THE UNIVERSITY OF NORTH CAROLINA
WATER RESOURCES RESEARCH INSTITUTE

Office of the Director
124 Riddick Building
North Carolina State University
Raleigh, North Carolina, 27607
Telephone: 919:755-2815

July 26, 1972

TO: WHOM IT MAY CONCERN

FROM: David H. Howells, Director

SUBJECT: Institute Report No. 69--"Some Features in the Diurnal Variation of Rain and Wind over North Carolina"--by Dr. W. J. Saucier, Department of Geosciences, North Carolina State University

This is an interim report for a study of Precipitation Variability over North Carolina which explores diurnal variations of precipitation, surface wind speed, and temperature. It includes climatological probabilities of rainfall occurrence at selected sites in North Carolina.

Recommendations from potential users as to areas in need of clarification and elaboration to better meet their requirements are solicited to guide subsequent phases of the study.

DHH:va

UNC-WRRI-72-69

SOME FEATURES IN THE DIURNAL VARIATIONS OF RAIN AND WIND OVER NORTH CAROLINA

By

W. J. Saucier
Professor of Meteorology
Department of Geosciences
North Carolina State University
Raleigh, North Carolina 27607

The work upon which this publication is based was supported in part by funds provided by the Office of Water Resources Research, Department of the Interior, through the Water Resources Research Institute of the University of North Carolina as authorized under the Water Resources Research Act of 1964.

Interim Report No. 1

Project No. A-061-NC
Agreement No. 14-31-0001-3533, F. Y. 1972

June 1972

ACKNOWLEDGEMENTS

This study was performed in part through support provided by the Water Resources Research Institute of the University of North Carolina from both state and federal funds.

A. V. Hardy, NOAA State Climatologist for North Carolina, kindly provided copy of data employed in this investigation, and also assisted throughout the course of the study in readily supplying information desired on the sources and the nature of the data.

Some of the ideas on the seasonal and diurnal variations, especially those of the winds, were initiated while performing various related meteorological studies under part-time appointment with the Environmental Sciences Department, Engineering and Environmental Sciences Division, Research Triangle Institute. Valuable discussions came through interests of scientific staff of that department (J. R. Smith, W. D. Bach, F. M. Vukovich) in those vital aspects of the regional environment.

All of the above assistance in developing this report is gratefully acknowledged.

ABSTRACT

An exploratory study is made of the diurnal variations of precipitation occurrence and of surface wind speed from summaries of hourly observations during the decade 1951-1960 at U.S. Weather Bureau (now National Weather Service) airport stations in and neighboring North Carolina. The breadth of possible public interests in these topics urged a compromise of technical and popular modes of presenting this study.

Results are presented in the form of climatological probabilities of rainfall occurrence for each hourly period of the day in four months (January, April, July, and October) for nine sites in the region, including Cape Hatteras. Geographic patterns of these diurnal trends in hourly rain occurrence are given for the month of July in two categories of rainfall amounts during the hourly intervals, namely, measurable rain and quarter-inch rain. Significant geographic variations are found.

Diurnal variations of surface wind speed are presented and analyzed for those four months at the coastal and piedmont stations. The most prominent feature resulting is the tendency for winds from south-southwest and those from north-northeast, the two modal directions for the region, to have radically different and in certain respects reversed diurnal trends of wind speed. This is evident inland and also at the marine location of Hatteras. These are related to diurnal changes in the temperature pattern of the atmosphere's boundary layer under the differing controls by the continental and marine surfaces. Impacts on other weather elements locally and on the various processes and activities in the biosphere remain to be explored.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY AND CONCLUSIONS

Value of weather and climate information is what the user makes of it. Uses are as diverse as the interests and activities of mankind in adapting beneficially to his earthly environment, that is, man's geophysical ecology. Frequently he is unaware of useful information existing, how it bears on his specific problems, and what articulation is needed to realize value. Meteorological resources can be available well beyond awareness of the spectrum of needs for them to the economic benefit and public progress. In service to the broad consumer with information so naturally sensitive and complex, meteorology has acknowledged limitations in serving everybody with everything. So it is that potentially valuable information on the atmospheric environment to one segment of society often goes unused in the realistic want of communication--or of cognizance of values--between supplier and ultimate user.

The information given in this report is in many respects an example in point. The data employed have been available for years in published form. All that was done by this modest study was to analyze those for a geographic region and to attempt interpretations for potential uses, particularly as background in various water resources applications, in some ignorance of the breadth of interests and the depth of utility in all cases. A purpose in providing this preliminary information, which is presently limited in basis and crude in potential uses, is to sound perspectives and generate dialogues among investigators and users of such weather information for planning efficient future courses of study. That work is therefore by no means complete. Further, this report summarizes only a small part of the investigations proceeding under the Water Resources

Research Institute project with which author and work are identified. Because this segment was easily detachable in both purpose and public appeal, it is provided as a separate technical report without summarizing other research findings of the project to date. In this context, the usual sections of a report dealing with summary, conclusions, and recommendations assume modified meaning.

Measurable rain occurs on the average about one day in three. That frequency varies with the season, being higher in the summer and lower in the autumn. Within any season or month there are geographic variations across the region in the frequency of rain days, and those are expected to be more pronounced the shorter the time frames considered. The average rainfall per rainy day is, on the whole, somewhat higher in summer than in other seasons. But the upper piedmont and eastern mountain areas of North Carolina differ from this general pattern in having more rain per rainy day in winter (or early spring) than in summer.

Generally between four and eight percent of the hourly weather reports give measurable rain in the preceding hour. On the whole about an equal additional number of hourly intervals during which rain was reported accumulated less-than-measurable amount in the hour. Rainfall intensities, as determined from dividing the monthly rainfall total by the number of hourly reports during the month having measurable rain, average about 2.5 times as large in summer as in winter, and the transitional seasons are nearer to winter in this respect. For measurable rain amounts, the number of rainy hourly intervals per rainy day is about six in winter and three in summer. In these figures there are some distinct geographic variations with latitude and even more with distance from ocean and mountains. In statistics such as rainfall the variance is expected to grow rapidly as length of time period considered is decreased.

The principal element sought and presented is the diurnal variation in rainfall occurrence, as indicated by percentage frequencies of rain observed in each of the 24 hourly intervals of the day. These climatological probabilities of measurable rain during the hour are given for four months of the year (January, April, July, and October) for nine National Weather Service stations in the region. These bring out the extent of the diurnal variation in rain frequency as well as dependence on season and geography. The most distinct diurnal cycle is that in the warm season rain, and it differs distinctly from western to eastern North Carolina. Geographic patterns of hourly rain occurrence as function of the clock in July are presented for measurable rains and also for quarter-inch per hour rains. Because of the large diurnal variations in evaporation from the surface in the summer, the peculiar diurnal patterns in rain occurrence are expected to have decided impacts on the assessments of runoff and infiltration from daily, weekly, or monthly raingage measurements.

The second part of the report, dealing with diurnal variations in surface wind speeds, finds a wider set of public interests and, so far, a less clear and weighty role in water resources. Because winds are one of several interdependent factors in such important processes at and near the surface interface as evaporation, fog and dew and frost formation, cooling rates of water bodies, and the transport and diffusion of effluents, it was decided to add this interesting phase of local weather. There are expected to be relationships both statistical and physical between the diurnal variations of rain and of wind patterns, but no attempt was made to examine those here.

The significant finding is that, in addition to the known general diurnal variation of wind over land due to the much larger diurnal temperature range at the surface than in levels above, in this region east of the Appalachians there is an added component of wind variation ascribed to diurnal oscillation in the horizontal distributions of temperature and mass of the lower atmosphere arising from the less variant surface temperatures of the ocean than of the continent. That added effect is direction dependent, controlled by physiography, so that diurnal variations in wind speed are more pronounced when winds blow with ocean to the right (southerly winds) than from the opposite direction. The differing effects are most apparent with clear skies over land. Southerly flow at the surface has large drop in speed from the afternoon high temperature of land to the low temperature near sunrise. In comparison, northerly flow has somewhat reduced afternoon speeds but augmented early morning speeds. This effect appears over the piedmont, the coastal plains, and some distance at sea. An analysis was made of this phenomenon at Cape Hatteras, the site for which there were individual monthly summaries of wind by clock hours readily available.

There are various natural impacts of direction dependence in the diurnal pattern of wind speeds, some known and others unknown. There are implications to short-period weather forecasting, in regard to the surface winds as well as the detailed conditions attending them. There are ramifications to a host of human activiites on the land, at the coast, and nearshore at sea, all of which are beyond the scope of this initial presentation.

RECOMMENDATIONS

In some parallel with the intent of this report, more questions are raised than are resolved. The purpose was to describe some important elements of weather which bear in various ways on man's quest for either improved adaptations to nature or modifications of nature according to his desires.

The study reported is incomplete intentionally, for it is based on limited periods of readily available data in summary form, minimum effort could be devoted specifically to this task, and the report was issued early in order to ascertain priorities for further investigation before proceeding far along any line. Doubts can be raised on the statistical significance of results pertaining to minor-duration rainfalls in the limited samples employed here, when in reality one very abnormal year can bias statistics of many years. This and other aspects might merit more attention to serve as basis for intelligently planning water systems and uses or deciding courses of other research in the hydrologic cycle over land.

It appears that rainfalls of summer and of winter can be rather clearly typified with due allowance for the geography, and hence they are subject to meaningful descriptions or models from simplified approaches in data analysis. Little is said in this report about the variations occurring in spring and autumn, although those are recognized to bear as well on agriculture and water supply. It is believed that descriptions of transitional season rains will merit some kind of classification into those of winter and summer circulation types, and perhaps also into some which may be peculiar to spring or autumn.

The wind data employed did not permit the kind of analysis needed to assess the role in evaporation, which is a complex of weather elements. Nor were those wind data of form adequate to describe the full nature of the diurnal wind patterns under different flow regimes. The latter deserves more detailed description in contexts other than water resources research, for instance, in matters of the transport and dispersion of air pollutants, the likely impacts of cooling lakes and towers on the natural environment, and even the water circulation in estuaries and sounds.

The major recommendation made by this preliminary study is that of seeking recommendations from potential users of the information on aspects in need of clarification or elaboration for their particular uses. More meaningful results then can be obtained from the larger amounts of data already on record.

DATA SOURCES

In 1963 the U. S. Department of Commerce published a series under Climatography of the United States No. 82 which was entitled Decennial Census of United States Climate--Summary of Hourly Observations, 1951-1960, for various airport weather stations. Included in the series were stations in North Carolina (No. 82-31), South Carolina (No. 82-38), and Virginia (No. 82-44). The data were presented in five tables for each month of the year: Table A, Temperature and Wind Speed - Relative Humidity Occurrences, by intervals of temperature, humidity, and wind speed; Table B, Percentage Frequencies of Direction and Speed, by 16 wind directions and nine intervals of speed; Table C, Occurrences of Precipitation Amounts, by hour of day and intervals of rain intensity; Table D, Percentage Frequencies of Ceiling-Visibility, by intervals of cloud ceiling and horizontal visibility; and Table E, Percentage Frequencies of Sky Cover, Wind, and Relative Humidity, by hour of day, three intervals of cloud cover, four intervals of wind speed, and six intervals of relative humidity. Only Tables B, C, and E were employed for the analysis which follows.

