In this connection a comparison of the percentage of growth on days having the same temperature but different humidity with that for other days on which the conditions were reversed will be especially instructive. Let us take for example the 3d and 5th and 17th and 18th of July. The mean percentage of growth on the 3d and 18th, the days having relatively the lower humidity, was 8.6 per cent, while the 5th and 17th showed only 8.8 per cent. This comparison would seem to show that the greater humidity produced the greater growth, but the very reverse would have been found if we had taken the 4th instead of the 3d. On the 27th and 28th of June the humidity was the same, while the temperature was different, and this is practically true for the 29th and 30th of June and also the 20th and 21st of July. For the first two days the growth was greater on the day of higher temperature; for the second two days the reverse is found, while the third pair is similar to the first. The mean for the three days of relatively lowest temperature is 6.3 per cent, while for the three highest it is 8.3 per cent. This would indicate that the temperature is the most important factor in determining the rate of growth.

MOISTURE OF THE SOIL.

The following table shows the mean percentage of growth on the three days with greatest and least moisture content of the soil:

Mean percentage of growth on three days of—	First period	Second period.	Third period.
	Per cent.	*Per cent.*	*Per cent.*
Greatest moisture	20.5	8.2	8.5
Least moisture	14.5	8.2	8.6

The figures for the first period would seem to indicate that the greater moisture content was decidedly more favorable, but it should be noted that the days with lowest moisture content coincided with days of extremely low temperature, which doubtless accounts for the marked difference of growth. The other two periods show practically no difference in growth, and we seem justified in concluding that the variation in moisture here had no influence in determining the rate of growth. However, the moisture never fell lower than 11.8 per cent, and this quantity was doubtless sufficient for the needs of the tobacco plants under existing conditions as to sunshine, temperature, and wind; so that much greater changes in the moisture content must be made before its influence can be determined.

SUMMARY.

To sum up: The data would indicate that the moisture in the soil was always sufficient in quantity, and that the relative humidity of the air had very little if any influence upon the rate of growth, but that a decided rise or fall in temperature was followed by an acceleration or diminution, respectively, in the rate of growth of the plants. When, however, the change in temperature was small there were other unknown factors that had a more important influence. If the measurements had been taken to one-sixteenth of an inch, a closer relation might have been shown here also.

STUDIES OF FROST AND ICE CRYSTALS.

By WILSON A. BENTLEY. Dated Jericho, Vt., May 28, 1906. Revised July, 1907.

PREFACE.

(1) Object of this memoir.

This paper is intended as a companion memoir to my "Studies among the snow crystals during the winter of 1901–2", etc., published by the Weather Bureau in 1902.[1] It is my hope that the present study may serve to reveal the forms, structure, life history, and general relations of the frost and ice crystals even more fully than did the memoir on snow crystals.

The forms that occur among the frost, ice, hoarfrost, window-frost, and window-ice crystallizations are hardly less beautiful, varied, and interesting than are those other marvelously beautiful crystals from cloudland that we call snow. The great beauty and diversity of the frost and ice crystals early attracted the author's attention and study, and his first photomicrographic work, while he was yet in his "teens", was directed to this subject. He secured his first photomicrographs of frost crystals in December, 1884. This work has been continued by him, mostly at his home in Jericho, Vt.,[2] at intervals ever since. A few, and sometimes many, forms were photographed each winter, so that now his collection numbers over seven hundred specimens, of which no two are alike.

His endeavor has been not only to learn all possible regarding their manner of formation, habits of growth, and the conditions under which various varieties form and develop, but also to secure a fairly complete series of photographs that should preserve for the student the semblance of each and every type and species of crystal of frost and ice. This has proved to be a task of no small difficulty, requiring a vast amount of time and necessitating no little expense. Some types of frost and ice proved to be very difficult subjects for photography, and in some cases it became necessary to construct special apparatus in order to secure satisfactory photographs. All the half-tone reproductions are made from original photographs of natural crystals. In this connection it is perhaps well to state that the author's photographic work on both snow and frost crystals has been carried on entirely at his own personal expense, and, as is commonly the case when investigations must be conducted solely at private expense, a lack of means has greatly hampered the work. This must be his apology for a lack of excellence in the technique of some of the photographs. Many of them could have been greatly improved by recopying.

