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# The interaction of eolian sand transport, vegetation, and dune geomorphology: Currituck Spit, Virginia-North Carolina

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# THE INTERACTION OF EOLIAN SAND TRANSPORT, VEGETATION, AND DUNE GEOMORPHOLOGY CURRITUCK SPIT, VIRGINIA-NORTH CAROLINA



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by

Andrew L. Gutman

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APPROVAL SHEET

This thesis is submitted in partial fulfillment of

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MASTER OF ARTS

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## ABSTRACT

The three most important variables influencing eolian sand transport in the coastal zone are wind, vegetation, and moisture. Eolian sand transport, resulting from the interaction of these variables, is the dominant physical process responsible for the development, migration, and orientation of sand dunes along Currituck Spit, Virginia/North Carolina. Due to the present lack of overwash fans and inlets along the spit, eolian transport has also become the major source of cross-barrier sediment transport. The interaction of eolian sand transport, dune dynamics, and cross-barrier sediment transport was the subject of this study.

A detailed wind climate was compiled from one year (February 1, 1976-January 31, 1977) of local wind data acquired as part of this study, and 18 years of data (1953-1970) from Cape Hatteras, North Carolina 115 km to the south. The local wind regime along Currituck Spit is directionally polymodal, with prevailing winds from the north and southwest (20% and 32% of all observations, respectively) and dominant winds from the northeast, north, and northwest (mean wind speed approximately 8.0 m/sec). The strongest average wind speeds occur during December and the lowest in July. Rather than four distinct seasonal wind regimes, there is a long period of high velocity winds (October-June) and a shorter low velocity period (July-September). The comparison with Cape Hatteras wind data determined that the local record was typical of the long-term distant wind regime.

These wind data analyses support the assertion (Goldsmith, et al., 1977) that the Currituck Spit multidirectional wind regime is responsible for the development of medano sand hills, by gathering together sand spread out over a sand sheet or old overwash fan, resulting in a heightened and steepened dune.

An increase in the moisture content of sand increases the threshold shear velocity, thereby decreasing the eolian sand transport for a given wind speed. When the moisture effects are included, there was a good correlation between the measured migration rate (6 m/year) of a sand hill and the rate predicted by an eolian sand transport model. If the effect of moisture had been ignored, the predicted migration rate would have exceeded the measured by 30%.

Vegetation is the most important variable other than wind in the eolian transport process. An increase in the vegetation density and/or height increases the value of the surface roughness parameter, thus reducing the transport rate. Varying amounts of vegetation along Currituck Spit, along with the wind and precipitation, control the migration and development of dunes, and the cross-barrier flux of sand.

The mean orientation (North 8° East) of a parabolic dune field is hypothesized to have resulted from the interaction between local wind climate and maritime forest vegetation. A vector wind resultant, compiled by taking into account the effect of vegetation, and the location of the sand source, compared well (within 20°) with the mean orientation of the parabolic dunes. This resultant was dramatically different from a resultant (West 30° North) based on only wind climate.

An eolian sand transport empirical model was developed to calculate the net directional movement of sand, after careful consideration of the coastal eolian transport mechanisms. One year of precipitation, temperature, and wind data were input into the model consisting of eolian transport equations of Hsu (1971) and Bagnold (1941), threshold shear velocity equation of Kadib (1964), and an experimental relation between precipitation and soil moisture content developed from field measurements. After verification by comparison with field measurements of eolian sand transport, the model was run for varying levels of vegetation density reflecting both the north-south and past-present differences in vegetation cover.

Forty years ago Currituck Spit contained a completely unvegetated sand sheet. The model predicts only a very small (2,000 kg/m/year) net onshore sand transport (despite a large gross transport). For the vegetation characteristic of twenty years later in False Cape State Park and today near Corolla, North Carolina (i.e., mostly sparse dune grass) the model predicts a net onshore transport of 10,000 kg/m/year.

A continuous 40 year sand fencing program in False Cape State Park succeeded in creating a high (2-4 meters) multiple-ridge foredune. Vegetation has become very dense across the interior. The model predicts in this case a net onshore sand movement that will be mostly trapped by the vegetated foredune system.

The understanding of dune dynamics, cross-barrier sediment flux, and the interaction of wind, sand, moisture, vegetation, and dunes determined in this study are used to suggest certain coastal resource management techniques (e.g., the planning design and effects of a sand fencing program). These studies indicate that the protection and encouragement of vegetation for stabilizing shifting eolian flat sands and migrating sand hills should be a prime coastal resource management objective.

# THE INTERACTION OF EOLIAN SAND TRANSPORT, VEGETATION, AND DUNE GEOMORPHOLOGY CURRITUCK SPIT, VIRGINIA-NORTH CAROLINA

# INTRODUCTION

## Eolian Coastal Processes

Wherever a large supply of sand is available to be transported by the wind in a temperate coastal zone, an interaction exists between wind energy, vegetation, and eolian sand transport and deposition. As sand is deposited on the beach by waves via longshore transport, onshore winds transport this material towards the interior sometimes winnowing out the fines. The net movement of this sand depends on the local wind regime and vegetation. With a unimodal onshore wind regime there will be a net movement of sand towards the interior regardless of vegetation. In coastal areas, such as the southeast coast of the United States, the wind regime consists of both onshore and offshore components. In a vegetation-free environment the net movement of sand will be in the direction of the dominant wind component. However, vegetation is an important factor determining the net movement of sand and the development of dunes.

Vegetation lowers the wind velocity both within, and down-wind of, the vegetation as a function of both the vegetation height and density. Where vegetation is downwind of a source of sand, perhaps a beach, deposition will occur in and around this vegetation. The vegetation which thrives with some but not too much sand burial, will continue to grow upwards, resulting in dune development. However, if vegetation (especially shrub and maritime forest) is upwind of a sand supply it will act to decrease the sand transport by reducing the downwind velocity. Therefore, the presence or absence of vegetation along with the local wind regime, will determine the net direction and amount of sand transport, either inland from the beach or seaward onto the beach, as well as the resulting development of dunes.

Moisture is another important variable in the eolian sand transport process. Soil moisture increases the wind velocity necessary to initiate sand transport. Since rain is often associated with maximum wind speeds, moisture can diminish the net movement of sand by wind during the time of maximum eolian sand transport. It is this interaction of sand transport, vegetation, moisture, and dunes which was investigated in this study.

## Geologic and Geographic History

Currituck Spit, extending from Cape Henry, Virginia to Oregon Inlet, North Carolina (Figure 1) is part of a long barrier island system that extends along the Virginia-North Carolina Coast. It has been hypothesized that these barrier islands have been migrating landward since their formation (Field and Duane, 1977; discussed in Zellmer, 1977), in response to the rise in sea level of approximately 1 cm/year over the last 6,000 years (Milliman and Emery, 1969) and 0.1 cm/year over the last 40 years (Hicks, 1973). Sutton et al. (1977) have documented the historical shoreline changes since 1850 along Currituck Spit. At False Cape (Figure 1) there has been an anomalous accretion trend of less than 1 m/year, while near Corolla, North Carolina historical erosion has averaged 2 m/year. Maximum historical erosion along northern Currituck Spit is about 4 m/year at Dam Neck.

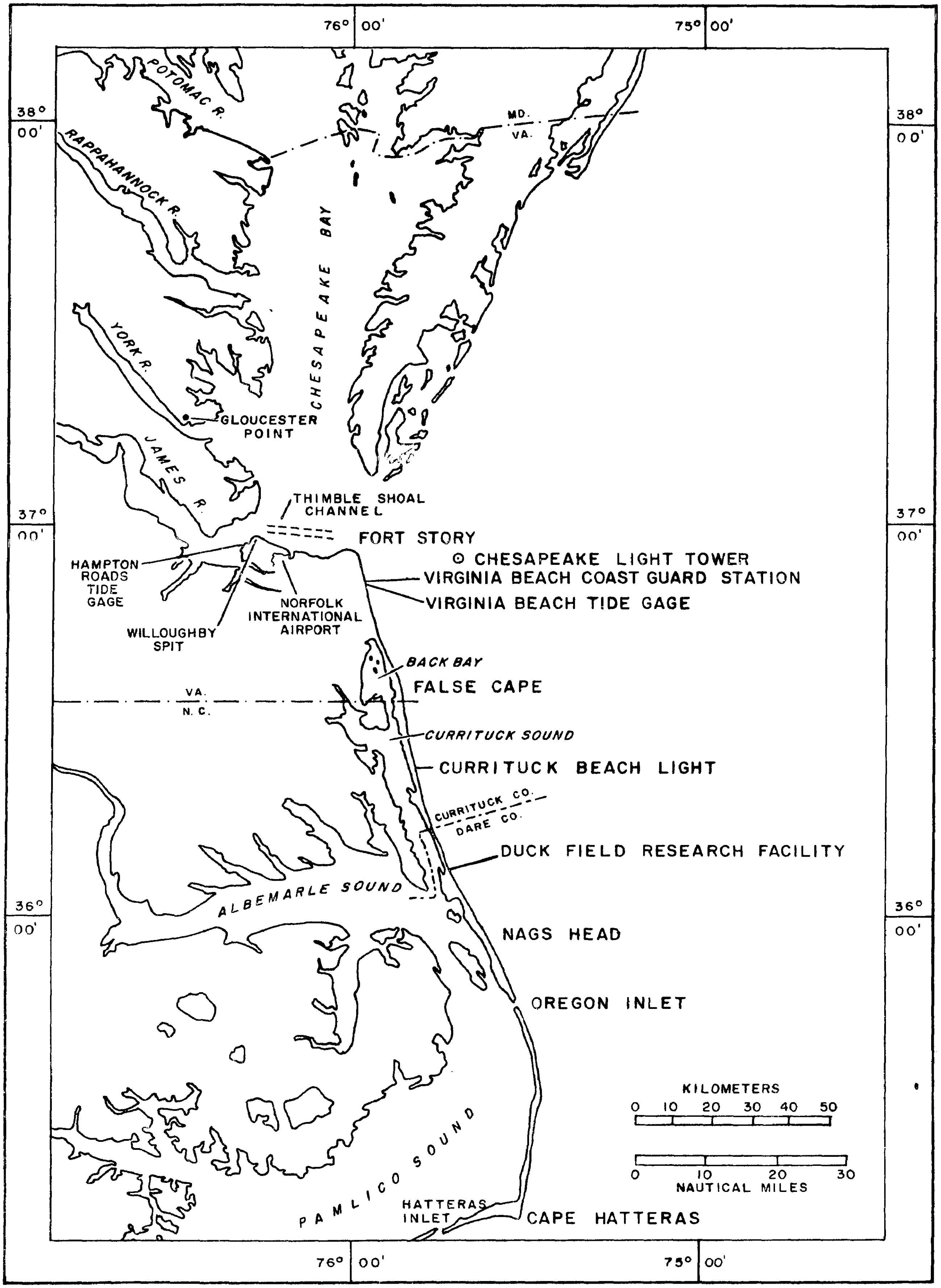



Figure 1. Regional location map.

The islands making up the Virginia-North Carolina barrier chain including Currituck Spit are generally narrow (0.5 km to 2 km) with elevations about 3 m except for the higher foredunes at False Cape (about 10 m) and the sand hills (up to 25 m). Washover channels and fans are presently rare and generally unimportant features due to the stabilization of foredunes by sand fencing and vegetation planting. However, over-washing was extensive in the past and as recently as 1962. Along Currituck Spit there are presently no inlets over a distance of 130 km. However, two inlets were present along Currituck Spit in the eighteenth and early nineteenth century (Hennigar, 1978): old Currituck Inlet, at the Virginia-North Carolina stat line, which closed in 1729 and New Currituck Inlet near Corolla which closed in 1812. Therefore, although Currituck Spit is a dynamic ecosystem responding to wave and wind energy, vegetation, and a slowly rising sea level, it is (geographically) very different today than in the historical and recent past.

Present Geography and Management of Currituck Spit

Currituck Spit presents a complex picture of coastal land use. Previously undeveloped sections south of the North Carolina/Virginia border are undergoing development as residential subdivisions. To the north, False Cape State Park and Back Bay National Wildlife Refuge preserve the section of barrier island south of Sandbridge, Virginia, from development pressures by prohibiting development, and in the case of Back Bay, by limiting access. However, these areas are subject to increasing pressures from recreational users, and the entire area may undergo rapid and complex usage changes in the next decade. The barrier island represents a fragile balance between the physical processes that form and maintain it. The ability of such a fragile ecosystem to withstand development pressures without major disruption is questionable.

To minimize the impact of development and recreational activities through coastal resource planning, an understanding is required of the interactive process and response system which determines the development, orientation and migration of sand dunes, the distribution of vegetation, the sediment dynamics, and the overall stability of the coastal ecosystem. Knowledge of coastal processes is required to evaluate coastal zone management problems and to initiate planning programs. The human and natural forces affecting the coastal zone, the present state of the ecosystem, and the effect of uses and prospective uses on coastal resources is important information for proper management of coastal ecosystems. This information can be best acquired through quantitative studies of the eolian processes in the area.

The most apparent and dominant geomorphic features in the study area are sand dunes. There are four basic dune types, discussed in detail by Goldsmith et al. (1977): (a) the medano sand hill or transverse dune ridge, (b) the parabolic or U-dune, and either the (c) artificially or (d) naturally created foredunes. These four dune types are unequally distributed along the Currituck Spit.

A cross barrier transect near Corolla traverses a very different environment than a transect at False Cape (see Figure 2A); the foredune system is lower (1-2 m) due to a lack of continual sand fencing (Hennigar, 1978), there is an absence of a shrub thicket and instead only sparse dune grass vegetation across the eolian flat, and large highly mobile medanos (10-25 m high) are presently invading the maritime forest. The nature of eolian sand transport is radically different in the two areas. The flux of sand across areas typified

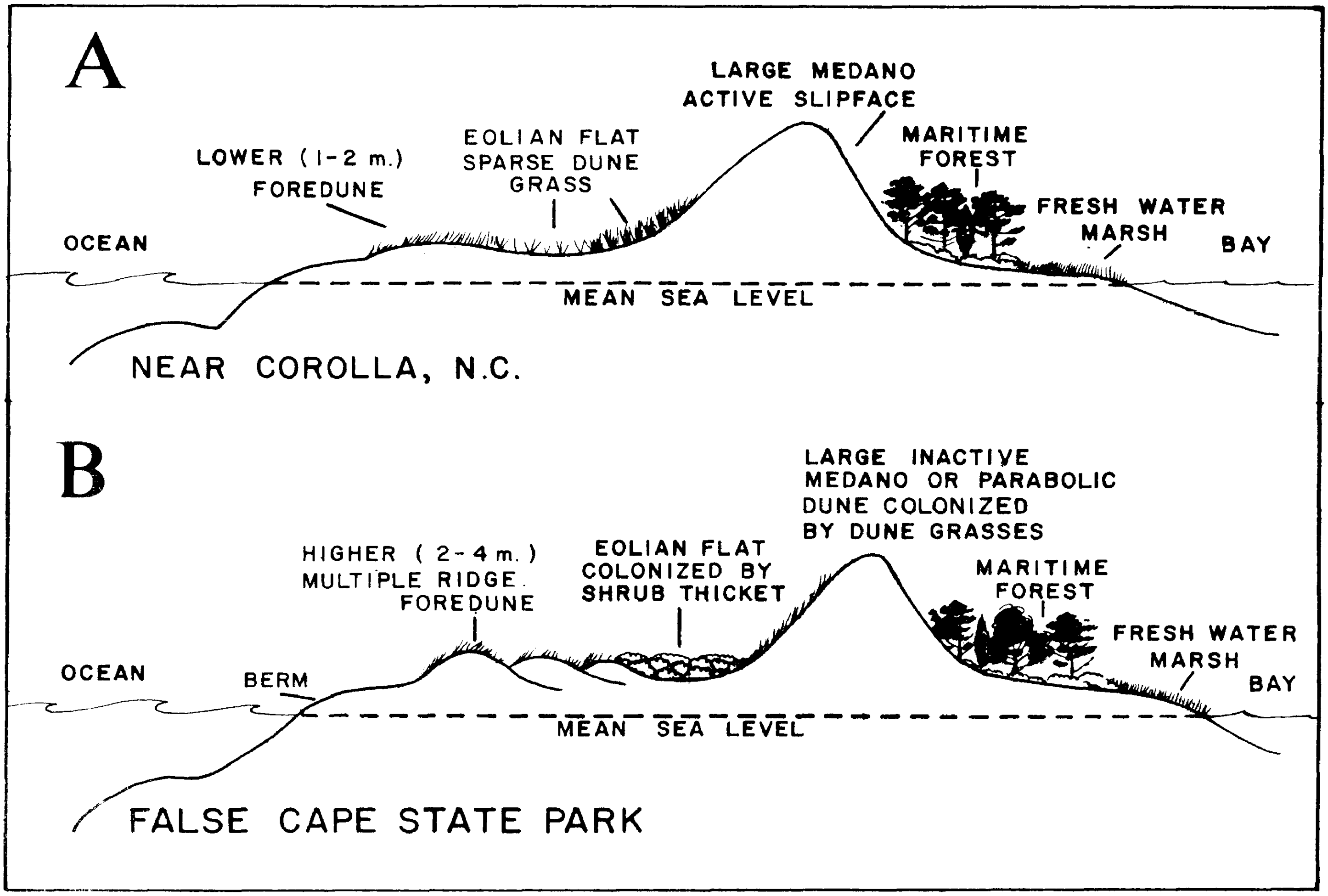



Figure 2. Schematic diagram of typical cross-barrier transects near Corolla, North Carolina (A) and False Cape State Park, Virginia (B). Notice the difference in the height of the foredunes and density of eolian flat vegetation.

by profile A (Figure 2) would be much greater than at areas similar to profile B due to the differences in vegetation cover.

A cross barrier transect in False Cape State Park (shown schematically in Figure 2B) first crosses a 2-4 meter high multiple ridge foredune system formed by 40 years of continuous sand fencing in the area (Hennigar, 1978). Landward along the transect, a 1-2 m high shrub thicket grows on the eolian flat. Then, depending on the location of the transect the next feature encountered is either a medano, or several parabolic dunes stabilized by dune grass vegetation. These dunes have been stabilized by dune grass at the edge of a maritime forest which grades into a freshwater marsh and then the Bay.

Pierce (1969), in constructing a sediment budget for a barrier island (Core Banks), concluded that not much of the eolian-transported sediment is permanently lost to the longshore system. A cursory look at Currituck Spit would show that millions of cubic meters of sand (Hennigar, 1978) are tied up in the many sand hills and parabolic dunes. Since these eolian deposits are eventually stabilized by vegetation and thus permanently lost to longshore system the conclusion drawn by Pierce for the Core Banks is not applicable to Currituck Spit. On the other hand, a Corps of Engineers report (New England Division, Corps of Engineers, 1968) estimated that over a period of twenty-five years, 1,000,000 $m^3$ of sand were blown from Nauset Beach, a barrier-spit, landward into Pleasant Bay. Of interest here is the fact that both of these estimates were derived from the amount of sand trapped by sand fencing. The estimates by Pierce and the Corps of Engineers probably represent the extremes.

A reliable quantitative and qualitative understanding of the interaction of eolian sand transport, vegetation and dunes is necessary for the purpose of estimating coastal sand budgets, for protection of structures from mobile dunes, for understanding the cause and effect relationship of human activities, for understanding the development, orientation, and migration of sand dunes, and to intelligently manage and protect the coastal ecosystem. This study addresses these fundamental and broad issues using methods outlined in the following section.

## METHODS

The specific details of the pertinent methods are included in each appropriate chapter. An overview of the methods used in this study is included here.

### Wind Regime

The most important variable determining the rate of sand transport, and the development, orientation and migration of sand dunes is the wind. Therefore a comprehensive wind climate was compiled for Currituck Spit detailing and comparing the long term, yearly, seasonal and monthly wind characteristics. A continuously recording anemometer was installed at the top of Currituck Light House (Figures 1 and 3) 53 m above mean sea level (MSL) for a one year period (February 1, 1976 to January 31, 1977) to determine an accurate and detailed local wind record. The data were digitized at 3 hour intervals and compared with long term wind data from the closest national weather station at Cape Hatteras, North Carolina. The wind climate determined from these data became the data input for a model of sand transport, for help in understanding sand size grading across the barrier spit and for the orientation and migration of the parabolic and medano sand dunes.

### Migration Rate of Sand Hills

The migration rate of large mendanos was determined by placing reference markers around the perimeter of two sand hills and then measuring the net movement of these dunes relative to the markers after

Figure 3. Views of Currituck Light House at Corolla, North Carolina, in February 12, 1977 (top) showing anemometer, and June 14, 1889 (bottom). The area that was pastureland for the light house keeper's fresh meat supply, was bare sand in the 1940's, is now being naturally revegetated.

a one year period. The migration rate thus determined was then compared with historical migration rates determined from aerial photographs, the wind climate over the same one year period, and the effects of vegetation.

## Orientation of Parabolic Dunes

Vegetation was also important in the development and orientation of parabolic dunes in False Cape State Park. The development of parabolic dunes was traced with a series of aerial photographs between 1939 and 1975 (discussed in detail by Hennigar, 1978). The orientation of the axes of the parabolic dunes were determined from recent vertical aerial photographs. These orientations were then compared with the vector wind resultants from the local wind data, the vegetation distribution, and shoreline orientation.

## Cross Barrier Eolian Sand Grading

Sand grading was investigated across two barrier spit transects, one in False Cape State Park, the other south of Corolla. Sand samples of the sand surface and the top 5.0 cm were collected at eight stations across each of the two transects, and then the grain distribution was analyzed using the Woods Hole Rapid Sediment Analyzer (Zeigler, 1960). The grain size statistics (expressed in sedimentation diameter) for these samples were plotted against distance across the transect. This eolian grading study was conducted in order to investigate the geologic processes responsible for the grain size differences in the subenvironments of the north and south transects, and to help clarify the role that eolian sand transport plays in the overall sediment dynamics of a barrier island.

Sand Transport Model

In order to quantitatively estimate the net movement of sand by wind across the spit in all directions an empirical eolian sand transport model was developed. This model utilizes equations developed by other investigators (Bagnold, 1941; Kadib, 1964; Hsu, 1973) as well as equations developed in this study. Field measurements of sand transport, wind profiles, and the relationship between soil moisture and threshold velocity were conducted for development and verification of the model, and for deriving an equation to predict soil moisture content using a canned computer linear least squares curve fitting program. Model output was utilized to aid in understanding the migration rate of sand dunes, the effects of moisture and vegetation on the transport process and for addressing the basic question of the role of eolian sand transport in the sediment dynamics of a barrier spit.

## WIND CLIMATE

Wind is the most important environmental variable determining the rate and net movement direction of eolian and transport, and the orientation and movement of sand dunes. A continuously recording anemometer was installed in February, 1976, 35 m above MSL on top of the Corolla Lighthouse (Figure 3) to provide an accurate and detailed local wind climatology. Wind data from the closest existing weather station at Cape Hatteras, North Carolina (approximately 115 km to the south) could not be used for description of the local wind regime without comparisons of simultaneous data, due to the possibility of regional variations in wind characteristics.

An anemometer was installed on top of the lighthouse because of its height, availability of electricity, and security for the equipment. The top of the lighthouse provided relatively unobstructed wind flow from all directions to the anemometer, while at other possible locations the anemometer would have been subject to eddies of wind caused by high sand dunes or forests. Nevertheless, the wind characteristics recorded by the anemometer were influenced by the lighthouse. The wind velocity at the top of the lighthouse (Figure 3) would increase due to compression of streamlines over the obstruction. Even though the anemometer was about 3 m above the top of the lighthouse the anemometer records winds effected somewhat by the lighthouse. Other investigators using these wind data in the future should keep this effect in mind.

A Bendix Aerovane Transmitter (model 120) was mounted on top of a 9 m telescoping tower which was bolted to the lower iron catwalk of the lighthouse. The transmitter was oriented north-south using the position of solar noon and then raised to its permanent position above the lighthouse. The electric output of the transmitter magneto (speed) and synchro (direction) were transmitted through a 20 m cable to a Bendix Aerovane Wind Recorder (model 141) which is a two-element recorder that simultaneously records, in separate channels, inked traces of wind direction and speed values on a strip chart. The chart paper operating at 3.81 cm/hour (1.5 inches/hour) was changed every 14 days and then returned to VIMS for digitizing. The anemometer has operated continuously since it was installed in February 1976 except 22 days (Appendix 1) for recorder repairs, withstanding wind speeds greater than 45 m/sec.

Date Analysis and Reduction

The wind data on the strip charts, now in storage at VIMS, were digitized by visually picking a wind speed and direction which represented an average value for each three hour period beginning at 0100 Eastern Standard Time. For each day eight average wind speeds and directions, the maximum wind speed for the day, and the direction associated with this gust, were recorded on a standard form for key-punching. This data format was chosen to coincide with standard National Weather Service procedures, in order to facilitate comparison of Corolla and National Weather Service wind records.

The wind data were initially processed using a computer program which lists each data point and the vector average wind speed and direction for each day. Appendix 1 is a listing of the twelve months of data processed using this program. To further aid in preparing a wind climate for Currituck Spit the digitized wind data were compiled into computer generated wind rose diagrams using the College of William and Mary Computer Center CALCOMP Model 665 digital plotter. The program which generates these plots is listed in Appendix 2. The average wind speed and duration for each direction in an eight point compass were computed according to the following relations:

$$A_i = s(\Sigma U_i/N_i)$$

and

$$B_i = s(N_i/\Sigma_{ni} \times 100)$$

where:

$A_i$ = average wind speed for each of eight wind directions
$B_i$ = average duration in percent for each wind direction
$U_i$ = wind speed for one three hour interval within each of eight class interval
$N_i$ = number of observations in each class interval
$\Sigma_{ni}$ = total number of observations for all eight wind directions
s = scaling factor for plotting
i = 1 to 8, for each wind direction class interval

Corolla Station Wind Climate

Figure 4 is a wind rose summarizing all data from the Corolla station anemometer for a one year period (February 1, 1976-January 31, 1977). The length and size of each arrow indicate the average wind speed and direction, while the shaded area indicates the duration of the wind from each direction. The highest average wind speed (8.0 m/sec) is associated with northerly winds, with both the northeast and southwest directions being within 0.5 m/sec of this average wind velocity. Thus, Figure 4 indicates at least three modes with respect to the highest average wind velocities (northeast, north, and southwest).

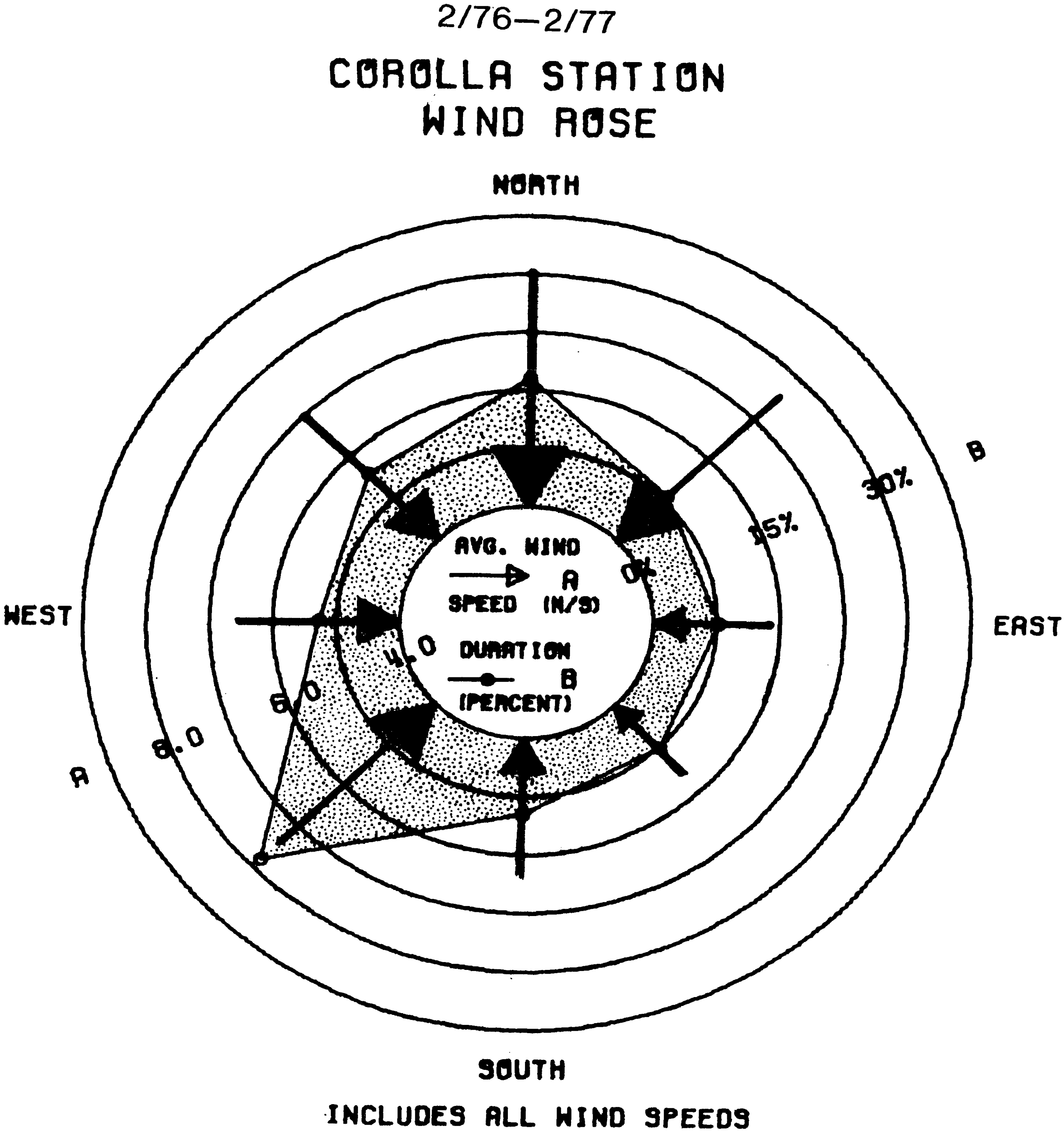



Figure 4. Corolla Station wind rose (February 1, 1976 to January 31, 1977) for all wind speeds. Average wind speed is indicated by arrows and scale A, while duration is indicated by shading and scale B.

The threshold wind velocity necessary to initiate sand transport is approximately 5.0 m/sec (Bagnold, 1941 for 0.25 mm sand). Therefore to establish a dominant (direction or directions from which highest velocity winds occur) and prevailing (direction or directions from which the most frequent winds occur) wind regime for Currituck Spit, it is more important to concentrate on higher wind speeds. Figures 5 and 6 are wind rose diagrams compiled by excluding all wind speeds less than 5.0, and 10.0 m/sec, respectively. In Figure 5 the highest average wind speeds are from the north and northeast (9.5 m/sec); however, the northwest, west, and southwest average velocities are only slightly lower. In Figure 6 the northeast, northwest, and north, directions have the highest average wind velocity (all > 13.0 m/sec).

Although the dominant wind regime changes only slightly in plots of increasing wind speeds, these plots show significant changes in the prevailing wind regime. In Figure 4, which includes all wind speeds, the southwest is clearly the prevailing wind direction with a duration of 30%, although there is a secondary mode in the north (15%). However, at higher wind speeds the north becomes increasingly important. In Figure 6, which excludes all winds less than 10.0 m/sec, the northerly winds are equal in duration to the southwest. Therefore these plots indicate no single dominant or prevailing wind direction but instead a polymodal wind regime. This has a profound impact on the dunes and sediment dynamics of the spit, and will be discussed in detail later in this thesis.

## Monthly and Seasonal Wind Regime

The Corolla station wind data summarized in Figures 4, 5, 6 and Appendix 1 were further broken down into monthly compilations to

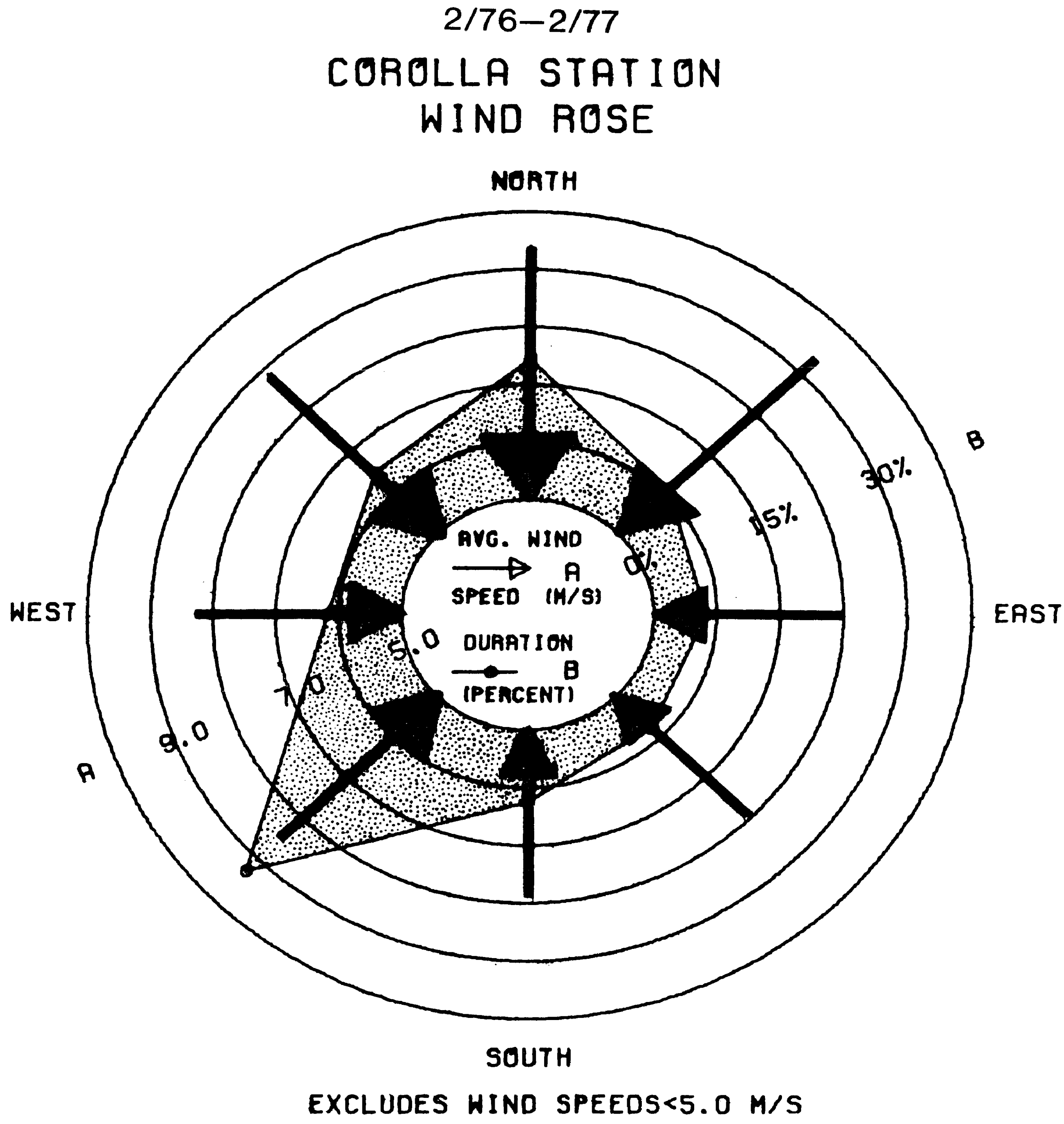



Figure 5. Corolla station wind rose (February 1, 1976 to January 31, 1977) for winds greater than 5.0 m/s.

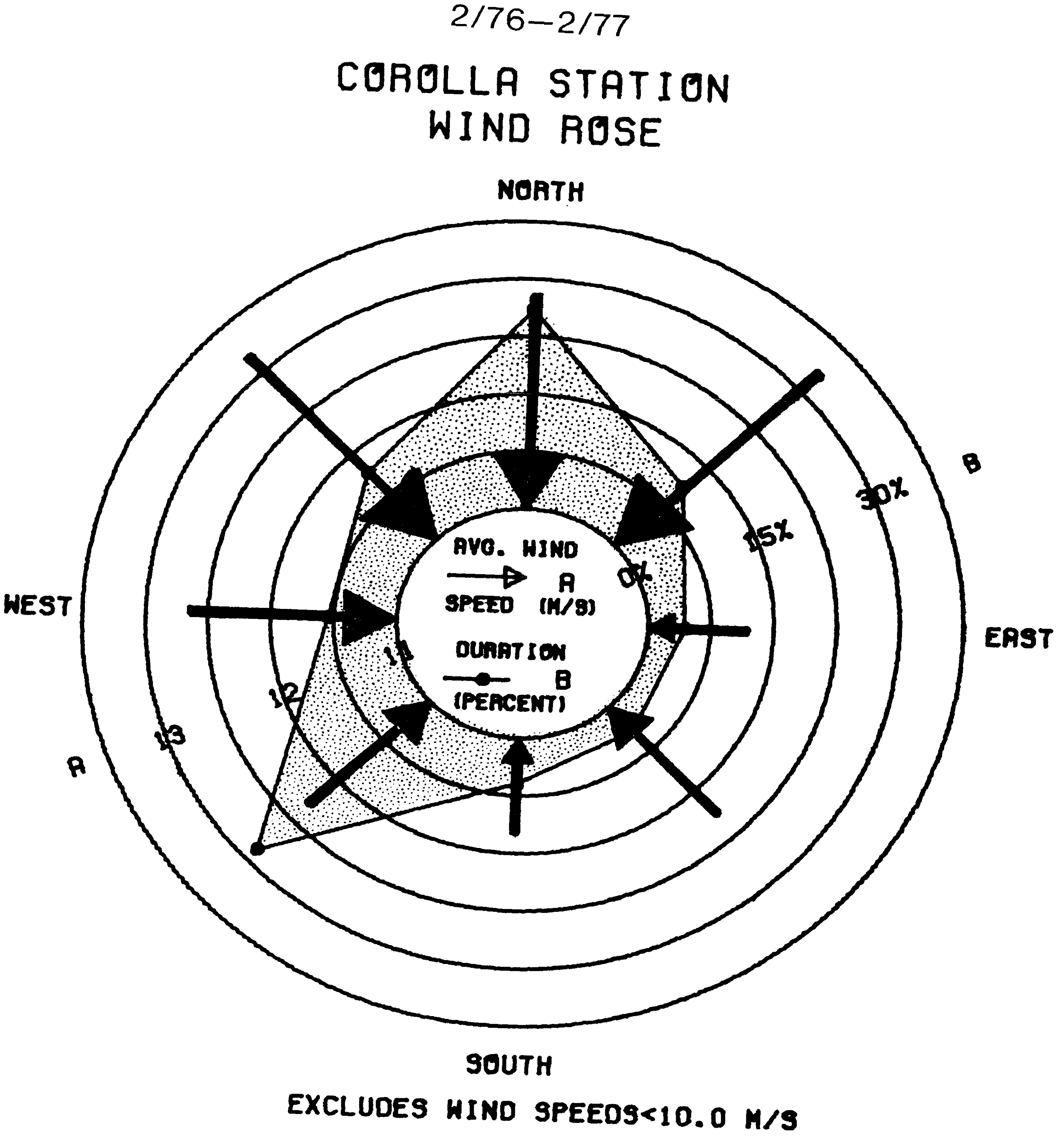



Figure 6. Corolla Station wind rose (February 1, 1976 to January 31, 1977) for winds greater than 10.0 m/s.

investigate the wind fluctuations on a shorter time scale.

Figure 7 shows the frequency of occurrence of wind speeds greater than both 5.0 and 10.0 m/sec on a monthly basis. Notice there is no obvious four-modal seasonality in this figure. Instead the lowest frequency occurrence of winds in both categories is during July, August, and September (55% > 5.0 m/sec, 10% > 10.0 m/sec) while between October and May over 65% of winds were greater than 5.0 m/sec and 20% were greater than 10.0 m/sec. Therefore rather than four distinct seasonal wind regimes there is only two indicated in this figure; a low velocity period during July-September and a higher velocity period during the rest of the year.

Figure 8 is a plot of the monthly mean wind speed. Table 1 lists the values plotted in this figure and the standard deviation associated with each monthly mean wind speed. The lower of the two lines in Figure 8 is a plot of the means computed from all wind speed data. Notice that this graph is very similar to Figure 7. Again there is no obvious seasonality but instead a period of low mean wind speeds (6 m/sec; July-September) and a longer period of higher mean wind speeds (7-8 m/sec; October-June).

The top of Figure 8 is a plot of the mean maximum wind speed foe each month. During digitizing of the strip charts a maximum wind speed and direction (see Appendix 1) were recorded for each day. The mean and standard deviation associated with each of these monthly maximum wind speeds are listed in Table 1. This figure, unlike the others, does indicate some groupings which can be loosely related to four distinct seasons. The summer period (June-September) has the lowest mean (11-12 m/sec), the winter and fall period have the highest

Figure 7.

PERCENT FREQUENCY OCCURRENCE OF WIND SPEEDS

GREATER THAN 5.0 AND 10.0 METERS/SECOND

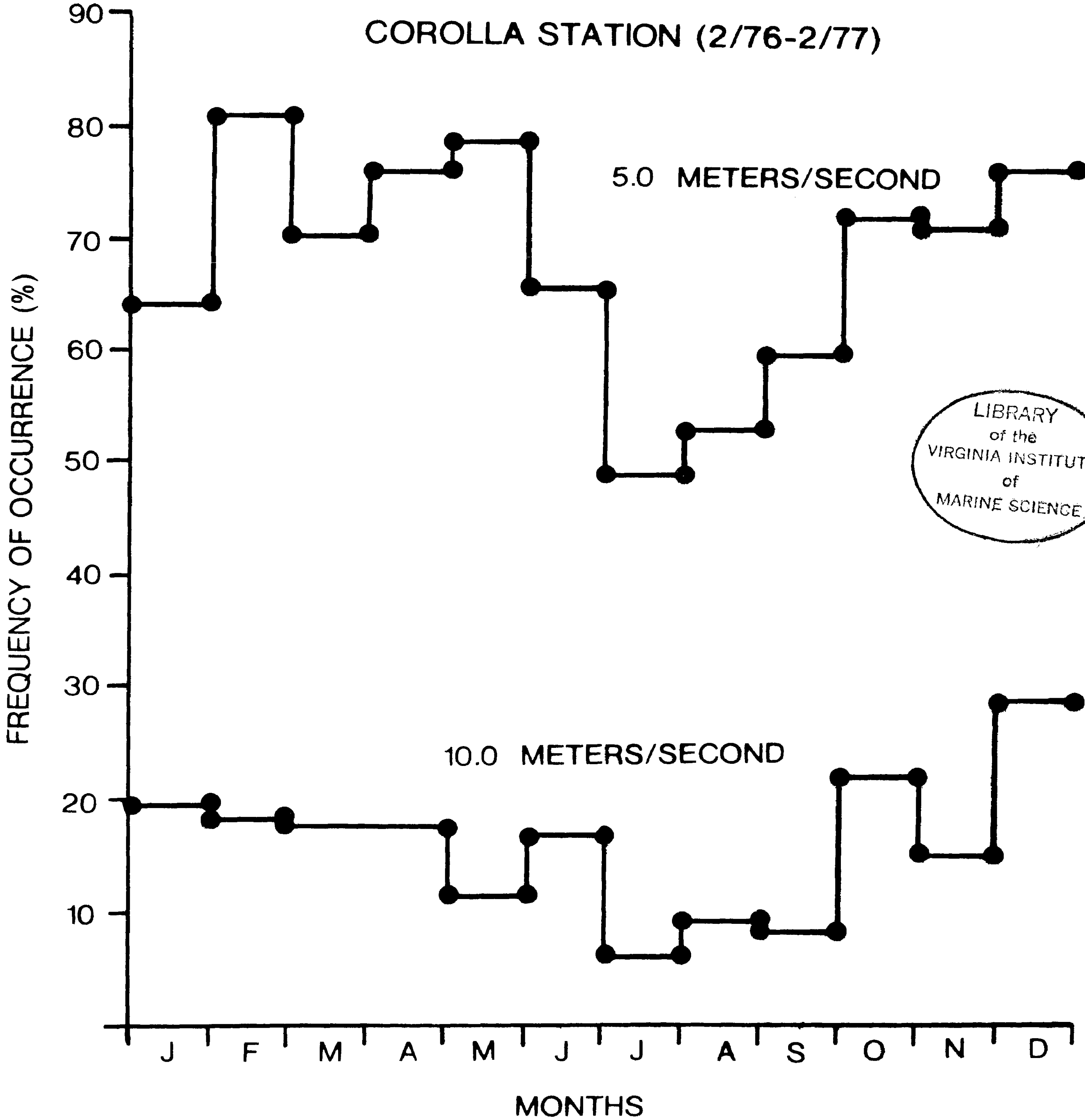


Figure 8.

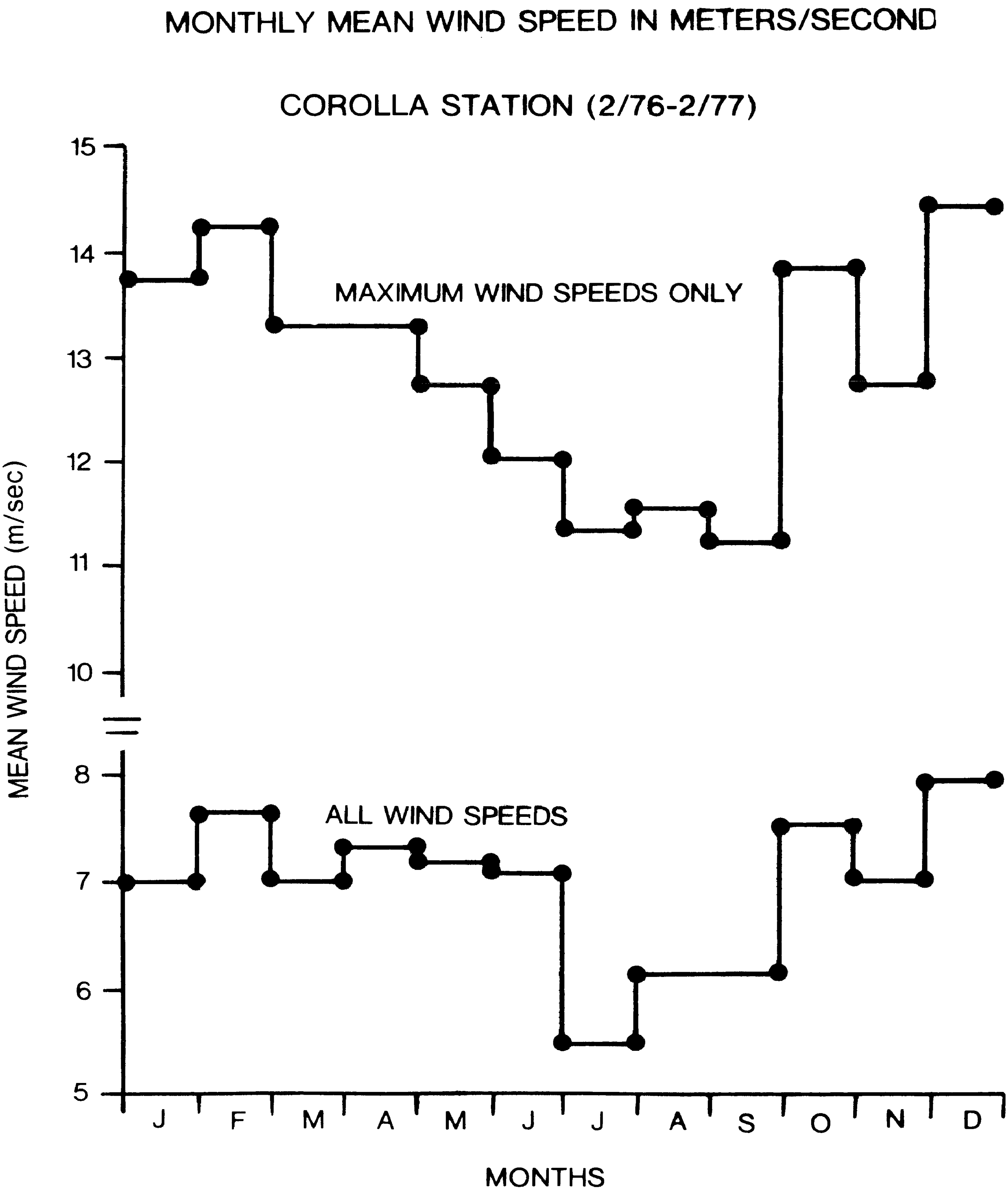

MONTHLY MEAN WIND SPEED IN METERS/SECOND
COROLLA STATION (2/76-2/77)
MAXIMUM WIND SPEEDS ONLY
ALL WIND SPEEDS
MEAN WIND SPEED (m/sec)
15
14
13
12
11
10
8
7
6
5
J F M A M J J A S O N D
MONTHS

TABLE 1

COROLLA STATION WIND DATA SUMMARY, FEBRUARY 1976-FEBRUARY 1977

| | % ≥ 5.0 m/sec | % ≥ 10.0 m/sec | All Winds (m/sec) Mean Wind Speed | All Winds (m/sec) Standard Deviation | Maximum Winds (m/sec) Mean Wind Speed | Maximum Winds (m/sec) Standard Deviation |
|---|---|---|---|---|---|---|
| January | 63.5 | 19.3 | 7.0 | 3.7 | 13.7 | 4.3 |
| February | 80.1 | 18.1 | 7.6 | 3.2 | 14.2 | 5.5 |
| March | 70.2 | 17.3 | 7.0 | 3.5 | 13.3 | 4.3 |
| April | 75.9 | 17.3 | 7.3 | 3.2 | 13.3 | 4.0 |
| May | 78.3 | 10.8 | 7.2 | 2.7 | 12.7 | 3.9 |
| June | 65.0 | 19.5 | 7.1 | 4.4 | 12.0 | 3.7 |
| July | 49.6 | 3.6 | 5.4 | 2.3 | 11.3 | 4.3 |
| August | 52.6 | 9.9 | 6.1 | 3.5 | 11.5 | 4.0 |
| September | 59.6 | 8.3 | 6.1 | 3.2 | 11.2 | 3.9 |
| October | 72.9 | 22.9 | 7.5 | 3.7 | 13.8 | 7.4 |
| November | 71.7 | 16.7 | 7.0 | 3.3 | 12.7 | 3.6 |
| December | 76.9 | 27.5 | 7.9 | 3.7 | 14.3 | 4.0 |

mean maximum winds speeds (14 m/sec), while the spring (March-May) is a transition period (13 m/sec). As indicated in this Figure and in Figure 7 both the greatest frequency of occurrence and highest velocity winds occur during December.

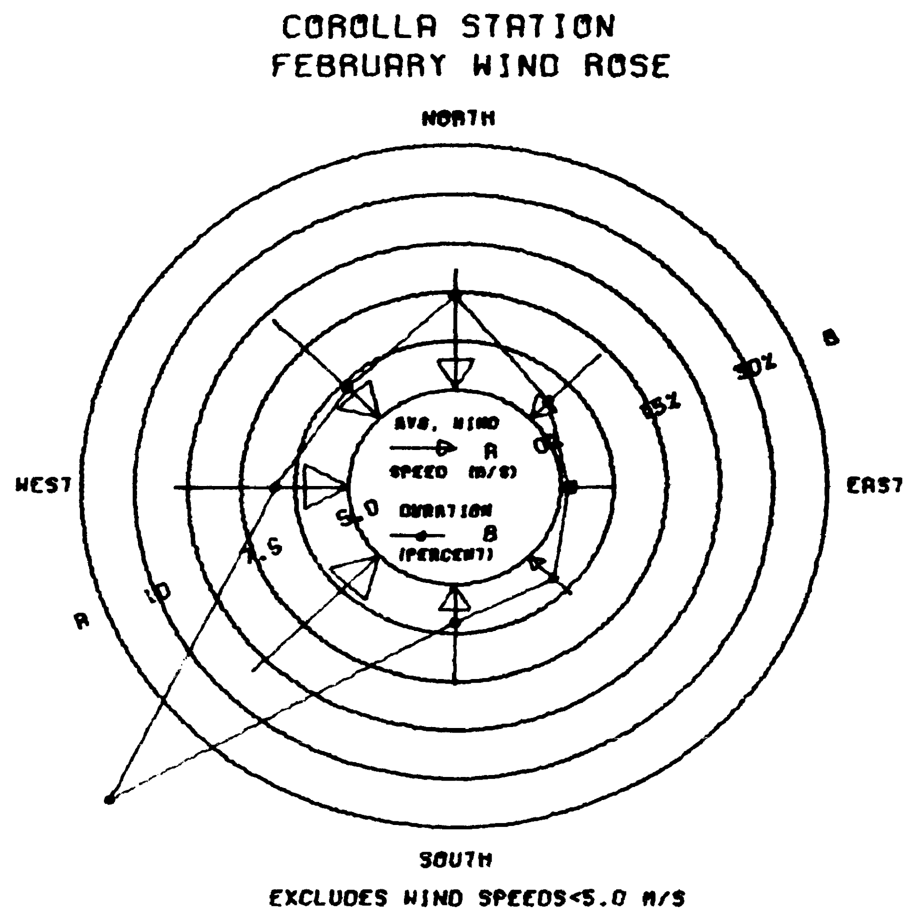
Figures 9-20 are monthly wind rose diagrams compiled for one year (February 1976 to January 1977) in the same manner as Figures 4-6 for both Corolla and Cape Hatteras. Wind rose diagrams for the Cape Hatteras Weather Station will be discussed in the next section. These twelve figures can be used to determine the monthly and seasonal, directional wind regime.

During October-January the northerly and northwesterly winds are clearly prevailing, accounting for about 55% of all wind observations. Beginning in February, and lasting until July, the southwest winds predominate (40%) while during August and September winds occur from all directions. Therefore, although the yearly summaries indicate a polymodal wind regime, monthly wind rose diagrams clearly indicate that these modes occur during separate times of the year. The northerly and northwesterly mode occurs between October and January while the southwesterly occurs between February and July.

## Cape Hatteras and Corolla Station Wind Data

The mean, extreme, and directional wind regime has been compiled from one year of Corolla station wind data. However, the question remains whether this wind climate is actually representative of the average long term wind regime in the area.

An anemometer operating at the Cape Hatteras National Weather Station is the closest (115 km south of Corolla) available source of wind data covering a fairly long period of time (25 years). Before



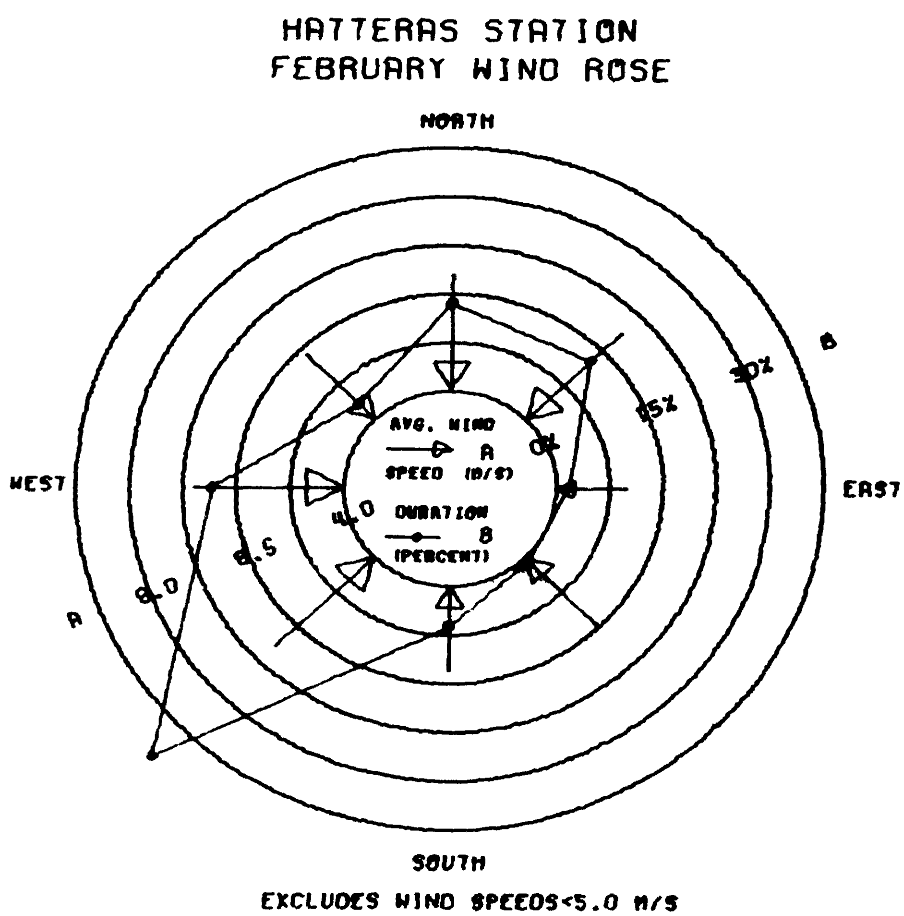




Figure 9. February 1976 wind rose diagrams.