Data for the following stations will be discussed here: Raleigh (Raleigh-Durham Airport), Greensboro (Greensboro-High Point Airport), and Charlotte (Douglas Municipal Airport) in North Carolina; Richmond (Byrd Field) and Norfolk (Municipal Airport) in Virginia; and Columbia (Columbia Airport) and Charleston (Municipal Airport) in South Carolina. For three of the stations (Norfolk, Columbia, and Charleston) the hourly rainfall data were for only the second half of the decade, 1956-1960. There was no such publication for Cape Hatteras. However, for that Weather Bureau station summaries were available for each month in the ten years 1953-1962, and in the course of this study those were compiled for presentation in form similar to the airport stations above. An earlier publication (Climatography of the U. S. No. 30-31, Summary of Hourly Observations) contained tabular data for Asheville (Asheville-Hendersonville Airport) summarized for the five-year period March 1950 to February 1955.

Because of the shorter data periods in the rainfall summaries for Asheville, Norfolk, Columbia, and Charleston, their results are not wholly compatible with the other stations. To some extent this reservation applies also to the Hatteras data, which covered a different 10-year period and also lacked hourly rainfall tabulations for a few individual months.

The decennial census summaries cited above were compiled primarily as a climatology of airport weather conditions affecting aeronautical operations. As such they have limitations in other objectives to which one might want to apply them, for example, in hydrologic investigations or interpretations. A deficiency in discussing diurnal variations of surface winds arises from the lack of tabulations of wind directions as function of hour of day. Nevertheless, the information at hand is useful for detecting certain interesting variations in weather and climate, which insight is capable of articulation by recourse to the detailed weather records. The purpose here is an overview of the data to bring out some immediate facts of public interest.

SOME SUMMARY STATISTICS ON DAILY AND HOURLY PRECIPITATION

Table 1 presents a summary of the observations of precipitation for the decade 1951-1960 in the four months January, April, July, and October, which more or less typify the four seasons. Except in part (c), the information pertains to measurable precipitation, that is, occurrences of 0.01 inch or more during a specified time interval, when rounded to the nearest hundredth of an inch. Less than 0.005 inch is defined as a trace of precipitation. In the discussion which follows the word precipitation implies this measurable amount unless otherwise specified. Parts of the cold season precipitation are in form of snow or ice, but those had been converted to liquid equivalents in the original data, and with this understood we may then refer loosely to all precipitation as rainfall, real and equivalent, in respect to water substance deposited on the surface.

Table 1(a) indicates that, on the whole, rainfall days are about one in three for this geographic region. Upon this average there are significant variations of phase depending on the latitude, the distance from the coast, and also the topography, and there are appreciable variations in rain-day sequences. Our choice of only four months of the year reduces

Table 1. Statistics on Precipitation Frequencies and Amounts (1951-1960; January, April, July, October)

(a) Percent of Days with Measurable Precipitation, ⩾0.01 in.

(b) Average No. of Hourly Reports per Month with ⩾0.01 in. in Preceding Hour

(c) Percent of the Hourly Reports with Precipitation in the Preceding Hour which were only Trace, <0.005 in.

Station	(a) J	(a) A	(a) J	(a) O	(b) J	(b) A	(b) J	(b) O	(c) J	(c) A	(c) J	(c) O
Norfolk*	32	31	41	33	64	43	43	64	49	49	48	51
Hatteras**	33	31	34	32	71	36	42	54	40	46	43	45
Charleston*	29	23	46	28	59	31	48	53	44	50	50	55
Richmond	34	35	34	25	59	52	35	46	51	49	54	52
Raleigh	29	31	35	22	53	50	37	41	52	46	52	57
Greensboro	32	35	37	26	59	54	33	44	52	48	54	59
Charlotte	29	34	37	23	59	51	34	39	46	43	52	55
Columbia*	32	30	39	31	63	46	41	54	43	42	47	56
Asheville***	35	34	43	21	51	37	38	23	70	65	54	59

(d) Average Precipitation (in.) during Days Having ⩾0.01 in.

(e) Average (in.) during Hours Having ⩾0.01 in.

(f) Ratio of (b) to No. of Rainy (⩾0.01 in.) Days per Month

Station	(d) J	(d) A	(d) J	(d) O	(e) J	(e) A	(e) J	(e) O	(f) J	(f) A	(f) J	(f) O
Norfolk*	.27	.32	.41	.45	.04	.06	.12	.07	6.4	4.7	3.4	6.3
Hatteras**	.49	.46	.58	.45	.07	.12	.14	.08	6.8	3.8	3.6	5.4
Charleston*	.35	.40	.69	.47	.05	.09	.21	.08	6.5	4.4	3.4	5.9
Richmond	.26	.33	.50	.46	.05	.07	.15	.08	5.4	5.0	3.4	5.9
Raleigh	.38	.42	.49	.42	.06	.08	.15	.07	5.9	5.4	3.4	6.3
Greensboro	.35	.38	.37	.39	.06	.07	.13	.07	5.8	5.2	2.9	5.6
Charlotte	.38	.40	.33	.33	.06	.08	.11	.06	6.6	5.0	2.9	5.4
Columbia*	.37	.44	.54	.46	.06	.07	.16	.08	6.3	5.1	3.4	5.6
Asheville***	.36	.28	.28	.24	.08	.08	.10	.07	4.8	3.6	2.9	3.6

*Five years, 1956-60.
**Hatteras, 10 years 1953-1962, less January 1958-59, April 1957-58, and July 1958.
***Asheville, five years, March 1950-February 1955.

somewhat the indicated ranges of seasonal variation and also partially obscures the phases of those variations. Table 1 is not intended to portray the details of seasonal and monthly variances in rainfall, but rather is to present background information for interpreting the diurnal patterns of rainfall to be presented.

The January rain days shown range from 29 to 35 percent, and perhaps part of that range arises from a combination of different data periods and long term variations in winter rain-day frequencies. October rain days average less frequent, but the geographic range in frequency is about double that of January. Further, the autumn season is the most unreliable in monthly rainfall.

The summer rains on the other hand, being more convective and localized in nature, might have been expected to show greater range in rain-day frequencies over the region in some accord with the physiographic influences. The range in rainy days in July among the stations is large, from 34 to 46 percent, but when converted to percentage range about a mean the geographic variation for July is smaller than in the transitional seasons represented by April and October. It is interesting that generally the coastal and mountain stations have more rain days in July than do the piedmont locations between. Cape Hatteras might stand out as an exception, but in terms of the physiographic controls on convective rain systems that site is marine rather than coastal. Coastal effects on summer showers are expected to be more pronounced some distances west and northwest of Hatteras.

An interesting feature of the April pattern in Table 1(a) is the general northward and inland increase in rain-day frequency. The figure shown for Raleigh (31 percent) is somewhat deficient in this distribution, and information to be given later shows that in the warm season Raleigh is more maritime in rain regime than its distance from the coast might suggest. In April the differences in surface temperature from ocean to land are near the annual low. Convective activity attending the weather systems ordinarily propagating seaward in this season thus is reduced upon reaching the coastal areas. Another factor is more global in nature. The subtropical "belt of high pressure" which inhibits or suppresses rainfall is farthest south in winter, over the West Indies and Florida. Its northward march in the spring induces "dry April" in southern South Carolina and later relatively rain-deficient periods in eastern North Carolina. The southward retreat in autumn is evident too, but more irregular and discontinuous.

Table 2 is given for purposes of comparing rain-day frequency in this region with other locations in the conterminous United States, especially in respect to interpretations that one might make of rain days in relation to various biological and economic activities regionally. The data in Table 2 are from the same source and for the same decade as Table 1. A difference in the tabulations presented is that the columns in Table 2 are averages over three months (DJF = December, January, February, etc.), and are therefore smoothed in comparison with Table 1.

A striking result is that the region of North Carolina is quite average in percentage of rain days, and also has considerable uniformity in rain-day distribution through the year. Some regions have extreme seasonal rain-day dependencies (for example Portland, Tucson, Miami) compared to the Carolina area of the eastern states. These results should not be

Table 2. Percent of Days with Measurable Precipitation by Three-Month Periods, 1951-1960, at Selected Stations in the United States

Location	DJF	MAM	JJA	SON
Portland, Ore.	65	48	18	40
Tucson, Ariz.	7	3	13	3
Houston, Texas	30	25	27	26
Minneapolis, Minn.	24	33	36	26
Indianapolis, Ind.	37	42	31	26
Nashville, Tenn.	39	37	27	24
Birmingham, Ala.	35	32	32	25
Miami, Fla.	22	26	47	48
Raleigh, N. C.	30	32	32	24
Boston, Mass.	39	41	34	33

generalized in any simple translation to obtain measures of rainfall amounts, or dependabilities in rain occurrences annually or within a season, for those relationships to the numbers presented are quite varied by season and location. For example, the eastern Great Lakes and New England region is known to be most reliable in annual rainfall amounts, and also has less interseasonal variance in rainfall than in regions to the south.

Table 1(b) gives the number of hourly periods per month during which measurable precipitation occurred. April is 720 hours in duration, and the other months listed are 744 hours each. The tabulated figures range from 23 to 71 hourly intervals per month with measurable rain, or 3.0 to 9.5 percent of the clock hours accumulating measurable rainfall. In this respect one is dealing with very small numbers. Precipitation of hydrologic significance is a rare occurrence everywhere in the region. Of course, it is this weather event so minor of duration which gives life to land.

The number of hourly intervals with measurable precipitation is high in January, when it averages about two per day, and this drops by almost half to July. The rainfall hours at the coast exceed those of the piedmont area by roughly 25 percent in summer. There is tendency of that sense also in October, but it reverses in April.

Table 1(f) provides a comparison of the data in Tables 1(a) and 1(b), namely, the ratio of the number of hourly intervals with rain to the number of rain days per month, in all cases excluding those hours and those days of only trace amounts deposited. Instances of light rains continuing for several hours at trace intensities per hour can accumulate more than 0.01 inch in a day and contribute to reduce the ratios in Table 1(f). If allowance is made for them, the ratios are increased by larger amounts in January than in July. On the other hand the hourly periods with measurable rain tend to be larger than the actual durations of rains, especially in the case of showers. Allowance for this in seeking measures of rain durations merits reduction of the warm season figures in Table 1(f) relative to the others.

Rains in July of rates 0.01 inch or more between hourly observations average about three hourly reports per rainy day in the upper piedmont and about a half hour longer in the eastern areas. The full significance in this geographic difference in duration of summer rains remains to be determined. Generally the winter ratios are about twice as large, that is, rains are twice as long. The values for April and October are little lower than those of January, except that April has lower values at coastal locations than inland. Because of Asheville's location in irregular terrain and its data being from a different period, there is hesitancy in drawing positive interpretations from its results. The overall closer agreement of April and October in this ratio with January than July is partly due to slower moving rain systems in the transitional seasons than in midwinter, although the systems are larger in area and of more uniform intensities in the winter.

A measure of the number of hourly observations with only trace amount deposited in the preceding hour is afforded by Table 1(c), which gives the percentage of hourly trace occurrences among the total hourly periods in which any precipitation was observed. From the information in Tables 1(b) and 1(c), one may obtain the average number of hourly intervals per month with observed precipitation whether or not measurable, by the following procedure: Subtract from 100 percent the value given in (c), divide that decimal difference into the value in (b), and the quotient is the number of monthly hour periods during which precipitation was observed. For example, at Greensboro in January that number is 59/0.48 = 123 hourly observations per month which showed precipitation of any form or duration in the preceding hour.