The author hopes that this memoir will not only impart to others the knowledge that he has gained, but will call the attention of all lovers of nature to this hitherto much neglected, yet most beautiful, subject. The publication at this time, with the half-tone pictures here reproduced[3], is due to the kindly appreciation of the Chief of the Weather Bureau and the Editor of the MONTHLY WEATHER REVIEW.

It need hardly be said that the half-tones, numerous tho they be, illustrate only a few of the almost infinitely varied individual forms of the frost and ice that occur in nature. They will but give a glimpse into the beauties of this fairy realm of snow, frost, and ice.

In view of the ease with which many varieties of frost and ice crystals can be obtained it is thought best to give a brief sketch of the methods that were, or that may be, employed, in securing photographs of such objects, in the hope that this information may be helpful to many.

(2) Methods employed.

Two distinct methods may be employed in this photographic work—one by oblique light and low magnifying powers, using an ordinary one-fourth size portrait lens or similar objective and extension camera; the other by direct transmitted light, using a three-fourths or one-half inch microscope objective, for higher magnification (15 to 30 diameters.) The great majority of the window-frost, and many window-ice crystals are perhaps best secured by the former oblique-light process. Many of the large feathery window designs require no extension camera; an ordinary view camera suffices equally well.

[1] See Monthly Weather Review, Annual Summary, 1902, Vol. XXX, p. 607-616 and Plates I-XXII.

[2] On a farm 16 miles east-northeast of Burlington, midway between Mount Mansfield and Camels Hump, 1500 feet above sea level—latitude 44° 30′ north, longitude 73° 00′ west.

[3] The half-tones illustrating this memoir will be published later.—EDITOR.

These are often of such large size as to require reduction, rather than magnification; the greater number, however, require magnifying from 4 to 8 diameters. This can be obtained with a one-fourth size portrait or rectilinear lens and an extension camera, capable of being extended about 44 inches. A simple, rigid, inexpensive, home-made extension, containing the lens coupled to an ordinary view camera, answers admirably in most cases.

Photographing by this method is done indoors; the camera is placed facing the window containing the frost or window-ice designs, and a black background, varying in size and distance from the window with the magnification employed, from 25 inches square to 45 by 60 inches, is placed out of doors directly in front, and at some distance 3 to 10 feet away from the object to be photographed. The size of the background and the distance from the window varies with the magnification used; the larger the lens and the less the magnification so much the larger must the background be and the farther away from the object, and vice versa. It is best to focus by using full aperture of lens, but to use a very small stop, one-seventh inch, while exposing the plate.

The methods used in securing more highly magnified pictures were as follows: A short brass tube containing a society screw at one end, and sliding by rack and pinion within another larger tube, was fitted with a collar (at a total cost of but $6) which was fastened in an extra front board to a view camera, as a substitute for an ordinary camera lens.

A microscope objective was screwed into the society screw at the end of the brass tube. The view camera was mounted upon a board, which in turn was mounted upon slats nailed horizontally across the window casings; the board supporting the camera was fitted with grooves and arranged so as to slide horizontally across and parallel to the windowpanes; a stop or diaphragm one-fourth of an inch in diameter, corresponding to that on the microscope, was mounted outside of the window, on adjustable sliding supports, capable of both vertical and horizontal movements; this was placed about one-half an inch from the windowpane, as a nearer approach causes melting. The tin cover of a pail, 6 inches in diameter, perforated in the center and blackened, served for the diaphragm. The centering was accomplished by removing the ground glass of the camera, placing the eye at the center of its frame, and sliding (or having someone outside slide) the diaphragm until the white spot representing the diaphragm appeared at the center of the microscope objective. After focusing, a large sheet of black paper was placed between the microscope objective and the window frost, so as to exclude the light while removing and drawing the slides. Such an apparatus would, of course, not be serviceable in a city on account of the tremors due to traffic, but in the country, where the inmates of the house can be kept quiet, it serves admirably.

