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The Surface Expression of Ice Segregation: Needle Ice, Pebble Ice, Ice Flowers and Hair Ice

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In 2003 the author found attractive, but unfamiliar, forms of ice seeming to grow on plant stems in a wooded area. Subsequently, many explorations were made on cold mornings to find something similar with marginal success. Two years later ribbons of ice on small plant stems were found near needle ice pushing up soil. That association with 'needle ice' provided a term to search on leading to "A Bibliography of Needle Ice". (Lawler, 1988) This bibliography contains 267 items dating back to 1824. While the focus of that bibliography is Needle Ice in soils by association some of the entries include ice on plant stems, dead wood and some solid objects formed by the process of ice segregation.

Lawler (1988, 295) wrote "Needle ice, a form of columnar, near-surface, ice segregation in soils . . ." The basic process is explained by Ozawa and Kinosita (1989, 113) who wrote "Ice segregation is the phenomenon in which, through freezing, ice grows out from moisture-containing porous material such as soil. . . .When the segregated ice forms on the ground surface it is called "needle ice" . . . when it forms inside the freezing soil it is called "ice lens" . . . a common feature, i.e., the suction of water toward the freezing front through microporous material and the resulting freezing of this water."

These researchers hypothesized that they could 'grow ice' through the physical process of ice segregation and measure all aspects with technical precision. Before committing to a detailed study, they carried out a preliminary test to see if they could 'grow ice'. They placed a microporous filter with 0.015 μm diameter pores over a stack of filter paper moistened with distilled water. Everything in the room was cooled to -0.5° ± 0.01°C.

"A tiny ice droplet was seeded on the filter when the surface temperature of the filter became slightly less than 0°C. . . . Water was then drawn from below toward the bottom of the ice seed on the filter and the ice began growing upward from the filter . . . the ice also grew laterally until it encountered the edge of the waterproof film . . . the growth of ice continued until the water below the filter began to freeze or was depleted. . . The growing ice column could be slid slowly and lifted from the filter during the experiment. It was found to have a flat bottom surface, which indicated the existence of a thin flat water layer between the bottom of the ice and the filter. However, there was no visible "water" on the filter or on the ice. When the ice was again placed on the filter, it continued to grow." (ibid., 115-6)

The results of that experiment illustrate the physical process that underlies the formation of needle ice in soils and similar occurrences of ice on plant stems, pebbles, and pieces of dead wood. Below is an examination of the processes and products of ice segregation at the Earth's surface.

Needle Ice

In the late 1960's Sam Outcalt investigated needle ice in the Vancouver area of British Columbia, Canada. He continued his work on needle ice in central Virginia, U.S.A.

"In susceptible soils, usually loams, ice segregation will occur at low soil water tensions (water relatively available). As tension is increased (water content reduced) beyond a critical value, segregation will cease, and the freezing plane will resume its descent and freeze the soil water in situ." (Outcalt, 1971a, 395) Near Vancouver, Outcalt (1971b) set up equipment to monitor ice segregation processes in detail at a bare sandy-loam site.

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He diagramed (ibid., fig. 4) how the temperature in the upper 4-6 cm layer of the soil changed with the ice segregation event on March 4-5, 1967.

Temperature declined systematically from 8°C at 1800 hours to -1.7°C near midnight. Then once freezing started the temperature rose more than a degree in a few minutes as needle ice formed, releasing latent heat, but the temperature remained below freezing. From the time needles started to form the temperature at that soil level remained rather uniform over 7 hours until morning when warming stopped the ice segregation process and thus needle ice growth. That nearly constant temperature in that upper portion of soil while needles formed was maintained by a balance between the gain of latent heat of fusion and heat loss to the atmosphere.

Outcalt monitored many needle-ice events in many environments and developed "An Algorithm for Needle Ice Growth." (1971a) He set -2°C as the threshold temperature for the initiation of nucleation but found only sub-freezing temperatures are necessary for continuation of the freezing process. According to this model, once started needle ice will continue to form as-long-as the temperature remains below freezing, water is present in the soil and is being brought to the freezing front to match the freezing rate. When there is an interruption in any of these situations the ice segregation process is disturbed which will be reflected in the nature of the needle ice.

