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HEADQUARTERS
QUARTERMASTER RESEARCH & ENGINEERING COMMAND
U S ARMY

TECHNICAL REPORT
EP-105

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GLAZE
ITS METEOROLOGY AND CLIMATOLOGY, GEOGRAPHICAL DISTRIBUTION, AND ECONOMIC EFFECTS

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QUARTERMASTER RESEARCH & ENGINEERING CENTER
ENVIRONMENTAL PROTECTION RESEARCH DIVISION

MARCH 1959

NATICK, MASSACHUSETTS

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HEADQUARTERS
QUARTERMASTER RESEARCH & ENGINEERING COMMAND, U S ARMY
OFFICE OF THE COMMANDING GENERAL
NATICK, MASSACHUSETTS

Major General Andrew T. McNamara
The Quartermaster General
Washington 25, D. C.

Dear General McNamara:

This report, "Glaze: Its Meteorology and Climatology, Geographical Distribution, and Economic Effects," presents a world-wide summary of the frequency and intensity of occurrence of ice caused by freezing rain and drizzle. Much of the information presented, for example, the maps showing conditions in the United States and the Soviet Union, is based on heretofore unpublished data. The study makes a contribution to the understanding of an element of the environment which can in certain areas pose a serious threat to Army equipment and military operations. The report will aid Army planners and development engineers to take steps to counteract the harmful effects of the heavy loads of ice and the extremely slippery surface conditions associated with severe glaze storms.

Sincerely yours,

C G Calloway
C. G. CALLOWAY
Major General, USA
Commanding

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EP-105

HEADQUARTERS
QUARTERMASTER RESEARCH & ENGINEERING COMMAND, US ARMY
Quartermaster Research & Engineering Center
Natick, Massachusetts

ENVIRONMENTAL PROTECTION RESEARCH DIVISION

Technical Report
EP-105

GLAZE

ITS METEOROLOGY AND CLIMATOLOGY, GEOGRAPHICAL DISTRIBUTION, AND ECONOMIC EFFECTS

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Environmental Analysis Branch

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FOREWORD

One of the common hazards of winter in many parts of the United States, Europe, and Asia is the thick layer of ice deposited by glaze storms. The weight of this ice is often sufficient to greatly damage telephone and electric power lines and poles, thus interrupting service, sometimes for several days. The slipperiness of the ice frequently slows down or even completely paralyzes highway and rail transportation and may make the movement of vehicles and men on foot across open terrain extremely difficult. Extensive breaking of limbs and trees in forests not only affects their timber potential and facilitates the spread of damaging decay and disease organisms, but also makes movement through wooded areas all but impossible, particularly while the ice is still present.

Despite these and other serious consequences of glaze, no overall major climatological study of the phenomenon has been made in the United States. The present report is an attempt to fill this void. For the first time data have been gathered from all available sources and used as the basis for a study that attempts to present a comprehensive picture of conditions in the entire country. In addition, considerable material is given on glaze in Europe and other parts of the world where it occurs.

The length of this report is due partly to the attempt to cover as many aspects of the problem as possible, and partly to the nature of the information available. In almost all countries, the thickness and duration of glaze is not a standard item of meteorological observation. Consequently, there is no mass of coherent data in existence on which a succinct tabular and graphical description of the climatology of the phenomenon can be based. Most of the material available is verbal and qualitative in nature, hence, its treatment in the report must be of the same nature.

The research on which the report was based and the preparation of the first draft of the manuscript were done for the Quartermaster Research and Engineering Command by the American Geographical Society of New York City under Contract DA44-109-qm-1496.

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CONTENTS

Part I. Meteorology and Climatology

Part II. Geographical Distribution

CONTENTS (Cont'd)

CONTENTS (Cont'd)

Part III. Economic Consequences

ABSTRACT

Most glaze is the result of supercooled rain or drizzle falling on surfaces with temperatures between 25° and 32°F. The precipitation is supercooled by passing through subfreezing air just before striking the ground. Thickness of glaze is determined by factors that include drop size, temperature, and rate of fall of precipitation; temperature, humidity, and wind velocity of ambient air; and temperature and conductivity of the solid surface.

Information is given on air mass and frontal conditions associated with glaze formation in different parts of the United States. Maps illustrate surface and upper air synoptic patterns of typical glaze storms. The widely-held belief that most glaze occurs in a warm frontal situation apparently is correct, but in some areas cold fronts are primarily responsible. The distribution of precipitation types in storms producing glaze, the size of areas affected by glaze storms, the influence of microclimate in determining the thickness of glaze in the storm areas, and wind conditions during and after glaze deposition are discussed.

Considerable new information is presented on the frequency, intensity, duration, and geographical distribution of glaze. Major emphasis is on the United States, but other parts of the world, particularly Europe, are included. New maps are based on data from electric power and telephone companies and the U.S. Weather Bureau. Maps for the Soviet Union are also presented.

The "glaze belt" of the United States includes almost all of the nation east of the Rocky Mountains, with the exception of the northern and southern sections of the High Plains, the Gulf Coast, the Atlantic Coast south of Virginia, and northern Maine. Many areas within the glaze belt have received as many as 2 storms in 3 years in which ice reached .25 inch or more in thickness, and 1 storm in 3 years in which thickness was .50 inch or more. Thicknesses greater than 1 inch have been experienced in almost all parts of the belt, and also in Louisiana. Thicknesses close to 2 inches have been experienced in New England, northern Texas, the Dakotas, and Michigan.

Highway traffic can be considerably reduced and even halted for short periods by a severe glaze storm. Bituminous or macadam highway surfaces are slightly superior to concrete in inhibiting glaze formations and in contributing to its rapid melting. Tests show that road ice is most slippery when air temperatures are near 32°F. Material from highway departments of 34 states describes icing conditions encountered and methods used to combat the ice.

Damage to electric power and telephone lines most commonly consists of stretched or broken transmission wires; this in turn may contribute to

collapse of supporting poles. Ice weight alone may inflict such damage, but a combination of ice weight and wind pressure is more often responsible.

Glaze is one of the principal agents of damage to forest, orchard, and shade trees in the eastern United States. Broken branches and downed trees may make movement through a forest all but impossible after a heavy storm.

Part I

Meteorology and Climatology

1. Definition and Physical Properties

a. Definition

As defined officially by the U.S. Weather Bureau (Haynes, 1947), glaze consists of "....homogeneous, transparent ice layers which are built upon horizontal as well as on vertical surfaces either from supercooled rain or drizzle, or from rain or drizzle, when the surfaces are at a temperature of 32°F or lower." This definition was adopted in 1916 as a result of the work of a committee appointed by the Chief of the Weather Bureau for the purpose of ending the confusion that had long existed over the terminology for the phenomenon (Abbe, 1916).* Before 1916, such terms as "sleet", "ice storm", "glazed frost", "silver thaw", "glare ice", and "glaze" had been used interchangeably by many people; the greatest confusion was the widespread use of the word "sleet" for both raindrops frozen solid while still falling through the air and ice formed on objects by rain freezing after it had fallen. This practice was particularly prevalent among the public and among representatives of the electric power and telephone industries (as it still is today). But, despite the fact that the official definition for sleet had been established in 1897,** even professional meteorologists perpetuated this confusion. As late as 1913, a reference in the *Monthly Weather Review* (Bennett, 1913) stated: "The sleet storm in northern New York [was due to] rain which froze upon contact with solid objects."

The official definition for glaze (above) has been adopted in essentially the same form over most of the world, and is represented by the international symbol ∾. In the United Kingdom and the other nations of the British Commonwealth, with the exception of Canada, it is given the name "glazed frost". Other foreign equivalents are the German *glatteis*, the French *verglas*, the Russian *gololed*, and the Spanish *lluvia helada*. The French carry their terminology one step further, distinguishing between *verglas de pluie* (rain-formed glaze) and *verglas de neige* (snow-formed glaze). The latter, however, is not a true form of precipitation, since it develops when freezing occurs after a snow cover has partially melted. The British likewise include more than one method of formation in their definition of glazed frost, stating in the *Meteorological Glossary* (Great Britain, 1948) that it ".... also occurs when a warm, damp wind supervenes upon severe cold, the moisture condensing on still freezing surfaces and thus producing a coating of ice."

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*See this same reference for an excellent discussion of early usage.

**The modern definition of sleet in this country, again quoting from Haynes (1947), is as follows: "Transparent or translucent globular or irregular hard pellets of ice, about 0.04 - 0.16 inch in diameter (approximately the size of raindrops); they rebound when falling on hard ground." This differs from usage in Europe where the accepted definition of sleet is : "Precipitation of snow and rain together or of melting snow and rain."

All of the above items refer only to deposits of ice in surfaces and should be carefully distinguished from the precipitation responsible for the formation of the ice. This precipitation is recognized in the International Meteorological Code by the present weather symbols:
56 ∾ (light freezing drizzle), 57 ∾ (moderate or heavy freezing drizzle),
66 ∾ (light freezing rain), 67 ∾ (moderate or heavy freezing rain), and
24 ∾ (freezing rain or drizzle in the past hour but not at the time of observation).

b. Physical properties

The definitions of glaze cited above are primarily genetic in nature and say little about the morphology of the ice. Physical description in the U.S. Weather Bureau definition, for example, is limited to the use of the adjectives "homogeneous" and "transparent", and in the British definition to the use of the adjective "smooth".

Glaze is somewhat related to two other forms of ice, rime and hoarfrost, but differs from them chiefly by its greater density. The high density of glaze results from the fact that the drops of precipitation responsible for its formation are large enough and freeze slowly enough to enable them to flow together before freezing, thus occluding almost all air from the formation. Also, glaze is more likely to be transparent and highly amorphous in structure (but not lacking entirely in crystal development as many seem to believe, see Oguchi, 1951, Part III),* whereas rime and hoarfrost are generally opaque or translucent and have highly developed crystal structure. There is, however, a form of rime recognized by meteorologists which approaches glaze in amorphous structure and density. This is the so-called "hard rime" indicated by the international symbol ∨. It is actually a transition between true rime and true glaze.

Of the three forms of ice, hoarfrost usually has the lowest specific gravity. It is a product of sublimation and generally is composed of delicate, feathery masses of crystals laced together into such a loose network of ice that most of the volume occupied by the formation consists of air spaces. Rime is primarily the product of the freezing of cloud or fog droplets which are very small in size and, consequently, are more capable of freezing before they have had an opportunity to coalesce; rime contains a large percentage of air held in interstices between the masses of ice.

No clear-cut limits can be established for the specific gravities of the various ice formations, because in nature they often grade from one into the other. Nevertheless, most cases of what, on the basis of origin, would be considered glaze, rime or hoarfrost, fall into certain

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*Oguchi (1951, Part III) found that the greater part of air contained in rime occurs between the ice crystals, while in glaze it occurs *within* the crystals.

density classes. Therefore, it would seem valid to establish broad categories of specific gravity for the various forms. Johnson (1954) in his book *Physical Meteorology* sets up three density classes for ice that forms on aircraft, assigning glaze a specific gravity of 0.9 or greater, rime and glaze mixed 0.6 to 0.9, and rime 0.6. or less.

Zikeev (1940, 1940a, 1941) analyzed weight measurements of glaze and rime in the Soviet Union where glaze is defined as ice formed from freezing rain or drizzle, and rime as ice formed from freezing fog. He found the specific gravity of glaze ranged from a low of 0.17 to a high of 0.89 and that of rime from 0.01 to 0.19. In one set of measurements he determined that most cases of glaze had specific gravities in the range of 0.70 to 0.89, while in another set the range extended from 0.56 to 0.84. He believes that where the specific gravity of glaze was reported below 0.30 the formation was a mixture of rime and glaze and was incorrectly reported by the observer. These figures agree with those calculated by Turoverov (1939) on the basis of 9 years of observations at Novo Pyatigorsk and show the specific gravity of glaze to vary between 0.30 and 0.90 and the specific gravity of rime between 0.01 and 0.12. Another Russian, Muretov (1930), determined that glaze varied from 0.60 to 0.90 and rime from 0.09 to 0.50. The specific gravity of ordinary solid ice as given by the *Smithsonian Physical Tables* is 0.917. Comparing this figure with those preceding, it can be seen that in many cases glaze approaches solid ice in density.

Another important physical characteristic of glaze is its ability to cling tenaciously to surfaces on which it forms. It does so more readily than rime or hoarfrost because there are more particles in contact with the surface and because it adheres closely to the form of the object (Byers, 1944). The fact that glaze is hard and lacking in friability adds to this tenacity.

The British definition refers to glaze as being smooth-surfaced. Generally, such is the case, but the admixture of snow or sleet may cause the surface to be rough.

2. Process of Glaze Formation

a. Temperature conditions

(1) Combinations of air and precipitation temperatures

Before proceeding with a discussion of the meteorological conditions responsible for the formation of glaze, it should be pointed out that data gathered during glaze storms may not be entirely valid because of the effect glaze deposits can have on the performance of meteorological instruments. Anemometers and wind vanes are especially vulnerable during glaze storms. The anemometer may be slowed or even stopped and wind vanes may be frozen in a fixed position. In addition, ice may pile up on the windward side of instrument shelters, closing or narrowing shutter openings and affecting the ventilation of instruments inside the shelter. During a severe storm with high winds, it is even possible that ice would infiltrate the shelter and settle on the instruments (Andreev, 1946). Furthermore, a thick coating of ice may make it impossible to open the shelter. This was the case for a 3-day period during the storm of January, 1935, at Clearbrook, Wash. (Fisher, 1935).

In "The Ice Storms of New England", C. F. Brooks (1914) states there are "....a number of combinations of different conditions of air temperature, rain temperature, and temperature of the object relative to freezing which may produce [glaze]":

I. Temperature of the <u>air below</u> 32°F.

II. Temperature of the <u>air above</u> 32°F.*
  A. Temperature of <u>the rain</u> ** below 32°F.
    1. From passing through a stratum of cold air.
    2. From cooling by evaporation in non-saturated air.
  B. Temperature of the rain above 32°F but temperature of the object below 32°F.
    1. From residual cold.
    2. From cooling by evaporation in non-saturated air.

In the opinion of this writer, these considerations are just as valid in the light of to-day's knowledge as they were 44 years ago. However, one reservation must be made. It should be assumed that the temperature of the air in category I is representative of the air temperature in immediate contact with the surface on which the ice forms. Data taken from the original observational records of 95 Weather Bureau stations in the United States show that for 91 there were in a 10-year period many instances of liquid precipitation occurring at air temperatures below 32°F, but with no glaze reported. At almost all of the stations where this was reported there were repeated cases; an example is 37 at Dubuque, Iowa, and this was by no means exceptional. Most cases occurred when the temperature was within a degree or two of 32°F, and they lasted for only 2 or 3 hours. However, light rain which did not freeze fell for approximately 14 hours at temperatures between 25° and 29°F during the night of December 2-3, 1940, at Dodge City, Kansas. On December 20, 1939, at Huron, South Dakota, liquid precipitation fell for 4 hours at temperatures ranging between 17° and 19°F and no glaze formed. Very likely these cases can be explained by the fact that the air temperature, which was observed at a height of 4 feet 6 inches above the ground in an instrument

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*Most of the conditions listed under II are also considered to be capable of occurring under I.

**It is assumed that the word "rain" here can refer to fog, drizzle, rain itself, or a mixture of any or all of these with any solid form of precipitation.

shelter, was not representative of temperature conditions on surfaces where glaze would be expected to form.

In most cases of glaze formation, the temperature of the air, precipitation, and surface are all at or below 32°F. In fact, it probably can be said that a coat of glaze heavy enough and long-lasting enough to be any menace at all forms only under these conditions. Brooks (1914) states on the basis of 29 years of record, that no considerable ice storm ever occurred at Blue Hill, Mass. (near Boston), under other than these circumstances, and more recent evidence from all other sources, foreign and domestic, bears this out. Glaze can and does form when the air temperature (recorded at standard height in an instrument shelter) is above 32°F; this is indicated by the fact that at Burlington, Vt. the maximum temperature was 33°F or higher during 14 out of 61 instances of glaze formation between 1939 and 1948. On one occasion the temperature rose as high as 37°F, and in 3 cases the lowest temperature recorded was 33°F. No recent records are available as proof that glaze can occur when precipitation temperature is greater than 32°F, but some of the many cases of freezing rain with air temperatures greater than 32°F, noted in the 1939-48 data for the 95 Weather Bureau stations, could have also included rain that was not supercooled. Hellman (1915) cites observations in northern Germany which he claims leave no doubt that ordinary rain can also produce an ice coating on frozen soil. In any event, glaze formed under either of these circumstances probably would not amount to much in thickness and would not last long. The warm rain or air would soon thaw the ice and warm the surfaces so that no further accumulation of ice could occur unless the general weather situation changed. Also the release of the latent heat of fusion as the ice forms would impede the process. Hellman also maintains that glaze formed under these last two conditions would occur only on (frozen) ground and not on vegetation and transmission lines. He probably is right because the latter could not act as a reservoir for considerable amounts of residual cold and their surface temperatures would rise above freezing almost as rapidly as the change occurred in the ambient air.

(2) Surface air temperature

A massive amount of observational evidence supports the contention that most glaze forms when the temperature of the air is below 32°F. This same evidence also shows that, although glaze can occur at temperatures far below 32°F, the vast majority of cases are grouped within a rather narrow range between 32°F and 25°. Temperature conditions observed during freezing precipitation at 95 Weather Bureau stations between 1939 and 1948, show that the mean minimum air temperature during glaze formation at most stations was around 27° or 28°F. In Table I, the temperature data for a selected few of these stations have been summarized. Note that, with the exception of these stations in the northern part of the country, approximately three-fourths of the observations of minimum temperature were recorded at temperatures above 25°F.

TABLE I

AIR TEMPERATURES (°F.) ASSOCIATED WITH FREEZING PRECIPITATION, 1939-1948

(Data: U. S. Weather Bureau)

Station	No. of cases	Max. Air Temp.			At least 75% of cases ≤ than:	Min. Air Temp.			At least 75% of cases ≥ than:
		Mean	Median	Range		Mean	Median	Range	
Providence, R.I.	50	31.3	32.7	21 to 37	33	27.9	30.1	13 to 34	25
Washington, D.C.	35	31.2	32.3	23 to 34	32	28.9	29.8	23 to 33	28
Allentown, Pa.	64	30.4	31.6	20 to 34	32	28.1	29.8	17 to 34	26
Dayton, Ohio	79	30.4	31.6	20 to 34	32	28.6	29.8	19 to 34	27
Lexington, Ky.	40	30.9	32.3	16 to 35	32	28.2	28.8	16 to 32	27
Springfield, Ill.	59	30.6	31.3	17 to 34	32	28.2	29.9	17 to 33	26
Des Moines, Iowa	74	28.2	30.8	9 to 34	32	26.4	29.0	8 to 34	23
Sault Ste. Marie, Mich.	62	28.9	30.3	15 to 35	32	25.7	27.2	13 to 33	23
Bismarck, N. D.	70	24.8	26.6	6 to 36	31	22.7	23.7	4 to 36	17
Oklahoma City, Okla.	54	30.8	32.1	18 to 34	32	27.3	29.4	10 to 33	25
Cheyenne, Wyo.	37	26.2	28.3	16 to 33	31	24.7	25.6	-5 to 32	21

The absolute minimum at most stations was seldom lower than 15°F., although at Cheyenne, Wyoming, temperatures as low as -5°F. were recorded during the occurrence of freezing drizzle. For all stations, the number of times glaze occurred with temperatures greater than 32°F. was low, with the highest percentage of such cases among the 95 stations being 13 per cent at Allentown, Pennsylvania. Temperature measurements made while glaze was forming at Weather Bureau stations during the winters of 1953-54, and 1954-55, show essentially the same results.

N.T. Zikeev (1940a) states that glaze occurring in the Stalingrad Oblast' and in Kalmyk ASSR of the Soviet Union between 1925 and 1929 was observed with air temperatures mostly from 0°C. (32°F.) to -5°C. (23°F.) and sometimes at temperatures as low as -7°C. (19.4°F.). The heaviest amounts of glaze were formed with temperatures between 0°C. and -3°C. (26.6°F.). Observations reported by Zikeev for the same period in other parts of the Soviet Union yielded similar results. Rossi (1938), reporting on 79 cases of glaze at Ilmala, Finland, gives the mean temperature of the air during glaze formation as -2.3°C. (27.9°F.), the lowest temperature as -9.0°C. (15.8°F.), and the highest temperature as 5°C. (41°F). According to Bider (1954), the overwhelming majority of cases of glaze at Basel, Switzerland, occur when the air temperature is between -4°C. (24.8°F.) and 1°C. (33.8°F.), although glaze has occurred with a temperature of -10°C. (14.0°F.) as a result of drizzling fog. Bider also believes that in most cases where the temperature is reported above 0°C., it is because the temperature is measured at some distance above the ground (1.8 meters or 5.9 feet in Switzerland) and that the temperature at the ground is at or below 0°C. Observations reported by Zhuk (1902) at Kiev and Novozybkov, USSR, between 1885 and 1901, show freezing rain occurring at air temperatures as high as 10°C. (50°F.) and as low as -8°C. (17.6°F.).

Discussing glaze in Hungary, Bell (1947) gives 0°C. to -5°C. (23°F.) as the most favorable temperatures for glaze formation, but adds that it has been observed at a temperature as low as -20°C. (-4°F.). A study made by Gaponov (1939) on the basis of 44 years of observations at Odessa in the Russian Ukraine, distinguishes between the temperatures at which rime and glaze form. The conclusion is that glaze can occur with fog at temperatures from 0°C. to -2.2°C. (28°F.) and rime can occur below -1.2°C. (29.8°F.). In the range between -1.2°C., to -2.2°C glaze and rime formation are both possible. The most favorable temperatures for glaze formation from fog are those very near 0°C. Observations at Novo-Pyatigorsk, Soviet Union, during 1930 to 1938 as reported by Turoverov (1939) show that glaze occurred at air temperatures from 0.0° to -5°C. (23°F.), and that 80 per cent of the cases were grouped between 0°C. and -2°C. (28.4°F.). Rime was observed in a lower range, at temperatures of -5°C. (23°F.) to -17°C. (1.4°F.). A study of glaze formation in forested areas of the North Caucasus by Elagin (1952) indicates glaze occurred at air temperatures ranging from 0°C. to -3°C. (26.6°F.).

(3) Precipitation temperature

Direct measurements of precipitation temperature during glaze formation are nonexistent; thus, any statement to the effect that falling drops of rain or drizzle are supercooled must be based on indirect evidence. Nonetheless, the theory is universally accepted by meteorologists. Before considering the matter further (Section 3) it would be proper to say something about the supercooling of water in the atmosphere.

4. Some characteristics of supercooled water

Although 32°F is commonly spoken of as the freezing point of water, it is doubtful if either distilled water or water containing solid or soluble impurities in any amount ever feeezes directly at this temperature. Curiously, chemically pure ice when heated always melts at 32°F. Clearly, this temperature should be referred to as the *melting* point of ice and not the freezing point of water. That even physicists, to a limited extent, are bound in their thinking by the concept of 32°F as the freezing point of water, is evidenced by their use of terms such as "supercooled" or "undercooled" to refer to liquid water at temperatures below that figure.

(1) Research of N. E. Dorsey

The leading authority on the behavior of liquid water in the supercooled state, exclusive of water in the atmosphere, is probably N. E. Dorsey of the National Bureau of Standards. In the 1930's he started a series of investigations of the supercooling of small samples of liquid water. This work cleared up much of the unknown concerning the behavior of water at temperatures below 32°F. Dorsey's work was performed in the laboratory, but much of what he learned is applicable to the behavior of liquid water in the atmosphere.

Experiments previous to Dorsey's had dealt with large masses of water and indicated, with one or two exceptions which later proved to be affected by impurities in the samples, that water undercooled only 5 to 10 degrees below 32°F before freezing spontaneously. But Dorsey (1940) found that his small samples in some instances did not freeze until they were cooled to as low as -20°C (-4°F) and that often the temperature would drop to between -10°C (14°F) and -15°C (5°F) before spontaneous freezing would set in.

A number of things discovered by Dorsey are pertinent to an understanding of the occurrence of supercooled rain and its conversion into a sheet of glaze upon encountering solid surfaces. For instance, saturation and non-saturation of water specimens with air apparently has no effect on the temperature to which they can be supercooled without freezing spontaneously. Although supercooled by several degrees, his samples could be agitated and poured from one end to the other of vials in which they were sealed, without causing the water to freeze. In most cases splashing did initiate freezing at temperatures above that at which spontaneous freezing occurs, but it had to be violent. There were indications that sometimes one splashing would not cause a sample to freeze, but that several in quick succession would induce instantaneous freezing in the same sample. Results also seem to show that if the temperature of supercooled water is more than 1 or 2 degrees (C) above the spontaneous freezing point, it is not easy to initiate freezing by splashing. In one experiment Dorsey squirted water at -3°C (26.6°F) through a glass nozzle which was at -4°C (24.8°F) and onto a test tube which also was at -4°C. The water did not freeze in the nozzle but did freeze when it hit the test tube.

(2) Supercooled water in the atmosphere

In the atmosphere, liquid water has been observed at temperatures well below those achieved by Dorsey in the laboratory. Experimental work by meteorologists, mostly on drops of sizes common in clouds and light rain, shows that, when chemically pure water is involved, the spontaneous freezing point of drops below a certain diameter is related to the size of the drops. The smallest drops seem to freeze when the temperature reaches the vicinity of -40°C (-40°F), and the larger drops freeze at correspondingly higher temperatures. No absolute value can be set for the spontaneous freezing of drops of a certain size because different investigators obtain different results for drops of a given size. An increase in size above approximately 500 microns (small raindrops or large drizzle droplets, both of which are capable of falling out of clouds where the upward moving currents are not of excessive velocity), apparently has little influence on the temperature at which freezing will occur. The behavior of drops larger than 500 microns appears to be comparable to the behavior of Dorsey's samples (Johnson, 1954).

c. Formation of glaze from supercooled rain

(1) Theory of precipitation

To return to the hypothesis that most glaze results from supercooled rain or drizzle, it will be remembered that evidence has been presented to indicate that most glaze forms when the air temperature (as recorded at 4 to 5 feet from the earth's surface in an instrument shelter) is between 25° and 32°F. This does not necessarily mean that liquid precipitation falling into a ground air layer within this range of temperature will be supercooled, because there is always the possibility of a pronounced inversion with temperatures greater than 32°F above the surface layer through which the rain is falling. In fact, just such an inversion does exist during the formation of almost all glaze.

According to the prevailing theories of precipitation, any but the lightest rain or drizzle in the middle latitudes will form first in clouds, parts of which are below freezing, and in which ice crystals have formed (Johnson 1954, Houghton, 1951).* In Figure 1 this would be

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*Recently, thinking has been modified somewhat from this point of view. It is now generally believed that in certain conditions, particularly at low latitudes, moderate and even heavy rain may form directly from supercooled clouds without recourse to the development of the ice crystal phase.

in the portion of the dry bulb lapse rate curve about level B. Of course, clouds with temperatures below 0°C can exist between the surface of the ground and level A, but no appreciable amounts of precipitation could fall directly from these clouds, since this zone is in the relatively stable, underrunning cold cP (continental polar) air mass, where very little lifting or adiabatic cooling takes place. The incipient precipitation above level B develops as ice crystals which finally become large enough to fall out of the cloud. As they fall they grow by sublimation, condensation, and collision with other ice particles or liquid droplets. Upon entering the layer of air below level B where temperatures are higher than 0°C, the ice particle melts (if the layer is warm enough and thick enough) and continues falling as a liquid water drop with a temperature above 0°C. It will retain a temperature above 0°C at least until it gets to the point where the wet-bulb curve crosses the 0°C line (level A). It can be seen, therefore, that any supercooling of the drop must occur in the surface layer of cold air that lies below level A. What is necessary, then, is to show that this surface layer of sub-freezing air is of such thickness that the drop will spend sufficient time in passing through it to be cooled below 0°C.

(2) Temperature relationships of freely falling drops of water

Kinzer and Gunn (1951) have studied, both theoretically and experimentally, the temperature relationships of freely falling drops of water. They have substantiated the accepted belief that a freely falling drop evaporates and cools, so that it is invariably at a lower temperature than its environment. In fact, they showed that such a drop becomes an ideal ventilated wet-bulb thermometer within a very short period of time and, to within errors of measurement of ± 0.3C degrees, will assume the wet-bulb temperature of the air through which it is falling.* In one series of experiments they found that drops having a diameter of 0.27 centimeter and a temperature of 28.3°C (82.9°F) when supported by a stream of air also at 28.3°C, but with a relative humidity of 22 per cent, required approximately 4.35 seconds to cool through a range of 4.8C degrees (8.64F degrees) of temperature. If no evaporation were taking place and the drop, traveling at terminal velocity, were being cooled entirely by conduction, it would require approximately 11 seconds** to cool the same drop 4.8C degrees. In actual situations where glaze is forming, the elapsed time necessary for this order of temperature change would be nearer the instance in which there was no evaporation, because an examination of upper air soundings taken during the occurrence of freezing precipitation indicates the relative humidity in the surface layer of sub-freezing air is close to 100

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*Tverskaia (1951) confirms these results.

**This figure was not arrived at on the basis of experimental work but represents a theoretical value calculated by the writer using a formula developed by Kinzer and Gunn (1951) for the determination of the thermal relaxation time of a non-evaporating drop.

per cent (see Figures 1 through 6).

(3) Behavior of drop in glaze-forming situation

The drop size used by Kinzer and Gunn was unusually large (0.27 cm) and of the magnitude of drops in heavy thunderstorms. Most glaze is formed from rain of moderate or light intensity, which means that the drops will usually have a diameter of 0.1 centimeter or less and fall through the air at a rate of 4 meters per second or less, as contrasted with almost 7 meters per second for the drop used by Kinzer and Gunn (1951). This indicates that raindrops of the size normally associated with glaze formation stand a greater chance than Kinzer and Gunn's drop of becoming supercooled by passing through the cold layer, because a longer period is spent in the layer. The glaze-forming drop, having a considerably smaller mass, also requires a shorter time to cool by conduction to the equilibrium temperature it acquires in the cold layer. Upper air soundings during 20 occurrences of freezing precipitation show that in 14 instances the thickness of the cold layer is at least 914.4 meters (3000 feet) as measured from the surface of the ground to the level where the lapse rate crosses to the positive side of the 0°C isotherm (see Figure 1). According to information given by Byers (1944), the Kinzer-Gunn drop would require approximately 130 seconds to fall through a layer this thick. The highest temperature indicated in the inversion on any of the soundings was 12°C, which means that for these occurrences this is the greatest amount (12C degrees) a drop would have to be cooled during its passage through the cold layer in order to become supercooled. Even in this extreme case the drop would not have to be cooled this far to reach 0°C, because the warmest temperature is not at the exact bottom of the inversion, but instead a considerable distance above the bottom. For some distance before leaving the inversion and entering the layer with temperatures below 0°C, the drop would pass through air with temperatures lower than 12°C. Assuming even the grossest errors by the writer in making the above calculations, it is easy to see that, in at least the 20 cases for which soundings have been prepared (a selected few of which are shown in Figures 1 to 6), any liquid precipitation occurring under these conditions would be supercooled when it reached the ground.

There is a possibility the cold air will be so thick that sleet (as defined by the U. S. Weather Bureau) instead of glaze will form, because the drops, falling a greater distance through the cold air, will be sufficiently cooled to freeze spontaneously before they reach the earth. This has been the standard explanation for the formation of sleet for a considerable number of years.* In addition to the time spent by the drop in the cold layer, it is also believed the temperature and degree of turbulence of the cold air are important factors. Okada (1914) states that the presence of turbulent motion in the cold air mass increases the possibility of the supercooled drops freezing into sleet masses.** There may be turbulence in the lower

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*See Byers (1944)

**Whether Okada was the first to propose this idea, the writer is not certain.

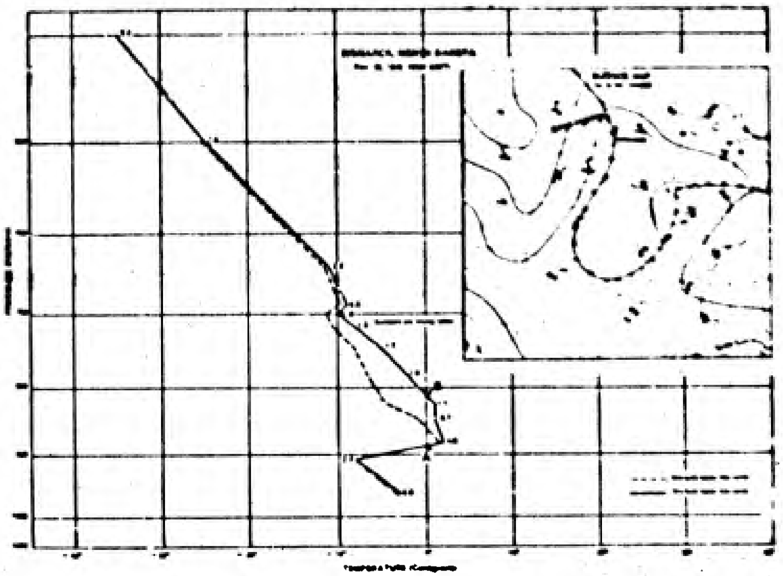

Figure 1. Cross-section of upper air conditions just before occurrence of freezing precipitation at Bismarck, N. D. Map shows later associated synoptic conditions (note 12½-hr. time difference between cross-section and map). The situation pictured here is typical of many that cause glaze at Bismarck. Freezing precipitation totaling .04 inch fell between 0500 and 1000 GMT, Nov. 30, 1946.

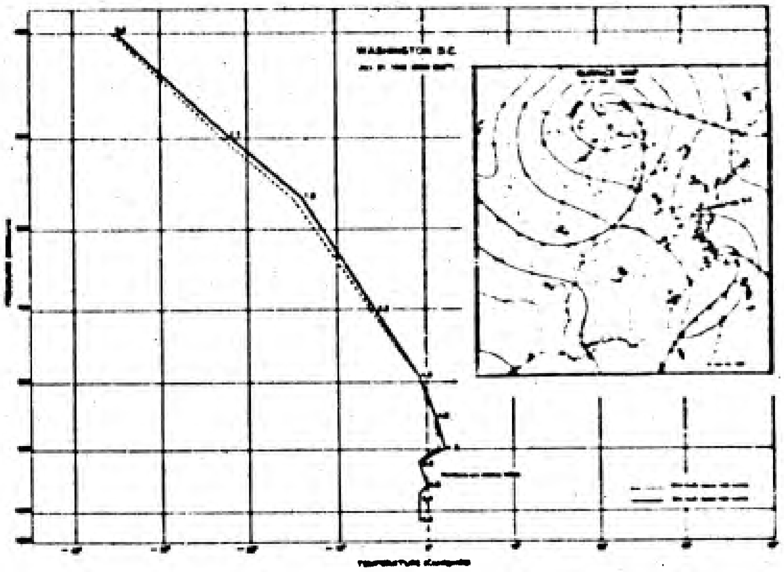

Figure 2. Cross-section of upper air conditions, Washington, D.C. Freezing precipitation totaling .34 inch fell between 0200 and 0700 GMT, Jan. 21, 1948

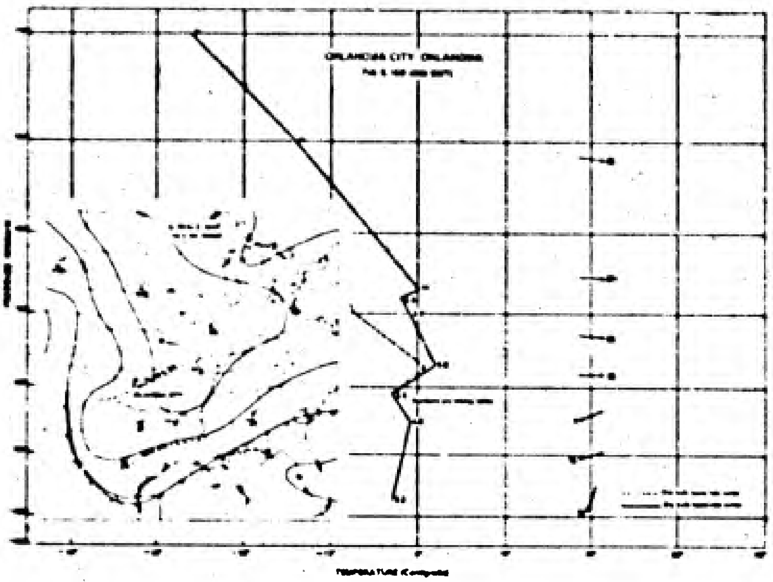

Figure 3. Cross-section of upper air conditions at Oklahoma City, Okla. Freezing precipitation totaling 0.49 inch fell between 1300 and 2300 GMT, February 7, 1948, as the cold front moved south over the Great Plains. The position of the front on two previous days is shown on the map.