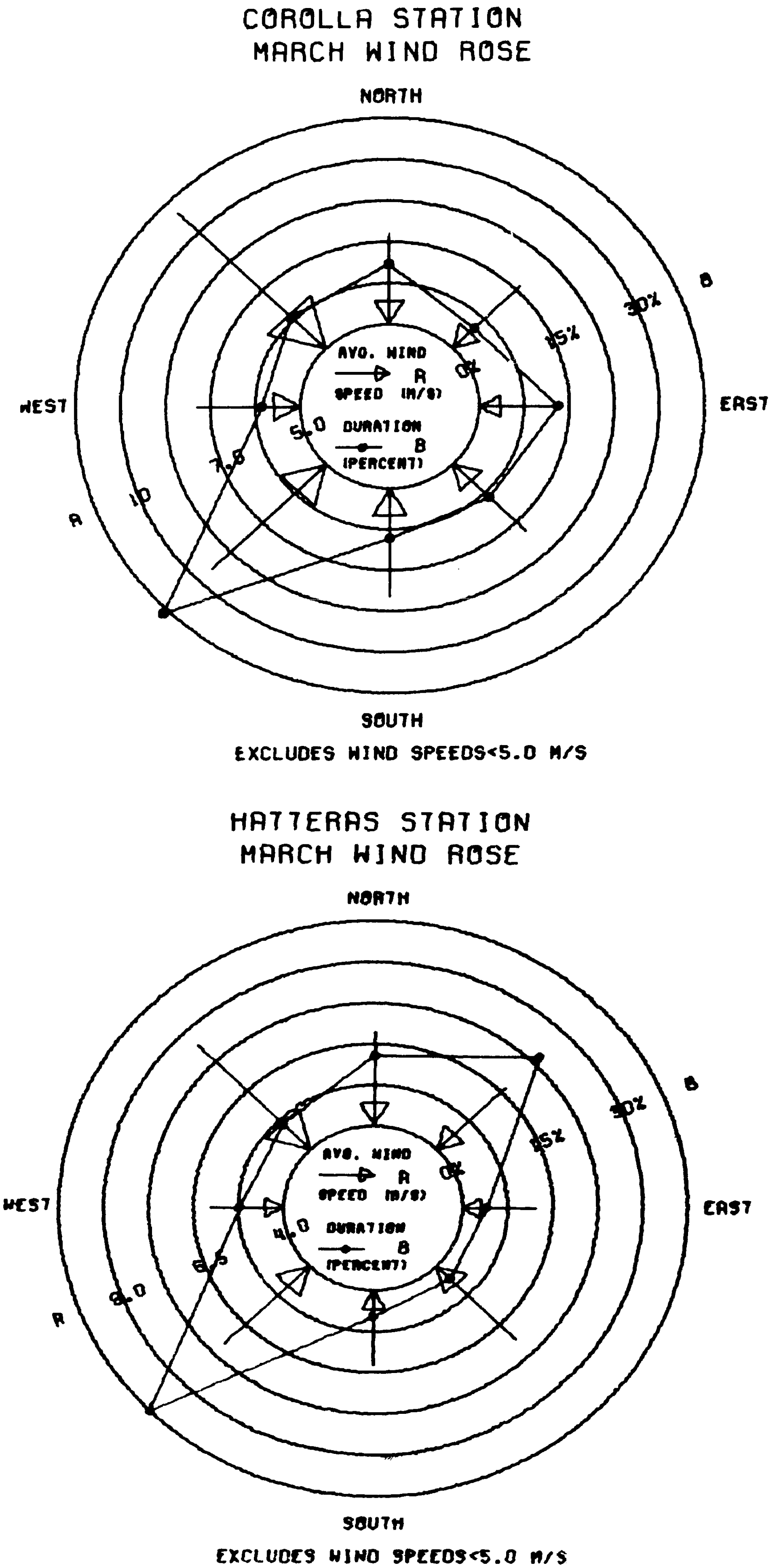
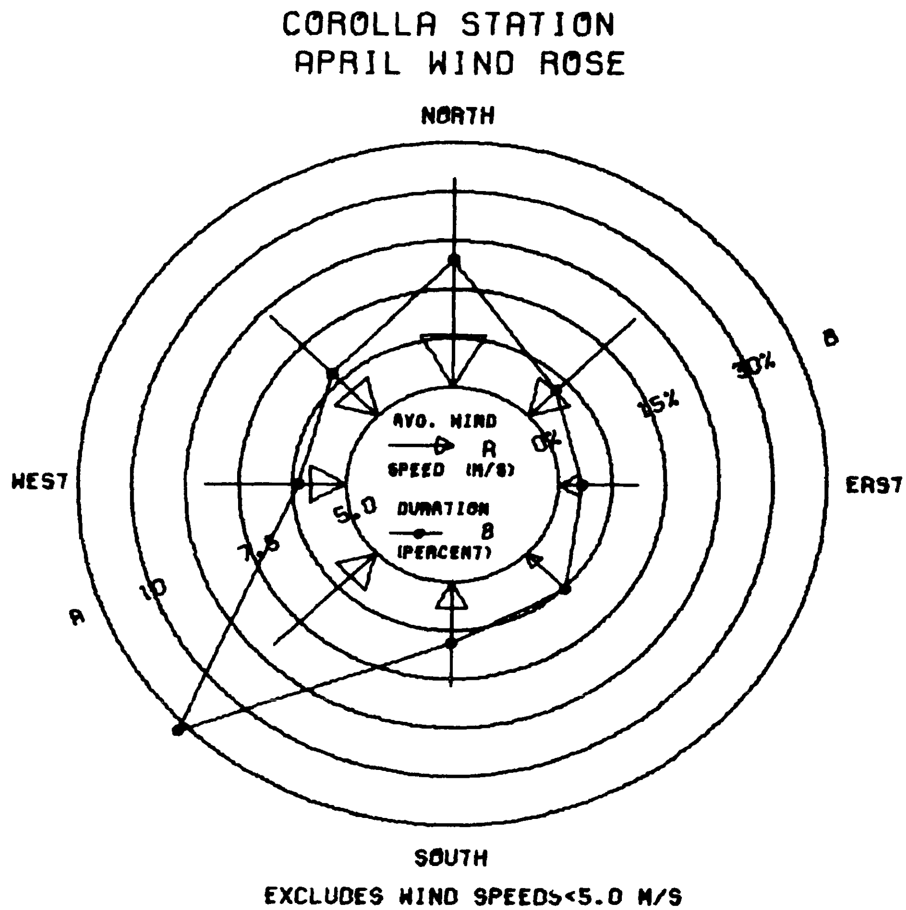



Figure 10. March 1976 wind rose diagrams.



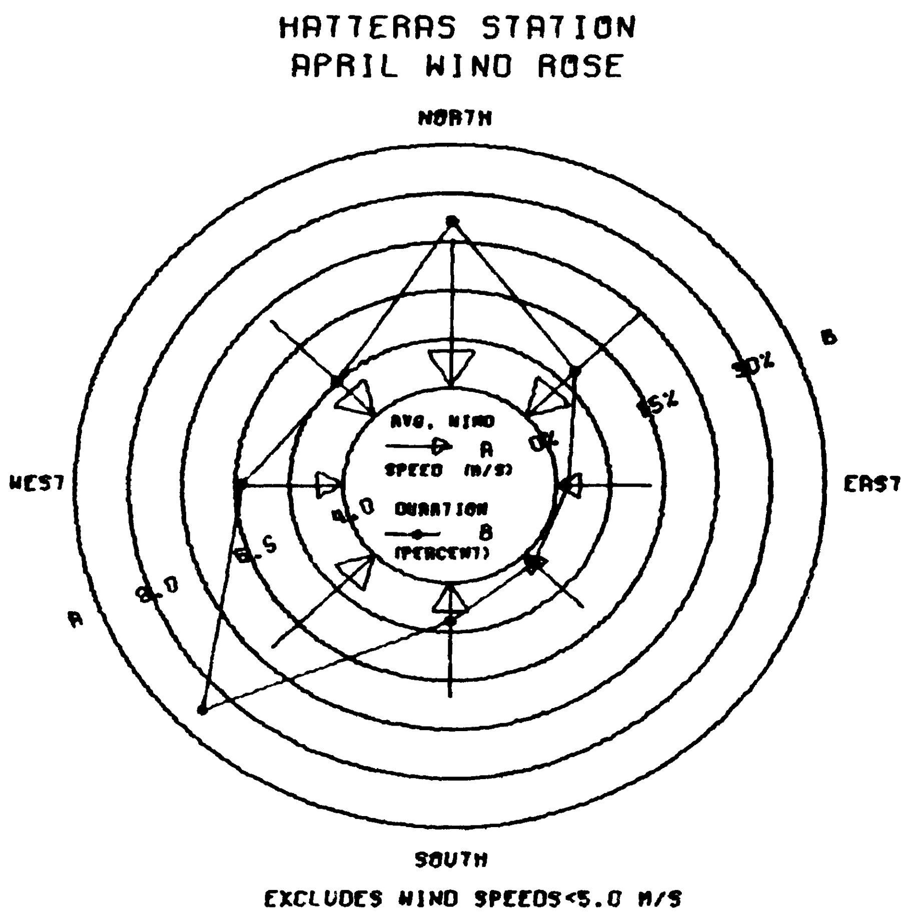
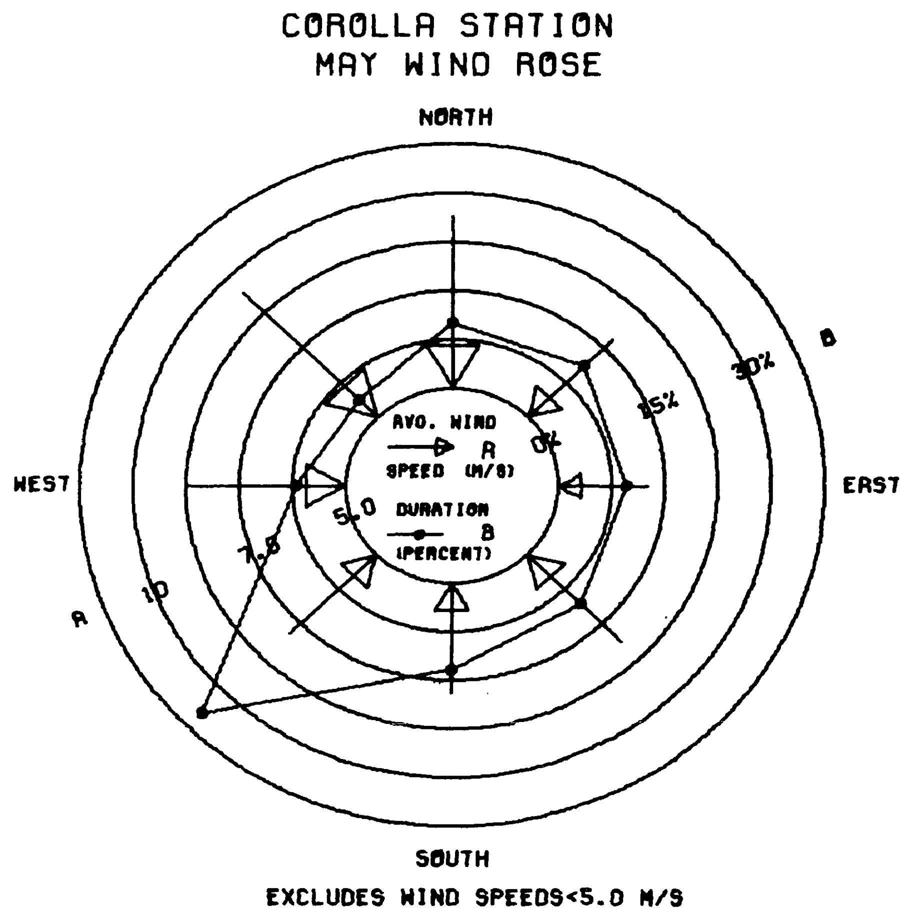




Figure 11. April 1976 wind rose diagrams.



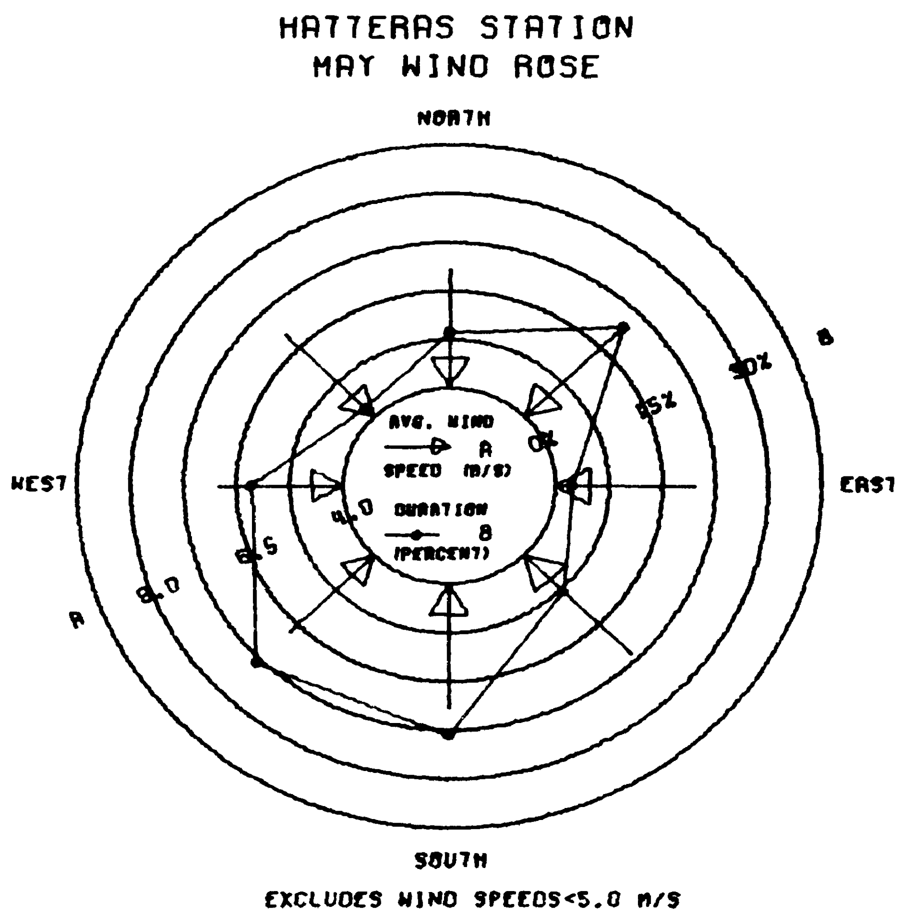




Figure 12. May 1976 wind rose diagrams.

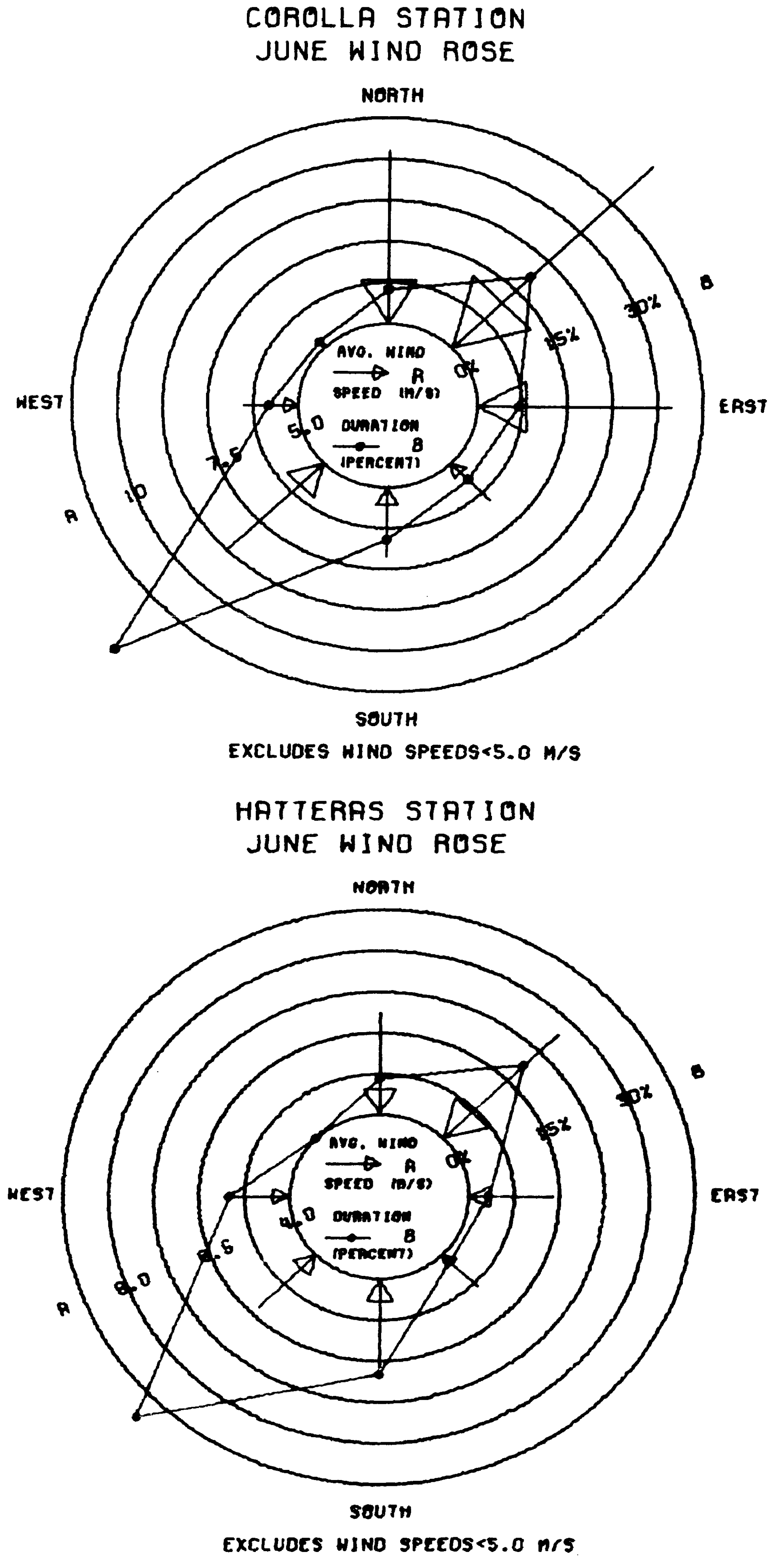
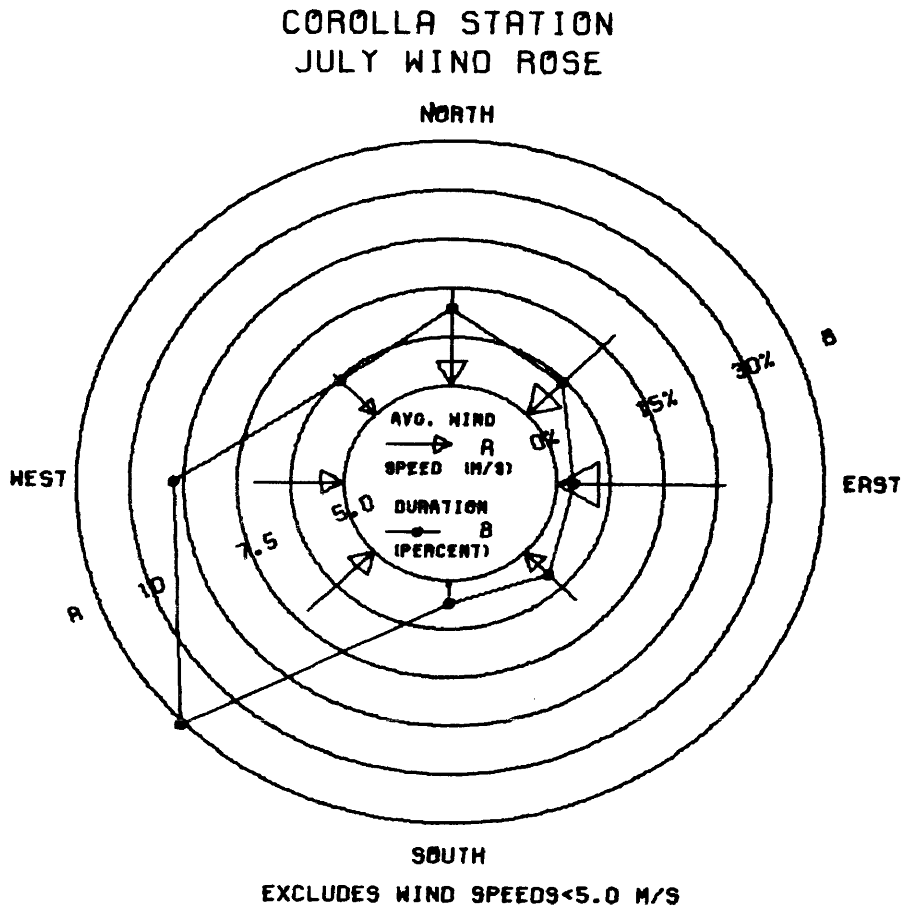



Figure 13. June 1976 wind rose diagrams.



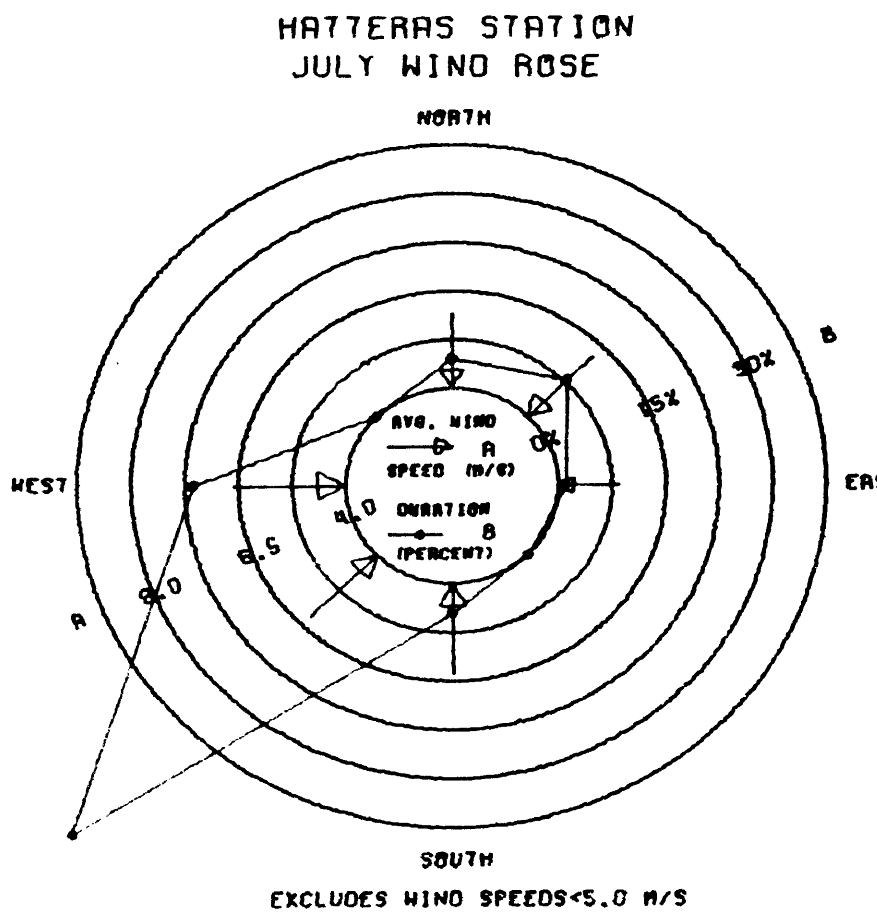




Figure 14. July 1976 wind rose diagrams.

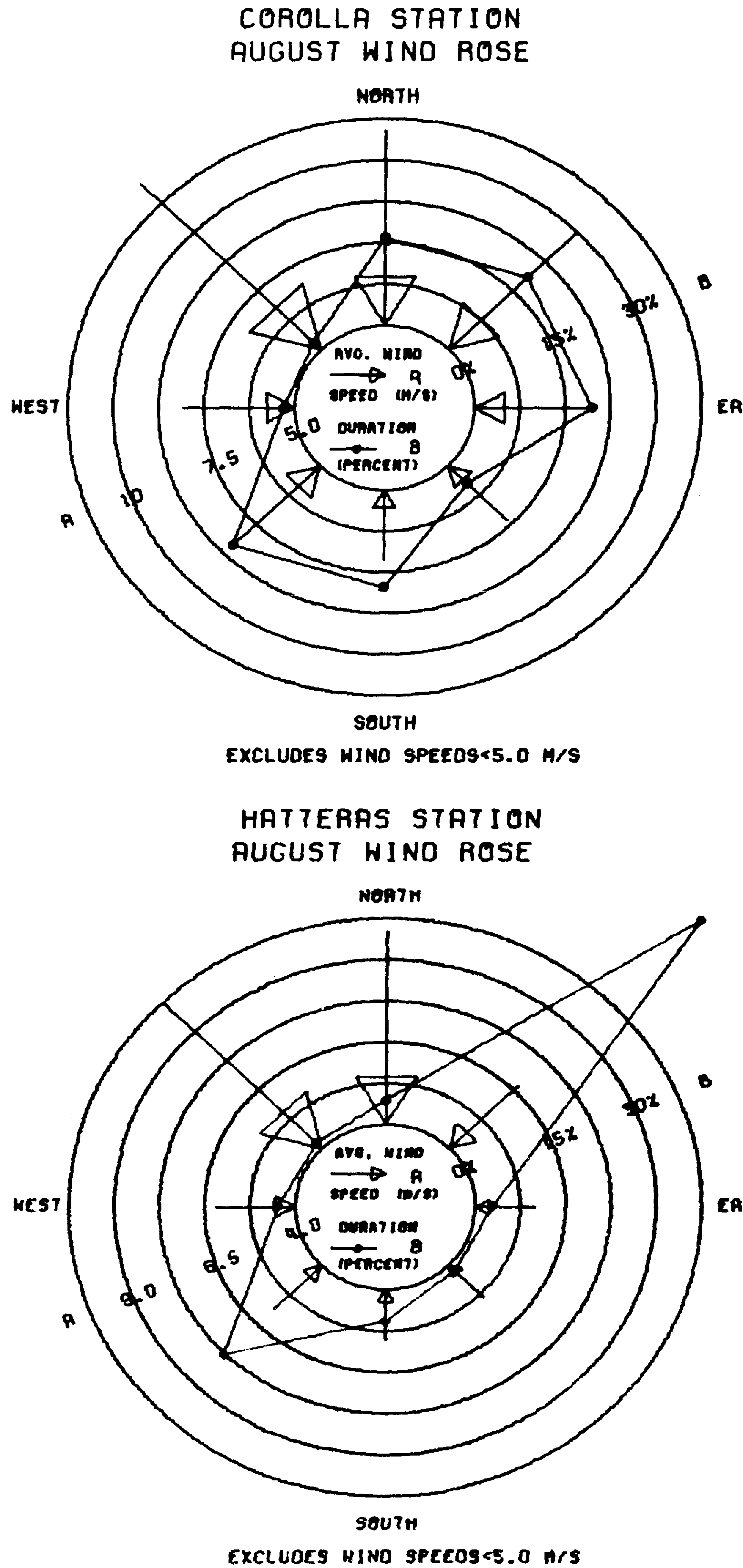
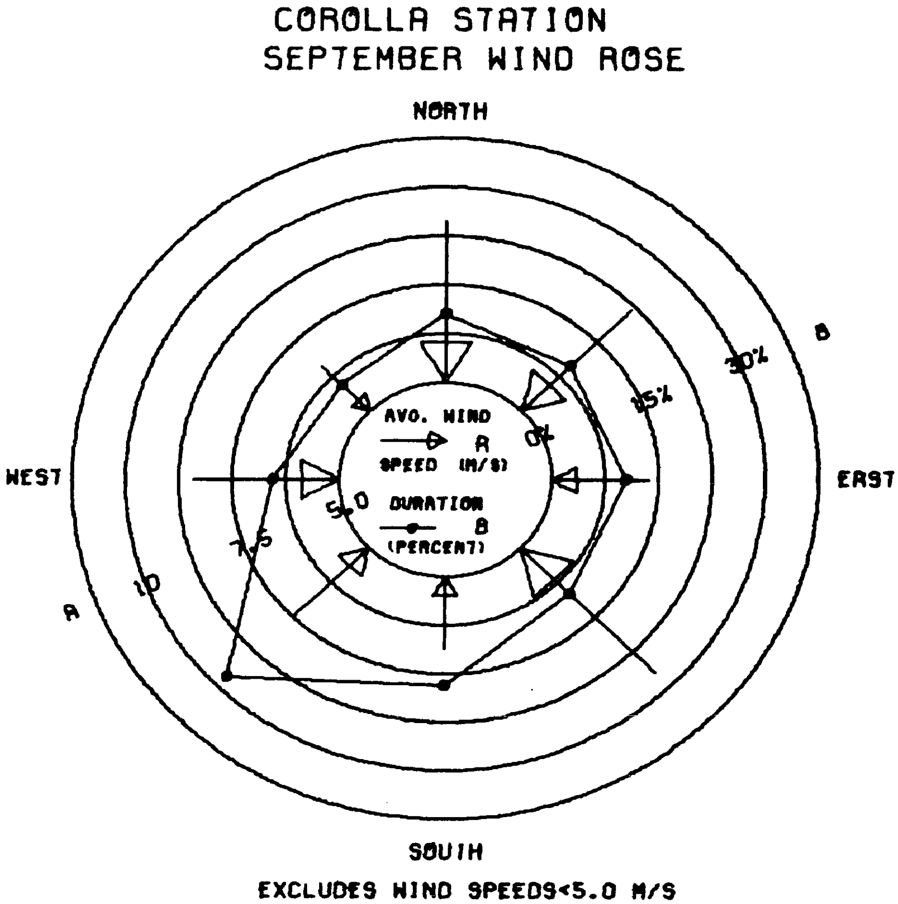



Figure 15. August 1976 wind rose diagrams.



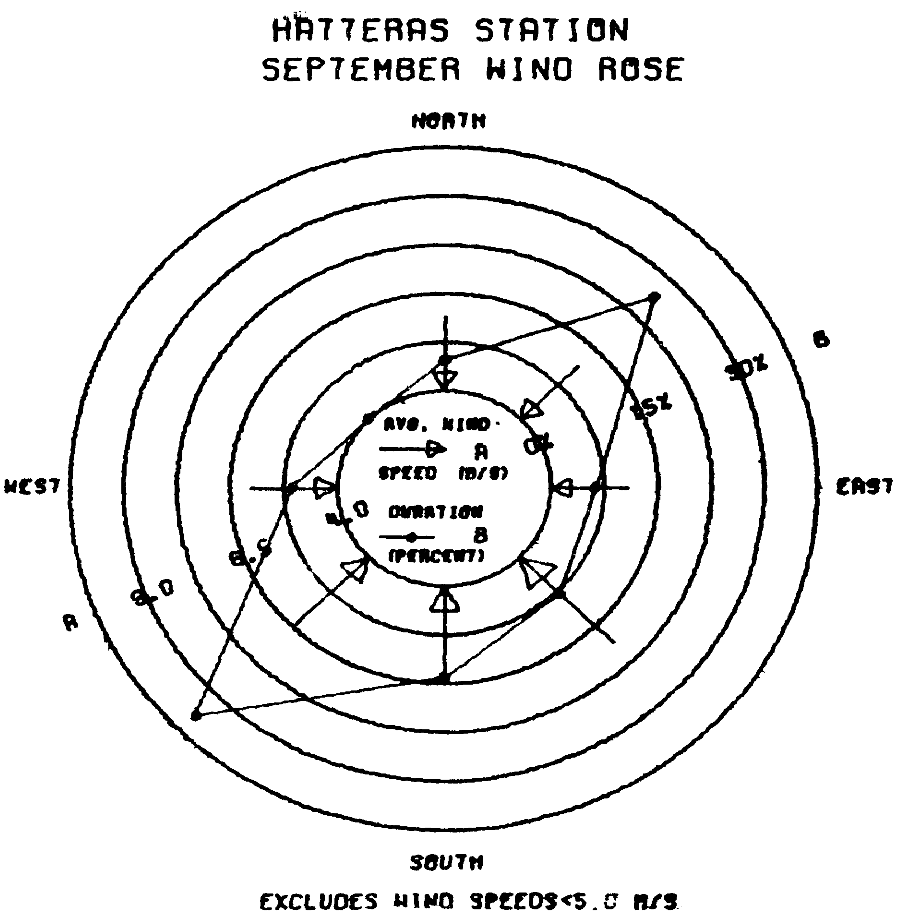




Figure 16. September 1976 wind rose diagrams.

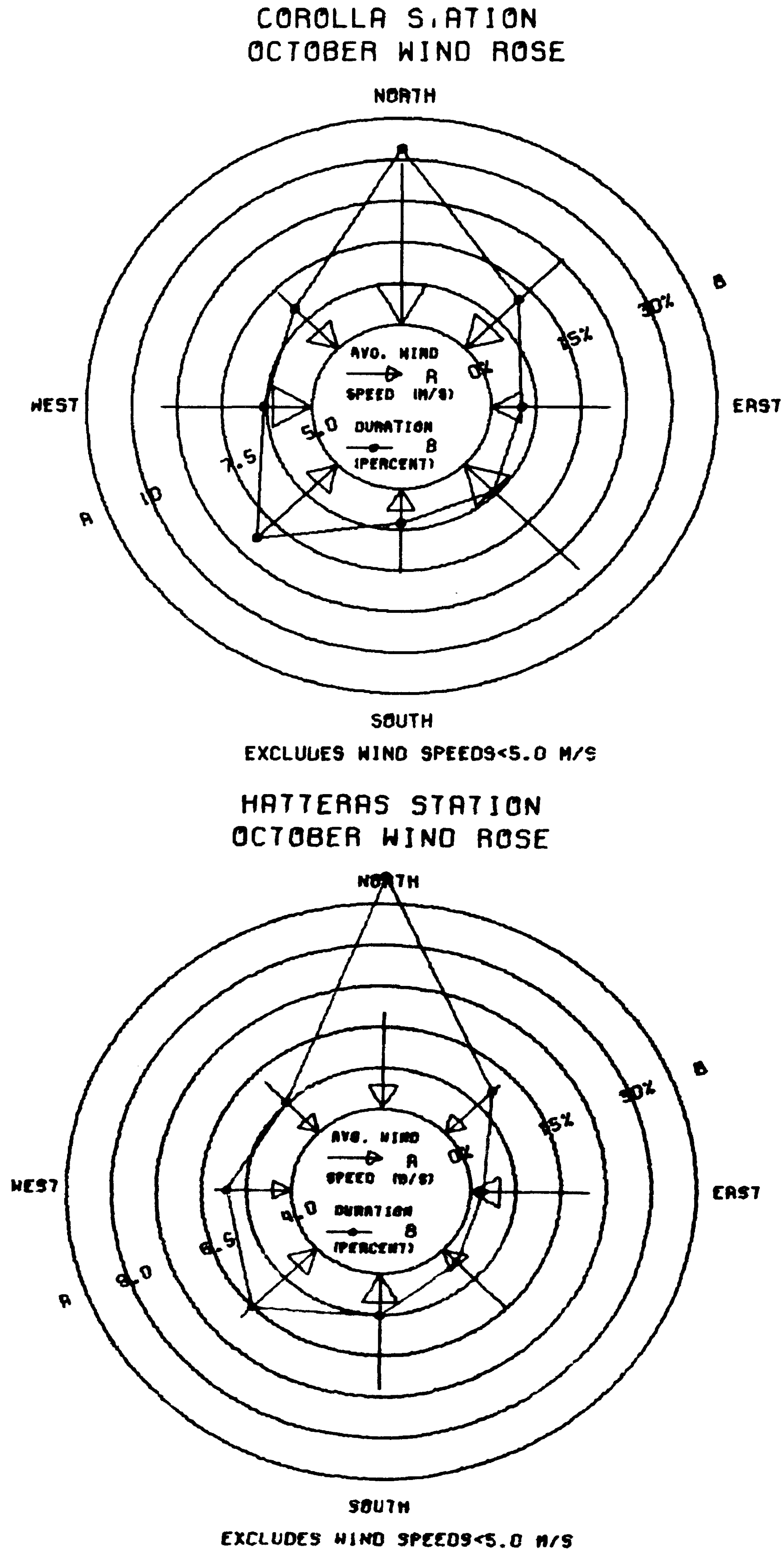



Figure 17. October 1976 wind rose diagrams.

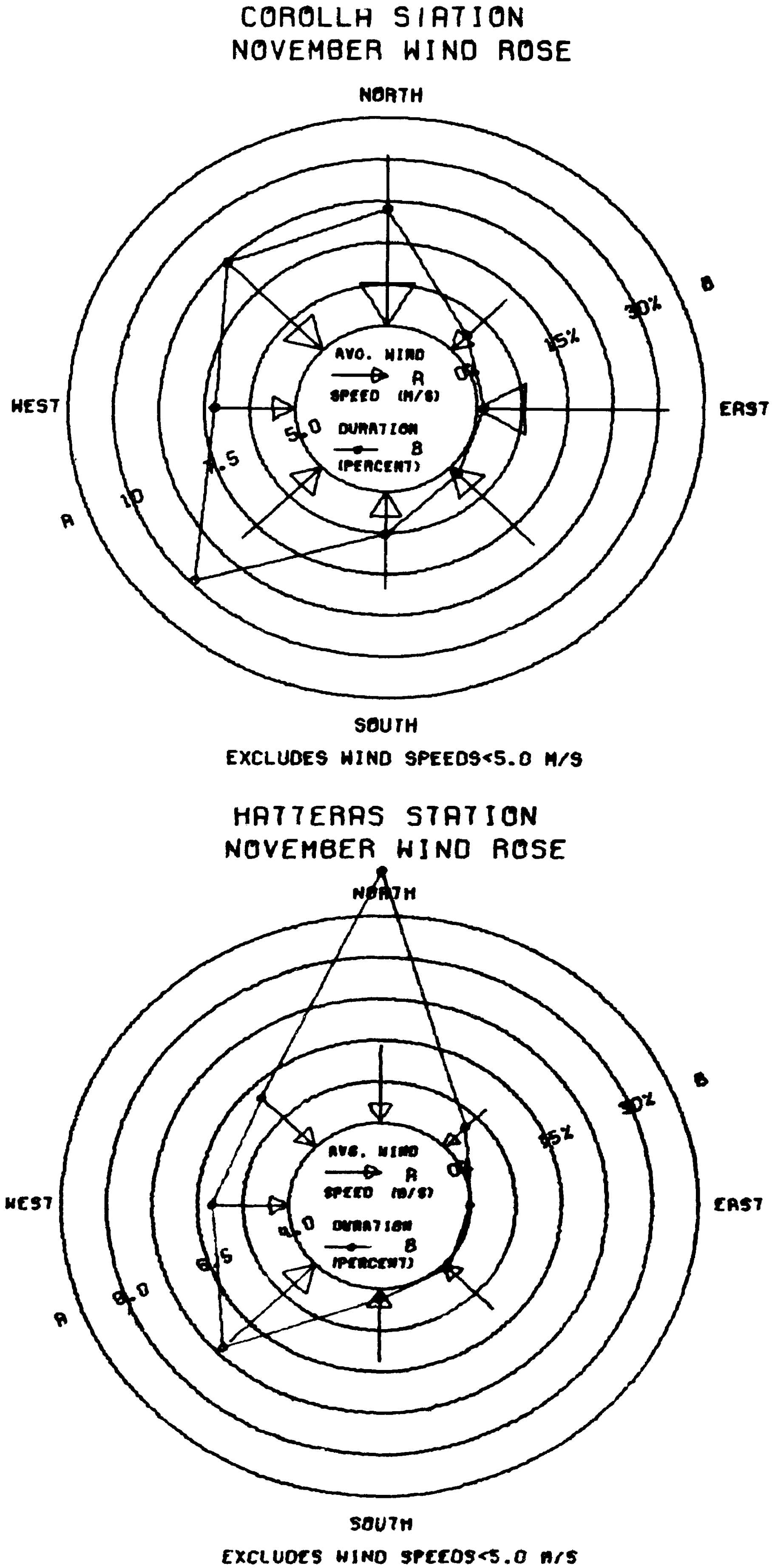



Figure 18. November 1976 wind rose diagrams.

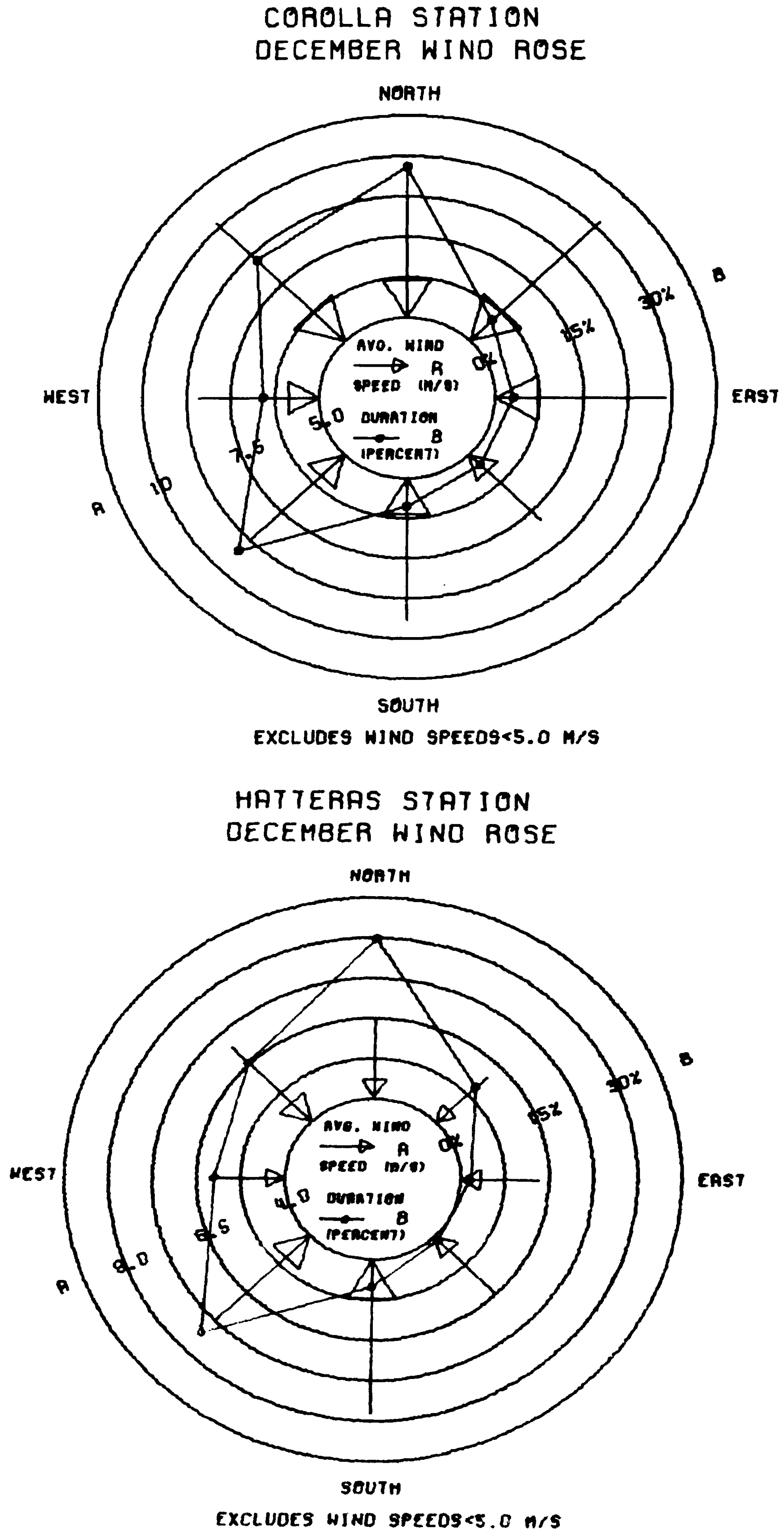
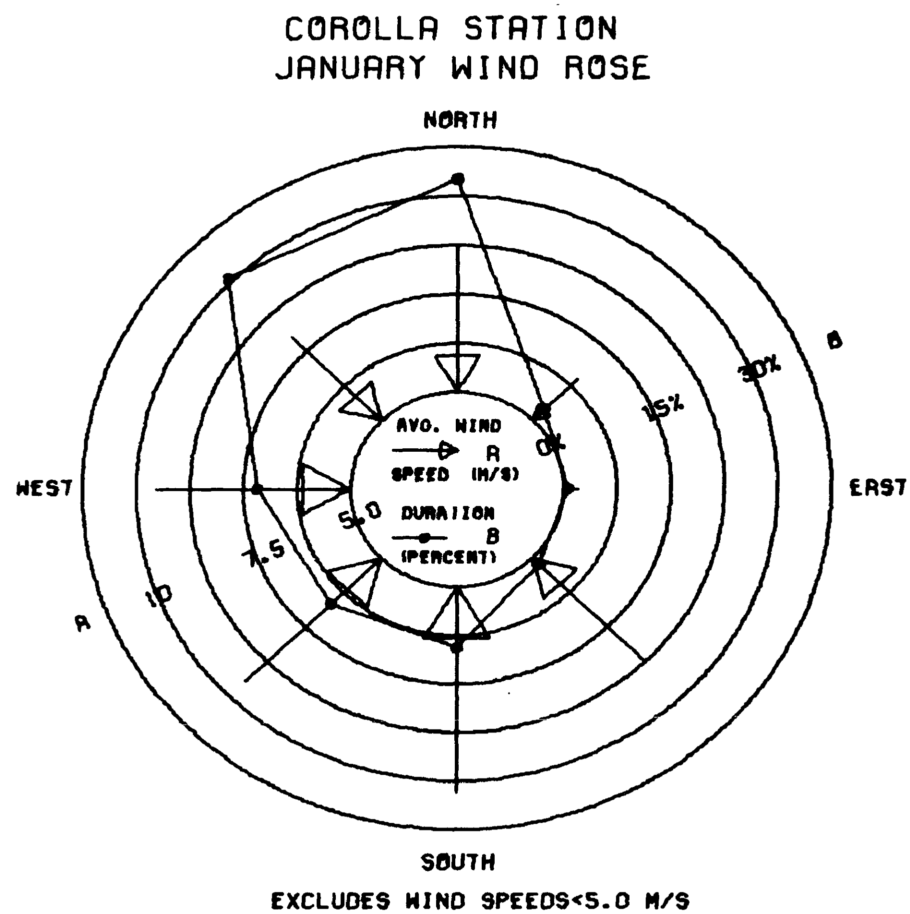



Figure 19. December 1976 wind rose diagrams.



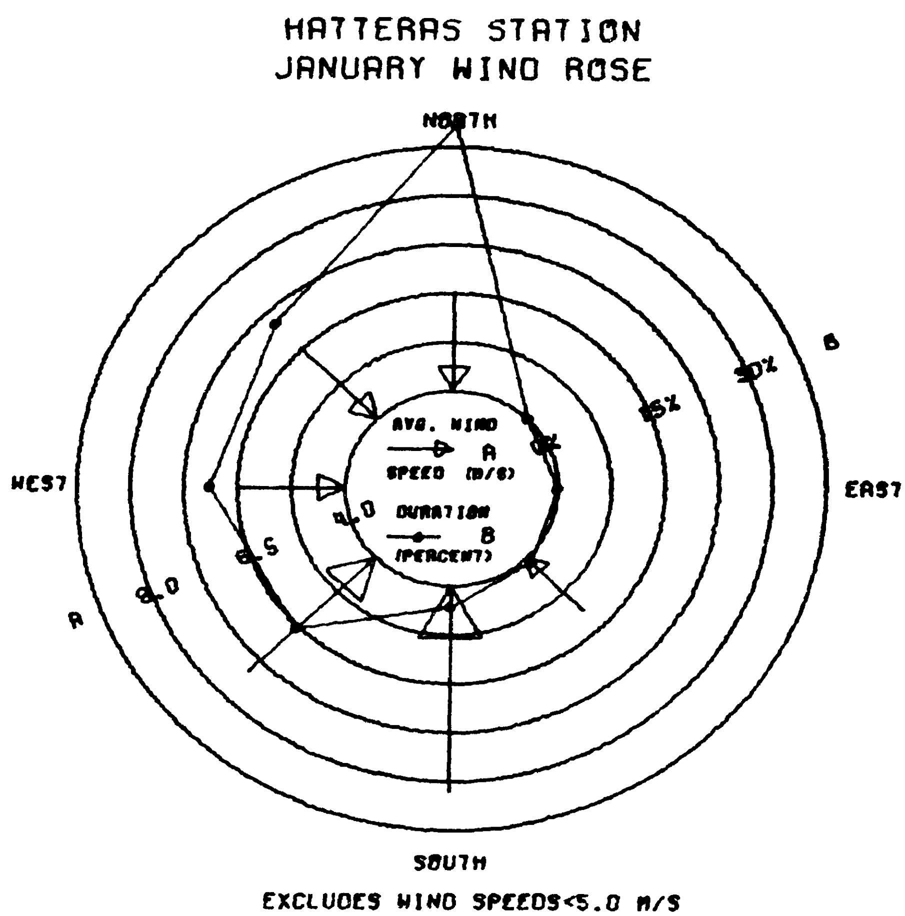




Figure 20. January 1977 wind rose diagrams.

application of these data it was necessary to investigate regional variation in wind characteristics to determine if the long-term Hatteras data were applicable to the local wind regime along Currituck Spit.

In order to determine if the wind regime measured at Hatteras and Corolla for an identical time period (2/76-2/77) was similar, an analysis of variance for paired comparisons using the t-test (Sokal and Rohlf, 1969) was conducted for the entire data sets from both stations. The t-test was chosen over others such as typical ANOVA tests because it allows for comparison of two time series of paired observations. The data from the two anemometers consists of a paired set of wind velocity and direction observations for each three hour interval throughout the one year period. The paired t-test compares each of these 2920 pairs (8/day for one year) while other tests compare one entire data set against the other.

In the paired t-test the difference between each pair of observations is compared with a hypothetical mean difference. The null hypothesis is that the mean difference between the two data sets is equal to zero.

Since the wind data consist of both wind velocity and direction observations, two tests were run on the data sets. The first comparison investigates if the wind speed measured at the two stations at each three hour interval for a one year period is similar. However, due to the difference in height of the two anemometers (53 m at Corolla and 6 m at Hatteras) a certain difference in the wind velocity measured at the two stations at the same time is expected. Since wind velocity theoretically varies as a function of the logarithm of elevation above the surface the two data sets were compared after compensating for the theoretical effects of anemometer elevation.

To compensate for the expected difference in wind speed measured at two elevations a series of profile curves of wind speed vs. logarithm of height were plotted. A maximum wind velocity was arbitarily selected (5,10,15,20,25 m/sec) for each profile at the 53 m level. A surface roughness ($Z_o$) of 5 cm was chosen. Since $Z_o$ is the elevation above the surface of zero wind velocity each profile was plotted to intersect the log height axis at 5 cm. From each profile could be read the expected wind velocity at 6 m based on an original velocity at 53 m. Then, the wind velocities at 6 m and 53 m were plotted on log-log paper. A graphical curve fitting method (Spiegel, 1961) was used to determine the equation of this line:

$$U_2 = .70 \times U_1^{.95}$$

where: $U_2$ = wind velocity at 53 m

$U_1$ = theoretical wind velocity at 6 m based on a logarithmic relation of wind speed and height

Using this derived equation the theoretical wind velocity at 6 m for each three hour interval was calculated from the observed at 53 m (Corolla Station). This calculated wind speed was compared with the corresponding observation at Hatteras to examine if there exists a significant difference in wind velocity measured by the two anemometers due to factors other than that accounted for by elevations of the two anemometers.

The mean difference ($\bar{D}$) in wind velocity measured at 6 m (Hatteras) and calculated from an observed at 53 m (Corolla) was .17 m/sec. The standard error $S_{\bar{D}}$ of this mean difference was .28 m/sec.

The t-test to determine the significance of this mean difference yields:

$$t = \frac{.17}{.28}$$

$$= .61$$

For degrees of freedom greater than 120 the probability of a t value larger than .61 is greater than .50. This means that a t of .61 is exceeded more than 50% of the time in sampling from a population with a mean difference of zero. This test then provides no evidence to reject the null hypothesis. It is concluded then that apart from differences due to sampling heights of the two anemometers the wind velocity measured at Corolla for the one year period (2/76-2/77) is similar to that measured at Hatteras.

A paired sample t-test was also applied to the wind direction data. However, in this case there was no relationship assumed between wind direction and elevation above the surface. Therefore, for each three hour interval the wind direction (expressed from 0-360 degrees) at Corolla was subtracted from the wind direction at Hatteras. The mean difference ($\bar{D}$) in wind direction for the entire one year record was 10.6° with a standard error of 9.4°. Therefore, the t-test yields:

$$t = \frac{10.6^\circ}{9.4^\circ}$$

$$= 1.13^\circ$$

The t-tables indicate a probability of around .30 for this value. In most cases the null hypothesis that the difference is nonsignificant, would not be rejected for $p > .20$.

A qualitative analysis of the data also supports the conclusion that the mean difference between the wind direction at Hatteras and

Corolla is not significant. Close examination of the data showed no constant clockwise or counter-clockwise pattern to the wind direction difference. Subtracting one direction from the other gave 908 positive and 1026 negative differences out of the total of 2920 pairs (the remainder were zero, calm conditions, or missing data points). This tends to support the conclusion indicated by the statistical test because no pattern is evident. If most of the observations at Hatteras, for example, were 20° clockwise of those at Corolla a different conclusion might have been indicated.

It should also be noted that a mean difference of 10.6° is small considering the fluctuations during each three hour interval. Each data point represents an 'eyeballed' mean value for the interval. However the direction at any one moment can be 5-10 degrees different from this mean value.

Finally, remember that wind data are generally reduced by dividing the 360° into eight or twelve intervals (northeast, east, etc.). In many cases a difference of 10.6° would not cause the pair of data points to be grouped into different directions. Qualitatively these two data points separated by 10.6° would be equivalent wind directions.

In conclusion, the statistical and qualitative analyses of wind speed and direction data from the Hatteras and Corolla stations indicate that the two records are very similar although certainly not identical. There was variability in both the wind speeds and directions measured at the two stations but most of the difference in wind speed was accounted for by the elevation of the two anemometers. There was considerably more variation between wind direction pairs than with wind speed, but the analysis supports the conclusion that the wind regimes monitored at the two stations are similar.

Comparison of yearly wind diagrams for the same 1976-1977 period for both stations indicate again a very similar wind regime. Figures 21, 22 and 23 are wind rose diagrams which were plotted for comparison with the corresponding Corolla diagrams (4, 5 and 6). Comparison of these plots for each station indicate only one important discrepancy. Notice in Figure 4 the northerly winds have the highest average wind speed while the Hatteras wind rose (Figure 21) indicates the lowest average wind speed for this direction. This discrepancy is also evident in comparisons of the wind rose diagrams for winds greater than 5.0 m/sec (Figures 5 and 22). However, Hatteras wind rose diagrams (Figures 24 and 25) compiled from 25 years of data indicate that the annual Corolla anemometer does reflect the true average velocity of these northerly winds. Figures 24 and 25 both indicate that one of the highest average velocities is associated with northerly winds.