Figure 1 – Needle ice with ragged needles at the bottom indicating that water was not brought to the freezing front fast enough to maintain the growth of all of the needles. Knoxville, Tennessee, December 19, 2015.

Outcalt (1971a) observed "Several morphologic structures that appear when needles are examined shortly after sunrise can be analyzed using this algorithm." (396) He recognized six different needle ice types, some more distinct than others. They are:

The Soil Cap "Ice needles at all but the wettest sites usually have a cap of normally frozen (hard frozen) soil riding atop the needles." (Outcalt, 1971a, 397) This occurs when the free water in the soil lies a little below the surface so when that water freezes it will lift what is above, being soil and other solid materials. Figure 1.

Dirty Needles are "the product of spatially heterogeneous ice intrusion . . .", another type according to Outcalt (1971a, 397). Figure 2 illustrates this type and a clear needle example.

Figure 2 - The juxtaposition of two types of needle ice in a yard formed over two nights. The clear ice above (3 cm) with some dried vegetation on top was formed when the soil was very wet. The needles did not melt entirely and the next night new needles (2 cm) formed pushing up the ice from the previous event. By the second night the soil was not as wet producing dirty needles. (Midlothian, Virginia, December 27, 2020)

Polycyclic or *'diurnal' bands'* needle ice types are likely to form when there ". . . is a brief period either of lowered surface temperature or limited soil water supply, followed by a slight rise in surface temperature or a heterogeneous descent of the freezing place to wetter soil layers below." (Outcalt, 1971b, 398)

Figure 3 – Needle ice in Midlothian, Virginia. The 'horizontal lines' perpendicular to these many needles (5 cm) suggests the growth varied in intensity with time, being polycyclic. There is no indication soil water had become depleted.

His other three types of Needle Ice are variations of *clear needles* formed in rather unusually wet conditions. Outcalt (1971a, 397) distinguished: Clear needles unfrozen at base; Clear needles frozen at base, and No cap, clear needles. The Needles in Figure 4 are of this nature for they have very little soil material at the top, have entrained no soil with their growth and the base of the needles do not appear to be connected to the loose soil. Note the upper part of the Needles in Figure 2 is another example of clear needles formed in wet conditions.

Figure 4 – Needle ice at a construction site in Boiling Springs, South Carolina, December 20, 2015. Little soil was lifted by the needles indicating water was near the surface of the soil and freezing started near the top of the soil. The base of the needles is separated from the soil. This is an illustration of clear needles in abnormally wet conditions.

Soil Texture and Needle Ice

Not all soils produce needle ice. Meetenmeyer and Zippin (1981) set out to quantify the relationship of 'soil moisture and texture controls' in terms of the formation and growth of needle ice. They recognized the many works preceding them and summarized those findings. They note "The term segregation ice . . . has customarily been used to define ice which grows by migration of water to a freezing front. In many soils this migration leads to horizontal ice bands and lenses; however, this ice form is distinct from needle ice, which grows as fine vertical bristles at or near the soil surface." (113) Here these authors note the distinction between ice segregation in the subsurface and the surface expression of ice segregation, the focus of this paper.

These authors (ibid., 1981) sought to identify the critical factors producing and limiting needle ice in soils. They noted: "Essentially, soil texture must be neither too fine to retard the flow of water to the freezing place nor too coarse to impede capillarity." (114) To address the factor of pore size and texture they created five 'more uniform' soils with particular portions of soil sizes by sifting and blending clean soil material. The five soils were distinguished by the proportions of Fines (defined as a combination of Clays and Silts) as shown in this table.

