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Use of Climatology to Predict Maximum Wind Speeds at the Kennedy Space Center and Cape Canaveral Air Station

Lisa K. Coleman

USE OF CLIMATOLOGY TO PREDICT MAXIMUM WINTERTIME WIND SPEEDS AT THE KENNEDY SPACE CENTER AND CAPE CANAVERAL AIR STATION

THESIS

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AFIT/GM/ENP/00M-04

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THESIS

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Lisa K. Coleman

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Abstract

This thesis uses statistical analysis to forecast the probability of meeting or exceeding the maximum allowable wind speeds for each of the launch pads at the Kennedy Space Center (KSC) and Cape Canaveral Air Station (CCAS). Wind data were collected from the Weather Information Network Display System (WINDS), a collection of 47 meteorological towers located throughout KSC and CCAS, over a period of five winters. A Fortran program was written to calculate conditional probabilities of meeting or exceeding a given threshold speed during eight consecutive one-hour periods, using the current wind direction and peak wind speed as inputs. Forecast probabilities were displayed in a table according to time period and wind direction.

Accuracy was measured by constructing contingency tables and calculating various measures of accuracy. Results were tested for significance by calculating p-values for the chi-square test. This method was found to have very little skill in forecasting maximum wind speeds. It is not recommended for operational use.

Use of Climatology to Predict Maximum Wintertime Wind Speeds at the Kennedy Space Center and Cape Canaveral Air Station

I. Introduction

1.1 Background

Launch Weather Officers (LWOs) at the 45th Weather Squadron (45 WS), Patrick Air Force Base (PAFB), are responsible for making "go/no-go" decisions during the space launch countdown based on the probability of violating various weather constraints. One of the biggest problems the LWOs face is accurately forecasting peak winds during the winter season, which is defined as November through March, at the Kennedy Space Center (KSC) and Cape Canaveral Air Station (CCAS). About eight hours before the launch time, the structure that supports the rocket and protects it from the elements is rolled away from the rocket, leaving it exposed and unsupported. If the wind speeds are too strong during this eight-hour countdown, a collision could occur between the rocket and its supporting structure. Therefore, if the wind speeds are expected to exceed a particular threshold, which varies depending on the launch vehicle and the wind direction, the launch must either be delayed or rescheduled. Of the 32 NASA and Air Force launches in 1999, six were delayed due to weather-related problems, costing the government up to $616,000 per day to postpone a launch (Frank, 2000 and White, 2000).

Strong winds at KSC and CCAS can occur at any time of the year. In the summer season, these winds are usually caused by thunderstorms and microbursts. Thunderstorms are rare in the winter season, however, and frontal passages are the main cause of strong winds. The four types of fronts affecting central Florida are discussed in Chapter 2.

Wind data are collected using one of the most densely instrumented meteorological mesonetworks in the United States, the Weather Information Network Display System (WINDS). It consists of 47 meteorological towers located throughout KSC and CCAS and covers an area of approximately 1200 km^2, with an average station density of one tower per 27 km^2. All of these towers measure wind speed, wind direction, and temperature, and selected towers also measure relative humidity. The sensors on these towers range in height from 6 feet to 492 feet. Observations are recorded at one- and five-minute intervals for a total of up to 8580 observations each minute (Raytheon, 1998).

1.2 Problem Statement

Personnel at the 45 WS have a vast amount of information available to them via the WINDS network. However, the LWOs have little guidance to help them forecast maximum wind speeds during the winter. Storch (1999) attempted to forecast wintertime wind speeds for KSC and CCAS using a neural network, but his results were inconclusive. In addition, there have been no previous climatological studies of wintertime wind speeds for KSC and CCAS. Thus, the goal of this thesis is to design a climatology-based, short-term (less than 8 hours) forecasting tool to assist the LWOs with their wind forecasts.

1.3 Scope

This project focuses on developing a conditional climatology program to help the LWOs predict peak winds more accurately. Personnel at 45 WS requested that only the WINDS towers located close to the launch pads be used in this study. These towers are listed in Table 1 and can be found on the map presented in Figure 1.

Only data from the 1994-95, 1995-96, 1996-97, 1997-98, and 1998-99 winter seasons have been included in this study because unreliable equipment reported inaccurate wind observations at the launch pads prior to 1994 (Roeder, 1999). In

Tower	Level (feet)	Side	Location	Rocket
0002	90	NW	Pad 17	Delta
0002	90	SE	Pad 17	Delta
0036	90	N/A	Pad 36	Atlas
1101	54	NW	Pad 40	Titan
1101	162	NW	Pad 40	Titan
1102	54	SE	Pad 41	Titan
1102	162	SE	Pad 41	Titan
0397	60	NW	Pad 39A	Shuttle
0398	60	SE	Pad 39A	Shuttle
0393	60	NW	Pad 39B	Shuttle
0394	60	SE	Pad 39B	Shuttle

Table 1 WINDS towers used in this study.

addition, previous studies on mesoscale systems such as thunderstorms, microbursts, and sea breezes have vastly improved wind forecasts during the summer (Roeder, 1999). The winter season continues to be a problem because LWOs are unfamiliar with how the relatively infrequent frontal passages affect wind speed, especially when the peak winds are already within a few knots of the threshold value.

1.4 Thesis Organization

The remainder of this thesis explores the viability of predicting maximum wind speeds over an eight-hour period at KSC and adjacent CCAS using conditional climatology developed from a limited database. Chapter 2 presents a brief overview of weather systems which affect central Florida and discussed recent studies which have looked at this same problem. Chapter 3 includes sensor accuracy and a description of the data, including a discussion of observed winds and their causes, as well as statistical methods used in the analysis of this data. Chapter 4 describes the steps taken to conduct this study and discusses the results. Chapter 5 draws conclusions about how the algorithm performed. Observed wind frequency tables for all of the WINDS towers used in this study and contingency tables used in the verification of the output are contained in the appendices.

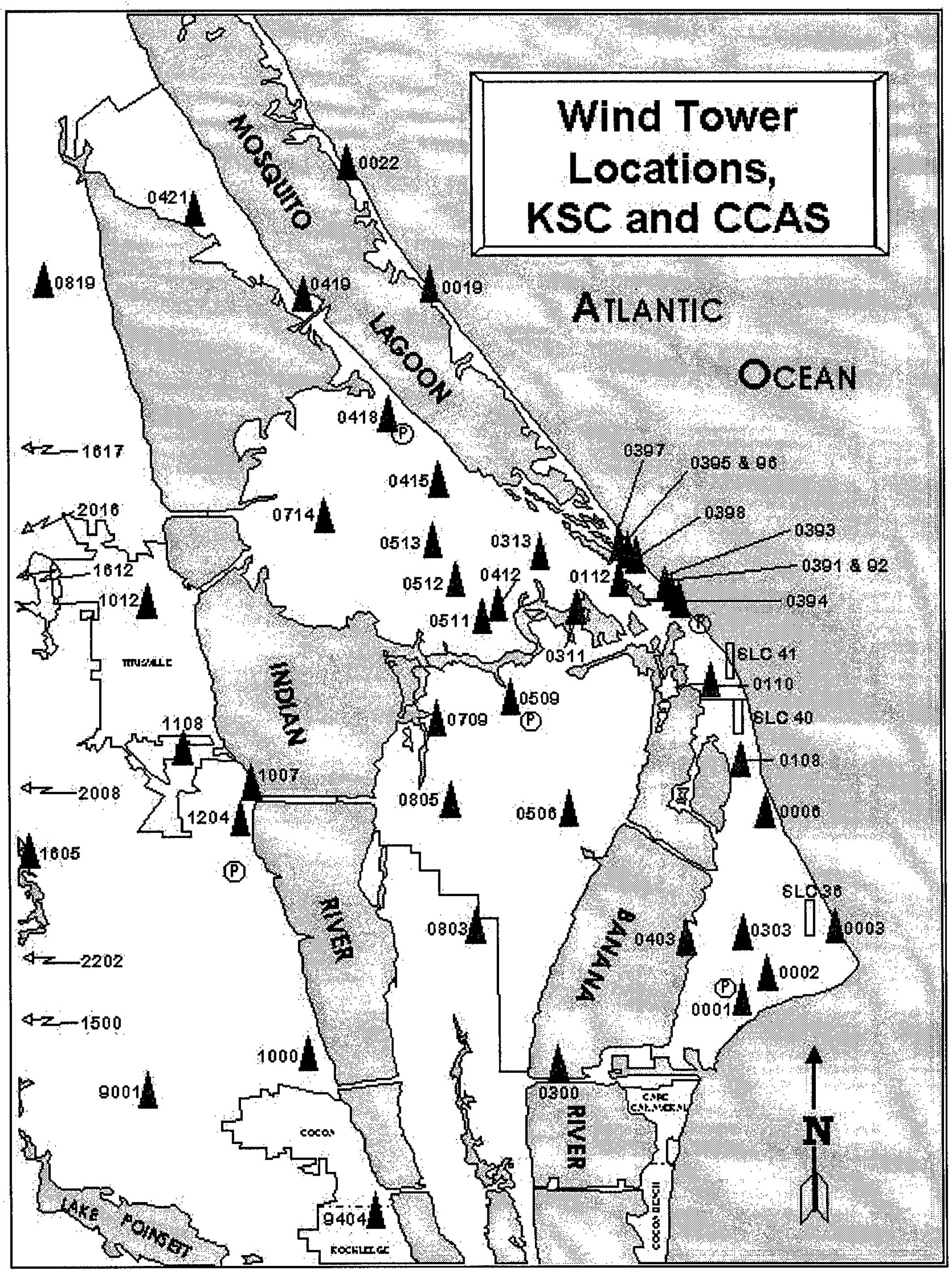

Figure 1 Location of the WINDS towers. Dark gray triangles represent WINDS towers. Thin rectangles represent launch pads. Towers of interest are 0002, 0036, 0393, 0394, 0397, 0398, 1101, and 1102.

II. Literature Review

Due to their locations in the northern hemisphere subtropics, PAFB and CCAS are affected by the subtropical ridge known as the Bermuda high throughout the year. The central Florida coast experiences two main seasons: the airmass regime, which runs from mid-May to late September, and the frontal regime, which takes place from late November to mid-March. During the frontal regime, winds can be tricky to forecast as relatively infrequent frontal passages occur. Additionally, two short transition seasons take place, one in the spring and another in the fall. A brief overview of each of the seasons is presented here. Seasonal descriptions were obtained from the *Terminal Forecast Reference Notebook* (1987).

2.1 Airmass Regime

The Bermuda high is strongest during the airmass regime, when it is centered around 30 degrees north latitude. The position and strength of the high prevents frontal passages from advancing over Florida, as shown in Figure 2. This season is dominated by maritime tropical air, also due to the position of the high. The days are characterized by a nearly continuous easterly wind and convective activity, both of which can cause strong winds.

2.2 Frontal Regime

Florida's frontal regime takes place from late November to mid-March. This regime is a mild winter, during which the Bermuda high weakens and retreats to around 20° north latitude, and true frontal passages occur. The four types of cold fronts which affect central Florida during the winter are categorized according to their orientations: north/south, northeast/southwest, east/west, and northwest/southeast. All of these fronts can cause strong winds at the launch pads.