The data in Table 1(c) represent a weather element which is sensitive to continuous monitoring of weather conditions and to the peculiarities of the sites both natural and man-modified. The uniformity in the results is therefore remarkable. On the average about half of the instances of precipitation observed in the preceding hour are below the threshold of measurement by raingages. Some of those occurrences are very light rains lasting several hours and accumulating more than 0.01 inch in a day. Other are the passing "false starts" which accumulate no more.

It is of interest to note the departure between the percent of hourly trace rains as given by Table 1(c) and the percent of rain days which recorded only trace. The latter, obtained by computing the ratio of the number of days with trace precipitation to the total number of days with precipitation, is generally 0.6±0.1 as large as the corresponding ratio for hourly periods. Stated inversely, an onset of precipitation is almost twice as likely to yield only a trace in a one-hour period as it is to end up only a trace for the day. Median values in this factor tend slightly larger in the warm season than in the cold season, about 9/5 in July compared to 8/5 in January, for most of the region; the southern stations suggest a seasonal trend slightly in the reversed sense. Meteorological interpretations will not be advanced here. These relationships are significant in relating precipitation events to raingage records, in assessments of surface evaporation from rainfall accumulations, and even in the impact of wetting on plant processes. Other significances of trace precipitation at the ground, especially in the warm part of the day, lie in the attendant cloudiness and also in the high proportion of the rain which evaporated before reaching the ground for measurement and so modified both temperatures and humidities of the life-environment lower atmosphere.

Table 1(d) presents the average depth of precipitation collected in a day during which measurable precipitation occurred, obtained from dividing the total monthly amount by the number of days having measurable amounts. When this is compared with Table 1(f), dispersions in event-duration-depth relations are found, some of which were anticipated and others not. The generally smaller daily rains in winter result from the low precipitation rates offsetting the long durations. The winter fields of temperature and humidity would suggest decreases in rain per rainy day from the coast inland and also from south to north. Charleston and Columbia appear deficient in this presumed pattern; yet both stations had higher January rainfall over those five years 1956-1960 than in the preceding five years which were omitted from the tabulation. Evidently an "activity field" exists in addition to the fields of temperature and humidity.

In general the daily rainfall rates are higher in the warm season. But the North Carolina piedmont area is anomalous in this respect. Greensboro has surprisingly uniform figures for the four months, and Charlotte appears to decrease in rain per rainy day from April to July. Apparently summer showers are somewhat stunted, and April showers invigorated, in this upper piedmont area.

Table 1(e) for the most part is as expected in the average intensities per hourly period during which measurable rainfall was observed. Again the North Carolina piedmont area appears somewhat deficient in the warm season. Overall the figures are two to three times as large in July as in January. If due allowance is made for the shorter durations of July rains, many of which are less than one hour in length but are counted in two hourly intervals, the ratio of July to January rainfall rates is raised correspondingly.

In the period 1956-1960, to which the Charleston, Columbia, and Norfolk data apply, the July rainfall at Charleston averaged about 25 percent above normal and that at Columbia about 18 percent above normal. The oddly high

July values in Tables 1(d) and 1(e) particularly for Charleston are likely biased by such anomalous rainfalls.

The information presented in Table 1 is of preliminary nature and is intended to serve only in preview. The rather short periods involved, and expecially their nonuniformity, leave some doubts as to statistical significance. Also, since only the averages are presented in the data of each station, the important characteristic of variance in precipitation at individual sites is left obscured. Those details remain to later investigations. Hopefully a value to be gained from Table 1 is its suggestion of directions for useful further investigations.

DIURNAL VARIATIONS IN PRECIPITATION OCCURRENCE

The above-referenced Decennial Census publications gave for each month the tabulations of occurrences of precipitation in the preceding hour for the 24 clock hours of the day, for the following intervals in inches: Trace, 0.01, 0.02 to 0.09, 0.10 to 0.24, 0.25 to 0.49, 0.50 to 0.99, 1.00 to 1.99, 2.00 and over, and Total. Summarized in Table 3 are the occurrences of 0.01 inch or more, that is, the Total occurrences less the Trace occurrences. Those were converted to percentages of occurrence through division by the number of observations for each clock hour aviation weather report. The results then give a climatological probability of measurable rain occurring during the hour preceding the reference time.

It should be noted here that during the decade of data employed, 1951-1960, the record time of hourly observations was changed from every hour on the clock half-hour to every hour on the clock hour. That change effectively smoothed the interhourly variances in the data summaries. During months of significant diurnal variation of precipitation brought about by the diurnal

Changes in Times of Sunrise and Sunset (minutes) over the Course of the Calendar Month, at 35N Latitude

	Jan	Apr	July	Oct
Sunrise	-8	-37	+19	+25
Sunset	+28	+23	-14	-36
Sunlight Period	+36	+60	-33	-61

cycle of the sun, there is also smoothing introduced by changes in the solar period relative to the clock over the course of the month. Those sun-clock shifts are indicated above for latitude 35N. All figures increase in magnitude northward. Time measured from sunrise, the beginning of the daily solar heating, gains more than half an hour relative to the clock in April but just a few minutes in January. On the other hand, sunset delays by almost a half hour in the course of January and less in April. There are other shifts in sun relative to clock during other months which are combined effects of the Equation of Time and of seasonal course in the sun's declination.

Table 3 presents the hourly percentages of measurable rainfall occurrence, in these four months of the year at eight of the stations. The data for Asheville are presented separately as Table 3a. The last column of figures is the average for all of the 24 hours, and it corresponds directly to the information in Table 1(b). Those values are most consistent among stations in winter and summer, when the percentage occurrences average highest and lowest, respectively. In viewing the interhourly variations at individual stations in Table 3, and in comparing those among the stations, the reader should recall that short periods of data involving such a relatively rare occurrence as measurable hourly rainfall can produce some

Table 3. Percentage Frequency of Occurrence of ≥0.01 in. Rain during the Hour Ending at (E.S.T.):

	01	02	03	04	05	06 a.m.	07	08	09	10	11	12	13	14	15	16	17	18 p.m.	19	20	21	22	23	24	Av.
JANUARY																									
Norfolk*	8	8	10	11	10	11	8	9	8	7	8	9	9	6	8	9	10	8	8	9	6	8	8	10	9
Hatteras**	10	11	9	11	8	11	10	11	10	11	10	11	10	8	7	9	10	10	8	8	7	7	10	10	9
Charleston*	7	9	10	11	10	10	8	8	10	9	11	12	9	6	8	6	7	8	4	4	4	6	5	6	8
Richmond	8	8	9	9	8	9	9	9	9	8	8	8	8	8	7	7	7	6	7	7	7	7	7	8	8
Raleigh	8	8	8	8	8	8	7	7	7	8	8	7	6	6	6	6	6	6	6	7	7	8	7	7	7
Greensboro	8	8	8	8	8	9	10	9	8	8	7	7	6	6	5	5	6	8	9	8	8	8	8	8	8
Charlotte	9	8	8	8	8	8	8	9	8	8	8	8	7	7	6	6	7	8	9	9	9	8	8	8	8
Columbia*	12	10	8	10	8	10	12	10	10	7	7	9	7	6	6	6	6	5	7	7	8	8	10	12	9
APRIL																									
Norfolk*	5	5	5	8	8	7	7	6	5	7	7	7	5	1	7	5	6	7	5	5	9	6	6	5	6
Hatteras**	7	5	6	6	6	8	4	5	4	6	6	6	4	4	3	4	4	4	5	5	4	5	4	5	5
Charleston*	4	6	4	6	5	5	3	3	3	4	4	4	7	6	8	3	3	2	3	3	4	3	4	4	4
Richmond	8	7	7	8	8	8	9	8	6	5	5	4	5	7	5	8	10	8	9	8	7	8	8	7	7
Raleigh	8	9	9	8	7	8	4	5	4	3	3	6	6	6	7	7	8	8	7	8	10	8	8	8	7
Greensboro	10	7	8	7	7	6	7	8	7	5	5	8	8	7	7	8	7	8	9	8	9	8	7	9	8
Charlotte	7	8	8	7	7	8	9	7	7	7	7	5	7	8	5	7	8	9	8	7	5	7	6	7	7
Columbia*	6	6	5	5	5	5	5	7	7	5	7	5	7	4	7	7	9	9	6	6	6	8	7	7	6
JULY																									
Norfolk*	4	4	4	5	5	5	4	1	3	5	4	5	7	8	9	9	9	9	11	9	9	3	6	5	6
Hatteras**	6	6	7	8	8	8	6	4	5	4	4	5	5	5	6	5	6	6	8	8	5	5	4	4	6
Charleston*	3	5	4	4	3	4	5	4	1	4	7	7	7	9	13	14	14	9	10	11	9	5	5	3	7
Richmond	4	4	4	2	3	4	2	1	2	3	3	4	4	4	6	7	9	8	8	8	7	5	7	5	5
Raleigh	3	3	4	3	4	5	5	4	3	1	1	2	3	3	5	8	6	10	9	10	8	7	8	4	5
Greensboro	5	2	2	5	4	3	2	2	1	1	2	4	5	5	5	5	10	8	9	7	7	5	4	5	5
Charlotte	5	3	5	3	1	2	1	2	3	3	2	4	3	5	5	5	8	10	9	8	6	6	6	6	5
Columbia*	3	3	5	3	3	2	2	3	4	5	4	5	8	8	8	5	9	7	8	9	10	8	7	7	6
OCTOBER																									
Norfolk*	10	8	9	12	11	10	10	10	6	7	10	6	8	8	7	9	10	8	6	8	7	7	9	8	9
Hatteras**	9	8	9	7	4	6	7	7	8	6	6	7	6	6	8	8	7	6	6	6	8	8	9	9	7
Charleston*	6	8	10	10	9	8	8	6	8	8	7	8	7	4	5	8	8	6	6	5	4	4	5	8	7
Richmond	5	6	7	6	8	8	8	7	7	7	6	5	5	6	4	5	5	6	6	6	5	7	5	7	6
Raleigh	7	6	8	7	6	6	5	7	6	6	5	4	5	3	4	4	4	5	6	5	5	4	5	5	6
Greensboro	7	7	8	8	9	8	7	7	4	4	4	4	5	4	4	4	5	6	6	7	6	5	6	6	6
Charlotte	6	6	6	6	5	7	7	7	6	6	5	4	3	3	4	4	5	4	6	5	5	3	4	5	5
Columbia*	10	9	8	7	6	3	6	4	5	7	7	7	8	6	6	8	9	6	9	8	7	8	7	8	7

*Five years, 1956-60.
**Hatteras, 10 years (1953-62), less January 1958-59, April 1957-58, and July 1958. Other stations 10 years 1951-60.

Table 3a. Table 3 Data for Asheville (March 1950-February 1955)

	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Av.
JANUARY	7	6	8	10	6	6	7	9	7	6	7	5	7	5	3	3	6	5	5	7	7	8	12	10	7
APRIL	4	6	7	6	6	3	5	4	5	3	3	3	3	6	6	6	6	5	6	8	7	9	6	5	5
JULY	5	4	4	1	3	3	2	4	4	5	4	5	4	10	10	12	11	6	7	7	3	4	3	4	5
OCTOBER	4	3	5	3	3	2	3	3	5	3	3	3	1	3	5	4	3	3	2	2	3	4	4	4	3

misleading irregularities in the hour-to-hour trends, and the round-off errors in computation are then exaggerated. It is suggested that the figures given in the table be subjected to smoothing accordingly. The need is made evident on comparing the diurnal series of the ten-year stations with those of the five-year stations. In obtaining Tables 3 and 3a, the occurrences were smoothed over three consecutive hourly intervals with double weight given to the central one, but in some instances even that is insufficient.

