STUDIES OF FROST AND ICE CRYSTALS.

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

(Continued from September Review.)

(36) Type WLF. Solid lamellar crystals.

Crystals of this type, like the preceding, form upon tiny ice or frost particles on the window glass, and grow detached from the glass, except where their nuclei are in contact with it. They develop in the form of thin hexagonal laminæ, or plates, growing in practically the same manner and under the same general conditions, except at somewhat colder temperatures, that prevail during the formation of crystals of type WSE; and are like them a type of indoor hoarfrost. They grow in a slow and intermittent, rather than in a continuous manner, and preserve the plain hexagonal form intact, except possibly at brief intervals, when new additions begin to grow outward from each of the six corners of the lamellar hexagons.

Perhaps the most interesting features about them are the systems of lines and shadings that thread their interiors, due to included air. These have a similar aspect and arrangement to those that occur within many solid tabular snow crystals. In some cases they even possess delicate circular lines encircling nuclear portions corresponding to those which occur within certain types of snow crystals, and which Mr. A. W. Waters called "meandering lines". They differ, however, in most cases from solid tabular snow crystals in this, that the air tubes and shadings within them, going to form their interior structure, lack the perfect symmetry of arrangement of the similar features that occur within the snow crystals. Yet in some cases almost perfectly symmetrical solid tabular hexagonal structures are built up around such imperfect nuclei or nuclear portions. No. 171 is a case in point, and it will be noted how closely this one and No. 180 A resemble some of the solid snow crystals.

The series of photographs, Nos. 32, 53, 58, 59, 117, 129, 171, and 180 A, portrays typical and fine examples of this type of window-frost crystals. Photograph No. 180 B shows a beautiful group of such crystals. Among the more interesting specimens of this series is No. 180 A. It shows two crystals, one of them a very interesting "twin" crystal. No. 129 shows two solid tabular crystals lying so close one to another that it is very likely that could they but have grown a little longer they also would have united and formed a twin crystal similar to the one in No. 180 A. It is interesting to note that the outlying portions and segments of each of these crystals grew much faster and to a greater size than did the segments of each that lay closest to the neighboring crystal. The photograph No. 117, showing tiny, solid hexagonal crystals clustered around a window-frost crystal of type WFC, is of very great interest as showing how in some cases changes in temperature and humidity cause certain types of crystals to cease to grow, and cause crystals of another and opposite type to form and grow around them. In this case the tiny, outlying, solid, hexagonal crystals formed in a much colder, and presumably somewhat drier atmosphere than that in which the curving nuclear crystal was formed.

(37) Type WCG. Columnar forms.

This type of window frost occurs in the form of short, square-ended hexagonal columns. They correspond to the solid, hexagonal, columnar forms of snow and hoarfrost crystals, but unlike them they form in such a way, with one of their sides in contact with and attached to the window glass, that they rarely grow in the form of complete hexagonal columns, but in most cases in segmental form only; i. e., so as to resemble solid columns bisected longitudinally. They are very cold-weather types and form only in cold rooms, and in a very cold atmosphere. In many cases crystals of this type form when the outdoor temperature ranges from —10° to —30° F., and the indoor from 15° F. downward. They are rarely found distributed evenly over the whole surface of a given windowpane, but usually occur in clustered array upon some one or more local portions only. In many cases they occur associated together upon the same pane of glass with types WSE and WLF. They are usually quite small in size, and evidently belong to the class of crystals that grow slowly, and that form freely only within a very cold and somewhat humid atmosphere. Within the coldest of my rooms they formed most freely at humidities of 83 to 86 per cent, and within the warmer rooms only when the relative humidity exceeded 60 per cent. Photograph No. 156 shows a group of such crystals, while No. 157 shows some of them viewed endwise. The latter are magnified much less than the former.

It is of interest to note that the interior structures of such crystals and the figures outlined therein closely resemble those that occur within the solid tabular snow crystals. The writer's photographs of solid columnar snow crystals, reproduced in the memoir "Studies among the snow crystals, winter of 1901–2",[5] exhibit sets of shadings and figures that resemble those within solid columnar window-frost crystals. The splendid and correct drawings of solid tabular snow crystals made by Mr. A. Dobrowolski, member of the Belgica Antarctic expedition, and published by him in his very interesting and richly illustrated work, entitled "La Neige et le Givre", also show structures and sets of interior figures that resemble those within solid columnar window-frost crystals.

(38) Type WOH. Open-structure forms.

It has proved impossible to find a word that will convey an impression of the forms of this singular type of window frost. It possesses primary and many tiny, slender secondary rays, and the whole is so arranged as to outline open hexagonal and other figures. The secondary rays usually project from the primary ones at angles of 60°. This type of crystal also is common only to cold rooms, and to medium and low temperatures. It is often found associated with types WSE, WLF, and WBB.

