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Climate, microclimate and vegetation relationships on north and south forest boundaries in New Jersey by Bruce A. Wales

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The William L. Hutcheson Memorial Forest (originally known as Mettler's Woods) is located in central New Jersey near the town of East Millstone. The forest was given to Rutgers University by the United Brotherhood of Carpenters and Joiners of America. It is endowed by funds contributed by many persons and organizations interested in the preservation and study of such a natural area.
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B.A.W.
Franklin (1955) relates how the Benedictine and Cistercian monks of the Eleventh Century took advantage of the warmth found on south-facing walls to grow grapes in an area where the climate was generally prohibitive to such a crop. In many respects, the periphery of a plant community such as a forest boundary influences microclimate in the same way as a vertical wall (Geiger 1951 and 1957). Dependent upon the direction of exposure, the boundary receives or is blocked from the direct rays of the sun, it impedes the wind, and it acts as a barrier to wind-driven rain and snow. In the northern hemisphere, the southern boundary receives more solar radiation and is generally warmer and drier than the northern boundary. In addition to the effect of exposure, the microclimate at the margin of the stand is conditioned to a greater or lesser extent by influences from both field and forest, and is therefore transitional in nature (Geiger 1957). Silviculturists have long taken advantage of the microclimatic conditions at the edge of the stand to favor the growth of tree seedlings (Touney 1947). The point to be made, however, is that while the general relationships have been known and put to use for some time, the basic dynamics of the microclimates themselves have been studied very little thus far (Geiger 1951 and 1957).

The principal aim of this study is to investigate certain microclimatic features of the north and south boundaries of a native deciduous forest in New Jersey. Specifically, the first objective was to evaluate changes in light penetration and temperature distribution within the layer near the ground (defined in this study as the layer from the surface of the ground to 2 meters for temperature and a height of 1 meter for light) at both boundaries, associated with changes in vegetation and weather from winter through spring into summer. Comprehensive evaluation of vegetative influences on the microclimates required the measurement and analysis of certain characteristics concerning the structure, composition and phenology of the natural vegetation growing on respective boundaries. Since the microclimate influences the vegetation and is in turn influenced by it, it was fully expected that certain ecological considerations would come to light. Although many biological studies have been conducted in the forest, little emphasis has been placed on boundary vegetation. Therefore, the second objective was to investigate, to some extent at least, inter-relationships between microclimate and vegetation at the margin of the stand.

The microclimatologist attempts to define the "constant significant features of the habitat (micro) climate" (Geiger 1957). However, all observations are influenced by conditions of weather and climate. It is known, for example, that slope microclimates vary from region to region depending upon prevailing winds, incidence of cloudiness and other factors (Touney 1947, Geiger 1957). In Europe, precipitation patterns around small hills are related to "precipitation falling obliquely from the west" (Geiger 1957). Although cognizance of these relationships between climate and microclimate is necessary to place microclimatic results from different regions in their proper perspective, few studies have considered them in detail. As in the case of slopes, the microclimate of the forest boundary is dependent upon the climate of the region. During the course of this study, it was discovered that wind-driven snow is distributed in such a way as to significantly influence the thermal differences between the two boundaries. Therefore, a third objective was formulated not only to investigate this relationship, but also to explore the influence of regional climate on the microclimates of north and south forest boundaries in New Jersey. The techniques used were those of dynamic climatology. It was hoped that a detailed study of the weather during the period would provide a means whereby the dynamic analysis of New Jersey's climate prepared by previous investigators at the New Jersey Agricultural Experiment Station could be extended into the micro-layer. Thus, as the title implies, the ultimate goal of this study is the analysis of some relationships between climate, microclimate and vegetation on north and south forest boundaries in New Jersey.

The study was conducted in Hutcheson Memorial Forest, a mature oak forest (Buell 1957) of 65 acres in extent situated about one mile east of East Millstone (40°30'N, 74°34'W) on the Piedmont in New Jersey. Adjacent to the woodland are gently-rolling fields planted to agricultural crops or covered with low-growing native vegetation characteristic of farmland in the early stages of abandonment. The forest has been described most recently by Monk (1957, 1961a and 1961b), who states that it is a variant of the oak-hickory forest type common to the Piedmont Plateau. However, it does not appear to possess the climax status which this community reaches in the Southern States, because the limited reproduction of oaks and hickories is probably not sufficient to maintain the prevalence of these species.

The forest shows a distinct vertical stratification
into four layers. In the upland portion where the study was carried out, the almost continuous main canopy is dominated by white oak (Quercus alba), black oak (Q. velutina), red oak (Q. rubra) and red hickory (Carya ovalis). It reaches to heights of 95 feet. Beneath this is a pronounced understory of flowering dogwood (Cornus florida) which reaches heights to 35 feet. The shrub layer consists primarily of maple-leaved viburnum (Viburnum acerifolium). The herb layer is best developed in spring when May-apple (Podophyllum peltatum) is abundant (Monk 1961a).

The area is underlain by Triassic red shale of the Brunswick Formation (Kümmel 1940). Wisconsin terminal moraine is located a few miles north of the forest, and Salisbury (1902) postulates that gravel scattered over the area represents fluvial material deposited by a river flowing south from the glacier. In a recent study by Ugolini (1964), the soil in the upland section of the forest is classed as a deep, well-drained silt loam. Although gravel is occasionally observed through the profile, the major influence is that of the shale. The characteristic red color of the soil as well as its poor profile development are inherited traits carried over from the shale, which is highly resistant to pedogenic processes.

Owned and set aside as a natural area by Rutgers - The State University, Hutcheson Memorial Forest has been the site of an ever-widening program of biological research. Although some microclimatic data have been collected in connection with these investigations, this work represents the first systematic study in microclimatology to be conducted in the area.
Review of the literature

Systematic studies of the atmospheric conditions within forests at all levels from the litter to above the canopy were initiated in Europe about forty years ago. The present literature concerning forest microclimatology is small, scattered and sometimes hidden because the titles of works contributed by ecologists and foresters often do not mention the subject as such. Radiation relationships at the edge of the stand have been deduced from theoretical considerations, and are reviewed by Geiger (1957). Actual data concerning temperature, wind and snow are difficult to find. This lack of previous research required an approach whereby principles demonstrated on slopes, near shelterbelts, and within the forest proper were re-evaluated and applied at the margin of the stand. The purpose here is to review the most pertinent material concerning solar radiation, temperature, wind and snow available from these sources. First, however, it is appropriate to set the stage by reviewing some of the dynamic aspects of the climate of New Jersey.

Climate of New Jersey. Situated on the east coast of a wedge-shaped continent which provides no effective mountain barriers to block the meridional sweep of contrasting air masses, New Jersey displays a climate characterized by many unique features. Many of these features have been investigated by Biel (1938), Havens (1948) and others (Blood 1953, Pereira 1961, Shulman 1964) working at the New Jersey Agricultural Experiment Station down through the years, and this discussion originates from these sources.

As opposed to an independent climate which is primarily controlled by the sun (latitude), New Jersey’s dependent climate is influenced more by the transport of air masses (advection) than by solar influence, which consequently plays a smaller role in determining the climate. The presence of semi-permanent pressure systems, developed in response to thermal differences between land and sea, determine the advection of different air masses over the State. These controls act on a seasonal basis. In winter, for example, the intensification of the semi-permanent anticyclone or Continental High over the cold interior of the continent results in a high frequency of winds from northern quadrants and a predominance of dry sub-polar air masses over New Jersey. Frequent storms, generated along the Polar Front by strong thermal contrasts between air masses of polar and sub-tropical origin respectively, also influence the State. Since New Jersey is situated to the south of New England where the paths of these storms tend to converge, it experiences some of the most frequent and intense weather changes in the world. In winter, days with at least one air mass change occur 58 percent of the time, and days with two or more air mass changes are not uncommon.

In summer, on the other hand, the controlling feature of the circulation pattern is the Bermuda High located over the area extending from the Sargasso Sea region of the Atlantic Ocean to the Eastern Gulf of Mexico. Anticyclonic flow around this semi-permanent sub-tropical high pressure area results in a high frequency of winds from southern quadrants and a predominance of humid sub-tropical air masses over the State. Weaker thermal contrasts exist between opposing air masses. The Polar Front moves north and air mass changes occur only 45 percent of the time. Spring and fall are transitional seasons.

Although this seasonal shift in controlling air masses demonstrates a monsoonal tendency in New Jersey’s climate, frequent wind shifts associated with the passing storms mask this tendency in the surface winds. Trenton wind statistics, nevertheless, show that winds from northern quadrants (NW clockwise through NE) blow 53 percent of the time as opposed to 26 percent of the time for southern quadrants (SE clockwise through SW) during winter. The corresponding figures in summer are 45 percent for southern quadrants and 35 percent for northern ones.

Due to the close proximity of major storm tracks and high frequency of thunderstorms in summer, average monthly precipitation in New Jersey is high, relatively reliable and spread rather evenly throughout the seasons. The maximum occurs in late summer as a result of thunderstorms and occasional tropical cyclones. Slight minima occur in November and February. New Jersey’s precipitation regime represents a transitional type between the uniquely uniform seasonal distribution of New England and the sub-tropical Atlantic type characterized by a conspicuous rainfall maximum in late summer and fall.

Microclimate. — Solar radiation.1 Geiger’s (1957) calculations of the incidence and extent of shade in front of forest boundaries of different exposure near Munich (48°N) show the importance of solar climate (azimuth and zenith angles of the

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1 Solar radiation refers to the full solar spectrum. Light refers to only the visible wavelengths (0.36-0.76 μ). Dependent upon objectives, present research is about equally divided between the two.
sun, daylength, etc.) in determining radiation relationships near the margin of the stand. Tables and figures providing these values for Hutcheson Memorial Forest (40°N) are readily available in List (1951). Calculations of the seasonal variation in the daily amount of solar radiation available on slopes (0° = horizontal surface, 90° = vertical wall or forest boundary) of various exposures for conditions of mean cloudiness in the New York City area (40°N) also proved useful in interpreting the results of the present study. For these values the reader is referred to Brooks (1959).

Although determined on mountain slopes, Geiger's (1957) "law" concerning the influence of cloudiness on the difference-of-exposure is equally applicable to forest boundaries. The degree of cloudiness determines the relative amounts of short-wave radiation available from sun and sky. With clear skies, for example, direct radiation predominates. Since this radiation is dependent upon direction, it acts primarily on southern exposures in the northern hemisphere, delivering vast amounts of solar energy not available on the northern exposure. However, as cloudiness increases the ratio of diffuse radiation to total radiation also increases. Since diffuse radiation is non-directional, it acts equally on all exposures and differences between them diminish. With a complete overcast, nearly equal although diminished amounts of energy are delivered to all exposures.

Direct and diffuse radiation, most active under clear and overcast skies respectively, also determine the relative amounts of radiation which penetrate through the deciduous canopy to the forest floor. Geiger (1957) discusses the work of Lauscher and Schwabl as well as that of Trapp in this connection. In an ash forest, Lauscher and Schwabl found that 80 percent of the non-directional diffuse light available in the open on an overcast day passed through the leafless canopy to the forest floor. On clear days, however, more of the direct light was reflected by branches and twigs so that only 40 percent reached the forest floor. Under foliated conditions, the percentages under both clear and overcast skies were approximately 25 percent. This implies that the relative amount of light passing through the foliated canopy is independent of sky condition. The absolute amount, of course, is very different. Similar results are reported in a beech stand by Trapp.

It should be noted that Lauscher and Schwabl's work extended across the boundary of the ash stand. However, this aspect of their work is not discussed in further detail, since difference in forest type, boundary structure, exposure and the treatment of sunflecks on clear days make comparisons with this work impractical.

In addition to cloudiness, wind speed influences the intensity of light which penetrates to the forest floor. Working in several foliated deciduous stands near Minsk, Sakharov (1949) reports increases of 5 and 15 percent in average light intensity and range of fluctuation respectively, with an increase in wind speed from 0 to 15 mph.

In addition to cloudiness and wind, stand characteristics such as tree species and forest structure, density and condition determine the amount of light which penetrates to the forest floor. Summarizing several works, Geiger (1957) presents the general limits which, aside from extreme values, have actually been observed in oak forests. Expressed as percent of light intensity in the open, the values ranged from 3 to 35 percent for the foliated condition to 43 to 69 percent for the unfoliated one. The range of values for each condition reflects the influence of individual stand characteristics. In general, light penetration decreases with increasing density and/or with the number of canopy layers in the stand.

While methods of integrating sunflecks and shade light found under broad-leaved forests have provided data useful for many purposes, Evans (1956) considers this approach as an unrealistic one. At any moment under clear skies, light under the broad-leaved canopy is comprised of two components. The basic pattern of shade light is composed of sun and sky light filtered through the leafy green mass above plus sky light which passes through holes in the canopy. Superimposed on this is a patchwork of sunflecks dominated by sunlight which passes directly through holes in the canopy. Since it is unidirectional, the penetration of direct light is a function of the elevation angle of the sun. The spectral composition of the shade light has been investigated recently by Robertson (1964). Expressed as ratios of energy available in the red (640 mµ = 1.3X10^-5 ly/min/mµs), shade light under a hardwood stand near Ottawa showed the following values at 336, 440, 532, and 740 mµ respectively: 0.4, 1.4, 2.0, 7.3. Similar maxima in the green and far-red portions of the visible spectrum have been reported in other broad-leaved stands by Evans (1936). Coomer (1957) and others. Sunflecks, on the other hand, have the composition of sunlight (Evans 1956). It seems logical, therefore, that these components should be accounted for separately.

Working in a Southern Nigerian rain forest, Evans (1956) developed methods and instrumentation whereby the intensity and aerial and temporal distribution of sunflecks over a large area could be determined. Present only at midday during winter, sunflecks covered about 20 percent of the forest floor, but contributed 70 percent of the average daily light energy available under the stand. Sunflecks affected a particular spot on the forest floor for one hour a day, on the average. Intensities followed a curve of exponential decay. Although dependent upon several subjective estimates and an approximation concerning the spectral composition of shade light, Evans's results show the tremendous contribution which sunflecks make to the light environment in a broad-leaved tropical stand. Work of this nature in mid-latitude
broad-leaved deciduous stands is lacking at present.

**Temperature.** Temperature relationships both with regard to exposure microclimate and to the distribution of temperature within the stand proper are determined primarily by the radiation relationships discussed above. While research on the exposure microclimate of the forest boundary is lacking, that on slopes is fairly easy to find. Cantlon (1953), for example, investigated the temperature distribution near the ground on the wooded slopes of Cusheetunk Mountain, N. J. He points out that differences between north and south exposures were at a maximum during clear skies and practically nil during overcast, rainy weather. Averages based on all weather conditions showed that the margin by which the south was warmer was greatest at ground level, and decreased with height. Differences between slopes were greatest during fall and spring, and least during summer when the altitude angle of the sun was high.

In an oak forest with beech understory near Schweinfurt, Geiger and Amann (1931) found that temperature differences between sampling levels from the forest floor to above the canopy were greatest during clear skies, but practically nil during overcast, rainy weather. Under fair daytime skies, the upper foliated oak canopy was found to be the primary active surface, controlling temperatures immediately above the forest as well as those in the trunk space below. Temperatures decreased downward from the oak crown through the beech canopy to the forest floor. This lapse rate, of course, varies with the density of the stand. Geiger (1957), for example, reports a weak secondary maximum near the litter layer in thin stands where more solar radiation reaches the forest floor. By night, the canopy is the primary radiator, and thermal differences within the stand are small.

It is well known that with the loss of leaves the primary active surface shifts to the forest floor. However, systematic studies extending through all seasons are difficult to find. Working in a beech forest in Central Ohio, Christy (1952) found total deactivation of the forest floor during summer. As the leaves fell during autumn, greater amounts of insolation passed through the thinning canopy to activate the forest floor. During winter maximum and minimum temperatures within the stand characteristically occurred at the forest floor. However, the pattern was modified by the presence or absence of snow. Air temperatures at the surface of the snow were not measured, but differences between sensing elements within and at some distance above the snow recorded its insulating effect. This amounted to values well over 10°F. Similar results are reported by Sparkes and Buell (1955).

In spring, the leafing out of the trees returned the active surface to the forest canopy. The period before closure, during which maximum radiation penetrates into the stand, was marked by the development of extreme temperatures near the forest floor. Christy reports an extreme value of 121°F immediately over the litter, and a value of 109°F has been reported in oak forests in Central Europe (Geiger 1957). In discussing the latter study, Geiger states that Firasu found that the danger of extreme minimum temperatures was reduced because even the leafless trees formed an effective screen against outgoing radiation at night. Geiger (1957) also discusses Schmidt's results concerning the thermal conductivities of common active surfaces, and it is interesting to note that leaf litter showed the lowest conductivity of the substances studied. It was approached only by the low conductivity of snow. Irradiated litter quickly and efficiently returns large percentages of the heat energy incident upon it to the adjacent air. As demonstrated during spring, litter microclimate is one of extremes.

**Wind.** Air currents which encounter a forest move both over and into the stand. According to Geiger (1957), the currents are forced upward at the windward edge of the forest. The result is a dead air zone near the ground, estimated at 1.5 stand-heights in width. Both Iznka (1952) and Stoeckeler (1962) report a similar effect in the deflection of air currents in front of windbreaks. In the latter study, wind speed on the windward side near the barrier was reduced to 60 percent of that in the open, and a reduction of 10 percent or more extended to a distance of five barrier-heights in front of the windbreak. The fate of the wind which passes into the forest was shown in Woelfle's study reviewed by Geiger (1957). With weak winds, wind speed within the edge of a spruce stand was 20 to 30 percent of that in the open. With stronger winds, the percentage value decreased. The reduction in speed was attributed largely to the breaking action of the thick low growth characteristic of the edge of the stand. This was verified in Nesterova’s study reviewed by Molga (1962). Wind speed in a pine stand near Moscow was markedly reduced near the forest margin, but only slight additional reductions occurred within the stand. Within the forest proper, Geiger and Amann (1931) showed that the vertical wind speed distribution in a deciduous woodland is a function of both the structure and condition of the stand. Wind profiles within a pure oak stand (Stand 1) and an oak stand with beech understory (Stand 2) were fundamentally different. Within Stand 1, the wind speed was sharply reduced at the upper crown surface to a fairly low and uniform value within the canopy. It increased slightly in the trunk space, however, to show a relative maximum before falling off sharply at the forest floor. Within Stand 2, the wind speed was reduced at the upper surface of the oak crown, but remained stronger than the wind in Stand 1 throughout the upper levels, only to be gradually
reduced within the beech understory to speeds below those observed in the trunk space of Stand 1. This indicated that the wind penetrated more easily into Stand 1, and tended to flow both over and under the crowns. In Stand 2, however, the wind penetrated less easily and tended to converge at upper levels above the understory. These relationships existed during both the foliated and unfoliated condition, but wind speeds increased at all levels within both stands after the loss of leaves. Similar results are reported by Reifsnyder (1955), who compared his wind profile from an isolated pine stand without understory to profiles from both deciduous and conifer stands with and without understories.

The stagnation of air within a two-story forest is shown by the number of calm hours registered in the trunk space of the oak-beech stand discussed above (Geiger and Amann 1931). Calms occurred 67 percent of the time during the unfoliated condition, but increased to 98 percent during the foliated condition. Calms were defined as hours during which the anemometer did not move (starting speed 0.7 m/sec).

Although few studies are available concerning the wind distribution in the lee of the forest, the situation is similar to that observed in the lee of a shelterbelt (Geiger 1957). Wind speeds increase away from the stand as the currents forced over the canopy return to lower levels. In the windbreak study cited above, Stoeckeler reports wind speed reductions to 70 percent in the dead air zone immediately behind the barrier. Reductions as high as 50 percent were observed as far as 12 barrier-heights away from the windbreak.

Snow. Early investigators held conflicting views concerning the interception and distribution of snow in woodlands (Horton 1919). Problems in evaluating stemflow, snow drop from trees and winter evaporation rates, as well as the measurement of snow itself, have discouraged work on the dynamic aspects of the problem. Recent studies in New England have concentrated on snow accumulation and melt in relation to the hydrologic value of different forest types. The principles governing snow deposition at forest boundaries have received attention in shelterbelt research, a similar problem.

In Connecticut, Maule (1934) found that hardwood stands ranging from 20 to 80 years in age allowed almost equal amounts of snow to reach the ground as fell in the open. No significant differences in initial snow density occurred between fields and hardwood stands, and no drifting was observed within any forest. Hardwoods tended to retain individual snows an average of 0.5 days longer than surrounding fields. This tendency was proportional to the depth of snow; that is, shallow snows melted faster, proportionally, than deep ones. Conifers of various types accumulated less snow than hardwoods, but snow retention was longer in the conifers because of shading. Snow retention was longest in open fields or hardwoods where the ground was shaded by adjacent conifer stands. Pierce et al (1958) and Eschner and Satterlund (1963) present similar results concerning the hydrologic value of conifers versus hardwoods in the Northeast.

In mixed forests in the Adirondacks, Lull and Rushmore (1960) showed a consistent inverse relationship between average canopy closure and average snow accumulation and melt for the stands as a whole. However, the relationship broke down when individual points were considered, indicating that snow accumulation and melt were a function of canopy area other than that measured directly over the points in the study.

After summarizing several western studies, Kittredge (1948) concluded that maximum snow accumulation occurs in open stands where the trees or groups of trees have openings or glades between them. On the other hand, minimum accumulation occurs in dense stands where snow interception is at a maximum. The mature forest with many glades is therefore ideal for the accumulation of snow.

Stoeckeler (1962) showed that shelterbelt width and density influence the distribution of snow in and around the stand. Narrow and somewhat permeable plantings, involving one to six rows which are open at the ground line, lodge as much as 60 to 80 percent of the snow on the fields. Wider and denser plantings, involving seven or more rows which are dense near the ground, retain most of the snow within the shelterbelt. Working in Russia, Molchanov (1963) drew particular attention to the underbrush, which was very effective in reducing wind and consequently in depositing snow within the stand.

In a somewhat more basic approach, Finney (1934) investigated wind eddies and the drifting of flake mica and sawdust to leeward of model fences of 50 percent density in a wind tunnel. The distance to leeward of the fence at which the maximum depth of drift was found increased with the height of the fence, with the wind velocity and with decreasing density of the "snow."
Experimental design and methods

Description of sites. As seen in Figure 1, Hutcheson Memorial Forest is essentially an L-shaped woodland with its long axis oriented along a line extending from 105 degrees to 285 degrees. The extension from the main body of the forest on the south, and the triangular-shaped section extending from the top of the “L” on the northwest are not considered part of the main stand for purposes of this study. Representative sites on the north and south boundaries of the forest which were reasonably unobstructed from the rays of the sun and free flow of the wind, except for screening normally provided by the main body of the stand, were selected. These sites have similar soil profiles, and have had a similar vegetational history.

The north site, which was established approximately halfway (330 m) between the inside of the base of the “L” and the most northern point at the western section of the forest, actually faces an exact heading of 015 degrees. This position is unobstructed to wind between headings of 310 degrees clockwise to 090 degrees. Screening of the sun other than that normally caused by the main stand is limited to brief periods after and before sunrise and sunset respectively, during the summer half of the year. The base of the “L” on the east, for example, temporarily screens the horizon only near the time of the equinox. The forest extension on the west, on the other hand, is effective only near the summer solstice when the sun sets at its most northern point. The solar climate is therefore generally typical of any deciduous forest margin which faces slightly east of north. Topography is gently rolling with a slight grade of 2 percent sloping toward the west. The adjacent field was covered with orchard grass (Dactyliis glomerata) hay during the period of study.

The south site, which was established halfway (125 m) between the southwest corner of the main stand and the southern extension of woods, actually faces an exact heading of 195 degrees. This position is unobstructed to wind between headings of 165 degrees clockwise to 285 degrees, except that a block of woods to the west appears to reduce wind between 275 degrees and 285 degrees. The most serious disadvantage to this site is the presence of forest in the southeast quadrant. However, the disadvantage is not as great as might be expected because, as will be shown later, wind flow over the region is generally least frequent and weakest from the southeast. Although these woods screen the sun for a brief period after sunrise during winter, the influence is minimized because the trees are defoliated at the time. During the summer half of the year when the sun rises at azimuths north of the east point, the problem is eliminated because the main body of the forest rather than the southern extension screens the morning sun. The solar climate is therefore generally representative of any forest margin which faces slightly west of south. Topography is flat. The adjacent field was covered with soybean stubble during the winter months, but replanted to soybeans (Glycine max) in spring. A basic disadvantage at both sites was the lack of control of the cover on adjacent fields.

A forest station was established halfway (130 m) between the two boundary sites. Topography within the forest is flat except that a slope of 1 percent occurs just south of the north boundary. An old trail provides easy access between the three sites. All three are located on deep, well-drained silt loam according to Ugozini's (1964) soil map, although the south site is near a soil boundary beyond which moderately-drained land is found.

The section of the forest where the study was carried out has never been cleared and has seen a minimum of man's influence (Buell 1957). Cleared

![Fig. 1. Hutcheson Memorial Forest and vicinity. True north is directly at top of photograph. Solid lines indicate L-shaped main body of stand. Dotted lines indicate extensions of the forest or other obstructions. X= north site; X= south site; X= center site. See text for discussion. (Reproduced from U.S.D.A. photo.)](image-url)
during colonial times, the fields adjacent to the study sites have been worked agriculturally ever since (Buell 1957, F. Rogoginski, personal communication). The forest, then, is mature and unmanaged, and is characterized by gaps caused by blowdowns which eventually fill in with transgressive growth. The boundaries are well-stabilized, and have grown up to form a maze of growth characteristic of stand margins which have gone unattended for a number of years. The structure of the vegetation at the boundaries is basically different from that within the forest, and therefore is worthy of discussion.

The vegetation at the station in the center of the forest is stratified into the four distinct layers described by Monk (1961a). The tall, straight trunks of the oaks and dogwood tower over the shrub and herb layers, represented by maple-leaved viburnum and May-apple respectively, during early spring. Although not described by previous investigators, the dogwood layer appears to be present as two sub-layers in many places, with heights of lower and upper layers ranging from 15 to 25 feet and 25 to 35 feet respectively. The oak crowns occur between 40 and 95 feet.