In their Table II: Soil moisture and soil texture limits of needle ice growth

Soil No.	Soil Texture		
	(% Fines)	(% Clay)	(% Silt)
1	24.1	9.1	15.0
2	20.7	6.2	14.5
3	17.7	5.2	12.5
4	11.4	3.9	7.5
5	7.9	2.6	5.3

They then created a refrigerated environment in which they could evaluate the potential of these 'more uniform' soils to produce needle ice. They observed that "As textures become more coarse, the water holding capacity of the soil is diminished as well as its ability to translocate water by capillary flow." (ibid.,118) Soils 1 – 4 produced needle ice consistently, the quantity increasing with increasing amounts of soil moisture. Soil 5, the more-coarse of the samples, with least proportions of Fines, Clay and Silt only ". . . produced incipient needle ice forms and small ice pimples . . ." thus this soil ". . . must therefore, be near the grain size limit of needle ice growth." (118)

As delineated here Needle Ice may form in soils where the spacing is too small to permit ice crystals to penetrate into the soil and if soil water is available in sufficient quantity, it will be wicked up to the ice crystal and freeze, forming needle ice. By contrast, when and where the soil is more open/porous soil water will not be wicked up and with declining temperatures the ground will freeze irrespective of how much water is present.

Recognizing Multiple Forms of Ice Segregation at the Surface

The science literature includes reports of unusual ice observations at the Earth's surface but satisfactory explanations for the formation of such ice have been wanting. In 1833 Sir John Herschel (110-11) wrote about finding ice on the stems of plants and included three sketches of forms of that ice. In 1850 Dr. John LeConte (329-30) cited Herschel and others before presenting his observations concerning ". . . the remarkable accumulations of voluminous friable masses of semi-pellucid ice around the footstalks of the *Pluchea* . . ." (330) He also made observations about what we now call needle ice and argues "that both of the phaenomena must be referred to the *same cause*." (336) He expressed frustration not being able to find an explanation for such ice. In 1880 Argyll wrote ". . . a peculiar form of ice-crystal is often formed upon rotten branches lying on the ground . . . of long silky filaments, from two to three inches long, like finely spun glass." (Jan. 22, 1880, 274) He rejected possible explanations offered by many. (Feb. 19, 1880, 368)

Early in the 20th Century two studies advanced understanding of the processes. Both authors were familiar with the works of the earlier investigators and built on that literature. Coblentz (1914) observed needle ice and ice fringes on bushy Dittany *Cunila origanoides* plants in Washington, D.C. He carried out experiments on Dittany plants in place, on plants put in soil in containers and on cutoff stems in glass tubes. In test tubes he grew ice on cut off stems of Dittany demonstrating that roots and soil are not necessary for the growth of ice 'fringes.' Wegener (1918) studied Haareis/Hair Ice. "He observed hair ice in winter 16/17 in the Vosges Mountains, and in Feb 18 in Northern Germany at Rheinsberg in der Mark. He was able to grow hair ice on the branches that he found. Wegener assumed a relationship between the formation of hair ice and the mycelium visible on the branch surface." (Mätzler, et.al., 2013, 8) Both researchers reported on their ability to grow ice, as well as their observations of ice in natural settings.

Decades later photography and communication advances facilitated sharing information about findings of such relatively rare occurrences in nature. Means (1985 a and b) published photos and descriptions of Ice Flowers on *Verbesina virginica* he found in northern Florida. In 1993 a black/white photo of an ice flower graced the cover of the *Journal of Glaciology* (1993). That image, very similar to those of Means (1985), was taken at 16,000 feet in northern India. Those Himalayas were the location of "A Different Kind of Ice Plant" that Thomas (2008) posted on his web site showing ice flowers, similar to those observed on *Verbesina virginica.*

"Frost Flower" was the title Swihart (2000) used in her often-cited article where she describes the intricacies of such ice and notes it is most likely to form on one or more of the *Verbesina* plants. By this time short articles and observations with photos started to appear in newsletters, local publications, on web sites and in blogs. Means (2004) produced more articles about his findings of such ice. Carter posted web pages discussing findings of ice on *Verbesina virginica* in Tennessee (2004) and Kentucky (2005). McCormick (2006) wrote about finding Ice Flowers on *Cunila origanoides* (Dittany) over many years in North Carolina. Research led her to Means (2004) and she elaborated on the nature of plants that might have such ice. In 2006 Carter (2020b) created web pages summarizing many of the historic perspectives referenced by Lawler (1988) and provided links to many web pages that showed or referenced such ice.