I.—FROST CRYSTALS IN GENERAL.

(3) General atmospheric conditions under which hoarfrost crystals form.

True hoarfrost crystals are formed directly from the tiny invisible water molecules held by heat or motion in solution within the atmosphere. Any process or condition, such as evaporation, radiation, or darkness, that tends to stop or retard the various motions of the molecules of water within the air, or to chill the objects or surfaces with which these water particles come into contact, favors frost formation. Except for the absence of clouds, and the presence of a support to rest upon, frost crystals form in much the same manner as do snow crystals. At the beginning groups of water vapor molecules are drawn to or collide with, and, as crystals of ice, attach themselves to some cold chilled object or substance, either of their own making (as in the case of the snow crystals in air and ice crystals in water), or, as is most commonly the case during frost formation, upon some foreign object or surface, either mineral or vegetable. Thence forward growth takes place because the icy crystalline nuclei draw to themselves such water molecules as may float into their immediate vicinity. The immediate source from which the vapor of water is drawn to build them up of course varies in different cases. Hoarfrost crystals form in the open, e. g., on grass blades, fences, shrubs, etc., only on cold, calm, clear nights, and draw their supplies directly from the free air close about them, but ultimately from the soil, as well as from unknown distant sources. Hoarfrost formed within confined situations, as on windowpanes, cavities within the snow, etc., draws its moisture from supplies near at hand, as from that supplied thru evaporation, steaming kettles, or exhaled in the breath of animals, etc. In general, hoarfrost forms in a calm, quiet, cloudless atmosphere, and only when the air near by is so cooled as to be supersaturated for a given temperature.

(4) The nuclei and surfaces on which frost forms.

When conditions are suitable frost forms on a great variety of objects and surfaces that lie upon or near the surface of the ground. In autumn, winter, and spring hoarfrost collects on all forms of vegetation, and on such objects as boards, fallen twigs, pieces of metal, stones, etc. It collects both on evaporative and nonevaporative objects and surfaces, tho perhaps in greater quantity upon the former. In winter it collects indoors on windowpanes and sometimes on doors; outdoors it forms within cavities in the snow and within other inclosed compartments, as also in the open on the surface of the snow, ice, shrubs, fences, etc., and more rarely on the trees within valleys or on plains, or on those growing on the hilltops. The clouds in winter often deposit some of their moisture in the form of long slender needles of frost, and this often collects in quasi crystalline or granular form on the trees on mountain tops, even when winds are blowing. It always extends downward on the mountain slopes just as low but no lower than did the cloud stratum that deposited it; hence it can always be distinguished from snow, because a well-defined, straight, horizontal line of demarkation extends across a mountain and bounds the upper region, wherein frost exists, from the region below, wherein it is absent.

(5) Form of crystals as affected by their environment and nuclei.