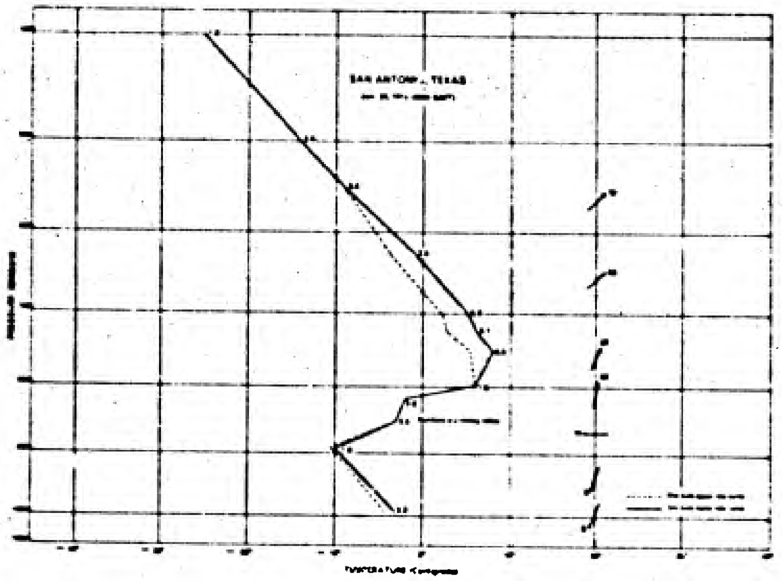

Figure 4. Cross-section of upper air conditions at San Antonio, Texas. This storm was associated with a cold front which stagnated over the Gulf of Mexico after moving south from Canada. Note the strong advection aloft of mT air, as indicated by the arrows plotted along the 20°C. line. Freezing precipitation totaling 0.07 inch fell between 1200 GMT, January 27, and 0700 GMT, January 29, 1948.

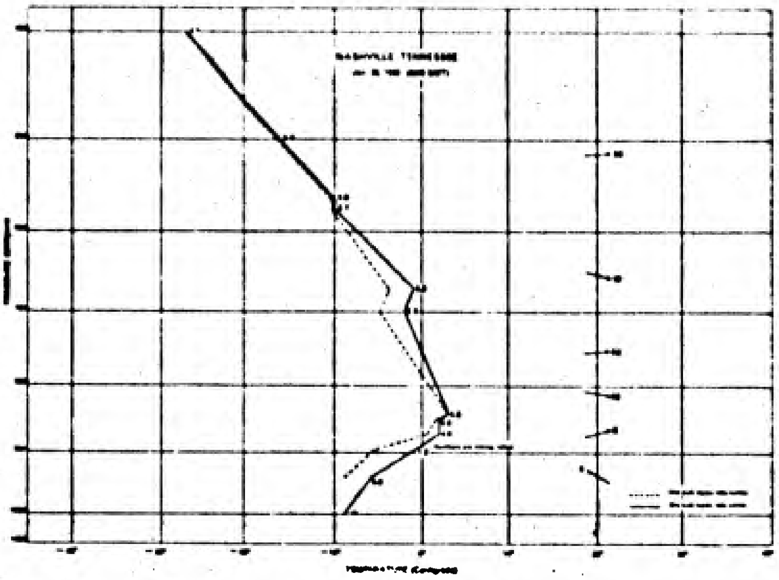

Figure 5. Cross-section of upper air conditions, Nashville, Tenn. Freezing precipitation totaling 0.06 inch fell between 0500 GMT, January 29, and 1400 GMT, January 31, 1948. It was associated with a wave which formed in the eastern Gulf of Mexico on the front described in Figure 4. The wave moved northeast across Florida and up the Atlantic coast.

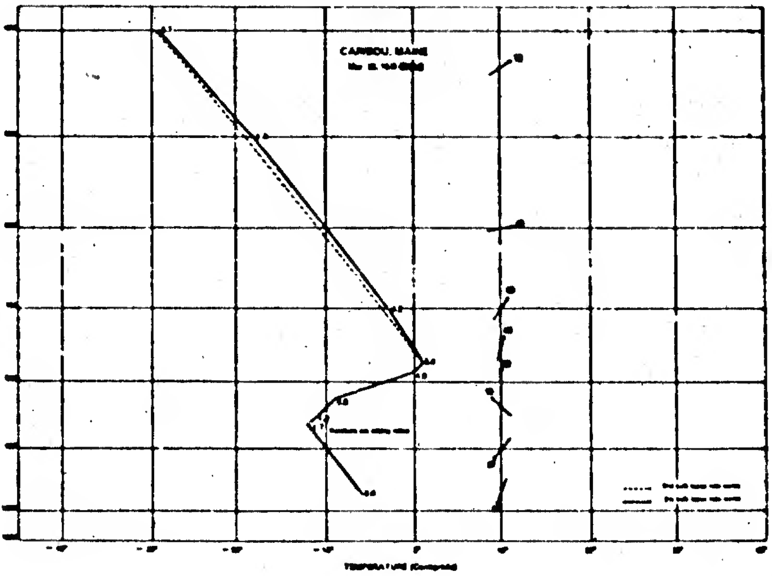

Figure 6. Cross-section of upper air conditions at Caribou, Me., Mar. 28, 1948. This storm was associated with a polar front wave which formed on the northern Great Plains and then moved eastward, with the tip of the wave passing approximately over Caribou.

portions of the cold air, particularly if it is cK air traveling over a relatively warm ground surface and being heated from below, or if there is a strong surface wind blowing. In the light of Dorsey's discovery that small samples of supercooled water can be poured from one end to the other of a vial or squirted through a nozzle without freezing, there seems to be some question whether turbulence of the degree encountered in situations of this nature could initiate freezing. However, if the drops are large, they may be split apart by turbulent action and possibly this would be a mechanical shock violent enough to trigger freezing. It should also be pointed out that in addition to mechanical stress, the drops would be subjected to extreme temperature stress from loss of heat through evaporation or ventilation.

This concept of the mechanism of sleet formation has been questioned recently (Taylor, 1954). It is now believed by many that the drops freeze, at least in part, when they come in contact with small ice crystals, probably from falling into an ice cloud in the cold layer. Once part of the drop changes to ice, the remaining portion can do so by growing on the ice crystals already formed. Dorsey points out that this is the characteristic behavior of supercooled water when a mass of ice is introduced into it.

Before leaving this phase of the subject, it might be interesting to note that Brooks has described some rather marked changes in precipitation form over the short vertical distance of 400 feet from the top to the bottom of Blue Hill, Mass. In one instance (Brooks, 1935a) he observed sleet at the top (air temperature 32°F) and non-freezing rain at the bottom (air temperature 33°F); in another (Brooks, 1932) he observed non-freezing rain at the top and sleet plus some glaze at the base. On yet another occasion he observed snowflakes at the top of the hill and sleet particles at the bottom (Brooks, 1936). It should be pointed out that there is a possibility that horizontal rather than vertical separation of the observation sites was the principal factor accounting for these differences. (The shortest horizontal distance from the observatory site at the top to the base of the hill is approximately 1500 feet.)

(4) Evidence to support hypothesis

Brooks (1920) lists as observed facts that support the theory of glaze formation from supercooled rain: (1) the occurrence of drops that freeze to objects without entirely flattening out (also cited by Lane, 1940), (2) the formation of glaze from rain on twigs and roofs when snowflakes had just been melting on these same surfaces, and (3) the dryness of icy posts on which drops of freezing rain are continually falling. Evidence of a similar nature is presented by Harwood (1945). He states that rain froze on the clothes and even the faces of observers on Ben Nevis in Scotland. It is extremely doubtful that non-supercooled rain would freeze on the skin of a person's face.

d. Mechanics of freezing of supercooled rain

(1) Force of impact in freezing

Assuming the validity of the proposition that most glaze is caused by supercooled liquid precipitation, the next item to consider is the mechanics of the process involved when the precipitation hits a solid object and freezes. Dorsey (1948) demonstrates that a violent agitation will induce spontaneous freezing in a mass of water, and the experiment in which he squirted supercooled water through a nozzle onto a test tube shows that splashing of a type somewhat similar to that caused by a falling drop striking a solid surface would do the same. Thus it seems that the phase change from liquid to solid is at least triggered by the violent mechanical disturbance to the drop as it strikes the solid surface.

The first formation of ice crystals within the shattered mass can be considered to occur instantaneously with impact, with the result that during this stage there is assumed to be no flow by conduction of heat in either direction between the shattered drop and its environment. Only a fraction of the drop will freeze in this initial step because of the inhibiting influence of the release of the latent heat of fusion which raises the temperature of the resulting mixture of ice and water to 0°C. The percentage of the drop undergoing immediate phase change to ice is proportional to the ratio between the latent heat of fusion and the degrees of temperature the drop is supercooled at the moment of impact. It is explained by the expression

$$80x = T_s m$$

where x is the mass of ice produced, T_s is the number of degrees (C) the drop was supercooled, m is the mass of the original supercooled drop, and 80 is the heat of fusion of water in calories per gram. If the drop is at a temperature of -8°C (17.6°F) at the moment of impact, $x = 0.1m$, thus one-tenth of the mass of the drop will be involved in this initial phase change. When freezing rain is undercooled even less than in this example, as is often the case, it can readily be seen that there is a possibility that a large percentage of precipitation will not become glaze, particularly on objects such as trees and wires where the unfrozen portion can drip off.

(2) Loss of heat by drop to ambient air

In most cases of glaze formation, however, other factors enter the picture and cause an appreciably larger percentage of the impinging precipitation to freeze. Probably of greatest importance is the loss of heat by the mixture of ice and water through conduction, both to the atmosphere and to the solid surface with which the drop has collided. The amount of heat lost to the atmosphere in this manner is a balance of several factors. First, when air moves over a surface (and it can be assumed that there will be such movement in almost all cases of glaze formation), even though the motion may be turbulent, a thin film of stagnant air will exist on the surface and protect it from extremely rapid loss of heat. Assuming a smooth surface, the thickness of this film will be a function primarily of the wind velocity in the ambient air. Other important factors will be the thermal conductivity of the air, and the temperature difference between the mixture of ice and water and the ambient air. Schumann (1938) expresses the interrelation of all these factors in the following term:

$$h_2 = \frac{K\theta}{B}$$

where h_2 is the amount of heat lost per second per unit area of surface, K is the thermal conductivity of air, θ the difference in temperature between the ice-water mixture and the ambient air, and B the thickness of the film of stagnant air.

(3) Conduction of heat from drop to solid surface

Heat will also be lost by conduction to the surface on which the glaze forms. In the beginning this may be quite high or low depending on the temperature and conductivity of the material involved. In the case of a metal at a temperature considerably below 0°C, the volume of heat conducted from an impinging drop might be so rapid that the entire drop would freeze almost immediately upon impact. However, once an appreciable layer of ice begins to form, the conductivity and temperature of the solid material decline in importance and the conductivity and temperature of the ice become ascendant. Ice is a poor conductor of heat, consequently, as it increases in thickness there will almost always be a decrease in conductivity to the solid surface. This may be of importance for determining whether glaze or rime will form.

(4) Loss of heat by evaporation

A certain amount of water will evaporate from the surface of the ice, diffuse through the stagnant film, and escape into the free air, carrying the latent heat of evaporation with it. Evaporation rather than condensation will prevail on the surface of the actively-forming glaze layer because the constant partial freezing of new drops as they strike the surface and the associated continual addition of the latent heat of fusion keeps the temperature of the immediate surface very near 0°C, or, as in virtually all cases of glaze formation, warmer than the ambient air. Schumann points this out in connection with the formation of hailstones. He adds that the theory is given support by the fact that at Kew Observatory, England, the existence of a supercooled fog that was freezing on exposed surfaces caused the temperature of an ice-covered thermometer to be higher than the temperature of the air. Ikeda (1941) notes the same gradient of temperature from an actively-forming ice surface to adjacent free air in observations made during the formation of rime and glaze. The fact that the temperature increase was greater in the glaze (formed entirely by the freezing of supercooled water) than in the rime (which, in this instance, was formed largely from ice crystals in a fog) gives additional weight to the above ideas concerning the part played by the latent heat of fusion.

(5) Factors determining type of precipitation formed

Various factors determine the type of ice (hoarfrost, rime, glaze, or a combination of these) to be formed in the freezing process just described. If precipitation is entirely the result of sublimation, the chances are that hoarfrost will form. However, there are accounts of instances where rime or even a glaze-like formation was caused by sublimation from moist air at temperatures very near 0°C passing over a surface that was only slightly cooler. The formation of a glaze-type ice is fairly common on the poorer-conducting parts of the surfaces of ships at sea in areas such as the North Atlantic, where very moist and relatively warm air masses prevail during the winter. According to Ekström (1941), ice of the hardness and smoothness of glaze forms in this way rather frequently on roads that run immediately adjacent to the coast of southwestern Sweden.

Where ice results from the precipitation of liquid water onto surfaces, rime, glaze, or a transitional type between the two will be formed. Rate of freezing, drop size, and rate of drop impingement appear to be the most important considerations affecting the type of ice thus formed. Ideal conditions for the formation of rime result when freezing takes place rapidly, drop size is small, and the drops strike the surface at a slow rate. When this combination exists, there is a strong chance the individual drops will freeze before they can coalesce, resulting in the occlusion of large quantities of air in the interstices between the frozen drops and the formation of an ice mass of low density.

Rodert (1951) has summarized some of the factors which usually play an important role in determining the speed with which freezing takes place. When the following conditions, listed by him as contributing to rapid freezing, are highly developed, rime can result:

1. The degree of supercooling at which the drop strikes the surface.
2. The conduction of heat through the boundary-layer air.
3. The evaporation of water from the wetted component surface.
4. The conduction of heat away from the vulnerable region through the solid boundary.

The first three of these should remain fairly static throughout the period of ice formation, unless there is a weather change; but the rate of conduction of heat away from the vulnerable region through the solid boundary may change appreciably as the ice grows thicker. The thermal conductivity of ice is different from that of many common substances on which it will form outdoors. The 1954 edition of the "Smithsonian Physical Tables" gives the thermal conductivity of solid ice at 0°C as $0.0053\ \text{cal}/(\text{cm}^2\text{sec}^\circ\text{C/m})$. Figures are not given for the conductivity of rime (which would vary considerably according to porosity), but snow with a specific gravity of 0.1 is listed with a conductivity of 0.00018. Metals likely to be found in exposed structures vary in conductivity from approximately 0.11 for most steel to 0.5 for aluminum and 1.0 for pure copper. As ice builds up on a surface composed of one of these materials, conduction of heat from the drop to the solid material decreases and freezing proceeds at a slower pace. Johnson (1954) points out that in ice formation on airplane surfaces, this may result in the formation of rime in the beginning and then glaze on top of the rime as the ice grows in thickness. This same sequence can no doubt be found in situations where ice is being deposited on bare utility wires by a supercooled fog. Assuming the conductivity of highly porous rime is about that of the snow cited above, it is possible this sequence can also be observed occasionally on materials with relatively low conductivities such as the wood in buildings (from about 0.00023 to 0.00090) or brick (0.000091 to 0.00042).

On the other hand, Rodert lists as factors inhibiting rapid freezing:

1. Conduction of heat to the vulnerable region through the solid boundary.

2. Minor factors, such as the conversion of kinetic energy of the water droplet to thermal energy upon impact, and radiant thermal energy from the sun and surroundings.

Drop size also has an influence on the rate of freezing. The heat capacity of small drops is less than that of large drops; and, therefore, a small drop, in striking a solid surface, completes the process of freezing more rapidly than a large drop. Another influence of drop size is due to the surface tension of the drop. If the ratio of surface tension to drop mass is large, as it is in small drops, there is less chance for the shattering of the drops from the force of impact (Byers, 1944). On the other hand, large drops are more easily broken to form a film of water over the affected surface. However, it is the writer's opinion that only drops the size of those found in fog have a sufficiently large ratio between surface tension and mass to be able to resist breaking upon collision. Certainly, drops large enough to be classified as drizzle or rain and hitting with the impact of such precipitation would almost invariably shatter when they strike a solid object.

Johnson (1954) explains the part played by drop impingement by stating "...only when droplets arrive at the surface in such profusion...that the surface on which they are impinging cannot conduct heat away from them fast enough to freeze them completely before the next drop hits does...[the density of the resulting ice equals] the densities given in physical tables.. Under these conditions all the spaces between the drops fill in, giving a solid ice mass of maximum density."

e. Summary

In most glaze formation, the temperature of the air, precipitation, and affected surface are all at or below 32°F. A large mass of observational evidence indicates that most cases of glaze occur when the temperature of the surface air lies between 25°F and 32°F, although there have been occasions when glaze was observed forming with the temperature as low as -5°F and as high as 37°F. Direct measurements of precipitation temperature during glaze formation are non-existent, but theoretical considerations lead to the universally held conclusion that rain or drizzle responsible for glaze formation is supercooled.

Dorsey shows that water can be supercooled far below 32°F without spontaneous freezing, and numerous other investigators have observed the presence of supercooled water droplets in the atmosphere. Upper-air soundings during freezing rain reveal a surface air layer with temperatures below 32°F, above which is a warm layer with temperatures above 32°F. Precipitation falling from the warm into the cold air is cooled below the freezing point, due to loss of heat through evaporation and conduction, but remains liquid. Upon striking a solid object, the force of impact and loss of heat through evaporation to the air and conduction to the object struck and to the ambient air, cause the precipitation to freeze. The type of ice formed (hoarfrost, rime, glaze, or a combination of these) depends upon the speed with which freezing occurs, the size of drops, the rate of drop impingement, and the degree of supercooling. Slow rate of freezing, large drop size, rapid rate of impingement, and slight supercooling favor glaze formation.

3. Synoptic meteorology of glaze in the United States

a. Limited information summarized

(1) Absence of information in literature

Meteorological literature contains little information dealing with the synoptic meteorology of glaze. Studies of this aspect of the subject in the United States were made by Brooks (1914), Frankenfield (1917) and Meisinger (1920), at a time when the modern concept of fronts and air masses was not fully developed. Riehl (1952) has included a brief description of conditions producing glaze in the Chicago area in his monograph, "Forecasting in Middle Latitudes". Studies have been made in Europe by Lyr (1927), Winter (1936), Rossi (1938), Bell (1947), and Sebastian (1949). However, these are generally limited to an examination of the situation in a particular storm or in a series of storms that affected one certain locality, and since they deal exclusively with European conditions, they cannot be taken as necessarily representative of the situations which produce glaze in the United States. A fairly large number of descriptions of individual storms occurring in this country is available, and some include material dealing with the synoptic conditions responsible for the storms (see Harlin, 1952, and McQueen and Keith, 1956).

In the discussion which follows, an attempt is made to summarize the combinations of meteorological conditions most favorable for the occurrence of glaze. The discussion is based on material taken from many of the sources mentioned above and on material resulting from an independent study carried on by the writer. This study was in the nature of a survey, and did not by any means exhaust all the possible means and areas of investigation.

(2) Riehl's analysis of Chicago area

First, Riehl's discussion (1952) of the synoptics of glaze storms will be presented. This is an excellent though brief treatment of conditions in the Chicago Forecast District of the U. S. Weather Bureau.

> "With very few exceptions, ice storms occur during the northeastward advance of a low center, and they are quite uncommon with lows that move eastward to southeastward. We distinguish two types of ice storm situations:
>
> (1) A polar front wave moves northeastward along the eastern edge of a continental polar outbreak [Fig. 7].
>
> (2) A broad southwesterly current ascends over a sluggish body of cold air to the east [Fig. 8]. In this case the western surface low can be very weak. A good prediction depends on the correct forecast of the flow aloft and of the high to the east.
>
> "The two types differ as to the rate of ice accumulation and the pattern of precipitation. When a low advances northeastward, we observe the classical precipitation model most closely. Glaze accumulation is rapid. Only in severe instances, however, does it last more than 12 hours, and within those few cases it ends within 18 hours. The southern edge of the

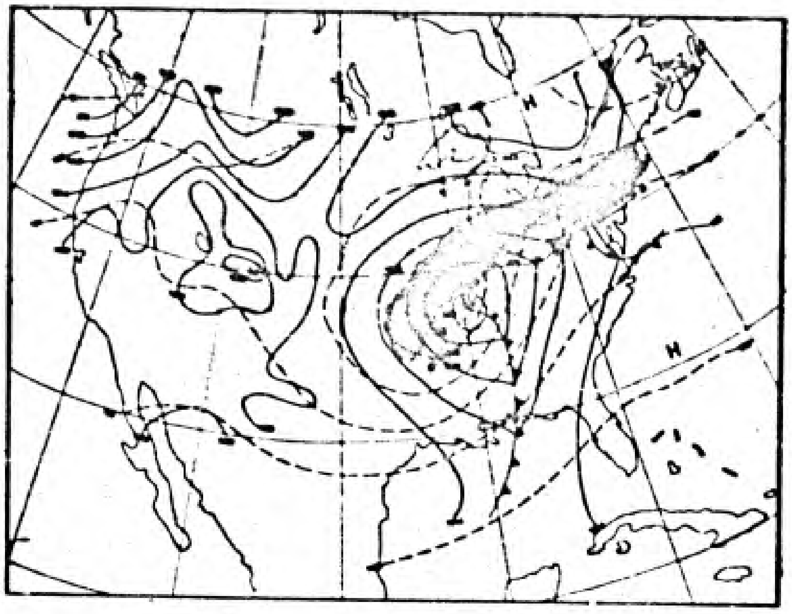

Figure 7. Synoptic map of January 1, 1948, 1230 GMT. Solid lines represent surface isobars; dashed lines, 500 mb. contours. Glaze area is stippled. From a map in Riehl (1952). Reproduced with the permission of the American Meteorological Society.

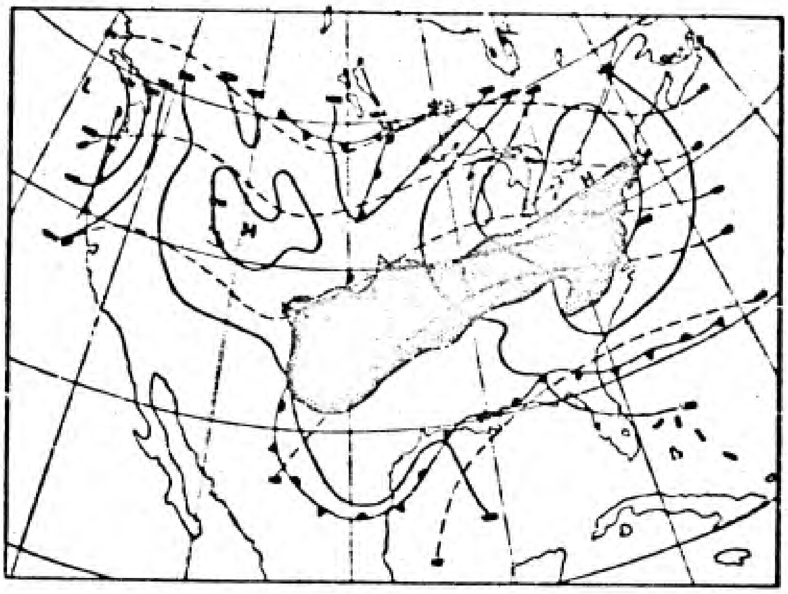

Figure 8. Synoptic map of December 27, 1944, 0630 GMT. Solid lines represent surface isobars; dashed lines 500 mb. contours. Glaze area is stippled. From a map in Riehl (1952). Reproduced with permission of the American Meteorological Society.

> icing area averages 50 miles or more to the north of the warm front. Its width is 100-125 miles. We observe snow to its north and rain to its south. Precise location of the ice area depends on the temperature forecast. Temperatures must be below freezing in a shallow layer near the ground, but higher above the warm front surface so that rain rather than snow forms. The freezing rain or sleet changes to snow or quickly ends after the axis of the low has passed. With broad southwesterly currents we observe ice accumulation that is usually slower and lasts longer than in the situations just described. But the icing area may be elongated along the jet so that a much larger area experiences ice at the same time. The same arguments concerning temperature and relative position of warm front and icing area apply as stated above.
>
> "A brief period of ice may occur in connection with many other storms of winter when surface temperatures range from 25°-35°F. Freezing drizzle falls for an hour or two after the warm front snow ends and before the cold front snow flurries start. This may produce an ice slick on highways."

(3) <u>General characteristics of glaze-forming situations</u>.

The widely-held belief that most freezing rain is associated with warm fronts is probably true, but it also occurs frequently with cold fronts or stationary fronts; in fact it would appear that in some parts of the United States most freezing rain is associated with one of the last two types of fronts. In other sections of the country, polar front waves which have occluded seem to be the most frequent type of front connected with occurrence of freezing rain. Furthermore, glaze apparently can result from freezing rain or drizzle that is entirely non-frontal in nature. Indeed, it would seem that freezing drizzle frequently is non-frontal and can occur in a wide variety of meteorological situations and over a wide range of temperature. Probably most cases of freezing precipitation at very low temperatures involve drizzle coming from supercooled stratus-type clouds in a non-frontal situation.

For almost every synoptic situation producing glaze, another that is almost identical in origin, history, and final form can be found that did not produce glaze. It is not possible to say, for example, that all or even most of the polar front waves that develop over the eastern half of the Gulf of Mexico in winter and move northward along the Atlantic coast will bring glaze to any area or location along their paths, even though a fair percentage of the glaze experienced in this part of the country is caused by such storms. Nor is it possible to say that such storms will yield glaze when associated with a particular distribution and intensity of high pressure or any other feature of the synoptic pattern. Undoubtedly, an exhaustive and careful study would reveal subtle differences in the history of glaze-forming and non-glaze-forming storms, but they are almost certain to be slight, since very small variations in temperature, both in the overrunning warm air mass and in the cold wedge, determine whether or not glaze is to form.

The problem is made more complex when it is realized that glaze-producing storms do not necessarily cause glaze everywhere along their paths. Factors of local weather just prior to the storm and factors of the microclimate may cause one area to experience glaze while another close by escapes entirely or experiences ice of a heavier or lighter intensity.

b. Analysis of synoptic conditions

(1) Data

The results of a survey made by the author of this report of synoptic conditions associated with glaze formation in the United States are summarized in Tables XII and XIII in Appendix B. Two sets of data were used to determine the occurrence of glaze.

The data used as a basis for Table XII were abstracted from the original observational records of the U. S. Weather Bureau stations which give the beginning and ending times of freezing precipitation, the water equivalent of the precipitation, and the maximum and minimum temperatures recorded during the period of freezing precipitation. Despite the fact that it includes no information on ice thickness, these data have been selected because they are the most systematic and reliable available, and because they are all from predetermined and fixed locations, thus allowing an analysis of a sizeable number of situations that affected one certain spot.

The information in Table XIII is based on an analysis of conditions which produced the glaze recorded in the "sleet rack" observations (Association of American Railroads, undated) conducted by certain utility and communication companies and a few U. S. Weather Bureau stations. Ice thickness (radial thickness on wires) is included in these data, but little or no information concerning weather during ice formation is given because almost all measurements were made at sites where there were no reliable facilities for taking observations of weather conditions.

A major handicap to an accurate analysis of both groups of data is the fact that the time of day of formation of the deposits is seldom given. This, of course, makes difficult the task of correlating the development of the ice with the synoptic condition responsible.

The Northern Hemisphere Historical Weather Maps published by the Joint Meteorological Committee of the United States Navy, Air Force, and Weather Bureau were used in making the analyses of synoptic conditions. The continuity of these maps is on the basis of a 24-hour period; therefore, another difficulty appears in tying together the formation of glaze and the associated weather pattern.

(2) General conclusions

An examination of Tables XII and XIII reveals several points. It is evident that, excluding the far northeastern and northwestern portions of the country, the cold air mass involved in the formation of glaze is almost always cP, while the warm air is invariably mT. In New England, the cold air often is cP that has been partially modified to mP by a short trajectory over the ocean. The few reports available for the Pacific Northwest indicate that the warm air is fresh mP from the Pacific, while the cold air is either cP or so-called Polar Basin Air (Pacific mP which has stagnated in an anticyclonic circulation over the Great Basin for several days and has been considerably modified by strong subsidence aloft and by loss of moisture as it crossed the mountains). Another exception is found over the extreme northern portion of the Great Plains: at Bismarck, N. D., the evidence indicates the presence of mP air, rather than mT, above the frontal surface on most occasions when glaze is forming.

The tables also show a predominance of warm fronts over any other type in creating conditions favorable for glaze. There is an exception to this on the southern Great Plains, where cold fronts moving from the north are of importance. Table XIII, which is based on storms of probably heavier intensity than those recorded in Table XII, particularly shows the importance of warm fronts over any other type.

(3) Analysis of regions

(a) The Northeast

The most typical synoptic condition for glaze formation in the northeastern United States is a polar front wave with an active warm front moving in a north or northeasterly direction toward the region. A high pressure area almost always is found north of New England, with the center of the ridge or cell usually located somewhere northeast of Newfoundland. This distribution causes a flow of cP air over the area from the north or east, and mT air up from the south behind the warm front. In this situation the overrunning mT air is frequently warmer than 32°F, while the cold cP air beneath the front has temperatures from 20° to 30°F, and a situation almost ideal for the formation of freezing rain or drizzle results.

The waves originate in almost any part of the North American continent, although few come from northern or eastern Canada; also, they take almost any path as they move toward the northeast. However, by examining the source and paths of waves that brought glaze to Caribou, Maine, Providence, R. I., New Haven, Conn., and Chester, N. J., it is seen that certain areas are favored. Out of 69 cases* at these locations, 34 were caused by storms that originated in the vicinity of the Gulf of Mexico (Texas, East Gulf, and South Atlantic source regions).** (See Figures 9-13 for maps showing a storm that brought glaze to the northeastern section of the country.) The remaining were fairly evenly divided between the other source regions of the North American continent.*** In Caribou, Maine, 7 out of 26 came from as far away as Alberta or the Pacific Coast. Storms originating in the South Atlantic and East Gulf areas generally move directly up the coast, with the tip of the wave passing almost over the affected areas or to the east out to sea. In storms moving out to sea, freezing precipitation seems to occur when the wave tip and warm front are located east or east-southeast of the affected area, although in order to determine this accurately, maps drawn at no more than 12-hour intervals would have to be used. In storms moving from the south or southwest, and whose centers pass to the west or northwest of the region, glaze almost always forms when the warm front is oriented in an essentially east-west direction and is located 100 to 300 miles south of the affected location (see Fig. 7). Even in waves originating in western and northern parts of the country, freezing precipitation most frequently comes from an east-west extending warm front located south of the region and moving northward. The principal exceptions to this are waves moving from the west which become occluded and in which the front generally is aligned essentially north-south or northwest-southeast. The center of the low pressure from which these occlusions extend often passes several hundred miles north of the area where glaze forms. Where the center of the storm is over the sea as it passes, the cold cP air mass is pulled from a northwest through northeast direction, with the result that it is either completely unmodified by passage over the sea or only slightly modified, whereas the farther inland the route of the storm, the greater the chance of highly modified Cp mP air being pulled over the area.

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* Because these data are tabulated on the basis of the number of times glaze occurred at each station, rather than on the basis of storms over the whole region, some storms have been counted more than once in this regional summary.

**For designation of areas in which storms developed, see the divisions of North America presented in Figure 16 of U. S. Weather Bureau (1952).

***McQueen and Keith (1956) give an example of a storm (January 7-10, 1956) in which the glaze-producing warm front moved from east to west over the region.

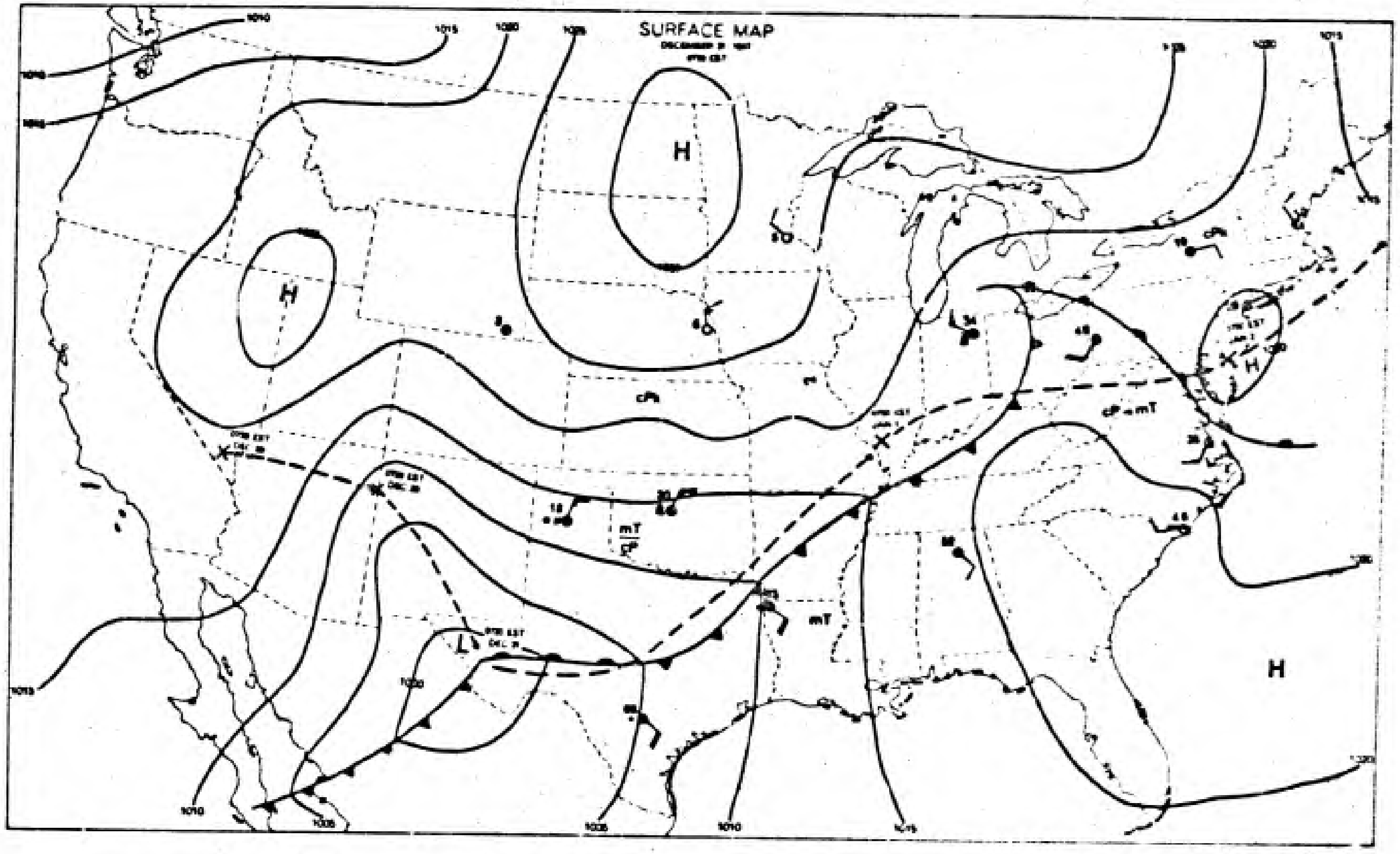


Figure 9. The storm of January 1 and 2, 1948, as it appeared in an early stage. Daily positions of the storm center are shown. This storm, shown in greater detail in Figure 7 and Figures 10 through 13, deposited a thick layer of glaze from Oklahoma to New England. The above map is adapted from one in the Northern Hemisphere Historical Weather Maps series of the U.S. Air Force.

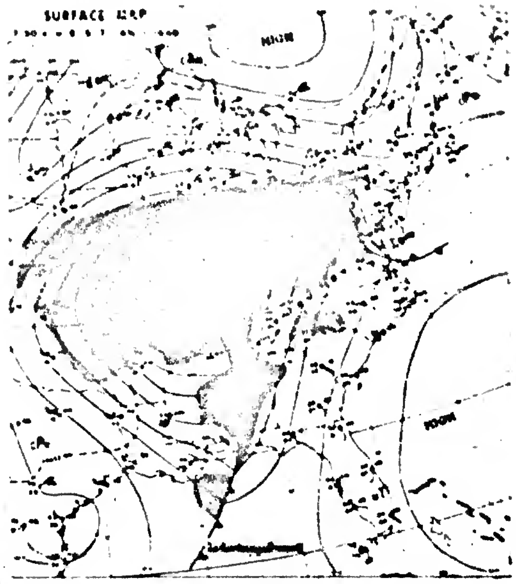


Figure 10. The storm of January 1 and 2, 1948, in a highly developed stage. At the time of this map, freezing rain was falling in parts of Missouri, eastern Iowa, Illinois, Indiana, and northern Ohio. In some places, ice accumulations up to two inches in diameter resulted. Map reprinted from Daily Weather Maps, Analyzed Series No. 37, Set No. 1 (M.E. Ellinwood), by permission of the U.S. Weather Bureau.

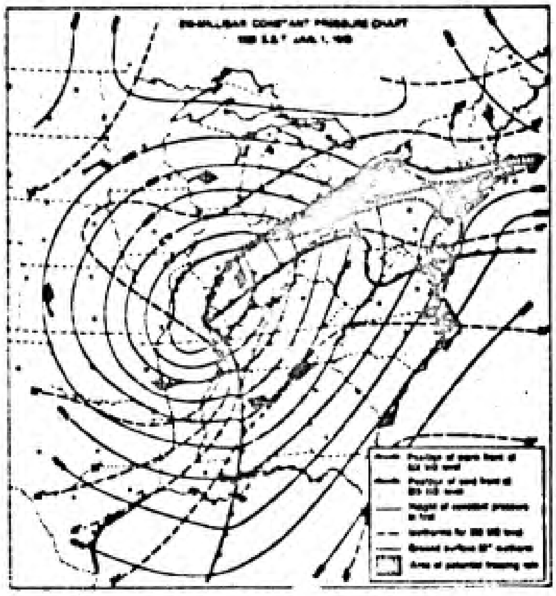


Figure 11. The upper air picture at 1030 EST on January 1, 1948, three hours after the time of Figure 10. Note the strong flow of air from the southeast as indicated by the wind arrow in eastern Illinois. The area of potential freezing rain corresponds fairly closely with the actual glaze area shown in Figure 7. Same source as Figure 10.