## Long Term Wind Regime

One year of wind data from the Corolla station anemometer was compiled into a detailed monthly, seasonal, and yearly wind climate for Currituck Spit. This wind climate, as discussed in the following section, became the basis for investigation of the development, orientation, and migration of sand dunes, and the net flux of sand across the barrier spit due to wind transport. From comparisons of the Hatteras and Corolla wind data for the same one year period it was concluded that the long term Cape Hatteras wind climate compiled from 13 years of data could be compared directly with the Corolla wind climate determined from only one year of data. Unfortunately

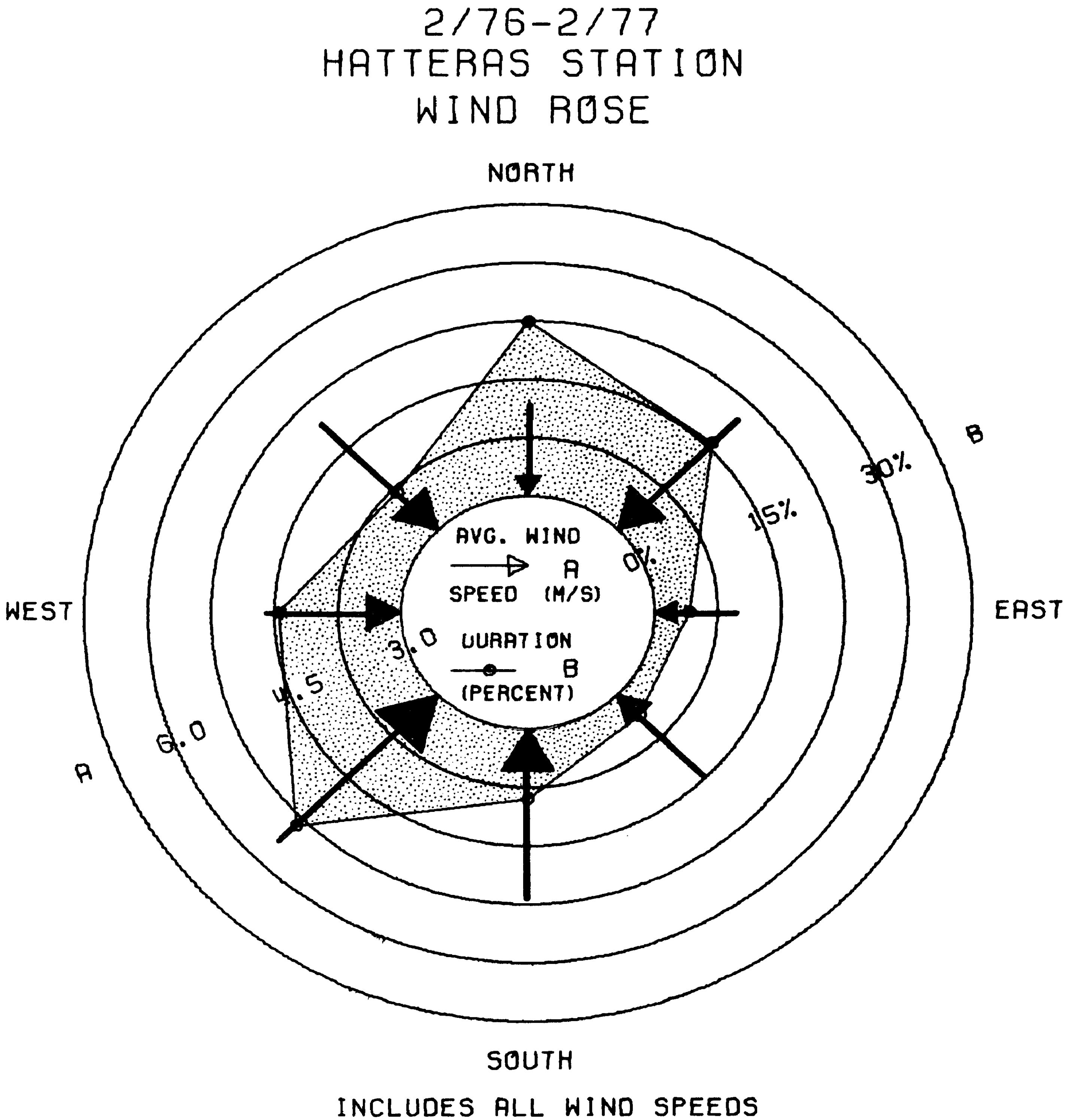



Figure 21. Hatteras station wind rose (February 1, 1976 to January 31, 1977) for all wind speeds.

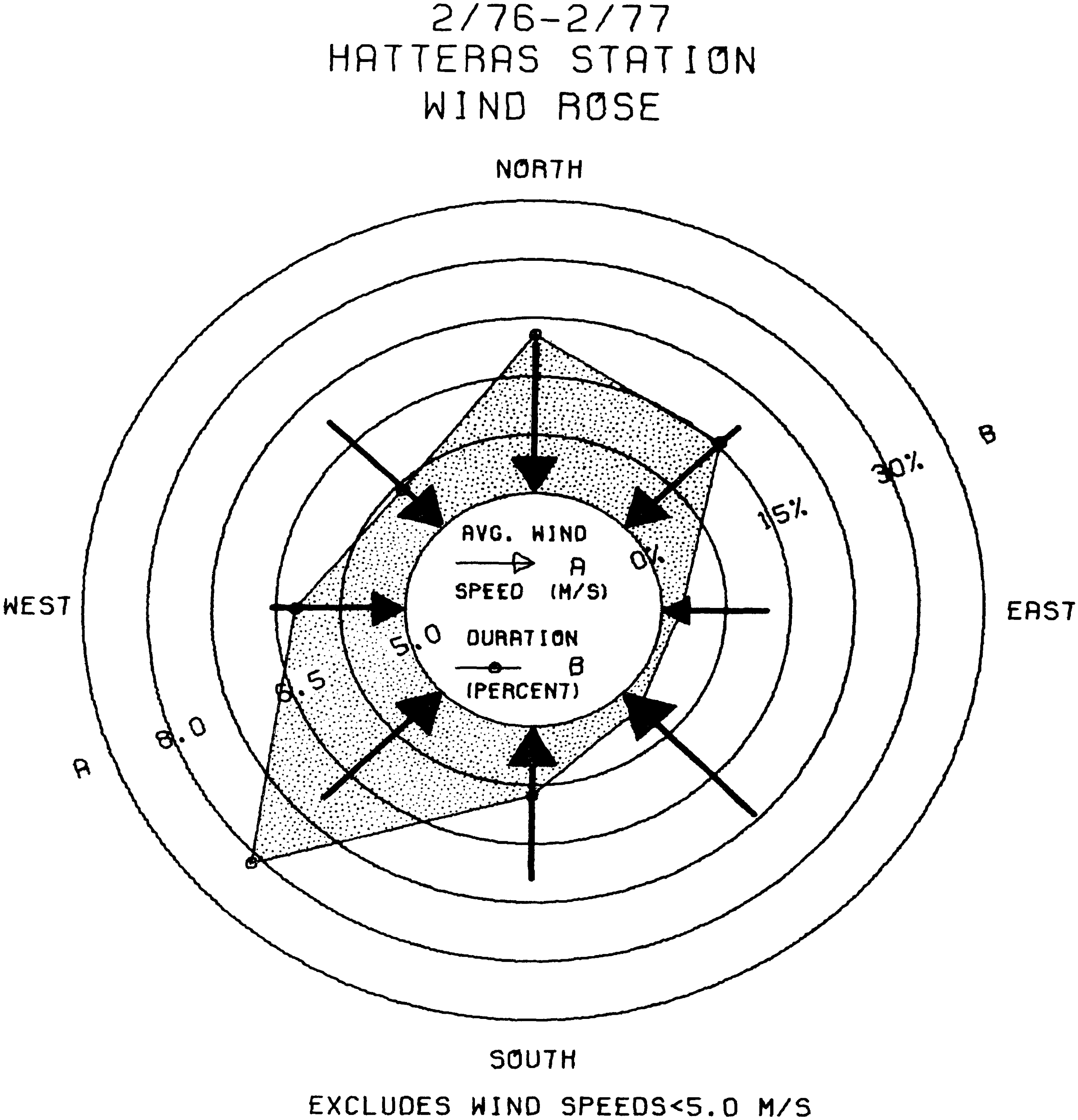



Figure 22. Hatteras station wind rose (February 1, 1976 to January 31, 1977) for all wind speeds greater than 5.0 m/s.

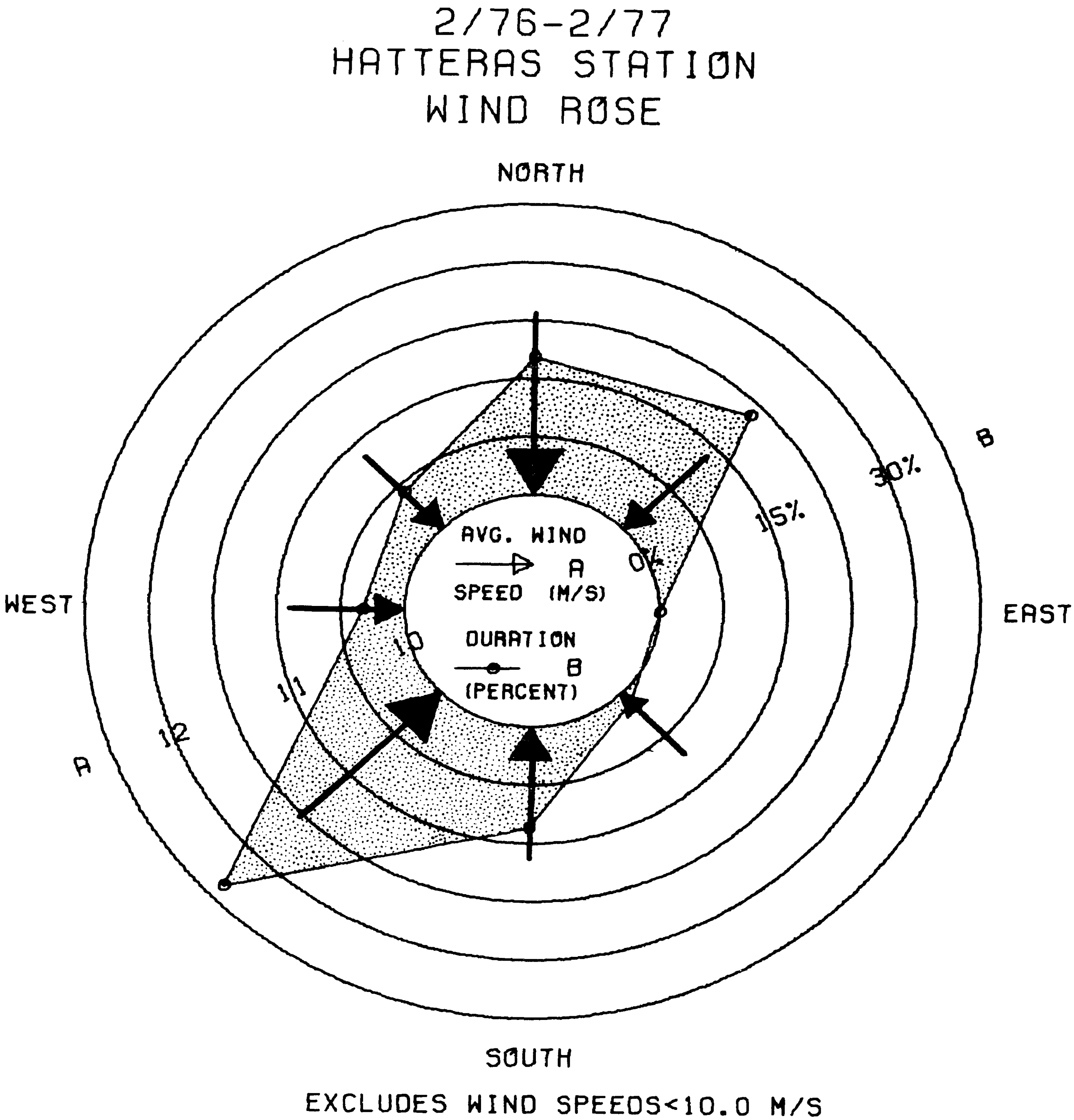



Figure 23. Hatteras station wind rose (February 1, 1976 to January 31, 1977) for all wind speeds greater than 10.0 m/s.

only a visual qualitative comparison was possible since the 18 years of data from Cape Hatteras were unavailable for statistical tests of similarity.

Figures 24 and 25 cover the period 1953-1957 and 1956-1970, respectively. These figures show again a polymodal wind regime with modes in the northeast, north, northwest, and southwest with the highest average velocities from the northerly directions and the south. This appears to be essentially the same wind climate determined from the one year of Corolla data, and the local one year wind climate determined from a limited amount of data should represent a typical year. Therefore the conclusions, based upon this local one year record are applicable to the typioal long term dune and sediment dynamics of the spit.

Conclusions

1. A detailed wind climate was determined for Currituck Spit from compilations of monthly, seasonal, and yearly wind data from a local source (one year of data) and a nearby source (18 years of data).

2. The wind regime at Currituck Spit is polymodal, with prevailing winds from the north and southwest, and dominant winds from the northeast, north, and northwest.

3. The highest frequency occurrence of winds (including all winds) is from the southwest (32%) while the northerly winds had the highest average velocity (8.0 m/sec).

4. There was no obvious seasonality with regard to the mean wind speed or frequency of occurrence of winds greater than 5.0 and

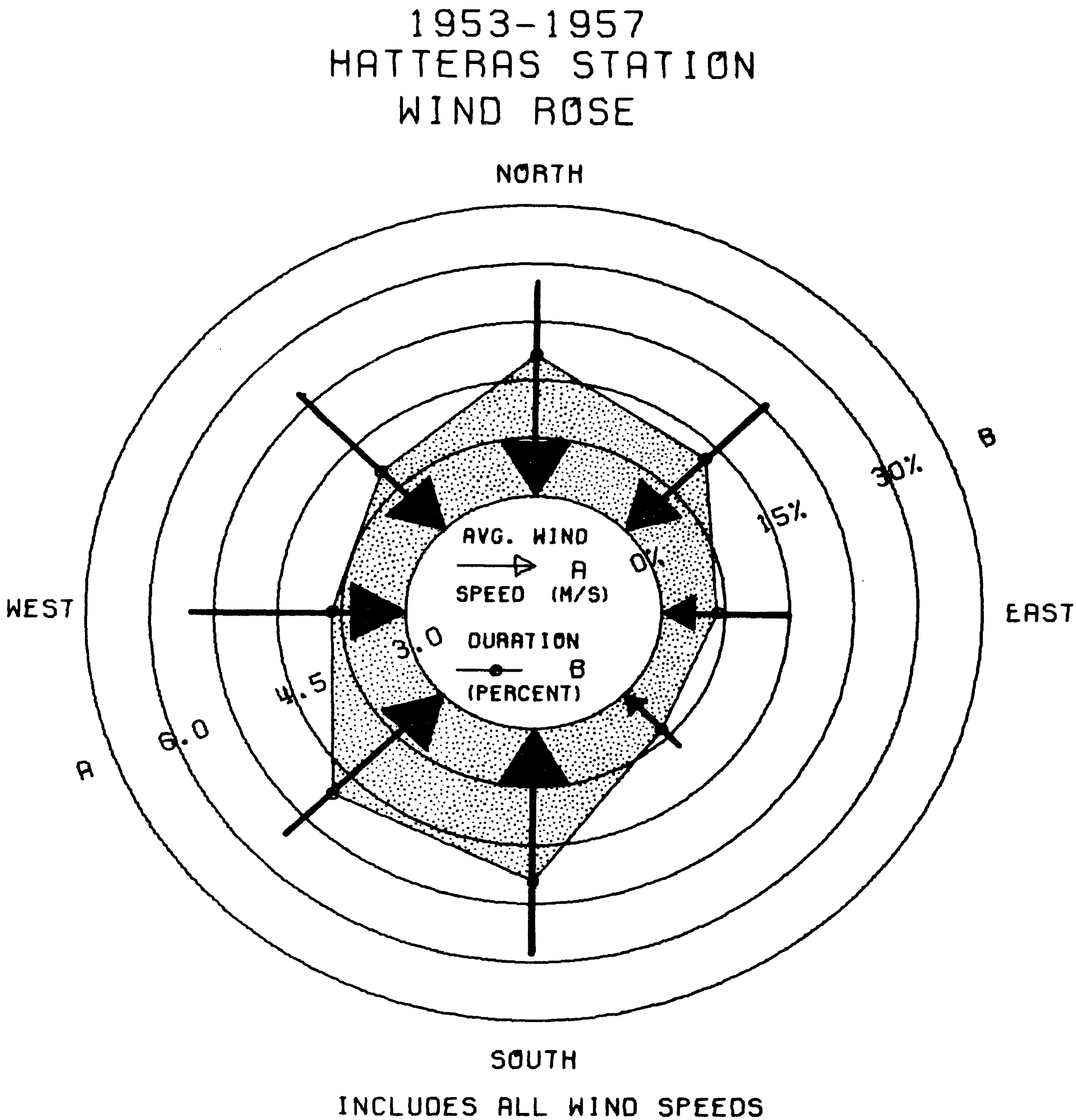



Figure 24. Hatteras station wind rose compiled from five years of Corps of Engineers wind data (1953-1957).

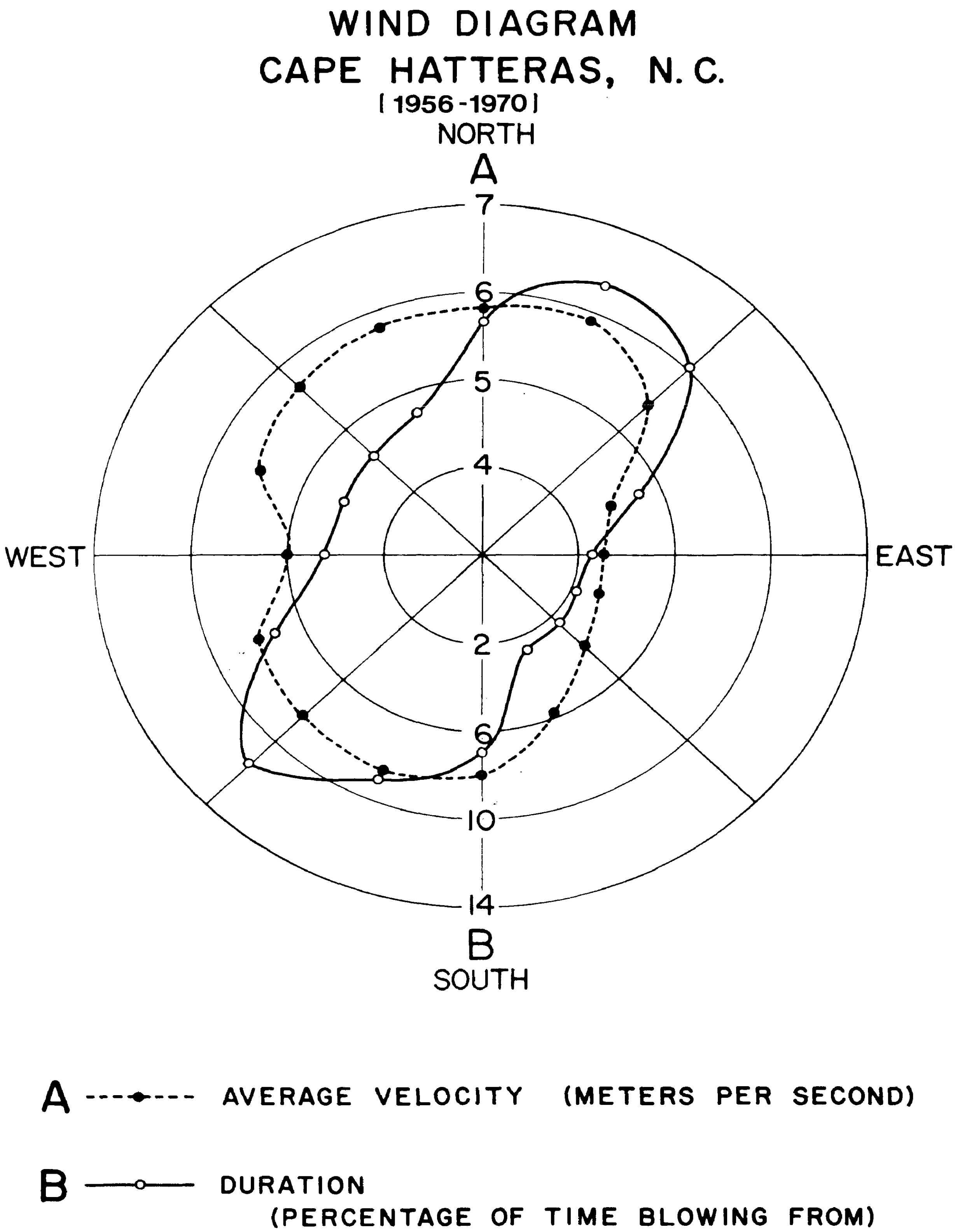



Figure 25. Hatteras Station wind rose compiled by NOAA Environmental Data Service from fifteen years of data ( 1956-1970 ).

10.0 m/sec. Instead there was a long period of high velocity winds (October-June) and a shorter low velocity period (July-September).

5. Statistical comparison of the one year Corolla Station wind data with data for the same period from the Cape Hatteras Weather Station indicates very little variation in wind regime between the two stations separated by 115 km.

6. The long term wind regime compiled from 18 years of Cape Hatteras data was found to be very similar to the wind regime determined from one year of Corolla wind data. Therefore this detailed monthly, seasonal, and yearly wind climate is representative of the local long term wind regime. This conclusion lends credence to the following sections which relate this one year local wind climate and concomitant field data, to the long-term interaction of eolian sand transport, vegetation, and sand dunes, as evidenced by the flux of sand across the barrier spit and the development, orientation and migration of large sand dunes.

## MOVEMENT OF LARGE SAND HILLS

Large sand dunes, or medanos (10-25 high), represent a significant amount of sand removed from the longshore transport system. Such dunes are found along Currituck Spit between False Cape, Virginia and the Duck Research Facility, North Carolina (Figure 1). Many of these large dunes are migrating landward towards the southwest, obliquely across the barrier island. These dunes are significant in terms of the sediment budget of the spit and also due to their effects on development in the area.

Mobile dunes in the area are notorious for interfering with and often destroying towns, roads and forests. Henry Lathrobe, Esq. (1814), referring to the Cape Henry area, warned that these mobile dunes would eventually "swallow up the whole swamp, and render the coast a desert indeed, for not a blade of grass finds nutriment on this sand". Though the mobile dunes are still a problem 163 years after Lathrobe wrote these words, the coast of Virginia-North Carolina is not a desert. Aerial photographs have, in fact, shown a trend of increasing vegetation since the 1930's, with a concomitant decrease in the amount of shifting sands. The largest increase in vegetation seems to have occurred in False Cape, the northern part of the study area.

False Cape State Park is characterized by a large variety of eolian features including relatively high (2-4 m), continuous, multiple foredune ridges, thick shrub vegetation across the eolian flat, stabilized parabolic dunes (5-10 m high) with axis' uniformally oriented to the north, several large (15-20 m) mobile dunes or sand hills (i.e., medanos), and a maritime forest which is presently being invaded by the mobile dunes.

The area near Corolla, North Carolina is quite different than False Cape approximately 30-40 km to the north. Here there is a lower (1-3 m), non-continuous foredune ridge, only sparse dune vegetation across the eolian flat, and large medanos (10-25 m) which are highly mobile and temporaly varying in orientation. These dunes are also invading a maritime forest on the bay side.

Migration Rates

The migration rates of large dunes on Currituck Spit are useful data for evaluating the role of dunes in the sediment dynamics of the spit, the effect of the differences between the northern and southern regions, and for predicting the problems which will occur after development in the terrain surrounding these mobile dunes. Dune migration rates can be determined from studies of aerial photographs, maps and ground measurements. Air photos provide a longer record of migration rates than field measurements, though the rates from air photos may represent an average for a number of years rather than an actual rate for each of the years. Given the increase in vegetation over the last thirty years a rate determined from old photographs should represent a faster mean rate than expected today. Figure 26 shows a typical large dune in Currituck Spit and its migration since 1961. Over 16 years, the dune has moved south-southwest obliquely toward the bay at about 8 m $\pm$ 0.6 m per year (accuracy of these measurements is discussed in detail by Hennigar, 1978). Accuracy depends on the photo-

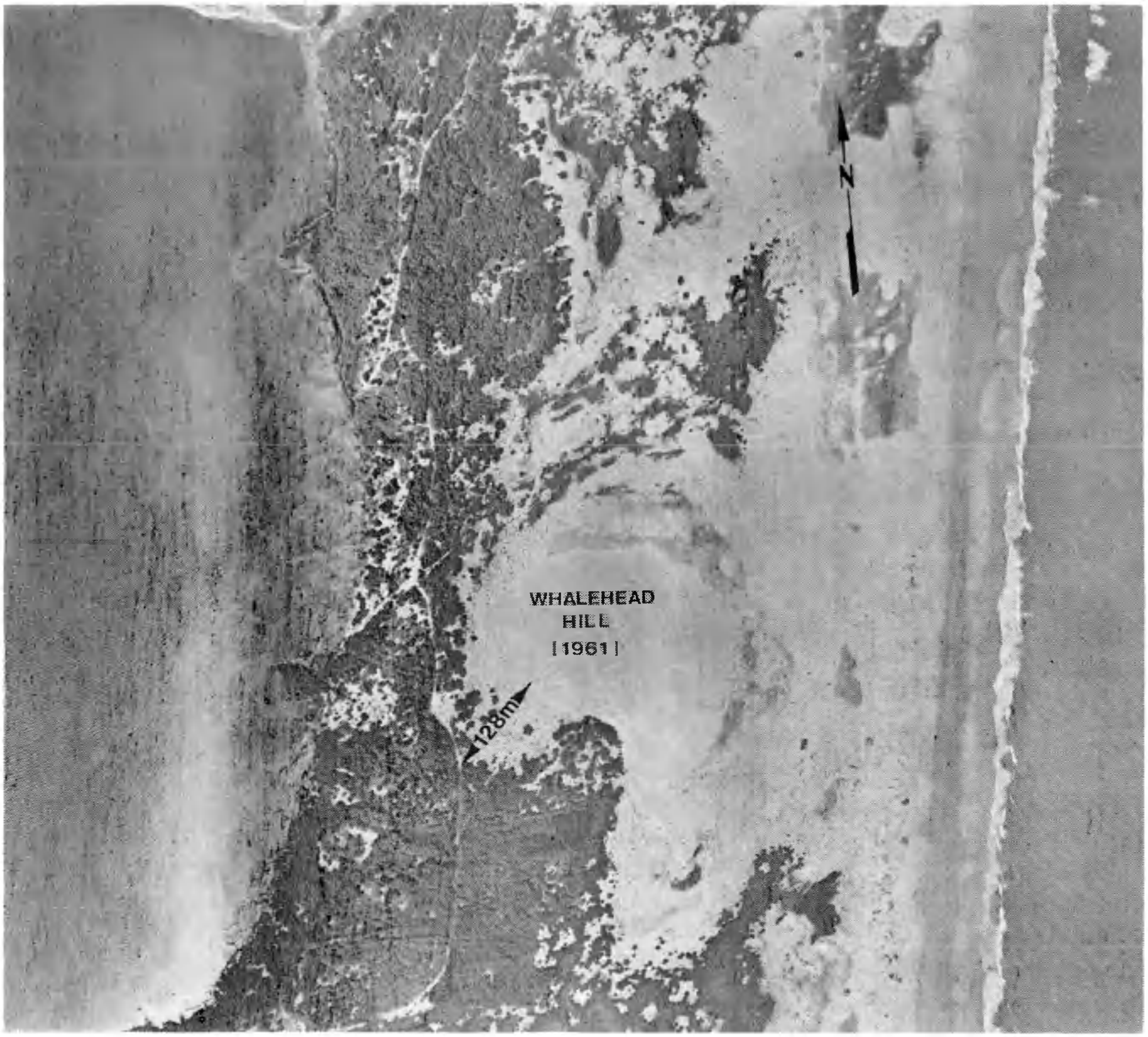



Figure 26. Distance travelled by Whalehead Hill (1:6000 scale). 1961-1977

scale, and suffers in comparing dune movements in this area because it is free of landmarks. Table 2 lists migration rates determined by other investigators for coastal dunes throughout the world. To determine the actual present yearly migration rate, measurements must be made in the field.

In February of 1976, reference markers were placed around the perimeters of Whalehead Hill (Figure 27) located just south of Corolla, and Barbours Hill (Figure 28) located at False Cape, Virginia. Both sand hills are approximately 15-20 m high with active slipfaces (5.5 m in height) oriented approximately west-northwest - east-southeast, and advancing to the south-southwest. Nine other sand hills south of Whalehead Hill show an approximate uniformity in height and spacing, therefore, suggesting that the migration rate measured for Whalehead Hill is typical of the sand hill field to the south.

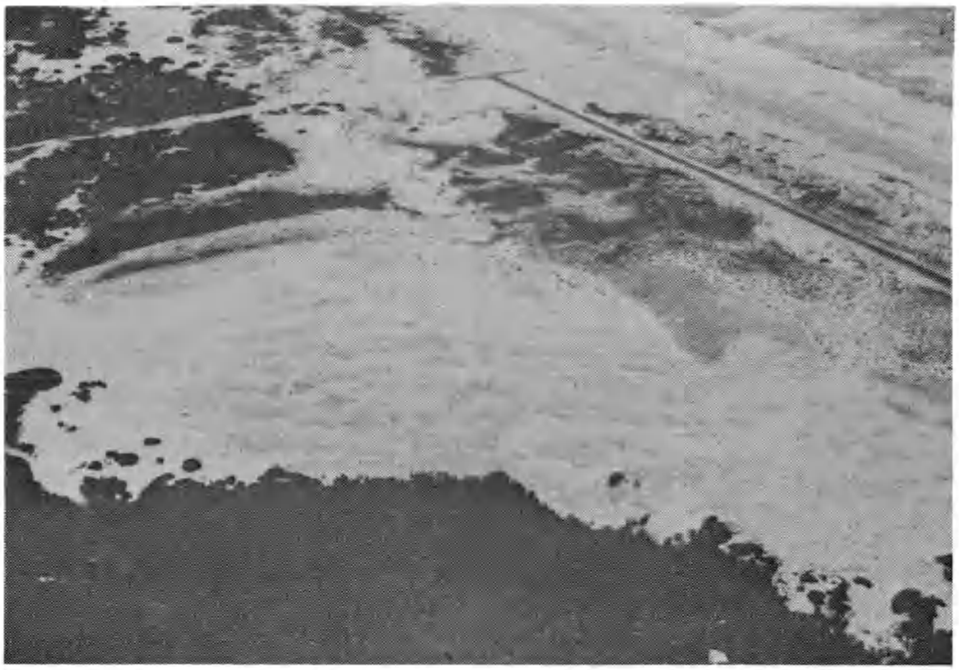
Figure 29 shows a schematic illustration (not to scale) of the net 12 month movement of the two dunes between February 1976 and February 1977, as measured by the difference to the control points. This distance can be determined accurately only at the slipface, for only there does the sand hill show a line of demarkation between the dune and the surrounding terrain. On all other flanks the dunes grade slowly into hummocks and small dunes, making measurement difficult. In addition, only the slipface movement indicates a migration of the entire dune. Extensions along the other flanks reflect sand being blown off the dune and onto the surrounding eolian flat. Cross movements of the dune occur in all directions. However along the slipface there is a steady (determined from aerial photos and field measurements) net movement.

TABLE 2

ANNUAL RATE OF COASTAL SAND DUNE MOVEMENT
AT VARIOUS LOCATIONS THROUGHOUT WORLD

from Pickard (1968)

| Location | Rate (m/year) | Source |
|---|---|---|
| Coast of France | 9.1 | Salisbury, 1952 |
| Lancashire, U.K. | 5.5–7.3 | Salisbury, 1952 |
| Newborough, Warren, U.K. | 1.5–3.1 | Ranwell, 1958 |
| Lake Michigan, U.S.A. | 2.0–4.0 | Ranwell, 1958 |
| Cronulla, Australia | 8.0–9.0 | Pickard, 1968 |



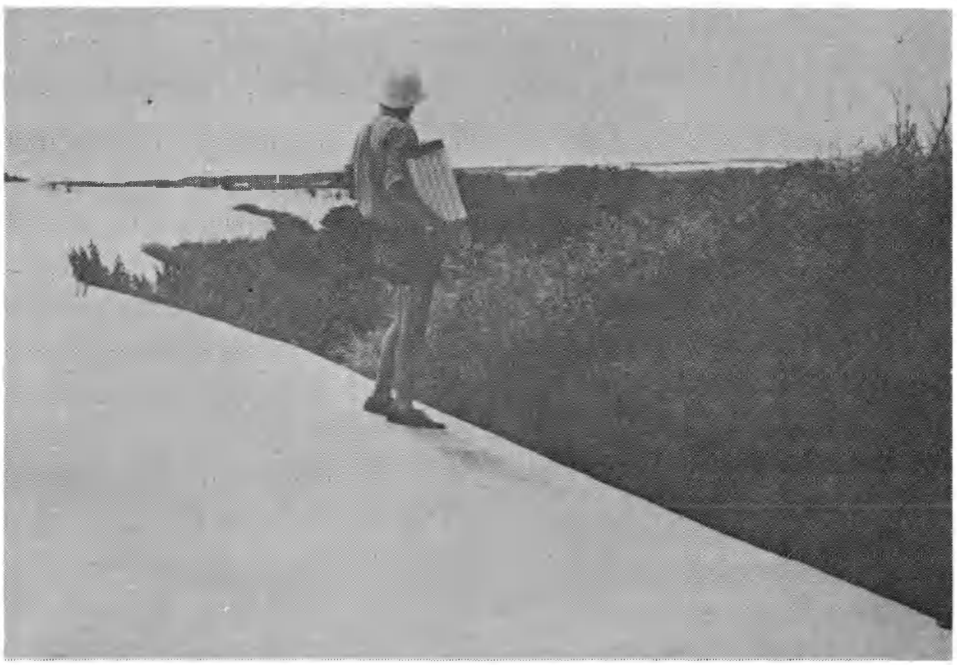


Figure 27. Whalehead Hill Medano looking southwest (top, October, 1976) and southeast ( bottom, March 1977). The slipface, 5.5 m high, has migrated 6 m/year to the south-southwest ( 1976-1977)

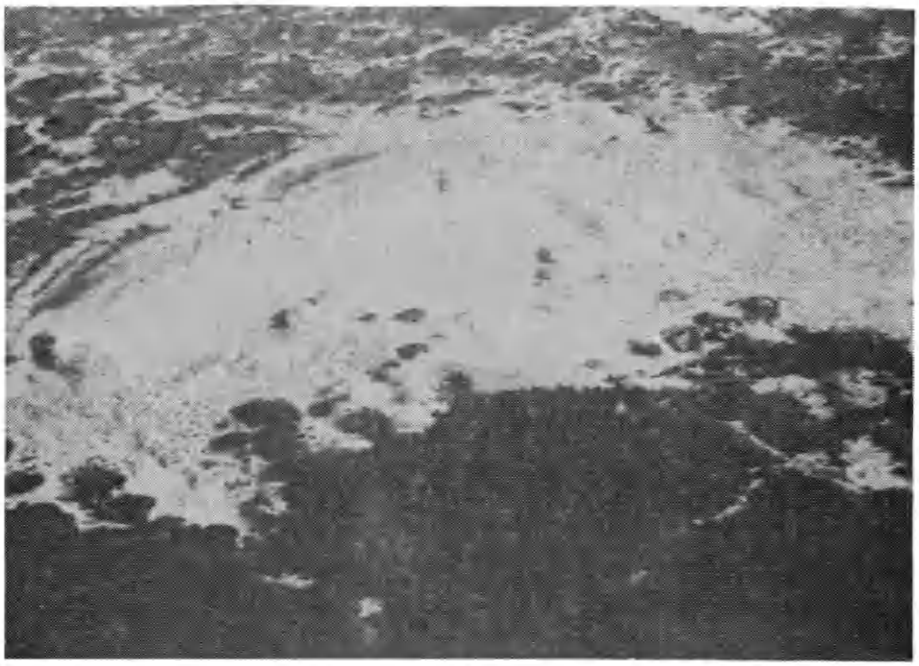


Figure 28. Aerial views of Barbour Hill looking northeast (top, January, 1975) and southwest (bottom, April, 1976). Note extensive vegetation surrounding sand hill.

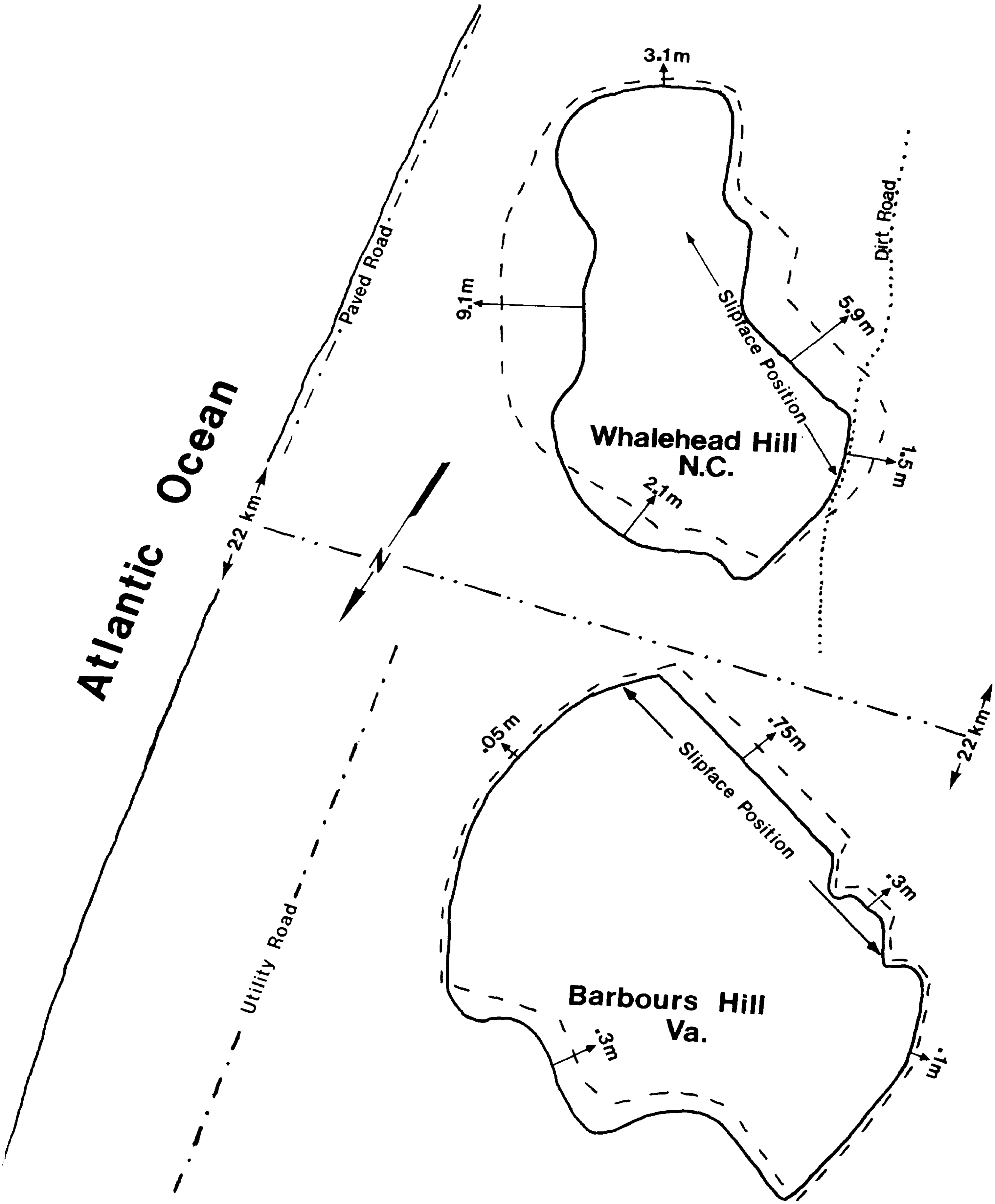



Figure 29. Schematic illustration of the movement of two large sand hills (Feb. 1, 1976 to Jan. 31, 1977 ). Dashed line indicates new dune position.

Figure 29 shows that the south-southwest movement of Whalehead Hill, as measured at the slipface, was eight times greater than the Barbours Hill rate (6 m as opposed to 0.75 m). At Whalehead, a lobe with a low (2 m) slipface marched about 1.5 m across an old unpaved road. This movement was particularly evident since travel past the dune along the road, which at the start of this study in 1976 was possible, is now no longer possible (Figure 30). Notice also that the largest net change occurred on the east flank of Whalehead Hill, which showed a movement of some 9 m over one year.

As evident in Figure 4, the highest wind duration was from the southwest. It is not surprising then that the east flank of Whalehead Hill showed a net lateral accretion of 9 m derived from sand blowing off the dune onto the adjacent flat. This movement of Whalehead Hill is particularly significant considering that the new paved road leading to Corolla is located only 100 m farther to the east of the dune. On many occasions this new (1975) road has been covered by sand blowing off the large medanos during strong westerly winds (Figure 31).

## Northern and Southern Differences in Migration Rate

The present rate of south-southwest migration of Whalehead Hill is approximately 6 m/year while at Barbours Hill this rate is less than 1 m/year. Old aerial photographs (Figure 26) indicate that the migration rate of Whalehead Hill, which has averaged 8 m per year over the last 16 years, was considerably greater in the past. These past-present and north-south differences are evident even though the dunes are very similar in size (approximately 17 m high and 200 m across), the height of the slipface in both cases is about 5.5 m,

Figure 30. Eolian transport of sand off of Whalehead Hill covering paved road to the east (top).

Figure 31. Slipface of Whalehead Hill advancing to the southwest covering dirt road (bottom).

and these dimensions have not changed much in the past 16 years. Therefore other factors must account for the large differences in migration rate.

The migration rate of large dunes is controlled by sand transport, anchoring vegetation, and the wind regime. Sixteen years ago (Figure 26) there was only scarce vegetation to the east and north of Whalehead Hill to impede sand transport. Therefore, the dune moved at the maximum rate possible under the existing wind regime of the area.

However, when vegetation colonizes the eolian flat and a foredune system is formed, the surface roughness upwind of the dune increases and the wind velocity over the dune crest decreases. This will cause the dunes to decrease their rates of migration. Vegetation colonization has proceeded farther at False Cape than at Corolla (Figure 28). A stable multiple-ridge foredune system has effectively cut off sand transport to the interior allowing thick shrub vegetation to colonize the eolian flat. Dune grasses have colonized much of Barbours Hill, further slowing its advance.

Sand transport measurements (detailed and discussed in a later section) illustrate this effect of vegetation colonization. During 15 m/sec onshore winds a zero transport rate was measured across the eolian flat to the east of Barbours Hill. During the same 15 m/sec onshore wind conditions the transport rate across the eolian flat at Whalehead Hill was 0.2-.3 g/cm·sec. In the Whalehead Hill region there are only low, discontinuous foredunes, little eolian flat vegetation, and therefore a greater flux of sand between the beach and the sand hill (compare Figures 27 and 28). No vegetation has colonized

Whalehead Hill and the upwind surface roughness is much less at Whalehead Hill than Barbours Hill. Therefore, Whalehead Hill shows a much faster migration rate than Barbours Hill, though still less than the migration rate of Whalehead Hill 16 years ago.

Slipface Orientation and Movement Direction

Examination of the Corolla station wind diagrams (Figures 4-6) leads to the obvious question as to why there is no persistent slipface oriented normal to the southwest winds. Indeed, slipfaces were seen throughout the period on the easterly flanks of Whalehead Hill. However, these were only temporal features lasting until a change of wind direction occurred. On the contrary, the slipface on the south flank of Whalehead Hill is persistent, being evident in all old aerial photographs.

Notice in Figure 4 that the strongest average wind speeds were for the north and northeast directions. The northerly winds (20%) were second in duration only to the southwest winds (32%). However, the effectiveness of the southwest winds are greatly diminished by the presence of a thick forest with trees 15 m high, to the west of all the sand hills. Due to the blockage of the southwest winds, the northerly winds can be considered dominant. This explains the orientation of the slipface which is approximately normal to, and downwind of, these northerly winds. Once established, this high slipface (6 m) acts as a sink for any sand blowing over the crest, because the winds blowing over the forest can not develop the sheer velocity necessary to carry sand up the steeply sloping (32°) slipface. Therefore, all of the sand hills show a net movement to the south-southwest in response to the northerly winds, but only temporary movements in other directions in response to the multi-directional wind regime.

## Volume Discharge of Sand

The volume discharge of sand across the slipface of both Barbours and Whalehead Hills can be estimated if the size and rate of advance of the dune is known. Figure 32 shows a schematic of a slipface for a large dune such as Barbours or Whalehead Hill. The volume discharge is the area of the shaded portion times a unit width which is calculated according to the relation:

$$V = BB' * H * W$$

where:

$V$ = volume discharge/year/meter of slipface
$BB'$ = distance dune travelled in one year
$H$ = height at brink of slipface
$W$ = length of slipface crest (here set at 1 meter)

Similarly, the equivalent weight of sand discharged:

$$Q = V * \gamma$$

where

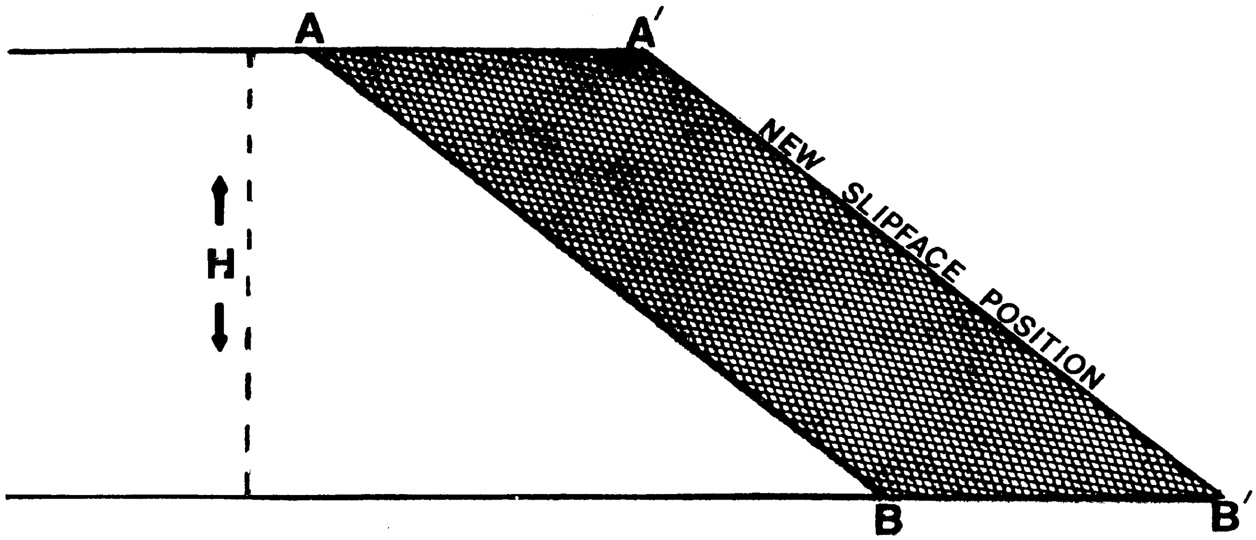
$Q$ = discharge in g/unit width
$V$ = volume discharge
$\gamma$ = bulk density of loosely packed sand which is about 1.4 $g/cm^3$ (Inman, 1966)

Therefore the discharge of sand for Barbours Hill is:

$$V = 0.75 * 5.5$$
$$= 4.1 \ m^3/\text{year/meter width}$$
$$Q = 1.3 * 10^{-3} \ cm^3/cm \cdot sec * 1.4 \ g/cm^3$$
$$= 1.8 * 10^{-3} \ g/cm \cdot sec$$
$$= 5.7 * 10^3 \ kg/m \cdot year$$

and for Whalehead Hill is:

$$V = 6.1 * 5.5$$
$$= 33.5 \ m^3/\text{year/meter width}$$




VOLUME DISCHARGE (SHADED AREA) OF A LARGE SAND DUNE BASED ON A KNOWN HEIGHT (H) AND MOVEMENT (BB').

$$V = BB' \times H \times W$$

WHERE:

V = VOLUME DISCHARGE/YEAR/METER OF SLIPFACE
BB' = DISTANCE DUNE TRAVELLED IN ONE YEAR
H = HEIGHT AT BRINK OF SLIPFACE
W = LENGTH OF SLIPFACE CREST (HERE SET AT 1 METER)

Figure 32. Volume discharge (shaded area) of a large sand dune based on a known height (h) and movement (BB').

$$
\begin{aligned}
Q &= 1.1 * 10^{-2}\ cm^3/8\ m\cdot sec * 1.4\ g/cm^3 \\
&= 1.54 * 10^{-2}\ g/cm\cdot sec \\
&= 4.9 * 10^4\ kg/m\cdot year
\end{aligned}
$$

Over 33 m (49,000 kg) of sand at Whalehead Hill, while only 4.1 $m^3$ (5,700 kg) of sand at Barbours Hill, was transported across one meter of slipface crest between March 1976 and March 1977. Therefore the transport of sand across the slipface at Whalehead Hill was about nine times greater than at Barbours Hill due to vegetation colonizing the eolian flat to the east of Barbours Hill.

Conclusions

1. Aerial photographs indicate that the migration rate of the large sand hills, Whalehead Hill, south of Corolla, North Carolina has averaged about 8 meters/year towards the south-southwest over the last 16 years.

2. Barbours Hill in False Cape State Park, Virginia has been nearly stabilized by vegetation and is now migrating at 0.75 m/year to the south-southwest. The volume discharged across the slipface was calculated to about 4 $m^3/m\cdot year$.

3. Whalehead Hill has not been stabilized as much by vegetation, and is now migrating to the south-southwest at about 6 m/year, corresponding to a calculated volume discharge of about 33 $m^3/m\cdot year$. In addition, the eastern flank of this dune has undergone 9 m of horizontal accretion in one year towards the new paved road leading to Corolla.

4. The persistent south-southwest slipface is attributed to the dominance of the north and northwest winds because of the adverse effect of the maritime forest to the southwest on the equally frequent and speedy southwest winds.

5. Apart from the wind, vegetation is the most crucial environmental variable in determining the migration rate and slipface orientation of large sand hills. As will be shown in the next section, vegetation is also very important in determining the development and orientation of coastal parabolic dunes.

## ORIENTATION OF COASTAL PARABOLIC DUNES AND REALTION TO WIND VECTOR ANALYSIS

One of the more striking features along Currituck Spit (Figure 1) is a field of parabolic (or U) dunes ranging from 3 to 10 m in height and extending south in False Cape State Park to the state line (Figure 33). Orientation of U dunes is a result of the interaction of many environmental variables including wind, vegetation, topography, standing water, and the location of the sand source. Landsberg (1956) and Jennings (1957) assumed wind was the dominant factor and therefore ignored the remaining environmental variables in their studies of the orientation of parabolic dunes in Denmark and Tasmania, respectively.

Landsberg (1956) first described the evolution of parabolic dunes. Figure 34 shows a four phase sequence which leads to the characteristic U shaped dunes found along many coasts of the world, including Currituck Spit. A large mobile sand mass (Phase 1) becomes increasingly stabilized by vegetation along the flanks which lag behind an advancing slip face and lead to the U shaped dune (Phase 2). Eventually the parabolic dune becomes completely stabilized (Phase 3) and the downwind end may even completely erode (Phase 4). This complete hypothetical evolutionary sequence of parabolic dunes is presently exhibited in Currituck Spit. Old aerial photos (1937) show a massive sand sheet in this area which eventually developed into the parabolic dune field according to the sequence shown in Figure 34 with the

Figure 33. High altitude aerial photograph (April, 1975) of parabolic dune field in False Cape State Park, Virginia, looking south.

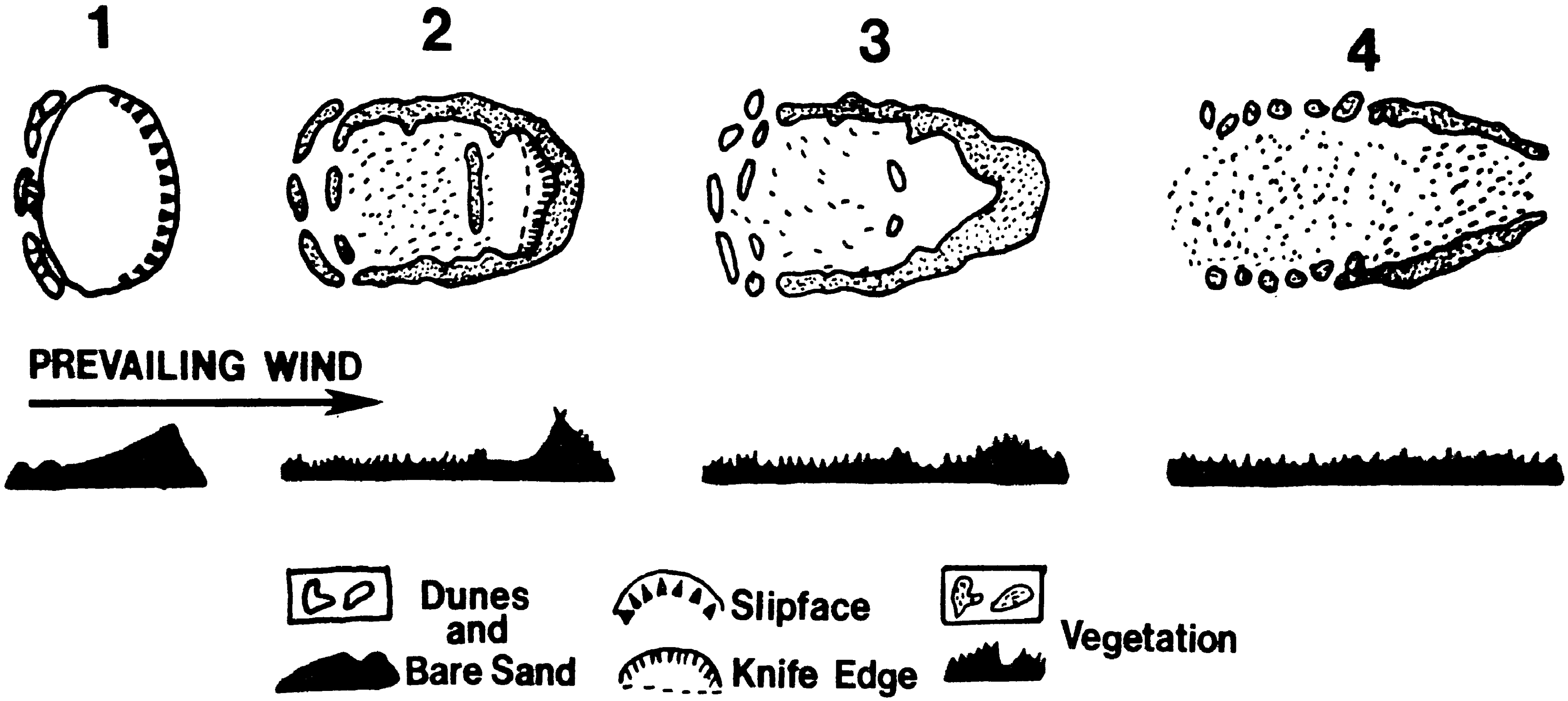



Figure 34. Diagramatic representation of parabolic dune phases (after Landsberg, 1956). See text for discussion.

exception that phase four has not been reached (Henningar, 1978).

Barbour Hill (Figure 28), discussed at length in the previous section, represents the first phase of U-dune development. A small number of Phase 2 active parabolic dunes (6 m in height) are evident to the south of Barbours Hill. However, most of these parabolic dunes are lower (three meters) and completely stabilized Phase 3 dunes. Figure 35 contains low altitude photographs of parabolic dunes in False Cape State Park.

It is clear that the wind regime and vegetation are both critical in determining the orientation of parabolic dunes. The remaining environmental factor which was considered in this study is the orientation of the beach relative to the dunes. Since the beach is the initial source of sand for dunes, it follows that the orientation of the beach relative to the prevailing and dominant wind regime, and the parabolic dune field will also play a role in determining the orientation of U-dunes.