At the boundaries all layers generally merge together to form a wall of vegetative growth. In the dogwood layer, most of the trees lean toward the adjacent fields, and it is not uncommon to observe trees with 75 to 100 percent of their branches on the field side of the tree (Figures 2 and 3). Although they are less marked, the same tendencies can be noted in the canopy layer (Figures 7 and 8, Pages 29 and 30). The mechanism, of course, is a phototropic response to the unidirectional light source during the growing season. The dogwood branching occurs close to the ground, and the height of the understory at the boundary seldom exceeds 12 to 14 feet. While the height of the overstory is less affected, branching occurs at lower levels and the crowns extend down over the shortened understory layer. Herbs and shrubs from the lower layers characteristically grow tall at the boundary and merge with the dogwood branches above them. Poison ivy (Rhus radicans) which grows up in clumps, as well as Japanese honeysuckle (Lonicera japonica) which often actually climbs the smaller trees, are especially effective in this manner. The merging of layers described here can also be seen in Figures 14 and 15 (Pages 40 and 41), which are actual vegetation profiles of the arborescent layers constructed from measurements made in the field. The north transect, on which the vegetation is more dense than the southern one, shows the transition toward the ecotone rather well.

The general composition of the vegetation at the three study sites is given in Table 1. The dominance of oak in the canopy is easily seen. Although different species contribute to the cover at the three sites, the total amount of cover and open space as well as the relative abundance are about the same. The most important difference between the sites from a microclimatic standpoint is the greater overlap at the boundaries, compared to the forest center site. Although some of this occurs back from the boundary, most of it is found within the wall of

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Fig. 2. North site. Winter aspect, looking east along boundary. Note form of vegetation and exposure of profile post and shelter housing hygrothermograph.

Fig. 3. South site. Winter aspect, looking east along boundary. Note same features as in Figure 2.
Table 1. Vegetative composition at study sites on north and south boundaries and in center of forest. Percent cover refers to the average linear distance covered by tree species or open space on three 50 m transects run perpendicular to the margin at each boundary and in the vicinity of station in center of forest. Number of trees (relative abundance) gives the total number of trees on the three transects at each site, and percent frequency gives their occurrence. Cover values greater than 100 reflect species overlap. Both the common and scientific names of each species are given when the species is the first mentioned in the text.

| CANOPY | North | | South | | | Center |
| --- | --- | --- | --- | --- | --- |
| % Cover | # Trees | % Freq. | % Cover | # Trees | % Freq. | % Cover | # Trees | % Freq. |
| Quercus alba | 28 | 5 | 100 | 30 | 8 | 100 | 43 | 6 | 100 |
| Q. velutina | 30 | 3 | 67 | 42 | 9 | 67 | 37 | 5 | 33 |
| Q. rubra & coccinea | 1 | 1 | 33 | 2 | 5 | 67 | 1 | 1 | 33 |
| Carya ovalis | 4 | 2 | 67 | 3 | 1 | 33 | 4 | 2 | 67 |
| Fagus grandifolia | 8 | 1 | 33 | 3 | 1 | 33 | 3 | 1 | 33 |
| Fraxinus americana | 72 | 15 | 100 | 38 | 10 | 100 | 64 | 11 | 100 |
| Acer rubrum | 82 | 13 | 100 | 72 | 15 | 100 | 111 | 108 | 102 |
| Total cover & trees | 100 | 108 | 100 | 100 | 100 | 100 |
| Open space | 29 | 100 | 72 | 15 | 100 | 38 | 100 | 100 |
| Total | 111 | 108 | 100 | 100 | 100 | 100 |

| UNDERSTORY | | | | | | |
| Cornus florada | 85 | 29 | 100 | 55 | 20 | 100 | 92 | 42 | 100 |
| Fraxinus americana | 13 | 5 | 67 | 8 | 6 | 67 | 6 | 6 | 100 |
| Prunus avium | 8 | 2 | 67 | 7 | 2 | 67 | 7 | 2 | 67 |
| Acer rubrum | 6 | 2 | 67 | 4 | 2 | 67 | 4 | 2 | 67 |
| Acer platanoides | 1 | 1 | 33 | 1 | 1 | 33 | 1 | 1 | 33 |
| Quercus alba | 4 | 1 | 33 | 6 | 2 | 67 | 5 | 1 | 33 |
| Q. rubra & coccinea | 1 | 1 | 33 | 1 | 1 | 33 | 1 | 1 | 33 |
| Carya ovalis | 5 | 1 | 100 | 25 | 10 | 100 | 109 | 112 |
| Total cover & trees | 117 | 50 | 50 | 84 | 45 | 45 | 102 | 49 | 49 |
| Open space | 5 | 100 | 25 | 100 | 10 | 100 |
| Total | 122 | 100 | 100 | 100 | 100 |

vegetation at the margin of the stand (Figures 14 and 15). It is in the understory that significant differences occur at the three sites. The dominance of dogwood in this layer is easily seen, but the cover and number of trees is less at the south boundary. The largest amount of open space occurs on the south. Referring once again to Figure 15, it can be seen that the openings typically occur toward the interior of the stand. Ten dead dogwood trees were noted in this area. Some of these trees are undoubtedly the same ones recorded by Small (1961), who surveyed dead and damaged trees throughout the entire forest after the drought of 1957. Dendrometer readings conducted by Buell, Buell, Small and Monk (1961) during 1957 showed that the effect of drought on the radial growth of trees throughout the forest was indeed great. It is interesting to note that drought has been prevalent during the years since these studies were made. During the 5-year period from 1960 to 1964, for example, every year was deficient in precipitation. The deficiencies ranged from approximately 2 and 5 inches in 1960 and 1961 to 5, 12 and 9 inches during 1962, 1963 and 1964. It is probable that these conditions have resulted in the increased mortality of dogwood observed at the south site.

Small percentages for oaks and hickory noted in the understory at both boundaries as opposed to the center of the forest once again reflect the coalescence of layers at the margin of the stand. The percentage of open space in the canopy at the center site is high in comparison to Monk's (1961a) value of 7 percent for the well-drained section of the forest as a whole. On the other hand, the understory is slightly denser than normal. Since the vegetation at the boundaries has not been studied in detail, comparable figures are not available for these sites. However, looking at the overall picture, the vegetation is dense on the north and thin on the south, with the center site intermediate between the two. Since this is reasonable from an ecological standpoint, it appears that the vegetation at the three sites is fairly representative of conditions as a whole.

Methods — microclimate and vegetation. — Light. A grid composed of three transects running perpendicular to the forest from one tree height within the stand across the margin to two tree heights in the adjacent field was established at each boundary site. These transects lay ½H apart. (Tree-height is designated as “H” in further discussion. The height of the canopy averages approximately 25 m in the vicinity of each site.) They will be referred to hereafter as the northeast, north center and northwest transects on the north boundary, and the southeast, south center and southwest transects on the south boundary. Light measurements were made at ⅛H intervals during winter and spring, but shortened to ⅛H (approx. 3 m) during the foliated season. In addition, a grid of 15 points was established at the station in the center of the forest.

The seasonal change in light intensity penetrat-
ing to a height of approximately 1 meter above the forest floor was determined by traversing the three grid systems with a Brockway Model S photometer between the hours of 1140 and 1220 EST periodically during the 9-month period. The time required to cover the grid ranged between 25 and 40 minutes. New Jersey is bisected by a standard meridian (75° W), and this time period closely approximates true solar noon. Observations were initially made during periods of both clear and overcast skies when the wind speed averaged less than 10 mph. However, the overcast observations were discontinued during spring and summer because of the inconsistency of the overcast and resultant shift in light values outside the stand. Haze and cloudiness limited the number of representative observations obtained during summer. In all, ten days of data were discarded because unfavorable conditions of cloudiness or wind developed during the observations. The remaining 28 observations, the periodicity of which was largely determined by the weather, are summarized according to season in Table 2.

Table 2. Periodicity of light measurements, by seasons.

<table>
<thead>
<tr>
<th>Season</th>
<th>Clear skies</th>
<th>Overcast skies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>25 Nov; 4, 16, 21, 30 Dec</td>
<td>6, 7, 21 Nov; 3, 12 Dec; 6 Feb</td>
</tr>
<tr>
<td>Spring</td>
<td>22 Feb; 13, 16, 19, 23 Mar; 1, 10, 16 Apr; 4, 11, 18, 25 May</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>5, 11, 18, 25, 26, 29 June</td>
<td></td>
</tr>
</tbody>
</table>

Field technique involved the measurement of a representative light intensity at each point on the grid. During winter and early spring, this could be obtained fairly easily because marked changes in intensity occurred only in shadows cast by individual trunks and large limbs. During the foliated season, representative values could be obtained only by separate measurement and analysis of shade and sunfleck light.

The Brockway Model S photometer is fairly inexpensive and has the advantage of maximum portability in the field. Covered with an opalescent hemispherical light collector, the horizontal sensor of this instrument is responsive to wavelengths within the visible spectrum (Brockway Camera Corp. 1957). It reads directly in foot-candles. Robertson and Holmes (1963), Evans (1956) and Saeki (1963) have commented on the advantages and disadvantages of this type of instrument when used in the field. Robertson and Holmes, for example, call attention to its non-linear response, while Evans points out that measurements in foot-candles cannot be converted to absolute energy units (langleys) unless the spectral composition of the light can also be determined. However, the instrument does provide a measure of solar radiation within the spectral range where most plant photochemical reactions occur, and is therefore more useful than a pyranometer for many purposes (Evans 1956, Saeki 1963).

Results of the light study are expressed in the commonly used "percentage penetration of light." It should be remembered that when determined with a photometer, this is not strictly a true percentage, because the ratio is a comparison of two different kinds of light. This is particularly true under foliated conditions, when the shade light of the forest is richer than the open light in the green and far-red portions of the visible spectrum. However, such arbitrary units have often been used effectively when the purpose was merely to distinguish light climates within adjacent areas of the stand. They have been employed here with this purpose in mind.

Temperature. The vertical temperature distribution near the ground at each boundary and within the forest proper was investigated through the establishment of profile posts at the center of the light grid at each location. At the boundaries the post was situated halfway between the trunk and periphery branches of the trees at the margin of the stand (Figures 2 and 3). Each location was representative of conditions found along the boundary as a whole. Although different species contributed to the cover, the amount of cover over each post was similar. A post was also established under average cover at the site within the stand. In selecting the levels for observation, an attempt was made to sample heights which would give meaningful meteorological results, and at the same time correspond to the layers of the vegetation in the forest. Therefore, the levels selected were 5 centimeters, 1 meter and 2 meters, which correspond to the herb, shrub and trunk space of the stand respectively. Two meters is also close to the height used for standard macroscopic weather observations.

Temperature measurements were made at the locations and levels mentioned above with standard weather bureau maximum and minimum thermometers housed in aluminum shields. These shields, originally designed by Thornthwaite, have been used effectively by investigators (Cantlon 1953, Sparkes and Buell 1955) at Rutgers - The State University, and have been briefly described in the literature by Baum (1949). They are designed to minimize radiation and precipitation effects, but at the same time allow maximum ventilation. The thermometers were read at bi-weekly intervals from November 22, 1963 to August 31, 1964.

In addition to the above readings, a continuous record of air temperature at approximately 5 cm above the ground at each site was obtained through the use of Belfort Model 594 bourdon tube-type hygrothermographs housed in miniature instrument
shelters (Figures 2 and 3). These shelters were constructed of aluminum louvers secured to a wooden frame with a slatted bottom and solid wooden top. They were placed close to the temperature profile post at each site, with the door of the shelter facing north. In view of the differences in construction between the shelters and shields, fairly good agreement was achieved between the two types of readings.

The main purpose of the hygrothermographs was to determine approximately when the maximum and minimum temperatures occurred at the thermometers on the profile posts. A cool, clear day favorable for the development of high temperatures near the ground might well be followed by a warm, overcast one, during which maximum temperatures at all levels were about the same. With this sequence of weather, it is not impossible to experience a maximum temperature at 5 cm from the first day, while upper levels record the maximum temperatures of the warmer second day. This occurs only when temperatures at all levels on the second day fall between those recorded near the ground and at the upper levels on the first day. It is fairly infrequent. Depending upon the sequence of weather in relation to when the thermometers were read, similar discontinuities were observed with minimum temperatures. This type of discontinuity may arise whenever the thermometers are read at intervals greater than one day, and was not previously reported in studies similar to this one. Although it is probably of less significance in descriptive studies, profile continuity was a necessity here. A tedious cross-check of temperatures in the shelters and shields with temperatures at similar levels observed on a daily basis at the nearby micro-meteorological station at the New Jersey Agricultural Experiment Station proved satisfactory for the elimination of unrepresentative data. In all, 16 out of 174 observations were discarded for this or similar reasons.

Spot measurements of soil, litter and air temperatures at various locations and times were made with a copper-constantan thermocouple and Leeds and Northrup portable potentiometer which read directly in degrees Fahrenheit.

Wind. Although actual measurement of the wind field at the margin of the stand was beyond the scope of this work, an idea of the general wind flow at the forest was determined through a system whereby Beaufort wind estimations made in the woods were compared to measurements of wind speed and direction observed at approximately the same time at the U.S. Weather Bureau Office in Newark. When these data were considered in relation to blocking angles and obstructions at the forest determined through the interpretation of an aerial photograph, results were obtained which gave an indication of the wind flow at the three sites studied.

Snow. Snow depth was measured on the same grid system that was used in the light study. Measurements were made with a calibrated stick at \( \frac{1}{2} \)H intervals on the grid, except that several locations were sampled in the immediate vicinity of the forest margins where considerable variation in depth occurred. The depth at any one location was determined by averaging the values of between three and seven measurements made at the spot. Initial snow distribution was determined on several occasions when it was practicable to get to the woods immediately after the snow stopped. Snow retention was determined through measurements taken on the scheduled bi-weekly trips to the woods. On several occasions the author remained in the forest during periods of light snow to observe drift angles and interception of falling snow.

Vegetation. The study of vegetative influences on microclimate was primarily an investigation of the composition, structure and phenology of the arborescent layers in the vicinity of the three study sites. The composition and structure of the vegetation were studied through the use of the line transect method described by Buell and Cantlon (1950), which was modified slightly for the purpose at hand. Three 30-meter transects were run at each site. At the site in the center of the forest these were run in an east-west direction, and were located at the temperature station and at distances of \( \frac{1}{2} \)H to the north and south. At the boundaries, the transects were run on the light grids. The cover contributed on the transects by each individual tree, its approximate height, length of crown and trunk, and dbh were determined. A range pole proved helpful in determining height. Both the range pole and a cover sight described by Buell and Cantlon were used to project crown distances to the ground where they were measured on a tape.

An attempt was made to determine as many dates as possible for phenological changes in the vegetation such as leaf fall, first vegetative growth in spring, first flowering and leaf expansion. Dates given represent the time when approximately half of the individuals of a particular species showed the event. Measurements of leaf expansion of flowering dogwood growing on both boundaries were made on a weekly basis with a millimeter ruler in order to quantify canopy closure in spring. The leaf buds selected for this work had a similar aspect on trees which were approximately the same height and dbh, and showed a similar habit of growth.


Methods — macroscale weather and climate. The study of the influence of macroscale weather and climate on microclimate followed two main paths of effort. The first involved comparisons between microclimate at the forest and macroscale weather as observed at a nearby weather station, whereas the second was a comparison between the weather during
the study period and climate.

Comparisons of weather and microclimate were made in a number of ways, and this aspect of the study was dependent upon the selection of a station where observations were made on a 24-hour basis which could be considered as representing general weather conditions over the region as a whole. The only station which met this requirement was the U.S. Weather Bureau Station at Newark Airport, which is located 25 miles northeast of the forest. A weather station at Trenton was not used because it did not function routinely on a 24-hour basis, while another at Philadelphia was too far (49 miles) from the forest. A question arose as to the representativeness of Newark's data because the station is located fairly close to the coast. However, discussions with the forecasters at Newark revealed that the influence of the ocean is minimal at the station, the most significant influence being the irregular occurrence of sea breezes during late morning and afternoon hours on clear, calm days during the warm season of the year. Biel (1958) has commented on the high continentality of all stations in New Jersey, and the fact that significant marine influence is restricted to an extremely narrow strip near the ocean. Although located only 1.9 miles from Newark Bay, Newark Airport is separated from the Atlantic Ocean by Staten Island, so that open water is actually over 10 miles away. Comparison of existing climatic normals (Blood 1953, U.S.W.B. 1962 and 1964) for Trenton,Philadelphia and Newark, mainly with regard to surface wind, showed only minor differences between the three. To the extent to which it was used, Newark data proved satisfactory for the purpose at hand. When daily data would suffice, observations from U. S. Weather Bureau climatological observation sites were employed. These included sites at Flemington, Somerville and New Brunswick, which were approximately 12, 5 and 8 miles distant from the forest respectively.

The evaluation of weather was in part a comparison of monthly frequencies of air masses and air mass changes during the current period to comparable climatic averages based on twenty years of data. As such, it represents an application of the dynamic climatology or "air mass calendar" prepared for New Jersey by Havens (1948). In the original work, the author listed four air mass types, defined their properties and discussed the synoptic situations under which they influenced the State. Based on surface weather features, the actual tabulations of the air mass frequencies were carried out through the examination and in some cases re-analysis of the Daily Weather Map issued by the U. S. Weather Bureau. The occurrence of each air mass, in days or fractions of a day (smallest unit 6 hr), as well as the incidence of frontal passages were tabulated, and the results expressed in terms of monthly frequencies of air masses and changes in air mass. When an air mass was significantly modified while situated over New Jersey, the change was listed as "gradual." Although only seven years of data were available for the original study, the work continued over the years, and 20-year averages were recently completed by Pereira (1961).

In the present study, nine months of data were examined and the results compared to the normals. Since the analysis is dependent upon the air mass definitions given by Havens, this information as summarized from the original work is given in Table 3. It will be noticed that two of the air masses are actually composite types, representing different air masses which give rise to the same weather over the State. For additional information, the reader is referred to Havens (1948).

Table 3. Air mass types influencing New Jersey, after Havens (1948).

<table>
<thead>
<tr>
<th>cP — Continental Polar Air:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>In winter, unmodified air with a direct trajectory from snow-covered regions of Canada. Coldest and driest air affecting New Jersey.</td>
<td></td>
</tr>
<tr>
<td>In summer, slightly modified air with direct trajectory from northernmost extremities of continent. Driest air affecting New Jersey.</td>
<td></td>
</tr>
</tbody>
</table>

| NeP — Neutralized Continental Polar Air: | |
| Modified Polar Pacific air (mPp) warmed and dried while passing over the Rocky Mountains |
| OR |
| Modified cP air warmed during a short traverse through southern states or rarely in summer by a slow-moving trajectory from Canada. Mild air mass, often very similar to mT air in summer but marked by cooler nights and lower humidity. |

| mP — Maritime Polar Air: | |
| Air which has experienced a long trajectory over the cold waters of the northwestern Atlantic Ocean, and consequently has been moistened. Fairly mild temperatures, bringing relief from cold cP in winter or mT in summer |
| OR |
| mT which has been moistened by evaporation from falling rain, regardless of whether or not a marine trajectory was followed. |

| mT — Maritime Tropical Air: | |
| In winter, slightly modified warm moist air from Caribbean Sea and Gulf of Mexico, reaching New Jersey only in warm sectors of traveling disturbances. |
| In summer, hot humid air occurring as above, or more commonly advected into New Jersey on southwest winds associated with intensification and northern development of Bermuda High. |

In studying some basic and applied problems concerning surface winds in New Jersey, Blood (1953) discussed the fact that while the surface
wind on a particular day is not necessarily an identifier of air mass, the predominant winds during each season are an indicator of the controlling air mass. On the assumption that the latter effect would apply during a shorter period of time, such as a month for example, the monthly frequencies of wind directions at Newark for both the current year and a 10-year period were computed from climatological data (U.S.W.B. 1962 and 1964) and compared in relation to the air mass frequencies discussed above. In addition, mean wind speeds by direction were also tabulated. The combination of these three parameters summarized with routine tabulations of individual elements such as temperature and precipitation gave a complete dynamic evaluation of the weather during the period in relation to climate. This information was called upon to interpret the microclimatic results obtained at the forest.
Results and discussion

Macroscale weather (Dec ‘63-Aug ‘64) versus climate. As part of a 5-year descriptive study of the microclimates of various habitats within a valley in Ohio, Wolfe et al (1949) plotted macroscale temperature and precipitation departures from climatic means in order to show that the weather during the period was a fair sample of climate. The fact that these values did not exceed published 50-year climatic extremes was taken to mean that the weather during the period was representative of climate. Similar although less elaborate descriptive comparisons of weather to climate often form a part of microclimatic studies. To cite only one recent example, Lull and Rushmore (1960) comment briefly on macroscale temperature and snowfall departures during the period of their study concerning snow accumulation and melt under mixed forest stands in the Adirondacks. Comparisons of this type are intended to show the influence of macroscale weather on microclimate, and to indicate the validity of microclimatic results based on a short period of weather. However, the statistical tabulations of individual weather elements such as temperature and precipitation used in these studies provide, by themselves, no more than a partial description of weather and climate. Such tabulations show nothing concerning the actual atmospheric dynamics involved.

Havens (1948) has stressed the point that the use of dynamic climatology helps to explain, in physical terms, how statistical tabulations of individual weather elements actually come about, and in addition, provides an excellent means of describing and explaining the effects of climate on plant and animal life. In the present study, Havens’ air mass calendar is supplemented by the use of wind data in order to evaluate the weather during the study period. The purpose was to present a dynamic comparison between weather and climate, so that the features of New Jersey’s climate best displayed during the period could be related in physical terms to microclimatic results obtained in the forest. In the discussion which follows, the 9-month period of study is divided into the three commonly-defined meteorological seasons, and the weather of each month is discussed within the season.

Winter. The fact that New Jersey’s winters are dominated by continental sub-polar control is readily seen in the averages shown in Tables 4, 5 and 6. In January, for example, continental and Polar air masses show frequencies of 72 and 98 percent respectively (Table 4). The most frequent air mass is the composite-type NCp, which is followed by cP, mP and mT air masses respectively. Perhaps the most striking feature is the low frequency of mT air. Days with air mass changes, which are usually but not always accompanied by precipitation, occur 58 percent of the time. In spite of veering and backing associated with these storms, the January wind regime at Newark shows that winds from northern quadrants (NW clockwise through NE) blow 50 percent of the time as opposed to only 25 percent for southern quadrants (SE clockwise through SW) (Table 5). Similar wind frequencies, used in part to demonstrate the monsoonal tendencies in New Jersey’s climate were noted earlier at Trenton (Biel 1958). The most frequent wind direction during winter at Newark is northwest, except during December when southwest and west winds prevail. The strongest winds are always northwest (Table 6), so

Table 4. Frequency (%) of air masses and air mass changes during winter in N.J. Dec 63-Feb 64 vs. averages 41-61. (a) indicates average values.

<table>
<thead>
<tr>
<th>cP</th>
<th>NCP</th>
<th>mP</th>
<th>mT</th>
<th>C</th>
<th>m</th>
<th>P</th>
<th>T</th>
<th>Days w</th>
<th>Days o</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec</td>
<td>49</td>
<td>10</td>
<td>0</td>
<td>90</td>
<td>10</td>
<td>100</td>
<td>0</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>Dec (a)</td>
<td>29</td>
<td>45</td>
<td>23</td>
<td>3</td>
<td>74</td>
<td>26</td>
<td>97</td>
<td>3</td>
<td>57</td>
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<tr>
<td>Jan</td>
<td>22</td>
<td>53</td>
<td>23</td>
<td>2</td>
<td>75</td>
<td>25</td>
<td>98</td>
<td>2</td>
<td>68</td>
</tr>
<tr>
<td>Jan (a)</td>
<td>30</td>
<td>42</td>
<td>26</td>
<td>2</td>
<td>72</td>
<td>28</td>
<td>98</td>
<td>2</td>
<td>58</td>
</tr>
<tr>
<td>Feb</td>
<td>40</td>
<td>34</td>
<td>26</td>
<td>0</td>
<td>74</td>
<td>26</td>
<td>100</td>
<td>0</td>
<td>69</td>
</tr>
<tr>
<td>Feb (a)</td>
<td>28</td>
<td>46</td>
<td>24</td>
<td>2</td>
<td>74</td>
<td>26</td>
<td>98</td>
<td>2</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 5. Frequency (%) of wind direction during winter. Dec 63-Feb 64 vs. averages 41-60. Newark, N.J.

<table>
<thead>
<tr>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
<th>Calm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec</td>
<td>9</td>
<td>14</td>
<td>3</td>
<td>2*</td>
<td>4</td>
<td>14</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Dec (a)</td>
<td>10</td>
<td>12</td>
<td>5</td>
<td>3*</td>
<td>7</td>
<td>22</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>Jan</td>
<td>11</td>
<td>13</td>
<td>8</td>
<td>3*</td>
<td>8</td>
<td>19</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>Jan (a)</td>
<td>14</td>
<td>12</td>
<td>5</td>
<td>2*</td>
<td>7</td>
<td>16</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Feb</td>
<td>12</td>
<td>11</td>
<td>6</td>
<td>2*</td>
<td>3</td>
<td>9</td>
<td>27</td>
<td>30</td>
</tr>
<tr>
<td>Feb (a)</td>
<td>12</td>
<td>12</td>
<td>8</td>
<td>4*</td>
<td>7</td>
<td>15</td>
<td>17</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 6. Mean wind speed (mph) during winter, by direction. Dec 63-Feb 64 vs. averages 41-60. Newark, N.J.

