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THE USE OF THE AIR FORCE ACADEMY HIGH WIND ALERT SYSTEM IN FORECASTING MODERATE INTENSITY WIND EVENTS FOR MILITARY BASES IN THE COLORADO SPRINGS AREA

A Thesis in

Meteorology

by

Douglas S. Clark

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ABSTRACT

A study of the problem of forecasting moderate intensity wind events in the Colorado Springs area, which are operationally significant to the military bases there, was conducted over a three year period. This study centered on the use of the United States Air Force Academy High Wind Alert System, a network of automatic observing stations in the foothills of the Air Force Academy. The usefulness of the High Wind Alert System as an aid to forecasting the onset of moderate intensity events at the other bases was investigated. The results of a statistical analysis of data taken from the High Wind Alert System on a number of days during which the synoptic conditions indicated the possibility of a moderate intensity wind event are presented, with emphasis on the correlation between the output from the High Wind Alert System and the time of onset of moderate intensity winds at the concerned bases. The results of this analysis, along with the possible empirical forecasting rules they suggest, are explained.

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Chapter 1
INTRODUCTION

Moderate intensity wind events, with gust speeds between 25 and 49 knots, are important to many military units in the Colorado Springs area. The airfield at the United States Air Force Academy (USAFA) has over 300,000 aircraft movements each year, almost all involving either student pilots or parachutists, and moderate intensity wind events therefore cause serious degradation in flight safety. At Peterson Air Force Base, flight operations and aircraft maintenance are affected by moderate winds, civil engineers are concerned with the safety of individuals working on ladders or utility poles during wind events, and base supply agencies are forced to protect property on loading docks. At Falcon Air Force Base, work on sensitive electronic equipment inside radomes cannot take place during wind events. At Fort Carson, helicopter flights and infantry exercises in the field both suffer interference from moderate winds.

The Air Weather Service units located at Colorado Springs area bases are charged with forecasting such moderate intensity wind events to a high degree of accuracy. Wind speeds above 25 knots require 30 minutes of lead-time in notification before an event starts. Winds above 35 knots require 45 minutes of lead-time. Failure to provide adequate lead-time can result in injury to personnel or damage to equipment. False alarm forecasts and excessive lead-times both result in agencies taking unnecessary protective measures and thousands of man-hours of lost productivity. Clearly, then, there is a strong financial impetus to make wind event forecasting as accurate as possible.

To date, the literature concerning wind event forecasting has focused primarily on events of severe intensity (speeds faster than 50 knots) utilizing synoptic-scale data. Much of this research is nevertheless useful for providing a starting point for this study. One of the assumptions of this study is that the forecaster knows whether or not there is a strong possibility that a wind event will occur during the course of his 8 or 12 hour shift. The background synoptic scale situation is therefore of great importance. The synoptic-scale patterns and pre-cursors of wind events, which previous authors have described in excellent detail (e.g. pressure field, pressure tendency, vorticity advection), must be fully understood by the forecaster in order to improve the timing and accuracy of forecasts using the results of this investigation.

One of these reports regarding the forecasting of gusty winds (Waters, 1970) identified a number of parameters useful for deciding whether gusty winds will occur. These predictive parameters included surface-pressure gradient, pressure tendency, low and mid-level maximum winds, and the tracks of cold pools.

Henz, Scheetz, and Fritsch (1974) added the importance of vorticity and "knowledge of local topography" to Waters' list. Using data from a number of windstorms that afflicted Boulder, Colorado, they quantified the important parameters and found critical limits for each that indicate an imminent severe wind event. Their criteria for severe wind events included temperature change of plus or minus 6 degrees in 12 hours at either 500 or 700 millibars, vorticity advection of plus or minus $6 \times 10^{-5}\ s^{-1}$ in 12 hours, and an isallobaric change of plus or minus 1 mb per hour. The present study is, in effect, an attempt to apply their criteria development technique to a smaller scale and less severe winds. Where their study used the trends in synoptic scale parameters applied to a larger area, this one uses mesoscale observations applied to a smaller area.

In another study, Sangster (1977) added mid-level vertical stability to this increasing list of predictors. The stability rule employed in the forecast worksheet he proposed is somewhat complicated, but its basic premise is to determine if conditions permit the possibility of hydraulic acceleration of the winds as they flow downhill.

The possibility of such linear instability being involved in down-slope windstorms was pursued further by Clark and Peltier (1977, 1984) and Peltier and Clark (1979). As will be discussed later, their results may assist with the explanation for a phenomenon of northerly wind events encountered in the Colorado Springs data. Smith (1985) and Laprise and Peltier (1989) provided additional insight on this aspect of the problem.

By compiling much of the above research into a simple forecast study, Brown (1986) produced an easy to use "decision tree" which encompasses all non-convective severe wind events that affect the Front Range and adjoining high plains. His decision tree is remarkably useful because it merely requires the forecaster to employ a set of yes or no questions, rather than having to complete any numerical calculations. Such "quick and dirty" techniques are often what a forecaster needs, given the workload of the usual duty shift.

Pre-dating most of the more scientific studies is the single Air Weather Service Technical Note which describes the wind forecasting guidelines for Colorado Springs (German and Miller, 1975). This is also the only work encountered by this author that deals with northerly wind events in addition to much-researched westerly or severe down-slope ones discussed by the above-mentioned authors. Northerly wind events, while rarely, if ever, severe, are far more common than westerly ones. The forecast techniques for these northerly wind events employed at the USAFA and Peterson AFB appear to be based almost exclusively on the rules described in this technical note (Peterson AFB Terminal Forecast Reference Notebook, 1992, and USAFA Terminal Forecast Reference Notebook, 1992).

The most popular parameter for determining the potential maximum wind speed in a northerly event, based on these documents, has been the pressure gradient. For northerly wind cases, the Denver to Colorado Springs pressure gradient is used. The empirical rule used is that a moderate wind event will occur within 2 hours after the sea level pressure at Denver becomes 2 millibars or more higher than the sea level pressure at Colorado Springs, and that it will end after the pressure gradient drops below this threshold. The wind speed in each event is estimated by multiplying the pressure difference between the two stations by 10. For example, if the DEN-COS pressure difference is 3.2 millibars, then the gust speed of the wind event will be 32 knots (German and Miller, 1975).

A summary of the traditional forecast techniques and parameters covering all wind events that afflict the Colorado Springs area is given in table 1 and figures 1 through 5.

Unfortunately, the synoptic scale charts and soundings used in these traditional methods are not produced with the frequency and timeliness necessary for obtaining the desired lead-times and near-zero timing errors. If the empirical rule for northerly cases described above is used, for example,

TABLE 1. Summary of wind events affecting Colorado Springs and the corresponding forecast parameters used. Compiled from Henz et al 1974, German and Miller 1975, Brown 1986, Peterson AFB TFRN 1992, and USAFA TFRN, 1992.