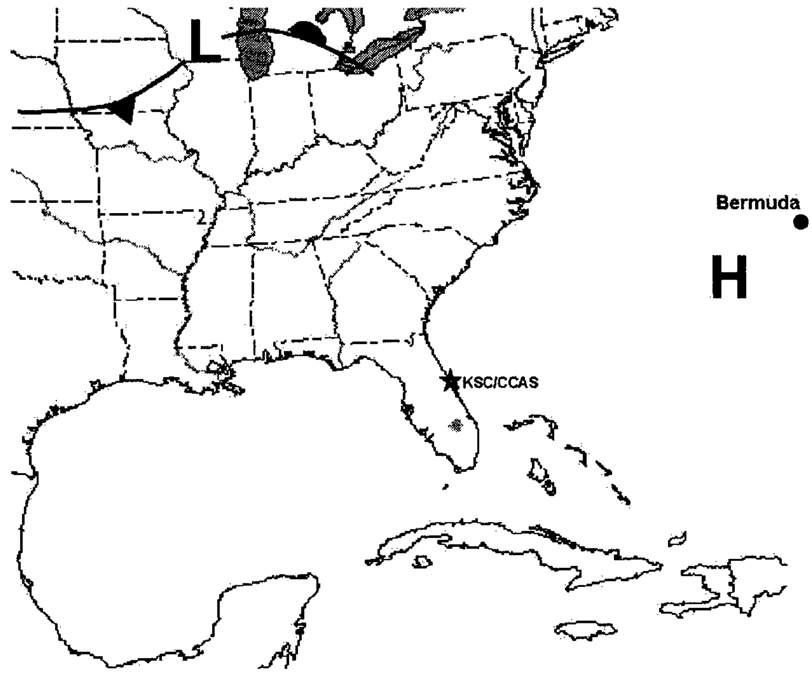

Figure 2   Position of the Bermuda high during the summer season.

2.2.1 North/South Oriented Fronts. The north/south oriented front is associated with a maritime polar front. As shown in Figure 3, the low-pressure center is positioned over east-central Alabama or west-central Georgia, and the high-pressure center is located over or just north of the central Gulf of Mexico. This synoptic situation can cause surface winds in excess of 35 knots along the east coast of central Florida.

2.2.2 Northeast/Southwest Oriented Fronts. The northeast/southwest oriented front can occur with either a maritime polar or continental polar airmass. The low-pressure center is usually located between North Carolina and Bermuda and the high-pressure center is located over Arkansas or Tennessee. "This type of front produces the most severe weather in Florida in the form of thunderstorms with high winds and hail" (*Terminal Forecast Reference Notebook*, 1987). However, because the front usually decelerates and weakens when it reaches the Florida Panhandle, most of the severe weather occurs in the northern part of the state. See Figure 4 for an example of this situation.

2.2.3 East/West Oriented Fronts. East/west oriented fronts are associated with a continental polar airmass. The low-pressure center is located northeast of Bermuda and the high-pressure center is located in eastern Ohio or western Pennsylvania. Northeasterly winds behind the front can exceed 20 knots. See Figure 5 for an example of this situation.

2.2.4 Northwest/Southeast Oriented Fronts. An east/west oriented front occasionally stalls between Jacksonville and Daytona Beach. Sometimes it begins to move south again, this time with a northwest/southeast orientation as shown in Figure 6. Strong westerly winds occur ahead of the front and become northeasterly behind the front.

2.3 Transition Seasons

The spring transition season lasts from late March to mid-May, when the subtropical ridge strengthens and shifts to the north. Frontal passages are less frequent, and winds become easterly.

The fall transition season lasts from early October to mid-November. Weak fronts begin to move through the area, and winds become northerly.

2.4 Previous Studies

As mentioned in Chapter 1, the problem of predicting winds at KSC/CCAS was examined by Storch (1999), who developed a neural network to forecast winds for the launch pads. Storch's results showed that his neural network performed no better than persistence. Cloys (2000) continued research in the neural network field. Cloys developed his network using a different method and found that his model performed better than persistence late in the forecast period.

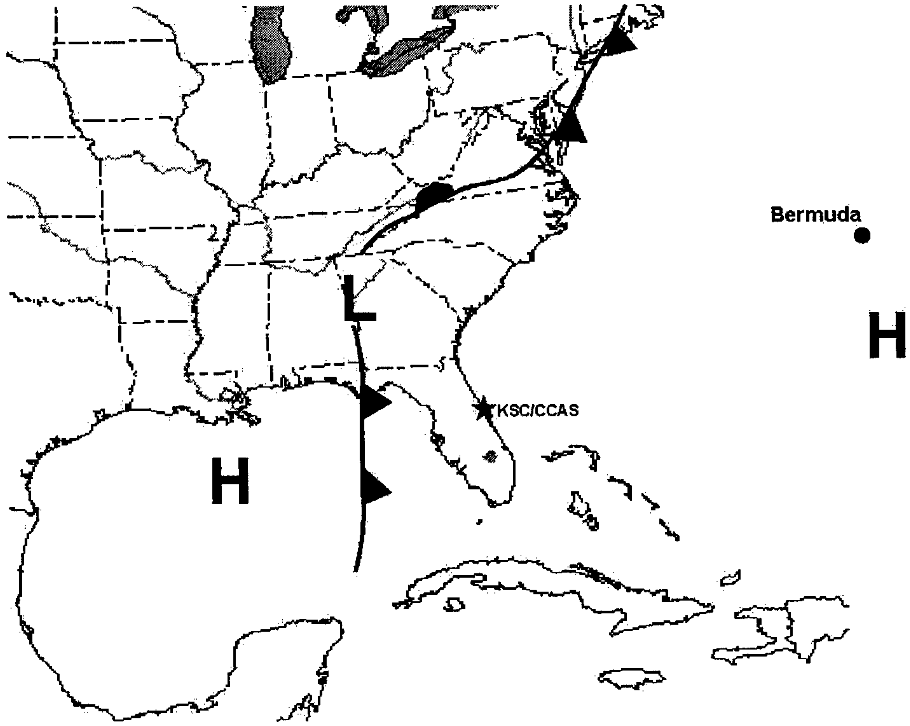

Figure 3 Typical synoptic pattern for the North/South oriented front.

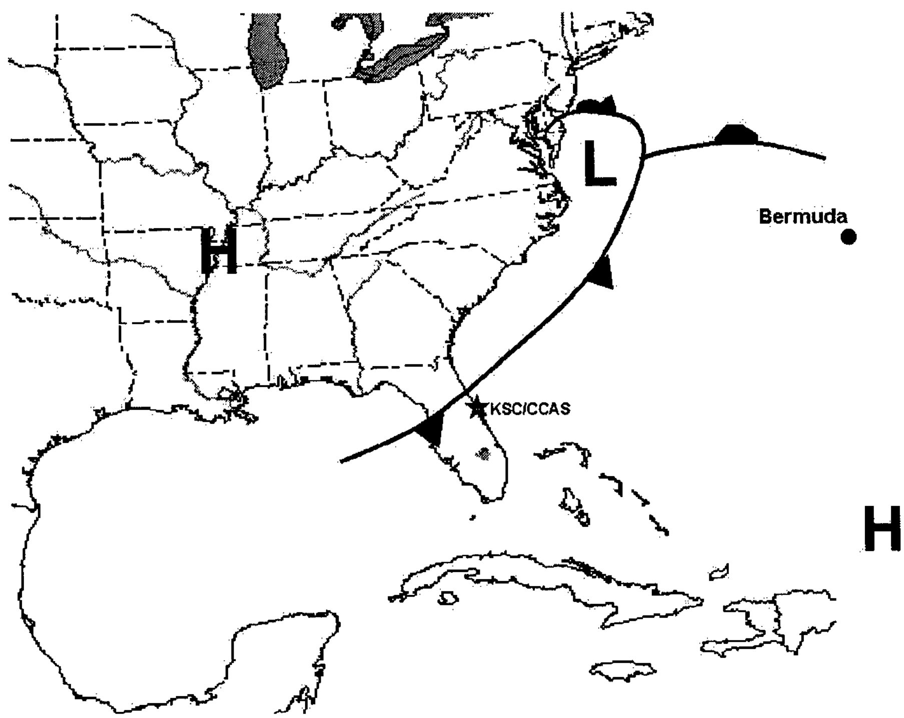

Figure 4 Typical synoptic pattern for the Northeast/Southwest oriented front.

Figure 5   Typical synoptic pattern in the East/West oriented front.

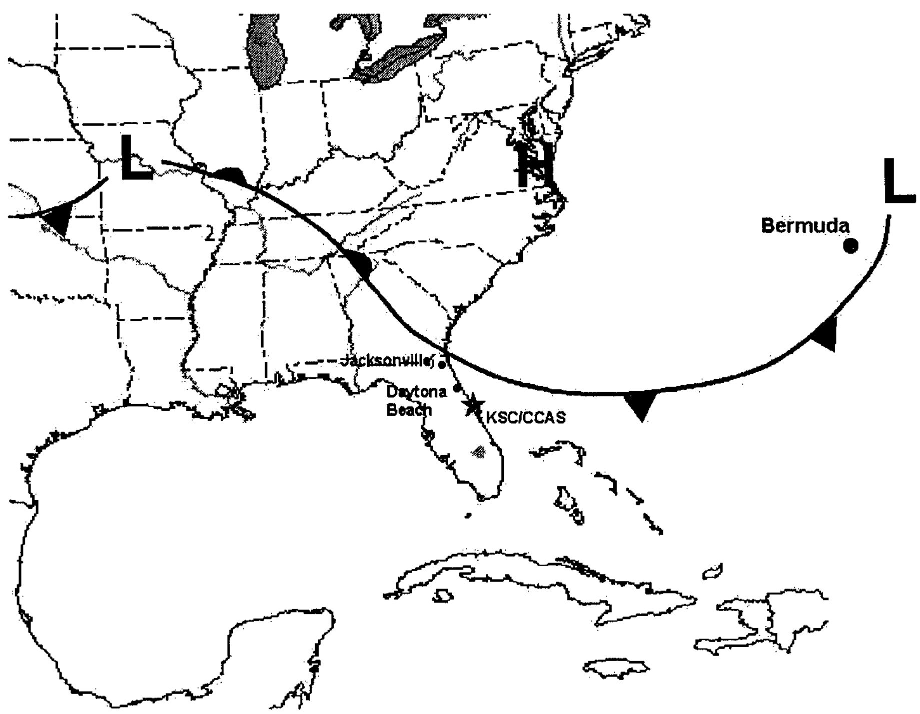

Figure 6   Typical synoptic pattern for the Northwest/Southeast oriented front.

III. Data Description and Analysis

3.1 Data Description

Personnel at the 45 WS provided wind observations gathered via the WINDS network from the 1994-95, 1995-96, 1996-97, 1997-98, and 1998-99 winter seasons. Observations were taken at five-minute intervals. Over the course of five winters, this adds up to 217728 observations for each tower and level, assuming no data are missing data.

3.1.1 Sensor Accuracy. The WINDS towers used in this study are equipped with the R. M. Young Model 05305-18 Wind Monitor-AQ sensor (Raytheon, 1998). These sensors are accurate to within 0.3 ms^{-1} for speed and within 3° for direction. Other sensor characteristics are listed in Table 2.

3.1.2 Description of Observed Data. Tables 3 through 8 contain observed wind speed and direction frequencies for Tower 1101 at the 162-foot level. Although wintertime winds can occur from any direction, two sectors appear to be predominant throughout the winter although there is a slight variation from month to month. As shown in Table 3, the most frequently-appearing wind directions are west through north, which occur in conjunction with frontal passages. A smaller but still significant maximum is seen from the southeast through south, which is sometimes accounted for by the Bermuda high and sometimes caused by the approach of a front.

Characteristic	**Speed (ms^{-1})**	**Direction (degrees)**
Operating range	$0.33 - 54$	$0 - 360$
Survival range	60	N/A
Accuracy	± 0.3	± 3
Starting Threshold	0.33	≤ 0.33 for 10° displacement

Table 2 Characteristics of wind speed and direction sensors (Raytheon, 1998).