Photographs Nos. 86, 120, 121, 127, and 132 will serve to give a much more correct idea of this odd type of crystal than words can convey. This type and also type WFJ seem to be common only to quite humid atmospheres, for they formed not at all within the least humid of my several rooms. They seem to form most freely at relative humidities of 55 to 65 per cent.

(39) Type WTI. Tooth-shaped crystals.

This type of crystal, as its name implies, assumes tooth-like or spike-like forms. It forms only within cold rooms and under practically the same conditions, temperatures, etc., as prevail during the formation of types WLF, WCG, WSE, and WMD, with which it is often found associated. Nos. 32 and 58 B contain specimens of the tooth-like crystals and No. 59 of the long spike or rod-like forms.

(40) Type WFJ. Fibroid crystals.

Window-frost crystals of this type consist of a vast number of slender, curving or straight, icy fibers lying close together or in partial contact one with another and all lying in the same general direction, as shown in photographs Nos. 28 A and 28 B. They form within relatively warm rooms and perhaps most often when a rapid and considerable fall in outdoor temperature is in progress. They seem to be common only to quite humid atmospheres, possessing a relative humidity of from 60 to 90 per cent, and to relatively mild temperatures (from 30° to 15° F. indoors).

This closes our mention of special types of window-frost crystals; yet there are others that are perhaps entitled to be considered distinct types. Those shown in photograph No.

[5] See Monthly Weather Review, Annual Summary, 1902.

166, for instance, are a case in point, but space forbids further mention of. particular types, except the one next to be considered.

(41) Type WGK. Granular window frost.

This type of frozen "granular dew-like" frost, if such it may be called, is of a noncrystalline character and is of very common occurrence. It is peculiarly the product of a very humid atmosphere and is most common to warm, artificially heated rooms. It consists, as first formed on windowpanes, of countless myriads of tiny, microscopic, liquid water particles crowded together upon the glass. In mild winter weather they may retain that liquid character for hours together, but during cold weather the tiny dewdrop-like liquid particles are frozen once they touch the glass and converted into tiny, rounded, icy granules thereon. (In rare cases the granules assume a more definite crystalline form.) The individual granules as deposited at the first stage vary in size from perhaps $\frac{1}{100}$ to $\frac{1}{300}$ of an inch in diameter, and lie for the most part near to, but slightly apart from, one another. Commonly the granules retain their original size and form only a short time, because deposits of moisture like themselves form upon and attach themselves to them, augmenting their size until eventually all, or nearly all, merge together and form a thin but continuous film of granular ice. This is its second stage of formation.

(42) Rapidity of formation.

Unlike true frost crystals, which usually form and grow slowly, granular window-dew frost often forms very rapidly; and in many cases, as during zero weather or when for any cause the air in immediate contact with the glass is momemtarily made more humid, it forms in instantaneous order.

(43) Experiments in formation and repulsion of window frost.

During zero weather most interesting experiments may be made by placing a lighted lamp close to a frosted windowpane and allowing it to remain until a large space at the center of the glass is made dry and free from moisture or water film. Around this dry space a film of water should be left upon the glass for window-ice crystals to form in. When the lamp is removed window-ice crystals begin to form around the outer edges of the water film and to shoot inward. They cease to grow where the edge of the space of dry glass is reached. Soon tiny true frost crystals of types WLA and WBB form upon certain lower outlying positions of the central dry glass space. Small patches of granular-dew frost, type WGK, soon form and occupy the dry spaces of glass lying around, but not in the immediate vicinity of, the true frost crystals. The latter seem to repel the tiny dew-like water particles while they are in the liquid state and thus prevent them from approaching close to the true crystals; hence a space of unoccupied dry glass is left immediately around such crystals. True frost crystals soon form a little above the upper limits of the granular-covered glass spaces, and are soon in turn once more succeeded by the formation of granular patches around and above them; and these processes are repeated in alternate order until the whole central dry glass space, except those portions lying immediately around the true frost crystals, is completely covered. Ofttimes, as the phenomenon proceeds, deposits of the granular-dew frost will flash forth in instantaneous order upon the glass and instantly cover relatively large glass spaces.

(44) Photographs of phases of repulsion.