<table>
<thead>
<tr>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec</td>
<td>11.0</td>
<td>9.6</td>
<td>7.5</td>
<td>9.5</td>
<td>7.0*</td>
<td>7.5</td>
<td>11.4</td>
<td>13.9</td>
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<tr>
<td>Dec (a)</td>
<td>10.2</td>
<td>9.0</td>
<td>7.8</td>
<td>7.0*</td>
<td>7.6</td>
<td>7.1</td>
<td>9.4</td>
<td>11.8</td>
</tr>
<tr>
<td>Jan</td>
<td>15.8</td>
<td>13.7</td>
<td>8.2*</td>
<td>8.5</td>
<td>9.0</td>
<td>8.9</td>
<td>12.9</td>
<td>16.2</td>
</tr>
<tr>
<td>Jan (a)</td>
<td>12.2</td>
<td>10.3</td>
<td>6.8</td>
<td>6.4*</td>
<td>7.5</td>
<td>8.4</td>
<td>11.4</td>
<td>14.4</td>
</tr>
<tr>
<td>Feb</td>
<td>14.1</td>
<td>13.8</td>
<td>11.1</td>
<td>7.1*</td>
<td>9.3</td>
<td>9.4</td>
<td>11.7</td>
<td>15.4</td>
</tr>
<tr>
<td>Feb (a)</td>
<td>12.2</td>
<td>10.3</td>
<td>8.0</td>
<td>7.2*</td>
<td>8.1</td>
<td>8.6</td>
<td>11.9</td>
<td>14.8</td>
</tr>
</tbody>
</table>

Bold numbers denote maximum frequency or wind speed. Italic numbers denote second greatest frequency or wind speed. * Denotes minimum frequency or wind speed.
that the most frequent wind is also the strongest wind during most of the winter. The least frequent and lightest winds are always southeast. The air mass regime is amazingly uniform over the 3-month period. Except for wind direction in December, the same fact can be noted concerning the wind data.

December, 1963 was characterized by a frequency of cP air which was 20 percent above the long-term mean. This was accompanied by a significant decrease in the frequency of each type of maritime air. Continental air masses were 16 percent above average, and days with air mass changes were reduced by 22 percent. This indicates that cold, dry air tended to stagnate over the State. The increased dominance of continental sub-polar control is also reflected in the wind data, where the most frequent directions shift to the west and northwest from more southerly quadrants. The month was divided into two regimes. From the 1st to the 8th NcP air from the Far West (modified Polar Pacific air, abbreviated mPp, and classed as NcP air by definition in this study) dominated, but from the 9th to the 31st cP air held almost complete control. Advection of this air from Northwestern Canada was favored by meridional upper air flow with a ridge over the West Coast. Two storms produced 1.52 inches of the 1.97-inch total precipitation recorded during the month. The first storm was a depression which moved along the Alberta track on the 8th, whereas the second was a Gulf low which moved up the Atlantic Coast on the 23rd. The latter dumped 7.4 inches of snow (0.69 in. melted precip.) at Newark. The high frequency of cP air accounts for an exceptionally cold December which was 5.4°F below average in monthly temperature. This, coupled with the decreased frequency of maritime air and reduction of air mass changes, brought about a negative precipitation deviation of 1.25 inches. On the other hand, snowfall was 2 inches above average, with approximately three-fourths of the total produced during the Gulf storm of the 23rd.

January, 1964 was characterized by a frequency of NcP air which was 11 percent above average. Under the influence of southwest flow in the upper air east of the Rocky Mountains, mPp air masses arrived in New Jersey in association with west and southwest winds. This situation is reflected in the wind data, which show a shift in maximum frequencies from northwest and west to west and southwest directions. Days with air mass changes were 10 percent above average. Continental Polar air masses, the frequency of which was 8 percent below average, tended to remain in Canada. A notable exception to this pattern occurred at mid-month, and played a role in producing the only significant snowstorm in January, which was also the largest single snowfall of the season. Since the synoptics will be discussed later, it suffices to say here that this storm originated over the Southeastern United States and adjacent waters, and eventually moved northeastward up the Atlantic Coast. As the storm moved north, Polar air was advected into the system. The combination of low temperatures, high winds and blowing snow brought near blizzard conditions to New Jersey. Almost 13 inches of snow (1.20 in. melted precip.) were recorded at Newark. However, the month as a whole was relatively mild. The increased frequency of NcP air which occurred near the beginning and end of the month accounts for a monthly temperature 1.0°F above average. The increased frequency of air mass changes accounts only in part for a positive precipitation deviation of 1.79 inches. Actually, 3.62 inches of the 5.12-inch total occurred during three storms, two of which originated in the Gulf of Mexico. One of these storms produced 13 inches of snow which is approximately twice the average amount recorded in January.

February, 1964 was marked by a frequency of cP air which was 12 percent above average. As opposed to December when the increase was accompanied by a decrease of maritime air, in February it was associated with a reduction (12%) of NcP air. Thus, the moisture lacking in December was available in February. The increased frequency of cP air is reflected in the wind data, where the percentages of northwest and west winds are increased by 7 and 10 percent respectively. Air mass changes were 9 percent above average. With a varied pattern in the upper air, the main features displayed on surface weather maps were the push of cold air southward and the development of Gulf lows. Triggered by cold air from the north, five waves developed into depressions and moved northeastward along the Atlantic Coast to bring precipitation to New Jersey. As opposed to January when these storms were noted for the quantity of precipitation produced by each storm, in February the significant thing was their frequency. Primarily because they moved off rapidly to the northeast, the amount of precipitation produced by any one storm averaged less than a half inch. However, the five storms accounted for 2.14 inches of the 2.59-inch total recorded during the month. Most of it occurred as snow, so that while the precipitation total was slightly below (0.21 in.) average, the amount of snow was double the long-term mean. Temperature was 1.8°F below average, largely due to the increased frequency of cP air.

The winter of the study period can be described in three words — cold and snowy. In February, mid-January and especially in December, the frequent occurrence of cP air masses kept temperatures below to much below average. This pattern was broken only during the early and later parts of January, when NcP air masses advected in from the southwest brought temperatures which were well above average. It is interesting to note that these two periods, centered on the 6th and 23rd respectively.
correspond to the time described by Wahl (1952), Duquet (1963) and others as favorable for the occurrence of January thaw. Furthermore, the synoptic pattern mentioned by these authors as being related to the occurrence of thaw can be noted on the maps during both periods. That is, Midwest trough-East Coast ridge, resulting in southwesterly flow over the East Coast. This apparent singularity has remained a controversial subject in the literature for years.

From the standpoint of microclimate, the significant fact is that except during the periods of thaw, the above average snowfall tended to remain on the ground for long periods. A snow cover of one inch or more covered the ground at most stations in Central New Jersey from the first significant snowfall of the season on December 12th to January 3rd during the first warm period. The 13-inch snowfall of January 13th was melted by rain on the 20th. In February, snow covered the ground almost continuously from the 10th to the 29th of the month. Thus, snow rather than forest litter functioned as the active surface during much of the period.

Perhaps more important than the above is the fact that every large snowstorm of the season was a depression which developed in the Gulf of Mexico or Atlantic Coastal Waters south of Cape Hatteras, and eventually moved up the Atlantic Coast. Since New Jersey usually experiences low ceilings and precipitation in association with strong northeast winds as the low center moves east of the State, these storms have been termed "northeasters" by the general public. They are well known to weather forecasters as producers of precipitation, especially snow. Thus, the above-average snowfall contributed largely by "northeasters," as well as the long periods of snow cover during the Winter of 1963-64, provided an excellent opportunity to study the dynamics of snow in New Jersey — from its production in the atmosphere to its distribution and eventual melt at the margins of the forest stand.

Spring. The fact that spring in New Jersey is a transitional season, characterized by a swing from continental sub-polar toward humid sub-tropical control, is readily seen in the averages shown in Tables 7, 8 and 9. In terms of air mass and wind direction frequencies, as well as mean wind speed by direction, March is similar to the winter months. Although there are slight shifts among the Polar air masses, perhaps the most significant thing is a 6 percent reduction in continental air. A notable feature is that March is the windiest month, showing mean wind speeds stronger than the other months for six of the eight directions. In April, cP air is reduced by 11 percent, whereas both of the maritime air masses increase slightly in frequency. Continental air is reduced an additional 7 percent. Wind direction frequencies show a swing from northern toward southern quadrants. However, it is in May that

major changes appear. A 13 percent decrease in cP air is coupled with a 12 percent increase in mT air. Continental air masses drop below 50 percent, and tropical air approaches a high near 20 percent. Wind frequencies for southern quadrants are slightly greater than those for northern ones. Although there is no prevailing wind, the emphasis is on southwesterly flow. Days with air mass changes during spring are similar to those experienced in winter. This brings to mind the fact that both air mass contrasts and intensity of circulation are greatest during winter and spring. Maritime Polar air masses show their maximum frequency during this period. However, the overall picture is one of a swing from continental sub-polar toward humid sub-tropical control. It is interesting to note that southeast winds remain the least frequent in direction, and that although southwest winds become the most frequent, the strongest winds remain from the northwest.

**MARCH, 1964** was characterized by near average values for both the air mass and wind data. In this case, it was the sequence of weather rather than marked departures from the totals and averages which made the weather interesting. With southwest flow

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**Table 7. Frequency (%) of air masses and air mass changes during spring in N.J. Mar 64-May 64 vs. averages 41-61. (a) indicates average values.**

<table>
<thead>
<tr>
<th>Days</th>
<th>Days</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>cP</td>
<td>NcP</td>
<td>mP</td>
</tr>
<tr>
<td>Mar</td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>Mar (a)</td>
<td>33</td>
<td>36</td>
</tr>
<tr>
<td>Apr</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>Apr (a)</td>
<td>22</td>
<td>39</td>
</tr>
<tr>
<td>May</td>
<td>12</td>
<td>47</td>
</tr>
<tr>
<td>May (a)</td>
<td>9</td>
<td>40</td>
</tr>
</tbody>
</table>

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**Table 8. Frequency (%) of wind direction during spring. Mar 64-May 64 vs. averages 51-60, Newark, N.J.**

<table>
<thead>
<tr>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
<th>Calms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar</td>
<td>11</td>
<td>12</td>
<td>4</td>
<td>8</td>
<td>17</td>
<td>15</td>
<td>20</td>
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<tr>
<td>Mar (a)</td>
<td>13</td>
<td>14</td>
<td>10</td>
<td>6</td>
<td>11</td>
<td>16</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Apr</td>
<td>11</td>
<td>11</td>
<td>24</td>
<td>8</td>
<td>9</td>
<td>16</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Apr (a)</td>
<td>10</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>16</td>
<td>13</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>May</td>
<td>10</td>
<td>11</td>
<td>13</td>
<td>7</td>
<td>6</td>
<td>23</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>May (a)</td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>9</td>
<td>10</td>
<td>19</td>
<td>12</td>
<td>4</td>
</tr>
</tbody>
</table>

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**Table 9. Mean wind speed (mph) during spring, by direction. Mar 64-May 64 vs. averages 51-60, Newark, N.J.**

<table>
<thead>
<tr>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar</td>
<td>12.3</td>
<td>10.3</td>
<td>10.2</td>
<td>9.9</td>
<td>9.1*</td>
<td>10.7</td>
<td>12.4</td>
<td>17.0</td>
</tr>
<tr>
<td>Mar (a)</td>
<td>12.5</td>
<td>11.2</td>
<td>10.4</td>
<td>10.1</td>
<td>9.1*</td>
<td>9.4</td>
<td>13.0</td>
<td>14.4</td>
</tr>
<tr>
<td>Apr</td>
<td>11.3</td>
<td>11.9</td>
<td>10.7</td>
<td>8.6*</td>
<td>10.0</td>
<td>9.4</td>
<td>10.3</td>
<td>14.6</td>
</tr>
<tr>
<td>Apr (a)</td>
<td>12.2</td>
<td>11.1</td>
<td>9.0</td>
<td>9.2</td>
<td>8.9*</td>
<td>9.8</td>
<td>12.1</td>
<td>14.1</td>
</tr>
<tr>
<td>May</td>
<td>11.1</td>
<td>10.1</td>
<td>9.6</td>
<td>11.0</td>
<td>8.7*</td>
<td>11.2</td>
<td>12.9</td>
<td>14.4</td>
</tr>
<tr>
<td>May (a)</td>
<td>10.8</td>
<td>10.2</td>
<td>8.4*</td>
<td>9.0</td>
<td>8.8</td>
<td>9.3</td>
<td>10.7</td>
<td>12.9</td>
</tr>
</tbody>
</table>

Bold numbers denote maximum frequency or wind speed. Italic numbers denote second greatest frequency or wind speed. * Denotes minimum frequency or wind speed.
in the upper air, three depressions moved from the Southern Plains northeastward over the Ohio Valley and to the St. Lawrence River during the first ten days of the month. Maritime Tropical air entered New Jersey preceding cold frontal passages on the 5th and 10th. Squall line activity developed in the warm, moist air ahead of the fronts on both occasions, and on the 10th a tornado caused damage in southern parts of the State. Precipitation from this activity was spotty, totaling less than one inch at most stations in Central New Jersey. Between the 11th and 16th of the month the primary storm track shifted northward into Canada. New Jersey continued to experience mild temperatures associated with mP air, but with only weak, trailing fronts influencing the State, precipitation was negligible. With a switch to meridional flow on the 17th, northwest winds east of the Rocky Mountains favored the advection of cP air southward from Canada. The push of cold air south dominated the weather for the rest of the month. It triggered the development of a low in the Gulf on the 19th, and as the storm moved up the Coast, it dumped 4 inches of snow (0.41 in. melted precip.) at Newark. Maritime Tropical air entered New Jersey briefly on the 26th, once again preceding an intense cold front which triggered squall line activity in the warm sector. The second tornado of the month was reported in Southern New Jersey. The below average temperatures recorded during the last third of the month did not fully compensate for the above average ones toward the beginning, so that the monthly temperature was 1.1°F above average. However, precipitation was below average at most stations. The 2.27-inch total at Newark represented a negative departure of 1.82 inches.

April, 1964 was characterized by a frequency of mP air which was 16 percent above average. This was associated largely with a decreased frequency of NeP air. Days with air mass changes were 25 percent below average. This indicates that cool, moist air tended to stagnate over the State. Realizing that the mP air mass in this study is a composite type, a question arises as to the origin of this air. The fact that it actually followed a maritime trajectory is indicated in the wind direction frequencies, where east winds show a 13 percent increase to become the most frequent direction during the month. The first ten days of April brought a continuation of the interaction between continental sub-polar and humid sub-tropical control experienced during March. Although record minimum temperatures were set in cP air on the 1st, 2nd and 5th, mT air entered the State on the 3rd, 7th and 8th. Seven changes in air mass occurred during the 10-day period. These came about as the result of frontal passages associated with the movement of two depressions from the Central Plains northeastward into New England. Between the 11th and the 18th, mPP air periodically entered the State. On one occasion it was carried far north over the Atlantic, where it took on maritime properties and was returned as mP air on east winds to the coast. However, by the 19th definite changes were apparent. A cP air mass from Alberta moved east to become stagnated over the Maritime Provinces. With only minor shifts, it remained in this position for the rest of the month. Moistened by the waters of the North Atlantic, this system advected mP air into New Jersey. The Polar Front was oriented in an east-west direction across Virginia during much of this period. Precipitation frequently spread northward because of over-running as periodic waves developed and moved eastward along the front. New Jersey remained in the mP air north of the front, and experienced east winds and cool, overcast weather with frequent periods of rain. As a result, monthly temperature was 3.2°F below average, and precipitation totaled 5.56 inches, which was 2.05 inches above average.

May, 1964 was characterized by a frequency of continental air which was 10 percent above average. Most of this was due to the increased frequency of NeP air. The wind directions also reflect the importance of NeP air, because of the increased emphasis in west and southwest flow. It is important to note that days with air mass changes were 16 percent below average. The general picture was one of stagnation, and the contribution of each air mass type was made by relatively long sieges during certain periods of the month. Almost all of the mP air, for example, occurred during the first five days of the month. The situation was similar to that in late April, except that the Polar Front was far to the south and no precipitation occurred. The only significant precipitation (0.51 in.) fell at mid-month when a depression developed over the Southern Plains and moved northeastward up the Ohio Valley into Southern New England. With this sole exception, the weather east of the Rocky Mountains was dominated by stagnated high pressure from the 5th to the 27th of the month. With a broad ridge in the upper air, the jet stream and storm track were restricted to Northern Canada. Three of the four weak cold frontal passages which did occur passed at night. These resulted in only isolated thunderstorms in line along the front. On the 27th, the regime changed when cP air moved down out of Canada. This represented the only prolonged period when cP air influenced the State. Radiational warming in the NeP air coupled with a near average frequency of mT air account for a mild May which was 2.9°F above average in monthly temperature. The increased frequency of continental air coupled with the lack of air mass changes account for an extremely dry month. Precipitation totaled only 0.52 inches, or 3.13 inches below average at Newark. This was representative of the State as a whole.

Weather experienced during the spring of the study period can be summarized in one word —
variable. The unique feature in March was the reversal of the normal temperature regime. This is highlighted by temperature records in Newark. A record daily maximum temperature (75°F) occurred when mT air entered the State on the 5th, while a record daily minimum (22°F) was established during the cP outbreak on the 31st. From the standpoint of microclimate, this meant the rapid melt of snow deposited in February, and the rapid thaw of the ground. In terms of vegetation, it meant an early start which was slowed considerably during the latter half of the month. Heat units (base 40°F), for example, totaled 2.5 times more during the period 1-7 March than they did during 29 March - 4 April. Although heat unit accumulations made rapid gains in mid-April, they dropped off during the cool, rainy period at the end of the month. However, overcast skies during the period favored high minimum temperatures, and reduced the danger of freeze. Overall, the season was near average. Above average rainfall in April saturated the ground and helped eliminate the deficieney experienced in March. Fair skies and adequate soil moisture favored plant growth in early May. However, low soil moisture reserves became a problem toward the end of the month.

Perhaps the outstanding feature of spring in New Jersey is the violent weather resulting from the interaction of mT and cP air. This was displayed rather well during March and early April of 1964. Entering the State as the warm sector of a traveling disturbance, the mT air brings unseasonably high temperatures and strong southwest winds. Although this weather is a welcome relief from the chilling winds of winter, it is of short duration and is usually climaxied by thunderstorm activity along a squall line or the cold front itself. It will be shown later that this chain of events, which is of great importance in terms of macroscale weather, produces rather unique results in terms of exposure of microclimate at the forest boundary.

Another representative feature of New Jersey’s climate in spring, which was displayed rather well during 1964, is the development of a stagnated mP high over the Maritime Provinces. As discussed above, this system advects cool, moist air over the State. It commonly occurs in spring, and probably accounts for the maximum frequencies of mP air masses shown in the long-term averages in Table 7. As with the warm sector, this particular synoptic feature is of great importance at the microclimatic level.

Summer. The fact that the shift toward humid subtropical control in New Jersey reaches its maximum in summer, especially in July, is readily seen in the averages shown in Tables 10, 11 and 12. As indicated earlier, mT air from the Gulf of Mexico and Caribbean Sea is advected over the hot land area of the Southeastern States by anticyclonic flow around the Bermuda High. It usually enters New Jersey in association with south or southwest winds. Maritime Tropical air reaches its maximum frequency in July, and is followed by NcP, mP and cP air respectively. Perhaps the most striking feature is the low frequency of cP air. Although NcP is the most frequent air mass in June and August, this reflects a change in moisture rather than temperature. Radiational warming under fair summer skies in NcP air makes it difficult to distinguish NcP from mT on the basis of temperature alone. The main difference is one of moisture, which is manifested by less humid days and drier, cooler nights in the NcP air. NcP air is often gradually humidified into mT air over the State. These two air masses, both commonly associated with southwesterly flow, dominate the weather during summer. This dominance is reflected in the wind data, where south and southwest are the most frequent directions. Winds from southern quadrants occur 47 percent of the time as opposed to 29 percent for northern quadrants. East becomes the least frequent direction in summer. However, the frequencies for southeast winds are not significantly greater. While southwest winds are the most frequent,

<table>
<thead>
<tr>
<th>Table 10. Frequency (%) of air masses and air mass changes during summer in N.J. June 64-Aug 61 vs. averages 41-61. (a) indicates average values.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days w</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>cP</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>June</td>
</tr>
<tr>
<td>June (a)</td>
</tr>
<tr>
<td>July</td>
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<tr>
<td>July (a)</td>
</tr>
<tr>
<td>Aug</td>
</tr>
<tr>
<td>Aug (a)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 11. Frequency (%) of wind direction during summer. June 64-Aug 61 vs. averages 51-60. Newark, N.J.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>June</td>
</tr>
<tr>
<td>June (a)</td>
</tr>
<tr>
<td>July</td>
</tr>
<tr>
<td>July (a)</td>
</tr>
<tr>
<td>Aug</td>
</tr>
<tr>
<td>Aug (a)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 12. Mean wind speed (mph) during summer, by direction. June 64-Aug 61 vs. averages 51-60. Newark, N.J.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>June</td>
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<td>June (a)</td>
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<td>July (a)</td>
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<tr>
<td>Aug</td>
</tr>
<tr>
<td>Aug (a)</td>
</tr>
</tbody>
</table>

Bold numbers denote maximum frequency or wind speed. Halic numbers denote second greatest frequency or wind speed. * Denotes minimum frequency or wind speed.
the strongest winds remain from the northwest. Days with air mass changes occur only about 45 percent of the time. The overall picture is one of southern rather than northern control. Thus, the reversal of controlling air masses coupled with a corresponding shift in wind flow vividly demonstrates, from the dynamic point of view, the monsoonal tendencies in the climate of New Jersey.

JUNE, 1964 was characterized by a frequency of cP air which was 12 percent above average. This was accompanied mainly by a reduced frequency of maritime air, which was 9 percent below average. Increased northern control is also reflected in the wind direction frequencies, where emphasis shifts from southern to more northern quadrants. Days with air mass changes were 12 percent above average. This implies a frequent exchange of air masses, and indeed the month was one of extremes. Below to much below average temperatures were recorded in cP and mP air during the first nine days of the month as a result of the sub-polar controls established in late May. A record minimum temperature (48°F) for the date was set in cP air on the 4th. However, a rapid exchange of all air masses occurred during the last two-thirds of the month. With the primary storm track far to the north, lows from the Dakotas were carried northeastward over the Upper Great Lakes toward extreme Northeastern Canada. Cold outbreaks were associated with the passage of each depression. Continental Polar or slower-moving NcP air masses from the northwest were advected over the mid-Atlantic States, where they stagnated or continued to move southeastward to merge with the Bermuda High. In either case, the cold front became oriented in an east-west direction across the Southeast, where it remained stationary for several days. The Polar air was warmed and moistened with the advent of southwest winds as it moved slowly to the coast. The front eventually degenerated, or if a wave developed farther to the west, it moved northward as a warm front preceding mT air. The sequence, therefore, was from cP to NcP to mT air. This was repeated, with slight variation, several times during the month. Record maximum temperatures were set for the date on the 10th and 30th in mT air. However, the extremes of hot and cool air tended to cancel. Overall, the month was 1.1°F below average. This was largely due to the increased frequency of cP air during the early period. Precipitation occurred almost exclusively as thunderstorms associated with frontal activity. As such, it was scattered. Although Newark was only 0.53 inches below average, many stations in Central New Jersey experienced negative departures of well over an inch, June was considered a dry month.

JULY, 1964 was a unique summer month. Maritime Polar air was 17 percent above average. The combined frequency of mP and mT air was 73 percent. The dominance of these two air masses is strongly reflected in the wind data. The near average frequency of mT air is accompanied by the usual emphasis on southwest flow, and the increase in mP air is accompanied by a sharp rise in easterly flow. East winds, usually the least frequent direction, became the second most frequent direction of the month. Days with air mass changes were 15 percent below average. The key to the month's weather lay in the upper air. With a deep trough or closed low aloft between the 1st and 15th, traveling disturbances tended to develop or intensify directly over the mid-Atlantic States. Two depressions between the 8-10th and 13-15th resulted in widespread shower and thunderstorm activity over the state. This precipitation totaled over 3 inches at most stations in Central New Jersey. Between the 16th and 31st a broad ridge of high pressure over the entire United States favored the intensification and northern migration of the Bermuda High. With only trailing fronts influencing the Northern States, New Jersey was dominated by mT air. However, between the 20th and 25th high pressure to the north of the Polar Front built up over the Maritime Provinces. On two occasions New Jersey experienced "backdoor" cold fronts from the northeast, and as a result, the dominance of mP air for several days. With an outbreak of slow-moving NcP air from the northwest on the 29th, continental controls were re-established. Frequent precipitation during the latter part of the month occurred as the result of thunderstorm activity. Thus, with a dominance of maritime air masses and an above average frequency of mP air, July was a cool, moist month. Monthly temperature was 1.3°F below average, while precipitation totaled 4.74 inches or 1.07 inches above average at Newark. Totals in excess of 7 inches occurred at several stations in Central New Jersey.

AUGUST, 1964 was characterized by a 19 percent higher frequency of continental air, compared to average. Polar air was 10 percent above average. The increases came about largely as a result of decreases in the frequencies of both mP and mT air. Increased continental sub-polar control is reflected in the wind direction frequencies, where the emphasis shifts from southern toward northern directions. Days with air mass changes were 17 percent above average. The sequence of the weather for the entire month was similar to that described during the latter two-thirds of June. However, while the sequence was similar, important differences existed in the timing and frequencies of the air masses involved. During the period in June, mT air was 11 percent more frequent than in August, and occurred during three prolonged periods during which well-established southwesternly flow advected large quantities of moisture northward. In August, on the other hand, mT air was 11 percent less frequent, and occurred during short periods during
which southwesterly flow never really became well-established. Thus, much of the moisture available during the period in June was absent in August. August precipitation totals recorded at many stations in New Jersey were the lowest values ever experienced in the history of the stations. At Newark, the 0.50-inch total represented a negative departure of 3.93 inches. As in June, there were periods of extremely hot and cool weather. However, the month was 1.5°F below average in temperature. This was largely due to the increased frequency of cP air.

Weather experienced during the summer of the study period can be summarized in six words — cool and dry, but with extremes. Under the influence of increased continental sub-polar control, both June and August were cooler and drier than average. August was exceptionally dry. The influx of fresh cP air resulted in the establishment of record minimum temperatures during both months. On the other hand, record maxima were also established in mT air. Thus, both months were noted for periods of extremely hot and extremely cool weather. Although air mass changes were above average during both months, the high frequency of dry continental air kept thunderstorm activity to a minimum. This was especially true in August. These two months may be distinguished dynamically from May, which was warm and dry. In May, milder NcP rather than cP air contributed most of the increased continental influence, and air mass changes were much below average. These three months may be distinguished from July, which was cool and very wet as the result of mP and mT control.