Relative to his web pages many persons corresponded with Carter sharing findings or asking for explanations of what they had found. Jerry Green in Alabama sent photos showing ice that appeared to have grown up from small rocks. Jared Wilson in Missouri sent similar images of clear ice on top of more angular pebbles. The first photos of Hair Ice on dead wood came from Geoff in Wales and more photos arrived from England, Sweden, and the Pacific Northwest in North America and many of these photos were posted on a Carter web page with permissions or links were made to existing web sites. In 2008 a scientist in Germany sent Carter an email noting Dr. Gerhart Wagner in Switzerland was researching Hair Ice/Haareis. Wagner (2005) had published his first paper on Haareis in 2005.

"Unusual Ice Formations: Studying the Natural Growths of Ice from Soils, Stems, Branches, and Rocks" was published in *Weatherwise* in early 2009 with the stated purpose ". . . to bring these four types of ice formations together in one discussion, in large part to stimulate others to look for such ice and report findings." (Carter, 2009, 39) Six photos showed Ice Flowers on *Verbesina virginica,* White crownbeard, and one on *Cunila origanoides*, Dittany. Two photos showed Needle Ice. Three photos illustrated Pebble Ice, one from Wilson in Missouri and two from Green in Alabama.

Hair Ice was discussed and was illustrated with three photos from Bobbi Fabellano in Washington State. It was noted that Dr. Gerhart Wagner of Switzerland ". . . believes a fungus has to be present for the formation of such ice on rotted pieces of wood." (ibid., 38) With this article the four different expressions of ice segregation at the Earth's surface were integrated in print, with photos, although ice segregation was not identified as the common process. Within days of publication a couple sent photos of multi-day needle ice along the Appalachian Trail in Virginia, fulfilling the stated purpose of the article.

In 2013 the *American Scientist* featured an Ice Flower on their cover with the title 'The delicate physics of Ice Flowers'. The accompanying article entitled "Flowers and Ribbons of Ice" (Carter, 2013) included five full-page color photos of ice flowers on stems of *Verbesina virginica,* White crownbeard, a smaller image of ice on this plant, a photo of that multi-day needle ice formed over two nights along the Appalachian Trail, three photos of Pebble Ice grown in a refrigerator and a photo of Hair Ice observed in Washington State. Ice Segregation was identified as the common causal factor. The article summarized some of the more significant writings about such ice in the 19thand early 20th Centuries. This article was reprinted with slight variations in French, German and Spanish journals.

The Nature of Ice Flowers

Ice flowers occur on a variety of plants, native and cultured. In North America such growth is most commonly found on *Verbesina virginica*, white crownbeard, with its single stem extending up to 2 meters. Dr. Forrest M. Mims III (2008) has a time-lapse video on YouTube showing the growth and decay of a 'Frost Flower' on this plant. The video shows ice forming on the bare portion of the stem and as it grows out it pushes the bark away. In the warmth of the next morning the ice falls away in large pieces and the stem is still intact.

There are many names that have been given to the formations of ice on plant stems such as frost flower, ice flower, ice ribbon, rabbit ice, ice fringes . . . based on what people see in these unique and varied forms. 'Ice Flower' is preferrable to the fairly common 'Frost Flower' because there is another 'Frost Flower' that occurs on freshly formed sea ice and that name is recognized in the science literature. (Style and Worster, 2009) The late Dr. Robert Harms (2016) coined the name 'Crystallofolia' based on the Latin roots for 'frost' and 'leaf' and integrated that name into his extensive discussion of his observations and the history of the writings in the 19th and early 20th Centuries of such ice on plant stems.

Unable to find places to observe ice flowers, in 2007 Carter planted seeds of *Verbesinas* in his yard in central Illinois, 40.5°N. The first time he observed ice on the *Verbesina* he found ice on Salvia stems already in the yard. Other plants were added to the yard, including Dittany, *Cunila origanoides*. Harms (2016) shows photos of ice on *Pluchea*, one of the plants cited in the 1800's. That plant was not available to add to the garden, nor were some 'other probable ice-flower-plants' including *Helianthemum Canadense*.