The above described repulsion phenomenon is of such interest as to have induced the writer to secure a large set of photographs showing the various phases and stages of the phenomenon, and the diverse ways in which it manifests itself. The following photographs best show this phenomenon of repulsion: Nos. 48, 100, 103, 106, 107, 108, 122, 125, 128, 144, 148. Nos. 17, 80, and 81 are highly magnified photographs, showing the forms and arrangement of the individual particles or granules of which type WGK is composed. Photographs Nos. 128 and 144 show sections of granular films, but slightly magnified. Nos. 100, 106, and 144 exhibit the potency and intensity of this repulsion phenomenon, and the relatively considerable distances from the crystals at which it manifests itself. It will be noted that in these cases it extended outward upon the glass over a region double or treble that of the diameters of the crystals that exerted it. Excessive humidity particularly overcomes the influence and potency of the repulsion agencies, and under such conditions the dew-like granular-frost particles are from the very first forced, as it were, to approach more closely to the true frost crystals than is the case under less excessive conditions of humidity. When such excessively humid conditions continue for a long time granular dew-frost particles are forced to form and to approach progressively nearer and nearer to, and at last to unite with, true frost crystals. For further mention of this phenomenon, and of its probable cause, see section 29.

V.—WINDOW-ICE CRYSTALS IN GENERAL.

(45) Conditions of formation.

Under this title are grouped the various forms of so-called window frost that develop within a very thin film of liquid water on the windowpanes within dwellings, offices, etc., and that are cases of true ice crystallizations.

Window-ice crystals are of very frequent occurrence and assume exquisitely beautiful and varied forms. Countless windowpanes in northern climes are beautified thereby in wintertime, hence their forms and many varied charms must have been made familiar to nearly every one. They are very noticeable because of their large size and feather-like forms. The only condition essential to the formation of window-ice crystals is that there be a film of liquid water upon a windowpane, and that the outdoor temperature be at some point below the freezing point of water. The size of individual window-ice crystals depends upon and is limited only by the area of glass surface covered by such water film, and the time that a single crystal can develop unimpeded therein, i. e., without meeting other growing ice crystals progressing in opposite directions.

(46) The types and method of formation.

Two types of window-ice crystal occur in nature. The crystals of one of these types grow in the form of feathers and feathery plumes, and because of this the type has been called the "feather form" of window-ice crystal; while the other or opposite type grows in the form of delicate branching twigs or trees, and hence is called the "arborescent" type or form. The crystals of the former type are perhaps of most frequent occurrence, and are much more striking and prominent than are those of the opposite type.

The feather-form crystals possess both primary and secondary rays, while arborescent crystals lack such primary rays, and consist of secondary rays only. In the case of feather-form crystals the primary ray or quill comes slightly first in the order of formation, and hence always extends slightly in advance of the secondary rays; and the latter grow outward in general at angles of 60° from the primary ray; and in general both primary and secondary rays grow outward in straight, or but slightly curving fashion. But in the case of the arborescent crystals each of the many secondary rays of which they are composed grows onward independent of the others, in a sinuous and meandering, rather than straight or gently curving, manner. Their respective and differing manners of growth would seem to suggest the idea that the feather form is the result of a relatively powerful and well-defined crystallic tendency, directed forward regardless of obstacles, in straight or but slightly curving manner, whereas the opposite branching type is the result of a much feebler, or at least more diffused, crystallizing tendency, directed also forward, but in so feeble a manner, that each separate crystallic ray is deflected and must pick its way around, instead of passing straight over, the many tiny obstacles encountered in its path.

(47) Habits of formation.

Window-ice crystals in general seem not to repeat or duplicate the forms assumed at a given time, or at least do so only after long intervals of time, when perhaps identically the same conditions that produced a given design repeat themselves. They form within thin films of water rather than, as in the case of the window-frost crystals, directly upon the dry glass; and hence are much less influenced by scratches or other features of the glass plate than are the latter.

Other conditions being the same, crystallization within thin films of water, spread evenly upon windowpanes, will occur first upon the colder portions of the glass. Subsequent development and habits of growth are doubtless greatly determined by relative temperatures and by variation in the thickness of the water film. In the case of feather-form crystals, curving habits of growth are doubtless in many cases induced as a result of their endeavors to grow away from neighboring crystals, or to seek out and grow toward the cooler regions on the glass, or to avoid the warmer ones.

(48) Factors determining type.

In the case of window-ice crystals, the factors that determine the type and form are as yet but partially known. Both types of crystals grow side by side upon the glass. Yet it frequently happens that, for some inscrutable reason, one type will suddenly cease to grow, and be succeeded by the opposite type. The line of demarcation between the one and the other type is always sharp and well-defined. Possibly the following may be determining factors:

1. Thickness of the water film.
2. Variation in the thickness of the window glass, and—
3. Consequent variation in the temperature of its different portions.
4. Condition of the water film, whether continuous or broken.

(49) Development of window-ice crystals.

