OCS Study MMS 2007-011

Study Final Report

for the

Beaufort Sea Meteorological Monitoring and Data Synthesis Project

September 2007

prepared for the

Minerals Management Service
Alaska Outer Continental Shelf Region
3801 Centerpoint Drive, Suite 500
Anchorage, Alaska 99503

Contract 1435-01-05-CT-39307

prepared by

Key Authors:
J.R. Wilcox
Brent Veltkamp

Hoefler Consulting Group
3401 Minnesota Dr. Suite 300
Anchorage, Alaska 99503
907-563-2137

ACKNOWLEDGMENT
This study was funded by the Minerals Management Service, U.S. Department of Interior, Washington, D.C., under Contract Number 1435-01-05-CT-39307.

DISCLAIMER
The opinions, findings, conclusions, or recommendations expressed in this report or product are those of the authors and do not necessarily reflect the views of the U.S. Department of the Interior, nor does mention of trade names or commercial products constitute endorsement or recommendation for use by the Federal Government.

This report has been prepared and reviewed by the following:

HCG Project Manager:
Chris Lindsey
Name

9/5/07
Date

Signature

HCG Staff Scientist:
Brent Veltkamp
Name

9/5/07
Date

Signature

HCG Meteorologist:
Alan M. Trbovich, CCM
Name

9/11/07
Date

Signature

TABLE OF CONTENTS

ABSTRACT **1**

1 INTRODUCTION **3**

2 STUDY BACKGROUND **5**

2.1 MMS METEOROLOGICAL MONITORING STATION HISTORY 5
2.2 PRIOR RESEARCH 5
2.3 OVERALL CLIMATOLOGY OF THE REGION 9

3 METHODS **10**

3.1 ELEMENTS OF THE STUDY 10
3.1.1 Collection of New Meteorological Data 10
3.1.2 Collection of Supplemental Wind Data 10
3.1.3 Development of Meteorological Database 10
3.2 MMS STATIONS 11
3.2.1 Locations 11
3.2.2 Instrumentation 22
3.2.2.1 Wind Speed and Direction 23
3.2.2.2 Temperature 24
3.2.2.3 Barometric Pressure 24
3.2.2.4 Solar Radiation 25
3.2.2.5 Relative Humidity 25
3.2.2.6 Data Acquisition and Telemetry 25
3.2.3 Operating History 26
3.2.3.1 Data Validation 26
3.2.3.2 Data Capture 28
3.2.4 Wind Data Quality at Northstar 28
3.3 SUPPLEMENTAL STATIONS 30
3.3.1 Locations 30
3.3.2 Comparison of Supplemental Stations with MMS Stations 31
3.3.3 Data Review at Supplemental Stations 34

4 RESULTS **35**

4.1 WIND SPEED 35
4.1.1 Long-Term Wind Speeds at Supplemental Stations 43
4.2 WIND DIRECTION 45
4.2.1 Wind Roses 45
4.2.2 Wind Direction by Category 63
4.3 WIND SIGMA 74
4.4 TEMPERATURE 76
4.5 BAROMETRIC PRESSURE 82
4.6 SOLAR RADIATION 84
4.7 RELATIVE HUMIDITY 86

5 DISCUSSION **88**

5.1 OROGRAPHIC EFFECTS 88
5.2 SEA BREEZE EFFECTS 88
5.3 LATITUDINAL EFFECTS 94

5.4 INTER-STATION CORRELATION AND CROSS-CORRELATION 95
5.4.1 Correlation 95
5.4.2 Cross-Correlation 96
5.5 ANEMOMETER ICING 100
5.5.1 Icing at Endicott and Cottle Island 100
5.5.2 Icing at Supplemental Stations 100
5.6 POSSIBLE VARIATIONS ON WIND DIRECTION ANALYSIS 102
5.7 BEST OPERATING PRACTICE 104
5.7.1 Best Wind Sensor Arrangement 104
5.7.2 Lower Power Demand in Mid-Winter 104
5.7.3 Audit schedule 105
5.7.4 Station Communications 105

6 CONCLUSIONS 106

7 REFERENCES 107

LIST OF TABLES

TABLE 3-1. MMS STATION COORDINATES 11
TABLE 3-2. PRIMARY MMS METEOROLOGICAL MONITORING EQUIPMENT 23
TABLE 3-3. ADJUSTMENT TO SEA-LEVEL PRESSURE 25
TABLE 3-4. DATA CAPTURE SUMMARY 28
TABLE 3-5. SUPPLEMENTAL STATION INVENTORY 30
TABLE 3-6. SUPPLEMENTAL STATION RANKING 33
TABLE 4-1. WIND SPEED STATISTICS FOR THE MMS STATIONS (M/S) 35
TABLE 4-2. WIND SPEED STATISTICS FOR THE SUPPLEMENTAL STATIONS (M/S) 36
TABLE 4-3. FREQUENCY OF WIND DIRECTION BY CATEGORY (DAYS/YR) 63
TABLE 4-4. AVERAGE DURATION OF WIND DIRECTION BY CATEGORY (HOURS) 64
TABLE 4-5. WIND SIGMA STATISTICS (°) 74
TABLE 4-6. TEMPERATURE SUMMARY STATISTICS (°C) 76
TABLE 4-7. TEMPERATURE STATISTICS FOR JUNE – OCTOBER (°C) 78
TABLE 4-8. TEMPERATURE STATISTICS FOR NOVEMBER – MAY (°C) 78
TABLE 4-9. DEGREE DAY STATISTICS (°C) 81
TABLE 4-10. STATISTICS FOR SEA-LEVEL BAROMETRIC PRESSURE (MB) 82
TABLE 4-11. RELATIVE HUMIDITY DATA SUMMARY 86
TABLE 5-1. CORRELATION OF MMS STATIONS WIND SPEED USING R-SQUARED VALUES (R^2) 95
TABLE 5-2. CORRELATION OF SUPPLEMENTAL STATIONS WIND SPEED USING R-SQUARED VALUES (R^2) 96

LIST OF FIGURES

FIGURE 2-1. EFFECT OF A CYLINDER ON A WIND FIELD 6
FIGURE 2-2. WIND SPEEDS FOR NORTHEASTERLY WIND 7
FIGURE 2-3. WIND SPEEDS FOR EASTERLY WIND 8
FIGURE 2-4. WIND SPEEDS FOR NORTHWESTERLY WIND 8
FIGURE 3-1. PROJECT LOCATION MAP 13
FIGURE 3-2. METEOROLOGICAL STATION LOCATION MAP 15
FIGURE 3-3. BADAMI MMS STATION 17
FIGURE 3-4. COTTLE ISLAND MMS STATION 18
FIGURE 3-5. ENDICOTT MMS STATION 19

FIGURE 3-6. MILNE POINT MMS STATION 20
FIGURE 3-7. NORTHSTAR MMS STATION 21
FIGURE 3-8. AERIAL VIEW OF NORTHSTAR SHOWING STATION LOCATION 29
FIGURE 4-1. MEAN WIND SPEED VS. DISTANCE OFFSHORE 37
FIGURE 4-2. MEAN ADJUSTED MONTHLY WIND SPEED, MMS STATIONS 38
FIGURE 4-3. MEAN MONTHLY WIND SPEED, SUPPLEMENTAL STATIONS 39
FIGURE 4-4. SPATIAL DISTRIBUTION OF WIND SPEEDS, MEAN AND MAXIMUM 41
FIGURE 4-5. ANNUAL WIND SPEED AVERAGES AT SUPPLEMENTAL COASTAL STATIONS 44
FIGURE 4-6. WIND ROSE WIND SPEED LEGEND (M/S) 45
FIGURE 4-7. BADAMI WIND ROSE 46
FIGURE 4-8. COTTLE ISLAND WIND ROSE 47
FIGURE 4-9. ENDICOTT WIND ROSE 48
FIGURE 4-10. MILNE POINT WIND ROSE 49
FIGURE 4-11. NORTHSTAR WIND ROSE 50
FIGURE 4-12. BARROW WIND ROSE 51
FIGURE 4-13. BARTER ISLAND WIND ROSE 52
FIGURE 4-14. BETTY PINGO WIND ROSE 53
FIGURE 4-15. DEADHORSE WIND ROSE 54
FIGURE 4-16. FRANKLIN BLUFFS WIND ROSE 55
FIGURE 4-17. KOMAKUK BEACH WIND ROSE 56
FIGURE 4-18. NUIQSUT WIND ROSE 57
FIGURE 4-19. SAGWON WIND ROSE 58
FIGURE 4-20. SPATIAL DISTRIBUTION OF WIND ROSES, BEAUFORT SEA COAST 59
FIGURE 4-21. SPATIAL DISTRIBUTION OF WIND ROSES, PRUDHOE BAY REGION 61
FIGURE 4-22. FREQUENCY OF OFFSHORE WINDS AT MMS STATIONS 66
FIGURE 4-23. FREQUENCY OF OFFSHORE WINDS AT SUPPLEMENTAL STATIONS 67
FIGURE 4-24. FREQUENCY OF ONSHORE WINDS AT MMS STATIONS 68
FIGURE 4-25. FREQUENCY OF ONSHORE WINDS AT SUPPLEMENTAL STATIONS 69
FIGURE 4-26. FREQUENCY OF SHORE-PARALLEL WINDS AT MMS STATIONS 70
FIGURE 4-27. FREQUENCY OF SHORE-PARALLEL WINDS AT SUPPLEMENTAL STATIONS 71
FIGURE 4-28. FREQUENCY OF VARIABLE WINDS AT MMS STATIONS 72
FIGURE 4-29. FREQUENCY OF VARIABLE WINDS AT SUPPLEMENTAL STATIONS 73
FIGURE 4-30. MEAN MONTHLY WIND SIGMA 75
FIGURE 4-31. TEMPERATURES (MEAN MONTHLY, HOURLY MAXIMUM AND MINIMUM) 77
FIGURE 4-32. TEMPERATURE HISTOGRAMS FOR MMS STATIONS 2001 - 2006 79
FIGURE 4-33. MEAN MONTHLY BAROMETRIC PRESSURE ADJUSTED TO SEA-LEVEL 83
FIGURE 4-34. MEAN DAILY SOLAR FLUX AT MILNE POINT 84
FIGURE 4-35. MEAN MONTHLY SOLAR RADIATION 85
FIGURE 4-36. MEAN MONTHLY RELATIVE HUMIDITY 87
FIGURE 5-1. FREQUENCY RATIO OF ONSHORE TO OFFSHORE WINDS BY MONTH, MMS STATIONS 91
FIGURE 5-2. FREQUENCY RATIO OF ONSHORE TO OFFSHORE WINDS BY MONTH, SUPPLEMENTAL STATIONS 92
FIGURE 5-3. JUNE WIND DIRECTION RATIO VS. DISTANCE OFFSHORE 93
FIGURE 5-4. FREQUENCY RATIO OF ONSHORE TO OFFSHORE WINDS VS. LATITUDE 94
FIGURE 5-5. CROSS-CORRELATION OF WIND SPEED TO MILNE POINT AT VARIOUS LAGS 98
FIGURE 5-6. PEAK LAG VS. DISTANCE FROM MILNE POINT 99
FIGURE 5-7. CLIMATRONICS VS. RM YOUNG MEASURED WIND SPEED 101
FIGURE 5-8. ANEMOMETER ICING AT BETTY PINGO, WINTER 2002-2003 103

ABSTRACT

This report summarizes meteorological data collected from five Minerals Management Service (MMS) stations, along with existing data from supplemental stations along the Beaufort Sea coast. Data were collected for the MMS stations from January 2001 through September 2006 spanning a 100 km stretch of the Beaufort Sea coast centered on Prudhoe Bay, Alaska. The MMS meteorological monitoring stations were located at Milne Point F Pad, Cottle Island, Northstar Island, Endicott Satellite Drilling Island, and Badami. Data from the five MMS meteorological monitoring stations, along with wind data from 29 third party supplemental monitoring stations dating to 1984 has been compiled in the *MMS Nearshore Beaufort Sea Weather Database, 1984-2006.* The database contains nearly 1.7 million hours of meteorological data and spans from Barrow to Hershel Island, Yukon Territory. For this study, eight of the 29 supplemental stations were selected for wind speed and direction comparison and data analysis with the five MMS stations. Supplemental stations were selected for comparison based on the stations location, operational history, and data quality.

The data are generally similar among most of the sites, although statistically significant differences are shown to exist among different sites and among seasons. The data support the meteorological effects theorized by Dr. Thomas Kozo in the 1980s of a summer sea breeze effect and orographic effects of the Brooks Range. The data indicate that the sea breeze effect is stronger in the summer months of May through July than the remainder of the year, although it is evidenced through September. During the early summer, onshore winds dominate local weather patterns in terms of both wind direction frequency and duration. The sea breeze effect is most pronounced at sites closest to the coastline; with the ratio of onshore to offshore winds in summer indicating a strong correlation to distance offshore. Summer wind speeds appeared to be highest centered on the coast, with wind speeds dropping with both distance offshore and inland. However, offshore data is limited to islands within several miles of the mainland.

The dominance of onshore winds correlates to latitude as well in the Beaufort Sea region for most stations in the study area. A higher ratio of onshore winds to offshore winds was observed as a function of north latitude for the stations included in the study, with the exception of Barrow, which receives influences from the Chukchi Sea.

The increasing wind speeds and the flattening of the wind roses as one moves east corroborate Kozo's prediction of orographic influences of the Brooks Range. This is especially noticeable at the easternmost stations, where wind direction tends to parallel the longitudinal axis of the Brooks Range. The close proximity of the mountains has the greatest effect at Komakuk Beach, where the Brooks Range is just 10 km from the coast.

In addition to comparisons of wind patterns among the stations, other meteorological data from the five MMS stations were analyzed. Temperatures were found to exhibit a bimodal distribution, with temperatures for approximate open water periods centered more tightly around 0 degrees Celcius (°0 C), and approximate iced ocean periods varying more widely. A wider temperature range was observed at stations just a few miles inland from the coast. Parameters of barometric pressure, solar radiation, and humidity were found to vary slightly from station to station, while varying significantly on a seasonal basis.

It was discovered over the course of this project that 3-cup anemometers will pack with snow and under-report wind speed in mid-winter at some arctic coastal sites. It was demonstrated through simultaneous operation that propeller-style wind sensors are a far more reliable means of collecting wind data in this region. Therefore, the use of propeller-style wind instruments is recommended in all future studies where icing might be an issue.

1 INTRODUCTION

This report presents the results of the 2001- 2006 Nearshore Beaufort Sea Coast Meteorological Monitoring Project commissioned by the U.S. Department of the Interior Minerals Management Service (MMS). This work was performed by HCG, Inc., d.b.a., Hoefler Consulting Group (HCG) under MMS Contract No. 1435-01-05-CT-39307.

The purpose of this study was to gather meteorological data by combining existing data sets from the Beaufort Sea region and by deploying five new meteorological monitoring stations in the Prudhoe Bay area. This methodology provided a comprehensive time-series of wind data of the nearshore Beaufort Sea for use in MMS models, such as the Oil Spill Risk Analysis (OSRA), Coastal Zone Oil Spill (COZOIL), the future Beaufort Sea Mesoscale Meteorological model, and oil weathering and nearshore circulation models. MMS predicts that in the near future oil and gas development will expand in the nearshore region of the Beaufort Sea, and additional wind modeling is needed in these areas. Data sets collected prior to this study were not suitable for use in MMS models because the data sets were too limited (e.g. three month offshore exploration projects) or the distance from the area of interest was too great (e.g. Barrow or Barter Island).

For nearly six years, the five new MMS meteorological monitoring stations were deployed by HCG along the Beaufort Sea coast near Prudhoe Bay, in regions of current oil production. Four of the five meteorological monitoring stations (Badami, Endicott, Milne Pt., and Northstar) were installed in late 2000, and began collecting data in January 2001. A fifth monitoring station was installed in August 2002 on Cottle Island. Stations installed and operated for this study collected data for wind speed and direction, wind sigma (a measure of turbulence), temperature, relative humidity, solar radiation, and barometric pressure.

In addition, this study includes data from a total of twenty nine supplemental meteorological monitoring sites spanning 650 km along the Beaufort Sea coast from Barrow in the west to Herschel Island in the east. These twenty nine stations have been operated by other private, educational, and government entities.

The primary purpose of this report is to focus on the most pertinent data and results. Because this program was foundationally a study to aid in modeling wind fields to predict oil spill movements, the main emphasis of this report is on the wind speed and direction data. Variables of secondary interest (e.g. temperature, wind sigma, barometric pressure, solar radiation and relative humidity) are included but given less thorough treatment.

The Background section for this report details the history of the MMS stations, as well as prior research used for the study. Section 3, Methods, describes the collection of new meteorological data, as well as collection of data from supplemental stations. Section 4, Results, presents results of data analysis in both statistics and graphs for both the MMS and supplemental stations, followed by Section 5, Discussion, additional analysis of data and comparisons to prior research. Finally, Section 6 summarizes the conclusions of the key findings of the study, with recommendations for future research.

The study concludes that a sea breeze effect characterized by strong onshore winds is present during the summer months, especially during May through July. Onshore winds during this time

frame dominate in both frequency of onshore direction, and duration of the wind events. The sea breeze effect is most pronounced at sites closest to the coastline; with the ratio of onshore to offshore winds in summer indicating a strong correlation to distance offshore, and summer wind speeds appearing higher near the coast. In conjunction with the sea breeze effects, the orographic effects imposed by the Brooks Range on climatology of the region are exhibited at stations toward the eastern and inland portions of the study area.

2 STUDY BACKGROUND

2.1 MMS Meteorological Monitoring Station History

The five MMS meteorological monitoring stations built and operated by HCG span about 100 km along the Beaufort Sea coast from western Simpson Lagoon to Mikkelsen Bay. These stations collected a variety of parameters, including wind speed and direction, wind sigma (a measure of turbulence), temperature, relative humidity, solar radiation, and barometric pressure.

Four of the five stations were located at facilities operated by BP Exploration (Alaska) Inc. (BPXA): the Badami storage pad, the Endicott Satellite Drilling Island (SDI), the top of the Northstar personal living quarters (PLQ) on Seal Island, and Milne Point F-Pad. These four stations were installed in the early winter of 2000, and began collecting data January 1, 2001. The fifth station on the east end of Cottle Island was added to the study beginning on August 21, 2002.

Data collection by HCG for this project effectively ended September 30, 2006. The Northstar station has been decommissioned; however, the other four monitoring stations are still in operation. The University of Alaska, Fairbanks (UAF) Water and Environmental Research Center (WERC) has assumed ownership of the Badami, Milne Point, and Cottle Island stations as of early 2007. Information and data from these stations can be publicly accessed at the WERC website, http://www.uaf.edu/water/projects/nsl/nslakes.html. BPXA has assumed ownership of the Endicott station through at least the end of 2008.

Over the life of this project HCG prepared 23 Quarterly Data Reports for MMS, which summarize the stations' operating history, equipment and collected data in detail. Two previous reports were prepared as part of the meteorological monitoring project during the course of data collection. The *Interim Analysis Report for the Beaufort Sea Meteorological Monitoring and Data Synthesis Project* (HCG, July 2003) analyzed data collected for the first two years of the study, while the *Final Study Report for the Beaufort Sea Meteorological Monitoring and Data Synthesis Project* (HCG, July 2006) included the first 4½ years of study data. Both of these reports analyze only data collected by the MMS stations and supplemental station data are not included.

2.2 Prior Research

Research by Dr. Thomas Kozo in the 1980s demonstrated that arctic regional circulation models based upon upper air pressure fields are inaccurate predictors of surface winds within 20 to 30 kilometers (km) of the Beaufort Sea Coast. The two major effects predicted to explain the differences are:

1. The existence of an arctic sea breeze effect [Kozo, 1982]; and
2. Orographic effects caused by the Brooks Range on Alaska's eastern Beaufort Coast [Kozo and Robe, 1986].

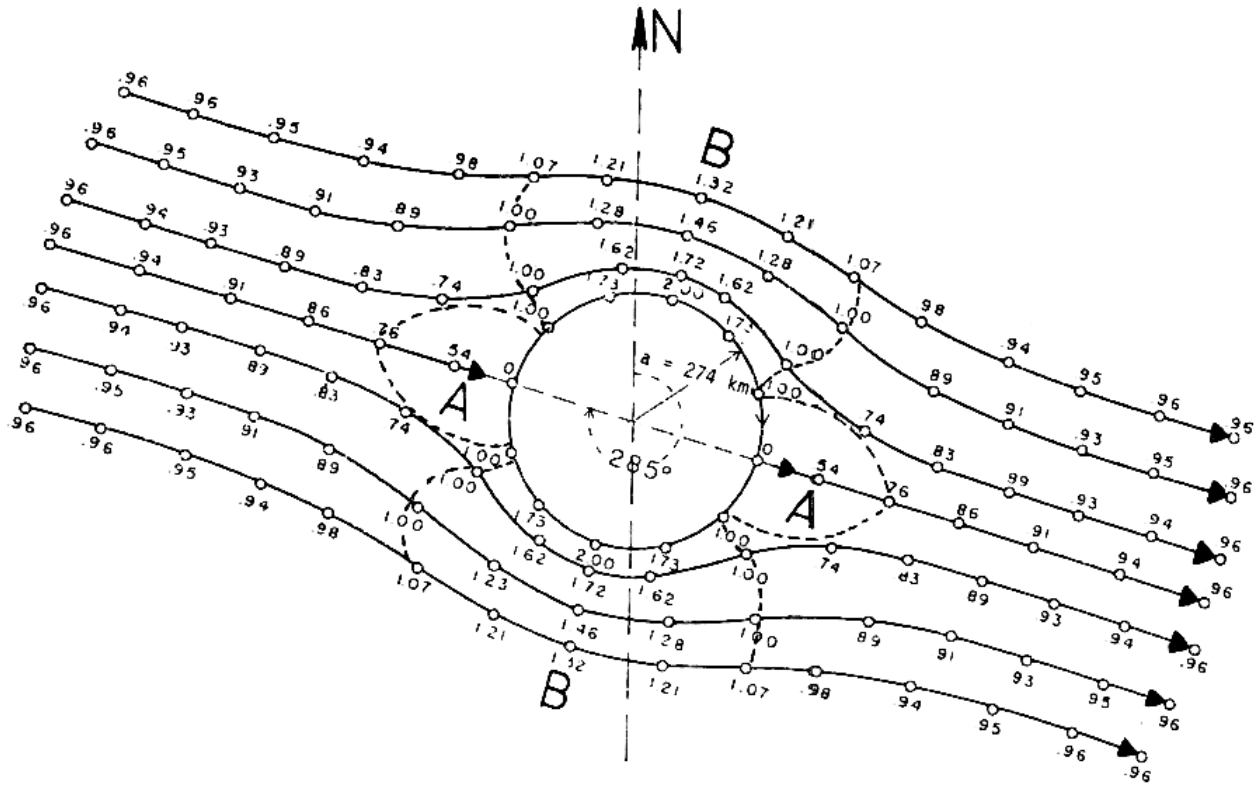
Kozo suggests that the sea breeze effect influences an area centered along the coastline that is approximately 40 km in width, while orographic effects of the Brooks Range influence an area extending at least 50 km offshore from Camden Bay to Mackenzie Bay.

The arctic sea breeze effect described by Kozo [1982] occurs during the summer, when ice-free conditions occur and daylight is almost constant in the Arctic. The long days lead to a land-sea thermal imbalance, with the land always being warmer. This causes the upper air surface to slope seaward, causing offshore pressure to rise and inducing a shoreward wind (east to north-east in the Beaufort). In contrast to the well-known sea breeze effect of the lower and mid-latitudes, this wind is consistently shoreward. Because the sun does not set for long periods during the arctic summer, there is never a reversal of temperature gradients resulting in a lack of seaward breezes that are commonplace in coastal areas at lower latitudes.

The effects of the Brooks Range are somewhat more complex than the arctic sea breeze effect. Due to the stable atmospheric boundary layer typical in the Arctic, air flow around the Brooks Range almost always presents less of an obstacle than air flow over it. This effect leads to changes in wind speed and direction relative to in model predictions. The exact nature of the diverted flow is dependant on the orientation of the wind field.

Figure 2-1 [Dickey, 1961] shows the effect of a cylindrical barrier of infinite height on a non-rotating wind field. Zones A and B are areas of subgeostrophic and supergeostrophic[1] speeds, respectively. The major effect of the obstacle extends approximately one radius away from the cylinder.

Figure 2-1. Effect of a Cylinder on a Wind Field



[1] "Geostrophic" wind speed is the speed resulting from the balance between the Coriolis force and the pressure gradient force acting on a parcel of air in the absence of friction or terrain effects. Most of the atmospheric wind outside the tropics is close to geostrophic flow most of the time. "Supergeostrophic" and "subgeostrophic" refer to wind speeds above and below what would be predicted by the geostrophic approximation, respectively.

Dickey found that the 600 meter elevation contour of the Brooks Range acts as the top half of such a cylinder with a 274 km radius. That finding translates into an effect which has significant influence over most of the Beaufort Sea coast, stretching from Teshekpuk Lake in the west to the far side of the Mackenzie River delta in the east.

Select model results presented by Kozo and Robe [1986] are reproduced in Figure 2-2 through Figure 2-4. These maps show the orographic effects of the Brooks Range in multiples of the geostrophic wind speed for synoptic-scale flow from the northeast, east, and northwest. The coastline shown by these maps stretches from just west of Prudhoe Bay to the Mackenzie River delta. The bold dotted semicircle represents the 600 meter elevation contour. To aid in understanding the relevance of these results to the stations discussed in this study the location of the stations at Deadhorse, Badami, Barter Island, and Komakuk Beach have been labeled with a red "D", "B", "BI", and "K", respectively.

Figure 2-2. Wind Speeds for Northeasterly Wind

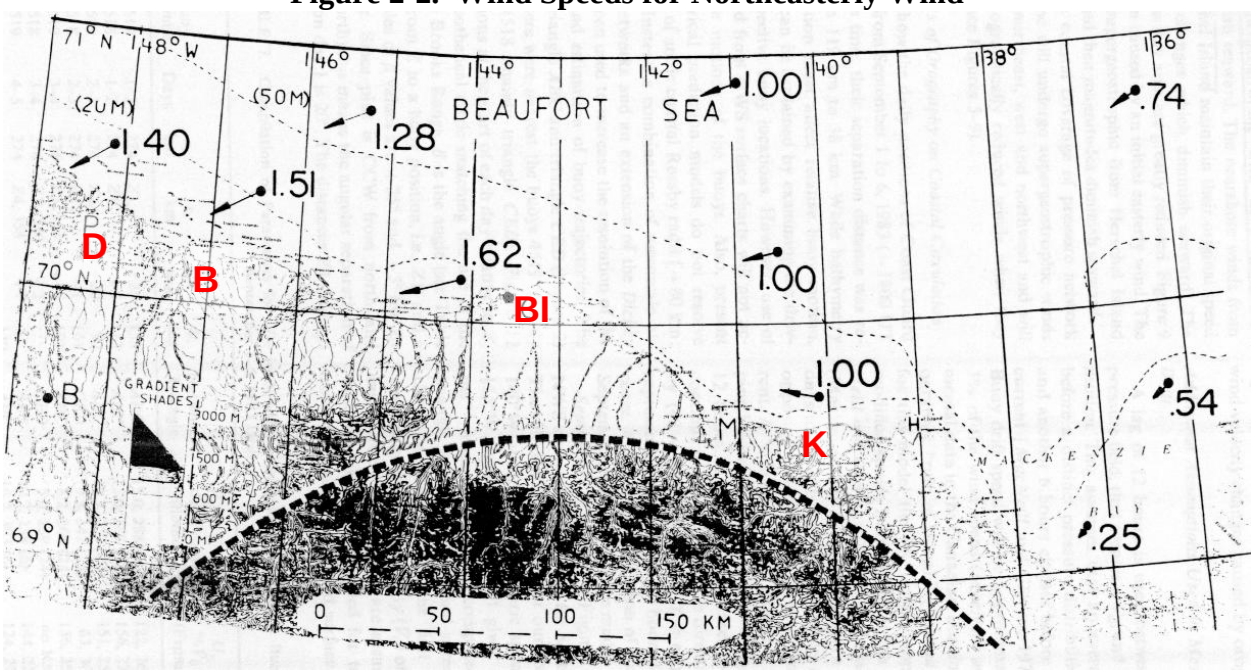


Figure 2-3. Wind Speeds for Easterly Wind

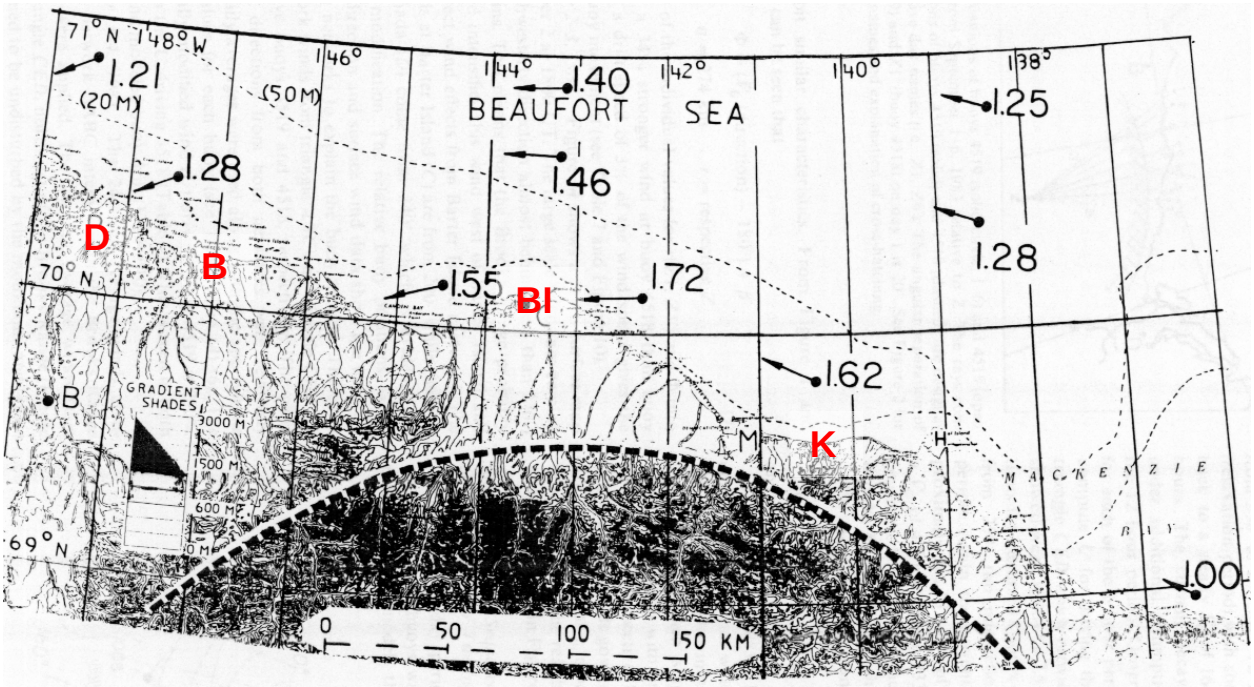
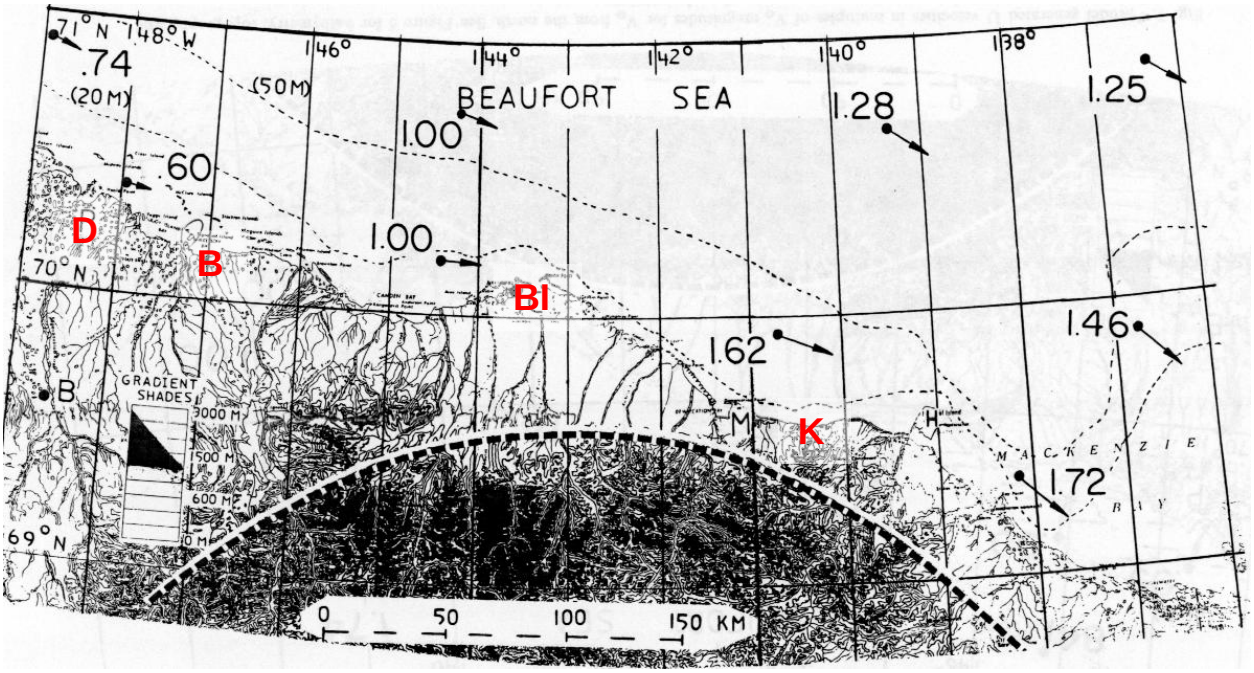


Figure 2-4. Wind Speeds for Northwesterly Wind



2.3 Overall Climatology of the Region

The climate of the nearshore region of the Beaufort Sea is a polar maritime subtype within the arctic climate zone. The arctic climate is characterized by high spatial variability, and includes both polar maritime and continental climate subtypes. The polar marine climate subtype is influenced by the ocean, versus the polar continental climate subtype which is more influenced by large land masses. The southern limit of the Arctic and the region of arctic climate is commonly placed at the Arctic Circle, latitude 66 degrees, 32 minutes North. However, the arctic climate zone has also been defined as:

- The area north of the treeline (e.g., the northern limit of upright tree growth); or
- Locations in high latitudes where the daily average summer temperature is less than 10 degrees Celsius (°C).

The main constant of any arctic climate such as the nearshore region of the Beaufort Sea is that the area is affected by the extreme solar radiation conditions of high latitudes. The low sun angle in summer means that minor topographic features, such as low hills, can cause major differences in climate at the local level because of shading. The high reflectivity or albedo of snow and ice surfaces minimizes absorption of solar radiation. As a result, heat gain during the summer is small and highly dependent on surface properties such as a topography and albedo.

In general, the weather is controlled by semipermanent low pressure systems that are weakly developed in summer, but stronger in winter. A semipermanent high pressure system over the Canadian Arctic Archipelago also exerts a strong influence on winter weather. The result is that the nearshore region of the Beaufort Sea is typified by cold winters with frequent storms. Temperature inversions in which warm air lies above colder air are common during calmer winter periods.

Summers are typically cloudy but mild. Summertime temperature inversions are less frequent and weaker. Permafrost is common, so that thawing in summer occurs only in the top few meters of ground. The result is poor water drainage, waterlogged soils, numerous lakes and ponds, and a humid atmosphere.

3 METHODS

3.1 Elements of the Study

This study included four key elements:

(1) Collection of new meteorological data,
(2) Collection of supplemental wind data,
(3) Development of meteorological databases for the collected data, and
(4) Analysis of the collected data in quarterly reports and this report.