EVENT TYPE	SYNOPTIC CONDITIONS	FORECAST GUIDELINES
North Pressure Surge	Cold front advancing south along the Front Range. Isobars oriented west to east.	Winds will begin with apparent frontal passage. Estimate speed based on DEN-COS pressure gradient. Commonly occurs shortly after sunset.
North Isobaric	Same, but isobars oriented north-south.	Estimate speed by adding 5 knots to DEN speed.
West or Northwest Down-slope	Strong pressure gradient caused by a high west or south of Colorado and a surface cyclone east or south. Jet support is required.	Winds will begin after nocturnal inversion is broken. Speeds will equal 80% of 500 mb speed.
Southwest	Pressure trough southwest of Colorado, southwesterly jet into south-central Colorado.	Onset coincides with jet reaching Continental Divide. Speed will equal fastest speed below 500 mb.
Southeast	Strong temperature gradient from plains to slopes.	Mid-day diurnal winds may exceed 25 knots.

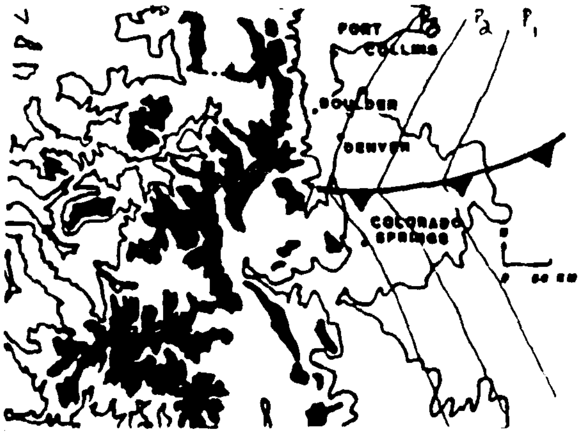

Figure 1. Conditions prior to northerly isobaric wind event, showing pressure field and cold front.

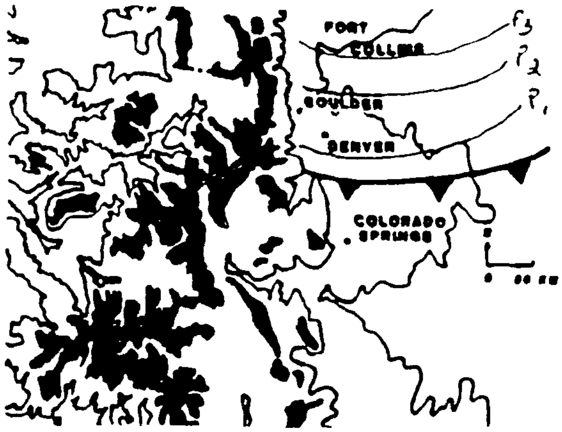

Figure 2. Conditions prior to northerly cross-isobaric wind event, showing pressure field and cold surge.

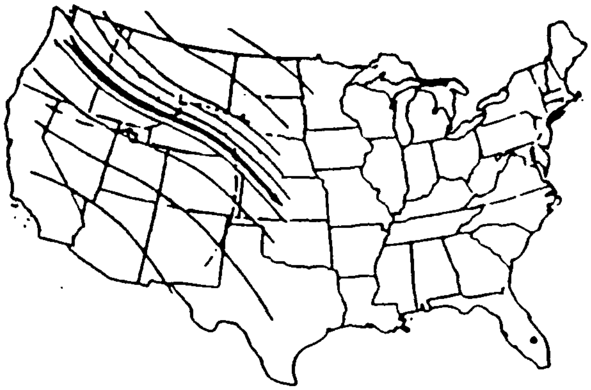

Figure 3. Conditions prior to westerly or northwesterly wind event, showing pressure field and jet stream (Brown, 1986).

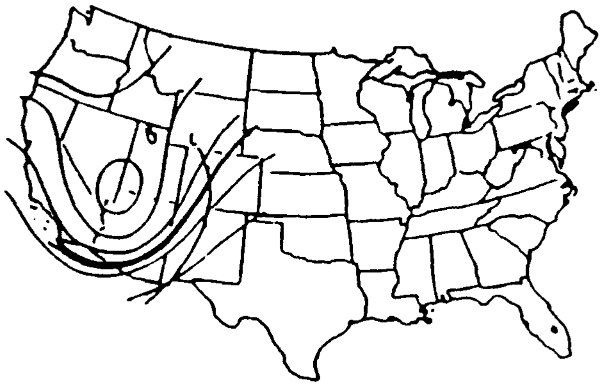

Figure 4. Conditions prior to southwesterly wind event, showing pressure field and jet stream (Brown, 1986).

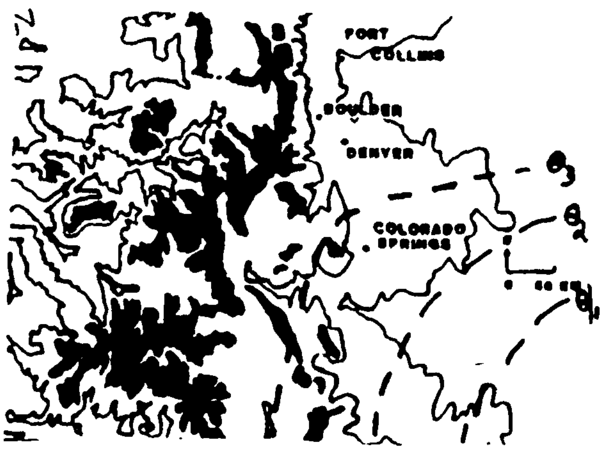

Figure 5. Conditions prior to southeasterly wind event, showing the temperature field.

then the timing error for the start of each warning could be as high as two hours, and the unnecessary hesitation for terminating each warning could be as much as an additional hour (based on the hourly availability of surface observations). Since some of the northerly events which occurred during the course of this study only lasted for a single hour, the lost work time resulting from warnings which followed the current rule could have been four times what was actually needed for safety. In the cases where momentum mix-down from aloft is the concern, the twice-daily availability of rawinsonde data could cause even greater timing errors.

Furthermore, the complex terrain surrounding and separating the different military bases around Colorado Springs allows wind events to affect some bases while bypassing others. "It is not uncommon to have westerly wind gusts of 30-40 knots at the USAF Academy and Fort Carson while Peterson AFB has light easterly winds" (USAFA TFRN, 1992). It is therefore an additional concern to know *which* bases in the area will be affected by each event. It is possible that a single event will exceed the 35 knot threshold at one base, the 25 knot threshold at a second, and will not affect a third at all.

Therefore, in order to reduce the injury and destruction caused by wind events, and to decrease the cost to the public caused by lost work time due to wind event forecasts, it is important to develop more sophisticated forecast techniques based on newly available data. Such forecast techniques must nevertheless be simple.

If the goal of each forecaster is to obtain a 45 minute lead-time, with minimal timing error and a false alarm rate near zero, for every wind event, then the purpose of this study must be to help the forecasters come closer to this achievement by developing new empirical rules. These empirical rules should combine data unavailable to previous authors who have studied this problem with the results that these authors have already obtained. Any empirical rule developed must be user-friendly: it must be based only on readily available data, must not require any complicated calculations, and must only take a minimum of the forecaster's time. If the forecaster needs 45 minutes lead-time and zero timing error, then any forecast method that requires an hour of his time before reaching a decision is useless. Instead, the forecast method must be based on a small number of directly-observable parameters that the forecaster can mentally assimilate to determine if a wind advisory or warning is required.