Ice crystals as first formed, or in the first stage of existence, are very thin and transparent. At this stage they are quite difficult objects to photograph. During extreme cold, or under the influence of a rapid and continued fall in temperature, they become progressively thicker and more opaque, and are easily photographed. The moisture that collects upon them, once they are organized, is largely of a subcrystalline, or granular dew-like character, and merely increases their thickness and opacity, without altering their type.

Singularly enough, the feather form, IFA, and the branching form, IAB, of window-ice crystals, do not grow or increase in thickness and opacity in the same ratio; the former grows much the faster. During intense and long continued cold, the feathery crystals often increase in thickness to such a degree as to represent a third stage, when they stand out in relief from the branching designs, resembling beautiful sculptured scroll work wrought in *alto-rilievo.*

In somewhat cold but moist rooms, as within barns and mountain observatories, the development of window-ice crystals often proceeds to yet another or fourth stage, in that it is superseded by a species of hoarfrost crystallization, due to the formation of columnar or solid tabular hoarfrost crystals upon the surface of a thick opaque window-ice film. Such crystals develop, in perpendicular fashion, outward from the glass or normally to the ice film.

VI.—CLASSIFICATION OF WINDOW-ICE CRYSTALS.

(50) Type IFA. Feather-form crystals.

We have secured a large number of photographs of these beautiful crystals and have selected the following numbers from among them for illustrative purposes:

Nos. 49, 50, 51, 52, 62, 63, 66 A, 68 A, 68 B, 72, 74, 75, 78, 79, 82, 83, 88, 89, 91, 92, 93, 101, 113, 133, 134, 135, 136, 138, 139, 140, 142, 150, 151, 152, 164, 182, 183, and 189. Many of these are greatly reduced in size, while many others are magnified a few diameters. Some few sections are highly magnified.

(51) Stages of growth.

Nos. 49 and 62 show the crystals during their first or skeleton stage of formation; Nos. 133, 135, 136, 138, and 139 show the second stage, and the manner in which the spaces between the first or skeleton branches are filled in by subsequent growth; while Nos. 66 A, 68 A, 68 B, 72, 88, 134, 140, and 142 show the third stage of formation, and the thick coat of subcrystalline frost-ice, or granular dew-like window-frost, type WGK, that collected on them as the result of their being subjected for some time to a very and increasingly humid atmosphere, due in part to a rapid and considerable fall in outdoor temperature, and in part to steaming kettles indoors.

(52) Special cases.

Many of the photographs of the feather form of window-ice crystal are of great interest and deserve especial mention. No. 62, for example, is among these. This photograph is not, as might be readily supposed, a railroad map, but a highly magnified section of a window-ice crystal. Yet the invisible, but potent, something that we blindly call crystallic impulse, or tendency, which traveled along those tiny crystallographic main lines, is perhaps just as wonderful in a way, if viewed from an atomic or molecular standpoint, as are the ponderous engines of human construction that thunder along the railroad lines represented upon actual railroad maps. We can but wonder whether those mysterious inter-atomic forces, or agencies, that traveled along those tiny microscopic lines, constructing them as they went along, pulled molecules and atoms along with them to build up those complex structures; or whether they drew such from either side; or indeed, whether they did not in fact push atoms and molecules to one side as they past along.

No. 74 also is a highly magnified section of window-ice crystal, type IFA, but in this case crystallic lines are much broader and possess scalloped or rounded, instead of straight, edges, as tho tiny atmospheric or liquid whorls aided in the building of them.

In No. 189 the secondary branches are seen growing and projecting perpendicularly to the primary quill ray. This arrangement is somewhat unusual. Nos. 79, 88 and 93 are fine and instructive examples of further magnified sections of feather-form crystals.

Nos. 136, 138, 139, and 140 are most strange and rare specimens of beautiful feather-form window-ice crystals. They somewhat resemble in form sections of evergreen vine. They formed during sunny zero weather, on a calm afternoon (January 5, 1905), just preceding the terrible hurricane wind of January 6, 1905. Possibly a brief statement of the general conditions that favored their formation may be of interest. The windowpane whereon they formed had a southern exposure, but an adjoining building to the westward gradually cut off the sunlight during the afternoon, leaving it in shadow. This was done in such a way that the sunlight was shut off from the western edge of the window first, and the eastern edge last, hence the region of shade gradually extended across the window from west to east, and of course this operated to cause the western edge of the windowpane to cool off first. As a result, window-ice crystals formed first within the water film covering the western edge of the windowpane, and slowly progressed from west to east, and in horizontal order, across it. Had the windowpane been of a more equal temperature thruout, and as cold at its eastern as at its western edge, window-ice crystals would have formed as quickly at the eastern edge of the pane as at the western, and hence have developed outward therefrom, and have met and thus interfered with the complete development of the crystals under consideration. Many long, slender, feathery window-ice crystal plumes doubtless owe their origin to causes similar to those just set forth. Long feathery plumes that form at the bottom of windowpanes and develop upward along the central regions of the glass, are cases in point. In this case they form first upon the colder (lower) portions of the glass, and progress upward toward the warmer portions, but enter these only after the glass has become cooled by exterior cold to a point that favors their development thereon.