With the possible exception of certain plant leaves and flowers, and the excreta of certain animals, the objects upon which hoarfrost forms seem not to determine or affect the form and structure of the frost crystals. But the position and environment of those same objects, and especially their location as regards the bare earth, i. e., whether they lie close to or directly upon it, or somewhat removed and isolated from it, does in some cases seem directly or indirectly and to a large degree to affect and control their form and structure. That this is so is proved by the fact that frequently the frost crystals that collect close to the earth, and on the under sides of objects lying in direct contact with the bare ground, are of an opposite type from those that form elsewhere. In general, the great majority of the frost crystals that form over wide areas during a given night are of but one type, i. e., either columnar or tabular. The fact that one type (columnar type) of crystals almost invariably forms over large areas whenever the temperature at nightfall is so high that tiny dewdrops form previous to the formation of frost, and the fact that the other or opposite type (tabular) forms over areas equally large whenever the temperature at nightfall is so low that true frost crystals come first in the order of formation, would seem to be strong proof that the form and nature of the nuclei may be the controlling factor in form determination. The additional fact that columnar hoarfrost is the prevailing type during the so-called destructive frosts in early autumn and late spring, when dew forms during a given night, previous to the frost, and that tabular frost is the prevailing type in the winter, when no dew forms previously, gives additional support to the hypothesis that in general columnar hoarfrost forms upon and around tiny rounded liquid or frozen dew nuclei, and tabular hoarfrost directly upon the dry nuclei furnished by the foreign objects and substances upon which it collects.

The influence that position and environment exert on the forms and structure of frost crystals is shown in many cases, especially in the case of frost formed in confined situations, as within buildings, on the walls of cavities in snow extending around or below the objects of wood, etc., embedded therein, and perhaps leading down to moist earth or water, or in the case of those that form upon the walls and ceilings of barns, cellars, water tanks, etc. In all, or most all, of these cases frost crystals form either in a very moist atmosphere, or in one that is slowly but steadily receiving fresh supplies of moisture thru evaporation, etc., and many of them form and grow in a manner markedly different from those that form and grow in the open.

The influence that position and environment exert upon frost crystals is still further shown in the case of hoarfrost crystals that form on bare compact earth (soil), or directly on the surface of ice, and lie flat on these surfaces, as contrasted with those that form on but grow upward from those same substances. In the former case the frost crystals almost invariably grow in the form of long slender columns, but in the latter case, in a branchy, tabular manner. Frost crystals that form in a strong but moist current of air, as in small cracks or apertures thru which air circulates between two compartments, are apt to grow in a more or less amorphous manner. So are those that form upon trees crowning mountain tops. Physicists and crystallographers have learned that crystals in general, when not hampered in their habits of growth by position and environment, tend to grow in a more or less solid or branch-like manner, according as they grow slowly or rapidly, and in a relatively tenuous, nonviscous or dense, viscous solvent.[4] The writer's own observations and studies have led him, however, to the belief that crystals sometimes tend to grow differently, one from another, even under the same identical conditions, positions, environments, etc.; hence he would add that mysterious something that is called individuality to the other factors that determine the form and habits of growth.

(6) Internal structure of frost crystals.

The internal structure of frost crystals varies from one type to another, and to some extent even among those of the same type. Some are completely solid, so that the lines and shadings due to excluded air are absent. Others are of a loose, fibrous, or amorphous nature. However, the great majority of the tabular frost crystals, and certain subtypes among the columnar crystals, possess a structure practically identical with that of the snow crystals. Lines and shadings due to included air are found within them. In many cases the aspect, form, position, and general arrangement of the features due to included air correspond so closely to those that occur with snow crystals that there can be but small doubt that both frost and snow crystals have been due to the same or similar causes. With rare exceptions, however, the markings that occur within the frost crystals lack the beautiful and perfectly symmetrical manner of arrangement of those found within the snow crystals. Microscopic observation of natural frost crystals while growing in natural positions would doubtless reveal the precise manner in which the air-tubes, shadings, and all interior figures are formed. Direct microscopic observation of growing frost crystals is a task of no little difficulty; it can not be carried on continuously for any length of time, because the natural heat of the body disturbs the equilibrium of the air around the growing crystals, and causes them to cease their growth.

(7) Habits of growth of frost crystals.