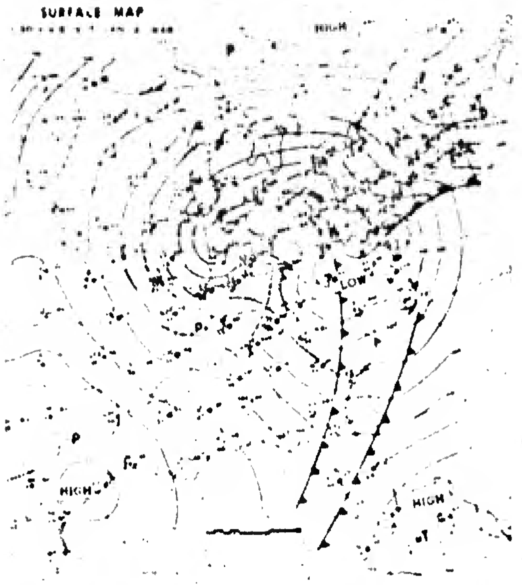
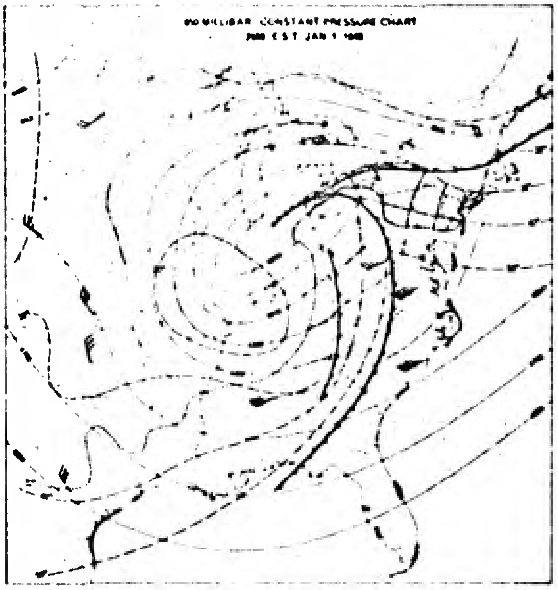


Figure 12. Final stage of the storm of January 1 and 2, 1948. Heavy freezing rain is falling from Pennsylvania to Massachusetts. Map reprinted from Daily Weather Map analyzed Series No. 37, Set No. 2 (M. E. Ellinwood), permission of the U. S. Weather Bureau.

Figure 13. The upper air picture at 2030 EST, January 1, 1948, 5 hours before the time of Figure 12. In this instance there is poor correspondence between the area of potential freezing rain and the actual glaze area shown in Figure 7. From same source as Figure 12.



The data for Caribou and Providence (Table XII) show cP→mP occurring only slightly more often than unmodified cP. The picture indicated by Table XIII is different because almost without exception the cold air listed as occurring in the storms at New Haven, and Chester, N.J. is cP→mP. This could be of some significance since the average intensity of the storms in Table XIII is greater than for those in Table XII. In 24 storms at Caribou and 23 at Providence there seems little doubt the warm air mass is genuine mT, while in 3 storms at each place it probably is a cP air mass that has been warmed by a long trajectory over the ocean (but not enough to be called mT) before returning northward or westward to the land.

In many storms the surface air, with temperatures above 32°F. in the warm sector of the wave, never passes over the glazed area. This is particularly true of occluded storms or, if open, storms in which the tip of the wave passes to the east or southeast. As such storms pass, the temperature usually drops even farther below 32° F. as fresh cP air moving from the west or north immediately replaces cP or cP→mT air which has been blowing from a more easterly direction. However, examination of temperature conditions on the day following glaze at New Haven, Connecticut and Chester, New Jersey, shows a maximum temperature above 32° F. in most cases (usually between 35° and 45° F.). If the daily maximum temperature remains below 32° F. after the storm, it generally does so for only one day. Data giving the duration of ice on utility wires in Massachusetts, Connecticut, and New Jersey (see Fig. 19) indicate that glaze deposits in those states seldom last longer than 24 to 36 hours, as compared with considerably longer durations in some other sections of the country.

The freezing precipitation causing the glaze lasts only a few hours in most storms. In 55 storms at Providence, Rhode Island, and Caribou, Maine, it continued 20 times for 6 hours or more and continued 7 times for 10 hours or more. In the storm of January 30 and 31, 1946, freezing rain fell almost continuously for nearly 20 hours and deposited 0.85 inch (water equivalent) at Caribou, and 0.20 inch at Providence. However, the resulting ice possibly did not amount to much because the storm was not reported in the severe storm summaries of the U.S. Weather Bureau. There seems to be little difference in the duration of freezing precipitation with different types of fronts; the mean value for occlusions and warm fronts were nearly the same at Caribou and Providence. The durations were 2, 2, and 1 hours respectively for 3 cold fronts at Providence, and 13 hours for 1 cold front at Caribou. The mean value per storm of the water equivalent of freezing precipitation at Caribou and Providence was slightly less than 0.10 inch. The few cases of prolonged and heavy freezing precipitation in this area are generally caused by warm fronts which become stationary as they move up the coast or which move only very slowly. Table XIII and Figures 25 through 27 show the thickness of glaze commonly experienced in this region.

As in other parts of the country, freezing rain or drizzle seldom occurs by itself in this region. Sleet or snow often falls at the same time, and one or both of these, plus rain, frequently occurs before or after the freezing precipitation. A common areal distribution of precipitation in this part of the country is a strip of non-freezing rain along the immediate coast, some combination of freezing precipitation in a belt next to this farther inland, and then a considerable area with snow. Along the coast the temperature of the cold air is too warm for super-cooling, and in the snow area inland the temperature of the overrunning warm air does not rise above 32° F.

(b) Northern Ohio and Western New York - Storms analyzed for locations in northern and western New York State and in northern Ohio indicate that, synoptically, approximately the same conditions prevail during glaze formation as in the region just discussed. The layout of fronts, pressure systems, and air masses shown in Figure 10 is typical of many storms affecting the area. Another type of storm that is fairly common is shown in Figure 14. Riehl's type No. 2 (Figure 8) apparently was the responsible situation in 3 out of 18 cases at Cleveland. One principal difference to be noted between this region and the far Northeast is that fewer of the storms originate in the area near the Gulf of Mexico; out of 39 storms reported, only 12 came from the Texas, East Gulf, or South Atlantic source regions. Twenty storms originated in either the Colorado, Northern Rocky, or Central regions, and the rest came from Alberta or the Pacific Coast. The avenue of approach of waves to this area can be from almost any direction from south through northwest. Seven moved down on Cleveland from the northwest, although the movement of the warm front, in the case of those that were open waves, was from the southwest as it passed over the station.

Cold fronts also come from the northwest or even from the north. A storm that deposited glaze at Canton, Ohio, East Ithaca and Erie, N.Y., in March 1936 retrograded so that its north-south trending warm front moved toward the area from due east in New England.* The duration and amount of precipitation is considerably less for systems moving from the west or north than for those which move from the south or southeast. In all cases where storms approach Cleveland from west to north, a large cP anticyclone, with its ridge line oriented north-south and located near the east coast of the continent, sends a strong flow of cP→mT or mT air up the Mississippi and Ohio valleys. In addition, the 500-millibar chart indicates a strong flow from the south aloft.

The storms in Table XIII show little difference with regard to the amounts of ice deposited; the 3 in which cold fronts were active deposited as much or more ice than those in which warm or occluded fronts

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* As did the previously mentioned storm described by McQueen and Keith (1956).

were active. Cold fronts apparently cause glaze more often in this section (at least at Cleveland) than in the far Northeast, although the amount of precipitation is small (a trace in 4 of the 5 that occurred at Cleveland and 0.01 inch in the 5th). Also, the cold air is nearly always unmodified cP; Atlantic cP→mP air may occasionally reach as far as central New York and be associated with glaze formation, but rarely will it get as far west as northern Ohio. The circulation of the cold air frequently is from east to west, but seldom does it extend far enough east to have any trajectery over the Atlantic. The warm air is dominantly mT, although it may be somewhat more modified than in the extreme Northeast (especially for points in northern Ohio), due to its path up the Mississippi Valley rather than over the Atlantic coastal waters. In two storms at Cleveland, the air mass histories indicate Pacific mP air could have been the warm air mass. The centers of most storms cross the region in their journey northeastward somewhere between Lake Huron and eastern Pennsylvania, but an occasional storm in which the wave is located entirely over the Atlantic Ocean produces glaze as far west as Cleveland.

(c) The Great Lakes and Upper Mississippi Valley - Only a small proportion (13 out of 47) of the storms in this region originate in the vicinity of the Gulf. However, a fairly large percentage of those from the west do swing down over the lower portion of the Great Plains of the Mississippi Valley, and therefore have ample opportunity to pick up mT air and carry it along on the northeastward swing back up the valley. Riehl's contention (1951) that glaze rarely occurs in the Chicago area with lows moving from the west or northwest is not necessarily borne out by the storms analyzed by the present writer. In 18 out of 42 cases of glaze at stations extending from Sault Ste. Marie, Mich., to Springfield, Ill., in which there is a well-developed wave and cyclonic center, the movement is from the west or northwest. This does not include storms which originate in the west or northwest and because they swing far south over the Great Plains, actually move toward the affected area from the southwest; nor does it include several cold fronts without wave formation which advance upon the area from the northwest. It was noted, however, that the storms in Table XII which move in from the west or northwest deposit less precipitation than those coming in from the southwest. On the other hand, of 23 storms in Table XIII, 5 come from the west or northwest and deposit respectively 0.08, 0.10, 0.20, 0.53 and 0.20 inches of ice; and 13 storms come from the southwest, and deposit 0.33, trace, trace, 0.18, 0.17, 0.23, 0.04, 0.10, 0.14, 0.08, trace, trace, and 0.33 inches. Apparently, storms from the west or northwest cause glaze as thick as that left by storms from the southwest, but a larger percentage of storms from the southwest deposit measurable thicknesses of ice. Of course, a larger number of storms would have to be analyzed before any conclusions such as these could be considered valid.

One contrast between this region and the Northeast, particularly the New England section, is that in a larger percentage of the storms the tip of the wave passes to the south of the glazed area, which means fewer cases where the surface air in the warm sector with its 32°F., or higher, temperature passes over the glazed area. Often fresh cP air with temperatures well below 32°F. replaces air in which glaze forms, and then dominates the area for several days. In most of the states in this section, ice on utility wires lasts 48 hours or longer in at least 25 percent of the storms. (See Figure 19.)

Riehl's type No. 2 (Figure 8) probably is responsible for the formation of glaze in 11 or 12 cases. In most of these situations, a cold front or stationary front is found to the south or southwest of the glaze area. To the south of this front is old cP air which has been warmed somewhat, but not above 32°F. Farther south, along the Gulf coast, or possibly out over the Gulf, is another front, generally a fairly active warm front. To the south and above this front is very warm mT air which has moved northward in a broad current over the two frontal systems to the north, bringing moist air with temperatures greater than 32°F. over the glaze area.

With regard to air masses, both tables show cP and mT prevailing almost exclusively, though Pacific mP could be the warm air mass in 3 of the storms at Milwaukee and in the 1 at Springfield, Ill.

(d) The Southeast and the Gulf Coast - Accumulations of glaze at points in the south and southeast sections of the country are caused primarily by polar front waves which originate over or near the Gulf. Very few of the waves from farther north or west that bring glaze to points in the central or upper Mississippi Valley or the Northeast cause freezing precipitation in the South, even though they might swing far down over the area. The explanation possibly lies in the fact that temperatures in the cold air mass are warmed to above 32°F. by the time the air reaches these southern latitudes. Probably of greater significance is the fact that the air in such storms, especially those that come in across the Colorado source region, seldom is fresh cP, but instead a mixture of cP and Pacific mP or simply Pacific mP. Furthermore, it has been warmed more adiabatically than cP air which comes directly down the Great Plains from the north.

At any rate, 12 of 14 storms producing freezing precipitation at Washington, D.C., originate in the Texas, East Gulf, or South Atlantic source regions, and of the 8 storms shown for this region in Table XIII, every one originates over or very near the Gulf. One is from as far south as the Yucatan peninsula. Maps for storms in this section usually indicate a large cP high, occupying virtually the entire Mississippi Basin from Canada to the Gulf and from the Rockies to the Appalachians. After the cold front which leads this air south and east moves to the Gulf, and has remained there 24 hours or so, the occurrence of cyclogenesis along the front results in the formation of a wave which then moves northeast carrying freezing rain or drizzle with it.

Wave formation does not seem to be necessary in order for glaze to occur. Freezing rain has been reported at Atlanta, Baton Rouge, and San Antonio, both while the cold front was actively moving south over them and after it had become stationary over the Gulf and before wave formation had begun. Tannehill (1929) has described the occurrence of these latter storms along the Gulf Coast, calling them "Wet-Northers." However, he found glaze associated with only 3 of them in the period 1901 to 1925. Occasionally, one of these long cold fronts may become stationary before it moves south and east off the continent, in which case freezing rain and snow may develop along the front (Figures 14-15.)

As has been suggested above, the cold air mass associated with glaze formation in this region is invariably cP that has come almost directly from the source region, although the one case at Richmond, Va., seems to involve a cold air mass that might be called cP→mT. The only warm air mass indicated for this region is mT.

Below-freezing temperatures seldom last more than a few hours after glaze storms in this section of the country. Polar continental air generally prevails after a storm but it warms to temperatures above 32° F. very rapidly. After 7 of the 8 storms in Table XII, the maximum temperature on the following day is indicated as being above 32° F. and after the 8th storm it is exactly 32° F. Nevertheless, glaze can remain on objects for extended periods in this region. The mean duration of ice on utility wires is:

State	No. of storms	Mean duration (Hours)
Texas	7	60
Alabama	3	26
Georgia	4	54
North Carolina	8	21
South Carolina	10	23
Tennessee	6	54
Virginia	6	15

These storms are probably heavier than average because they have been taken from the Edison Electric Institute data which are based primarily on storms serious enough to inflict damage to utility installations.

(e) The Southern Great Plains - Based on the data for Oklahoma City in Table XII, most glaze in this area is brought by cold fronts that advance rapidly southward over the plains ahead of cP outbreaks. Out of 20 storms at Oklahoma City, 14 are the result of this stituation. Only 6 of the storms consist of well-developed

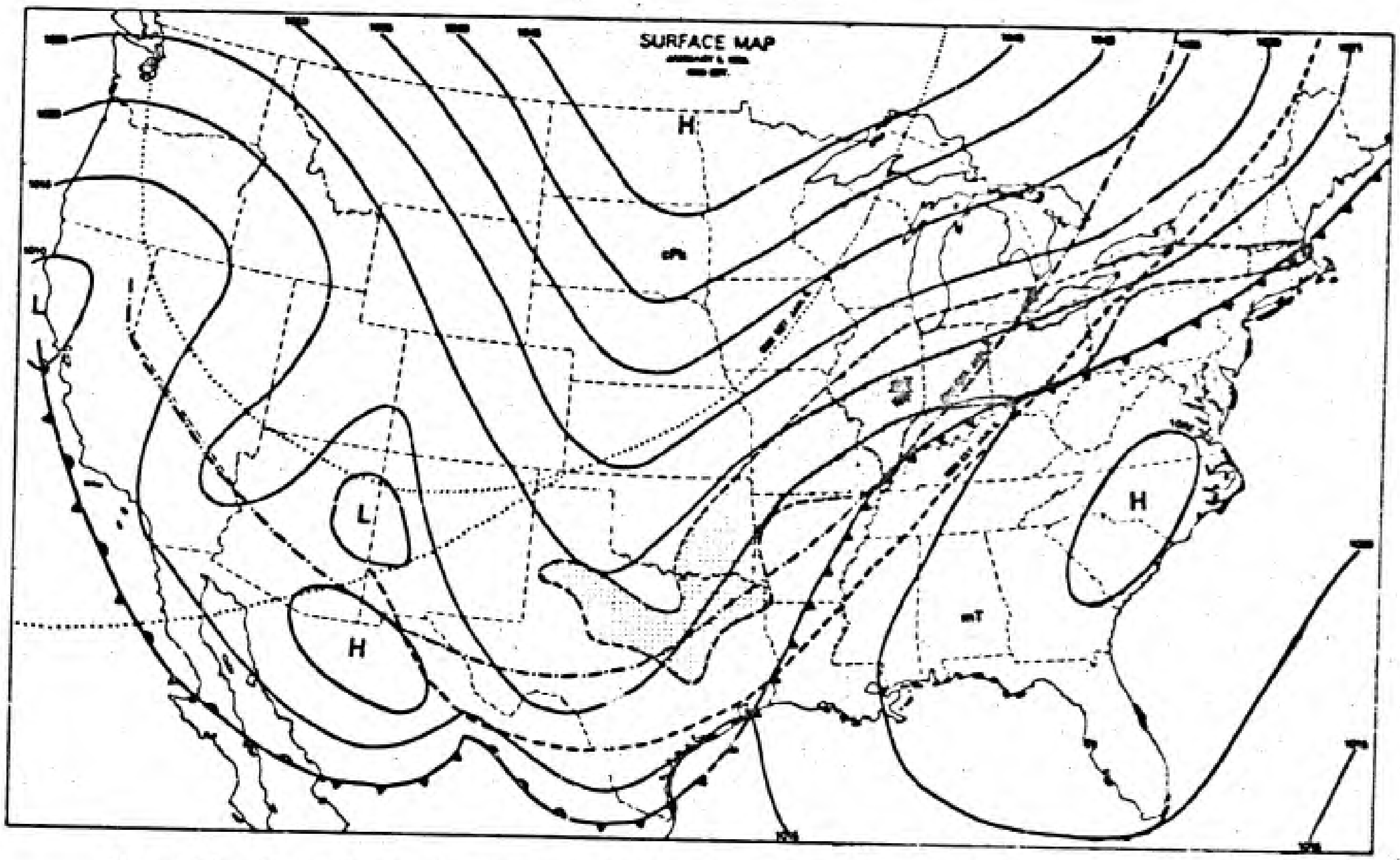

Figure 14. Synoptic conditions associated with the widespread glaze storm of January 6 to 9, 1930 (see Figure 15). The cold front which moved rapidly down from Canada stagnated across the eastern United States, causing widespread overrunning of mT air above sub-freezing cP air. Twenty-four-hour positions of the front are shown on the map. The area in which glaze actually occurred is stippled.

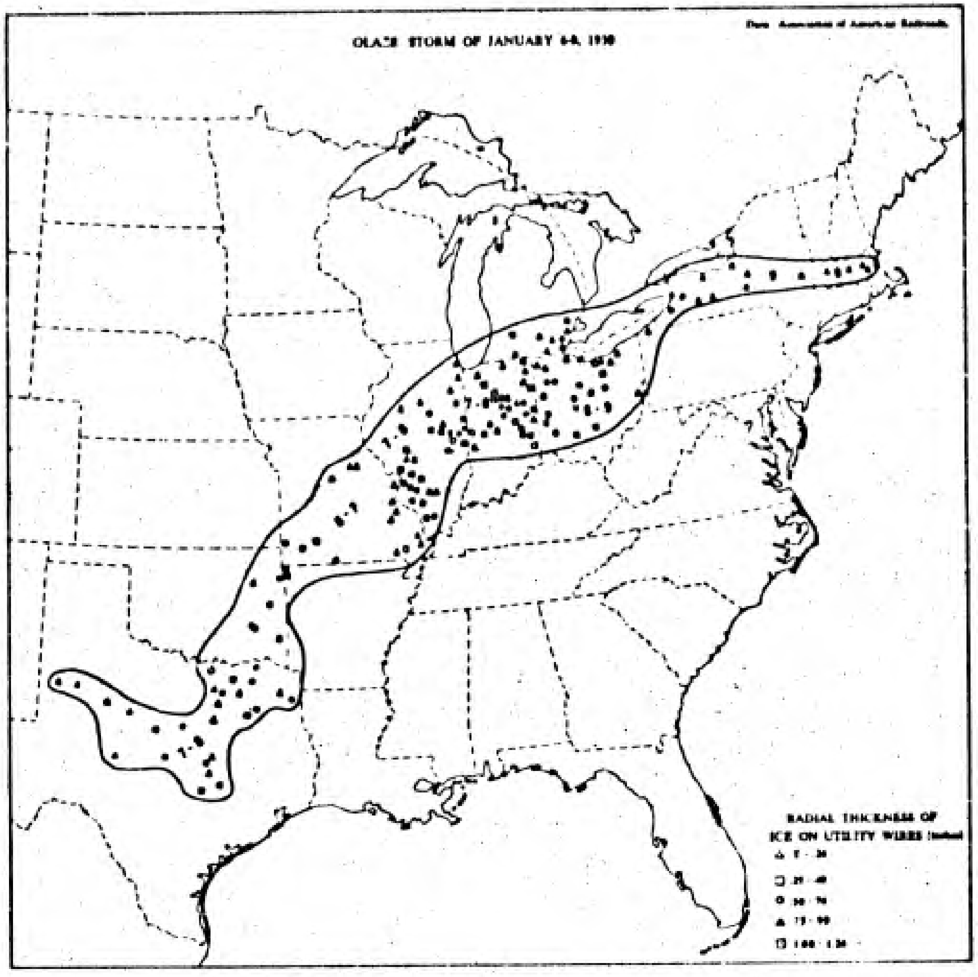

Figure 15. The numbers on the map indicate the dates on which freezing rain fell in the various states. Many measurements of ice thickness could not be plotted because of the small scale of the map. This is one of the most widespread glaze storms to have occurred in the United States. The average glaze storm does not affect more than 1 to 3 states.

polar front waves such as bring freezing precipitation to locations farther east and north. As would be expected under these conditions, fresh cP and mT are usually the associated air masses. There is evidence in 3 storms, however, that cP is the overrunning air mass, in 2 storms, cP with a short trajectory over the Gulf and which, therefore, should be called cP/mT, is the overrunning air mass.

Most of the storms at Oklahoma City show deposits of less than 0.10 inch of freezing precipitation and there is no apparent difference in the amount deposited by the various types of storms. One of the simple cold fronts dropped 0.46 inch of freezing rain, more than any storm in which a warm front was involved, and the cold front listed in Table XIII deposited 0.27 inch of ice. The upper cold front for Dodge City, which moved in from the northwest, deposited 0.33 inch of glaze.

Temperatures lower than 32°F. commonly prevail for several days after a glaze storm in this region. The ice lasted an average of 53 hours after 16 storms in Kansas and 44 hours after 9 storms in Oklahoma (Table XV).

(f) <u>The Northern Great Plains</u> - On the northern Great Plains (from Nebraska north), there are four situations which produce glaze. <u>The first</u> involves the establishment of a stationary front along the western edge of the Rockies, with the front generally extending from Alberta southeastward into Colorado or Texas, and separating a recent cP outbreak to the east from Polar Basin or cP air west of the Rockies. Fronts of this type may remain stationary for several days and occasionally for a week or more, and then move slowly east or northeast. On the maps analyzed, it is during this moving out stage that most of the freezing precipitation was shown to occur at Bismarck. The movement of the stationary front seems to be stimulated on some occasions by the passage aloft of a weak front or trough associated with the eastward movement of mP air. Of 22 cases where it was possible to get an idea of the nature of the warm air at Bismarck by examining the surface map, mP or Polar Basin air is indicated 18 times. These two air masses are not markedly different once they move east of the Rockies, since both are dry and relatively warm. The main difference is usually the greater subsidence, warmth, and dryness (as measured by mixing ratio values) found in the Polar Basin air at an elevation of 2,000 to 5,000 feet above the surface. In 3 out of 5 glaze storms, the presence of mP air above Bismarck has been verified by analysis of the upper air sounding; on the other two occasions it was mT.

The question may be asked why glaze occurs more frequently at Bismarck than in the northern portion of the Great Basin, since the Pacific mP air that supposedly brings glaze to Bismarck must pass across the Great Basin. The answer probably lies in the fact that the mP or Polar Basin air is usually a surface air mass in the Great Basin, but is found overrunning cP air at Bismarck.

The cold air is nearly always cP at Bismarck and, with this type of situation, seems to be about equally divided between fresh cP air blowing from a north-northeasterly direction and return-circulation cP from the southeast. If the stationary front moves across Bismarck to the east, temperatures above 32° F. generally follow closely in its wake, possibly accompanied by a mild "chinook" effect. Note that in Table XV the mean duration of ice after 3 storms in Nebraska was only 14 hours, and after 2 storms in Montana, it was 20 hours— values considerably lower than those for areas farther south.

The second situation is created when a polar front wave moves eastward toward the Great Plains from the North Pacific or southeastward from Alberta. The wave frequently follows a day or so after a cP outbreak has occupied much of the eastern half of the United States and then begun to move out over the Atlantic. Some of the waves are open and some are occluded. In open waves, the glaze is associated with the warm front. The important condition is that warm mP air is brought in from the Pacific above cP air at the surface. On one occasion, however, mT air has been pulled north over Bismarck as the overrunning air mass. The cold air usually is returning cP from the southeast, but on some occasions it may be relatively fresh cP from the northeast or north. In 10 years, 11 cases of glaze were recorded at Bismarck in which the temperature dropped below 15° F. during actual glaze formation; on one occasion it went to 5° F. and on another to 4° F. A new cP outbreak from Canada, carrying sub-freezing or even sub-zero temperatures, often follows directly on the heels of the low as it moves eastward across the plains; thus glaze may persist for long periods after this type of storm.

The third situation occurs when a wave forms in Colorado or Northern Texas and moves northeastward. The wave usually develops on the west side of a large cP anticyclone and travels northeastward as the high moves over the Atlantic or the Gulf. The passage of the wave across the central part of the country frequently brings a fresh outbreak of cP air into the plains area, while mT is pulled north into the storm. This type is the least common of the 3 mentioned thus far, being responsible for only about 1 occurrence of glaze in every 5 or 6 at Bismarck. Undoubtedly, this type becomes progressively more important southward on the plains.

A fourth situation that brings glaze to the northern Great Plains is found when a cold front moves rapidly southward over the region. If the cP air behind the front replaces an air mass warm enough to have temperatures above freezing after being lifted over the front, freezing rain or drizzle result.

The amount of freezing precipitation deposited at Bismarck by any of the storms usually amounts to only a trace or, at best, a few hundredths of an inch. Both mP and mT air would be comparatively dry by the time it reached this far inland. Nevertheless, ice of major thickness can form occasionally in the northern Great Plains (Figure 27).

(g) The Great Basin and Rocky Mountains - Glaze is a relatively rare phenomenon in the Great Basin and Rocky Mountain area; therefore, few maps are available for analysis. However, a description of 5 situations that caused glaze in this region will be presented: 2 for Lander, Wyo., 2 for Elko, Nev., and 1 for Grand Junction, Colo. Spokane, Wash., which is located in the northern portion of the Basin and which apparently has a higher incidence of glaze than the rest of the region, will be discussed separately.

One storm at Lander was caused by an open wave which moved in from the Pacific across Puget Sound bringing mP air with it. The tip of the wave passed directly over Lander. The freezing precipitation, which lasted for two hours, occurred shortly after the tip moved on to the southeast at a time when the surface wind was bringing cP from the northeast. The other storm was the result of the movement southwestward of a cold front associated with a rapid cP outbreak over the northern Great Plains. In this case, it is impossible to tell the nature of the warm air by examining either the surface or the 500-millibar chart.

The earlier storm at Elko, which lasted only one hour and deposited barely a trace of precipitation, occurred with the passage southward of a cold front from Washington and Oregon. The warm air was Pacific mP or mT pulled northward aloft by a low centered over Reno and another just off the northern California coast. In the other storm, precipitation again was only a trace, but lasted for 6 hours. A ridge of high pressure lay to the east of Elko along a line through western New Mexico, Salt Lake City, and Pendleton, Ore. A low was located off the coast of southern California and may have been causing a broad current of Pacific air to flow aloft over the Basin air moving southwestward from the ridge of high pressure.

The storm at Grand Junction was associated with the rapid passage of a Pacific occlusion aloft over cP air located at the back of a huge cP outbreak. The precipitation lasted for approximately 2 hours and amounted to a trace.

Seven maps were analyzed for Spokane and they fall into essentially two situations. Five involved the passage of an occluded Pacific wave inland across eastern Washington. In two of these cases, the occlusion moved aloft over a well-developed Great Basin high. In some cases the wave originated in the Aleutian area and in others as far south in the Pacific as 35° N. Lat., but in either event the warm air carried into the system came from the southerly zone in the ocean. This probably is a requirement for the formation of glaze in the Spokane region, because mP from farther north would seldom be warm enough in winter to maintain temperatures above 32°F. after being lifted 2000 feet or so. The largest amount of freezing precipitation left by these storms is 0.08 inch, and its duration was not more than 2 to 4 hours. Two of the maps for Spokane show quite another type of situation as responsible for glaze formation. These resemble closely the second storm at Elko, Nev., where a low off the southern California coast and a high over the Great Basin combined to force the flow of southern trajectory Pacific mP air aloft over the Great Basin area. There is a possibility in this instance that the precipitation was air mass in nature and came from low stratus clouds which covered the area.

(h) The Pacific Coast - Glaze formation is associated with only a small percentage of the winter storms that strike the coast of northern California, Oregon, and Washington, due primarily to the general absence of cP air in the area. Southern trajectory mP air warm enough to remain above 32°F. after being lifted over the cold air mass comes on shore frequently in this area in the winter, so that if there were a high incidence of cold cP air along the coast, glaze storms would be frequent. Furthermore, because of the high moisture content of the mP air, glaze storms along the Pacific coast undoubtedly would be severe. However, the right combination of air masses does not often occur and then for only short periods, with the result that when glaze deposits form they often are not very thick. There are exceptions to this and one which occurs occasionally will be discussed shortly.

The two cases of glaze at Seattle occurred when cP air was forced across the mountains and onto the Pacific coast. On one of the occasions the air was forced over the mountains by a strong high located over the Great Basin, and on the other occasion by a ridge of high pressure extending from northern Alberta to northern California. In both cases an occlusion passed inland over the top of the cP air.

The two storms at Troutdale, Ore., were caused by essentially the same situation — a high over the Great Basin which forced cP air down through the Columbia gorge while a Pacific low carried southern trajectory mP air onto the coast and over the cold air. The ice left by these storms was 0.05 and 0.30 inch, respectively.

The first occurrence of glaze at Blue Canyon, Calif. resulted from the formation of a wave extending from Montana to the Pacific across central California. This wave caused Polar Basin or partly modified mP air to flow from the northeast over Blue Canyon and warm mP air to flow up from the southwest. Where they met, just southeast of Blue Canyon, a warm front formed. The second storm involved the rapid movement of an occluded wave southwestward across Oregon and into Nevada. The cold air appeared to be northern trajectory mP, while the warm air was mP with a more southern trajectory (from southwest of San Francisco).

In a study dealing with ice breakage in stands of Douglas fir, W. F. McCulloch (1943) describes a storm involving the invasion of the coastal lowlands by cP air and which, in contrast to the storms mentioned above, deposited a thick layer of ice on all surfaces and inflicted heavy damage on forest trees.*

"A polar continental air mass covered the Pacific Northwest and Northern Rocky Mountain and Plains states at the beginning of January, 1942. Temperatures ranged between 0 and -10 degrees F. between the Cascades and the Rockies. At this time, a weak cyclone developed rapidly over west-central Canada and the dome of cold polar air behind the cold front was deep and very cold. By the fourth of January, this dome of cold air had spread southward and blended with the older polar continental air mass over the western United States, so that the entire United States from the Mississippi Valley to the Sierras and the Cascades was dominated by a very cold air mass.

"Continental polar air drained into the valleys west of the Cascades until a layer approximately 400 feet deep covered most of the area west of the Cascades and north of the Siskiyou Mountains. On the morning of the sixth [January] pressure began to fall from San Francisco to Vancouver Island with light rains reported from coastal stations in northern California. Overrunning warm air from the south attained a depth of approximately 10,000 feet by the seventh. The boundary between the continental polar air and the maritime polar air on the sixth was situated in an east-west position over the Siskiyou Mountains with this overrunning warm moist air coming inland from off the coast. Rain falling from the overrunning warm air, as it ascended the slope of the dome of continental polar air north of the Siskiyous was chilled considerably in its descent through the continental polar air that filled the valley west of the Cascades. Here temperatures had been below freezing since the first of the year. As a result, this chilled rain froze immediately upon striking the ground or any object, forming a layer of ice on all surfaces. During the entire period, continental polar air continued flowing from the Columbia Basin via the Columbia gorge and the other mountain passes, maintaining the supply of cold air in the valley west of the Cascades in northwestern Oregon."

In addition to the above description, it might be of value to quote from another by Donald B. Lawrence (undated) in which he describes the manner of occurrence of glaze storms in the Columbia River gorge area.

"A glaze storm at Crown Point is regularly preceded by a freezing winter gale without precipitation, which blows through the gorge from the east for a week or longer. Sooner or later, relatively warm coastal air begins to move inland over the gorge from the west, the velocity of the persistent east wind begins to abate and precipitation results. At

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* The description of meteorological conditions in this storm was prepared by Louis R. Jurwitz of the U.S. Weather Bureau Office in Portland, Ore.

first, this has the form of ordinary snow, accompanied by a strong east wind and slowly rising temperatures. The initial snow is apt to change within a few hours into graupel, and somewhat later into sleet. The solid particles that make up these forms of precipitation are driven westward almost horizontally at perhaps 30 miles per hour or more. After the graupel or sleet has continued for a few hours, freezing rain supervenes. Driven by the strong east wind, with velocity still not greatly diminished, the glaze accumulates mainly on the eastern side of trees, covering every needle and twig of the crown and even the bole.

"A glaze storm may continue for twenty-four hours, with east-west velocities between 25-30 miles per hour, while branches and twigs on the east and northeast sides of a fir crown may become covered with ice coatings as much as 3 or 4 inches thick. As a glaze storm comes to an end the air temperature and the rain become warmer, and the east wind abates and is supplanted by a gentle southwest breeze. The temperature continues to rise and warm rain continues to fall for several days; consequently the storm ends in a rapid thaw and the ice soon disappears..."

According to Lawrence, such storms occur in midwinter or later. A few winters have been characterized by several of them, whereas other winters have passed without any occurring.

Wells (1921) describes the rapid thaw that may follow these storms in writing of one that occurred November 19 to 22, 1921. During this particular storm, the wind at Portland was from the east and temperatures remained around 29°F. Within approximately half an hour after the lower level of clouds was observed to be moving from the southwest (on the afternoon of Nov. 21), instead of from the east as all through the storm, the temperature rose 10 (F) degrees and the ice rapidly disappeared. The synoptic situation for November 19 - 22, as given in the Northern Hemisphere Historical Map series, indicates that from Nov. 19 to 21 an east-west-extending warm front lay just to the south of the Columbia River. To the north of the front, cold cP air was forced westward by a ridge of high pressure located over the Northern Rockies. A high off the California coast caused very warm Pacific maritime air from about 35° latitude to flow northward over the warm front. On Nov. 21 the wave, of which the warm front was a part, moved inland carrying onshore mP air with temperatures above 32°F.

c. Summary

Since the appearance of the pioneer works of Brooks (1914), Meisinger (1920), and Frankenfield (1917), all before 1921, meteorological literature has been almost totally devoid of studies dealing with the synoptic meteorology of glaze in the United States. An exception is Riehl's recent study (1952) on glaze in the Chicago area.

A study made by the writer of this report has led to the following conclusions. Most freezing rain or drizzle appears to be associated with warm front activity, but it also frequently occurs with cold fronts, as on the Southern Great Plains, or stationary fronts, as on the Northern Great Plains. In addition, glaze apparently can result from freezing rain or drizzle which is entirely non-frontal in nature. The cold surface air mass involved in glaze formation almost invariably is cP with the exception of certain areas such as New England where the cold air usually is cP partially modified to mP. The overrunning warm air is almost always mT, except in the Pacific Northwest where it is more likely to be mP. The commonly held idea, that in the central part of the country heavy glaze is associated only with polar front waves moving from southeast to northeast, does not seem to be valid.

4. Characteristics of Glaze Storms

a. Size of storms

Figure 16 shows the variation in the size of glaze storms in the United States during the winter of 1936-37. For reasons pointed out elsewhere in this report, the boundaries of the storms on this map cannot be considered definitive, and cannot consequently be used to draw conclusions with exactness. However, they probably are accurate enough to give a fairly good indication of storm size and configuration. Note that most of the storms appear to be wholly local, whereas some cover huge areas encompassing large parts of several states. The biggest storm on the map, that of January 6 to 9, extends from west central Texas to central Wisconsin. The storm of January 6 to 9, 1930, illustrated in Figure 15, is even larger, covering an area from Texas to New England. Such outsized storms, however, are rather unusual. During the 9-year period for which maps similar to the one in Figure 16 were prepared, some winters passed without any occurring. The average storm of more than local size probably is 200 to 600 miles in length and covers parts of 1 to 3 states. Although it is not shown quite as clearly on this map as on most of the others, there is a general tendency east of the Rockies for the glazed areas to be longest in a northeast-southwest or east-west direction, probably because most storms in this section of the country travel across the area from west to east or from southwest to northeast. A few of the storms occurring on the Great Plains, north from Nebraska, had their long axes oriented along a northwest-southeast line, corresponding to the path of movement of lows from Canada.

b. Distribution of glaze within storm areas

As a glaze-producing storm moves across the country, it does not necessarily deposit ice everywhere along its path, especially if it is a light storm capable of laying down only a thin layer of ice. In some cases, a large glaze-covered area has scattered spots where no ice formed at all. Other storms leave ice in widely separated locations with the area in between remaining virtually free of deposits. An example is the storm of January 21, 1937, which deposited ice in central Texas and then left an ice-free gap nearly 300 miles in length between that area and central Arkansas. In addition to this unevenness of distribution of glazed and non-glazed areas, most storms show a wide variation in the thickness of ice deposited.