The first three tasks above were conducted as follows:

3.1.1 Collection of New Meteorological Data

A primary element of this study was the collection of new meteorological data from the nearshore Beaufort Sea region of Alaska. The study included a total of five meteorological monitoring stations. Four new stations were established for this study at Badami, Endicott, Northstar, and Milne Point in January 2001. To address concerns about wind interferences at Northstar, a fifth station was installed on Cottle Island in August 2002. The observed parameters for this study were wind speed, wind direction, air temperature, barometric pressure, relative humidity, and incoming solar radiation. All parameters were monitored continuously. Data collection for MMS continued through September 2006.

3.1.2 Collection of Supplemental Wind Data

In addition to the HCG-operated MMS stations, wind data for 29 other sites were obtained from public and private sources, representing all available wind data collected near the Beaufort Sea coast for the period 1984 through September 2006. Many of these data sets consist of only a few months of data. Only wind data collected approximately every hour was included in the database. Data sets were limited to an area stretching from Barrow to Herschel Island (just east of the Alaska-Canada border). An updated version of the database was presented to MMS in June 2007.

3.1.3 Development of Meteorological Database

A system of data management was developed to support the collection of the new and historical meteorological data. After reformatting and quality assurance, these data were compiled into an Access database entitled the "MMS Nearshore Beaufort Sea Weather Database, 1984-2006."

Throughout the study period, newly collected data from the five MMS stations were downloaded every working day to an Anchorage-based server. After review, the data were posted to a web-enabled database, and was available for public access on the Beaufort Sea Meteorological Monitoring and Data Synthesis Project website.

The supplemental meteorological data sets were identified, collected, and quality-assured to the extent practical and delivered to MMS as an electronic Access database. This database represents a comprehensive collection of weather observations for the Beaufort Sea coast, containing all available valid hourly data collected by any significant station operating along the

U.S. or Canadian coastline from 1984 through 2006. This collection of nearly 1.7 million station-hours of data should prove to be a valuable resource for MMS and the public in modeling the meteorology of this region.

3.2 MMS Stations

3.2.1 Locations

This study includes a total of 34 meteorological monitoring sites spanning 650 km along the Beaufort Sea coast from Barrow in the west to Herschel Island in the east. This station set includes the five MMS stations operated by HCG and the 29 supplemental weather stations operated by other parties. Table 3-1 provides the coordinates for each MMS station in decimal degrees.

Table 3-1. MMS Station Coordinates

Site	Latitude	Longitude
Badami	70.136° N	147.009° W
Cottle Island	70.499° N	149.093° W
Endicott	70.323° N	147.865° W
Milne Point	70.507° N	149.662° W
Northstar	70.490° N	148.698° W

The MMS monitoring sites were selected to measure the nearshore winds along the Beaufort Sea coast in the vicinity of proposed offshore oil and gas development. These sites were located in a manner consistent with the Environmental Protection Agency (EPA) Prevention of Significant Deterioration (PSD) criteria for surface meteorological data collection. Data collection at the Badami, Endicott, Milne Point, and Northstar stations began on January 1, 2001, and at Cottle Island on August 21, 2002.

As mentioned in Section 2.1, the Badami, Endicott, Milne Point, and Northstar stations were located at facilities operated by BPXA, for which they are named. The Badami site was located on the Badami storage pad, the Endicott site was on the Endicott Satellite Drilling Island (SDI), the Northstar site was located on top of the Northstar living quarters (PLQ) on Seal Island, and the Milne Point Site was located on top of a pipe rack at the Milne Point Unit F-Pad. The Cottle Island site was located on the east end of Cottle Island, on land owned by the state of Alaska. All five stations were situated in flat areas near sea level. The Endicott, Northstar, and Cottle Island stations were located on islands and considered “offshore” stations. The Badami and Milne Point stations were located on the mainland, and are considered “onshore” stations.

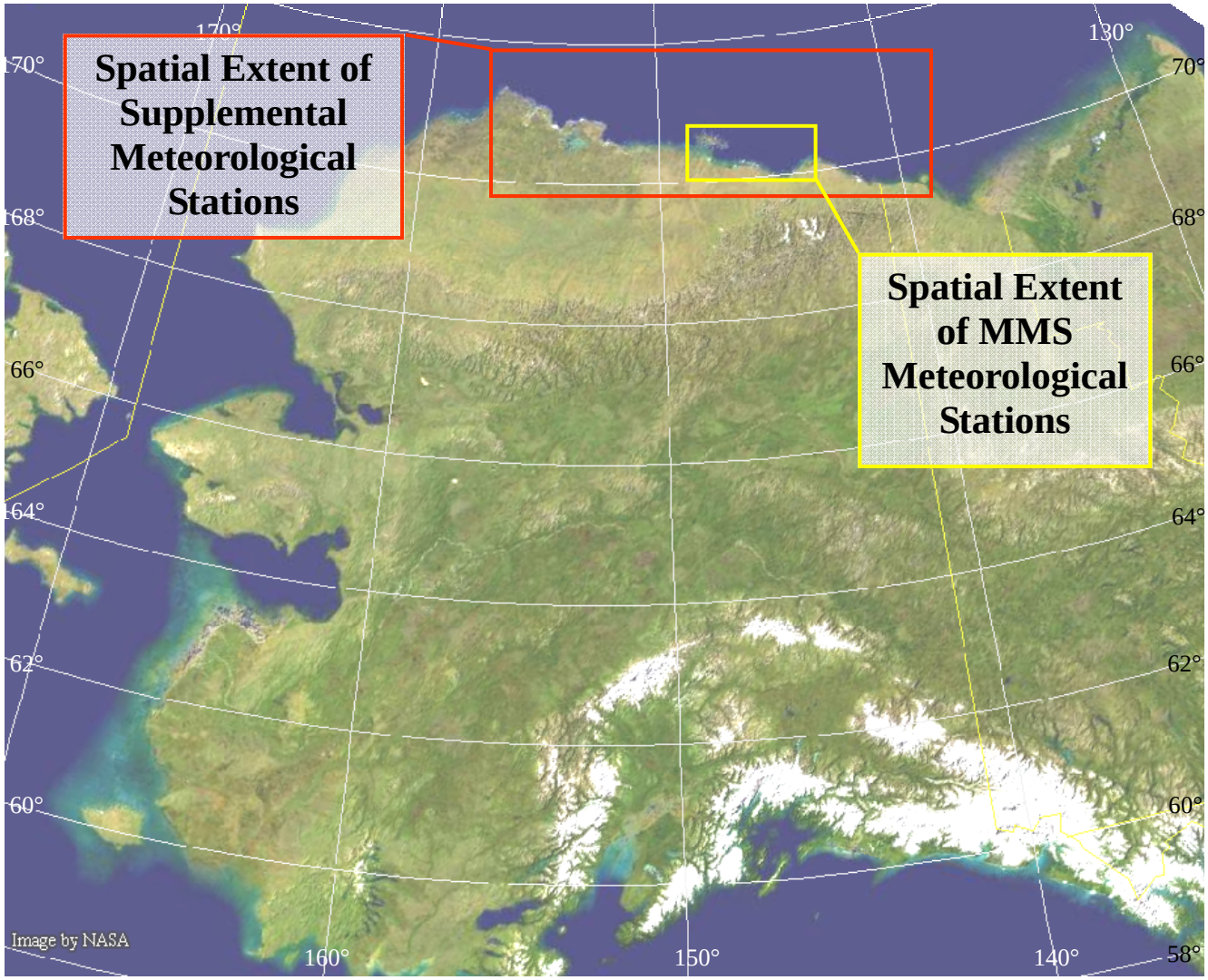
Endicott Satellite Drilling Island (SDI) is located about 3 km offshore from the mouth of the Sagavanirktok River and is connected to shore by a causeway. Northstar’s Seal Island is a two hectare (five acre) gravel island 10 km offshore. Although situating a monitoring station at the ideal 10-meter height was not possible at Northstar, the site was chosen nonetheless due to accessibility compared with other offshore sites. The Cottle Island monitoring station was located five km offshore on an undeveloped barrier island separating the Beaufort Sea from Simpson Lagoon. Milne Point Unit F-Pad sits on a point surrounded by ocean on three sides,

with tundra to the south. As with Northstar, a 10-meter tower was not possible at the site, however, a suitable, coastally located, easily accessed, alternative site could not be found. The Badami storage pad is somewhat inland, separated from the Beaufort Sea by two km of tundra.

The land in this region is flat, treeless tundra. During the short summer (June through August), land cover consists of mosses, lichens, grasses, and low-growing arctic tundra bushes. The landscape (both onshore and offshore) is covered by wind-swept snow and ice for most of the year.

Figure 3-1 presents the Project Location Map, indicating the MMS Study Area, as well as the study area for supplemental station data collection. Figure 3-2 shows the location of all the stations included in the MMS Nearshore Beaufort Sea Weather Database. Photographs of the five MMS sites are presented in Figure 3-3 through Figure 3-7.

Figure 3-1 Project Location Map



(This Page is Intentionally Left Blank)

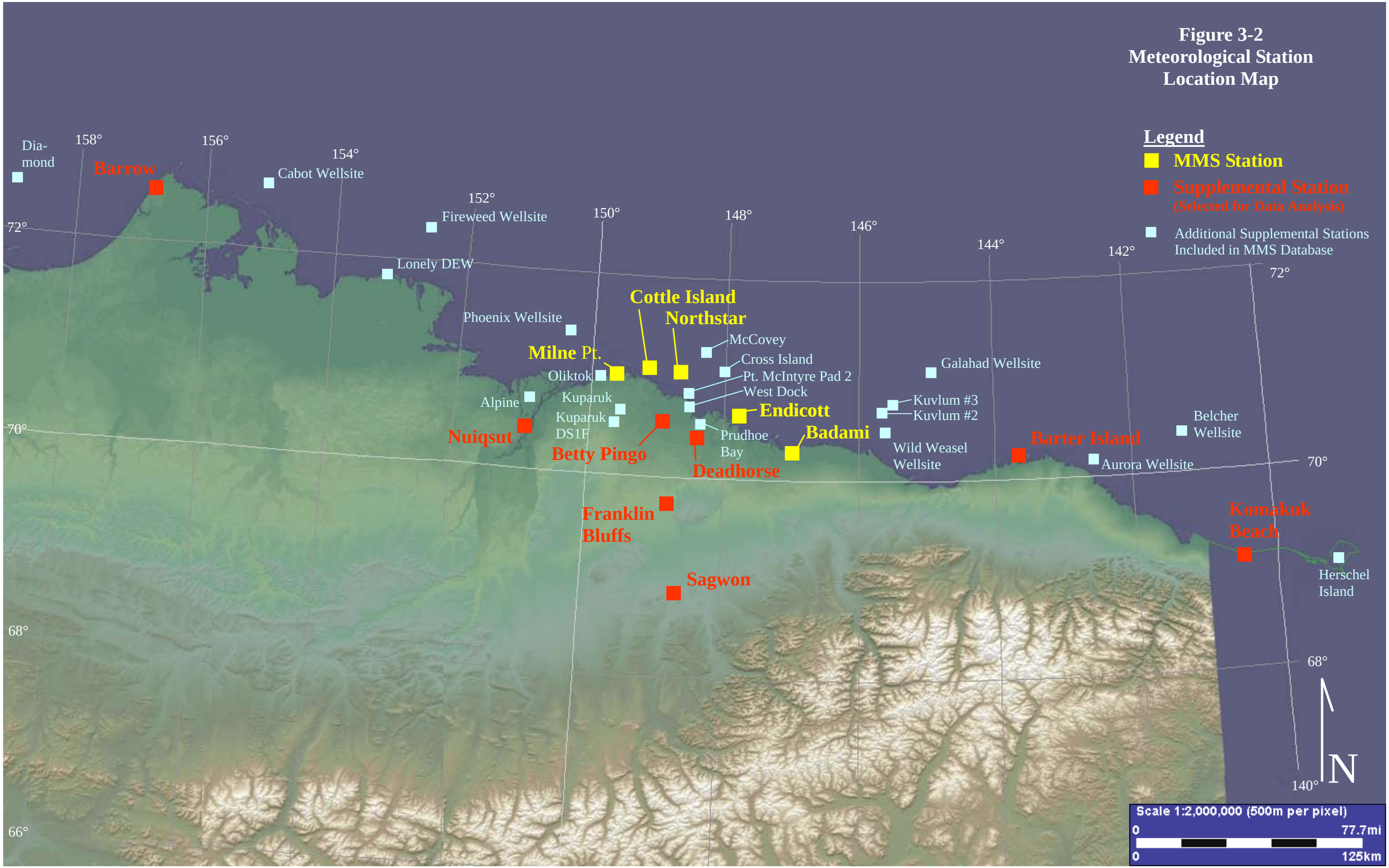


Figure 3-2
Meteorological Station
Location Map
Legend
MMS Station
Supplemental Station
(Selected for Data Analysis)
Additional Supplemental Stations
Included in MMS Database
Dia-
mond
Barrow
Cabot Wellsite
Fireweed Wellsite
Lonely DEW
Phoenix Wellsite
Cottle Island
Northstar
Milne Pt.
Oliktok
McCovey
Cross Island
Pt. McIntyre Pad 2
West Dock
Endicott
Galahad Wellsite
Kuvlum #3
Kuvlum #2
Alpine
Kuparuk
Kuparuk
DS1F
Nuiqsut
Betty Pingo
Prudhoe
Bay
Deadhorse
Badami
Wild Weasel
Wellsite
Barter Island
Aurora Wellsite
Belcher
Wellsite
Franklin
Bluffs
Sagwon
Komakuk
Beach
Herschel
Island
158°
156°
154°
152°
150°
148°
146°
144°
142°
140°
72°
70°
68°
66°
N
Scale 1:2,000,000 (500m per pixel)
0
77.7mi
0
125km

(This Page Is Intentionally Left Blank)

Figure 3-3 Badami MMS Meteorological Monitoring Station

Figure 3-4 Cottle Island MMS Meteorological Monitoring Station

Figure 3-5 Endicott MMS Meteorological Monitoring Station

Figure 3-6 Milne Point MMS Meteorological Monitoring Station

Figure 3-7 Northstar MMS Meteorological Monitoring Station

3.2.2 Instrumentation

All five MMS stations used identical instrumentation. All instruments met or exceeded the stringent EPA PSD requirements for range accuracies, thresholds, response times, resolutions, damping ratios, and other performance measures. The meteorological monitoring program collected hourly data for the following parameters at each MMS monitoring location:

- Wind speed (meters per second [m/s]);
- Wind direction (degrees [°]);
- Wind direction standard deviation (wind sigma [σ_θ]);
- Air temperature, motor-aspirated shield (degrees Celsius [°C]);
- Air temperature, motor-aspirated shield, backup (degrees Celsius [°C]);
- Barometric pressure (millibar [mbar]);
- Incoming solar radiation (watts per square meter [W/m^2]); and
- Relative humidity, motor-aspirated shield (percent [%]).

Each site also recorded the minimum and maximum instantaneous temperature and the maximum instantaneous wind speed during the previous hour. All parameters were collected as hourly averages, except barometric pressure which was recorded at the start of each hour. All measured parameters (except barometric pressure and solar radiation) were audited and calibrated semiannually.

Mean hourly temperature, minimum instantaneous temperature, and maximum instantaneous temperature are similar most of the time. Mean hourly temperature is defined as the average temperature recorded for every second of the specified one-hour interval. Minimum instantaneous temperature is defined as the lowest temperature recorded in the one-second measurements throughout the specified one-hour interval. Maximum instantaneous temperature is defined as the highest temperature recorded in the one-second measurements throughout the specified one-hour interval.

Wind speed, wind direction, and wind sigma were measured at a height of approximately 10 meters above ground level at Badami, Cottle Island and Endicott, and at approximately 14 meters and 23 meters above ground level at Milne Point and Northstar, respectively. Temperature and relative humidity were measured at a height of two meters above ground level at Badami, Cottle Island, and Endicott, and at 11 meters at Milne Point and 21 meters at Northstar, above ground level.

Barometric pressure was measured between one and two meters above ground level at Badami, Cottle Island, Endicott, and Milne Point, and at 21 meters above ground level at Northstar. Solar radiation was measured at a height of approximately five meters above ground level at Badami, Cottle Island, and Endicott, at 13 meters above ground level at Milne Point, and 22 meters above ground level at Northstar.

A listing of each parameter and sampling method used during the monitoring program is provided in Table 3-2.

Table 3-2. Primary MMS Meteorological Monitoring Equipment

Parameter	Make/Model	Range	Method
Wind Speed	Climatronics F460	0.0 to 60 m/s	Three-cup anemometer assembly
Wind Speed/ Direction*	RM Young 05305-AQ	0.0 to 50 m/s 0° to 360°	Propeller anemometer mounted on a vane (DC voltage from conductive plastic potentiometer)
Wind Direction	Climatronics F460	0° to 360°	Vane, potentiometer voltage output proportional to wind direction
Wind Sigma	Campbell Scientific CR10X-XT	---	DAS calculated, 15-minute root mean square values averaged to 1-hour values
Temperature	Climatronics 100093-2	-50°C to +50°C	Platinum 4-wire probe and thermistor in a motor-aspirated shield
Barometric Pressure	Campbell Scientific 105	600 to 1,060 mb	Silicon capacitive pressure sensor
Relative Humidity	Campbell Scientific HMP-45C	-40°C to +60°C (0% - 100% RH)	Capacitive polymer H chip in a motor-aspirated shield
Solar Radiation	Campbell Scientific LI200X	400 to 1,100 nm	Silicon photovoltaic detector mounted in cosine-corrected head
Datalogger	Campbell Scientific CR10X-XT	-55°C to +85°C	1.0-second scans, processed to hourly averages recorded on the hour

*****RM Young wind speed sensors were used at Cottle Island and Endicott as backup sensors.

3.2.2.1 Wind Speed and Direction

Wind speed and direction were measured continuously using Climatronics F460 Wind Sensors and RM Young Model 05305-AQ Wind Monitors. RM Young sensors were installed to be backup sensors; if data from the primary Climatronics sensors were determined to be invalid, data from the backup sensor were substituted. The Climatronics sensor uses a three-cup anemometer to measure wind speed. The cup rotation produces a signal frequency proportional to wind speed, which is recorded by the datalogger. RM Young sensors were deployed at Cottle Island and Endicott for part of the monitoring period to take parallel wind speed measurements using a propeller anemometer. The propeller rotation produces a signal frequency proportional to wind speed, which is recorded by the datalogger.

Both Climatronics and RM Young wind direction sensors consists of a wind vane with a 360-degree potentiometer for a signal transducer. The wind speed sensor and wind direction sensor are separate instruments on the Climatronics assembly. The standard deviation of the wind direction (wind sigma [σ_θ]) is computed by the Campbell CR10X-XT datalogger using the EPA-preferred Yamartino (1984) method.

Wind speed measurements were adjusted at Milne Point and Northstar due to differences in instrument height from the ten meter standard. Theoretically, wind speed is equal to zero at the ground, then increases logarithmically with height. The rate of increase depends upon the surface roughness (z_0). If the surface roughness is known, and if the wind speed M_1 at height z_1 is known, then wind speed M_2 at height z_2 can be estimated using the formula:

$$M_2 = M_1 \cdot \left(\frac{\ln(z_2 / z_0)}{\ln(z_1 / z_0)} \right)$$

Heights are in meters and speeds in meters per second (m/s). At Milne Point the assumed surface roughness was 0.005 meters, which is defined by the Davenport-Wieringa roughness length classification as "smooth," representing surfaces such as beaches, pack ice, and snow covered fields. The above formula can then be used to determine that the wind speeds observed at 14 meters at Milne Point should be multiplied by 0.958 to estimate the wind speed at ten meters height.

Adjusting the height at Northstar was more problematic, because the general area around the station has a surface roughness length between 0.0002 ("sea") and 0.005 ("smooth"), but the area around the site was greater than 2, or "chaotic," representing city centers or irregular forests with scattered clearings. This situation is further complicated by uncertainty in determining "ground height." For example, in a forest the tree tops are considered "ground height", but structures are present on Seal Island that are taller than the wind sensor, leaving the ground height ambiguous.

Assuming that the surface of the island is effectively ground height and the surface roughness is 0.005, it is estimated that the wind speed should be multiplied by 0.929 to approximate the wind speed at ten meters. However, if a surface roughness of 2 is applied, then the multiplier falls to 0.659.

All data in the historical database, on the website, and in the wind roses represents the raw unadjusted data. The summary tables in Section 4.1 have been adjusted by 0.958 for Milne Point for 0.929 at Northstar.

3.2.2.2 Temperature

Temperature probes were located at a height of two meters at Badami, Endicott, and Cottle Island, 11 meters at Milne Point, and 19 meters at Northstar. Recorded temperatures were not adjusted to take instrument height into account, as frequent temperature inversions in the Arctic make the relationship between height and temperature variable.

Two separate temperature probes were located at each site, a Climatronics Temperature Sensor Model 100093-2 and a Campbell Model HMP-45C instrument, which is a slightly modified version of the Vaisala HMP45 dual temperature/relative humidity probe. The Campbell Model HMP-45C instrument has a similar temperature measurement range as the Climatronics probe, but is not certified for accuracy below -40 °C. Data from the Campbell probe were used to back up and verify data from the primary Climatronics probe.

3.2.2.3 Barometric Pressure

Pressure was measured using a Campbell CS105 (Vaisala PTB-101B) Barometric Pressure Sensor housed inside the Campbell datalogger enclosure. This model of barometric pressure sensor takes an hourly instantaneous reading. No user-serviceable parts are present on the sensor.

Barometric pressure varies from site to site, but some of this variation is due to the height of the sensor. The Badami, Endicott, Milne Point, and Cottle Island stations have their sensors

mounted at two meters above ground level, while the Northstar station measured barometric pressure at 21 meters above ground level. Estimates of the total elevation of the sensors and the corresponding estimated adjustment to sea-level are shown in Table 3-3. The pressure was corrected using the formula:

$$\Delta P = \frac{\rho \cdot g \cdot \Delta z}{100}$$

Where,

ΔP is the change in pressure in Pascals, ρ is density (1.225 kg/m^3), g is the force of gravity (9.8 m/s^2), and Δz is the change in height in meters. Pascals are converted to millibars by dividing by a factor of 100. All data in the historical database represents the raw, unadjusted data. The adjustments shown in Table 3-3 have been added to the summary tables in Section 4.5 where noted.

Table 3-3. Adjustment to Sea-Level Pressure

Station	Sensor Elevation (m)	Adjustment (mbar)
Badami	17	+2.0
Cottle Is	5	+0.6
Endicott	5	+0.6
Milne Pt	7	+0.8
Northstar	21	+2.5

3.2.2.4 Solar Radiation

A Campbell LI200X Silicon Pyranometer, manufactured by Li-Cor, measures solar radiation at each of the sites. The pyranometer measures sun plus sky wavelengths between 400 and 1,100 nanometers (daylight spectrum). The instrument has an absolute error in natural daylight of plus or minus five percent. Occasional artificial light sources (facility lighting, flaring) have caused false readings at some sites. Suspect solar radiation readings are especially noted at Northstar due to the nearby facility flare.

3.2.2.5 Relative Humidity

Relative humidity was measured at the same heights as the temperature probes using a Campbell Model HMP-45C, which is a Vaisala HMP-45A dual temperature/relative humidity probe. The probe uses a capacitive polymer H chip for the relative humidity measurement and operates in a -40 °C to +60 °C temperature range.

3.2.2.6 Data Acquisition and Telemetry

A Campbell Scientific Model CR10X-XT 12-channel datalogger monitored all instruments. The datalogger collects a continuous stream of data from the instruments and then stores hourly averages, peaks, and/or instantaneous readings in the datalogger storage module. The data were

then downloaded from the storage modules to the HCG office in Anchorage by cell phone on a daily basis.

3.2.3 Operating History

The five-station network generally performed well during the five and three quarters years of the study (January 2001 through September 2006). However, the study was not without some periods of lost data due to equipment failures, equipment damage, station audits, and other factors. Frozen anemometers, broken or corroded wind vanes and broken relative humidity sensors were the most common equipment problems. The Northstar station, in particular, had significant periods of missing data due to wind direction sensor damage and repeated relative humidity sensor failures.

3.2.3.1 Data Validation

Meteorological data collected during this study were validated using guidelines set forth in *On-site Meteorological Program Guidance for Regulatory Modeling Applications* (EPA, 1995) and screened based on EPA suggested screening criteria (EPA, 2000). The data validation criteria are also outlined in the *Minerals Management Service Meteorological Monitoring and Quality Assurance Plan (*Hoefler, 2001).

HCG staff monitored the operation of the stations on a regular basis (daily, when possible) to ensure that data were being correctly logged. Daily polling of the system alerted personnel to adverse operations and enabled a response, if necessary, for recognized problems to minimize data loss. During site visits, meteorological data were downloaded directly into a laptop computer. These data were compared to data acquired from the cell-phone modem as a means of validating the modem-acquired data.

The field operation personnel were responsible for the first phase of data validation, wherein first-hand knowledge of instrument performance was required to determine data quality. The data manager was responsible for the second phase of data validation. The data manager reviewed selective field data documentation and calibration data to ensure adherence to tolerances and procedures, and to provide the review essential to quality control. A Certified Consulting Meteorologist (CCM) from HCG performed a final review of the collected data for accuracy.

In order for data from the meteorological sensors and systems to be considered valid, a number of requirements needed to be satisfied, as detailed in the *Meteorological Monitoring and Quality Assurance Plan.* In general, requirements were two-fold, (1) those related to calibration, and (2) those related to individual instrument performance. Calibration requirements included correct instrument calibration, valid semi-annual audits and calibrations, and proper documentation of audits and calibrations. For each instrument, a set of performance criteria were reviewed pertaining to the individual meteorological parameter. Criteria included the following:

- checking that readings from the instrument were within the proper range of expected readings,
- checking instrument function as evidenced by normal data variation as opposed to flat readings or unanticipated large swings,

- ensuring that the operating ambient temperature range of the instrument was not exceeded, and
- comparing data to data from other stations to look for inconsistencies.

Data flagged under the EPA or HCG criteria were carefully examined, but were generally not removed unless the following was observed:

- values were outside the normal range of variation,
- the values became almost constant for an unidentified reason,
- maintenance activity had occurred at the site,
- instruments had been damaged, or
- if the flags continued uninterrupted for an extended period without explanation.

Where possible, valid data from redundant sensors were used in place of invalid data from primary sensors. Data that were determined to be invalid were removed from summary spreadsheets and databases, and were not included in calculations or statistics within the reports.

Invalid data were removed from summary spreadsheets, and were not included in station databases. Statistical calculations were thus performed from a slightly smaller data set. The deletion of invalid data affected the data capture percentage goals for the project that were set at 90% capture per quarter, as discussed below. It is unknown, however, whether the omission of invalid data biased the overall results.

The unpublished Quarterly Data Reports for the MMS stations provided a discussion of all significant occurrences of lost or questionable data. In addition, a Significant Events table has been included in the *MMS Nearshore Beaufort Sea Weather Database* to summarize instances of deleted or missing data. The most common problems encountered with the data included low wind speeds during winter months usually attributed to anemometer icing, incorrect wind direction readings due to corroded or damaged wind vanes, and instrument damage or failure. The largest deletion of invalid data occurred at Northstar in 2002, when over seven months of wind direction data did not agree with data from other MMS meteorological stations. Data recovery at Northstar for wind direction reflects this data loss. Other significant periods of data removal occurred during winter months when icing conditions led to anemometer freezing conditions. This would often affect several stations at once, and would lead to missing data for days or possibly weeks at a time. Anemometer icing was less frequent at stations with line power where bearing heaters were installed; at self-powered stations, visits by facility personnel to de-ice anemometers were sometimes required.

In 2002, The EPA data validation screening criteria were not effective in identifying an error in wind direction measurements. As a result, additional wind direction validation procedures were developed and implemented in December 2002 to notify HCG of any errors in wind direction data collection. Wind direction, as well as other parameters, was graphically reviewed side by side as part of the initial data review process to watch for data anomalies.

3.2.3.2 Data Capture

Data recovery from the stations was quite good, especially considering the remoteness of the sites and the extreme weather conditions. Data recovery is expressed as a percentage equal to the number of valid hourly measurements divided by the total number of hours. Data recovery for each parameter at all sites was above 90 percent, with exception of Northstar. This performance complies with the rigorous EPA PSD air quality modeling data capture requirements, with exception of Northstar. Data capture is summarized for each major parameter by station in Table 3-4.

Table 3-4. Data Capture Summary

Station	Wind Speed	Wind Direction	Wind Sigma	Temperature	Barometric Pressure
Badami	98.9%	99.0%	98.4%	99.6%	99.7%
Cottle Island	98.1%	94.7%	90.8%	99.4%	99.5%
Endicott	93.0%	92.2%	90.7%	94.4%	99.1%
Milne Point	97.6%	98.4%	97.0%	99.9%	99.9%
Northstar	95.6%	83.4%	92.6%	99.6%	99.6%

3.2.4 Wind Data Quality at Northstar

The wind data quality at Northstar station is poor relative to the other four MMS stations. Despite the ideal geographic location, the number of large obstacles that created interference makes it impossible to have confidence that the wind data collected is representative of the larger region. A large process module arrived in August 2001, which interfered with wind surrounding that station. Figure 3-8 shows the problematic structural environment surrounding the Northstar station. The current site is overshadowed by other structures and does not sit at ten meters above grade. Wind speed is considered accurate, but wind direction and wind sigma data results were likely affected for periods during this study due to the presence of a process module, drill rig and crane, all of which exceed the height of the meteorological tower. Therefore, the results of the Northstar wind direction data in this study should be considered suspect. Any deviations from the expected wind direction results in this study for the Northstar station are likely the result of interference from the neighboring objects on the island.

The station was installed on top of the PLQ building in December 2000 with wind instrumentation at 23 meters. The large building in Figure 3-8 is the South Process Module, which is approximately 36 meters tall and located 100 meters north of the monitoring tower. The drill rig and crane are taller than the process module and are mobile. When the process module was installed on August 10, 2001, alternative station sites on the island were investigated but an adequate location without wind interference could not be identified.

The Northstar station also experienced unusually rapid corrosion, which led to data capture problems when a corroded tail broke free of the wind vane in 2002.

Figure 3-8 Aerial View of Northstar Showing Station Station

3.3 Supplemental Stations

3.3.1 Locations

In addition to the MMS stations discussed in the previous section, data from 29 other meteorological monitoring stations have been included in the MMS Nearshore Beaufort Sea Weather Database. Maps of the study area and the station locations are shown in Figure 3-1 and Figure 3-2. Table 3-5 provides a station inventory and coordinates for each supplemental station.

Table 3-5. Supplemental Station Inventory

Station	Latitude	Longitude	Start Date	End Date	Source
Alpine	70.333° N	150.933° W	6/8/2004	9/30/2006	NCDC
Aurora Wellsite	70.109° N	142.785° W	9/12/1987	9/12/1988	Tenneco/MMS
Barrow Airport	71.284° N	156.778° W	1/1/1984	10/1/2006	NCDC
Barter Island	70.133° N	143.583° W	1/1/1984	10/1/2006	NCDC
Belcher Wellsite	70.275° N	141.513° W	9/1/1988	8/31/1989	Amoco/MMS
Betty Pingo	70.280° N	148.896° W	5/27/1994	1/1/2005	WERC (UAF)
Cabot Wellsite	71.324° N	155.216° W	10/31/1991	2/29/1992	Arco/MMS
Cross Island	70.49° N	147.95° W	9/7/2002	9/18/2004	MMS
Deadhorse Airport	70.200° N	148.467° W	1/1/1985	10/1/2006	NCDC
Diamond Wellsite	71.333° N	161.680° W	8/31/1991	10/5/1991	Chevron/MMS
Fireweed Wellsite	71.088° N	152.603° W	10/14/1990	12/20/1990	Arco/MMS
Franklin Bluffs	69.893° N	148.77° W	12/15/1986	1/1/2005	WERC (UAF)
Galahad Wellsite	70.561° N	144.96° W	9/13/1991	10/14/1991	Amoco/MMS
Herschel Island	69.567° N	138.917° W	10/16/1986	10/1/2006	Environment Canada
Komakuk Beach	69.583° N	140.183° W	1/1/1985	10/1/2006	Environment Canada
Kuparuk Airport	70.317° N	149.583° W	2/4/1991	12/31/2004	NCDC
Kuparuk DS-1F	70.290° N	149.680° W	1/1/1991	6/30/2002	CPAI
Kuvlum Wellsite #2	70.310° N	145.538° W	7/19/1993	8/30/1993	Arco/MMS
Kuvlum Wellsite #3	70.327° N	145.404° W	8/31/1993	9/30/1993	Arco/MMS
Lonely	70.917° N	153.233° W	1/1/1985	3/25/1988	NCDC
McCovey	70.528° N	148.187° W	11/30/2002	2/9/2003	MMS
Nuiqsut	70.218° N	150.993° W	4/9/1999	10/1/2006	CPAI
Oliktok	70.500° N	149.883° W	1/1/1985	9/26/1995	NCDC
Phoenix Wellsite	70.717° N	150.428° W	9/2/1986	9/9/1987	Tenneco/MMS
Pt. McIntyre Pad 2	70.40° N	148.517° W	5/17/2005	10/1/2006	NCDC
Prudhoe Bay	70.250° N	148.333° W	6/3/1987	6/14/1999	NCDC
Sagwon	69.423° N	148.693° W	10/11/1986	1/1/2005	WERC(UAF)
West Dock	70.381° N	148.561° W	7/14/1995	11/8/2004	WERC (UAF)
Wild Weasel Wellsite	70.229° N	145.499° W	9/30/1993	11/10/1993	Arco/MMS

Abbreviations
CPAI – Conoco Phillips Alaska, Inc.
NCDC – National Climate Data Center
WERC (UAF) – University of Alaska Fairbanks Water and Environmental Research Center

3.3.2 Comparison of Supplemental Stations with MMS Stations

Data sets from supplemental stations were evaluated to determine their comparability of the data with data from the MMS stations. The data sets were ranked from A (best) to D (worst) on the basis of four criteria discussed below. The results are shown in Table 3-6. Stations achieving ratings of A or B+ were chosen for comparisons with the MMS stations. Seven stations met these criteria: Barrow, Betty Pingo, Franklin Bluffs, Deadhorse, Komakuk Beach, Nuiqsut, and Sagwon. An eighth station, Barter Island, was given a B ranking, but was included in the study due to its geographic location with relation to other stations in the study, and its long operational history. These eight stations are referred to as the "supplemental stations" throughout the rest of this report.

The ranking system was used solely for station selection for the study. A low ranking does not imply that data from the source is poor; rather, data from that station is not appropriate for use in comparison with MMS station data for the purposes of this study. A series of four questions was posed of each station, and the answer was categorized from "A" as the highest to "D" as the lowest. In the final column, a total ranking was given to each station.

The overall ranking of a supplemental station reflects the following characteristics.

- "A" stations have excellent data capture percentages over the same time frame as the MMS stations, and have a long historical record.
- "B+" stations have a long history, but are either missing time periods that overlap with MMS stations, or have poorer data capture percentages, but are important for inclusion in the study.
- "B" stations have a good data history, but are missing data from the past six years, or have lower data capture percentages.
- "C" and "D" stations have short operating histories or no data overlapping the time frame of the MMS stations.

The following questions were posed of each location:

1. What is the length of data collection?[2]

   A Over 5 years
   B 3 to 5 years
   C 1 to 3 years
   D Less than 1 year

2. Is data available for the same time period as the MMS stations (Jan 2001 through Sept 2006)?[3]

   A Yes, for entire time period
   B Yes, but for only a portion of the time period
   C No, data does not overlap the time period

[2] Only stations ranked "A" here were considered in the following selections.
[3] Only stations ranked "A" or "B" were considered in the following selections.