## Wind Vector Analyses

If a clear relation exists between the sand transporting capabilities of wind and parabolic dune orientation, the vector mean of the Corolla Station wind data should correlate with the orientation. As will be shown, this is not necessarily true for coastal dunes. Bagnold (1941) showed experimentally that eolian sand transport is proportional to the cube of the wind velocity above a threshold level. Therefore, to accurately evaluate the wind field in relation to eolian transport a method originally proposed by Landsberg (1956) was used to determine the magnitude of individual vectors for each direction on

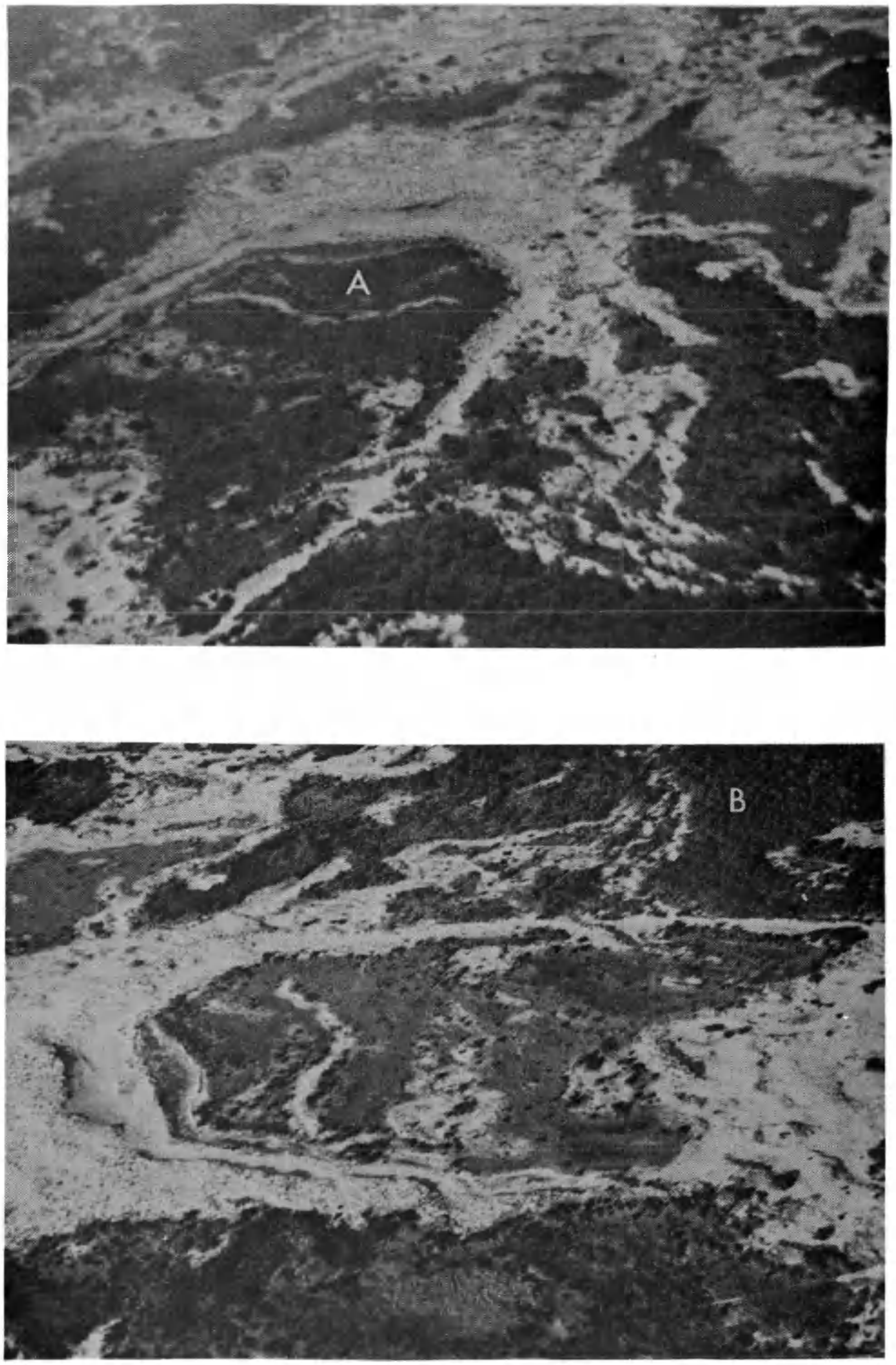



Figure 35. Parabolic Dunes
A. View toward south, note heavily vegetated blowout
B. View toward west of same dune

an eight point compass according to the relation:

$$b = s \sum_{i=1}^{i=n} (v-v_t)^3$$

where:

b = magnitude of individual vector, for each of eight directions
s = scaling factor for plotting
n = number of observations in class interval
v = wind speed in meters per second
$v_t$ = threshold velocity (5.0 m/sec)

After computing each value of b, the eight vectors were graphically added to determine a wind resultant. These calculations and the plots were generated by the computer program listed in Appendix 3.

The Corolla Station annual wind resultant (Figure 36) is oriented from the northwest to southwest. However, this resultant has no obvious relation with the average parabolic dune orientation.

Figure 37 shows the orientation of the field of parabolic dunes (Figure 33). The orientation was determined by bisecting the angle formed by lines tangent to the two arms of the U-dunes, and then measuring the angle of the bisector relative to north. Table 3 lists the orientation of all the dunes measured from vertical aerial photography along with calculations of the mean standard deviation and standard error of the mean. Several sets of imagery (ERTS frames) were utilized to determine orientation due to the difficulty of defining the actual location of flanks and slipfaces for certain dunes. The first column on the left in Table 3 lists the orientation of the 11 parabolic dunes shown in Figure 33 and additional dune measurements. The mean orientation of the 30 parabolic dunes is N 8°E. Notice the wind resultant (Figure 36) deviates by about 70° from the mean

TABLE 3

PARABOLIC DUNE ORIENTATION FROM AERIAL PHOTOGRAPHS

Orientation determined from bisector of two arms
(arranged by dates of aerial photo data sources)

| Dec., 1974 | | April, 1965 | | Dec., 1973 | |
|---|---|---|---|---|---|
| Dune No. | Compass Orientation of Bisectors | Dune No. | Compass Orientation of Bisectors | Dune No. | Compass Orientation of Bisectors |
| 1 | 6° | 12 | 2° | 22 | 16° |
| 2 | 8° | 13 | 359° | 23 | 10° |
| 3 | 8° | (April, 1975) | | (November, 1976) | |
| 4 | 14° | 14 | 14° | 24 | 8° |
| 5 | 352° | 15 | 11° | 25 | 12° |
| 6 | 12° | 16 | 7° | 26 | 0° |
| 7 | 13° | (June, 1973) | | 27 | 14° |
| 8 | 11° | 17 | 9° | 28 | 3° |
| 9 | 10° | 18 | 6° | 29 | 9° |
| 10 | 9° | 19 | 3° | 30 | 9° |
| 11 | 9° | 20 | 357° | | |
| | | 21 | 3° | | |

Mean Parabolic Dune Orientation = 7.9°

Standard Deviation = 5.5°

Standard Error of Mean = 1.04°

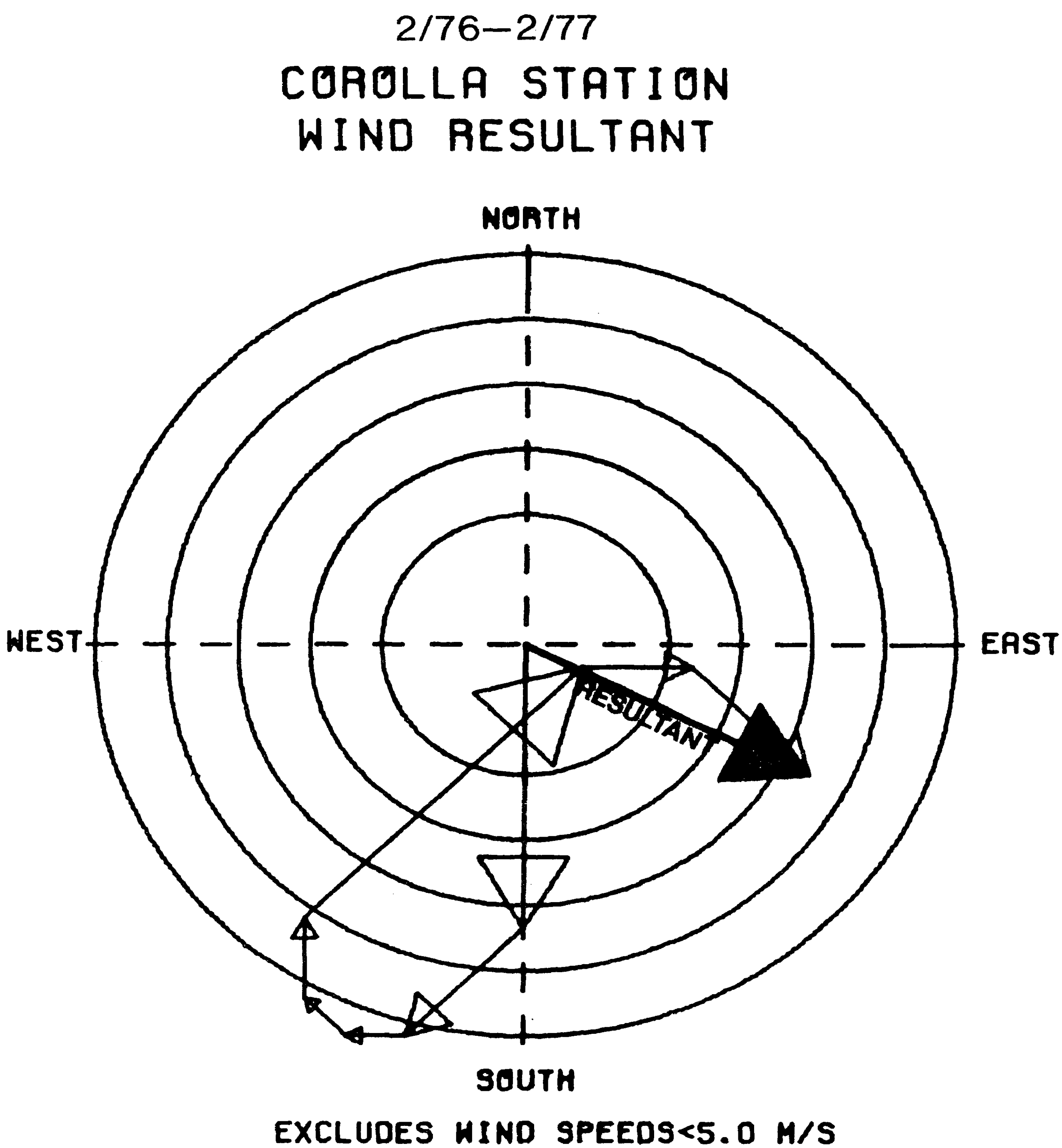



Figure 36. Corolla station annual vector mean wind resultant (February 1, 1976 to January 31, 1977).

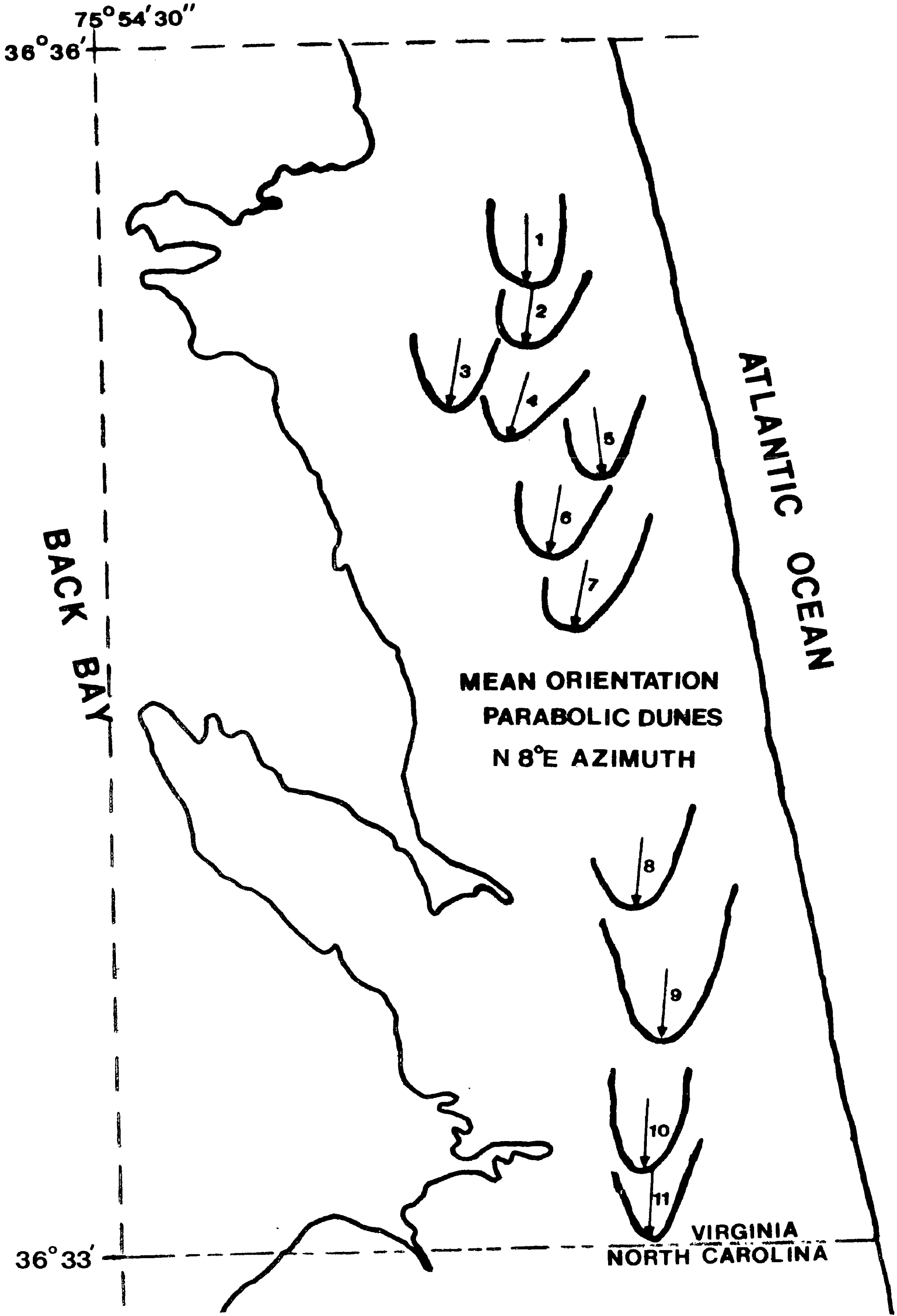



Figure 37. Parabolic dune field of False Cape, Virginia, illustrating location, plane view, and orientation of the dunes. The dunes are numbered and keyed to Table 3.

orientation. Therefore in using the simple vector mean of all cubed wind speeds there is no apparent correlation between wind regime and dune orientation. Jennings (1957) also found little correlation using this method in studies of King Island (Tasmania) parabolic dunes.

When two or more modes occur in a circular frequency distribution the vector mean is often not a useful measure (Potter and Pettijohn, 1963). Examination of the Corolla station wind rose for winds greater than or equal to 5.0 m/sec (Figure 5) show four general modes; northeast, north, northwest, and southwest. Figure 5, though it shows a northwest resultant, actually indicates the largest magnitude vectors are from the north and southwest. If, instead of examining just the vector resultant, we concentrate on the effects of vegetation on the individual vectors and the orientation of the shoreline, a much better relation emerges between the orientation of parabolic dunes and the important environmental variables.

Aerial photographs (Figure 33) show the parabolic dunes developed with a 15 meter high forest to the west of the dunes, which is higher than the height of the developing dunes. The wind velocity at the surface, and therefore the transporting capability of the wind, is dependent on the roughness characteristics of the surface. Vegetation, a surface roughness element, diminishes the wind velocity at the surface and downwind of the vegetation as a function of the density and height of vegetation (Bressolier and Thomas, 1977). Thus, the very thick and high forest of scrub pine and live oak, to the west of the parabolic dune field, greatly reduced the effectiveness of the westerly winds.

To the east of the parabolic dunes, at the time of their formation, was a sand flat with sparse dune grass vegetation. Easterly winds (i.e., northeast winds in this area) were thus unimpeded by vegetation in the transport of sand. The onshore winds should also be considered the important winds for they blow over the primary source of sand for deposition as parabolic dunes. Therefore, given the effects of vegetation in greatly diminishing the sand transporting capability of the westerly winds, and the location of the source of sand relative to the dune field, it was concluded that the onshore winds were dominant in determining the orientation of parabolic dunes.

Since the initiation of the parabolic dunes, a high foredune with abundant vegetation has formed upwind of the parabolics. Thus, the same situation may not be present now; i.e., the vegetation is now blocking sand transport from onshore winds, as well as the offshore winds.

Figure 38 is a wind resultant diagram constructed in the same manner as Figure 36 except all offshore winds are excluded. Notice this resultant is much closer to the mean orientation of the parabolic dunes than the resultant in Figure 36. The resultant is within about 20 degrees of the mean orientation and much closer for a number of the U-dunes listed in Table 3.

The Corolla wind data, from which these wind resultants were determined, covers only one year of data even though the orientation of these parabolic dunes was determined over a twenty year period. The question which naturally arises is if these one year wind resultants are actually representative of the long term wind regime. In a previous section of this thesis, it was shown that the one year of Corolla and Hatteras Station wind data were similar. Figure 39, a comparison of wind resultants (within 20°) from the two stations, supports this conclusion. It was also shown in the wind climate section

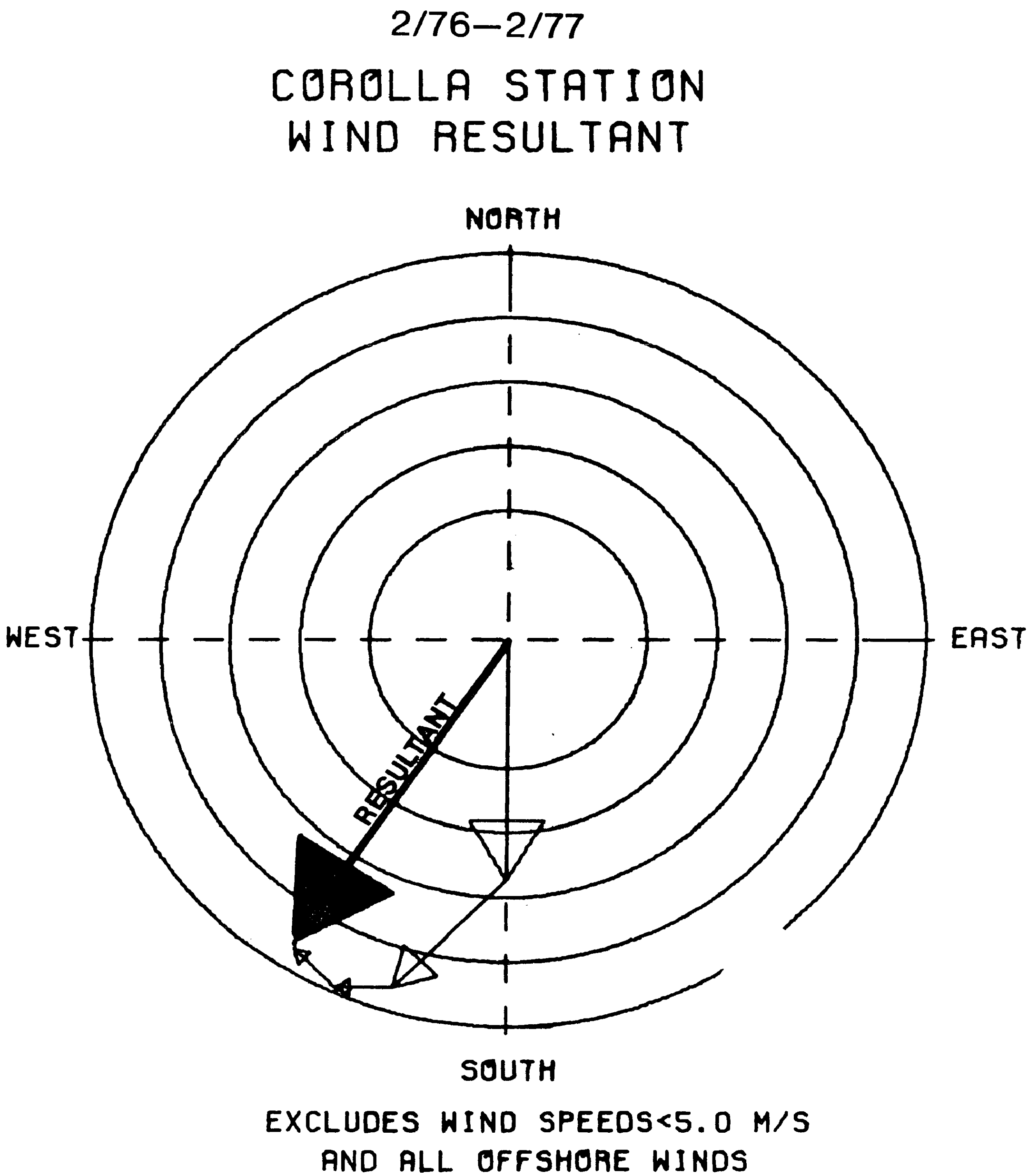
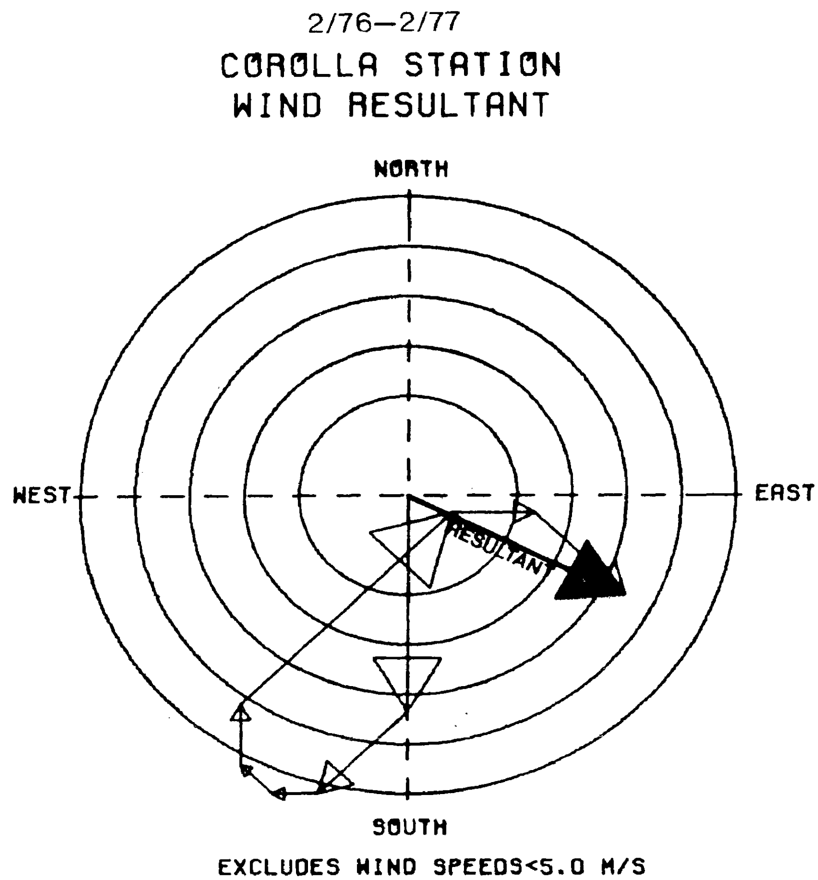



Figure 38. Corolla station wind resultant (February 1, 1976 to January 31, 1977) excluding all offshore winds.



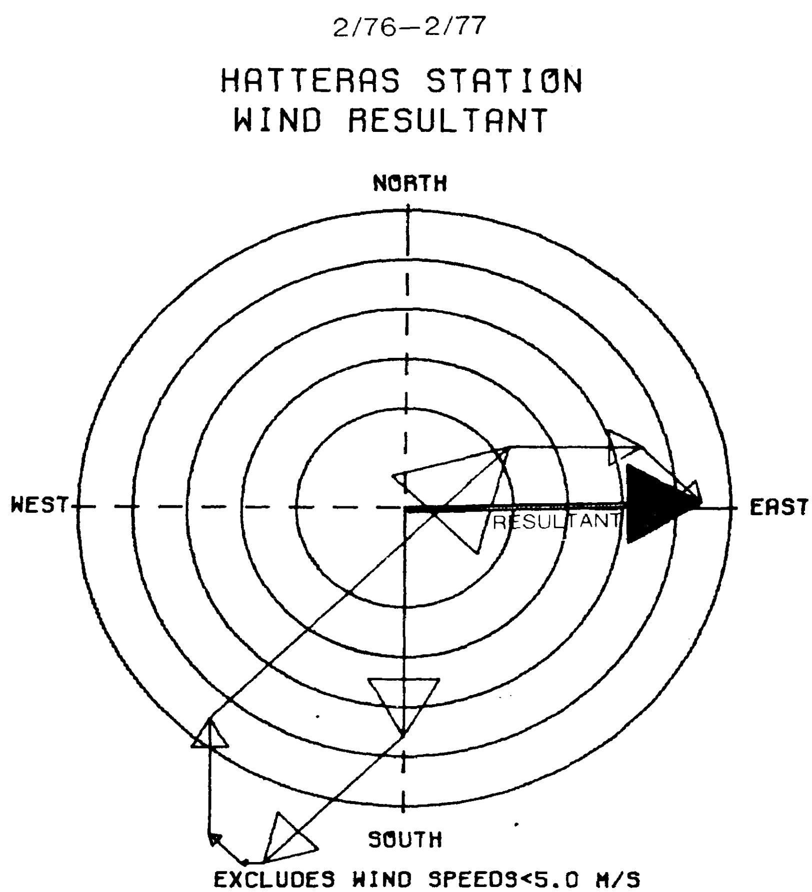




Figure 39. Comparison of Corolla and Hatteras Wind Resultants.

that the one year of Corolla wind data (February 1, 1976-January 31, 1977) from which these wind resultants were determined, was a fairly typical year relative to the long-term wind regime. Therefore, the Corolla wind resultants which were compared with the orientation of parabolic dunes should be similar to a wind resultant determined from long term data, if such data were available.

Conclusions

1. A relatively uniformally oriented field of parabolic dunes located in False Cape, Virginia, with a mean orientation of N 8° E, shows an evolutionary sequence similar to that detailed by Landsberg (1956).

2. It was concluded that a local one year (February 1, 1976 to January 31, 1977) wind resultant should be similar to a wind resultant determined from long term wind data for the area.

3. The vector mean wind resultant determined by cubing wind speeds above 5.0 m/sec showed no correlation with the mean orientation of the parabolic dunes.

4. Vegetation has an important effect in determining the development and orientation of parabolic dunes by stabilizing the arms of the developing U-dune and reducing the effective transporting capability of offshore winds.

5. It was assumed that the offshore winds were dominant in determining the orientation of the parabolic dunes because of a lack of vegetation seaward of the dune field (at the time of formation), and a high, dense maritime forest landward of the dune field. By making this assumption, the Corolla Station wind resultant was within 20° of the mean orientation of the False Cape parabolic dune field.

# EOLIAN GRADING OF SAND ACROSS TWO BARRIER ISLAND TRANSECTS

Textural studies of sands have been conducted in order to understand the environments of deposition of ancient geologic formations in connection with the search for stratigraphic oil traps (Friedman, 1961; Mason and Folk, 1958). Ahlbrandt (1974), however, concluded that the structures of deposits are more definitive of an ancient eolian environment than are the textures. Both Ahlbrandt (1974) and Sharp (1965) found that textural analyses of sand were useful in detailed analyses of known depositional environments.

Two very different depositional environments are evident on Currituck Spit (Transects A and C in Figure 40). A cross-barrier transect near Corolla, North Carolina includes a low, sparsely vegetated foredune ridge, shifting sands on the eolian flat and a large unvegetated medano (i.e., sand hill, Figure 27). To the north, in False Cape State Park a second transect crosses subenvironments quite different from those to the south. Here there are high multiple-ridge foredunes, dense eolian flat shrub thickets, and large vegetated parabolic dunes (Figure 28). Since textural parameters may be able to differentiate environments of deposition, a detailed sampling and analysis of sediment deposits across two transects was conducted with the hope that the textural parameters might indicate the geologic processes responsible for the differences in the subenvironments of the north and south transects, and help clarify the role that eolian sand transport plays in the overall sediment dynamics of a barrier island.

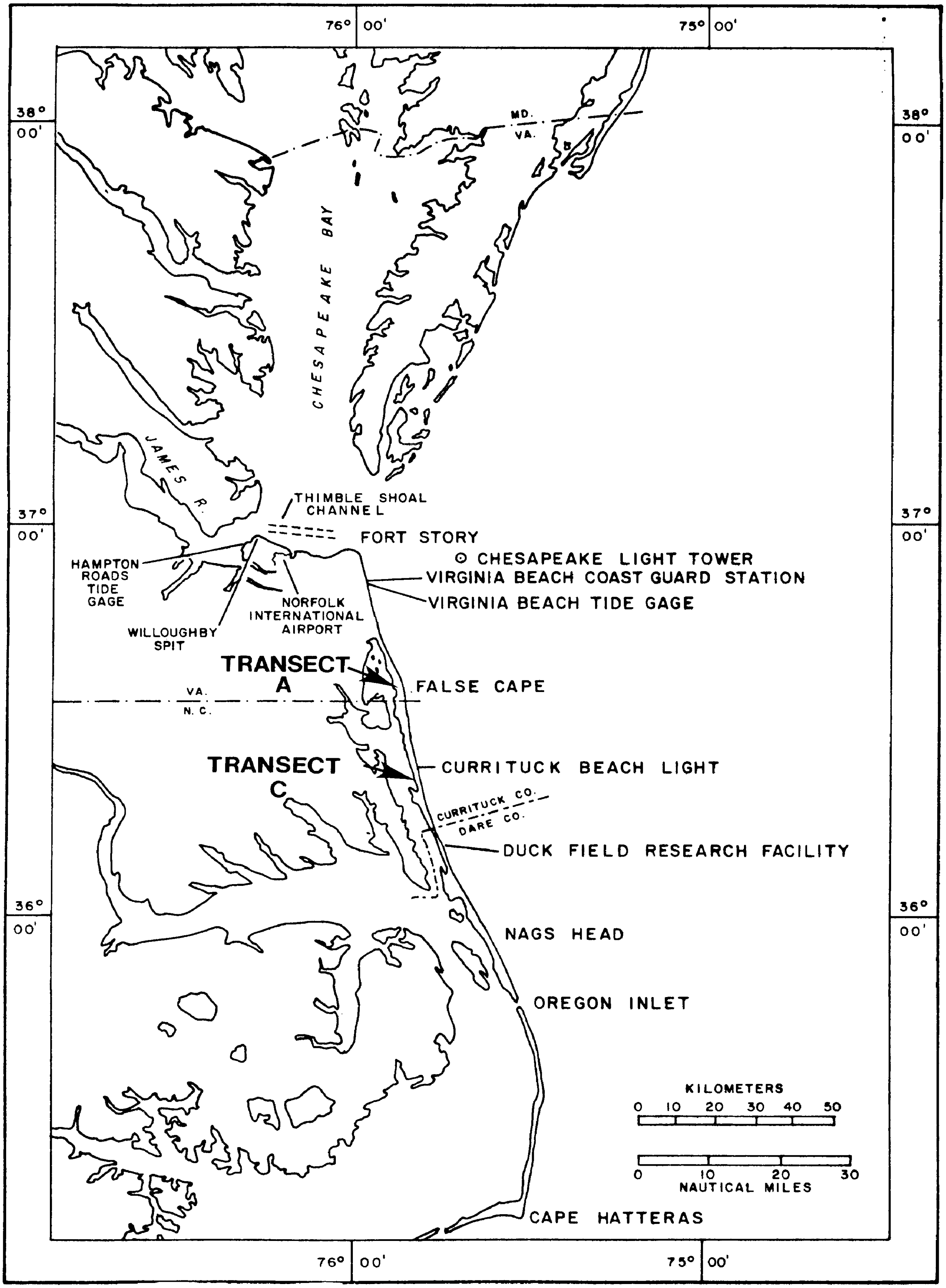



Figure 40. Regional location map showing two transects sampled.

Field Procedure

Field work for this study was conducted between January 1976 and January 1977. The field work consisted of sampling along two cross-barrier transects (Figure 40); one in False Cape State Park, Virginia, and the other just south of Corolla, North Carolina. The two transects were always sampled on the same day, as close to the time of low tide as possible.

Starting at the low water mark samples were collected across the transect at irregular intervals. In general the same number of samples were collected across the two transects. However, the distance between samples varied according to the width of the subenvironments that the transects crossed. The northern transect was 0.6 kilometers long with a wider and higher foredune system and a wider eolian flat, than the wouthern transect which was 0.45 kilometers long.

At each sampling site (Figure 41) on the transect two samples were collected. A surface sample was collected by scraping a thin layer of sand onto a sheet of cardboard and then storing it in a sample bag. This sample was supposed to represent the most recent response of the sediment to the wind regime. The sampling was conducted after a fairly long period (~72 hours) of winds above the threshold velocity for sand movement from a constant direction. Table 4 lists the wind data from the Currituck Light Station for the six day period prior to each of the two sampling periods. Notice that one sampling was conducted after a period of offshore winds while the other sampling was after a period of onshore winds. After collection of the surface sample a 2.54 cm diameter 5.0 cm deep core was taken at the same site and stored in a coded sample bag. This sample was supposed to represent many sedimentation

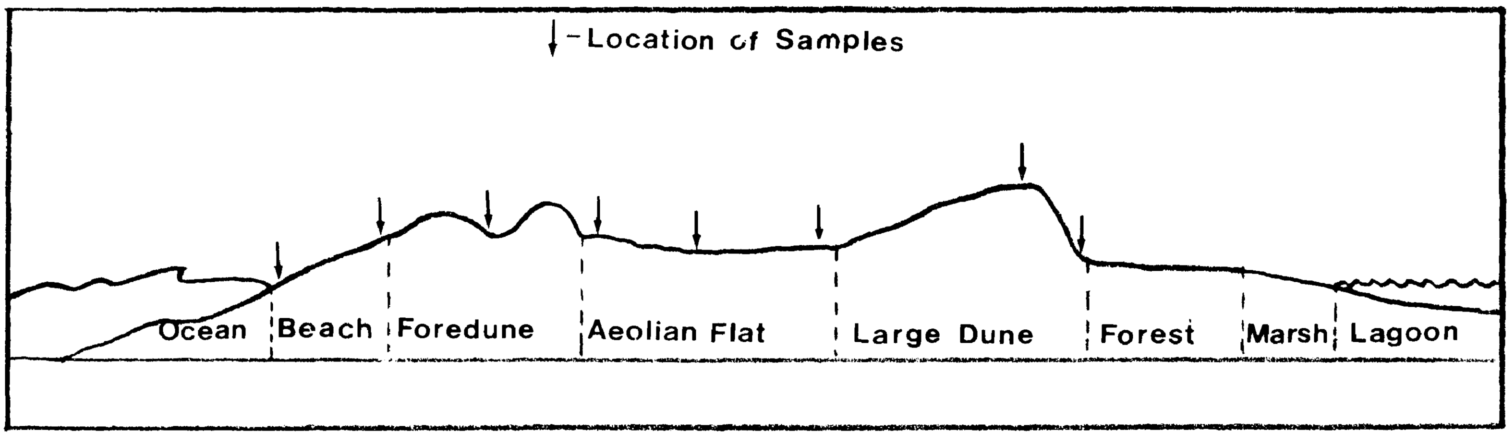



Figure 41. Profile of barrier island showing location of samples on transect.

TABLE 4

WIND DATA PRIOR TO SEDIMENT SAMPLING FOR SAND GRADING STUDY.

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG. FROM TRUE NORTH, SPEEDS MPH (Multiply By .44704 to get m/sec)

STATION-COROLLA LIGHT

| DATE/HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/6/76 | 16 | 255 | 14 | 245 | 14 | 255 | 8 | 255 | 18 | 235 | 20 | 225 | 22 | 215 | 24 | 235 | 30 | 215 | 16 | 236 |
| 2/6/76 | 22 | 245 | 12 | 235 | 12 | 235 | 4 | 275 | 16 | 65 | 24 | 65 | 26 | 75 | 24 | 65 | 32 | 55 | 5 | 74 |
| 3/6/78 | 20 | 65 | 26 | 75 | 24 | 65 | 24 | 75 | 20 | 65 | 26 | 55 | 26 | 55 | 82 | 65 | 28 | 75 | 30 | 64 |
| 4/6/76 | 26 | 65 | 26 | 65 | 32 | 55 | 32 | 55 | 32 | 45 | 32 | 55 | 36 | 55 | 34 | 55 | 42 | 45 | 31 | 55 |
| 5/6/76 | 36 | 55 | 36 | 55 | 32 | 55 | 36 | 45 | 38 | 55 | 30 | 45 | 32 | 35 | 38 | 35 | 42 | 55 | 34 | 47 |
| 6/6/76 | 24 | 35 | 20 | 35 | 20 | 35 | 20 | 35 | 8 | 65 | 6 | 85 | 8 | 165 | 10 | 165 | 28 | 35 | 10 | 50 |

Sampling Conducted June 6, 1976 Following Period of Onshore Winds.

| DATE/HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15/2/76 | 12 | 95 | 16 | 85 | 12 | 115 | 6 | 145 | 12 | 185 | 20 | 215 | 26 | 215 | 24 | 235 | 34 | 215 | 9 | 183 |
| 16/2/76 | 28 | 235 | 26 | 245 | 22 | 245 | 20 | 255 | 16 | 245 | 18 | 235 | 18 | 215 | 26 | 225 | 24 | 215 | 21 | 237 |
| 17/2/76 | 26 | 235 | 22 | 235 | 30 | 235 | 26 | 235 | 22 | 245 | 20 | 235 | 16 | 185 | 18 | 225 | 34 | 235 | 21 | 231 |
| 18/2/76 | 16 | 220 | 18 | 225 | 18 | 225 | 20 | 215 | 22 | 215 | 32 | 205 | 34 | 215 | 36 | 235 | 46 | 215 | 24 | 219 |
| 19/2/76 | 18 | 265 | 16 | 265 | 16 | 275 | 20 | 305 | 10 | 285 | 18 | 255 | 14 | 235 | 18 | 235 | 26 | 295 | 14 | 264 |
| 20/2/76 | 20 | 265 | 14 | 355 | 7 | 345 | 6 | 55 | 8 | 75 | 8 | 125 | 10 | 160 | 8 | 178 | 23 | 255 | 0 | 358 |

Sampling Conducted February 20, 1976 Following Period of Offshore Winds.

units though in many cases it may not have, due to the long duration of the undirectional winds prior to sampling.

At each transect, samples were gathered at the low water mark, berm, beach dune interface, foredune crest, midway down the landward foredune slope, and across the eolian flat (Figure 41). Then samples were collected along the slope, at the crest, and at the base of the slipface, of a large dune. After completion of both transects the samples were taken back to the laboratory for analyses.

## Textural Analyses

Grain size distributions for all samples were determined with the Rapid Sediment Analyser at the Virginia Institute of Marine Science. After oven drying, splits of samples were obtained using a Otte splitter. Several splits were necessary to get an optimum 5-15 gram sample size for the settling tube.

The Virginia Institute of Marine Science Rapid Sediment Analyser (RSA) is modelled after the unit designed by Zeigler et al. (1960) at Woods Hole. The falling velocity of particles over a one meter drop is measured by a differential pressure transducer which sends a voltage signal to a recording unit. Templates prepared from the tables of Zeigler and Gill (1959) are then used with a Gerber variable scale to determine from the record, sizes in sedimentation diameter (i.e., hydraulic radius) of ten percentiles along the curve. For simplicity and because the most important aspect of the study was detecting relative changes of texture, the grain size parameters from the settling tube were determined from the hydraulic radius.

The data from the settling tube analyses were input into a computer program for calculation of mean, standard deviation, skewness and kurtosis. Many different methods for calculating these four moments have been proposed. The graphic method of Folk and Ward (1957) was chosen for all calculations. McCammon (1962) found that the mean derived by this method had an accuracy of 88% relative to the result of the moment method, while the standard deviation had an accuracy of 79%. The graphic method is also much simpler and the ability to discriminate environments of deposition by the graphic method of Folk and Ward (1957) has been shown by many authors (Friedman, 1961; Mason and Folk, 1958; Ahlbrandt, 1975; Anan, 1971).

Graphic Mean: A measure of the average size of the sand particles was determined according to the relation:

$$\bar{x} = \frac{\phi\ 16 + \phi\ 50 + \phi\ 84}{3}$$

where:

$\phi$ = phi unit corresponding to some percent level on the cumulative frequency curve.

Graphic Standard Deviation: A measure of the sorting of the sediment, was calculated according to the relation:

$$\sigma = \frac{\phi\ 84 - \phi\ 16}{4} + \frac{\phi\ 95 - \phi\ 5}{6.6}$$

A low value of $\sigma$ indicates well sorted, while a high value indicates poorly sorted sediment.

Graphic Skewness: A measure of the symmetry of the grain size distribution about the mean, was determined according to the formula:

$$sk = \frac{\phi\ 16 + \phi\ 84 + 2\ \phi\ 50}{2\ (\phi\ 84 - \phi\ 16)} + \frac{\phi\ 5 + \phi\ 95 - 2\ \phi\ 50}{2\ (\phi\ 95 - \phi\ 5)}$$

Symmetrical curves have sk = 0.0; those with an excess of coarse sediment are negatively skewed, while those positively skewed indicate an excess of fine sediment.

Graphic Kurtosis: Is a quantitative measure of the departure from normality of the grain size distribution. Kurtosis measures the ratio between the sorting of the tails and the central portion of the probability curve. Kurtosis was calculated according to the formula:

$$kg = \frac{\phi\ 95 - \phi\ 5}{2.44\ (\phi\ 75 - \phi\ 25)}$$

A normal curve has a kg of 1.0. Curves with kurtosis greater than 1.0 are said to be leptokurtotic, that is the central portion is better sorted than the tails. A kg less than 1.0 indicates a platykurtotic curve where the tails are better sorted than the central portion.

After computer calculation (DeAlteris, 1974) of the grain size parameters, plots of the moments (Figures 42-45) versus distance across transect were generated on a Calcomp plotter.

False Cape Transect

Figures 42 and 43 are plots of the four grain size moments versus distance across the barrier at False Cape for a set of samples taken after period of intense southwest (Figure 42) and northeast winds (Figure 43). Notice that neither figure indicates any clear cross-barrier changes in the grain size moments. Only samples gathered in the foreshore where deposition is primarily by waves is there any marked change in the grain size characteristics. In this area the beach sand showed a coarser (about 1.0 phi), more poorly sorted (standard deviation about 0.49) sediment with a skewness indicating a tail of coarse sand (-0.1).

Landward of the zone of wave activity where eolian processes are dominant the sand becomes very uniform in grain size characteristics across the barrier. This eolian sand has a mean size of about 1.8 phi,

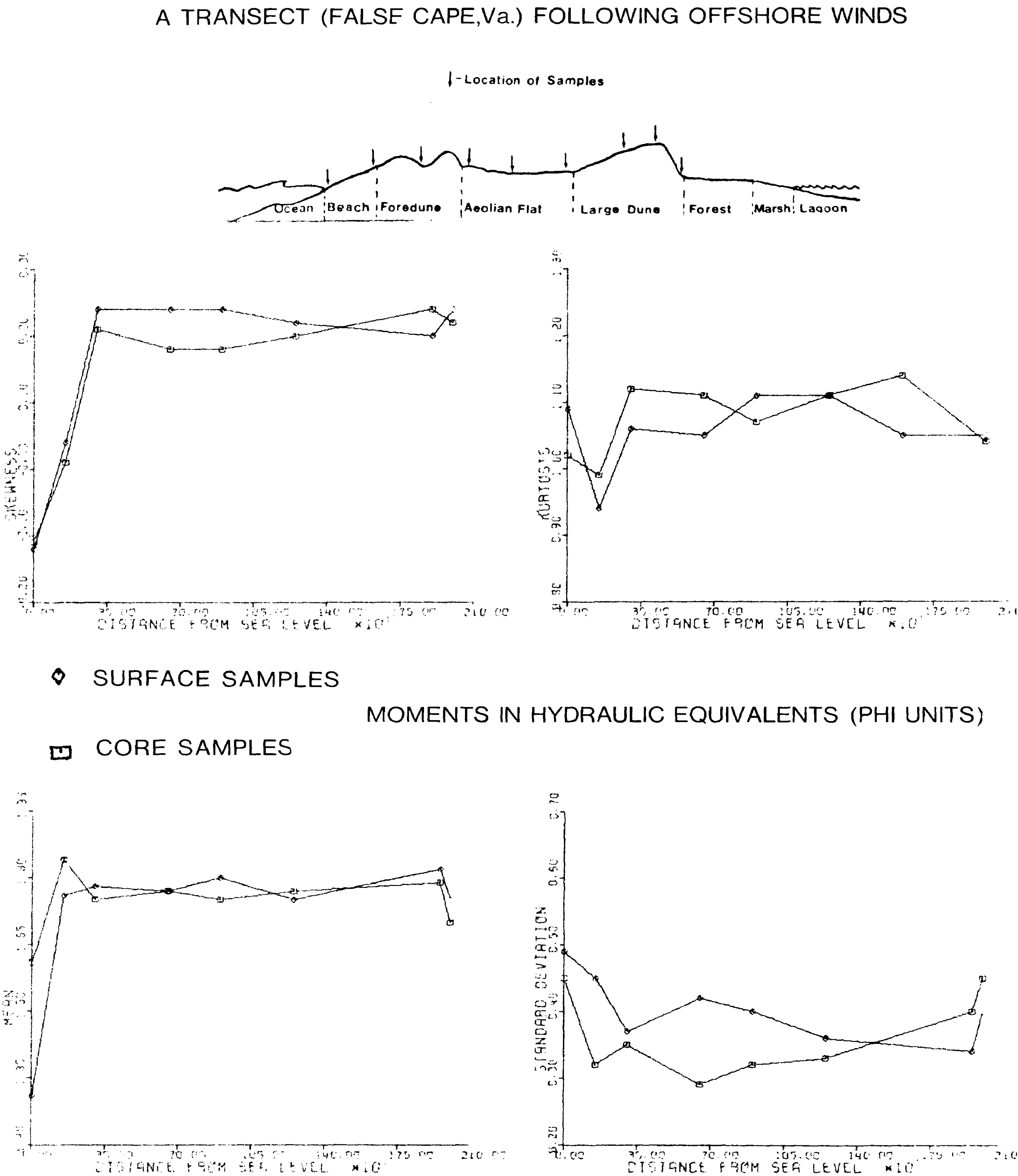



Figure 42. Grain-size moments across Transect A in False Cape State Park, Virginia (Barbours Hill).

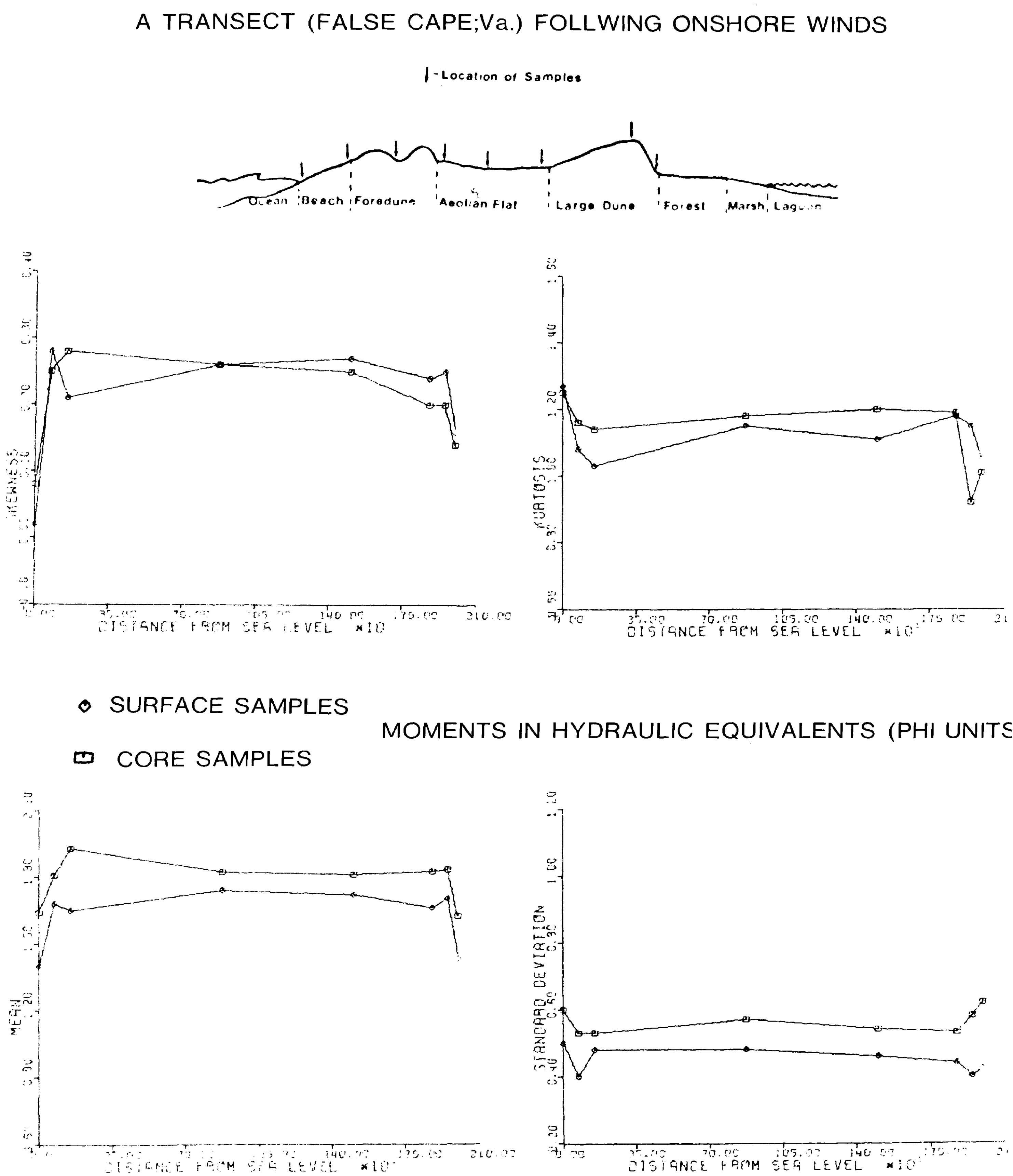



Figure 43. Grain-size moments across Transect A in False Cape State Park, Virginia (Barbours Hill).

is well sorted (standard deviation ~.3) and a positive skewness (~.3) indicating a tail of fine mate-ial. These general grain size characteristics are to be expected for eolian deposited sand. What is surprising however is the apparent lack of any clear grading of sand across the transect. If we assume that the beach is the source of sand for eolian deposition then it would follow that samples gathered at increasing distances from the source should show the following:

1. Mean grain size should decrease (phi increase) because finer sand should be differentially transported farther inland.

2. Standard deviation should decrease as sand becomes finer and more uniform in size.

3. Skewness should become increasingly positive as normal curve becomes skewed towards the fines.

4. Kurtosis may become leptokurtotic as the central part of the curve becomes better sorted.

Examination of Figures 42 and 43 indicate no such changes at the False Cape transect for either onshore or offshore winds.

It is especially surprising that after a period of onshore winds (Figure 43) none of these grading characteristics were evident.

A field examination of the transect reveals a high (3-5 meters) multiple ridge foredune system with a thick growth of dune grasses, impeding most, if not all, transport to the interior. Further downwind from the sand source a very thick shrub thicket growing across the entire eolian flat is effectively eliminating any flux of sand between the beach and the interior, or across the barrier island. Figure 28 is an aerial photograph of this area showing the general distribution of vegetation. Field measurements of sand transport (discussed in a later section) during 15 m/sec (35 miles/hour) onshore winds indicated a zero transport rate across the dunes and eolian flat. There is little cross-barrier sand transport in the False Cape region due to the presence of vegetation, so there could be no grading of sand. Therefore, it is suggested that this accounts for the lack of a change in trend in Figures 42 and 43.

Whalehead Hill Transect, South of Corolla

Figures 44 and 45 are plots of the four grain size moments versus distance across the Whalehead Hill transect south of Corolla (Figure 40), for the same dates as Figures 42 and 43, respectively. Figure 44 (following offshore winds) shows a slight seaward decrease from the large dune to the beach in mean size, and in skewness towards a fine tail in surface samples, relative to the Barbours Hill transect. A greater difference is that there is no great change in the moments at Whalehead Hill after offshore winds for the foreshore surface samples, even though the core sample at the foreshore does show typical wave-deposited sand characteristics. It is suggested that the relatively small mean grain size of the surface sample is a result of eolian sand blowing off the dunes and eolian flat onto the beach. The core sample in the foreshore zone may have penetrated through the recent layers of eolian deposition into typical wave deposited sand, therefore giving a somewhat coarser grain size. The deposition of eolian sand in the foreshore zone is not indicated by the Barbours Hill grading diagram (Figure 42) even though the sampling was conducted for Figures 42 and 44 on the same day. This is due to the large differences in the amount of sand carried onto the beach in the two areas. Sand transport measurements of sand blowing from the foredune and eolian flat onto

## C TRANSECT (COROLLA,N.C.) FOLLOWING OFFSHORE WINDS

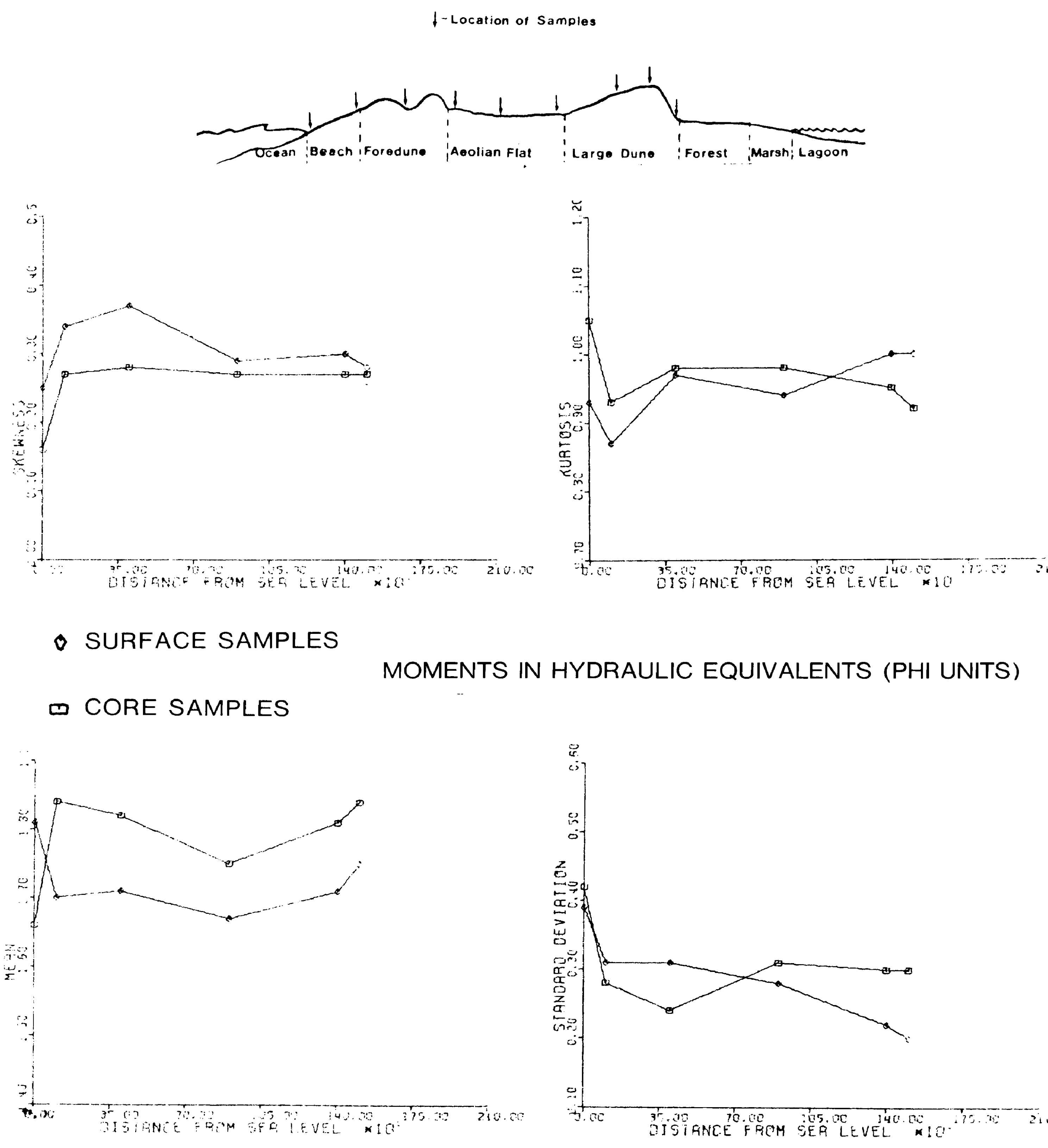



Figure 44. Grain size moments across Transect B south of Corolla, North Carolina (Whalehead Hill).