The lack of precipitation during much of the warm season was undoubtedly related to the decreased frequency of thunderstorms during the period. The 0.50-inch total rainfall in August, the month during which the highest average monthly totals are usually recorded, gives vivid testimonial of what happens when both hurricane and thunderstorm precipitation are lacking. Cry (1966) has recently completed an investigation of the contribution usually made by the former. A study of the latter is a worthwhile problem for the future.

From the standpoint of microclimate, the increased frequency of dry continental air favored radiational warming and cooling and therefore the development of microclimatic extremes. Soil moisture reserves which had reached low values during the drought in May continued to decline through June into early July. The dryness of the forest litter and soil decreased its thermal conductivity, thus influencing soil temperatures. In regard to vegetation, the above-ground portions of herbs and shrubs growing at the foot of the south forest boundary wilted, dried and turned brown. This influenced albedo. Rains between the 8th and 15th of July temporarily saturated the ground, and plants of the south forest boundary put forth new vegetative growth. However, by mid-August conditions had deteriorated to a point even drier than that in early July. The drought continued into fall, becoming severe in September and extreme during October and November according to the Palmer drought index (D.V. Dunlap, personal communication). Recalling the comments concerning drought and dogwood at the south site, it is interesting to note that both leaf coloration and leaf fall occurred significantly earlier than on the north boundary at this site. Similar observations made during other dry years within the last decade have been reported in the literature by Small (1961).

Summary. At the beginning of this work, the assumption was made that the predominant winds during each month would give a fair indication of the controlling air mass. Review of the 9-month period with respect to frequencies of air masses and wind directions shows that this was indeed a true assumption. In April, for example, the predominance of easterly flow is associated with the dominance of mP air. In July, the prevalence of southwest and easterly flow is associated with the co-dominance of mT and mP air. In February, the increased importance of northwest and west flow is associated with the dominance of cP air. Moreover, minor shifts in wind flow during the other months are related to corresponding shifts in the frequencies of certain air masses. In January and May, for example, increased frequencies of west and southwest winds are related to the increased frequency of NcP air. December appears as the possible exception. With cP air 20 percent above average, the large gain in west rather than northwest flow appears unusual. However, it is explained by the positioning of the Continental High, which remained stationary and spread southeastward over the mid-Atlantic States as a broad L-shaped ridge. Air mass changes were 22 percent below normal.

In retrospect, Havens’ air mass calendar has been combined with wind data in order to present a dynamic comparison between weather and climate. Thus, both weather and climate have been explained in terms of the frequency of occurrence of air masses, air mass changes and wind directions. This method facilitated discussions, by seasons, of the influence of the weather during the period on both vegetation and microclimate. Perhaps more important, it permitted the identification of certain representative synoptic events, such as the “northeaster” and the warm sector, which are especially interesting at the microclimatic level. Thus, it provided a dynamic link between climate, weather and microclimate which is often lacking in studies of this kind.

Snow. As discussed earlier, recent studies (Pierce et al 1958, Lull and Rushmore 1960, Eschner and Satterlund 1963) concerning snow under wood-
lands in the Northeast have dealt primarily with seasonal accumulation and melt in order to determine the hydrologic value of different forest types and/or cutting practices. In one earlier study (Maule 1934), the distribution and retention of individual snows within a number of forest types were measured, but no attempt was made to explain the actual dynamics of deposition or melt. The ability of shelterbelts of various types to catch and retain snow has received intensive investigation in the United States (Stoeckeler 1962) and in Russia (Molchanov 1963). Wind tunnels have been employed to investigate the role of wind in determining the distribution of simulated snow around windbreaks (Finney 1934). However, techniques used in wind tunnel experiments have not been widely employed in the field. That is, no study exists which attempts to explain the distribution of snow in and around a forest not only in terms of stand characteristics such as forest type and density, but also as a function of aerodynamic considerations such as snow density, drift angles and the speed and direction of the wind.

Since snow retention is determined by initial distribution as well as by the rate of melt, adequate understanding of accumulation, a net term, is dependent upon a more comprehensive understanding of the dynamics of both sides (deposition versus melt) of the snow equation. It became evident rather early in the present study that differential snow deposition and melt resulted in large thermal differences between various locations in and around the forest. Primarily for this reason, but also because previous work was lacking, the objectives of this study were broadened to include some of the dynamic aspects of snow.

Snow deposition at the forest. Even the casual observer has noted the great extent to which snow is driven and drifted by the wind. In view of the significant role which wind speed and direction play in determining the deposition of snow, the first logical question which should be asked within any particular geographical region is: What are the frequencies of the various wind directions during snow? Dynamic climatology pinpointed the “north-easter” as the primary synoptic event by which significant snows occurred in New Jersey. However, this point needed further elucidation. It is readily seen in Table 13 that northeast is indeed the most frequent direction during snow. Furthermore, it is seen that during the Winter of 1963-64 the wind direction was between northwest and east inclusive 76 percent of the time during snow. Moreover, it was confined to the northeast quadrant (north through east) 65 percent of the time during snow. That this is a regular part of New Jersey’s climate is shown by the fact that the corresponding values for the long-term means are 74 and 63 percent respectively.

| Table 13. Frequency (%) of wind direction during snow. Nov 63-Apr 64 vs. averages 56-62. Newark, N.J. |
|-----------------------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|
| Winter 1963-64 | N        | NE       | E        | SE       | S        | SW       | W        | NW       | Calms    |
| Winter (a)     | N        | NE       | E        | SE       | S        | SW       | W        | NW       | Calms    |
| 19              | 19       | 33       | 13       | 2        | 5        | 7        | 10       | 11       | 0        |
| 21              | 32       | 10       | 3        | 5        | 8        | 9        | 11       | 1        |

These directional considerations indicate that forest boundaries in New Jersey which face north through east, and particularly those facing northeast, are the windy ones during snow. Since the wind is significantly slowed in the vicinity of these boundaries, it is here that drifting is likely to occur. That this is true can be seen in Figure 4, which shows the distribution of three individual snows at Hutcheson Memorial Forest measured soon after the termination of snow. Although the extent and relative depth of drift vary greatly between the three storms, it is plainly evident that significant drifting is restricted to the northern boundary, which faces an exact heading of 015 degrees. The situation is similar to that at a shelterbelt. That is, dependent upon the horizontal component of drift which is determined primarily by the speed of the wind, snow is drifted across the boundary and into the forest. Especially during strong winds (Storm 3) when the horizontal component of snowfall is great, the density of the side rather than the top of the stand determines the distribution of snow. This was verified at the north boundary by the observation of drift angles during snow, and by the pattern of interception observed after the termination of snow. That is, snow is intercepted primarily on the north-eastern sides of the trunks of the trees, and the proportion of snow accumulated on the trunks as opposed to horizontal branches is greater with increasing wind speed.

In Figure 4, the upper lines within the drift zone for each storm indicate the depth and extent of drifts associated with areas of dense vegetation near the ground. The lower lines indicate the depth of snow not associated with such areas. Thus, the marked ability of low growth to catch snow reported in shelterbelt research (Stoeckeler 1962, Molchanov 1963) is equally effective at the windward forest boundary. As opposed to shelterbelts where this vegetation is usually uniform in nature, the vegetation near the ground at the unmanaged forest boundary is quite variable in height, density and horizontal extent. This accounts for the mosaic pattern of drifts at the forest, which were separated in this study into two height categories based on snow depth at the boundary and immediately within the stand.

As at the windward northern boundary, the deposition of snow at the center of the forest and across the southern boundary can be explained in terms of drift angles and density of the stand. Observations indicated that for all wind speeds
Fig. 4. Snow distribution at Hutcheson Memorial Forest, for the three storms described in Table 14, Winter 1963-64. Abscissa is horizontal distance in tree-heights. F = field; B = boundary; FC = forest center. Dotted lines indicate distances not to scale. Ordinate is snow depth in inches. Upper lines on north boundary indicate depth and extent of drifts associated with areas of dense vegetation near the ground. Lower lines indicate the depth of snow not associated with such areas.

excepting those approaching calm, the drift angle of snowfall is more nearly vertical at the center and south side of the forest than at the northern boundary. Although still primarily intercepted on the northeastern sides of the trees, the proportion of snow found on horizontal branches is greater than that on the trunks of the trees. These observations are in agreement with the probable wind profile within the stand, which is undoubtedly similar to the profile within the two-story oak-beech forest discussed earlier (Geiger and Amann 1934). Thus, with a more nearly vertical component in the fall of snow, canopy closure is a significant factor in determining the distribution of snow at sites other than those near the windward edge of the stand.

Although variations exist between storms, it can be seen in Figure 4 that throughfall (snow depth) during all storms is inversely proportional to cover at sites within the stand. For example, snow deposition is greatest between 1/2H and 1H inside the south boundary, which is the area characterized by the least cover, largely due to dogwood mortality (Table 1 and Figure 15). However, snow deposition is least just a short distance away at the south boundary. This is accounted for not only by the fact that vegetation is dense at the boundary, but also because of vegetation structure. That is, with trees near the margin of the stand both leaning and putting forth branches toward the adjacent field, open space is created toward the interior of the forest, while a dense hood or canopy is created at the margin of the stand. The loss of canopy interception, coupled during intermediate and strong winds (Storms 2 and 3) with a reduction of wind speed in the dead air zone at the lee of the stand (Geiger 1957), account for the increased depth of snow away from the stand. The extent of this effect is unknown, since measurements were not made in the south field.

Although variations exist between storms, snow depths at the site in the center of the forest for all three storms are less than those recorded at sites 1H inside the forest at both boundaries. These depths are less than those at the south site primarily because cover is greater at the center of the forest. Although canopy cover is greatest on the north, snow depths in this area are largely the result of drifting determined by the density of the side of the stand. The effect is plainly evident during Storm 3 (strong winds), but less marked during the other two storms.

Variations in snow deposition between individual storms. Perhaps more interesting than the above is

<table>
<thead>
<tr>
<th>Storm No. and Date</th>
<th>Type Snow</th>
<th>Snow Depth (in.)</th>
<th>Water Equivalent (in.)</th>
<th>Direction (degrees)</th>
<th>Mean Speed (mph)</th>
<th>Range (mph)</th>
<th>Peak Gust (mph)</th>
<th>Wind Direction Tendency</th>
<th>Mean Temp. (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 10-11 Feb</td>
<td>S—</td>
<td>2.9</td>
<td>0.27</td>
<td>000-050</td>
<td>14</td>
<td>9-18</td>
<td>25</td>
<td>Constant</td>
<td>22.5</td>
</tr>
<tr>
<td>2. 18-20 Feb</td>
<td>S—, SW—</td>
<td>6.7</td>
<td>0.73</td>
<td>070-350</td>
<td>16</td>
<td>2-32</td>
<td>46</td>
<td>Back</td>
<td>30.7</td>
</tr>
<tr>
<td>3. 12-14 Jan</td>
<td>S—, S</td>
<td>12.8</td>
<td>1.20</td>
<td>040-360</td>
<td>25</td>
<td>16-38</td>
<td>55</td>
<td>Back</td>
<td>16.5</td>
</tr>
</tbody>
</table>

The explanation of the variations in snow deposition associated with the three storms. By considering their individual characteristics (Table 14), the three storms can be distinguished from one another in a number of ways, and these differences can then be used to explain variations in the distribution of snow at the forest. Although the three storms differed in depth, this is of little importance except that it facilitated the plotting of the three snow distributions on the same graph for comparison without overlap. The significant feature to be noted in Figure 4 is the slopes of the lines, which indicate the relative depth of snow at the various locations for each storm.

The three storms are arranged in order of ascending wind speed in Table 14. Storms 1 and 3, which both occurred as light or moderate snow during periods of relatively cold temperatures, produced dry powder snow (densities 0.093 and 0.094 respectively). As indicated by the mean wind speed and range of the hourly winds, as well as by the peak gust, these storms represented opposite ends of the wind scale. On the other hand, Storm 2 occurred as light snow or light snow showers during a period when temperatures were just below freezing, and produced wet snow (density 0.110). Although similar to Storm 1 in mean wind speed, it can be seen from the range and peak gust that speed was quite variable during this storm. The lowest hourly value, for example, is less than the corresponding value in Storm 1, whereas both the highest hourly value and peak gust approach the values recorded during Storm 3. Winds during Storm 1 had a fairly constant direction, whereas Storms 2 and 3 were characterized by backing winds. Wind directions were at or between the values given in the table approximately 75 percent of the time. Of the two storms characterized by backing winds, Storm 2 showed the widest range in direction. However, all directions during all storms were generally confined to the northeast quadrant. Although wind direction tendencies indicate a genetic difference between Storm 1 and Storms 2 and 3, this factor plays a minor role in determining variations in the snow distributions associated with the three storms. Rather, it is wind speed and density of snow which primarily determine the variations in the three distributions of snow.

The ability of the northern boundary to catch snow depends not only on the unidirectional nature of wind during snow and stand characteristics such as structure, height and density, but also on the speed of the wind. With relatively weak winds (Storm 1, dry snow), no increase in depth is noted between open fields and positions at 1H and 1/2H in front of the stand. At the boundary, areas with vegetation fairly open near the ground line show a barely perceptible increase in snow depth. However, areas characterized by dense patches of vegetation near the ground, such as clumps of fall-flowering Composites or poison-ivy, which grow upward toward the lower dogwood branches, show a 38 percent increase in depth. Drifting is limited in extent to the area at and immediately adjacent to the boundary, and the maximum depth of drift occurs at the margin of the stand.

On the other hand, with strong winds (Storm 3, dry snow), much of the snow which might otherwise fall on adjacent fields is distributed in front of and at the boundary as well as within the stand. The increase in depth is strikingly evident even in areas fairly open near the ground line. As opposed to Storm 1, depths do not level off between 1/2H and 1H within the stand. Although measurements were not made, it is probable that the effect of “blow through” associated with less dense areas at the boundary extends much beyond 1H into the stand. However, drifting associated with the dense low vegetation does not extend beyond 1H, because the snow is trapped by the greater reduction of wind at the edge of the stand. The depth associated with these areas represents a 47 percent increase over depth associated with areas lacking dense vegetation near the ground. Both the aerial extent and relative depth of drift is greatest with strong winds, and the maximum depth of drift is displaced to a position well within the stand.

As opposed to Storms 1 and 3, Storm 2 was characterized by variable wind speed and fell as wet snow. The resultant snow distribution across the northern forest boundary shows characteristics generally intermediate between the other two storms. Snow depth at 1H is slightly greater than that observed within the open field, and the slope of the line indicating increasing depth in front of the stand is intermediate between the slopes of the other two
storms. However, the increase (38%) in depth associated with dense vegetation is identical to Storm 1, and depths level off within the stand. The maximum depth of drift occurs at the margin of the stand. As indicated shortly, these effects are related to the density of snow as well as to wind speed.

The snowfall distributions across the northern forest boundary in this study compare favorably with the results of wind studies made by other investigators at the margin of the stand. That is, both Woellle (Geiger 1957) and Reifsnyder (1955) report greater percent reductions in wind speed with stronger winds. This accounts for the increased drifting with stronger winds. Furthermore, the present results compare at least qualitatively with wind tunnel results reported by Finney (1934). That is, the distance to the lee of an obstruction at which the maximum depth of drift was found decreased with the speed of the wind (Storm 3 vs. Storm 1), and with increasing density of snow (Storm 2). In this case, the obstruction is the vegetative “wall” created by merging layers at the edge of the stand.

As at the northern boundary, variations in the distribution of the three snows at the other locations within the stand can be explained in terms of wind speed and density of snow. The weaker the wind, the greater is the vertical component of snowfall. This applies regardless of the density of snow. However, the large flakes of wet snow are intercepted to a greater extent than dry snow (Geiger 1957). Thus, the distribution for Storm 1, which was characterized by dry snow and the most vertical components of snowfall, shows only minor variations according to canopy density at the various locations within the stand. Moreover, depth at 1H in the south field is similar to that in the open as measured within the field on the north.

On the other hand, during Storm 3 the effect of strong wind is readily apparent. Greater relative depth (58% increase over forest center site) is observed in the area between 1/2H and 1H within the forest on the south for this storm as opposed to Storm 1 (40% increase). Geiger (1957) indicates increased turbulence (eddies) and a greater percent reduction in wind speed at canopy level induced by open spaces of the general type involved here. The increased throughfall in this area during strong winds is undoubtedly related to these effects. As opposed to Storm 1, only a small reduction in depth occurs at the margin of the stand. Snow depth at 1/2H in the south field is greater than that observed in the open as measured in the north field. This is undoubtedly related to a reduction in wind speed at the lee of the forest as described by Geiger (1957).

The snow distribution for Storm 2 shows the influence of both intermediate winds and the greater interception of wet as opposed to powder snow. Greater differences are observed between all locations within the stand for Storm 2 than for the other storms. This occurs because the large flakes of wet snow cling easily to the branches and twigs within dense areas of the crown, but penetrate through the open areas between the branches in amounts similar to that for dry snow. Thus, differences in snow depth between dense and less dense areas in the canopy are accented with wet snow. The marked ability of dense vegetation to intercept wet snow accounts for the relatively shallow depth at the south margin of the stand. The differential interception of wet versus dry snow plus turbulence and a reduction in wind speed associated with the intermediate winds of Storm 2 account for an increased snow depth between 1/2H and 1H within the south boundary. The increase is similar to that which occurred with the stronger winds of Storm 3. Snow depth at 1/2H in the south field shows an increase over that in the open as in Storm 3, but the increase is not nearly as great because the winds were not as strong.

A comment is necessary concerning the measurements made in the north field. Except for Storm 3, they are in good agreement with snow depths in Central New Jersey, as determined by examination of a cross-section of stations from Newark to Trenton. The area near the forest received 11 inches of snow during Storm 3. The obvious explanation for the low depth at the exposed site in the north field is extensive drifting of snow. This will be discussed further in the next section.

Post-storm drifting and relative density of snow on the ground. Although snow densities were not measured, differences in the initial density of snow at various locations during storms characterized by strong winds were so great that they were apparent even without actual measurement. For example, snow on the ground in front of and at the northern boundary after Storm 3 was so dense that the observer could walk through drifts without sinking very far into the snow. On the other hand, the density of snow within the forest was such that it was easily compressed, and could be brushed and spread with ease.

While the packing action of strong northeast winds during snow is responsible for a large part of the increased density of snow near the windward edge of the stand, an important additional factor is the prevalence of strong northwest winds after the storm. These winds account for significant drifting and packing of snow after the actual termination of the storm. They account in large part for the shallow snow depths measured in the north field after Storm 3. The effect is rather striking, as observed by this investigator, who returned to the north boundary after a period of approximately 20 minutes on the south to find his footprints com-
completely filled with snow. It will be shown later that northwest winds normally occur at the termination of, as well as for some time after storms pinpointed as the typical snow producers in New Jersey.

The increased density of snow at the windward edge of the stand is of more than passing interest, since it means that the area of maximum deposition is also the area of greatest water content, per unit volume of snow. Although not previously reported in the Northeast, significant increases in snow density in areas exposed to high winds both in the Western United States and Greenland have been discussed by Church (1912).

Vegetation damage associated with wet snow. Although Lemon (1961) has discussed the ecology of ice storms in the Northeast, and Cantlon (1953) has attributed in part the openness of the stand on the north slopes of Cushetunk Mountain to the combination of ice and high winds, no observations are reported in the literature from the Northeast concerning damage associated with wet snow. Geiger (1957) states that when significant damage is reported it is almost always a case of wet snow. This was indeed the case in Storm 2. The interesting thing is that damage was not distributed evenly throughout the forest, but largely confined to the southern half of the stand. Although unevenly distributed, the damage was of a uniform nature throughout. It consisted of the splitting of primary branches and trunks of dogwood trees. The number of dogwood with split trunks or primary branches observed within the north, center and south sections of the forest is shown in Table 15.

Table 15. Number of dogwood trees showing split trunks or primary branches, as observed on several 100-m transects run parallel to the boundaries within the north, center and south sections of Hutchison Memorial Forest. Observations were made immediately after the snowstorm of 18-20 February, 1964 (wet snow).

<table>
<thead>
<tr>
<th>No. of trees</th>
<th>North</th>
<th>Center</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 - 3.5 in. dbh</td>
<td>1</td>
<td>2</td>
<td>10*</td>
</tr>
<tr>
<td>3.6 - 5.0 in. dbh</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

* Includes 3 dead trees

This damage is directly related to wet snow. Because of fairly strong winds and a horizontal component of snowfall, interception at the north was primarily on the trunks of the trees. Because of the more vertical component of snowfall within the stand, interception in these areas occurred primarily on the horizontal limbs and branches of the trees. With wet snow, interception became great. For example, interception on the top of a horizontal dogwood branch totaled twice the diameter of the branch. Although difficult to measure, accumulation within the lacework of small branches and twigs of the umbrella-shaped trees totaled several times this amount. Thus, it was toward the south where damage primarily occurred.

On the south, damage was concentrated in the area between 1/2H and 1H within the stand. This was by no mere chance, for the openness of the stand caused eddies and favored the increased deposition of snow. Although interception is great where the vegetation is dense, the compactness of the stand favors the growth of resistant cylindrical-shaped trees, and accounts for a more equal distribution of the snow load. In open areas, individual branches must carry the load. These factors, coupled with the poor condition of the trees induced by recent drought, account for the concentration of damage within the area near the south margin of the stand.

It is interesting to note that the processes active near the south margin represent an example of what Maruyama (1963) has termed the second cybernetics. That is, a deviation-amplifying system, or a system characterized by mutual positive feedbacks between the elements within it. In this case, snow damage during winter opens the canopy, thus increasing insolation, temperatures and wind flow. These factors accentuate the effect of drought during the summer months. The accentuated drought favors the death of trees, which results in openings in the stand. The openings, in turn, favor snow damage to the trees.

Synoptic climatology of significant snows. The reader is referred to the weather maps (U.S.W.B. 1964) in the Appendix, where he will find discussions of the synoptic situations associated with Storms 1-3.

It is interesting to note that although differences exist between the three storms, they have one highly significant feature in common. That is, regardless of the location of origin, all three storms passed along and/or off the Atlantic Coast immediately to the east or southeast of New Jersey. This accounts for the occurrence of winds from the northeast quadrant in each case. Furthermore, it pinpoints the fact that the Atlantic Ocean and Gulf of Mexico are the primary sources of moisture associated with the production of significant snows within the State. Storms such as 2 and 3, which originate over the Gulf and Atlantic Coastal Waters and adjacent Southeastern States, characteristically move along the Coast and advect moisture northward. However, the same can be said of systems such as Storm 1, which move in from the west and move off the Atlantic Coast to the south of the State. Dependent upon the intensity and extent of the system, the moisture in these cases may or may not (Storm 1) become available until the low approaches the Coast.

Since the East Coast of the United States is a cyclogenetic region, the formation of secondary lows
such as occurred during Storms 2 and 3 is a likely occurrence. When developed, secondaries favor the advection of additional moisture northward. The presence of a well-developed cold continental high centered well inland (Storms 1 and 3) provides a pool of cold air which favors the production of snow. This is especially true when the cold air is actively advected into the system (Storm 3).

Since several heavy snows are a normal occurrence during winter along much of the East Coast, much research has been devoted to the problem. As in any forecast situation, the exact path, speed and intensity of the depression as it moves into the area of concern are among the most important factors to consider. George (1960) states that heavy snows in the New York City area attend strongly developed or developing lows centered in a specific area to the southeast of the city. The critical area involved has been defined by Stakely and Whiting (1960), and is shown here in Figure 5. The depression must move within the indicated area in order for the New York area to experience a moderate to heavy snow. Storm centers which move through the small oval-shaped area directly east of New Jersey usually bring a heavy snow, while those which move through the other part of the critical area usually bring a light to moderate snow. In most cases, high pressure is centered over land to the north or northwest of the State. Although numerous factors determine the actual depth of snow produced, the most important single factor, according to George, is the speed of movement of the low through the critical area — the longer it remains in the critical area, the greater the snowfall.

Analysis of snowstorms during the 1963-64 season is interesting in the light of the above work. Measurable snowfall occurred throughout the New Jersey Piedmont Plateau (that is, at both Newark on the northeast and Trenton on the southwest) on fourteen occasions between 12 December, 1963 and 22 March, 1964. However, only four storms, the three discussed earlier, plus one additional Gulf storm, resulted in snow depths in excess of 4 inches. (The additional Gulf storm, which occurred 23 December, will be referred to hereafter as Storm 4. It originated in the Gulf and moved rapidly up the coast, passing through the critical area with a speed of 38 mph and a central pressure of 1008 mb. It resulted in a 7-inch snowfall throughout Central New Jersey.) Of the ten remaining snowfalls, only two exceeded depths in excess of 2 inches. The remaining eight snowfalls ranged in depth from 0.1 to 1.8 inches. The 4-inch, 2-inch and less than 2-inch depth categories accounted for 70, 14 and 16 percent of the total snow which fell in Central New Jersey during the season.

In Figure 5 it is readily seen that the four storms in the 4-inch category all passed through the heavy snow area. Furthermore, storms in the 2-inch category (29 Feb, 22 Mar, Figure 6) moved through the light-moderate snow area. Snowfalls of less than 2 inches were associated with: 1) well-developed storms which moved only briefly into the critical area on the north (12, 18 Dec, 15 Feb), or 2) systems which passed too far south (14 Dec), or 3) weak depressions which moved very rapidly through the critical area (27 Dec), or 4) very weak or ill-defined systems or snow flurry activity which were not plotted (31 Dec, 13 Feb, 12 Mar).

Variations in depth among the four heavy snows can be accounted for in terms of the speed and orientation of the low while moving through the heavy snow area. Considering first the three storms which moved through the heavy snow area on similar northeasterly tracks, it is evident that snow depth is inversely proportional to the speed of the storm. For example, the faster-moving storms (2 and 4) produced the least snow, while the slower-moving one (Storm 3) brought the greatest depth of the season. Storm 1 was actually made up of two lows which passed in rapid succession. Each moved

Fig. 5. Storm tracks of four heavy snows (depth greater than 4 in.) in Central New Jersey. Winter 1963-64, in relation to critical area as defined by Stakely and Whiting (1960). Times of indicated positions are 0100 and 1300 EST.
through the critical area on an easterly track. However, the first low moved briefly through the heavy snow area at a speed of 40 mph, whereas the second low moved through the light-moderate snow area at 20 mph. As might be expected, the contribution made by each low varied at different stations in Central New Jersey, but the most snow at many locations was contributed by the first low. Since this depression spent the least time in the heavy snow area, depths during Storm 1 fell short of those recorded during the other storms.