3. What is the data collection interval during the last six years?

   A Hourly
   B Hourly with 2 to 3 hour data gaps
   C Hourly with 4+ hour data gaps
   D Infrequent or random

4. What is the data capture percentage since January 1, 2001, for wind speed and wind direction?

   A 90 percent or greater
   B 75 to 90 percent
   C 50 to 75 percent
   D Less than 50 percent

Table 3-6. Supplemental Station Ranking

Station ID	Station Name	Length of Collection	Time Period	Collection Interval	Data Capture (% WS/WD)	Overall Rank
1	Aurora Wellsite	C	--	--	--	C
5	Barter Island	A	A	C	C – 68.3/68.4	**B**
6	Belcher Wellsite	C	--	--	--	C
7	Betty Pingo	A	B	A	A – 90.5/99.9*	**B+**
8	Cabot Wellsite	D	--	--	--	D
10	Diamond Wellsite	D	--	--	--	D
12	Fireweed Wellsite	D	--	--	--	D
13	Galahad Wellsite	D	--	--	--	D
14	Herschel Island	A	A	A	C – 64.2/64.2	B
15	Komakuk Beach	A	A	A	B – 76.8/76.8	**B+**
16	Kuparuk Airport	A	A	C	C – 55.8/54.4	B
17	Kuparuk DS-1F	A	B	A	C – 69.0/69.0	B
18	Kuvlum Wellsite #2	D	--	--	--	D
19	Kuvlum Wellsite #3	D	--	--	--	D
20	Lonely DEW	B	--	--	--	C
23	Nuiqsut	A	A	A	A- 97.0/97.0	**A**
25	Oliktok #2	A	C	--	--	C
26	Phoenix Wellsite	C	--	--	--	C
27	Prudhoe Bay	A	C	--	--	C
28	Wild Weasel Wellsite	C	--	--	--	C
29	West Dock	A	B	A	B – 77.6/95.0*	B
30	Alpine	C	--	--	--	C
32	Cross Island	D	--	--	--	D
33	Franklin Bluffs	A	B	A	B/A-87.7/98.9*	**B+**
34	Pt. McIntyre Pad 2	C	--	--	--	C
35	Sagwon	A	B	A	B/A-88.0/90.8*	**B+**
111	Badami	A	A	A	A – 98.9/99.0	**A**
222	Endicott	A	A	A	A – 93.0/92.2	**A**
333	Milne Point	A	A	A	A – 97.6/98.4	**A**
444	North Star	A	A	A	A – 95.6/83.4	**A**
499	Cottle Island	A	A	A	A – 98.1/94.7	**A**
555	McCovey	D	--	--	--	D
27406	Deadhorse	A	A	A	A – 97.2/97.2	**A**
27502	Barrow	A	A	A	A – 98.7/98.7	**A**

Red font indicates all stations achieving an "A" or "B" rating that were chosen for comparisons with the MMS stations in this study.
Data capture was defined as the number of valid hourly measurements divided by the total number of hours available for inclusion in the database.
*Data for UAF/WERC stations was available through 1/1/05.

3.3.3 Data Review at Supplemental Stations

Data obtained from supplemental stations was reviewed for inclusion into the Database and subsequent analysis with MMS stations. Only data from the eight supplemental stations chosen for comparison with MMS stations was reviewed. Data review was limited for the supplemental stations. Audit records, calibration records, and raw data were not available for the supplemental stations. However, in some cases data review by third parties had been conducted, and data qualifier flags were added to the data where missing or invalid data had been removed.

Data from supplemental stations were visually reviewed in graphic format and compared with nearby supplemental stations or MMS stations, if possible. Ultimately, the only data removed from the database was that attributed to anemometer icing. Suspected anemometer icing was a concern mostly at the unmanned stations of Betty Pingo, Franklin Bluffs, and Sagwon, although a few other periods of icing at manned sites were observed. Data were only considered to be invalid if readings were obviously incorrect (e.g. reading flat at or near zero for extended periods of time).

Periods of suspected anemometer icing lasting approximately 7 to 10 days or longer were removed from the database; shorter periods of anemometer icing remain in the database. Statistical calculations were performed from a slightly smaller data set after removal of larger periods of invalid data. Although data capture is slightly less for these parameters, the impact of the invalid data on the entire dataset is unknown, as winds during icing periods could have been any speed within the normal range for the area.

4 RESULTS

The following section presents summary tables and general discussion of descriptive statistics for wind speed, wind direction, wind sigma, temperature, barometric pressure, solar radiation and relative humidity for the study period January 2001 through September 2006. Wind speed and wind direction are analyzed for both the MMS and selected supplemental stations.

Because the Cottle Island station did not begin acquiring data until August 2002, this station has a smaller data set than the other stations. Throughout this section, the confidence interval given for the mean is the 95 percent confidence interval.

4.1 Wind Speed

Wind speed data sets from the MMS and supplemental stations were analyzed for the period January 2001 through September 2006. Descriptive statistics for wind speed are presented in Table 4-1 for the MMS stations and Table 4-2 for the supplemental stations. Wind speed data at the Milne Point and Northstar stations have been adjusted in Table 4-1, Figure 4-1, Figure 4-2, and Figure 4-4 to account for the monitoring height of the anemometer, as described in Section 3.2.2.1. Table 4-1 includes the mean hourly gust and maximum gust (instantaneous wind speed) recorded at each site. Table 4-2 does not include gust data, because this parameter was not available for the supplemental monitoring sites.

Table 4-1. Wind Speed Statistics for the MMS Stations (m/s)

	Badami	Cottle Is	Endicott	Milne Pt	Northstar
Mean	5.92	5.57	5.31	5.42	5.13
95% Confidence Interval (Mean)	5.89 – 5.96	5.53 – 5.60	5.28 – 5.34	5.39 – 5.44	5.11 – 5.16
Std Deviation	3.91	3.54	3.48	3.33	2.96
Median	4.97	4.80	4.44	4.67	4.66
Maximum	27.87	22.86	23.69	24.92	24.93
Mean Gust	7.9	7.6	7.3	7.2	7.5
Max Gust	35.5	32.8	30.6	33.8	36.2

Table 4-2. Wind Speed Statistics for the Supplemental Stations (m/s)

	Barrow	Barter Is.	Betty Pingo	Dead-horse	Franklin Bluffs	Komakuk	Nuiqsut	Sagwon
Mean	5.58	4.94[4]	4.93	5.35	4.11	6.26	4.80	3.89
95% Confidence Interval (Mean)	5.55 – 5.60	4.90 – 4.97	4.90 – 4.97	5.32 – 5.38	4.07 – 4.14	6.22 – 6.31	4.77 – 4.83	3.86 – 3.92
Std. Deviation	2.88	3.51	3.26	3.31	3.07	4.49	2.99	2.77
Median	5.20	4.10	4.30	4.60	3.50	5.28	4.20	3.50
Maximum	25.00	26.20	22.80	25.20	27.40	33.06	23.70	23.80

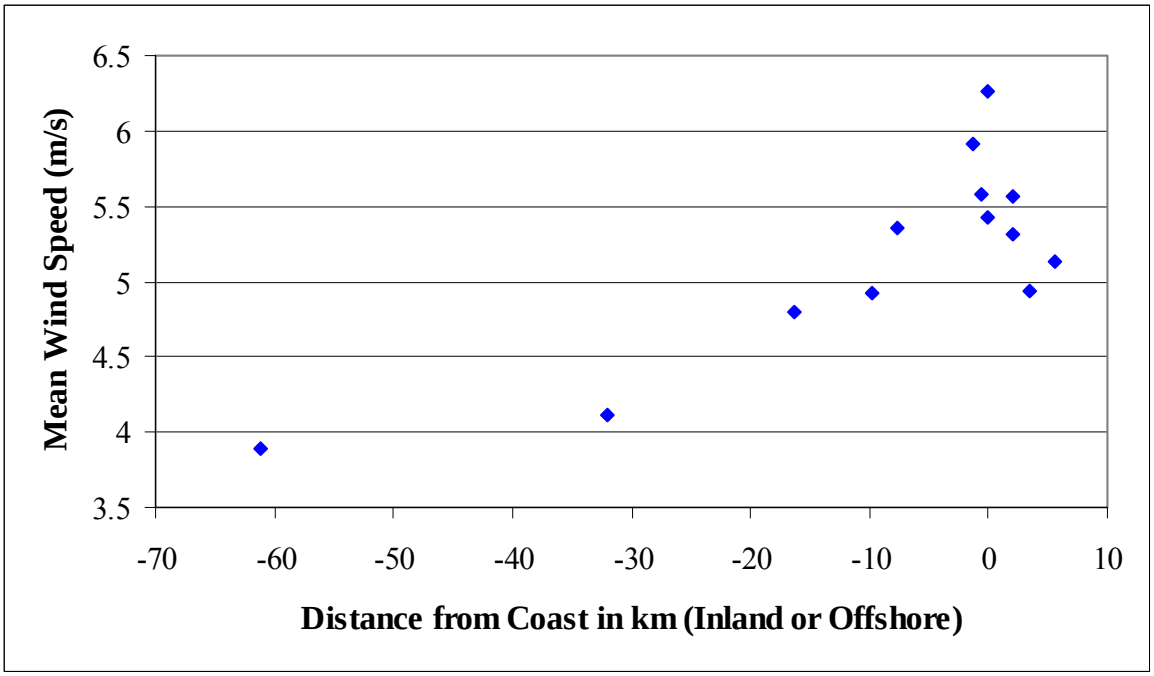
The low mean wind speed at Endicott may be partially due to anemometer icing problems (see Section 5.5). The Northstar wind speed may have been biased due to interference from on-site obstacles (see Section 3.2.4).

The relatively high wind speeds observed at Badami and Komakuk Beach would seem to support the findings of Kozo [1986], whose model predicted higher wind speeds in the east under most conditions due to the effects of the Brooks Range (see Section 2.2). The Barter Island mean wind speed, however, would be expected to be higher because of its proximity to the Brooks Range.[4]

Wind speeds also appeared to be highest nearest the coast. Figure 4-1 plots the distance offshore against the mean wind speed for each station.

[4] The Barter Island mean wind speed would be expected to be higher because of its proximity to the Brooks Range, more in the range of Badami and Komakuk Beach. It should be noted that the Barter Island data exhibited the lowest data capture of the supplemental stations in the 2001-2006 time frame; data capture was especially poor in 2001. As will be discussed below in Section 4.1.1, Long Term Wind Speeds at Supplemental Stations, in the mid-1980s, wind speed data from Barter Island shows a mean in the range of 6.1-6.4 m/s. The station was operated by the National Weather Service at this time, and data capture percentages were excellent. The exact cause of the data discrepancy between the two time periods could not be determined.

Figure 4-1. Mean Wind Speed vs. Distance Offshore



Annual variations in wind speed are presented in Figure 4-2 for the MMS stations and Figure 4-3 for the supplemental stations. Seasonal patterns become more apparent when averaged among all the stations. Average wind speeds appear to be the lowest in mid-summer from June through August, with many wind speed averages in the range of 5.0-5.2 m/s. Wind speeds increase slightly in the autumn months, peaking in the winter months in the 5.5 to 6.5 m/s range. Badami wind speed measurements appear to reflect the most cyclic pattern, which is not observed as strongly at the other MMS sites. Endicott shows a marked drop in December, probably due to anemometer icing (see Section 5.5).

At the supplemental stations, Komakuk Beach exhibits the largest annual variation in wind speed, with wind speeds highest in December and January, and lowest in mid-summer. Barter Island exhibits a similar pattern, although with less variation. This seasonal variation is similar to that observed at the Badami station. This effect may be due to the highly stratified mid-winter air presenting more of an obstacle to over mountain flow, which would force more air to move more rapidly around the Brooks Range. The inland site Sagwon indicates a pattern with higher wind speeds in the summer and lower winds speeds in midwinter, while Franklin Bluffs exhibits a similar pattern with lowest wind speeds in December.

Figure 4-4 provides a map of the spatial distributions of average hourly wind speeds and maximum hourly wind speeds along the Beaufort Sea coast.

Figure 4-2 Mean Adjusted Monthly Wind Speed, MMS Stations

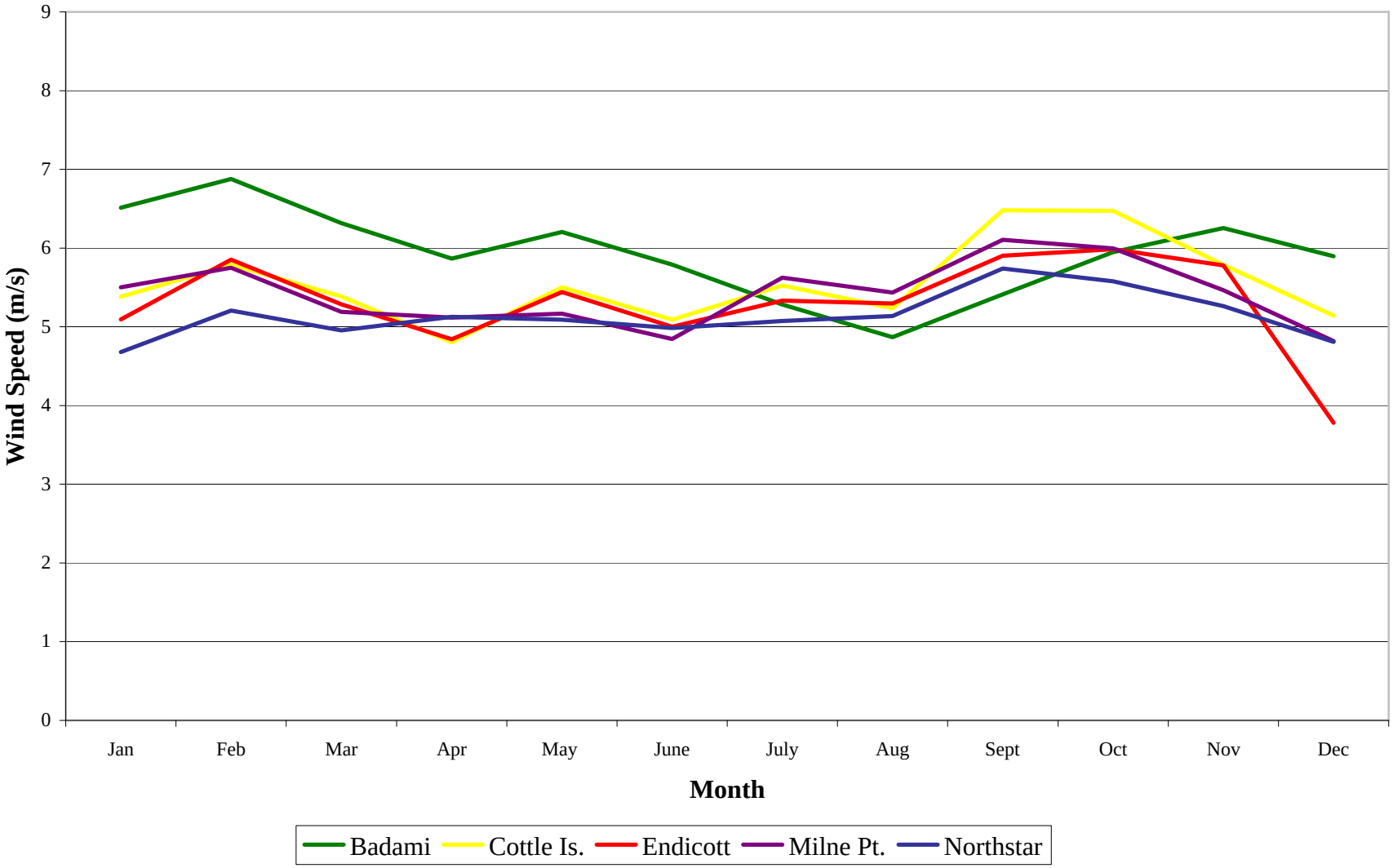
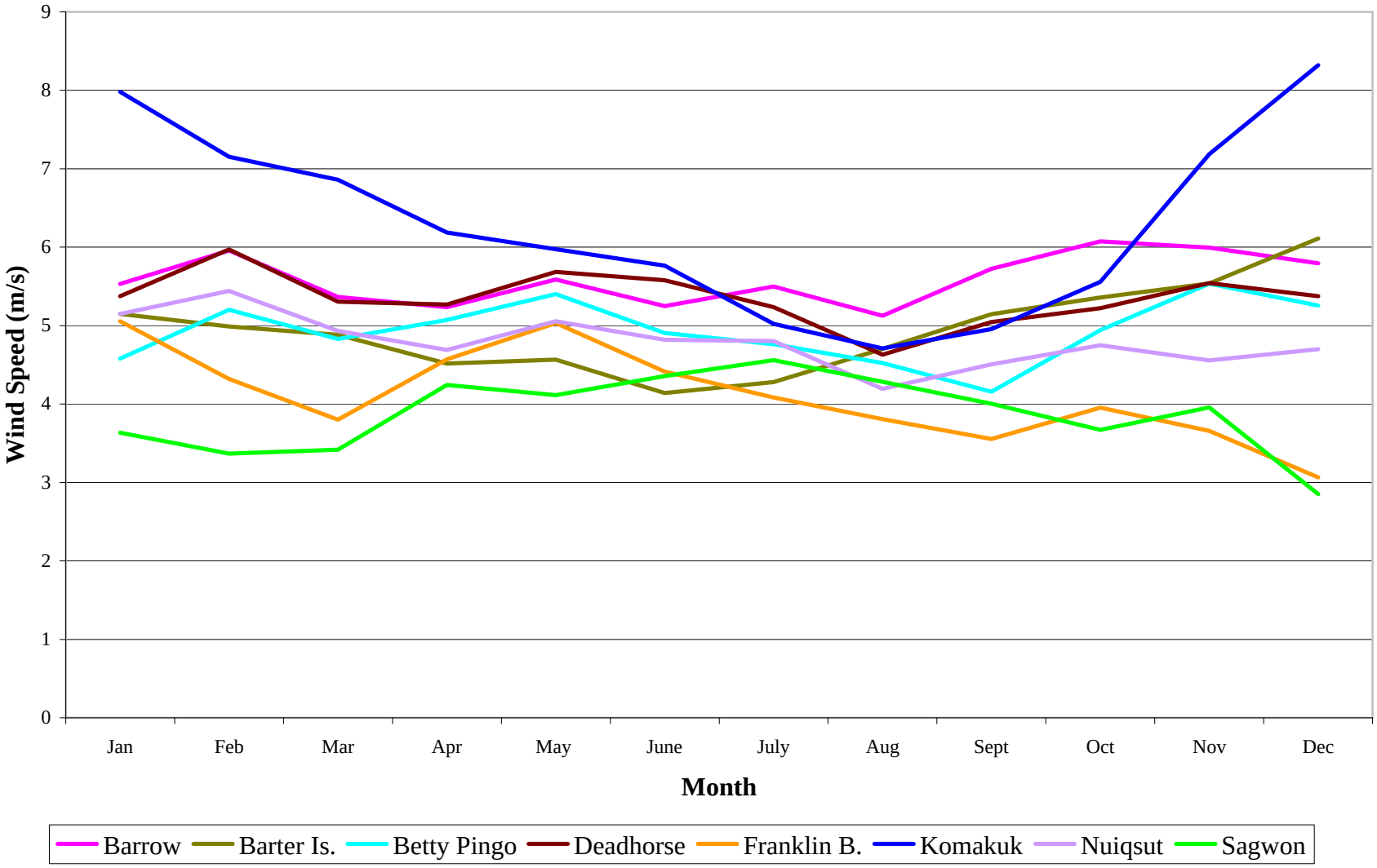


Figure 4-3 Mean Monthly Wind Speed, Supplemental Stations



(This Page is Intentionally Left Blank)

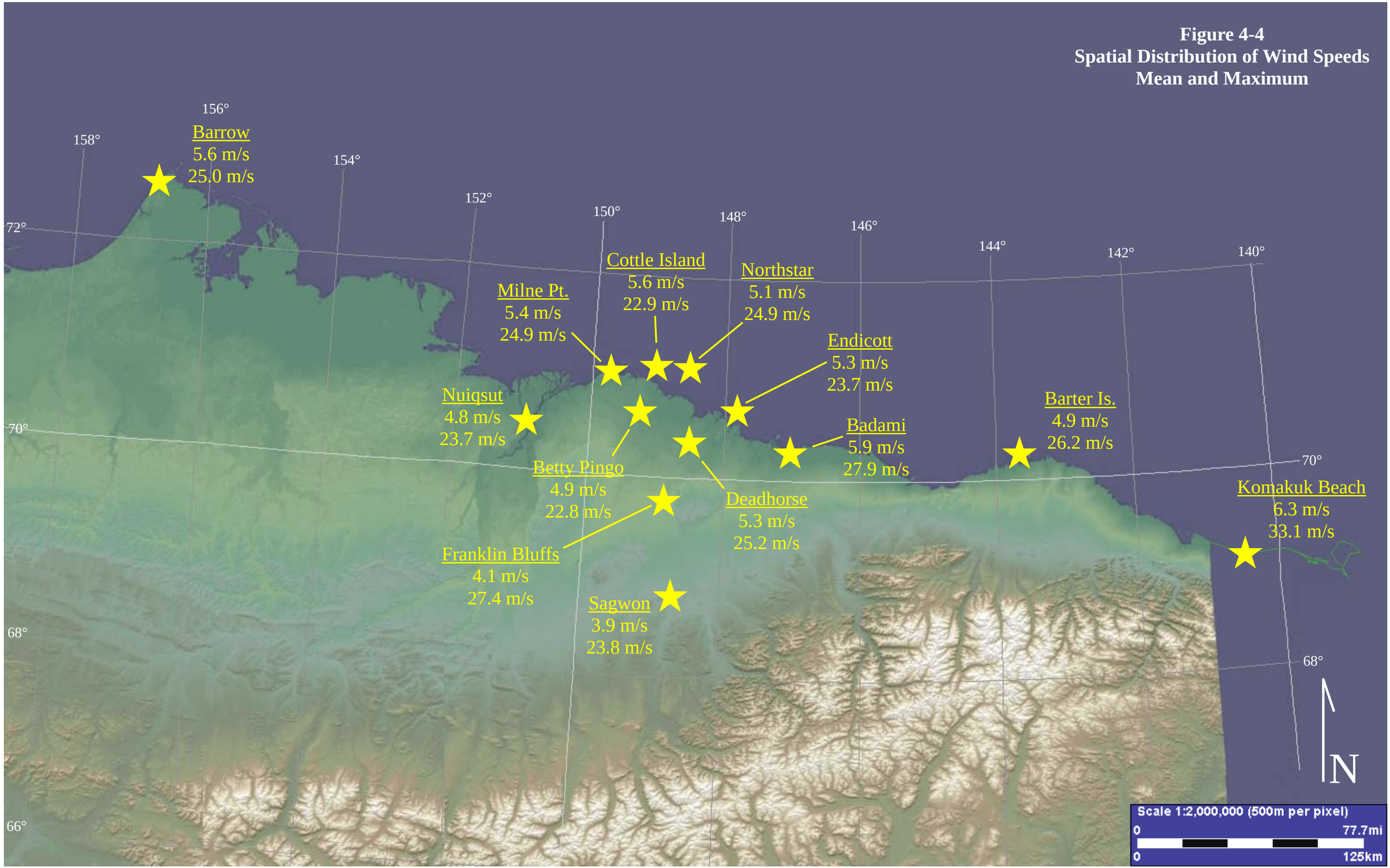


Figure 4-4
Spatial Distribution of Wind Speeds
Mean and Maximum
156°
158°
154°
152°
150°
148°
146°
144°
142°
140°
72°
70°
68°
66°
Barrow
5.6 m/s
25.0 m/s
Cottle Island
5.6 m/s
22.9 m/s
Northstar
5.1 m/s
24.9 m/s
Milne Pt.
5.4 m/s
24.9 m/s
Endicott
5.3 m/s
23.7 m/s
Nuiqsut
4.8 m/s
23.7 m/s
Barter Is.
4.9 m/s
26.2 m/s
Badami
5.9 m/s
27.9 m/s
Betty Pingo
4.9 m/s
22.8 m/s
Deadhorse
5.3 m/s
25.2 m/s
Komakuk Beach
6.3 m/s
33.1 m/s
Franklin Bluffs
4.1 m/s
27.4 m/s
Sagwon
3.9 m/s
23.8 m/s
N
Scale 1:2,000,000 (500m per pixel)
0
77.7mi
0
125km

(This Page is Intentionally Left Blank)

4.1.1 Long-Term Wind Speeds at Supplemental Stations

The MMS Nearshore Beaufort Sea Weather Database includes wind data dating back to 1984 for several of the "A" rated supplemental stations. Long-term wind speeds were evaluated to determine if a change in annual average wind speed has been occurring at coastal sites over the past 20 years. Stations included for this analysis are Barrow, Deadhorse, Barter Island, and Komakuk Beach, spanning the Beaufort Sea coast.

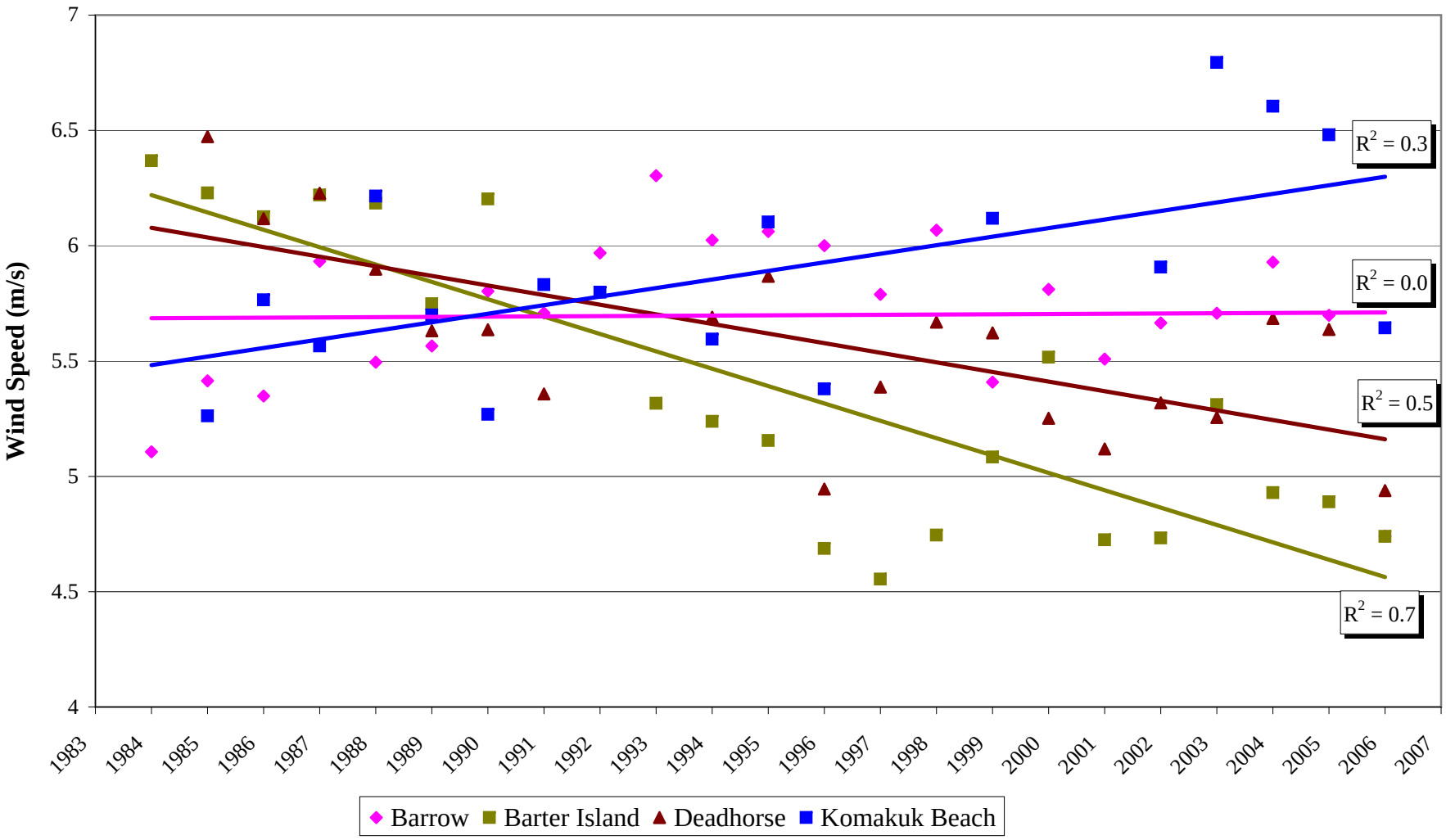
Figure 4-5 provides a graph of annual average wind speeds for these four coastal supplemental stations. It should be noted that a few years of data are missing from the graph due to occasional low data capture at some sites; only annual datasets with reasonable annual data capture were included in the chart. Linear trend lines indicate possible shifts in wind speeds over time. The graph shows the possibility of a slight decrease in wind speeds at Deadhorse and Barter Island, and a slight increase at Komakuk Beach. R-squared[5] values for the data sets were 0.3 for Komakuk Beach, 0.5 for Deadhorse, and 0.7 for Barter Island. The wind speed data from Barrow did not indicate a change over the past 20 years, with a poorly correlated r-squared value of nearly zero. It should be noted that in looking at possible shifts in wind speed over time, a 20 year period is not an exceptionally long time period, and that definite conclusions should take into account wind speeds from longer data sets.

As mentioned above in footnote 4, mean wind speeds at the Barter Island station over the same time period of operation as the MMS stations would have been expected to be higher, given the anticipated orographic effects of the Brooks Range in this region. The relatively higher wind speeds observed at Badami and Komakuk Beach seem to support the orographic effects of the mountains. As shown in Figure 4-5, wind speed averages for Barter Island from the mid-1980's are in the range of 6.1-6.4 m/s. This would seem to correlate better with what has been more recently observed at Komakuk Beach and Badami. During the 1984-1988 time period, the station was operated by the National Weather Service, and data capture percentages were excellent, in the upper 90 percent range. In the 2001-2006 time frame, data capture at Barter Island is the lowest of the supplemental stations chosen for comparison with the MMS stations, due in part to spotty data recording in 2001. The Barter Is. station has changed operators several times over the past 20 years, with data obtained from the National Weather Service and Air Force. The exact cause of the data differences between the two time periods could not be determined; the data set does not indicate periods of anemometer icing, and no reason to outright reject data was identified.

In addition to looking at annual wind speed averages, yearly data was split into two time periods, June through October, and November through May, to see if a time period during the year exhibited a shift in wind speed over the past 20 years. Analysis of this split data was inconclusive as to possible trends, and did not show any trends different than what was seen in the annual data as a whole.

[5] R-squared (R^2) is a statistical measure of goodness of fit, quantifying the proportion of variability (variance) in a data set that is accounted for by a statistical model. A model which perfectly matched the data would have $R^2 = 1.0$, whereas $R^2 = 0.0$ would denote a data set which was entirely random with respect to the model.

Figure 4-5 Annual Wind Speed Averages at Supplemental Coastal Stations With Linear Trendlines



4.2 Wind Direction

4.2.1 Wind Roses

Five and three-quarter year wind roses for each MMS Station and supplemental station are provided in Figure 4-7 through Figure 4-19. Wind roses were constructed to depict the frequency of occurrence of winds in each of 36 direction sectors (every 10°) and six wind speed classes (shown in Figure 4-6) for a given location and time period. Time periods were selected to include all wind speed and wind direction data available from January 1, 2001 through September 30, 2006. The wind roses were generated using the Lakes Environmental Software, WRPLOT View. Note that the percentage scale varies for the Komakuk Beach and Northstar wind roses, due to the prevalence of winds from a few directions.

Figure 4-20 provides a map of the spatial distributions of wind roses for stations along the Beaufort Sea coast. Figure 4-21 provides a map of the spatial distribution of wind roses for the Prudhoe Bay area from Milne Point to Badami, including the five MMS Stations and other supplemental stations in the region.

Discussion of the results can be found in Sections 5.1 through 5.3.