In November (Table 4), winds are most frequently from 300° to 329°, due to frontal passages, and 0° to 089°, partly due to frontal passages and partly due to the onshore gradient caused by the Bermuda high. Winds from the southeast through west are relatively infrequent. By December (Table 5), westerly through northerly winds (270° to 359°) occur with a much greater frequency and a slight increase in southeasterly and southwesterly winds (150° to 209°) begins to appear. This is also evident in January (Table 6) and February (Table 7). However, in February, the southerly winds become more southeasterly, shifting to between 120° and 179°. By March (Table 8), frontal passages begin to occur less frequently with the strengthening of the Bermuda high. Therefore, northerly winds are seen less frequently while southeasterly winds become more common.

Another feature worth noting is the frequency of wind speed. The vast majority of winds are between 5 and 19 knots, regardless of the month. Wind speeds of 4 knots or less generally occur less than 7% of the time. On average, wind speeds greater than or equal to 20 knots occur roughly 19% of the time and winds greater than or equal to 25 knots occur about 7% of the time. Wind speeds greater than 40 knots are extremely rare, although a slight increase in the frequency of stronger winds occurs from January to February.

Observed frequency tables for the other WINDS towers used in this study can be found in Appendix A.

3.2 Data Analysis

3.2.1 Conditional Climatology. Conditional climatology is frequently used by the meteorological community to quantify the likelihood that a particular event will occur, such as visibility decreasing to below one-half mile within the next hour, given that the visibility is currently two miles. Two specific examples of conditional climatology products commonly used in an Air Force weather station are Modeled Ceiling and Visibility (MODCV) and Wind-Stratified Conditional Climatology Ta-

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.33	1.97	2.10	2.57	1.24	0.50	0.06	0.02	0.01	8.81
30-59	0.22	1.77	1.20	1.15	0.60	0.28	0.10	0.11	0.02	5.44
60-89	0.26	1.87	1.78	2.23	1.41	0.41	0.10	0.06	0.01	8.13
90-119	0.28	2.51	2.44	2.03	0.71	0.17	0	0	0	8.15
120-149	0.33	2.47	2.84	2.93	1.50	0.48	0.04	0	0	10.6
150-179	0.24	1.82	2.69	2.14	1.36	0.61	0.28	0.10	0.02	9.25
180-209	0.20	1.85	1.92	2.08	1.00	0.21	0.02	0	0	7.30
210-239	0.27	1.87	1.58	1.35	0.63	0.24	0.04	0.02	0	6.00
240-259	0.29	1.97	2.00	1.41	0.62	0.36	0.13	0.08	0.03	6.88
270-299	0.29	1.94	2.71	2.19	1.19	0.85	0.24	0.10	0.03	9.53
300-329	0.31	2.59	2.90	2.13	1.32	0.26	0.03	0.01	0	9.55
330-359	0.22	2.21	2.57	2.32	1.82	0.96	0.16	0.03	0.07	10.4
Total	3.25	24.8	26.7	24.5	13.4	5.33	1.20	0.55	0.19	100

Table 3 Percent observed wind speed and directions for the entire winter, Tower 1101, Level 162, based on 130314 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.60	2.36	2.22	4.00	1.72	0.21	0	0	0	11.1
30-59	0.30	1.58	1.40	2.10	2.42	1.11	0.42	0.53	0.03	9.9
60-89	0.49	2.31	2.20	3.18	3.28	1.80	0.51	0.34	0	14.1
90-119	0.44	2.94	1.53	1.48	0.90	0.09	0	0	0	7.38
120-149	0.40	2.62	2.49	1.27	0.40	0.02	0	0	0	7.18
150-179	0.39	2.10	2.05	1.59	0.77	0.12	0	0	0	7.02
180-209	0.10	1.92	1.24	2.17	1.18	0.05	0	0	0	6.65
210-239	0.22	1.54	1.29	1.29	0.70	0.07	0	0	0	5.1
240-259	0.38	2.24	1.28	1.10	0.14	0.03	0	0	0	5.18
270-299	0.59	2.02	2.92	1.47	0.38	0.16	0.01	0	0	7.54
300-329	0.69	2.80	3.66	3.22	1.16	0.03	0	0	0	11.6
330-359	0.33	1.71	2.59	1.68	0.57	0.38	0	0	0	7.27
Total	4.94	26.1	24.9	24.5	13.6	4.06	0.94	0.87	0.03	100

Table 4 Percent observed wind speed and directions for November, Tower 1101, Level 162, based on 17695 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.75	3.55	2.19	1.80	0.51	0.01	0	0	0	8.81
30-59	0.41	2.67	1.26	1.14	0.14	0	0	0	0	5.63
60-89	0.74	3.14	1.65	1.23	0.17	0	0	0	0	6.92
90-119	0.53	1.67	0.45	0.20	0.01	0	0	0	0	2.85
120-149	0.49	1.63	1.16	1.14	0.57	0.16	0.01	0.01	0	5.18
150-179	0.38	1.44	2.33	2.78	1.11	0.34	0	0	0	8.38
180-209	0.52	2.78	2.71	2.21	0.57	0.04	0	0	0	8.84
210-239	0.41	1.59	1.67	0.70	0.30	0.04	0	0	0	4.71
240-259	0.36	1.52	1.49	1.22	0.91	0.47	0.08	0.04	0	6.10
270-299	0.48	2.88	2.72	3.62	2.30	1.02	0.11	0.04	0.03	13.2
300-329	0.72	4.91	5.79	4.33	2.31	0.59	0.03	0	0	18.7
330-359	0.42	3.52	1.76	2.48	1.42	0.96	0.14	0	0	10.7
Total	6.21	31.3	25.2	22.9	10.3	3.64	0.37	0.09	0.03	100

Table 5 Percent observed wind speed and directions for December, Tower 1101, Level 162, based on 23888 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.26	1.58	1.13	2.04	1.09	0.61	0.02	0	0	6.73
30-59	0.25	2.15	0.85	1.55	0.33	0	0	0	0	5.13
60-89	0.25	1.53	1.68	2.95	1.31	0.04	0	0	0	7.76
90-119	0.39	1.72	2.12	3.09	0.32	0	0	0	0	7.64
120-149	0.54	2.45	1.82	1.99	0.77	0.05	0	0	0	7.63
150-179	0.45	1.99	2.18	1.92	1.57	0.62	0.33	0.02	0	9.08
180-209	0.41	2.24	2.43	3.08	1.41	0.25	0.01	0	0	9.84
210-239	0.41	2.24	1.78	1.58	0.66	0.33	0.04	0.01	0	7.05
240-259	0.33	2.53	1.72	1.08	0.36	0.31	0.17	0.04	0	6.54
270-299	0.41	2.24	3.13	2.33	1.79	1.57	0.37	0.07	0.01	11.9
300-329	0.26	2.81	3.82	2.45	1.79	0.30	0.04	0.02	0	11.5
330-359	0.16	2.40	2.49	1.79	1.47	0.69	0.08	0	0	9.08
Total	4.11	25.9	25.1	25.9	12.9	4.78	1.07	0.15	0.01	100

Table 6 Percent observed wind speed and directions for January, Tower 1101, Level 162, based on 22411 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.28	1.70	2.12	1.50	0.93	0.21	0	0	0	6.75
30-59	0.10	1.42	1.12	0.93	0.06	0	0	0	0	3.63
60-89	0.12	1.19	0.28	0.32	0.06	0	0	0	0	1.97
90-119	0.15	1.96	1.82	1.29	1.02	0.44	0	0	0	6.68
120-149	0.15	3.09	2.68	2.03	1.49	1.07	0.16	0.02	0	10.7
150-179	0.07	2.33	2.84	2.92	1.53	1.06	0.33	0.30	0.07	11.5
180-209	0.09	1.78	2.54	1.98	0.72	0.37	0.06	0	0	7.56
210-239	0.12	2.00	2.08	1.86	0.68	0.06	0.01	0	0	6.81
240-259	0.17	2.35	2.42	1.93	0.62	0.24	0.16	0.26	0.11	8.24
270-299	0.23	2.56	3.15	1.91	1.16	1.21	0.61	0.60	0.13	11.6
300-329	0.35	3.42	2.80	2.32	1.70	0.68	0.11	0.04	0	11.4
330-359	0.20	2.67	3.74	3.59	2.37	0.68	0.01	0	0	13.3
Total	2.02	26.5	27.6	22.6	12.3	6.02	1.45	1.22	0.32	100

Table 7 Percent observed wind speed and directions for February, Tower 1101, Level 162, based on 22593 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.29	2.14	2.53	2.80	1.27	0.71	0.15	0.06	0.03	9.98
30-59	0.24	1.82	1.33	0.66	0.27	0.22	0.07	0.06	0.03	4.70
60-89	0.25	2.21	2.44	2.46	1.40	0.25	0.03	0.02	0.01	9.05
90-119	0.24	3.01	3.29	2.08	0.67	0.16	0.01	0	0.01	9.46
120-149	0.28	2.09	3.59	4.54	2.31	0.59	0.03	0	0	13.4
150-179	0.16	1.36	3.12	2.06	1.40	0.57	0.34	0.08	0.01	9.10
180-209	0.20	1.66	1.62	1.58	0.86	0.18	0.02	0	0	6.11
210-239	0.31	1.75	1.34	1.00	0.55	0.35	0.07	0.03	0	5.39
240-259	0.28	1.39	2.22	1.43	1.01	0.58	0.14	0.04	0	7.10
270-299	0.13	1.43	2.18	2.54	1.21	0.57	0.08	0.02	0	8.17
300-329	0.15	1.96	2.15	1.42	0.96	0.10	0	0	0	6.76
330-359	0.21	2.08	1.99	2.20	2.22	1.47	0.34	0.08	0	10.7
Total	2.75	22.9	27.8	24.8	14.1	5.76	1.26	0.38	0.18	100

Table 8 Percent observed wind speed and directions for March, Tower 1101, Level 162, based on 43727 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	SCT (B)	BKN (B/)	Horizontal Totals
TSRA (A)	35	65	100
No TSRA (A/)	65	35	100
Vertical Totals	100	100	200

Table 9 Conditional probabilities for the occurrence of thunderstorms versus cloud cover.

bles (WSCC), both of which are produced by the Air Force Combat Climatology Center.

As early as 1905, meteorologists were producing probabilistic forecasts based on simple contingency tables (Murphy and Winkler, 1984). A greater interest in evaluating these probabilistic forecasts did not come about until the mid-1950s, with the advances in computer technology and an increased interest in applying statistical techniques to produce weather forecasts (Murphy and Winkler, 1984). Some of these same methods are still used today, nearly 100 years later, and are described in the remainder of this chapter.

3.2.2 Conditional Probability. According to Wilks (1995), conditional probability is the probability that a specific event will occur, given that some other event has occurred or will occur in the future. The "conditioning event" is the event upon which subsequent events are contingent.

In general, conditional probability can be expressed by $P(A \mid B) = \frac{P(A \cap B)}{P(B)}$, where B is the conditioning event and A is the subsequent event.

Conditional probability can be explained by using the example of a thunderstorm (TSRA) forecast based on cloud cover. Suppose an amateur meteorologist counts the number of partly cloudy (SCT) days with and without thunderstorms, and the number of mostly cloudy (BKN) days with and without thunderstorms. The totals are then entered into a table similar to Table 9.