The two storms in the 2-inch depth category were similar in development and extent to the 4-inch storms, but did not enter the heavy snow area. Considering the storms in the less than 2-inch category, it is necessary to mention that the storm of 12 December (1.6 in. snow depth) which tracked north of the critical area was accompanied by a deep trough which fell just short of developing into a secondary closed low within the heavy snow area. Finally, it is interesting to note that the snow of 12 March (0.3 in. snow depth) fell as the result of an extremely weak low (1016 mb) which passed directly through the critical area.

The above-average snowfall during the 1963-64 season resulted from a high frequency of storms moving through the critical area. All significant (over 2 in.) snows, which accounted for 84 percent of the total seasonal snowfall, came about as the result of the movement of six well-developed storms through the critical area. Gulf and Atlantic Coast storms, which are well-known as frequent snow producers on the East Coast, accounted for five of the six storms. The sixth (Storm 1) originated over the Central United States. The tracks followed by these storms represent three of the nine typical paths of traveling disturbances within the United States as described by Bowie and Weightman (1914). That is, the East Gulf, South Atlantic and Central tracks.

It is of great significance to note that five of these nine favored paths of traveling disturbances within the United States pass through or fringe upon the critical area. These include the South Atlantic, South Pacific and Central tracks which bisect the heavy snow area, the East Gulf track which passes through the light-moderate area and fringes upon the heavy snow area, and the Colorado track which briefly intersects the critical area on the north. Furthermore, the Texas track passes in close proximity on the west. Only the Alberta, North Pacific and Northern Rocky Mountain tracks do not pass into the critical snow area situated east and southeast of the State. At this author's suggestion, these relationships were investigated in somewhat greater detail by his former colleagues at the N.J. Agricultural Experiment Station (Hovey and Shulman 1965).

In terms of snow distribution at the forest, the importance of the above is that significant snows occur almost exclusively with winds from the northeast quadrant. This occurs as the result of cyclonic flow around any well-developed low, regardless of origin, which moves directly through the critical area. Thus, although winds from the northeast quadrant occur 63 percent of the time during all snow, the percentages during significant snows are considerably higher than this. For example, the six significant snows, which all moved through the critical area and accounted for 84 percent of the total seasonal snowfall during 1963-64, show wind directions from the northeast 93 percent of the time during snow (Table 16). Furthermore, the only directions listed are east counterclockwise through northwest, which reflect the backing winds characteristic of these storms.

On the other hand, as a group, the snowfalls in the less than 2-inch category show no predominant wind direction during snow. However, the weak (27 Dec) and extremely weak (12 Mar) depressions which tracked through the critical area plus the
Table 16. Frequency (%) of wind direction during snow by snow depth categories. Nov 63-Apr 64. Newark, N. J.

<table>
<thead>
<tr>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
<th>Calms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant Snow (over 2 inches)</td>
<td>30*</td>
<td>52</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7*</td>
</tr>
<tr>
<td>Non-sig. Snow (less than 2 in.)</td>
<td>8*</td>
<td>13</td>
<td>15</td>
<td>3</td>
<td>21</td>
<td>21</td>
<td>13</td>
</tr>
</tbody>
</table>

* Denotes directions associated with flurry activity.

The storm of 12 December described earlier account for virtually all of the winds from the northeast quadrant. The other storms account for all winds other than those from the northeast quadrant. It is interesting to note that snow showers, usually denoting snow flurry activity, occur only with north and northwest winds, regardless of depth category. This snow falls from cumulus clouds which characteristically develop in unstable cP air masses, and seldom amounts to significant depths in New Jersey. However, the major point is that all of the intermediate and heavy snows, and many of the light snows all normally occur with northeasterly flow.

Snow retention. The total number of days with 1-inch or more of snow cover at locations in and around the forest and at climatological stations in Central New Jersey is shown in Line 1 of Table 17. Since the snow season during 1963-64 extended for 103 days, from 12 December, 1963 to 23 March, 1964, the figures in Line 1 represent the approximate percent of time that snow remained on the ground at the various locations during the season. This is important, for it gives a good indication of the amount of time that snow rather than forest litter acted as the active surface during the snow season.

An inch or more of snow covered the ground at most climatological stations in Central New Jersey approximately 46 percent of the time. Snow cover in the open (north field) at the forest was present three days longer than at the climatological stations, primarily because of differences between urban and rural climate. Most of the climatological stations are located within or on the fringe of fairly large cities and/or industrial complexes, while Hutcheson Memorial Forest is situated in a rural area. At the forest, days with snow cover increase toward the north boundary. They range from seven days greater than in the open (north field) at 1H in front of the boundary to 17 days at the boundary. This is primarily the result of increased initial snow deposition near the windward edge of the stand, and a retarded melt rate caused by the shade of the stand. On the other hand, days with snow cover increase away from the south boundary. They range from 22 days less than in the open at the boundary, to three to four days greater than in the open at 1/2H and 1H in the south field. The much decreased number of days at the south boundary is caused by decreased initial snow deposition, and by an accelerated melt rate favored by the sunny exposure at the south side of the stand. The increased snow retention at 1/2H-1H within the south field is the result of greater initial depths, associated with drifting in the lee of the forest which is favored by strong winds.

The figures indicate that snow retention varied from 45 to 51 days at locations within the forest proper (excluding boundaries). This is within the range between two days more and four days less

Table 17. Snow retention (no. of days 1 in. or more snow cover) at Hutcheson Memorial Forest and surrounding climatological stations. Values are given for the entire snow season, for the period when initial snow depth totaled 1 in. or more in the forest, and for accumulations primarily associated with the four heavy snows.

<table>
<thead>
<tr>
<th>Climato.</th>
<th>HMF</th>
<th>North</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stas.</td>
<td>Open</td>
<td>1H</td>
<td>1/2H</td>
</tr>
<tr>
<td>Entire season</td>
<td>46</td>
<td>49</td>
<td>56</td>
</tr>
<tr>
<td>Period when initial snow depth</td>
<td>51</td>
<td>45</td>
<td>27</td>
</tr>
<tr>
<td>1 in. or more in forest</td>
<td>51</td>
<td>45</td>
<td>27</td>
</tr>
<tr>
<td>Storm 1 (10-11 Feb 64)</td>
<td>4</td>
<td>5</td>
<td>6*</td>
</tr>
<tr>
<td>Storm 2 (18-20 Feb 64)</td>
<td>12</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Storm 3 (12-14 Jan 64)</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Storm 4 (23-24 Dec 63)</td>
<td>12</td>
<td>16</td>
<td>18</td>
</tr>
</tbody>
</table>

* Denotes snow retention terminated or significantly shortened by melted associated with warm temperatures and rain.

Denotes analysis not carried beyond number of days shown because of subsequent snowfall.

1 Values in table determined from cross-section of stations, including New Brunswick, Blackwells Mills, Somerville, Bound Brook, Plainfield and Railway as well as the first order station at Newark.
2 12 December, 1963 to 23 March, 1964 (103 days).
3 See text for explanation.
4 Values are for primary storms, plus, in some cases, smaller snows which occurred during the period. Where these additions seriously interfered with the retention pattern of original storm, analysis for that storm was terminated (Storm 1).
than that in the open. However, the figures are heavily influenced by an eight day period at the beginning of the season, during which three light snows maintained an inch or more of snow on the ground in the open and at the windward north boundary, but not within the stand. That is, snow depths within the forest never quite reached an inch in depth, because of interception. This situation demonstrates the great extent to which interception loss can influence snow retention. However, it is probably of extremely rare occurrence, since an unusually long period of cold dry air favored the prolonged retention of the shallow snow cover in the open (Part A). By excluding this period, the relationship between snow retention inside and outside the stand is placed in better perspective. That is, considering snow retention during the period when snow initially totaled an inch or more within the forest (Line 2), it is seen that retention totaled between five and ten days more at the locations within the forest than in the open. This, of course, is the result of shading within the stand. In general, the longest retention occurs in areas of heavy initial snow deposition associated with strong winds. An exception to this occurs at 1/2H within the south boundary, where the low retention is related to the increased melt rate toward the edge of the stand.

The north and south boundaries, which are characterized by the longest and shortest snow retention respectively, deserve special consideration. The south boundary is the only location in the forest which receives full sun during the entire period of the winter day. Because of low altitude angles, not even the overhanging oak branches at the boundary itself block the direct rays of the sun from reaching the edge of the stand. On the other hand, during winter the sun never shines directly on the north boundary as it does during the early morning and late afternoon hours during the summer half of the year. Furthermore, shade is intense, because the rays of the sun must penetrate the maze of vegetation at the boundary as well as the canopy of the stand. Therefore, additions of heat to the snow pack which are directly or indirectly related to the sun are favored on the south. These include heat from incoming solar radiation, heat from surrounding objects irradiated by the sun, and heat conducted from the soil below. With the exception of heat from below, which may be stored to some extent, all are fair weather phenomena.

These melt processes favor the rapid elimination of snow on the south, and retention on the north. However, the important point is that in New Jersey at least, the area of minimum initial snow deposition is the area of maximum rate of melt. With shallow snow depths on the south under fair skies, melt is especially rapid because the litter (low albedo) is exposed. With deeper snows, the melt rate is slower, but melt holes soon appear in front of the irradiated trunks, branches, twigs and stems of trees and underbrush all along the edge of the stand. Once open spaces form, intense heating of the irradiated litter accelerates the melt rate. In either case, the area immediately in front of the boundary is rapidly cleared of snow, and with time the clear area spreads in both directions. That is, into the field and forest (Figure 7).

On the north, conditions are reversed. That is, the area of maximum deposition is the area of minimum melt. The result is a condition directly opposite to that observed on the south. As seen in Figure 8, the snow line strikingly delimits the area of increased deposition and dense shade in front of the stand.

While the processes described above account for the 39 day difference in snow retention between the north and south boundaries, inspection of the retention of several individual snows shows that melt associated with warm moist southerly flow and rain also played a significant role during the 1963-64 snow season (Lines 3-6, Table 17). Three of the prolonged snowcovers were terminated to a greater or lesser extent by warm periods with rain. Since in two of the three cases (Storms 2 and 4), fair

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**Fig. 7.** South boundary site, looking northeast. Characteristic structure of vegetation as discussed under Description of Sites and characteristic snow retention pattern are shown. Date of photograph is 27 February, 1964, or 7 days after Storm 2. Snow on ground, in terms of snow depth and percent cover, from 1H in the south field across the boundary to 1H within the forest was recorded as follows: 1H field (foreground) 2.5 in., 100%; 1/2H field (small temperature post) 2.0 in., 60%; boundary, no snow; 1/2H forest 1.8 in., 85%; 1H forest 2.5 in., 100%. Width of cleared area extends from 1/4H in to 1/4H outside the stand. Note that no snow is seen on the trees.
weather radiative melt processes had already eliminated snow on the south, the effect of the warm, rainy period was to reduce the retention difference between north and south. Had it not been for the influence of warm temperatures and rain, exposure differences in snow retention might well have totaled an additional 20 days.

Compared to the fair weather melt processes, warm moist weather with rain results in a fairly uniform and rapid elimination of snow cover. However, it should be realized that this type of weather is often associated with southerly wind flow, so that even in this case melting is favored on the south because of the stronger wind speeds experienced there (Part D). This, of course, is related to the fact that in warm moist air masses turbulent exchange (convection) and condensation play the dominant role in the melt of snow (Light 1941). Condensation is especially important in the Northeast, because fog is common (Reifsnyder and Lull 1965). Compared to these processes, the effect of warm rain is slight (Wilson 1941).

In spite of the above, the influence of rain occasionally seems to be apparent under the stand. Eight inches of snow were melted in the open during the rain of the warm moist rainy period after Storm 3. In the forest, 4 to 10 inches of rain were melted. While different wind speeds at locations in and around the stand undoubtedly cause different melt rates associated with both condensation and convection, the uneven pattern of melt also brings to mind the fact that rain, like snow, is subjected to both interception loss and re-distribution within the stand. Snow depths in and around the stand, which originally ranged from 5 to 15 inches, required an additional two to four days to melt after the rain.

The sequence of weather after Storm 2 is especially interesting because it demonstrates all of the processes described above. Under fair skies and seasonable temperatures between 20-27 February, fair weather radiative melt processes dominated, resulting in the snow retention pattern shown in Figures 7 and 8. On the other hand, although snow fell on 28 February, the establishment of warm moist southerly flow favored the removal of all snow between the 1st and 5th of March. In general, the occurrence of such weather is probably the primary factor which limits the retention of snow in the central and southern parts of the State.

The invasion of mT air into the State on the morning of 5 March permitted the observation of an interesting phenomenon — "snow smoke". The only snow remaining at the forest was large patches along the north boundary of the stand. The sky was overcast, and although winds on the south side of the forest were estimated as south at 15 with gusts to 30 mph, winds on the northern lee were recorded as calm with occasional gusts from the south at 10 mph. Because of the windy overcast conditions, temperatures were uniform over the general area. The temperature recorded at 1 meter above the ground at 1/2H in the north field was identical to that at Newark (58°F), where the dew point was 55°F and the relative humidity 90 percent. At the north boundary, a veil of smoke hung over the snow, which was in reality advective fog formed by cooling and subsequent condensation in the warm moist air as it approached the snow. With each gust of wind, the fog was carried toward the north field, where it dissipated as the air was warmed above the dew point. This was verified by temperature measurements across the boundary of the stand. That is, at 5 cm temperatures ranged from 57°F at 1/2H within the forest to 53°F near the snow (32°F) at the boundary, to 54°F at 1/2H in the north field. At the height of 1 meter, the corresponding values were: 59°F, 58°F, 58°F.

Thus, while snow is deposited at the forest according to a specific set of circumstances, melt proceeds in a number of ways. In general, warm,
moist air masses and rain account for a fairly equal and rapid removal of all snow at locations within the stand, compared to fair weather radiative melt processes which favor elimination of snow at the south boundary, but retention on the north. During 1963-64, snow was present approximately 2.5 times more often on the north than on the south. This condition, pictured in Figures 7 and 8 and referred to hereafter as "split active surfaces", had a tremendous influence on temperature differences between the two boundaries of the stand.

Summary. It has been shown that all intermediate and heavy snows, as well as many light ones, which together account for practically all of the total seasonal snowfall in New Jersey, are associated with winds from the northeast quadrant. This situation arises as the result of cyclonic flow around developed or developing lows which move through a critical snow area to the east and southeast of the State. Traveling disturbances moving along five of the nine major storm tracks within the United States characteristically move into this area. Regardless of the location of origin, lows in the critical area are associated with snow, largely because of the advection of moisture northward from both the Atlantic Ocean and Gulf of Mexico, and because of cold temperatures usually associated with a well-developed cold continental high located in a position well inland. This is of great significance not only to the general climatology of New Jersey, but also to the distribution of snow in and around the forest stand.

The general distributional pattern of snow throughout the forest as a whole, as well as minor variations in the distribution of individual storms, have been explained not only in terms of stand characteristics, but also in terms of aerodynamic considerations such as drift angles and density of snow, and wind speed and direction. The unidirectional (northeast) nature of wind during snow and stand characteristics such as orientation, structure and density are the primary factors accounting for the general distribution of snow throughout the stand. On the other hand, snow density and drift angles (wind speed) account for minor variations between storms.

Considering deposition alone, the windward northern forest boundary in New Jersey shows tremendous potential for the accumulation of snow. The drifting and packing action of strong winds, not only during but also after the storm, compresses the snow in this area, so that the area of maximum deposition is the area of maximum water content, per unit volume of snow. Although open spaces in the canopy such as at 1/2H-1H within the south boundary are characterized by increased depths during storms with strong winds, these values do not approach depths recorded in the northern drift zone. The same can be said of snow depths in the lee of the stand. The south boundary itself is characterized by an extremely poor potential for the accumulation of snow. On the other hand, considering melt alone, snow retention during fair weather is favored on the north because of the shading of the stand. Snow elimination is favored on the south not only because of the sunniness of the site, but because shallow depths melt faster, proportionally, than deep ones at any location in the stand. Thus, the significant point is that in New Jersey at least, the area of maximum deposition is the area of minimum melt, and vice versa. This accounts for significant differences in snow retention at the two sites, which influences thermal differences.

The retention and accumulation of snow at all sites during any one season is determined by: 1) the frequency of lows moving through the critical area, 2) the frequency of fair weather favoring radiative melt and 3) the frequency of warm moist air masses and rain with respect to the occurrence of snow. In general, warm moist air and rain favor fairly equal and rapid elimination of snow, compared to fair weather radiative melt processes which are a function of exposure.

The amount of damage associated with wet snow was found to be influenced by many factors. These include: 1) the position and density of the site within the stand, which determine the amount of snow available for interception, and 2) the shape and condition of the trees, which determine the amount of snow actually intercepted and the ability of the trees to support the snow. Dogwood trees on the south side of the stand, especially those weakened by drought in an open area favorable for the accumulation of snow, showed the greatest damage associated with wet snow.

Directional considerations above suggest that forests and shelterbelts in New Jersey should be oriented with their long axis running from east-southeast to west-northwest for the maximum accumulation of snow. This appears to be the best orientation, taking into account not only the unidirectional nature of northeast winds during snow, but also the prevalence of strong northwest winds after many storms. Dependent upon the desired effect, special consideration should be given to the composition, density, height and horizontal extent of underbrush at the windward edge of the stand. Although the above has direct application in silviculture and watershed management, the results are also generally applicable to the placement of snow fences and the plowing of roads and driveways in forested areas on level terrain.

These results are applicable within the Mid-Atlantic States, and to a greater or lesser extent at all locations along the East Coast which are influenced by the so-called "northeaster". Application of these methods to the New England area would prove especially interesting, since many of the storm tracks.
considered here plus three others converge off the New England Coast.

**Light.** It is obvious that in deciduous stands, marked changes in the percentage penetration of light (\% of that in the open) occur between the foliated and unfoliated seasons of the year. However, it is less obvious that, at mid-latitudes, less marked seasonal variations in the percentage penetration of light also occur with unchanged stand conditions because of the seasonal variation in the altitude of the sun. Both types of changes have been observed in Hutcheson Memorial Forest, in connection with ecological studies conducted there. For example, Anderson (1955) reports that the percentage penetration of light at midday under clear skies at a site positioned inside the stand was 45 percent in January, but increased to 68 percent in late April, shortly before the canopy began to close. She attributed the increase to decreased interception of light within the canopy and trunk space of the stand, because of the higher altitude of the sun. After a rapid decrease during canopy closure in May, the percentage penetration of light averaged about 3 percent. As indicated earlier, one of the objectives of this study is to investigate these effects further, especially as they occur within the zones of transition at the north and south boundaries of the stand.

Incoming light comes from both sun and sky. The diffuse skylight on cloudless days comes from the light which is scattered out of the direct solar beam by both dry air and haze aerosols (dust, air pollution, etc.) (Brooks 1959). An idea of the seasonal variation in the proportions of direct and diffuse light within the Mid-Atlantic States is given by measurements made near Washington, D.C. (39°N) by Kimball (1914). At noon on cloudless days in December the ratio of sky to total light varied from 20 to 50 percent. The corresponding values in June were 10 and 33 percent.

It is interesting to note the wide variation in the ratio during each month because of hazy days, and the fact that the ratios overlap because of hazy days in summer. However, the point to be made is that in this region, direct light predominates on bright, clear days during all seasons of the year. It makes up approximately 80 percent of the available light on clear days in winter, and about 90 percent in summer. The study of the midday light climate of woodlands on such days is therefore primarily an investigation of the penetration of direct light into the stand.

Although diffuse skylight makes up only a small fraction of the total light on clear days, it cannot be completely ignored. It is sometimes forgotten that on clear days diffuse light is not equally distributed over the sky. According to Brooks (1959), about 45 percent of the diffuse light incident upon a horizontal surface is localized in a large cone around the sun. Very little diffuse light comes from the northern sky, even at midday. He states that the uneven distribution of skylight may be significant for limited sky exposures (such as those found in and around a forest), and suggests that half of the diffuse light be treated as direct beam light.

**Conventions and critical values.** In order to interpret the results of this work, it was necessary to formulate certain conventions and calculate critical values concerning solar climate in and around the stand.

Among other important factors, the altitude angle of the sun (Q) determines the angle at which direct light is incident upon the stand. As commonly defined, the astronomical seasons begin at the solstices and equinoxes and are therefore four nearly equal time periods of rising or falling sun (and solar energy). What is less evident is that the rate of rise or fall is not constant throughout the season. That is, if one plots the noon altitude of the sun as a function of time, he will find that the slope of the line is steepest near the equinoxes, and comparatively flat near the solstices. In view of the importance of Q in determining the solar climate near the margins of the stand, it seemed more reasonable, for the purpose of this study, to define the astronomical seasons with the solstices and equinoxes at the mid-point rather than at the beginning of the seasons. This concept is shown on the right hand side of Figure 9.

Winter is the season of relatively constant low sun. Q slowly changes from 34 degrees on 7 November to a low of 26.5 degrees at the solstice back to 34 degrees on 5 February for a net change of only 7.5 degrees (Figure 9a). Spring and fall are transitional seasons, during which the sun either climbs or falls at a relatively rapid rate. During spring, Q increases from approximately 34 degrees on 6 February through 50 degrees at the equinox to a high of 66.5 degrees on 5 May for a net change of 32.5 degrees (Figure 9b). Summer is the season of relatively constant high sun. Q changes from a low of approximately 66.5 degrees on 6 May to a high of 73.5 degrees at the solstice back to 66.5 degrees on 8 August for a net change of only 7 degrees (Figure 9c).

Because it is incident upon the stand with the altitude angle of the sun, sunlight penetrates directly to any location on the forest floor if and only if it is unobstructed by plant parts which lie within the stand along the line between the location and the sun. The distance along this line within the stand is the path length (PI) along which the sun's rays must pass in order to reach directly to the forest floor (Figure 9a-c). Assuming constant stand height (H) and vertical trees, it is evident that PI varies only with Q. It should be remembered that PI is merely a length, not a density, but that more plant
parts are normally found along longer path lengths than shorter ones within most fairly uniform layered stands.

Ground distance (Gd) is the horizontal distance along the ground which extends from the point directly below where the sun’s rays are incident upon the top (or side) of the stand to where they strike the ground if unobstructed within the stand (Figure 9a-c). By simple trigonometry, Gd is also a function of Q. It can be seen that Gd represents the length of shade which extends into the field on the north, and also the distance to which direct light penetrates into the south boundary through the side rather than the top of the stand. As shown by the sizes of the triangles in Figure 9, the magnitude of both Pl and Gd changes drastically with the seasons (that is, with Q). The actual values of these variables for various heights within Hutcheson Memorial Forest were calculated for the key astronomical dates discussed above. By using these values, or by interpolating between them, one can easily obtain the approximate values of Pl and Gd for any height on any day of the year (See Appendix).

In order to be consistent with the evaluation of weather in Part A, the following discussion is based primarily on the commonly-defined meteorological seasons. However, clear-day observations in this study were obtained, to the extent to which the weather would allow, according to the frame of reference given above. That is, winter and summer data were gathered on days clustered fairly uniformly around the equinoxes, and spring data were gathered on days spaced at fairly equal intervals between them (Table 2).

**Percentage penetration of light on clear days during winter.** The general pattern of light penetration across the north and south boundaries of the stand is shown in plan view in Figure 10. Isolines indicate 10 percent intervals in percentage penetration of light. It must be emphasized that the analysis, which is based on interpolation between observation points at 1/4H intervals on each of the transects, represents only a first approximation to the actual complex light penetration pattern which exists across the boundaries of the stand.

Perhaps the most striking feature in the figure is the variation in the percentage penetration of light which exists between many of the adjacent observation points. The high values, of course, are in areas dominated by sunflecks, and the low ones are in areas dominated by shade. However, compared to the other seasons, sunflecks are hard to define. Although they cover a large portion of the area, their intensities are not much greater than the shade light. Except for shadows cast by the trunks of the trees, which move across the forest floor with the movement of the sun (sundial effect), the boundaries between sunflecks and shade light are ill-defined.

Considering first the south boundary, it is evident that a considerable amount of light penetrates to a distance of approximately 1/2H into the stand. This is related to the cover of the side rather than the top of the stand, for the direct rays of the sun are more nearly normal to a south-facing vertical surface than a horizontal surface during the winter season of the year (Figure 9a). Light penetrating through the edge of the stand below the height of the dogwood canopy (approx. 15 ft near boundary) follows a short path length through the vegetation at the boundary and the relatively open trunk space beyond. On the other hand, light incident at upper levels follows a longer path length through the relatively dense canopy levels in addition to the other parts of the stand. Note that Gd for H 15 feet equals 30 feet (Appendix), which is the approximate distance to which the high light intensities extend into the stand. It is interesting to note that the high light intensities extend farthest into the stand on the southwest and least on the southeast, and that these transects had the least and most cover, respectively, within the dogwood layer near the edge of the stand. Spot measurements indicated that most of the 30 percent reduction between the boundary and 1/2H occurs within the dense vegetation at the edge of the stand.

By reference to "wall" studies found in Brooks (1959), it may be stated that more solar energy is
The intensity and extent of shade in front of the north boundary are determined primarily by the penetration of direct light through the vegetative layers near and at the edge of the stand. The dense shade immediately in front of the stand, where the light penetration averages between 20 and 30 percent, is cast by the dogwood layer. Note once again that Gd for H 15 feet, the approximate height of the dogwood layer, equals 30 feet, which is the approximate distance to which the shade extends into the north field. It is interesting to note that the light reaching much of this area characteristically passes through denser cover than is found at any other location within the stand. That is, it penetrates not only through the oak and dogwood canopies, but also through the dense dogwood growth which makes up the edge of the stand. On the other hand, small quantities of diffuse light are available in the area in front of the stand from the northern and unobstructed parts of the overhead sky (Brooks 1959). This contribution is evidently not enough to compensate for the increased interception within the stand, for light penetration in the area is equal to or below that found at positions within the stand.