The diurnal variations in precipitation occurrence reveal a cool season (January) pattern and a markedly different warm season (July) pattern. The transitional seasons (April and October) are composites of some cool season rain systems, of some warm season systems, and also of rain systems which are rather unique to the spring and autumn, notably the instances of organized advancing lines (squall lines) of thundershowers in spring and, in contrast, the slower moving bands of steady rain in autumn which are often local of presence.

The January diurnal pattern is characterized mainly by a nocturnal maximum in rainfall occurrence and a mid-afternoon minimum. That is quite the inverse to the diurnal trend of surface temperatures, and so discounts cause by convection from surface heating. Yet there are apparent geographic differences in this simple cycle. The coastal stations have high incidence extending well into the forenoon and also have a secondary peak period near dusk. That dusk peak vanishes from the coast inland to the lower piedmont, where it is then that the minimum likelihood of rain occurs (Richmond, Raleigh, Columbia). The upper piedmont region (as indicated by Greensboro, Charlotte, and Asheville) has a late afternoon and early evening pattern somewhat in phase with that at the coastal stations. Although the diurnal ranges in January are small and therefore the geographic differences are small also, it is interesting that the lower piedmont anomaly exists at all.

In July when diurnal variations in rainfall are of largest amplitude there are also appreciable geographic patterns superimposed. At most stations there is a late afternoon to early evening peak occurrence of rain, mostly of the shower type in this season, and a minimum in the forenoon. The phases vary somewhat over the region. Charleston, having a large diurnal range, peaks early, in mid-afternoon, and appears to have secondary peaks in addition, one of early evening and another after sunrise. The peaks at Columbia, Raleigh, and Greensboro occur somewhat later than at other piedmont stations, and the Asheville data indicate a mid-afternoon peak for the eastern mountains similar to Charleston. Near sunrise there are appreciable disparities over the piedmont. Raleigh has a prominent secondary peak near 0600 EST, when Charlotte, Columbia, and Asheville are minimizing for the day, and Raleigh's forenoon minimum is consequently delayed compared to those other stations. Richmond and Greensboro have somewhat intermediate trends in those morning hours.

The smallest diurnal variation is, as expected, at the most marine of the stations, Cape Hatteras. It has an appreciable range nevertheless, with two peaks, one before and near sunrise and another near sunset, in phase with Raleigh's diurnal pattern. The forenoon hours and late evening are the least rainy. Evidently summer showers are not completely controlled by the diurnal cycle of surface temperatures, nor by humidities of the lower levels. There are other mechanisms at work in geographic scales of the order of a hundred miles or more.

Before going into more detailed description of the summer pattern, we remark on a few points concerning the April and October profiles, in some difficulty of interpreting or explaining all of their features. There is subnormal rain occurrence at Charleston in April, when the diurnal phases also differ from other seasons. In October the diurnal trend at Hatteras differs from the other coastal stations, Columbia's pattern differs from Charleston's, and Charlotte and Asheville have different phases of diurnal variation. Those disparities hardly result entirely from differences in data periods or from the short periods employed. There must be some elements of reality in them.

The July profiles in Table 3 are presented with better geographic resolution in Figure 1, which contains time-distance sections extending Asheville-Charlotte-Raleigh-Hatteras and Charleston-Columbia-Charlotte-Greensboro-Richmond-Norfolk, and gives frequencies of hourly measurable-rain occurrences as function of time of day. The units of frequency are the number of days per month in which measurable rain occurred during the hour centered at the time indicated. These numbers were obtained from each station's hourly array of frequencies, already smoothed three-hourly by the method previously described, by merely further averaging those frequencies over two-hour periods. Consequently these are weighted four-hour averages. The purpose in smoothing is to reduce the variance in a series which arises from limited sampling. The process reduces also the real nonlinearities of peaks and dips in a profile in an inverse proportion to the period they span. Further, an event reported at a given time influences the results for 1.5 hours before and also after that time by the particular averaging.

The outcome is rather dramatic. The dominant feature in July is the peak frequency of rainfall in afternoon or early evening. Among these stations it appears earliest at Asheville and Charleston, two to three hours later at Charlotte, and yet another hour later at Raleigh and Hatteras. Oddly it is about three hours later at Norfolk and Hatteras than at Charleston, all stations on or near the coast. Richmond and Greensboro peak at the time of Charlotte, or just slightly earlier. Columbia's phase is somewhat different from the stations surrounding it, which is hardly all attributable to the short data period of five years and must reflect some reality. The afternoon diurnal peak is highest at Charleston, Asheville, Norfolk, and Charlotte, in that order, and lowest at Hatteras.

A second diurnal maximum of rainfall occurrence comes in the morning hours at the eastern stations, most notably at Hatteras where it centers at 0400 to 0500 EST as the principal diurnal peak. It diminishes in prominence toward Norfolk and Charleston, possibly in part due to shorter data periods. Its westward extension is evident at Raleigh and Greensboro, both well inland, and is less evident at Richmond and Columbia nearer the coast. It is thus more a feature of North Carolina than of adjacent states. The configuration of the Atlantic coastline lends immediate maritime influence to a much larger area of North Carolina than of South Carolina and Virginia. Implicitly much of the coastal plains of North Carolina has two diurnal peaks of summer showers, one near sunrise and the other near sunset, with depressions centered near midnight and just before noon. Quite the contrary, the western part of North Carolina has a dominant single diurnal cycle of warm season rains, with minimum occurrences near sunrise and maximum about 12 hours later, in general accord with the pattern of the continental interior and Gulf Coast region. The secondary diurnal cycle in

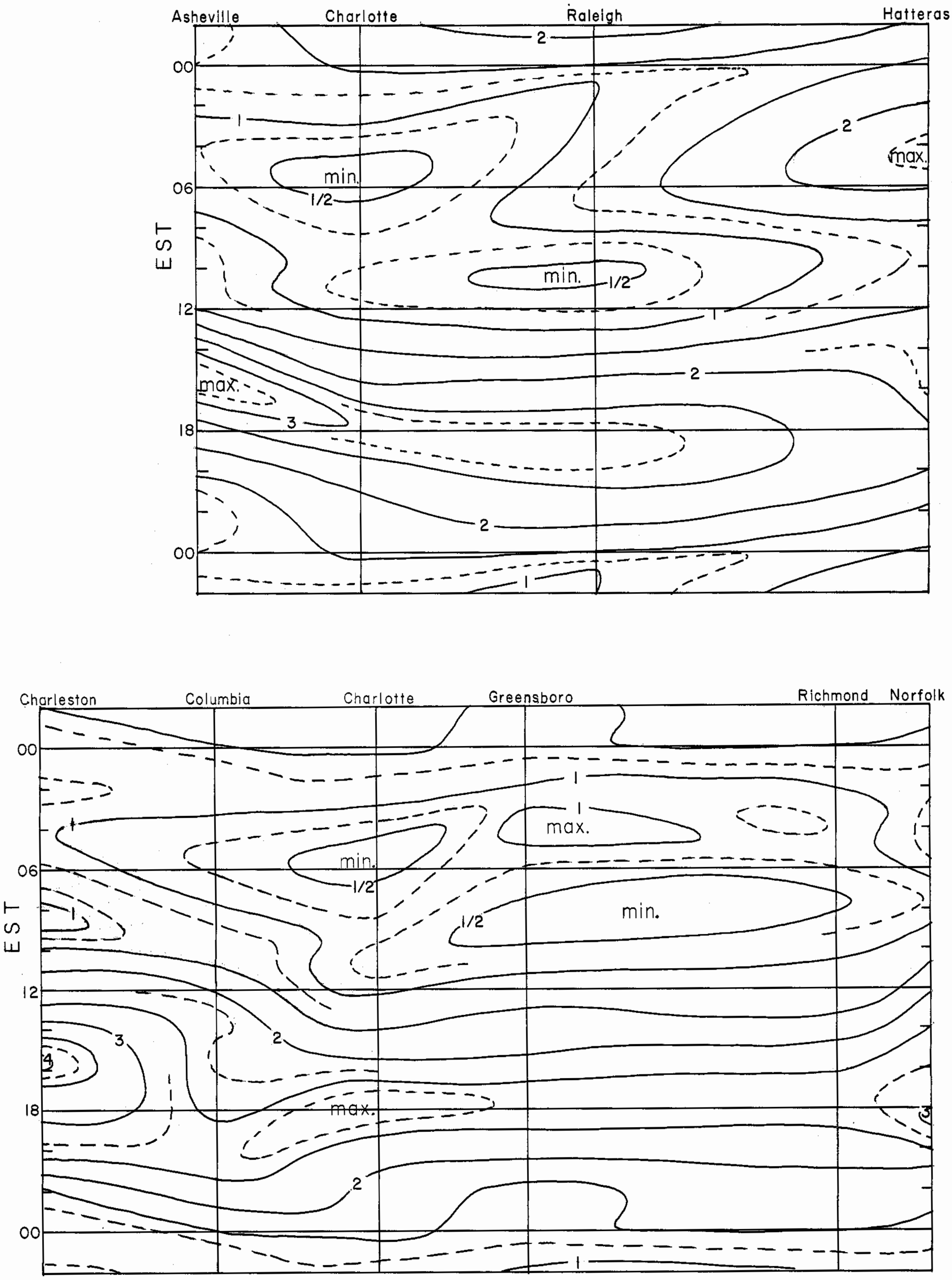

Figure 1. Time-Distance Sections of Monthly Occurrences of Measurable Rain During Hourly Intervals (July)