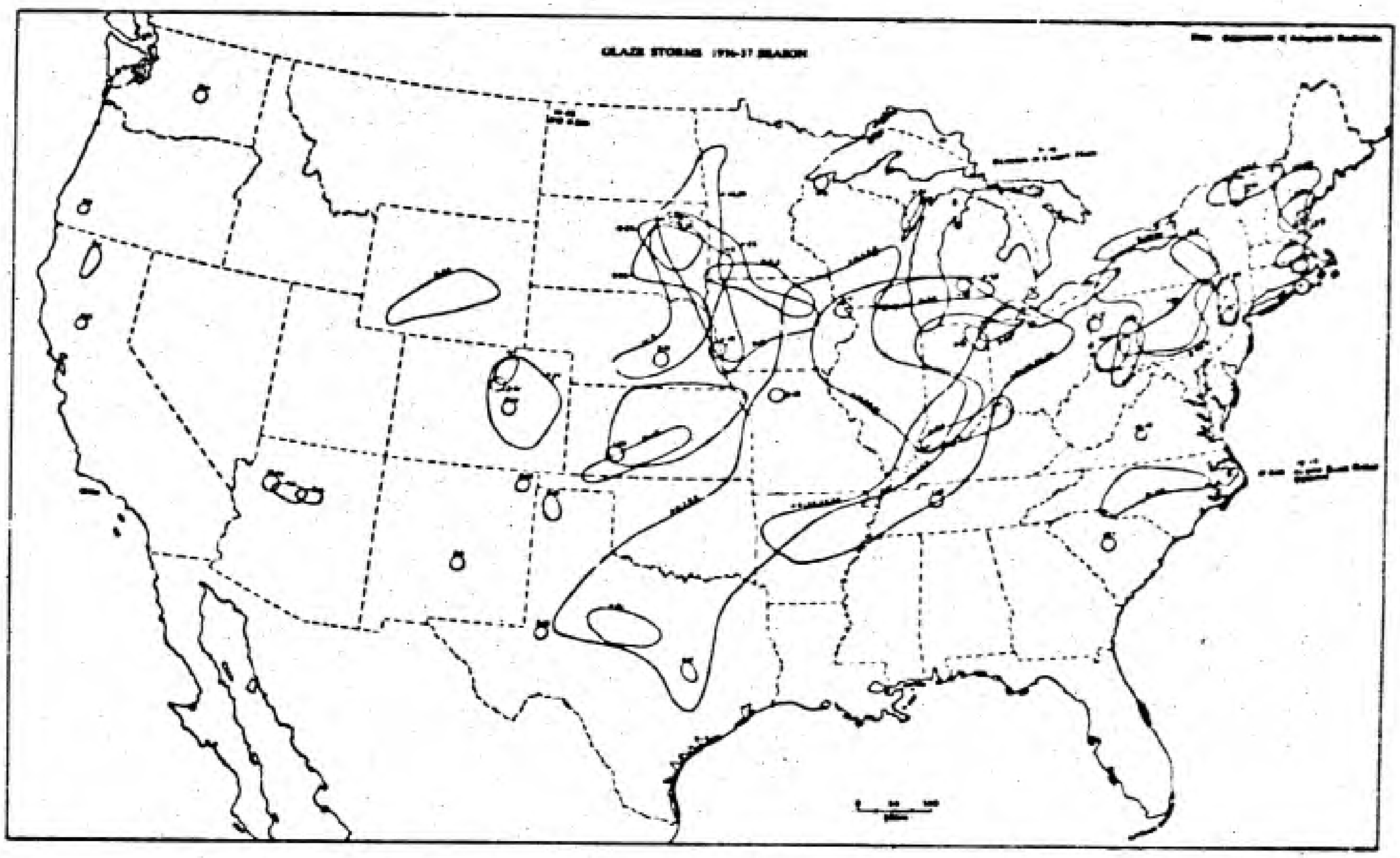

Figure 16. This is a copy of one of the annual maps prepared in analyzing the Association of American Railroads (undated) glaze-thickness data. The individual measurements of ice thickness have been omitted from this copy. The month and days of occurrence of each storm are given.

Frequently, ice of markedly different thickness is found in close proximity (see Figure 21). Much of this results from changing conditions within the storm itself, such as strengthening or weakening of cyclonic activity, although microclimatic influences often are equally important.

c. Influence of microclimate

Many of the changes just described can be explained on the basis of the influence of purely local factors related to the microclimate. In fact, in probably no other major type of storm will the complexity of the microclimate, as determined by elevation, aspect of slope, exposure to wind, composition of ground surface, etc., have as great an opportunity to express itself and cause large variations in storm intensity over short horizontal or vertical distances. This is brought out by the following statement by R. Geiger (1950).

> "Glaze is probably the most sensitive symptom of changing ground conditions. Whoever walks the streets with his eyes open when there is much glaze present cannot avoid astonishment, questions and research. Every street, every curb-side, every kind of ground, every kind of stone has its own (different) glaze formation. Long-filled excavations at the side of the street are plainly visible. Surface roughness, the thickness and type of stone facings, the inclination of the ground --- everything shows up. Truly, if anyone wants to take a hard test in microclimatology, let him take a walk when glaze has formed and answer all the questions that Nature compounds."

The particular influence of the microclimate referred to in this quotation is the heat-conducting and heat-storing ability of surface materials of various types, which is important because of the direct bearing it has on the surface temperatures of these materials. Because glaze usually occurs when the surface temperature is fairly close to 32°F. and the falling precipitation is not supercooled more than a few degrees, the variation in surface temperature from material to material can be a deciding factor in controlling the formation and thickness of glaze. More information on this can be found in the sections of this report dealing with the economic effects of glaze.

The temperature of the air near the ground is another factor in glaze formation, and like the temperature of surface objects, it is limited whenever glaze is developing to a narrow range of values in the neighborhood of 32°F. Data have already been presented indicating the values of this range of temperatures. Such a small range is less than the variations in temperature sometimes found within short horizontal and vertical distances due to changes in microclimate, even under cloudy and windy storm conditions when microclimatic influences are at a minimum. Brooks (1914) describes storms that were confined entirely to the top of Blue Hill because of slightly lower temperatures there than at the base. In writing about the December, 1929 storm in Massachusetts, he illustrates (1930) how changes in temperature over a short distance bring about a sharp demarcation of the boundary of a glaze storm.

"In Worcester, an altitude of 570 feet above sea level divided ice from bare areas. The line was so definite on trees that it could be described as at the level of the tops of first story windows in a certain house. While lower branches were bare, the tree tops bent under 1/4 inch of glaze."

According to Zikeev (1940), elevated areas open to the wind are especially subject to heavy glaze and he cites a case in the southern part of the Soviet Union where at the more exposed location of the Rostov Geophysical Observatory, the thickness reached 37 millimeters (1 1/2 inches) while at the same time the lower Rostov Hydro-Meteorological Station had only 12 millimeters (1/2 inch). He also points out that simultaneous observations at meteorological stations made at a height of 2 and 6 meters (6.6 and 19.7 feet) above the ground show glaze thickness can increase significantly in even this short distance. On occasions, conditions are favorable to a decrease in glaze thickness with height. At Toledo, Ohio, in March, 1928, observers noted that ice on objects 10 to 30 feet above the ground was only half as thick as on objects near the ground (Alexander, 1928). Finally, Zikeev (1940a) observes that the warmer microclimate of large cities affects the occurrence of glaze, as is evidenced by records which show that the meteorological station at Stalingrad experiences glaze of less intensity than the surrounding country.

In addition to its effect on thickness, microclimate can influence the duration of glaze.* Root (1924) gives an example of greater exposure to wind causing ice on trees to disappear more rapidly than ice on the ground. According to his description, after the storm of December 17 and 18, 1924, in Illinois, there was no thawing at all until December 30 and none of consequence until January 3. During this period the ice on trees gradually decreased in amount, but the ground conditions remained unchanged until the thaw. That glaze can be lost through evaporation when exposed to the wind even when the air temperature is far below 32°F., is shown by an observation made in Topeka, Kansas by S. D. Flora (1922). In this case a thin film of glaze disappeared during the night as temperatures dropped from 17°F. to 5°F. and while a strong wind blew from the northwest. By dawn of the next morning, the ice " ......was entirely gone, except in a few patches where the wind did not have free access to it." The heat-conducting and heat-storing capacity of surfaces may be an important factor in determining the duration of glaze, although most observations would indicate that under average conditions the ice will disappear almost as rapidly from one type of material as from another. It may be worthwhile to point out an observation made by Gold (1929), in which he states that the air temperature may rise 3 to 4 (F) degrees above freezing without causing any thawing of frozen ground because the frozen ground acts as a wet-bulb thermometer when moisture is present and will not thaw until the wet-bulb temperature reaches 32°F. This could have applications to the thawing of glaze.

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* See Figures 17, 18, and 19 on following pages for information on the duration of glaze in the United States as a whole and in certain states.

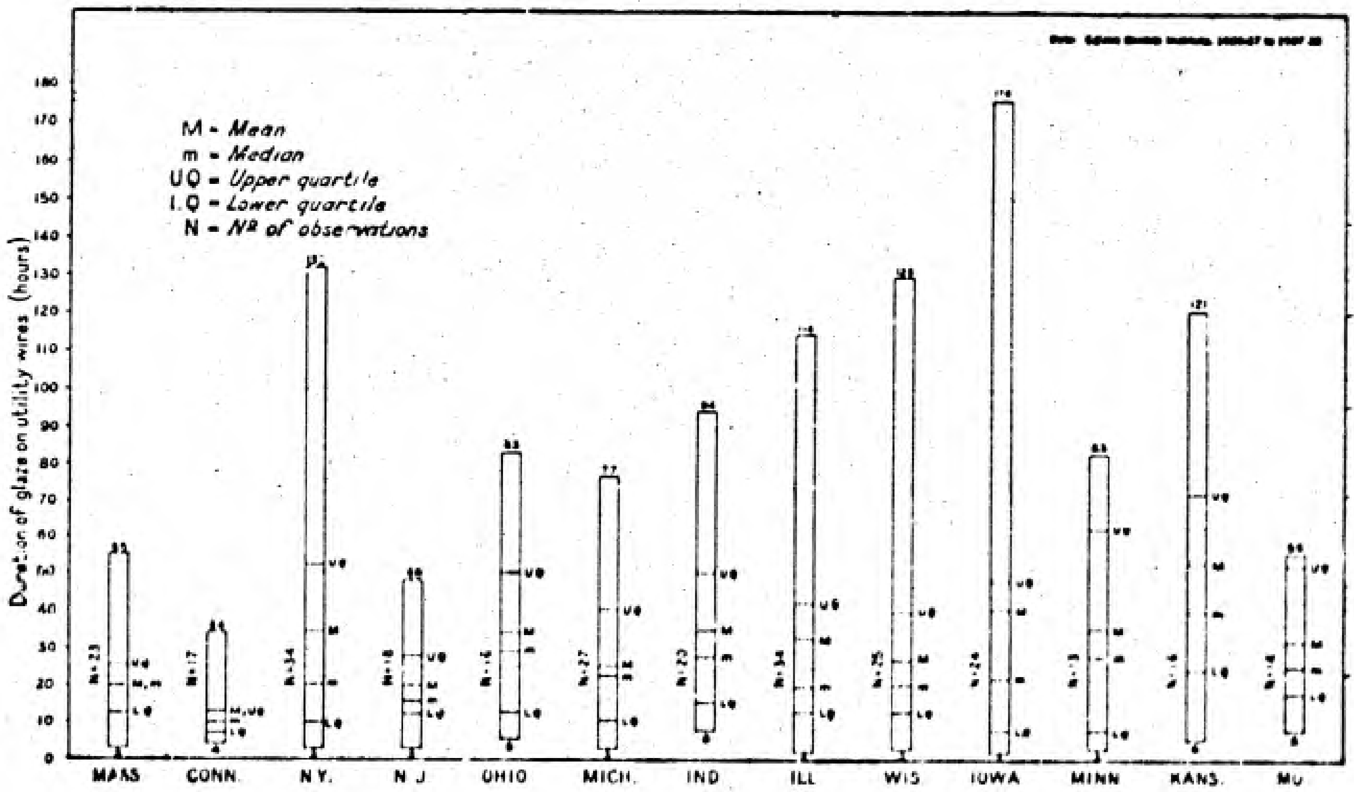

Figure 17. Duration of glaze on utility wires for selected states. If conclusions can be drawn on the basis of so few observations, the deposits do not persist nearly as long in New England as in the interior of the country.

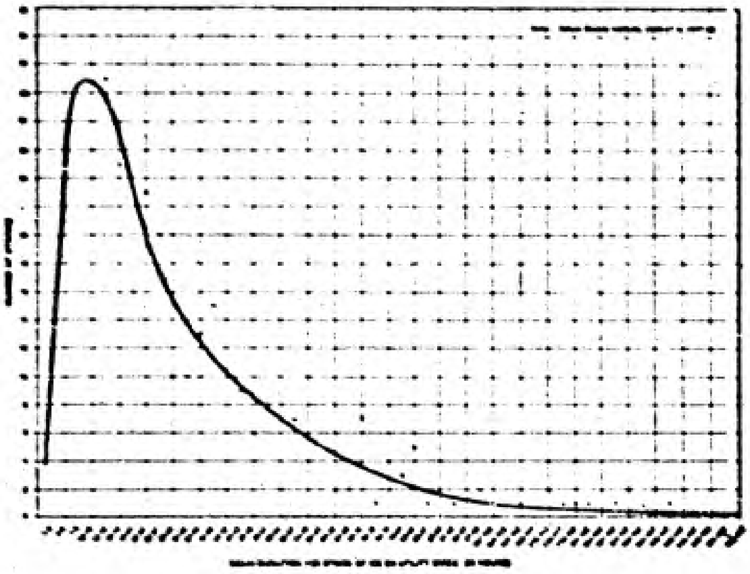

Figure 18. Mean duration per storm of ice on utility wires. The data plotted are for the entire United States, based on data for 452 storms occurring in period from 1926 to 1937-38

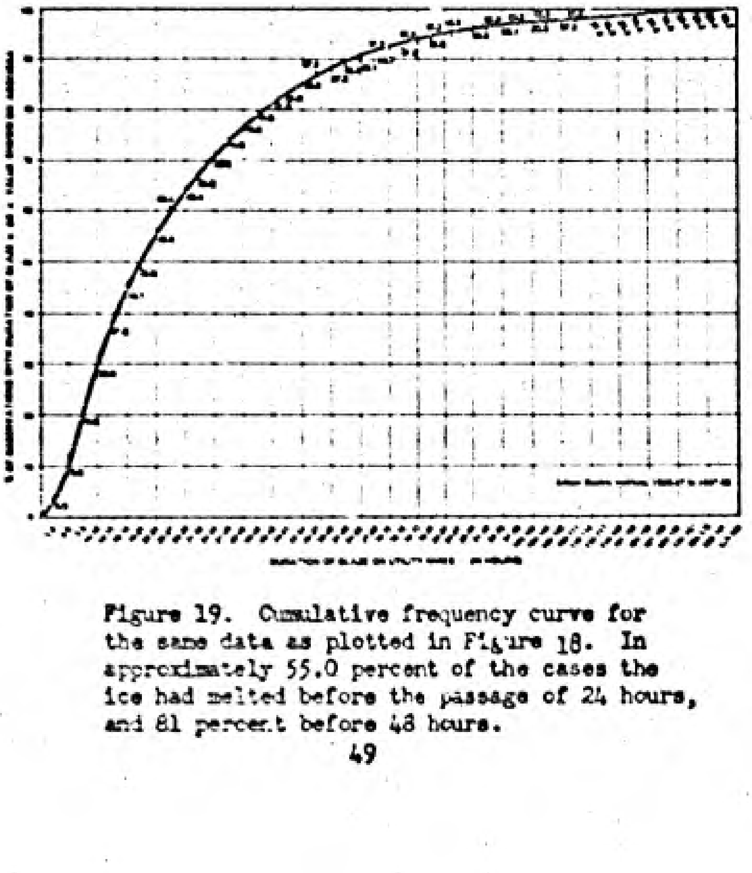

Figure 19. Cumulative frequency curve for the same data as plotted in Figure 18. In approximately 55.0 percent of the cases the ice had melted before the passage of 24 hours, and 81 percent before 48 hours.

Many other observers have presented evidence to show the importance of local influences in causing differences in glaze occurrence and intensity. Since most of this material concerns damage to trees, utility installations, and the like, it has been included in the sections of the report dealing with these subjects.

d. Distribution of precipitation types

A pure glaze storm, that is, one in which the only type of precipitation which falls is freezing rain or drizzle, is rarely seen. Some other form of precipitation normally precedes or follows, and even frequently accompanies the formation of the glaze. This is because storms with which glaze is associated are usually dynamic moving systems from which several types of precipitation are falling simultaneously. Where the storm consists of an active warm front, a classic pattern of precipitation may be observed (see Figure 20). If the warm front shown in this hypothetical case advances toward a certain location, snow, sleet, freezing rain, and finally non-freezing rain should be experienced, in that order. However, the situation is seldom this ideal and almost any combination or sequence of precipitation types can result. Brooks (1932), in describing a storm which occurred in the northeastern United States at the end of 1931 notes that the sequence was: heavy freezing rain, rain which did not freeze, and finally several inches of snow. A Louisiana storm of January, 1944, consisted of 36 hours of freezing rain followed by 4 inches of snow (McNayr, 1944). During a storm in Illinois in December, 1924, sleet and freezing rain alternated (Root, 1924). The storm of December 17 and 18, 1929, in western New York, had rain, sleet, and heavy snow in that sequence (Spencer, 1929).

Weather Bureau records for Trenton, N. J., from 1943 to 1952 show that in 41 storms the combinations of precipitation types occurring during glaze formation are distributed as follows:

		Storms
Freezing rain or drizzle	alone	15
	and sleet	13
	sleet and snow	8
	and snow	5

Most major storms involve all three forms, often occurring at the same time. Where freezing rain or drizzle alone occurs, the duration of the storm is frequently only an hour or so and often confined to the early morning hours. Where some form of precipitation precedes or follows the formation of glaze, non-freezing rain precedes on 2 occasions, and snow on 6, while non-freezing rain follows on 8 occasions, and snow on 5. Snow follows glaze at Trenton in about 1 case out of 9. When this occurs, extremely dangerous conditions are created, particularly for motor vehicles.

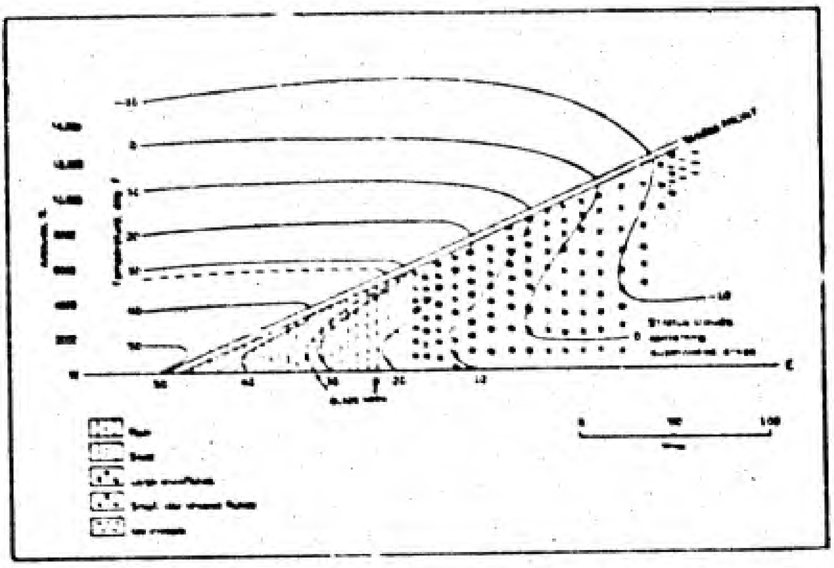

Figure 20. Cross section through a warm front during the occurrence of freezing rain. Most glaze is probably formed in a manner similar to this. Adapted by permission from General Meteorology, by Horace R. Byers Copyright, 1944, McGraw-Hill Book Company, Inc., N.Y.

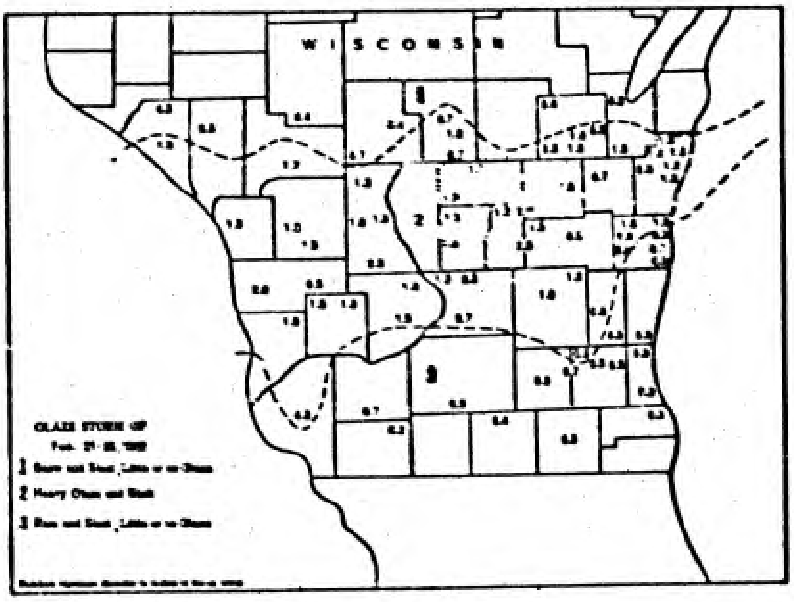

Figure 21. Distribution of ice thicknesses in Wisconsin resulting from the heavy glaze storm of February 21-23, 1922. Note the great variation of thickness over short distances. After a map in Lockwood (1922).

Considering the entire area affected by a storm and not merely a single point as in the above cases, the classic distribution of precipitation has been observed many times. One example is the great New England storm of November, 1921, in which heavy snow occurred in northern New England and heavy freezing rain in the south, while along the coast there was rain which did not freeze. In Figure 21, something approaching the classic distribution is given for a storm that struck the Great Lakes area on February 21 to 23, 1922.

In the average glaze storm, the area of freezing precipitation in generally located some distance ahead of the advancing frontal system; in the case of warm fronts in the central or eastern United States, 100 miles or so ahead of the front. This is the distance represented in Figure 20, and it checks fairly closely with those shown in Figure 7. Cave (1940) gives a similar figure for the January 27-29, 1940, storm in Great Britain.

The steeper gradient of cold fronts rapidly lifts the warm overrunning air to heights where temperatures drop below 32°F.; therefore the zone of active glaze formation is located closer to the front than it is with warm fronts. In addition, glaze follows rather than precedes the front, although a band of light freezing rain or drizzle sometimes is found ahead of a winter cold front. The writer observed glaze in this latter situation during the passage of a rapidly moving autumn cP cold front near Lincoln, Nebraska. The resulting ice was not thick, but was sufficient to make highways slippery and dangerous.

e. Wind conditions

Table II gives the wind speeds occurring with freezing rain and drizzle of various intensities at Indianapolis, Indiana, in the 5-year period 1948-1952. Moderate wind speeds were most typical, with approximately 92 percent of the observations recording speeds between 5 and 19 miles per hour.

TABLE II: FREQUENCY OF OCCURRENCES OF FREEZING RAIN OR DRIZZLE AT CERTAIN WIND SPEEDS JAN. 1948 THROUGH DEC. 1952; INDIANAPOLIS, IND.*

	Wind Speed (mph)					
	0-4	5-9	10-14	15-19	20-24	Total
January	6	33	33	3	2	77
February	0	1	26	7	1	35
March	0	9	13	4	1	27
November	0	0	1	3	1	5
December	1	6	14	14	1	36
Totals	7	49	87	31	6	180

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*Source: U. S. Weather Bureau

Of greater economic value than information on wind speeds recorded during actual glaze formation is information concerning the maximum wind speeds encountered during the period ice remains on the surface of exposed objects, particularly on trees and communication wires. Reliable information of this type is scarce, despite great efforts of interested parties, such as power company associations, to collect it. In three of the large groups of data available to the writer*, information concerning wind velocity was included; however, in almost all cases observations of ice thickness and wind velocity were not made at the same location. In fact, the ice measurement usually was taken at a power installation or some point where trouble was encountered on a line, while the wind observation was obtained from the nearest Weather Bureau station, which in some cases was 100 or more miles away.

A few observations in which ice thickness and wind velocity were taken at the same location are included in the Edison Electric Institute data. These have been summarized in Table III. The velocities given are the maximum 5-minute average during the period ice was on wires, and the thicknesses represent the greatest accumulation during the icing period. The two did not necessarily occur simultaneously. The range of wind velocities among the 148 cases varies from 0 to 50 miles an hour. The mean is 17.5; and 33.1 per cent of the cases indicate wind speeds of 20 or more miles per hour, and 14.9 per cent indicate wind speeds of 25 or more miles per hour. Of the 32 cases with ice 0.25 inch or more thick, 27 are associated with a wind of 15 or more miles per hour and 12 with speeds of 20 miles or more per hour. The mean wind velocity of cases with ice at least 0.25 inch in radius is 19.9 miles per hour. Considering some of the cases of extreme thickness, a 30-mile-per-hour wind is indicated with ice 2.87 inches in radius (probably not glaze, but the wind pressure effect on the lines would be the same), and for others the relationship is: ice 1.71 inches, wind 18 mph; ice 1.5 inches, wind 21 mph; ice 1.1 inches, wind 28 mph; ice 1.0 inch, wind 18 mph (3 cases). Considering the 6 cases with wind velocity 35 miles per hour or greater, the relationship is:

Ice thickness (inches)	Wind speed (mph)
0.39	35
0.78	35
0.30	40
0.26	45
0.79	45
0.19	50

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* Association of American Railroads data 1927 to 1937; Edison Electric Institute data 1926 to 1938; American Telephone and Telegraph Co. data 1917 to 1925 (all three unpublished).

It should be apparent that although combinations of high wind speeds and great ice thicknesses are unusual, they are entirely possible in the United States.

TABLE III: WIND VELOCITIES DURING PERIOD ICE WAS ON UTILITY WIRES

(Data: Edison Electric Institute, 1926-27 to 1936-37)

Wind velocity (mph)*	All cases No. of cases	All cases % of cases ≥ lower limit of category	No. of cases where ice was 0.25 inch or more in maximum thickness (radial thickness)
50 - 54	1	0.7	0
45 - 49	2	2.0	1
40 - 44	1	2.7	0
35 - 39	2	4.1	1
30 - 34	6	8.1	1
25 - 29	10	14.9	3
20 - 24	27	33.1	6
15 - 19	46	64.2	15
10 - 14	35	87.8	3
5 - 9	17	99.3	2
0 - 4	1	100.0	0
	148		32

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* Fastest average 5-minute wind speed during period ice was on wires

In an occasional glaze storm in the United States high winds may result from an accompanying thunderstorm, especially in those parts of the country where there is the possibility of conditionally unstable mT air becoming the overrunning warm air mass. During the storm of January 1951 in the southern states, very strong winds associated with a line of thunderstorms between southeastern Louisiana and north-central Mississippi caused damage to trees and utility lines and poles to be heavier than it would have been from the ice alone (Harlin, 1952). Severe thunderstorms added to the havoc of the New England storm of November 1921 (Brooks and Howe, 1921).

The state of the wind has been mentioned in some of the numerous descriptions of individual glaze storms found in the literature. These tend to support the statement of C. F. Brooks (1914) that during glaze in New England the wind may "blow a gale or not at all." Zikeev (1941) states that in the Soviet Union the probability of strong winds occurring with glaze is high, especially in those areas where glaze is heaviest and most frequent. In the Stavropol area (northern Caucasus), winds as high as 25m/sec (55 mph) have been observed, and in most storms the wind velocity will be at least 5 m/sec in velocity (11.2 mph). Of 9 weather stations scattered throughout the Stavropol district, 5 recorded speeds of 6 to 10 m/sec (13.4 to 22.4 mph) for 16 percent or more of the cases of glaze. Zikeev estimates that winds up to 20 m/sec (44.7 mph) are possible in most of the territory, with the exception of places in sheltered locations. He adds that mean velocities during glaze are generally very close to mean monthly velocities in that region during the winter period. If the same can be said of the United States, wind velocities during glaze are higher in this country, since on the average the wind blows harder in the central and eastern United States than in any comparable area in Europe. In fact, Zikeev's figures, which according to him indicate strong winds, would not be considered especially strong when compared with figures from the United States.

According to Winter (1936), strong winds seldom are experienced during freezing rain or drizzle at Vienna. More than half the total cases reported at Vienna from 1905 to 1935 had a wind velocity under 10 km/hr (6.2 mph). Fifteen out of 20 cases in which freezing drizzle alone occurred had wind velocities less than 10 km/hr.

f. Summary

The area affected by any one glaze storm varies in size from a few square miles to distances that extend from the central part of Texas to southern New England. The average storm of more than local size probably deposits ice on an area 200 to 600 miles in length. Due to the changing nature of the storms as they move and the influence of the microclimate, there is generally considerable variation in thickness of ice deposited within the affected area. Locations exposed to strong winds and in which temperatures are apt to be low during storms are most likely to receive heavy deposits.

Freezing rain or drizzle seldom occurs by itself. Snow, sleet or non-freezing rain or drizzle almost always precede or follow or even accompany the formation of glaze. A classic sequence of precipitation consisting of snow, sleet, freezing rain, and non-freezing rain, in that order, may be observed as a storm passes over a point, but almost any possible combination or sequence of precipitation types can occur.

Wind data during the period of glaze formation and the period during which ice remains on surfaces are scarce, but the small amount available suggests that moderate velocities prevail. However, speeds of 25 or more miles per hour are not unusual, and there have been cases of winds in excess of 40 miles per hour occurring with ice deposits 0.5 inch or more in thickness. Strong winds with glaze appear to be more common in the United States than in other parts of the world.

Part II

Geographical Distribution of Glaze

1. The United States

a. Sources and Methods of Evaluating and Presenting Data

Some features of the climatology of glaze in the Unites States are presented in Figures 22 to 32. It will be noted that many of these maps are characterized by a general irregularity of pattern and lack of smoothness of isarithms. This probably can be explained by the shortness of the period of record on which they are based. Few of the records exceed 10 years; therefore, it is not unusual to expect variabilities in frequency and intensity within areas which, given a longer record, would probably be homogeneous. The fact that glaze is a somewhat spotty, discontinuous phenomenon in its geographical distribution (as is thunderstorm precipitation, for example) adds to this. In locating isarithms, the author to a certain degree "drew for the data". Some generalizing is done, but not as much as is possible, primarily because the shortness of record does not seem to justify it. For example, in Figure 22 the 9 to 17 storms category that extends southward along the Cascade — Sierra Nevada Mountains very likely should be continued to the south to join the similar area in the mountains of southern California. Most of the maps are compiled on the basis of the total number of storms occurring within the periods covered by the data, instead of on the basis of the average number of storms per year. This is done to avoid giving the impression that there maps are representative of long-term frequencies.

Before proceeding with a detailed discussion of these maps and diagrams, the data on which they are based and the manner in which they are compiled will be described.

(1) U. S. Weather Bureau data

A limited amount of direct observational material pertaining to the thickness and duration of ice resulting from glaze storms was obtained from the U. S. Weather Bureau. With two exceptions, the Weather Bureau has not undertaken a systematic program of glaze observations; although, of course, freezing rain and drizzle are regularly observed. Daily measurements of the thickness of snow and ice on the ground are made at most stations but no distinction is made as to the nature of the ice or its origin. In the section entitled "Remarks, Notes and Miscellaneous Phenomena" of standard observational form No. 1130, occasional reference is made to the thickness and duration of glaze, but not on a systematic basis.

In the 1930's, the Bureau cooperated with the Edison Electric Institute and other electric utility organizations in the observation of glaze deposits on so-called "sleet racks." These consisted of frames, 5 to 6 feet high, upon which several sizes of wire were mounted. Approximately 30 Weather Bureau Stations cooperated in this program. According to information contained in an unpublished report by Smith (1936), 293 measurements of glaze were taken from these "racks" by Weather Bureau personnel.

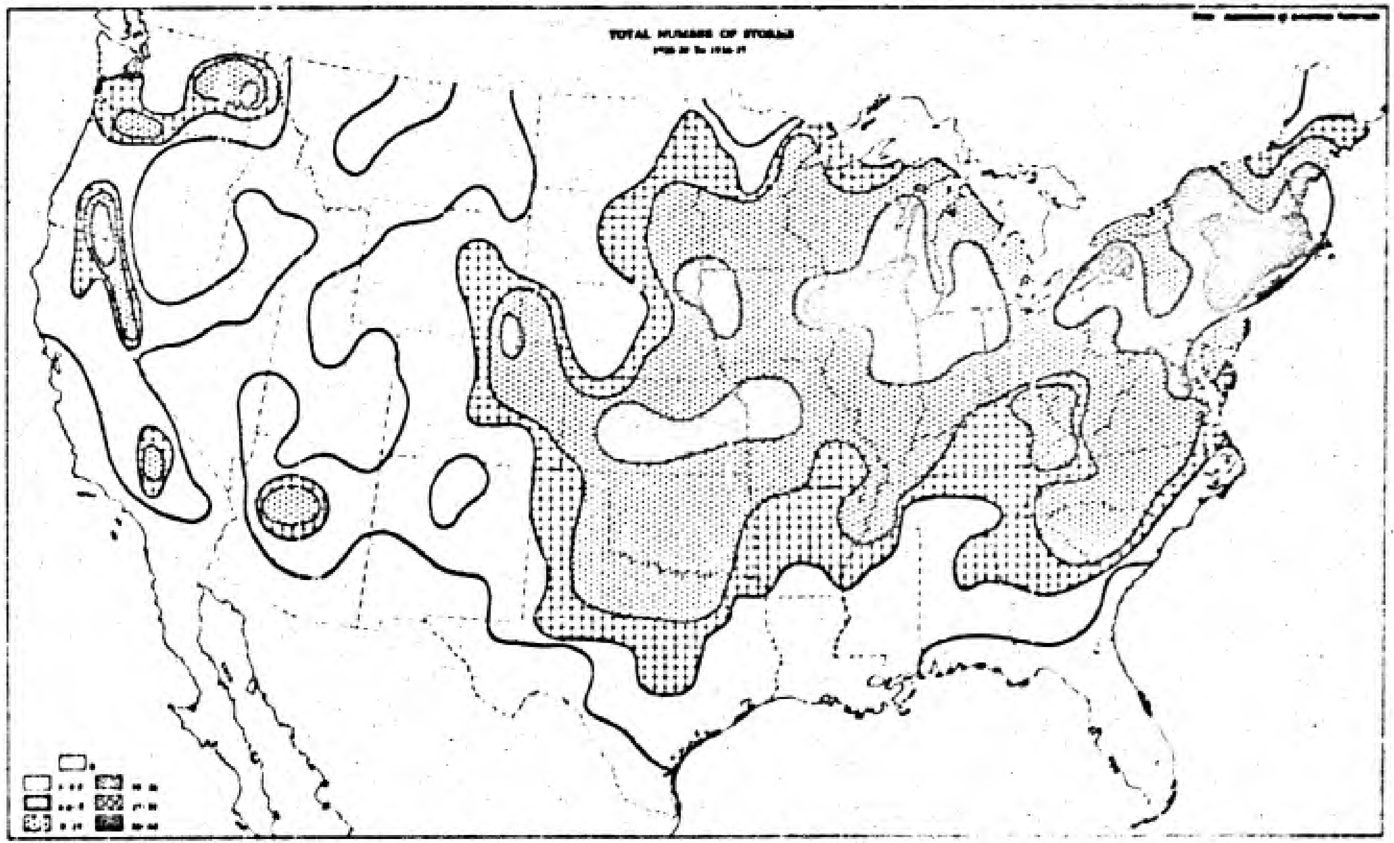

Figure 22. Total number of glaze storms, without regard to ice thickness, observed during the 9-year period of the Association of American Railroads study (undated).