Because of the need to maximize the amount of safe flight training time available, while minimizing the number of wind events that occur with insufficient lead-time, the USAFA recently installed a High Wind Alert System (HWAS). This system, described later in the text, is intended to give USAFA forecasters the necessary data to improve their wind event forecast ability by a significant amount beyond what was previously possible, as well as to provide an alarm system for both weather and flying units in the event that significant winds strike without prior warning. The intent of this study is to apply the data available from the HWAS to wind event forecasts for the Colorado Springs metropolitan area, and to determine some possible empirical rules which the forecasters, charged with such a difficult task, may use to optimize their support to their customers. Because the USAFA is located to the north and west of the other bases in the

Colorado Springs area, it is suspected that this upwind setting is a good location for providing warning lead-time to the downwind bases.

Chapter 2

GEOGRAPHY

The city of Colorado Springs is located at 38.49° north, 104.45° west, and is 6000 feet above mean sea level. 10 miles directly west of the city, Pikes Peak rises to 14,110 feet. The Rampart Range, which includes Pikes Peak, runs from southwest to northwest of the city, with most peaks around 9500 feet. 30 miles north of the city, the Palmer Ridge, over 7900 feet MSL in places, runs west to east. To the east, the terrain rises slightly for 30 miles before dropping off again. It drops off gradually and continuously to the south.

Peterson AFB is located 5 miles east of the city, at 6172 feet MSL. Falcon AFB is 8 miles east of Peterson, at 6355 feet MSL. Fort Carson borders the southern end of the city, sitting at the base of Cheyenne Mountain. The airfield on Fort Carson is 5790 feet MSL, and is 11 miles south of downtown Colorado Springs.

The Air Force Academy lies north and slightly west of the city. The airfield is 6572 feet MSL, approximately 5 miles east of the Rampart Range and 15 miles north-northwest of Peterson AFB. $4^1/_2$ miles northwest of the airfield is the cadet area, at 7329 feet MSL. The Palmer Ridge is 11 miles north of the USAFA. Figure 6 shows a map of the Colorado Springs area.

Situated south of the USAFA but north of Peterson AFB, Fort Carson, and downtown Colorado Springs, a narrow ridge known as Austin Bluffs rises quickly to 6800 feet in places and abruptly drops off again. The bluffs are oriented northwest to southeast. Falcon AFB is located at the southeastern end of these bluffs. It is speculated that this terrain feature

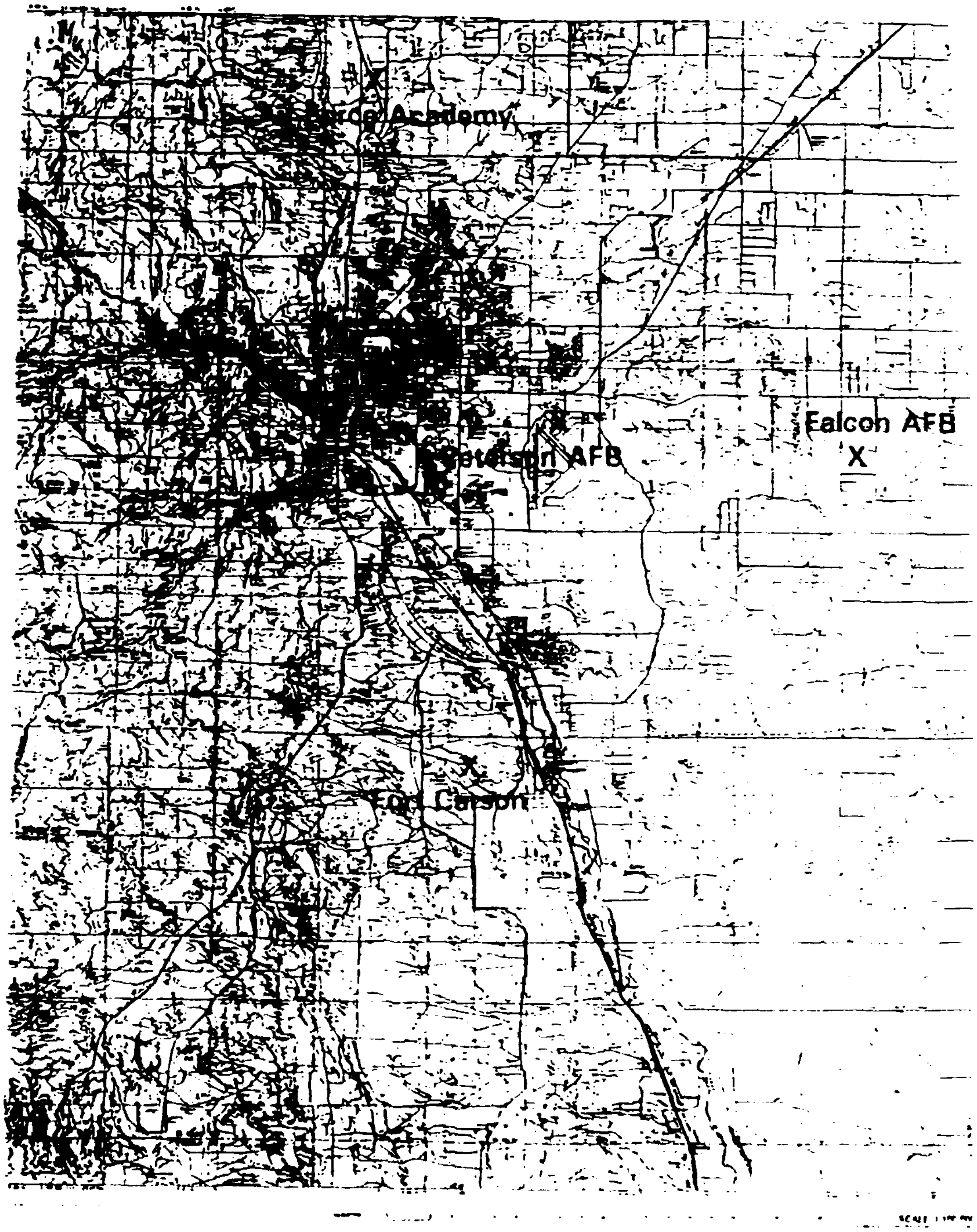

Figure 6. The Colorado Springs area, showing locations of military bases.

might have a major impact on northerly wind events at Peterson AFB and Falcon AFB.

There are numerous canyons along the foothills that may further affect the winds around the city. At the USAFA, Pine Valley is known to funnel winds onto the airfield, and the Community Center is also situated in a location known for funneling effects. Ute Pass, which opens into the southwestern neighborhoods of the city, alters the winds in that area, and on the southern face of Cheyenne Mountain is Dead Man's Canyon, which is suspected by the present staff of the Fort Carson weather unit to be involved in the formation of winds which impact that base.

