was observed for the wind component from the South. Low barometric pressure at Barrow with respect to Nome may also be a factor. However, the Yukon" Delta Polynya forms so infrequently it has not been possible to get a sufficiently large sample to statistically prove these theories.

The St. Lawrence Polynyi (D and E) and the St. Paul Island Climatic Variables

As the St. Lawrence Polynyi do not have long runs of continuous polynya area measurements, and there is no synoptic weather station closer than St. Paul Island to provide a meaningful and continuous climatic data base set, no daily time series were compiled for these polynyi. Polynya (D) is a south coast polynya, while Polynya (E) is a North Coast Polynya. Polynya (D) and Polynya (E) do not form at the same time and tend to be anti-correlated. Presumably this is because the means of formation for the Polynyi are different or are even related to reversals of phenomena related to their presence. Figure 4 shows the daily extent of these two polynyi during 1975. The extent of the St. Lawrence Island North polynya is shown as a solid line while the St. Lawrence Island South polynya is shown as a dotted line. This figure illustrates the tendency toward anti-correlation between these polynyi. (Note that the previous example of an anti-correlated pair of polynyi involved two polynyi located at opposite sides of a bay while in this example the two polynyi are on opposite sides of an island).

DESCRIPTIVE ANALYSIS OF POLYNYA FORMATION IN 1975

1975 was selected as a year for more intensive study because so many large polynyi formed that spring. The approaches considered for relating polynya formation to climatic events were 1) an attempt to relate the 700 mb pressure maps published in *Monthly Weather Review* (Taubensee, 1975) with polynya formation, and 2) an attempt to relate daily weather changes at Barrow, Kotzebue and Nome with some of the more dramatic polynya formation events in 1975.

The result of this intensive study is a suggestion that the causes for formation of polynyi are complex and probably cannot be fully described by atmospheric conditions alone, but may require oceanographic measurements such as current velocities, sea surface temperatures, etc.

An unusual meteorological condition was found in March 1975 associated with an atypically large area for the Chukchi polynya. This appeared to be a region of high pressure which may form anywhere over the Alaskan landmass or north of Alaska or the MacKenzie Delta. This condition persisted for more than two weeks, an unusual event for March. During that time we saw the formation of polynyi in atypical locations such as the North Coast Polynyi or of atypical size for the time of the year.