The crystals Nos. 136, 138, and 140, previously mentioned, were of large size and magnificent proportions. Our photographs show them reduced to one-third the diameters of the originals and at the second stage. Moisture continued to collect upon them during the afternoon of January 5, 1905, owing to a progressive fall in outdoor temperature, and as a result they assumed and past into the third or opaque window-frost stage. For some strange and inexplicable reason, certain local spots, situated at regular intervals along the greater radii, failed to attract as much moisture as others, or operated to repel moisture; hence such spots retained much of their original transparency, and this caused the formation of the wonderful and beautiful white and dark spots that appear, strung bead-fashion, along their radii. Our photograph No. 140 shows the general aspect of the crystals at this third or beaded stage; it shows them much reduced in size, and of course shows but little of the wonderful beauty of the originals. No. 142 is a short magnified section while at the second or beaded stage. There is some mystery why crystals of this type and form do not broaden out and meet one another, instead of growing in such a narrow, banded fashion.

(53) Other special cases of feather-form crystals.

No. 150 of our series shows exquisite scroll-like designs of window-ice crystals. No. 183 portrays a group of exceeding richness and complexity; some of the crystals resemble the evergreen-vine type shown in Nos. 136 and 140. No. 182 pictures a magnificent group of feathers, growing upward from the bottom of a windowpane.

No. 164 includes examples of both "feather" and "branching" forms of window-ice crystals. The latter type may be seen branching outward from the ends of the former. The abrupt manner in which one ceases development and in which the opposite type begins to grow outward, as also the well-defined line of demarcation between them, is well shown in this photograph and also in No. 101.

(54) Type IAB. Arborescent crystals.

The individual crystals of this type are much less beautiful and diversified in form than are those of type IFA. This explains the relative paucity of our photographs of this type. Nos. 84, 87, 92, 94, 149, 153, 164, 165 are typical examples.

No. 87 of this series is a most interesting photograph, showing the manner in which these tiny, slender, crystalline branches wander or meander in a general parallel direction on the glass. No. 165 is of nearly as great interest.

This completes our list of window-ice crystals. Those herein reproduced give but a glimpse into the beauties of the window-ice crystals, and show but a few of their many varied forms. They must be seen in the originals to be seen at their best. Photographs utterly fail to do them justice. It is a delight to know that our windowpanes will for all time be glorified and beautified in winter by these exquisite creations of window ice, and by those other elegant crystal structures that are next of kin to them, the window-frost crystals.

VII.—FORMATION OF ICE AND ICE CRYSTALS.

(55) Observation of crystallization.

The crystallization and solidification of water in mass, as on ponds, brooks, rivers, etc., by freezing in winter, is indeed a most marvelous and instructive phenomenon, and results in the formation of many beautiful and interesting groups of crystals. Yet so minute and very thin and transparent are most ice crystals at their nuclear stage, and so quietly and unobtrusively do they form and grow upon the water, that perhaps observers in general rarely witness them. It is, however, easy to study the wonderful formation, growth, multiplication, and eventual merging together of the myriads of tiny discoidal star-like and other ice crystals, which in the wintertime change the liquid water into crystal sheets or masses. The marvelous "alchemy" or mechanism of ice formation, which, as if by magic, converts a fluid into a seemingly structureless solid, can be seen to advantage only under just the right conditions of light, position, etc., and unfortunately nature unassisted rarely furnishes such.

The whole process, however, can easily be watched upon and beneath the surface of a water pail or dish holding water in process of freezing, if the vessel is set in front of a window and a large piece of looking-glass placed flat down on the bottom beneath the water. The water may be occasionally stirred very gently, and such crystals as form from time to time may be removed.

Ice crystals should possess a very great interest for the crystallographer and student of nature, for, as noted further on, certain types pass thru most strange and unusual phases of growth. Moreover, they are so very easily seen and studied if viewed under the proper conditions of light, etc., that they perhaps furnish the best opportunities that occur in nature for the general study of crystal forms. They should possess an added interest as crystallographic subjects, because they can very easily be subjected, while forming and growing, to diverse artificial and natural conditions, such as relate to temperature, location and environment; and thus they afford a means of ascertaining the effects that these various conditions have on the forms and habits of growth of crystals. Tho easily observed and studied, they are most difficult objects to photograph. The writer undertook the task of photographing them during the winter of 1904–5, but had poor success; and only after repeated failures succeeded in securing good photographs of them while floating and growing upon the surface of the water during the winter of 1905–6. Possibly these here given may be the first series of photographs that adequately portrays the form and structure of ice crystals of this character, while in actual process of formation and growth on the surface of liquid water.