The habits of growth of the crystals of each mineral species are of great interest, but those of the snow, frost, and ice crystals are perhaps the most interesting and instructive of any. The molecules of water, of which these crystals are constructed, have a wonderful freedom and facility of motion among themselves in the free air while arranging themselves in crystalline forms. No dense magma or solution, no state of excessive pressure hampers or prevents their arranging themselves in a perfectly free and natural manner, in harmony with the system of crystallization to which they belong. For this reason, and because they form under such a multiplicity of conditions, it is perhaps hardly to be wondered at that they assume such varied and beautiful forms. And yet we can but marvel why on given dates and seemingly under like conditions as to temperature and pressure the individual crystals should assume such diversified forms. This diversity of form is, however, the most prominent and universal characteristic of ice crystals of whatever species. The student commonly finds frost crystals of two or more different types formed and growing within the same cavity or upon the same pane of glass, and different types of ice crystals growing in the same body of water. Frost crystals in general form and grow in one of four types, i. e., in the form of a solid hexagonal column, in the form of a hollow hexagonal column, in the form of a hollow hexagonal funnel, or as thin tabular planes.

Owing no doubt to changes in the humidity of the air, and to corresponding changes in their rates of growth, many frost and ice crystals eventually undergo a radical change or reversal in their habits of growth, and cease to grow on the plan imposed by the original nucleus. In such cases they may resume, continue, and complete their growth in an entirely different manner from that characterizing the nucleus and basal portion. Many curious and interesting compound crystals result from this cause, as will be described hereafter in detail. Under such influences hollow columns form and grow upon the apices of solid columns; hollow, funnel-like additions grow outward from hollow columns; branch-like additions upon solid tabular crystals, etc.

Altho corresponding types are markedly similar in many regards, yet differences often exist in the dimensions of snow and frost crystals, respectively. The latter rest upon a support, and hence often grow for a much longer time and attain to a larger size than do the former. Furthermore, certain types of frost seem not to have corresponding prototypes among the snow crystals. As examples, see the frost that grows in the form of hollow hexagonal funnels or in the form of longitudinal bisected segments of hollow cylinders and funnels. Singularly enough, the compound form of snow crystal called "doublet" or the "cuff-button type" seems to have no prototype whatever among the frost crystals.

(8) The growth of frost crystals compared with snow crystals.

Were the frost crystals as free to grow and develop uniformly in all directions as are the snow crystals, they would doubtless assume forms equally beautiful, symmetrical, and complex. But environment and position, the character and the inequalities of the surfaces of the objects upon which they form, operate to prevent or impair perfect or symmetrical growth in all directions. For this reason many types of frost, especially the more beautiful tabular ones, necessarily develop largely or wholly either in the segmental form or on imperfect and more or less irregular plans. Were it not for this the resemblance of each type to the corresponding type of snow

[4] I am indebted to Prof. J. P. Iddings, University of Chicago, for kindly placing this information at my disposal. His most valuable and interesting book, entitled "Rock-making Minerals", treats at some length of the forms of crystals as formed in magmas and solvents of varying degrees of viscosity.—*W. A. B.*

crystals would be still more marked. When comparison is made between types of frost and snow, segments rather than whole crystals should be used for comparative purposes.

When this method of comparison by segments is employed then the many striking points both of similarity and of dissimilarity that exist between them are well brought out. Tho many types of frost grow largely in segmented form only, some few types grow in a complete and symmetrical manner. Solid and hollow columnar frost crystals and funnel-shaped ones are examples in point. It is of great interest to note that crystals of these respective types correspond as regards perfection of form with similar columnar snow crystals.

(9) General ideas as to forms and classification of frost and ice crystals.

The individual crystals of both hoarfrost and window-frost and also, tho in lesser degree, those of ice, assume a diversity of form and structure that is seemingly infinite; hence a complete grouping and classification of them all can not be undertaken as yet. Many, however, are found crystallized in special situations or upon special objects; others possess in general some one or more common characteristic; others are formed under certain temperatures and humidities. These or other conditions have served to impress in greater or less degree certain features and peculiarities of form or structure that serve to distinguish them. These considerations make it possible to roughly group the crystals possessing similar characteristics into types by themselves. The number of distinct types both of hoarfrost and window-frost crystals is quite considerable, and hence it becomes necessary to adopt some name or symbol to apply to each type so that it may be easy to identify each in a photograph or in nature. It has been thought best to adopt some form of "mnemonic" system adapted to our scheme of classification.