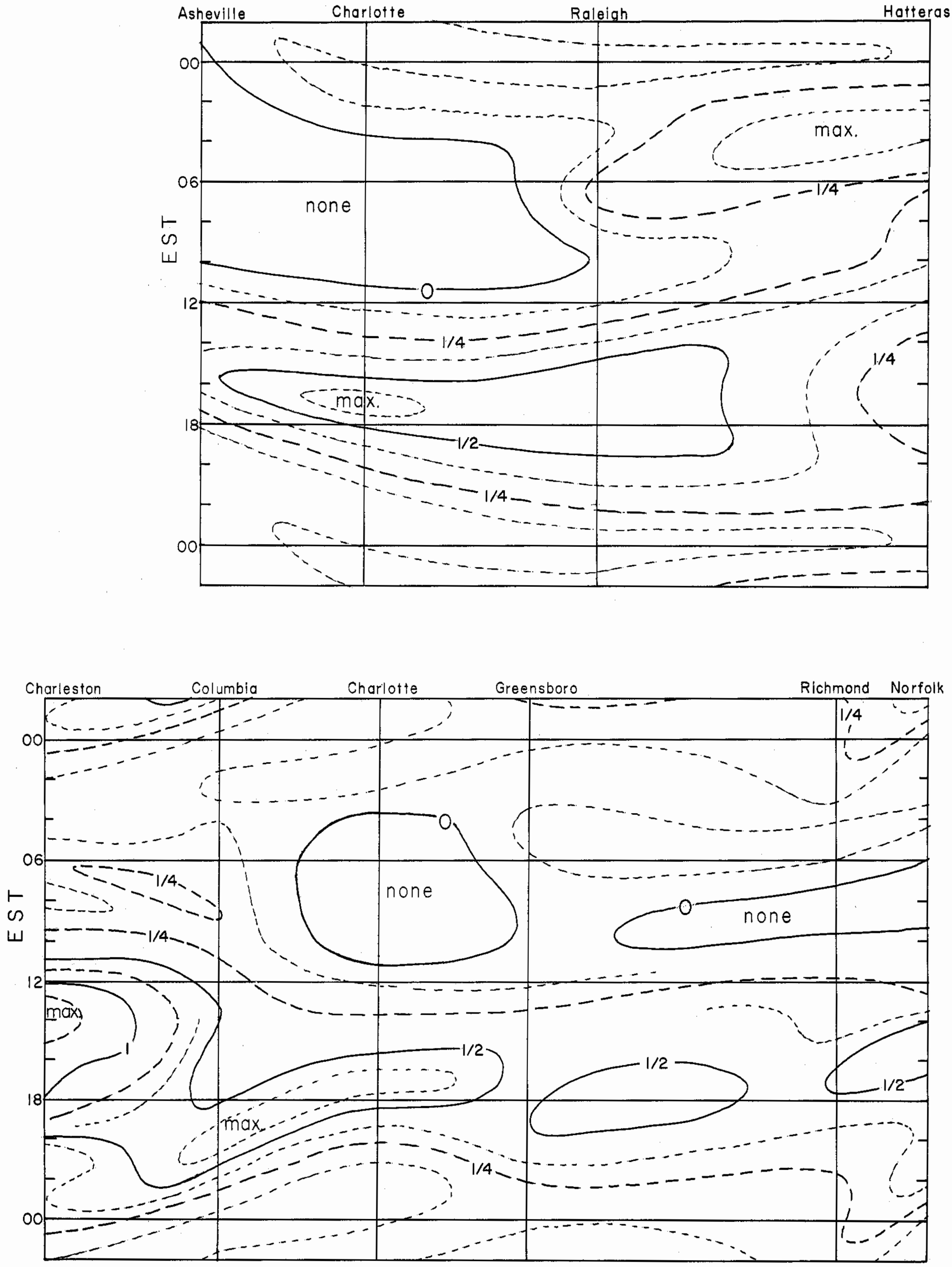

Figure 2. Time-Distance Sections of Monthly Occurrences of ⩾0.25-inch Rain During Hourly Intervals (July)

the western part of the state is only faint in comparison. The state's two diurnal regimes in summer rainfall imply different rainfall-runoff-infiltration-evaporation relationships applied to daily rainfall or to long term rainfall amounts for this summer month.

There are further interesting details in the patterns shown by Figure 1. In spite of the great smoothing employed, substantial interhourly changes remain in the rainfall probability of occurrence during the early afternoon from the mountains eastward over the piedmont, and from about 0700 to 1000 EST over the eastern piedmont and coastal plain as indicated by Raleigh and Hatteras. Further, there is faint indication of continuity in the morning maximum of rainfall occurrence extending westward to the mountains. It diminishes considerably in amplitude across the piedmont and appears delayed by several hours in the west, which phase displacement is perhaps in consequence of the dominance inland by the sunrise minimum and afternoon maximum. Also, the forenoon minimum, which appears most pronounced in the Greensboro and Raleigh data, is detectable west-east across the state with little phase shift. But it occurs earlier over Virginia and, from indications by the South Carolina data, less definitely to the south. Referenced to given times of day, the geographic gradients in probability of rainfall occurrence for July are evidently large near sunrise between coastal plain and piedmont of North Carolina and in early afternoon eastward and northward to Charlotte.

Rainfall-runoff relations are more sensitive to the higher rainfall intensities, and the proportion of the rainfall budgeted to immediate evaporation is higher for the lighter rains, depending on the attendant and subsequent atmospheric conditions. For those reasons Figure 2 was prepared from the tabulations of rain occurrences equal or exceeding 0.25 inch in the hourly interval, with similar procedures employed as in obtaining Figure 1. However, since instances of 0.25 inch rain in an hour are far fewer, the effects of data smoothing are proportionately larger and the results correspondingly less reliable than in Figure 1. New patterns are obtained, however, which are useful if taken with due discretions.

Comparison of Figures 1 and 2 reveals that July rains of 0.25 inch in an hour comprise only a small part of the measurable rain occurrences, and also that this fraction appears to vary diurnally as well as geographically. The number of hourly reports of 0.25 inch in ratio to all hourly reports of measurable rain is, expressed in percent, Asheville 7, Norfolk 13, Charlotte 14, Hatteras 15, Richmond 16, Greensboro 16, Raleigh 17, Columbia 19, and Charleston 27. The last figure is believed doubtful as a long term average, and the one for Asheville might be suspect also. At any rate, overall less than one-sixth of the measurable-rain hours in July are quarter-inch rains. Figure 2 shows how those few are distributed over the course of the day through the region.

A significant transition from Figure 1 to Figure 2 is the sharp loss of the morning maximum except over eastern North Carolina as the lighter rains are removed from the sample. The ratios in frequency of $\geqslant$0.25-inch rain to those $\geqslant$0.01 inch are 0.20 at Raleigh for hours 0600, 0700, and 0800 EST, 0.13 at Greensboro for hours 0400, 0500, and 0600, and zero at Charlotte for hours 0800, 0900, and 1000, all three-hour periods embracing that morning maximum at the respective stations. In that period at Charlotte only about 1/15 of the measurable-rain occurrences were as much as 0.10 inch per hour. While those morning rains of July are trivial in the upper piedmont area, that is not the case in the eastern part of the state. For hours 0300, 0400, and 0500 at Hatteras and 0600, 0700, and 0800 at Raleigh, the rains of ≥0.25 inch per hour represent 18 percent of the measurable rains in those hours, which is no less a ratio than in the afternoon-evening maximum of frequency at those stations.

The afternoon maximum is different. The ratios in freuqency of ≥0.25 inch rain to those ≥0.01 inch are 0.4 at Charleston for hours 1300, 1400, and 1500, 0.24 at Columbia for hours 1900, 2000, and 2100, 0.24 at Charlotte for hours 1600, 1700, and 1800, 0.19 at Greensboro for hours 1800, 1900, and 2000, and 0.20 at Raleigh for hours 1700, 1800, and 1900. West and southwest of Raleigh, and apparently also over eastern Virginia, the July rains of afternoon-evening typically are more intense than those of morning. East (and likely also southeast) of Raleigh the morning rains are proportionately no less intense than those of the late afternoon peak.

Comparison of Figures 1 and 2 reveals phase differences in the times of maximum occurrence. The afternoon rains of ≥0.25-inch per hour generally peak in frequency earlier than the ≥0.01-inch rains. The phase difference is large at Charleston and Norfolk where the intense rains peak early, and small at Columbia and Charlotte where they peak later in the day. At the latter stations there is rapid drop during the evening hours in frequencies of the heavy rains. Many individual rains have the characteristic of intense rainfall rates at their onset and then tapering off for hours afterward, but that is only part of the whole explanation. An earlier peak in the frequency of hourly 0.25-inch rains than in that of all measurable rains appears in the Hatteras morning maximum also, by about one hour, but not perceptibly at Raleigh.

There is an oddity in phases of the two patterns from Raleigh to Hatteras in the afternoon. While Figure 1 shows a maximum of rain frequency near 1900 EST at both stations, Figure 2 shows an apparent double maximum lengthening in time difference eastward, with rain intensities diminishing eastward for hours 1500 to 1900. (This oddity at Hatteras was not produced by the years 1961-62.) The broad or double maximum in late afternoon at Raleigh in Figure 2 also arose independently in the data for Columbia, Greensboro, and Richmond, with more or less distinction. In view of this feature, the large distance from Raleigh to Hatteras, and the likelihood that Hatteras departs significantly from the coastal region to the west, there arises some question about interpolation between those two stations to describe the coastal plains.

It is pertinent to suggest caution in generalizing these patterns with respect to life cycles and movements of individual rain systems. The swaths of maximum frequency in Figures 1 and 2 indeed are not to be confused with the paths of individual systems between stations, and two peaks in rain frequency diurnally over eastern North Carolina is hardly to suggest that a morning rain is followed by another about 12 hours later. Further, no correlations have been made between stations on a day-by-day basis.

Table 1(f) gave the ratios of hourly reports per month with measurable rain to the number of rainy days per month. Those ranged from 2.9 at the western North Carolina stations to 3.6 (longer rains per rainy day) at Hatteras. If similarly is done for rains of 0.25-inch threshold, the following ratios tending about unity are obtained: Asheville 0.5, Norfolk 0.8, Greensboro 1.0, Charlotte 1.1, Richmond 1.2, Raleigh 1.2, Columbia 1.3, Charleston 1.4, and Hatteras 1.4. For interpretations of these, the number of days per July having 0.25 inch or more are given: Charlotte 4.2, Hatteras 4.5, Richmond 4.7, Asheville 5.0, Greensboro 5.1, Raleigh 5.3, Charleston 5.4, Columbia 6.0, and Norfolk 6.6. The intensity-duration relationships so indicated have appreciable dispersion over the region. Part of that arises from different data periods, but any such contribution is only in proportion to the local interannual variance in the above relationship. The similar ratios for other months, January, April, and October, respectively, are for 10-year stations: Charlotte 0.5, 0.7, and 0.9; Greensboro 0.5, 0.5, and 1.1; Raleigh 0.6, 0.7, and 0.7; Richmond 0.3, 0.6, and 0.8.

One hydrologic impact of the diurnal variation of rainfall over land lies in its budget to the process of evaporation, the potential of which has a pronounced diurnal cycle also. A rain immediately followed by conditions favoring rapid evaporation -- a virtual siphon for water from the surface into the atmosphere -- is correspondingly reduced in runoff and soil infiltration. The residual, or the "net rain" after correction for that immediate evaporation, is appreciably less than what is collected in the raingage. On the contrary, the same rain followed by several hours of low or diminishing evaporation rates is able to (a) infiltrate the soil to depths inhibiting the rates of subsequent evaporation from the surface and (b) collect in streams and reservoirs with greatly reduced ratio of exposed surface area to mass of the water, both reducing the amount of water lost and losable to the air.

For given water supply at the surface, conditions favoring evaporation are high temperature of the surface (especially being heated by the sun), large temperature drop from the surface into the air above, and windy air.

Because a land surface rises in temperature under solar heating faster than does the surface of a body of water, a wet land surface can evaporate faster than a lake surface or an evaporation pan filled with water. While low moisture content of the overlying air also assists the evaporation, that is not the whole control, as is verified by the rapid drying of surfaces which occur even on a humid summer day. The diurnal courses of both temperature and wind imply that ordinarily a given brief rain has less infiltration and runoff if occurring near sunrise or during forenoon, and preferably followed by broken to clear skies, than if occurring near sunset or in the evening hours. The antecedent conditions, including soil capacity for water storage, may not be primary controls on the loss to evaporation in the succeeding few hours under meteorological conditions favoring evaporation. In the cold season the rapid movement (or local alternation) of weather systems give interdiurnal variations of evaporation potential which can overshadow the diurnal variations. Evaporation potential generally has most diurnal variation in the warm season over land, when also the interdiurnal variations are least.

Budgets of summer showers to soil water storage and runoff merit examination in light of the diurnal variations of both rainfall and evaporation In this respect, whether the raingage totalled six inches or four inches for the month is hardly translatable directly into specific impacts on vegetation or surface water supply. Evidently there are different physical regimes applying to warm season rain for the eastern and western parts of North Carolina.