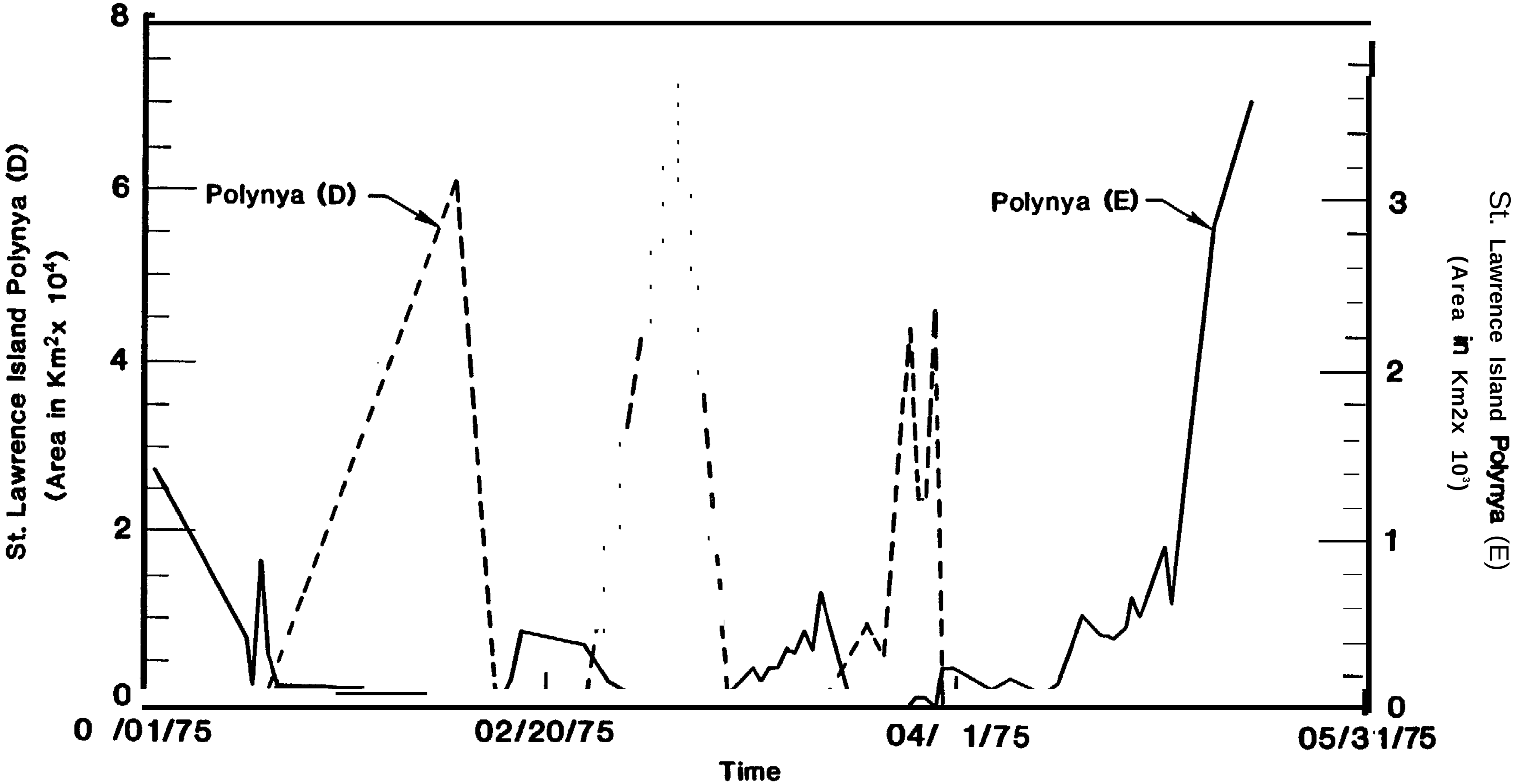

Figure 4. Daily area variation of the St. Lawrence Island Polynyi (D and E) in 1975 showing the tendency of the North Coast Polynya (E) to form when the south coast facing Polynya (D) is closed and vice versa

A CATALOG OF RECURRENT POLYNYA FORMATION OBSERVED IN THE BERING SEA AND CHUKCHI SEA

Stirling and Cleator (1981) describe the location and approximate dates of presence of recurrent polynyi in the Canadian Arctic. A similar description of the location and times of presence of twenty-one polynyi in the Bering and Chukchi Seas has been compiled. These descriptions derive from a study of six years of the size of polynyi in the months January through June. Good descriptions are possible for the typical size and shape of each polynya as well as for range of break-up dates. However, no data are given for the first time of formation other than that may be implied from average advance and retreat of the ice edge within the Bering and Chukchi Seas. Figure 2 displays the revised polynya formation sites as suggested by this study; Table 2 records the names of the sites.

THERMAL INFRARED ANALYSIS OF THE CHUKCHI POLYNYA (T+ U + V)

Thermal infrared analysis of the temperature structure of two polynyi in the Chukchi Sea using a series of AVHRR images have allowed limited confirmation of the recurrent formation of these polynyi.

The Chukchi Polynya (T + U + V) forms off the coast of Alaska from Cape Lisburne to Pt. Barrow. The Polynya is often present as small individual polynyi, not as a single continuous feature.

Examination of computer printouts of the Chukchi Polynya for the purpose of assembling a series of illustrations of how the polynya forms revealed that our original division of the Chukchi Polynya into three segments was not representative of a realistic description of the mechanism of formation of this Polynya. A division of the Chukchi Polynya in two halves at Pt. Franklin seems more correct. First, the polynya segment (V) seems to form independently of T and U. Evidence for this was obtained from the thermal infrared analysis of a series of nine AVHRR images of the Chukchi Polynya for the period March 13 through March 21, 1987. The thermal structure of the polynya south of Icy Cape was different from that north of Ice Cape.

SUMMARY OF RESULTS

1) The sites for the formation of twenty-two recurrent polynyi were identified. These sites have been located on a map, and written descriptions of the

time of formation and area extent are given where sufficient information exists for such descriptions.

2) Extensive tabulations of daily polynya area are available for twenty polynyi spanning the months January through June for six years (1974, 1975, 1976, 1977, 1979, 1983). These are available through OCSEAP project management as they are too extensive to report in this format.

3) Extensive statistical analysis attempting to relate polynya size to climatic variables has been performed. These met with mixed success. There is weak evidence for involvement of wind in formation of some polynyi, while others are weakly related to temperature.

4) The necessity for the compilation of a database of climatic measurements obtained near the polynyi formation sites in close conjunction with observable changes in polynya size has been suggested. Current synoptic weather stations are not able to provide such data.

5) The necessity for the compilation of an oceanographic database of measurements such as current velocities, sea surface temperature, etc., near the polynyi formation sites in close conjunction with observable changes in polynya size has been suggested as a possible source of data helping explain polynya formation.

6) Thermal infrared analysis of AVHRR imagery was found to be a useful tool in studying the internal structure of polynyi and for verifying the physical dimensions of the polynya.

7) It has been demonstrated that North Coast Polynyi form independently and in a somewhat anti-correlated manner from South Coast Polynyi in the cases of the St. Lawrence Island Polynyi, North and South, (D and E) and of the Kotzebue Sound Polynya (Q) and the Cape Thompson-Pt. Hope Polynya (R). This suggesta that the formation of these two polynyi may be related to reversals of some parameter we could not measure such as oceanic currents.

8) An unusual meteorological condition in March 1975 leading to an atypically large area for the Chukchi Polynya in March is described.

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