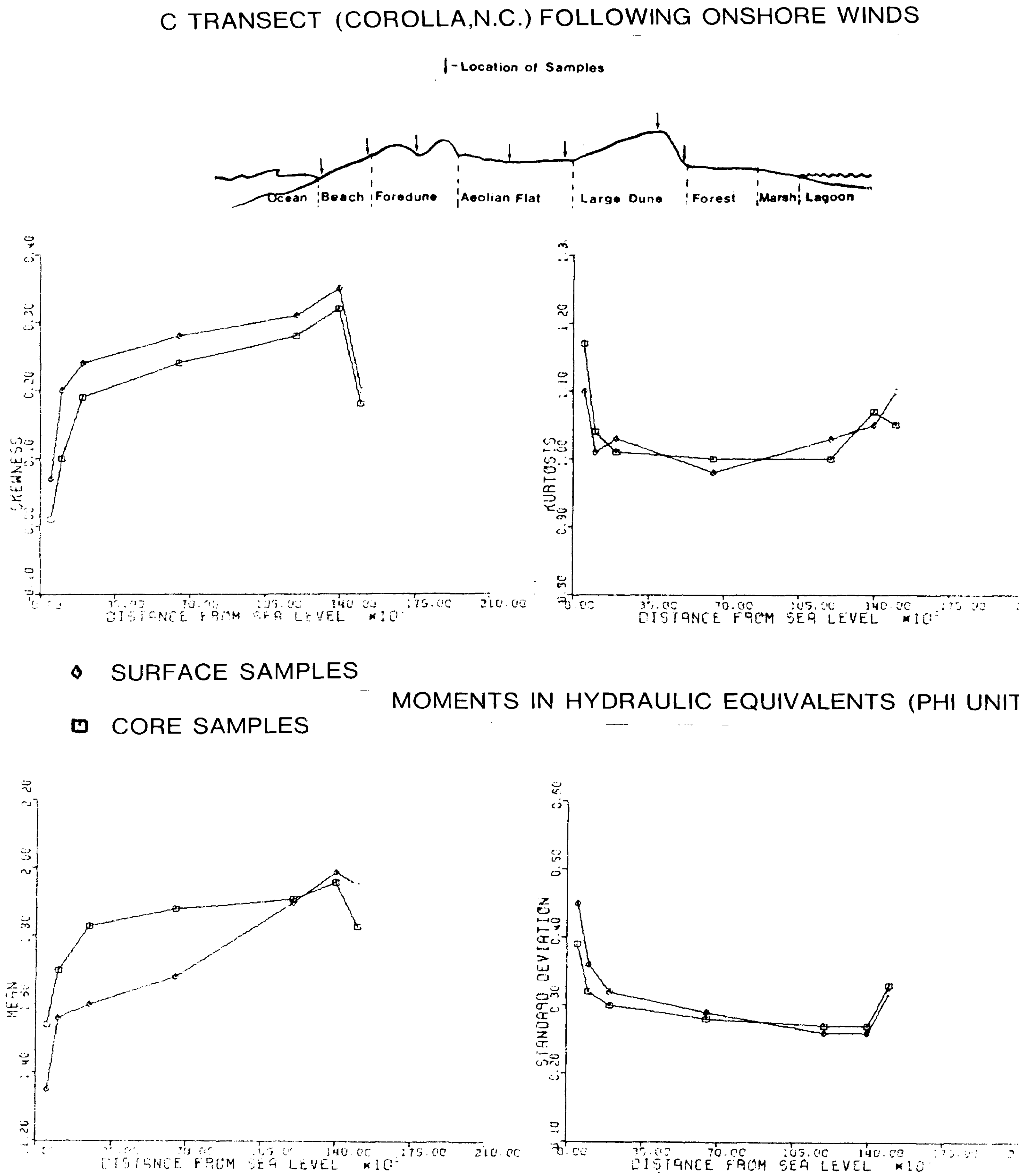



Figure 45. Grain-size moments across Transect B south of Corolla, North Carolina (Whalehead Hill).

the beach during 11 m/sec (24 miles/hour) winds (see Table 8) from the southwest were conducted at both areas. At the Whalehead Hill transect the transport rate was about 0.07 g/cm·sec while at the Barbours Hill transect it was only 0.01 g/cm·sec. For a one hour period and a one meter width, this is equivalent to a difference of over 20 kg of sand. The explanation for this large difference in transport rate is the lack of thick eolian flat and foredune vegetation in the Whalehead region which does not inhibit the flux of sand as it does in the Barbours Hill region.

Figure 45 contains plots of the four moments after a period of onshore winds (Table 4). Notice that in the first three moments there is a slight trend of increasing phi values (fining) across the barrier from the ocean beach, indicating some of the expected changes in grain size characteristics as the sediment is carried across the barrier under the influence of the onshore winds. The mean grain size decreases slightly, the sorting improves, and the skewness increases towards the fine tail as would be expected. Kurtosis does not indicate any clear trend. The cross-barrier trends in Figure 45 are not pronounced, but they do correlate with known transport measurements and vegetation characteristics. As indicated in Figure 27, the extent of vegetation and height of foredunes south of Corolla is much less than in False Cape. Due to this lack of vegetation there was a flux of sand, which extended a distance of approximately 0.5 km in response to both onshore and offshore winds, resulting in eolian grading of sand.

## Conclusions

1. No pronounced cross-barrier eolian grading of sand between the beach and dune was observed with the exception of surface samples

gathered on the transect south of Corolla at Whalehead Hill after onshore winds and after offshore winds.

2. The complete lack of grading in the Barbours Hill region is attributed to the effects of a thick vegetation cover which has effectively stabilized the interior of the barrier spit, thus precluding eolian grading of sand.

3. In the Whalehead Hill region, diagrams of the four moments indicate a greater flux of sand in response to onshore and offshore winds than is evident in the False Cape region. This greater flux is attributed to a lower foredune system and less extensive vegetation.

4. These grading characteristics corroborate field measurements of sand transport which indicate that there is a much greater sand transport rate during both onshore and offshore winds in the Whalehead Hill region than to the north in False Cape State Park.

5. The only pronounced changes across the transect were at the foreshore where wave activity resulted in a coarser sand in contrast with eolian deposition further inland. The ability to discriminate beach and dune depositional environments by grain size analysis confirms the studies of Mason and Folk (1958), Friedman (1961) and Ahlbrandt (1975).

## DEVELOPMENT OF A MODEL TO PREDICT EOLIAN SAND TRANSPORT

A quantitative estimate of the rate and amount of sand movement over a fairly long period is necessary to accurately evaluate the role of eolian sand transport with respect to:

1) Sediment dynamics of a barrier spit
2) Migration of large sand dunes
3) Orientation of parabolic dunes
4) Effect of northern and southern cross-barrier transect differences
5) Effect of sand fencing.

Field measurements of eolian sand transport can provide instantaneous transport rates for a particular set of environmental conditions but there is no instrument developed which will measure and record continuously the eolian sand transport. Therefore an empirical computer model was developed to compute directional eolian sand transport from one year (2/76-2/77) of wind and precipitation data. Unlike sand transport these environmental variables are easily measured and recorded by available instrumentation. The model was developed after careful consideration of the coastal mechanisms of eolian sand transport to determine the important variables in the transport process, the best equations of transport available, and what equations if any must be developed to compute eolian sand transport in the coastal zone. The model was then verified using field measurements of eolian sand transport.

## Mechanism of Eolian Sand Transport

Atmospheric winds blowing over a surface will, depending on the wind velocity, particle weight, and other environmental variables, initiate three different types of motion; suspension, surface creep, and saltation. For a particle to travel in suspension its settling velocity must be less than the upward eddy diffusion currents. During eolian transport, suspension is rarely the method of travel. Bagnold (1941) and Horikawa and Shen (1960) showed that for sand transported by wind, less than 5% of the material travels in suspension while some 20% travels as surface creep and 70% travels by a mechanism known as saltation. During saltation, as shown in Figure 46, individual grains are ejected from the surface and follow trajectories under the influence of gravity and shear stress. In reality the particles do not follow such distinct paths as in Figure 46. Instead observations suggest a more random trajectory which is reasonable considering the turbulence of the air and the randomness of impact of the particles. If the particles do not enter suspension they will travel with the wind a certain distance and then gradually descend to the surface when the particles may either rebound back into the so-called saltation layer, or eject other particles by the transfer of momentum and remain behind. The grains moving along the immediate surface, the surface creep, receive their momentum from grains returning to the surface. Surface winds are generally turbulent for any velocities that exceed 1.0 m/sec (Binder, 1973). Turbulence is indicated by irregular velocity fluctuations generally known as gusts. For the case of eolian sand transport, wind movement can be described as a turbulent boundary layer above an aero-

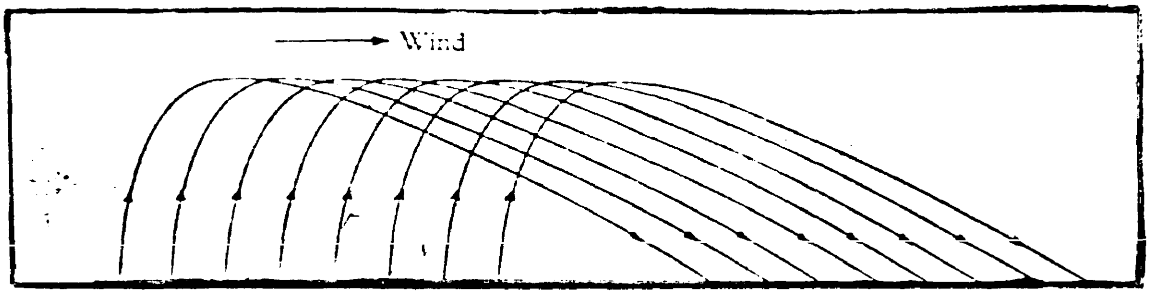



Figure 46. Saltation

dynamically rough surface.

As the wind flows over the surface of a particle, movement is initiated if the upward directed pressures exerted on the grain overcome the forces of gravity. The air as it flows over the surface of the particle, exerts a resultant force. One component, along the line of the wind velocity, is the resistance or drag. At right angles to the drag is the lift force. The total drag on a particle immersed in a fluid is dependent on the viscous and inertial forces. Therefore the drag is proportional to the Reynolds number. The drag component itself may be divided into components; skin friction and pressure drag. The skin friction component is due to the formation of the boundary layer on the surface of the particle. Pressure drag is caused by pressure differences upstream and downstream from the particle (Binder, 1973).

The velocity above the surface of a particle resting on a bed is greater than below the particle. It follows then, by the Bernoulli equation, that the pressure on the lower side of the particle will be greater than the pressure on the surface above. This pressure difference represents the lift component of the resultant force on a particle immersed in a flowing fluid.

Kadib (1966) described lift ($\bar{L}$) by the equation:

$$\bar{L} = C\ p\ \frac{U^2 A}{2}\ D^2$$

where:

C = lift coefficient

U = instantaneous velocity acting as a distance y from the surface

p = density of air

D = diameter of particle

A = shape factor for grain area

Chepil (1959) has shown that the equilibrium between the lift and drag, and velocity is influenced by the diameter, shape, and density of the grains, the angle of the repose of the grains with respect to the mean drag level of the wind, the closeness of packing of the top grains on the sediment bed, and the lift and drag impulses of turbulence. Chepil (1961) also showed that the ratio of lift to drag is greatest at the surface. The near vertical liftoff of a grain during saltation is a result of lift, the effect of rebounding, and the shear stress. However, it is the shear force which is critical in dislocating the particle from the surface. The observed low angle of descent of a saltating grain (Bagnold, 1941) is due to the acceleration induced by drag as the particle falls under gravity.

The nature of eolian transport is made very complex by the effects of turbulence, degree of hiding in the laminar sublayer, height of the saltation layer, and by many environmental variables which are listed in Table 5. Because of the complexity of the transport process, equations used to predict the quantity of sand transported have been largely empirically derived.

From wind tunnel and field data, Bagnold (1941) developed the following equation which is still the most widely used;

$$Q = C \frac{d}{D} \frac{p}{g} U_*^3$$

where:

$Q$ = amount of sand transported (g/cm·sec)
$U_*$ = shear velocity
$C$ = an empirical coefficient which varies with the uniformity of the sand
$d$ = diameter of the sand
$D$ = standard diameter of 0.25 mm sand
$p$ = specific weight of air
$g$ = gravity

TABLE 5

VARIABLES IN EOLIAN SAND TRANSPORT PROCESS

| Wind | Surface | Topography | Soil | Surface Effects |
|---|---|---|---|---|
| Speed | Roughness | Flat | Texture | Removal |
| Direction | Obstructions | Undulating | Structure | Deposition |
| | | Broken | Organic content | Surface markings |
| Temperature | Temperatures | | Moisture content | Dune formations |
| Humidity | Vegetation Cover | | Soil binders | |

Kawamura (1951) developed the equation:

$$Q = k \frac{p}{g} (U_* - U_{*_t}) (U_* + U_{*_t})$$

where:

$k$ = constant determined by the experiment
$U_{*_t}$ = threshold shear velocity which depends on the cohesive properties of the soil, such as moisture or organic binders

O'Brien and Rindlaub (1936) developed from field observations the expression;

$$Q = 0.036\ U^3$$

where

$U$ = wind velocity

Hsu (1971) recently developed the expression for transport over a beach

$$Q = k\ F^3 = k \ \frac{(U_*)}{(gd)^{\frac{1}{2}}}^{3}$$

where

$F$ = a special froude number
$k$ = constant

Here Q is proportional to the shear stress and inversely proportional to the product of gravitational acceleration (g) and mean grain size (d).

Yves-Belly (1964) tested the accuracy of the Kawamura, Bagnold, and O'Brien formulas and found the O'Brien equation to be inadequate and the Bagnold equation to be the best. These empirical equations of Bagnold and Hsu were used in development of a computer model. Unfortunately these equations were determined for conditions where the effects of vegetation, soil moisture and soil freezing were ignored. Obviously in the temperate coastal zone these factors cannot be ignored if an accurate model of eolian sand transport is to emerge.

Wind Data

The most important environmental factors (Table 5) in the transport process are the speed, direction, and structure of the wind. In this model the local Corolla station digitized wind data (see discussion of wind climate and Appendix 1) were input into the Bagnold and Hsu transport equations. However, first these wind data from 53 m above mean sea level had to be related to the shear velocity at the surface.

The standard profile of wind flowing over a surface can be expressed as (Binder, 1973):

$$U = \frac{2.3}{k} U_* \log \frac{z}{z_o}$$

where

$U$ = velocity at height $z$
$k$ = Von Karmon constant (approximately = 0.40)
$z_o$ = aerodynamic roughness height defined under the boundary condition that $U_z = 0$ at $z = z_o$. The value of $z_o$ depends on the underlying surface.

The velocity profile and therefore the value of $U_*$ is also influenced by the thermal stability of the wind profile. In general the profile will fit the theory under neutral conditions. However, when the air is thermally stratified such as during the night, the wind profile may be distinctly nonlogarithmic (Horikawa, 1960). Hsu (1971) has shown that a sea breeze can often exhibit a non-logarithmic velocity profile.

However, as an approximation Hsu (1973) used the logarithmic law, to compute shear velocity at the surface from routine wind data at standard heights, obtaining the expression:

$$U - U_t = \frac{U_*}{k} \ln \frac{z}{z_{ot}}$$

where

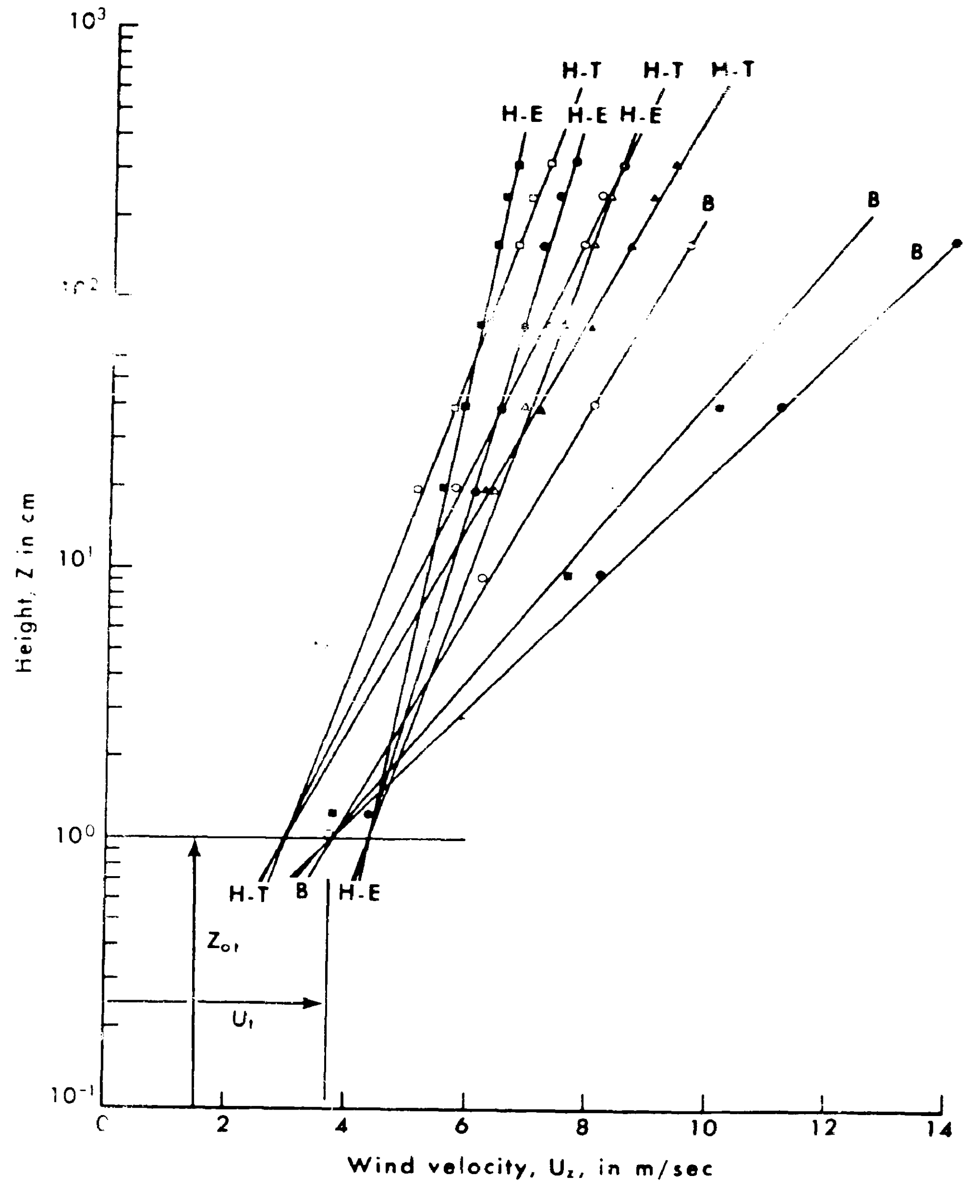
$U$ = wind velocity at anemometer
$U_t$ = threshold wind velocity
$U_*$ = shear velocity
$k$ = Von Karman constant (= .4)
$z$ = height of anemometer
$z_{o\,t}$ = roughness length defined under boundary condition that $U=U_t$ at $z=z_{o\,t}$

Figure 47 shows the data from which this equation was determined. This shear velocity equation was used in the eolian sand transport model to calculate the shear velocity from the recorded wind data (see subroutine SHRVL, Appendix 4).

In desert regions the use of shear velocity and transport equations would be sufficient for an eolian sand transport model. However, in the temperate coastal zone, precipitation, freezing of the sand, and vegetation must also be accounted for, because these environmental variables greatly influence the rate of sand transported. Kadib (1964) chose to ignore these variables in an overly simplistic calculation of sand transport by wind on natural beaches. As will be shown, ignoring these variables can lead to overestimates of eolian sand transport ranging from 20-40%.

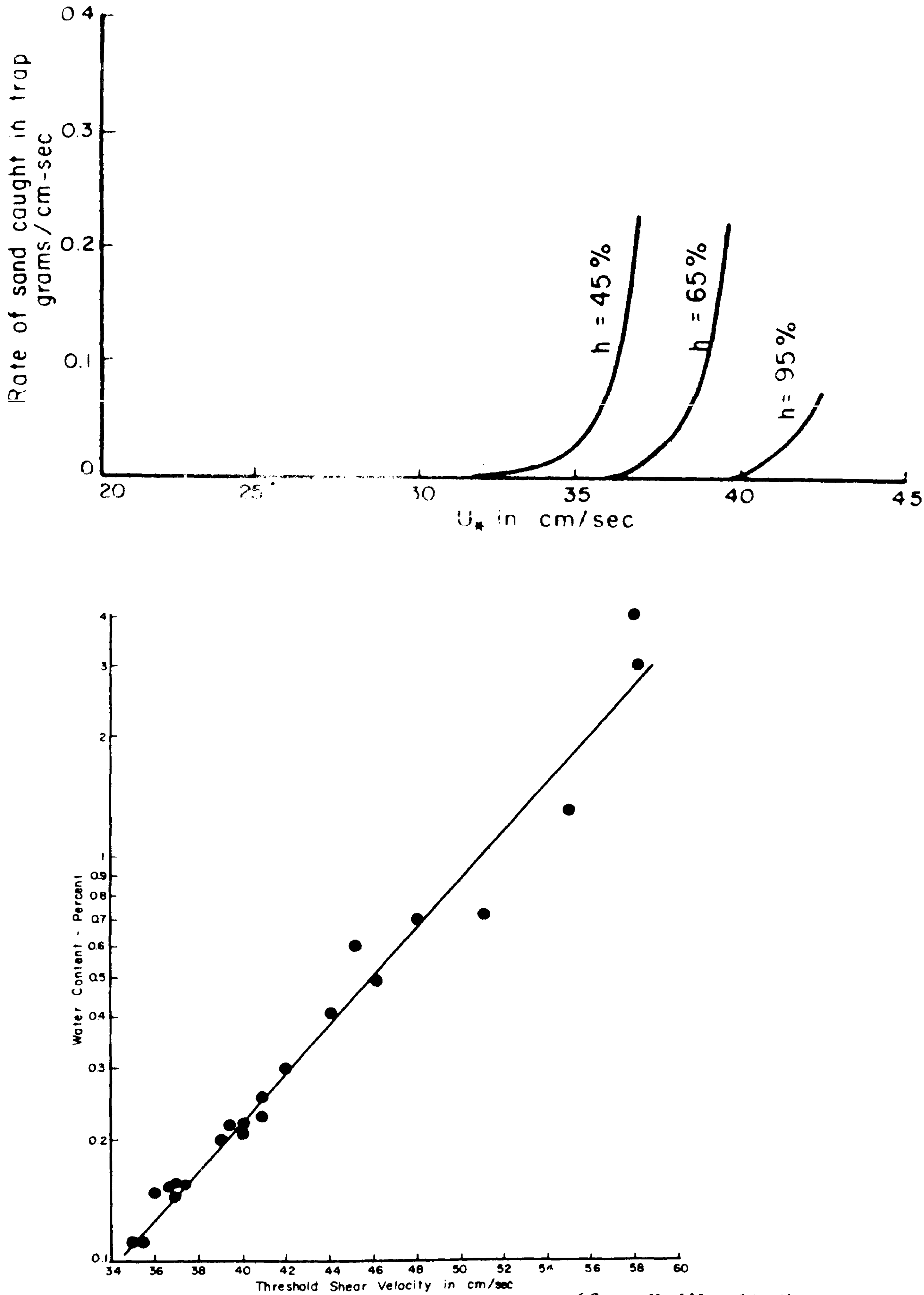
Soil Moisture Variable

Chepil (1956) and Johnson (1963) have investigated the effect of soil moisture on the erodibility of the soil. It was found that air humidity has only a small effect on the threshold shear velocity ($U_*t$) while water content of the soil greatly increases the strength of the wind necessary to initiate movement (Figure 48). Kadib (1964) suggested use of an equation to solve for $U_{*t}$ which takes the effect of moisture into account.




(from Hsu, 1971)

Figure 47. Observed wind velocity vertical distribution over sand surfaces when sand was in motion. The data lines are indicated by H-E, H-T, and B for measurements made by Hsu over an Ecuador and Texas beach, and by Bagnold for measurements made in the Libyan Desert.




(from Kadib, 1964)

Figure 48. Experimental data illustrating the effect of humidity (top) and soil water content (bottom) on the threshold sheer velocity.

$$U_{*t} = A(1+\tfrac{1}{2}(\frac{h}{100}))\frac{\sigma-p}{p}gd$$ for the effect of air moisture

$$U_{*t} = A(1.8+0.6\log w)\frac{\sigma-p}{p}gd$$ for the effect of soil moisture

where

w = soil moisture (%)
h = relative humidity
p = density of air
σ = density of the sand grains
A = fluid threshold value approximately = .1
g = gravitational acceleration

Chepil (1956) showed that the effect of the moisture was due to the cohesive force of adsorbed water films which surround the soil particles. The second equation listed above for the effect of soil moisture on the threshold shear velocity was including in this model (see subroutine THRSH, Appendix 4). In the model, if the calculated shear velocity for a three hour period does not exceed the calculated threshold shear velocity, due to either a large amount of rain or a low wind velocity, then no transport is calculated.

The problem in utilizing the above soil moisture equation was to develop a relationship between precipitation and actual soil moisture content because the threshold equation requires the input of this variable (w). Unfortunately calculation of soil moisture is very difficult because it is dependent on (Chang, 1968):

1) Precipitation

2) Amount of sunlight

3) Wind profile near ground

4) Vapor pressure profile near ground

5) Temperature

6) Amount of transpiration

7) Soil texture

8) Vegetation density

To calculate soil moisture from theoretical considerations, one must be able to predict the amount of moisture imparted to the soil by a given amount of precipitation and then calculate an evapotranspiration rate using all the environmental variables listed above. This type of data was not available for the one year period from local climatological monthly summaries and no equipment was available to measure evapotranspiration (lysimeters and evaporimeters) in the field. Therefore an empirical moisture equation, using the available data (wind velocity, temperature, and precipitation), was developed from field measurements of sand moisture content.

Fifteen sand samples were gathered during and after rain events on bare sand along Currituck Spit. In addition, 20 samples were collected for soil moisture determination after applying known amounts of water to a box filled with Currituck Spit beach sand. In both sets of samples the wind velocity, temperature, and precipitation during the sampling were recorded. The samples were returned to the lab and then weighed before and after drying. The moisture content was calculated according to the relation:

$$\%\ \text{water} = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Dry Weight}}(100)$$

Table 6 lists all the data collected for determination of a soil moisture equation.

## Soil Moisture Equation

The soil moisture measurements, as a function of wind velocity, temperature and precipitation, were input into a Computer Linear Least-Squares Curve Fitting Program which was on file at the College of William and Mary Computer Center. A detailed description of the program and

TABLE 6

LISTING OF SOIL MOISTURE DATA INPUT INTO LINEAR LEAST-SQUARES CURVE FITTING PROGRAM. SOIL MOISTURE WAS MEASURED AS A FUNCTION OF PRECIPITATION, TEMPERATURE AND WIND SPEED.

| Obsv. | Precipitation mm x $10^{-1}$ | | Temperature °C | | Wind Speed m/sec | | Moisture % by weight | |
|---|---|---|---|---|---|---|---|---|
| 1 | 8.63 | 01 | 1.11 | 01 | 1.23 | 01 | 6.50 | 00 |
| 2 | 8.63 | 01 | 1.60 | 01 | 1.23 | 01 | 3.00 | 00 |
| 3 | 1.14 | 02 | 8.94 | 00 | 2.40 | 01 | 1.23 | 01 |
| 4 | 1.01 | 02 | 1.78 | 01 | 2.12 | 01 | 2.00 | 00 |
| 5 | 3.81 | 01 | 8.94 | 00 | 1.28 | 01 | 1.00 | 00 |
| 6 | 2.54 | 01 | 1.56 | 01 | 1.00 | 01 | 5.00 | -01 |
| 7 | 8.89 | 01 | 1.56 | 01 | 2.40 | 01 | 1.40 | 00 |
| 8 | 1.01 | 02 | 1.78 | 01 | 2.96 | 01 | 1.00 | -01 |
| 9 | 6.35 | 01 | 8.94 | 00 | 1.56 | 01 | 3.40 | 00 |
| 10 | 5.08 | 01 | 1.34 | 01 | 7.28 | 00 | 1.50 | 00 |
| 11 | 7.62 | 01 | 1.11 | 01 | 2.12 | 01 | 3.00 | 00 |
| 12 | 7.62 | 01 | 1.11 | 01 | 1.00 | 01 | 5.40 | 00 |
| 13 | 7.87 | 01 | 1.34 | 01 | 1.00 | 01 | 5.00 | 00 |
| 14 | 6.35 | 01 | 1.56 | 01 | 2.40 | 01 | 4.00 | -01 |
| 15 | 2.54 | 01 | 2.23 | 00 | 1.79 | 01 | 7.00 | 00 |
| 16 | 5.08 | 01 | 2.23 | 00 | 1.79 | 01 | 1.20 | 01 |
| 17 | 7.62 | 01 | 2.23 | 00 | 1.79 | 01 | 1.60 | 01 |
| 18 | 1.01 | 02 | 2.23 | 00 | 1.79 | 01 | 2.00 | 01 |
| 19 | 1.27 | 01 | 2.23 | 00 | 1.79 | 01 | 4.20 | 00 |
| 20 | 3.81 | 01 | 2.23 | 00 | 1.79 | 01 | 7.20 | 00 |
| 21 | 1.27 | 01 | 4.02 | 00 | 2.40 | 01 | 1.00 | 00 |
| 22 | 2.54 | 01 | 4.02 | 00 | 2.40 | 01 | 3.00 | 00 |
| 23 | 3.81 | 01 | 4.02 | 00 | 2.40 | 01 | 5.00 | 00 |
| 24 | 5.08 | 01 | 4.02 | 00 | 2.40 | 01 | 8.20 | 00 |
| 25 | 7.62 | 01 | 4.02 | 00 | 2.40 | 01 | 1.40 | 01 |
| 26 | 1.01 | 02 | 4.02 | 00 | 2.40 | 01 | 1.90 | 01 |
| 27 | 2.54 | 00 | 4.02 | 00 | 2.40 | 01 | 2.00 | -01 |
| 28 | 1.27 | 01 | 6.70 | 00 | 2.40 | 01 | 1.00 | -01 |
| 29 | 3.81 | 01 | 1.11 | 01 | 2.40 | 01 | 5.00 | -01 |
| 30 | 1.27 | 01 | 7.15 | 00 | 1.73 | 01 | 4.00 | -01 |
| 31 | 2.54 | 01 | 7.15 | 00 | 1.73 | 01 | 3.00 | 00 |
| 32 | 3.81 | 01 | 7.15 | 00 | 1.73 | 01 | 3.50 | 00 |
| 33 | 5.08 | 01 | 7.15 | 00 | 1.73 | 01 | 6.50 | 00 |
| 34 | 7.62 | 01 | 7.15 | 00 | 1.73 | 01 | 1.25 | 01 |
| 35 | 1.01 | 02 | 7.15 | 00 | 1.73 | 01 | 1.70 | 01 |

the least-squares method can be found in the book by Daniel and Wood (1971) which accompanies the program. Simply stated the least-squares method finds the values of constants in a chosen equation which minimize the sum of the squared deviations of the observed values from those predicted by the equation. The form of the equation predicted by this program is

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3$$

where

$Y$ = dependent variable (soil moisture)
$x_1, x_2, x_3$ = dependent variables
$b_o, b_1, b_2, b_3$ = constants calculated from the data

Table 6 is a listing of the input data. The first independent variable is precipitation in tenths of mm. The second independent variable is temperature in degrees centigrade while the third variable is wind speed in m/sec. The one dependent variable is the measured moisture content in percent.

Table 7 lists the statistics, coefficients, and ordered residuals for the data set listed in Table 6. The fitted linear least-squares equation has the form:

$$\% \text{ moisture} = 8.4 + (.159 \times \text{Precipitation}) + (-1.02 \times \text{Temperature}) + (-1.73 \times \text{wind velocity})$$

Since the standard error of the coefficients is about 0.03, the values of the coefficients, might well be written as $b \pm 0.03$.

The F-value can be compared with tabulated values to give a joint test of the hypothesis that all coefficients are zero against the alternative that the equation as a whole produced a significant reduction in the total sum of squares (Daniel and Wood, 1971). The tabular value for F (99.5, 31, 3) is about 42.3 therefore there is a highly significant (greater than 99.5%) fit. The multiple correlation coefficient squared

TABLE 7

OUTPUT OF LINEAR LEAST-SQUARES CURVE FITTING PROGRAM

ORDERED BY RESIDUALS

| Obsv. | Obs. Y | Fitted Y | Ordered Resid. | Seq. |
|---|---|---|---|---|
| 6 | 0.500 | -5.278 | 5.778 | 1 |
| 35 | 17.000 | 14.242 | 2.758 | 2 |
| 26 | 19.000 | 16.273 | 2.727 | 3 |
| 34 | 12.500 | 10.207 | 2.293 | 4 |
| 14 | 0.400 | -1.652 | 2.052 | 5 |
| 25 | 14.000 | 12.237 | 1.763 | 6 |
| 29 | 0.500 | -1.122 | 1.622 | 7 |
| 16 | 12.000 | 11.097 | 0.903 | 8 |
| 17 | 16.000 | 15.132 | 0.868 | 9 |
| 31 | 3.000 | 2.136 | 0.864 | 10 |
| 18 | 20.000 | 19.168 | 0.832 | 11 |
| 28 | 0.100 | -0.591 | 0.691 | 12 |
| 33 | 6.500 | 6.171 | 0.329 | 13 |
| 30 | 0.400 | 0.118 | 0.282 | 14 |
| 24 | 8.200 | 8.202 | -0.002 | 15 |
| 10 | 1.500 | 1.527 | -0.027 | 16 |
| 15 | 7.000 | 7.061 | -0.061 | 17 |
| 27 | 0.200 | 0.534 | -0.334 | 18 |
| 13 | 5.000 | 5.480 | -0.480 | 19 |
| 2 | 3.000 | 3.563 | -0.563 | 20 |
| 4 | 2.000 | 2.603 | -0.603 | 21 |
| 32 | 3.500 | 4.153 | -0.653 | 22 |
| 19 | 4.200 | 5.044 | -0.844 | 23 |
| 3 | 12.300 | 13.268 | -0.968 | 24 |
| 7 | 1.400 | 2.383 | -0.983 | 25 |
| 8 | 0.100 | 1.146 | -1.046 | 26 |
| 21 | 1.000 | 2.149 | -1.149 | 27 |
| 22 | 3.000 | 4.166 | -1.166 | 28 |
| 23 | 5.000 | 6.184 | -1.184 | 29 |
| 20 | 7.200 | 9.079 | -1.879 | 30 |
| 12 | 5.400 | 7.360 | -1.960 | 31 |
| 1 | 6.500 | 8.585 | -2.085 | 32 |
| 5 | 1.000 | 3.104 | -2.104 | 33 |
| 11 | 3.000 | 5.417 | -2.417 | 34 |
| 9 | 3.400 | 6.654 | -3.254 | 35 |

| Ind. Var (I) | Name | Coef. B(I) | S.E. Coef. | T-Value | R(I)SQRD |
|---|---|---|---|---|---|
| 0 | | 8.41702D 00 | | | |
| 1 | PRECIP | 1.58879D-01 | 1.09D-02 | 14.6 | 0.1575 |
| 2 | WIND | -1.02152D 00 | 7.11D-02 | 14.4 | 0.1834 |
| 3 | | -1.73447D-01 | 6.15D-02 | 2.8 | 0.0402 |

TABLE 7 (Continued).

| | |
|---|---|
| No. of Observations | 35 |
| No. of Ind. Variables | 3 |
| Residual Degrees of Freedom | 31 |
| F-Value | 99.9 |
| Residual Root Mean Square | 1.87622951 |
| Residual Mean Square | 3.52023719 |
| Residual Sum of Squares | 109.12735287 |
| Total Sum of Squares | 1163.71600000 |
| Mult. Correl. Coef. Squared | .9062 |

is .9062. This indicates that 91 percent of the total sum of squares of y is accounted for by the fitted equation.

Figure 49 is a plot generated by the computer program of the empirical distribution of residuals. The residuals fall, as they should, approximately on a straight line. There are no outliers (wild data points). Figure 50 is a plot of the residuals versus the fitted values of y. The points fall, as they should on both sides of the zero line.

The linear equation derived from soil moisture data has a highly significant F value, a high multiple correlation coefficient, and a normal distribution of residuals. Therefore this equation represents a very good fit of the data. The moisture equation was used in the empirical model to predict the soil moisture content every three hours from precipitation, wind velocity and temperature data (see subroutine moist, Appendix 4).

## Vegetation Effects

As indicated in Table 5, vegetation is another variable influencing the transport of sand by wind. Vegetation, as shown in Figure 51, increases the value of the surface roughness parameter ($Z_o$) and thus reduces the sand transport rate. Bressolier and Thomas (1977) have shown that the increase in $Z_o$ is a function of the height and density of the vegetation. For a typical dune grass (Ammophilla sp.) they suggest a $Z_o$ ranging from 0.29-6.30 centimeters. A bare sand surface has a $Z_o$ of approximately 0.1 cm (Yves-Belly, 1964). Along Currituck Spit vegetation cover varies widely. Therefore, a range of $Z_o$ values (1.0, 3.0, 6.0, 9.0 and 12.0 cm) were input into the model to reflect differing vegetation distributions.

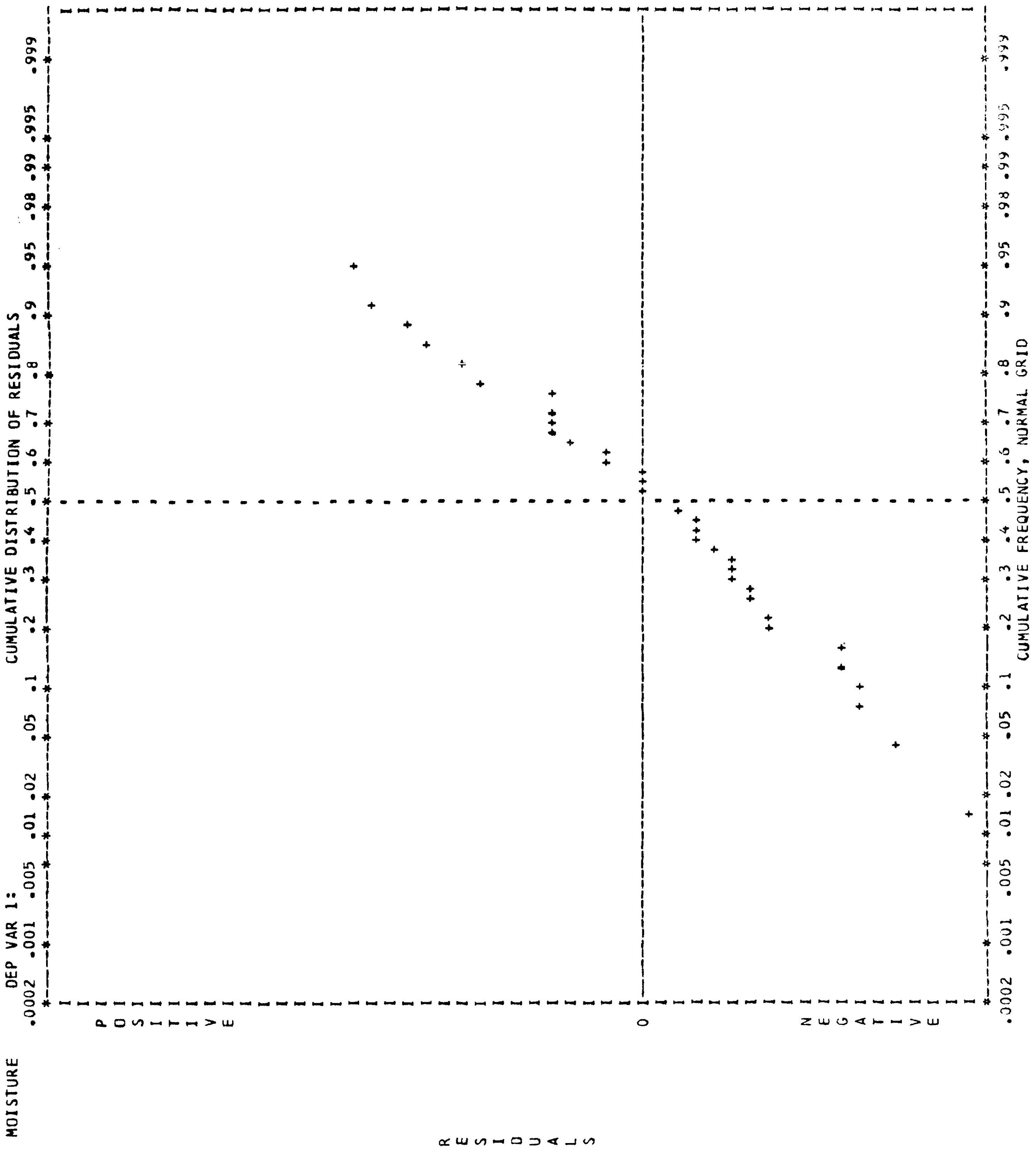



Figure 49. Computer generated plot of the empirical distribution of residuals determined from sand moisture data.

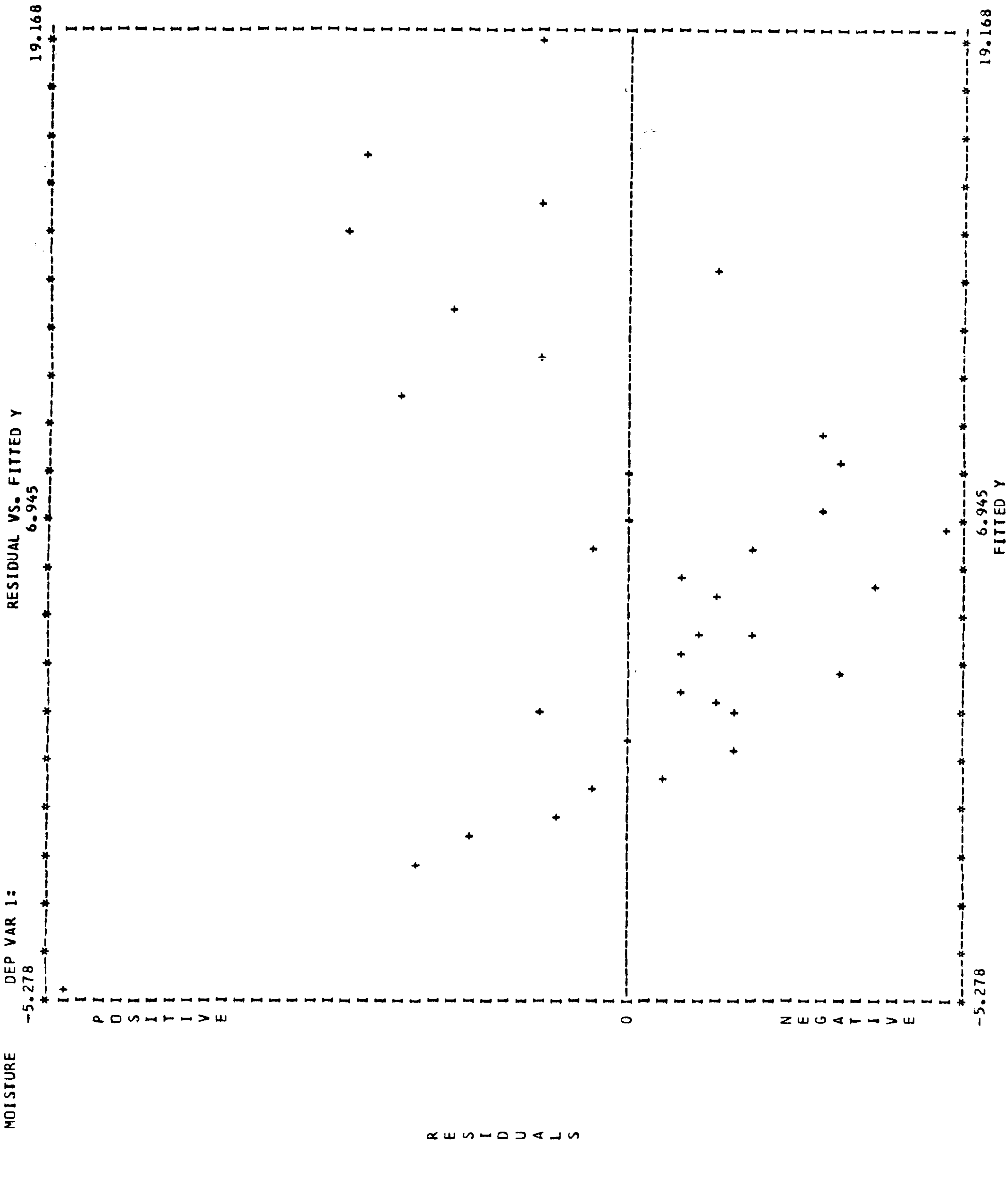



Figure 50. Computer generated plot of the residuals versus the fitted value of y ( sand moisture content ).

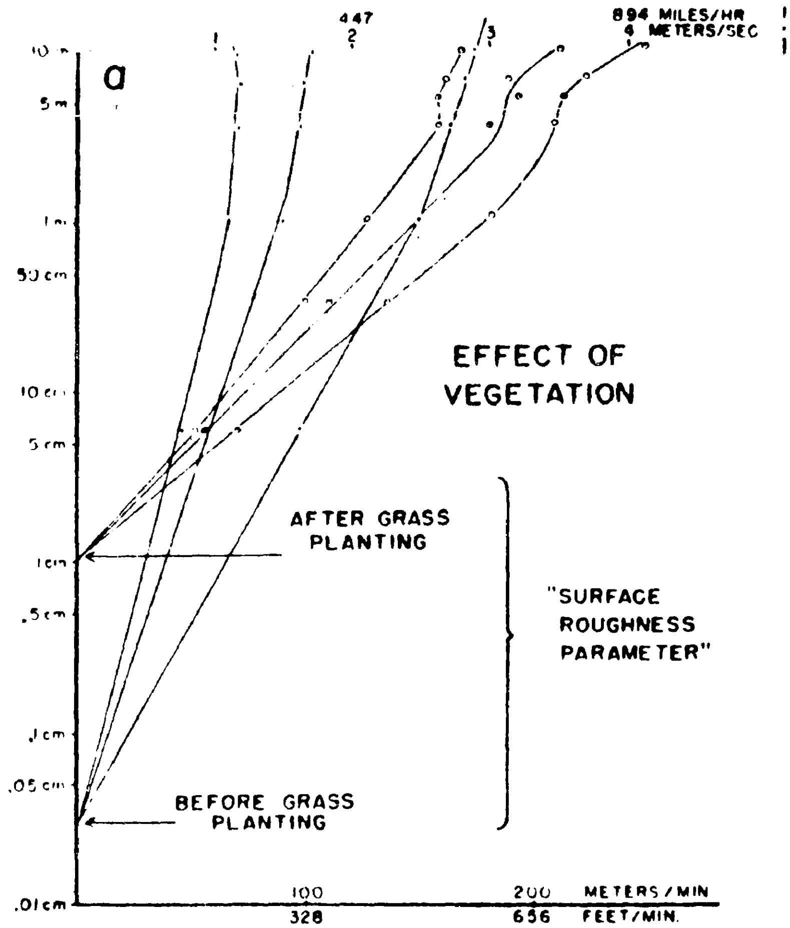



Figure 51. The change in surface roughness parameter and dune wind profiles before and after grass planting on an Indiana coastal sand dune. (after Olson, 1958)

Vegetation, by reducing the wind velocity at the surface, also increases the soil moisture content relative to a bare sand surface. The equation which computes soil moisture content was developed for bare sand conditions. Chang (1968) estimated that under identical environmental conditions the moisture content of a vegetated surface will be 20 percent greater than a bare surface. Therefore, in the MOIST subroutine (Appendix 4), the computed moisture content is multiplied by 1.2 for transport across vegetated surfaces.

Summary of Model

From considerations of the mechanism of eolian sand transport and development of an empirical moisture equation, a model was developed which computes the transport of sand by wind for an entire year of record. During each three hour period (8 per day) the wind velocity, temperature, and precipitation data is read into the model. If the temperature is less than -1.0°C the model skips to the next three hour period because field observations indicated that the soil was frozen below this temperature and therefore no transport could occur. Comparison of the model run with and without the inclusion of the freezing variable indicate that the sand freezing decreases total transport by only three percent (offshore transport) or nine percent (onshore transport). However, at low temperatures the evaporation rate is slow and therefore, given a certain amount of precipitation the soil moisture content will be greater than at higher temperatures, as shown in the derived soil moisture equation.

The next step in the model is calculation of a soil moisture content as a function of the temperature, wind velocity, precipitation, and soil moisture content of the previous three hour interval. Then the model calculates a threshold shear velocity for this soil moisture content. For a soil moisture of 0.0 percent the threshold shear velocity was determined by Kadib (1964) to be about 30.0 cm/sec and his value was adopted for this model. The wind velocity from the Corolla Station anemometer for the three hour period is then used to calculate a shear velocity at the surface. If this shear velocity is not greater than the calculated threshold shear velocity, no transport is computed and the model moves to the next three hour interval. However, if the shear exceeds the threshold a sand transport rate ($g/cm \cdot sec^{-1}$) is calculated using the equations of Bagnold (1941) and Hsu (1973). The model was then run for differing vegetation densities by changing the value of the surface roughness parameter (Z0). Table 8 is a sample of the output from the model.

## Variables Not Included in Model

Eolian sand transport is a very complex process. This transport model includes only wind speed and direction, temperature, moisture, vegetation and grain size as variables. However, other important variables (Table 5) were not included in development of the model. The shear velocity equation assumes a neutral atmosphere with a logarithmic wind profile although Hsu (1971), who developed the equation, has shown that this assumption may not always be valid. In addition the effects of topographic and surface obstructions were not considered. Instead the model calculates transport across a flat surface assuming that surface formations (ripples, dunes etc.,) affect all directions of transport equally. Binding of the sand by salt, which would increase the threshold shear velocity, was also not a variable included in the model. Studies by Svasek and Terwindt (1974)

TABLE 8

RESULTS OF SAND TRANSPORT CALCULATIONS

| Date | Wind Direction | Wind Speed m/sec | Thresh Velocity cm/sec | Sheer Velocity cm/sec | Hsu Transport g/cm/sec | Bagnold Transport g/cm/sec | Rain cm | % Water |
|---|---|---|---|---|---|---|---|---|
| 2/02/76 | 215. | 15. | 28.00 | 44.42 | 0.14 | 0.20 | 0.0 | 0.00 |
| 2/02/76 | 275. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |
| 2/02/76 | 295. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |
| 2/02/76 | 285. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |
| 2/02/76 | 305. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 6/02/76 | 5. | 10. | 28.00 | 29.15 | 0.04 | 0.07 | 0.01 | 0.00 |
| 6/02/76 | 15. | 11. | 28.00 | 33.62 | 0.06 | 0.11 | 0.0 | 0.00 |
| 7/02/76 | 5. | 10. | 28.00 | 29.15 | 0.04 | 0.07 | 0.0 | 0.00 |
| 7/02/76 | 5. | 10. | 28.00 | 29.15 | 0.04 | 0.07 | 0.0 | 0.00 |
| 8/02/76 | 255. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 10/02/76 | 215. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 10/02/76 | 235. | 13. | 28.00 | 37.32 | 0.09 | 0.12 | 0.0 | 0.00 |
| 11/02/76 | 235. | 13. | 28.00 | 35.55 | 0.07 | 0.10 | 0.0 | 0.00 |
| 11/02/76 | 245. | 11. | 28.00 | 28.46 | 0.04 | 0.05 | 0.0 | 0.00 |
| 13/02/76 | 245. | 11. | 28.00 | 28.46 | 0.04 | 0.05 | 0.0 | 0.00 |
| 14/02/76 | 25. | 12. | 28.00 | 38.08 | 0.09 | 0.16 | 0.0 | 0.00 |
| 15/02/76 | 215. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 16/02/76 | 235. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 16/02/76 | 245. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 16/02/76 | 225. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 17/02/76 | 235. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 17/02/76 | 235. | 13. | 28.00 | 37.32 | 0.09 | 0.12 | 0.0 | 0.00 |
| 17/02/76 | 235. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 18/02/76 | 205. | 14. | 28.00 | 40.87 | 0.11 | 0.15 | 0.0 | 0.00 |
| 18/02/76 | 215. | 15. | 28.00 | 44.42 | 0.14 | 0.20 | 0.0 | 0.00 |
| 18/02/76 | 235. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |

TABLE 8 (Continued).

| Date | Wind Direction | Wind Speed m/sec | Thresh Velocity cm/sec | Sheer Velocity cm/sec | Hsu Transport g/cm/sec | Bagnold Transport g/cm/sec | Rain cm | % Water |
|---|---|---|---|---|---|---|---|---|
| 22/02/76 | 215. | 18. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 22/02/76 | 215. | 15. | 28.00 | 44.42 | 0.14 | 0.20 | 0.0 | 0.00 |
| 22/02/76 | 215. | 15. | 28.00 | 44.42 | 0.14 | 0.20 | 0.0 | 0.00 |
| 22/02/76 | 225. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 22/02/76 | 215. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 22/02/76 | 245. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |
| 22/02/76 | 5. | 12. | 28.00 | 38.08 | 0.09 | 0.16 | 0.0 | 0.00 |
| 23/02/76 | 355. | 11. | 28.00 | 33.62 | 0.06 | 0.11 | 0.0 | 0.00 |
| 29/02/76 | 215. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 5/03/76 | 245. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 5/03/76 | 245. | 13. | 28.00 | 37.32 | 0.09 | 0.12 | 0.0 | 0.00 |
| 5/03/76 | 245. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 5/03/76 | 215. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 6/03/76 | 245. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 9/03/76 | 95. | 13. | 28.00 | 47.02 | 0.17 | 0.30 | 0.05 | 0.00 |
| 9/03/76 | 105. | 13. | 28.00 | 47.02 | 0.17 | 0.30 | 0.10 | 0.00 |
| 9/03/76 | 335. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 9/03/76 | 5. | 11. | 28.00 | 33.62 | 0.06 | 0.11 | 0.0 | 0.00 |
| 12/03/76 | 140. | 11. | 28.00 | 33.62 | 0.06 | 0.11 | 0.0 | 0.00 |
| 12/03/76 | 195. | 13. | 28.00 | 37.32 | 0.09 | 0.12 | 0.06 | 0.00 |
| 13/03/76 | 225. | 13. | 28.00 | 37.32 | 0.09 | 0.12 | 0.0 | 0.00 |
| 13/03/76 | 225. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |
| 13/03/76 | 225. | 14. | 28.00 | 40.87 | 0.11 | 0.15 | 0.0 | 0.00 |
| 13/03/76 | 235. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |
| 13/03/76 | 245. | 14. | 28.00 | 40.87 | 0.11 | 0.15 | 0.0 | 0.00 |
| 13/03/76 | 315. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |
| 13/03/76 | 325. | 13. | 28.00 | 37.32 | 0.09 | 0.12 | 0.0 | 0.00 |

TABLE 8 (Continued).

| Date | Wind Direction | Wind Speed m/sec | Thresh Velocity cm/sec | Sheer Velocity cm/sec | Hsu Transport g/cm/sec | Bagnold Transport g/cm/sec | Rain cm | % Water |
|---|---|---|---|---|---|---|---|---|
| 16/03/76 | 235. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.01 | 0.00 |
| 16/03/76 | 315. | 18. | 28.00 | 55.05 | 0.28 | 0.38 | 0.01 | 0.00 |
| 17/03/76 | 315. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 19/03/76 | 245. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 21/03/76 | 215. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 21/03/76 | 225. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 21/03/76 | 225. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |
| 21/03/76 | 245. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 25/03/76 | 275. | 13. | 28.00 | 37.32 | 0.09 | 0.12 | 0.0 | 0.00 |
| 27/03/76 | 215. | 14. | 28.00 | 40.87 | 0.11 | 0.15 | 0.04 | 0.00 |
| 28/03/76 | 25. | 10. | 28.00 | 29.15 | 0.04 | 0.07 | 0.0 | 0.00 |
| 28/03/76 | 25. | 11. | 28.00 | 33.62 | 0.06 | 0.11 | 0.0 | 0.00 |
| 31/03/76 | 135. | 10. | 28.00 | 29.15 | 0.04 | 0.07 | 0.0 | 0.00 |
| 31/03/76 | 165. | 10. | 28.00 | 29.15 | 0.04 | 0.07 | 0.0 | 0.00 |
| 31/03/76 | 145. | 11. | 28.00 | 33.62 | 0.06 | 0.11 | 0.01 | 0.00 |
| 1/04/76 | 185. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 2/04/76 | 285. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 2/04/76 | 315. | 15. | 28.00 | 44.42 | 0.14 | 0.20 | 0.0 | 0.00 |
| 2/04/76 | 345. | 14. | 28.00 | 40.87 | 0.11 | 0.15 | 0.0 | 0.00 |
| 3/04/76 | 345. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 4/04/76 | 265. | 14. | 28.00 | 40.87 | 0.11 | 0.15 | 0.0 | 0.00 |
| 4/04/76 | 25. | 13. | 28.00 | 47.02 | 0.17 | 0.30 | 0.0 | 0.00 |
| 5/04/76 | 5. | 12. | 28.00 | 38.08 | 0.09 | 0.16 | 0.0 | 0.00 |
| 8/04/76 | 55. | 12. | 28.00 | 38.08 | 0.09 | 0.16 | 0.01 | 0.00 |
| 8/04/76 | 55. | 11. | 28.00 | 33.62 | 0.06 | 0.11 | 0.0 | 0.00 |
| 9/04/76 | 45. | 13. | 28.00 | 47.02 | 0.17 | 0.30 | 0.0 | 0.00 |
| 9/04/76 | 35. | 13. | 28.00 | 47.02 | 0.17 | 0.30 | 0.0 | 0.00 |
| 9/04/76 | 25. | 16. | 28.00 | 60.42 | 0.36 | 0.63 | 0.0 | 0.00 |
| 9/04/76 | 25. | 15. | 28.00 | 55.95 | 0.29 | 0.50 | 0.0 | 0.00 |
| 9/04/76 | 25. | 16. | 28.00 | 60.42 | 0.36 | 0.63 | 0.0 | 0.00 |
| 9/04/76 | 15. | 12. | 28.00 | 38.08 | 0.09 | 0.16 | 0.0 | 0.00 |

TABLE 8 (Continued).

| Date | Wind Direction | Wind Speed m/sec | Thresh Velocity cm/sec | Sheer Velocity cm/sec | Hsu Transport g/cm/sec | Bagnold Transport g/cm/sec | Rain cm | % Water |
|---|---|---|---|---|---|---|---|---|
| 10/04/76 | 355. | 10. | 28.00 | 29.15 | 0.04 | 0.07 | 0.0 | 0.00 |
| 11/04/76 | 305. | 16. | 28.00 | 47.96 | 0.18 | 0.25 | 0.0 | 0.00 |
| 11/04/76 | 5. | 13. | 28.00 | 47.02 | 0.17 | 0.30 | 0.0 | 0.00 |
| 12/04/76 | 5. | 12. | 28.00 | 38.08 | 0.09 | 0.16 | 0.0 | 0.00 |
| 12/04/76 | 25. | 13. | 28.00 | 47.02 | 0.17 | 0.30 | 0.0 | 0.00 |
| 12/04/76 | 15. | 13. | 28.00 | 47.02 | 0.17 | 0.30 | 0.0 | 0.00 |
| 12/04/76 | 5. | 12. | 28.00 | 38.08 | 0.09 | 0.16 | 0.0 | 0.00 |
| 21/04/76 | 215. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 25/04/76 | 235. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 25/04/76 | 235. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 25/04/76 | 225. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 25/04/76 | 225. | 13. | 28.00 | 37.32 | 0.09 | 0.12 | 0.0 | 0.00 |
| 25/04/76 | 215. | 12. | 28.00 | 30.23 | 0.05 | 0.06 | 0.0 | 0.00 |
| 25/04/76 | 255. | 13. | 28.00 | 37.32 | 0.09 | 0.12 | 0.0 | 0.00 |
| 25/04/76 | 225. | 13. | 28.00 | 33.78 | 0.06 | 0.09 | 0.0 | 0.00 |
| 26/04/76 | 25. | 12. | 28.00 | 38.08 | 0.09 | 0.16 | 0.0 | 0.00 |
| 26/04/76 | 5. | 11. | 28.00 | 33.62 | 0.06 | 0.11 | 0.0 | 0.00 |

indicate that the effect of a surface crust formed from salt is small because the crust is easily broken by saltating grains coming from areas where no crust is present.