Figure 4-6. Wind Rose Wind Speed Legend (m/s)

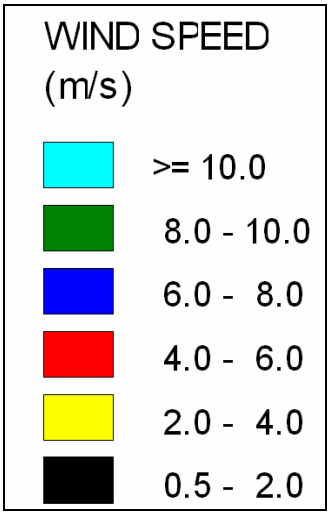
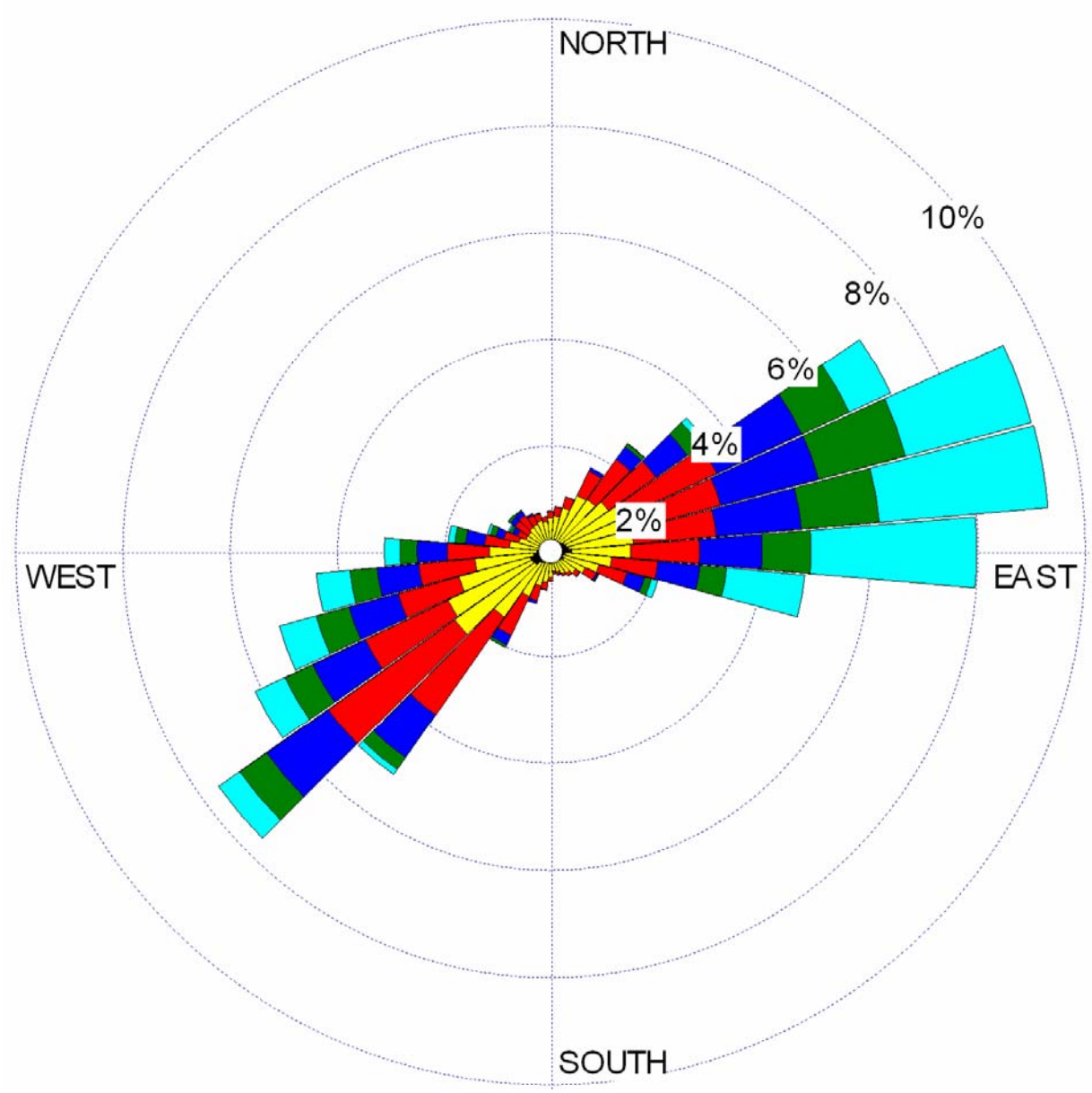
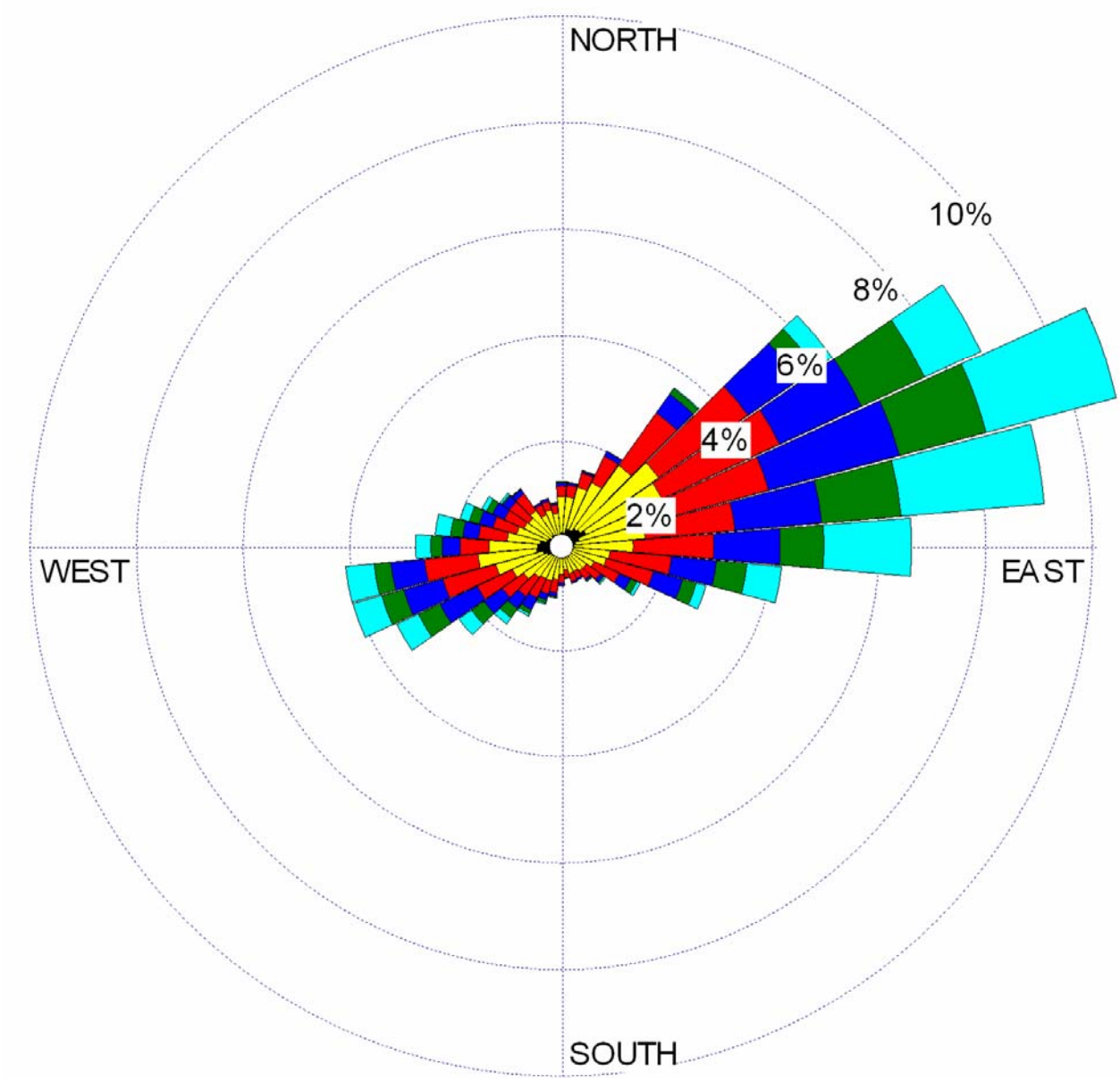