(10) System of classification and mnemonics.

The words descriptive of our types may be conveniently condensed so that we may designate our various types by the several letters of the alphabet. In applying this system the first letter to be used will be the initial letter of the word that indicates the kind of frost or place of deposition, whether hoarfrost (H), window-frost (W), window-ice (I), massive ice (M), or hailstone (S). The second letter will be the initial letter of the word designating the form characteristic of the type; while the third letter will indicate the approximate relative frequency of occurrence of the type of crystal under consideration. For instance, the first letter H signifies hoarfrost, W window-frost, and I window-ice; the second letter, if it be T, signifies tabular type, if C, columnar type, etc.; while the third letter A signifies the most common type, B the next most common type, and so on down to the last letter which will denote the rarest type of all. This system will be applied to each and every group of frost and ice crystals that may hereafter be considered. Hoarfrost crystals come first under our scheme of treatment and will receive first mention. The great majority of individual hoarfrost crystals may be grouped into one or two primary classes or types, i. e., columnar or tabular. Those grouped under the former head form and develop in solid or hollow hexagonal cylindrical columns, while those grouped under the latter head develop in thin tabular planes. Tabular hoarfrost crystals are most varied both in form and structure, as there are a number of distinct subtypes that require to be presented separately.

This text is accompanied by about 275 half-tones, arranged very nearly in chronological order as shown by the List No. 1, but also rearranged by types in List No. 2. The statistics of frequency of each type are shown in Tables 1, 2, and 3. The linear magnification of the original photographs reproduced herein is approximately indicated by the small figures following the multiplication sign, ×, placed immediately after their serial numbers on the plates and in List No. 1. A reduction is shown by the use of a fraction. The published half-tones are, however, occasionally somewhat smaller than the original photographs.

II.—CLASSIFICATION OF HOARFROST CRYSTALS.

(11) Type HTA. Tabular hoarfrost.

Crystals of this type consist of solid tabular hexagons or segments thereof, superimposed in many-storied fashion, one above another.

This type of crystal is a moderately cold weather type, and occurs most frequently in late autumn, in winter, or in early spring. Crystals of this type form in autumn and spring when air temperatures at the earth's surface range from 30° to 15° F., but in winter, during intense cold, they, together with some other types, often form a hoary lining to cavities under the snow, and on the under sides of blocks of wood, etc., embedded therein. They also form in winter on the under sides of water trough covers; in similar moist situations; in the open upon the surface of the snow; upon the grass blades, shrubs, etc; more rarely upon the trees. Photograph No. 0 shows them as collected on the surface of a board, and portrays their general aspect and manner of arrangement. No. 38 C shows them as formed on and around the edges of a plant leaf, while No. 38 D shows them as arranged on a grass blade.

The present collection of half-tones from our photographs contains fifteen illustrations of this very common type of hoarfrost crystal, as follows: Nos. 0, 1, 2, 6, 9, 12, 26, 38 A, 38 B, 38 C, 38 D, 46, 118, 155, 191.

(12) Type HTB. Single solid tabular hexagons.

This type of crystal forms both in the open and within inclosed air chambers, and one variety forms indoors upon windowpanes. (See 36.) They have a general resemblance to crystals of type HTA, and often form under the same general conditions; but they differ from them in most cases in this, that they form upon and grow outward from slightly raised nuclei or projections, and in a horizontal rather than in a vertical position relative to the general surface of the objects or surfaces that they form upon.