The normal diurnal wind condition for the Colorado Springs area is a classic mountain breeze. During the day, the Rampart Range and the Palmer Ridge have a higher potential temperature than the surrounding air over the plains, which results in a steady southeasterly flow. After sunset, the slopes cool faster than the surrounding air over plains, leading to a northwesterly flow. This diurnal cycle occurs every day in the absence of any stronger effects.

Denver, the location of the nearest routine rawinsonde observation, is 70 miles north of Colorado Springs, on the other side of the Palmer Ridge, and 1000 feet lower in elevation.

Chapter 3

OBSERVING SYSTEM

The High Wind Alert System is a network of seven sensors placed at strategic locations around the Air Force Academy, six in the foothills and one on top of one of the peaks of the Rampart Range (figure 7). Each sensor is built around a Synergetics model 3400 remote computer system, and samples the wind speed, direction, and air temperature once per second. The Rampart location (on a mountain peak close to the 700 mb level) has, in addition, a barometric pressure sensor. The maximum, minimum, and average wind speed, average wind direction and standard deviation, and average temperature (and also barometric pressure at the Rampart sensor) are calculated once per minute, and this data is transmitted via VHF to the receptor located at the USAFA weather station. Each sensor location is powered by a battery which is recharged by an 18 Watt solar panel. The wind sensors are protected by ice skirts, and the temperature sensors have sun shields. An eighth sensor, to be located at the cadet area, is planned.

The receptor is built around an 80286 personal computer. The display at the receptor shows the real-time data from each of the sensors. It is possible, through simple keystrokes, to change the display to show the temporal trend from a single sensor, or to obtain hard-copy output at any time. A secondary display at the Peterson AFB weather station displays the same information as at the USAFA. The software of the receptor is configured to save the 10,000 most recent values from each sensor variable. Twice weekly, these data are archived onto floppy disks. The

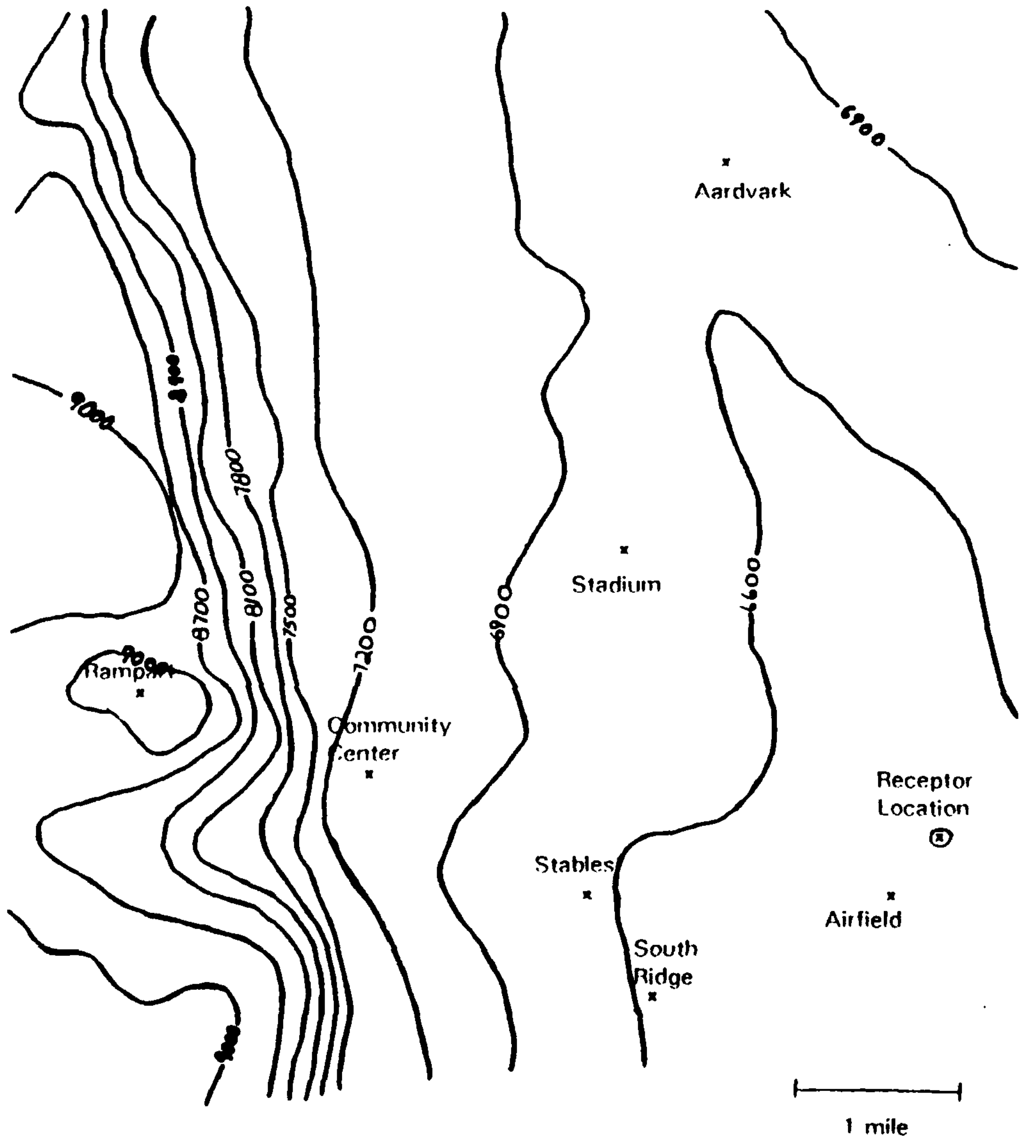

Figure 7. Topography of the United States Air Force Academy and locations of High Wind Alert System sensors.

current practice is to save the single-minute data values from each 15 minute interval onto the disks.

It is possible to configure each sensor to transmit an alarm signal whenever an established threshold in one of its observed variables is exceeded. Currently, alarms sound at the USAFA weather station and USAFA flying units when sensors exceed 25 or 35 knots.

In addition to HWAS data, the USAFA weather station takes standard hourly observations whenever the airfield is in use. The official NWS observation for Colorado Springs is taken by an ASOS at the municipal airport, which is co-located with Peterson AFB. A third observation is taken each hour by the weather personnel at Fort Carson. Falcon AFB has a wind recorder, but no observations or forecasts originate there.

The sum of these parts is a grid of available data with unusually high spacial and temporal resolution. All data mentioned are available at the USAFA and Peterson AFB at all times. Fort Carson does not readily have access to the HWAS. Therefore, this study focuses on the applications of the observing system to the requirements placed on Peterson AFB and USAFA forecasters.

Chapter 4

METHODS

The availability of these archived mesoscale observations makes this study an attractive prospect because it allows unique avenues of approach that are not possible when attempting to solve forecast problems at other locations.

Because of the complexity stemming from the number of bases involved, the study was broken into two parts. The goal of the first part was to gain an understanding of the differing impact of a single wind event on the various bases around the Colorado Springs area. During the 18 month period from January 1990 through June 1991, local records of many wind events were kept by the forecasters at each of the affected bases. These records were then periodically compiled and each event was grouped with other events showing similar characteristics. All events that were the result of convective activity were excluded from the study. Convective outflow, combined with the complexity of the terrain, was thought to create a forecast problem so difficult that it was not cost effective to pursue, and one which the instrumentation was not equipped to solve. Rather, only those events which resulted from larger scale pressure gradient, pressure surge, and frontal passage effects were investigated.