Figure 4-7. Badami Wind Rose



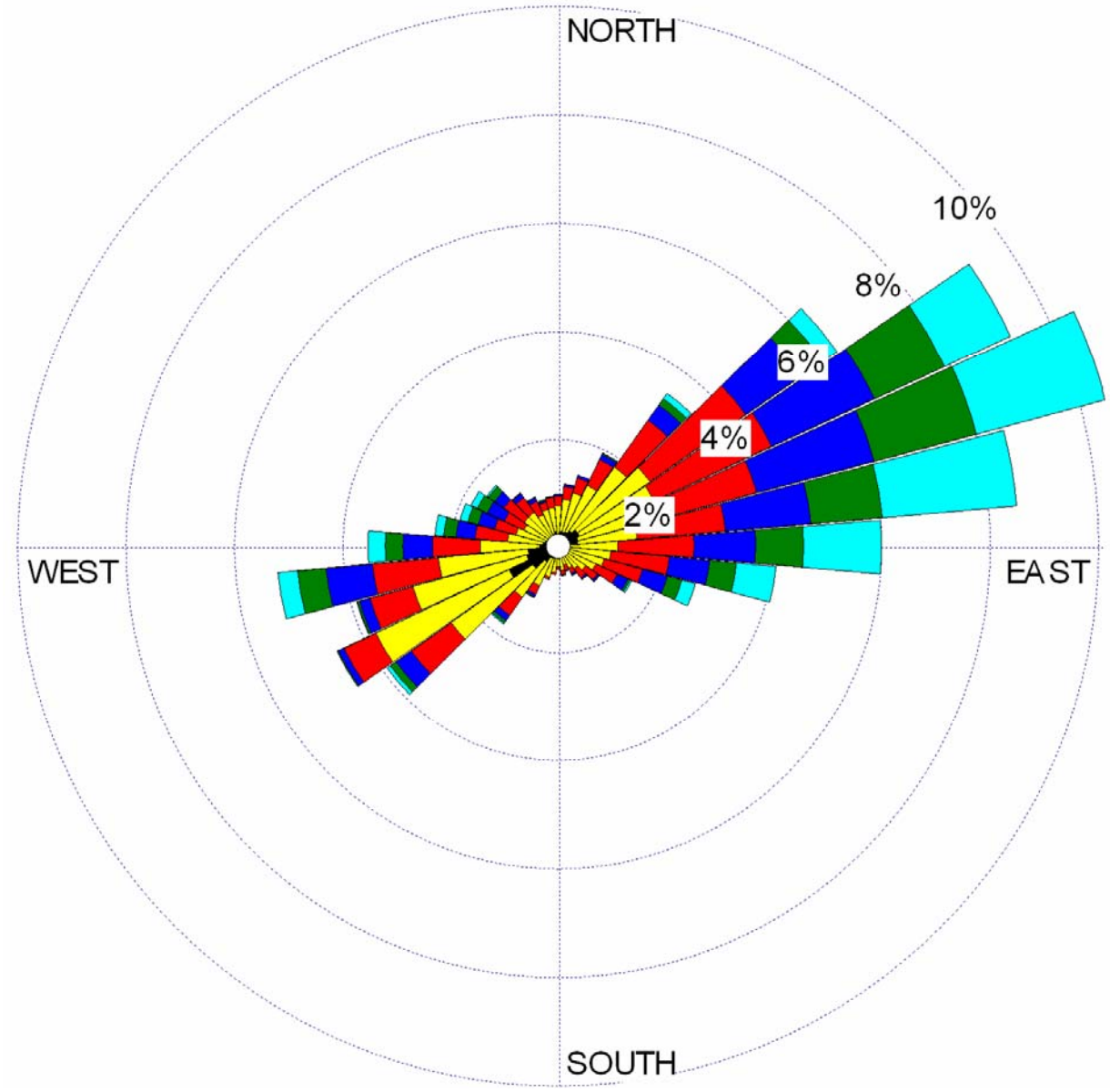
Calms = 0.78%

Figure 4-8. Cottle Island Wind Rose



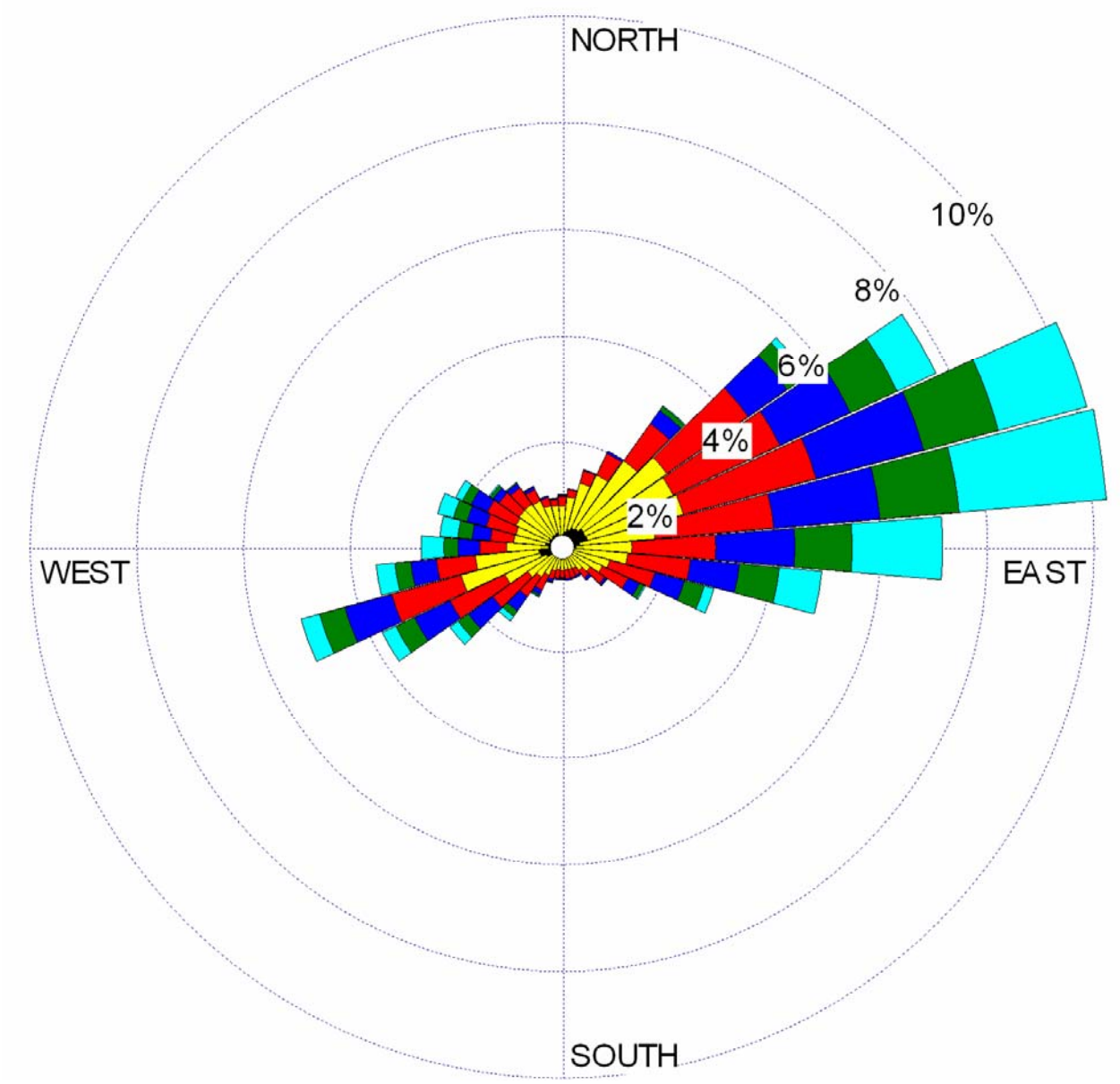
Calms = 1.54%

Figure 4-9. Endicott Wind Rose



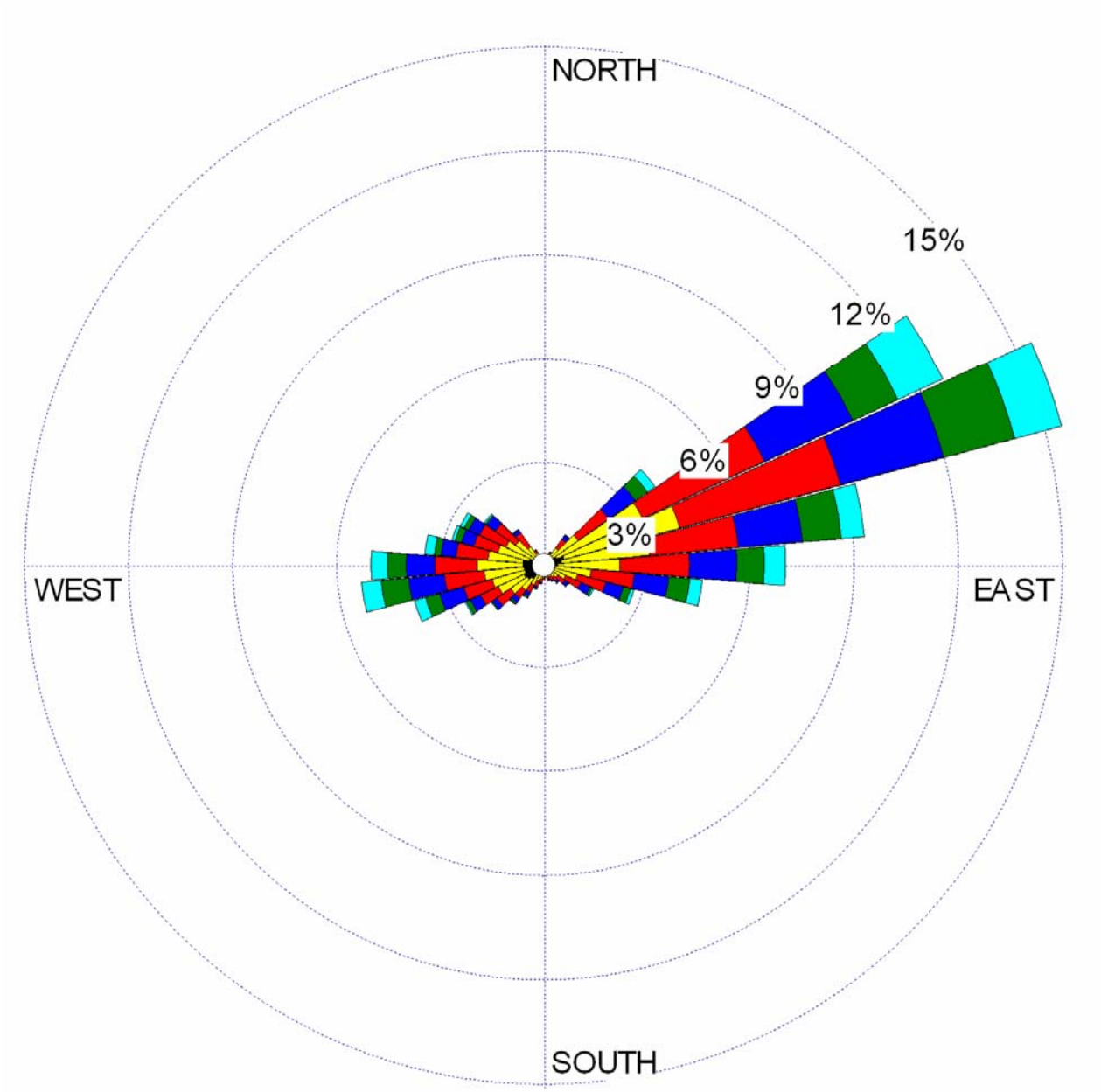
Calms = 1.48%

Figure 4-10. Milne Point Wind Rose



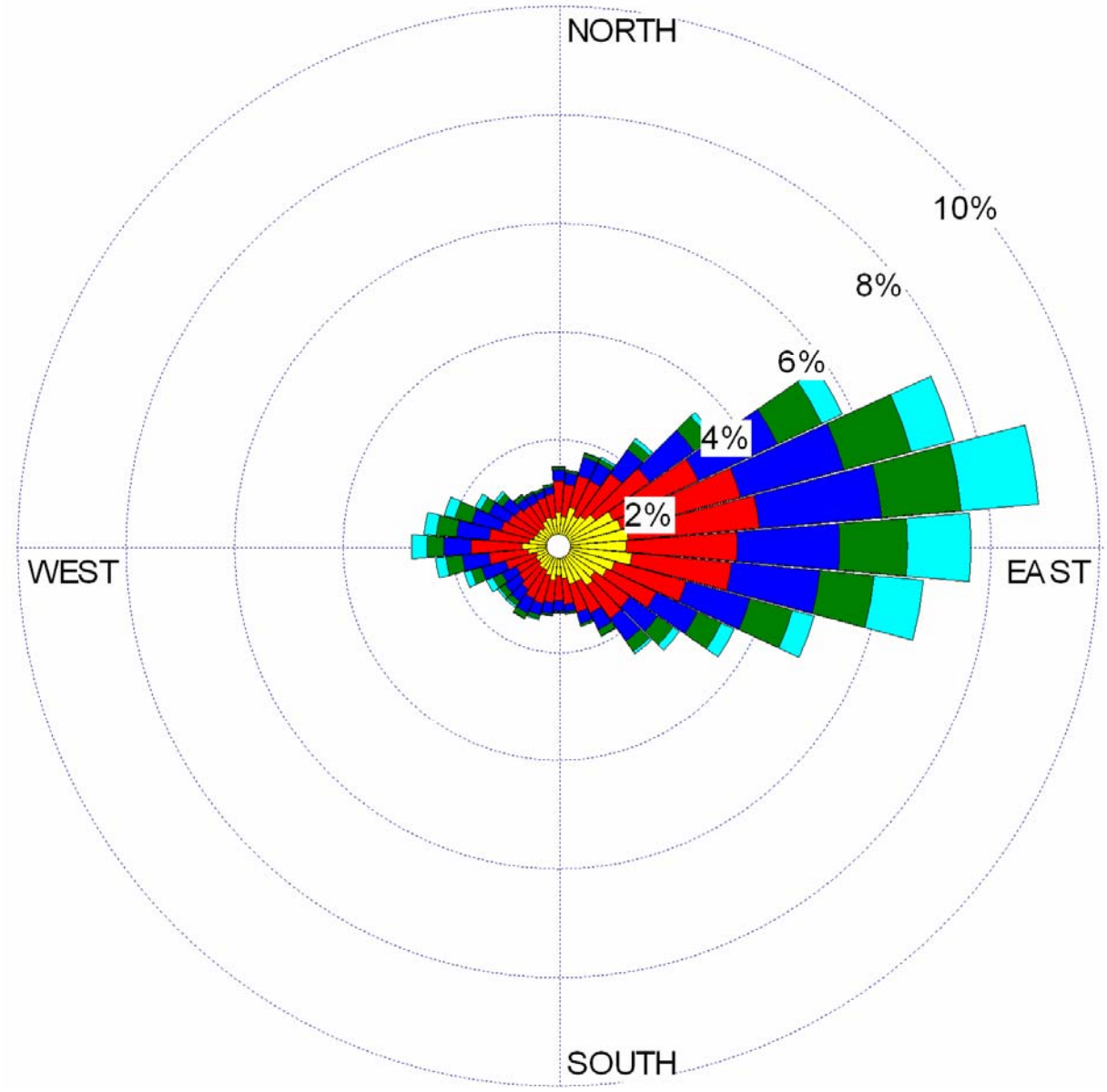
Calms = 0.59%

Figure 4-11. Northstar Wind Rose



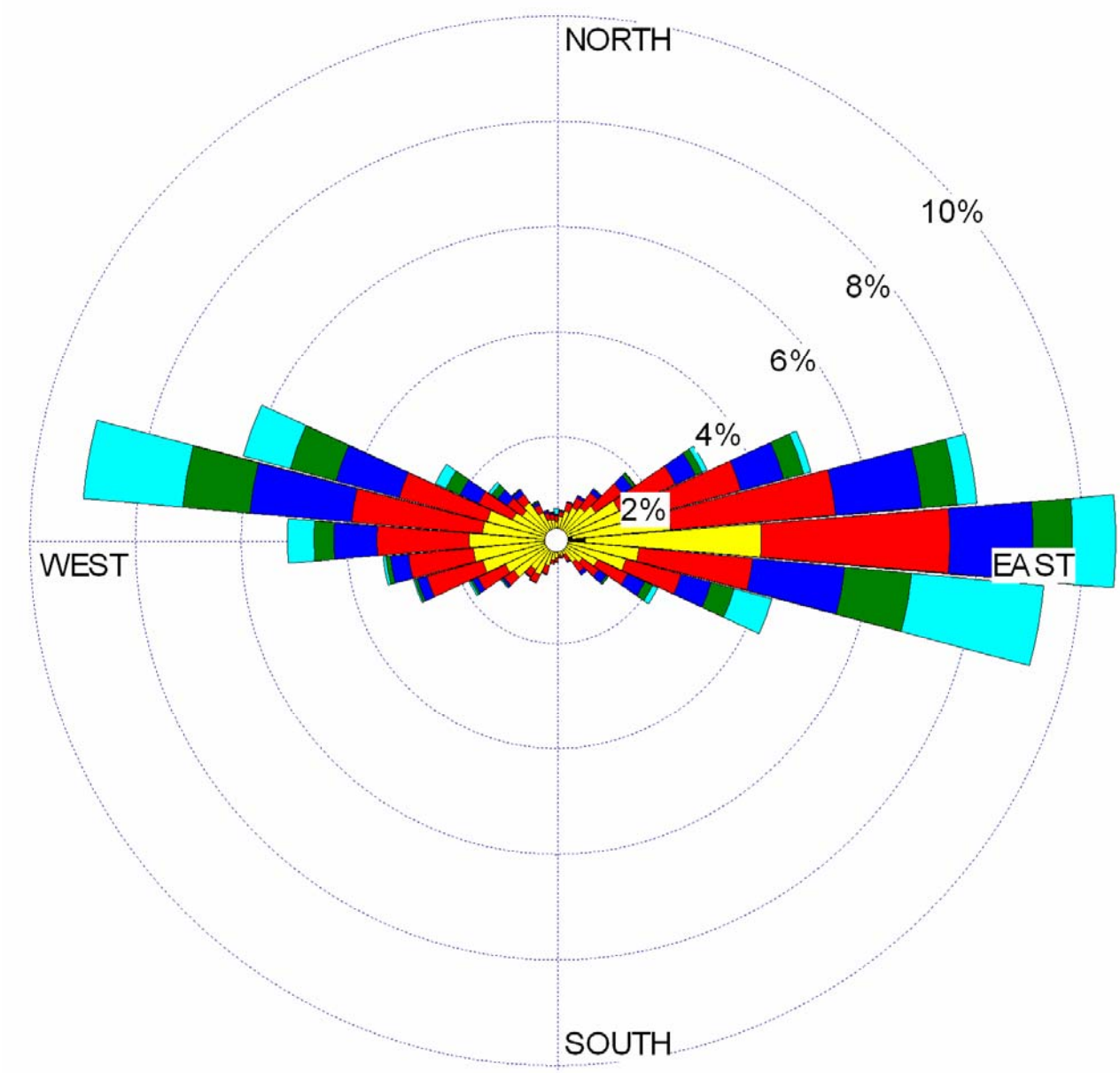
Calms = 0.59%

Figure 4-12. Barrow Wind Rose



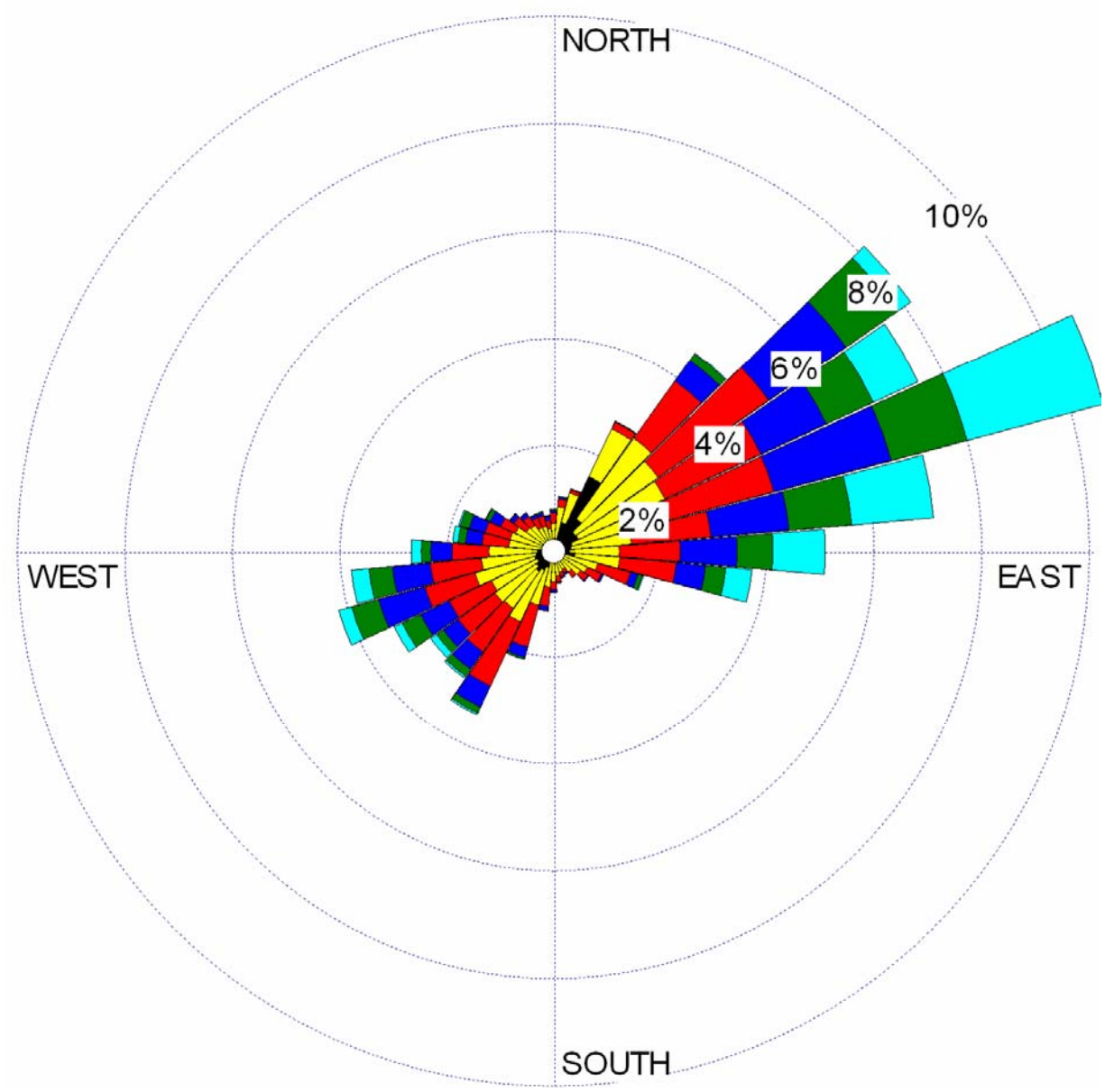
Calms = 3.0%

Figure 4-13. Barter Island Wind Rose



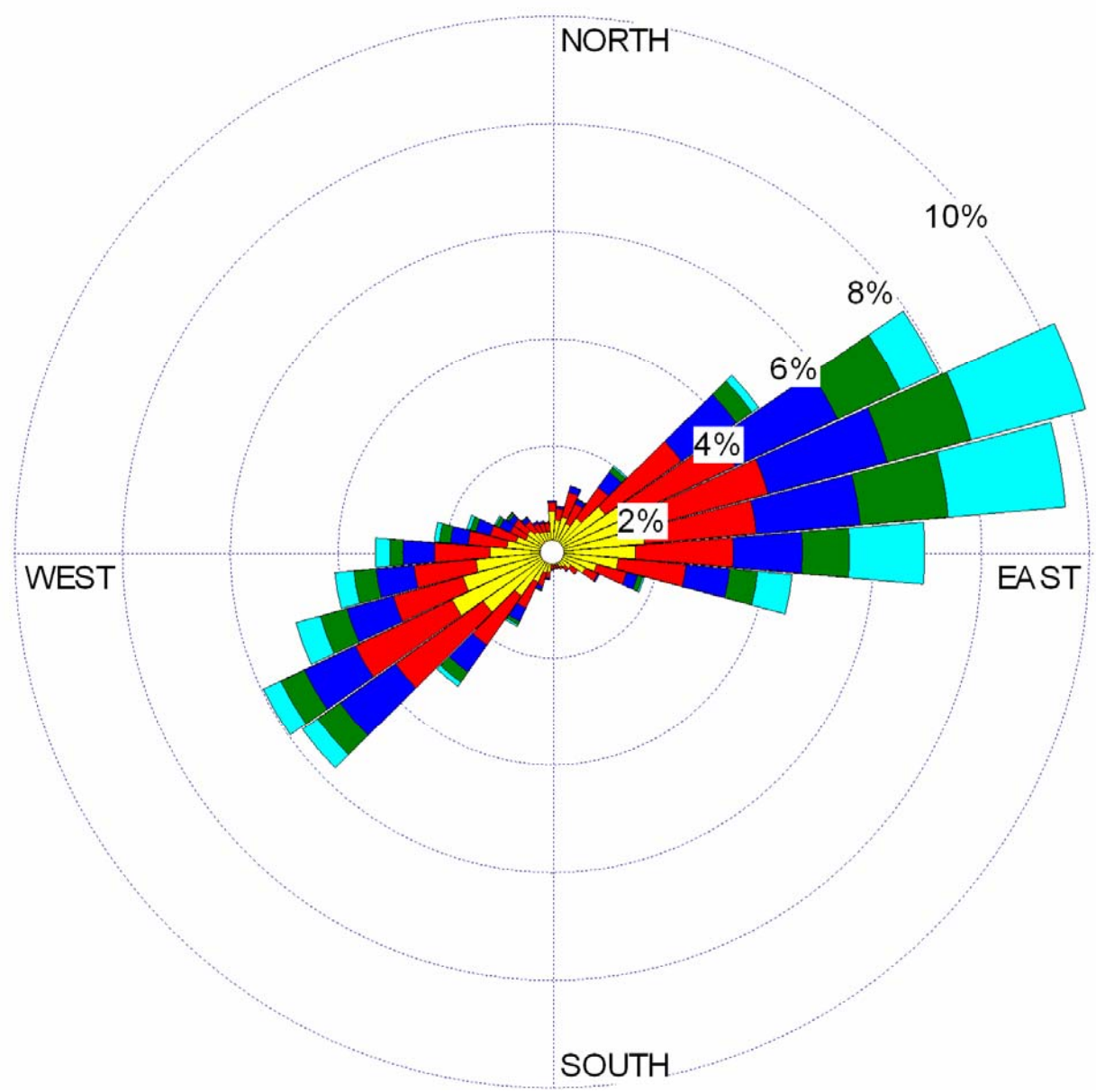
Calms = 7.7%

Figure 4-14. Betty Pingo Wind Rose



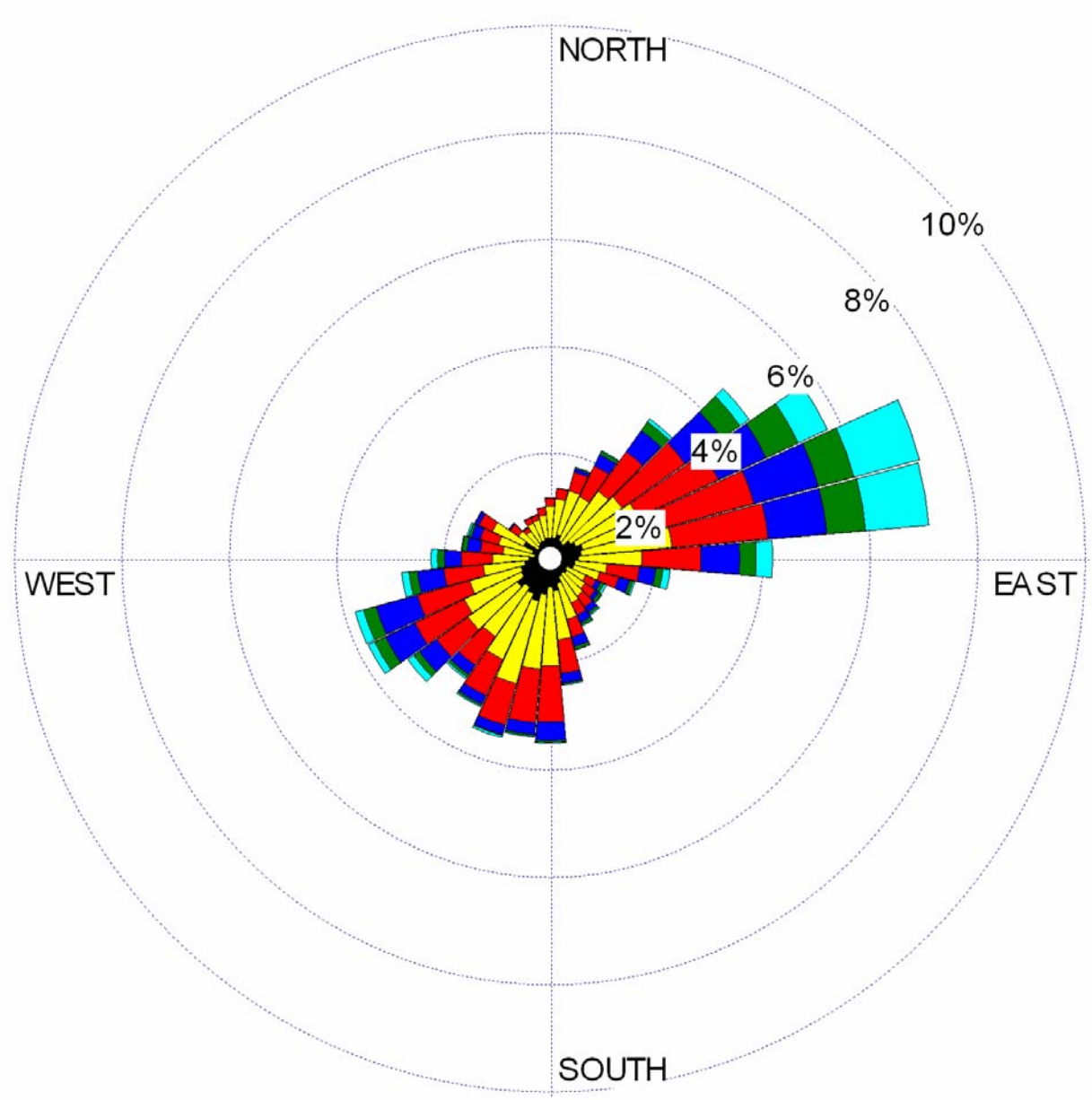
Calms = 4.9%

Figure 4-15. Deadhorse Wind Rose



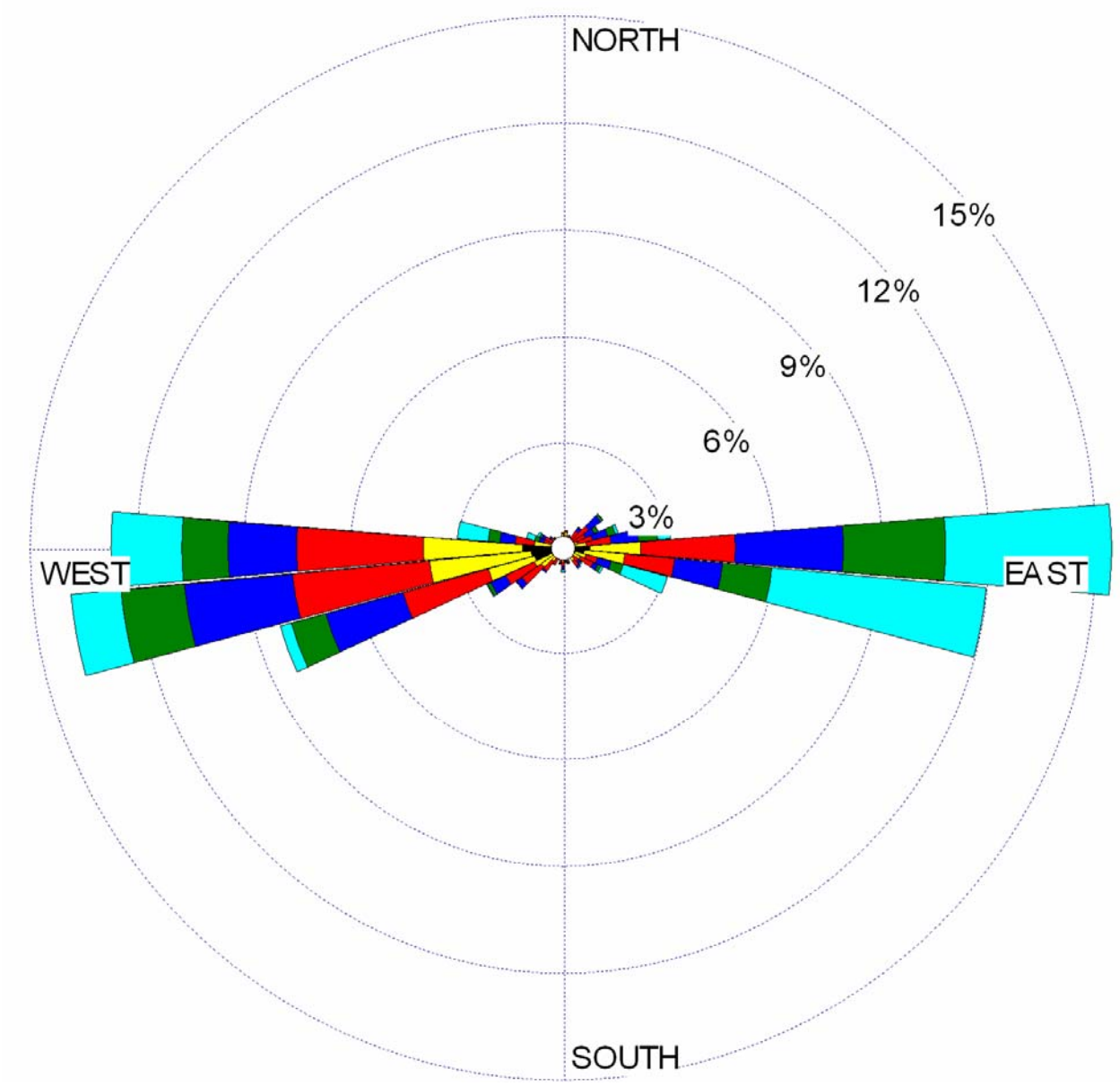
Calms = 5.7%

Figure 4-16. Franklin Bluffs Wind Rose



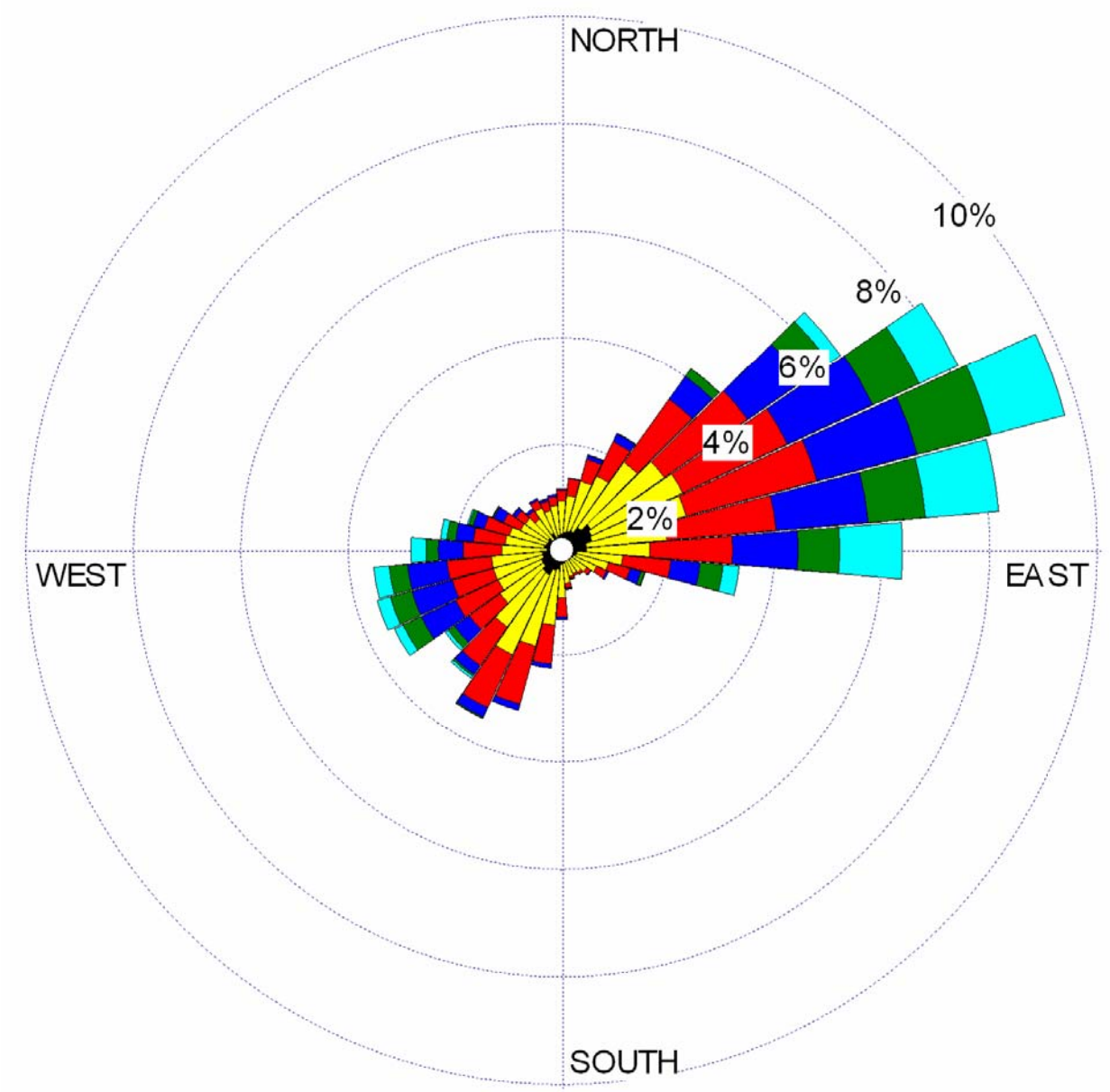
Calms = 6.8%

Figure 4-17. Komakuk Beach Wind Rose



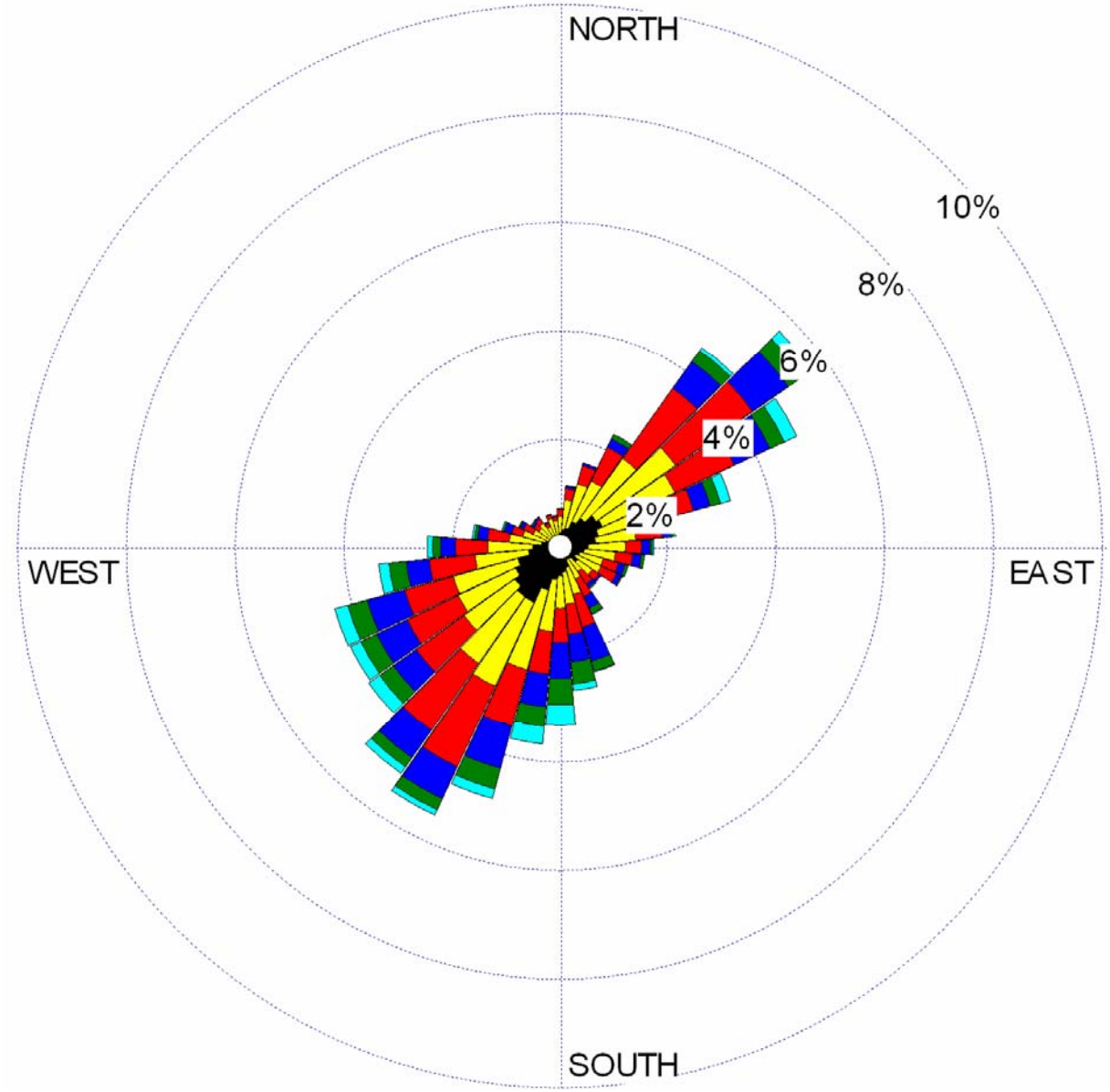
Calms = 6.4%

Figure 4-18. Nuiqsut Wind Rose



Calms = 0.8%

Figure 4-19. Sagwon Wind Rose



Calms = 11.3%

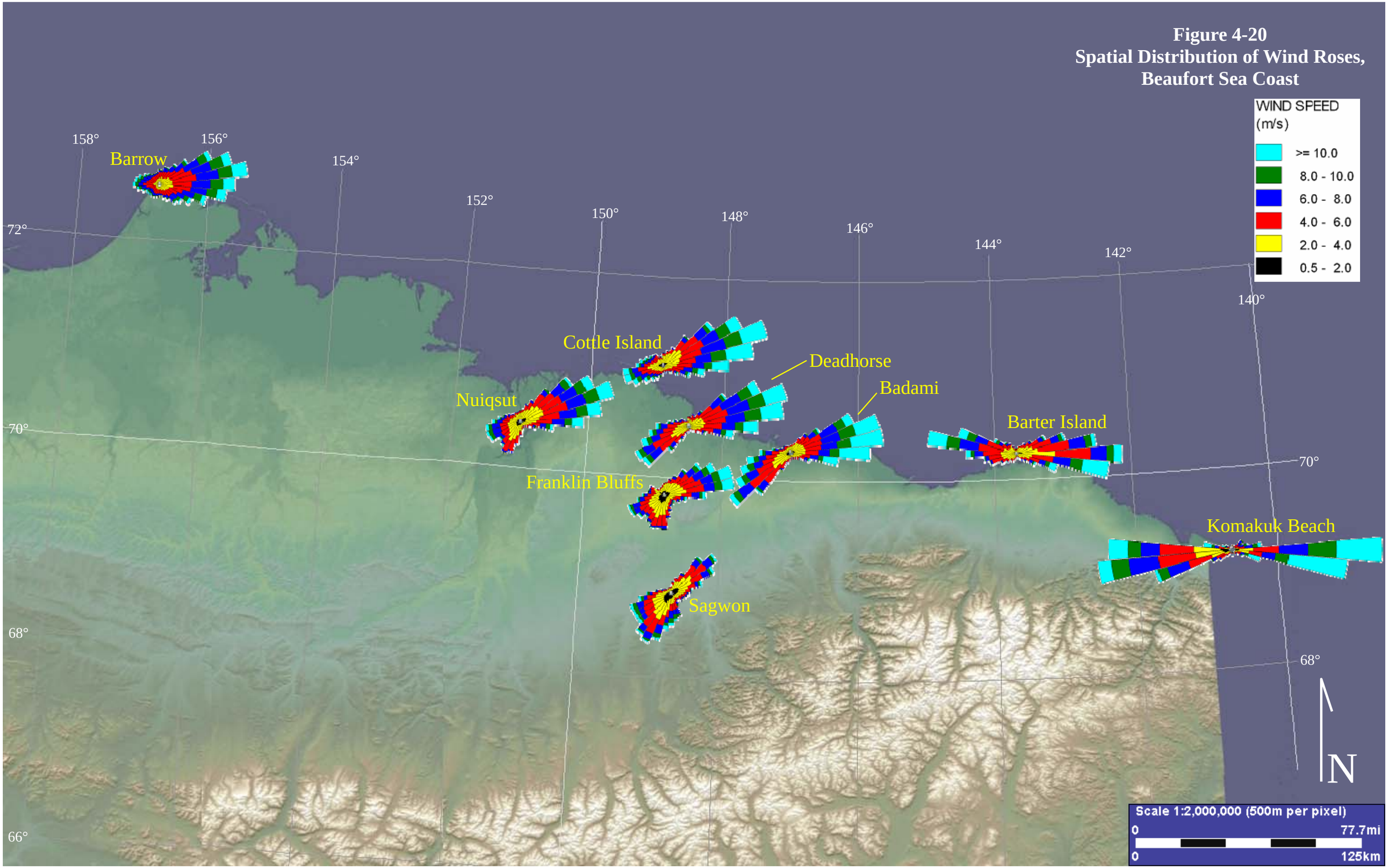


Figure 4-20
Spatial Distribution of Wind Roses, Beaufort Sea Coast

(This Page Is Intentionally Left Blank)

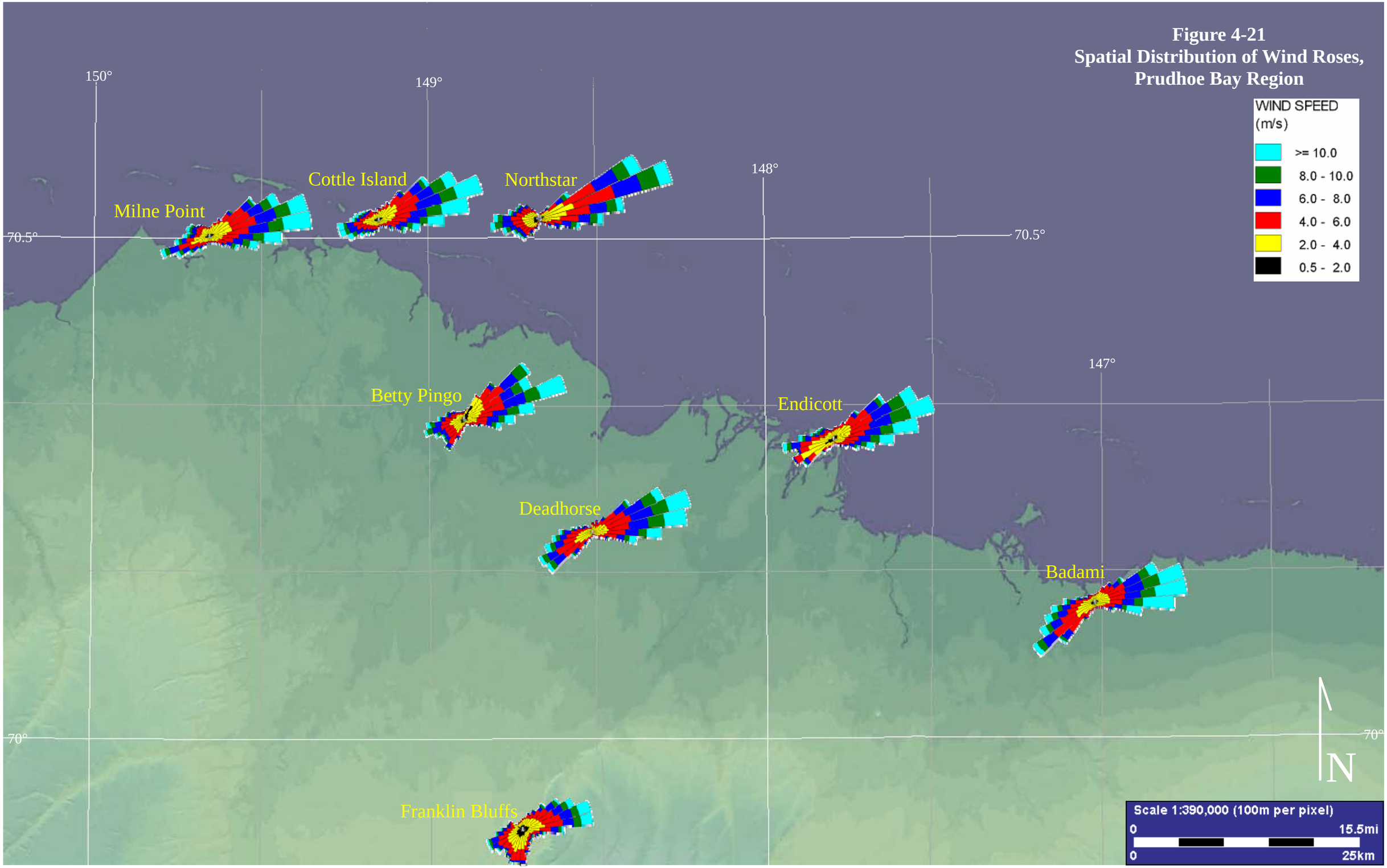


Figure 4-21
Spatial Distribution of Wind Roses, Prudhoe Bay Region

(This Page Is Intentionally Left Blank)

4.2.2 Wind Direction by Category

An in-depth categorical summary of wind direction and duration for the five MMS Stations and eight supplemental stations was performed. Wind direction categories were selected based on the general orientation of approximately 75 miles of coastline stretching from Milne Pt. to Badami. For the sake of comparison between stations, consistent wind direction categories were used for all stations. The assigned wind direction categories were as follows:

- Onshore: greater than or equal to 310° and less than or equal to 100°,
- Offshore: greater than or equal to 130° and less than or equal to 280°, and
- Shore Parallel: greater than 280° and less than 310°, or greater than 100° and less than 130°.

The results of the analysis are presented in Table 4-3 and Table 4-4, and Figure 4-22 through Figure 4-29. Data presented here included analysis of all data collected during the 2001 through 2006 study period.

Table 4-3 shows the average number of days per year the wind blew from one of these directions for more than two thirds (67 percent) of the time. A day was considered "variable" if no single condition persisted for 67 percent of the day or more. Days with fewer that 16 hours of data were not included in this analysis.

Table 4-3. Frequency of Wind Direction by Category (Days/Yr)

Station	Offshore	Onshore	Shore Parallel	Calm	Variable
MMS Stations					
Badami	122	157	4	0	83
Cottle Island	77	187	10	1	90
Endicott	90	175	8	1	92
Milne Point	73	187	14	0	91
Northstar	75	179	13	0	97
Supplemental Stations					
Barrow	80	178	10	0	97
Barter Island	72	134	10	0	148
Betty Pingo	84	174	3	2	102
Deadhorse	102	168	0	1	94
Franklin Bluffs	112	135	2	8	109
Komakuk B.	139	105	0	0	121
Nuiqsut	97	178	3	0	87
Sagwon	139	120	1	7	99

Onshore winds were the most common at every site with the exception of Komakuk Beach and Sagwon. Most of the coastal stations observe winds that are in the onshore wind direction category for approximately six months in a typical year. Stations located nearest to the Brooks

Range (Sagwon and Komakuk Beach) exhibit more frequent winds from the offshore direction, as well as a strong variable component. Shore parallel winds were the least frequent condition at all sites.

Table 4-4 shows the average uninterrupted hourly duration of winds by category. Only wind conditions which persisted for three hours or more were counted towards duration.

Table 4-4. Average Duration of Wind Direction by Category (Hours)

Station	Offshore	Onshore	Shore Parallel	Calm
MMS Stations				
Badami	23	27	5	19
Cottle Island	19	35	6	22
Endicott	18	30	6	16
Milne Point	19	33	7	12
Northstar	17	33	7	13
Supplemental Stations				
Barrow	17	27	6	4
Barter Island	10	15	5	5
Betty Pingo	18	30	5	14
Deadhorse	20	25	4	6
Franklin Bluffs	17	21	5	32
Komakuk	17	14	4	4
Nuiqsut	18	29	5	5
Sagwon	21	21	5	20

Onshore winds are not only the most common condition, but also the most persistent. Onshore winds have the greatest duration of any wind category at Cottle Island, Milne Point, and Northstar. Like frequency, in general the duration of onshore winds increase seaward. Offshore winds increased in duration as one moved landward, as can be seen at Badami and Sagwon. Shore-parallel winds were not long in duration, with average durations of seven hours or less. With the notable exception of Cottle Island, calm periods tended to persist longer the farther the station was from the coast. Extended calm periods at Cottle Island may be due to anemometer icing problems (see Section 5.5.1)

The annualized data in Table 4-3 mask the highly seasonal nature of wind direction. Figure 4-22 through Figure 4-29 display the average days each condition occurs each month. The frequency of offshore winds is the most exceptionally seasonal, becoming almost non-existent in June at most sites, with the notable exception of Barrow. Note that Barrow receives ocean wind influences from the Chukchi Sea as well as the Beaufort Sea due to its location at the intersection of both water bodies, as observed in ocean wind maps (University of Alaska GINA, 2007). In Figure 4-23, Komakuk Beach and Sagwon show the highest occurrence of offshore winds throughout the year, while Barter Island shows the lowest occurrence during much of the year.

Onshore winds by contrast are most dominant in the summer, again with the exception of Barrow. All MMS stations show a predominance of onshore winds in midsummer, with the exception on Northstar, where the onshore wind component is skewed due to building interference. The greatest overall onshore component is seen at Cottle Island. For the Beaufort Sea supplemental stations, Deadhorse exhibits the highest occurrence of onshore winds from May through July, while Komakuk shows the least amount of onshore winds.

Shore-parallel winds are most common in the autumn at the MMS stations, as well as Betty Pingo and Barter Island, but were inconsistent elsewhere. Variable wind conditions are most likely in the late summer and early autumn at most of the stations.

Further discussion of wind direction and contributing factors is presented in Section 5. Section 0 presents a discussion on possible variations of wind direction analysis, using varying shoreline categories.