The exclusion of these variables from the model is not the only source of potential error in calculating eolian sand transport. Although the mechanism by which vegetation affects sand transport is understood, quantifying this effect is very difficult. The density and height of the vegetative cover on the dunes and eolian flat along Currituck Spit is very variable. Therefore, the transport rates calculated by the model represent average values assuming a uniform vegetation cover instead of being specific to a particular geographic location. Another problem is the transport equations which were derived for a bare sand surface. Therefore, the computed transport rates taken as estimates only.

Verification of Model with Sand Transport Measurements

In order to evaluate the accuracy of the calculations the model was compared with field measurements of sand transport. Tables 9 and 10 are lists of sand transport measurements along Currituck Spit conducted under a variety of wind, moisture and vegetation conditions. The rate of sand transport was measured with a vertical, mechanical sand trap. The sand trap (Figure 52) was modeled after a design described by Horikawa and Shen (1960). They determined an efficiency, which is the ratio of trapped sand to total sand in transport, of about 80 percent for this particular design.

On days when the wind velocity was sufficient to initiate sand transport, the sand trap and portable anemometers were set up at a number of locations along Currituck Spit to measure the transport

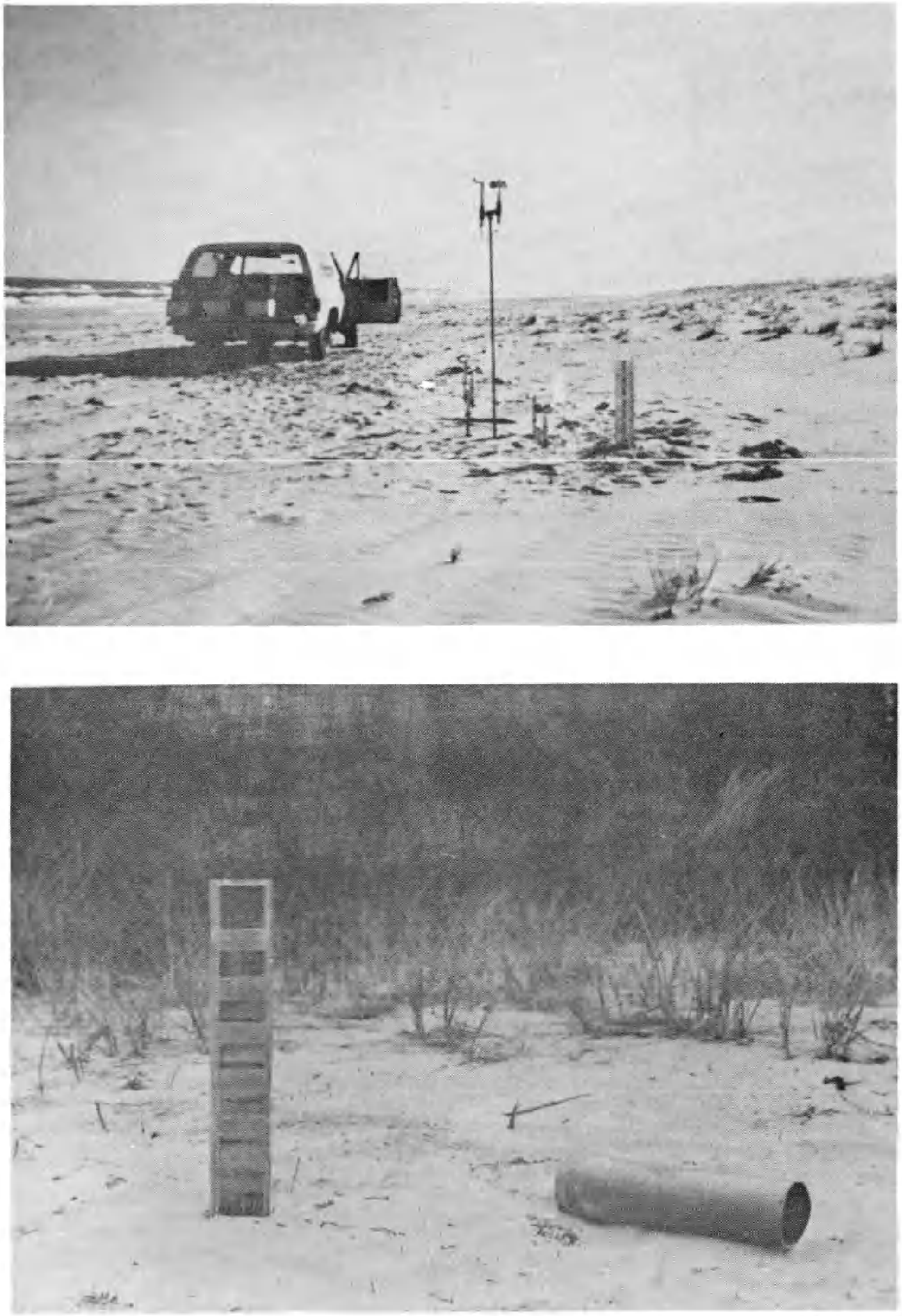


Figure 52. Sand trap and portable anemometers used to measure eolian sand transport. Section of PVC pipe (bottom) was used to dig a whole for placement of sand trap.

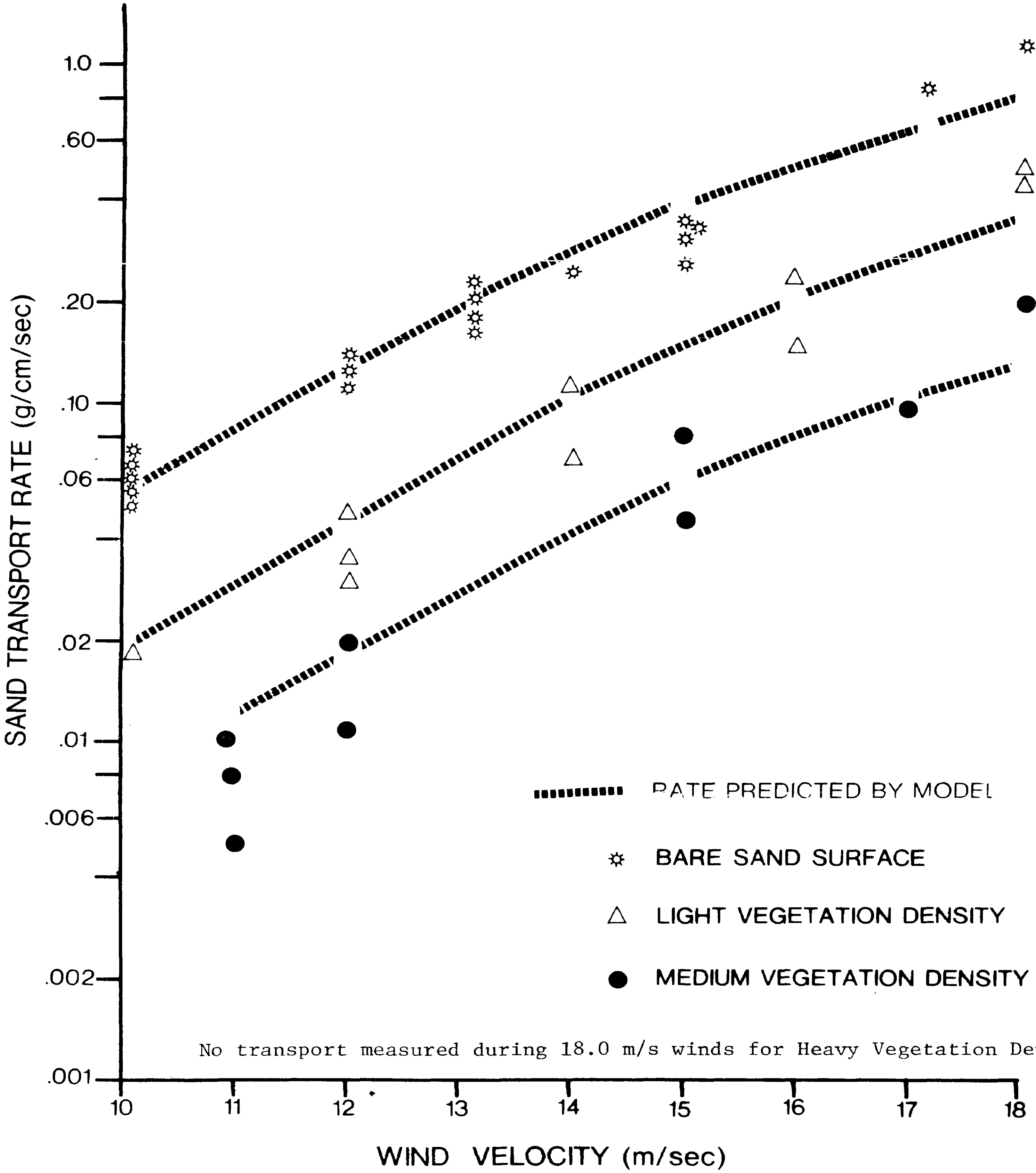
rate. The sand trap was installed by digging a hole with a cylinder of a slightly larger inside diameter than the base of the sand trap. This procedure caused only minimal disturbance of the sand surface. The sand transport was measured for a period of time ranging from 1-30 minutes depending on the wind velocity and vegetation cover. Measurements during offshore winds were taken in areas with very light, light, medium and high density vegetation cover (see Table 9). The wind velocity at the surface was measured and then compared with the wind velocity measured at the Corolla station anemometer. The trapped sand was returned to the laboratory, dried and then weighed. The sand transport rate, expressed in g/cm·sec, could then be computed using an assumed sand trap efficiency of 80%.

Comparison of the measured and computed transport rate was very simple because both sets of data were expressed in terms of the wind velocity and direction as measured at the Corolla Station anemometer.

Figure 53 is a comparison of measured transport rates (data listed in Tables 9 and 10) with the rate predicted by the eolian transport model. The predicted lines are the average of the rate computed by the Bagnold and Hsu equations for three different vegetation densities. The vegetation density was a subjective measure of the vegetative cover upwind of the sampling site. "None" refers to bare sand; "very light" to sparse dune grass (Figure 54); "light" to typical dune grass (Figure 54); "medium" refers to dense dune grass and other herbaceous vegetation (Figure 55); and "heavy" to a shrub thicket (Figure 55). The sand trap was positioned on the beach just seaward of the dunes to measure the transport from the beach to the dunes,

Figure 53.

SAND TRANSPORT RATE (g/cm/sec) AS A FUNCTION OF WIND VELOCITY (m/sec) AND VEGETATION DENSITY




No transport measured during 18.0 m/s winds for Heavy Vegetation Density

Figure 54. Typical "very light" density (top) and "light" density (bottom) vegetation along Currituck Spit.

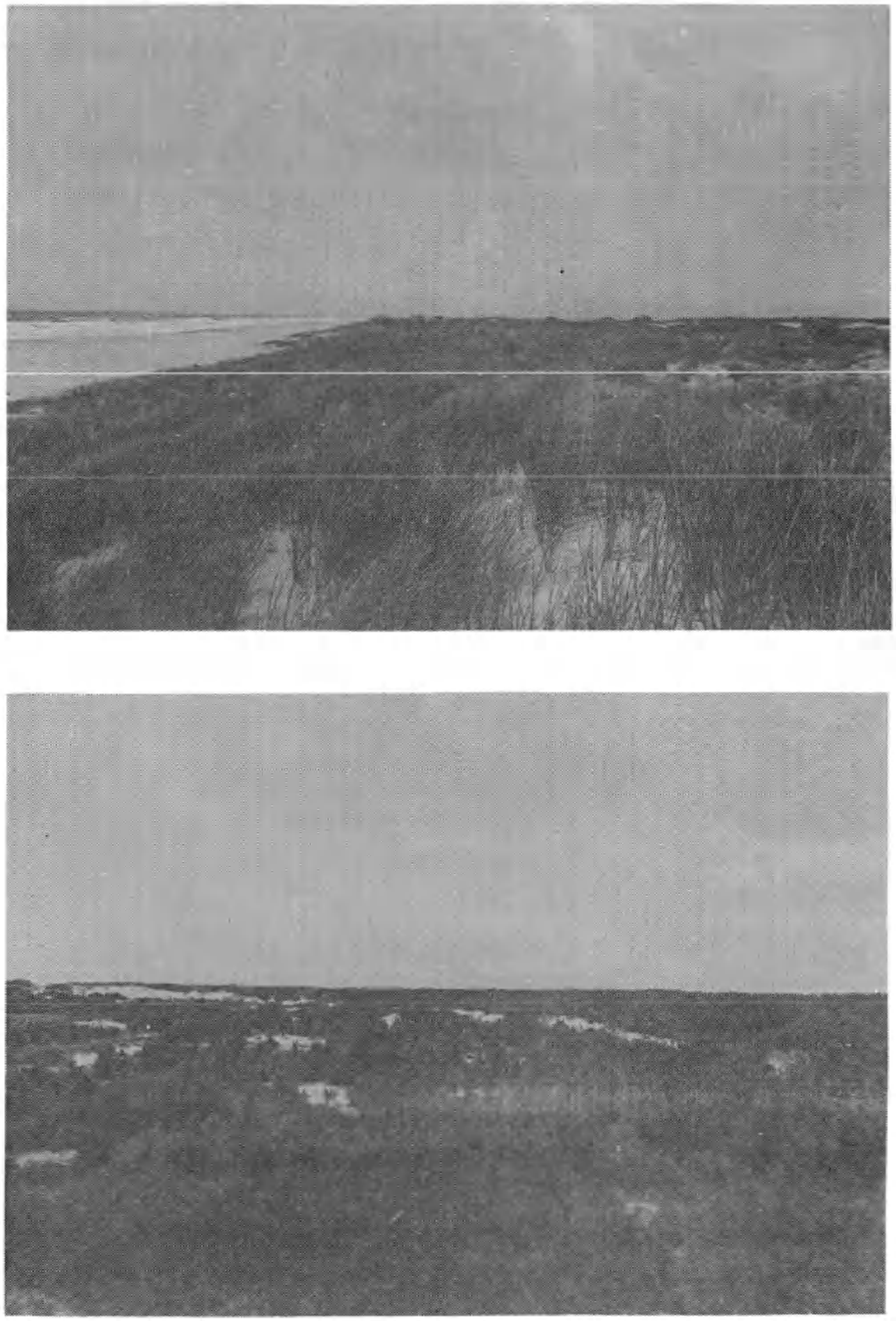


Figure 55. Typical "medium" density (top) and "heavy" density (bottom) vegetation along Currituck Spit.

TABLE 9

SAND TRANSPORT MEASUREMENTS NEAR FALSE CAPE, VIRGINIA (F)

AND COROLLA, NORTH CAROLINA (C) WITH NO VEGETATION COVER

| Wind Velocity m/sec | | Wind | Transport Rate | |
|---|---|---|---|---|
| 1 meter | 53 meters | Direction | g/cm/sec | Location |
| 8 | 10 | E | .06 | Across Beach (F) |
| 8 | 10 | E | .06 | Across Beach (F) |
| 8 | 10 | E | .07 | Across Beach (F) |
| 8 | 10 | E | .05 | Across Beach (C) |
| 8 | 10 | E | .06 | Across Beach (C) |
| 8 | 10 | E | .05 | Across Beach (C) |
| 9 | 12 | S | .11 | Across Beach (C) |
| 9 | 12 | NE | .12 | Across Beach (C) |
| 9 | 12 | NE | .10 | Across Beach (C) |
| 10 | 13 | NE | .18 | Across Beach (F) |
| 10 | 13 | NE | .15 | Across Beach (F) |
| 10 | 13 | NE | .20 | Across Beach (C) |
| 10 | 13 | NE | .19 | Across Beach (C) |
| 11 | 14 | NE | .25 | Across Beach (C) |
| 12 | 15 | NE | .30 | Across Beach (F) |
| 12 | 15 | NE | .32 | Across Beach (F) |
| 12 | 15 | NE | .34 | Across Beach (C) |
| 13 | 15 | NE | .35 | Across Beach (C) |
| 14 | 17 | W | .6 | Across Foredune (C) |
| 14 | 18 | W | .9 | Across Foredune (C) |

TABLE 10

SAND TRANSPORT MEASUREMENTS NEAR FALSE CAPE, VIRGINIA (F) AND COROLLA, NORTH CAROLINA (C) WITH VARYING VEGETATION COVER

| Wind Speed m/sec | | Wind | Transport Rate | | Upwind Vegetation |
|---|---|---|---|---|---|
| 1 meter | 53 meters | Direction | g/cm/sec | Location | Density |
| 7 | 12 | SW | .06 | Across Eolian Flat (C) | Very Light |
| 7 | 12 | SW | .04 | Across Eolian Flat (C) | Very Light |
| 12 | 15 | SW | .2 | Across Eolian Flat (C) | Very Light |
| 6 | 10 | SW | .02 | Across Foredune (C) | Light |
| 7 | 12 | SW | .03 | Across Foredune (C) | Light |
| 7 | 12 | SW | .04 | Across Eolian Flat (C) | Light |
| 11 | 14 | W | .07 | Across Foredune (C) | Light |
| 11 | 14 | W | .08 | Across Foredune (C) | Light |
| 13 | 16 | W | .15 | Across Foredune (C) | Light |
| 13 | 16 | W | .20 | Across Foredune (C) | Light |
| 13 | 18 | W | .5 | Across Foredune (C) | Light |
| 13 | 18 | W | .4 | Across Foredune (C) | Light |
| 6 | 11 | SW | .009 | Across Foredune (F) | Medium |
| 6 | 11 | SW | .007 | Across Foredune (F) | Medium |
| 5 | 11 | SW | .004 | Across Foredune (F) | Medium |
| 7 | 12 | SW | .02 | Across Foredune (F) | Medium |
| 8 | 12 | SW | .01 | Across Foredune (F) | Medium |
| 10 | 15 | W | .04 | Across Foredune (F) | Medium |
| 11 | 15 | W | .08 | Across Foredune (F) | Medium |
| 12 | 17 | W | .09 | Across Foredune (F) | Medium |
| 13 | 18 | W | .2 | Across Foredune (F) | Medium |
| 12 | 18 | W | 0.0 | Across Eolian Flat (F) | Heavy |
| 12 | 18 | W | 0.0 | Across Eolian Flat (F) | Heavy |

and back to the beach during both onshore and offshore winds. Transport was also measured across the eolian flat to monitor cross-barrier flux of sand.

Comparison of measured and predicted transport rates indicate that the model is fairly accurate for onshore wind conditions. For example, the measured transport rate during 13 m/sec onshore winds was 0.18-.20 g/cm·sec (samples T-14, T-15, T-34, and T-35). The model predicted (Table 8, March 9, 1976) a transport rate of 0.17-.30 g/cm/sec for identical conditions. Similarly during 15 m/sec onshore winds the measured transport rate was .30-.35 g/cm·sec (samples T-17, T-36, T-37, and T-38) while the model predicted (Table 8, April 9, 1976) a transport rate of .29-.50 g/cm·sec. Therefore the model predicted onshore transport rates which compare well with measured values.

Calculation of sand transport during offshore wind conditions using the same surface roughness parameter ($Z_o$) as during onshore winds, would greatly exceed the measured values. Table 8, however, is a listing from computations with a $Z_o$ = 6.0 cm input for all offshore winds. There is a very good correlation between the observed and predicted transport rate for offshore winds blowing over a lightly vegetated surface. For example the measured ransport rate for samples T-3, T-4 and T-5 compares well with the calculated values in Table 8. However, for the medium vegetated surfaces, comparisons of observed and predicted indicate a poor correlation. For these medium density vegetation conditions a $Z_o$ of 9.0 cm, was used and as shown in Figure 53 there is a fairly good correspondence between the measured and predicted transport rate. Therefore it was concluded that good estimate of the sand transport rates during both onshore and offshore wind conditions is possible with a reasonable value of $Z_o$, and that the $Z_o$ can be chosen which correlates with vegetation density.

Verification of Sand Transport Using Migration Rate of Medanos

In a previous section the transport of sand, across the slipface of two large sand hills was determined from the migration rate of the dunes (see Figure 32). The sand transport across the Whalehead Hill slipface was about 49,000 kg/meter slipface/year while across Barbours Hill the sand transport was 5,700 kg/m/year.

Inman et al. (1966) and Tsoar (1974) have compared the measured rate of dune movement with that calculated from empirical equations of eolian sand transport. Both found that the calculated rate exceeded the measured amount by some constant amount. Inman attributed the discrepancies to calibration of the anemometer or problems associated with the equations. Tsoar attributed the differences to reduction of the transport by soil moisture.

Table 11 lists the output of the model using wind, temperature, and precipitation data covering the period of measured dune movement. Notice that the northeast and southwest are by far the dominant directions with respect to eolian sand transport. Table 11 also indicates the discharge calculated across a slipface oriented approximately west-northwest to east-southeast. This total was determined by adding together each three hour interval sand transport rate for wind directions between 300° and 100° azimuth. It was assumed that this 160° arc would include all wind directions contributing to sand transport across the slipface.

The total value for calculated sand transport across the slipface (35,000 and 59,000 kg/m/year for Bagnold and Hsu equations)

TABLE 11

TOTAL TRANSPORT CALCULATED BY EOLIAN SAND TRANSPORT MODEL (2/76-2/77) ASSUMING A $Z_o$ OF 3.0 CM FOR ALL OFFSHORE WIND DIRECTIONS

| Direction | (Bagnold Equation) Total Transport of Sand for Year kg/m/year | (Hsu Equation) Total Transport of Sand for Year kg/m/year |
|---|---|---|
| North | 22488. | 13193. |
| Northeast | 27198. | 15575. |
| East | 4420. | 2531. |
| Southeast | 3758. | 2152. |
| South | 2105. | 1493. |
| Southwest | 12493. | 9157. |
| West | 2875. | 2107. |
| Northwest | 6758. | 4953. |
| Onshore Transport (180-340 Degrees AZ) | 49463. | 28325. |
| Offshore Transport (0-160 Degrees AZ) | 32632. | 22837. |
| Transport Across Slipface (300-100 Degrees AZ) | 35002. | 59030. |

TABLE 12

TOTAL TRANSPORT CALCULATE BY EOLIAN SAND TRANSPORT MODEL

(2/76-2/77) ASSUMING A $Z_o$ OF 6.0 CM FOR ALL

WIND DIRECTIONS

| Direction | (Bagnold Equation) Total Transport of Sand for Year kg/m/year | (Hsu Equation) Total Transport of Sand for Year kg/m/year |
|---|---|---|
| North | 10413. | 6236. |
| Northeast | 11810. | 6763. |
| East | 1556. | 891. |
| Southeast | 1225. | 701. |
| South | 1592. | 1148. |
| Southwest | 10747. | 7877. |
| West | 2492. | 1826. |
| Northwest | 5856. | 4293. |
| Onshore Transport (180-340 Degrees AZ) | 20466. | 11720. |
| Offshore Transport (0-160 Degrees AZ) | 25223. | 18015. |
| Transport Across Slipface (300-100 Degrees AZ) | 17300. | 28396. |

agrees well with the measured value for Whalehead Hill (49,000 kg/m/year). Notice that the total predicted by the Bagnold equation and Hsu equation straddle the measured discharge. This comparison of measured and computed discharge correlates better than the studies of Inman (1966) and Tsoar (1974). Tsoar attributed a discrepancy of 10-40% between the measured and computed advance of barchan dunes to precipitation effects. Without considering the effects of precipitation the model would have indicated 20-30% greater sand transport rates than the computed discharge for a large unvegetated sand hill.

Notice however, that a comparison of the transport across the Barbours Hill slipface (5,700 kg/m/year) with the predicted amount (Table 11) using a $Z_o$ of 3.0 shows a very poor correlation. This is attributed to the effects of vegetaion. At Barbours Hill, all wind directions which contribute to the movement of the sand hill blow over a light to medium density vegetation cover. Table 12 is output from model which was run with a larger $Z_o$ input of 6.0 cm for all wind directions. In this case we see a much better correlation between the observed (5,700 kg/m/year) and predicted transport rates (20,000 kg/m/year).

Therefore, there seems to be a good correlation between the eolian sand transport predicted by the model and the transport determined from the migration of large sand hills. The best fit between observed and predicted is for bare sand surface conditions (Whalehead Hill). However, with use of an appropriate surface roughness parameter, (calibrated with vegetation density) the model predicts a fairly reliable transport for vegetated surfaces.

Conclusions

1. After a detailed investigation of the local coastal mechanisms of eolian sand transport an empirical model was developed to predict sand transport from routine wind, precipitation and temperature data.

2. Equations in the model included those by Kadib (1964) (to calculate the threshold shear velocity including the effects of moisture), Hsu (1973) (to calculate shear velocity and transport), and Bagnold (1941) (to calculate transport).

3. An equation was developed, using field measurements of soil moisture content and a multiple linear least-squares curve fitting program, to predict percent moisture content of sand from routine climatological data.

4. Values of the surface roughness parameter ($Z_o$) were chosen from studies by Bressolier and Thomas (1977) to represent in the model the effects of varying levels of upwind vegetation density.

5. The accuracy of the model was checked with field measurements of sand transport, and total transport determined from the migration of large sand dunes. The model predicts the transport rate best for bare sand surfaces. However, the model was also fairly accurate for winds blowing over vegetated surfaces when the surface roughness parameter was chosen to reflect the density and/or height of the upwind vegetation.

## APPLICATIONS OF SAND TRANSPORT MODEL

The eolian sand transport model developed in this thesis predicts the rate and quantity of sand transport from routine metereological data. The model could be used in many areas of the world where suitable metereological data are available after only limited field measurements of soil moisture/grain size relations, vegetation effects, and threshold shear velocity to check the calculations. For example, in central and east Africa eolian transport of sand both inland from the coast and south from the Sahara Desert often endangers productive agricultural land, housing developments, oil rigs and other structures. A sand transport model which could predict the net quantity and direction of sand movement could greatly aid in the design of sand stabilization projects to protect these developments. Along Currituck Spit and other east coast barrier islands two major applications of the model are immediately evident.

### Sand Fencing and Dune Growth

Sand fencing and vegetation planting (Figure 56) have been and continue to be used extensively along Currituck Spit and other east and Gulf Coast barrier islands for the formation and stabilization of foredunes (Hawk and Sharp, 1967; Savage, 1969; Dahl et al., 1975). These foredunes are created, at great expense (Gibbs, 1961), to protect inland structures from damage during storms. The planning and execution of a sand fencing and vegetation planting program would be greatly

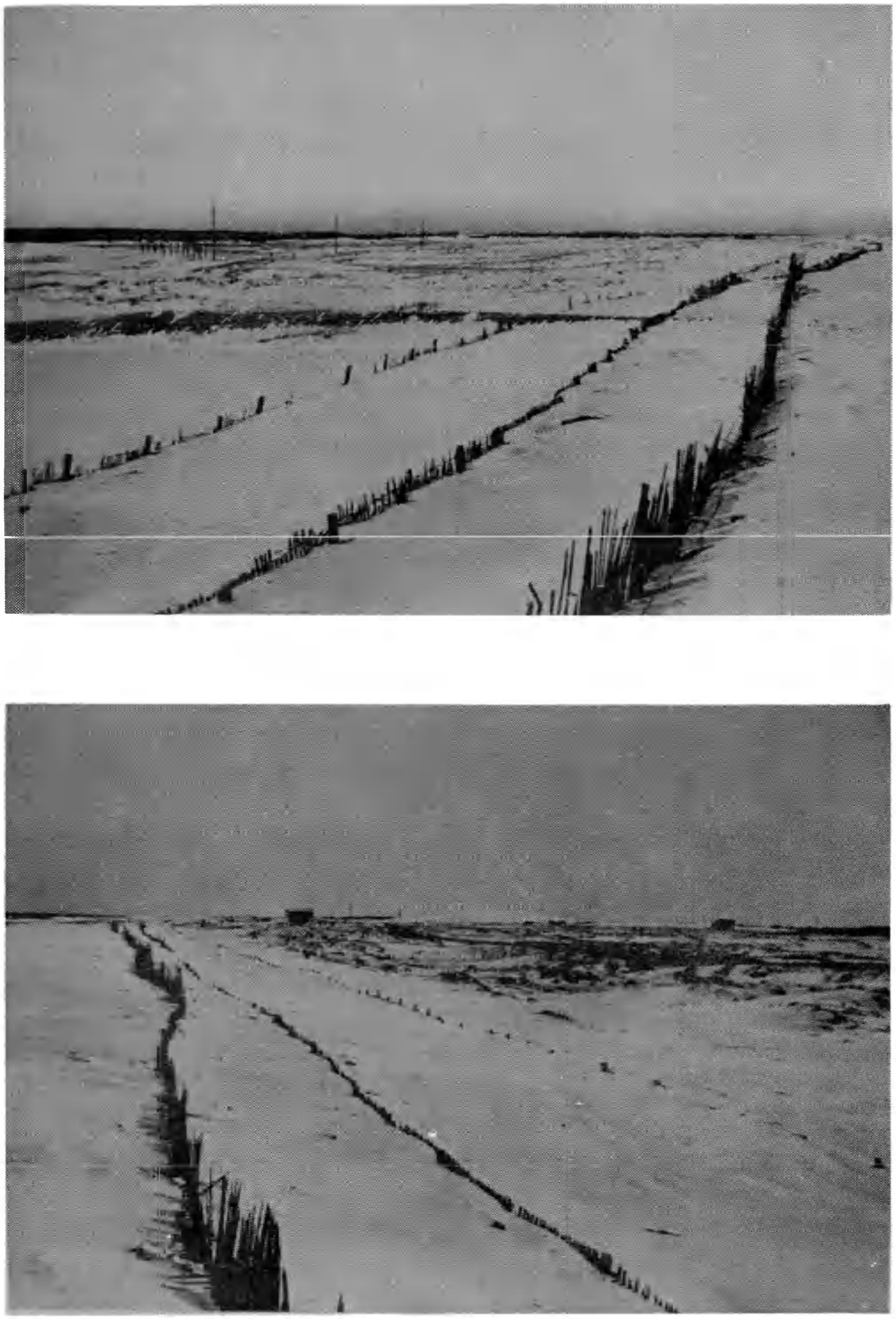


Figure 56. Sand fence created foredunes north of Corolla, N.C.

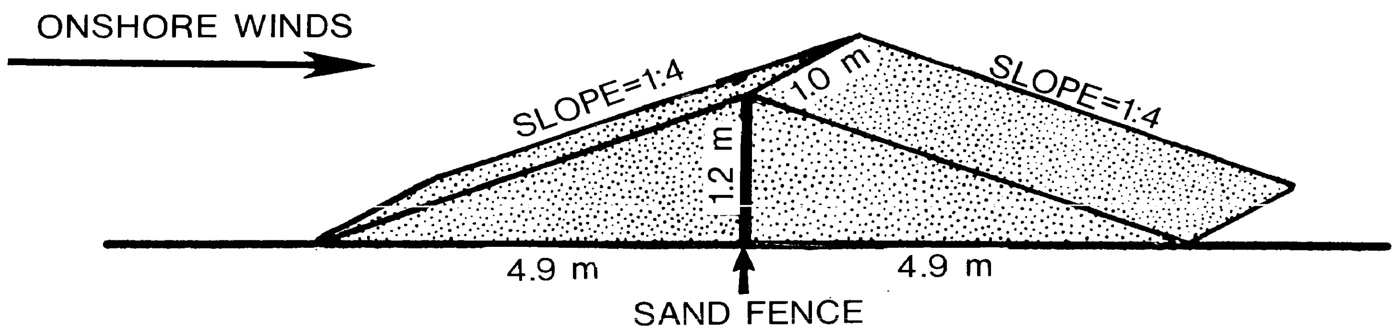
facilitated by a detailed knowledge of the local wind regime and eolian sand transport. For example, the use of either a single or double-row sand fence depends on the expected average wind speeds because a double row fence is much more efficient at trapping sand at high wind velocities (Manohar, 1970).

The amount of sand fencing material necessary for continual buildup of a foredune is determined by the rate of deposition caused by the sand fence. Generally, when one set of sand fences become covered by sand, another set is placed over the old ones to continue dune construction. The eolian sand transport model could be used to roughly estimate the rate of dune formation and therefore the amount of sand fencing material needed on a yearly basis.

A typical double-row sand fence is constructed with two rows of 1.2 m high (4 feet) sand fencing spaced 4.9 m (16 feet) apart (Manohar, 1971) while the single-row sand fence has only one line of snow fencing. If a 1:4 slope (Manohar, 1971; Goldsmith et al., 1977) of both the onshore and offshore sides of the artifically constructed foredune is assumed, then the volume of sand trapped by a completely buried single and double row fence (see Figure 57) is about 6 $m^3$ per linear meter of foredune (single-row) and 12 $m^3$ per linear meter (double-row). This volume of sand trapped by the sand fence could then be compared with the annual transport rates calculated with the model to determine the rate at which the dune will grow and the number of additional rows of sand fencing needed in a given period of time.

Table 11 lists the output of the transport model for one year of Corolla wind data. The onshore and offshore transport rates were computed by converting each calculated transport rate (g/cm·sec)

## SINGLE ROW SAND FENCE

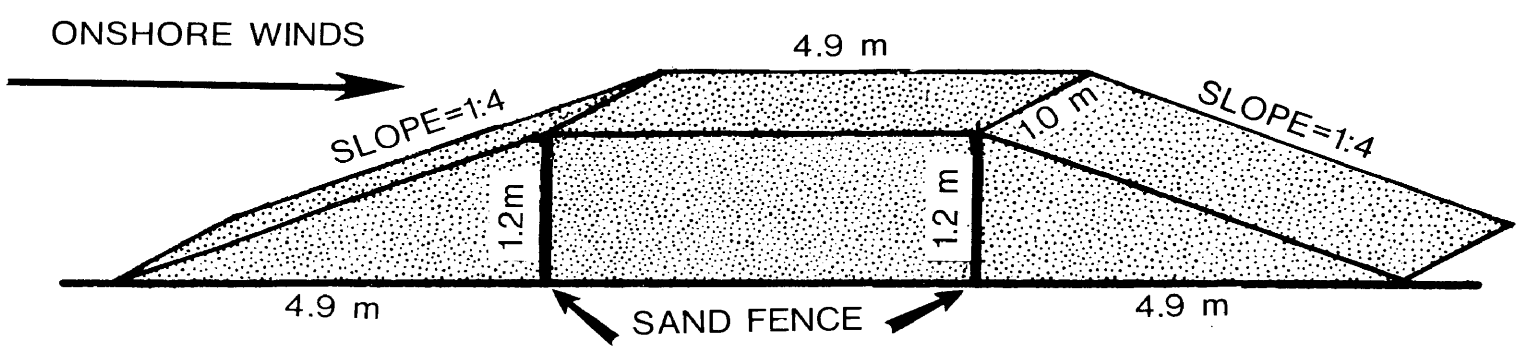



VOLUME (of a Triangle) = 0.5 x BASE x HEIGHT x WIDTH

= .5 x 9.8m x 1.2m x 1.0m

= 5.9 $m^3$

## DOUBLE ROW SAND FENCE




VOLUME = .5 x ( $BASE_1$ + $BASE_2$ ) x HEIGHT x WIDTH

= .5 x ( 14.7 + 4.9 ) x 1.2m x 1.0m

= 11.8 $m^3$

Figure 57. Calculation of the volume of sand trapped by a single row (top) and double row (bottom) sand fence with a 1:4 onshore and offshore slope.

to a transport rate expressed in kg/meter/3 hours. Then the entire year of transport rates (eight/day) were added together for all directions which contribute to onshore (0°160° AZ) and offshore (180°-340° AZ) transport. This 160° arc normal to the orientation of the shoreline was assumed to contain all directions which contribute to onshore and offshore transport.

If it is assumed that only onshore winds supply sand for growth of a foredune (either due to dense vegetation or development across the interior of the barrier island) then the model predicts between 28,000 and 49,000 kg/m/year would be transported from the beach inland for dune growth. Sand transport measurements indicate that the mid point of this range (about 38,000 kg/m/year) would be a reliable estimate of the total transport. Assuming a bulk density for the sand of 1.4 $g/cm^3$, then the predicted transport of 38,000 kg/m/year of sand is approximately equivalent to 27 $m^3/m/year$.

A typical double row sand fence has an efficiency (ratio of sand trapped to total sand transport) of about 40% (Manohar, 1970) although the efficiency varies with the wind speed. Single row sand fencing has a lower efficiency (approximately 20%) and at high wind speeds (greater than 17 m/sec) traps no sand. Using these efficiency ratios, the model predicts that a double row sand fence installed along Currituck Spit would trap about 11 $m^3/m/year$ while the single row would trap about 8 $m^3/m/year$. Since a double row sand fence can accomodate only 12 $m^3$ (Figure 56) of sand per meter of dune then the model predicts that this sand fence would fill in a little over a year. The single row sand fence would accumulate the limit of sand in about 9 months. Of course if a sand supply was available in the interior for transport by onshore winds to the growing foredune, then the sand fencing would fill more rapidly. Observations of eolian deposition on sand fencing at Cape Hatteras, N.C. (Gibbs, 1961) indicate that the one year estimate is reasonable for the amount of time necessary to create a 1.2 meter high foredune. Observations by Goldsmith (personal communication, 1977) indicate that a single-row sand fence at Back Bay Wildlife Refuge in "light" vegetation density became $^3/_4$ filled in one year (1973-1974). Therefore an immediate application of the eolian sand transport model would be for aiding in the planning and design of sand fencing programs.

Net Movement of Sand Across a Barrier Spit; Historically and Presently

Forty years ago the False Cape area (Figure 1) was covered by an unvegetated sand sheet extending uninterrupted from the ocean to the bay (Figure 58-A). Today dense vegetation covers most of the area (Figure 58-D). Hennigar (1978) attributes this vegetation colonization over the last forty years to continual sand fencing which has succeeded in creating a high (3-4 meters) multiple ridge foredune system. This foredune system reduced sand transport from the beach to the interior. Shrub vegetation, which cannot tolerate continual sand burial, colonized the interior stabilizing the shifting sands of the eolian flat. Sand transport measurements (Table 8) during strong offshore winds indicate a zero transport rate across the eolian flat near False Cape.

The net movement of sand across Currituck Spit during periods of low density vegetation cover (1930's) and high density cover (1970's) was estimated by computing the transport model with different values of the surface roughness parameter.

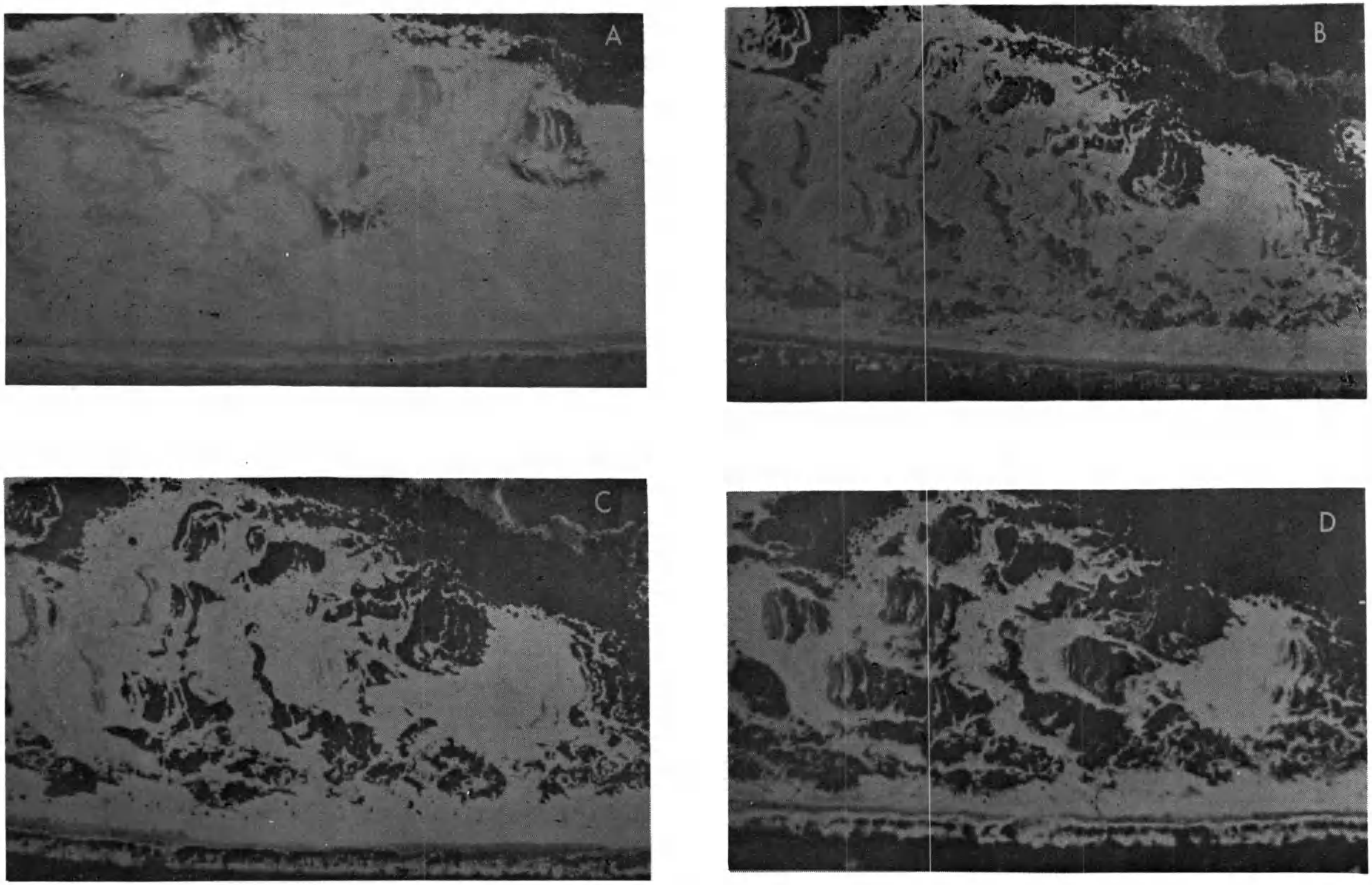



Figure 58. False Cape State Park
A-1947; B-1955; C-1963; D-1975

Table 13 is the output of the model with an input of $Z_o$=1.0 (bare sand) for all wind directions. Notice that the onshore transport exceeds the offshore by only a small amount. The net transport of sand would be only slightly onshore. Assuming the wind climate 40 years ago is similar to today (this is supported by long term wind records), this predicted small net direction of transport should apply to the transport conditions in False Cape 40 years ago. Therefore when the barrier spit was covered by a sand sheet (Figure 58), the net movement of eolian sand was only slightly onshore. Most of the sand which blew inland probably was blown by offshore winds back onto the beach. However, it is more than likely that significant amounts of sand were blown all the way across the island during storm wind conditions and then permanently deposited in the bay. This permanent loss of sand to the longshore driftsystem may have been offset by new beach sand supplied on the seaward side.

Table 14 is the output of the model assuming a high vegetation density ($Z_o$ = 6.0) across the barrier island. In this case there is a very pronounced net movement of sand onshore. However, field measurements of sand transport in False Cape State Park indicated that very little sand was carried beyond the foredunes into the eolian flat, even during strong onshore winds. Instead most of the onshore transport was trapped in the multiple ridge foredune system. The model indicates that most sand transport across a barrier spit with a dense vegetation cover would be onshore, however, this sand would be trapped by the foredune system. Thus, once vegetation begins to be effective via a small foredune for example, the processes are such as to cause the maximum accumulation in the foredune.

TABLE 13

TOTAL TRANSPORT CALCULATED BY EOLIAN SAND TRANSPORT MODEL (2/76-2/77) ASSUMING A $Z_o$ OF 1.0 CM

| Direction | (Bagnold Equation) Total Transport of Sand for Year kg/m/year | (Hsu Equation) Total Transport of Sand for Year kg/m/year |
|---|---|---|
| North | 22933. | 13537. |
| Northeast | 27198. | 15575. |
| East | 4420. | 2531. |
| Southeast | 3758. | 2152. |
| South | 3175. | 2277. |
| Southwest | 18177. | 13324. |
| West | 4399. | 3224. |
| Northwest | 9058. | 6640. |
| Onshore Transport (180-340 Degrees AZ) | 49463. | 28325. |
| Offshore Transport (0-160 Degrees AZ) | 43654. | 30935. |

TABLE 14

TOTAL TRANSPORT CALCULATED BY EOLIAN SAND TRANSPORT MODEL (2/76-2/77) ASSUMING A $Z_o$ OF 6.0 CM FOR ALL OFFSHORE WIND DIRECTIONS

| Direction | (Bagnold Equation) Total Transport of Sand for Year kg/m/year | (Hsu Equation) Total Transport of Sand for Year kg/m/year |
|---|---|---|
| North | 22109. | 12934. |
| Northeast | 27198. | 15575. |
| East | 4420. | 2531. |
| Southeast | 3758. | 2152. |
| South | 1786. | 1259. |
| Southwest | 10747. | 7877. |
| West | 2492. | 1826. |
| Northwest | 5856. | 4293. |
| Onshore Transport (180-340 Degrees AZ) | 49463. | 28325. |
| Offshore Transport (0-160 Degrees AZ) | 28903. | 20122. |

Eolian sand transport seems to be most important in carrying sand from the beach to the interior when the barrier island is covered by only light density vegetation. False Cape State Park twenty years ago (Figure 58-B) and south of Corolla today (Figure 59-C) are characterized by such a vegetation distribution. Table 11 is the output of the model for a $Z_o$ input of 3.0 cm (light vegetation). Notice that in this case there is a net movement of a large amount of sand onshore. In this case the foredunes do not trap the transport. Strong onshore winds (19 m/sec) were observed to transport sand from the beach across the low, sparsely vegetated foredunes near Corolla, and onto the eolian flat. Therefore, field observations and the model indicate that there is a net movement of sand onshore in areas with a low density vegetation cover. The Corolla region today and False Cape 20 years ago are typical of such a vegetation distribution.

Therefore the eolian transport model can be applied to predicting the net movement of sand across a barrier spit covered by varying densities of vegetation. The transport regime can be estimated for coastal ecosystems typical of today and those typical twenty and forty years ago as determined from old aerial photographs.

## Conclusions

1. The eolian sand transport model, though developed for Currituck Spit, could conceivably be used to evaluate sand drifting problems along other barrier islands and other parts of the world.

2. The transport model can be used to compute the rate of deposition of sand on typical single and double row sand fences. According to the model it would take about 9 months with a single row

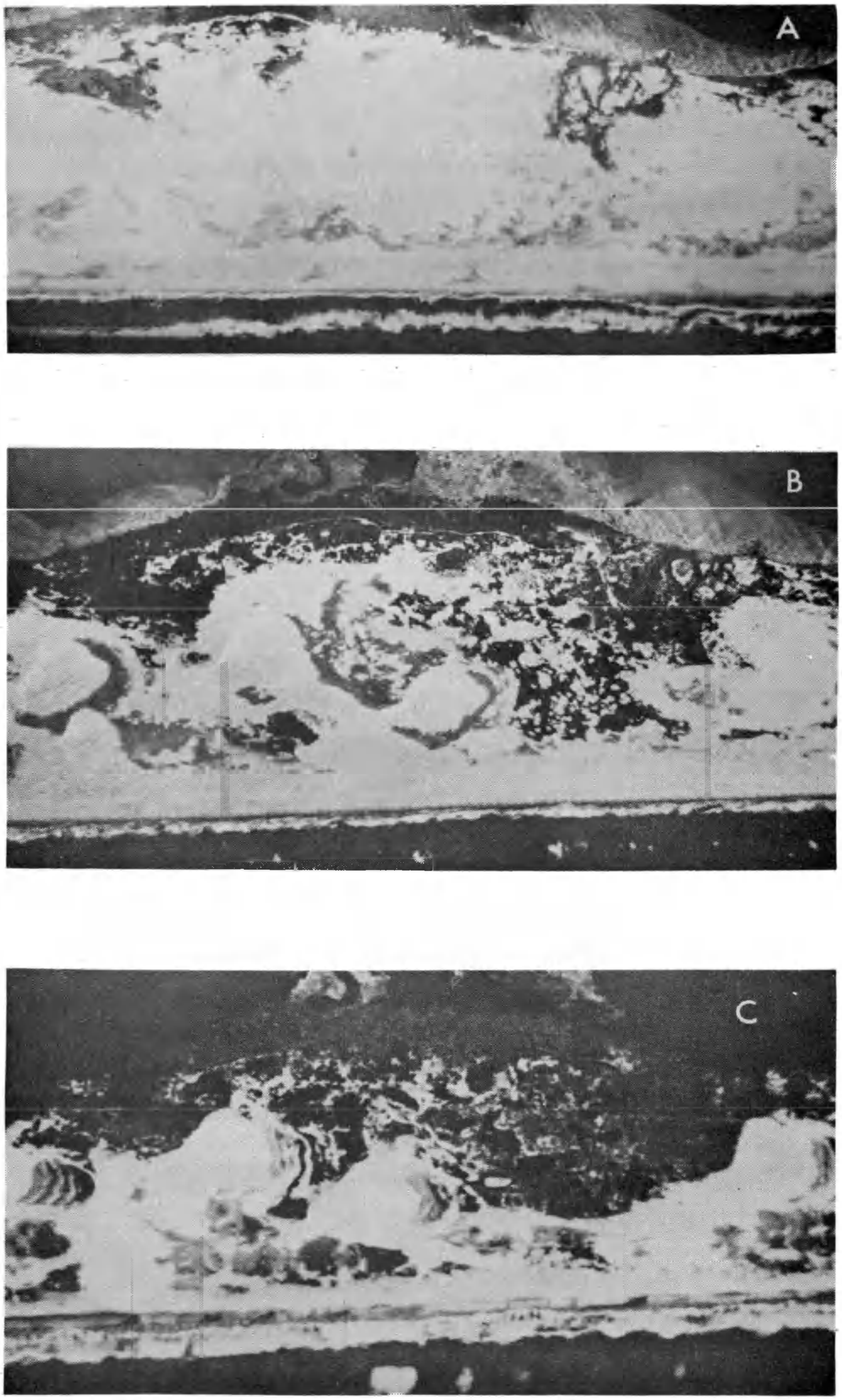


Figure 59. Corolla, North Carolina
A-1940; B-1955; C-1975

and about 13 months with a double row sand fence to create a 1.2 meter high foredune with a 1:4 onshore and offshore slope, assuming no vegetation. This information could be very valuable for planning, design and execution of sand fencing programs.

3. The model could also be very useful for estimating the net movement of sand across the barrier spit under varying levels of vegetation density. The model predicted only a small net onshore movement of sand across a barrier spit completely covered by bare sand. If the interior of the spit is covered by dense vegetation (Figure 58), according to the model there would be a strong net movement onshore. However, most of this sand would be trapped by the high, multiple ridge foredune system. Finally, according to the model if the spit is covered by sparse vegetation (Figure 58) there would be a significant net movement of sand onshore from the beach to the interior of the spit.

# DISCUSSION AND MANAGEMENT IMPLICATIONS

Eolian sand transport is the dominant physical process along Currituck Spit responsible for the development, orientation, and migration of sand dunes. Due to the present lack of overwash fans and inlets along the spit, eolian transport has also become the major source of cross-barrier sediment transport. Unfortunately, development of a quantitative relationship between eolian sand transport, coastal dune dynamics, and cross-barrier sand flux is very difficult due to the complexity of the transport process. No instrumentation exists which can monitor sand transport over a long time period (e.g., months or years) and indirect calculations of sand transport are very difficult due to the large number of environmental variables which influence the transport process (wind speed, direction, and profile, soil texture and moisture content, surface obstructions, vegetation, and topography). In this study the interaction of eolian sand transport, dune dynamics and cross barrier sediment transport was investigated as a function of the three most important environmental variables influencing the transport process in the coastal zone; wind, vegetation, and moisture.

## Wind

A detailed wind climate was compiled from one year (2/76-2/77) of data from a local source (Corolla, North Carolina) and 18 years of data from a nearby source (Cape Hatteras, North Carolina). The local wind regime along Currituck Spit is directionally polymodal, with prevailing winds from the north and southwest (20% and 32%, respectively) and dominant winds from the northeast, north, and northwest (mean wind speed ~8 m/sec). This polymodel wind regime has profound implications for the development, orientation and migration of sand dunes and in the movement of sand across the spit. The effect of the wind regime is most apparent with the dynamics of the unvegetated sand hills or medanos.

Over a dozen large medanos (Figure 27) extend along Currituck Spit from north of Corolla to the south. The local polymodal wind regime may be responsible for the formation of these large sand hills (discussed at length in Goldsmith et al., 1977 and Hennigar, 1978). The dunes developed where a large supply of sand was available, such as on old overwash fans or areas recently denuded of vegetation. The high frequency and high velocity winds, which occur along Currituck Spit from several directions, would tend to gather this available sand together forming a heightened, steepened dune. Once formed a sand hill would continue to grow and maintain its form, due to the effect of a lee side eddy (Figure 60). Winds transporting sand from any direction would deposit sand on the lee side of the dune due to the zone of lower wind velocity. In this manner the local polymodal wind climate alone may be responsible for the development of medanos along Currituck Spit. However, the migration of these medanos, the development of parabolic dunes, and the cross barrier flux of sand are also influenced by the effects of vegetation and moisture.