***Verbesina virginica,* White crownbeard**

By the end of that first winter, ice was found on *Verbesina virginica* multiple times. (Carter, 2007) The next year much more was learned about such ice. (Carter, 2008) The ice extends relatively high up on the stem early in the season and is at ground level later in the season. At no time was ice found on stems of other plants if there was no ice on the *Verbesina virginica*. The three other varieties of *Verbesina*, all with yellow flowers and similar physical form, were in the yard or have been observed in nature but only *Verbesina virginica* has been confirmed to produce ice flowers. This white variety *Verbesina virginica* is commonly called as 'frostweed'.

The nature of the Ice Flowers varies in part because of the amount of time the ice segregation process continues, and soil water is available. Three photos below present variations on the same stem illustrating the effects of time-in-growth.

Figure 5 – Examples of Ice Flowers formed on a longer stem of *Verbesina virginica* early in the season. Left, a small start. Middle, ice grew out from the stem but not reaching the length and mass sufficient to bond together. Note in both photos the volume of ice is quite uniform along the length of the stem. The flower on the right shows the ice grew to such length and mass that much of the ice bonded together to take on unique forms, being far more massive at the base. Photos November 13, 14 and 24, 2012.

The ice can take many forms which can be appreciated when observed over many years.

Figure 6 –Left, a cutoff stem of *Verbesina virginica* viewed from above shows blades of ice growing out, merging, and looping around into intricate patterns. Right, the blades merged into three massive branches which grew out, up and back to the central stem. November 29, 2012, and December 26, 2020.

***Cunila origanoides,* Dittany,**

Dittany is the plant on which Coblentz (1914) was able to grow 'ice fringes' in a lab and on which Carter (2003) first found ice. It is a bushy plant growing to 40 cm in width, with small purple flowers in summer, showing as white nubs on seed pods in winter. The stems are 1-5 mm in diameter and the ice typically grows from many places along the stems.

Figure 7 – Images of Ice Flowers on stems of *Cunila origanoides,* Dittany. The small, many branched stems produce Ice Flowers in many places. December 4, 2015, and January 20, 2020.

Dittany will produce Ice throughout the winter. The plants retain their leaves well into winter and the stems may rupture but will still produce Ice Flowers. The unique character and image of the Dittany "*Cunila*" was captured in 1856 by Mr. J. Stauffer who wrote:

"…Our *Cunila* has attached to the stem a shell-work of ice, of a pearly whiteness, beautifully striated, sometimes, like a series of shells one in another—at others curved round on either side of them like an open, polished, bi-valve; then, in others, again, curled over in every variety of form, like the petals of a tulip. No other herb or grass had any such frost-work around them; while at least fifty specimens of the *Cunila* were so ornamented. The root manifested a vigorous young bud underground." (Bay, 1894, 325-6)

Figure 8 – Ice flowers on ruptured stems of Dittany, *Cunila origanoides,* while 'vigorous young buds' of new growth emerge. March 6, 2016

Ice Flowers on Other Plants in the Garden

There are many varieties of Salvia in a range of sizes and over the years Salvias have been part of the garden. On occasion they have produced attractive displays of ice. (Carter, 2008)

Figure 9 –On the left ice on a Vista Salvia stem and on Victoria Blue Salvia *Farinacea* to the right. Photos November 13 and 14, 2012. Any ice on Salvia is more common early in the season.

Penta *Pentas lanceolatais* one of the ice-producing plants that Jan in South Carolina wrote about. (Carter, 2014b) Early in the season abundant ice is often found on this plant (Fig. 10). If the plant still has leaves and bark, freezing turns these to gel. Penta ice is less abundant with time and ever lower down.

Figure 10 – Penta was found to produce abundant Ice on all branches extending up from the broad base. In this case the leaves and bark were removed before freezing occurred on December 3, 2015

Carlo noted he had very attractive ice on *Japonica keiskea*. Photos of ice on this plant in Japan have been posted over many years. Live plants were purchased online. The Japonica consists of multiple, tall stems growing up from a large base. The most massive ice forms at the beginning of the season.

Figure 11 – Abundant Ice extends up the many stems of *Japonica keiskea*. The more massive growths of ice are about 25 cm tall. November 13, 2019.