Figure 4-22 Frequency of Offshore Winds at MMS Stations

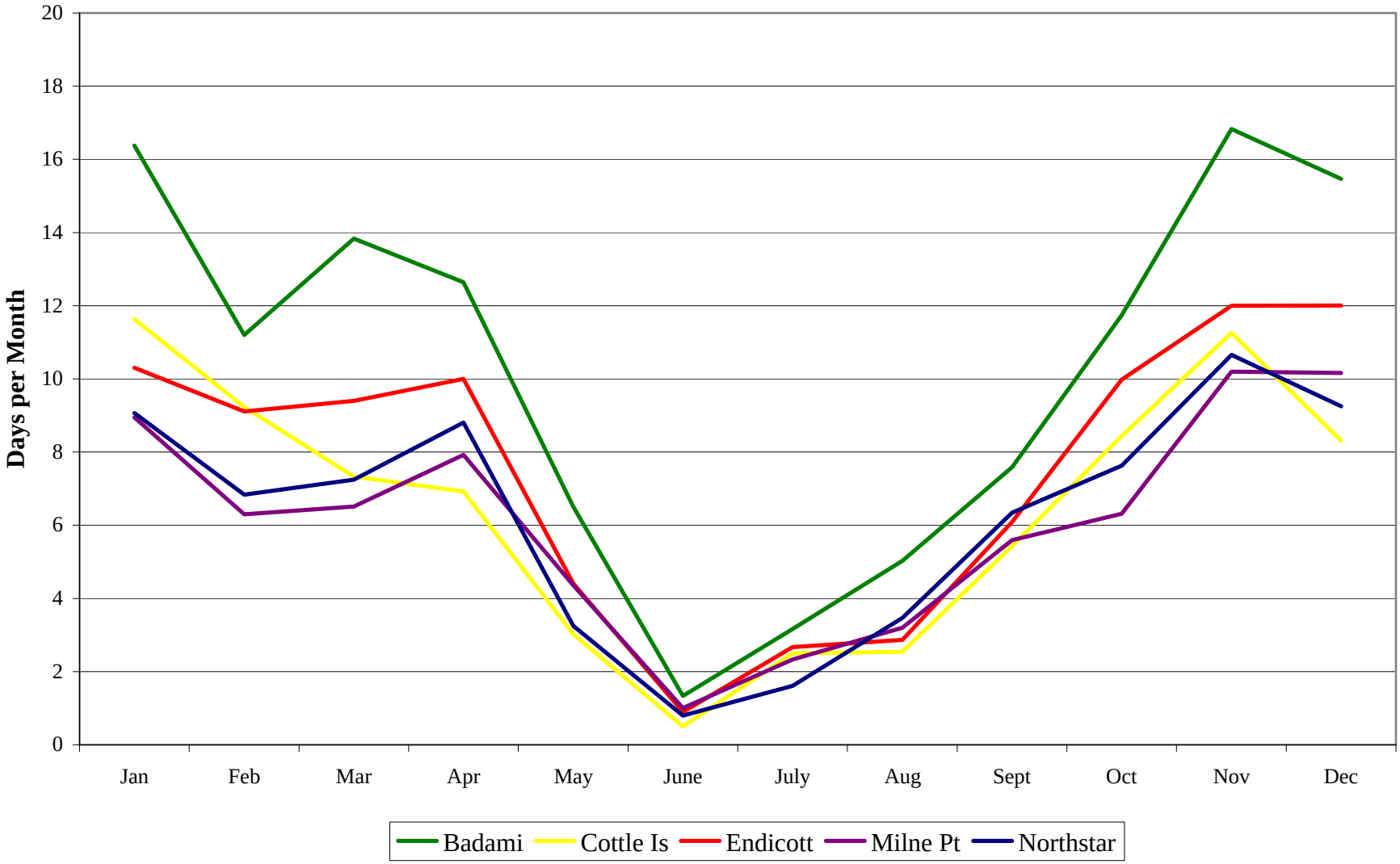


Figure 4-23 Frequency of Offshore Winds at Supplemental Stations

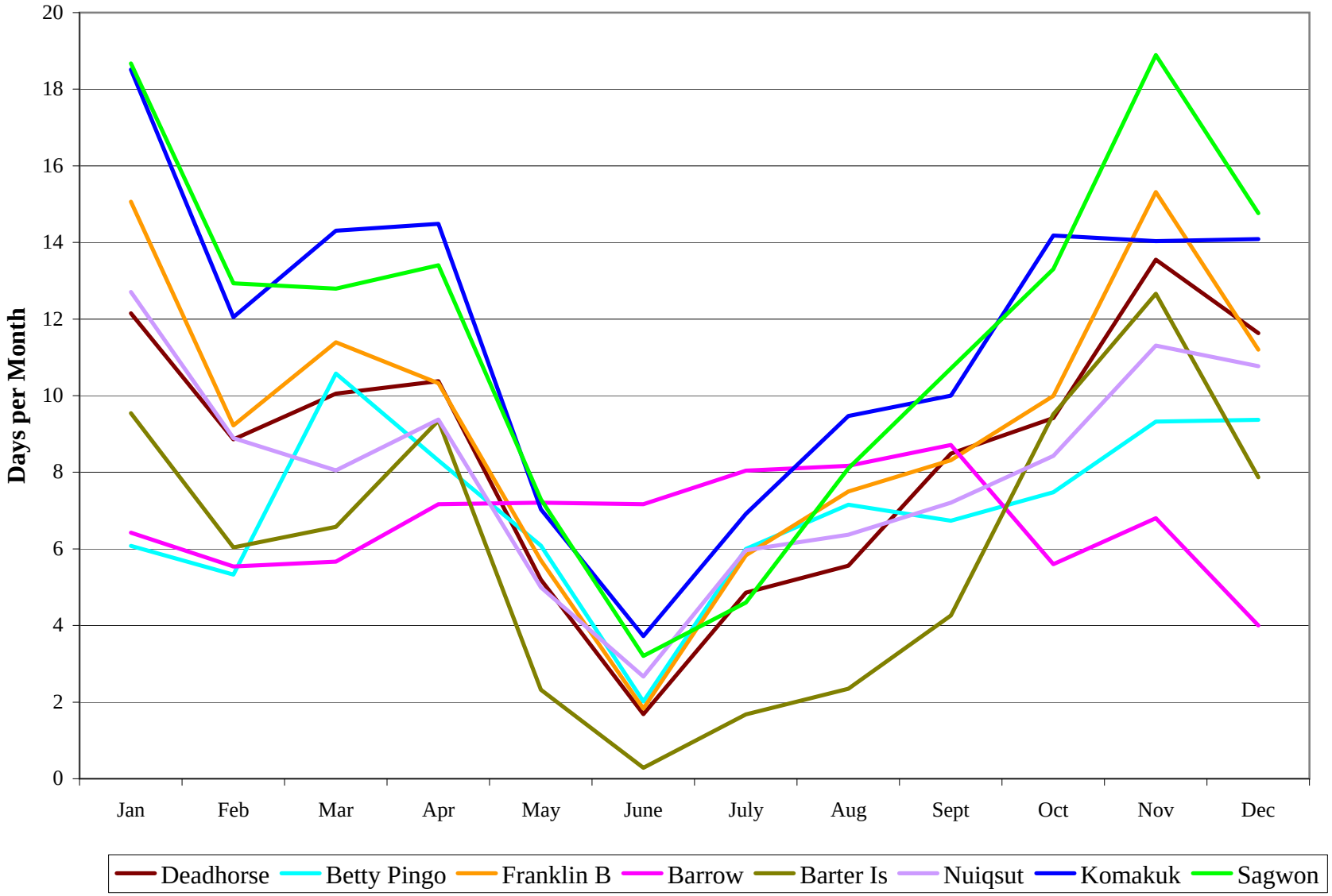


Figure 4-24 Frequency of Onshore Winds at MMS Stations

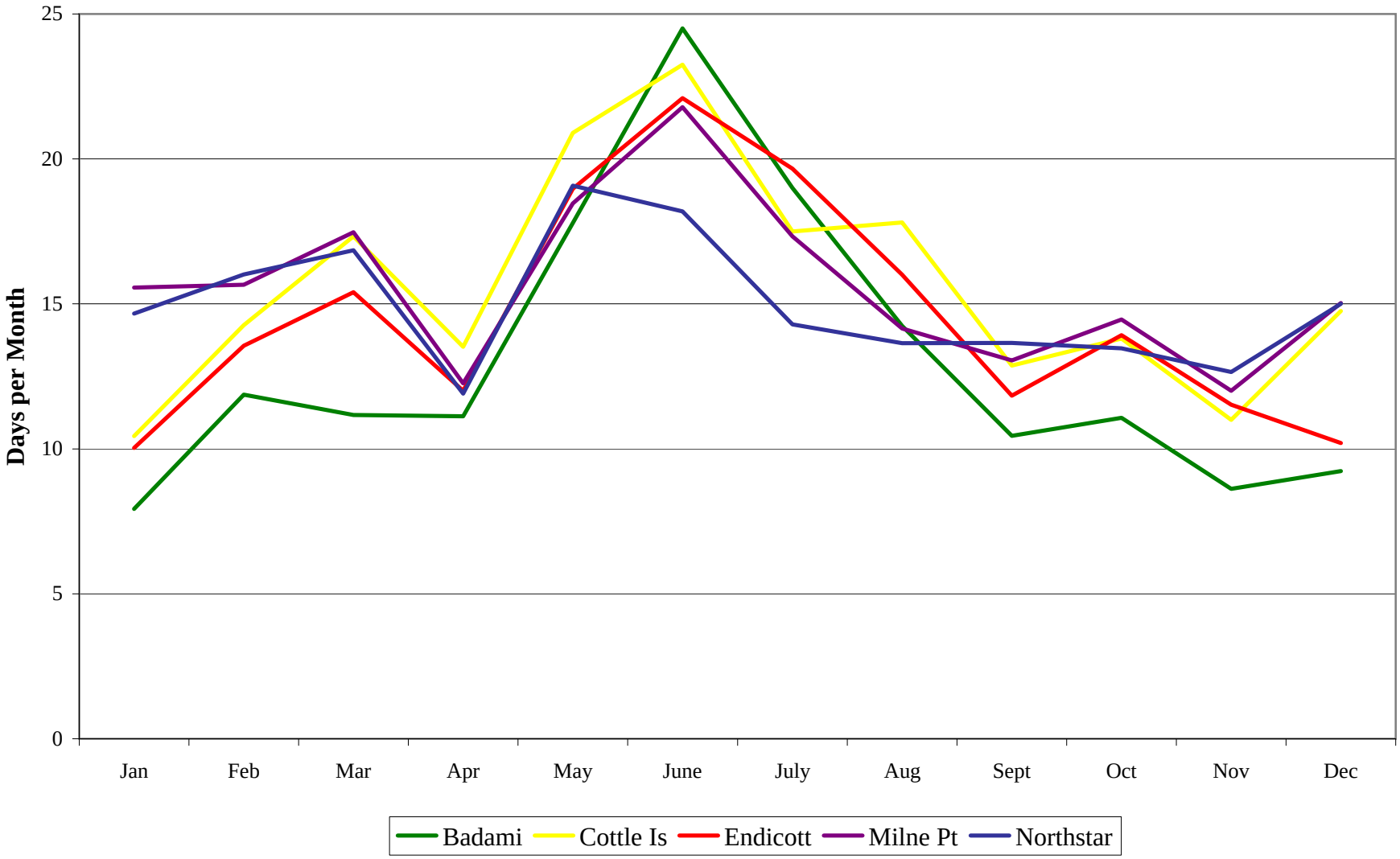


Figure 4-25 Frequency of Onshore Winds at Supplemental Stations

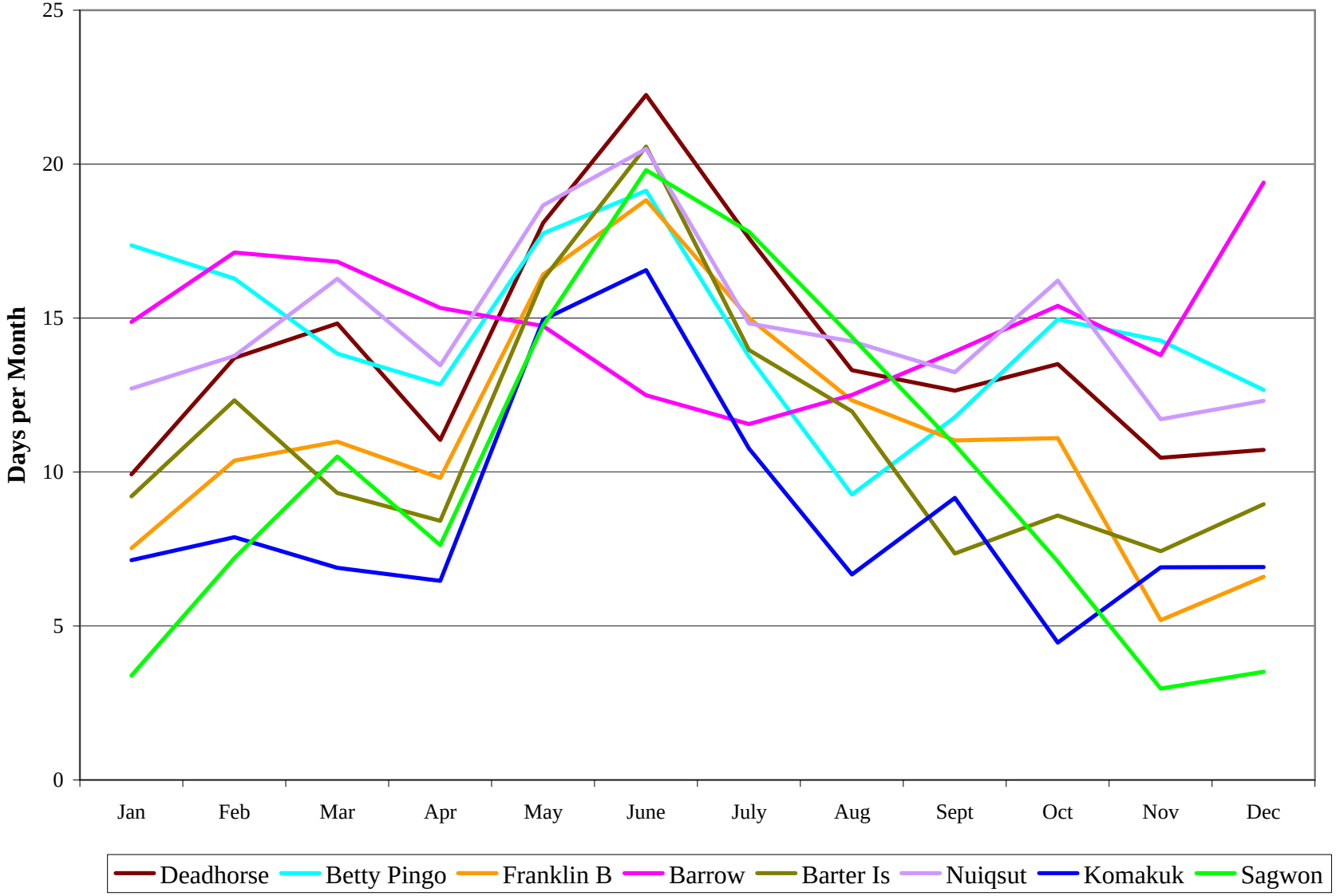


Figure 4-26 Frequency of Shore-Parallel Winds at MMS Stations

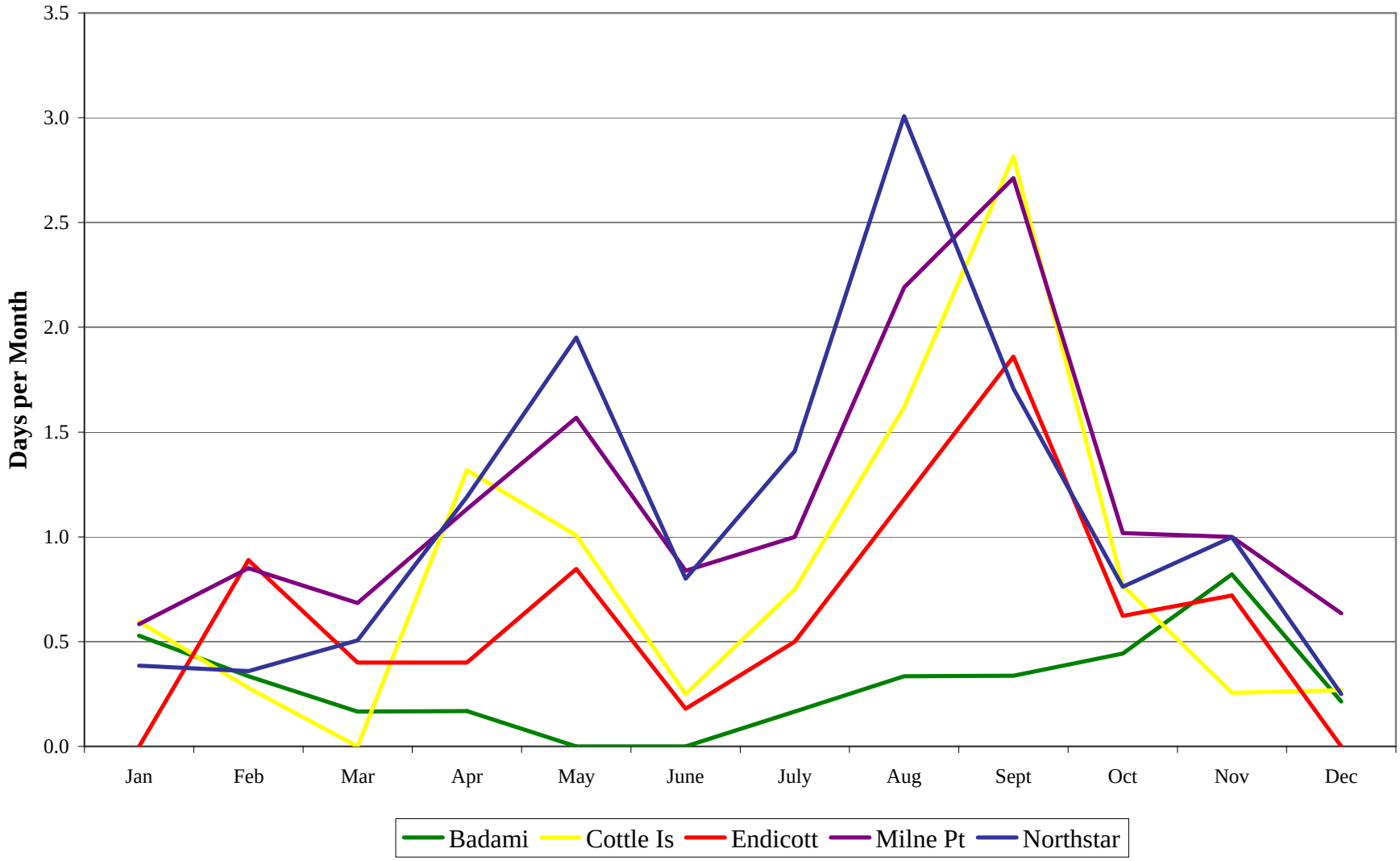


Figure 4-27 Frequency of Shore-Parallel Winds at Supplemental Stations

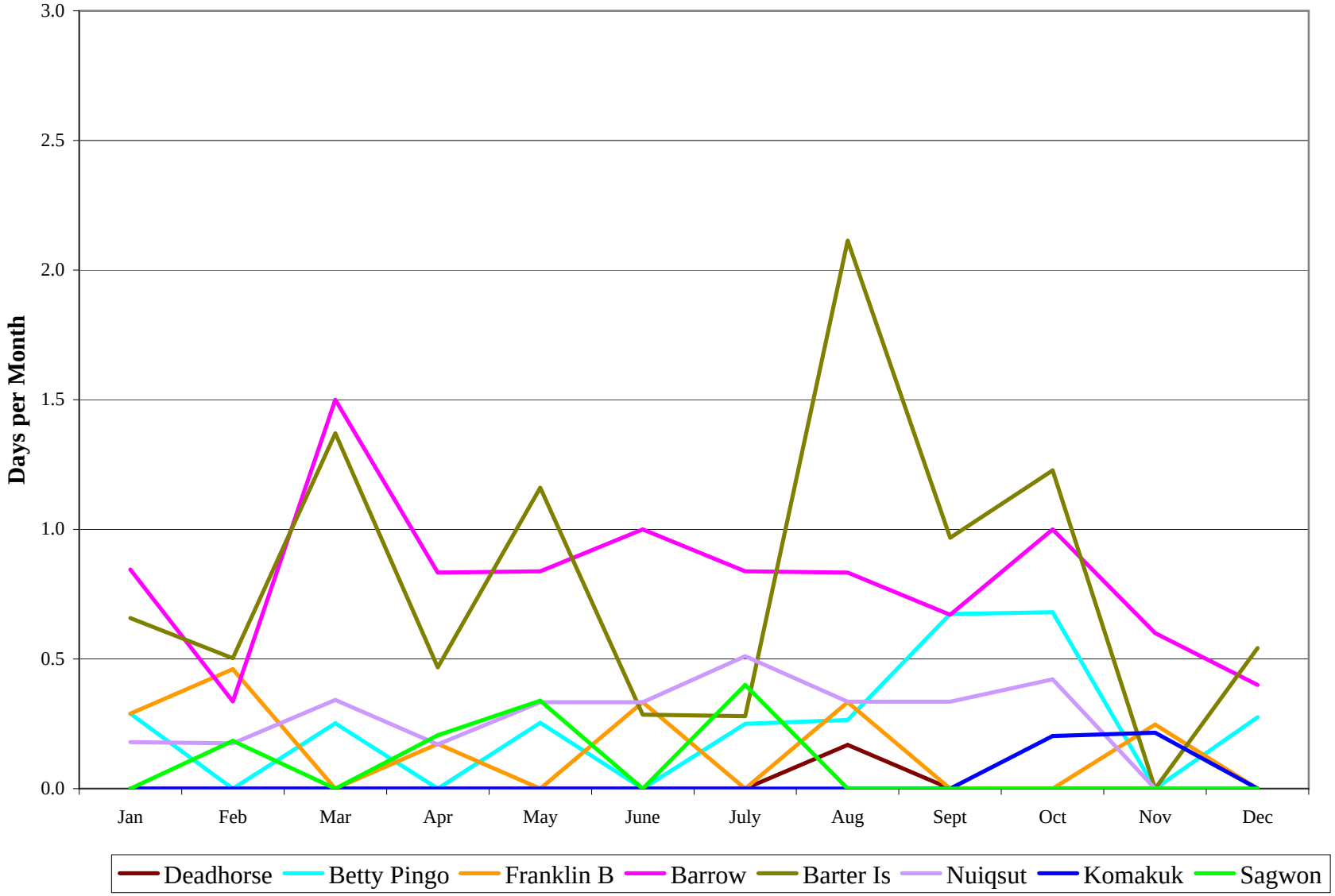


Figure 4-28 Frequency of Variable Winds at MMS Stations

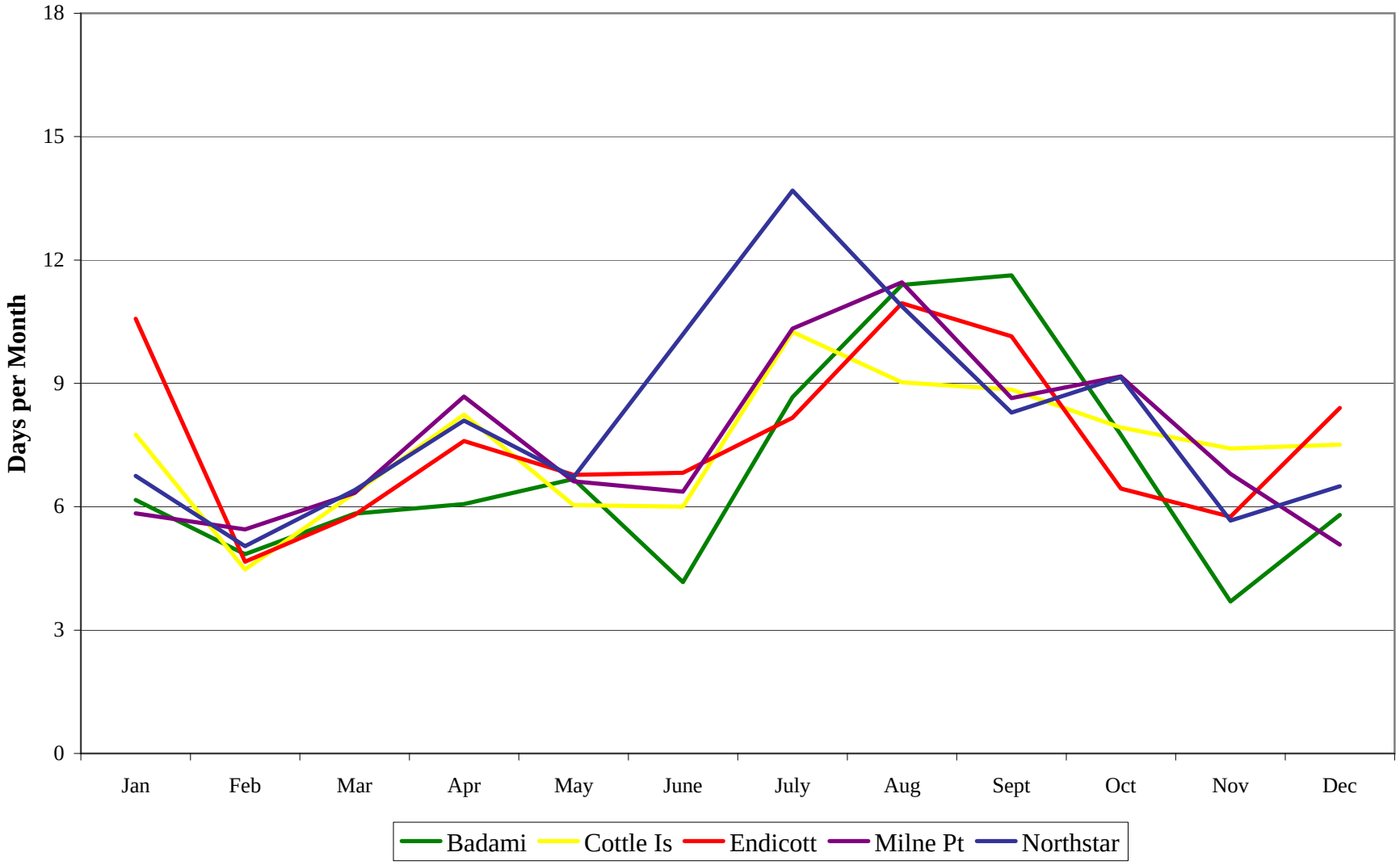
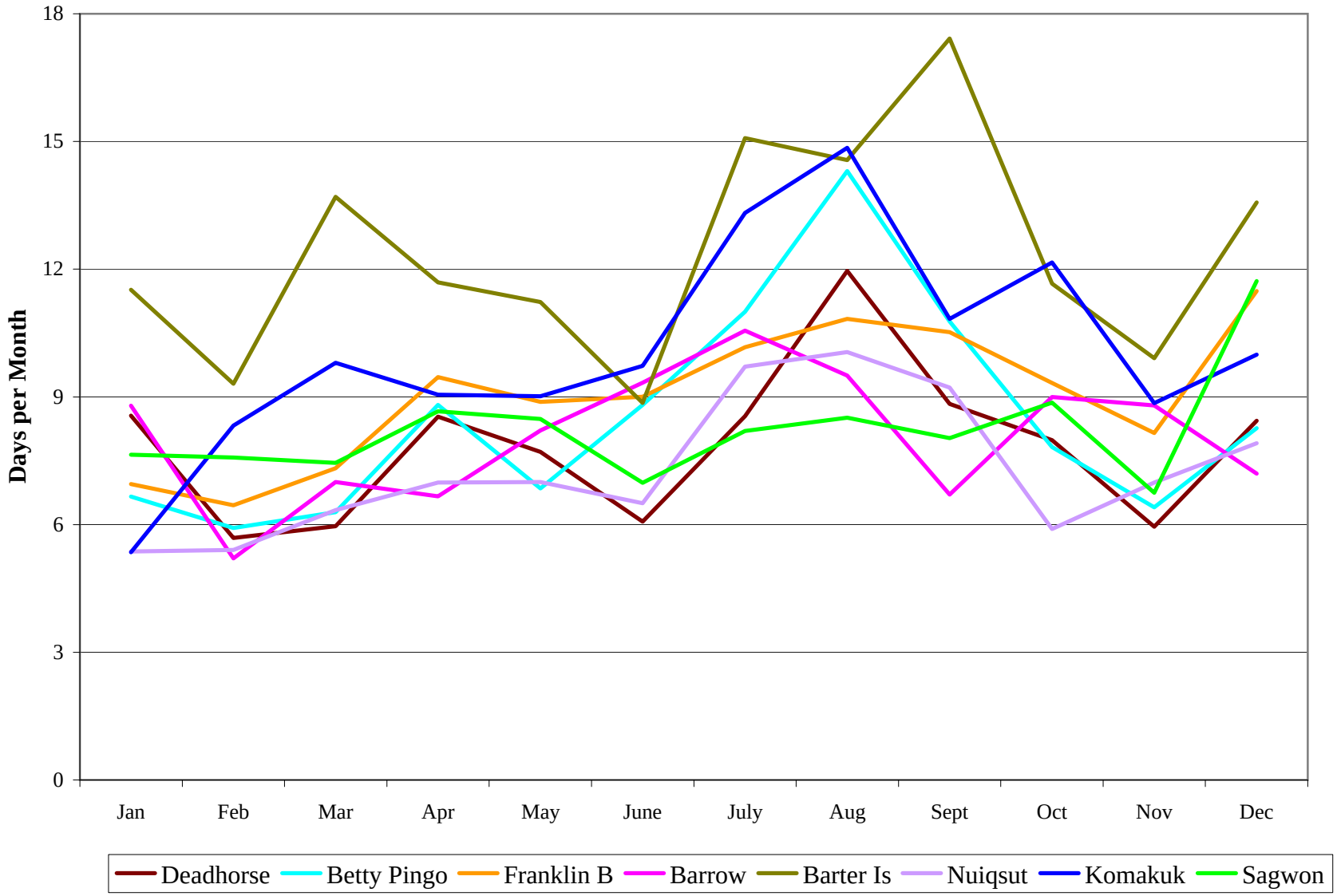


Figure 4-29 Frequency of Variable Winds at Supplemental Stations



4.3 Wind Sigma

Table 4-5 provides a summary of wind sigma data for the five MMS stations for the period of January 2001 through September 2006. Wind sigma is measured at a height of ten meters at Badami, Cottle Island, and Endicott, and at 14 meters and 23 meters at Milne Point and Northstar, respectively. No proven method exists for adjusting wind sigma for height.

Table 4-5. Wind Sigma Statistics (º)

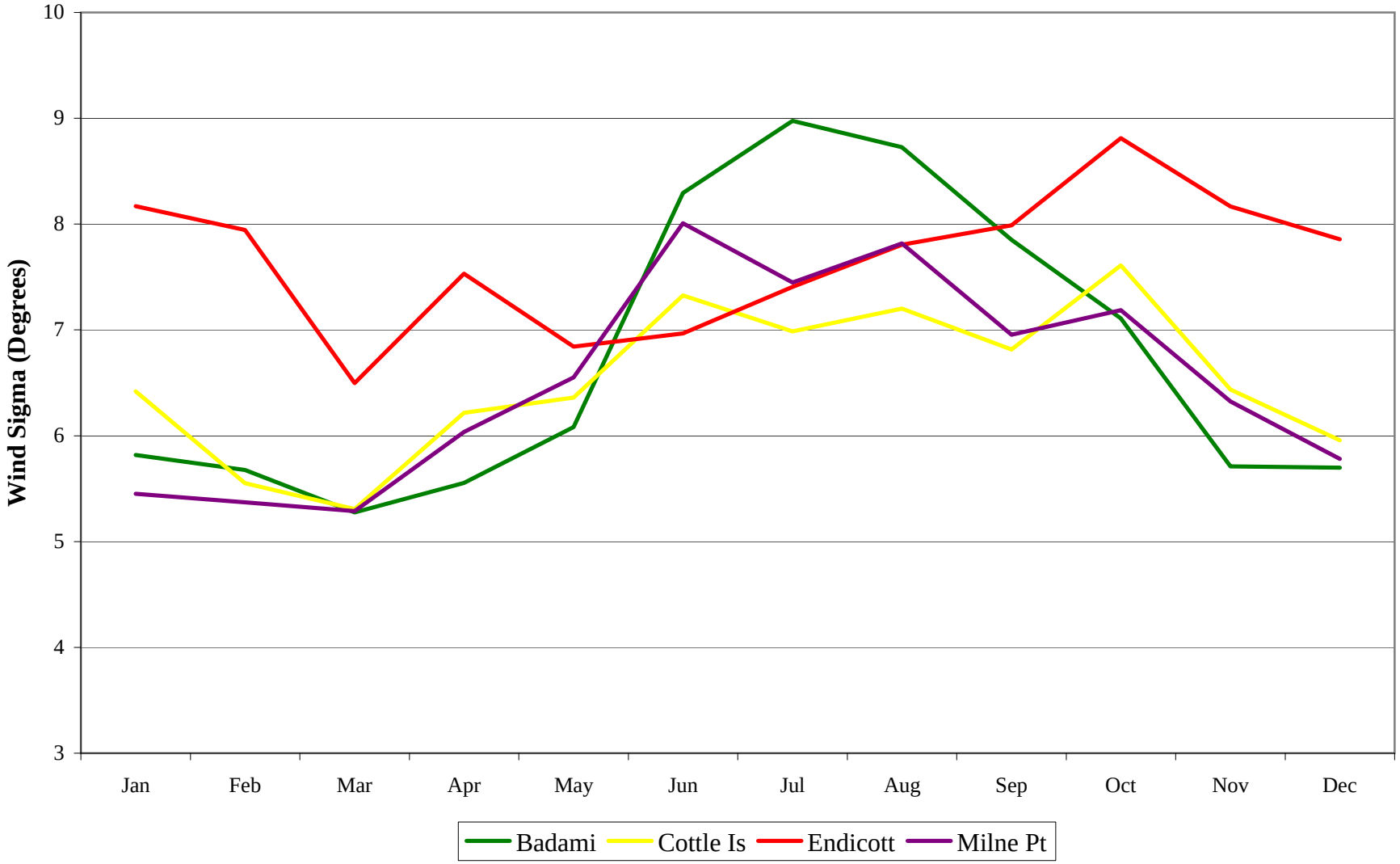
	Badami	Cottle Is.	Endicott	Milne Pt	Northstar
Mean	6.77	6.58	7.63	6.55	12.88
95% Confidence Interval (Mean)	6.71 – 6.82	6.53 – 6.63	7.57 – 7.68	6.50 – 6.60	12.76 – 13.00
Std Deviation	6.05	4.62	6.12	5.33	13.32
Median	5.20	5.46	5.46	4.92	8.57
Minimum	0.22	0.19	0.00	0.20	0.00
Maximum	74.80	83.10	103.90	81.70	98.20

The most striking property of the wind sigma data is that the mean of 12.88º at Northstar is considerably larger than the second highest average wind sigma of 7.63º at Endicott. This difference is indicative of turbulence generated in the obstacle-rich environment at Northstar (see photo, Figure 3-8).

The statistics above show that the mean wind sigma is statistically different among the different stations, although this difference is probably more of an artifact of the individual station local environment rather than the area at large. Endicott is not as prone to interference as Northstar, but the presence of a large number of structures to the south and east of the station on the Endicott SDI no doubt increases the wind sigma above background. The sites with the lowest means are Milne Point, Badami, and Cottle Island, reflecting the relatively unobstructed environment at these sites. Cottle Island is the only site without man-made obstacles nearby. The true wind sigma value for the region is expected to be in the 6.5º to 6.7º range, based on the results from stations where minimal interferences exist.

Mean annual variation in wind sigma is shown in Figure 4-30 for all sites but Northstar, which was excluded because that station wind sigma is not reflective of natural conditions (as discussed in Section 3.2.4) and detracts from the seasonal pattern shown at the other sites. While variation exists among sites, wind sigma follows a similar pattern of troughing in February and March and peaking in the late summer or fall.

Figure 4-30 Mean Monthly Wind Sigma



4.4 Temperature

Table 4-6 summarizes temperature measurements during the study period at the MMS stations. Seasonal temperature variation was pronounced in the region, ranging between -45 °C and 26 °C. For the majority of the year, temperatures are below freezing (0 °C). Mean temperatures in the area covered by the MMS stations were above freezing from about June 14 to about September 19, with the average year having approximately 100 days above freezing.

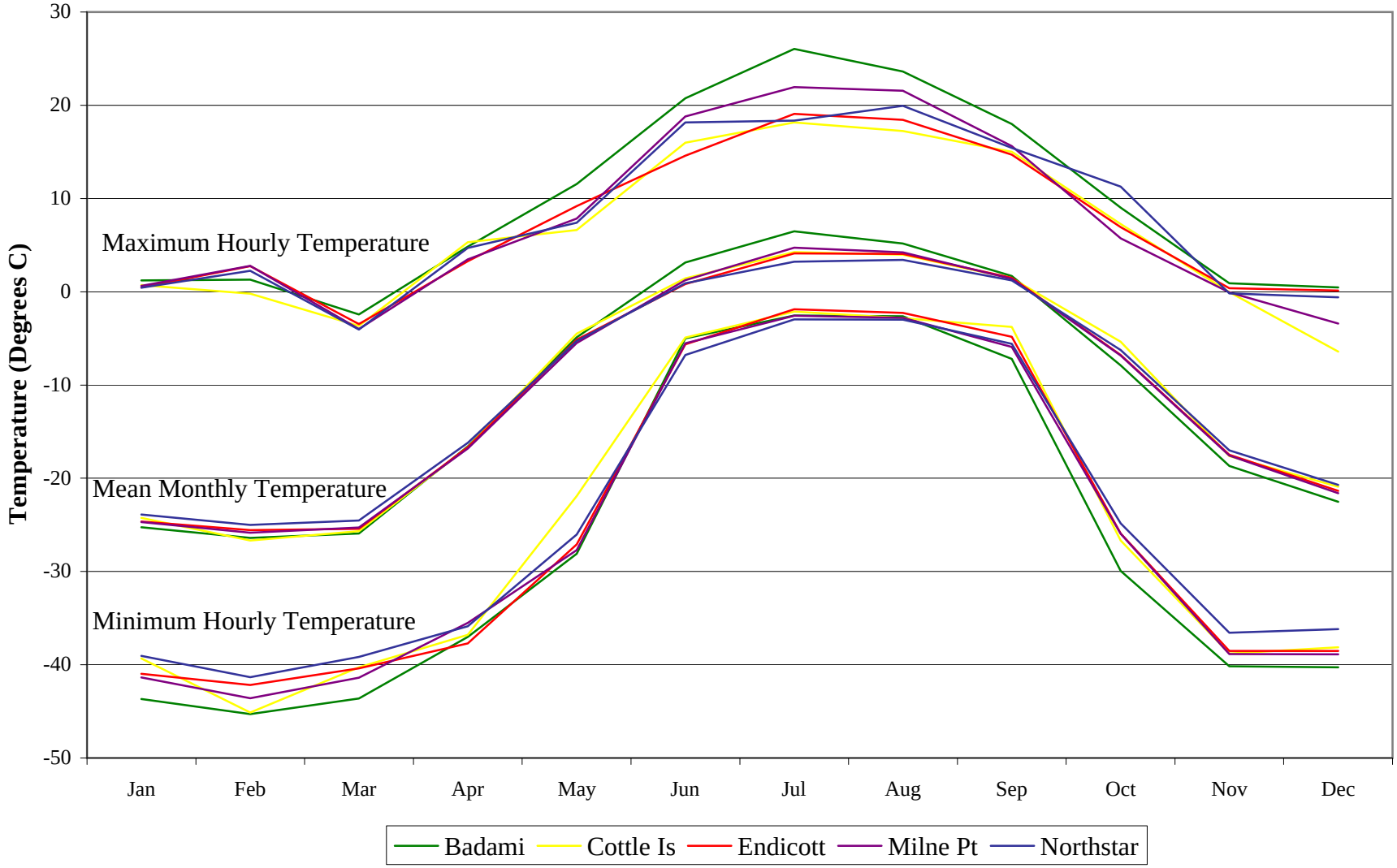
Figure 4-31 presents a graph of mean, maximum, and minimum hourly temperatures by month for each station.

Table 4-6. Temperature Summary Statistics (ºC)

	Badami	Cottle Is	Endicott	Milne Pt	Northstar
Mean	-10.65	-10.41	-10.41	-10.79	-10.63
95% Confidence Interval (Mean)	-10.77 – -10.52	-10.55 – -10.28	-10.53 – -10.30	-10.90 – -10.67	-10.74 – -10.52
Std Deviation	14.14	13.01	12.97	13.16	12.45
Median	-9.07	-7.35	-7.96	-9.35	-8.94
Minimum	-45.28	-45.13	-42.16	-43.60	-41.34
Maximum	26.05	18.17	19.09	21.95	19.93

Mean annual temperature was not found to be significantly different among the five MMS stations. By contrast, the standard deviation does depend on the distance of the station from the shore, owing to the damped diurnal cycle at the offshore sites. Maximum temperature was closely tied to distance from the coast; with the site located farthest onshore, Badami, reporting a maximum temperature nearly 8 ºC warmer than Cottle Island.

Figure 4-31 Temperatures (Mean Monthly, Hourly Maximum and Minimum)



Temperature histograms for every site are shown in Figure 4-32. The histograms show two overlapping distributions with different means and shapes. Two distinct thermal regimes appear to exist in the area. The two regimes were empirically determined to exist from June through October and from November through May, and are indicated by different colors in Figure 4-32.

Summary temperature tables for two seasonal periods are shown in Table 4-7 and Table 4-8.

Table 4-7. Temperature Statistics for June – October (ºC)

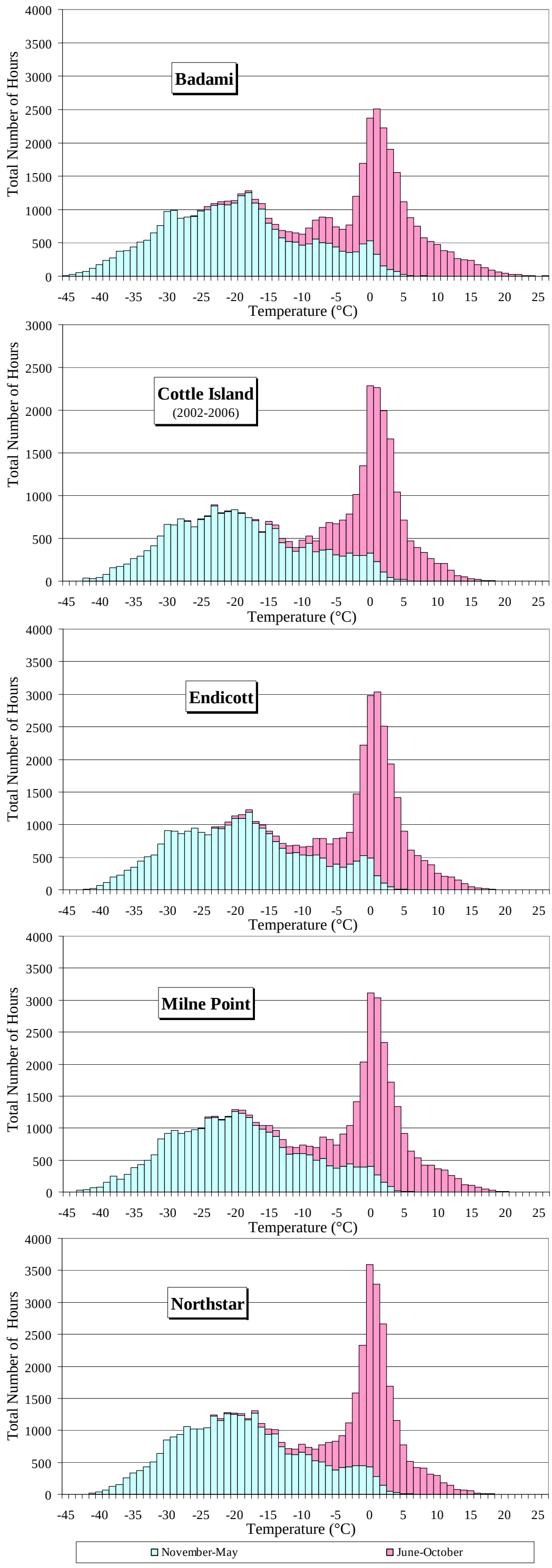
	Badami	Cottle Is	Endicott	Milne Pt	Northstar
Mean	2.05	1.21	1.00	1.22	0.74
95% Confidence Interval (Mean)	1.96 – 2.14	1.13 – 1.28	0.93 – 1.07	1.14 – 1.29	0.68 – 0.81
Std Deviation	6.82	4.79	5.33	5.66	4.94
Median	2.03	1.28	1.19	1.10	0.82
Minimum	-29.94	-26.69	-25.93	-25.95	-24.84
Maximum	26.05	18.17	19.09	21.95	19.93

Table 4-8. Temperature Statistics for November – May (ºC)

	Badami	Cottle Is	Endicott	Milne Pt	Northstar
Mean	-19.93	-19.38	-19.31	-19.56	-18.89
95% Confidence Interval (Mean)	-20.05 – -19.81	-19.52 – -19.25	-19.43 – -19.20	-19.67 – -19.44	-19.00 – -18.78
Std Deviation	10.39	9.87	9.81	9.70	9.37
Median	-20.45	-20.27	-19.77	-20.17	-19.60
Minimum	-45.28	-45.13	-42.16	-43.60	-41.34
Maximum	11.55	6.63	9.18	7.86	7.41

Once the data for the two periods are separated, a significant difference in the mean temperatures between the offshore and onshore sites is revealed, with the onshore sites being significantly warmer in the summer periods and significantly cooler in the winter season than the offshore sites. During the June – October period oceanic influence creates a relatively mild coastal regime with the temperature not deviating widely from 0 ºC. During the November – May period the ocean is mostly covered by ice, causing the climate to become colder and more "continental" with wider swings in temperature.

Figure 4-32
Temperature Histograms
For MMS Stations
(2001-2006)



(This Page Is Intentionally Left Blank)

Table 4-9 gives total and monthly mean degree day statistics for degree freezing days, degree above freezing days, and heating degree days for the MMS stations. The table shows the mean year July through June because the "freezing year" and "heating year" during which freezing and heating degree days are accumulated begins on July 1. The statistics are compiled from a daily average for all five MMS stations, averaged over the 2001-2006 time period.

Degree freezing days measure the daily negative difference between the mean temperature and 0 °C. Degree above freezing days measures the daily positive difference between the mean daily temperature and 0 °C. Degree heating days measure the daily negative differences between the mean temperature and 18.3 °C (65 °F), a value set by the U.S. National Oceanic and Atmospheric Administration (NOAA) to approximate the level of energy used to keep inhabited structures warm. Degree heating days is used by NOAA in comparing climatology of regions throughout the US.

Table 4-9. Degree Day Statistics (°C)

Month	Degree Freezing Days	Degree Above Freezing Days	Degree Heating Days
July	0	141	426
August	0	130	438
September	8	50	506
October	206	0	773
November	530	0	1,079
December	664	0	1,231
January	763	0	1,330
February	723	0	1,236
March	786	0	1,354
April	498	0	1,047
May	158	0	726
June	2	48	504
Total	**4,339**	**369**	**10,649**

4.5 Barometric Pressure

Descriptive statistics for barometric pressure are presented in Table 4-10. Pressure values in the table have been adjusted to sea-level as described in Section 3.2.2.3 to provide a more meaningful comparison between stations.