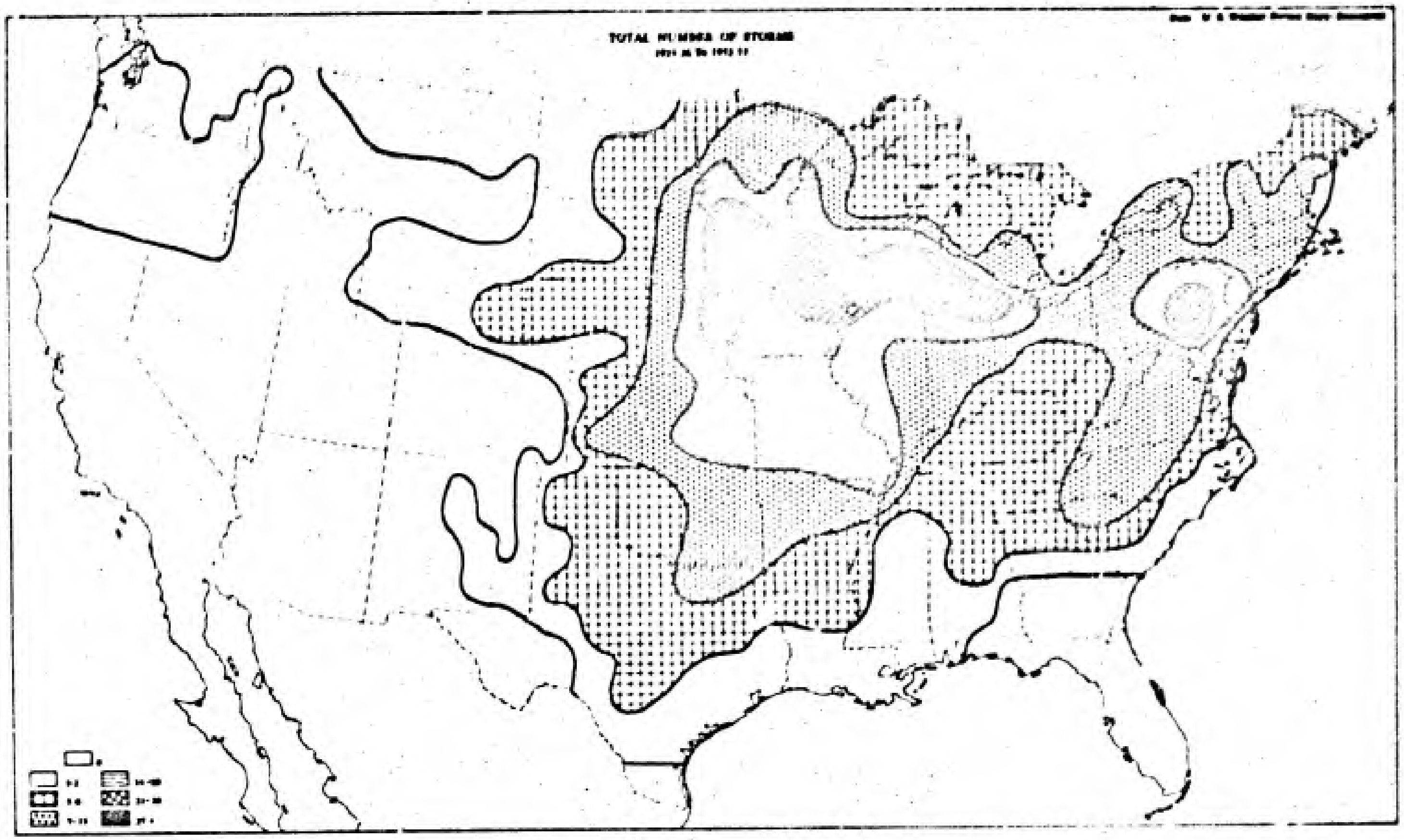

Figure 23. Total number of glaze storms for a 28-year period ending with the winter of 1952-53, as reported in "Storm data and unusual weather phenomena", Climatological Data, National Summary, U. S. Weather Bureau. (Before 1950 these storm reports appeared in the Monthly Weather Review under the title "Severe Local Storms".)

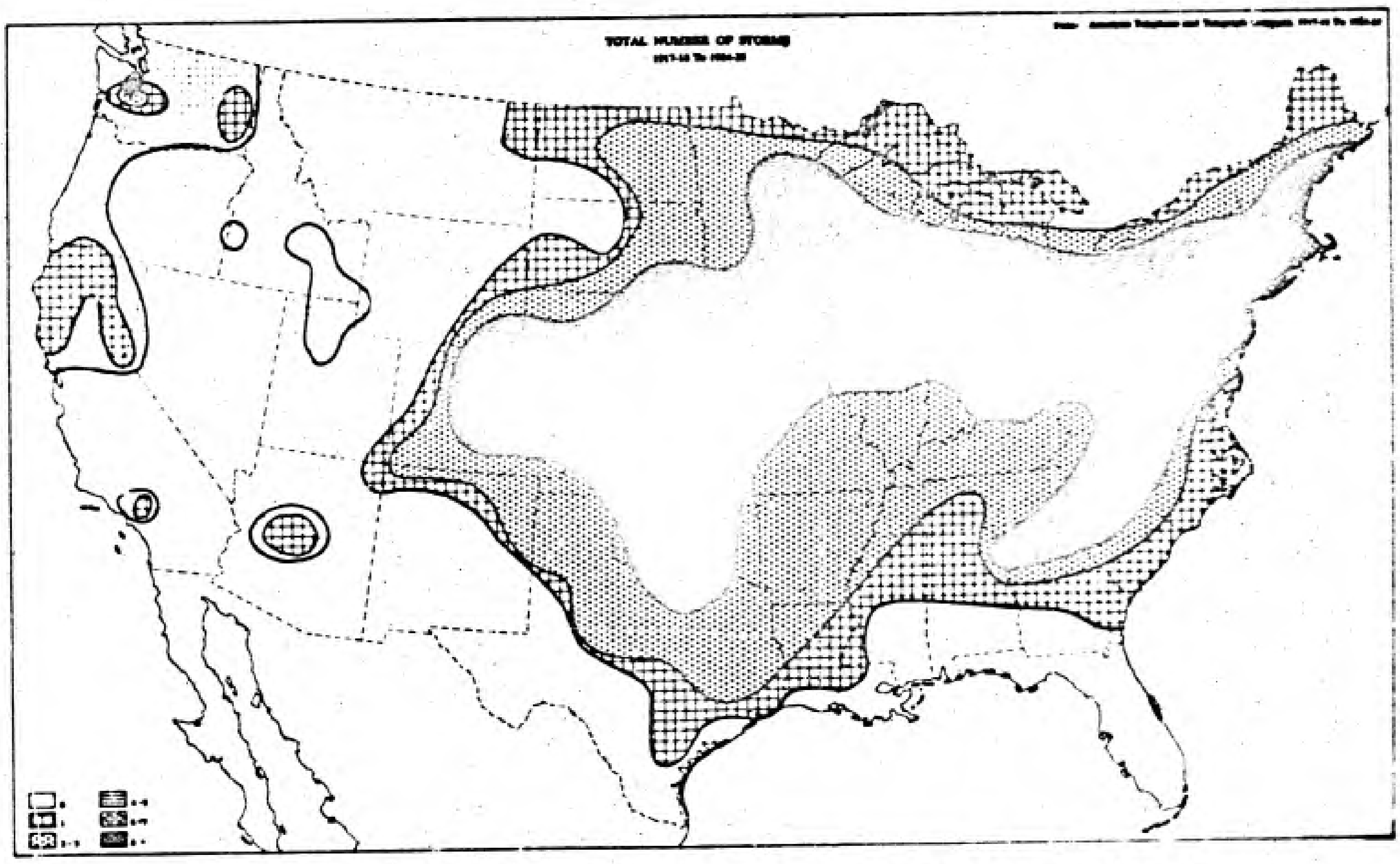

Figure 24. Total number of glaze storms observed during the 8-year period of a study conducted by the American Telephone and Telegraph Company. Only storms inflicting damage on lines or poles were reported; consequently, the map must be considered as representing only the heavier-than-average storms occurring during the period.

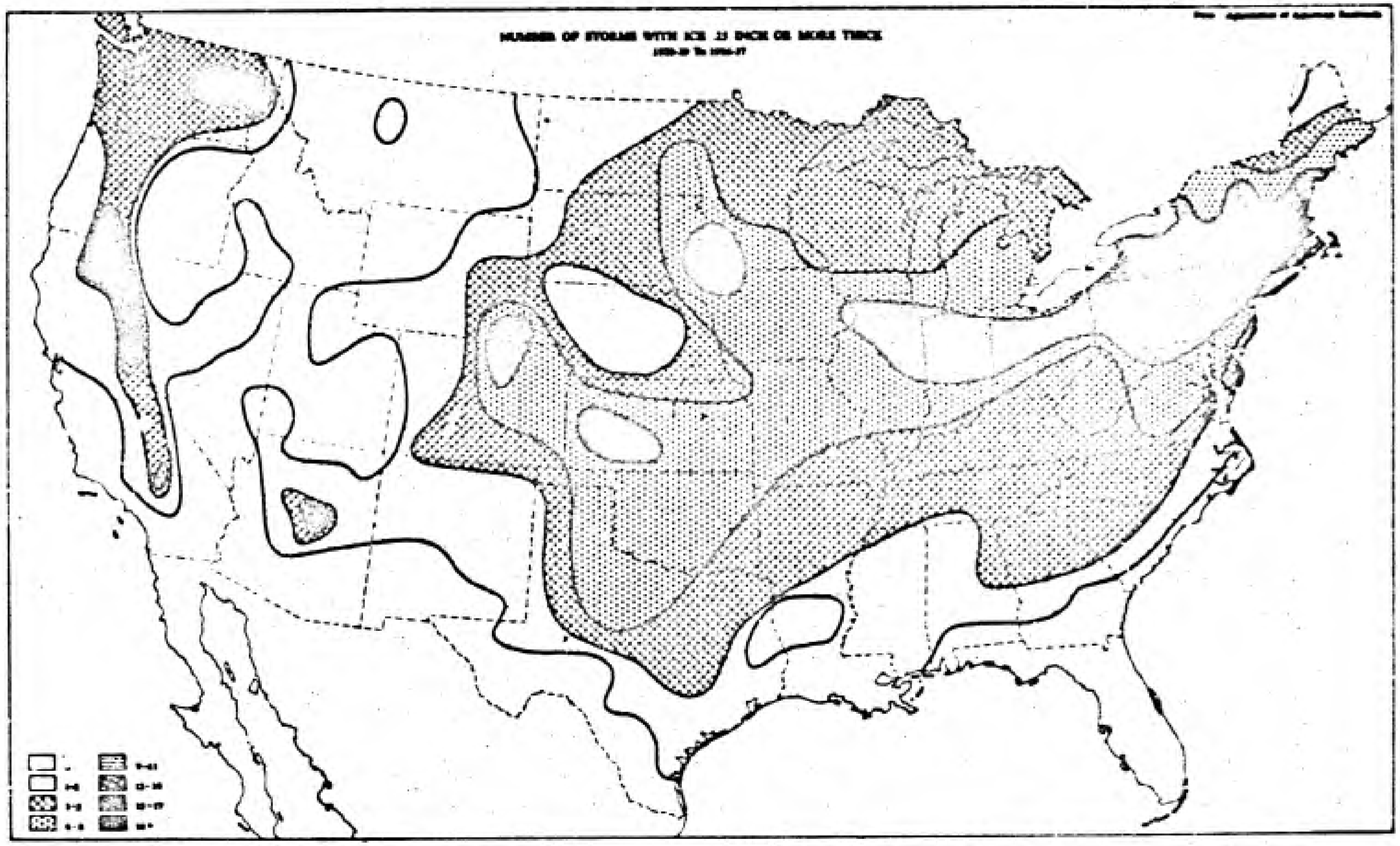

Figure 25. Number of times ice 0.25 inch or more thick was observed during the 9-year period of the Association of American Railroads study (undated). Note that the Columbia River gorge area, in which thick glaze is fairly common, does not show up as an area of high frequency on this map.

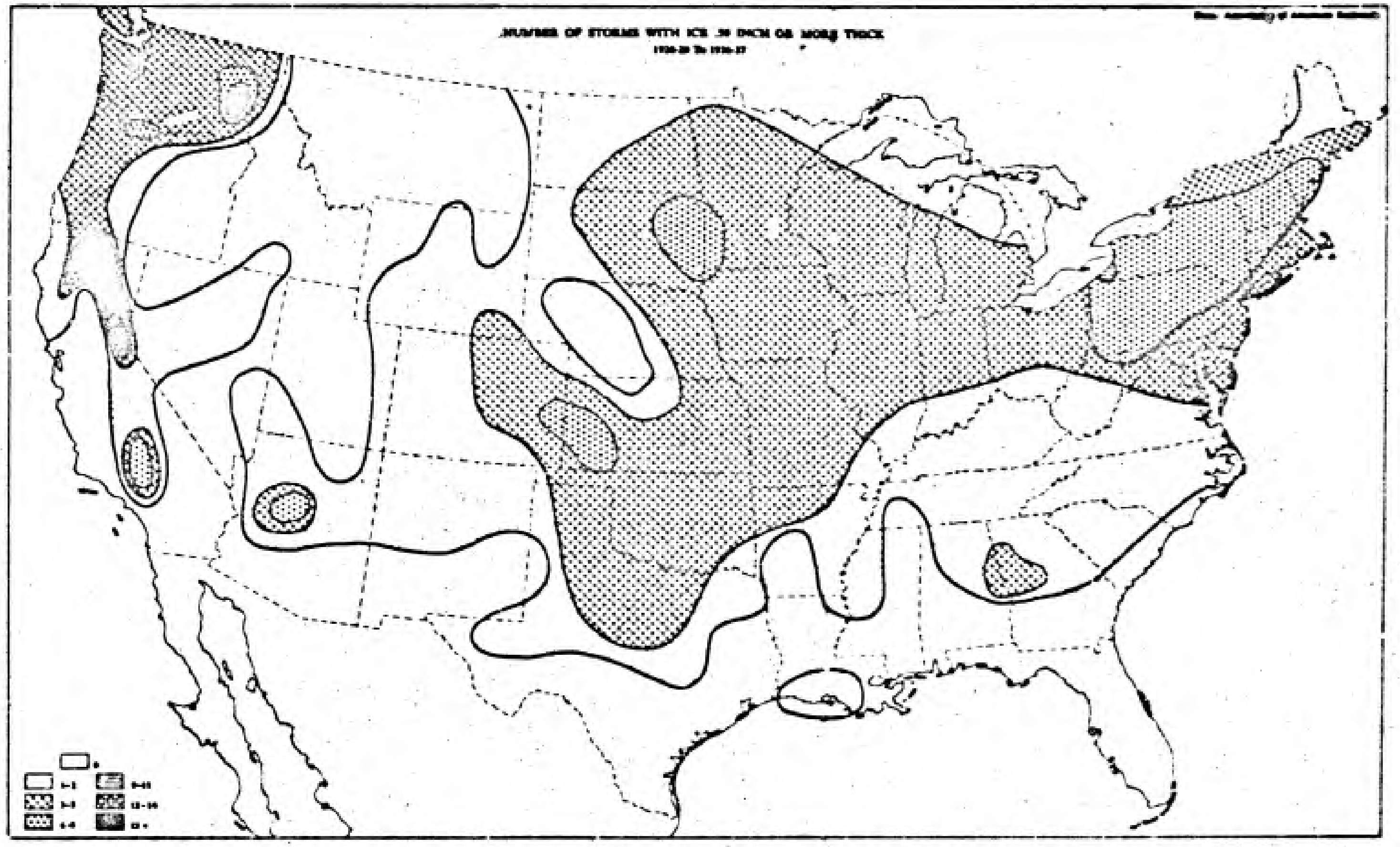

Figure 26. Number of times ice 0.50 inch or more thick was observed during the 9-year period of the Association of American Railroads study.

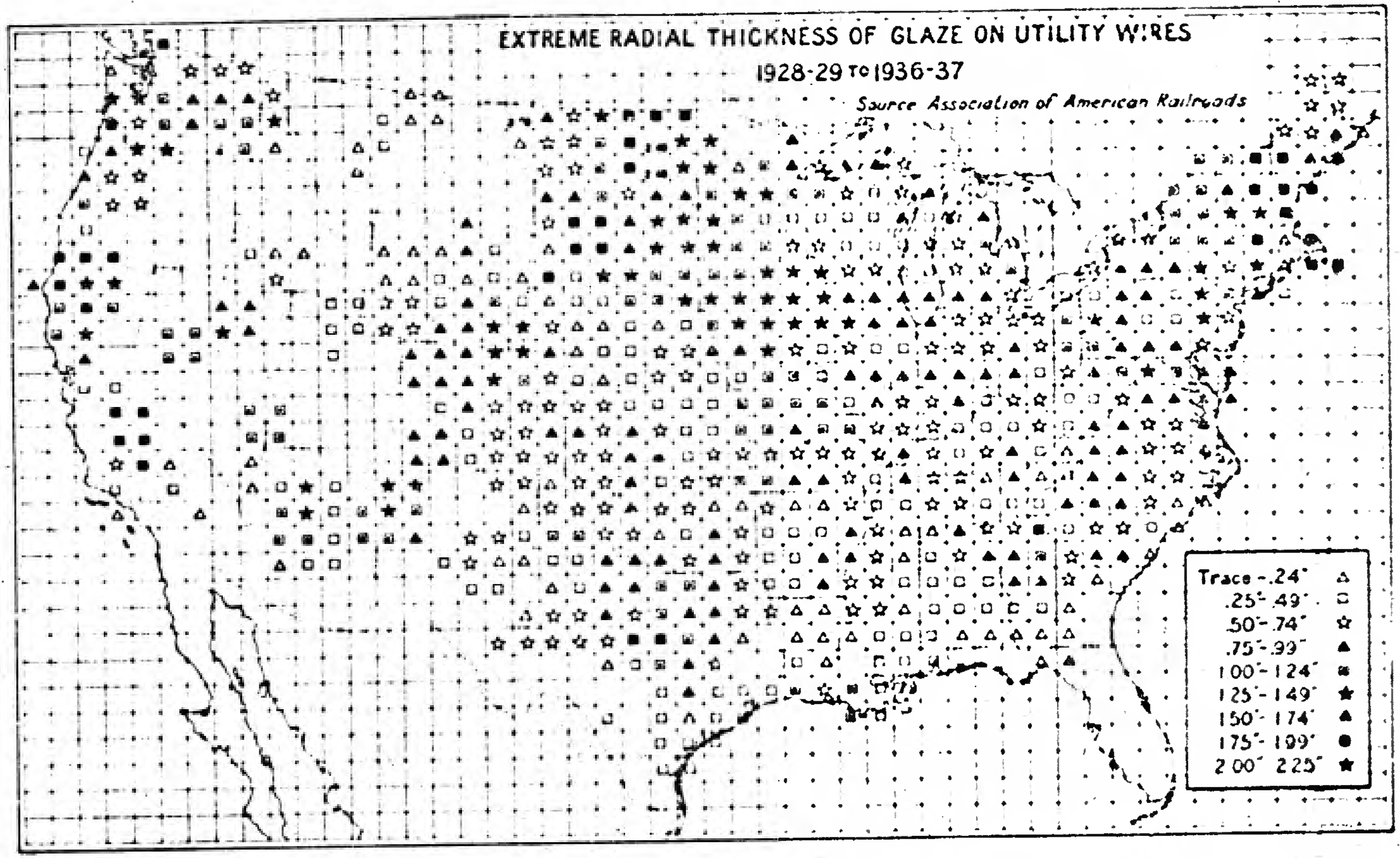

Figure 27. Greatest thickness of ice observed in each grid square during the 9-year period of the Association of American Railroads study.

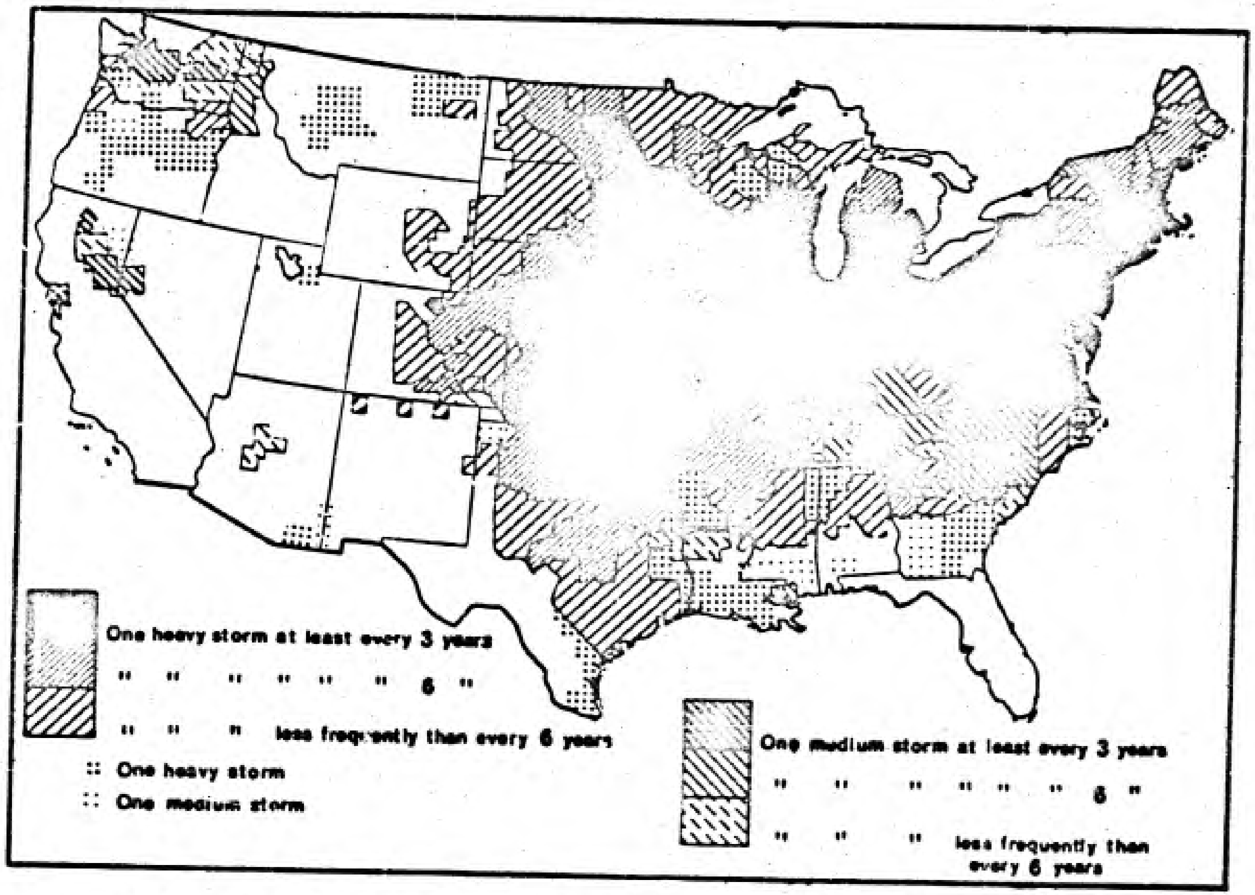

Figure 28. This version of the "Sleet Storm Map" of the American Telephone and Telegraph Company (1933) is reprinted, with permission of the author and publisher, from Dr. George H. T. Kimble's book Our American Weather, New York, McGraw-Hill, 1955. Cartographic work for this version was done by Mr. Jean Paul Tremblay of the American Geographical Society. The map is based on data for the period ca. 1911-1933.

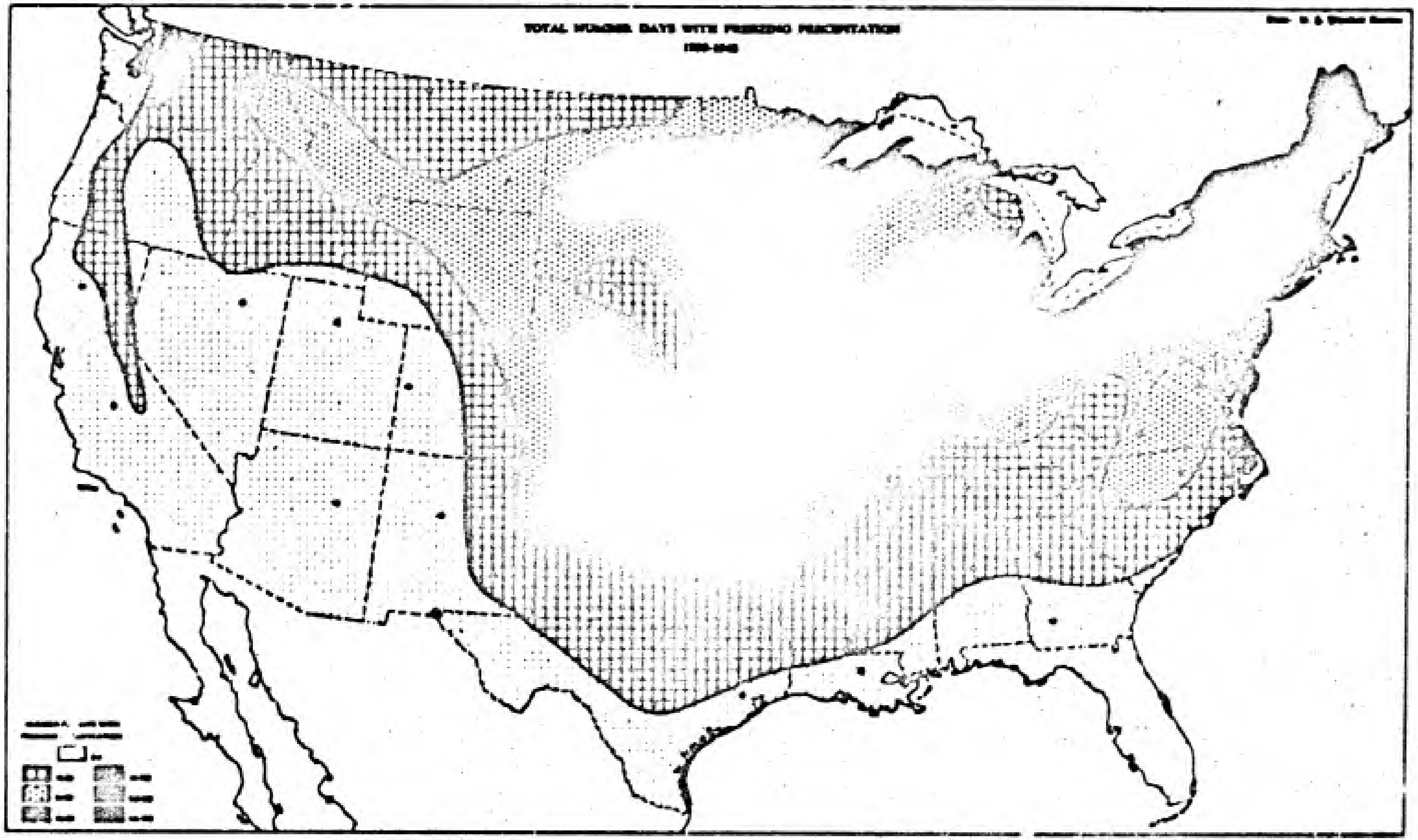

Figure 29. Total number of days with freezing rain or drizzle in the 10-year period from 1939 to 1948. Based on data from 95 Weather Bureau stations (small circles on the map).

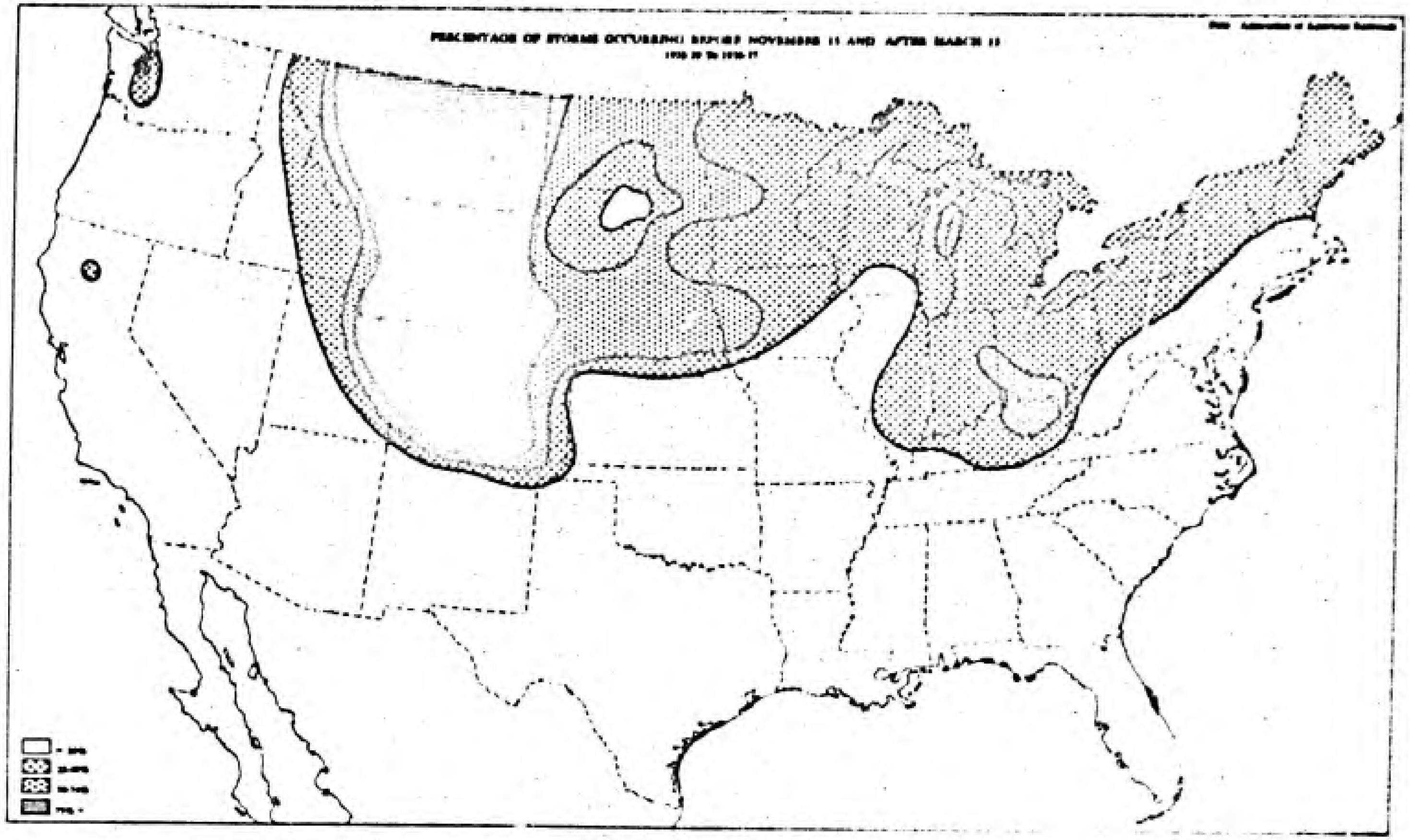

Figure 30. In the northern states, and particularly in Colorado, Wyoming, and Montana, there is a definite concentration of glaze storms in the period before November 15 and after March 15. In the vicinity of Cheyenne, Wyoming, up to 90 percent of the storms reported by the Association of American Railroads study occurred in either of these periods.

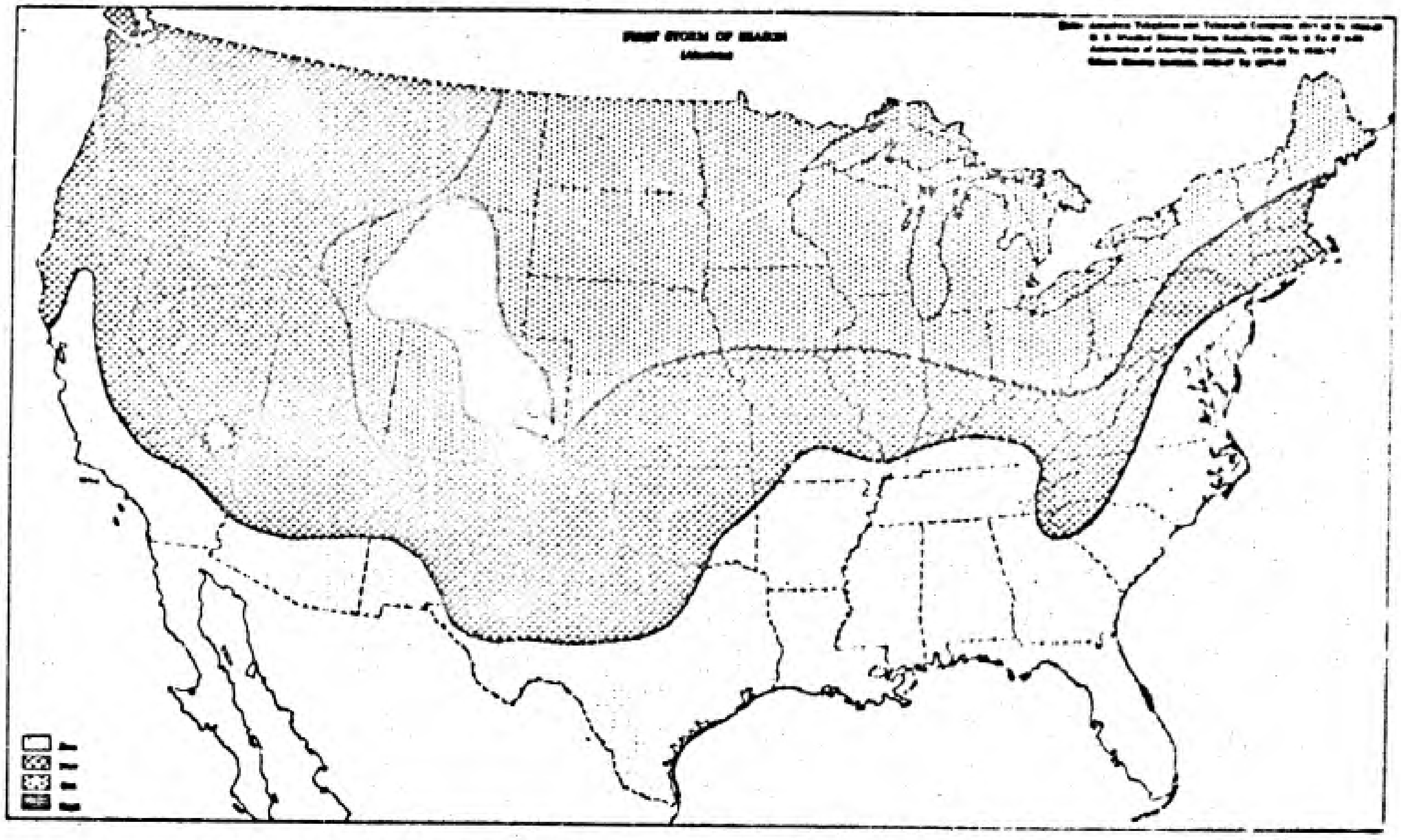

Figure 21. Earliest month of the season in which a glaze storm was reported by the four sources of data listed on the map.

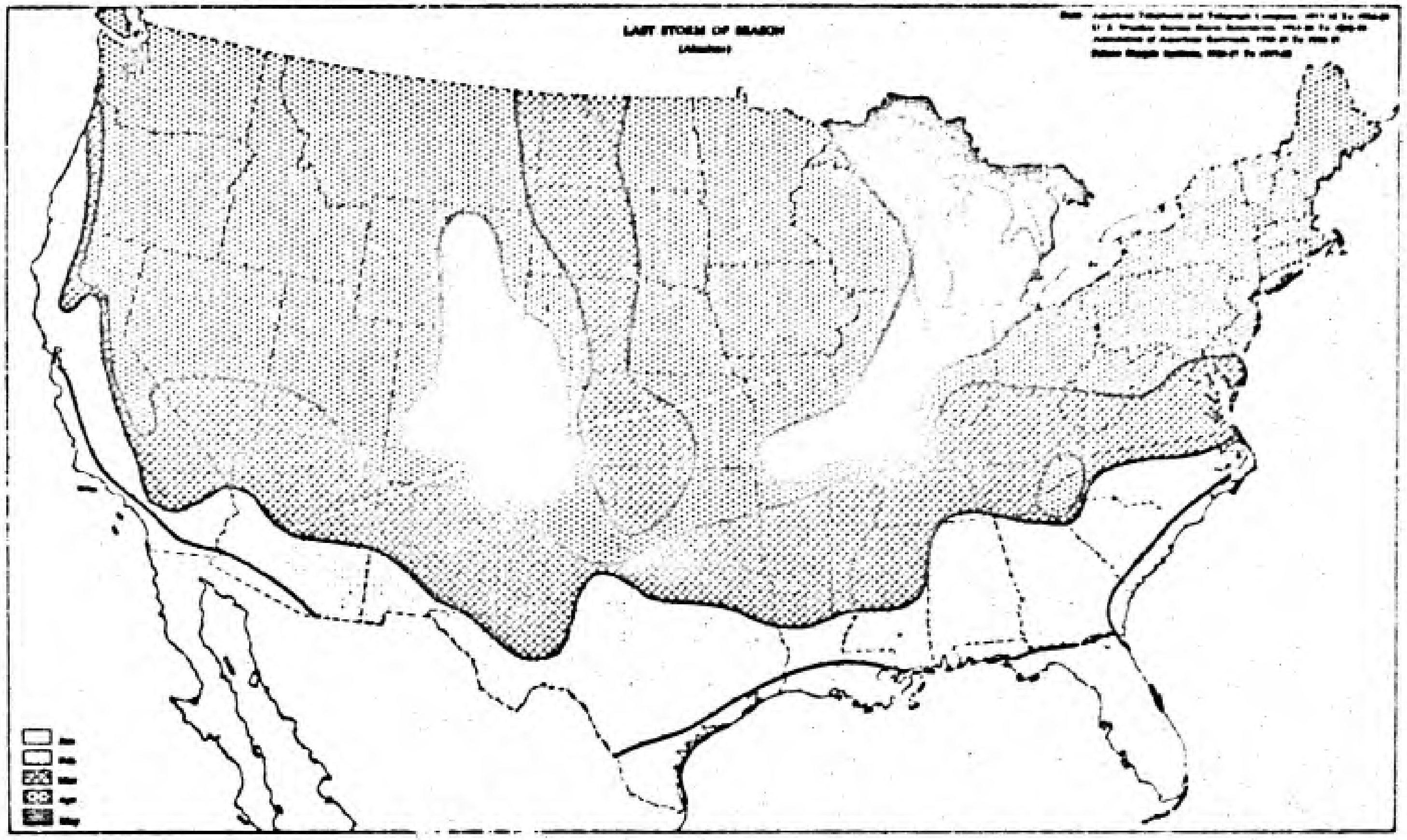

Figure 32. Latest month of the season in which a glaze storm was reported by the four sources of data listed on the map.

Although these data are small in quantity and some are missing, they are of value, particularly in providing information regarding ice duration on wires. With similar information collected at telephone or power company installations, the data have been used as the basis for the material on the duration of ice presented in Table XV and Figures 19 through 21.