To calculate the probability of thunderstorm occurrence given that it is now mostly cloudy, simply divide the number of mostly cloudy days with thunderstorms,

$(A \cap B')$, by the total number of mostly cloudy days, (B'). In this case, $\frac{65}{100} = .65$ or 65%. Similarly, the probability that it is mostly cloudy given that there are no thunderstorms can be computed by dividing the number of mostly cloudy days without thunderstorms, $(B' \cap A')$, by the total number of days without thunderstorms (A'). This comes out to $\frac{35}{100} = .35$ or 35%.

3.2.3 Contingency Tables. Contingency tables can be used to extract measures of accuracy from yes/no forecasts. According to Wilks (1995), a contingency table is used to display the possible combinations of forecasted and observed event pairs. An example of a 2 x 2 contingency table is shown in Figure 7. A perfect forecast would produce zeroes in blocks b and c, the total number of "yes" forecasts in block a, and the total number of "no" forecasts in block d. Imperfect forecasts need to be measured in some way. Several of these measures are summarized in the following section.

Strong Winds Observed

Strong Winds Forecast	Yes	No	
Yes	a	b	a+b
No	c	d	c+d
	a+c	b+d	n=a+b+c+d

Figure 7 Contingency Table According to Wilks (1995).

3.2.4 Measures of Accuracy. A measure of accuracy describes the average correspondence between a forecast event and the event that actually occurred (Wilks, 1995).

3.2.4.1 Hit Rate (H). The hit rate is a basic measure of accuracy and can be described as the proportion of correct forecasts. Using the terminology introduced in Figure 6, the hit rate is calculated by:

$H = \frac{a+d}{n}$ where a is the number of times strong winds were forecast and observed, d is the number of times strong winds were not forecast and not observed, and n is the total sample size.

3.2.4.2 Critical Success Index (CSI). Also known as the threat score, the critical success index is the number of correct "yes" forecasts divided by the number of times strong winds were forecast and observed. The critical success index is given by:

$CSI = \frac{a}{a+b+c}$ where b is the number of times strong winds were forecast but did not occur, and c is the number of times strong winds occurred but were not forecast.

3.2.4.3 Probability of Detection (POD). The probability of detection is the likelihood that strong winds were forecast, given that strong winds occurred. The probability of detection is given by:

$POD = \frac{a}{a+c}$.

3.2.4.4 False Alarm Rate (FAR). The false alarm rate is the proportion of forecast events that do not occur (Wilks, 1995). The false alarm rate is given by:

$FAR = \frac{b}{a+b}$.

3.2.4.5 Bias (B). Bias is the comparison of the average forecast with the average observation, and is usually expressed as a ratio (Wilks, 1995). A bias equal to 1 indicates that strong winds were forecast the same number of times they occurred. A bias less than 1 indicates that strong winds were underforecast, while a bias greater than 1 indicates that strong winds were overforecast. Bias is computed by:

$$B = \frac{a+b}{a+c}.$$

3.2.5 Skill Score. A skill scores is a measure of relative accuracy. One should not rely on skill score alone because different skill scores perform differently. Wilks (1995) explains this inconsistency by stating that skill scores are "scalar measures of forecast performance in what is intrinsically a higher-dimensional setting." The most popular measure of forecast accuracy is the Heidke skill score.

3.2.5.1 Heidke Skill Score (HSS). The Heidke skill score uses the hit rate as the basic measure of accuracy. The reference measure of accuracy is the hit rate that would be achieved by random forecasts, provided that the marginal distributions of forecasts and observations in the contingency table for the random forecasts is equal to the marginal distributions in the verification data set (Wilks, 1995). Using Figure 6 as an example, $\frac{a+b}{n}$ and $\frac{a+c}{n}$ in the forecast set should be the same as $\frac{a+b}{n}$ and $\frac{a+c}{n}$ in the verification set. A perfect forecast has a Heidke score equal to one. The Heidke skill score is computed as follows:

$$HSS = \frac{2(ad-bc)}{(a+c)(c+d)+(a+b)(b+d)}.$$

3.2.6 Testing for Significance. Statistical measures of accuracy, bias, and skill are meaningless unless a connection between the observations (columns) and forecasts (rows) in the contingency table can be shown. Otherwise, the observed and forecast data are said to be independent and seemingly-impressive accuracy measures are obtained by chance. Results were tested for significance at the 0.05

level by calculating p-values for the chi-square test. If the p-value is less than 0.05, the notion of independence is rejected and the type of wind speed observed (yes/no) is considered dependent on the forecast category.

IV. Methodology

4.1 Preparing the Observations

Observations from the WINDS network were first filtered with a simple Fortran program which removed all but the towers and levels of interest listed in Table 1. Because this study only used wind direction and peak speed as inputs and in its calculations, unnecessary information such as temperature and relative humidity was also removed. The remaining data were organized into separate text files according to month, tower number, and level. For example, wind data for tower 1101 at the 54-foot level from February 1995, February 1996, February 1997, and February 1998 were collected in a file named "feb1101-54.txt." Another file called "feb99-1101-54.txt" was used to store data for tower 1101 at the 54-foot level from February 1999. Data from the second file were used to verify the conditional probability forecasts based on data from the first file. After the forecasting algorithm was tested, both of these files were combined for operational use, assuming output from the algorithm would prove to be valuable.

Erroneous observations were removed manually. Plots of peak speed versus time and wind direction versus time were created for each month (see examples in Figures 8 and 9). Any obvious spikes on the speed plot were compared to speeds leading up to and following the spike, as well as direction for the same time. If the spike was preceded by or led up to strong winds and was accompanied by a wind shift, it was considered to be correct and was not removed from the file. If the spike was not accompanied by strong winds or a wind shift, it was considered to be erroneous and removed from the file. Only two observations were removed using this method.

Next, the data were screened for missing values. If either the wind direction, speed, or peak speed were missing, all three values were replaced with "-9999." This

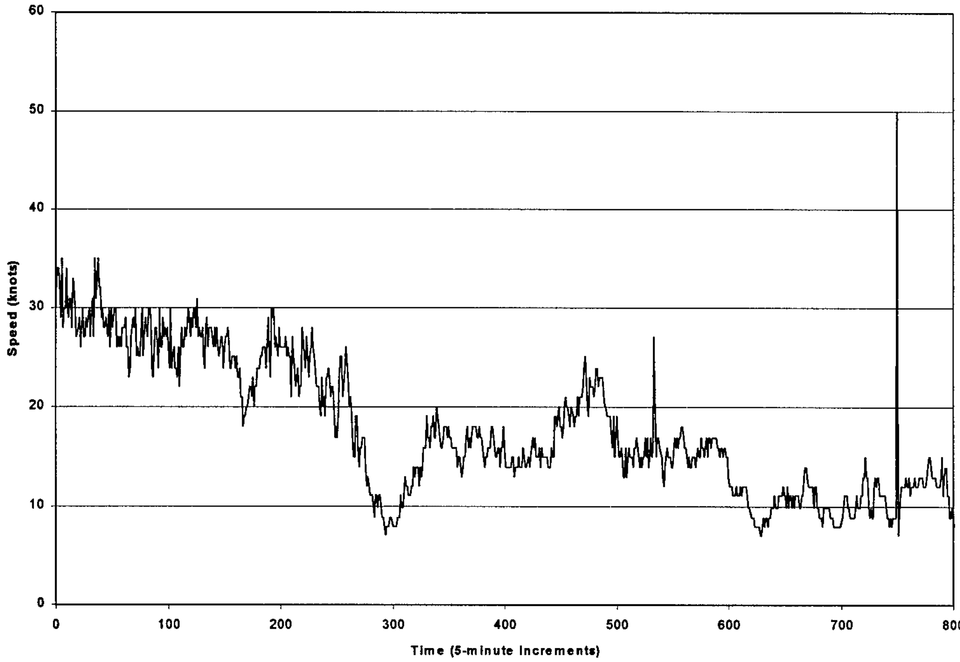

Figure 8 Sample of peak wind speeds from Tower 1101, 162-foot level, February 1999.

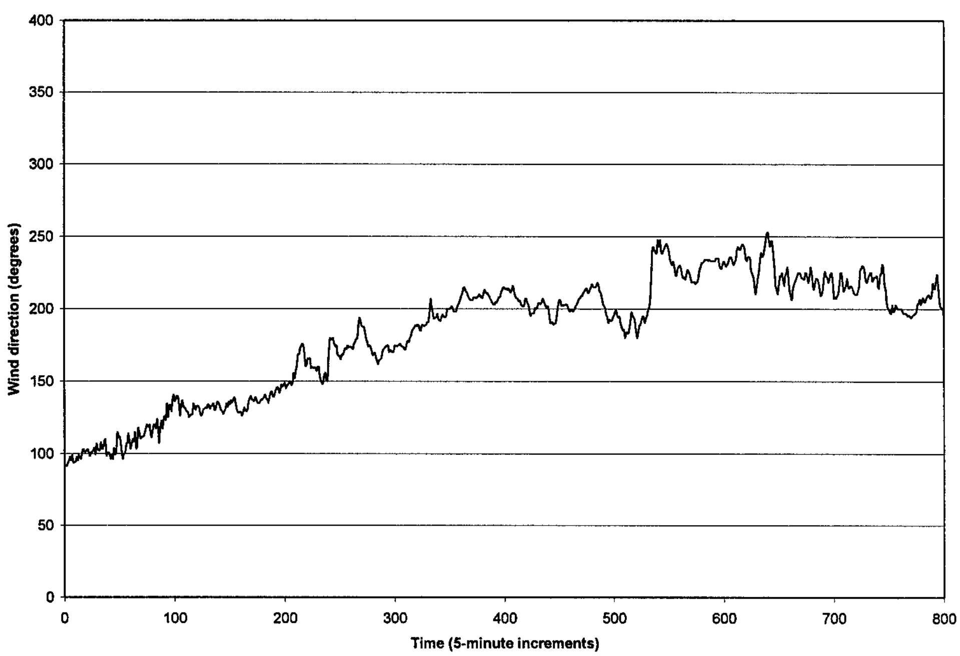

Figure 9 Sample of wind directions from Tower 1101, 162-foot level, February 1999.

replacement value allowed the time position to be retained in the dataset while telling the Fortran program (discussed in the following section) to disregard these values in its calculations.

4.2 Calculating the Conditional Probabilities

A Fortran program was written to calculate the conditional probabilities of meeting or exceeding a certain speed, hereafter referred to as the threshold speed, using the current wind direction, current peak speed, and threshold speed (which varies depending on wind direction and type of rocket) as inputs. These forecast probabilities were created for eight one-hour periods following the initial time.

First, the user selects the current month, tower number, and sensor height. This allows the program to open the appropriate file. Current direction, peak speed, and threshold speed are also input at this time.

Next, bins are created for each observed wind direction and peak speed. For example, wind directions between 0° and 9° are assigned to direction bin 1, directions between 10° and 19° are assigned to direction bin 2, et cetera, until a total of 36 direction bins is reached. Wind speeds are handled in a similar fashion. Peak wind speeds between 0 and 4.9 knots are assigned to speed bin 1, speeds between 5 and 9.9 knots are assigned to speed bin 2, and so on, until a total of 14 speed bins is reached.

Third, the number of times each possible conditioning event (combination of wind direction and peak speed) occurred together was totaled. For example, the program counted the number of times direction bin 1 occurred with speed bin 1, the number of times direction bin 1 occurred with speed bin 2, et cetera. The resulting 36 by 14 "conditioning event array" was saved for later computations. An example of a 3 by 3 conditioning event array is shown in Table 10.