PREVAILING WIND DIRECTIONS

Percent frequencies of wind directions in the four months April, July, October, and January are given in Table 4 for nine National Weather Service stations in the region. Also given are the mean monthly wind speeds to the nearest mile per hour averaged from the hourly observations. The data for all stations except Hatteras were taken from the respective Decennial Census (1951-1960) publications. Those for Hatteras were compiled from its published monthly summaries for the 10 years 1953-1962.

In the published data for any month and station the sum of the frequencies for the 16 directions plus the frequency of calm totals 100 percent. In obtaining the figures in Table 4, smoothing was done to reduce the evident bias for reporting more winds from the eight directions N, NE, E, SE, S, SW, W, and NW than from the eight intermediate directions. They were smoothed by averaging the frequencies over three consecutive directions with double weight assigned to the middle one. Those averages rounded to the nearest whole percent are presented, and the new frequencies may then total slightly different from 100 percent in some columns. As usual, smoothing reduces the prominence of real peaks and dips in a distribution.

There are differences between stations which are real and others unreal. Some geographic variation exists over the large area covered. There are differences due to major physiographic features, notably the marine exposure of Hatteras and the orographic controls at Roanoke, and to minor ones locally also. Exposures of the instruments at the sites vary considerably, especially in their altitude above ground. Because of the large vertical gradient of wind speed near the surface in stratified conditions such as exist generally over land at night, one anemometer situated nearer the ground

Table 4

Percent Frequencies of Wind Directions in April, July, October, and January (1951-1960)

	ROANOKE (52,60ft)				RICHMOND (67ft)				NORFOLK (55,39ft)			
	A	J	O	J	A	J	O	J	A	J	O	J
N	4	4	6	4	5	5	10	7	5	2	8	10
	4	5	8	3	5	5	9	6	6	4	11	9
NE	4	5	8	3	4	4	6	4	7	7	12	6
	3	3	5	2	4	4	4	3	6	7	8	4
E	2	2	3	2	4	5	3	2	5	5	5	2
	5	4	5	4	4	5	3	3	4	5	3	2
SE	7	7	6	6	5	5	4	4	5	5	3	2
	6	6	5	4	7	8	6	6	6	6	4	4
S	4	4	3	2	9	11	8	9	8	9	6	7
	6	5	3	3	11	12	8	9	11	13	8	9
SW	8	8	4	6	10	10	7	9	11	14	8	8
	9	9	5	8	8	7	6	8	8	9	6	7
W	8	7	6	10	6	5	5	8	5	4	4	6
	8	6	7	13	5	4	5	7	4	3	4	7
NW	7	5	7	13	5	4	7	7	4	2	4	8
	6	4	5	7	6	4	9	8	4	2	5	9
Calm %	9	16	16	9	1	2	2	1	1	4	2	2
$\overline{V}$ mph	10	7	7	10	9	7	7	8	12	8	11	11

	GREENSBORO(56,20ft)				RALEIGH (32,26ft)				HATTERAS (1953-62)			
	A	J	O	J	A	J	O	J	A	J	O	J
N	4	4	6	6	5	4	10	6		3	11	
	5	5	10	6	5	4	10	5		5	15	
NE	6	7	13	7	4	5	9	4		6	12	
	5	7	10	5	4	5	6	3		5	6	
E	3	4	4	2	3	4	3	3		4	3	
	2	2	2	1	4	3	3	3		3	3	
SE	2	2	2	1	4	3	2	3		3	3	
	3	3	2	2	6	6	4	3		5	3	
S	6	6	4	4	10	10	5	5		13	4	
	13	12	8	10	12	12	6	9		18	5	
SW	16	16	9	14	11	11	6	10		15	5	
	11	11	7	10	8	7	4	8		8	5	
W	8	5	4	6	6	4	4	7		4	5	
	5	4	4	6	5	3	4	8		2	5	
NW	5	3	5	8	4	2	4	8		1	6	
	5	4	5	8	4	3	6	7		2	8	
Calm %	3	5	7	4	7	14	13	9	1	2	2	1
$\overline{V}$ mph	10	7	8	9	9	7	7	8	14	11	12	13

	CHARLOTTE(85,20ft)				COLUMBIA (36ft)				CHARLESTON(73,77,20ft)			
	A	J	O	J	A	J	O	J	A	J	O	J
N	5	5	11	7	4	3	9	4	3	4	13	6
	5	5	13	7	4	5	11	5	4	5	15	6
NE	5	6	11	6	4	6	10	5	4	5	10	6
	4	5	6	5	4	6	6	4	4	4	5	4
E	3	4	6	3	4	5	3	3	4	4	3	3
	4	4	3	3	4	5	2	2	5	5	3	3
SE	5	5	4	3	4	5	2	2	7	6	3	3
	8	7	5	5	5	5	2	2	8	8	3	3
S	11	9	6	8	7	7	3	4	10	10	3	5
	12	10	6	10	10	10	4	7	10	12	3	8
SW	10	9	5	9	10	11	5	10	9	11	4	10
	7	7	4	7	8	8	5	10	7	7	5	9
W	4	4	3	7	6	4	4	8	6	4	4	8
	4	3	4	6	5	3	3	7	5	3	4	8
NW	5	3	5	7	4	3	4	6	4	2	6	7
	5	4	8	7	4	2	6	5	3	3	8	6
Calm %	3	6	4	3	11	12	20	16	6	8	8	6
$\overline{V}$ mph	9	7	8	9	9	7	6	7	11	8	8	10

than another will indicate the lighter mean speeds and the more frequent calms. The fewer calms reported at Richmond than at Raleigh and Columbia undoubtedly owes in some part or all to this. During the decade of data there were changes in location of the wind instruments at some of the stations (as indicated by altitudes given in Table 4) which affected particularly the wind speeds and frequency of calms. With the relocation of the observation site from Cape Hatteras to adjacent Buxton in 1957 the calm frequencies became greater than 0.5 percent.

Perfect calms are everywhere much fewer than indicated by the reports, for a threshold of air flow is required to turn the anemometer. In fact, there are more reports of calm than of one and two miles per hour. In comparing the wind direction frequencies at two stations it may be necessary to allow for the difference in calm frequencies. For example, in October the winds from north and northeast are indicated more prevalent at Charlotte than at Columbia, but when allowance is made for the difference in calms the comparison reverses. Although the distribution of very light winds which are reported as calms might be directionally dependent, there is some justification for the above adjustment.

The coastal and piedmont stations reveal a pronounced bimodal distribution of wind directions. The principal mode for the year is from southwest or south, and among the months listed it is most prominent in April and July, although evident in less dominating frequencies in other seasons. The other mode is from the opposite direction, north or northeast. It is the principal mode of autumn, is less pronounced in winter, and is still less a feature of other seasons. Those two opposing modes of wind direction are roughly parallel to the Appalachian chain and the Atlantic coastline, and are about along the contours of physiography. Winds from east and southeast are transitional and infrequent. In winter the additional component of flow from west acting on the regionally favored modes from SSW and NNE result in an apparent third mode from northwest, as if from turning the NNE winds into NW, and, also as added flow from west would imply, the SSW wind regime is turned into directions more southwesterly and is somewhat accentuated in frequency.

The dominant bimodal distribution of directions is determined by the Atlantic Ocean on the east and, in less influence, by the Appalachian Mountains to the west. This reversal is not really in the sense of a land-and-sea breeze type of circulation, which occurs diurnally and perpendicular to a coastline, nor is it a mountain-and-valley breeze. It is littoral of direction. In seasonal dependence and geographic breadth the opposing modes of directions comprise more nearly a monsoon, which is a seasonal reversal. With reference to the pressure distribution, the southerly flow is associated with "the Bermuda high" (and with lower pressures over the continent) while northerly flow is associated with continental high pressure (and with lower pressures offshore). The land-sea temperature contrast is such as to favor near sea level higher pressure over the ocean in spring and summer, higher pressure over the continent in autumn and winter, and thereby the seasonal reversal in prevailing winds.

High pressure cells attending cold outbreaks toward the southeastern states in autumn and winter have an apparent tendency to slow their displacement or stall for a while over the southern Appalachian region, as if hesitant to embark upon the warm waters of the Gulf of Mexico and Atlantic Ocean. That stagnation is effected much less by the mountains than by the great continental lobe bounded by the north-south Atlantic coast and the east-west Gulf of Mexico coast, with the Florida peninsula neglected in virtue of its small width. These situations give persisting northerlies to the Atlantic coast states, especially noticeable in autumn when circulation systems displace more slowly than in winter. To the broadscale thermal field of winter, with the warm Gulf Stream Current arc offshore and cooler Atlantic on its northern flank, can be attributed also the frequent "Cape Hatteras low pressure" systems and attendant rainy northeasters affecting the seaboard of North Carolina and Virginia.

With this background of prevailing winds and seasonal dependence, some of the peculiarities in the diurnal variations of winds will be examined. The tabulations employed of wind reports by hour of day were in respect to speeds and not directions, and the discussion is so limited. Wind, being the vector horizontal air flow, varies in a manner with speed and direction interdependent. While one cannot analyze the whole in physical terms by looking at wind speeds separately, the speed is itself of interest in a host of natural processes and human activities. Among the many things it controls or on which it bears are sailboating and kite-flying, wind waves on water, circulation in estuaries and sounds, fumigation or dusting with insecticides, cooling power and human comfort, evaporation from wet or humid surfaces, concentrations of air pollutants downwind from a source, visibility or atmospheric transparency, winnowing of chaff from grain, spread of pollen and seeds and leaves, aircraft takeoff and landing, fog and dew and frost formation, nocturnal temperature drop at the surface, snowdrift and dustblow, and others, including even the potentials for mosquito biting and other nuisances by flying insects outdoors.

WIND SPEED FREQUENCY DISTRIBUTION

As indicated by Table 4, we are dealing with surface winds of average monthly speed lying between 5 and 15 mph. Wind speeds are bounded at one end of their range, namely zero or calm, and unbounded at the other. The frequency distribution is greatly skewed. The mode of wind speeds is considerably nearer zero than to the highest values observed, and near-calm conditions are more common than are winds twice the speed of the mode. The average speed is larger than the prevailing or modal speed.

The shape of the frequency distribution of speeds does vary with respect to day and night, the season, the height above ground, the sky and other weather conditions, and also the wind direction. Over a month or a year at a land station, for instance, the distribution of surface daytime winds compared to nighttime winds should have broader range of speeds, higher mean speed, fewer calms, and lower frequency at the mode. Such are characteristics of wind speed distributions, and variations in them, which underlie the discussion to follow.

Wind speed frequencies by hour of day were given tabulated in the Decennial Census (1951-1960) publications by wind speed categories 0 to 3, 4 to 12, 13 to 24, and 25 mph or over. Because so few of the winds exceeded 24 mph, for this analysis the last two categories were combined into one, for 13 mph and over. The middle bracket of the remaining three contained most of the observations as well as almost all of the central tendencies. A simplified procedure was applied to those tabulations for obtaining certain elemental results sought, in lieu of complicated statistical procedures or recourse to the mass of original observations. First, the 4 to 12 mph category was ignored. Next, the frequency of hourly wind reports $\geq$13 mph was subtracted from the frequency of 0 to 3 mph. This difference F in percentage frequency between the lightest wind category and the strongest wind category is an index to the dominance of light winds as well as to the skewness of the distribution. Finally those differences were normalized for each station to give mean value zero for any month of the 10 years for the station, because the object is to examine the diurnal trends in the wind speed apart from the seasonal variation of the winds already given by Table 4. That crude measure should suffice for the purpose at hand. But is has shortcomings, a primary one being the sensitivity to unequal intervals of speed in the three categories of the initial tabulation.