So far as this writer knows, the only other systematic observations of glaze by the Weather Bureau are those taken for the present report, during the winters of 1953-54 and 1954-55 at 40 stations east of the Rockies. In selecting the stations, an attempt was made to choose those located where personnel could observe the behavior of ice on the ground and highway surfaces with a minimum of departure from their customary routine; therefore, it was not possible to obtain an ideal geographical distribution of stations. However, because the primary purpose of the observations was not to establish a pattern of the climatic distribution of glaze in the United States, but to collect information which would allow comparisons to be made of glaze behavior on different surfaces, this defect in distribution is probably not of great significance.

The Weather Bureau furnishes brief descriptions of most glaze storms occurring in the United States in the section of its monthly publication, Climatological Data, National Summary called "Storm Data and Unusual Weather Phenomena." (Before 1950 these descriptions appeared in the Monthly Weather Review under the title "Severe Local Storms.") The writer extracted all information pertinent to glaze storms in these summaries for the period 1925-26 to 1952-53. This material, however, is not of a quantitative nature and the amount and type of information provided varies from summary to summary. In some instances no distinction is made between sleet and glaze. In such cases an attempt has been made by the author to clear up the uncertainty by sending a questionnaire to first-order Weather Bureau offices in the storm area. All questionnaires were filled in and returned; therefore it has been possible to resolve virtually every case. Sometimes storm areas are accurately described, but more often the description is general (e.g., a storm will be reported as having occurred in northeastern Minnesota, or possibly only one city or town will be mentioned as having experienced the storm, without specifying to what extent it occurred in the surrounding area). In addition to the location and dates of storms, information is often given concerning the estimated cost of damage and any injuries or deaths caused by the storm. Occasionally, descriptions of storm conditions and economic effects are complete, but in general they vary so much in the quantity of information that they cannot be used as the basis for an investigation. Definite data are rarely given on ice thickness. The coverage of storms in these summaries has not been the same throughout the period during which they have been published. More than 2 or 3 times as many storms of all types have been reported recently as were reported in earlier years. But even in recent years, some storms of fairly large size and severity have been omitted. Despite these disadvantages, it is felt the value of this material warrants preparation of the map in Figure 23. It should be used with caution.

(2) Public utilities data

Because of the effect glaze has on their operations, various railroad, electric power, and telephone associations have taken great interest in the collection of glaze data. The studies conducted by these associations were, of course, designed to meet their own particular needs, consequently the data sometimes have deficiencies for purposes of general climatic analysis. For example, virtually all thickness measurements pertain to ice on wires of various diameters, height above the ground, and general exposure. To apply these data to ground and structural surfaces would be unrealistic. Another handicap is that none of the material represents the period after 1937, and none covers a span in excess of 10 years. Considering the somewhat cyclic nature of climate in North America, it becomes obvious that use of the data could give an unrepresentative picture of the present-day frequency and distribution of glaze in the United States. Another drawback is that generally no clear distinction is made among the different types of solid precipitation which form on wires. There is no doubt that the thicknesses of wet snow and rime deposits have been included along with glaze measurements. The great difference in the density of the three forms would make the use of such data rather dangerous as a reliable basis for structural design. Another difficulty is that a sizeable percentage of the observations were not made at fixed and predetermined locations; most appear to have been taken at random locations wherever a line crew happened to be repairing some damage. A final limitation arises from uncertainty whether a standardized technique was employed in making the thickness measurements.

(3) Association of American Railroads data

The most useful of the studies referred to is one made by the Association of American Railroads for the entire country, covering the period from the winter of 1928-29 to the winter of 1936-37. The data, all pertaining to the occurrence of ice on utility wires, are drawn from three sources:- railroads, power companies, and a few Weather Bureau stations. The compilation consists of ice-loading and wind-loading measurements taken at more or less random locations. Because the technique used by the present writer in preparing this group of data for mapping is also used for data from several other sources, it will be described in some detail.

(4) Analyzing and mapping public utility data

The data for each state were separated as nearly as possible on the basis of individual storms. Each measurement of ice thickness was plotted in its proper location on an outline map. The 1:5,000,000 county outline map of the Bureau of the Census was used for this purpose. A total of more than 1,600 measurements were plotted on the 9 annual maps prepared. Once this was accomplished, an attempt was made to delineate storm areas by drawing boundaries around the edges of the storms. In doing so it was assumed glaze would extend approximately 20 miles in all directions from a site where an observation was taken. There is no doubt that, drawn in this manner, the size and configuration of storms are far from being precise. It is not known, for example, whether glaze formed at every point within the area thus bounded, although this was assumed in carrying out the next step. Certainly some of the storms must extend considerably more than 20 miles beyond the drawn boundary, especially when it is recalled that a large percentage of the observations were taken only at sites where damage occurred. Observations in a few of the storms apparently were confined to points along railroads. One storm, for instance, follows the route of the Burlington Railroad across Iowa and Nebraska, and another follows a railroad line extending from Atlanta, Ga., northeastward into South Carolina. Figure 15 presents an example of the method just described. Because of the limitations of map scale, all of the measurements for this particular storm are not shown nor are they precisely located.

The annual maps (see Figure 16, for an example of one of them) have been combined into single maps representing different aspects of the glaze climatology of the entire 9-year period of the study. Because of the random location of the sites from which the data were collected, ordinary procedures of climatological mapping could not be followed. Instead, a grid of squares 60 miles on a side (see Figure 27) was drawn on a sheet of heavyweight, transparent vinylite; this was placed in turn over each of the 9 annual maps in order that a tally could be made of the number of storms occurring in each square.* Notation was made of the date of occurrence and the thickness of the ice. Where several measurements were made in one square, the maximum thickness value was chosen. In some cases, no measurements were taken in a particular square, yet it seemed likely glaze had formed there, because the area was surrounded by locations in which it did form. When this was encountered, a storm was considered to have occurred in the square and a value for the ice thickness was obtained by interpolating between the given observations.

With the completion of this tallying process, the next step was to choose the form of the final maps to be published. It was decided that the grid was fine enough (975 squares to cover the United States) to permit the drawing of isarithms, by using the center of each grid square as a reference point.

(5) Edison Electric Institute data

Another group of data was obtained from the Edison Electric Institute of New York City. These data were measurements of ice thickness and weight on utility wires, plus wind and temperature data from the nearest Weather Bureau station, which in many cases was 20 or more miles away.

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* The maps are all constructed on the Albers equal-area projection; therefore, each grid square represents on the map precisely the same area as every other square.

The data were collected in 34 states; some important states, such as Pennsylvania, were not represented. In some states, data were collected during the period 1926 to 1938; in others, during the periods from 1927 or 1928 to 1935 or 1936. Most of the observations appearing in this group are also included in the Association of American Railroads data. A few observations in the Edison data and not in the Railroads data are used to supplement the latter.

(6) American Telephone and Telegraph Company data

The American Telephone and Telegraph Company began systematically compiling information of glaze on utility lines from their local affiliates throughout the country in 1911 and continued the practice until 1933. Most of the original data have been lost, but one group, covering the period from the winter of 1917-1918 to 1924-25, remains. The data, which are for the entire United States, give ice thickness, coincident wind velocity, and number of poles downed at locations in each storm. The information on ice thickness and wind does not seem reliable and this information has not been used, but the geographical location of storms has been mapped using the method outlined for the Railroad data. The map in Figure 24 gives these results. The observations on which the map is based are limited almost entirely to storms in which damage occurred to telephone lines or poles; therefore, it can be considered as a map of only the more severe storms during the period in question.

Figure 28 is a version of a map made by the American Telephone and Telegraph Company on the basis of the data they collected between 1911 and 1933. Like the data above, it also represents only those storms which inflicted damage to telephone installations. The preparation of the map has been explained in a letter to the writer from C. M. Mapes, Assistant Chief Engineer in the New York office of the American Telephone and Telegraph Company:

"The local Telephone people throughout the country were requested to report from field observations such pertinent material as distance in north-south and east-west direction between the destructive limits of the storm and the center of greatest damage; diameter of ice-coated wire ...and the amount of damage in terms of poles down, wires broken, etc.

"These data were reported each spring by all operating companies of the Bell system, and associated with previously reported data, the whole analyzed anew each year.

"...the 'heavy and medium' storms used in this report were not the 'heavy and medium' storms as defined by the National Electrical Safety Code. When the diameter of the ice covering the wires was 3/4 inch or greater, the storm was treated as a heavy sleet [glaze] storm. Also, in certain cases where the thickness of the ice was not reported, sleet [glaze] storms were classified as heavy in consideration of the amount of damage having been commensurate with that occurring in storms in which the diameter of the ice was 3/4 inch or greater. When the diameter of the ice was less than 3/4 inch, but sufficient to cause appreciable damage to plant, the storm was treated as a 'medium' storm."

(7) Pennsylvania Electric Association data

The Pennsylvania Electric Association, a state power agency, has been active in compiling glaze data. Between 1927 and 1944, data concerning ice thickness and weight on wires were obtained at approximately 60 locations scattered throughout the state. Wind and temperature data also were taken for many storms but, as in the case of previously described data, the information was obtained from the nearest weather station. In addition to this standard information, the approximate percentage of the area of Pennsylvania covered by each storm is given. It is interesting to note that 21 percent of the 110 storms reported covered at least 40 percent of the state (an area of about 18,000 square miles), and that 32 percent covered 10 percent or less. Again, there are certain limitations to the use of the data, in that some of the stations were not established at the beginning of the period and others were moved subsequent to being established.

(8) Data from individual public utility companies

Most of the major utility companies of the nation have compiled detailed ice data about their own systems. However, only a very small amount of this has been used by the writer, primarily because most of it is in a loosely tabulated form and a tremendous amount of time and money would have been required to prepare enough of it to obtain a picture of conditions in the country as a whole, or for even large sections of the country. In addition, much of these data are not comparable, having been collected for different periods of time and under different observational conditions. Requests were sent to some utility companies asking if they could furnish information describing the effect any individual storms might have had on their plants. A few responded, some with very good descriptions which have been of great value to the study.

b. Geographical distribution

(1) Location of "Glaze Belt"

In paragraph 3b of Part I of this report, it is shown that most glaze storms in the United States involve the interaction of mT and cP air masses in a frontal situation. It is natural, therefore, to expect the greatest frequency of glaze in the part of the country where these two air masses are most commonly brought together under cyclonic conditions. According to a map by Borchert (1953), showing the mean stream flow and zones of air mass interaction in January, this meeting of the air masses would be along a line extending from southern New England west-southwest to Ohio, then gradually curving into the southwest and south across Indiana, Illinois, Missouri, eastern Oklahoma, and northwestern Texas. Reference to Figures 22, 23, and 24 will reveal that this line lies near the southern margin of the principal glaze region of the country. That the line is found near the southern margin of the glaze belt is understandable, since glaze almost invariably forms in the area dominated by the cold air mass on the poleward side of the frontal zone. Also, the line would be located farther south in January than in any other month. Haurwitz and Austin (1944) place the mean January position of the polar front, which is essentially what Borchert's line is, far to the south, over the Gulf of Mexico and Florida. The most frequent meeting of mT and cP on the surface will take place somewhere in the wide area between the Borchert position and the Haurwitz and Austin position. As pointed out above, with freezing rain developing after mT has overrun the cP for some distance, one would expect most glaze development to be located to the north of this zone of most frequent surface contact.

However, to understand why the glaze belt lies where it does, the temperature must be considered. As Brooks (1938) says, the glaze belt is found in the central portion of the eastern United States because, "Toward the south, the temperatures of the lower air fall below freezing less often. Toward the north, the frequency of upper air temperatures above freezing diminishes." Monthly maps of the average daily minimum temperature in the Atlas of American Agriculture (U.S. Dept. of Agriculture, 1936) locate the 30°F. isotherm from December through February along a line from southeastern Virginia across central North Carolina, northern Georgia, southern Tennessee, and northern Arkansas, then southwestward across southeastern Oklahoma and into north-central Texas. South of this line, fewer than 60 days each year have temperatures below 32°F. and most of these occur under conditions of strong anticyclonic circulation when there is little or no chance for the overrunning of mT air. Similar information concerning the location of a line north of which temperatures in the overrunning air seldom are above 32°F. is lacking. Brooks (1938) explains the small number of storms experienced west of the glaze belt on the basis of the weakness of the cyclones occurring in that area. Actually, the weakness of the cyclones and the low frequency of glaze are both in large measure results of the same thing -- the infrequent occurrence of warm, moist, and conditionally unstable mT air in the area.

For the reasons previously pointed out, the writer hesitates to make generalizations on the basis of any of the maps. However, if the shortcomings of the maps and the data are kept in mind, certain points may be made.

To describe the location of the glaze belt of the country more accurately, one would say it includes virtually all of the United States east of the Rockies with the exception of the north-south strip immediately east of the Rockies occupying what is sometimes called the High Plains, a strip about 200 miles wide along the Gulf coast, a narrow section 50 to 75 miles wide along the Atlantic coast south from southeastern Virginia (Florida is completely outside), extreme northern New England, and possibly the extreme northern portion of the Great Lakes area. These excluded areas experience glaze, but not with the regularity of the areas within the belt. According to Figure 25, 1 or 2 storms where glaze reaches at least 0.25 inch in thickness can be experienced in a 9-year period along the western half of the Gulf coast and in northern Maine. These figures are to be contrasted with frequencies of from 6 to 8 to as high as 10+ in the heart of the belt. Despite the low frequency of storms, these areas outside of the glaze belt can experience glaze of unusual thickness. Glaze with a radius of 1 to 1 1/4 inches has been observed on utility wires along the Louisiana coast and in northern Vermont. Ice with a 3-inch radius has been reported from northeastern Montana, but it is not certain whether it is actually glaze.* (See also Figures 26 and 27.)

There are some areas within the belt which appear to have frequencies considerably below the rest of the area. Some authorities may disagree with the frequencies shown for the central and southern Appalachians, but it appears that this area plus almost all of Kentucky and Tennessee fall into a low-frequency category. This is borne out by all of the maps and most significantly by the map showing the total number of days with freezing precipitation (see Fig. 29). Before the preparation of this last map, it was thought the low frequency of storms shown for the areas on the other maps was probably observational in origin; the maps are based on data from telephone, electric power, and railroad sources and these have only very limited facilities in the mountains. But when Weather Bureau stations, notably Asheville, N. C., and Parkersburg, W. Va., also show low frequencies, it is obvious the idea that the central and southern Appalachians is an area of rather frequent glaze occurrence is not necessarily true.** Plant ecologists in particular have held to this belief, very likely because glaze damage to trees in the mountains is more noticeable than on the adjacent lowlands because the mountains are generally more heavily forested. There is a possibility that the Green and White mountains of New England and the Adirondacks of New York also are areas of lower frequency of glaze than the surrounding lower country. If the mountains are areas of lower glaze frequency, and the writer is by no means completely convinced this is true, the explanation is believed to be as follows. A short increase in elevation of 1000 feet*** will very likely result in an increase in glaze occurrence because the cold air mass will frequently have a temperature below 32°F. after having been lifted this distance. At higher elevations, the frequency of glaze should decrease

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* For accounts of possibly the thickest ice ever deposited widespread in the United States, see Henry (1921, 1922).

** Of these two places, only Asheville is situated within the mountains and it is located in a basin.

*** This figure is chosen only for purposes of illustration.

because there is a possibility of the warm air mass being lifted so high it cools to below 32°F. The fact that the mean temperature of winter mT air at an elevation of 3 kilometers (approximately 10,000 feet) over Due West, S. C., as given by Pettersen (1940), is 3°C. (37.4°F.), possibly invalidates this idea. However, since Pettersen's figure is a mean, there would be a possibility of a fair number of cases in which the temperature was below 32°F.

In the Great Plains region there is an extension of the low frequency area southeastward into northwestern Nebraska and possibly even into northern Kansas. It was also believed that this was observational in nature, but Figure 29 again shows that it has some basis in fact.

On the basis of the maps, it is impossible to determine positively the expected frequency and intensity of glaze that might be expected in the glaze belt within a certain period of time; most parts of the belt will experience ice between 0.25 and 0.50 inch thick once every 3 years. (Figure 25, 26, 28). Virtually the entire portion of the country east of the the Rockies, with the exception of the southern half of Louisiana, Mississippi, Alabama, Georgia, and South Carolina, and all of Florida, can expect ice of this thickness once in 6 years. The worst area from the standpoint of high frequency and severity of storms apparently extends from eastern Iowa across northern Illinois, Indiana, and Ohio, into Pennsylvania, southern New York and northern New Jersey and southern New England. Figure 22, which probably is the best of all the maps showing total number of glaze storms (it has been verified by information from other sources and is not limited to storms serious enough to cause damage), indicates that as many as 18 to 26 storms have occurred in this area within a 9-year period. The eastern portion of this area from eastern Ohio to southern New England appears on most of the maps to have even higher frequencies of occurrence than the western portion. From 27 to 35 storms of varying intensity occurred in this section and approximately one-third of these recorded glaze of 0.25 inch or more in thickness. Northern Connecticut and most of Massachusetts had from 36 to 44 storms in the 9-year period represented by Figure 22.

(2) Glaze west of the Rocky Mountains

West of the Rockies, glaze is relatively uncommon for reasons explained earlier in this report. It is practically unknown in the Great Basin. Nevertheless, freezing rain is not entirely unknown in at least the northern Rockies and Great Basin and the Cascade-Sierra Nevada Mountains. Figure 29 reveals that most of this area had a total of at least 10 to 29 days with freezing precipitation in 10 years (1939 to 1948). Some of the maps, particularly Figure 22, indicate a high frequency and intensity of occurrence in the mountains of northern California and on the Columbia Plateau in eastern Washington. The writer cannot offer an explanation for the latter, but in the mountains of California most of the reported cases of glaze appear to be deposits of rime or wet snow that increase in density as a result of alternate thawing and freezing as it clings to utility lines (Pajalich, 1953). The area on the Pacific Coast which probably has the highest incidence of true glaze, the Columbia River Gorge, does not stand out on most of the maps.

(3) Occurrence of severe storms

The data presented in Figure 27 show that almost every section of the country, including those where glaze is uncommon, can be visited by severe storms. Various places in the Great Basin have had ice over an inch in radial thickness develop on power and communication wires. In February 1936, telephone lines approximately 40 miles west of Elko, Nev. accumulated ice 1.45 inches in radius. Northern Maine has known ice nearly 0.75 inch thick, and in northwestern North Dakota it has exceeded that figure. Curiously, the highest values recorded during the 9-year period represented by Figure 27 did not occur in the main portion of the glaze belt; ice under 1.50 inches in thickness was the heaviest reported from most of this area.* Only in north central Texas and Massachusetts, at the two extremes of the belt, were measurements taken in excess of 1.50 inches. In the heart of the glaze belt, eastern Iowa to southern New England, most places experienced glaze thicker than 0.25 inches during a relatively small percentage of the storms. For example, in northern Illinois only 20 to 25 percent of the storms deposited ice heavier than 0.25 inches in the period 1928-29 to 1936-37. During the same years, the maximum deposit in this area amounted to 1.25 inches.

(4) Seasonal distribution of storms

With the exception of the Rocky Mountains and High Plains areas, and the extreme northern part of the country along the Canadian border, the occurrence of glaze appears to be confined largely to the period from the middle of November to the middle of March. Figure 30 shows that in all of the West and South and in approximately the southern half of the glaze belt, less than 25 percent of the storms take place either before November 15 or after March 15. In the northern half of the glaze belt, where these percentages range between 25 and 49 per cent, values close to 49 per cent are not found until the Canadian border is approached. In the greater part of Nebraska and a large part of the Dakotas, 50 to 74 per cent of the storms occur before November 15 or after March 15, and in Colorado, Wyoming, and Montana the figure is 75 percent or more. In the vicinity of Cheyenne, Wyo., 15 of 18 storms occur before or after these dates. Storms as early as September or as late as May are almost entirely limited to Colorado and Wyoming, although a stretch of country from southwestern Missouri to the Great Lakes has experienced storms in May.

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* See paragraph 7 of Part III for accounts of ice on trees that surpassed any of these amounts.

In states bordering the Gulf of Mexico and along the Atlantic coast south of Chesapeake Bay, virtually all glaze storms occur in December, January, or February (see Figs. 31 and 32). Over the Great Basin and northern Pacific Coast, storms are encountered from November to April. Along the northern half of the Atlantic coast the first storm of the year seems somewhat later compared with those areas west of the Appalachians, but no similar effect is noted with regard to the last storm of the year. Southern New Jersey, for example, has experienced storms from December to April, whereas directly west in Ohio the season has extended from October to April. In southern New England, northern New Jersey, and eastern Pennsylvania, the earliest storms occur in November (and almost entirely after November 15), and the latest storms in April.

Using the data for freezing rain (Table XIV) as a basis for establishing the month of highest frequency, an interesting pattern emerges. Along the Atlantic coast north of Washington, D.C., December, January, and February seem to be about equal as the months with the maximum number of days of freezing precipitation. March also ranks high. At most stations, January has a slightly larger total than December or February. From Washington south, the three months continue to be the most important, but January becomes pre-eminent. West of the Appalachians the same months are the most important, but from Indiana eastward, January has a larger percentage of the total than east of the Appalachians. West of Indiana, December takes over as the leading month. South of Oklahoma City, most storms occur in January. On the Great Plains from Kansas north, no one month seems to stand out.

c. Summary

Glaze is a common phenomenon in most of the United States east of the Rocky Mountains, with the area of most frequent occurrence found in a broad belt extending from north-central Texas to southern New England. Most parts of this belt experience a storm with ice 0.25 to 0.50 inch thick once every 3 years. Virtually the entire portion of the country east of the Rockies (with the exception of the southern half of Louisiana, Mississippi, Alabama, Georgia and South Carolina, and all of Florida), expects ice of this thickness once in every 6 years and deposits of 1 inch or more have been recorded in most of this area. December, January, and February are the months of greatest frequency although in most sections of the country the season lasts from mid-November to mid-March. In Nebraska and the Dakotas 50 percent or more of the storms occur before mid-November and after mid-March; for Colorado, Wyoming, and Montana the corresponding figure is 75 percent or more.

2. Outside the United States

a. North America

(1) Canada and Alaska

Although the principal area in North America in which glaze occurs lies almost entirely in the United States, the phenomenon is far from unknown in other sections of the continent. Figure 33 is a map prepared by the U.S. Army Air Forces (1943) showing the distribution of wet snow and freezing rain in North America. Wet snow was considered as snowfall at temperatures above 32°F., and freezing rain was assumed to have occurred whenever liquid precipitation fell with air temperatures at or below 32°F. Glaze will not necessarily form when these conditions are met; therefore, the value of the map as a guide in determining the distribution of glaze frequencies is sharply limited. It is doubtful that as much glaze forms over Newfoundland and southern Alaska as the map indicates, and most of that which does form probably consists of light deposits resulting from fog or light drizzle in stable mP air.

A group of data for Canada (undated) consisting of the total number of days with freezing rain during 1951 and 1952 has been mapped in Fig. 34. This shows the maximum frequency occurring in the Maritime Provinces. Gander, Newfoundland, has the absolute maximum with a total of 85 days. Torbay, Newfoundland, is next with 53 days. It is impossible to interpret these high values for Newfoundland in terms of actual glaze because, as Hare points out in his "Climate of the Island of Newfoundland" (1952): "No precise statistics of the frequency of ice accretion exist." He also states that, "...freezing rain and drizzle ...are significant elements of the climate in winter." This is borne out by the material in Table IV taken from Hare's study.

TABLE IV

Monthly Frequency of Freezing Rain or Drizzle at Gander, Newfoundland, as a Percentage of all Observations, 1944-47

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3.8	6.3	5.2	3.1	1.6	0.4	0.0	0.0	0.0	0.2	2.6	4.8

Referring again to Figure 34, the total number of days with freezing precipitation varies from 13 to 36 in the St. Lawrence Valley and the Ontario peninsula. In the west and north of Canada values range from 0 to 20 days, with none recorded at Whitehorse, Yukon Territory and 20 days at Yellowknife on Great Slave Lake. There is a sharp decrease in values from east to west across the Prairie Provinces. Vancouver and Victoria, British Columbia, report only 4 and 2 days respectively.

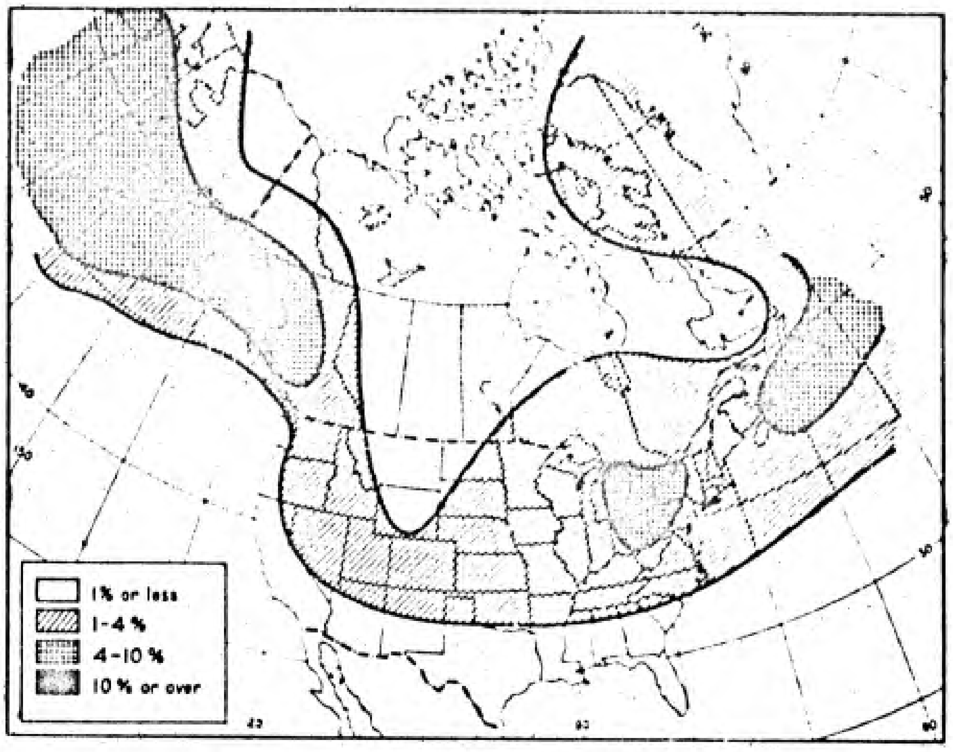

Figure 33. Mean annual percentage of hourly weather observations with freezing rain, North America. Based on a map prepared in 1943 by the Weather Information Service of the U.S. Army Air Forces.

Another set of Canadian data (for 105 first-order stations with lengths of records varying from 5 to 12 years) is presented in Figure 35 and Table V, and essentially confirms the information just presented. The highest frequencies are found in Newfoundland, Nova Scotia, and New Brunswick, with Gander and Torbay, Newfoundland, again leading all other stations by a considerable margin. High values are found, however, in the entire eastern half of the country; proceeding westward, it is not until the Prairie Provinces are reached that frequencies drop appreciably. Values are lowest in the Rocky Mountains and along the Pacific coast of British Columbia, with most stations within the latter area having values which indicate that freezing rain and drizzle are seldom experienced. Surprisingly high values are indicated for Fort Churchill, Manitoba and Fort Smith and Yellowknife in the Northwest Territories, considering the infrequent invasion of the area by warm maritime air masses.

Figure 34. Total number of days with freezing precipitation for the 2-year period 1951-1952. Based on data obtained from the Meteorological Service of Canada. The distributional picture presented in this map compares favorably with that of the more complete data in Figure 35.

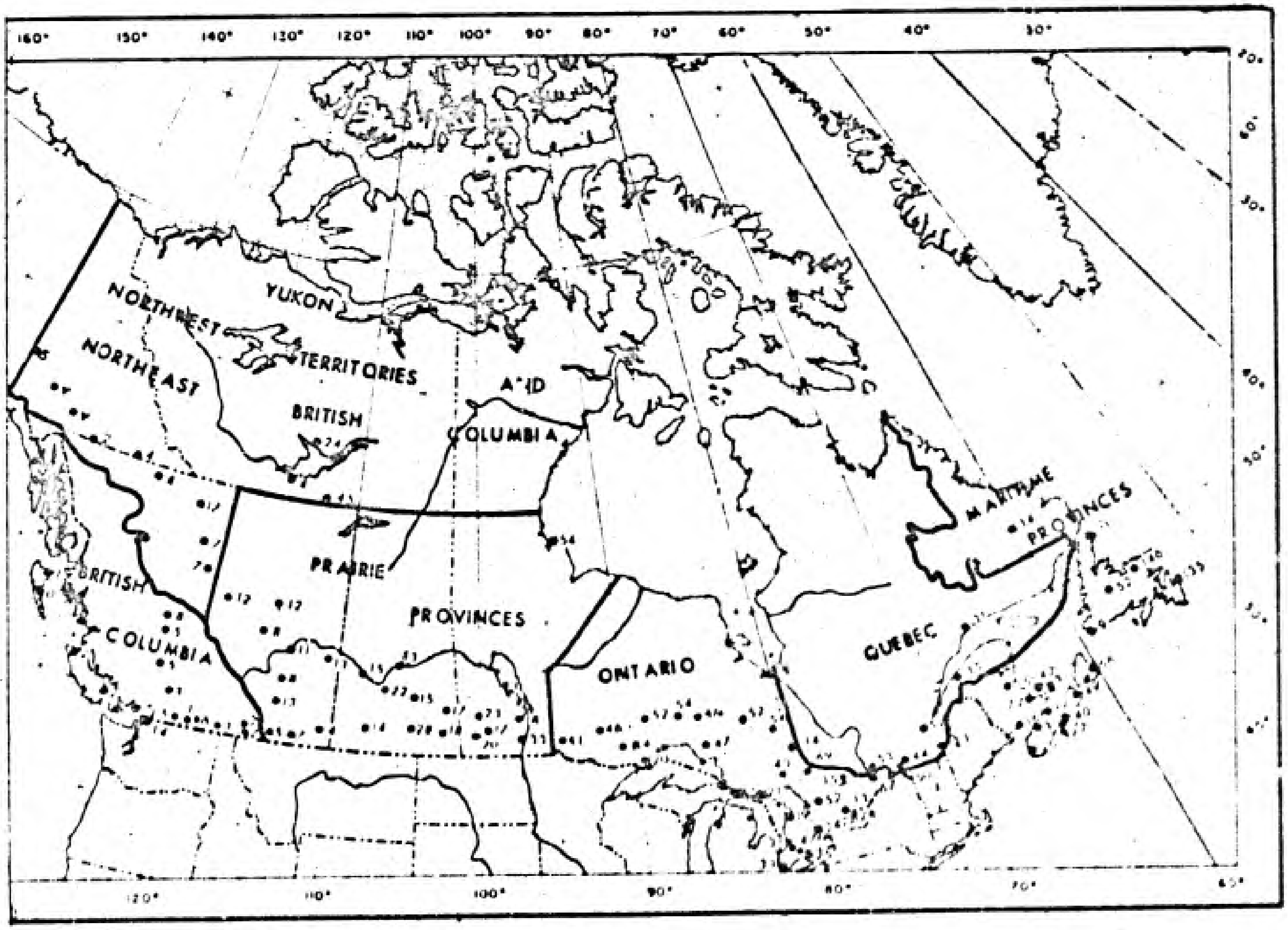

Figure 35. Mean annual number of hours with freezing rain and drizzle, Canada. Based on data from 105 stations of the Meteorological Division of Canada. Length of record varied from 5 to 12 years.

TABLE V

MONTHLY DISTRIBUTION* OF FREEZING RAIN AND DRIZZLE IN CANADA**

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Maritime Provinces	---	0.1	3.9	9.7	20.7	23.3	27.3	12.8	2.1	v
Quebec	---	0.4	7.7	20.4	32.8	13.6	19.1	4.7	1.3	---
Ontario	v	1.4	16.2	20.5	27.8	17.4	12.7	3.0	1.0	v
Prairie Provinces	0.7	5.0	30.5	17.1	11.2	10.2	11.0	7.4	5.7	1.2
Yukon (N.W. Terr., N.E. Brit. Col.)	1.5	16.3	66.7	4.7	3.1	2.3	3.9	1.5	v	---
British Columbia	v	v	21.7	21.7	42.0	13.1	1.5	v	v	---

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* These figures represent the percentage of the total annual average number of hours with freezing rain and drizzle occurring in each month. The figure "v" represents values of less than 0.1 percent.

** Canada (1955). Based on data from 105 stations of the Meteorological Division of Canada. The length of record for the various stations varied from 5 to 12 years. See Figure 35 for the areal extent of these regions.

The data presented in Table V indicate that almost all parts of Canada experience freezing rain and drizzle from November through April. In some areas, notably the Prairie Provinces, it occurs as early as September and as late as June. Close examination reveals that the months of heaviest concentration shift progressively from fall in the west, to late winter in the far east. In the area consisting of the Yukon, Northwest Territories, and northeastern British Columbia, 83.0 percent of the total annual hours reporting freezing rain and drizzle occur in October and November, with November alone having 66.7 percent. On the Pacific Coast and in the Rocky Mountains, as represented by the figures for British Columbia, November, December, and January clearly are the leading months, with January the standout at 42.0 percent. In the Prairie Provinces, November and December constitute the primary season, while January through March are of secondary importance. All the months from November to February rank high in Ontario, but January is the leader. December through March lead in Quebec, with January again having the highest percentage. In the Maritime Provinces, the period of highest frequency shifts entirely to the period after January 1, with March ranking highest and April being fairly important.

(2) Mexico

Glaze very likely occurs in northern Mexico although undoubtedly at rare intervals. Occasionally, cP air with temperatures below freezing will be observed in Chihuahua and Coahuila, and it is possible for warm Pacific or Gulf air to be found aloft on these occasions. Any freezing rain resulting from such a situation would probably be light.

(3) Greenland

Conditions favorable to the formation of glaze apparently develop occasionally over the Greenland icecap. Matthes and Belmont (1950) present evidence to indicate that cyclonic disturbances that cross the island or move along its west or east coasts are unable to sweep away entirely the cold layer of air characteristically found at the surface of the icecap. As a result, the warmer marine air carried by the disturbances is forced to rise over the cold air, creating a situation analogous to the warm front with which most glaze is associated. They cite an instance described by Belknap (1941) in which rain fell on the surface of the icecap at a time when the temperature of the air was -2.2°C (28.0°F) producing an ice crust on the surface of the snow. In a review of the Matthes and Belmont paper, C. E. P. Brooks (1951) states, "This condition [the occurrence of freezing rain or glaze] . . . is probably quite common in Greenland." The present writer believes this is too sweeping a generalization and that the relatively meager observational information available for the icecap indicates glaze rarely is observed on the icecap proper and then only during the summer months. On the margins of the icecap it is apparently more common, but data giving frequencies are lacking.

b. Southern Hemisphere

(1) Southern hemisphere in general

Like tornadoes, glaze storms are weather phenomena most typically associated with North America. Both are products of the optimum conditions in the eastern two-thirds of the North American continent for clash between cold, dry cP air and warm, moist mT air. In searching other parts of the world for areas in which glaze might occur, one should look primarily for those in which there is a frequent chance for these two air masses to come together with marked differences in their properties, particularly temperature. This means they should be relatively fresh from their source regions.

In the southern hemisphere, there is little chance for a meeting of these air masses, primarily because of the absence of cP air. Air from the Antarctic undoubtedly is cold enough when it leaves the source region, but by the time it reaches southern Africa, Australia, or South America, it has traveled a long distance over open water so that the possibility of its temperature being below 32°F, is relatively small. Of the three areas mentioned, southern South America stands the greatest chance of experiencing glaze; southern Africa the smallest. Glaze undoubtedly occurs occasionally in southern Chile and Argentina, and in the latter could possibly occur as far north as Buenos Aires. Freezing drizzle from relatively stable mP air must certainly occur at times in the extreme south of Chile, and rime or glaze from supercooled fog very likely is not uncommon in the mountains of southern Chile and Argentina. The southern tip of Africa extends to only 35°S. latitude and has a July mean temperature of 50° to 60°F. (the lowest temperature ever recorded at Capetown is 31°F.); consequently, it is difficult to imagine the formation of glaze in this area. It also is doubtful that glaze would be experienced in Australia, although there is a possibility for its occurrence in Tasmania.

(2) New Zealand

A possible area for glaze development in the southern hemisphere is New Zealand. Leslie Curry of the Department of Geography in Auckland University College was kind enough to collect and send to the writer information pertaining to glaze in that country. From this information, it seems fairly certain that glaze from supercooled rain or drizzle involving a frontal situation seldom occurs in New Zealand, although it is experienced occasionally on the Canterbury Plain and in the mountains. Rime or glaze from freezing drizzle or supercooled fog may be fairly frequent phenomena in the higher parts of both the North and South Island, but there is little direct evidence to testify to the accuracy of this assumption.

To quote from a letter by M.A.F. Barnett, Director of the Meteorological Branch of the Air Department in the government of New Zealand: "It is this last condition [the lack of temperatures below 32°F in the cold air beneath warm fronts affecting New Zealand] which makes the occurrence of glaze frost in New Zealand so infrequent, except possibly at high altitudes. This country is separated by many hundreds of miles from the nearest source of cold Antarctic air masses. By the time any air mass from the south reaches our shores, the surface air layer has been warmed considerably by contrast with the sea surface. In exceptional cases the arriving air mass has its surface layers at a temperature in the lower thirties, but seldom, if ever, is it below 32°F. During the Canterbury snowstorm of July 14, 1945, heavy deposits of what is referred to in the newspapers as 'wet snow' collected on telegraph lines, trees, etc., and caused much disruption to the telegraph service, through broken wires and poles. This deposit was probably a form intermediate between glazed frost and rime. Glazed frost probably occurs at times in the South Island above 1000 feet, and in the North

Island above 2000-3000 feet, but authentic reports are lacking, mainly due to the sparseness of population at high altitudes in New Zealand."