Fourth, the program determines the maximum peak wind speed (the subsequent event) which occurs for each cell in the conditioning event array for each of

Bins	1 (0-4.9 kt)	2 (5-9.9 kt)	3 (10-14.9 kt)
1 (0-119°)	75	100	200
2 (120-239°)	75	100	200
3 (240-359°)	50	100	100

Table 10 Sample 3 by 3 conditioning event array for n = 1000 observations.

the next eight hour-long forecast periods. Once the maximum speed is found, it is matched to its corresponding direction. Table 11 shows a sample of the data for one hour and ten minutes. Beginning at time zero (line 1), the direction is 270° and the peak speed is 8.0 knots. To find the maximum peak speed over the next hour, the program examines the next 12 observations (lines 2 through 13). In this case, the maximum speed of 13.9 knots occurs at time 4500 (line 10). Both the direction and speed for line 10 are converted to their respective bins, and those values are saved in a subsequent event array. This process is repeated for each observation. The result is a set of 504 subsequent event arrays, one for each cell of the conditioning event array. An example of a 3 by 3 subsequent event array for the first hour is shown in Table 12. This array corresponds to direction bin 3 and speed bin 2 shown in Table 10.

Lastly, each total in the subsequent event array is converted to a conditional probability by dividing by the total in the corresponding cell of the conditioning event array (see Table 13). These conditional probabilities are summed for each speed bin greater than or equal to the threshold bin, according to direction. For example, if the user was only interested in maximum wind speeds meeting or exceeding 5 knots, conditional probabilities in column 1 would be discarded, conditional probabilities in columns 2 and 3 are added together, and the result is shown in the last column in Table 14. This step allows the user to see the total conditional probability of meeting or exceeding the threshold speed by direction, not just the probability of observing winds in individual speed bins. To make the output easier to interpret and verify, these probabilities are then summed over all directions. In this case, the total conditional probability of meeting or exceeding wind speeds of 5 knots from

Line Number	Date	Time	Direction	Peak Speed
1	99060	0	270	8.0
2	99060	500	272	4.9
3	99060	1000	272	4.9
4	99060	1500	275	8.0
5	99060	2000	274	8.0
6	99060	2500	274	8.0
7	99060	3000	273	9.9
8	99060	3500	273	10.9
9	99060	4000	272	11.0
10	99060	4500	273	13.9
11	99060	5000	270	12.0
12	99060	5500	269	12.0
13	99060	10000	268	12.0
14	99060	10500	268	16.0

Table 11 Example of data used in determining maximum wind speed forecasts. Direction is in degrees and speed is in knots.

Bins	1 (0-4.9 kt)	2 (5-9.9 kt)	3 (10-14.9 kt)
1 (0-119°)	10	15	25
2 (120-239°)	5	5	20
3 (240-359°)	5	5	10

Table 12 Sample 3 by 3 subsequent event array corresponding to the 100 observed cases shown in direction bin 3 and speed bin 2 of Table 10.

Bins	1 (0-4.9 kt)	2 (5-9.9 kt)	3 (10-14.9 kt)
1 (0-119°)	$\frac{10}{100} = .10$	$\frac{15}{100} = .15$	$\frac{25}{100} = .25$
2 (120-239°)	$\frac{5}{100} = .05$	$\frac{5}{100} = .05$	$\frac{20}{100} = .20$
3 (240-359°)	$\frac{5}{100} = .05$	$\frac{5}{100} = .05$	$\frac{10}{100} = .10$

Table 13 The cells of the subsequent event array are divided by the corresponding cell of the conditional event array to obtain conditional probabilities.

Bins	2(5-9.9 kt)	3(10-14.9 kt)	Directional Probability
1 (0-119°)	.15	.25	.40
2 (120-239°)	.05	.20	.25
3 (240-359°)	.05	.10	.15
Total Probability			.80 or 80%

Table 14 After discarding conditional probabilities for low wind speeds, the remaining probabilities are summed by direction.

any direction is 80%. The entire process described in this section is repeated for each hour of the eight-hour forecast period.

Table 15 contains a sample probability forecast for Tower 1101 at the 162-foot level using data from February 1995, 1996, 1997, and 1998. Input conditions were: current wind direction of 225°, current peak speed of 5 knots, and a threshold speed of 15 knots. The output tells the user the percent probability of meeting or exceeding the given threshold speed from each 10° increment for each hour over the next eight hours. For example, for wind directions between 340° and 349°, there is a 2.8% chance that winds will meet or exceed the 15-knot threshold during the fifth, sixth, seventh, and eighth hours. Wind speeds can be expected to meet or exceed the threshold value from any direction when the total of any column meets or exceeds 30%. In this case, winds equal to or in excess of 15 knots are expected to occur sometime during every hour beginning with the fifth hour.

Direction (degrees)	Hr 1	Hr 2	Hr 3	Hr 4	Hr 5	Hr 6	Hr 7	Hr 8
0-9	.0	.0	.0	.0	.0	.0	.0	.0
10-19	.0	.0	.0	.0	.0	.0	.0	.0
20-29	.0	.0	.0	.0	.0	.0	.0	.0
30-39	.0	.0	.0	.0	.0	.0	.0	.0
40-49	.0	.0	.0	.0	.0	.0	.0	.0
50-59	.0	.0	.0	.0	.0	.0	.0	.0
60-69	.0	.0	.0	.0	.0	.0	.0	.0
70-79	.0	.0	.0	.0	.0	.0	.0	.0
80-89	.0	.0	.0	.0	.0	.0	.0	.0
90-99	.0	.0	.0	.0	.0	.0	.0	.0
100-109	.0	.0	.0	.0	.0	.0	.0	.0
110-119	.0	.0	.0	.0	.0	.0	.0	.0
120-129	.0	.0	.0	.0	.0	.0	.0	.0
130-139	.0	.0	.0	.7	2.8	.0	.0	.7
140-149	.0	.0	.0	.0	.0	3.4	4.8	2.1
150-159	.0	.0	.0	.0	.0	.0	.7	.0
160-169	.0	.0	.0	.0	.0	.0	.0	.0
170-179	.0	.0	.0	.0	.0	.0	.7	6.9
180-189	.0	.0	.0	.0	.0	.0	.0	.0
190-199	.0	.0	.0	.7	2.1	2.8	.0	.0
200-209	.0	1.4	.0	.0	2.1	.7	.0	.0
210-219	.7	.7	1.4	2.8	8.3	6.9	2.8	2.8
220-229	.0	.0	.0	2.1	2.8	2.1	6.2	9.7
230-239	.0	.0	2.1	3.4	7.6	13.8	8.3	10.3
240-249	.7	5.5	2.1	4.1	.7	.7	4.8	9.0
250-259	.0	1.4	4.1	1.4	4.1	3.4	9.0	7.6
260-269	.0	2.1	.0	2.8	1.4	4.8	4.1	4.1
270-279	.0	.0	1.4	.8	.0	.0	.0	.0
280-289	.0	.0	.7	.0	.0	.7	.7	.0
290-299	.0	.0	.0	.0	.7	.7	.0	.0
300-309	.0	.0	.0	.0	.0	.7	.0	.0
310-319	.0	.0	.0	.0	.0	.0	.0	.0
320-329	.7	.0	.0	.0	.0	.0	.0	.0
330-339	.0	.0	.0	.0	.0	.0	.0	.0
340-349	.0	.0	.0	.0	2.8	2.8	2.8	2.8
350-359	.0	.0	.0	2.1	.0	2.1	2.1	2.1
Total	2.1	11.0	11.7	20.7	35.2	45.5	46.9	57.9

Table 15 Sample forecast for Tower 1101 at the 162-foot level for February. This forecast is based on a current direction of 225 degrees, current peak speed of 5 knots, and threshold speed of 15 knots.

4.3 Testing the Algorithm

To ensure the program was correctly calculating the probability forecasts, a test forecast was created using 288 observations (1 day). The forecast was then recalculated by hand, and it was determined that the algorithm was working correctly.

The algorithm was tested for accuracy by calculating 36 different conditional probability forecasts for each month (one for each direction bin) using the data from the first four winters. The fifth winter was used to verify the forecast. If the total conditional probability was equal to or greater than 30%, winds equal to or greater than the threshold value were expected to occur. If the total conditional probability was less than 30%, strong winds were not expected. Contingency tables were constructed based on these total probabilities and the verification data, and measures of accuracy were calculated.

4.4 Results

Figures 10 through 16 display measures of accuracy, bias, and skill scores for tower 1101 at the 162-foot level. February shows the best results by far, with hit rates above 70% in all time periods and increasing skill over eight hours. However, the high hit rate is due to the relatively high number of correct "no" forecasts rather than the number of correct "yes" forecasts (see contingency table in Table 16). False alarm rates could not be calculated for the first three hours because the "yes" rows in the contingency tables were zero. After the first three hours, false alarm rates range from 32% to 51%. Throughout the eight hours, critical success indices range from 0% to 24%, and probabilities of detection range from 0% to 32%. Bias ratios show the algorithm is consistently underforecasting the occurrence of strong winds, although they do increase with time. Even though February's scores are the best out of all five months, they still leave a lot to be desired.

Results from November, December, January, and March also show high hit rates. However, false alarm rates are dramatically higher, ranging from 51% to

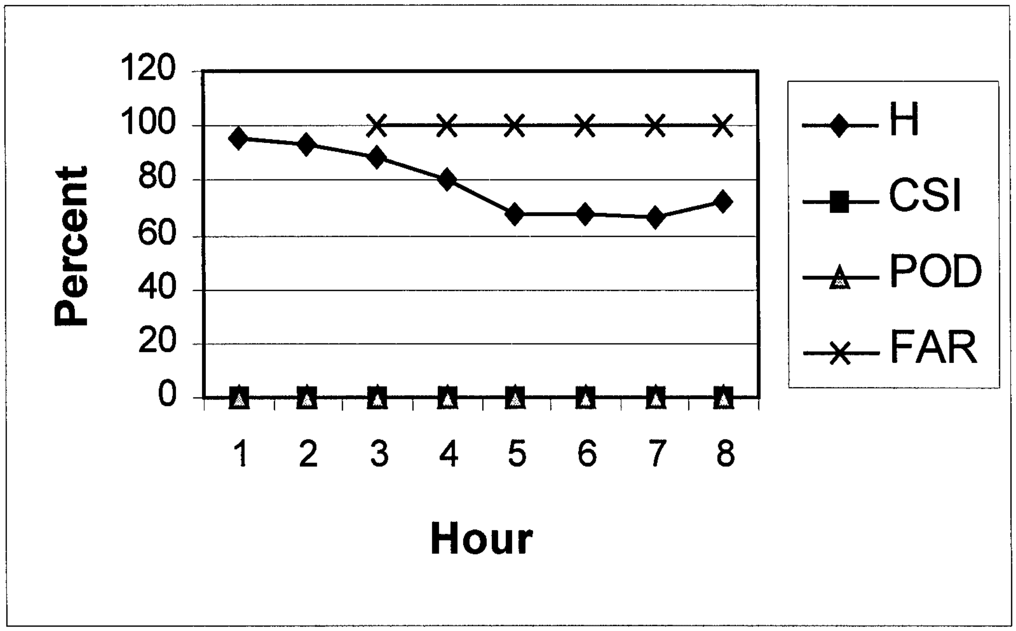

Figure 10 Hit Rate (H), Critical Success Index (CSI), Probability of Detection (POD), and False Alarm Rate (FAR) for November, Tower 1101 at the 162-foot level.

100% because of the extremely high number of incorrect "yes" forecasts. Critical success indices range from 0% to 16% and probabilities of detection range from 0% to 27%. Bias ratios reveal that the algorithm is underforecasting strong winds in the first three hours, then begin to increase to near one by the eight-hour point. The only exception is November, in which bias ratios show the algorithm overforecasting strong winds. Heidke skill scores are negative or very close to zero for all four months. Contingency tables for November, December, January, and March can be found in Appendix B.