(56) The merging together of crystals into massive ice.

The forms and habits of growth, and the mode of arrangement of the individual crystals of ice, as well as the manner in which they merge and freeze together to form sheets and masses of solid ice, necessarily vary in different cases, and in the case of different types under varying conditions of temperature, environment, etc. The solid ice itself, when new, rarely discloses the manner in which it was formed, or the forms and manner of arrangement of the many individual crystals of which it is composed, because, in general, those crystals are so completely and perfectly merged together during the process of freezing that in many cases every trace of their forms, outlines, and arrangements within the ice is completely obliterated. In most cases ice crystals grow outward from a given constituted ice nucleus, by attracting and drawing water molecules to their apices and edges. The only exception seems to be in the case of the formation of ice columns in peaty or gravelly soil.[6] Such seem to grow in an inverse order, thru additions drawn upward thru the pores of the soil and deposited beneath the bases of the columns.

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[6] See article by Prof. Cleveland Abbe in the American Meteorological Journal, April, 1893, vol. ix, pp. 523–525; reprinted in the Weather Review for April, 1905, vol. xxxiii, pp. 157–158.

The manner in which, in general, solid films or sheets of ice of considerable thickness are formed upon the surface of pond, and of gently flowing brook water, consists, in many cases, of the following steps:

1. The formation of a very thin film of ice upon the surface of the water, thru the formation and growth and merging thereon of myriads of needle-shaped, discoidal and branch-like crystals and ice flowers.

2. The gradual thickening of this film thru additions from below, deposited upon its under surface.

3. The formation on the under side of such an ice film, and the growth downward into the water beneath, of various needle-shaped and branch-like ice crystals.

4. The formation, within the free water beneath such a film, of ice flowers and other crystals which rise to the under surface of the film, and grow within the compartments that exist between the downward-growing crystals and branches.

5. The continual formation and growth of new nuclei, and the continuation of the growth of the older crystals until all merge and freeze together and form a second and thicker solid ice film below, but merging with the original one. During long continued cold, this process repeats itself from time to time, until solid ice sheets of great thickness are formed. Brook and river ice, however, as formed over swiftly flowing water, grows in thickness thru accretionary processes, i. e., by liquid particles freezing to the lower surfaces of the ice, without the formation of typical ice crystals.

(57) The structure of old ice.

From the foregoing it will be seen that, in general, a mass of solid ice is not formed wholly, and perhaps not mainly, thru the formation and merging of a vast number of tiny, symmetrical flower-shaped crystals, but rather thru the growth and merging of diverse types of crystals, and of segments of such, differing greatly in size, form, and structure. When closely examined, old ice, as a result of slight internal melting, or of changes of structure due to its being repeatedly subjected to cold and changes of temperature, often reveals traces of its former open crystalline "pre-solid" character. Such old ice presents faint evidence of a cellular or honeycomb-like structure, the cell walls being mainly normal to the surface of the ice. Photograph No. 230 B shows the cellular structure of such old ice; the cells and cell walls are irregular in form and arrangement.

In general, the long, slender air tubes, which are the only conspicuous internal feature of such ice, are arranged perpendicularly to its surface, but ofttimes parallel to and at the lines of intersection of two or more of the faintly outlined cell walls. Their perpendicular arrangement may be due, in part, to the fact that in general the longer radii of the crystals of which such ice is formed also lie perpendicular to or at angles of 60° with the surface of the ice. Yet the main cause, in most cases, must be attributed to the fact that such ice sheets undergo lateral expansion and contraction during and subsequent to solidifying. Such internal stresses tend to squeeze the air into the ice along the lines of fracture and of least resistance, i. e., into the so-called cell walls, or their points of intersection.

(58) Frazil ice.

The so-called frazil ice, or mush ice, of rivers and flowing streams forms only during extreme cold and only when the whole body of water within such streams or rivers becomes chilled to the freezing point. Multitudes of tiny discoidal and other ice crystals form and grow both upon and beneath the surface of such chilled flowing water. The water currents always present within flowing water tend to keep many crystals submerged, and to draw surface crystals downward into the water, and to cause them to diffuse themselves therein. As a result of this forced submergence myriads of them come into contact with submerged stones, soil, etc., upon the sides and bottoms of such flowing streams, and attach themselves thereto and to one another, and grow therefrom.

(59) Anchor ice.