The more perfect examples of this type of crystal, whether formed upon windowpanes, or in the open, invariably form around some tiny projecting frost or ice or other raised nuclei, and develop parallel to, and but slightly raised from, the general surface of the object or glass that supports them and their nuclei. They are commonly fastened so strongly to the objects that they form upon, that it is rarely the case that they can be secured entire for photographic purposes. Nos. 7, 20, 33, 34, 61, and 199 are, however, typical forms, and will serve to give a correct idea of this type of crystal. As will be noted, they possess systems of interior lines and shadings due to air tubes, etc. These correspond so closely in aspect, position, and arrangement with those that occur within the solid tabular portions of snow crystals as to leave but little doubt that they have a common manner of origin. Crystals of this type vary greatly in size one time with another, and one with another. They rarely attain a large size. Commonly they vary in size from one-eighth to one-twenty-fifth of an inch in greater tabular diameter, and in thickness from perhaps one-fiftieth to one-sixteenth of an inch.

(13) Type HTC. Solid tabular hoarfrost crystals exhibiting various stages of trigonal development.

Crystals of this type and character form under the same general conditions as exist during the formation of types HTA and HTB, and are often found associated upon the same object, or within the same confined spaces with them.

Why crystals so dissimilar in form should be the product of forces and factors seemingly so identical is one of the mysteries of crystallization. There is evidently much more in our crystallographic philosophy than we dream of, or understand. As previously set forth, it would seem that in some cases crystallic form and growth is guided and determined by interior and nucleal, or individual, rather than by external and abstract conditions.

Solid tabular hoarfrost crystals exhibiting various phases of trigonal development, are by no means rare, but it so happens that but few photographs of such have been secured for our collection. Nos. 8, 47 A, and 47 B will serve to convey an idea of their forms and structure. Lines and shadings, due to air inclusions, are prominent features of their interior structure.

Hoarfrost crystals of types HTB and HTC are usually of small size, viz, from one-twelfth to one-fourth inch in diameter.

(14) Type HTD. Open branch or tree-like forms.

Hoarfrost crystals grouped under this head possess an open branch-like structure, and commonly have one or more primary and many secondary rays all arranged in a very thin plane. This beautiful and frail type of hoarfrost seems to form most frequently during intense cold, when the temperature falls rapidly to zero or below. The crystals form upon and grow outward from various objects and in various situations, e. g., within barns and from the inside surfaces of barn doors, upon cobwebs and straw litter therein, and in the open upon ferns, grasses, etc., that overhang icy terraces or pools of water, the surfaces of brooks and pond ice, etc. Beautiful crystals of this variety often line open cavities in the snow or other partly closed cavities leading down to moisture, water, or wet soil. Individual crystals of this type sometimes attain to relatively large size, e. g., from 1 to 3 or more inches along their greater diameter

Photographs Nos. 11, 15, 16, 24, 158, 159, 160, and 190 portray a few of these beautiful frost creations, and also a few of the objects on which they form and which they adorn. No. 158 is a photograph of this type of frost, strung along the cobwebs hanging from a barn roof. No. 159 shows a beautiful plume-like cluster of such crystals arranged upon and around a straw stalk. No. 160 pictures them as formed in heavy white masses of clustered crystals upon the hay, barn roof, timbers, etc., of a barn loft above the stalls where cattle were kept. These, and also Nos. 24 and 158, are due to the condensation and crystallization of moisture exhaled in the breath of animals. No. 24 is an exquisitely beautiful example of this form of crystal. No. 190 is hardly less beautiful, and most remarkable because of its close resemblance to a tree.

(15) Type HTE. Less open, branch or tree forms.