The second part of the study was to determine the usefulness of the High Wind Alert System to aid with timing the onset of each type of event. HWAS data from the period May 1991 through March 1993 were combined with the surface observations from the Colorado Springs airport to create a substantial database of wind activity in the area. The 15 minute temporal resolution of the archived HWAS data was thought to be sufficient for the intent of the study: a forecaster on duty cannot be expected to refer to the output from the system more than once every 15 minutes or so when the other requirements of his job are taken into account.

The usefulness of the High Wind Alert System was gauged using a skill-score based form of logistic regression that utilized an iterative approach, similar to that employed by Vislocky and Young (1988). Where Vislocky and Young used iterations of the per cent likelihood of event thresholds, this study employed iterations of the whole number threshold wind speeds from the HWAS. The output of the HWAS was used as the predictor set, with the wind speeds at Peterson AFB and the USAFA airfield as the predictands. The regression method used involved several steps.

The first step was to set the predictand wind speed for each observation to a value of "event" or "non-event" based on whether or not it exceeded a criterion speed. The second step was to make a first guess for a threshold wind speed for each predictor sensor. The threshold wind speed was defined as the value which indicated that an "event" at the predictand would occur within 60 minutes. Based on this first guess threshold speed, the wind speed values of the predictor sensors were set to "predict event" and "do not predict event." For example, if the South Ridge sensor was the predictor and the threshold speed was set to 20 knots, then every time the speed at this sensor exceeded 20 knots the forecast would be for a wind event to occur during the next 60 minutes, and every time it fell below 20 knots for 4 consecutive observations (at 15 minute intervals) the forecast would be for the wind event to end.

The third step was to calculate the success rate, false alarm rate, and skill score from each predictor. These values were defined as follows:

$$\text{SUCCESS RATE} = \frac{\text{Number of events forecast}}{\text{Total number of events which occurred}}$$

$$\text{FALSE ALARM RATE} = \frac{\text{Number of non-events forecast to be events}}{\text{Total number of non-events}}$$

$$\text{SKILL SCORE} = \text{SUCCESS RATE} - \text{FALSE ALARM RATE}$$

The threshold speed of each predictor sensor was then adjusted to different values, and the skill scores were re-calculated from the revised predictions. Many threshold speeds were tried for each predictor. The threshold speeds which resulted in the highest success rates and highest skill scores were noted for each sensor. From these results, the "best" sensors were chosen for use in multiple-sensor prediction schemes.

The multiple-sensor predictors used the two or three HWAS sensors speeds at a single time. Whereas in the example above only the South Ridge sensor was of concern, an example of a multiple-sensor predictor would be "if the South Ridge sensor speed exceeds 20 knots, and either the Airfield or Stadium sensor exceeds 15 knots, then predict an event at Peterson AFB."

The success rates, false alarm rates, and skill scores for the multiple sensor predictors were calculated. The threshold speeds for each sensor within each multiple-sensor predictor were again adjusted, and the skill scores were recalculated with each adjustment. Many iterations of these above steps were completed in an effort to determine the best overall prediction schemes and the empirical rules for forecasters in which they resulted.

In addition to the use of HWAS sensor wind speeds as predictors, an investigation into the usefulness of the temperature data from the sensors was also conducted. Because the HWAS has sensors that range in elevation from 6500 feet to above 9000 feet over a small horizontal distance, the ability to reconstruct the pseudo-vertical sounding every 15 minutes was thought to be a potentially useful benefit of the system. The occurrence of wind events versus changes in the vertical sounding up to the Rampart sensor was therefore studied. Also, the trends in bulk Richardson numbers obtained from the HWAS data were plotted for many events, and the implications of these trends on the occurrence of events were investigated.

Chapter 5
RESULTS

Differing Effects Between Falcon AFB and Peterson AFB

In studying the effects of wind events on each base, it was found that each wind event that affects Colorado Springs area can be assigned to one of four distinct classes. The class of each event can, for the purposes of this section, be determined purely by the direction of the surface flow. While previous studies employed a classification scheme based on the synoptic conditions, and while it is certainly prudent to do so when determining significant forecast variables, it was found that, where effects around Colorado Springs are concerned, only surface wind direction needs to be considered.

The four directional classes found were northerly, westerly, southwesterly, and southeasterly. The northerly events all had directions between 330° and 030°. The westerly ones were all 230° to 330°. The southwesterly ones were 180° to 230°, and the southeasterly were 150° to 180°.

In the northerly cases, caused by either cold frontal passages or cold air pressure-surges, it was found that Falcon AFB had maximum gust speeds which were faster than those at Peterson AFB. A total of 43 northerly cases were documented during the period of January 1990 to June 1991, although there were probably many more that went undocumented. Of these 43 cases, 40 of them resulted in a faster wind speed at Falcon than at Peterson. In 18 of those 40 cases, Peterson AFB never exceeded the threshold value of 25 knots. The average maximum wind speed, for the duration of each event, was 9 knots higher at Falcon than at Peterson. Falcon AFB exceeded the threshold value in every case. For the 25 cases in which both Falcon AFB and Peterson AFB reached or exceeded the threshold speed, Falcon's onset time averaged more than one hour earlier than Peterson's.

For the westerly (down-slope) events, the distinction was not as great. 21 such events were recorded, in 12 of which Falcon had the faster winds and 9 of which Peterson had the faster. In 3 of the 12 cases in which Falcon had the faster gusts Peterson did not exceed warning or advisory criteria. It should also be noted that 2 of the cases in which Peterson had the faster winds resulted in at least one gust above 50 knots at that location. The onset time of this class of events also showed no selectivity based on location, nor was there any correlation between the location which blew first and the location which blew fastest.

The southwest events showed the same distinction as the northerly ones. There were 20 such occurrences, in 19 of which Falcon was the windier base. Peterson failed to reach threshold in 7 of these 19. Falcon averaged 8 knots faster per event than Peterson, while there were 2 cases in which the difference exceeded 20 knots. The timing difference, for the events in which both reached criteria speeds, was less. Falcon usually reached threshold 30 minutes before Peterson.

Only 2 southeasterly cases were recorded. Southeasterly flow is the diurnal condition that exists is Colorado Springs in the absence of stronger effects. An anomalously strong potential temperature gradient between the high plains and the foothills of the Rampart Range must be present for the diurnal winds to reach significant speeds. In both of these cases Falcon AFB exceeded the threshold speed while Peterson AFB did not.

Differences Between Peterson AFB, the USAFA, and Fort Carson

Two significant features were noted regarding the differing impact of wind events between the USAFA, Fort Carson, and Peterson AFB. The first is that northerly cross-isobaric wind events do not affect the USAFA or Fort Carson enough to cause winds to exceed advisory criteria. Events which cause 25 knots at Peterson, and 35 knots at Falcon, cause less than 20 knots at the two other locations. It is suspected that their close proximity to the mountains is part of the cause of this (Peterson AFB TFRN, 1992).