Where p-values could be computed (where "yes" forecast rows are not equal to zero), p-values were found to be zero. This shows that there is an association between the observations and forecasts, i.e., the observations are dependent on the forecasts for the 0.05 significance level.

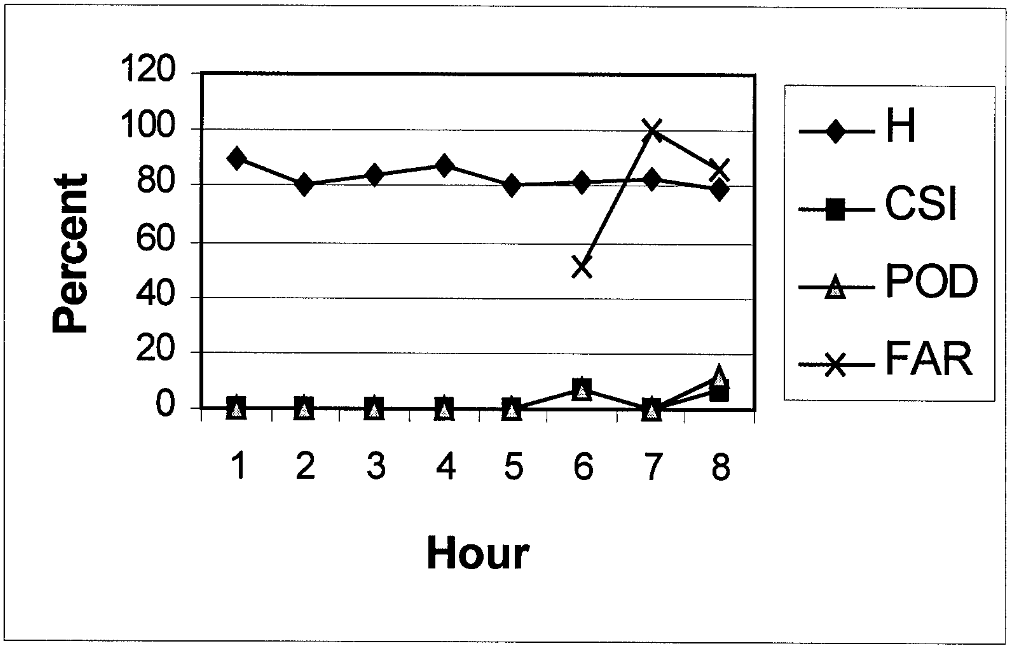

Figure 11 Hit Rate (H), Critical Success Index (CSI), Probability of Detection (POD), and False Alarm Rate (FAR) for December, Tower 1101 at the 162-foot level.

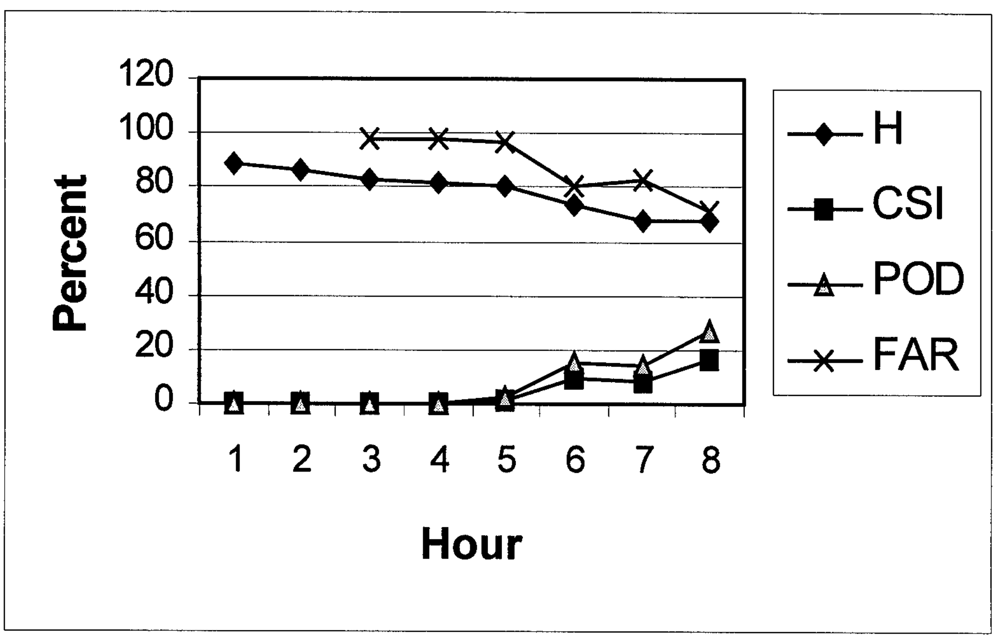

Figure 12 Hit Rate (H), Critical Success Index (CSI), Probability of Detection (POD), and False Alarm Rate (FAR) for January, Tower 1101 at the 162-foot level.

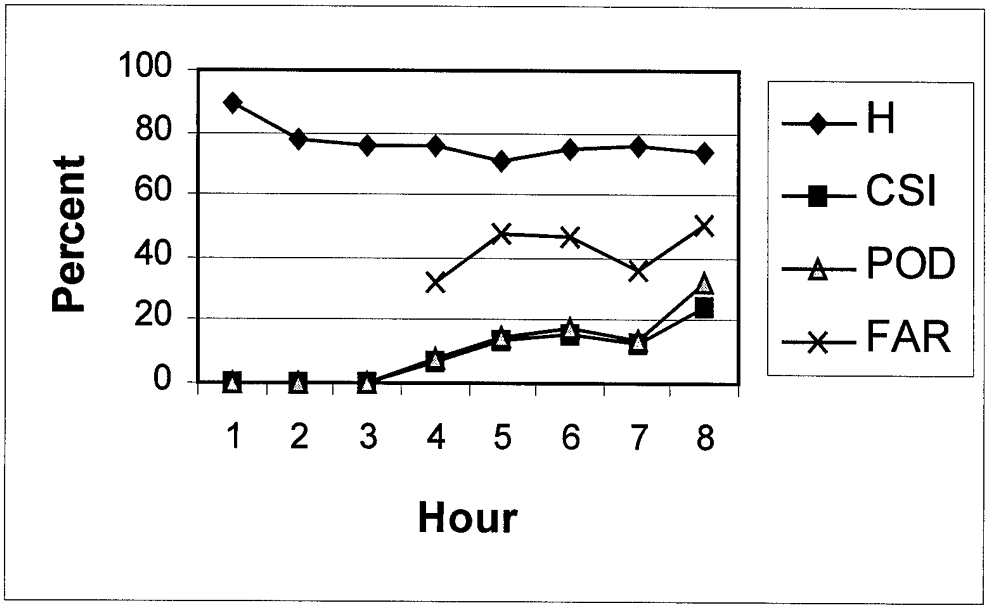

Figure 13 Hit Rate (H), Critical Success Index (CSI), Probability of Detection (POD), and False Alarm Rate (FAR) for February, Tower 1101 at the 162-foot level.

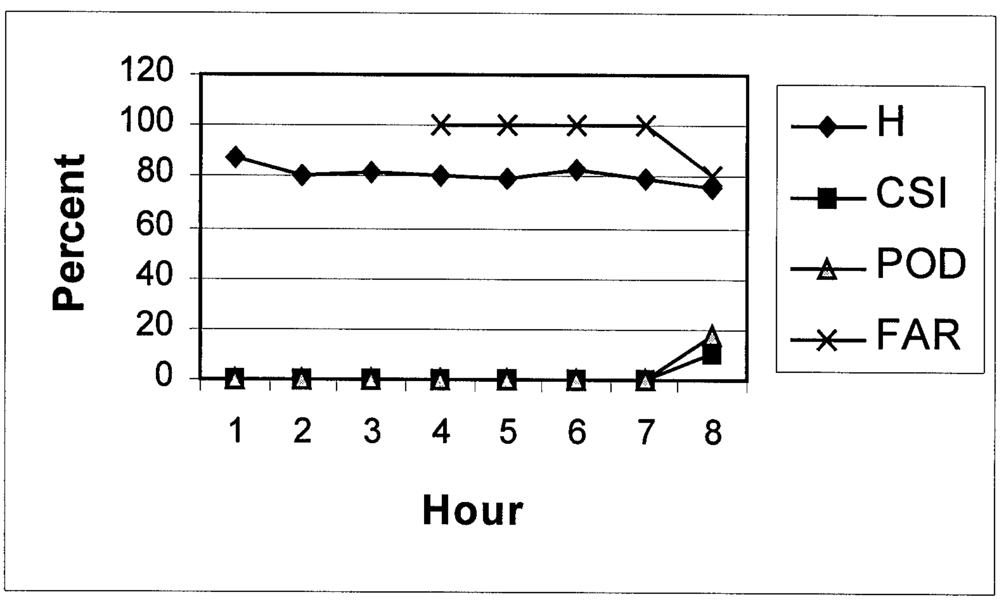

Figure 14 Hit Rate (H), Critical Success Index (CSI), Probability of Detection (POD), and False Alarm Rate (FAR) for March, Tower 1101 at the 162-foot level.

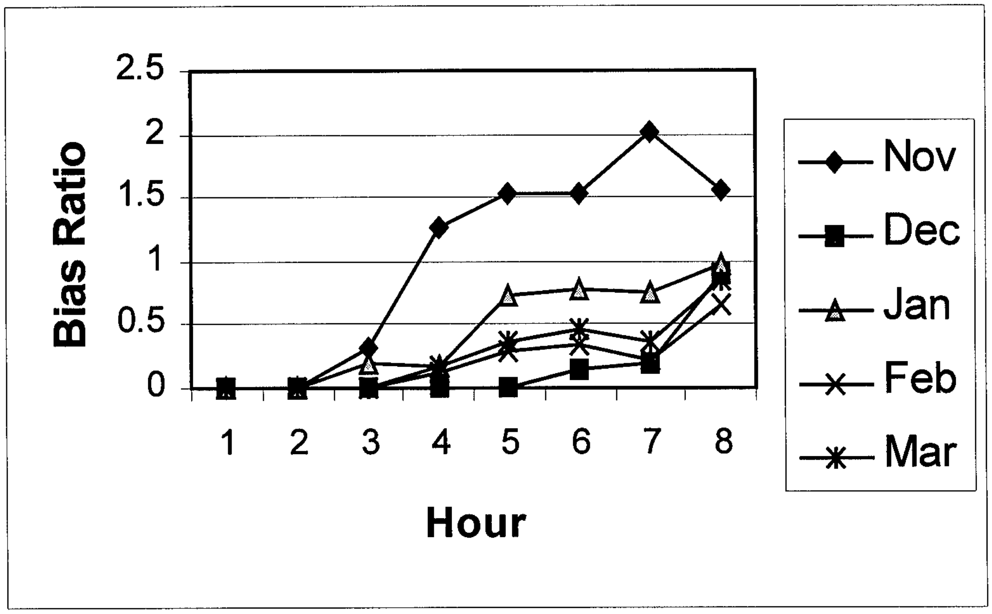

Figure 15   Bias ratio by month for Tower 1101 at the 162-foot level.