DIURNAL VARIATIONS IN WIND SPEEDS

Table 5 gives those results for the five piedmont stations and three coastal stations of Virginia, North Carolina, and South Carolina, for April, July, October, and January. There is a column for each hour, beginning at midnight (MN). The last column on the right gives the mean of the speeds from each hourly observation in the month for the decade. The two columns immediately preceding it give the average percentages of winds 0 to 3 mph and of winds ≥13 mph. It is the difference $\overline{F}$ between these two columns that was employed in normalizing the results in this table. An example will clarify procedure and results.

At Richmond in April the 10-year average was 9 percent of winds 0 to 3 mph, 21 percent of winds 13 mph or more, and therefore 70 percent of winds 4 to 12 mph. The difference $9 - 21 = -12 = \overline{F}$ was subtracted (algebraically) from the actual difference F of 15 percent winds 0 to 3 mph and 14 percent winds ≥13 mph at midnight to obtain $F - \overline{F} = (15 - 14) - (-12) = 13$ percent shown for that time. At the next hour the mean difference of light winds

Table 5. Percent of Winds 0-3 mph Minus Percent of Winds ≥13 mph, Normalized to Mean Zero

	MN		2		4		a.m. 6		8		10		E.S.T. N		2		4		p.m. 6		8		10		MN		2		Av. Daily 0-3 mph	Av. Daily ≥13 mph	$\bar{V}$ mph
RICHMOND (1951-60)																															
Apr	13	17	20	20	18	20	22	17	3	7	14	17	21	23	23	20	23	16	6	2	7	4	8	7	13	17	20	20	9	21	9.2
Jul	16	12	17	19	17	20	15	8	1	6	9	15	20	19	23	25	23	21	12	3	5	7	9	10	16	12	17	19	18	6	6.9
Oct	8	11	9	11	8	12	9	14	0	9	16	17	21	20	22	21	10	3	8	10	8	9	12	10	8	11	9	11	15	10	7.4
Jan	5	5	8	9	8	5	7	10	8	3	8	16	12	19	17	14	4	3	7	6	5	2	4	5	5	5	8	9	14	16	8.2
RALEIGH (1951-60)																															
Apr	11	15	19	21	19	25	25	12	7	9	15	19	22	25	25	26	26	13	11	17	9	4	5	7	11	15	19	21	11	26	9.3
Jul	11	13	18	21	24	28	19	2	5	10	15	16	17	19	20	22	19	13	4	8	8	7	9	9	11	13	18	21	21	9	6.7
Oct	12	15	17	12	16	19	16	16	1	16	27	25	29	22	25	21	12	10	12	9	5	5	9	8	12	15	17	12	20	15	7.4
Jan	10	8	9	13	11	11	10	16	10	5	12	22	20	24	25	25	12	7	12	3	4	0	2	2	10	8	9	13	16	20	8.3
GREENSBORO (1951-60)																															
Apr	17	17	17	19	16	22	21	13	7	16	20	25	21	25	31	31	24	19	3	11	10	15	15	15	17	17	17	19	12	27	9.6
Jul	15	19	17	19	17	17	21	3	9	13	15	18	22	23	23	23	24	20	12	1	12	16	20	19	15	19	17	19	23	8	6.8
Oct	13	11	10	13	14	14	16	12	0	17	29	26	24	18	14	13	11	2	14	14	14	10	13	12	13	11	10	13	21	17	7.9
Jan	13	12	11	13	10	15	15	16	8	0	14	22	22	25	25	27	17	3	7	8	8	10	13	15	13	12	11	13	18	22	8.6
CHARLOTTE (1951-60)																															
Apr	14	14	17	21	20	23	20	15	2	19	17	23	27	26	28	28	28	20	2	7	11	9	13	12	14	14	17	21	14	25	9.4
Jul	13	18	18	22	25	26	24	9	2	12	18	11	19	23	23	22	32	24	9	0	6	8	11	10	13	18	18	22	25	9	6.7
Oct	7	9	8	12	13	11	13	8	2	12	18	18	19	21	18	20	16	7	10	7	3	9	8	12	7	9	8	12	20	15	7.7
Jan	9	13	15	14	17	17	16	11	13	1	12	18	21	29	25	30	18	1	5	6	5	8	10	9	9	13	15	14	18	22	8.6
COLUMBIA (1951-60)																															
Apr	22	22	25	29	30	34	35	19	4	19	27	24	31	34	41	39	42	36	19	4	11	13	15	21	22	22	25	29	18	25	8.8
Jul	21	21	32	32	33	35	31	14	6	4	17	15	27	30	33	33	37	30	23	10	2	10	12	16	21	21	32	32	21	10	6.7
Oct	21	17	22	24	20	23	21	14	2	12	30	35	40	38	39	34	28	17	6	14	14	19	16	20	21	17	22	24	32	9	6.0
Jan	22	18	20	17	21	20	18	15	13	5	20	26	34	40	38	39	31	13	0	9	9	16	13	14	22	18	20	17	28	18	7.2
NORFOLK (1951-60)																															
Apr	14	15	19	20	22	20	17	2	13	17	20	22	24	23	25	26	25	25	1	11	13	16	14	10	14	15	19	20	9	42	11.5
Jul	23	15	22	?	23	23	12	4	9	15	16	20	23	29	26	26	23	17	10	3	16	17	20	18	23	15	22	?	21	19	8.1
Oct	12	13	10	12	11	8	10	3	6	17	18	25	23	24	18	17	4	11	14	12	18	14	10	11	12	13	10	12	12	36	10.6
Jan	7	3	3	4	?	6	?	0	6	12	14	17	18	16	16	9	3	13	15	18	14	10	12	12	7	3	3	4	9	41	11.4
HATTERAS (1953-62)																															
Apr	10	6	9	7	10	10	8	5	0	7	9	7	9	13	12	12	8	7	3	1	5	6	6	7	10	6	9	7	1	51	13.5
Jul	12	15	16	22	24	26	25	17	8	4	1	11	10	17	18	16	15	8	4	1	5	6	9	10	12	15	16	22	4	39	11.3
Oct	5	6	8	7	3	4	3	1	1	6	9	11	10	11	6	9	4	1	3	4	11	7	5	6	5	6	8	7	5	41	11.6
Jan	5	1	2	1	0	0	1	1	1	2	8	12	12	11	9	5	1	8	8	11	10	8	4	5	5	1	2	1	3	49	13.0
CHARLESTON (1951-60)																															
Apr	24	27	31	27	25	30	29	24	5	15	17	23	25	33	40	44	46	38	15	6	13	16	23	19	24	27	31	27	10	35	10.7
Jul	24	22	30	32	34	30	27	13	0	7	6	15	19	31	33	45	42	36	20	7	4	12	16	22	24	22	30	32	14	20	8.4
Oct	17	20	16	11	8	10	13	8	8	16	18	23	26	25	29	26	19	7	11	11	13	18	19	17	17	20	16	11	14	18	8.3
Jan	19	14	12	10	15	13	13	10	7	6	18	24	24	31	30	26	24	9	3	11	15	17	15	16	19	14	12	10	11	29	9.9

minus strong winds increased by four percent to 17, and so on. It maximizes near sunrise, indicating the highest relative frequency of light winds at that time of day, and drops rapidly (increasing wind speeds) over the succeeding few hours. Negative values are shown underlined within the table. In late afternoon the light winds grow rapidly in frequency relative to the strong winds, but through the evening there is little change.

In many respects this diurnal pattern of wind speed frequencies is repeated for other months and other stations. To that extent there is a generalized diurnal variation of wind speed near the ground. Although these variations are mostly smaller at Hatteras than elsewhere, perhaps more surprising is that Hatteras has any significant diurnal variation in view of its marine exposure and the small diurnal variations in surface temperature and in the stratification of the lower atmosphere at sea. Notably in July, when the winds at Hatteras are most definitely of long marine trajectory, the diurnal course in wind speeds is truly continental in aspect. Implied here is the operation of a diurnal process beyond the one usually explaining diurnal variations in surface winds, the latter of which involves frictional drag on the wind by the surface in proportion to the wind speed and also the downward flux of momentum through vertical mixing of the air convectively over a surface heated during the day.

Figure 3 should help in visualizing and interpreting the data in Table 5. Illustrated are diurnal profiles of such data for Nashville (Tennessee) and Raleigh for these four months. Nashville is referenced because it is in similar latitude but is more typical of the continental interior. There we observe large diurnal variations, greatest amplitude of variation in summer and least in winter, winds peaking in speed in afternoon earliest in January and latest in July in accord with diurnal temperature cycles, and for the most part a single cycle over the 24 hours. The lack of significant drop in winds during January nights is surprising in view of the mean wind speeds and also the mean frequencies in all speed categories being about the same for January and April. The difference lies in the correlated diurnal variations in surface temperature and wind. At Nashville, January averaged 77 percent more hourly reports of rain and 35 percent more hourly reports of 80 to 100 percent skycover by clouds as compared to April, which is in accord with the difference in diurnal patterns of wind speeds shown there.

Raleigh is about 35 minutes earlier than Nashville in solar time, but their Standard Times differ by one hour, so that in the time scale given Nashville's diurnal cycle should be almost a half hour earlier than Raleigh's. Departures are seen at Raleigh in peak speeds of April delayed an hour or two and those of October occurring at noon or earlier. Another difference is the prominence of the wind lull near sunset at Raleigh in all months, though more marked in other months than in the July average when higher incidence of showers at that time of day has a smoothing effect on the profile. Another feature of the Raleigh profiles is the smallness of the rise appearing in the October and January curves from mid-evening to sunrise, and yet the sky conditions and low humidities favor larger diurnal variations in October than in April. At both stations there are rapid changes in the two hours following sunrise and also in late afternoon, which are the periods of coupling to and uncoupling from the more freely flowing air above the boundary layer of atmosphere.

In comparison with the Nashville profiles, certain peculiarities of the Raleigh curves are seen repeated at other stations of North Carolina and

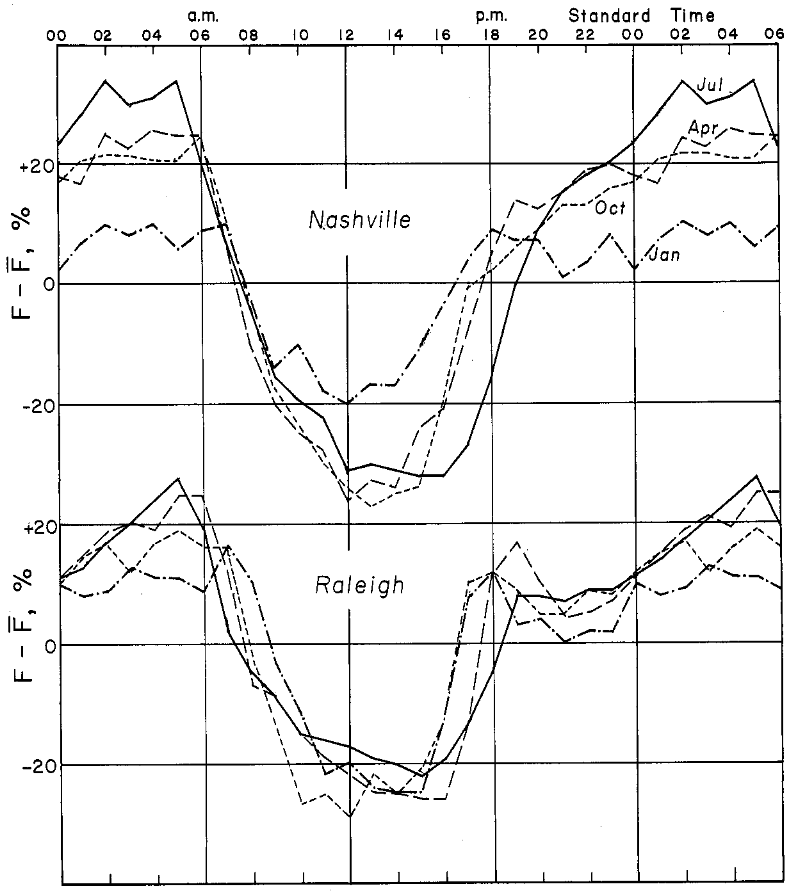

Figure 3. Diurnal Distributions of Normalized Difference in Frequency of Winds 0-3 mph and Winds >13 mph, Nashville, Tennessee, and Raleigh, North Carolina, 1951-1960.