Beyond the area shaded by the dogwood layer, shade is variable and inefficient because light penetrates easily through the relatively open oak crowns. Detectable shade is present only where the trunks and large limbs cast shadows on the ground, and the theoretical maximum width of shade (Gd for H 85 ft equals 170 ft) is not reached at any point. Higher percentage penetration of light is noted on the northwest transect, which has the least cover, particularly within the dogwood layer near the edge of the stand. The percentage penetration of light within the stand on the north is similar to that at the forest center site.

It is evident that radiation relationships in front of a north-facing forest boundary are only approximated by those on the north side of a vertical wall. Whereas the shading in front of the wall is complete, considerable amounts of solar energy penetrate through the unfoliated stand to contribute to the small amounts of diffuse radiation incident upon the area in front of the stand. As indicated earlier, the area of maximum snow deposition is the area of minimum melt at the north edge of the stand. The balance between snow deposition and melt under fair skies is such that a sharp snow line is established at 1H in front of the stand (Figure 8). It is interesting to note that the dense vegetation near the ground not only favors the increased deposition of snow, but also favors its retention under fair skies, because of the increased shade in front of the stand.

The three light penetration values at each boundary of the stand, which were obtained at the edge of the dogwood canopy, were averaged and compared with the percentage penetration of light.
at the center of the stand, with the following result: north 35%, center 40%, south 100%. Thus, the difference-of-exposure between north and south at noon on clear days is 65 percent. Light penetration at the northern boundary is actually less than that at the forest center site, primarily because of the increased density of the dogwood growth in the edge of the stand, as opposed to the trunk space within the forest. The percentage penetration of light at the forest center site compares favorably with Anderson's (1955) result. As was the case in her study, the winter value was lower than any of those obtained in spring.

Snow completely covered the ground on two of the five days during which the winter light observations were made. The effect of snow, commonly known for its high albedo, is to increase the absolute amounts of available light, because of an increase in diffuse light originating from reflections from the snow. This accounts for the fairly high average value (5100 ft-candles) of light in the open. However, no difference in the percentage penetration of light could be detected between the days with and without snow. Similar results were noted for the total short-wave spectrum by Vézina (1964), who worked in a pine forest near Ottawa City, Canada.

**Percentage penetration of light under overcast skies during winter.** With a uniform, heavy overcast, direct sunlight is scattered and reflected by water drops within the clouds so that the sky is dominated by diffuse light (Huschke 1959). Under such conditions, there is no appreciable effect from the sun, and the brightness of the sky increases toward the zenith (Anderson 1964a). Investigators have found that: 1) the uneven distribution of light caused by sunflecks is eliminated (Evans 1956, Geiger 1957), 2) the percentage penetration of light within unfoliated woodlands is increased over that on clear days (Geiger 1957) and 3) exposure differences are diminished (Geiger 1957). With the exception of Statement 3, which Geiger claims is true by analogy to research on mountain slopes, all of the above are conclusions based on research conducted at sites positioned well within the stand. It should be noted that Statement 2 is dependent upon the treatment of sunflecks on clear days, and is applicable only to studies where sunflecks and shade have been averaged, as is the case with the winter and spring data in this study.

As indicated in the methods section, winter was the one season of the year during which observations were obtained on both clear and overcast days, in order to investigate some of the fundamental differences between the penetration of light at the boundaries of the stand on such days. Although most of the overcast observations were made under low stratus or nimbostratus overcasts, it was observed that a bright spot often existed in the vicinity of the sun. This resulted in a concentration of brightness in the southern rather than the zenith sky, the consequences of which will be pointed out in Figure 11. It can be shown, nevertheless, that most of the three statements above are valid near the edges of the stand.

Perhaps the most striking feature in Figure 11 is the evenness of the light penetration pattern, compared to that on clear days. The marked variations between adjacent points caused by sunflecks are eliminated. Instead, there are merely different degrees of "shade". Thus, Statement 1 is substantiated near the boundaries of the stand. It is interesting to note that other observations made during this study indicate that sunflecks fade considerably on hazy days, and tend to be eliminated on days when cirrus covers the sun. In other words, there is a gradual attrition of sunflecks with an increase in the ratio of diffuse to total light.

The consequences of the uneven distribution of diffuse light are readily apparent at the boundaries of the stand, where the forest itself screens light from certain vast sections of the sky. The area at and in front of the south boundary, which is exposed to the lightest section of the sky, is lighter than the corresponding area on the north. Furthermore, the "shadow" cast by the stand as a result of the screening of light from the northern and overhead

![Fig. 11. Percentage penetration of light across the north and south boundaries at noon under overcast skies during winter, and difference between light penetration on overcast and clear days (overcast minus clear). Difference is in parenthesis. Isolines indicate 10 percent intervals in light penetration.](image-url)
portions of the sky extends only a short distance into the south field. On the north, the “shadow” extends farther into the field, because of the screening of light which predominates in the southern sky. As in the case of clear skies, the pattern indicates effective screening by the dense dogwood canopy, and less effective screening by the oak.

Whereas the average difference in the percentage penetration of light between positions at the north and south boundaries is 65 percent at noon on clear days, it is reduced to 15 percent at noon under the overcast skies in this study (Figure 11). Some of the observations obtained when the overcast was more uniform indicate that under these conditions the difference-of-exposure approaches nil. There is, nevertheless, a considerable reduction even when the brightness is centered in the southern rather than the zenith sky. This substantiates Statement 3. It is interesting to note that the difference-of-exposure between positions at and in front of the north and south boundaries is reduced on an overcast day because of an increase in the percentage penetration of light on the north, and a decrease on the south, compared to clear days. This is readily seen from the figures in parentheses (Figure 11).

Statement 2 is a consequence of the non-directional nature of diffuse light, which easily penetrates into the stand from above, whereas direct light follows a longer angular path at locations within the stand. It is immediately apparent from the figures in parentheses (Figure 11) that the percentage penetration of light is increased on overcast days at all locations under the canopy except those near the south side of the stand. It should be recalled from the previous section that these positions are dominated by direct light on clear days, and correspond to the area where direct light penetrates into the forest by following short path lengths through the lower parts of the side of the stand. On the north, small differences between 0 and 9 percent are noted only at observation points which showed high light intensities on clear days, because of the high proportion of direct light. Otherwise, the increase on overcast days averages about 20 percent. It may well be that in uneven aged stands, some points within the forest will show decreases, because of a high proportion of direct light passing through gaps in the stand. However, decreases are consistently found near the south boundary, so that Statement 2 cannot be substantiated at this boundary of the stand.

It is interesting to note that had a uniform overcast existed, the percentage penetration of light would have been slightly lower on the south and higher on the north, at least at the boundaries of the stand. This means that the influence of the increased light in the southern sky was actually to diminish the differences between clear and overcast days, in the areas mentioned.

**Percentage penetration of light on clear days during spring.** Based on the interaction of the astronomical and phenological seasons, the transitional season of spring can be logically divided into two phases in the mid-latitude, deciduous stand. The first phase is the period of rapidly rising sun during which the sun’s rays penetrate into an unfoliated stand. This corresponds to the period during which Anderson (1955) found an increase in the percentage penetration of light. The second phase is the period which extends from bud break to canopy closure, and it corresponds to the time during which the sun begins to level off in its ascent toward the summer zenith. This phase, of course, is characterized by a marked decrease in the percentage penetration of light. By the definition suggested in Figure 9, the first phase of spring in New Jersey extends from 6 February to bud break in late April. The second phase extends from the April date into late May, or possibly early June. Naturally, the length of these phases varies with the weather from year to year at the same locality, and with the geographical location within mid-latitudes. However, each phase is characterized by unique features, in terms of its light climate.

The average percentage penetration of light at both margins of the stand and at the forest center site during both phases of spring are shown in Figure 12. Observations at the margins were made at the edge of the dogwood canopy, and represent the approximate amounts of light available to leaf buds at the edge of the stand. The curves on the right quantify canopy closure in terms of the elongation of dogwood leaves at the edge of the stand. Dogwood bud break (23 April) separates the two phases of spring. Lines of best fit are constructed through the data during the early period. It is unfortunate that cloudiness did not permit observations during the critical period between 16 April and 4 May. However, stagnated high pressure during all of May brought fair skies, permitting observations at weekly intervals during the entire second phase of spring (Part A).

At the forest center site, there is an increase of approximately 30 percent in the percentage penetration of light between the winter value of 40 percent and the 70 percent value recorded shortly before bud break. If the line is extended backward in time, at the slope indicated in the figure, it strikes the 40 percent point in mid-January. This is a reasonable “effective” date for the winter average, especially since the slope undoubtedly tapers off before 6 February. Furthermore, this result compares favorably with Anderson’s (1955) results.

The increase in the percentage penetration of light is related to the increase in the altitude angle of the sun. With higher altitudes, the path length is significantly reduced and fewer plant parts inter-
cept the direct rays of the sun. By interpolation (See Appendix), direct light passes through approximately 58 feet of oak canopy, 40 feet of dogwood canopy, and 17 feet of trunk space, a total of 98 feet during late April, in order to reach the forest floor. This distance is about one-half of that available on the winter solstice, and about two-thirds of that on 6 February. The increase in direct light is directly observable in the pattern of light (sunflecks) and shade cast across the forest floor. As opposed to winter, the shadows cast by the trunks of the trees are shorter, and cover less total area across the forest floor. The remainder of the area is dominated by sunfleck light. However, it is important to note that while increases occur at most observation points within the stand, they do not occur at all points, because of the arrangement of gaps and other irregularities in the forest. Such structural considerations become critical near the margins of the stand.

At the south margin, the percentage penetration of light remains at 100 percent during the first phase of spring because the sun does not get high enough so that its direct rays are intercepted by the overhanging oak branches at the edge of the stand. It is interesting to note that the foot of the south boundary is the only location within the stand where litter receives the direct rays of the sun for the best part of the spring day (sun rises and sets at northern azimuths after 23 March).

With Q reaching approximately 60 degrees at noon, more solar energy is available on the horizontal than the vertical surfaces at the edge of the stand (Brooks 1959).

At the north margin, there is little or no increase in the percentage penetration of light. Although the slope of the line indicates an increase of approximately 10 percent, the values obtained during late February and March do not differ significantly from many of those recorded during the winter period. This situation is related to both the structure and density of the vegetation near the edge of the stand. Although path lengths are shorter within the canopy layers during spring, the number of plant parts available to intercept the rays of the sun tends to increase because of the increased density of the vegetation near the edge of the stand. With Q at about 60 degrees, the sun's rays penetrate through the wall of growth at the margin of the stand rather than the relatively open trunk space at low levels within the stand. Furthermore, the path length within this dense growth is actually increased over winter, because the growth is higher than it is wide at this fixed point in the stand. These effects tend to cancel the influence of the shortened canopy path lengths, and the result is little or no increase in the percentage penetration of light at the north margin of the stand.

Figure 13 shows the percentage penetration of
light across both boundaries of the stand on 16 April, with a few isolines drawn in order to indicate the general light penetration pattern near the edges of the stand. The difference in the percentage penetration of light between 16 April and winter (16 April—winter average) is also shown. Compared to winter, there are a large number of observation points with very high light intensities indicating the domination of sunflecks, and a small number of points with low intensities, indicating a domination by shade.

Within the north boundary, the percentage penetration of light is similar to that at the center of the forest. Large increases are noted except in a few areas dominated by shade. Light penetration at the boundary remains low, for the reasons given above. The deep shade in front of the boundary is cast by the dogwood layer (Gd for H 15 ft equals 9 ft), while the inefficient shade is cast by the oak (Gd for H 85 ft equals 47 ft). As at noon during winter, the small amounts of diffuse light incident upon the area in front of the stand from the northern and unobstructed parts of the overhead sky are supplemented by direct light penetrating through the side of the unfounded stand. However, since the sun rises and sets at northern azimuths after 23 March, direct light is actually incident upon both horizontal and vertical surfaces at the margin of the stand during the early morning and late afternoon after this date.

The light penetration pattern within the south boundary provides only a partial picture of the complex conditions which actually exist there. With Q at approximately 60 degrees, the rays of the sun are more nearly normal to the top of the stand than to the south side (Figure 9b), so that the ground distance associated with direct light penetrating through any part of the edge of the stand does not exceed 47 feet; that associated with the dogwood layer equals 9 feet (Appendix). Although detailed analysis of the first 9 feet was not made, it was evident that most of the reduction between the boundary and 1/4H occurs at the edge of the stand. There does not appear to be any systematic difference in light penetration between that at 1/4H and 1/2H and that at positions farther back in the stand. Evidently, the slightly shorter path lengths associated with penetration through the side of the stand at the level of the oak are offset by the increased density of the vegetation near the edge of the stand. Increases in light penetration over winter are consistently low or negative at 1/4H and 1/2H within the stand, compared to the other areas. This is primarily due to the increased penetration through the side of the stand during winter, as explained earlier.

Changes in the pattern and intensity of light at the forest center site associated with the expansion of the foliage during the second phase of spring are best appreciated by a consideration of changes at different points, as well as by changes in the overall average percentage penetration of light.

On 4 May, the pattern and intensity of light within the forest were determined by a delicate balance between the effect of higher solar altitude (approx. 66°), which tends to increase the penetration of light, and the expansion of the leaves, which tends to decrease it. Dogwood leaves averaged 20 mm or about 20 percent of their full length, but they were not unfolded. The number of observation points showing increases in the percentage penetration of light over that observed on 16 April (4 May—16 April) about equaled those showing decreases. However, while most of the increases ranged between 0 and 10 percentage points, the decreases ranged between 0 and 35 percentage points. The average percentage penetration of light dropped to 60 percent. It is interesting to note that near the boundaries of the stand, the number of points where decreases were recorded slightly outnumbered those showing gains, and the magnitude of the decreases was greater than that at observation points at the center of the stand. This was due to the increased abundance of sweet cherry and maples (Norway and red) near the boundaries.
(Table 1), which leaf out earlier than the other trees.

On 11 May, after the unfolding of the leaves, the pattern of light cast across the forest floor was a complex mosaic of light and shade. The dominant factor was clearly the development of the leaves. Dogwood leaves attained about 46 percent of their full length, but average leaf area was only about 18 percent of the full size. Marked decreases in the percentage penetration of light over 4 May (11 May — 4 May) occurred at all observation points within the stand, except three points near gaps in the canopy. The decreases over the previous week ranged from 0 to 60 percentage points, while the increases ranged between 0 and 5 points. Average percentage penetration of light dropped to 36 percent. The shadows cast by the sweet cherry and maples near the edges of the stand blended into the basic pattern of light and shade.

On 18 May, after continued rapid development of the leaves (dogwood leaves attained 70% full length, 46% full area), the light penetration pattern was clearly dominated by shade. As during the previous week, marked weekly decreases (0—80) in the percentage penetration of light occurred at all observation points, except those few which were dominated by direct light passing through gaps in the stand (no significant change). Light penetration averaged only 5 percent. The succeeding three weeks brought a reduction of only about 2 percent in the percentage penetration of light, associated with the development of the leaves to full size. It is interesting to note that the thermal inversion associated with the partial deactivation of the forest floor occurred between 11 and 18 May.

As indicated above, the percentage penetration of light was reduced from 73 percent to 5 percent with increases from 0 percent to about 70 and 46 percent in leaf length and area respectively, between bud break and the 18th of May. Further increases in leaf length and area resulted in only a slight reduction in the percentage penetration of light, from about 5 percent on the 18th to 3 percent thereafter. This suggests a negative curvilinear relationship between leaf development and the percentage penetration of light. Almost all of the reduction occurs with and immediately after the unfolding of the leaves. Similar relationships are noted at the north and south margins of the stand (Figure 12).

At the south boundary, the rapid decline in percentage penetration of light is the result of the unfolding of the oak leaves at about the time that the sun gets high enough so that its rays are intercepted by the overhanging oak branches at the edge of the stand. Since this vegetation is fairly open, the percentage penetration of light remains fairly high. The noon value is undoubtedly greater than that recorded during the early morning and late afternoon, but less than that at mid-morning and mid-afternoon, because the sun rises and falls at northern azimuths and attains a high altitude angle at noon during this time of year.

At the north boundary, the percentage penetration of light drops off rapidly with the unfolding of the leaves, and levels off to a value similar to that at the center of the forest. Very little light penetrates through the foliated stand. As is indicated even by the characteristic growth form of the trees (Figures 2, 3, 7 and 8), the major source of light at the north margin during the growing season is from the north. At noon there are only small amounts of diffuse light from the northern and unobstructed parts of the overhand sky, but during early morning and late afternoon direct sunlight is incident upon the north side of the stand.

It is interesting to note that the differences between the light climates at the north and south margins of the stand are evidently sufficient to influence the size of the dogwood leaves. Whereas the southern leaves were actually slightly larger than the northern ones at the beginning of the period, this condition was reversed by the time the leaves reached full size (Figure 12). Similar, although more drastic differences have often been noted between sun and shade leaves. Anderson (1955), for example, found that dogwood leaves growing within Hutcheson Memorial Forest were 1.8 times larger (area) than those growing in the open. In this study, the difference between the northern and southern leaves was less (northern 1.2 times larger) because of the less drastic differences between the light climates of the south and north boundaries, compared to those between full sun and forest shade.

While the values shown on the right hand side of Figure 12 provide an adequate description of the percentage penetration of light at the margins and within the stand during summer, a more comprehensive picture is provided by a partial analysis of sunflecks versus shade light.

Percentage penetration of light on clear days during summer — sunflecks and shade light. The pattern of light cast across the forest floor on clear days during summer is extremely complex. The intensity of light frequently varies fifty-fold in a matter of inches, for superimposed on the basic pattern of shade light is a patchwork of sunflecks, varying in size from "pinhole" images of the sun to areas which cover several feet. Under such conditions, it seemed appropriate to sample separately for sunflecks and shade light at each point in the stand, in order to get a better picture of light penetration in relation to the amount and quality of vegetation overhead. The technique involved the use of a photometer with a sensing element approximately one inch in diameter, which was moved throughout an area of about 12 square inches at
Fig. 14. Percentage penetration of light for both shade and sunfleck components, in relation to arborescent cover on the north center transect, at noon under clear skies during summer. A value for mean shade and values for sunfleck extremes are shown at each point. No lower extreme for sunflecks indicates that they were not always recorded at that point. See text for further discussion.

Each point in order to record the lowest shade and highest sunfleck light. Sunflecks were recorded only when they were well-defined, and covered the sensing element. Shade was recorded in the absence of sunflecks.

This technique was carried out at noon on four relatively calm, clear days during June. Since data could be gathered on only four days, rigorous statistical treatment hardly seems appropriate. However, expressed in terms of percentage of full light, values for the shade component were often identical on two, three and sometimes four of the observation days. The spread between high and low values was seldom very great. On the other hand, while sunfleck values tended to be either high or low, no definite indication of central tendency was observed. Therefore, a value for mean shade and values for sunfleck extremes have been plotted at each observation point in Figures 14 and 15, in relation to arborescent cover which is drawn to scale.

Except for an open gap on the southwest transect, there is a basic pattern of shade light within the stand. On the relatively dense north transect, the penetration of this light generally ranged between 1.5 and 1.9 percent, but dropped to 1.0 percent under the dense vegetation at the edge of the stand. On the south, the range of shade light was from 1.8 to 3.1 percent, with the highest value in the vicinity of the sunny gap, and the lowest under the dense vegetation at the edge of the stand. This distribution suggests that shade light may be determined by the nature of the vegetation directly overhead.

There is an increase in shade light within the shady zone in front of the north boundary, until the rapid transition to full sun occurs. At the south boundary, the transition occurs at the margin of the stand. The light conditions at the foot of the boundary are in reality a mosaic of shade and full sun, which is determined by the intermingling of branches at the edge of the stand.

The distribution of sunfleck intensities in relation to the arborescent cover indicates that the intensities are a function of both the quantity and quality of path length cover involved. There is a decrease in sunfleck intensity associated with an increase in the number of layers contributing cover along the path length. This is displayed rather well immediately within the south boundary, at the north boundary and near 1/2H on the north. It is interesting to note that no sunflecks were recorded at the north margin, which has the densest cover of any location studied within the stand. On the other hand, at 1/4H and near 1H on the north there are increases in intensity associated with decreases in the amount of path length cover involved.

Each tree species has a characteristic shape and arrangement of leaves. Oak, for example, is noted
for its vertical-shaped open crown, whereas dogwood has an umbrella-shaped dense one. Therefore, it is not surprising to note that sunfleck intensities are high at the south margin and within the sunny gap, which are shaded for the most part only by oak. On the other hand, intensities are low under the dogwood and maple near the gap, because of the dense cover of these species. While separate examples of the influence of both path length quantity and quality have been cited above, it should be remembered that in reality, the amount of light penetrating to any one spot is determined by both factors acting together under the stand.

The intensity of light in sunflecks observed in this study ranged from below the sensitivity of the instrument to 97 percent of full sunlight. In many of the locations where sunflecks were not recorded, visible sunflecks were observed but had intensities so weak that readings could not be obtained. In isolated instances, small intense sunflecks with diameters smaller than the diameter of the sensing element were ignored.

It should be remembered that sunflecks and shade are two distinct kinds of light. According to Evans (1956), shade light is composed of filtered direct and diffuse skylight plus diffuse skylight passing through holes in the stand. Since the transmissivity (diathermance) of green leaves is greater in the green and far-red portions of the visible spectrum, the shade light is richer in these wavelengths than light in the open (Coombe 1957, Robertson 1964). On the other hand, sunflecks are dominated by sunlight (Evans 1956).

While good correlations between the distribution of shade light and forest undergrowth have sometimes been obtained, the relationships between sunflecks and undergrowth have not been ascertained (Anderson 1964a). It is interesting to note in passing that little or no shrub or herb cover was noted at the north margin of the stand. While this condition is undoubtedly the result of numerous factors, it is obvious that light is one of the factors involved. In this case it may well be the limiting factor, because mean shade was lower than at any other location studied in the stand, and no sunflecks were observed.

Summary. Seasonal changes in the percentage penetration of light at noon on clear days within Hutcheson Memorial Forest and across the north and south boundaries of the stand have been explained in terms of changes in both solar altitude and the vegetative state of the stand. Differences in light penetration between overcast and clear days during winter are discussed in terms of the different characteristics of direct and diffuse light. A comprehensive view of the light climate during summer is provided by a partial analysis of sunflecks versus shade light.
Winter (Dec, Jan, Feb) is the season of low sun, low solar energy (on horizontal) and low percentage penetration of light within the unfoliated stand. Low values in the percentage penetration of light at the forest center site are directly related to the low altitude angles of the sun. Long path lengths at low angles within the stand result in an increase in the number of plant parts available to intercept the direct rays of the sun.

The length of shade cast in front of the north boundary, which is at a maximum during winter, corresponds to the distance to which direct light penetrates into the south boundary through the side rather than the top of the stand. On the north, the shade cast by the dogwood layer is especially deep because the light penetrates through the dense “wall” of vegetation within the edge of the stand, in addition to the canopy layers. On the other hand, light penetration within the south boundary is high because light incident upon the stand below the height of the canopy penetrates only through the “wall” of vegetation at the edge of the stand. The difference-of-exposure between north and south margins of Hutcheson Memorial Forest at noon on clear days during winter equaled 65 percent.

Under overcast skies, the uneven distribution of light caused by sun flecks on clear days is eliminated; there are only different degrees of “shade”. Even haze and cirrus are effective in eliminating sun flecks, which disappear completely with a shift to a dominance of diffuse light. The percentage penetration of light within the unfoliated stand on overcast days is increased over that on clear days, except for large gaps, there is a basic pattern of shade light under the forest. Lowest light penetration occurs within the wall of growth at the edges of the stand. The data suggest that the penetration of shade light is determined by the nature of the vegetation directly overhead.

Spring (Mar, Apr, May) is the season of rapidly rising sun and solar energy (on horizontal). It can be divided into two phases within the mid-latitude, deciduous stand. By definition, the first phase extends from 6 February to bud break. Within the center of the forest there is an increase in the percentage penetration of light, associated with shorter path lengths at higher solar altitudes resulting in a decrease in the number of plant parts available to intercept direct light. Thus, the period of rapidly rising solar energy in the open is coincident with the period of increased percentage penetration of light. In a paper published as the present work was drawing to a close, Anderson (1964b) terms this period the “absolute light phase”, and shows that in England at least, more solar energy penetrates into the stand during this period than at any other season of the year.

At the south margin the percentage penetration of light remains at 100 percent, because the sun does not get high enough to be intercepted by the oak branches at the edge of the stand. At the north margin, there is little or no increase in the percentage penetration of light, because of the density and structure of the merging layers at the edge of the stand. Both the length of shade in the north field, and the penetration of light through the south boundary are reduced, because of higher sun.

The second phase of spring extends from bud break to full closure of the canopy, and is marked by a dramatic but by no means regular decrease in the percentage penetration of light. The data suggest a negative curvilinear relationship between leaf development and the percentage penetration of light. At the center of the forest, almost all of the reduction occurs with and immediately after the unfolding of the leaves. Similar relationships are noted at the margins of the stand.

Differences between the light climates of the two boundaries are sufficient to influence the size of the leaves; dogwood leaves on the north margin attained areas 1.2 times larger than those growing on the south side of the stand.

Summer (June, July, Aug) is the season of high sun, high solar energy (on horizontal) and low percentage penetration of light into the foliated stand. Except for large gaps, there is a basic pattern of shade light under the forest. Lowest light penetration occurs within the wall of growth at the edges of the stand. The data suggest that the penetration of shade light is determined by the nature of the vegetation directly overhead.

On the other hand, sun flecks are a function of the quantity and quality of the path length cover involved. They become less frequent and less intense with an increase in the number of layers and/or the density of the vegetation along the path length within the stand. Whereas the light climate at the south margin is a mosaic of direct light and shade, that at the north margin is one of deep shade. The area of low herb and shrub cover corresponds to the area of deep shade with no sun flecks within the margin of the stand.

“Wall studies”. Radiation relationships in front of the south margin are similar to those described in “wall” studies, except during summer when the boundary is shaded by overhanging oak branches at the edge of the stand. Radiation relationships at the north margin are only approximated by “wall” studies, at least during winter and early spring when radiation penetrates through the side of the stand, especially within the zone of relatively open oak crowns. The major light source at the north margin is from the north only during the growing season.