The second is that northerly winds associated with an isobaric situation affect the USAFA and Fort Carson with roughly the same speeds as Peterson. These events distinguish themselves by the existence of a pressure gradient opposite to the climatological norm. Through a number of mesoscale pressure and temperature charts produced using the available data on days when there was no significant weather, it was determined that the USAFA and Fort Carson have a sea level pressure that is routinely 1 to 2 millibars lower than at Peterson. This is not surprising, given their closer proximity to the Rampart Range and thus their higher potential temperature and greater buoyancy of the air above them. Similar mesoscale charts produced during isobaric wind events showed that this pressure gradient was seen reverse somewhat, with the pressure at Peterson becoming slightly lower than that at Fort Carson.

Results from the High Wind Alert System Data

The stochastic analysis of the HWAS data was limited to improving the timing of wind events at the USAFA and at Peterson AFB only. Since the forecasters at Fort Carson do not have direct access to the HWAS yet, empirical rules based upon it are of little use to them. Falcon AFB no longer has any weather unit concerned with local observations. While there was such a unit in place during the first part of this study, all warnings for Falcon AFB are now issued by the duty forecaster at Peterson AFB, mostly based on the Colorado Springs observations. Also, the data from the Falcon AFB wind recorder are not archived as they are at Peterson AFB and the USAFA, thus making direct study of the wind speed there very difficult .

In 39% of the northerly events at Peterson AFB, none of the sensors of the HWAS showed winds above the criterion speed before they occurred at Peterson. This finding is particularly intriguing because the USAFA, and thus the HWAS, lies upwind of Peterson AFB during northerly wind events. One explanation for this departure from self-advection may be that the Austin Bluffs are causing a wave effect of the type described by Clark and Peltier (1977, 1979, 1984). The bluffs rise a dramatic 100 meters above the surrounding terrain on their northern side, and a more dramatic 175 meters on their southern side, with a half width of 1 to 1.5 kilometers. This creates an aspect ratio between 0.07 and 0.18. The Froude number, the dynamic parameter used by Clark and Peltier, is stated as $Fr = a^2N^2/U^2$, where a is the half-width of the topography, N^2 is the Brunt-Vaisala frequency, and U is the background wind speed. For a half-width of 1000 meters, an N^2 value of 1×10^{-4} (assuming a potential temperature increase of 3^o Kelvin in 1000 meters, using the South Ridge and Rampart sensor data), and a wind speed of 10 m/s impinging on the northern side of the Bluffs, the Froude number is on the order of 1. According to Peltier and Clark, this indicates waves in the internal gravity wave regime in which, if a critical aspect ratio is exceeded, the wind may form rotors and breaking internal waves. This highly non-linear condition leads to the down-slope flow being much greater than would be expected by linear theory (Peltier and Clark, 1979). While much more study would have to be conducted before this explanation for the faster northerly winds at Peterson could be fully justified, it is nonetheless a plausible argument at this time.

Therefore, because the winds at the HWAS sensors are so frequently lower than those at Peterson during northerly events, the threshold values assigned to the sensors used as predictors, as described in the methods, were significantly less than the criterion speed. An example of the performance of individual sensors is provided by table 2. Figure 8 shows a example of a plot of the Peterson AFB wind speed versus the wind speed at a predictor sensor 45 minutes before.

From individual sensor data such as those in table 2, the "best" sensors were chosen, and were grouped together to form multiple sensor predictors. The multiple sensor predictors which had the highest success rates and highest skill scores for predicting wind events at Peterson AFB are shown in table 3.

As shown by tables 2 and 3, the most successful multiple-sensor predictors proved to be significantly better than the best single-sensor

TABLE 2. Relative forecast ability of High Wind Alert System sensors to predict onset of wind events at Peterson AFB. Data are averaged from 30, 45, and 60 minute lead-times. The threshold speed used is 20 knots.

SENSOR	SUCCESS RATE	FALSE ALARM RATE	SKILL SCORE
Community Center	65%	42%	23
Airfield	60%	36%	24
South Ridge	73%	36%	37
Stables	48%	31%	17
Aardvark	36%	17%	19
Rampart	64%	61%	3
Stadium	49%	28%	21

Table 3. Relative forecast ability of several multiple-sensor predictors to forecast the occurrence of wind events at Peterson AFB. An event was considered "predicted" if the required thresholds were exceeded at any of the 30, 45, or 60 lead-time observations. A predicted event at any of the 30, 45, or 60 minute lead-time observations which did not occur was considered a false alarm.

PREDICTOR	SUCCESS RATE	FALSE ALARM RATE	SKILL SCORE
South Ridge >22kts, and either Stadium or Airfield >20 kts	77%	32%	45
South Ridge >22kts, and either Stadium or Airfield >18 kts	80%	36%	44
South Ridge >20kts, and either Stadium or Airfield >20 kts	80%	36%	44
South Ridge >21kts, and either Stadium or Airfield >20 kts	77%	36%	41