Hoarfrost crystals of this type grow in a somewhat less open, branch-like manner than type HTD. They often consist of a large number of tiny solid tabular hexagons attached one to another, or to very short and broad branches, and arranged one outside another, all in a very thin plane. The facets of the many tiny hexagons gleam and glisten like so many diamonds and give a jewel-like appearance to the whole. These most interesting frost structures, like the preceding (type HTD), are very cold weather or zero (Fahrenheit) types. They form most frequently and in greatest number upon the bare surface of brook and river ice. They almost invariably grow upward and away from the surface of the ice. During long-continued below-zero weather large areas of river and pond ice may be thickly or completely covered with these beautiful leaf-like frost creations. Sometimes myriads of them are found clustered together into groups, like flower beds, on the surface of the ice, in the manner shown in photograph No. 170. This variety sometimes forms during a very cold night, and is found associated with other types of hoarfrost, particularly the types HTA and HTE, upon the trees and shrubs that clothe hillside and valley. Nos. 110, 111, and 208 formed in this manner upon the branches of trees, and were detached therefrom for photographic purposes.

The deposition of a heavy coat of hoarfrost of this description upon the trees in wooded regions produces a most beautiful effect, and sometimes converts a grove of trees into a fairyland.

Photographs Nos. 13, 14, 110, 111, 168, 169, 170, 172, 173, 174, and 208 serve to reveal the forms and general outlines of this type of hoarfrost crystals. Photograph No. 174, of this series, is of more than ordinary interest. These crystals grew upward from basal points just below the streak of "Canada balsam" shown on the photograph and used by me to attach them to the glass microscope slide. At a late stage in their growth the fine frost work suddenly became of a more solid character than the portions formed before and after, as shown by the bands of larger crystals crossing the tabular structure. Atmospheric conditions were evidently such, during the formation of this more solid portion, as to cause a retardation in its rate of growth, and to favor the formation of nearly solid crystalline structures. Yet, after a time, the general conditions, such as prevailed during the formation of its basal portion, were reestablished, whereupon the crystals resumed their former and more open habits of growth.

(16) Type HTF. Stelliform crystals.

These form under identically the same conditions of temperature, humidity, position, etc., as those grouped under type HTB, and are often found associated with them upon the same objects. Why they fail to develop forms identical with those of type HTB can hardly be explained, except upon the supposition that nuclear differences exist, and impart their especial habits of growth to all subsequent accretions around the nuclei.

Tabular hoarfrost crystals of this description greatly resemble in all but symmetry certain solid tabular types of snow crystals. However, they rarely or never develop on a perfectly symmetrical plan as do many of the latter; commonly they develop in segmental form, because they usually crystallize upon objects in such a manner that but three or four of the six corners of the hexagon have an opportunity of growing outward from the nucleus.

[To be continued.]

COTTIER'S RESISTANCE OF ELASTIC FLUIDS.

The pressure of the wind for any given velocity, or the resistance of the air to a moving body, is one of the fundamental questions in the physics of the atmosphere. The subject has been treated experimentally by practical engineers and laboratory physicists for three centuries past; but their measurements have mostly served to show how little we understand the flow of air around and behind an obstacle. The physicist needs the guiding hand of a master in analytical mechanics. Summaries of the present state of experimental knowledge of the subject were attempted by myself in my lectures of 1882,[1] and in my Treatise on Meteorological Apparatus and Methods[2]; in a memoir by Capt. W. H. Bixby, U. S. Army Engineer Corps, in 1891; in Schreiber's Studien über Luftbewegungen, 1898; and in Bigelow's "Relations between wind velocities and atmospheric pressures".[3] The fundamental hydrodynamic formulas are given by Lamb, Basset, Love, Helmholtz, Wien, Auerbach, Saint Venant, Boussinesq, and other writers on hydrodynamics.

The late J. G. C. Cottier, author of the memoir on "The equations of hydrodynamics in a form suitable for application to problems connected with the movements of the earth's atmosphere",[4] left several excellent manuscripts bearing on

[1] Ann. Rep. C. S. O., 1882, pt. 1, p 98.
[2] Ann. Rep. C. S. O.,1887, pt. 2.
[3] Monthly Weather Review, October, 1906, (vol. XXXIV, p. 470).
[4] Monthly Weather Review for July, 1897, (vol. XXV, p. 296).