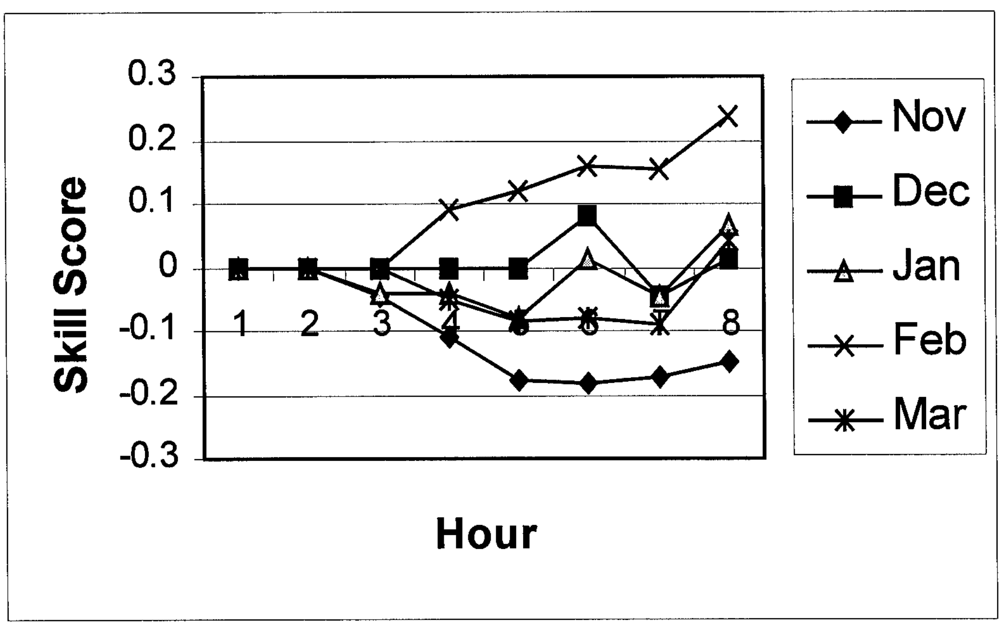

Figure 16   Heidke Skill Score by month for Tower 1101 at the 162-foot level.

		Observed		Total	P-values
Hour 1		Yes	No		
Forecast	Yes	0	0		
	No	30067	260201	290268	Div/0
Hour 2		Yes	No		
Forecast	Yes	0	0		
	No	63542	226726	290268	Div/0
Hour 3		Yes	No		
Forecast	Yes	0	0		
	No	69749	220519	290268	Div/0
Hour 4		Yes	No		
Forecast	Yes	5473	2590		
	No	67230	214975	290268	0
Hour 5		Yes	No		
Forecast	Yes	12794	11395		
	No	72298	193781	290268	0
Hour 6		Yes	No		
Forecast	Yes	12838	11351		
	No	60847	205232	290268	0
Hour 7		Yes	No		
Forecast	Yes	10300	5826		
	No	63350	210792	290268	0
Hour 8		Yes	No		
Forecast	Yes	23741	24637		
	No	50102	191788	290268	0

Table 16 Contingency tables and p-values for February, Tower 1101 at the 162-foot level. "Total" column is the total number of observations for each hour.

V. Conclusion and Recommendations

5.1 Conclusion

Conditional climatology can be a useful tool for predicting the occurrence of strong winds at the Kennedy Space Center and Cape Canaveral Air Station. However, as shown in Chapter 4, accuracy and skill are severely limited in this study. This method of forecasting maximum wind speeds is not recommended for operational use.

5.2 Recommendations for Future Research

The results of this study would likely improve if more observations were collected and included in the dataset. This method could be repeated after data from at least five more winters are obtained. Additionally, different total probabilities, such as 10%, 20%, and 40% should be tested for accuracy and skill in forecasting strong winds. It is possible that a total probability other than 30% might be a better predictor of strong winds. It is also possible that the "optimal" total probability could vary by month or by hour.

A better option for predicting strong winds at KSC/CCAS would be to perform a regression analysis. In addition to current wind speed and direction, variables such as temperature or pressure change with time, temperature or pressure gradient, wind speed or direction change with time, gust spread, or wind speeds at upstream stations can be included in the study. Again, the accuracy of such a study would likely benefit from a larger dataset, as stratifying the data any further would limit the number of observed cases.

Appendix A. Observed Frequency Tables

Listed on the following pages are observed frequency tables for the entire winter for each WINDS tower and level used in this study.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.56	4.66	2.51	1.17	0.71	0.10	0.01	0	0	9.72
30-59	0.37	4.17	1.48	0.42	0.28	0.06	0	0	0	6.78
60-89	0.42	3.11	1.01	0.61	0.50	0.07	0.06	0.01	0	5.81
90-119	0.60	7.40	2.16	0.67	0.22	0.20	0.07	0.01	0	11.3
120-149	0.72	6.99	2.73	1.98	0.62	0.10	0	0	0	13.1
150-179	0.36	4.25	2.21	1.19	0.85	0.34	0	0	0	9.2
180-209	0.38	2.12	0.98	0.95	0.34	0.02	0	0	0	4.8
210-239	0.31	2.94	1.48	0.66	0.31	0.08	0.05	0	0	5.82
240-259	0.31	2.34	1.08	0.42	0.33	0.15	0.01	0	0	4.66
270-299	0.43	3.46	1.41	0.80	0.21	0	0	0	0	6.32
300-329	0.48	5.37	3.47	2.30	0.52	0.05	0	0	0	12.2
330-359	0.51	4.43	2.32	1.47	1.05	0.40	0.07	0.01	0	10.3
Total	5.47	51.2	22.8	12.6	5.94	1.56	0.29	0.03	0	100

Table 17 Percent observed wind speed and directions for the entire winter, Tower 2, northwest side, at the 90-foot level, based on 40505 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.52	4.66	2.53	1.18	0.69	0.15	0.01	0	0	9.74
30-59	0.39	3.91	1.28	0.35	0.23	0.05	0	0	0	6.20
60-89	0.39	3.07	0.99	0.63	0.38	0.05	0.05	0.02	0	5.59
90-119	0.40	6.04	2.58	0.77	0.29	0.13	0.13	0.05	0	10.4
120-149	0.60	5.82	3.03	1.85	0.53	0.21	0.02	0	0	12.1
150-179	0.38	4.76	2.50	1.29	1.00	0.22	0	0	0	10.2
180-209	0.36	2.31	0.98	0.88	0.41	0.04	0	0	0	4.98
210-239	0.25	2.83	1.56	0.82	0.24	0.10	0.03	0	0	5.84
240-259	0.34	2.53	1.17	0.46	0.36	0.13	0.02	0	0	5.01
270-299	0.54	3.55	1.68	0.75	0.14	0.01	0	0	0	6.67
300-329	0.58	5.83	4.17	2.06	0.42	0.07	0.02	0	0	13.1
330-359	0.57	4.22	2.27	1.51	1.22	0.40	0.05	0.02	0	10.3
Total	5.31	49.5	24.7	12.6	5.91	1.55	0.33	0.10	0	100

Table 18 Percent observed wind speed and directions for the entire winter, Tower 2, southeast side, at the 90-foot level, based on 40513 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	1.07	2.86	1.50	1.80	1.25	0.64	0.05	0.08	0.02	9.27
30-59	0.21	2.28	0.62	0.92	0.26	0.08	0.06	0.08	0.02	4.52
60-89	0.20	1.49	0.64	0.88	0.63	0.08	0.02	0.01	0.01	3.97
90-119	1.33	10.7	4.92	1.77	0.24	0.10	0.02	0	0	19.1
120-149	0.29	1.81	1.50	1.13	0.28	0.05	0	0	0	5.06
150-179	0.26	2.67	2.54	1.31	0.48	0.10	0	0	0	7.36
180-209	0.29	3.15	2.80	1.37	0.17	0.01	0	0	0	7.79
210-239	0.21	2.44	1.44	0.93	0.3	0.07	0.01	0	0	5.39
240-259	0.24	2.83	1.94	1.04	0.4	0.26	0.04	0	0	6.75
270-299	0.31	3.02	2.20	1.40	1.02	0.64	0.14	0.03	0	8.76
300-329	0.36	4.70	3.54	2.83	1.01	0.17	0.05	0.01	0	12.7
330-359	0.31	3.14	1.47	1.72	1.39	1.04	0.08	0.11	0.09	9.36
Total	5.1	41.1	25.1	17.1	7.43	3.24	0.49	0.32	0.14	100

Table 19 Percent observed wind speed and directions for the entire winter, Tower 36, at the 90-foot level, based on 41772 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.48	3.34	1.64	2.12	1.08	0.31	0.10	0.09	0.02	9.17
30-59	0.51	2.75	0.83	1.28	0.56	0.17	0.04	0.04	0.01	6.19
60-89	0.36	1.96	0.82	0.96	0.29	0.03	0.03	0.02	0.01	4.50
90-119	0.34	2.18	1.81	0.90	0.27	0.08	0.01	0	0	5.59
120-149	0.25	1.89	1.50	0.98	0.31	0.07	0.01	0	0	5.02
150-179	0.42	3.53	3.00	1.67	0.66	0.13	0	0	0	9.42
180-209	0.87	3.78	1.50	1.35	0.41	0.09	0.04	0	0	8.05
210-239	0.70	2.91	1.70	1.57	0.59	0.26	0.06	0.01	0	7.80
240-259	0.53	3.83	2.38	1.59	0.77	0.58	0.26	0.05	0	9.98
270-299	0.70	4.83	3.00	2.38	1.59	0.69	0.10	0.01	0	13.3
300-329	0.53	2.85	1.86	2.10	1.56	0.44	0.05	0	0	9.39
330-359	0.49	2.45	1.66	1.90	2.11	1.81	0.68	0.15	0.32	11.6
Total	6.18	36.3	21.7	18.8	10.2	4.67	1.37	0.38	0.37	100

Table 20 Percent observed wind speed and directions for the entire winter, Tower 393 at the 60-foot level, based on 34062 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.32	3.38	2.35	2.67	1.48	0.51	0.07	0.05	0.02	10.9
30-59	0.28	2.79	1.14	1.15	0.43	0.16	0.05	0.05	0.02	6.07
60-89	0.28	1.97	0.93	1.24	0.64	0.06	0.02	0.02	0.01	5.18
90-119	0.23	1.75	1.29	0.66	0.27	0.08	0.02	0.01	0	4.31
120-149	0.34	2.26	1.67	1.39	0.64	0.10	0.01	0	0	6.42
150-179	0.42	3.41	2.59	1.40	0.56	0.14	0	0	0	8.52
180-209	0.59	3.48	1.36	1.34	0.45	0.08	0	0	0	7.30
210-239	0.49	2.74	1.51	1.46	0.58	0.22	0.06	0	0	7.06
240-259	0.54	3.02	1.86	1.54	0.52	0.40	0.27	0.08	0	8.23
270-299	0.43	3.98	3.57	1.97	1.17	0.68	0.18	0.06	0.01	12.1
300-329	0.66	3.18	2.76	2.80	1.37	0.37	0.03	0.01	0	11.2
330-359	0.49	2.53	2.12	2.20	2.50	1.72	0.77	0.25	0.25	12.8
Total	5.06	34.5	23.1	19.8	10.6	4.52	1.47	0.54	0.31	100