Wind. In a region where Biel (1958) has described the climate as dependent or advective in nature, an investigation of the microclimates of
north and south forest boundaries would be incomplete without a brief consideration of the wind conditions at the boundaries of the stand. Wind flow across any particular forest border depends first upon the position of the border with respect to the direction of the prevailing winds. An unobstructed north boundary receives the full impact of north winds which blow directly perpendicular to it. Northwest and northeast winds, meeting the boundary at angles of 45 degrees, are also of major importance at the north margin of the stand. Similarly, south, southwest, and southeast winds are of major importance at the south margin of the stand. With these considerations in mind, a first approximation to wind conditions which exist at any forest border may be derived from the seasonal wind regime presented in Part A.

During winter, the north boundary is the windy boundary of the stand (Part A-1). On the other hand, during summer the most frequent winds are incident upon the south margin of the stand (Part A-3). Spring is the season of transition; whereas the north boundary is the windy one during March, the winds become slightly more frequent on the southern boundary during May (Part A-2). As indicated by the monthly mean wind speeds, the strongest winds are always incident upon the north margin of the stand (Tables 6, 9 and 12). Since March is the windiest month, the strongest winds characteristically penetrate into an unfoliated stand.

No wind instrumentation was available for this study. Therefore, a method was developed whereby estimates of wind direction and speed (Beaufort) made at the forest were compared to the macroscale wind observation at Newark Airport, for the time nearest the observations at the forest. The purpose was to establish a general relationship between the two, so that with a knowledge of the wind at Newark, one could express a reasonable estimate of the wind flow at the three study sites at the forest stand. With regard to wind direction, comparison of arrays of wind observations from the forest and Newark verified the blocking angles derived independently through the interpretation of an aerial photograph. That is, wind speeds for the north and south boundaries showed breaks at the directions indicated on the photographs. These angles were discussed in the Methods Section. By averaging wind speeds according to blocking angles (Table 18), it is possible to gain an appreciation of the drastic differences in wind speed which exist between the forest center and north and south margins of the stand.

When the wind is incident upon the north margin (that is, when it is between 310 degrees clockwise to 090 degrees) wind speed is negligible at the center and south side of the stand (Lines 1 and 5, Table 18). On the other hand, when the wind is incident upon the south margin (165 de-

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### Table 18. Mean wind speed (mph) by direction (deg), for Newark (anemometer) and locations at Hutchens Memorial Forest (Beaufort), during foliated and unfoliated seasons. Observations near forest margins were made at 1/4H within fields.

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<td>285-300</td>
<td>15.2</td>
<td>10.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

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43
the behavior of game and other wild life. On the other hand, the high frequency of winds incident upon the south margin during the warm season directly influences the vegetation through increased evapotranspiration and increased fire hazard. These factors are undoubtedly critical ones during drought years. During spring, the period of strong winds is coincident with the period of increasing insolation under the unfoliated stand. While litter may be drier, and therefore the incidence of fire greater during other seasons, the fact that fires occurring in spring are likely to be more devastating, because of high winds, is a factor of more than passing concern. Such fires occurred in the vicinity of Hutcheson Memorial Forest during the Spring of 1962.

Consideration of the influence of wind (turbulence) on thermal stratification is best reserved for Part E.

**Temperature.** Temperature relationships at the edges of the stand are determined by all that has been discussed to this point. That is, they are dependent upon the type and condition of active surface and upon weather conditions including solar altitude, cloudiness and wind (actually turbulence associated with movement of air). As indicated in the literature review, thermal relationships within stands on both level terrain and wooded slopes have been investigated in some detail. No data are available concerning temperature near the edges of a stand. The purpose of this section is to provide information concerning 1) the lapse rates at the north and south boundaries of Hutcheson Memorial Forest during winter, spring and summer, and 2) the temperature differences between the boundaries during these seasons of the year. The results are discussed in terms of seasonal changes in the causative factors listed above.

**Relationships applicable to all seasons.** Results equally applicable to all seasons are perhaps most appropriately discussed at the outset. Regardless of season, lapse rates during overcast, rainy weather are essentially isothermal and little (plus or minus 1°F) or no difference in temperature exists between boundaries. On the other hand, strong lapse rates and maximum differences in temperature between boundaries are experienced during clear, calm conditions. Very few of the observations in Figures 16, 17 and 19-22 represent overcast conditions, because maximum and minimum thermometers read at bi-weekly intervals tend to record extreme temperatures experienced on fair days. This was discussed in greater detail in the Methods Section (III-B-2). Numerous spot temperatures obtained during overcast, rainy weather on the bi-weekly trips to the forest verified the fact that both the vertical and horizontal temperature differences were nil. This result was entirely expected, primarily because of the radiation relationships involved (See Geiger's "law" concerning difference-of-exposure, etc., page 4).

Similarly, because of the influence of direct radiation during the day, maximum temperatures show strong lapse rates and large differences in temperature between boundaries compared to minimum temperatures (Figures 16-22). Lapse rates of minimum temperature and temperature differences between boundaries are small. This is true because outgoing radiation is influenced by vegetative cover but not by exposure. Although greater insolation produces higher maximum temperatures on the south, the radiating surfaces lose much of their heat before morning, so that differences between minimum temperatures at the boundaries are not very great. For this reason, emphasis was placed on the study of maximum temperatures.

The third generality applicable to all seasons is the fact that stronger lapse rates are experienced near the ground. That is, the difference in temperature between the 5 cm and 1 meter levels is greater than that between 1 and 2 meters (Figures 16-22). This applies primarily to maximum temperatures developed under fair skies. However, it is also true on overcast days (Table 19) and with minimum temperatures, when differences between levels are so small that the profiles, for practical purposes, can be considered to be isothermal. It follows from the nature of the lapse rates that thermal differences between boundaries are always greatest near the ground. Cantlon (1953) found similar relationships on the north and south slopes of Cashetunk Mountain.

The fact that the lapse rates at the boundaries are stronger near the ground is readily understandable at least during winter and spring, since it is widely accepted that the forest floor functions as the primary active surface during these seasons of the year. On the other hand, during summer the canopy is usually considered to be the primary active surface. In Hutcheson Memorial Forest the litter layer is only partially deactivated during summer, since strong positive lapse rates are associated with the movement of sunflakes across the forest floor. This occurs both within the stand proper and at the south margin (Figure 18c). On the north where no intense sunflakes are found (Part C-5), an inversion (temperature increase with height, negative lapse rate) is maintained by the lack of incoming radiation and the stagnation of air within the dense low growth over the radiating ground (Figure 18c). Other investigators (Byram 1948, Cantlon 1953) have offered a similar explanation for the presence of an inversion on north-facing slopes. The point is that lapse rates are stronger near the ground within the first 2 meters of the stand, even during summer when the canopy functions as the primary active surface.

**Lapse rates and thermal differences between**
boundaries during winter. The lapse rates and temperature differences between boundaries during winter are different than those experienced during the other seasons. With regard to maximum temperatures (Figure 16a), the lapse rate over litter at the north boundary is essentially isothermal (29 Nov-9 Dec, 25 Jan-7 Feb). When snow covers the lower shield (25 Dec-6 Jan, 15-21 Jan, 12 Feb, 20 Feb-5 Mar), an inversion exists at the north margin of the stand. The largest differences in temperature between 5 cm and 2 meters are observed during periods when deep snow completely covers the lower shield, and mild NcP air persists over the State. Although the slight cooling influence of the snow can be noted even between 1 and 2 meters, in this situation the difference in temperature between 5 cm and 2 meters is essentially the difference between the relatively mild air mass temperature and the temperature of the melting snow. With shallower snow cover or temperatures below 32°F (usually cP air), the difference in temperature is smaller. This accounts for the typical "V" shape with time characteristic of the periods with snow. With shallow snow under the shield (15-22 Dec, 9 Jan, 14-18 Feb), the lapse rate is slightly positive or negative, dependent upon the depth and cover of snow, cloudiness, wind and temperature of the air mass involved.

At the south boundary, the lapse rate is positive over litter (29 Nov-9 Dec, 17-22 Dec, 6-9 Jan, 21 Jan-18 Feb, 26 Feb-5 Mar). Under fair skies and with gentle winds, the lapse rate between 5 cm and 1 meter averages about 4°F. With deep snow over the lower shield (15-17 Jan) or shallow snow beneath it (13 Dec, 25 Dec-3 Jan, 20 Feb), the same types of lapse rate as are developed under these conditions at the north margin are observed. It should be noted that in all cases the lapse rates at both boundaries are more intense near the ground. As indicated in Part B, during the winter of study deep snow was the most common condition on the north while litter was the most common condition on the south.

At 5 cm, the south boundary is always the warmest margin of the stand (Figure 16b). Except for occasional days, the same is true at upper levels. As would be expected from the nature of the lapse rates, the margin by which the south boundary is warmer is greatest near the ground, and on the average it decreases with height, the individual differences between the two upper levels ranging only from 0 to 1 degree. With litter at both boundaries (29 Nov-9 Dec, 25 Jan-7 Feb), the temperature near the ground is about 5°F warmer on the south. The margin by which the south boundary is warmer is greatest (10-20°F) during periods when deep snow exists on the north, but either litter or shallow patchy snow is found on the south (split active surfaces—25 Dec-6 Jan, 21 Jan, 12 Feb, 20 Feb-5 Mar). With shallow snow on the north and litter on the south (17-22 Dec, 9 Jan, 14-18 Feb), temperatures near the ground range between 3 and 10°F warmer on the south. In this situation, the temperature difference between boundaries is dependent upon weather conditions and the cover and depth of snow on the north.

Midday thermal profiles obtained with thermocouple and portable potentiometer substantiate the profiles obtained with thermometers and shields, and in addition, provide information concerning temperatures below the level of the 5 cm shields (Figure 18a). The data were obtained at approximately 1500 hours, on 22 February, 1964, a clear, calm day during which afternoon air temperatures remained below 32°F. Split active surfaces existed at the margins of the stand. At the north margin, temperatures increase in both directions away from the surface of the snow, that is, toward both the air and soil. The lapse rate is the typical "nighttime" type (Geiger 1957), indicative of outgoing radiation. In this case, there is no significant difference in temperature between the litter and 1 meter level. Note, however, that the temperature difference between boundaries at the litter level is approximately 22 degrees. The lapse rate at the south boundary is the normal "daytime" type (Geiger 1957). Temperatures decrease away from the litter into both the
air and soil. The temperature difference between the litter and 1 meter level is 20 degrees. This measurement was obtained in a dry area. It was evident that by taking successive measurements toward damp areas associated with recently melted snow, or by taking measurements during windy periods, one could obtain smaller lapse rates at the south margin of the stand.

With regard to minimum temperatures (Figure 17a), the lapse rate over litter at the north boundary is an inversion (25 Nov-12 Dec, 12 Jan, 29 Jan-4 Feb). The temperature increase with height between 5 cm and 1 meter averages about 2.5°F. A similar lapse rate is experienced with snow under the lower shield (13-21 Dec, 8 Jan, 15-18 Feb). When snow covers the lower shield (26 Dec-6 Jan, 15-18 Jan, 23 Feb-4 Mar), the temperature difference between 5 cm and 1 meter is essentially a measure of the insulating quality of the snow. Largely dependent upon the actual depth of snow, temperature differences ranging between 1 and 17°F are found. The actual lapse rate between the top of the snow and 1 meter probably approximates the lapse rate experienced with snow under the lower shield, since between 1 and 2 meters, the lapse rate is similar to that experienced with snow under the lower shield.

![Diagram](image)

**Fig. 18.** Thermal profiles obtained with thermocouple and portable potentiometer at the north and south boundaries during winter (A), spring (B) and summer (C). Abscissa is °F, ordinate is cm.

At the south boundary, lapse rates over litter (26 Nov-12 Dec, 17-21 Dec, 6-12 Jan, 29 Jan-4 Mar) or with snow under the lower shield (13-15 Dec, 26-31 Dec) are either slightly positive or negative. With snow over the lower shield (15-18 Jan), lapse rates similar to those experienced under similar conditions on the north are found. In general, lapse rates at both boundaries are more intense near the ground, but both vertical and horizontal temperature differences are small, compared to maximum temperatures.

In the absence of snow, slightly warmer (range 0.5-3.5°F) minimum temperatures are usually experienced on the south (Figure 17b—26 Nov-12 Dec, 12 Jan, 29 Jan-4 Feb). This pattern is not significantly changed by the presence of shallow snow at the north (17-21 Dec, 8 Jan, 15-18 Feb) or at both margins (13-15 Dec) of the stand. However, with deep snow on the north and litter or shallow, patchy snow on the south (split active surfaces—26 Dec-6 Jan, 23 Feb-4 Mar), the south margin is the coolest margin of the stand. At 5 cm, the margin by which the north is warmer ranges from 0 to 17°F. This, of course, is due to the insulating
effect of the snow, and the magnitude of the difference between boundaries is largely determined by the depth of snow on the north.

During winter, the nature and intensity of lapse rates and therefore the thermal differences between the north and south boundaries are determined largely by the presence or absence of snow. Two major regimes have been described at the margins of the stand. That is, the no snow or litter-litter regime, when litter functions as the active surface at both margins, and the split active surfaces regime (Figures 7 and 8), when snow functions as the active surface on the north and litter as the active surface on the south. Dependent upon the frequency and amount of snow during a particular year, one or the other regime predominates at the margins of the stand.

In the absence of snow, the lapse rate of maximum temperature (5 cm minus 1 m) on fair days at the forest center site averages about 1°F. This value is slightly higher than that observed at the north margin (0°F), but lower than that on the south (4°F). The relative intensity of these lapse rates is related to the relative amount of light incident upon each of the three sites, as discussed in Part C. It is interesting to note further that the winter lapse rates are less intense than those observed during spring (Figures 16 and 19). In other words, the expression of an active thermal microclimate is small. This is to be expected, since winter is the season of low sun, low solar energy (on horizontal) and low percentage penetration of light within the stand (Part C-6). Furthermore, it is the windiest season (Part A-1).

During winter in New Jersey, the most frequent and strongest winds are incident upon the north margin (Part A-1). This factor undoubtedly has an additive effect upon the influence of low radiation on the north, both factors contributing to the development of the isothermal lapse rate of maximum temperature there. On the other hand, the lack of wind on the south supplements the influence of the sunny exposure, both factors contributing to the strong positive lapse rate experienced there. Similarly, the influence of wind on the north should influence minimum temperatures, favoring more intense thermal stratification on the south. However, since the lapse rate of minimum temperature is usually stronger on the north, not only during winter but also during the unfoliated phase of spring (Figures 17 and 20), other factors must come into play.

The more intense inversion found at the north margin is accounted for by the nature of the vegetative cover in the vicinity of the profile posts. It is similar at each site, but not identical. Although the vegetation is less dense on the south, the openings occur toward the interior of the stand, so that the cover in the dense wall of growth at the margin over the post is actually slightly more dense on the south. Furthermore, what may be more important, this vegetation overhangs farther into the adjacent field (Figures 14 and 15). Quoting Firbas, Geiger (1957) indicates that even defoliated trees are effective in reducing outgoing radiation at night. The denser vegetation over the post on the south, coupled with the fact that more of the night sky is cut off by the overhanging limbs, accounts for the less intense lapse rates developed there. Except for extreme cases (20 Mar., 16 Apr.), this factor outweighs the influence of wind at the margins of the stand.

What is the influence on maximum temperatures of the slight difference in cover over the posts? There is little or no effect, since maximum temperatures are determined by direct radiation which never (at this latitude) penetrates to a particular spot within the stand from above, but rather, as we have seen (Part C-1), from some angle to the south determined by season. Discussion of this point emphasizes the fact that maximum and minimum temperatures within the stand are determined by different factors, a point which will become more apparent in the discussion of lapse rates and temperature differences within the foliated stand.

As indicated above, the nature of the lapse rates at the margins is modified by the presence of snow. The difference in temperature between 5 cm and 1 meter is about the same at both margins for maximum and minimum temperatures respectively, when deep snow (which covers the lower shields) exists at both margins of the stand. This condition is temporary, however, and there follows a rapid transition to the split active surfaces regime. Not only does the presence of snow influence the nature of the lapse rates, but the almost daily changes in the wetness of the surface come into play. Wetness means increased thermal conductivity, and lower potential for high surface temperatures and strong lapse rates. Obviously, weather conditions influence the thermal profiles regardless of the condition of the active surface. This accounts for some of the minor variation in lapse rates during the various regimes. The point is that during winter when the potential for active thermal microclimate is low, the nature of the lapse rates can be summarized largely according to the presence or absence of snow and other changes in active surfaces within the stand.

The physical environment presented to plant growth is drastically different at the north and south margins of the stand. Since under the litter-litter regime, the difference between minimum temperatures is small, it is maximum temperatures which account for the differences between the margins of the stand. On fair days, the litter temperature on the north is probably not significantly different from that of the air, while on the south
it ranges up to 20°F warmer than the air. Under this regime, the number of hours above any critical value for growth, such as 32°F, is obviously much greater on the south. During the split active surfaces regime, maximum temperatures are suppressed and often do not exceed 32°F on the north. On the other hand, minimum temperatures are much higher, because of the insulating effect of the snow. The application of a summation index is at first a tempting thought, but it does not work in this case for a number of reasons. Perhaps the most obvious one is that mean temperatures under the split active surfaces regime are often similar on the north and south, despite the fact that the number of hours above 32°F is much greater on the south.

Natural phytometers observed along the margins during mid-February flourished along the south, but were less vigorous or absent on the north. Those observed only on the south included butter and eggs (Linaria vulgaris) and goldenrod (Solidago sp.), which are fall-flowering plants. These herbs flourished within the litter, but perished when left exposed.

Lapse rates and thermal differences between boundaries during spring. The transitional nature of the spring season is clearly evident in the lapse rates and temperature differences between the margins of the stand. With regard to maximum temperatures (Figure 19), the period 26 February-5 March shows the split active surfaces regime characteristic of winter. On the other hand, on and after 19 May an inversion characteristic of summer is developed at the north margin of the stand. Between 5 March and 19 May four different regimes are noted, three of which are characteristic of and unique to spring.

On 9 and 15 March and 8 April the lapse rates at both margins are slightly positive or negative, and the temperature differences between boundaries are small. Low overcast clouds and rain occurred during the daylight hours on these days. This regime, as previously noted, occurs during any season, but shows up infrequently in the data because maximum and minimum thermometers read at bi-weekly intervals tend to record extreme temperatures on fair days. In fact, a break in the low clouds or a partial lifting of the overcast for a short period on an overcast, rainy day results in the development of a weak positive profile, especially at the south margin. Since the overcast is variable even on the cloudiest of days, the daily temperature data show more variability in lapse rates and temperature differences between boundaries than do spot observations made during periods of low overcast and rain, which never show variations of more than 1 degree. This explains why the south boundary is 2°F warmer than the north, even on overcast, rainy days (Table 19).

Excluding the overcast days, it is apparent that the lapse rates are always positive at both bounda-

![Lapse rate and temperature differences between boundaries during spring.](image)

Fig. 19 a-b. - a. Lapse rate (5 cm minus 1 m and 1 m minus 2 m) of maximum temperature at the north and south margins during spring. - b. Difference between maximum temperatures (south minus north), by levels, at the north and south margins during spring.

ries during spring (Figure 19a). During what will be termed Regime 1 (17, 20 Mar, 1, 13 Apr, 3, 4, 11 May), the lapse rates are greater on the south. On the other hand, during Regime 2 (25, 26 Mar, 3, 27 Apr), lapse rates are greater on the north. During Regime 3 (18, 23 Apr, 8 May), lapse rates are similar at both margins of the stand. Furthermore, during Regime 1 the south margin is always the warmest margin (Figure 19b). On the other hand, during Regime 2 the north margin is the warmest one. Similarly, as would be expected from the nature of the lapse rates, there is little difference in temperature between boundaries during Regime 3.

Between 5 March and 19 May there were obvious vegetative changes within the stand. During April poison ivy leafed out around the temperature profile post on the north, and Aster (Aster sp.) grew in front of the post on the south. The closure of the canopy and resultant changes in the amount of radiation penetrating into the stand were discussed in Part C. Partial deactivation of the forest floor at the forest center site (Part C-4), and more or less complete deactivation at the north margin (Figure 19a) occurred quite suddenly after 11 May. This was associated with the unfolding of the leaves.
rather than with bud break (23 Apr) or early
derivation (3 May) of the leaves. The point is that
minor changes in the condition of the active
surfaces, especially between 4 and 11 May, do not
account for the occurrence of the three markedly
different and sporadically distributed temperature
regimes. As indicated below, these regimes are associ-
ated with specific patterns of cloudiness and wind.

Days during Regime 1 were characterized by
clear skies or scattered low, middle or high clouds.
Thus, all were fair days. Wind speeds ranged from
light and variable (speed less than 5 mph, direction
variable) to speeds as high as 18 mph. When
strong (greater than 10 mph) winds occurred, they
were never incident upon the south margin of the
stand (that is, they were not from headings between
165 and 275°). On such days, the lapse rate on the
south is approximately double that on the north,
and the south boundary is the warmest margin of
the stand (Table 19).

Days during Regime 2 were usually character-
ized by low broken clouds and strong southwest
winds. These winds, of course, were always incident
upon the south margin of the stand. Prevailing wind
speeds were usually in excess of 15 mph, and on
two of the four days gusts greater than 40 mph
occurred. On such days, the lapse rate on the north
is approximately double that on the south, and the
north boundary is the warmest margin of the stand
(Table 19). However, the magnitude of the lapse
rate on the north is less than that developed on the
south during Regime 1.

Days during Regime 3 were characterized by
variable conditions of cloudiness and wind. These
conditions were different from those experienced on
days during the other regimes. Furthermore, each
day was different from the others, so that they do
not form a distinct group. However, similar lapse
rates occur at both margins of the stand, the
magnitudes of which fall between those of the lapse
rates developed on the calm and windy sides of the
stand during Regimes 1 and 2. No significant tem-
perature difference exists between the margins of
the stand (Table 19).

As during winter, midday thermal profiles ob-
tained with thermocouple and portable potentiometer
substantiate the profiles obtained with thermometers
and shields, and in addition, provide information
concerning temperatures of the ground during spring
(Figure 18b). The data were obtained at approxi-
ately 1330 hours, 16 March, 1964, a clear day on
which strong winds were incident upon the north
margin of the stand (310°, 22 mph). Such a day,
of course, would be classed in Regime 1. The lapse
rates at both the north and south boundaries are the
normal “daytime” type (Geiger 1957), showing a
decrease in temperature away from the litter toward
both the soil and upper air. Air temperatures are
warmer than those of the soil at both boundaries,

Table 19. Average lapse rate of maximum tempera-
ture at the north and south boundaries during spring,
and thermal difference between boundaries (south
minus north), by conditions of cloudiness and wind
(see text for description of Regimes 1 – 3).

<table>
<thead>
<tr>
<th>Lapse Rate (°F)</th>
<th>Thermal Difference (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5cm – 1m – 2m</td>
<td>South</td>
</tr>
<tr>
<td>1m – 2m</td>
<td>North</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1m – 2m</td>
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<td>Regime 3</td>
<td>5.8</td>
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</table>

a condition to be expected in spring. The lapse rate
between the litter and 1 meter level on the north
is 10 degrees. The corresponding value on the south
is 30 degrees. The margin by which the south is
warmest is greatest in the litter (21°F), and de-
creases toward both the soil (2°F) and upper air
(5 cm = 6°F, 1 meter = 2°F). The above measure-
ments were obtained in relatively dry areas. It was
evident that by taking successive measurements to-
ward more moist areas, or by taking measurements
during windy periods, one could obtain smaller
lapse rates at both margins of the stand.

As in the case of maximum temperature, the
lapse rates of minimum temperature and thermal
differences between boundaries reflect the transi-
tional nature of spring (Figure 20). The period
28 February—4 March shows the split active sur-
faces regime characteristic of winter, while the de-
velopment of a weak positive profile at the south
margin on and after 12 May indicates the initia-
tion of the summer regime. Except for two nights
(21, 30 Apr), inversions exist at both margins of
the stand. The inversions are stronger on the north,
except on 19 and 24 March when they are equal
and 20 March and 16 April when they are stronger
on the south. As with the maximum temperatures,
the intensity of the lapse rates is usually greatest
near the ground. Because of the nature of the lapse
rates, there are only insignificant differences in
temperature between the boundaries of the stand.

Definite thermal regimes such as those eluci-
dated for the maximum temperatures are not ap-
parent with the minimum temperatures. However, it
can be stated that 21 and 30 April, on which
vertical and horizontal temperature differences were
nil, were overcast nights. The other nights had fair
skies. All of these nights except 20 March and 16
April had wind speeds equal to or less than 7 mph,
or if speeds were greater, the wind was incident
upon the west side of the stand. On 20 March and
16 April, winds greater than 7 mph were directly
incident upon the north margin of the stand. On
both nights, lapse rates were stronger on the south.

On fair days during spring, the lapse rates of
maximum temperature at both margins (Figure 19)
and within the stand are more intense than those
experienced during winter, at least until the unfolding of the leaves. In other words, the expression of active thermal microclimate is large. This is to be expected, since the transitional spring season is the period of rapidly rising sun, increased solar energy (on horizontal) and increased percentage penetration of light within the unfoliated stand (Part C-6). This unique combination of vegetative and weather factors does not occur at any other season of the year. As already noted, Anderson (1964b) has recently termed this period the "absolute" light phase within the stand, and other investigators in both the United States (Christy 1952) and Central Europe (Geiger 1957) have described the high litter temperatures and strong lapse rates which develop within the stand during early spring.

At the margins, the strong lapse rate on the south is caused by the fact that this margin receives the full influence of the sun at midday. On the north, the positive lapse rate is the result of the increased solar energy (on horizontal) characteristic of spring, but not necessarily increased percentage penetration of light through the boundary of the stand (Part C-4). It is obvious, however, that radiation relationships alone do not account for the observed variation in the intensity of the positive lapse rates at the margins. Other factors must also be involved.

During Regime 1, the lack of wind on the south has an additive effect upon the influence of sunny exposure, both factors favoring the development of strong lapse rates. On the other hand, winds often incident upon the north supplement the influence of shady exposure, both factors often contributing to the weaker lapse rates experienced there. Thus, the situation is similar to that described for winter. But spring is the season of shifting advective control, and is characterized by an increase in southwesterly flow (Part A-2). Regime 2 represents one example of such southerly control.