A variety of flowers have been planted over the years and left in the garden to see if and when the plants might produce anything approaching Ice Flowers. From northern Florida, Chuck sent photos of ice on Lantana and Connie photos of ice on Mexican Heather. These plants were added to the yard and at times both have produced segregated ice. On occasion, rather abundant ice has been found at the base of tall stems of Bee Balm and Turtlehead and on the lower portions of stems of bushy plants that branch out in many directions, such as Marigold and Mums. How and why does Ice Segregation regularly produce abundant ice formations on some plants, occasionally small growths of ice on other plants and seems to have no impact on most plants? (Carter, 2019)

A list of plants on which persons in Europe and North America reported to have found ice flowers was posted, with attribution to the person submitting the information. (Carter, 2014a). That list is incomplete and contains errors, but it shows that products of ice segregation on plants is not that exotic.

Pebble Ice – Clear Ice Growing on Pebbles

Growths of clear ice formed by water moving up through the pebble and taking on the cross-section shape of the underlying pebble, are shown in Figure 12.

Figure 12 – Examples of Pebble Ice, the form of Ice Segregation on individual pebbles. Photos from Jared Wilson, Missouri. (March 26, 2008, left and February 17, 2009, right)

Jerry Green (2020) and Jared Wilson provided photos that were used in the 2009 *Weatherwise* article. In 2021 Ian Cross in the UK sent a photo similar to these noting "I often see them forming on stony, heathland tracks . . . seem to grow from a pebble or polished stone. . . They are often produced in hundreds or even thousands in one particular spot." (Cross, 2021, 2) He labeled the object in his photo "Ice Horn".

Green and Wilson sent pebbles to Carter who placed them in areas known to produce needle ice. Clear ice formed on top of these pebbles when needle ice formed, and sometimes the ice on the pebbles did not melt entirely during the next day although the needle ice did. If needle ice formed the next night new ice formed on the pebbles pushing up any ice from the night before. (Carter, 2020c) This presence of two days of ice on pebbles was similar to the two-day needle ice shown in Fig. 2 and found along the Appalachian Trail (referenced earlier).

To replicate the ice-segregation process a growth environment was created in an upright refrigerator in the Geography-Geology Department of Illinois State University. Over many years this environment accomplished that purpose and more. At first soil was used as the medium to hold pebbles but the soil produced needles of ice lifting the pebbles, rather than serving as a medium to carry water to the pebbles. Sand was used subsequently as the medium to hold pebbles. Tap water proved to be as effective as distilled water. (Carter, 2020c)

This setup in the freezer produced pebble ice many times giving insights into the ice segregation process. The few examples here illustrate some successes.

Figure 13 – On the left, two wings of ice grew out and curved up. One wing of ice shows distinctly a regular sequence of alternating growth ridges. On the pebble on the right, striations parallel to the direction of the growth of the ice are obvious. Photos March 10, 2010, and June 23, 2010

In the examples in Figure 13, ice curves up from the base showing that more water was available at the base of the pebble than higher up. Using a recording thermometer, it was found those alternating ridges in the ice were produced by the freezer cycling on and off revealing insights into the sensitivity of the ice segregation process.

Sometimes the ice formed up on the pebble a cm or more above the sand. Other times ice formed on the pebble and in the top few mm of the sand bonding the pebble to the sand. Sometimes the sand froze. (Carter, 2020c) To select pebbles that might conduct water to the surface tests were developed such as weighing a dry pebble, placing it on a moist sponge for a fixed period and then reweighing it. Pebbles that took up no water were eliminated. Similarly, the test of touching a pebble to the tongue to see if it wicks water was used. These were not perfect tests and not all pebbles which scored high on such tests produced Pebble Ice, but such tests eliminated many pebbles that were not likely to produce ice. Some pebbles produced ice frequently, but no pebble produced ice every try.

And most of the time if there was any ice produced it was neither abundant nor attractive. Some of the more productive pebbles were given names or codes to build a database on the growth of ice in this environment.

But rocks are not eternal and occasionally pebbles were degraded. This photo sequence of 'Tan Dome' illustrates how the ice segregation process contributes to soil formation and surface erosion.