The so-called anchor ice is in many cases doubtless due to the same causes. But possibly in some cases ice-crystal nuclei may form and grow in the first instance directly upon and from submerged stones and objects lying upon the bottoms of such streams. The primary cause of the formation, or rather retention, of masses of frazil or anchor ice at the bottom and sides of flowing rivers is doubtless due to radiation of heat from the bottom upward, as set forth by Prof. Howard T. Barnes in his very interesting and instructive book, "Ice Formation".[7]

(60) Ice flowers.

Tho in general the process of merging and solidification destroys all visible traces of the forms and outlines of the individual crystals, of which solid masses of ice are formed, the crystals may in many cases be rejuvenated and made visible again by the proper treatment. Tyndall's method, whereby the ice is subjected for a time to the gentle heat of the sun's rays, causing a very slight internal liquefaction to take place, will generally reveal them anew. This gentle heat operates in such a way as to liquefy the special less dense portions of the ice lying between the crystals proper, and hence brings them into view again. Star-shaped ice crystals, those termed "ice flowers" by Tyndall, come out most plainly within blocks of such sun-laved ice. They appear most frequently within pond and lake ice, but sometimes also within river and brook ice. The ice flowers that are found so embedded within the solid ice vary greatly in size, form, complexity, and symmetry, but all, or nearly all, lie so that their tabular planes are parallel to the surface of the ice. They differ in one important respect from ice flowers newly formed upon the surface of freezing water, in that large air bubbles form their nuclei, whereas the latter possess none.

In most cases, after the ice flowers are made visible as heretofore described, if the ice be then subjected to intense cold for a time the contraction of the ice will cause the nuclear air bubbles to diffuse themselves outward in a nebulous aspect around the whole radius of the ice flowers, and cause the destruction of the latter, as shown in photograph No. 232. The author has made but few photographs of embedded ice flowers. No. 231 is the only one thought best to reproduce; it shows some embedded in brook ice.

Fortunately other students of ice, notably Prof. Benjamin W. Snow of the University of Wisconsin, and Prof. H. Schoentjes of Université de Gand, have made a large number of excellent photographs of embedded ice flowers. Professor Snow has kindly furnished a few of his photographs to be used to illustrate the beautiful forms of the embedded ice flowers. (See Nos. 228, 229 A, 229 B.) Professor Schoentjes has made an extended study of these and of ice formation, and has written a very interesting and helpful book treating of them.[8]

(61) Structure of pond and lake ice.

There is much of interest about the structure of pond and lake ice, aside from that relating to the ice flowers embedded therein. The forms and arrangement of the air tubes therein, and the changes these and the structure of the ice undergo under the influences of sunlight and mild weather, are of especial interest. In general, pond and lake ice, when viewed horizontally, presents a banded appearance. This is due to the fact that some sections or layers are thickly threaded with air tubes, which give a white, milky appearance to them; while others contain few or no air tubes, and hence are very clear and transparent. This banded appearance shows in our photograph of pond ice, No. 230 A. The upper layer usually consists of white, opaque snow, and water ice, and commonly the layers

[7] Ice Formation, by Howard T. Barnes of McGill University, Montreal, Canada. Published by John Wiley & Sons, New York, U. S. A. 1906.

[8] Fleurs de la Glace, by Prof. H. Schoentjes, Université de Gand.

containing most air tubes lie within the upper half of a given section of ice. The presence or absence of air tubes within ice is doubtless largely due to the rapidity of the rate of the growth of the ice. All things being equal, ice that forms rapidly and during intense cold will contain many air tubes, while conversely, ice that forms slowly will possess but few air tubes. Ice that forms by accretionary processes over swiftly flowing water contains but few air tubes. The forms and sizes of the air tubes within the pond and lake ice vary greatly from one section or layer to another. Some layers may contain only long and slender tubes, others cigar-shaped ones, while others may contain small or large, oval or round tubes. (See photograph No. 230 C). They seem to be subjected to great pressure, for they are often foreshortened as tho by intense stress. This seems proved from the fact that air tubes of a given size, after the ice has been subjected for a time to sunlight or to mild temperatures, are found to extend farther than in the first instance, owing to the fact that a slight internal melting has resulted in revealing the original former dimensions of the tubes as they existed before internal pressure constricted them. (See photograph No. 230 D.)

(62) Various ice-crystal forms.

Ice crystals develop largely if not wholly upon thin tabular or discoidal planes, and a large proportion form and grow in segmental form only. The great majority assume branch-like, leaf-like, or needle-like forms, but complete crystals or "ice flowers" having six leaf or branch-like rays, arranged symmetrically like those of snow crystals, are not rare. Ice crystals seem rarely or never to assume the form of the solid or hollow six-sided column, or to develop in a trigonal manner. They nearly all resemble one another in this, that their outlines are soft and curving, rather than hard, abrupt, and facet-like, and in this they vary markedly from most snow crystals. The primary or germ forms of each of the several types of ice crystals are at first very dissimilar in form one to another; but as they develop, they tend to grow more and more in a common branch-like manner, and hence when mature resemble one another more closely than at birth.