Moisture

The threshold shear velocity (shear velocity necessary to initiate sand transport) increases as the moisture content of the

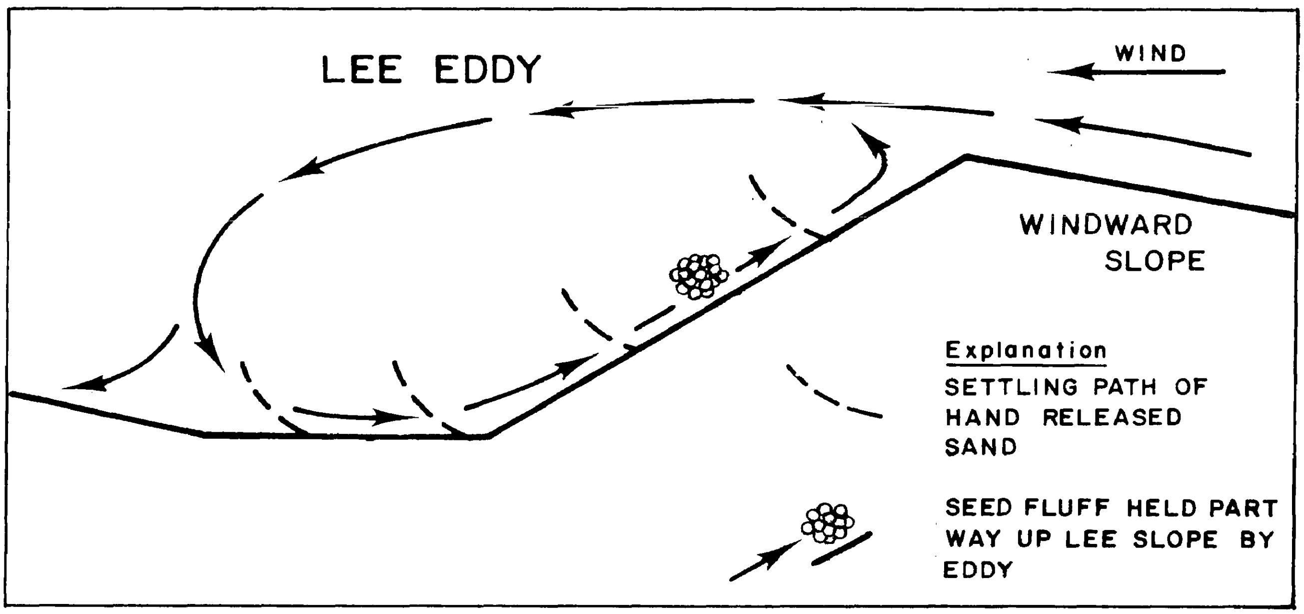



Figure 60. Lee side eddy (from Sharp, 1965)

sand increases (Figure 48). Therefore, precipitation will decrease the total amount of sand transport. In desert regions, the effect of moisture on sand transport rates has been largely ignored for obvious reasons. However, in a temperate coastal zone this variable can become very important. The measured migration rate (six m/year) of a large sand hill (Whalehead Hill) was compared with the rate predicted by the eolian transport model. It was determined that the model could predict the migration rate of these large medanos. However, if the effect of soil moisture had been ignored in the model, the predicted migration rate would have exceeded the measured by 30%. As an environmental variable influencing sand transport, moisture content of the sand is secondary in importance to the wind where vegetation is absent (e.g., sand sheet 40 years ago, Figure 58; or sand hills of 16 years ago, Figure 26). However, where present, vegetation is secondary only to the wind in determining the development, orientation, and migration of sand dunes and the flux of sand across a barrier spit.

Vegetation

Vegetation increases the value of the surface roughness parameter ($Z_o$) in the transport equations as a function of the height and density of the vegetation (see Figure 51). Therefore, increasing vegetation cover will decrease the rate of sand transport by wind. Forty years ago (Figure 58) vegetation was totally absent along the entire spit. However vegetation has colonized the area in varying degrees, aided by foredunes formed by sand fencing. These foredunes which reduced the sand transport from the beach to the interior allowed vegetation to survive. Vegetation colonization has proceeded the farthest near False Cape, due to continual sand fencing, and least near Corolla, where sand fencing has not been continually maintained (Hennigar, 1978). Vegetation colonization has, in part, determined the development and orientation of parabolic dunes in False Cape State Park. The north-south differences in vegetation cover also account for differences in sand hill migration rates, and cross-barrier sand flux between the two regions of Currituck Spit (Corolla and False Cape).

Interaction of Wind, Vegetation and Parabolic Dunes

A series of vertical aerial photographs (Figure 58) indicate a development sequence beginning with a completely unvegetated sand sheet and culminating in a parabolic dune field. The key to this development sequence (Figure 34) is vegetation which colonizes the flanks of a sand hill. As the slipface migrates downwind the anchored flanks lag behind forming a U-shaped dune.

However, the orientation of the parabolic dune axis is not simply a function of the local prevailing or dominant wind regime. The Corolla vector wind resultant is oriented approximately west-northwest (Figure 35) while the parabolic dunes are oriented to the north-northeast. Instead the orientation of parabolic dunes is a result of both the local wind regime and the effect of vegetation on the wind. Due to the presence of a tall (15 m high) maritime forest to the west of the developing parabolic dunes (Figure 58) and an unvegetated sand sheet to the east of the dunes, the offshore winds were of minimal importance in determining the orientation of the parabolic dunes. A north-northeast oriented vector wind resultant compiled by excluding offshore winds correlates very well with the orientation of the parabolic dunes. Therefore this interaction of wind regime and vegetation was responsible for the development and orientation of the parabolic dune field in False Cape State Park. This interactive process is also responsible for the present north-south differences in both sand hill migration rate and in cross barrier sand flux along Currituck Spit.

## North-South Differences: Migration Rates and Cross Barrier Sediment Transport

The migration rate of a large sand hill near Corolla (Whalehead Hill, Figure 27) was six meters/year while a dune in False Cape State Park (Barbours Hill, Figure 28) migrated only .75 m/year. The difference in the migration rate of these two sand hills cannot be related to differences in dune dimensions, wind regime or precipitation. The density of the vegetation cover surrounding the two dunes accounts for the discrepancy.

Whalehead Hill (Figure 27) is surrounded on the east by only sparse dune grass vegetation, and is therefore attached to its source of sand, the beach. At Barbours Hill (Figure 28) however, there is a 2-3 meter shrub thicket to the east of the dune which has effectively isolated this sand hill from its source of sand. Due to these differences in vegetation cover, Whalehead Hill migrated eight times faster to the south-southwest than Barbours Hill.

The amount of vegetation cover in the two areas is also responsible for differences in the amount of cross-barrier sand flux. A cross-barrier sand grading study indicated no transport across a transect in False Cape State Park (Figures 42 and 43). However, the plots of grain size moments against distance across the barrier spit transect near Corolla indicated some grading (Figures 44 and 45) of sediments and thus a cross-barrier flux of sand. This conclusion is also supported by sand transport measurements (Tables 8 and 9) and the transport model.

For a cross-barrier transect with a low foredune system and low-density vegetation across the eolian flat (typical of Corolla, in 1977) the model predicts a net onshore sand transport of approximately 10,000 kg/m/year (Table 11), but with large amounts of sand moving both onshore and offshore. If the barrier spit is covered by a dense growth of vegetation (False Cape State Park, in 1977) then the model predicts very little onshore-offshore transport across the interior. Instead there is a net movement of sand onshore from the ocean beach which would almost all be trapped by the high, multiple-ridge foredune system.

## Management Implications

During the next few decades Currituck Spit will be undergoing rapid and complex changes due to increased development pressures. Back Bay National Wildlife Refuge and False Cape State Park will be subject to increased pressures as public recreational facilities while the section of the spit in North Carolina will see the development of private coastal recreational communities. In each of these areas the question now is how to efficiently and intelligently manage this coastal resource to minimize the environmental impact of increased development activities. The interactive process-mechanisms which relate eolian sand transport, vegetation, moisture, and dune dynamics, detailed in this thesis, has immediate management and planning implications. The control of large sand hills which can and do migrate over forests and towns is one such implication.

A source of sand and a polymodal wind regime is necessary for the formation of a medano. Therefore the most logical approach to avoiding the formation of medanos would be the elimination of the sand supply. Primarily, this could be accomplished by limiting the use of recreational vehicles, grazing animals, and foot traffic across the dunes and eolian flat. This would protect the vegetation so that no source of sand would become available for dune formation.

Protection of the vegetation and foredune is not only important for avoiding the development of medanos, but also for limiting their migration rate. The migration rate of a sand hill (Whalehead Hill) located in an area of low vegetation density migrated eight times further to the southwest over a one year period than a sand hill (Barbours Hill) located in an area with a high density vegetation cover. In fact both Barbours Hill and the previously mobile parabolic dunes in False Cape State Park have become stabilized by vegetation. Therefore the protection and encouragement of vegetation should be a prime coastal resource management objective.

The varying levels of net cross-barrier transport predicted by the eolian sand transport model also has important coastal resource management implications. The model indicates that sand fencing can have both beneficial and detrimental effects on the coastal ecosystem. The aim of most sand fencing programs is creation of a high (3-4 meters) multiple ridge foredune system. The model, field measurements, and old aerial photographs indicate that this high foredune system reduces sand transport from the beach to the interior. This reduction in sand transport allows colonization of the eolian flat by vegetation and stabilization of shifting sand. However, this reduction in transport can be considered detrimental because the interior of the barrier spit will no longer buildup vertically by sand deposition. This would allow more inundation of low lying areas during storm surges than there might be otherwise. The decision to initiate a sand fencing program must be made by weighing the positive and negative effects relative to management objectives. The model, however, can aid in reaching an intelligent decision.

If it is decided to launch a sand fencing program, then the model can greatly aid in the design, planning and execution of the program. In particular, the location, orientation and amount of the sand fencing material needed can be determined from the eolian sand transport model.

This study has concentrated on determining the overall role of eolian sand transport in the coastal zone, by delineating the development, orientation and migration of sand dunes, and the net flux of sand across a barrier spit. Sand transport by wind is a complex, interactive process resulting from the combined effects of the local wind climate, vegetation, moisture and surface dune morphology.

# REFERENCES

Ahlbrandt, T. S. 1975. Comparison of textures and structures to distinguish eolian environments, Killpecker dune field, Wyoming. The Mountain Geologist, V. 12, p. 61-73.

Anan, F. S. 1971. Provenance and statistical parameters of sediments of the Merrimack embayment, Gulf of Maine. Unpublished Ph.D. Thesis, University of Massachusetts, Amherst, Massachusetts, 377 p.

Bagnold, R. A. 1941. The Physics of Blown Sand and Desert Dunes: William Morrow and Co., New York, 265 p.

Binder, R. C. 1973. Fluid Mechanics: Prentice-Hall Inc., Englewood Cliffs, New Jersey, 401 p.

Bressolier, C. and Y. Thomas. 1977. Studies on wind and plant interactions on French Atlantic coastal dunes: Journ. Sed. Petrology, v. 47, p. 331-338.

Chang, J. H. 1968. Climate and Agriculture, An Ecological Survey: Aldine Publishing Company, Chicago, 249 p.

Chepil, W. S. 1939. Comparative study of soil drifting in the field and in a wind tunnel: Scientific Agriculture, v. 19, p. 249-257.

________. 1956. Influence of moisture on erodibility of soil: Proceedings of Soil Science Society, v. 20, p. 288-291.

________. 1959. Equilibrium of soil grains at the threshold of movement of wind: Proceedings of Soil Science Society, v. 23, p. 422-428.

________. 1961. The use of spheres to measure lift and drag on wind eroded surfaces: Proceedings of Soil Science Society, v. 25, p. 343-345.

Corps of Engineers, Department of the Army, New England Division. 1968. Pleasant Bay Survey Report.

Dahl, B. E., B. A. Fall, A. Lolse and S. G. Appan. 1975. Construction and stabilization of coastal foredunes with vegetation: Misc. Paper No. 9-75, U.S. Army Coastal Engin. Res. Center, C.E., Washington, D. C.

Daniel, C. and F. S. Wood. 1971. Fitting Equations to Data: Wiley-Interscience, New York, 342 p.

DeAlteris, J. T. 1973. The Recent History of Wachapreague Inlet, School of Marine Science, College of William and Mary, Williamsburg, Va., Unpublished M.S. Thesis, 86 pp.

Folk, R. L. and W. C. Ward. 1957. Brazo River Bar: A study in the significance of grain size parameters. Jour. of Sed. Petrology, v. 27, p. 3-26.

Friedman, G. M. 1961. Distinction between dune, beach and river sands from their textural characteristics. Jour. of Sed. Petrology, v. 31, p. 514-529.

Gibbs, R. F. and E. Nash. 1961. Beach and sand dune erosion control: Amer. Soc. Agr. Eng. Trans., v. 4, p. 122-127.

Goldsmith, V. 1973. Eolian sedimentation in coastal areas. VIMS Contribution No. 533, 138 p.

Goldsmith, V., H. F. Hennigar and A. L. Gutman. 1977. The VAMP coastal dune classification: _in_ Goldsmith, V., (ed.) Coastal Processes and Resulting Forms of Sediment Accumulation, VIMS SRAMSOE No. 143, p. 26-1 - 26-20.

Hawk, V. B. and W. C. Sharp. 1967. Sand dune stabilization along the North Atlantic Coast. Journ. Soil and Water Cons., v. 22, p. 143-146.

Hennigar, H. F. 1978. Historical evolution of coastal sand dunes, Currituck Spit, Virginia-North Carolina: M.S. Thesis, VIMS, Gloucester Point, Virginia, _in prep_.

Horikawa, K. and H. W. Shen. 1960. Sand movement by wind action: U.S. Army Corps of Eng., Tech. Memo No. 119.

Hsu, S. 1971a. Wind stress criteria in eolian sand transport: Journ. Geophys. Res. v. 76, p. 8684-8686.

________. 1971b. Measurement of shear stress and roughness length on a beach: Journ. Geophys. Res. v. 76, p. 2880-2885.

________. 1973. Computing eolian sand transport from shear velocity measurements: Journ. Geology, v. 81, p. 739-743.

Inman, D. L., et al. 1966. Coastal sand dunes of Guerrero Negro, Baja California, Mexico: G.S.A. Bull., v. 77, p. 787-802.

Jennings, J. N. 1957. On the orientation of parabolic or u dunes: Geog. J., v. 123, p. 474-480.

Johnson, J. W. 1963. Sand movement on coastal dunes: U.S.D.A. Misc. Publ. No. 970, p. 747-755.

Kadib, A. 1963. Calculation procedure for sand transport by wind on natural beaches: U.S. Army Coastal Eng. Res. Center, Misc. Paper No. 2-64.

Kadib, A. 1964. Sand movement by wind: U.S. Army Corps of Engineers, Tech. Memo., No. 1.

Kawamura, R. 1951. Study of sand movement by wind: Report of the Institute of Science and Technology, v. 5, n. 3/4.

Landsberg, S. Y. 1956. The orientation of dunes in Britain and Denmark in relation to wind: Geog. J., v. 122, pp. 176-189.

Lathrobe, H. B., Esq. 1814. On the sand hills of Cape Henry in Virginia: Trans. Amer. Phil. Soc., v. 4, p. 439.

Manohar, M. 1970. Mechanics of dune growth by sand fences: Dock and Harbour Authority, v. 51, p. 243-252.

Mason, C. S. and R. L. Folk. 1958. Differentiation of beach, dune and aeolian flat environments by size analysis, Mustang Island, Texas. Jour. of Sed. Petrology, v. 28, p. 211-226.

McCammon, R. B. 1962. Efficiency of percentile measures for describing the mean size and sorting of sedimentary particles. Journ. of Geology, v. 70, p. 453-465.

O'Brien, M. P. and B. D. Rindlaub. 1936. The transportation of sand by wind: Civil Eng., May, 1936.

Olson, J. S. 1958. Lake Michigan dune development, 1-2-3: Journ. Geol., v. 56, p. 254-263, p. 345-351, p. 413-483.

Pickard, J. 1970. Rate of movement of transgressive sand dunes at Cronulla, New South Wales: Journ. of Geol. Soc. Australia, v. 19, p. 213-216.

Pierce, J. W. 1969. Sediment budget along a barrier island chain: Sed. Geol., v. 3, p. 5-16.

Potter, P. E. and F. J. Pettijohn. 1963. Paleoccurrents and Basin Analysis, Academic Press, Inc., New York, 296 pp.

Ranwell, D. 1958. Movement of vegetated sand dunes at Newborough Warren, Anglesey: Journ. Ecology. v. 46, p. 83-100.

Savage, R. P. and W. W. Woodhouse. 1968. Creation and Stabilization of Coastal Barrier Dunes: U.S. Army Corps of Eng. CERC Reprint 3-69.

Sharp, R. P. 1965. Kelso dunes, Mojave Desert, California. Geological Society of America Bulletin, no. 77, p. 1046-1073.

Sokal, R. R. and F. J. Rohlf. 1969. Biometry. W. H. Freeman and Company, San Francisco, 776 p.

Spiegel, M. R. 1961. Theory and Problems of Statistics. Schaum Publishing Company, New York, 359 p.

Svaskek, J. N. and J. H. Terwindt. 1974. Measurements of sand transport by wind on a natural beach: Sedimentology, v. 21, p. 311-322.

Tsoar, H. 1974. Desert dunes morphology and dynamics, El Arish (Northern Sinai), Z. Geomorph. N.S. Suppl. 3d. 20, pp. 41-61.

Woodruff, N. P., et al. 1965. Sediment transportation mechanics: Wind erosion and transportation: J. Hydraulics Div. Proc. Amer. Soc. Civil Engrn. v. 91, p. 267-287.

Yves-Belly, P. 1964. Sand movement by wind: U.S. Army Corps of Engrs. Tech. Memo. No. 1.

Zeigler, J. M. and B. Gill. 1959. Tables and graphs for the settling velocity of quartz in water, above the stoke's law. References No. 59-36, Woods Hole Oceanographic Institution, Woods Hole, Mass., 13 p.

Zeigler, J. M., G. G. Whitney and C. R. Hayes. 1960. Woods Hole rapid sediment analyser. Journ. of Sed. Petrology, v. 30, p. 490-495.

# APPENDIX 1.

## COROLLA STATION WIND DATA

Appendix 1 contains a monthly listing of the entire wind record from the anemometer operating on the Corolla Lighthouse ( 2/76-2/77 ).

Wind speeds are in miles/hour. To convert to m/sec multiply by .44704.

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/ 2/76 | 12 | 195 | 8 | 205 | 16 | 185 | 10 | 195 | 16 | 205 | 14 | 185 | 22 | 175 | 24 | 175 | 42 | 175 | 14 | 186 |
| 2/ 2/76 | 34 | 215 | 36 | 275 | 36 | 295 | 36 | 285 | 28 | 305 | 14 | 305 | 8 | 295 | 4 | 295 | 81 | 305 | 21 | 279 |
| 3/ 2/76 | 2 | 145 | 12 | 205 | 12 | 145 | 14 | 155 | 10 | 125 | 10 | 125 | 4 | 25 | 8 | 335 | 25 | 145 | 5 | 146 |
| 4/ 2/76 | 4 | 318 | 4 | 225 | 12 | 225 | 14 | 230 | 14 | 245 | 16 | 235 | 12 | 245 | 12 | 245 | 20 | 245 | 10 | 239 |
| 5/ 2/76 | 12 | 245 | 17 | 55 | 19 | 45 | 18 | 35 | 14 | 15 | 13 | 35 | 12 | 15 | 6 | 135 | 24 | 15 | 9 | 35 |
| 6/ 2/76 | 22 | 225 | 24 | 235 | 20 | 265 | 18 | 5 | 12 | 15 | 20 | 5 | 22 | 5 | 24 | 15 | 32 | 5 | 9 | 327 |
| 7/ 2/76 | 22 | 5 | 22 | 5 | 16 | 5 | 11 | 355 | 18 | 335 | 14 | 335 | 10 | 355 | 6 | 275 | 35 | 355 | 13 | 351 |
| 8/ 2/76 | 10 | 245 | 16 | 235 | 24 | 235 | 24 | 245 | 28 | 255 | 18 | 285 | 11 | 325 | 14 | 304 | 34 | 245 | 16 | 259 |
| 9/ 2/76 | 11 | 315 | 11 | 315 | 16 | 335 | 19 | 355 | 14 | 355 | 12 | 35 | 12 | 25 | 7 | 5 | 34 | 355 | 11 | 352 |
| 10/ 2/76 | 0 | 35 | 9 | 235 | 8 | 215 | 14 | 225 | 19 | 215 | 24 | 214 | 28 | 215 | 30 | 235 | 37 | 215 | 16 | 221 |
| 11/ 2/76 | 29 | 235 | 22 | 245 | 25 | 245 | 21 | 235 | 20 | 256 | 21 | 315 | 10 | 37 | 3 | 355 | 28 | 305 | 14 | 256 |
| 12/ 2/76 | 6 | 85 | 3 | 85 | 12 | 55 | 8 | 45 | 8 | 65 | 8 | 145 | 12 | 155 | 16 | 155 | 12 | 155 | 6 | 107 |
| 13/ 2/76 | 18 | 185 | 10 | 235 | 14 | 235 | 25 | 245 | 18 | 255 | 18 | 255 | 20 | 245 | 15 | 240 | 25 | 245 | 16 | 238 |
| 14/ 2/76 | 22 | 255 | 16 | 285 | 20 | 5 | 20 | 25 | 26 | 25 | 20 | 35 | 18 | 65 | 18 | 65 | 36 | 25 | 12 | 17 |
| 15/ 2/76 | 12 | 95 | 16 | 85 | 12 | 115 | 6 | 145 | 12 | 185 | 20 | 215 | 26 | 215 | 24 | 235 | 34 | 215 | 9 | 183 |
| 16/ 2/76 | 28 | 235 | 26 | 245 | 22 | 245 | 20 | 255 | 16 | 245 | 18 | 235 | 18 | 215 | 26 | 225 | 24 | 215 | 21 | 237 |
| 17/ 2/76 | 26 | 235 | 22 | 235 | 30 | 235 | 26 | 235 | 22 | 245 | 20 | 235 | 16 | 185 | 18 | 225 | 34 | 235 | 21 | 231 |
| 18/ 2/76 | 16 | 220 | 18 | 225 | 18 | 225 | 20 | 215 | 22 | 215 | 32 | 205 | 34 | 215 | 36 | 235 | 46 | 215 | 24 | 219 |
| 19/ 2/76 | 18 | 265 | 16 | 265 | 16 | 275 | 20 | 305 | 10 | 285 | 18 | 255 | 14 | 235 | 18 | 235 | 26 | 295 | 14 | 264 |
| 20/ 2/76 | 20 | 265 | 14 | 355 | 7 | 345 | 6 | 55 | 8 | 75 | 8 | 125 | 10 | 160 | 8 | 178 | 23 | 255 | 0 | 358 |
| 21/ 2/76 | 14 | 155 | 12 | 155 | 16 | 140 | 20 | 145 | 16 | 185 | 20 | 195 | 16 | 195 | 22 | 205 | 32 | 195 | 15 | 174 |
| 22/ 2/76 | 28 | 215 | 34 | 215 | 34 | 215 | 26 | 225 | 28 | 215 | 36 | 245 | 10 | 325 | 26 | 5 | 50 | 235 | 20 | 231 |
| 23/ 2/76 | 16 | 5 | 24 | 355 | 16 | 5 | 16 | 335 | 20 | 335 | 16 | 45 | 10 | 35 | 2 | 115 | 28 | 335 | 13 | 2 |
| 24/ 2/76 | 10 | 175 | 14 | 225 | 16 | 245 | 18 | 245 | 20 | 235 | 20 | 215 | 22 | 235 | 24 | 235 | 24 | 235 | 17 | 229 |
| 25/ 2/76 | 18 | 235 | 18 | 235 | 14 | 255 | 14 | 245 | 16 | 235 | 18 | 215 | 24 | 215 | 18 | 225 | 28 | 215 | 17 | 230 |
| 26/ 2/76 | 16 | 225 | 12 | 225 | 14 | 225 | 14 | 235 | 14 | 215 | 14 | 225 | 16 | 235 | 20 | 225 | 22 | 205 | 14 | 226 |
| 27/ 2/76 | 14 | 265 | 11 | 285 | 12 | 315 | 8 | 335 | 16 | 25 | 20 | 25 | 14 | 45 | 10 | 185 | 26 | 15 | 6 | 346 |
| 28/ 2/76 | 14 | 225 | 19 | 230 | 18 | 235 | 20 | 245 | 18 | 255 | 24 | 235 | 16 | 225 | 18 | 235 | 28 | 245 | 18 | 236 |
| 29/ 2/76 | 16 | 235 | 14 | 225 | 16 | 225 | 16 | 225 | 20 | 235 | 26 | 215 | 24 | 215 | 20 | 225 | 30 | 215 | 18 | 224 |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/ 3/76 | 18 | 225 | 18 | 225 | 14 | 235 | 14 | 265 | 14 | 235 | 14 | 175 | 16 | 205 | 16 | 215 | 20 | 225 | 14 | 222 |
| 2/ 3/76 | 12 | 225 | 10 | 235 | 10 | 245 | 6 | 245 | 20 | 175 | 16 | 175 | 16 | 215 | 20 | 235 | 24 | 175 | 12 | 213 |
| 3/ 3/76 | 18 | 230 | 14 | 245 | 6 | 35 | 2 | 35 | 10 | 45 | 18 | 45 | 14 | 75 | 10 | 95 | 20 | 55 | 3 | 61 |
| 4/ 3/76 | 8 | 145 | 4 | 155 | 10 | 25 | 0 | 125 | 8 | 155 | 12 | 135 | 18 | 215 | 20 | 215 | 26 | 215 | 5 | 179 |
| 5/ 3/76 | 22 | 235 | 20 | 235 | 24 | 245 | 26 | 245 | 30 | 245 | 26 | 245 | 26 | 215 | 22 | 235 | 38 | 245 | 24 | 237 |
| 6/ 3/76 | 26 | 245 | 24 | 255 | 22 | 255 | 14 | 275 | 20 | 35 | 6 | 75 | 10 | 85 | 12 | 105 | 38 | 245 | 5 | 262 |
| 7/ 3/76 | 8 | 105 | 2 | 140 | 14 | 335 | 10 | 355 | 8 | 335 | 10 | 205 | 14 | 245 | 14 | 275 | 20 | 235 | 4 | 291 |
| 8/ 3/76 | 16 | 245 | 18 | 305 | 10 | 315 | 8 | 325 | 4 | 65 | 4 | 125 | 12 | 25 | 6 | 45 | 20 | 305 | 5 | 322 |
| 9/ 3/76 | 6 | 105 | 16 | 75 | 30 | 95 | 30 | 105 | 20 | 65 | 2 | 195 | 26 | 335 | 24 | 5 | 44 | 335 | 12 | 62 |
| 10/ 3/76 | 20 | 345 | 20 | 25 | 20 | 15 | 16 | 5 | 10 | 15 | 12 | 35 | 4 | 95 | 6 | 355 | 36 | 355 | 12 | 13 |
| 11/ 3/76 | 2 | 275 | 10 | 275 | 10 | 255 | 10 | 295 | 20 | 25 | 10 | 65 | 12 | 85 | 12 | 85 | 24 | 25 | 3 | 21 |
| 12/ 3/76 | 18 | 85 | 16 | 105 | 14 | 95 | 20 | 95 | 18 | 125 | 24 | 140 | 20 | 175 | 30 | 195 | 38 | 215 | 15 | 132 |
| 13/ 3/76 | 16 | 225 | 30 | 225 | 36 | 225 | 32 | 225 | 36 | 235 | 32 | 245 | 36 | 315 | 30 | 325 | 47 | 315 | 24 | 250 |
| 14/ 3/76 | 20 | 315 | 16 | 355 | 10 | 335 | 16 | 15 | 8 | 80 | 12 | 225 | 12 | 225 | 14 | 255 | 30 | 325 | 6 | 312 |
| 15/ 3/76 | 12 | 255 | 14 | 275 | 8 | 295 | 6 | 95 | 6 | 145 | 10 | 155 | 12 | 215 | 16 | 215 | 24 | 235 | 6 | 224 |
| 16/ 3/76 | 2 | 125 | 4 | 155 | 6 | 125 | 10 | 185 | 20 | 245 | 28 | 215 | 28 | 235 | 40 | 315 | 53 | 345 | 10 | 244 |
| 17/ 3/76 | 26 | 315 | 24 | 305 | 22 | 285 | 20 | 325 | 20 | 305 | 20 | 295 | 20 | 315 | 24 | 335 | 32 | 305 | 21 | 310 |
| 18/ 3/76 | 14 | 5 | 14 | 5 | 4 | 45 | 6 | 5 | 16 | 155 | 24 | 195 | 22 | 205 | 18 | 215 | 32 | 215 | 4 | 200 |
| 19/ 3/76 | 20 | 230 | 24 | 235 | 22 | 235 | 26 | 245 | 22 | 245 | 24 | 215 | 28 | 215 | 20 | 230 | 34 | 235 | 22 | 230 |
| 20/ 3/76 | 18 | 235 | 14 | 235 | 12 | 235 | 14 | 255 | 16 | 215 | 16 | 195 | 20 | 205 | 22 | 215 | 30 | 215 | 15 | 221 |
| 21/ 3/76 | 24 | 225 | 24 | 225 | 26 | 215 | 26 | 225 | 36 | 225 | 28 | 245 | 10 | 55 | 6 | 125 | 42 | 205 | 18 | 224 |
| 22/ 3/76 | 12 | 185 | 12 | 5 | 20 | 45 | 20 | 35 | 20 | 55 | 16 | 75 | 18 | 75 | 12 | 95 | 30 | 45 | 12 | 60 |
| 23/ 3/76 | 18 | 95 | 18 | 95 | 18 | 65 | 14 | 55 | 12 | 55 | 12 | 105 | 13 | 115 | 10 | 135 | 18 | 55 | 12 | 90 |
| 24/ 3/76 | 10 | 155 | 6 | 155 | 2 | 155 | 6 | 145 | 14 | 155 | 20 | 155 | 20 | 185 | 20 | 185 | 22 | 165 | 11 | 166 |
| 25/ 3/76 | 12 | 185 | 13 | 185 | 10 | 205 | 12 | 215 | 30 | 275 | 20 | 245 | 6 | 285 | 4 | 285 | 30 | 255 | 10 | 236 |
| 26/ 3/76 | 0 | 165 | 8 | 105 | 6 | 55 | 8 | 75 | 6 | 85 | 12 | 115 | 17 | 145 | 16 | 145 | 18 | 155 | 7 | 116 |
| 27/ 3/76 | 20 | 145 | 14 | 185 | 12 | 205 | 12 | 205 | 24 | 195 | 32 | 215 | 22 | 215 | 24 | 225 | 38 | 215 | 18 | 201 |
| 28/ 3/76 | 21 | 245 | 22 | 25 | 24 | 25 | 16 | 25 | 14 | 55 | 18 | 55 | 2 | 185 | 2 | 165 | 30 | 15 | 8 | 28 |
| 29/ 3/76 | 4 | 195 | 6 | 275 | *** | *** | 12 | 35 | 12 | 75 | 4 | 105 | 4 | 175 | 6 | 165 | 12 | 35 | *** | *** |
| 30/ 3/76 | 6 | 285 | 6 | 85 | 14 | 75 | 16 | 85 | 10 | 115 | 10 | 125 | 16 | 105 | 10 | 105 | 18 | 85 | 9 | 97 |
| 31/ 3/76 | 12 | 95 | 18 | 105 | 18 | 115 | 18 | 125 | 22 | 135 | 22 | 165 | 24 | 145 | 20 | 185 | 34 | 185 | 17 | 136 |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/ 4/76 | 26 | 185 | 20 | 205 | 24 | 215 | 24 | 345 | 8 | 65 | 14 | 135 | 16 | 165 | 14 | 185 | 38 | 205 | 9 | 187 |
| 2/ 4/76 | 14 | 245 | 14 | 275 | 14 | 285 | 12 | 295 | 26 | 285 | 16 | 315 | 34 | 315 | 32 | 345 | 39 | 315 | 17 | 302 |
| 3/ 4/76 | 26 | 345 | 20 | 335 | 20 | 345 | 12 | 355 | 8 | 65 | 10 | 125 | 0 | 125 | 10 | 215 | 30 | 345 | 8 | 349 |
| 4/ 4/76 | 18 | 225 | 20 | 235 | 24 | 245 | 20 | 245 | 20 | 225 | 32 | 265 | 12 | 95 | 30 | 25 | 42 | 15 | 12 | 249 |
| 5/ 4/76 | 26 | 5 | 22 | 345 | 14 | 345 | 20 | 25 | 10 | 55 | 10 | 145 | 18 | 185 | 18 | 215 | 36 | 5 | 5 | 4 |
| 6/ 4/76 | 16 | 235 | 16 | 235 | 16 | 235 | 14 | 255 | 12 | 245 | 20 | 45 | 16 | 75 | 12 | 135 | 22 | 35 | 4 | 224 |
| 7/ 4/76 | 8 | 215 | 12 | 275 | 18 | 25 | 16 | 35 | 16 | 55 | 12 | 105 | 14 | 135 | 14 | 125 | 24 | 35 | 5 | 75 |
| 8/ 4/76 | 12 | 115 | 10 | 115 | 16 | 95 | 20 | 95 | 10 | 15 | 20 | 65 | 26 | 55 | 24 | 55 | 34 | 55 | 15 | 73 |
| 9/ 4/76 | 30 | 45 | 30 | 35 | 36 | 25 | 34 | 25 | 36 | 25 | 26 | 15 | 20 | 5 | 20 | 5 | 42 | 35 | 28 | 24 |
| 10/ 4/76 | 20 | 325 | 20 | 335 | 20 | 335 | 22 | 355 | 12 | 35 | 8 | 55 | 12 | 195 | 10 | 205 | 38 | 355 | 9 | 340 |
| 11/ 4/76 | 18 | 245 | 20 | 245 | 20 | 245 | 22 | 245 | 14 | 225 | 24 | 275 | 36 | 305 | 30 | 5 | 44 | 25 | 16 | 273 |
| 12/ 4/76 | 26 | 5 | 30 | 25 | 30 | 15 | 26 | 5 | 20 | 35 | 16 | 45 | 2 | 15 | 4 | 185 | 38 | 15 | 17 | 19 |
| 13/ 4/76 | 14 | 215 | 10 | 255 | 6 | 275 | 4 | 285 | 14 | 145 | 20 | 155 | 12 | 215 | 20 | 235 | 26 | 155 | 9 | 208 |
| 14/ 4/76 | 14 | 245 | 12 | 235 | 12 | 275 | 4 | 305 | 14 | 55 | 10 | 55 | 10 | 155 | 12 | 155 | 18 | 235 | 2 | 209 |
| 15/ 4/76 | *** | *** | *** | *** | *** | *** | 14 | 155 | 14 | 155 | 18 | 185 | 20 | 185 | 18 | 215 | 24 | 235 | *** | *** |
| 16/ 4/76 | 20 | 225 | 16 | 235 | 18 | 245 | 18 | 245 | 16 | 245 | 16 | 225 | 20 | 215 | 20 | 245 | 24 | 255 | 17 | 234 |
| 17/ 4/76 | 18 | 265 | 12 | 275 | 12 | 305 | 8 | 335 | 10 | 55 | 16 | 85 | 10 | 115 | 8 | 185 | 16 | 305 | 1 | 308 |
| 18/ 4/76 | 4 | 155 | 0 | 145 | 8 | 135 | 8 | 125 | 4 | 115 | 8 | 145 | 12 | 155 | 12 | 185 | 16 | 165 | 6 | 149 |
| 19/ 4/76 | 12 | 195 | 6 | 265 | 4 | 205 | 10 | 215 | 14 | 165 | 18 | 155 | 18 | 195 | 16 | 215 | 26 | 175 | 10 | 192 |
| 20/ 4/76 | 16 | 235 | 14 | 245 | 10 | 255 | 14 | 235 | 14 | 215 | 20 | 175 | 20 | 205 | 20 | 215 | 22 | 235 | 14 | 218 |
| 21/ 4/76 | 18 | 235 | 14 | 235 | 14 | 245 | 14 | 225 | 16 | 155 | 16 | 185 | 24 | 195 | 26 | 215 | 30 | 215 | 15 | 210 |
| 22/ 4/76 | 18 | 215 | 16 | 215 | 18 | 225 | 16 | 215 | 22 | 215 | 24 | 205 | 16 | 235 | 12 | 235 | 28 | 225 | 17 | 218 |
| 23/ 4/76 | 14 | 275 | 10 | 305 | 10 | 15 | 12 | 45 | 6 | 105 | 10 | 175 | 20 | 195 | 10 | 215 | 22 | 25 | 2 | 227 |
| 24/ 4/76 | 12 | 145 | 16 | 165 | 6 | 215 | 6 | 205 | 12 | 215 | 20 | 235 | 22 | 215 | 24 | 235 | 28 | 235 | 12 | 209 |
| 25/ 4/76 | 28 | 235 | 26 | 235 | 28 | 225 | 30 | 225 | 26 | 215 | 30 | 255 | 24 | 225 | 28 | 225 | 52 | 305 | 26 | 230 |
| 26/ 4/76 | 22 | 245 | 20 | 245 | 18 | 15 | 18 | 305 | 12 | 205 | 12 | 55 | 26 | 25 | 24 | 5 | 34 | 25 | 7 | 330 |
| 27/ 4/76 | 20 | 5 | 16 | 5 | 10 | 345 | 10 | 335 | 12 | 35 | 8 | 85 | 8 | 95 | 18 | 5 | 28 | 35 | 10 | 14 |
| 28/ 4/76 | 20 | 335 | 20 | 335 | 18 | 335 | 14 | 335 | 10 | 65 | 10 | 95 | 6 | 215 | 8 | 315 | 26 | 335 | 9 | 343 |
| 29/ 4/76 | 16 | 345 | 14 | 335 | 12 | 325 | 8 | 335 | 10 | 55 | 6 | 145 | 8 | 165 | 8 | 195 | 20 | 35 | 3 | 344 |
| 30/ 4/76 | 16 | 169 | 8 | 215 | 6 | 235 | 10 | 215 | 16 | 205 | 24 | 215 | 22 | 215 | 16 | 215 | 26 | 215 | 14 | 208 |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/ 5/76 | 12 | 215 | 16 | 195 | 20 | 185 | 20 | 165 | 32 | 185 | 30 | 185 | *** | *** | *** | *** | *** | *** | *** | *** |
| 2/ 5/76 | *** | *** | *** | *** | *** | *** | *** | *** | 10 | 45 | 10 | 115 | 10 | 155 | 20 | 155 | 20 | 165 | *** | *** |
| 3/ 5/76 | 12 | 225 | 12 | 235 | 16 | 275 | 12 | 265 | 20 | 305 | 16 | 335 | 16 | 55 | 14 | 95 | 44 | 25 | 5 | 294 |
| 4/ 5/76 | 12 | 95 | 10 | 35 | 18 | 35 | 20 | 25 | 16 | 35 | 12 | 75 | 10 | 125 | 16 | 185 | 34 | 45 | 9 | 61 |
| 5/ 5/76 | 12 | 195 | 18 | 215 | 16 | 235 | 18 | 245 | 18 | 225 | 23 | 215 | 18 | 215 | 26 | 215 | 30 | 215 | 18 | 220 |
| 6/ 5/76 | 20 | 225 | 22 | 225 | 12 | 235 | 18 | 225 | 14 | 245 | 18 | 215 | 28 | 215 | 24 | 215 | 32 | 215 | 19 | 223 |
| 7/ 5/76 | 22 | 225 | 24 | 225 | 22 | 225 | 20 | 215 | 24 | 265 | 10 | 155 | 18 | 215 | 18 | 235 | 40 | 245 | 18 | 226 |
| 8/ 5/76 | 10 | 255 | 22 | 15 | 14 | 25 | 26 | 25 | 18 | 45 | 12 | 45 | 12 | 35 | 6 | 65 | 36 | 15 | 12 | 27 |
| 9/ 5/76 | 4 | 35 | 6 | 45 | 10 | 355 | 8 | 35 | 10 | 55 | 10 | 105 | 10 | 225 | 10 | 155 | 10 | 125 | 3 | 66 |
| 10/ 5/76 | 12 | 195 | 10 | 185 | 2 | 205 | 2 | 215 | 12 | 155 | 14 | 155 | 14 | 165 | 16 | 185 | 18 | 185 | 9 | 174 |
| 11/ 5/76 | 14 | 215 | 10 | 215 | 12 | 205 | 10 | 185 | 16 | 205 | 20 | 195 | 14 | 215 | 18 | 205 | 28 | 195 | 14 | 204 |
| 12/ 5/76 | 14 | 235 | 12 | 245 | 10 | 305 | 26 | 15 | 26 | 35 | 14 | 75 | 12 | 95 | 12 | 85 | 32 | 15 | 6 | 33 |
| 13/ 5/76 | 12 | 125 | 14 | 105 | 18 | 95 | 24 | 105 | 18 | 105 | 14 | 155 | 26 | 155 | 18 | 155 | 26 | 105 | 16 | 125 |
| 14/ 5/76 | 20 | 185 | 12 | 175 | 16 | 185 | 12 | 185 | 16 | 185 | 20 | 175 | 20 | 195 | 20 | 215 | 24 | 185 | 16 | 188 |
| 15/ 5/76 | 14 | 215 | 14 | 215 | 10 | 195 | 8 | 185 | 10 | 185 | 20 | 185 | 16 | 205 | 20 | 205 | 28 | 185 | 13 | 199 |
| 16/ 5/76 | 14 | 195 | 18 | 205 | 16 | 205 | 14 | 215 | 22 | 185 | 16 | 185 | *** | *** | 20 | 205 | 28 | 205 | *** | *** |
| 17/ 5/76 | 20 | 225 | 16 | 155 | 16 | 215 | 18 | 215 | 16 | 195 | 16 | 205 | 20 | 215 | 16 | 215 | 28 | 215 | 16 | 206 |
| 18/ 5/76 | 20 | 235 | 18 | 245 | 18 | 245 | 10 | 225 | 20 | 225 | 28 | 215 | 30 | 305 | 38 | 345 | 50 | 225 | 15 | 262 |
| 19/ 5/76 | 30 | 315 | 22 | 315 | 22 | 285 | 24 | 285 | 30 | 275 | 24 | 285 | 20 | 275 | 12 | 85 | 34 | 295 | 19 | 292 |
| 20/ 5/76 | 12 | 175 | 16 | 245 | 16 | 295 | 16 | 285 | 8 | 305 | 14 | 275 | 20 | 245 | 18 | 235 | 24 | 305 | 12 | 257 |
| 21/ 5/76 | 20 | 245 | 18 | 255 | 16 | 255 | 10 | 245 | 12 | 215 | 22 | 245 | 22 | 245 | 18 | 245 | 30 | 245 | 16 | 244 |
| 22/ 5/76 | 18 | 265 | 14 | 325 | 18 | 15 | 10 | 35 | 12 | 65 | 10 | 105 | 10 | 125 | 12 | 135 | 24 | 15 | 4 | 42 |
| 23/ 5/76 | 16 | 145 | 14 | 185 | 14 | 235 | 0 | 325 | 18 | 35 | 14 | 45 | 22 | 45 | 14 | 65 | 24 | 45 | 5 | 76 |
| 24/ 5/76 | 18 | 45 | 20 | 65 | 22 | 55 | 30 | 75 | 32 | 65 | 24 | 35 | 28 | 35 | 20 | 35 | 40 | 65 | 23 | 52 |
| 25/ 5/76 | 18 | 35 | 18 | 25 | 24 | 35 | 20 | 45 | 18 | 55 | 18 | 55 | 18 | 55 | 20 | 55 | 24 | 35 | 18 | 44 |
| 26/ 5/76 | 16 | 65 | 16 | 65 | 16 | 65 | 12 | 55 | 12 | 65 | 14 | 35 | 14 | 75 | 14 | 85 | 20 | 65 | 13 | 64 |
| 27/ 5/76 | 10 | 95 | 8 | 105 | 8 | 65 | 6 | 75 | 10 | 55 | 10 | 95 | 6 | 125 | 8 | 155 | 12 | 95 | 7 | 93 |
| 28/ 5/76 | 10 | 145 | 8 | 125 | 12 | 95 | 16 | 95 | 18 | 105 | 20 | 95 | 16 | 135 | 18 | 145 | 22 | 95 | 13 | 115 |
| 29/ 5/76 | 22 | 145 | 18 | 135 | 22 | 125 | 32 | 145 | 22 | 135 | 22 | 145 | 22 | 135 | 12 | 145 | 34 | 135 | 21 | 138 |
| 30/ 5/76 | 6 | 225 | 4 | 215 | 10 | 215 | 6 | 305 | 10 | 215 | 10 | 185 | 18 | 225 | 10 | 215 | 22 | 175 | 8 | 219 |
| 31/ 5/76 | 14 | 225 | 10 | 245 | 6 | 255 | 2 | 245 | 14 | 215 | *** | *** | 14 | 215 | 20 | 235 | 36 | 285 | *** | *** |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/ 6/76 | 16 | 255 | 14 | 245 | 14 | 255 | 8 | 255 | 18 | 235 | 20 | 225 | 22 | 215 | 24 | 235 | 30 | 215 | 16 | 236 |
| 2/ 6/76 | 22 | 245 | 12 | 235 | 12 | 235 | 4 | 275 | 16 | 65 | 24 | 65 | 26 | 75 | 24 | 65 | 32 | 55 | 5 | 74 |
| 3/ 6/76 | 20 | 65 | 26 | 75 | 24 | 65 | 24 | 75 | 20 | 65 | 26 | 55 | 26 | 55 | 82 | 65 | 28 | 75 | 30 | 64 |
| 4/ 6/76 | 26 | 65 | 26 | 65 | 32 | 55 | 32 | 55 | 32 | 45 | 32 | 55 | 36 | 55 | 34 | 55 | 42 | 45 | 31 | 55 |
| 5/ 6/76 | 36 | 55 | 36 | 55 | 32 | 55 | 36 | 45 | 38 | 55 | 30 | 45 | 32 | 35 | 38 | 35 | 42 | 55 | 34 | 47 |
| 6/ 6/76 | 24 | 35 | 20 | 35 | 20 | 35 | 20 | 35 | 8 | 65 | 6 | 85 | 8 | 165 | 10 | 165 | 28 | 35 | 10 | 50 |
| 7/ 6/76 | 6 | 215 | 6 | 275 | 0 | 215 | 2 | 235 | 4 | 185 | 10 | 185 | 8 | 195 | 6 | 175 | 14 | 165 | 4 | 202 |
| 8/ 6/76 | 6 | 135 | 8 | 85 | 16 | 45 | 20 | 25 | 20 | 15 | 14 | 25 | 4 | 15 | 8 | 225 | 26 | 15 | 8 | 34 |
| 9/ 6/76 | 14 | 235 | 12 | 265 | 4 | 295 | 2 | 275 | 10 | 165 | 14 | 175 | 12 | 225 | 12 | 225 | 20 | 175 | 7 | 221 |
| 10/ 6/76 | 10 | 235 | 6 | 215 | 6 | 205 | 12 | 165 | 6 | 185 | 10 | 205 | 10 | 205 | 10 | 215 | 18 | 165 | 8 | 203 |
| 11/ 6/76 | 8 | 265 | 10 | 245 | 12 | 245 | 10 | 245 | 16 | 215 | 14 | 235 | 14 | 235 | 16 | 235 | 20 | 215 | 12 | 237 |
| 12/ 6/76 | 10 | 255 | 12 | 305 | 12 | 325 | 4 | 35 | 4 | 95 | 16 | 105 | 20 | 95 | 22 | 95 | 30 | 95 | 4 | 76 |
| 13/ 6/76 | 26 | 95 | 26 | 95 | 26 | 95 | 20 | 95 | 16 | 115 | 10 | 115 | 10 | 115 | 8 | 115 | 32 | 95 | 17 | 101 |
| 14/ 6/76 | 8 | 115 | 6 | 135 | 8 | 105 | 6 | 125 | 12 | 135 | 16 | 165 | 16 | 175 | 12 | 205 | 20 | 155 | 8 | 152 |
| 15/ 6/76 | 8 | 215 | 6 | 195 | 8 | 245 | 4 | 245 | 24 | 225 | 24 | 215 | 20 | 225 | 18 | 215 | 30 | 225 | 13 | 221 |
| 16/ 6/76 | 12 | 225 | 16 | 215 | 20 | 215 | 16 | 215 | 30 | 215 | 32 | 215 | 30 | 215 | 26 | 215 | 34 | 235 | 22 | 215 |
| 17/ 6/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 18/ 6/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 19/ 6/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | 10 | 165 | 22 | 215 | 28 | 225 | 32 | 225 | *** | *** |
| 20/ 6/76 | 16 | 235 | 16 | 215 | 16 | 205 | 20 | 175 | 26 | 205 | 32 | 215 | 20 | 215 | 24 | 205 | 36 | 235 | 20 | 208 |
| 21/ 6/76 | 18 | 185 | 22 | 185 | 22 | 205 | 26 | 205 | 24 | 205 | 12 | 195 | 14 | 215 | 12 | 195 | 36 | 215 | 18 | 199 |
| 22/ 6/76 | 24 | 205 | 16 | 225 | 6 | 155 | 18 | 155 | 10 | 185 | 14 | 205 | 8 | 175 | 4 | 225 | 26 | 205 | 11 | 192 |
| 23/ 6/76 | 0 | 295 | 8 | 155 | 16 | 175 | 16 | 165 | 16 | 175 | 12 | 215 | 10 | 235 | 4 | 275 | 20 | 195 | 8 | 187 |
| 24/ 6/76 | 0 | 95 | 12 | 155 | 16 | 155 | 18 | 215 | 16 | 215 | 20 | 225 | 20 | 235 | 18 | 235 | 24 | 195 | 12 | 210 |
| 25/ 6/76 | 14 | 245 | 14 | 255 | 20 | 245 | 20 | 245 | 18 | 225 | 20 | 245 | 18 | 255 | 18 | 245 | 24 | 245 | 17 | 244 |
| 26/ 6/76 | 16 | 275 | 8 | 315 | 14 | 55 | 12 | 55 | 4 | 85 | 6 | 235 | 2 | 255 | 2 | 285 | 28 | 285 | 2 | 344 |
| 27/ 6/76 | 2 | 5 | 4 | 35 | 6 | 95 | 6 | 95 | 4 | 145 | 4 | 225 | 8 | 265 | 10 | 295 | 12 | 55 | 0 | 297 |
| 28/ 6/76 | 4 | 325 | 0 | 185 | 6 | 105 | 14 | 155 | 14 | 175 | 16 | 225 | 12 | 49 | 12 | 255 | 18 | 155 | 3 | 185 |
| 29/ 6/76 | 12 | 245 | 10 | 245 | 10 | 215 | 18 | 175 | 20 | 205 | 20 | 215 | 14 | 225 | 18 | 245 | 24 | 195 | 14 | 218 |
| 30/ 6/76 | 16 | 225 | 20 | 215 | 20 | 215 | 24 | 225 | 36 | 215 | 30 | 225 | 26 | 235 | 20 | 245 | 46 | 215 | 23 | 224 |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/ 7/76 | 20 | 245 | 10 | 245 | 14 | 225 | 10 | 215 | 10 | 225 | 18 | 265 | 10 | 215 | 2 | 25 | 34 | 255 | 10 | 237 |
| 2/ 7/76 | 4 | 15 | 10 | 45 | 8 | 75 | 10 | 105 | 10 | 155 | 12 | 175 | 12 | 185 | 10 | 245 | 14 | 45 | 4 | 142 |
| 3/ 7/76 | 8 | 245 | 6 | 235 | 12 | 225 | 12 | 155 | 20 | 215 | 10 | 155 | 12 | 315 | 12 | 25 | 30 | 215 | 5 | 219 |
| 4/ 7/76 | 16 | 5 | 8 | 5 | 6 | 335 | 6 | 55 | 30 | 65 | 8 | 45 | 10 | 15 | 10 | 5 | 14 | 35 | 10 | 29 |
| 5/ 7/76 | 16 | 15 | 8 | 35 | 4 | 75 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 6/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 7/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | 10 | 225 | 20 | 205 | 22 | 235 | 14 | 235 | 24 | 215 | *** | *** |
| 8/ 7/76 | 14 | 245 | 12 | 255 | 8 | 255 | 14 | 235 | 16 | 235 | 10 | 235 | 16 | 235 | 14 | 255 | 20 | 245 | 12 | 242 |
| 9/ 7/76 | 14 | 235 | 6 | 235 | 12 | 215 | 26 | 25 | 14 | 135 | 6 | 305 | 8 | 305 | 6 | 325 | 38 | 15 | 2 | 287 |
| 10/ 7/76 | 16 | 15 | 8 | 55 | 8 | 155 | 12 | 185 | 16 | 215 | 16 | 235 | 20 | 255 | 16 | 235 | 26 | 245 | 6 | 229 |
| 11/ 7/76 | 22 | 245 | 20 | 245 | 18 | 255 | 20 | 255 | 18 | 295 | 26 | 275 | 10 | 335 | 8 | 305 | 46 | 335 | 15 | 270 |
| 12/ 7/76 | 16 | 285 | 18 | 285 | 26 | 245 | 16 | 25 | 14 | 5 | 16 | 5 | 10 | 355 | 10 | 305 | 34 | 245 | 10 | 315 |
| 13/ 7/76 | 14 | 275 | 14 | 275 | 14 | 275 | 18 | 245 | 16 | 325 | 16 | 5 | 8 | 305 | 10 | 335 | 22 | 15 | 10 | 296 |
| 14/ 7/76 | 12 | 325 | 0 | 85 | 10 | 265 | 12 | 265 | 12 | 255 | 12 | 275 | 8 | 285 | 10 | 305 | 14 | 325 | 8 | 281 |
| 15/ 7/76 | 6 | 335 | 10 | 125 | 22 | 135 | 12 | 245 | 14 | 225 | 10 | 245 | 12 | 255 | 6 | 295 | 44 | 185 | 5 | 215 |
| 16/ 7/76 | 6 | 305 | 10 | 165 | 12 | 235 | 16 | 255 | 16 | 255 | 16 | 285 | 12 | 315 | 8 | 335 | 26 | 325 | 8 | 270 |
| 17/ 7/76 | 10 | 35 | 8 | 95 | 12 | 145 | 8 | 105 | 10 | 105 | 10 | 85 | 18 | 65 | 20 | 75 | 24 | 75 | 10 | 85 |
| 18/ 7/76 | 18 | 55 | 20 | 75 | 16 | 65 | 12 | 55 | 10 | 75 | 10 | 65 | 12 | 65 | 10 | 75 | 22 | 75 | 13 | 65 |
| 19/ 7/76 | 10 | 65 | 10 | 75 | 10 | 85 | 10 | 85 | 8 | 125 | 6 | 95 | 2 | 55 | 6 | 55 | 10 | 85 | 7 | 82 |
| 20/ 7/76 | 8 | 65 | 4 | 125 | 10 | 145 | 12 | 205 | 12 | 225 | 12 | 245 | 10 | 245 | 6 | 265 | 18 | 245 | 5 | 212 |
| 21/ 7/76 | 10 | 215 | 12 | 215 | 16 | 205 | 16 | 215 | 18 | 215 | 22 | 235 | 14 | 225 | 2 | 245 | 22 | 215 | 13 | 219 |
| 22/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 23/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 24/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | 6 | 245 | 10 | 215 | 18 | 265 | 16 | 335 | 26 | 285 | *** | *** |
| 25/ 7/76 | 8 | 355 | 20 | 35 | 10 | 45 | 12 | 65 | 8 | 75 | 6 | 65 | 6 | 15 | 10 | 65 | 24 | 35 | 9 | 45 |
| 26/ 7/76 | 10 | 95 | 10 | 175 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 27/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 28/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 29/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 30/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 31/ 7/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 2/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 3/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 4/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 5/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 6/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 7/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | 18 | 165 | 16 | 175 | 19 | 170 | 17 | 165 | 21 | 165 | *** | *** |
| 8/ 8/76 | 14 | 195 | 16 | 195 | 20 | 205 | 12 | 205 | 18 | 195 | 4 | 215 | 4 | 5 | 12 | 125 | 26 | 185 | 10 | 192 |
| 9/ 8/76 | 11 | 65 | 14 | 55 | 23 | 35 | 40 | 5 | 45 | 355 | 40 | 295 | 22 | 270 | 12 | 245 | 70 | 345 | 16 | 344 |
| 10/ 8/76 | 10 | 235 | 6 | 235 | 9 | 175 | 10 | 185 | 12 | 165 | 15 | 165 | 10 | 245 | 6 | 275 | 24 | 305 | 7 | 200 |
| 11/ 8/76 | 6 | 35 | 4 | 35 | 8 | 35 | 6 | 25 | 6 | 55 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 12/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 13/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 14/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | 20 | 205 | 20 | 215 | 20 | 215 | 28 | 215 | *** | *** |
| 15/ 8/76 | 22 | 225 | 20 | 215 | 18 | 235 | 18 | 245 | 16 | 215 | 20 | 215 | 22 | 215 | 24 | 155 | 24 | 225 | 18 | 214 |
| 16/ 8/76 | 14 | 265 | 14 | 325 | 8 | 295 | 6 | 25 | 18 | 35 | 8 | 55 | 14 | 45 | 14 | 65 | 26 | 245 | 6 | 13 |
| 17/ 8/76 | 20 | 35 | 22 | 35 | 24 | 35 | 18 | 25 | 22 | 25 | 14 | 55 | 14 | 35 | 10 | 45 | 28 | 45 | 17 | 34 |
| 18/ 8/76 | 10 | 15 | 10 | 335 | 10 | 25 | 22 | 45 | 28 | 45 | 28 | 45 | 26 | 55 | 30 | 55 | 36 | 55 | 19 | 42 |
| 19/ 8/76 | 26 | 65 | 30 | 65 | 30 | 65 | 24 | 65 | 26 | 65 | 26 | 55 | 24 | 55 | 28 | 65 | 34 | 65 | 26 | 62 |
| 20/ 8/76 | 22 | 75 | 18 | 85 | 24 | 75 | 24 | 85 | 22 | 75 | 22 | 75 | 26 | 75 | 20 | 95 | 26 | 75 | 22 | 79 |
| 21/ 8/76 | 20 | 95 | 18 | 95 | 16 | 95 | 16 | 95 | 16 | 85 | 14 | 115 | 12 | 85 | 12 | 95 | 22 | 95 | 15 | 94 |
| 22/ 8/76 | 8 | 95 | 10 | 85 | 8 | 65 | 6 | 65 | 6 | 95 | 8 | 85 | 6 | 115 | 8 | 165 | 12 | 115 | 6 | 94 |
| 23/ 8/76 | 12 | 185 | 10 | 215 | 6 | 305 | 4 | 265 | 10 | 155 | 10 | 165 | 14 | 195 | 14 | 215 | 16 | 175 | 8 | 198 |
| 24/ 8/76 | 10 | 225 | 6 | 265 | 2 | 305 | 0 | 335 | 12 | 55 | 14 | 75 | 14 | 95 | 18 | 95 | 20 | 105 | 5 | 90 |
| 25/ 8/76 | 12 | 85 | 10 | 85 | 14 | 95 | 8 | 75 | 8 | 75 | 10 | 125 | 12 | 145 | 10 | 165 | 14 | 45 | 8 | 106 |
| 26/ 8/76 | 12 | 185 | 6 | 185 | 6 | 255 | 2 | 285 | 5 | 145 | 14 | 175 | 18 | 165 | 14 | 175 | 22 | 175 | 8 | 179 |
| 27/ 8/76 | 16 | 185 | 10 | 215 | 8 | 255 | 4 | 255 | 6 | 195 | 20 | 165 | 18 | 195 | 18 | 205 | 24 | 205 | 11 | 197 |
| 28/ 8/76 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | 20 | 165 | 16 | 185 | 18 | 215 | 26 | 215 | *** | *** |
| 29/ 8/76 | 20 | 235 | 22 | 245 | 22 | 235 | 20 | 245 | 18 | 225 | 22 | 235 | 4 | 305 | 18 | 235 | 30 | 235 | 17 | 238 |
| 30/ 8/76 | 16 | 45 | 30 | 35 | 36 | 35 | 26 | 25 | 24 | 25 | 20 | 25 | 18 | 25 | 18 | 35 | 38 | 35 | 23 | 31 |
| 31/ 8/76 | 20 | 35 | 20 | 45 | 18 | 45 | 18 | 75 | 10 | 75 | 30 | 95 | 20 | 125 | 10 | 145 | 26 | 55 | 15 | 76 |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/ 9/76 | 12 | 145 | 12 | 165 | 6 | 215 | 4 | 135 | 10 | 145 | 12 | 175 | 18 | 53 | 16 | 195 | 20 | 175 | 7 | 153 |
| 2/ 9/76 | 18 | 205 | 10 | 225 | 4 | 225 | 4 | 205 | 18 | 25 | 20 | 55 | 10 | 85 | 8 | 85 | 24 | 75 | 2 | 90 |
| 3/ 9/76 | 1 | 265 | 18 | 35 | 12 | 55 | 14 | 65 | 22 | 55 | 16 | 55 | 22 | 55 | 18 | 75 | 26 | 65 | 14 | 55 |
| 4/ 9/76 | 20 | 85 | 12 | 75 | 22 | 65 | 16 | 75 | 16 | 65 | 10 | 75 | 8 | 95 | 8 | 95 | 24 | 65 | 13 | 76 |
| 5/ 9/76 | 8 | 145 | 50 | 235 | 6 | 275 | 4 | 255 | 10 | 135 | 12 | 165 | 12 | 185 | 14 | 195 | 18 | 145 | 11 | 206 |
| 6/ 9/76 | 10 | 225 | 34 | 55 | 26 | 35 | 28 | 45 | 20 | 35 | 20 | 35 | 10 | 65 | 6 | 85 | 38 | 45 | 16 | 45 |
| 7/ 9/76 | 4 | 55 | 6 | 315 | 10 | 65 | 10 | 335 | 10 | 65 | 8 | 95 | 6 | 185 | 12 | 195 | 18 | 235 | 2 | 71 |
| 8/ 9/76 | 12 | 235 | 14 | 245 | 12 | 275 | 10 | 285 | 6 | 235 | 16 | 225 | 12 | 215 | 16 | 235 | 20 | 235 | 11 | 241 |
| 9/ 9/76 | 14 | 245 | 14 | 265 | 12 | 275 | 10 | 275 | 8 | 255 | 12 | 235 | 14 | 205 | 22 | 225 | 24 | 225 | 12 | 244 |
| 10/ 9/76 | 18 | 235 | 18 | 245 | 18 | 225 | 22 | 215 | 18 | 215 | 20 | 5 | 26 | 25 | 12 | 315 | 32 | 325 | 7 | 259 |
| 11/ 9/76 | 16 | 335 | 18 | 345 | 14 | 335 | 16 | 335 | 10 | 305 | 8 | 65 | 20 | 175 | 10 | 215 | 18 | 325 | 6 | 324 |
| 12/ 9/76 | 10 | 255 | 14 | 275 | 14 | 305 | 10 | 315 | 12 | 35 | 10 | 65 | 8 | 125 | 6 | 185 | 16 | 35 | 3 | 310 |
| 13/ 9/76 | 6 | 125 | 4 | 255 | 4 | 275 | 2 | 315 | 4 | 95 | 6 | 145 | 4 | 155 | 2 | 185 | 8 | 275 | 1 | 161 |
| 14/ 9/76 | 0 | 175 | 2 | 65 | 10 | 95 | 10 | 85 | 14 | 95 | 12 | 95 | 18 | 95 | 22 | 105 | 22 | 105 | 10 | 95 |
| 15/ 9/76 | 22 | 105 | 22 | 115 | 28 | 115 | 26 | 115 | 22 | 125 | 30 | 125 | 26 | 145 | 28 | 145 | 42 | 135 | 24 | 124 |
| 16/ 9/76 | 30 | 155 | 12 | 155 | 12 | 165 | 10 | 185 | 10 | 155 | 16 | 155 | 18 | 175 | 20 | 195 | 38 | 155 | 15 | 167 |
| 17/ 9/76 | 14 | 225 | 16 | 215 | 6 | 215 | 10 | 225 | 12 | 235 | 12 | 225 | 8 | 215 | 10 | 205 | 18 | 215 | 10 | 220 |
| 18/ 9/76 | 16 | 225 | 8 | 225 | 10 | 235 | 10 | 265 | 3 | 245 | 10 | 245 | 10 | 295 | 10 | 285 | 36 | 295 | 8 | 251 |
| 19/ 9/76 | 14 | 295 | 10 | 315 | 6 | 325 | 6 | 35 | 8 | 65 | 6 | 75 | 8 | 125 | 8 | 175 | 14 | 295 | 1 | 2 |
| 20/ 9/76 | 8 | 215 | 8 | 245 | 12 | 245 | 18 | 225 | 18 | 215 | 18 | 225 | 18 | 215 | 26 | 225 | 32 | 225 | 15 | 224 |
| 21/ 9/76 | 12 | 235 | 18 | 255 | 14 | 255 | 10 | 265 | 8 | 315 | 10 | 245 | 12 | 245 | 14 | 345 | 30 | 235 | 10 | 265 |
| 22/ 9/76 | 8 | 35 | 16 | 345 | 16 | 355 | 50 | 345 | 6 | 275 | 8 | 75 | 8 | 55 | 8 | 15 | 20 | 345 | 12 | 358 |
| 23/ 9/76 | 4 | 45 | 2 | 75 | 6 | 145 | 14 | 195 | 16 | 155 | 16 | 175 | 18 | 85 | 16 | 193 | 22 | 165 | 8 | 155 |
| 24/ 9/76 | 10 | 225 | 12 | 235 | 8 | 245 | 10 | 265 | 6 | 195 | 12 | 185 | 16 | 185 | 14 | 205 | 18 | 213 | 9 | 214 |
| 25/ 9/76 | 6 | 225 | 4 | 255 | 4 | 245 | 4 | 255 | 10 | 125 | 14 | 155 | 16 | 165 | 14 | 185 | *** | *** | 6 | 178 |
| 26/ 9/76 | 14 | 215 | 12 | 225 | 10 | 205 | 16 | 205 | 14 | 215 | 24 | 185 | 18 | 215 | 20 | 215 | 30 | 185 | 15 | 208 |
| 27/ 9/76 | 20 | 235 | 14 | 255 | 24 | 255 | 20 | 265 | 26 | 285 | 22 | 265 | 24 | 245 | 26 | 265 | 30 | 255 | 21 | 259 |
| 28/ 9/76 | 28 | 285 | 20 | 325 | 18 | 35 | 14 | 35 | 22 | 55 | 18 | 75 | 14 | 75 | 12 | 95 | 32 | 235 | 10 | 30 |
| 29/ 9/76 | 14 | 35 | 14 | 165 | 12 | 35 | 14 | 185 | 12 | 95 | 8 | 185 | 10 | 175 | 10 | 175 | 18 | 165 | 5 | 139 |
| 30/ 9/76 | 16 | 95 | 16 | 155 | 20 | 175 | 18 | 175 | 14 | 175 | 10 | 175 | 14 | 225 | 12 | 325 | 40 | 175 | 9 | 171 |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/10/76 | 14 | 345 | 4 | 345 | 8 | 285 | 23 | 39 | 27 | 41 | 10 | 41 | 2 | 85 | 10 | 345 | 14 | 245 | 9 | 18 |
| 2/10/76 | 10 | 5 | 10 | 235 | 12 | 15 | 16 | 245 | 16 | 225 | 16 | 295 | 10 | 305 | 10 | 265 | 22 | 225 | 7 | 278 |
| 3/10/76 | 10 | 275 | 12 | 265 | 14 | 285 | 14 | 345 | 18 | 345 | 18 | 25 | 18 | 5 | 20 | 5 | 22 | 5 | 11 | 339 |
| 4/10/76 | 16 | 55 | 12 | 85 | 12 | 85 | 10 | 5 | 14 | 45 | 20 | 85 | 26 | 40 | 26 | 65 | 28 | 85 | 15 | 59 |
| 5/10/76 | 20 | 55 | 12 | 55 | 14 | 55 | 16 | 65 | 20 | 45 | 18 | 65 | 18 | 85 | 12 | 35 | 24 | 45 | 15 | 58 |
| 6/10/76 | 10 | 245 | 10 | 255 | 6 | 255 | 4 | 85 | 6 | 95 | 10 | 65 | 14 | 175 | 10 | 195 | 18 | 195 | 3 | 193 |
| 7/10/76 | 12 | 215 | 6 | 235 | 0 | 35 | 4 | 205 | 10 | 205 | 12 | 195 | 12 | 175 | 14 | 165 | 16 | 205 | 8 | 194 |
| 8/10/76 | 14 | 185 | 10 | 175 | 8 | 181 | 8 | 175 | 8 | 275 | 12 | 155 | 0 | 165 | 16 | 215 | 26 | 215 | 8 | 190 |
| 9/10/76 | 22 | 225 | 24 | 205 | 38 | 215 | 34 | 275 | 30 | 225 | 26 | 265 | 24 | 305 | 32 | 335 | 100 | 275 | 21 | 254 |
| 10/10/76 | 26 | 345 | 20 | 355 | 18 | 355 | 16 | 25 | 14 | 355 | 10 | 325 | 14 | 5 | 8 | 345 | 24 | 355 | 15 | 354 |
| 11/10/76 | 10 | 315 | 14 | 325 | 14 | 345 | 14 | 15 | 14 | 35 | 16 | 35 | 12 | 15 | 14 | 5 | 24 | 35 | 11 | 3 |
| 12/10/76 | 24 | 35 | 24 | 65 | 20 | 65 | 18 | 55 | 20 | 35 | 18 | 25 | 16 | 55 | 10 | 55 | 26 | 35 | 18 | 48 |
| 13/10/76 | 10 | 35 | 14 | 335 | 12 | 345 | 8 | 305 | 8 | 245 | 16 | 215 | 10 | 235 | 20 | 235 | 24 | 235 | 6 | 273 |
| 14/10/76 | 26 | 255 | 22 | 285 | 12 | 295 | 10 | 5 | 14 | 5 | 16 | 5 | 8 | 5 | 6 | 325 | 32 | 255 | 10 | 315 |
| 15/10/76 | 8 | 245 | 12 | 225 | 16 | 205 | 18 | 205 | 20 | 235 | 16 | 215 | 20 | 215 | 20 | 225 | 26 | 225 | 15 | 219 |
| 16/10/76 | 22 | 245 | 18 | 235 | 14 | 245 | 10 | 345 | 14 | 35 | 14 | 55 | 20 | 85 | 26 | 75 | 26 | 75 | 2 | 50 |
| 17/10/76 | 26 | 85 | 24 | 65 | 32 | 65 | 26 | 65 | 36 | 35 | 34 | 35 | 38 | 15 | 40 | 5 | 46 | 15 | 28 | 41 |
| 18/10/76 | 26 | 355 | 36 | 5 | 22 | 335 | 20 | 335 | 28 | 5 | 20 | 15 | 16 | 25 | 14 | 35 | 44 | 15 | 21 | 1 |
| 19/10/76 | 10 | 55 | 10 | 65 | 16 | 85 | 18 | 105 | 16 | 47 | 16 | 115 | 14 | 155 | 24 | 155 | 24 | 75 | 11 | 104 |
| 20/10/76 | 18 | 155 | 24 | 145 | 24 | 145 | 26 | 145 | 22 | 175 | 46 | 155 | 26 | 185 | 36 | 265 | 58 | 145 | 21 | 168 |
| 21/10/76 | 28 | 215 | 30 | 275 | 20 | 285 | 24 | 315 | 10 | 335 | 10 | 225 | 14 | 285 | 16 | 301 | 30 | 285 | 15 | 277 |
| 22/10/76 | 12 | 335 | 12 | 305 | 16 | 285 | 16 | 265 | 20 | 305 | 18 | 305 | 12 | 295 | 8 | 285 | 28 | 285 | 13 | 297 |
| 23/10/76 | 6 | 305 | 5 | 295 | 10 | 335 | 16 | 35 | 10 | 35 | 8 | 80 | 4 | 125 | 10 | 135 | 18 | 295 | 4 | 34 |
| 24/10/76 | 10 | 155 | 4 | 205 | 6 | 215 | 4 | 295 | 20 | 135 | 16 | 155 | 18 | 185 | 14 | 215 | 34 | 135 | 9 | 174 |
| 25/10/76 | 16 | 225 | 12 | 235 | 12 | 255 | 12 | 225 | 18 | 235 | 8 | 185 | 16 | 155 | 18 | 165 | 26 | 175 | 11 | 209 |
| 26/10/76 | 22 | 185 | 30 | 205 | 18 | 235 | 30 | 355 | 40 | 355 | 30 | 355 | 22 | 5 | 28 | 5 | 44 | 355 | 12 | 339 |
| 27/10/76 | 26 | 5 | 24 | 5 | 36 | 15 | 28 | 335 | 24 | 5 | 26 | 355 | 18 | 315 | 30 | 5 | 38 | 15 | 25 | 357 |
| 28/10/76 | 28 | 15 | 28 | 15 | 28 | 5 | 36 | 5 | 28 | 25 | 18 | 5 | 14 | 355 | 12 | 345 | 36 | 15 | 23 | 8 |
| 29/10/76 | 10 | 285 | 10 | 285 | 12 | 295 | 12 | 275 | 4 | 275 | 14 | 195 | 12 | 215 | 14 | 225 | 16 | 215 | 8 | 252 |
| 30/10/76 | 12 | 235 | 12 | 245 | 12 | 235 | 10 | 235 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/11/76 | 26 | 155 | 26 | 185 | 16 | 215 | 22 | 225 | 14 | 235 | 10 | 35 | 16 | 305 | 24 | 335 | 32 | 345 | 8 | 223 |
| 2/11/76 | 20 | 335 | 22 | 345 | 22 | 345 | 30 | 355 | 28 | 355 | 24 | 355 | 16 | 5 | 18 | 355 | 30 | 355 | 22 | 351 |
| 3/11/76 | 26 | 355 | 30 | 35 | 26 | 5 | 20 | 5 | 10 | 25 | 8 | 75 | 6 | 185 | 10 | 195 | 34 | 335 | 11 | 16 |
| 4/11/76 | 10 | 205 | 10 | 205 | 6 | 205 | 4 | 295 | 4 | 235 | 6 | 165 | 8 | 155 | 8 | 185 | 12 | 275 | 5 | 196 |
| 5/11/76 | 8 | 235 | 10 | 265 | 6 | 235 | 10 | 275 | 4 | 105 | 12 | 135 | 18 | 155 | 20 | 185 | 20 | 235 | 6 | 193 |
| 6/11/76 | 12 | 195 | 16 | 215 | 12 | 215 | 8 | 245 | 16 | 245 | 18 | 295 | 12 | 265 | 20 | 305 | 32 | 255 | 11 | 252 |
| 7/11/76 | 26 | 325 | 18 | 305 | 14 | 285 | 14 | 295 | 14 | 255 | 18 | 215 | 14 | 225 | 16 | 225 | 30 | 335 | 12 | 270 |
| 8/11/76 | 18 | 245 | 18 | 245 | 14 | 255 | 12 | 255 | 18 | 215 | 20 | 225 | 14 | 235 | 12 | 225 | 20 | 215 | 15 | 236 |
| 9/11/76 | 34 | 15 | 38 | 355 | 22 | 345 | 22 | 305 | 20 | 315 | 30 | 335 | 32 | 325 | 20 | 335 | 50 | 325 | 25 | 339 |
| 10/11/76 | 16 | 305 | 14 | 305 | 12 | 305 | 14 | 195 | 20 | 205 | 20 | 195 | 24 | 185 | 26 | 225 | 28 | 225 | 12 | 226 |
| 11/11/76 | 26 | 235 | 20 | 245 | 24 | 235 | 24 | 245 | 18 | 285 | 16 | 295 | 8 | 245 | 10 | 225 | 32 | 235 | 16 | 249 |
| 12/11/76 | 10 | 225 | 20 | 5 | 20 | 35 | 6 | 325 | 6 | 355 | 10 | 165 | 12 | 55 | 16 | 55 | 24 | 25 | 6 | 30 |
| 13/11/76 | 18 | 75 | 28 | 75 | 24 | 355 | 26 | 25 | 34 | 35 | 30 | 5 | 20 | 5 | 16 | 335 | 32 | 355 | 20 | 24 |
| 14/11/76 | 18 | 335 | 20 | 335 | 20 | 325 | 20 | 345 | 18 | 355 | 18 | 5 | 12 | 345 | 8 | 305 | 28 | 355 | 16 | 340 |
| 15/11/76 | 6 | 275 | 8 | 275 | 8 | 315 | 6 | 305 | 6 | 215 | 12 | 215 | 6 | 235 | 8 | 245 | 14 | 225 | 6 | 256 |
| 16/11/76 | 10 | 245 | 6 | 5 | 12 | 55 | 22 | 65 | 22 | 45 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| 17/11/76 | *** | *** | *** | *** | *** | *** | *** | *** | 18 | 5 | 16 | 15 | 8 | 5 | 6 | 335 | *** | *** | *** | *** |
| 18/11/76 | 6 | 335 | 8 | 345 | 8 | 355 | 6 | 335 | 4 | 35 | 2 | 355 | 4 | 275 | 12 | 255 | 16 | 255 | 4 | 323 |
| 19/11/76 | 16 | 265 | 18 | 265 | 20 | 285 | 28 | 305 | 18 | 305 | 16 | 285 | 10 | 275 | 12 | 235 | 36 | 295 | 16 | 281 |
| 20/11/76 | 14 | 235 | 18 | 235 | 22 | 235 | 24 | 255 | 20 | 255 | 16 | 225 | 24 | 235 | 24 | 255 | 26 | 255 | 19 | 242 |
| 21/11/76 | 18 | 345 | 30 | 25 | 22 | 35 | 14 | 35 | 6 | 35 | 6 | 85 | 8 | 145 | 6 | 155 | 36 | 25 | 10 | 33 |
| 22/11/76 | 6 | 215 | 8 | 225 | 2 | 295 | 6 | 5 | 12 | 65 | 10 | 95 | 6 | 175 | 34 | 305 | 36 | 305 | 2 | 309 |
| 23/11/76 | 24 | 285 | 26 | 305 | 20 | 285 | 24 | 295 | 20 | 305 | 22 | 305 | 16 | 285 | 20 | 295 | 32 | 285 | 21 | 295 |
| 24/11/76 | 16 | 295 | 18 | 295 | 20 | 295 | 16 | 305 | 14 | 305 | 14 | 295 | 12 | 275 | 12 | 265 | 22 | 285 | 14 | 292 |
| 25/11/76 | 10 | 275 | 12 | 295 | 10 | 305 | 6 | 275 | 4 | 215 | 14 | 225 | 16 | 305 | 20 | 225 | 24 | 225 | 9 | 265 |
| 26/11/76 | 16 | 235 | 16 | 265 | 10 | 325 | 4 | 335 | 0 | 5 | 12 | 195 | 18 | 195 | 20 | 215 | 24 | 205 | 8 | 231 |
| 27/11/76 | 18 | 225 | 16 | 235 | 18 | 215 | 16 | 225 | 16 | 215 | 12 | 225 | 14 | 195 | 24 | 195 | 30 | 195 | 16 | 215 |
| 28/11/76 | 16 | 205 | 10 | 215 | 6 | 160 | 12 | 255 | 4 | 275 | 16 | 215 | 18 | 235 | 16 | 235 | 24 | 195 | 11 | 224 |
| 29/11/76 | 16 | 245 | 16 | 245 | 10 | 225 | 16 | 195 | 12 | 225 | 16 | 195 | 16 | 185 | 26 | 205 | 30 | 215 | 14 | 213 |
| 30/11/76 | 26 | 215 | 34 | 225 | 16 | 265 | 22 | 235 | 22 | 35 | 20 | 5 | 18 | 5 | 16 | 345 | 40 | 215 | 7 | 281 |