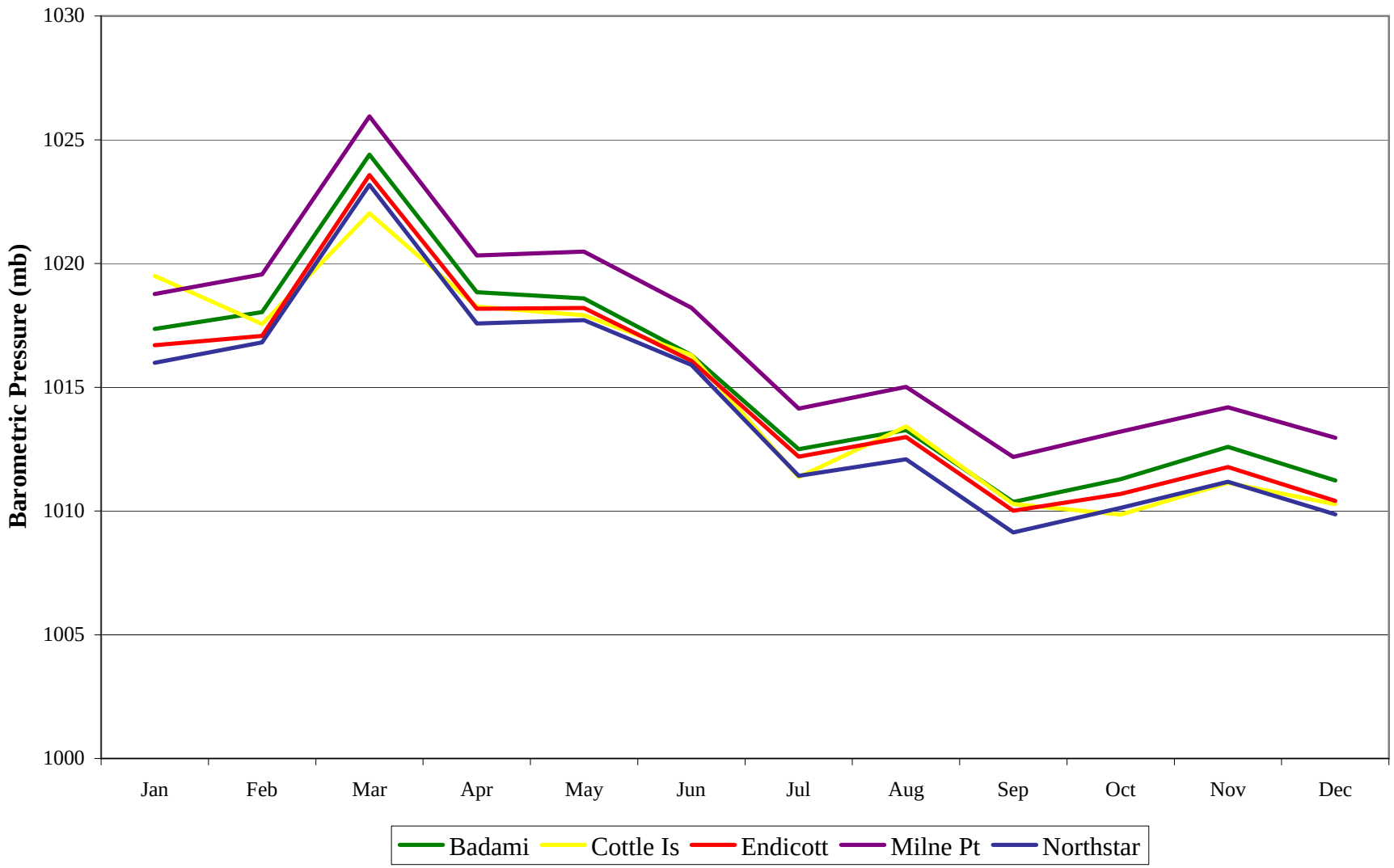
Sea-level pressure ranged from 973 mb to 1,057 mb. After adjusting pressure to sea-level, Milne Point had the highest mean pressure, followed by Badami. The difference in means between Endicott and Cottle Island was not statistically significant. Northstar has a lower mean pressure than the other sites, even after adjusting the readings to sea-level.

Table 4-10. Statistics for Sea-Level Barometric Pressure (mb)

	Badami	Cottle Is	Endicott	Milne Pt	Northstar
Mean	1,015.6	1,014.7	1,015.0	1,017.2	1,014.0
95% Confidence Interval (Mean)	1,014.9 – 1,016.2	1,014.1 – 1,015.4	1,014.3 – 1,015.6	1,016.6 – 1,017.9	1,013.8 – 1,014.7
Std Deviation	10.7	10.6	10.6	10.6	10.6
Median	1,015.0	1,014.6	1,014.6	1,016.8	1,013.5
Minimum	976.0	973.6	974.6	975.8	972.5
Maximum	1,056.0	1,051.6	1,055.6	1,056.8	1,054.5

Barometric pressure shows a consistent seasonal pattern at all sites, as shown in Figure 4-33. Pressure remains relatively low from July through December, then rapidly increases, peaking in March. The mean monthly pressure in March is higher than November by 13 to 14 mb at all sites.

Figure 4-33 Mean Monthly Barometric Pressure Adjusted to Sea-Level



4.6 Solar Radiation

As expected, solar flux is enormously seasonal in the study area, as shown in Figure 4-34 and Figure 4-35. Sensor output is mean hourly watts per square meter. Figure 4-34 shows the summary of mean daily solar flux by month and captures not only the seasonal variation in intensity, but also in duration of daylight. Because very little site-to-site variation exists, Figure 4-34 shows only Milne Point.

Because any sea-breeze effect in the area would be driven by the difference in the heat rate of land and sea, such an effect would seem to be much stronger earlier in the summer. For instance, the mean daily solar flux in June at Milne Point is roughly 2.5 times higher than in August and roughly 4.5 times higher than in September.

Figure 4-34. Mean Daily Solar Flux at Milne Point

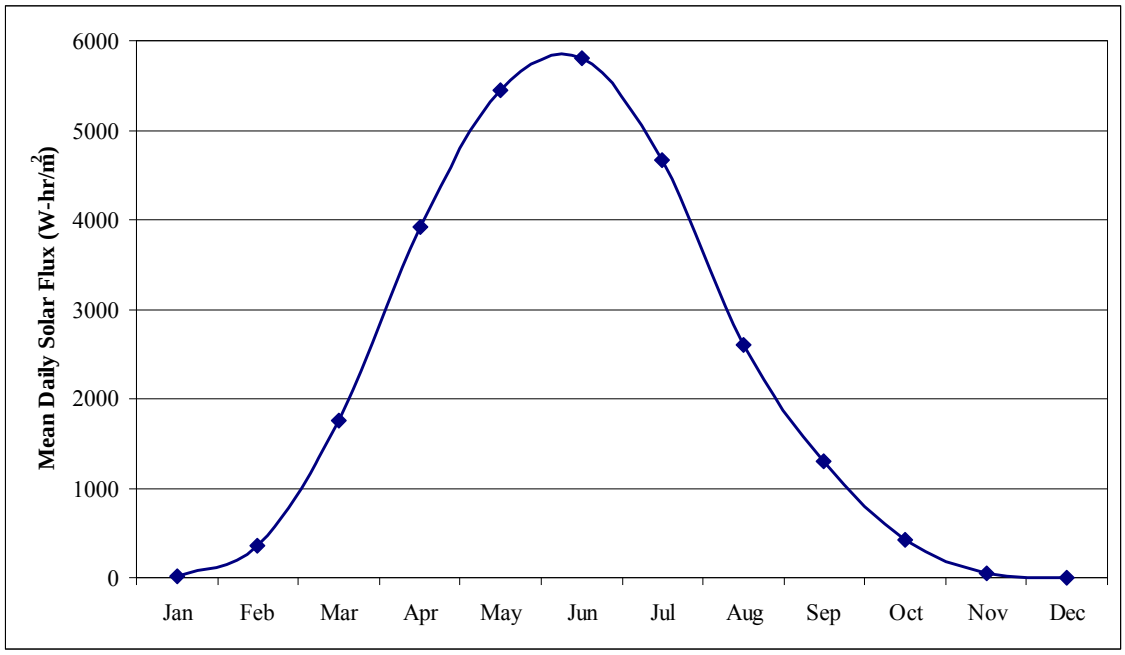
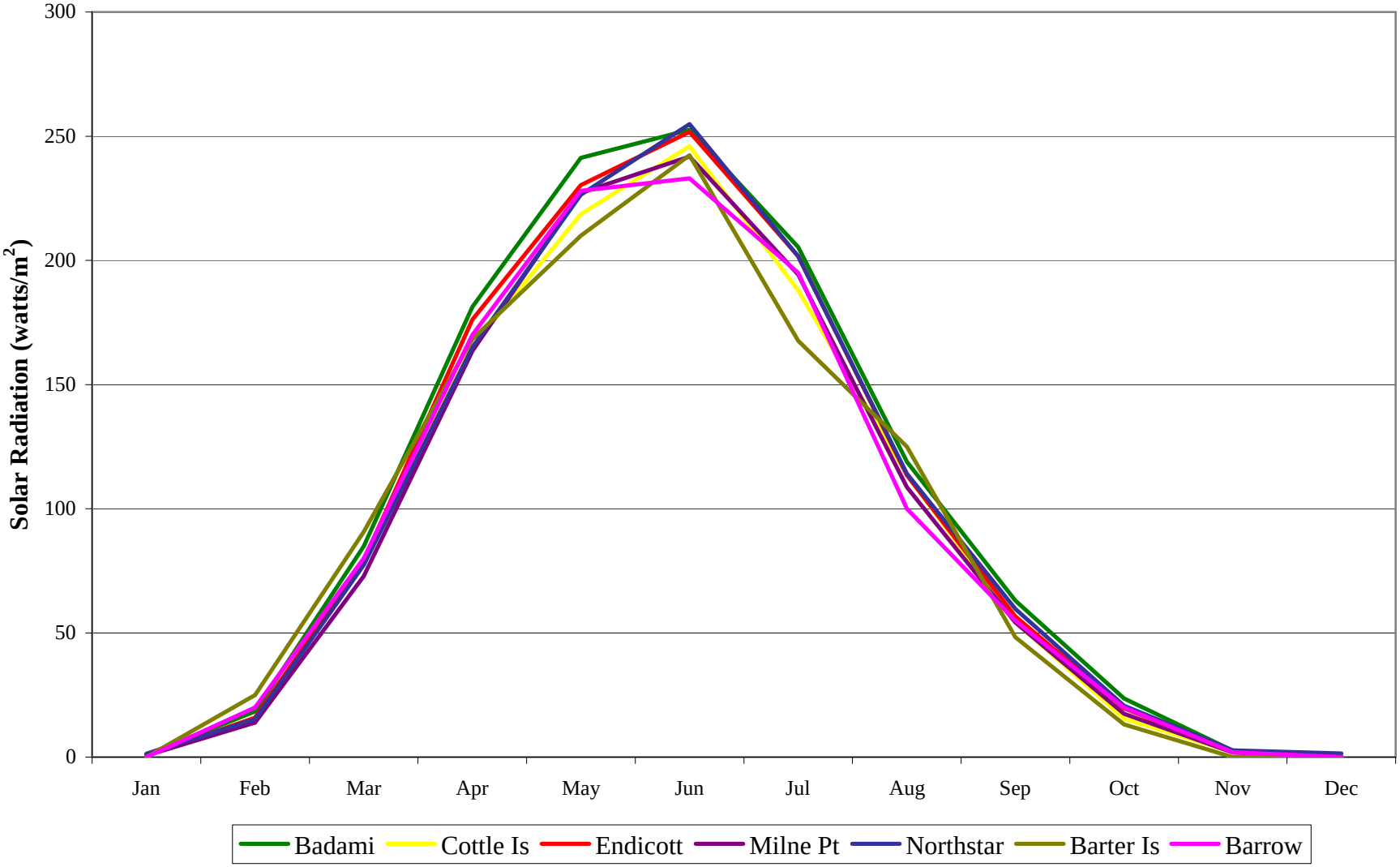


Figure 4-35 shows the mean monthly solar radiation for each MMS site, as well as Barter Island and Barrow. Solar flux is quite unevenly distributed about the summer equinox, probably due to significantly increased cloudiness during the open-water period. Cottle Island appears to experience a cloudier July than the other sites. However, a shorter time series exists at Cottle Island than at the other sites, so some variability is expected. Barrow exhibits lower solar radiation throughout the summer, possibly due to extended foggy periods.

Figure 4-35 Mean Monthly Solar Radiation



4.7 Relative Humidity

Table 4-11 provides a summary of the relative humidity at each site during the study period, while Figure 4-36 provides a graph of mean monthly relative humidity at each site. Relative humidity monthly averages generally ranged between 75 and 95 percent, as shown in Figure 4-36. Little real difference exists among the various sites, except that the Northstar relative humidity remains higher in the winter. Instrument error for relative humidity is plus or minus three percent, so no real certainty exists that any of these sites display significantly different means for relative humidity.

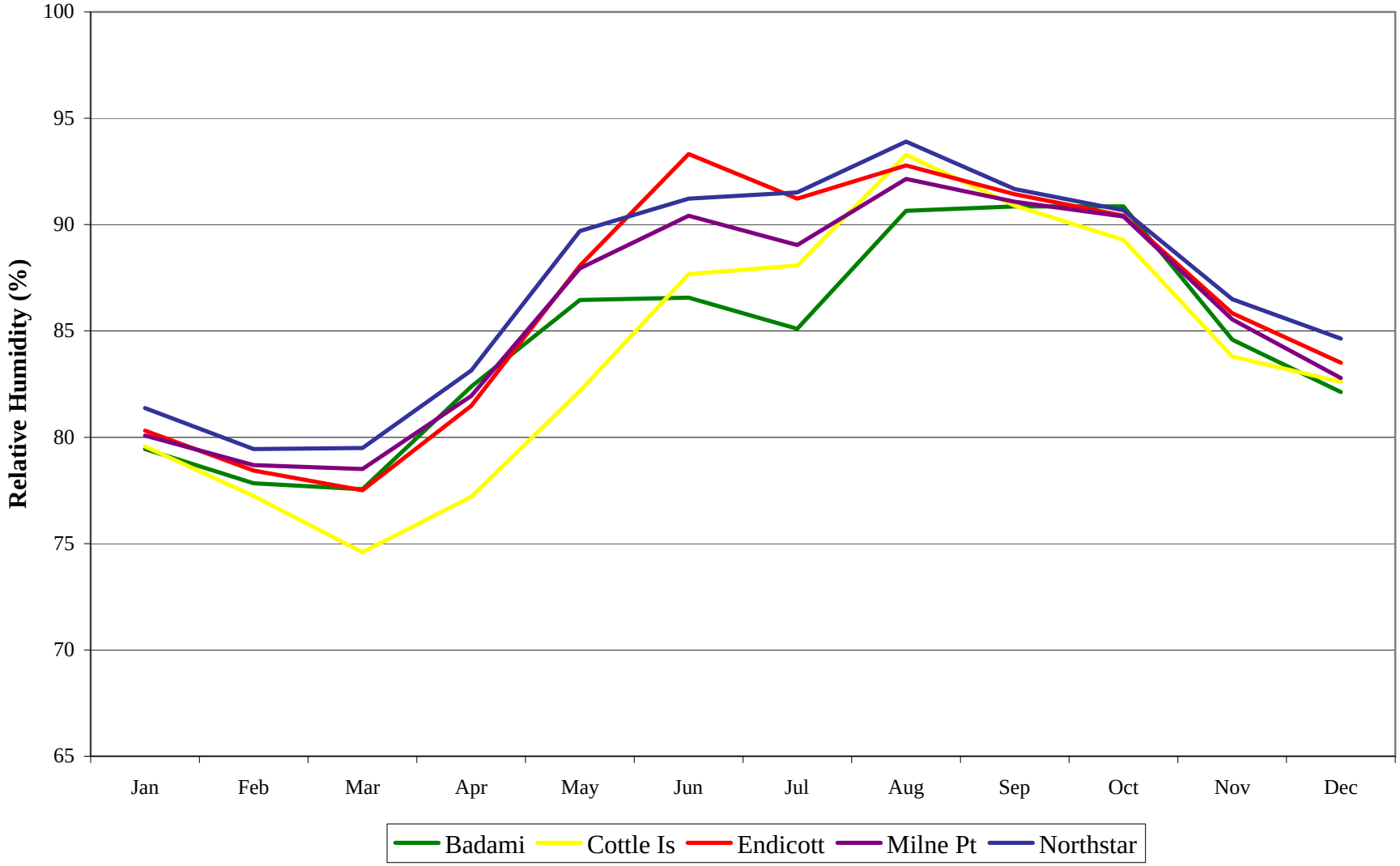
Table 4-11. Relative Humidity Data Summary

	Badami	Cottle Is.	Endicott	Milne Pt	Northstar
Mean	85%	84%	86%	86%	87%
Std Deviation	10%	10%	9%	9%	9%
Minimum	30%	27%	39%	31%	45%
Maximum[6]	100%	100%	100%	100%	100%

Relative humidity shows a consistent seasonal pattern at all sites, as shown in Figure 4-36. The humidity is higher during the months of May through October, likely because of the presence of surface water.

[6] Actual sensor readings occasionally exceeded 100 percent due to the instrument error of ±3 percent.

Figure 4-36 Mean Monthy Relative Humidity



5 DISCUSSION

5.1 Orographic Effects

Kozo's model results predict that orographic effects on wind speed and direction should become greater moving eastward from Prudhoe Bay (see Section 2.2). In summary, the mean wind speed should increase for the dominant wind directions, and there should be an increased tendency for winds along the east-west axis paralleling in Brooks Range.

Figure 4-20 and Figure 4-21 show some of the interrelationships between the region's orographic effects and sea breeze effects. The increasing wind speeds and the flattening of the wind roses toward the eastern side of the study area corroborate Kozo's prediction. The Brooks Range runs in a rough arc toward the eastern side of the study area (see Figures 2-2 through 2-4). The approximate 600 meter contour of the Brooks Range is predicted to define the influences of the range's orographic effects. Due to the size of the range, these influences are predicted to affect all meteorological stations in the study area, with the exception of Barrow. Wind roses in Figure 4-20 and Figure 4-21 reflect the orographic effects, as the major wind direction classes parallel this 600-meter line for most sites.

Orographic effects are especially noticeable when comparing the eastern stations at Badami, Barter Island, and Komakuk Beach. The close proximity of the Brooks Range appears to have the greatest effect at Komakuk Beach, where the range is just 10 km from the coast. As a result, this site experiences very high wind speeds and winds which almost always are along the east-west axis. The Barter Island data shows a predominance of orographic effects as well, with wind directions flattening in an east-west direction. Badami, the easternmost site in the immediate Prudhoe Bay vicinity, exhibits strong wind components in a northeast-southwest direction.

The wind roses of meteorological stations from the central Beaufort Sea region reflect the orographic effects of the mountains, with strong northeast to southwest wind components running roughly parallel to the 600-meter contour line. A strong onshore wind component can be noticed at these sites situated near the coast due to sea breeze effects, as discussed in Section 5.2.

The site farthest from the coast, Sagwon, displays a predominance of winds parallel to the Brooks Range, and a stronger wind component from the southwest, as opposed to the coastal stations of the Prudhoe Bay region. The wind rose for Franklin Bluffs indicates a similar pattern as Sagwon, with a minor component of wind effects from the coast. Barrow, far to the west of the study area, indicates a major component of wind direction from the Beaufort Sea, although the winds do not exhibit the orographic effects seen toward the east.

The greater spatial variability and deviation from the geostrophic approximation on the eastern side of the area of interest may be an important consideration for the design of any future regional meteorological monitoring.

5.2 Sea Breeze Effects

Kozo [1980] predicted the existence of a unidirectional onshore sea breeze effect within a 40 km area centered along and running parallel to the arctic coastline during the summer. This phenomenon is driven by a thermal gradient between the relatively warm land and cold sea.

Unlike coastal areas at lower latitudes, this flow would not reverse at night due to the 24-hour sunlight during the arctic summer.

The frequency and duration analyses discussed in Section 4.2.2 show that most winds at all sites are either onshore or offshore with winds parallel to the shoreline representing only a minor component. At all MMS sites, onshore winds dominate over offshore winds, both in terms of frequency and average duration. At the supplemental stations, the same relationship is true with the exception of the two stations closest to the Brooks Range, Sagwon and Komakuk Beach. These data appear to support the influence of a sea breeze effect on the measured winds. However, difficultly exists differentiating the influence of any sea breeze effect from that the influence of the larger synoptic-scale conditions, because both favor winds from the east and northeast.

The wind roses in Section 4.2 show a predominance of onshore winds from the east, east-northeast, and northeast, while offshore winds from the west, west-southwest, and southwest represent a secondary, yet significant, component. The dominance of onshore winds can be represented as the frequency ratio of onshore to offshore winds (i.e., the number of hours when onshore winds occur divided by the number of hours offshore winds occur).

Figure 5-1 shows the seasonal dominance of onshore breezes at the MMS stations, while Figure 5-2 shows the same ratios at the supplemental stations. As expected, the sea breeze effect is most pronounced at the sites closest to the coastline and is most evident during the summer months. While the frequency ratios of onshore to offshore winds at the MMS stations are similar during the summer months, the ratios at the more inland stations Badami and Milne Point remain lower than the ratios of the more offshore locations. Northstar's ratio may be biased downward, because the large process module to the north of the station (see Section 3.2.4) interferes with the recording of onshore breezes, however, the magnitude of the seabreeze effect is also expected to lessen as one moves further offshore.

The onshore to offshore wind frequency becomes more noticeable with distance from the coast when the supplemental stations are considered. The most offshore location, Barter Island, shows the highest ratio of onshore to offshore wind frequency, while inland locations such as Franklin Bluffs and Sagwon are less than half the ratio, displaying more frequent offshore winds compared to the coastal sites.

The farthest distant supplemental stations from the main study area, Barrow and Komakuk Beach, do not correlate well with the other stations with regard to wind frequency ratio. Onshore and offshore wind components vary at these sites due to other influences not present in the main study area. As mentioned above, Komakuk Beach exhibits substantial influence from its proximity to the Brooks Range, presumably overshadowing a portion of the sea breeze effect. The location of Barrow on a point between the Chukchi and Beaufort Seas alters the general orientation of the shoreline relative to the other stations.

While Kozo's research used only August data, Figure 5-1 and Figure 5-2 show that the effect is most pronounced in June. In late May and most of June, snow cover over land has diminished lowering the land-surface albedo. This reduction allows for a greater transformation of solar energy into thermal energy over the land surface than over the ocean, which remains covered with reflective snow and ice during this period. This difference can exaggerate the land-sea

thermal gradient leading to a magnified sea breeze effect. June also has the highest daily solar flux, as shown in Figure 4-34. Mean daily solar flux in June is 2.5 times greater than in August, and 4.5 times greater than in September.

Figure 5-3 shows the onshore/offshore ratio for June plotted against the distance offshore of each station in kilometers. The sea breeze effect of the Beaufort Sea can be seen as a strong correlation of this ratio to distance offshore. The farthest site from the ocean, Sagwon, exhibits the lowest onshore/offshore wind direction ratio for June, and the sea breeze effect is barely noticed at Franklin Bluffs as well. Nuiqsut exhibits the outer reach of the sea breeze effect, while the group of stations slightly offshore exhibits the highest ratio. The data from the Northstar station seems to support the hypothesized reduction in sea breeze effect toward the open ocean. However, as mentioned above, the data from this site is somewhat suspect (see Section 3.2.4). Due to the data biases discussed above, Barrow and Komakuk Beach were not included in the analysis.

Figure 5-1 Frequency Ratio of Onshore to Offshore Winds by Month, MMS Stations

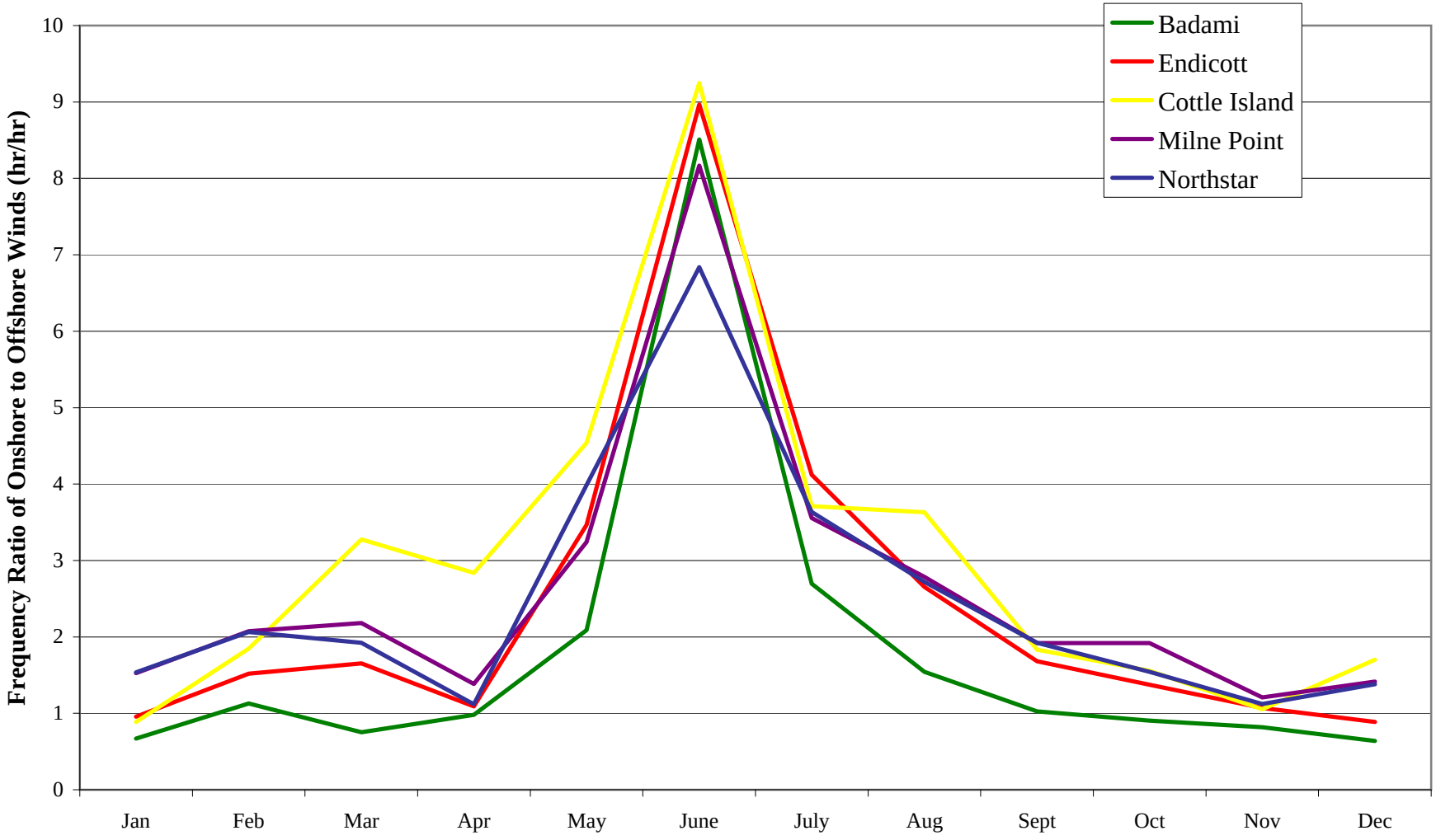


Figure 5-2 Frequency Ratio of Onshore to Offshore Winds by Month, Supplemental Stations

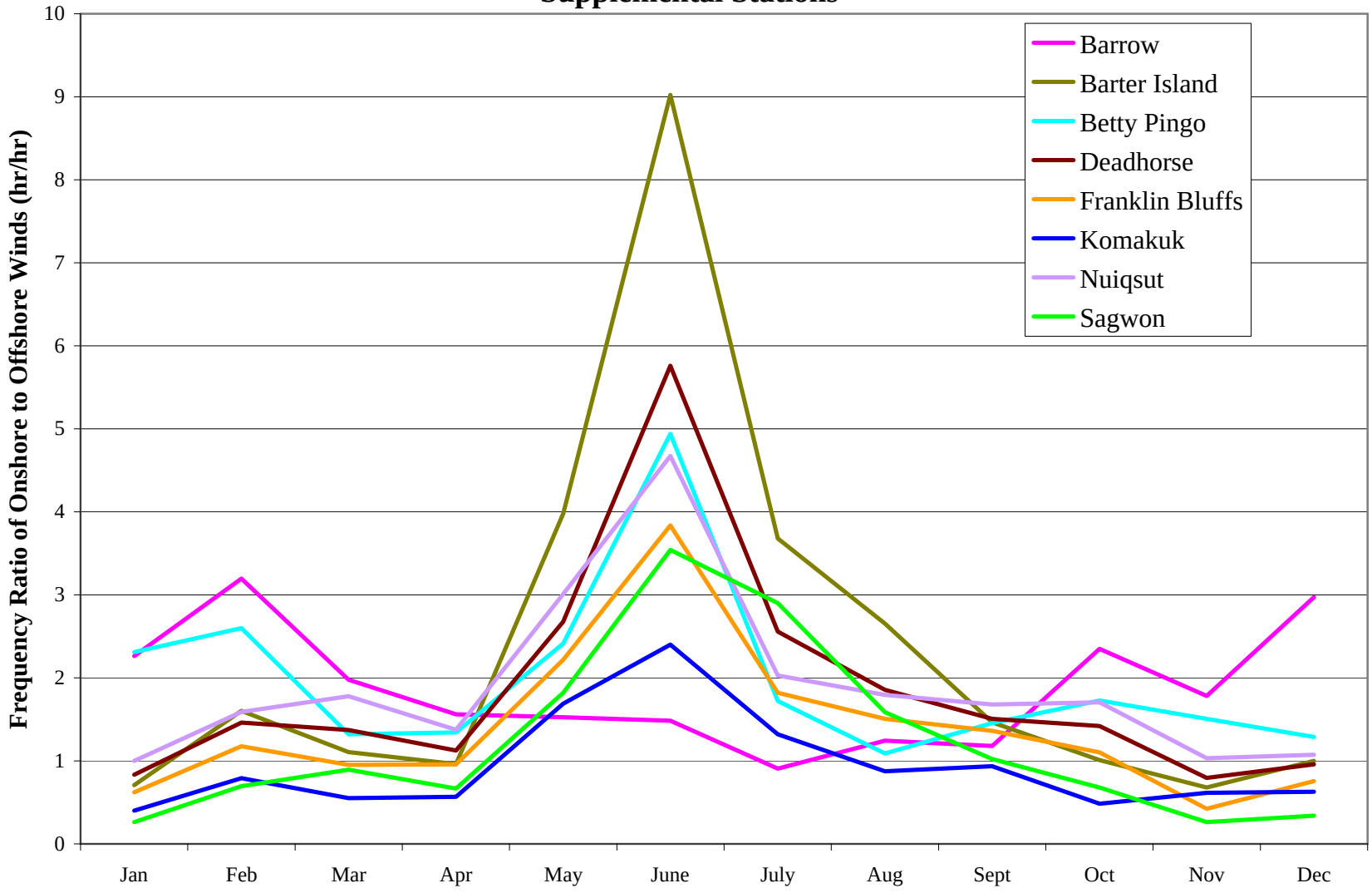
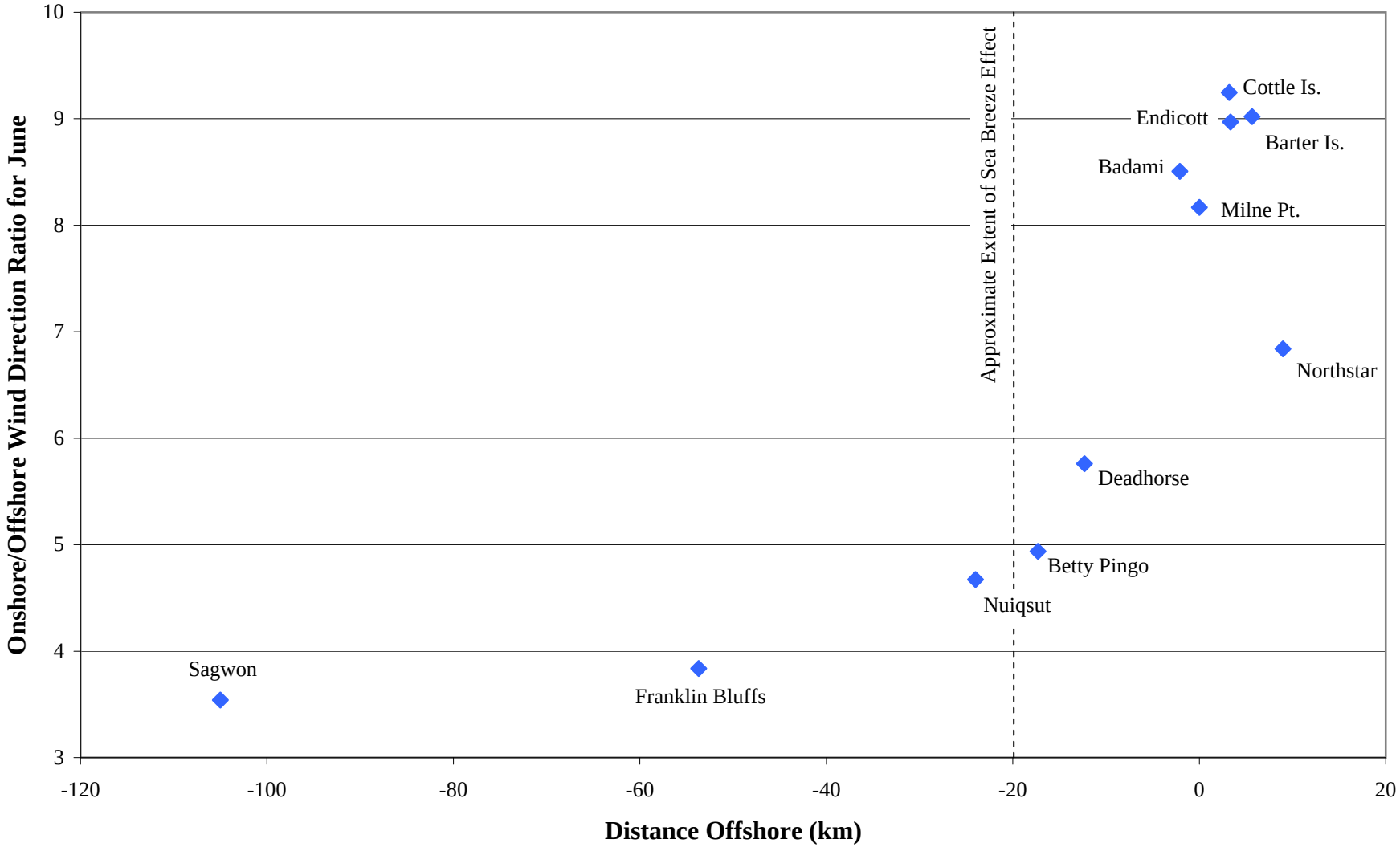


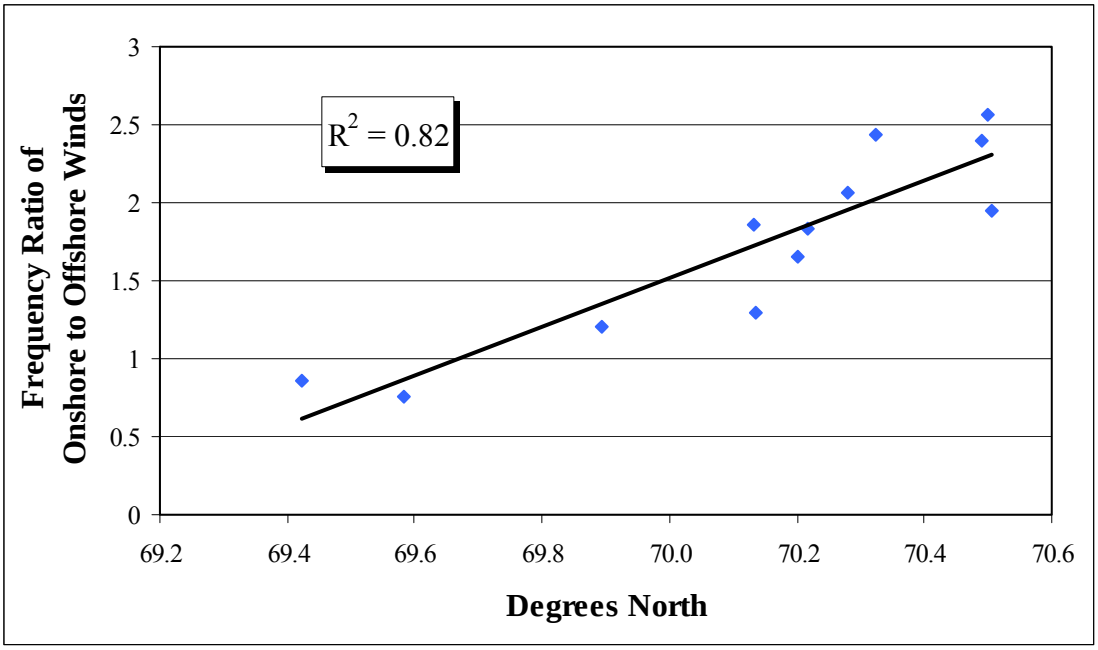
Figure 5-3 June Wind Direction Ratio vs. Distance Offshore



5.3 Latitudinal Effects

The dominance of onshore winds correlates better to latitude, than to distance from shore in the Beaufort Sea region. Figure 5-4 shows the ratio of onshore winds to offshore winds as a function of decimal degrees north for all stations except Barrow, which is much farther north (71.3º N). By comparison, the R-squared of the wind frequency ratio to distance offshore is quite weak (R^2 = 0.33).