P.N. Cryer, Director General of the General Post Office has the following to say about damage to communication lines in New Zealand:

". . . I have, by direction, to say that no precise details are available regarding damage to telephone lines by glaze storms. In general, however, damage is confined to mountainous areas in the North Island and to Canterbury, Central Otago, and mountainous areas of the South Island . . . If conditions are severe enough, the ice load builds up to such proportions that wires and poles give way. Such conditions are more common in Canterbury, where the last major breakdown occurred in July, 1945."

c. Eastern Asia

(1) Asiatic mainland

Apart from the eastern part of North America, the best area for frequent contact between cP and mT air is found along the eastern coast of Asia, particularly the coasts of China and Japan. However, whereas in North America mT often penetrates far inland during the winter, the pronounced anticyclonic circulation that dominates Asia in winter limits such invasions to rare occasions (Haurwitz and Austin, 1944). The strength and persistence of the anticyclone results in the almost continual winter-long dominance of cold, dry, cP air over the entire area from eastern Europe to the Siberian and Chinese coasts. Kendrew (1953) describes this dominance of the east coast of Asia by cold dry continental air as follows:

"The prevailing and nearly constant winds are NW and N in north China, N to NE in central China, and NE and ENE in south China. The winter monsoon is shallow and is overlain at about 6000 feet by westerlies, dry and probably fairly constant winds of great velocity."

In North America a large percentage of the low pressure systems which originate over the subtropical oceans to the south and southeast of the continent actually move across a part of the continent; along the eastern coast of Asia the great bulk of lows have a completely oceanic trajectory (Klein, 1955). Only occasionally will a low swing close enough to the coast to force mT air over cP, thus making it possible for freezing rain to occur. Cyclonic disturbances that develop rather frequently in the western section of the Yangtze Valley in winter and travel eastward across China can be an agent for bringing mT air is aloft over the China mainland, but because they are very shallow and feeble their tendency to do so is not pronounced. Periodically, a cold burst of cP air, led by a cold front oriented in an east-west direction, will sweep down over central and eastern China; but they replace older cP air which is too cold to provide 32°F. temperatures aloft.

The net result of all this is that the eastern portion of Asia has very little precipitation of any type in winter, especially inland away from the immediate coasts, and that glaze in particular is rare. Any glaze that develops would probably do so most commonly in the early fall or late spring when the anticyclone is relatively weak.

(2) Japan

Owing to their greater exposure to maritime lows from the south (Klein, 1953), the Japanese islands undoubtedly experience more glaze than the mainland of Asia. The climate of the east coasts of Honshu and Hokkaido is somewhat similar to that of the Atlantic coast of North America from about Virginia north to Newfoundland. The writer is unable to present any data concerning the incidence of glaze in these areas, but descriptions of two storms that struck Japan are available (Okada, 1914). From these reports it seems that conditions prevail that are similar to those found along the eastern coast of the United States during glaze formation. To quote from one of these:

"On the early morning of January 8, 1902, a remarkable glaze frost occurred at Tokyo and in the neighboring districts. The branches and leaves of trees and all exposed objects were covered with transparent ice of a thickness of about 5 to 10 millimeters [3/16 to 3/8 inch]. The ground was also covered with a coating of ice . . . . The temperature of the air remained 1 degree below the freezing point, but that of the surface of the ground was a little above it. The winds blew from the northwest, the force being moderate. Rain fell since 2 A.M. of the day. At about 4 A.M. it turned into sleet. We have no observations from the upper air at Tokyo, but fortunately we have hourly observations taken on the summit of Mount Tsukuba, (870 meters [2,854 feet] high) at a distance of 65 kilometers [40.4 miles] to the northeast of Tokyo. From these observations we know that at the height of 870 meters above sea level strong winds from the southwest were blowing and rain was falling slightly. The temperature of the air was above the freezing point and was about 3 or more degrees higher than at Tokyo."

In the other storm, which occurred at Asahigawa (east central Hokkaido) on March 7, 1914, glaze 1.2 centimeters (0.47 inch) in radial thickness developed on telephone wires, and the roofs and the walls of the meteorological observatory were covered with 0.6 centimeter (0.23 inch) of ice. Glaze resulted from freezing rain during a north wind, and followed a heavy snowfall; sleet also occurred. The temperature during the freezing rain varied from -0.8°C. to -2.2°C (30.6° to 28.0°F). Very heavy damage was done to trees and communication poles and wires. The ice remained unmelted until March 10.

d. Europe

(1) Europe in general

Glaze can occur in Europe from the British Isles to the Urals (and beyond into Central Asia), from as far north as Scandinavia and Murmansk, U.S.S.R., to as far south as Greece and Italy, and at least one case has been reported in Algiers in North Africa. However, south of a line from the Cantabrian Mountains (Spain) and Pyrenees Mountains eastward through the French, Swiss, Austrian, and Dinaric Alps to the Balkan Mountains of Bulgaria, cases of glaze formation are rare in the lowlands and only slightly less uncommon in the mountains. The primary reason for this low frequency in the Mediterranean region is the rare appearance at the surface of continental air masses with subfreezing temperatures. Figure 36 probably presents a fairly good picture of glaze distribution in western and central Europe. The areas in Great Britain affected by glaze storms are shown in Figure 37. Figures 40 - 43 show conditions in the European part of the Soviet Union.

Though glaze is fairly common in parts of Europe, frequencies are probably nowhere as high as in the major portion of the glaze belt of the central and eastern United States. Most of Europe does not experience the extremes of winter climate resulting from the frequent clash of cP and mT air common in North America. The dominant maritime air mass in winter is Atlantic mP which, unless it has trajectory relatively far south over the Atlantic, is too cool to provide temperatures above 32°F. when it becomes the overrunning warm air mass. Mean temperatures at 1750 meters (5740 feet) in winter mP air over Europe are -4°C. (24.8°F.) at Lyon, -5°C. (23.0°F) at Nancy, and -4°C (24.8°F) at Berlin.* Maritime tropical air, despite the customary long trajectory over the cool northern portion of its source region, generally reaches western Europe with surface temperatures of around 50°F. which is sufficiently warm for glaze-forming purposes. At 1800 meters (5904 feet) elevation over Nancy, it has a temperature of 3°C. (37.4°F). This is compared with a temperature of 9°C. (48.2°F.) at approximately 6500 feet over Boston. After it has passed inland as far as Berlin, the average temperature at 1800 meters is 1°C (33.8°F.). Over Moscow, mT has a mean temperature of -3°C. (26.6°F.) at an elevation of approximately 5000 feet. A contrast between mT air in Europe and in North America, which has a bearing on the intensity of glaze formation, is that the European air is not as conditionally unstable. This is because air coming from the

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*These temperature values and those that follow were taken from Petterssen (1940).

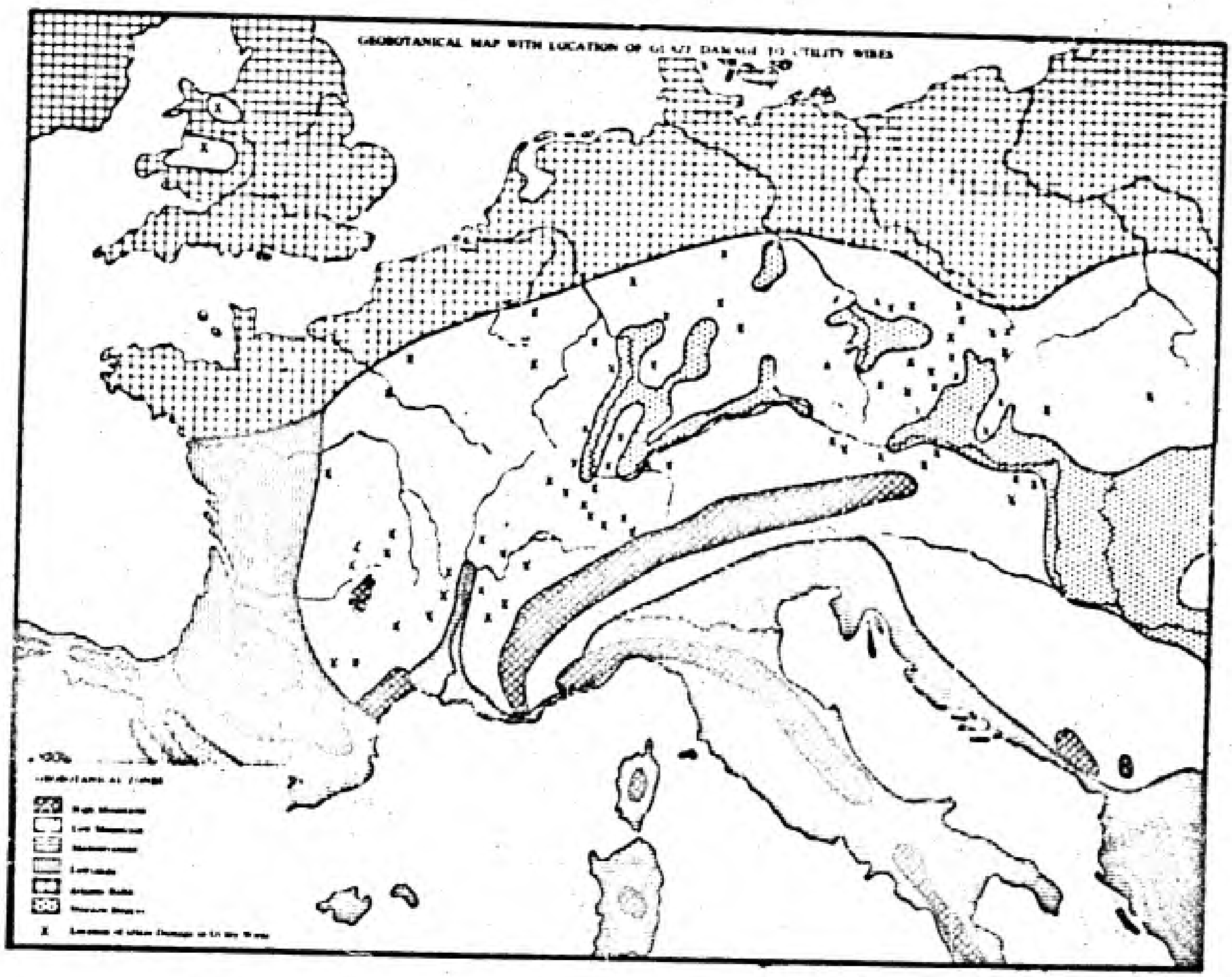

Figure 36. Location of glaze damage to utility lines in western Europe. No information was given in the original source concerning the period of time on which the map was based. After a map in Wald (1950).

eastern sides of the subtropical high pressure centers experiences greater subsidence than air on the western sides. As a result, glaze formation in Europe will usually develop at a slower rate.

Just as the warm air masses are cooler in Europe than in North America, the cold air masses are warmer in Europe. There are two sources from which cold air can be pulled into Europe. Maritime Arctic air from the north frequently invades Europe in the rear of deep cyclones centered over northern Europe, but by the time it reaches the continent it is warmed in the surface layers by passage over the Atlantic and usually has a surface temperature of 2° to 4°C. (35.6° to 39.2°F.) upon arrival, thus eliminating it as a partner in glaze formation in most instances. Outbreaks of cP air from the Eurasian anticyclone frequently invade eastern and central Europe in the winter and occasionally reach as far west as the Atlantic. Considerable warming takes place during the westward surge of this air but temperatures well below freezing are still common. The mean surface temperature at Munich during domination by winter cP is -11°C. (12.2°F.), and at Nancy -6°C. (21.2°F.).

There is a moderate amount of descriptive material dealing with glaze in Europe available in the literature and some fairly detailed studies of glaze meteorology and climatology exist, but data for whole countries or large sections of countries are almost totally lacking, with the exception of a moderate amount of material collected in the Soviet Union.

(2) Great Britain

Figure 37 represents essentially all the information available on the climatology of glaze in the British Isles. Although the map shows only relative values, and is not complete, it indicates that most storms in Great Britain are limited to the higher portions of the island. In speaking of the effect of glaze on power and communication lines, Grimmitt (1945) states that it appears as if trouble can be expected every winter at elevations above 1000 feet. Elevations of this order are found in Great Britain in the extreme southwest in Dartmoor and Exmoor, in Wales, the Pennines, and in the Southern Uplands and the Highlands of Scotland. Glazed frost apparently is well known in Dartmoor, where it is called by the dialect name <u>ammil</u> which is derived from an old English word <u>amel</u>, meaning enamel (Botley, 1940).

Douglas (1928) points out that (despite the implication in Figure 37) the eastern counties of England are not immune to glaze, and he cites instances which occurred in that area on December 31, 1927, January 19, 1941, January 10, 1943, and January 30, 1945, in which ice in amounts ranging up to at least a quarter of an inch formed in the east Midlands, and somewhat lesser amounts formed in East Anglia. A check of the Northern Hemisphere Historical Weather Maps by the writer of the present report

Figure 37. Glaze in England and Wales. Map represents information for a period of about 25 years. Based on a map in Grimmitt (1925).

showed that the December 31, 1927, storm apparently was caused by modified Arctic air from a high pressure center which had moved down from northeastern Greenland and occupied all of Europe from Scandinavia to the Balkans, coming in contact with warm mP air moving over Great Britain behind a north-south aligned occluded front. There is a strong possibility mT air was aloft in the occluded portion of the front.

According to Harrower (1945), glazed frost is rare at low levels in Scotland, but common on mountains above 2000 feet. From the descriptions he gives, there is a possibility Harrower has confused glaze with rime and what the British call "silver thaw".* Harwood (1945) reports 198 cases of silver thaw in six years on Ben Nevis (maximum elevation 4,406 feet), but he also mentions occasions on which rain froze on the clothes and even the faces of observers; so apparently glaze can actually occur at that height. He points out that Eskdaemuir (800 feet above sea level) in Dumfriesshire has recorded only 3 cases of definite glaze since 1917 (to 1945) but on the other hand has had 36 cases of rime. The present writer believes that much of the glaze reported in the highland areas of Great Britain is actually, as suggested above, rime or, in cases where the density of the ice is higher, glaze formed from supercooled drizzle or light rain in situations where no front is involved. In speaking of damage in Scotland, Grimmitt (1945) says none has been experienced in central Scotland and along the west and east coasts, but that frequent sleet storms have been reported in the Grampians, although without serious damage.

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* In the Meteorological Glossary (Great Britain, 1948) silver thaw is described: "After a spell of severe frost the sudden setting in of a warm, damp wind may lead to the formation of ice on objects, which being still at a low temperature cause the moisture to freeze upon them and give rise to a silver thaw."

Smith (1955), while pointing out that glaze is an uncommon phenomenon in the United Kingdom, describes 4 occurrences within 3 successive years within a valley on the western flanks of the Pennine Mountains. All 4 occurrences were in January (1953, 1954, 1955). On one of the occasions, ice on trees, houses, and telephone lines persisted for 5 days after formation.

One of the most serious glaze storms ever to strike Great Britain took place on January 27 to 29, 1940, with ice of unusual thickness reported in certain areas.* In Worcestershire an automobile was covered with 6 inches of ice, and ice 4 inches thick was common on twigs (Newbold, 1940). In Wiltshire, ice formed to a thickness of 0.75 inch on telegraph wires (Gunther, 1940). At another location, ice on a telegraph wire was 2.4 inches in diameter (Pattinson and Dines, 1940). At some sites the glaze stayed on trees and wires seven days after the storm. This storm was associated with a stationary front that lay across Great Britain and the English Channel in a northwest — southeast direction from January 27 to 30. To the southwest of the front, winds were southwesterly with a temperature of 50°F., and to the northeast, the wind was easterly with a temperature below freezing. There was a belt of precipitation 200 miles wide northeast of the front, with freezing rain extending in a belt 100 to 140 miles from the front between non-freezing rain to the southwest and snow to the northeast.

(3) Scandinavia

Information on glaze frequency in Scandinavia is extremely scarce, and only three references on the subject were uncovered by the writer. One (Ekström 1941) deals with glaze on highway surfaces and this, therefore, is discussed in the section of this report dealing with transportation. Another consists of a short statement made by Sandström (1922) that in Sweden glaze, along with moist snow and hoarfrost, is limited to the mountainsides in alpine regions. The final reference consists of a paper published by Rossi (1938). Data for this last study were obtained from the meteorological observatory at Ilmala, Finland, from the winter of 1926 - 27 through the winter of 1935 - 36. During these 10 years, glaze was observed on 84 days which were divided among the different months as follows:

	Nov	Dec	Jan	Feb	Mar	Apr
Number of days on which glaze was observed:	9	12	20	23	17	3

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* Brooks and Douglas (1956) present an excellent and thorough discussion of this storm, with particular emphasis given to the synoptic conditions responsible for its occurrence.

Mention is also made of a series of observations, which Rossi believes did not include all storms, made over a period of 30 years (1883 - 1912) at Helsinki, in which a mean of 3.6 days of glaze occurred annually, and the month of maximum occurrence was January. Returning to the Ilmala data, 5 of the observations were of glaze that was a carryover from the previous day, consequently, there were only 79 cases of actual glaze formation. Out of these, in only

"...26 cases could the beginning of glaze formation be established exactly. These cases can be divided among the various aerological conditions as follows: 1 during a cold front, 2 during a warm front, 17 during an occluded front, and 6 during a relatively warm air mass. The mean temperature of the air was -2.3°C [27.9°F] in these cases, and the relative humidity 96 percent. The lowest temperature read -9.0°C [15.8°F] and the highest 0.5°C [32.9°F].

"An analysis of the weather situation emphasized the fact that glaze occurred most frequently on the side of the cold air mass preceding the oncoming front. Thus we can conclude that in 76 percent of all observations the warm or quasi-warm front was the cause of glaze formation. In general, this front is not very strong, since most of the cyclones are occluded before they reach Finland. This fact is further substantiated by the fact that in 19 cases where glaze has formed in conjunction with a front, the air pressure fell on the average of 0.5 mm Hg within 3 hours.

"If glaze forms during a relatively warm air mass, it is most frequently influenced by mP, or in some cases by mT air, from the SW or W. In the six cases reported, the temperature was -1.5°C [29.3°F] on the average, and the humidity 91 percent when glaze began to form. In one case (Jan. 29, 1934), measurements in the free atmosphere indicated a rather strong air current from the west bringing mP air. On the ground the temperature ranged from -3° to -5°C [26.6° to 23°F]; toward the west a few positive temperatures were observed. According to aerological measurements, Utti (Lat. 60° 53'N., Long. 26° 58'E.) and Sortavala (Lat. 61°40'N., Long. 30° 41'E.) experienced a strong ground inversion about 9:00 A.M., above which the temperature was 8° to 10°C. higher than on the ground. At 10:30 fog was observed at the observatory at Ilmala which continued for the whole day. At 1900, [7 P.M.] glaze formation began; the temperature was -0.2°C [31.6°F]. Glaze, therefore, occurred in conjunction with fog which was probably formed by the mixture of the stagnant cold air layer with the warmer air above. The weather map of 2000 [8 P.M.] showed only a few negative ground temperatures."

(4) France

France is a country for which virtually no information has been uncovered. Figure 36, however, shows that glaze (or at least some type of ice) has on several occasions damaged electric power lines in France, with most of the damage sites being located in or around the Central Massif.

(5) Switzerland

Glaze in Switzerland is described by Bider (1954) who states that glaze from supercooled rain can attain considerable thicknesses in Switzerland, up to as much as 2 to 3 centimeters (.79 to 1.18 in) on horizontal surfaces and 4 centimeters (1.57 in) in diameter on telephone wires. According to what Bider considers rather comprehensive and reliable observations, Basel had 24 cases of glaze in the 20 years from 1931 to 1950, distributed on a monthly basis as follows: November, 1; December, 4; January, 16; February, 3. A description of temperature conditions during these cases will be found in paragraph 1a of Part I of this report. Bider's report on meteorological conditions is as follows:

"... well distributed cases of glaze occur essentially at a south, west, or sometimes southeast exposure, where high, warm, moisture-laden air from the south, west, or southeast is present above stagnant ground air of a previous high, precipitation resulting as a consequence. Later, the warm air also penetrates the lower layers. The weather map usually indicates strongly developed depressions over the Bay of Biscay or the English Channel, and an eastward-moving warm front. Frequently, a föhn* situation develops, in which the föhn overrides the cold air over Mittelland. At times, a depression is situated in northern Italy, with bize** present in the lower layers over which the warm moist air from the southeast glides. The warm air layer with a temperature over 0°C. is usually only a few hundred meters in height, which is sufficient to cause falling snow to melt and change to rain by the time it reaches the lower cold air layers...

"The few cases of glaze originating by falling temperatures are interesting to consider. Here a wedge of cold air displaces the warm air of the lower air layers. Rain falling into the below-freezing air layer is supercooled and freezes on hitting the ground. Usually rain changes to snow in these cases if the cold air reaches high enough, and the snow consequently covers the layer of glaze.

"Striking cases of this type were observed in Basel on January 1, 1941, and April 1, 1952. On both days, cold air from the north-northwest moved slowly over the country... In Basel it rained for hours at temperatures below the freezing point, forming a conspicuous layer of ice, until the rain changed to snow."

(6) Spain

Glaze can be expected occasionally in the Iberian Peninsula, but probably is limited to mountain areas and the Central Plateau.

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* föhn (or foehn) a warm, dry, southerly wind.
** bize (or bise) a cold northeast wind.

One case of ice damage to electric power lines is shown for the Pyrenees in Figure 36, although it is not certain what type of ice it was. The Boletin Mensual Climatológico del Servicio Meteorologico Nacional published by the Air Ministry of the government of Spain gives monthly totals of the number of days weather elements of various types occur at 117 meteorological stations in Spain. An examination of this information for the years 1947 - 54 revealed 2 stations reporting only 1 day each with glaze. These were Oviedo, on the north coast in the foothills of the Cantabrian Mountains, and Leon which is on the Plateau just south of the Cantabrians. It was impossible to determine whether these two occurrences were related. During the period of years mentioned above, sleet (U.S. Weather Bureau definition) occurred on several days at a fairly large number of locations, thus indicating that conditions at least close to those necessary for glaze formation must occur rather often in Spain. Across the Mediterranean Sea, in at least one instance, what appears to have been glaze formed on electric power lines near Algiers (Haour, 1939). Development of the formation followed a series of violent thunderstorms accompanied by snow.

(7) Italy

Two references to ice formation on power lines in Italy were uncovered (Crestani, 1942 and Eredia, 1942), but the present writer was unable to obtain the publications in which they appeared. However, an abstract of one of them (Eredia, 1942) appearing on a SIPRE* bibliography card stated that ice formation is frequent on power lines running west to east in Italian valleys.

(8) Greece

A brief description of the occurrence of glaze in Greece is given by Mariolopoulos (1938). He states that records of glaze occurrence have never been kept systematically in Greece and, therefore, it is impossible to say just what is the true picture. Rime is fairly common in Greece, but glaze apparently is rare and is noted only in northern Greece and the high places of the south. Two documented cases of glaze at the Meteorological Institute in Thessalonika, one during February 1932 and the other during 1936 are mentioned. Phillippson (1948) describes an occurrence of glaze in March 1893 at 1200 feet above sea level on the north slope of Mt. Parnassus.

(9) Germany and the Netherlands

Sebastian (1949) presents a interesting discussion of the glaze storm of January 11 and 12, 1948, in the Netherlands and northwestern Germany. The formation developed from freezing rain

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* Snow Ice Permafrost Research Establishment, Corps of Engineers, U.S. Army.

associated with the passage of a warm front. Translated excerpts from Sebastian's discussion follow. Figures 38 and 39 have been adapted from his paper and where he refers to them, numbers corresponding to those in this report have been substituted.

"The heaviest formation occurred in the coastal region. At Norderney, for example, on the evening of January 11 a transparent ice layer, 2 1/2 to 3 mm. in thickness was observed on the ground and on objects — this being very unusual for the East Frisian Islands. Schleswig-Holstein and the Hamburg area were also exposed to heavy glaze of several hours' duration starting in the early hours of the 12th of January, while the southern part of the affected area experienced less glaze of an interrupted nature.

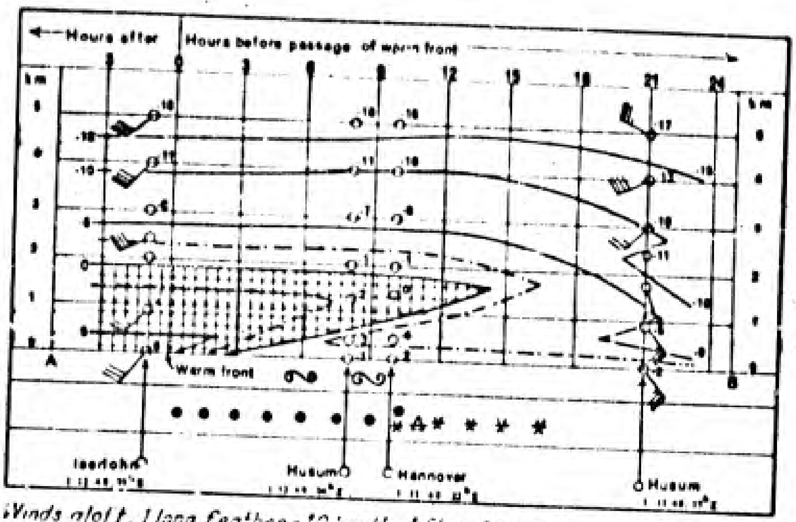
"On January 10 northwestern Germany came under the influence of a cold air mass which followed on the heels of a low moving towards central Russia. The southern boundary of this cold air ... is characterized by a convergence almost coinciding with the 0° isotherm. Along this boundary, a 150-km. band of snow and rain cuts diagonally across Germany forming the precipitation associated with a new warm front over Holland ... Figure 38 shows a vertical section of the frontal zone of the warm front, giving the conditions around midnight from the 11th to the 12th of January; by this time the warm front had practically caught up with the slowly retreating southern limit of cold air ... The advancing air at high altitude with temperatures over 0°C. is clearly shown in the diagram. After it attained sufficient extent, the snow in front of the warm front changed to graupel or a mixture of snow and rain, and then to supercooled rain.

"Figure 39 depicts schematically the various phases of the development of the transition of snow into rain and the position of the 0° isotherm on the ground. The two lines first approached each other on the morning of January 11 over northern Holland, and as soon as they had crossed, the prerequisites for the formation of glaze were met. The wider the enclosed area, the more intensive the glaze formation. The points of intersection of both lines indicate the southern limit of glaze. If the actual boundary after the onset of glaze runs about 30 to 50 km. farther north ... it is due to the fact that the surface air layers with temperatures under 0° petered out towards the south; the air layer must be of a certain extent (in this case about 300m. [328 yd.]) in order to provide a sufficient supercooling of the rain.

"In conclusion, it is noteworthy that the ground temperatures rose above 0°C. shortly before the advent of the warm front, whereby the removal of glaze was facilitated ..."

(10) Austria

Data concerning the occurrence of glaze in Vienna between November, 1905, and March, 1935, have been analyzed by H. Winter 1936. During this period, there were a total of 244 days in which the phenomenon was observed. According to Winter:



Winds aloft: 1 long feather = 10 km/h, 1 flag = 50 km/h, e.g.: = 65 km/h

Figure 38. Vertical section along line A-B (see Figure 39) through frontal zone of the glaze storm of January 11 and 12, 1948, in northwestern Germany. After a diagram in Sebastian (1949).

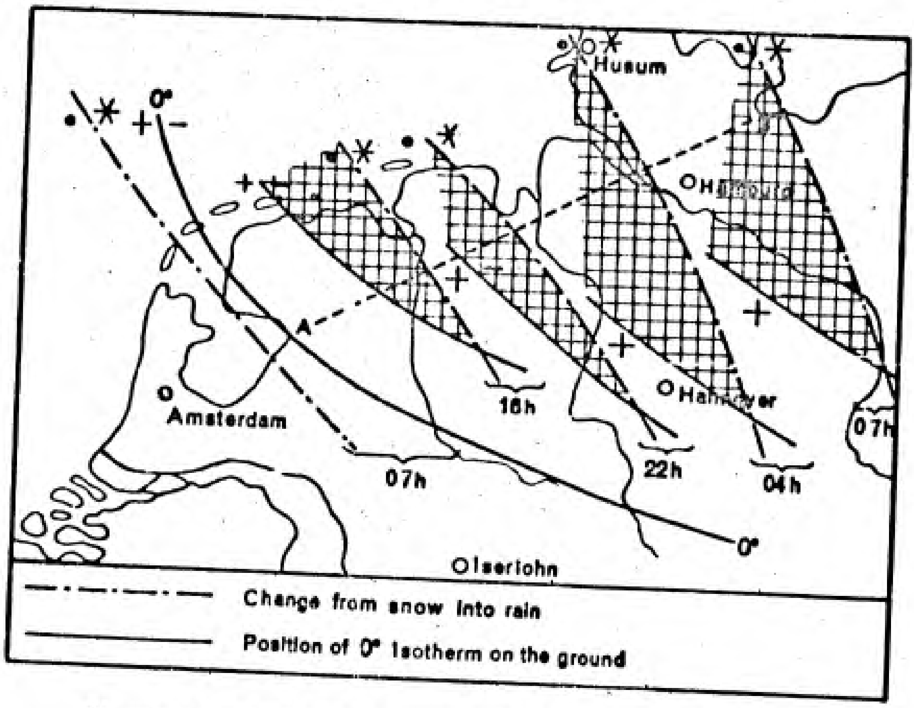


Figure 39. Eastward migration of the area of freezing rain during the glaze storm of January 11 and 12, 1948, in northwestern Germany and the Netherlands, and the relationship of the 0°C. surface isotherm to the areas of precipitation. For a complete explanation see the text. After a map in Sebastian (1949).

"The origin of formation of the 244 cases were attributed to: drizzling fog in 60 cases, a mixture of rain and snow, perhaps accompanied by sleet or graupel in 41, pure rain or freezing rain in 38, pure snowfall in 33, snow with drizzling fog in 12, drizzling fog with rain or freezing rain in 8, and a mixture of drizzling fog, rain and snow, perhaps with freezing rain or graupel in 4 cases. Of the remaining 48 cases, no particular form of precipitation could be detected. However, in 32 cases thereof fog had been observed. A great many of these undetermined cases can be traced back to residual glaze from the previous day.

"The annual distribution of the 244 cases of glaze is classified as follows:

	Nov	Dec	Jan	Feb	Mar	Total
Number of cases:	30	86	82	44	2	244

"The maximum lies in December. However, if all cases are omitted that are not considered to be glaze in the strictest sense, i.e., those that did not occur by supercooled rain, ice storm, drizzling fog at temperatures below 0°C., at least on a frozen surface, there remain 106 cases which can be distributed thus:

	Nov	Dec	Jan	Feb	Mar	Total
Number of cases:	7	40	46	12	1	106"

He also describes the meteorological conditions associated with two individual cases of glaze formation. The first deals with glaze that developed from two successive days of what Winter calls drizzling fog. The Northern Hemisphere Historical Weather Maps show that during the two days a high pressure center, which had come from the Soviet Union, dominated all of Europe from the Urals to the Atlantic and from northern Scandinavia to North Africa; therefore, the freezing drizzle very likely was not frontal in nature. Heavy damage to telephone facilities in Vienna resulted from the ice.

Winter's second example of heavy glaze formation in Vienna, February 14, 1935, involved the passage of a north-south oriented warm front carrying behind it southern trajectory mP air from the Atlantic. Polar continental air from the east had dominated Austria and the rest of central Europe for two or three days previous to the approach of the warm front.

Another part of Winter's paper, in which he describes the conditions observed following glaze formation, is interesting:

"... the rule that glaze is followed by a rapid thaw ... is limited. Only after glaze due to freezing rain is a strong temperature increase apparent in the great majority of cases. Out of 20 cases, a temperature rise of 4°C. within 24 hours occurs in 15 cases: most frequently a temperature increase between 4° and 6° takes place. Also, within the next 24 hours, the temperature, as a rule, is higher than at the time of glaze formation; most frequent, again, is the range between 4.0° and 5.9°. However, occasionally after a previous temperature increase a cooling-off period sets in. A totally different temperature procedure occurs after glaze formation due to drizzling fog. A substantial temperature rise of 4° or more within the next 24 hours is not present in 17 out of 19 cases; in 14 cases it even remains below 2°, inasmuch as no cooling-off in general has followed. The very prominent maximum of frequency now lies in the range of 0° to 1.9°. Within the additional 24 hours, the cases are distinctly divided into those where a temperature increase follows, which, however, proceeds at a much slower pace than after freezing rain, and those where a cooling-off period follows. A strong temperature increase occurs only in exceptional cases after this type of glaze. Also, a temperature rise of at least 4° after 48 hours can only be expected in 3 out of 19 cases."

(11) Hungary

Bell (1947) describes a severe glaze storm that occurred in Hungary on February 11 to 13, 1947. Ice from freezing rain along a stationary front that lay in a north-south direction just to the west of Budapest during this period formed up to 3 centimeters thick on trees, buildings, and the surface of the ground. Tremendous damage was inflicted upon crops, trees, electric power and communication lines, and transportation. In some areas, very heavy snows followed the glaze, virtually paralyzing all outside activity for several days. Glaze apparently is not unusual in the Alfold region of Hungary, but in 45 previous years no storm anywhere approaching this one in severity had been known to occur.

(12) Soviet Russia

Going eastward from western Europe toward the heart of Eurasia, one moves farther from the source of warm maritime air masses, and therefore, into an area where glaze frequency should become less. Eastern Europe and Russia are dominated a large percentage of the time in winter by the Asiatic anticyclone and farther east, Siberia comes under its domination almost continually throughout the winter. At the surface, invasions of mT air are extremely rare, especially from Russia eastward. At upper levels, mT air is pulled into the area during periods of strong cyclonic activity. This last is uncommon, however, since most Atlantic lows weaken perceptibly as they move eastward. By the time mT air penetrates any of these areas, it has undergone considerable modification and is characterized by only moderately high temperatures. Petterssen (1940) gives a temperature of -3°C. (26.6°F) for winter mT air at the 800-millibar level (approximately 6000 feet) over Moscow and Slutsk. This is compared with a temperature of 1°C (33.8°F) at Berlin, 3°C, (37.4°F) at Cologne and approximately 9°C (48.2°F.) at Boston, Mass. Nevertheless, in eastern

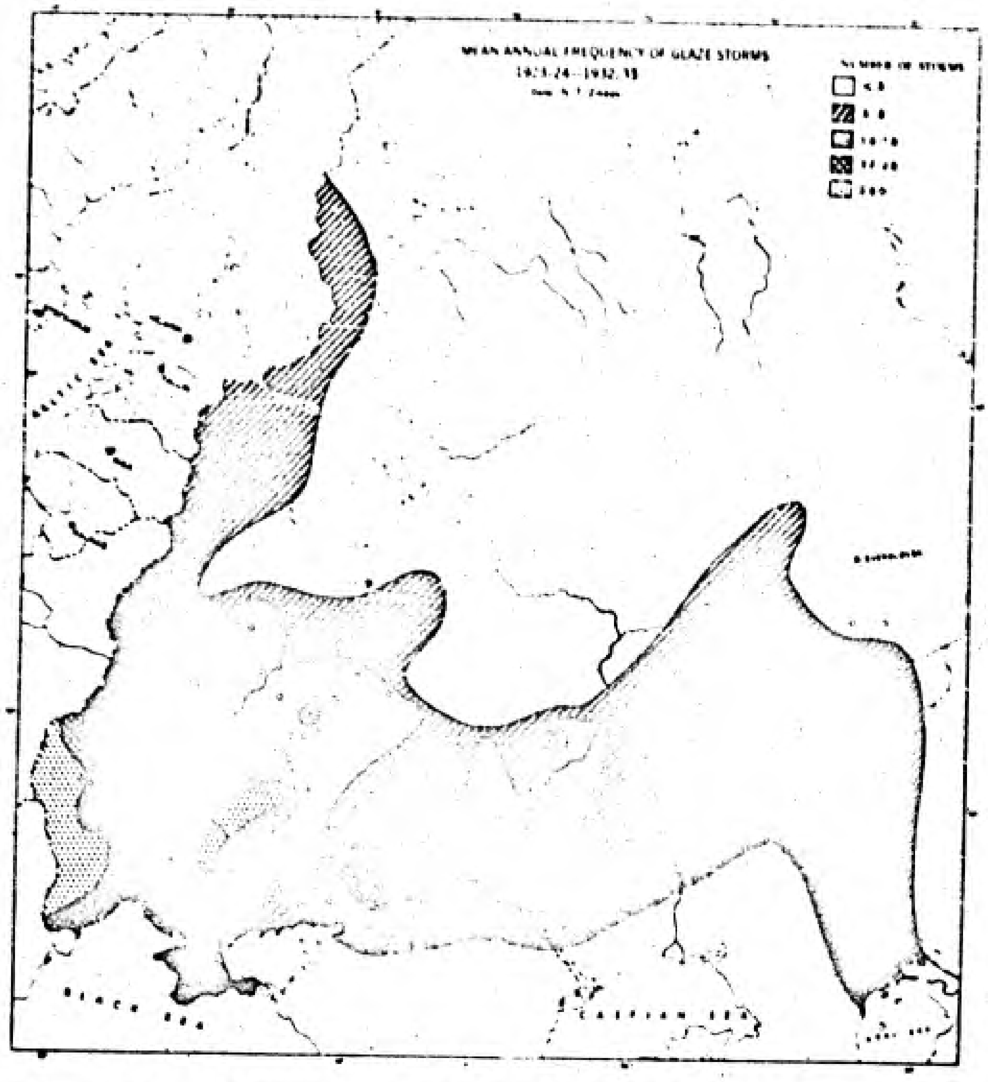


Figure 40. Mean annual frequency of glaze storms in the European section of the U.S.S.R. for the 10-year period from 1923-24 to 1932-33. Based on data obtained from N. T. Zikeev.