Figure 14 – Three views of a dome-shaped pebble 3-cm long that had been a regular producer of segregated ice. The center view shows that a large column of ice grew from the top of the pebble and then the pebble split horizontally and subsequently ice grew from the base of the split. The view on the right shows the split pebble after most of the ice on top melted. Photos June 12, 2012

This photo sequence illustrates the process that goes on in any medium subject to ice segregation. The formation and growth of ice will exert forces that sometimes break down soil, plant stems and pieces of wood, as well as rocks. Over the years, pieces of weathered brick and pottery produced decent growths of ice in this refrigerator setup. Nelson (2010) shows examples of "Ice on Rocks" near needle ice. In his 2013 post, Nelson shows photos of ribbons of ice growing on small rocks in the pavement of a parking lot. Mätzler, et.al., (2013, 7) show small ribbons of ice on a tile, observed in Germany by Erich Herzig, 2012.

In 1914 Coblentz grew 'ice fringes' on cutoff stems of Dittany in a lab. Thus, it was appropriate to see if pieces of plant stems would produce Ice Flowers in this refrigerator setup. They did.

Figure 15 – Short pieces of stems of Penta and *Verbesina virginica* were placed in wet sand and produced good ice flowers in the freezer setup. November 4, 2014, and November 14, 2014, on a stem of *Verbesina virginica.*

The freezer setup succeeded in producing ice on pebbles year-round. It also produced Needle Ice which was not intended but that gave insights. Later it was used to grow ice on cutoff plant stems and ultimately it was used to grow Hair Ice on pieces of wood with the requisite fungus. It was a relatively simple setup but sufficient to show that ice segregation is a physical process given the right combination of factors within small windows of possibilities.

Hair Ice – Forming on Dead Wood

Hair Ice was one of those mysteries debated by Europeans in the 19th Century and addressed by Wegener in 1918. Carter was introduced to Hair Ice in early 2006 when persons in Europe sent him photos and links to images of ice on pieces of dead wood relative his web pages showing Ice Flowers. In 2008 Carter was linked up with Dr. Wagner in Switzerland who was researching Hair Ice. Hair Ice was included as one of the four forms of surface ice in the *Weatherwise* article. (Carter, 2009b) The next year Carter put together a web page on Hair Ice showing images from others and providing links to many Hair Ice web sites. That page has been updated over the years. (Carter, 2020a) In 2020, Nelson who was cited for his writings on Pebble Ice in 2010 and 2013 devoted a page to Hair Ice. (Nelson, 2010, 2013, 2020)

Hair Ice is unique from the other products of Ice Segregation at the Earth's surface because the ice as we recognize it grows as individual hairs which remain separate and distinct.

Figure 16 – Hair Ice on a piece of wood standing vertical near Halifax, Nova Scotia, Canada. The Hair Ice forms in the dead wood and as in this example pushes bark away. Note the few crystals of snow on the Hair Ice. Source: Sybil Nunn. December 24, 2018

Dr. Wagner and his colleagues in Switzerland have continued to investigate Hair Ice. In 2013 Mätzler (et.al.) brought together the contributions of persons who had been exploring Hair Ice. Gisela Preuss, a biologist in Germany, examined samples of wood from a variety of species that produced Hair Ice. She found the presence of one fungus species (*Exidiopsis effusa*) in every hair-ice producing piece of wood. First there were only hyphae visible within the wood cells by microscope but, in the course of the winter the fruiting body appeared on the Hair Ice area covering it partially. (ibid., 12-13) Dr. Mätzler measured the detailed temperature variations at the surface of the wood during freezing tests. (ibid., 18-25)

On pieces of wood that formed hair ice the temperature declined until freezing started, then increased quickly as the latent heat of fusion was added and then leveled off and remained at about -0.2° C while Hair Ice was produced. (ibid., Fig. 12) This temperature pattern with cooling until ice segregation sets in is the same observed by Outcalt (1971b)

In 2015 Hofmann, Preuss and Mätzler published "Evidence for Biological Shaping of Hair Ice" in *Biogeosciences*. Dr. Wagner, then in his mid-90's, chose to not participate in this paper. This publication integrates of much of the work noted above.