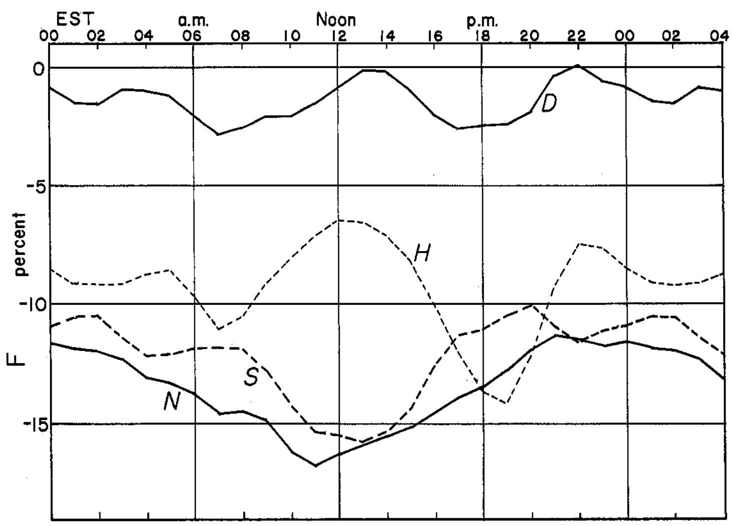

Figure 4. Difference in Frequency of Winds 0-3 mph and of Winds ≥13 mph for Selected Months of October, 1953-1962, at Cape Hatteras.

vicinity in Table 5. Among these are the tendency of wind to lull near sunset while generally the surface temperatures are coursing downward to minimize near sunrise, and the differences of the October profile from those of July and April. These features are all the more dramatic when allowance is made for the change by one-half hour in observation times effective in 1957, by the changes in sunrise or sunset by up to 36 minutes over the course of the month, and by virtue of these comprising all the observations regardless of positive or negative circumstances in the weather. The tendency for October winds to peak in speed near or even before noon and to persist in speeds through the night is evidenced with more or less clarity at all of the piedmont and coastal stations. That it appears so generally over the region, at Hatteras and well inland, obviates explanations by localized controls or such diurnal circulations as the land-and-sea breeze.

Table 4 indicates that in October the prevailing mode of wind direction is from near NNE. Winds from the quadrant centered on that mode constitute about 40 percent of the October observations. Those from the opposite quadrant comprise about two-thirds as many. The principal mode occupies less than half the time in October, but this direction is most prominent in that season. The opposite mode prevails in July and April, when diurnal variations in surface winds are greatest. Since the diurnal distributions given comprise all of the observations, we anticipate that the differences in the diurnal variations of NNE and SSW winds are greater if situations are selected only with winds from those directions with partly cloudy to clear skies. That is possible to investigate employing the original hourly observations, but not from the summary data at hand.

With individual monthly summaries available for Hatteras over the period 1953-1962, it was possible to examine some of the difference in diurnal variation of winds from the two modal directions, although not in the detail that this phenomenon merits. Of the ten October monthly summaries, three were selected having the highest percentages of winds from north and northeast (1953, 1956, 1957), comprising sample N. An equal sample S consisted of the three Octobers in which the north-northeast winds were least frequent compared to the south-southwest winds (1954, 1955, 1959). For each hour of the day average values were obtained for sample N and for sample S of the difference in percent frequencies of winds 0 to 3 mph and 13 mph or more. After smoothing over consecutive three-hour periods the results were presented in Figure 4.

Sample N averaged slightly stronger winds than sample S, as evidenced by the different heights of the diurnal profiles in Figure 4. Even though N contains a significant fraction of winds with the S mode, and S has such a fraction of winds with the N mode, and both contain winds from other sectors as well as the monthly composite of weather conditions, a difference appears in the diurnal courses of wind speed. Curve N describes more nearly a single cycle per day, with winds generally on the decrease from late forenoon to late evening and increase over the other half-day. Curve S dips (strong winds) in early afternoon, is highest about seven hours later, and has two other cycles of less amplitude, one of them associated with lighter winds near sunrise. In early afternoon, shortly before midnight, and also near 0400 EST these two curves have quite similar differences in frequencies of the lighter and the stronger winds. At other times of day, near 0700, 1800, and 0200 EST, the separation in height of the curves is largest.

Curve D gives the difference between curves N and S for each hour of the day. Doubts might arise on the significance of D in view of its range being only three percent and the curve was determined from data tabulations rounded to the nearest whole percent. But curve D has half the range of curves N and S, and it has consistency and periodicity which could not result from errors of observation or computation. Under the breadth of circumstances in the data of N and S, those curves are only damped and mixed versions of the real nature of diurnal variations typical of the individual N and S modes.

Comparison of curves D and H serves to illustrate this point. From among the three months in each sample N and S, the Octobers of most dominant flow from north-northeast (1956) and from south-southwest (1954) were compared, and curve H shows the difference between those two months. The amplitude of H is greater than the amplitudes of the diurnal curves for the two individual months (which are not shown); that is, the difference in the diurnal variation between the modes of flow exceeds the diurnal variation in either mode. The S mode had about 40 percent larger range than the N mode.

Interpretations of these results should have cognizance of the tendency in weak flow for winds to reverse in direction under the effect of diurnal variation of the temperature field, with subsequent increase of wind speed at the times of day when under the same physical control the stronger winds of other days which do not reverse direction are decreasing in speed. The effect of diurnal reversal of wind direction is to enhance wind speeds at those times of day when non-reversing winds would have minimum speed, near sunrise and some hours before in the general SSW flow, and near sunset and some hours before in the general NNE flow. The sense of corrections implied for Figure 4 is to raise curve S in the pre-sunrise period and to raise curve N in the pre-sunset period; thereby curve D is lowered in that morning period and raised in the afternoon period, and similarly for curve H. Without such consideration the use of speed distributions alone tends to obscure and even negate some of the real wind variations diurnally. In this connection it is worth repeating that a shift of wind from south 5 mph into north 5 mph makes no difference in the ventilation rate at a point nor in the whirl of the anemometer, but it is a difference of 10 mph in drag on the surface and in the displacement of the air and substances within it.

In the manner that seasonally the cool continent and warm ocean favor NNE winds near the Atlantic coast, and warm continent and cool ocean favor SSW winds, the larger diurnal variations of temperature over land than over ocean produce diurnal variations in the mass and pressure distribution of the lower atmosphere, and therefore also in the wind which is driven by the pressure distribution. For a given pressure pattern above the atmospheric layer of diurnal temperature change, heating the land in effect contributes there to pressure fall at the surface and to air motion from SSW, while cooling the land contributes there to pressure rise at the surface and to air motion from NNE. The rise in terrain from sea level at the coast to a few thousand feet within 250 miles inland enhances in both cases the low level redistribution of mass and pressure in response to the diurnal temperature variation. Through favorable sky conditions, large diurnal temperature changes over land are sufficient even to reverse weak pressure patterns near the surface, and thus also the wind directions, from day to night. (There are compensating and other related diurnal variations taking place in the upper part of the boundary layer, lending the early morning "low level jet" over land, and other weather phenomena, but those are beyond the present scope.)

With flow from SSW the daytime rise in temperature of the land effectively increases the wind speed over land and adjacent sea, in addition to its increasing the surface wind over land through convective mixing of momentum. The cooling of land at night reduces the pressure gradients and therefore the winds also, over land and coastal sea, and the stratification of air over the cool land surface serves there to further subdue the surface winds. These large diurnal effects on SSW winds are verified by the preceding data. With NNE winds, however, the diurnal pattern is reversed. Daytime heating of the land reduces the pressure difference from land to sea, and nocturnal cooling of the land augments it, with greatest drive applied to the wind in the cool of early morning and least in the warm part of the day. This is more or less offset over land by the diurnal cycle in vertical exchange of momentum, but the result remains that over land NNE winds diminish less overnight than do SSW winds, and where diurnal variations in vertical mixing are small (such as at Hatteras) the winds may gain speed through the night. The effects are most pronounced when the controlling diurnal variation of temperature over land is greatest, under dry atmosphere. Cloudy conditions minimize those differences.

In Figure 3 the rapid drop to the curves in the two to three hours following sunrise is the increase in surface winds through convective mixing forming a couple with the faster-moving air above and the increasing depth of that mixing as surface temperature rises. The lull near sunset is the virtually discontinuous uncoupling of the surface air through diminished convection and onset of stratification. The surface air is now unhitched and abandoned by the air above, so to speak, and readjusts its motion in accord with the pressure distribution at its level and increasingly independent of distributions above. The immediate effect is rapid loss of wind at the surface. Then in the readjustment the local pressure force may take command and actually increase the air motion for a short while from a changed direction. What happens in the course of the night is a matter of frictional drag by the surface and the increased stratification of the air above subduing wind near the surface, and of the particular transitions in the horizontal pattern of pressure which are taking place overnight. Because the local pressure gradient provides the sole driving force for wind speed in stratified conditions, and frictional drag the retarding force, the wind is sensitive to the broad and the local developments in the pressure pattern, which over the course of the night may be increasing or decreasing or merely turning.

With SSW flow the diurnal increase of pressure gradient through daytime heating of the land is evidenced by the increase of winds from late forenoon through midafternoon in April and July at Raleigh and neighboring stations in Table 5. In NNE flow the daytime temperature rise over land reduces the pressure gradient, which contributes to the indicated decreases of wind from noon to midafternoon. With these principles in mind, explanations for the appreciable and peculiar diurnal wind patterns at Hatteras are facilitated, and also are those at other locations east of the Appalachians.

REFERENCES

U. S. Weather Bureau (now National Weather Service), 1963: Decennial Census of United States Climate--Summary of Hourly Observations, 1951-1960, Climatography of the United States No. 82, Department of Commerce, Washington.

____________________, 1956: Summary of Hourly Observations (Asheville, North Carolina), Climatography of the United States No. 30-31, Department of Commerce, Washington.

____________________, (monthly): Local Climatological Data, Cape Hatteras, North Carolina, Department of Commerce, Washington.

Carney, C. B., and Hardy, A. V., 1964: Weather and Climate in North Carolina, Bulletin 396 (reprint), Agric. Exp. Station, North Carolina State University, Raleigh.