Since a fairly strong lapse rate develops at least at one margin during Regime 2, one must conclude that considerable amounts of radiation penetrate between breaks in the low broken clouds. Any pyrheliometer trace obtained on such a day shows that this is indeed the case. The fact that stronger lapse rates develop on the north can be attributed to the relative calm there (Part D), compared to the windy conditions at the south margin of the stand. The point is that while radiation relationships (clear versus overcast, north versus south) are primarily responsible for the lapse rates at the margins, the pattern, at least in extreme cases, can be significantly modified by wind. As indicated earlier, this is also demonstrated by minimum temperatures (20 Mar, 16 Apr).

Regime 3 is composed of three days which do not form a distinct group, in terms of weather experienced on those days. Because of different combinations of cloudiness and wind, all three resulted in intermediate type lapse rates within the stand. It is admittedly a catchall group.

Each of the regimes described during spring encompasses a variety of synoptic situations which, because of relationships established in Part A, can be summarized by indication of dominant air mass. The most clear-cut example is Regime 2, which the synoptician has undoubtedly recognized as warm sector weather. During spring, this phenomenon is usually associated with mP air. Regime 1 encompasses most cP air masses, many NcP air masses especially when weak gradients favor light and variable winds, and some mP air when the Polar front lies far to the south. However, mP air is largely synonymous with overcast weather, not only because of synoptic conditions, but because of the way in which the air mass is defined (Table 3). Regime 3 is a catchall. Conspicuously absent in the sample are fair days with moderate southerly flow, associated with NcP air.

With the relationships established above, one can make two types of estimates concerning the microclimate at the boundaries of the stand. Given a particular synoptic situation and air mass temperature, one can, by means of the established lapse rates and temperature differences, make a reason-
able prediction of the present “microweather” at the boundaries of the stand. On the other hand, given the frequencies of the air masses (Table 7), one can make a climatic estimate of the relative importance of the various microclimatic regimes during spring. For example, from Table 7 it is seen that of the regimes sampled, Regime 1 is by far the most common. Overcast weather is the next most important, followed by Regime 2 which is rare.

What influence do the various microclimatic regimes have on the vegetation at the boundaries of the stand? Since regardless of regime the differences in minimum temperature between boundaries are small, the answer lies in consideration of maximum temperatures. During Regime 1, litter temperatures on the south are as much as 30°F higher than those at the upper levels. On the other hand, litter temperatures on the north are only as much as 10°F higher than those of the air (Figure 18b). Judging from the shield data, these conditions are probably reversed during the relatively rare Regime 2. During overcast weather, of course, differences between the boundaries are nil.

When Regime 1 is experienced during early spring when air temperatures are low, the south is the most favorable boundary of the stand. However, later in the season when air temperatures are high, and/or moisture reserves low, the north boundary is the most favorable one. This may be noted in the growth of the dogwood leaves (Figure 12). Since Regime 2 is rare, its influence on the vegetation is small. Overcast conditions, of course, mediate the influence of exposure on vegetation at the margins of the stand. It should be recalled that mP air was 16 percent above normal during the April of the study (Table 7).

The emergence of herbs such as spring beauty (Claytonia virginica) and May-apple is associated with the high litter temperatures characteristic of the first phase of spring. Botanists have long observed that ecological spring arrives at the forest floor first, and progresses upward with time. That this occurred during the study year is indicated in Figure 12, at least for two layers of the stand. However, no significant phenological differences directly attributable to microclimate were observed between the north and south margins during spring. The fact that mP air was above average in April may account for this.

Different dates are noted for the initiation of summer lapse rates of maximum and minimum temperature respectively (Figures 19 and 20). This highlights the fact that these temperatures are determined by different factors operating within the stand. However, discussion of thermal relations associated with canopy closure is best deferred until the next section.

Lapse rates and thermal differences between boundaries during summer. Compared to the winter and spring seasons, lapse rates and temperature differences between boundaries during summer are less variable from day to day. Considering maximum temperatures (Figure 21a), it is apparent that except for 10 and 24 June, lapse rates on the south are always fairly strongly positive (average 6.6°F), while those on the north are always weakly negative (average -2.4°F). Lapse rates at both boundaries are stronger near the ground. There appears to be a gradual trend toward stronger positive lapse rates on the south and weaker inversions on the north from June to August.

At 5 cm, the south boundary is always the warmest margin of the stand (Figure 21b). Except for isolated instances, the same is true at upper levels. As would be expected from the nature of the lapse rates, the margin by which the south is warmer is greatest near the ground, and on the average it decreases with height. The difference between 5 cm and 1 meter is much greater than that between the two upper levels, where the individual differences range from 0 to 1 degree. Largely because of the increased intensity of the positive lapse rate on the south during August, the margin by which the south is warmer increases toward the end of summer.

Some interesting relationships and suggested
trends are apparent in Table 20, where monthly lapse rates at the south boundary are summarized according to conditions of cloudiness and wind. In this case, overcast weather is defined as sky conditions characterized by broken low, middle and high clouds. Usually, cumulonimbus is present. On the other hand, fair means clear, scattered clouds and/or high thin broken clouds. Lapse rates on overcast days during June and August show weaker values than those on fair days. On the other hand, they sometimes (August) are greater than those obtained on overcast days during winter and spring. This is to be expected, since summer cloud patterns developed in the dominant NcP and mT air masses (Part A-3) are quite variable in both their temporal and spatial distribution over the sky. In other words, even on cloudy days holes frequently occur so that positive lapse rates develop within the stand. It will be indicated later how the fortuitous distribution of clouds in relation to the sun at different times of the day can significantly influence the type of lapse rate developed at a particular spot within the foliated stand, even with comparatively few clouds in the sky.

Table 20. Average summer lapse rate (5 cm minus 1 m, °F) at the south boundary, by months and conditions of cloudiness and wind direction (deg). See text for definitions of fair and overcast weather.

<table>
<thead>
<tr>
<th>Month</th>
<th>Ave.</th>
<th>310-090</th>
<th>100-155</th>
<th>165-275</th>
<th>285-300</th>
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</thead>
<tbody>
<tr>
<td>June</td>
<td>3.3</td>
<td>—</td>
<td>—</td>
<td>0.8</td>
<td>—</td>
</tr>
<tr>
<td>Ovc.</td>
<td>0.8</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Fair</td>
<td>5.0</td>
<td>4.0</td>
<td>4.0</td>
<td>6.0</td>
<td>—</td>
</tr>
<tr>
<td>July</td>
<td>5.1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Ovc.</td>
<td>5.1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Fair</td>
<td>5.1</td>
<td>6.0</td>
<td>6.5</td>
<td>3.9</td>
<td>6.5</td>
</tr>
<tr>
<td>Aug</td>
<td>10.8</td>
<td>6.5</td>
<td>—</td>
<td>6.5</td>
<td>—</td>
</tr>
<tr>
<td>Ovc.</td>
<td>11.3</td>
<td>16.5</td>
<td>—</td>
<td>10.5</td>
<td>11.5</td>
</tr>
<tr>
<td>Fair</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It should be noted that the overcast weather observations in Table 20 are all associated with southwesterly wind flow incident upon the south margin of the stand. Similar flow on fair days leads to the development of stronger lapse rates at the south margin. Wind flow from directions other than those incident upon the south margin leads to the development of still stronger lapse rates on the south during July and August. The relationship breaks down in June. It should be noted that in Table 20 no consideration is given to wind speed. No relationship between weather patterns and lapse rates could be found at the north margin.

Discussion of thermal relationships during summer is incomplete without at least a brief consideration of sunflecks within and at the margins of the stand. At the north margin the only observable thermal profile is an inversion (Figure 18c). This is associated with the absence of sunflecks (Part C-5). Within the forest proper, the pattern of light cast across the litter is a mosaic of sunflecks and shade. Moderately large sunflecks (approx. 15 x 30 cm) are characterized by a fairly strong positive lapse rate (high litter temperature), while in shady areas isothermal conditions exist. At the south boundary the pattern is one of light, sunflecks and shade. That is, there is a sharp line of demarcation between open light and shade cast by the oak and dogwood branches overhead. Superimposed upon the shade are sunflecks associated with gaps in the foliage. Lapse rates within the light areas and sunflecks are strongly positive, while isothermal conditions exist in the shade. On clear days, the shade line at the south boundary, as well as sunflecks at the boundary and within the stand appear, migrate and disappear with the movement of the sun across the sky.

As during the other seasons, lapse rates of minimum temperature and temperature differences between boundaries are small (Figure 22). The summer values show less day to day variation than those of the other seasons. The lapse rate at the north margin is usually negative, ranging from 0 to -2.5°F and averaging -0.9°F (between the 5 cm and 1 meter levels). On the other hand, the lapse rate on the south margin is almost always positive, ranging from 0 to 2.0°F and averaging 1.0°F. The intensity of the lapse rates increases slightly toward
the ground. Practically all observations occurred on
nights with fair skies and light and variable winds.
No patterns of weather or vegetative change could
be found to account for the minor daily variations
in the lapse rates and temperature differences dur-
ing summer.

Since summer is the season of high sun and
high solar energy (on horizontal), thermal rela-
tionships near the floor of the foliated stand are deter-
mained largely by the daily movement of sunflecks.
At the forest center site, for example, strong sun-
flecks are present at various times during the day,
but the most extensive coverage occurs between
1500 and 1600 hours daily, when sunlight passes
through a small gap to the southwest of the site.
If clouds obstruct the sun during this period, the
lapse rate is isothermal or only weakly positive,
but if they do not block it, the lapse rate is much
more intense. Thus, the daily nature of the lapse
rate is determined almost exclusively by the fortui-
tous positioning of clouds in relation to the sun
during a short period each day.

As described earlier (Part E.1), the inversion
at the north boundary is due in part to the failure
of sunflecks to penetrate through the vegetation
near the margin of the stand. The strong positive
lapse rate on the south is associated not only with
sunflecks, but also with actual open light incident
upon the foot of the boundary at various times
during the day.

The above emphasizes the fact that comprehen-
sion of the thermal stratification near the forest
floor is dependent upon an appreciation of the
angular penetration of direct light. Yet, few papers
are available concerning the spatial and temporal
distribution of sunflecks, sunfleck microenvironment
or the influence of sunflecks on plant growth.
Early studies by Lundegardh, reported in Evans
(1956), appeared to show that sunflecks might
represent the only periods during the day when a
particular plant (Oxalis montana) received light
above the compensation point. It is interesting to
note that in this study the area of least cover in
the undergrowth layer coincides with the only area
deficient in sunflecks. However, this area also had
the lowest mean shade light.

The trend toward increased positive lapse rates
of maximum temperature at the south margin,
which results in increased thermal differences be-
tween boundaries during summer (Figure 21), is also
apparent in Table 20. The trend holds not only for
mean monthly lapse rates, but also for the average
monthly lapse rates by wind direction,
except for southerly winds on fair days in June.
This trend is probably associated with gradual
changes in the condition of the active surface
throughout the season, especially dryness at the
south margin. Although precipitation in July was
above average, one must remember first that forest
precipitation is subject to interception loss. Second,
phenological observations indicate that the relief
associated with this precipitation was brief (Part
A.3).

Lapse rates of minimum temperature are weakly
positive at the south margin, but a weak inversion
is found on the north (Figure 22). A possible
explanation to account for these small but consistent
differences between boundaries lies in the relative
amount of cover directly over the instruments at
each site. That is, on the south where the vegetation
is dense, air cooled in the canopy may remain in
and above the crowns. This is reported to occur
within dense stands (Geiger 1957). On the north,
where the vegetation over the instruments is less
dense, the cold air may sink to the forest floor.
At any rate, the major point is that both vertical
and horizontal differences in minimum temperature
are small. From the above paragraphs, it is easy to
see why canopy closure does not influence maximum
and minimum temperatures at the same time
(Figures 19 and 20).

It is obvious that during summer the micro-
climate is influenced by the vegetation to a much
greater extent than during the other seasons. Never-
thess, the relationships and trends shown in Table
20 indicate the influence which different conditions
of cloudiness and wind can have on lapse rates at
least at the south margin of the stand. Because of
the strong vegetative control and similarity between
the predominant mT and NCp air during summer
(Table 3), it is difficult to distinguish definite
weather regimes, although the greater cloudiness
characteristic of mT air undoubtedly has a mediating
effect upon thermal differences at the margins of
the stand. Maritime tropical air was associated
with five of the six overcast observations during
June and August. Both air masses are associated
with southwesterly flow. Thus, the influence of
wind tends to reduce thermal stratification at the
south margin during summer. In terms of vegeta-
tion, however, this is of minor importance com-
pared to the increased evapotranspiration associated
with the wind.

The high temperatures and high evapotranspira-
tion at the south margin place considerable stress
on the vegetation, especially during dry years.
Observations substantiating this are found in Part
A.3 and under the description of experimental sites.
It is interesting to note that drought had its greatest
influence upon the herbs and dogwood trees. Thus,
all phenological differences between the two mar-
gins, which admittedly were few in number, indicate
that the largest differences occur near the ground.
This, of course, is related to the greater differences
in microclimate experienced there. Cantlon (1953)
noted a similar result on the north and south slopes
of Cusheetunk Mountain, and also showed that dif-
fences in the composition of the vegetation between

53
the two slopes increased toward the ground. In terms of both microclimate and vegetation, the differences between forest borders are much more subtle than those on slopes. A detailed study of the boundary vegetation would therefore be of great interest at this time.

**Climate, boundary microclimate and vegetation in retrospect.** Although the investigations of light penetration, wind flow, thermal stratification and snowfall at the margins of the stand are of interest in themselves, it is only when they are viewed as an integrated whole in relation to the comparison of weather and climate that the ultimate goal of the entire work is fulfilled. Stated in terms slightly different than those employed in the introduction, this goal is essentially the demonstration of a regional dynamic microclimatology, as found at north and south forest boundaries in New Jersey.

Perhaps the majority of investigators working in the field of microclimatology are in quest of general rather than regional results. Consequently, the literature is developed to the point where we are aware of the general characteristics of shelter-belts, of north and south slopes, of fields and forests. In spite of the emphasis placed on these generalities, if one reads carefully, he continually observes that local results are unavoidably found. For example, it is known that slope microclimates vary from region to region dependent upon prevailing winds, incidence of cloudiness, and other factors (Tourney 1947, Geiger 1957). Furthermore, in Europe, precipitation patterns around small hills are related to "precipitation falling obliquely from the west" (Geiger 1957). The constant mention of these factors, despite the fact that they have seldom been emphasized, demonstrates the importance of the role of regional weather and climate in determining microclimate. Cognizance of these relationships is necessary in order to place microclimatic results from different regions in proper perspective. Yet, few studies have attempted to deal with them in detail, in spite of the fact that they are discussed from time to time.

Much of the discussion concerning relationships between climate and microclimate has centered upon the regional role of radiation in determining exposure microclimate. This is perhaps best summarized by Geiger's (1957) "law of latitude". It states that the maximum effect of exposure difference is to be found in mid-latitudes, because they represent the middle ground between the conditions of high energy and small difference-of-exposure experienced in the Tropics, and the conditions of low energy and large difference-of-exposure found near the Poles. Biel (1961), on the other hand, has commented upon the importance of the total physical climate in determining microclimate in eastern North America. According to Biel, the number of clear and calm days, and with them the intensity of microclimatic features, increases from New England toward sub-tropical latitudes. That is, from the convergence area of storm tracks in the Northeast toward regions distant from the paths of disturbances. Kittredge (1948) has shown that "forest influences" vary in character and intensity from region to region, and he cautions that conclusions drawn in one region should not be applied in others without verification. Since much of the work in forest microclimatology has been accomplished in Europe, the problem in North America is a real one.

One actual study cutting across the disciplines of climatology, microclimatology and ecology in order to demonstrate relationships between climate, weather, microclimate and vegetation is that of Wolfe, Wareham and Scofield (1949). As indicated in Part A, this study was statistical in nature and did not deal with dynamics. Nevertheless, it is significant from the standpoint that it attempted to evaluate relationships between the weather and microclimate of the region, and to determine the validity of microclimatic results based on a short period of weather. Havens (1948) stressed the point that the use of a dynamic climatology such as the one he developed for New Jersey provides an excellent means of describing and explaining the effects of climate on plant and animal life. Cantlon (1953), in his concluding remarks concerning the vegetation and microclimate of Cushetunk Mountain, suggested that Havens' dynamic climatology would prove useful in future studies of that kind. These three works provided the inspiration which led to the development of the basic approach and methods employed in the present work.

Part A is significant in at least two respects. In the first place, it represents the first application of Havens' dynamic climatology to a problem dealing with microclimatology and ecology. The air mass calendar is combined with wind data by this investigator in order to present a dynamic comparison between weather and climate. This facilitated discussions, by seasons, of the influence of weather during the period on both vegetation and microclimate. Perhaps more important, it facilitated the identification of certain synoptic situations, such as the northeaster and warm sector, which are especially interesting at the microclimatic level. Thus, Part A facilitated the development of the necessary dynamic link between weather, climate and microclimate which is seldom, if ever, found in studies of this kind.

The second significant aspect of Part A relates to climatology rather than to microclimatology or ecology. The comparison of present weather to climate, expressed in terms of monthly frequencies of air masses, air mass changes and deviations in wind flow, summarizes and explains in physical terms, the weather experienced during any particular month. For example, the analysis clearly indi-
cates that the lack of precipitation during two cool summer months (June and August) was related to increased continental polar control. On the other hand, the lack of precipitation during one warm spring month (May) was related to a sharp reduction in the number of frontal passages (stagnation), and increased frequency of NcP air. Thus, the analysis vividly demonstrates why New Jersey experienced drought during three particular months, all of which occurred during an exceptionally long period of drought. Similar comparisons of unusual periods of weather with the air mass calendar and wind flow may prove useful in future work.

For the author, Part B is perhaps the most rewarding aspect of the present work. It provides clear evidence of the dependence of boundary microclimate upon the climate of the region. The characteristic distribution of snow within the stand is determined by the unidirectional nature of winds during snow, which is the result of a specific synoptic situation (the northeaster) characteristic of the region. Furthermore, since there is increased deposition of snow at the shady northern boundary compared to the sunny southern one, it is evident that in New Jersey at least, the area of maximum deposition is the area of minimum melt and vice versa at the edges of the stand. The differential deposition and melt at the margins results in a characteristic melt pattern, which significantly influences both the active thermal microclimate and the vegetation at the two sites. There is perhaps no better example demonstrating the interrelationships between climate, microclimate and vegetation within a particular region.

The analysis of the seasonal variation in the light climate at the margins and within the stand presented in Part C is based upon the solar climate of the region. Although the present work deals for the most part only with the percentage penetration of light at noon on clear days, the future analysis of pyrheliograph data obtained at five locations within the forest on both clear and overcast days for a period of 12 months should prove useful in defining the total regional forest light climate.

Perhaps the most significant aspect of Part C is the fact that it demonstrates that we know far less concerning the light climate of woodlands than much of the literature implies. For example, there is no adequate, much less standard method available for measuring light climate which takes the presence of sunflecks into account. As a consequence, much of the literature contains conflicting and non-comparable results concerning light climate. The evaluation of the influence of forest light on the growth of understory plants must be considered incomplete until both the spatial and temporal distribution of sunflecks is taken into account. The author sincerely hopes that his partial analysis of sunflecks, developed as a simplification of the method of Evans (1956), will stimulate interest in these interesting yet elusive rays of light.

The existence of particular microclimatic regimes at the north and south margins of the forest during particular synoptic situations, such as the warm sector, suggests the possibility of forecasting microweather at the margins of the stand. Furthermore, because particular synoptic situations are characteristically associated with particular air masses within a region, the air mass can also be employed to summarize particular microclimatic regimes. At least one such study dealing with slope microclimate has been completed in Europe (Geiger 1957), and Gwinner (1964) recently carried out a similar analysis in the Ouachita Mountains of Arkansas. The present study is evidently the only one in which such relationships are established at forest boundaries. It is interesting to note that both North American studies were most successful during spring. This is undoubtedly due to the fact that while the active thermal microclimate is weak during winter, the air masses tend to lose their identity during summer and fall. It is only during spring then, that an association between well-defined air masses and a well-developed microclimate is found.

As demonstrated in Part E, given an air mass calendar and an association between air masses and microclimatic regimes, it is possible to make a climatic estimate of the relative importance of various microclimatic regimes. The significant point is that while the analysis may not be completely successful in all instances, it does provide conclusive evidence supporting the existence of a regional microclimate. The generality then, is that microclimates vary between regions, just as the climates upon which they depend.
Literature cited


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Maule, W.J. 1934. Comparative values of certain forest cover types in accumulating and retaining snowfall. J. Forestry 32:760-765.


Author's note. — During preparation of the manuscript, the translation of Geiger's 4th German edition appeared (Geiger, R. 1965. The climate near the ground. Translated by Scripta Technica, Inc. Harvard Univ. Press. Cambridge, Mass.). Although the old edition is cited in the text, the factual content of all citations has been verified in the new book.
Appendix

Synoptic conditions associated with Storm 1, 10-11 Feb 64. At 1300 EST 9 Feb Polar Front with three minor depressions extended from Ohio Valley northwestward to Alberta, separating cP air in north from NeP air in south and west. By 1300 EST 10 Feb cP air pushed into Central Plains, Kentucky low moved northwestward over West Virginia, Maryland and Delaware to position off Coast 200 miles ESE of New Jersey. Iowa-Missouri low moved southeastward into Tennessee. New Jersey remained in cold air north of the front, and experienced light snow with passage of the Kentucky low. By 1300 EST 11 Feb cP air pushed well into Gulf, first low moved well out to sea and Tennessee low moved east-northeastward across North Carolina-Virginia border to position 120 miles east of Coast. Snow stopped in New Jersey after passage of first low, but resumed a few hours later as second low moved off Coast southeast of the State. By 1300 EST 12 Feb second low moved well out to sea, cP high dominated East, bringing clear skies, cold temperatures and northerly winds.

Thus, the passage of two fairly weak depressions (1012 mb) across the offshore waters southeast of the State accounted for two periods of snow classified as Storm 1. These events account for the fairly weak northeast winds (note gradient) of constant direction during Storm 1. Speeds of first and second lows were 40 and 20 mph respectively. Snow depths in Central New Jersey ranged from near 3 in. in the northeast to approximately 6 in. in the southwest.

Synoptic conditions associated with Storm 2, 18-20 Feb 64. Between 1300 EST 17 Feb and 1300 EST 18 Feb cold air from West Texas moved into the South to trigger the development of a Gulf low. Meanwhile, high pressure moved off the East Coast. By 1300 EST 18 Feb the Gulf storm had occluded over South Carolina, and a secondary had developed over the offshore waters. This situation is similar to that in Storm 3, but an important difference is the conspicuous absence of the cold continental high. Primary low filled as secondary intensified and moved northeastward along the Atlantic Coast to become located east of New Jersey at 1300 EST 18 Feb. New Jersey experienced wet snow and snow showers with passage of the low. Speed in vicinity of New Jersey was 23 mph, and lowest central pressure was 984 mb. By 1300 EST 20 Feb the storm moved over the Maritimes. High pressure moved slowly southeastward, and brought clear skies and northwest winds, but fairly mild temperatures as a result of air mass modification during its slow movement south.

The absence of a cP high over the Central United States accounts for differences in weather experienced during Storms 2 and 3. Without the pool of cold air, temperatures remained just below freezing during the snow, and although winds were gusty in nature, speeds equal to those in Storm 3 were not attained (note gradient). Although wind directions were more variable than during Storm 3, the winds backed in characteristic fashion with passage of the storm. Snow depths in Central New Jersey ranged from near 7 in. in the northeast to approximately 2 in. in the southwest.

Appendix Table 1. Values of ground distance (Gd) and path length (Pd) for various vegetation heights (H) on key dates throughout the year (40° N). Values are accurate to nearest foot.

<table>
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<tr>
<th>Date</th>
<th>Solstice</th>
<th>Equinox</th>
<th>23 Sep</th>
<th>6 Aug</th>
<th>22 Jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Nov</td>
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<td>50.0</td>
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<td></td>
</tr>
<tr>
<td>22 Dec</td>
<td>Q</td>
<td>Gd</td>
<td>Pd</td>
<td>Gd</td>
<td>Pd</td>
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<td>Pd</td>
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</table>

Appendix Fig. 1. Maps 9-12 on top of opposite page show synoptic conditions associated with Storm 1, 10-11 Feb 64 discussed at left.

Appendix Fig. 2. Maps 17-20 on bottom of opposite page show synoptic conditions associated with Storm 2, 18-20 Feb 64 discussed above.
Appendix Fig. 3. Maps 11-14 above show synoptic conditions associated with Storm 3, 12-14 Jan 64 discussed below.

Synoptic conditions associated with Storm 3, 12-14 Jan 64. Between 1300 EST 11 Jan and 1300 EST 12 Jan cP air pushed south to the Gulf. Disturbance from Central Plains moved toward Gulf where it intensified and progressed through life cycle to become stagnated as occluded front over the Southeastern States west of the Appalachians. By end of period secondary low was well-developed off South Carolina Coastal Waters. This pattern is identical to that described as the typical “northeaster” in the McGuire APB Terminal Forecast Manual (1962). It also conforms to typical heavy snow situation in New York City area as described by George (1960). The center of high pressure is well inland, and its curved axis is oriented east-west and is concave toward the south. Between 1300 EST 12 Jan and 1300 EST 13 Jan both lows moved northeast. Primary filled as secondary intensified. System slowed (16 mph), and passed directly east of New Jersey with central pressure of 992 mb. By 1300 EST 14 Jan, low moved northeast over the Maritimes. East dominated by cP high bringing clear skies, frigid temperatures and strong northwest winds.

As the storm moved up the Atlantic Coast, cP air was actively advected into the system. Combination of cold temperatures (range 13-21°F), high winds (peak gust 55 mph, note gradient) and blowing snow brought near-blizzard conditions to much of the State. Northeast winds during snow characteristically backed to northwest with passage of low. Snow depths in Central New Jersey ranged from more than 12 in. in the northeast to approximately 9 in. in the southwest.