Table 21 Percent observed wind speed and directions for the entire winter, Tower 394 at the 60-foot level, based on 42118 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.39	3.70	1.66	1.86	0.79	0.20	0.05	0.07	0.06	8.77
30-59	0.34	2.43	1.02	1.39	0.49	0.10	0.02	0.01	0.01	5.82
60-89	0.24	2.61	0.78	0.82	0.52	0.03	0.01	0.01	0	5.02
90-119	0.26	2.34	2.01	0.92	0.30	0.01	0	0	0	5.84
120-149	0.24	2.03	1.93	0.87	0.49	0.14	0	0	0	5.71
150-179	0.48	3.93	2.10	1.20	0.46	0.11	0	0	0	8.28
180-209	0.57	3.26	1.33	1.37	0.73	0.21	0.04	0	0	7.50
210-239	0.44	3.39	1.69	1.73	0.58	0.22	0.05	0	0	8.11
240-259	0.44	3.67	1.29	1.26	0.81	0.46	0.20	0.07	0	8.19
270-299	0.64	4.53	3.24	2.69	1.56	0.49	0.11	0.02	0.01	13.3
300-329	0.65	3.20	2.18	2.05	1.85	0.89	0.16	0.04	0	11.0
330-359	0.49	2.04	2.16	2.75	2.41	1.78	0.45	0.14	0.25	14.5
Total	5.19	37.1	21.4	18.9	11.0	4.64	1.08	0.35	0.33	100

Table 22 Percent observed wind speed and directions for the entire winter, Tower 397 at the 60-foot level, based on 42116 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.36	4.39	1.43	1.53	0.62	0.22	0.06	0.09	0.05	8.74
30-59	0.37	2.33	0.84	1.58	0.65	0.08	0.03	0.02	0	5.90
60-89	0.22	1.59	1.05	0.56	0.28	0.04	0	0	0	3.74
90-119	0.33	2.18	1.83	1.21	0.37	0.03	0	0	0	5.96
120-149	0.33	2.45	2.05	1.02	0.56	0.17	0.14	0	0	6.59
150-179	0.39	3.17	1.73	1.13	0.38	0.17	0	0	0	6.97
180-209	0.57	3.21	1.13	1.35	0.69	0.20	0.05	0.02	0	7.21
210-239	0.45	3.06	1.77	1.91	0.58	0.24	0.09	0.02	0	8.11
240-259	0.41	3.89	1.33	1.30	0.93	0.54	0.18	0.07	0.01	8.65
270-299	0.51	4.08	3.91	2.70	1.06	0.38	0.08	0.01	0	12.7
300-329	0.67	3.34	2.57	2.50	1.88	0.86	0.10	0.05	0.09	11.7
330-359	0.52	3.15	2.62	3.38	2.21	1.38	0.17	0.04	0.21	13.7
Total	5.12	36.6	22.3	20.1	10.2	4.31	0.76	0.31	0.36	100

Table 23 Percent observed wind speed and directions for the entire winter, Tower 398 at the 60-foot level, based on 42197 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.76	3.63	2.18	2.14	1.53	0.30	0.06	0.05	0	10.7
30-59	0.34	2.82	1.38	0.60	0.19	0.12	0.05	0.02	0.02	5.54
60-89	0.40	2.49	1.04	0.97	0.19	0.06	0.02	0.01	0	5.18
90-119	0.44	2.26	1.37	0.62	0.13	0.04	0	0	0	4.86
120-149	0.47	3.32	2.27	1.28	0.34	0.04	0	0	0	7.72
150-179	0.46	3.90	1.94	0.92	0.29	0.06	0.01	0	0	7.59
180-209	0.54	3.12	2.36	1.72	0.35	0.05	0.01	0	0	8.15
210-239	0.78	2.98	1.27	1.05	0.53	0.16	0.03	0	0	6.79
240-259	0.61	3.18	1.65	1.19	0.58	0.38	0.18	0.03	0	7.79
270-299	1.02	3.01	2.36	1.97	1.33	0.85	0.26	0.10	0	10.9
300-329	1.54	4.21	3.44	2.85	1.64	0.43	0.04	0.03	0	14.2
330-359	1.07	2.95	1.53	1.96	1.74	1.06	0.12	0.17	0.06	10.7
Total	8.45	37.8	22.8	17.3	8.85	3.54	0.77	0.40	0.08	100

Table 24 Percent observed wind speed and directions for the entire winter, Tower 1101 at the 54-foot level, based on 35425 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	1.60	3.79	2.36	2.20	1.02	0.20	0.04	0.02	0	11.2
30-59	0.27	3.18	1.47	0.49	0.17	0.10	0.02	0.02	0.01	5.73
60-89	0.38	2.28	1.18	0.90	0.16	0.04	0.01	0.01	0	4.96
90-119	0.31	2.07	1.10	0.60	0.16	0.04	0	0	0	4.27
120-149	0.39	2.87	1.97	1.13	0.21	0.03	0	0	0	6.60
150-179	0.43	3.70	1.54	0.77	0.25	0.05	0	0	0	6.74
180-209	0.41	3.25	2.25	1.70	0.28	0.02	0	0	0	7.90
210-239	0.56	3.27	1.43	1.23	0.58	0.18	0.03	0	0	7.28
240-259	0.56	2.94	1.61	1.30	0.57	0.36	0.16	0.07	0	7.56
270-299	1.71	4.05	2.82	2.04	1.11	0.54	0.14	0.03	0	11.9
300-329	2.03	5.38	3.16	2.58	0.97	0.10	0.01	0	0	14.2
330-359	0.77	2.92	1.89	2.52	1.97	1.15	0.14	0.16	0.06	11.6
Total	8.88	39.7	22.8	17.5	7.46	2.80	0.56	0.31	0.07	100

Table 25 Percent observed wind speed and directions for the entire winter, Tower 1102 at the 54-foot level, based on 42105 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	>40	Total
0-29	0.58	3.15	2.54	3.00	1.39	0.52	0.08	0.06	0.03	11.3
30-59	0.28	2.56	1.27	1.37	0.39	0.10	0.04	0.06	0.01	6.07
60-89	0.15	1.71	1.05	1.19	0.66	0.05	0.02	0.01	0	4.84
90-119	0.21	1.71	1.04	1.02	0.65	0.14	0.02	0.01	0	4.81
120-149	0.23	1.99	1.88	1.97	0.78	0.08	0	0	0	6.92
150-179	0.26	1.97	2.29	1.63	0.61	0.11	0.02	0	0	6.89
180-209	0.30	2.54	2.20	2.24	1.04	0.10	0.02	0	0	8.44
210-239	0.24	2.11	1.57	1.67	0.93	0.31	0.05	0.03	0	6.89
240-259	0.23	1.57	2.00	1.75	0.64	0.38	0.17	0.10	0	6.84
270-299	0.49	3.21	2.88	2.14	1.18	0.56	0.14	0.05	0	10.7
300-329	0.69	4.14	3.94	3.22	1.50	0.20	0.02	0	0	13.7
330-359	0.38	2.80	2.47	2.32	2.21	1.69	0.37	0.11	0.22	12.6
Total	4.03	29.5	25.1	23.5	12.0	4.24	0.94	0.43	0.26	100

Table 26 Percent observed wind speed and directions for the entire winter, Tower 1102 at the 162-foot level, based on 42101 observations. Wind speeds (first row) are in knots and wind directions (first column) are in degrees.

Appendix B. Contingency Tables

Contingency tables and p-values for Tower 1101 at the 162-foot level for November, December, January, and March.

Hour		Forecast	Observed Yes	Observed No	Total	P-values
Hour 1	Forecast	Yes	0	0		
		No	12534	298506	311040	Div/0
Hour 2	Forecast	Yes	0	0		
		No	19528	291512	311040	Div/0
Hour 3	Forecast	Yes	0	8640		
		No	27234	275166	311040	0
Hour 4	Forecast	Yes	0	34560		
		No	27599	248881	311040	0
Hour 5	Forecast	Yes	156	60324		
		No	39456	211104	311040	0
Hour 6	Forecast	Yes	13	60467		
		No	39852	210708	311040	0
Hour 7	Forecast	Yes	36	69084		
		No	34357	207563	311040	0
Hour 8	Forecast	Yes	89	51751		
		No	33328	225872		0

Table 27 Contingency tables and p-values for November, Tower 1101 at the 162-foot level. "Total" column is the total number of observations for each hour.

		Observed		Total	P-values
Hour 1		Yes	No		
Forecast	Yes	0	0		
	No	32309	289099	321408	Div/0
Hour 2		Yes	No		
Forecast	Yes	0	0		
	No	64554	256854	321408	Div/0
Hour 3		Yes	No		
Forecast	Yes	0	0		
	No	53252	268156	321408	Div/0
Hour 4		Yes	No		
Forecast	Yes	0	0		
	No	40475	280933	321408	Div/0
Hour 5		Yes	No		
Forecast	Yes	0	0		
	No	63019	258389	321408	Div/0
Hour 6		Yes	No		
Forecast	Yes	4378	4550		
	No	55811	256669	321408	0
Hour 7		Yes	No		
Forecast	Yes	7	8921		
	No	46198	266282	321408	0
Hour 8		Yes	No		
Forecast	Yes	4863	30849		
	No	35313	250383	321408	0

Table 28 Contingency tables and p-values for December, Tower 1101 at the 162-foot level. "Total" column is the total number of observations for each hour.

			Observed		Total	P-values
Hour 1			Yes	No		
	Forecast	Yes	0	0		
		No	37434	283974	321408	Div/0
Hour 2			Yes	No		
	Forecast	Yes	0	0		
		No	42794	278614	321408	Div/0
Hour 3			Yes	No		
	Forecast	Yes	166	8762		
		No	46767	265713	321408	0
Hour 4			Yes	No		
	Forecast	Yes	166	8762		
		No	49512	262968	321408	0
Hour 5			Yes	No		
	Forecast	Yes	789	25995		
		No	35601	259023	321408	0
Hour 6			Yes	No		
	Forecast	Yes	8511	36129		
		No	48358	228410	321408	0
Hour 7			Yes	No		
	Forecast	Yes	9494	44074		
		No	60721	207119	321408	0
Hour 8			Yes	No		
	Forecast	Yes	20278	51146		
		No	53947	196037	321408	0

Table 29 Contingency tables and p-values for January, Tower 1101 at the 162-foot level. "Total" column is the total number of observations for each hour.

		Observed		Total	P-values
Hour 1		Yes	No		
Forecast	Yes	0	0		
	No	41762	279646	321408	Div/0
Hour 2		Yes	No		
Forecast	Yes	0	0		
	No	64675	256733	321408	Div/0
Hour 3		Yes	No		
Forecast	Yes	0	0		
	No	58150	263258	321408	Div/0
Hour 4		Yes	No		
Forecast	Yes	25	8903		
	No	52370	260110	321408	0
Hour 5		Yes	No		
Forecast	Yes	48	17808		
	No	47554	255998	321408	0
Hour 6		Yes	No		
Forecast	Yes	14	17842		
	No	39551	264001	321408	0
Hour 7		Yes	No		
Forecast	Yes	31	17825		
	No	49658	253894	321408	0
Hour 8		Yes	No		
Forecast	Yes	8969	35671		
	No	43553	233215	321408	0

Table 30 Contingency tables and p-values for March, Tower 1101 at the 162-foot level. "Total" column is the total number of observations for each hour.

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13. ABSTRACT *(Maximum 200 words)*
This thesis uses statistical analysis to forecast the probability of meeting or exceeding the maximum allowable wind speeds for each of the launch pads at the Kennedy Space Center (KSC) and Cape Canaveral Air Station (CCAS). Wind data were collected from the Weather Information Network Display System (WINDS), a collection of 47 meteorological towers located throughout KSC and CCAS, over a period of five winters. A Fortran program was written to calculate conditional probabilities of meeting or exceeding a given threshold speed during eight consecutive one-hour periods, using the current wind direction and peak wind speed as inputs. Forecast probabilities were displayed in a table according to time period and wind direction. Accuracy was measured by constructing contingency tables and calculating various measures of accuracy. Results were tested for significance by calculating p-values for the chi-square test. This method was found to have very little skill in forecasting maximum wind speeds. It is not recommended for operational use.

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