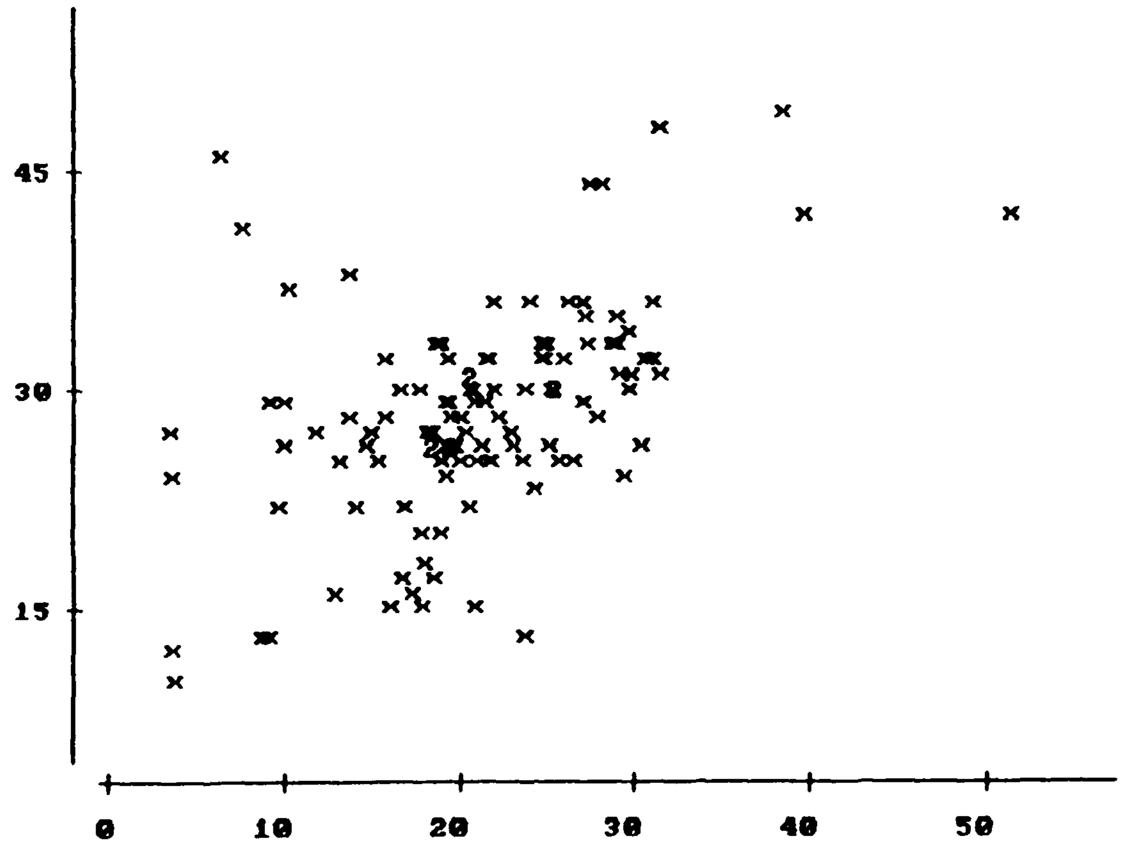

Figure 8. Scatter plot of Peterson AFB wind speeds (vertical axis) versus South Ridge sensor wind speeds 45 minutes earlier.

predictors for forecasting events at Peterson AFB. Unfortunately, the success rates were not high enough to be acceptable, and the false alarm rates were high enough that they would result in much unnecessarily-lost work time due to un-needed wind warnings. While it was possible to achieve a near-zero false alarm rate with the available data, the success rates when this was achieved were lower than those shown in the table. Likewise, all attempts to improve the success rate above the 90% level resulted in a false alarm rate above 50%.

Due to these low success rates and high false alarm rates, it is difficult to suggest any empirical rules for forecasting wind events at Peterson AFB based on wind speed data from the HWAS. A success rate of 80% and a false alarm rate of 36% are both worse scores than those acceptable to Air Weather Service. Forecasters at Peterson AFB must employ other data in addition to the HWAS in order to achieve the required success rates when forecasting moderate intensity wind events.

However, the success rates for single HWAS sensors when forecasting wind events for the USAFA airfield were significantly better than they were for forecasting wind events for Peterson AFB. These success rates, false alarm rates, and skill scores are shown in table 4.

As the table shows, the higher success rates were accompanied by higher false alarm rates as well. Table 5 shows the multiple sensor predictors that had the highest success rates and skill scores. It is apparent, when tables 4 and 5 are compared, that the use of multiple sensor predictor schemes resulted in increases in the false alarm rates over single sensor predictors, while the success rates were not significantly increased above those from the best single sensors.

Table 4. Relative forecast ability of individual High Wind Alert System sensors to predict wind events at the USAFA airfield with 30 minutes of lead-time. Threshold speed for all sensors is 20 knots.

SENS R	SUCCESS RATE	FALSE ALARM RATE	SKILL SCORE
Community Center	95%	46%	49
South Ridge	98%	50%	48
Stables	87%	31%	56
Aardvark	58%	24%	34
Rampart	76%	60%	16
Stadium	79%	38%	41

Table 5. Forecast ability of various combinations of the South Ridge, Stadium, and Stables HWAS sensors for forecasting wind events at the USAFA airfield. Scores are based on the 30, 45, and 60 minute lead-time predictions of the predictor variables.

PREDICTOR	SUCCESS RATE	FALSE ALARM RATE	SKILL SCORE
Any two speeds >25 knots	92%	38%	54
One speed >25 knots, one other >22 knots	94%	46%	48
One speed >25 knots, one other >20 knots	96%	51%	45
One speed >22 knots, one other >20 knots	98%	58%	40
Any two speeds >20 knots	98%	60%	38

Nevertheless, these success rates are good. They demonstrate that the HWAS is a valuable asset to the USAFA forecasters for forecasting moderate intensity wind events. While the false alarm rates indicate that additional data outside of the HWAS is required to maximize the amount of available safe flight training time, the number of missed events and events forecast with insufficient lead time can be dramatically reduced when the HWAS is properly employed.

In addition to the benefits of the system described above, a separate aspect of this study, conducted independently by Staff Sergeant Jack Cooksey, produced a highly useful empirical rule from the HWAS data. It was discovered that, when the Rampart sensor showed a speed exceeding 35 knots, the Community Center sensor will experience the same wind speed 30 to 45 minutes after the temperature difference between the two sensors first exceeds 12 degrees Fahrenheit (Cooksey, 1993). Not surprisingly, this temperature difference corresponds to an adiabatic lapse rate between the two elevations. This rule was tested using the available data and found to work 83% of the time. This method provides an empirical rule for issuing wind warnings for the cadet and housing areas of the Academy, which is a requirement placed on the USAFA forecasters. This rule is useful for the USAFA airfield and for Peterson AFB because forecasters traditionally watch for the Community Center winds to reach criteria speeds before issuing warnings for the lower elevations.

Efforts similar to those of Staff Sergeant Cooksey were made using the lower elevation sensors in an attempt to forecast the onset of wind events at the airfield directly, without having to rely on the Community Center sensor. In contrast to the success of the Community Center, no empirical rules of any statistical significance using this method have yet been found for the other USAFA sites. The adiabatic mix-down of the 700 millibar wind speed to the surface is, of course, nothing new. What is significant is that it is now possible to determine when, to the exact minute, the vertical sounding reaches adiabatic, what the 700 millibar winds overhead are at the same time, and that an old forecast technique which previously involved elements of extrapolation and a little guess-work has now been verified by modern technology.

However, in addition to the skill-score based logistic regression results above, study of the trends in various bulk Richardson numbers derived from the HWAS data provided another possible empirical rule. Several bulk Richardson numbers, each using the data from two sensors, were tried. The two sensors that proved most useful in this endeavor were South Ridge and Aardvark.

In every case of a northerly wind event at Peterson AFB, a visible spike in the South Ridge to Aardvark Richardson number trend appeared during the 90 minutes before onset. This Richardson number normally had values very close to zero, due to the very small potential temperature gradient between the two sensors. For a spike to have appeared in its trend, either the potential temperature gradient must have become very large, or the wind difference must approach zero. What was discovered is that, for a short time with the passing pressure-surge or cold front, the wind vectors at the two sensors became nearly identical. This occurrence appears to be a tell-tale sign that an expected pressure surge has crossed the Palmer Ridge and is on its way to Peterson AFB. An example is shown in figure 9.