(63) First formation of ice crystals.

Ice crystals when first formed, tho free from air tubes and inclusions, are yet lighter than water, and if unattached to anything always rise to the surface and remain resting thereon, usually with their tabular planes lying parallel to the surface. In general, germ ice crystals form more slowly in perfectly calm than in slightly agitated water. When the whole of a body of water becomes chilled to a certain degree, a gentle stirring of the water, a jar, or a rocking of the receptacle containing it causes myriads of germ crystals to form with amazing suddenness both upon and beneath the surface of the water.

(64) Diversity of types.

Perhaps the most surprising fact in connection with the formation and growth of ice crystals is this, that so many diverse types form and grow, each perhaps in a different manner, at the same time within or upon a given body of water, and apparently under the same identical conditions of temperature, air pressure, environment, etc. Photograph No. 262 shows crystals of various types, formed and growing in the manner described. Changes of temperature seem not to lead to either a marked increase or a decrease in the number of different germ types forming at a given time; tho cold hastens and milder temperatures retard the passage of crystals from one stage of growth to another, and seem to influence the exterior character (i. e., whether it be frail and branch-like, or otherwise) of the superstructure that grows outward from immature crystals of each of the various types. This seems to forge one more link in the chain of proof that, tho exterior conditions and environment exert a great influence in determining and modifying crystallic forms and structures, yet there is a mysterious something—individuality, or whatever it may be called—inherent within the crystals themselves, that enters into the problem of form determination. This exerts an influence causing the parent or germ crystal to impart its own peculiar habits of growth to the molecules of water that such parent crystals, as growth progresses, draw to and incorporate upon and around themselves, in the form of new growth.

(65) Merging and thickening of ice crystals.

Ice crystals of whatever type freely merge and freeze together, one to the other. They are, when first formed, and for some time thereafter, exceedingly thin as regards tabular thickness, hardly thicker in fact than thin paper, probably having a thickness between the one hundred and fiftieth of an inch and the two hundred and fiftieth of an inch. They gradually, but very surely, become thicker with age and increase in size.

(66) Variation in size.

Ice crystals, even as first formed, vary greatly also one from another in greater diameter. Many ice-crystal nuclei are mere specks, with diameters of less than one-fiftieth of an inch; while others, when they come into visible existence, possess forms of considerable size, one-fourth of an inch or even more in greater diameter. Intense cold seems to favor the formation of tiny nuclei, and a milder degree of cold that of larger nuclei. Intense cold seems to favor branch-like, and a mild temperature solid growth. Ice crystals vary much more markedly as to the ratio of thickness to diameter than do snow crystals.

Germ ice crystals, floating and growing upon the surface of calm water, seem to draw their growth material almost wholly from a thin film of chilled surface water. They seem to draw little from below. That this is the case is proved by the fact that whenever two or more crystals lie close together, or even some distance apart, growth occurs fastest and in the greatest degree upon the portions of each crystal that lie the farthest away from the neighboring crystal, or crystals. (See photographs Nos. 264 and 265.) If it were the case that they drew their growth supplies from below, their contiguity would make but little difference in the rates of growth of the crystals so situated, because the source to be drawn from would be relatively limitless.

[*To be continued.*]

METEOROLOGICAL STATIONS IN SOUTHERN NIGERIA.

C. FITZHUGH TALMAN, Assistant Librarian.

The past decade has witnessed an extraordinarily rapid extension of the network of meteorological stations in Africa. The distribution of stations eight or ten years ago is shown on the chart which forms the frontispiece of Bartholomew's Atlas of Meteorology (1899). At that time meteorological observations were well organized in Algeria and south Africa, and work had begun, in a small way, in several British colonies, under the supervision of the British Association Committee on the Climatology of Africa. A few widely scattered stations existed in the Congo State.

In 1900 a general meteorological service was organized in Egypt, and its network of stations has been pushed southward until now it includes the whole basin of the upper Nile, in the heart of central Africa, and adjoins the meteorological system of British East Africa. The latter was organized as an independent service about three years ago, and this year, 1907, embraces about 50 stations of all orders. The British Central Africa Protectorate had, in 1905, a network of 40 stations. Southern Rhodesia has 48 stations, nearly all of which are less than ten years old. (See map in the MONTHLY WEATHER REVIEW for March, 1907, p. 124.) The Transvaal had 375 stations in operation during the year 1906, of which 32 were equipped with barometers. The Orange River Colony had, in 1905, 9 second-order stations and 74 rainfall stations.