Figure 5-4. Frequency Ratio of Onshore to Offshore Winds vs. Latitude



5.4 Inter-Station Correlation and Cross-Correlation

5.4.1 Correlation

The correlation and cross-correlation of wind speed between two stations provides valuable information about the similarity of the weather patterns affecting the sites. Using the R-squared value (R^2), the correlation of wind speed among the various stations shown in Table 5-1 and Table 5-2 demonstrates which sites are most representative of a general area, which sites are outliers, and which sites may be gathering data which would be redundant for most purposes.

Table 5-1 compares the data sets collected by the five MMS stations to each other, the eight supplemental stations, and two sites not otherwise considered in the study, Cross Island and McCovey. These two additional sites did not have data sets long enough for broader consideration in the study. However, the data for these two stations were of good quality, and enough data were available to obtain correlations to the other stations. Table 5-2 compares the data sets collected by the eight supplemental stations to each other. Very good correlations (R^2 greater than 0.70) are shown in bold red text, good correlations (0.70 greater than R^2 greater than 0.50) are shown in bold orange text, moderate correlations (0.50 greater than R^2 greater than 0.30) are shown in bold blue text, and poor correlations (R^2 less than 0.30) are shown in plain black text.

Table 5-1. Correlation of MMS Stations Wind Speed Using R-squared Values (R^2)

	Badami	Cottle Is	Endicott	Milne Pt	Northstar
Badami	-	**0.64**	**0.58**	**0.60**	**0.46**
Cottle Is	**0.64**	-	**0.64**	**0.84**	**0.67**
Endicott	**0.58**	**0.64**	-	**0.66**	**0.61**
Milne Pt	**0.60**	**0.84**	**0.66**	-	**0.64**
Northstar	**0.46**	**0.67**	**0.61**	**0.64**	-
Barrow	**0.33**	**0.43**	**0.31**	**0.43**	0.30
Barter	**0.49**	**0.41**	0.25	**0.35**	0.27
B Pingo	**0.71**	**0.77**	**0.67**	**0.78**	**0.57**
Deadhorse	**0.74**	**0.65**	**0.54**	**0.62**	**0.46**
F Bluffs	**0.31**	0.28	0.25	0.27	0.18
Komakuk	0.25	0.21	0.15	0.18	0.15
Nuiqsut	**0.62**	**0.64**	**0.50**	**0.63**	**0.43**
Sagwon	0.05	0.04	0.02	0.05	0.08
Cross Is	**0.51**	**0.66**	**0.68**	**0.64**	**0.69**
McCovey	**0.63**	**0.60**	**0.54**	**0.57**	**0.69**

Table 5-2. Correlation of Supplemental Stations Wind Speed Using R-Squared Values (R^2)

	Barrow	Barter Island	Betty Pingo	Dead-horse	Franklin Bluffs	Koma-kuk	Nuiqsut	Sagwon
Barrow	-	0.20	**0.45**	**0.37**	0.15	0.11	**0.45**	0.03
Barter Is	0.20	-	**0.41**	**0.38**	0.07	**0.35**	**0.30**	0.01
Betty Pingo	**0.45**	**0.41**	-	**0.70**	**0.34**	0.22	**0.70**	0.07
Deadhorse	**0.37**	**0.38**	**0.70**	-	**0.33**	0.17	**0.68**	0.07
Franklin B.	0.15	0.07	**0.34**	**0.33**	-	0.02	**0.34**	0.16
Komakuk	0.11	**0.35**	0.22	0.17	0.02	-	0.15	0.00
Nuiqsut	**0.45**	**0.30**	**0.70**	**0.68**	**0.34**	0.15	-	0.06
Sagwon	0.03	0.01	0.07	0.07	0.16	0.00	0.06	-

Generally, the distance between two stations is inversely proportional to the strength of the correlation in the wind speed patterns. The poor-to-moderate correlation of Franklin Bluffs to the other sites and the extremely poor correlation of Sagwon to the other sites indicate that the weather patterns change much more rapidly over distance heading inland as opposed to along the coast. This lack of correlation is probably due to the direction of the prevailing winds and the greater influence of the Brooks Range to the south. Consider that the Deadhorse and Betty Pingo stations correlate better to Barrow, which is approximately 325 km to the west, and Barter Island, which is approximately 200 km to the east, than to Franklin Bluffs, which is only 40 km to the south. Barrow and Barter Island, which are 500 km apart, correlate better than Franklin Bluffs and Sagwon, which are 50 km apart.

The Cross Island and McCovey stations were included in Table 5-1 because those stations are located further offshore, 16 and 19 km, respectively, than any of the MMS stations. Both stations appear to correlate well with all of the MMS stations, indicating that that the nearshore monitoring network may be somewhat representative of the conditions offshore.

5.4.2 Cross-Correlation

A better measure of the similarity between the wind speed patterns between two stations is to measure the value of the cross-correlation function between the two data sets. The cross-correlation function $\rho_{xy}(k)$ is the covariance between time series ***X*** at time ***t*** and time series ***Y*** at time ***t*** + ***k*** standardized to a scale between zero and one, as shown in the equation below:

$$\rho_{xy}(k) = \frac{Cov(X_t, Y_{t+k})}{\sqrt{Cov(X_t, X_t) \cdot Cov(Y_t, Y_t)}}$$

One advantage to the cross-covariance function is that the correlation between two series can be investigated at various lags (values of ***k***). This ability can be important because not all time series are best correlated by comparing simultaneous data points. For example, the correlation between average monthly temperature and sea ice thickness in the Arctic might be rather poor, because the coldest month is January, but the sea ice is thickest in March. However, the cross-correlation at a lag ***k*** of 2 months would show an excellent relationship between the two time series.

Figure 5-5 shows the wind speed cross-correlation between Milne Point at time ***t*** and every other station at time ***t + k*** at lags from minus 15 hours through plus 15 hours. Milne Point was chosen as the reference station because of its central location and because the Milne Points data set was the most complete. Two sites not elsewhere considered, West Dock and Kuparuk Airport, are included in this graph. Both stations received a "B" ranking, and are especially valuable for this analysis because of their close location; Kuparuk Airport is just slightly east, and West Dock is slightly west of Milne Pt.

Note that the peak values of the cross-correlation functions are not always at lag equal zero. Barrow correlates best with Milne Point at ***t – 3*** hours, Nuiqsut at ***t – 1***, Endicott at ***t + 1***, and Komakuk at ***t + 6*** hours. This correlation means that variations in wind speed tend to occur at Barrow three hours before occurring at Milne Point on average. Kuparuk Airport correlates best with Milne Point at approximately ***t – 0.5*** hours, while West Dock correlates best at ***t + 0.5*** hours.

Figure 5-5 Cross-Correlation of Wind Speed to Milne Point at Various Lags

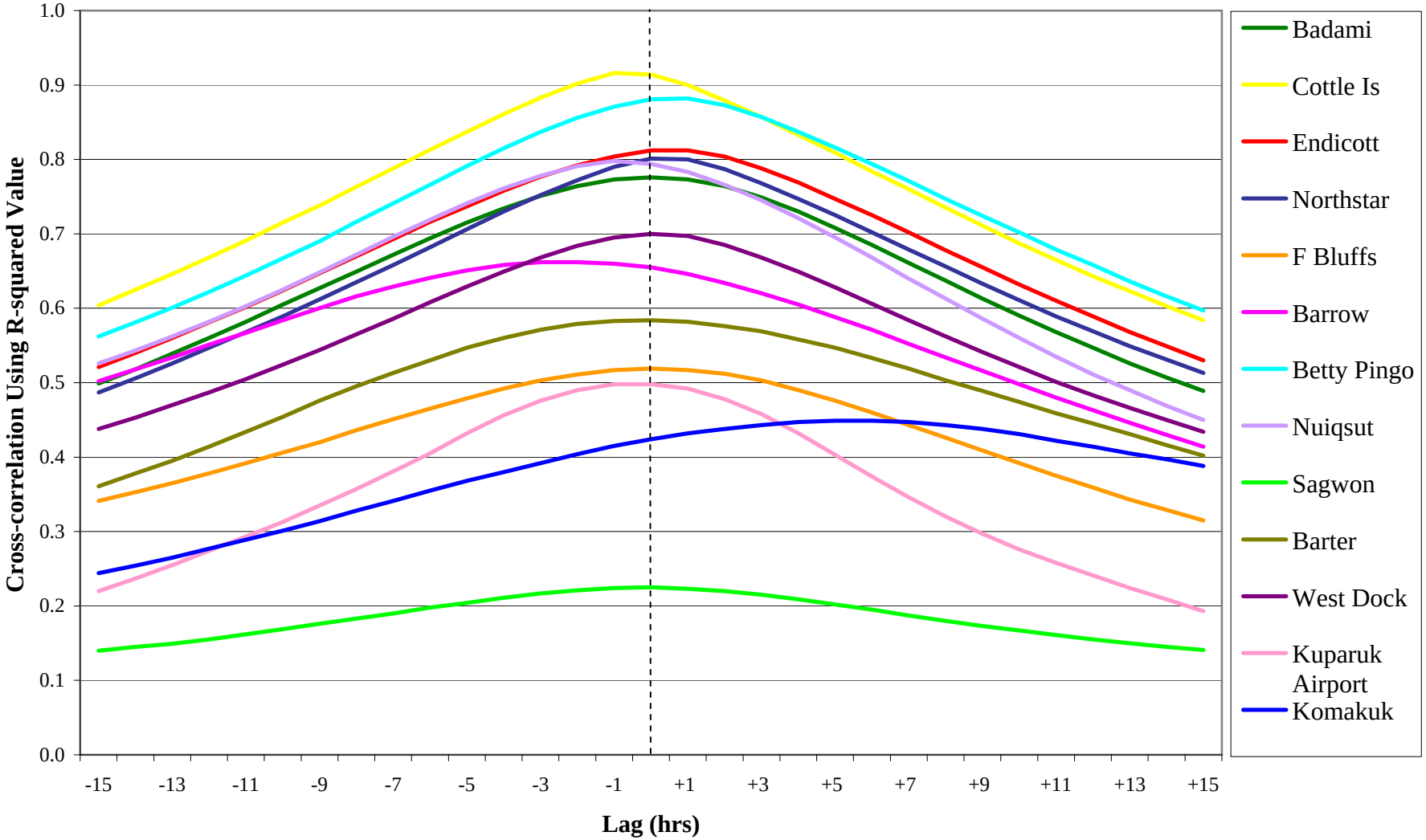
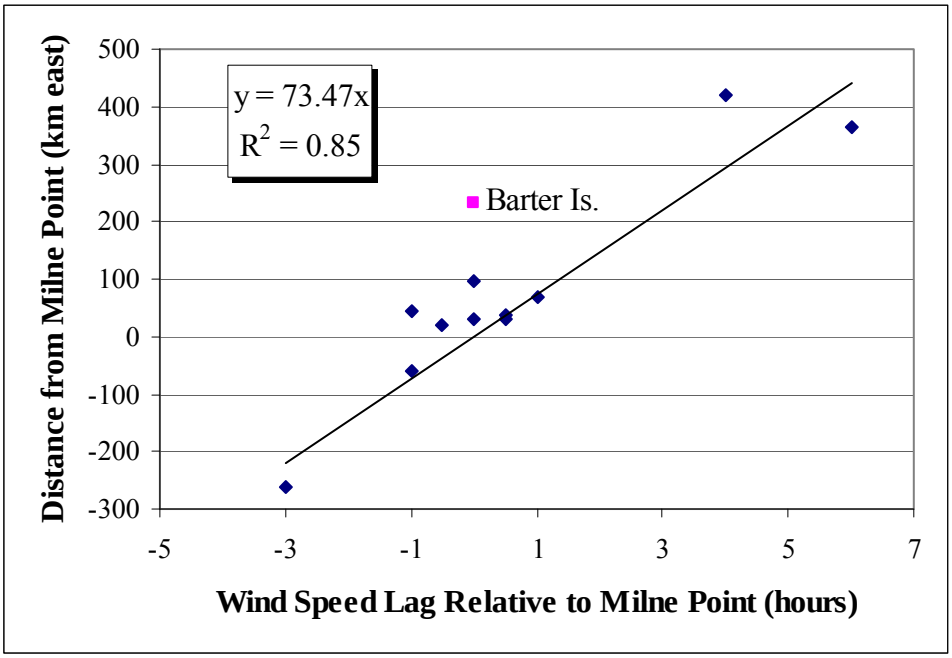


Figure 5-6 plots the lag at which the maximum cross-correlation occurs as a function of distance eastward. Where the cross-correlations were within 0.005 of each other, the values were assumed to be tied and the lag values were averaged (e.g. for Betty Pingo lag is considered to be 0.5 because lag 1 and lag 0 were of equal significance). Herschel Island is included in this graph as well.

Barter Island appears to be an outlier, displaying a peak correlation to Milne Point at lag equal to zero. The cause of this anomaly could not be determined, however, this correlation suggests that the Barter Island data set in the National Climatic Data Center archive may have been shifted two or three hours forward.

Figure 5-6. Peak Lag vs. Distance from Milne Point



5.5 Anemometer Icing

5.5.1 Icing at Endicott and Cottle Island

Measured winter wind speeds are biased at Endicott and, to a lesser degree, Cottle Island due to rime ice impeding and occasionally stopping the anemometer. The measured winter wind speeds at these sites should be viewed with this caveat in mind, although icing will obviously not be problematic during warmer months.

Endicott and Cottle Island wind speed was primarily measured by a three-cup anemometer, which computes wind speed by the number of revolutions per second the sensor makes. The mass of the cups increases as snow and ice freeze onto the cups. Therefore, the same amount of wind stress will cause the iced-over cups to experience fewer revolutions. As the anemometer became more sluggish, the instrument may completely freeze. Six site visits to the MMS stations were made to repair or replace frozen anemometers. Additionally, in other cases the anemometer became unstuck of its own accord, or was merely slowed. These periods could not be detected without redundant equipment.

Heating the cups would not have been effective even if 110 volt power were available on-site because heat applied to the main body of the instrument would not radiate effectively down the long, thin, spinning arms connecting the sensor body to the cups.

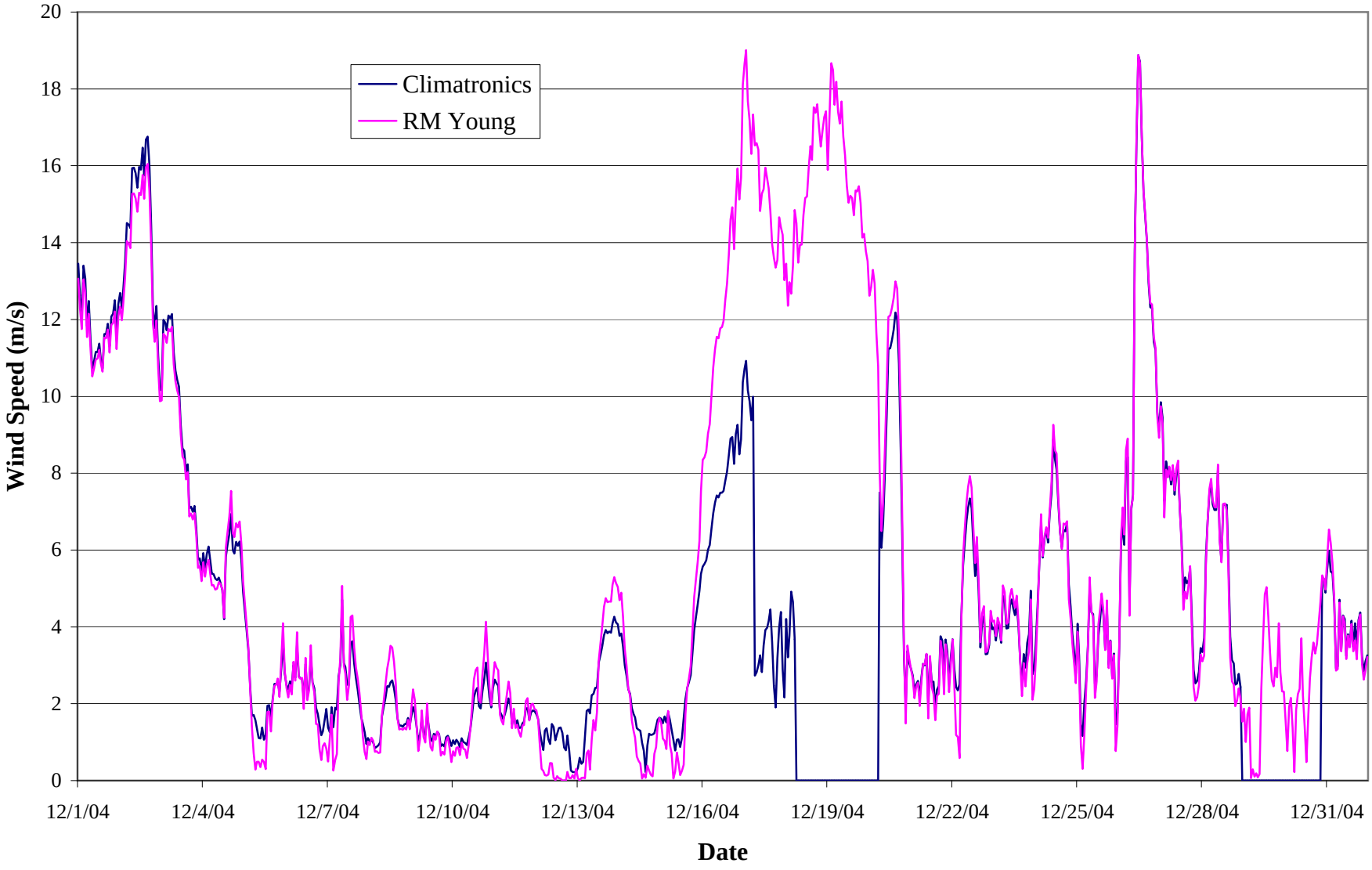
While the three-cup anemometer design is the most popular for weather stations, another design using a propeller is also common. The propeller design would prove to be more resistant to icing for a number of reasons. First, and most importantly, no cups exist to fill up with snow and ice. Second, the propeller-style anemometer rotates 2.5 times faster at any given wind speed than the three-cup design. Lastly, the anemometer shaft is horizontal as opposed to vertical, making accumulation of blowing snow around the shaft more difficult.

A comparison of wind sensors was conducted at Endicott and Cottle Island by installing RM Young O5305AQ propeller anemometers as redundant wind sensors in October 2004. The Endicott system was removed in December 2005, but Cottle Island system continues to operate. The three-cup and propeller anemometers gave identical wind speeds most of the time, except in the winter periods when the propeller anemometer gave substantially higher readings than the co-located three-cup anemometer. Wind speed measurements from the two systems at Endicott for the month of December 2004 are shown as an example in Figure 5-7. Because it is extremely unlikely that an anemometer could over-read wind speed, the fault almost certainly lies with the three-cup anemometer.

5.5.2 Icing at Supplemental Stations

The quality assurance review of data in the MMS Nearshore Beaufort Sea Weather Database revealed periods during the winter at many stations of anemometer icing having taken place. Sites where icing was most likely to occur were unmanned stations, where an iced anemometer would go unnoticed and uncorrected until weather conditions changed. Most of the recorded icing, as exhibited by zero wind speeds for days at a time, occurred at Betty Pingo, Franklin Bluffs, and Sagwon (three-cup anemometers were used at these three sites.). Stations located in

Figure 5-7 Climatronics vs. RM Young Measured Wind Speed



populated communities, such as Barrow, Deadhorse, or Barter Island did not show these same extended periods of anemometer icing.

Processing of data from supplemental stations included deletion of wind speed data during periods of obvious anemometer icing. Wind direction data was not deleted during these periods. Summary statistics were generated after deletion of the compromised data. Only data from periods of obvious icing were deleted. Wind speed data during iced periods usually dropped to the minimum speed registered by the datalogger at the site, and remained at this minimum value constantly for days or weeks. Figure 5-8 shows a graph of hourly wind speed for both Betty Pingo and Deadhorse from December 5, 2002, through February 12, 2003, indicating periods of anemometer icing at Betty Pingo. Wind speed data from extended time periods with zero wind speed were deleted from the database.

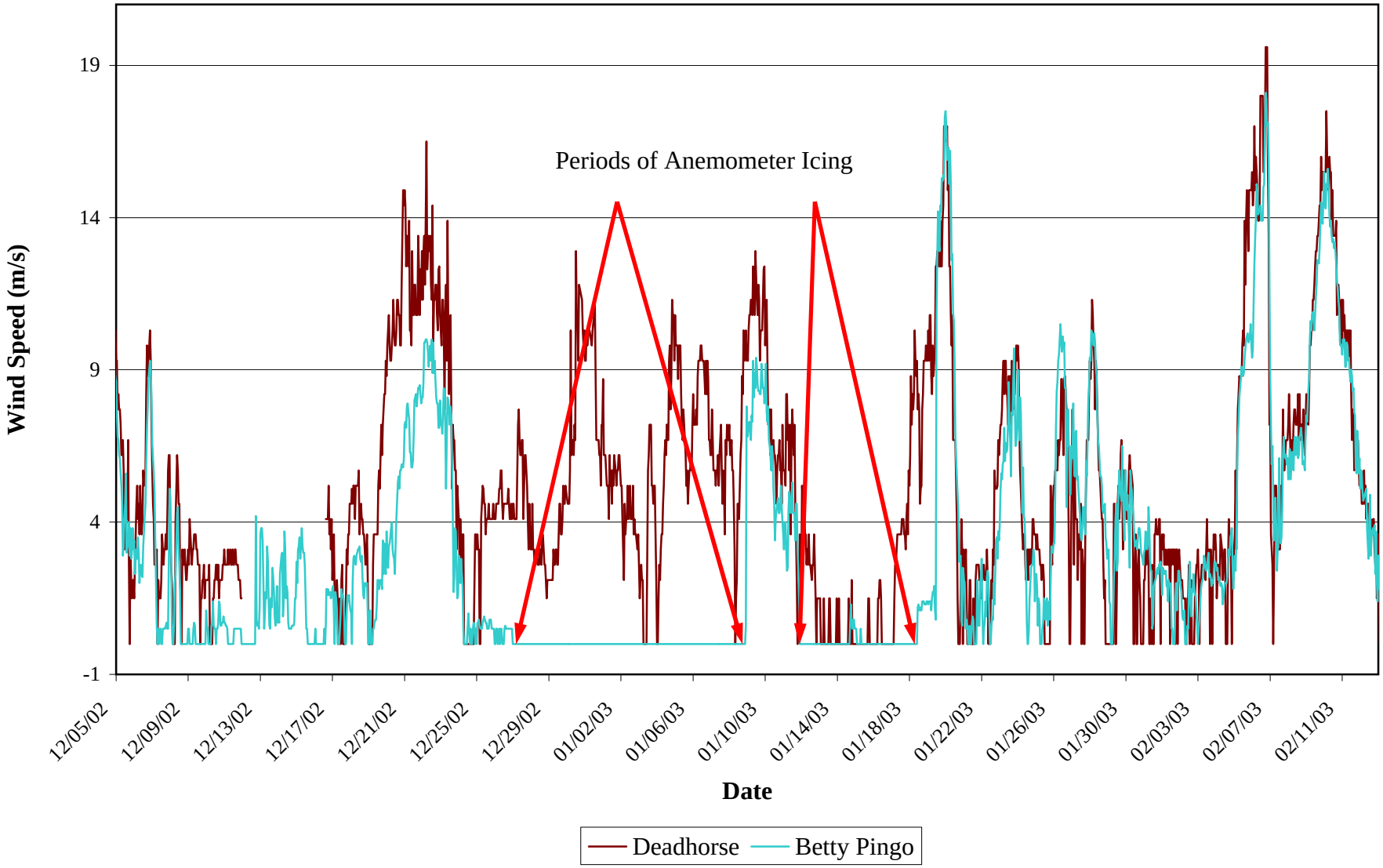
5.6 Possible Variations on Wind Direction Analysis

For this study, categorical summary of wind direction and duration for the five MMS Stations and eight supplemental stations was performed using consistent wind direction categories for all stations. Wind direction categories were selected based on the general orientation of approximately 75 miles of coastline stretching from Milne Pt. to Badami. The wind direction categories included two 30° sections of compass direction along the coastline as Shore Parallel, to the north of these two sections was Onshore, and to the south Offshore. The use of consistent wind directions is most appropriate for the central study area centered on Prudhoe Bay. The use of consistent wind directions for all stations, however, is not without shortcomings, as variations of coastline direction and distance from the Brooks Range has a significant effect on the farther distant stations of Barrow, Barter Island, and Komakuk Beach. Additional analysis of wind direction could provide further detail for wind fields along the arctic coast.

The most unbiased variation on wind direction analysis would be a comparison all stations based on four equal sized compass directions, such as 0°-90°, 90°-180°, etc. Analysis of this type would not take into account the orientation of coastline or proximity of the Brooks Range. Use of these wind direction categories might provide similar statistics to those previously generated for the Prudhoe Bay region, as wind roses for this regions show a predominance of winds falling in these quadrants, and some of the category cut-offs for the assigned wind directions are similar to these limits. Analysis of four equal categories would likely be most appropriate at Barrow, where assignment of a general coastal orientation is difficult due to Barrows location on a point between the Chukchi and Beaufort Seas. In addition to a coastline quite different from the other stations in the study, the wind field for the Chukchi Sea heavily influences Barrow, and can be quite different from that of the Beaufort Sea. Analysis of four equal compass directions oriented north to south would likely be inappropriate at Barter Island and Komakuk Beach, however, as the areas exhibit a predominance of winds in a general East to West axis, and these would be split arbitrarily into different categories.

Another variation on wind direction category analysis would be to account for the variations of coastline orientation and axis of the Brooks Range individually at each station. Any selection of wind direction categories should take a long section of coastline into account, as local variations of a few miles likely do not have much effect on overall wind fields. For the Prudhoe Bay region, this is essentially what was analyzed in this study, although more variation is present in

Figure 5-8 Anemometer Icing at Betty Pingo, Winter 2002-2003



the coastline toward the ends of the region, at Nuiqsut and Badami. As mentioned above, selection of a coastal orientation at Barrow is somewhat arbitrary, due to its location on a point. At Barter Island and Komakuk Beach, however, substantial influence from the proximity to the Brooks Range is seen in the wind field, presumably overshadowing a portion of the sea breeze effect. The coastline at Barter Island varies locally, as the island is located off of a bulge in the coastline, while the coast at Komakuk Beach is similar to Prudhoe Bay. The axis of the Brooks Range toward the east of the study area is roughly east to west, and accounting for this strong influence by shifting wind direction categories could provide statistics more reflective of regional wind differences.

5.7 Best Operating Practice

In the process of conducting this project, several specific findings were made regarding best practices for operating weather stations in the region that should aid in any future monitoring projects in the region.

5.7.1 Best Wind Sensor Arrangement

As discussed in Section 5.5, propeller-style wind sensors are far more resistant to icing than three-cup anemometers. The data show that three-cup anemometers can under-read wind speed during the winter months and, in some circumstances, freeze up entirely. This bias appears to affect many historical data sets as well, as discussed in Section 5.5.2, because the use of three-cup anemometers is very common. A strong recommendation is made to use only propeller-style wind sensors for future monitoring in this or any other region where icing is likely to occur. Another advantage of the propeller-style wind sensors is that these units are far more resistant to corrosion than a metal wind vane. Metal wind vanes had an observed operating life of only two years. If a wind vane/three-cup anemometer setup is used near a coastal area, a wind vane with a corrosion resistant tail should be chosen, due to increased corrosive effects of salt water near the coast.

Redundant sensors save money and improve data capture. The cost of site visits in this area is very high relative to the cost of equipment, and on several occasions site visits proved impossible. Redundant sensors should be installed for all important measurements, especially wind speed and direction. Because propeller-style wind sensors combine wind speed and direction sensors into one instrument, the ideal configuration would consist of a horizontal crossbar with a propeller-style wind sensor at either end and positioned at the ten meter height.

5.7.2 Lower Power Demand in Mid-Winter

Mid-winter monitoring is costly and far less useful for oil-spill modeling. Winter site visits are difficult and designing a power system allowing for daily cell-phone calls for uploading data requires the installation of a wind turbine. Wind turbines are more expensive than solar panels and need to be replaced almost annually.

Large cost savings could result from emphasizing data collection during the warmer part of the year. Solar capacity should be boosted (from 40 watts to 85 watts, for example) and wind turbines eliminated. Communications would be programmed to shut down at the end of November, and resume in mid-March. The station would continue to record data but would not

turn on the cell phone (or radio, as discussed below). Once the station resumed communicating, all of the data collected during the mid-winter would be uploaded. If station repairs were required, the repairs would be deferred until spring.

5.7.3 Audit schedule

Semi-annual audits and calibrations were probably excessive. A single annual calibration in the spring would be adequate. For remote site access close to the road system, transport via snowmobile in April or May is a low-cost, effective option. Access to sites using a small plane would be a preferred alternative. Helicopter access is very expensive relative to the other costs. Boat access during open water periods has shown potential and is low-cost, but has proven to be unreliable due to unpredictable sea conditions.

5.7.4 Station Communications

The best way to communicate with the stations would be to use spread-spectrum radios to transmit data to Ethernet-connected hubs. This methodology would conserve power, eliminate the charges associated with cell phones or satellite communications, and allow for much more frequent uploads. This methodology could be used to create a real-time monitoring network.

Communications are by far the biggest power demand at a station, and alternative modes of communication that use minimal power make station design and maintenance less expensive. A Freewave spread-spectrum radio draws 500 milliamps (mA) of power compared to 3,000 mA used for cell phone communications. More importantly, a Freewave spread-spectrum radio would use only 5 mA during standby compared to 300 mA for a cell phone.

With a range of 50 miles, any conceivable offshore site could transmit to an Ethernet port at a facility somewhere on the North Slope. This type of data transmission could be used to create a real-time monitoring network to update a website hourly, for example.

If data collection is concentrated on the warmer part of the year, the stations could potentially transmit hourly data from April through October and be scheduled to transmit data on a weekly, or less frequent, basis throughout the winter.

6 CONCLUSIONS

The primary goal of this study was to collect scientifically sound meteorological data for the nearshore Beaufort Sea region. The data set collected by the five MMS monitoring stations is the highest-quality and most comprehensive to be collected over a multi-year period anywhere on the North Slope. These data are supplemented in the MMS Nearshore Beaufort Sea Weather Database by wind data from 29 other stations from 1984 through September 2006. This data set is expected to be a valuable resource for researchers and modelers seeking to do work in this region.

The key recommendations for future monitoring best practices are:

1) Use redundant, propeller-style wind sensors to lower costs and increase data capture.
2) Limit communication with the station during the mid-winter to greatly reduce costs and prolong station life.
3) Conduct an annual calibration schedule to reduce cost without adversely impacting data quality.
4) Use spread-spectrum radios to transmit data where possible to conserve power, reduce cost, and make real-time monitoring possible.

The key findings from analyzing the combined data sets are:

1) This data set appears to confirm Kozo's theory of the orographic effect of the Brooks Range.
2) Winds throughout this region are bimodal, with a primary "onshore" component centered on east-northeast , and a secondary "offshore" component roughly from west-southwest.
3) Onshore winds become more dominant moving northward.
4) The dominance of onshore winds increases seasonally, peaking in June. The seasonality appears to be related to the proximity to the coastline. This observation appears to support Kozo's postulated sea breeze effect. This arctic sea breeze effect differs from the seabreeze effect seen in the mid-latitudes in that the arctic sea breeze is highly seasonal and unidirectional.
5) Cross-correlation analysis suggests a surprising amount of similarity in the wind data series over fairly large distances along the Beaufort Sea coast. Wind patterns change fairly quickly further inland.

7 REFERENCES

Chatfield, C., 1999. *The Analysis of Time Series, 5th Ed.*, Chapman & Hall/CRC, Boca Raton, FL.

Dickey, W., 1961. A study of a topographic effect on wind in the Arctic, *J. Meteorology*, Vol. 18, pp. 790-803.

Environment Canada, 2006. Climate data for two Beaufort Sea meteorological monitoring stations. http://climate.weatheroffice.ec.gc.ca/Welcome_e.html.

Hoefler Consulting Group, 2006. Nearshore Beaufort Sea Meteorological Monitoring and Data Synthesis Project. OCS Study MMS-2005-069

Hoefler Consulting Group, 2006. Study Final Report for the Beaufort Sea Meteorological Monitoring and Data Synthesis Project. July 2006.

Hoefler Consulting Group, 2003. Interim Analysis Report for the Beaufort Sea Meteorological Monitoring and Data Synthesis Project. July 2003.

Hoefler Consulting Group, 2001. Meteorological Monitoring and Quality Assurance Plan for the Nearshore Beaufort Sea Meteorological Monitoring and Data Synthesis Project. October 2001.

Kozo, T.L., 1982. An Observational Study of Sea Breezes Along the Alaskan Beaufort Sea Coast: Part I, *J. of Applied Meteorology,* Vol. 21, No. 7, pp. 891-905.

Kozo, T.L. and R.Q. Robe, 1986. Modeling Winds and Open Water Buoy Drift along the Eastern Beaufort Sea Coast, including the effects of the Brooks Range, *Journal of Geophysical Research,* Vol. 91, No. C11, pp. 13011-13032.

National Climate Data Center (NCDC), 2006. Climate data for seven Beaufort Sea meteorological monitoring stations. http://www.ncdc.noaa.gov/oa/ncdc.html.

Stull, R. B., 2000. *Meteorology for Scientists and Engineers*, Brooks/Cole Pub., Pacific Grove, CA.

U.S. Environmental Protection Agency, 1987. *Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD).* U.S. EPA OAQPS. Research Triangle Park, NC. EPA-450/4-87-007.

U.S. Environmental Protection Agency (EPA), 1995. *On-Site Meteorological Program Guidance for Regulatory Modeling Applications.* Revised. Office of Air Quality Planning and Standards, Research Triangle Park, NC. EPA-450/4-87-013. Revised August 1995.

U.S. Environmental Protection Agency (EPA), 2000. *Meteorological Monitoring Guidance for Regulatory Modeling Applications.* Office of Air Quality Planning and Standards, Research Triangle Park, NC. EPA-454/R-99-005.

University of Alaska, Fairbanks, Water and Environmental Research Center (WERC), 2006. Climate data for four Beaufort Sea meteorological monitoring stations. http://www.uaf.edu/water/projects/NorthSlope/northslope.html.

University of Alaska Geographic Information Network of Alaska (GINA), 2007. NASA Bluemarble maps, North Slope Digital Elevation Model basemaps, and Ocean Wind maps. http://sv.gina.alaska.edu/.

Yamartino, R.J., 1984. A Comparison of Several "Single-Pass" Estimators of the Standard Deviation of Wind Direction. *J. Climate Appl. Meteor*., Vol. 23, pp. 1362-1366.