***- DATA MISSING

WIND DIRECTION AND SPEED DATA
DIRECTIONS 0-360 DEG.FROM TRUE NORTH, SPEEDS MPH

STATION- COROLLA LIGHT

| DATE/ HOUR | 1 | | 4 | | 7 | | 10 | | 13 | | 16 | | 19 | | 22 | | MAX. | | VECTOR AV. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D | S | D |
| 1/12/76 | 16 | 355 | 20 | 5 | 20 | 5 | 26 | 5 | 14 | 15 | 14 | 5 | 12 | 5 | 16 | 265 | 28 | 5 | 14 | 357 |
| 2/12/76 | 0 | 155 | 14 | 325 | 14 | 325 | 12 | 305 | 6 | 195 | 12 | 245 | 14 | 255 | 22 | 355 | 34 | 5 | 8 | 304 |
| 3/12/76 | 30 | 15 | 24 | 15 | 30 | 5 | 24 | 35 | 16 | 35 | 10 | 35 | 4 | 35 | 12 | 355 | 36 | 5 | 18 | 18 |
| 4/12/76 | 8 | 75 | 8 | 75 | 10 | 75 | 4 | 355 | 8 | 105 | 2 | 135 | 8 | 215 | 6 | 355 | 12 | 15 | 3 | 76 |
| 5/12/76 | 14 | 25 | 16 | 35 | 20 | 55 | 24 | 35 | 22 | 35 | 24 | 35 | 22 | 55 | 22 | 55 | 26 | 35 | 20 | 41 |
| 6/12/76 | 24 | 75 | 22 | 85 | 24 | 75 | 28 | 85 | 22 | 75 | 22 | 65 | 14 | 135 | 28 | 145 | 32 | 155 | 20 | 90 |
| 7/12/76 | 28 | 175 | 28 | 165 | 24 | 275 | 40 | 195 | 20 | 235 | 18 | 325 | 12 | 345 | 14 | 15 | 52 | 195 | 10 | 218 |
| 8/12/76 | 18 | 35 | 26 | 15 | 30 | 25 | 26 | 5 | 26 | 345 | 28 | 335 | 22 | 325 | 16 | 345 | 38 | 325 | 22 | 358 |
| 9/12/76 | 12 | 285 | 14 | 275 | 10 | 315 | 10 | 325 | 0 | 315 | 12 | 205 | 8 | 215 | 8 | 215 | 16 | 285 | 6 | 265 |
| 10/12/76 | 2 | 115 | 2 | 165 | 2 | 275 | 4 | 235 | 2 | 245 | 12 | 215 | 18 | 215 | 16 | 215 | 20 | 215 | 6 | 215 |
| 11/12/76 | 14 | 235 | 14 | 305 | 12 | 295 | 12 | 305 | 2 | 65 | 10 | 105 | 16 | 135 | 10 | 165 | 18 | 225 | 2 | 239 |
| 12/12/76 | 10 | 175 | 6 | 175 | 6 | 255 | 6 | 261 | 10 | 260 | 10 | 225 | 14 | 245 | 20 | 265 | 26 | 275 | 8 | 239 |
| 13/12/76 | 26 | 305 | 18 | 325 | 30 | 5 | 24 | 15 | 26 | 35 | 26 | 25 | 20 | 25 | 24 | 45 | 36 | 15 | 20 | 9 |
| 14/12/76 | 20 | 45 | 16 | 65 | 14 | 125 | 10 | 145 | 8 | 155 | 8 | 175 | 12 | 165 | 16 | 155 | 22 | 55 | 8 | 121 |
| 15/12/76 | 22 | 175 | 8 | 35 | 10 | 75 | *** | *** | 12 | 105 | 26 | 55 | 26 | 55 | 30 | 55 | 36 | 55 | *** | *** |
| 16/12/76 | 26 | 35 | 28 | 15 | 20 | 345 | 18 | 335 | 16 | 325 | 8 | 325 | 10 | 255 | 20 | 275 | 30 | 5 | 13 | 341 |
| 17/12/76 | 20 | 305 | 14 | 275 | 20 | 301 | 20 | 275 | 34 | 265 | 26 | 235 | 26 | 245 | 28 | 5 | 42 | 265 | 18 | 279 |
| 18/12/76 | 30 | 15 | 20 | 5 | 12 | 345 | 12 | 345 | 20 | 35 | 4 | 5 | 6 | 245 | 6 | 245 | 30 | 15 | 10 | 2 |
| 19/12/76 | 4 | 175 | 8 | 215 | 10 | 225 | 12 | 205 | 18 | 205 | 24 | 215 | 22 | 215 | 18 | 215 | 26 | 215 | 14 | 211 |
| 20/12/76 | 14 | 225 | 16 | 235 | 18 | 215 | 22 | 215 | 24 | 205 | 20 | 215 | 30 | 215 | 22 | 235 | 36 | 225 | 20 | 218 |
| 21/12/76 | 30 | 335 | 28 | 305 | 30 | 305 | 38 | 305 | 40 | 295 | 42 | 305 | 32 | 305 | 26 | 305 | 48 | 265 | 32 | 306 |
| 22/12/76 | 26 | 305 | 20 | 305 | 18 | 305 | 10 | 325 | 8 | 165 | 18 | 225 | 20 | 215 | 18 | 225 | 30 | 305 | 11 | 267 |
| 23/12/76 | 16 | 235 | 18 | 245 | 18 | 245 | 14 | 285 | 18 | 255 | 16 | 245 | 18 | 245 | 24 | 275 | 26 | 265 | 17 | 253 |
| 24/12/76 | 14 | 275 | 24 | 335 | 26 | 355 | 22 | 355 | 26 | 5 | 10 | 345 | 4 | 355 | 4 | 265 | 34 | 5 | 14 | 343 |
| 25/12/76 | 10 | 195 | 8 | 235 | 12 | 215 | 18 | 215 | 16 | 235 | 12 | 185 | 14 | 185 | 20 | 175 | 30 | 215 | 12 | 203 |
| 26/12/76 | 10 | 305 | 12 | 215 | 22 | 5 | 22 | 345 | 30 | 355 | 20 | 355 | 8 | 355 | 16 | 255 | 42 | 345 | 12 | 336 |
| 27/12/76 | 24 | 255 | 36 | 325 | 24 | 315 | 30 | 325 | 16 | 325 | 18 | 295 | 12 | 195 | 24 | 195 | 40 | 335 | 15 | 294 |
| 28/12/76 | 32 | 215 | 40 | 235 | 10 | 225 | 26 | 235 | 26 | 235 | 16 | 235 | 16 | 235 | 18 | 215 | 30 | 235 | 22 | 229 |
| 29/12/76 | 20 | 235 | 18 | 265 | 24 | 325 | 6 | 245 | 14 | 345 | 22 | 295 | 8 | 355 | 22 | 285 | 40 | 285 | 13 | 292 |
| 30/12/76 | 18 | 305 | 22 | 315 | 22 | 305 | 16 | 295 | 8 | 245 | 20 | 205 | 24 | 215 | 22 | 225 | 36 | 205 | 13 | 263 |
| 31/12/76 | 26 | 235 | 22 | 235 | 20 | 305 | 20 | 315 | 32 | 5 | 30 | 5 | 16 | 355 | 14 | 5 | 38 | 15 | 13 | 324 |

***- DATA MISSING

# APPENDIX 2.

## WIND ROSE DIAGRAM PROGRAM

Appendix 2 contains a listing of the computer program which generates the wind rose diagrams illustrated in figures 4 thru 6, and 9 thru 23.

```
//VCTRPLT JOB (4891,WMVE,02,30,700,,1),'GUTMAN(VIMS)',MSGLEVEL=(1,1),
// CLASS=R,REGION=256K
/*ROUTE  PRINT LOCAL
/*MESSAGE       PUT IN VIMS BIN PLEASE     THANK YOU
/*SETUP  TAPE VS0302,RINGIN,BIN 0-029,SL
/*SETUP  PLOT VS0302
// EXEC FPLOTL,TAPE=VS0302,LABEL=1
//FORT.SYSIN DD *
      DIMENSION TITL(6),X(100),IBUF(1800),A(50),R(4000),THETA(4000)
      DIMENSION XD(100),XP(100),YP(100)
      CALL PLOTS(IBUF,1800)
      CALL FACTOR(.8)
      READ(5,1)N,TITL
    1 FORMAT(I6,6X,6A4)
      READ(5,2)(R(I),THETA(I),I=1,N)
    2 FORMAT(22X,16F3.0)
   50 CONTINUE
  666 CONTINUE
      DO 210 I=1,8
      X(I)=0.0
      XD(I)=0.0
      XP(I)=0.0
      YP(I)=0.0
  210 CONTINUE
      NUMB=N
      DO 300 I=1,N
      IF(R(I).GT.150.0)GO TO 299
C     CONVERTS KNOTS TO M.P.H.
      R(I)=R(I)*1.2
      R(I)=R(I)*.44704
      IF(THETA(I).LE.22.5) GO TO 51
      IF(THETA(I).LE.67.5) GO TO 52
      IF(THETA(I).LE.112.5) GO TO 53
      IF(THETA(I).LE.157.5) GO TO 54
      IF(THETA(I).LE.202.5) GO TO 55
      IF(THETA(I).LE.247.5) GO TO 56
      IF(THETA(I).LE.292.5) GO TO 57
      IF(THETA(I).LE.337.5) GO TO 58
      IF(THETA(I).LE.395.0) GO TO 51
      GO TO 300
   51 X(1)=X(1)+R(I)
      XD(1)=XD(1)+1.0
      GO TO 300
   52 X(2)=X(2)+R(I)
      XD(2)=XD(2)+1.0
```

```
      GO TO 300
   53 X(3)=X(3)+R(I)
      XD(3)=XD(3)+1.0
      GO TO 300
   54 X(4)=X(4)+R(I)
      XD(4)=XD(4)+1.0
      GO TO 300
   55 X(5)=X(5)+R(I)
      XD(5)=XD(5)+1.0
      GO TO 300
   56 X(6)=X(6)+R(I)
      XD(6)=XD(6)+1.0
      GO TO 300
   57 X(7)=X(7)+R(I)
      XD(7)=XD(7)+1.0
      GO TO 300
   58 X(8)=X(8)+R(I)
      XD(8)=XD(8)+1.0
      GO TO 300
  299 NUMB=NUMB+(-1.0)
      GO TO 300
  300 CONTINUE
      PRINT 9,NUMB
    9 FORMAT(I6)
      DO 760 I=1,8
      PRINT 7,I,X(I),XD(I)
    7 FORMAT(I6,2F12.6)
  760 CONTINUE
C
C
C     COMPUTES THE AVERAGE WIND SPEED AND DURATION FOR EACH VECTOR
C
C
      DO 770 I=1,8
      X(I)=((X(I)/XD(I))-3.0)/2.0
      XD(I)=(XD(I)/NUMB)*100.0
      PRINT 8,I,X(I),XD(I)
    8 FORMAT(I6,2F10.6)
      XD(I)=XD(I)/15.0
  770 CONTINUE
      YN=0.0
      XNE=0.0
      YNE=0.0
      XE=0.0
      YE =0.0
```

```
XSE=0.0
YSE=0.0
XS=0.0
YS=0.0
XSW=0.0
YSW=0.0
XW=0.0
YW=0.0
XNW=0.0
YNW=0.0
YN=6.0+X(1)
XNE=(.7071*X(2))+5.7071
YNE=XNE
XE=6.0+X(3)
XSE=(.7071*X(4))+5.7071
YSE=((-.7071)*X(4))+4.2929
YS=4.0-X(5)
XSW=((-.7071)*X(6))+4.2929
YSW=XSW
XW=4.0-X(7)
XNW=((-.7071)*X(8))+4.2929
YNW=(.7071*X(8))+5.7071
XP(1)=5.0
YP(1)=6.0+XD(1)
XP(2)=(.7071*XD(2))+5.7071
YP(2)=XP(2)
XP(3)=6.0+XD(3)
YP(3)=5.0
XP(4)=(.7071*XD(4))+5.7071
YP(4)=((-.7071)*XD(4))+4.2929
XP(5)=5.0
YP(5)=4.0-XD(5)
XP(6)=((-.7071)*XD(6))+4.2929
YP(6)=XP(6)
XP(7)=4.0-XD(7)
YP(7)=5.0
XP(8)=((-.7071)*XD(8))+4.2929
YP(8)=(.7071*XD(8))+5.7071
XP(9)=XP(1)
YP(9)=YP(1)
CALL SYMBOL (0.0,1.0,0.35,'CORROLLA WIND DATA',90.0,18)
CALL PLOT (1.0,-11.0,-3)
CALL PLOT(0.0,1.5,-3)
CALL PLOT (6.0,5.0,3)
CALL CIRCL(5.0,5.0,0.0,360.0,1.0,2)
```

```
      CALL PLOT(6.5,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,1.5,2)
      CALL PLOT(7.0,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,2.0,2)
      CALL PLOT (7.5,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,2.5,2)
      CALL PLOT (8.0,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,3.0,2)
      CALL PLOT(8.5,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,3.5,2)
      CALL SYMBOL(4.7,8.7,.14,'NORTH',0.0,5)
      CALL SYMBOL(8.70,4.95,.14,'EAST',0.0,4)
      CALL SYMBOL(3.50,.70,.14,'INCLUDES ALL WIND SPEEDS',0.0,24)
      CALL SYMBOL(4.70,1.10,.14,'SOUTH',0.0,5)
      CALL SYMBOL(.90,4.95,.14,'WEST',0.0,4)
      CALL SYMBOL (3.4,9.6,.21,'HATTERAS STATION',0.0,16)
      CALL SYMBOL(3.3,9.2,.21,TITL,0.0,24)
      CALL SYMBOL(6.78,5.7,.14,'15%',22.5,3)
      CALL SYMBOL(5.8,5.35,.14,'0%',22.5,2)
      CALL SYMBOL(7.68,6.1,.14,'30%',22.5,3)
      CALL SYMBOL(3.95,4.60,.14,'3.0',22.5,3)
      CALL SYMBOL(3.05,4.2,.14,'5.0',22.5,3)
      CALL SYMBOL(2.13,3.80,.14,'7.0',22.5,3)
      CALL SYMBOL(1.49,3.55,.14,'A',22.5,1)
      CALL SYMBOL(8.51,6.45,.14,'B',22.5,1)
      CALL SYMBOL(4.45,5.6,.11,'AVG. WIND',0.0,9)
      CALL PARROW(4.4,5.4,5.0,5.4,1)
      CALL SYMBOL(5.3,5.3,.14,'A',0.0,1)
      CALL SYMBOL(4.4,5.1,.11,'SPEED',0.0,5)
      CALL SYMBOL(5.1,5.1,.11,'(M/S)',0.0,5)
      CALL SYMBOL(4.5,4.7,.11,'DURATION',0.0,8)
      CALL PLOT(4.4,4.5,3)
      CALL PLOT(4.9,4.5,2)
      CALL SYMBOL(4.7,4.5,.07,1,0.0,-1)
      CALL SYMBOL(5.3,4.45,.14,'B',0.0,1)
      CALL SYMBOL(4.45,4.25,.11,'(PERCENT)',0.0,9)
      CALL PLOT(0.0,0.0,-3)
      CALL BLOKNO(NNN)
      PRINT 10,NNN
   10 FORMAT(' THE BLOCK NO. IS ',I4)
      CALL PARROW(5.0,YN,5.0,6.0,1)
      CALL PARROW(XNE,YNE,5.7071,5.7071,1)
      CALL PARROW(XE,5.0,6.0,5.0,1)
      CALL PARROW(XSE,YSE,5.7071,4.2929,1)
      CALL PARROW(5.0,YS,5.0,4.0,1)
      CALL PARROW(XSW,YSW,4.2929,4.2929,1)
      CALL PARROW(XW,5.0,4.0,5.0,1)
      CALL PARROW(XNW,YNW,4.2929,5.7071,1)
      CALL LINO(XP,YP,9,1,1,1,0.0,1.0,0.0,1.0)
      CALL PLOT (15.0,0.0,-3)
      CALL PLOT (20.0,-11.0,999)
      STOP
      END
```

# APPENDIX 3.

## WIND RESULTANT PROGRAM

Appendix 3 contains a listing of the computer program which generates the wind resultants illustrated in Figures 35 and 38.

```
//WINDPLT JOB (4911,MV35,01,30,300,,1),'GUTMAN(VIMS)',MSGLEVEL=(1,1),
// CLASS=R,REGION=256K
/*ROUTE  PRINT LOCAL
/*MESSAGE      PUT IN VIMS BIN PLEASE    THANK YOU
//FORT.SYSIN DD *
      DIMENSION TITL(6),X(100),IBUF(1800),A(50),R(4000),THETA(4000)
      CALL PLOTS(IBUF,1800)
      CALL FACTOR(.5)
      DO 999 M=1,12
      READ(5,1)N,TITL
    1 FORMAT(I6,6X,6A4)
      READ(5,2,END=666)(R(I),THETA(I),I=1,N)
    2 FORMAT(22X,16F3.0)
  666 CONTINUE
      DO 210 I=1,8
      X(I)=0.0
  210 CONTINUE
C
      DO 300 I=1,N
      IF(R(I).GT.150.0)GO TO 300
      IF(R(I).LE.10.0) GO TO 300
      IF(THETA(I).LE.22.5) GO TO 51
      IF(THETA(I).LE.67.5) GO TO 52
      IF(THETA(I).LE.112.5) GO TO 53
      IF(THETA(I).LE.157.5) GO TO 54
      IF(THETA(I).LE.202.5) GO TO 55
      IF(THETA(I).LE.247.5) GO TO 56
      IF(THETA(I).LE.292.5) GO TO 57
      IF(THETA(I).LE.337.5) GO TO 58
      IF(THETA(I).LE.395.0) GO TO 51
      GO TO 300
   51 X(1)=X(1)+(R(I)**3)
      GO TO 300
   52 X(2)=X(2)+(R(I)**3)
      GO TO 300
   53 X(3)=X(3)+(R(I)**3)
      GO TO 300
   54 X(4)=X(4)+(R(I)**3)
      GO TO 300
   55 X(5)=X(5)+(R(I)**3)
      GO TO 300
   56 X(6)=X(6)+(R(I)**3)
      GO TO 300
   57 X(7)=X(7)+(R(I)**3)
      GO TO 300
```

```
 58 X(8)=X(8)+(R(I)**3)
    GO TO 300
300 CONTINUE
    DO 400 I=1,8
    X(I)=(X(I)*.00001)/5.0
    PRINT 8,I,X(I)
  8 FORMAT(I6,F10.6)
400 CONTINUE
    XN=5.0
    YN=0.0
    XNE=0.0
    YNE=0.0
    XE=0.0
    YE =0.0
    XSE=0.0
    YSE=0.0
    XS=0.0
    YS=0.0
    XSW=0.0
    YSW=0.0
    XW=0.0
    YW=0.0
    XNW=0.0
    YNW=0.0
    YN=5.0-(X(1))
    XNE=5.0-(.7071*X(2))
    YNE=YN-(.7071*X(2))
    XE=XNE-(X(3))
    YE=YNE
    XSE=XE-(.7071*X(4))
    YSE=YE+(.7071*X(4))
    XS=XSE
    YS=YSE+X(5)
    XSW=XS+(.7071*X(6))
    YSW=YS+(.7071*X(6))
    XW=XSW+X(7)
    YW=YSW
    XNW=XW+(.7071*X(8))
    YNW=YW-(.7071*X(8))
    CALL SYMBOL (0.0,1.0,0.35,'CORROLLA WIND DATA',90.0,18)
    CALL PLOT (1.0,-11.0,-3)
    CALL PLOT (0.0,.5,-3)
    CALL PLOT (6.0,5.0,3)
    CALL CIRCL(5.0,5.0,0.0,360.0,1.0,2)
    CALL PLOT (6.0,5.0,3)
```

```
      CALL CIRCL(5.0,5.0,0.0,360.0,1.0,2)
      CALL PLOT(6.5,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,1.5,2)
      CALL PLOT(6.5,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,1.5,2)
      CALL PLOT(7.0,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,2.0,2)
      CALL PLOT(7.0,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,2.0,2)
      CALL PLOT (7.5,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,2.5,2)
      CALL PLOT (7.5,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,2.5,2)
      CALL PLOT (8.0,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,3.0,2)
      CALL PLOT (8.0,5.0,3)
      CALL CIRCL(5.0,5.0,0.0,360.0,3.0,2)
      CALL DASHLN(1.95,5.0,8.05,5.0,.2)
      CALL DASHLN(5.0,1.95,5.0,8.05,.2)
      CALL SYMBOL(4.7,8.2,.14,'NORTH',0.0,5)
      CALL SYMBOL(8.20,4.95,.14,'EAST',0.0,4)
      CALL SYMBOL(3.3,1.2,.14,'EXCLUDES WIND SPEEDS<5.0 M/S',0.0,28)
      CALL SYMBOL(4.70,1.60,.14,'SOUTH',0.0,5)
      CALL SYMBOL(1.40,4.95,.14,'WEST',0.0,4)
      CALL PLOT(0.0,0.0,-3)
      CALL BLOKNO(NNN)
      PRINT 10,NNN
   10 FORMAT(' THE BLOCK NO. IS',I4)
      CALL SYMBOL(4.20,9.50,.21,'2/76-2/77',0.0,9)
      CALL SYMBOL(3.3,9.2,.21,'HATTERAS STATION',0.0,16)
      CALL SYMBOL(3.0,8.8,.21,TITL,0.0,24)
      CALL PARROW(5.0,5.0,XN,YN,1)
      CALL PARROW(XN,YN,XNE,YNE,1)
      CALL PARROW(XNE,YNE,XE,YE,1)
      CALL PARROW(XE,YE,XSE,YSE,1)
      CALL PARROW(XSE,YSE,XS,YS,1)
      CALL PARROW(XS,YS,XSW,YSW,1)
      CALL PARROW(XSW,YSW,XW,YW,1)
      CALL PARROW(XW,YW,XNW,YNW,1)
      CALL PARROW(5.0,5.0,XNW,YNW,1)
      CALL PLOT (15.0,0.0,-3)
  999 CONTINUE
      CALL PLOT (20.0,-11.0,999)
      STOP
      END
```

## APPENDIX 4.

## EOLIAN SAND TRANSPORT MODEL

Appendix 4 contains a listing of the eolian sand transport computer program.

```
C
C     MAIN PROGRAM WHICH COMPUTES SAND TRANSPORT
      DIMENSION THETA(400,10),R(400,10),PRECP(400,10),X(15),XD(15),
     1WAT(400,10),TEMP(400)
      INTEGER DATE(400)
      COMMON SHEER,THRES,WATER,RAIN,ZO,U,GRAIN,OLDWAT,TMP,WIND,DIND
      QBAG=0.0
      QHSU=0.0
      TOTQH=0.0
      TOTQB=0.0
      WAT(1,8)=0.0
      DO 210 I=1,11
      X(I)=0.0
      XD(I)=0.0
  210 CONTINUE
      READ(5,1)N
    1 FORMAT(I6)
    7 FORMAT(' ',I6)
      PRINT 7,N
      PRINT 60
      PRINT 61
      PRINT 62
      PRINT 64
      DO 011 K=2,N
C
C     READ WIND DATA
C
      READ(5,2,END=666) DATE(K),(R(K,I),THETA(K,I),I=1,8)
    2 FORMAT(I6,16X,16F3.0)
C
C     READ TEMP AND PRECIPITION DATA
C
      READ(5,3,END=667) TEMP(K),(PRECP(K,I),I=1,8)
    3 FORMAT(F3.0,8F5.2)
  011 CONTINUE
C
C     IF SOIL IS FROZEN SKIP TO NEXT DATA CARD
C
      DO 988 K=2,N
      IF(TEMP(K).LE.31.0)GO TO 988
      DO 111 I=1,8
      IF(R(K,I).EQ.999.)R(K,I)=0.0
      IF(I.GT.1)GO TO 40
      OLDWAT=WAT(K-1,8)
      GO TO 41
   40 OLDWAT=WAT(K,I-1)
   41 CONTINUE
      RAIN=PRECP(K,I)
```

```
      TMP=TEMP(K)
      WIND=R(K,I)
      DIND=THETA(K,I)
C
C     CALCULATE SOIL MOISTURE
C
      CALL MOIST
      WAT(K,I)=WATER
C
C     COMPUTE THE THRESHOLD VELOCITY FOR THIS MOISTURE REGIME
C
      IF(DIND.LT.170.0)GO TO 21
      IF(DIND.GT.350.0)GO TO 21
      ZO=5.0
      GRAIN=.025
      C=.0002
      GO TO 23
   21 ZO=1.0
      GRAIN=.04
      C=.0004
   23 CALL THRSH
C
C     GIVEN THRESHOLD VELOCITY COMPUTE SHEER VELOCITY
C
      U=R(K,I)*.44704
      CALL SHRVL
      IF(SHEER.LT.THRES)GO TO 111
C
C     COMPUTE SAND TRANSPORT WITH HSU EQUATION
C
      QHSU=(C*((SHEER/(SQRT(980.0*GRAIN)))**3))
C
C     COMPUTE SAND TRANSPORT WITH BAGNOLD EQUATION
C
      QBAG=((1.8*(SQRT((GRAIN*10.0)/.25)))*.00000125)*(SHEER**3)
      RAIN=RAIN*2.54
C
C     PRINT RESULTS
C
      PRINT 63,DATE(K),THETA(K,I),U,THRES,SHEER,QHSU,QBAG,
     1PRECP(K,I),WATER
   60 FORMAT( 21X,38HRESULTS OF SAND TRANSPORT CALCULATIONS)
   61 FORMAT('0',12X,4HWIND,8X,4HWIND,5X,6HTHRESH,6X,5HSHEER,5X,3HHSU,
     17X,7HBAGNOLD)
   62 FORMAT(' ',6H  DATE,3X,9HDIRECTION,3X,7H  SPEED,4X,8HVELOCITY,3X
     18HVELOCITY,2X,9HTRANSPORT,2X,9HTRANSPORT,2X,4HRAIN,3X,7H% WATER)
   63 FORMAT(' ',2X,I6,5X,F4.0,7X,F4.0,5X,F6.2,5X,F6.2,2X,F7.2,4X,F7.2
     13X,F6.2,4X,F5.2)
```

```
 64 FORMAT(' ',23X,5HM/SEC,5X,6HCM/SEC,5X,6HCM/SEC,2X,
   18HG/CM/SEC,3X,8HG/CM/SEC,3X,2HCM)
 70 FORMAT(' ',28HWIND+DIRECTION DATA FINISHED)
 71 FORMAT(' ',39HTEMPERATURE+PRECIPITATION DATA FINISHED)
    QBAG=QBAG*10800.0
    QHSU=QHSU*10800.0
    IF(THETA(K,I).LE.22.5)GO TO 51
    IF(THETA(K,I).LE.67.5)GO TO 52
    IF(THETA(K,I).LE.112.5)GO TO 53
    IF(THETA(K,I).LE.157.5)GO TO 54
    IF(THETA(K,I).LE.202.5)GO TO 55
    IF(THETA(K,I).LE.247.5)GO TO 56
    IF(THETA(K,I).LE.292.5)GO TO 57
    IF(THETA(K,I).LE.337.5)GO TO 58
    IF(THETA(K,I).LE.395.0)GO TO 51
    GO TO 300
 51 X(1)=X(1)+QHSU
    XD(1)=XD(1)+ QBAG
    GO TO 300
 52 X(2)=X(2)+QHSU
    XD(2)=XD(2)+QBAG
    GO TO 300
 53 X(3)=X(3)+QHSU
    XD(3)=XD(3)+QBAG
    GO TO 300
 54 X(4)=X(4)+QHSU
    XD(4)=XD(4)+QBAG
    GO TO 300
 55 X(5)=X(5)+QHSU
    XD(5)=XD(5)+QBAG
    GO TO 300
 56 X(6)=X(6)+QHSU
    XD(6)=XD(6)+QBAG
    GO TO 300
 57 X(7)=X(7)+QHSU
    XD(7)=XD(7)+QBAG
    GO TO 300
 58 X(8)=X(8)+QHSU
    XD(8)=XD(8)+QBAG
    GO TO 300
300 CONTINUE
    IF(THETA(K,I).LT.160.0)GO TO 59
    IF(THETA(K,I).GT.360.0)GO TO 59
    X(10)=X(10)+QBAG
    XD(10)=XD(10)+QHSU
    GO TO 112
 59 X(9)=X(9)+QBAG
    XD(9)=XD(9)+QHSU
```

```
112 CONTINUE
    IF(THETA(K,I).LT.100.)GO TO 600
    IF(THETA(K,I).GT.300.)GO TO 600
    GO TO 111
600 X(11)=X(11)+QBAG
    XD(11)=XD(11)+QHSU
111 CONTINUE
988 CONTINUE
    DO 977 I=1,11
    X(I)=X(I)/10.0
    XD(I)=XD(I)/10.0
977 CONTINUE
    PRINT 90
    PRINT 91
    PRINT 92
    PRINT 93
    PRINT 80,XD(1),X(1)
    PRINT 81,XD(2),X(2)
    PRINT 82,XD(3),X(3)
    PRINT 84,XD(4),X(4)
    PRINT 85,XD(5),X(5)
    PRINT 86,XD(6),X(6)
    PRINT 87,XD(7),X(7)
    PRINT 88,XD(8),X(8)
    PRINT 89
    PRINT 99,X(9),XD(9)
    PRINT 101
    PRINT 100,X(10),XD(10)
    PRINT 102
    PRINT 100,XD(11),X(11)
 90 FORMAT('1',2X,9HDIRECTION,5X,18H(BAGNOLD EQUATION),8X,
   114H(HSU EQUATION))
 91 FORMAT(' ',16X,18HTOTAL TRANSPORT OF,6X,18HTOTAL TRANSPORT OF)
 92 FORMAT(' ',18X,13HSAND FOR YEAR,12X,13HSAND FOR YEAR)
 93 FORMAT(' ',20X,9HKG/M/YEAR,17X,9HKG/M/YEAR)
 80 FORMAT(' ',4X,5HNORTH,10X,F9.0,16X,F9.0)
 81 FORMAT(' ',4X,9HNORTHEAST,6X,F9.0,16X,F9.0)
 82 FORMAT(' ',4X,4HEAST,11X,F9.0,16X,F9.0)
 84 FORMAT(' ',4X,9HSOUTHEAST,6X,F9.0,16X,F9.0)
 85 FORMAT(' ',4X,5HSOUTH,10X,F9.0,16X,F9.0)
 86 FORMAT(' ',4X,9HSOUTHWEST,6X,F9.0,16X,F9.0)
 87 FORMAT(' ',4X,4HWEST,11X,F9.0,16X,F9.0)
 88 FORMAT(' ',4X,9HNORTHWEST,6X,F9.0,16X,F9.0)
 89 FORMAT('0',5X,38HONSHORE TRANSPORT (180-340 DEGREES AZ))
 99 FORMAT(' ',19X,F9.0,16X,F9.0)
101 FORMAT('0',5X,37HOFFSHORE TRANSPORT (0-160 DEGREES AZ))
100 FORMAT(' ',19X,F9.0,16X,F9.0)
102 FORMAT('0',3X,46HTRANSPORT ACROSS SLIPFACE (300-100 DEGREES AZ))
```

```
      SUBROUTINE MOIST
C
C     CALCULATES SOIL MOISTURE FROM PRECIPITATION,WIND AND TEMPERATURE DAT
      COMMON SHEER,THRES,WATER,RAIN,ZO,U,GRAIN,OLDWAT,TMP,WIND,DIND
      IF(RAIN.GT.0.0)GO TO 1
      XWAT=.532*((TMP*WIND)/(-100.0))
      GO TO 2
    1 XWAT=11.5 + (40.*RAIN)+((-.097)*TMP) + ((-.46)*WIND)
      WATER=XWAT
      GO TO 3
    2 WATER=OLDWAT+XWAT
    3 IF(DIND.LT.170.0)GO TO 5
      IF(DIND.GT.350.0)GO TO 5
      WATER=WATER*1.2
    5 IF(WATER.GT.0.0)GO TO 6
      WATER =.000001
    6 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE THRSH
C
C     USES EQUATION OF KADIB
      COMMON SHEER,THRES,WATER,RAIN,ZO,U,GRAIN,OLDWAT,TMP,WIND,DIND
C     CALCULATE PERCENT WATER FROM PRECIP DATA
      IF(WATER.GT..10)GO TO 15
      THRES=28.0
      GO TO 20
   15 THRES=(.1*(1.8+(.6*(ALOG10(WATER)))))*(SQRT(2359929.1*GRAIN))
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SHRVL
C     USES EQUATION OF HSU TO COMPUTE SHEER VELOCITY AT THE SURFACE
C     FROM CORROLA STATION ANEMOMETER
      COMMON SHEER,THRES,WATER,RAIN,ZO,U,GRAIN,OLDWAT,TMP,WIND,DIND
      SHEER=((U-4.0)/(ALOG(3000.0*ZO)))*40.0
      RETURN
      END
```

# VITA

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