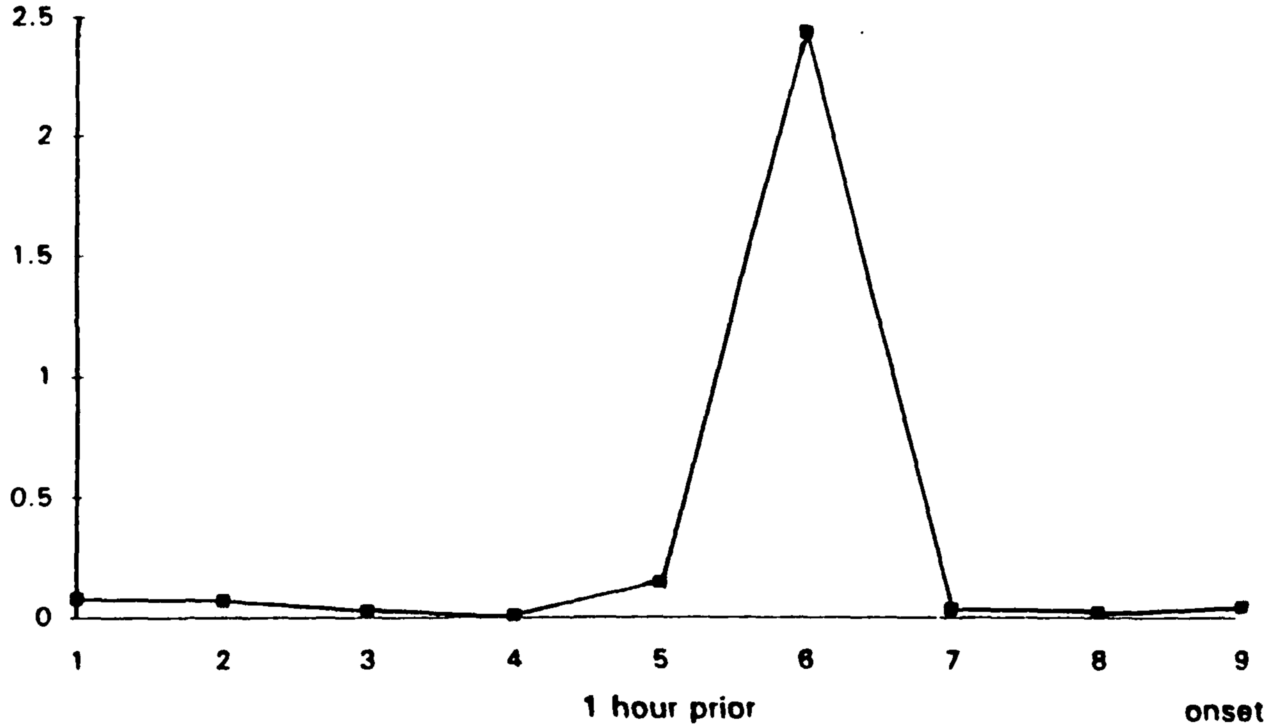

Figure 9. Temporal trend of the South Ridge to Aardvark bulk Richardson number (vertical axis) preceeding the onset of a wind event at Peterson AFB. Each time step (horizontal axis) represents 15 minutes.

Unfortunately, the implication of these results for improving wind event forecasts for Falcon AFB is that the HWAS presently remains of little use. Since Falcon AFB experiences the northerly wind events as much as an hour or more before Peterson AFB, the lead-time provided by this use of the HWAS for Peterson AFB is insufficient for Falcon AFB. Peterson AFB forecasters charged with issuing wind warnings for Falcon AFB must continue to rely on present methodology.

Chapter 6

CONCLUSIONS

The usefulness of the Air Force Academy High Wind Alert System as a tool to aid in forecasting the timing of moderate intensity wind events at various locations around the city of Colorado Springs was investigated through a statistical analysis of the data archives of the system from days on which the synoptic conditions indicated the possibility of a moderate intensity wind event. A skill score-based form of logistic regression was used to determine the capability of the individual sensors, as well as multiple sensor combinations, of the High Wind Alert System to aid forecasters with timing the onset and end of wind events. The results of this statistical analysis did not lead directly to any empirical rules useful for forecasters, because the forecasting ability of the system by itself showed skill scores which were little better than those obtained by forecasters prior to the installation of the High Wind Alert System.

However, four possible empirical rules for forecasting wind events in the Colorado Springs area were determined during the course of the study, two of which use the output from the High Wind Alert System. The first is that, if Peterson AFB is expected to experience a northerly wind event, based on synoptic conditions, the onset of winds should be predicted to occur 45 minutes after the onset of similar winds at Falcon AFB, but they are not likely to be as fast as Peterson AFB as they are at Falcon AFB. The fact that Falcon AFB is situated at a higher elevation than Peterson AFB is the most likely reason why this is the case. The presence of the feature known as the Austin Bluffs, which may temporarily shield Peterson AFB from northerly winds for a short period before time of onset of an event is also a plausible explanation for this.

The second empirical rule is that if Falcon AFB experiences a southwesterly wind event, Peterson will follow within 30 minutes, but again with winds generally slower. Again, Falcon's location, which is higher and 8 miles further away from the mountains of the Rampart Range, is the most likely cause for this.

The third rule, from the HWAS, is that Peterson AFB should expect a (previously-anticipated) northerly wind event one half hour after the South Ridge and Aardvark sensors exhibit identical velocities. This phenomenon, initially noticed as a spike in the Richardson number trend using those two sensors, appears to indicate that the anticipated cold front or pressure surge has crossed the Palmer Divide to the north of the Air Force Academy.

The fourth empirical rule is that the upper areas of the USAFA will encounter wind speeds equal to those found at the 700 millibar level one half hour after the vertical temperature profile to the 700 millibar level becomes adiabatic. The constant availability of real-time 700 millibar data from the Rampart sensor makes this rule very useful, and it verifies that the forecasting technique of predicting the surface wind speed in a wind event from the 700 millibar wind speed, used for many years, remains valid.

In addition to these empirical rules, the usefulness of the High Wind Alert System for forecasting moderate intensity wind events was found to be greater for the USAFA airfield than for Peterson AFB. The "best" single sensors and multiple sensor forecast schemes have been stochastically determined, and show that success rates are acceptable when the system is employed at the USAFA, but are not acceptable when the system is employed at Peterson AFB. For both bases, the false alarm rates caused by using the system independent of other forecast guidelines are unacceptably high.

The implications of this study for other meso-scale networks at other locations appear to indicate that, in complex terrain, the data from such a system is more applicable closer to the sensors, and that locations as little as 15 miles from the sensors require additional information where there are requirements for issuance of wind warnings. In all cases, a human forecaster with a strong knowledge of the synoptic precursors of wind events is necessary in order for the output from such systems to be properly interpreted and employed.

When this study was initiated, it was hoped that the High Wind Alert System would be the solution to the vexing problem that the wind has always presented in Colorado Springs. It was thought that, for each type of wind event, at least one of the HWAS sensors would provide key information that would give an hour lead-time before the wind affected any of the other bases in the area. This has not been the case. However, with further analysis, it is possible that additional empirical rules may be discovered based on the system output.

One problem with the HWAS that must be remedied first is the replacement or repair of the hard disk that stores the data prior to archival. Much of the Rampart sensor data was damaged or lost, and the reason for this has only recently been discovered as a faulty hard-disk at the receptor. With a larger data set from the Rampart sensor, guidelines for forecasting the onset of westerly and southwesterly winds may be discovered.

This study is, by no means, terminated. Without doubt, Staff Sergeant Cooksey will continue his pursuits while he is stationed at the USAFA. The staff of the Fort Carson weather unit has requested that this research be expanded to discern the causes of unexpected 50 knot gusts that occasionally plague their customers. The author will not be satisfied until all events are forecast with sufficient lead-time and little timing error.

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