Of particular note from this 2015 *Biogeosciences* paper are the following:

"Hair ice grows on porous substrates containing liquid water. We call this ice type a "basicryogen", in order to distinguish it from ice that grows from atmospheric water. Different basicryogens grow on different substrates and with different ingredients. The co-existence of liquid water, ice, and the porous substrate at the ice front are common to all basicryogens. This general phenomenon is called ice segregation." 4263

"The fungus activity plays a minor role with regard to the rate and amount of ice formation. Hair-ice branches with active and with killed fungus undergo similar temperature curves, indicating that the freezing rates are very similar and that fungal metabolism is too weak to cause a measurable temperature enhancement. The difference must be in shaping the ice. Whereas the untreated branches produce hair ice, the heat-treated ones produce crusty ice sticking to the wood surface. Although the fungus effect is still a mystery, it must be directly related to the hair-ice shape because the suppression of hair-ice growth acts immediately after the fungus activity is stopped." 4271

"The similarity of the temperature and thus of the rate of ice growth means that ice segregation is the common mechanism for ice production on the wood surface. The role of the fungus is in shaping the ice as hairs and to prevent it from recrystallisation. This is the main result from the physics of hair ice." 4269

In 2020 Preuss updated her work on Haareis and included perspectives from other observers of Haareis. She also provided some background on the foundation work of Dr. Gerhart Wagner and her own work on the abundant Hair Ice resources she has in Germany.

Reflections on Ice Segregation at the Earth's Surface

The Internet has greatly increased our exposure to findings of such ice. Needle Ice in soil and Pebble Ice are essentially global within the constraints of temperatures cycling around freezing and adequate liquid moisture. Photos and reports about attractive Ice Flowers are common in the southeastern U.S. but we now know of such ice in other parts in North America, Europe, Japan and northern India. Photos and reports of Hair Ice on pieces of dead wood reveal it is relatively common in western Europe and North America poleward of about 45°N latitude, based on the presence of one or more fungi.

On his web pages Carter noted that he had never seen Hair Ice because he lived too far south to find wood with the requisite fungus. In 2017 a person in Washington State expressing appreciation for the explanation of the Hair Ice he had been observing for thirty years sent Carter pieces of wood that had produced Hair Ice. In central Virginia (37°N) Carter had Salvia and Penta plants growing in an area known to produce needle ice. He placed pieces of that wood and pebbles known to produce Pebble Ice. More than once this 'Ice Segregation Garden' bloomed on frosty mornings demonstrating the commonality of the process. (Carter, 2018)

Figure 17 – Ice Segregation in nature produced the Four Components of an Ice Flower Garden: Ice Flower on Penta, Needle Ice in soil, Hair Ice on a piece of wood with a fungus, and Pebble Ice on a small rock, all within a square meter in central Virginia, 37°N. January 31, 2018

Conclusions

Many interesting and sometimes attractive growths of ice on solid objects at the Earth's surface on frosty mornings are produced by 'ice segregation'. The process is relatively simple but not well recognized as a surface phenomenon. The environments in which this process occurs requires a supply of water, a solid medium able to conduct water but with pore spacings too small to permit ice crystals to pass through, cooling to temperatures slightly below freezing producing super-cooled water and the presence of ice crystals to initiate the ice segregation process. Ice segregation has the potential to occur worldwide where temperatures fluctuate around freezing, frost is present, and there is an adequate supply of water during freezing periods.

The physical process of growing segregated-ice was demonstrated and quantified in a controlled laboratory environment by Ozawa and Kinosita, 1989. This same process occurs in nature in the surface boundary layer in many different forms. The Ice Segregation process forming needle ice and pebble ice is physical. Ice Flowers have been observed to form on cutoff plant stems showing that part of the process is physical but annually plants must build the stems and root systems that permit the formation of Ice Flowers. Hair Ice forms on certain types of dead wood, but it requires the presence of specific fungi to produce and shape the Hairs.

In the past two decades we have assembled many observations of surface expressions of Ice Segregation because in many cases these 'icy objects' are physically attractive, and persons have captured images. With the Internet many persons have shared their photos and observations. Such activities by so many are important when these growths of ice are normally quite small, occur once or perhaps a few times a year, last only hours, can be found in only a few places, and in weather conditions that often are not pleasant. Appreciation is expressed to those persons who have captured images and shared their observations in print, by posting their own pages and photos or sharing them with those who maintain such pages.

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