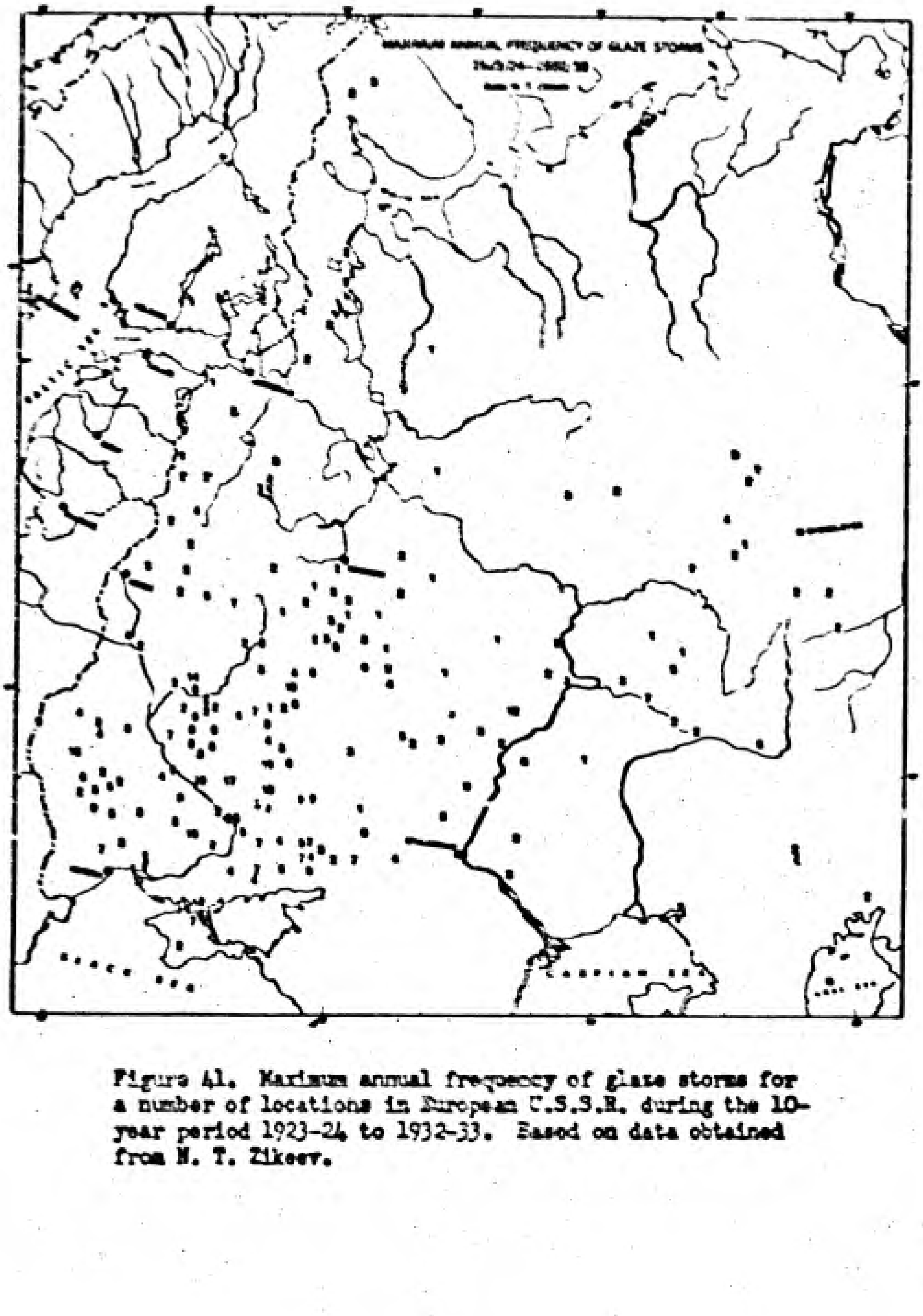


Figure 41. Maximum annual frequency of glaze storms for a number of locations in European U.S.S.R. during the 10-year period 1923-24 to 1932-33. Based on data obtained from N. T. Zikeev.

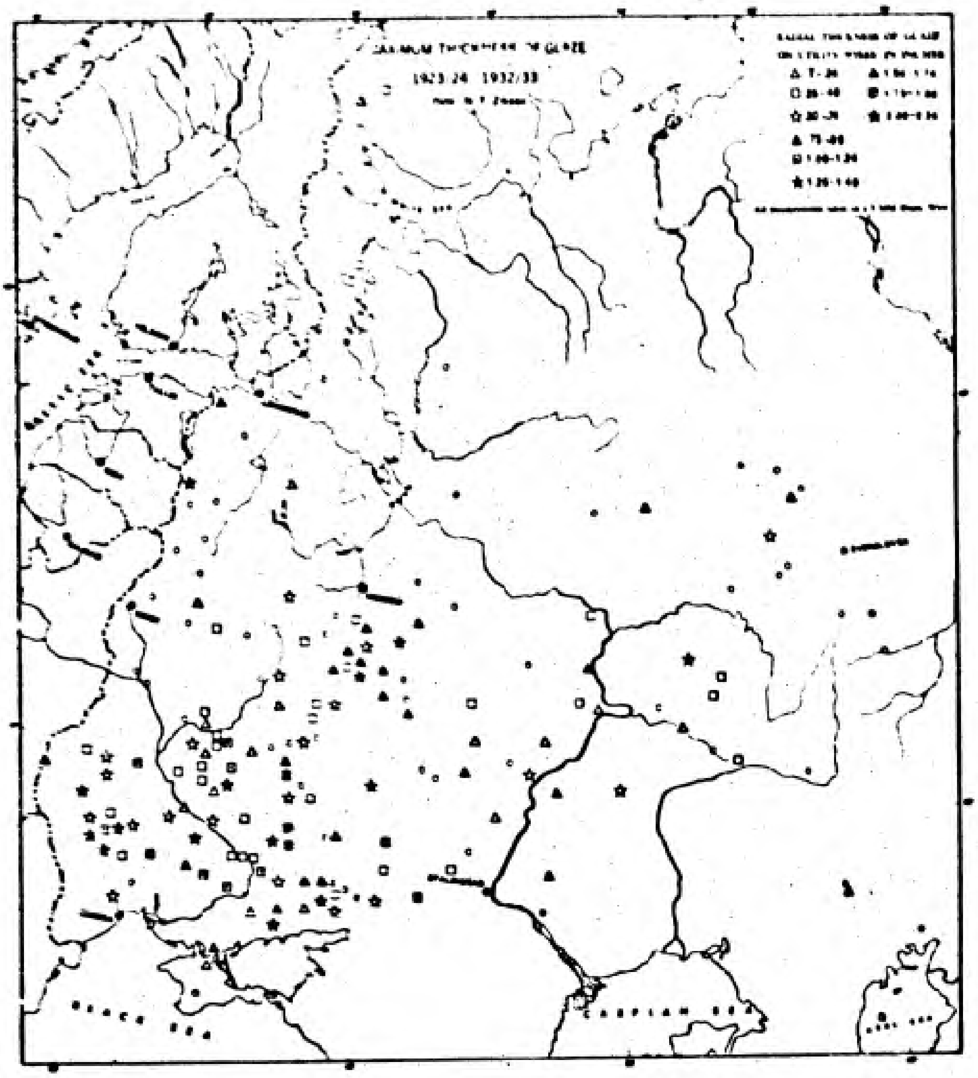


Figure 42. Maximum thickness of glaze at various locations in the European portion of the U.S.S.R., during the 10-year period 1923-24 to 1932-33. Based on data obtained from N. T. Zikeev.

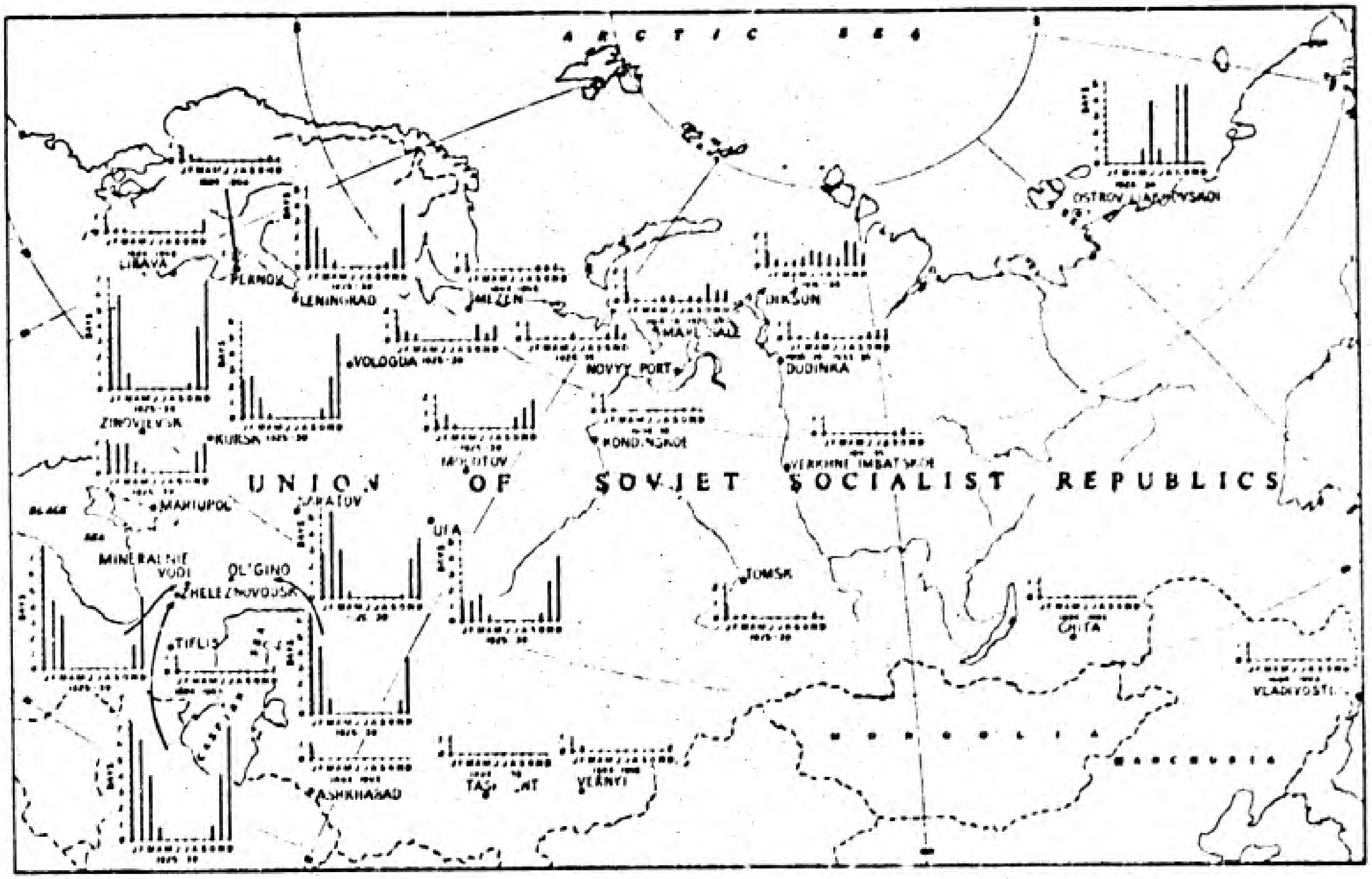


Figure 43. Mean monthly frequency of number of days on which glaze deposits were observed during periods indicated on map for each station. Data supplied by N. T. Zikeev.

Europe and much of Russia, glaze occurs frequently enough to be a problem that must be reckoned with. In extreme northern and eastern Russia and virtually all of Siberia, glaze is a comparatively rare phenomenon and probably does not amount to much when it does form.

In the Soviet Union, glaze most frequently occurs in an area shaped roughly like an "L" that extends from the general vicinity of Leningrad south to the southern Ukraine along a line that keeps west of Moscow, then east to or beyond Stalingrad (Figures 40 and 41). Throughout most of this area the mean frequency of glaze storms is at least 1 per year in the 10-year period 1923-24 to 1932-33 (Figure 40). North and east of Moscow, the frequency falls to less than 1 storm in every 2 years.

In the Ukraine and Don regions, which appear to be the most susceptible parts of the L-shaped area, frequencies of storms run from 1.0 to 5.9 storms per year. Figure 41 shows that in most of the Ukraine and Don regions the maximum number of storms experienced in any one year is at least 3, and runs as high as 10 to 17 for a few places. The intensity of storms, as shown by the maximum radial thickness of ice on utility wires in Figure 42, also appears to be heavier in the southern and western portions of the L-shaped region than elsewhere, although ice 0.75 inch thick has been recorded almost as far east as the Urals.*

An interesting feature of the distribution shown in Figure 40 is the fact that the zone in which an average of one storm a year occurs, extends as far east as the Aral Sea. This is an extremely arid region with very little winter precipitation, and it is surprising to see as many storms occurring here as in the more moist regions located farther west.

Figure 43 and Tables VI and VII show the seasonal occurrence of glaze in the U.S.S.R. In the European part of the country the seasonal distribution seems to be much the same as it is in the central and eastern United States, with November to March representing the glaze season. On the Arctic coast east of 60°E. Long., a sizeable portion of the glaze, if it is true glaze, occurs during the warm half of the year. Twenty years of data at Dikson (Arctic coast of Siberia near mouth of the Enissi River) show a fairly even year-round distribution of the number of days with glaze.

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* Shishkina (1955) describes an exceptionally severe glaze storm in the area of Tuapse (north shore of the Black Sea east of Sea of Azov) in which ice up to 5cm (1.97 in.) thick formed on wires and trees and remained for almost 5 days.

TABLE VI

NUMBER OF DAYS WITH GLAZE IN SIBERIA, 1894 - 1903*

Station	Jan	Feb	Mar	Apr	May	Sep	Oct	Nov	Dec	Yr
Tomsk	5		2		1	1			3	12
Omsk								1		1
Barnaul								4	3	7
Chita				1						1
Rykovskoe				1	5		4	6		16
Vernyi		4							4	8
Vladivostok							1			1

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* Data supplied by Mr. N. T. Zikeev

TABLE VII

TOTAL NUMBER OF DAYS WITH GLAZE*
(ARCTIC COAST OF USSR)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Vaigach Is. (1924-1934)			93	7	17	20	9	4	8	7		
Yugorski Shar (1924-34)			27	1	18	21	11	9	6	12		
Dikson Island (1924-34)			2	5	7	9	4	4	5	27		
Novyi Port (1924-1934)			0	1	0	0	0	0	0	2		
Komsomolsk Pravdy (yrs not given)	0	0	0	0	1	2	3	9	5	0	0	0
Great Liakhov Is. (1928-1934)	0	0	0	0	6	34	12	1	30	37	3	0
Tiksi Bay (1932-1934)	1	1	0	0	5	2	0	0	1	1	0	0
Bulun (1925-1928)	0	0	0	0	0	0	0	0	0	0	0	0
Chetyrekhstolbovoi Is. (yrs. not given)						17	25	12	9			
Cape Otto Schmidt (yrs. not given)						10	3	3	5			
Uelen (yrs. not given)						5	0	3	1			

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* Source: Air Weather Service (1946).

Table VII contains data for several stations located on or near the Arctic coast of the U.S.S.R. These data confirm the occurrence of glaze during the warmer part of the year in this area. From 1924 to 1934, Vaigach Island (between Novaya Zemlya and the mainland) and Yugorski Shar (on the mainland opposite Vaigach Island) experienced a total of 20 and 21 days respectively with glaze during the month of June. Great Liakhov Island (Ostrov Liakhovskoi in Figure 43) had 34 days in June, 30 in September, and 37 in October from 1928 to 1934. In contrast, Bulun (near the mouth of the Lena River) received no glaze from 1925 to 1935 and Novyi Port (southern tip of Gulf of Ob), reporting only for the months March through October, received a total of just 3 days from 1924 to 1934.

In addition to the data presented above, small amounts of data on glaze are found in Russian literature. This information is presented below.

Data collected from 1926 to 1935 (Kozlov, 1937) indicate a rather high frequency of glaze on the shores of Yugor Strait (Yugor Shar) located just off the Arctic coast of Europen U.S.S.R. An average of 23 days per year is reported with glaze, with the highest monthly frequency being 9 days in May. It is not made clear whether this refers to days on which glaze actually forms, that is, freezing rain is actually observed, or whether it merely refers to days on which glaze remains on the ground. The maximum thickness of glaze reported during this period is 13 mm. (0.51 inch).

Observations taken on Sergei Kamenef Islands in the Kara Sea (Rusinova, 1936) from October 1930 through August 1934 show glaze occurring on an average of 4 times a year.

Data for 22 weather stations in the vicinity of the Kara Sea and from ships in the Kara Sea indicate glaze formation occurring between 1895 and 1939 on about 10 days per year, primarily during spring and autumn (Prik, 1946).

Another reference (Riazantseva, 1937) gives glaze frequencies for two locations on the Arctic coast of Siberia in the vicinity of the mouth of the Lena River. Lyakhovsky Island averages 7 days per year with glaze and Tikso Bay, 2 days.

A paper by Muretov (1930) discusses briefly the results of glaze observations made at 130 places in the U.S.S.R. in the 1920's. Ice 25 mm. (0.98 inch) thick is reported in 7 percent of all the cases recorded. The maximum thickness encountered is a diameter of 114 mm. (4.49 inches) on a 5 mm. (0.20 inch) diameter wire at Tokmak in the Chu Valley of the Kirghiz Republic. This particular ice deposit lasted 10 days before disappearing. The author observes that, in the study as a whole, intensive glaze lasts on the average from 1 to 5 days.

Between 1885 and 1901, freezing rain occurred 65 times at Kiev and was observed in all months but July and August (Zhuk, 1902).

In the period 1912 to 1925, glaze was observed on an average of 4.1 days per year at Voronezh in the Don Valley (Shipchinskii, 1928). The season of occurrence lasted from October to April with a maximum of 1.1 days in December.

Observations at Bogoroditskoe-Fenino in Kursk Province (130 miles south of Moscow) between 1882 and 1906 indicate a maximum of 11 days with glaze per year (Pul'man, 1907).

A report by Lebedeva (1937) states that glaze is usually not observed more than twice a winter in Estonia and Latvia. At Tallin on the Gulf of Finland, it is most commonly observed in January, at other locations in November or December.

e. Summary

Glaze is a weather phenomenon most typically associated with the United States, but is not uncommon in Canada and Alaska and is even known in northern Mexico.

In the southern hemisphere, cP air is largely unknown, consequently conditions favorable for glaze formation probably do not occur very often. Nevertheless, it has been reported from New Zealand and very likely has been experienced in Argentina and Chile.

The pronounced anticyclonic circulation that dominates Asia in winter prevents the incursion of mP air into the mainland of Asia and keeps the incidence of glaze to a minimum. Data for eastern Asia are almost non-existent, but one set of old data was obtained and shows Vladivostok, Siberia, experiencing 1 day with glaze in a 10-year period. Due to a greater exposure to low pressure centers moving from the south, the Japanese islands undoubtedly experience more glaze than the mainland of Asia. Descriptions of two storms that struck Japan indicate conditions similar to those found along the eastern coast of the United States.

Glaze is common in many parts of Europe, particularly in the central and eastern sections, although frequencies apparently are considerably below those reported for the United States. The principal area of occurrence appears to be a broad belt lying to the north of the Pyrenses-Alp-Balkan mountain complex and extending from eastern France to south-central European U.S.S.R. Vienna, which is well within this area, had an average of better than 10 days a year with glaze on the ground between 1905 and 1935. Data for the Soviet Union show at least 1 storm per year during a 10-year period in an L-shaped area that runs from Leningrad to the southern Ukraine and eastward past Stalingrad and extends as far north as Moscow. Frequencies of 2 to 3 storms per year are common north of the Black Sea and Sea of Azov.

Part III

Economic Consequences of Glass

1. Utilities*

a. Damage and Economic Effects

(1) Economic effects

With the possible exception of forest and woodlot, the greatest economic loss from glaze storms is suffered by the electric utility, telegraph, and telephone industries. Glaze on highways is responsible for inconvenience and actual monetary loss because of delayed deliveries and missed trips, and considerable sums of money are necessary to pay for the repair or replacement of automobiles and trucks damaged in traffic accidents on slippery roads, but none of this can compare with the financial setback of the utility company unfortunate enough to have its outside facilities subjected to a severe glaze storm.** It is not uncommon for the total cost of repairing damage to lines and poles and the loss of revenue from suspended service to exceed several hundred thousand dollars for companies in an area struck by a heavy storm; on many occasions damage has run into the millions.*** The secondary effects of such storms on factories, businesses, and schools, which must suspend operation because of the loss of electric power service, may swell this figure to a considerably larger total.

(2) Types of damage

The damage inflicted by glaze storms on utility operations most commonly is of a mechanical nature and is limited primarily to the wire system. Electrical damage can also occur, and mechanical injury may also extend to include insulators, transformers, switches, poles, and even house meters. Nevertheless, wire-damage remains pre-eminent because electrical damage is seldom important and mechanical damage of the kind just mentioned is almost always initiated by line trouble in the form of greatly increased tension, violent agitation, or outright breakage.

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* The term "utilities" when used alone refers to electric power, telephone, and telegraph companies.

** Nothing, of course, is of greater consequence than the human suffering resulting from injuries and loss of life in traffic accidents caused by glazed highways.

*** The storm of February 21-24, 1922 in the Great Lakes area inflicted $8,000,000 damage to utilities in Wisconsin alone (Lockwood, 1922). This amounted to one-half of the total investment in utilities in the state.

(3) Cause of damage

There are three principal causes of wire damage: (1) ice load acting alone, (2) ice load and wind working in combination, (3) ice-broken trees and tree limbs which fall across lines. Any study of the effects of glaze storms on utility operations should, therefore, be focused on the methods of formation, and the thickness, frequency, and duration of ice on wires and the wind conditions which can be expected to accompany ice formations of different intensities. Ice on trees is discussed at length elsewhere in this report.

b. Types of ice hazardous to wires

Although this report is concerned primarily with glaze formed by freezing rain or drizzle, other types of ice, such as rime, hoarfrost, and wet snow, may form on utility wires and do great damage. These other types, however, are not as a rule as serious a danger as glaze, largely because of their lower densities. An exception to this is found in some high mountain areas where the thicknesses of rime and wet snow on lines can reach considerable proportions.

(1) Hoarfrost

Hoarfrost is a common phenomenon on utility wires, but seldom is it the cause of serious mechanical damage. In the rare case where frost is responsible for the injury to conductors, it apparently is because the ice deposit, with the aid of the wind, has initiated the phenomenon known as "dancing conductors."* In a report furnished the writer by the dispatcher's office of the Northwestern Public Power Company of South Dakota, listing and explaining the reasons for all outages experienced by the system's lines, 4 instances out of a total of 50 in a 7-year period, indicate that lines were taken out of service because of dancing conductors caused by frost. Whether injury to lines actually occured in these cases is not specified. Hoarfrost deposits on wires usually are of short duration, most commonly forming on lines in the early morning and dissipating a few hours later as the sun comes up and the temperature rises. Infrequently, they may remain on wires for several days. Various methods have been tried to remove hoarfrost from lines, for example, dragging a rope along the lines; but such practices are not widespread because this type of ice is not considered a serious threat to line safety.

(2) Rime

More nearly approaching glaze as a serious peril to utility wires is rime. This may occur wherever conditions are favorable for

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* For a more complete description of this phenomenon, see par. d (5), this section.

ice formation, but is encountered most frequently in mountain regions where it probably occurs much more often than glaze. It is particularly well-known in the mountains of western Europe, in the Caucasus of the southern part of the Soviet Union, in the Cascade, Sierra Nevada, and Coast Range mountains of the Pacific coast of North America, and in the highest elevations in the northern Appalachians. It probably also occurs frequently in the Atlas Mountains of North Africa and in the mountains of southern Chile and southwestern New Zealand. As has been pointed out earlier in the report, rime has a lower specific gravity than glaze and therefore is not as often the cause of mechanical damage to wires. Nevertheless, in mountain regions subject to invasion by moist, stable, air masses, rime can reach such great thicknesses that sufficient weight is added to wires to cause their failure. The Public Service Company of Colorado (L. H. Robertson, 1953) reports rime ice up to a foot or more in diameter on its lines crossing the Continental Divide. If, under such conditions, a moderate or strong wind is blowing, the chance of line failure is great.

Methods of combating rime are the same as those used for glaze, with one possible exception. Long wooden poles equipped with hooks have been used successfully to knock rime off wires but have not proved practical for glaze removal.

None of the types of ice being discussed always occur on wires in its purest form. Rime, for example, can vary from ice that has such a low specific gravity it should properly be called hoarfrost to ice that approaches glaze in character (see par. 1b, Part I). In addition, different types of ice are often found on the same wire. For reasons explained earlier, the deposition of ice on a wire may first take the form of rime, then gradually change to glaze. Also, alternate thawing and freezing of the outer layer of a thick rime deposit may change that part of the deposit to ice with a density approaching glaze. Barray (1939), studying rime formation on electric wires in France, found that when this form of ice remains on wires for prolonged periods, it usually increased in density daily. Hrudicka (1936) found that the specific gravity of rime and hoarfrost deposits on wires increased from 0.1 to 0.8 with age.

(3) Wet snow

Deposits of wet snow also build up on utility wires, but usually not in sufficient quantities to cause breakage. In the Sierra Nevada and Cascade mountains, and undoubtedly elsewhere, a condition can exist that may result in the formation of extremely heavy loads of wet snow on wires. It has been described in a personal communication from the Public Utilities Commission of California (Pajalich, 1953) as follows:

"In California the problem does not appear to be one of glaze storms. Instead, a deposit may form on conductors due to a series of storms leaving layers of wet snow on lines. In the interval between successive storms, little or no unloading may occur because of overcast conditions accompanied by little solar heating and below freezing air temperatures."

This effect can obtain through alternate thawing and freezing of snow, causing it to cling more tenaciously and therefore remain on the wire until the next storm deposits a new load of snow. Such a condition is not necessary, however, for wet snow to cause breakage of utility wires. Cases have been reported, and not always in mountainous regions, in which the weight of snow from a single storm with possibly a moderate assist from the wind, has been responsible for broken wires. C. P. Corey (1949) of the New England Power Company, reports that heavy, wet snow is particularly troublesome on that system due to the danger of rapid unloading when the temperature rises, causing slapping together of electric conductors and consequent arcing. To prevent burn-downs from the arcing, it is often necessary to take affected lines out of service if winds are strong enough to whip the spans together.

(4) Glaze

True glaze probably is not observed on utility wires as frequently as hoarfrost and rime, or even wet snow, but except for a few special areas it undoubtedly is responsible for more damage to outdoor utility installations than all the other types together. Its greater specific gravity and high degree of tenacity are, of course, responsible.

c. Formation, and thickness of glaze on wires

(1) Temperature of wires and precipitation

Appreciable amounts of glaze may be deposited occasionally on other surfaces by precipitation warmer than 32°F., but the writer believes that in virtually all cases of glaze on wires the drops of precipitation are supercooled. Wires respond so quickly to changes in air temperature that it is difficult to imagine dry wires with temperatures sufficiently lower than the surrounding air as to cause non-supercooled rain to freeze as it strikes. Furthermore, since a wire has so little mass to be heated, warm rain would probably quickly raise the temperature above 32°F.; and because the balance between freezing and non-freezing is so delicate in such a situation, the release of the latent heat of fusion by any small amount of water that might freeze would be another important factor in negating appreciable ice formation. Glaze could build upon a wire which had a temperature above freezing during the incipient stage of ice formation from supercooled precipitation, but the temperature of the wire would soon be depressed below 32°F. by the impinging drops. In almost all cases of glaze formation on utility lines, both wires and precipitation probably are below freezing in temperature.

(2) Glaze on wires from fog

Fog can be responsible for glazed wires, but probably not as often as for glazed highways and trees. Since the metal in bare wires is an excellent conductor of heat, it very rapidly removes from the surface of the wire the small amount of heat released when fog droplets freeze, thus enabling the entire droplet to freeze at once and become part of a rime formation. On trees, highways, and non-metal structures, conduction of heat away from the drops is poor and they freeze more slowly, making coalescence before freezing a greater possibility, thereby yielding glaze, or ice that approaches it in density. However, as has been pointed out before, a fog-induced rime formation on wires might very likely be coated with glaze after a moderate layer of rime forms, because ice itself is a poor conductor of heat and conditions similar to those just described for tree and highway surfaces would then exist.

(3) Thickness of ice

An area of uncertainty concerning glaze formation on utility lines is the thickness of ice deposited on a wire by a given quantity of precipitation. On horizontal surfaces the problem is not as great, for there is less chance for loss by runoff, and the amount of ice formed should approach in depth the water equivalent of the precipitation. For wire surfaces, the various significant factors are so variable and so difficult to measure, that no meaningful relationship among them has ever been established. Among the factors that have to be considered are: wind velocity, air temperature, and relative humidity at wire height; rate of fall of the water drops; size, conductivity and specific heat of the wire; rate and duration of precipitation; and size and temperature of the drops. Some of these can be readily determined, but others would defy accurate quantification. If an adequate number of appropriate observations were available, some kind of average relationship might be established empirically, but unfortunately such observations have never been taken.* Little value could result from examining the vast quantity of measurements of ice on lines taken by utility companies because in almost all instances the observations are taken at sites some distance from the nearest weather station where the coincident precipitation and other meteorological data are available. Recently an attempt was made to correlate a group of these utility observations taken in Pennsylvania with temperature and precipitation data from the closest weather stations, but the results are of no great practical value (Lenhard,1955). During the 1920's and 1930's a small number of measurements of ice on so-called "sleet racks" were taken at Weather Bureau stations, but these were so few in number that they could not possibly yield significant results. In addition, the wires in these racks were located only 5 to 6 feet off the ground, thereby exposing them to wind and temperature conditions significantly different from those existing at the higher levels at which utility wires are usually found.

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* The writer of this report had no facilities at his disposal for carrying out controlled experiments of this type.

Many utility engineers seem to believe that the radial thickness of ice on conductors is of the order of 30 to 40 percent of the precipitation. This probably stems from an analysis made in the early part of this century which was published in one of the leading journals in electrical engineering (Fowle, 1910). In this analysis it was assumed precipitation would strike a wire at a uniform rate over a known period of time, that all of the ice would adhere to the wire and that it would be deposited uniformly over the surface of the wire. The expression derived for ice thickness was r = 0.318 pt, where r is the radial thickness of the ice, p the constant rate of precipitation, and t the duration of precipitation. The assumption that all the precipitation would freeze to the wire is unsound. The work is of value, however, because it shows that, since ice must be spread over the entire face of a cylinder exposed to the precipitation only in cross section, in theory at least the ice thickness can never equal the precipitation.

Usually a good deal of water will flow or be blown off wires before freezing, with the proportion lost rising rapidly as the wind velocity, rate of precipitation and drop size increase (Arenberg, 1940). There is a possibility however that the over-all effect of greater wind speed is to cause an increase in the thickness of ice that forms because the increased number of drops striking the wire at higher wind speeds offsets the greater loss through "blowoff". A decrease in temperature, on the other hand, causes the percentage that adheres to grow larger. The explanation of this temperature effect is found in the relationship between the degree of supercooling of the drop and the amount of latent heat of fusion released when the drop begins to freeze (see par. 1d of Part I). The lower the temperature of the drop, the larger the proportion frozen upon impact.

There has long been considerable question whether there is a relationship between wire diameter and thickness of ice deposits. Some investigators suggest that less ice should be expected on larger wires, others that less should be expected on wires of smaller diameter, and still others that there is no relationship. Matters seem to have been resolved in favor of those who believe wire size has no great influence on ice thickness. The Association of American Railroads data show no consistent relationship between thickness of glaze deposits and wire diameter.

(4) Shape of ice: icicles

Ice is seldom completely uniform in its development around a utility line. Sometimes it is thicker on the top of the line and sometimes on the bottom, depending on such factors as the rate of rainfall, drop size, temperature and wind velocity. In addition, there is frequently a variation between horizontal and vertical thickness. Several hundred measurements taken by utility companies under the auspices of the Edison Electric Institute show that horizontal and vertical dimensions of ice on conductors can differ by as much as 3 to 1. Nearly circular deposits may be the result of the ice cover turning on the wires as the weight becomes unbalanced (Lockwood, 1922), or of torsion on the part of the wire (Gunther, 1940).

A highly developed formation of icicles will completely upset the essential symmetry of ice formations and add considerably to the total load upon the line. Fortunately, icicles do not form at all, or are relatively small and unimportant, in about four storms out of five. The Association of American Railroads concluded on the basis of the massive amount of data they collected that icicle formation was significant in only 14 percent of the storms reported. In fact, they decided to ignore icicles in making computations of the vertical ice load on lines.

The writer analyzed the "sleet rack" data (Association of American Railroads, undated) in which icicle formation was carefully measured and found that of the 95 observations where information on the presence or absence of icicles is provided, there were 48 cases completely without icicles, and 75 cases (79 percent) in which they were less than one inch in length. The longest icicles reported were 4 inches and were spaced along the wire at an average distance of one per inch. The average radius of the main sheath of ice on the wire in this extreme case was 0.38 inch in the horizontal dimension and 0.50 inch vertically; as much or more weight was concentrated in the icicles as in the main sheath. Other sources of information indicate icicles on lines may sometimes be at least 6 to 8 inches in length (Fischer, 1936).

It is the writer's opinion that icicles are most common in the heavier-than-average storm, and probably develop most fully when supercooled rain of more than usual intensity falls at temperatures very near 32°F. They probably do not develop to any extent in severe storms in which the ice coating requires a considerable time in which to form from light freezing rain or drizzle. Finally, icicles very often form when the ice on wires begins to melt, in which case they cannot be considered an increment to the original ice load.

(5) Differences in ice accumulation

There likewise has been some uncertainty whether there is any difference in ice accumulation between live and dead electric conductors, and between electric conductors and telephone wires. The answer, again based on the Association of American Railroads data, apparently is that all of these are equally capable of acquiring ice loads, but because of structural differences some telephone lines are subject to considerably more damage than most electric power lines. Data collected by the Pennsylvania Electric Association (Zehfuss, 1945) substantiate this in that they indicate there is no difference in shape or thickness of ice coating on wires that are electrically dead and those that are alive. As far as difference in damage experienced by telephone and electric power lines is concerned, the Pennsylvania material includes a description of a storm with glaze ranging from a trace to 7/8 inch, in which few electric power lines were affected but considerable destruction was sustained by communication lines. They report another storm with heavy damage to trees and communication wires, but very little to power lines.

(6) Differences on upper and lower level wires

In lines with several layers of wires, the upper levels accumulate more ice. At least, this is reported by Turoverov (1939), Rozanov (1952) and Zikeev (1941). Whether the difference in ice thickness between upper and lower levels is significant enough to be a factor in designing the structural strength of lines is not known.

d. Electrical effects of glaze on utility lines

As has been pointed out before, ice damage is usually mechanical in nature, but it can have electrical effects, chief of which is an increase in corona loss. In most storms this amounts to very little, but occasionally it can become serious, and in these instances, according to Kuhn (1935), it is due entirely to the greater discharge of current over the insulators, the corona loss on the line not being affected by weather conditions.

e. Damage from weight of ice

(1) Unequal loading of lines

A common way ice load alone inflicts damage on the wire system of utility companies is through unequal loading or unloading of lines. Grimmitt (1945) in writing of conditions in Great Britain, states that the most frequent type of damage to overhead lines is caused by ice falling off conductors, which then rise abruptly and come in contact with higher level conductors. This causes a short circuit, which may burn and rupture the affected wires. Experience in the United States indicates that rapid unloading of conductors or the failure to unload simultaneously are important sources of damage to utility lines, but that these do not necessarily rank first. (American Telephone and Telegraph Co., 1944, Corey, 1949, Shealy, et. al., 1952, Zehfuss, 1945.)

An excellent description of what can happen to lines when rapid unloading takes place is given by an employee of the Duquesne Light Company of Pennsylvania (Zehfuss, 1945). The incident occurred where a 1437-foot span of high-voltage line crossed a river.

"At the time, I was looking to determine how much sag was in the bottom wire because it was the only conductor at the time of this observation that had any ice load...the loaded conductor had 15 to 20 feet more sag than the unloaded conductors...the ice formation including the conductors was approximately 4 inches in diameter...the ice started to fall off the conductor at a point approximately 400 feet from the south tower. The ice started to strip off the wire toward midstream and when it had dropped approximately 200 feet the conductor started to whip up and down. The ice was breaking off in pieces from 1 - 3 feet in length. As the ice began to fall more rapidly, the magnitude of the wave increased until the bottom conductor reached the top conductor (normal clearance between top and bottom conductor, 24 feet) which continued for five times before the wave started to die down. As the whipping action subsided, I noticed a terrific tension exerted on the strain insulators supporting the span and I thought for a moment the insulators would separate and leave the conductor to fall in the river. Very little horizontal motion occurred during the period the conductor was in vertical motion."

In this same storm, at another river crossing nearby, similar action caused the failure of one conductor and heavy damage to three others.

Another quotation demonstrates that unloading does not have to produce such violent actions as just described in order to create a dangerous condition (Zehfuss, 1945).

"The 12 conductors in two parallel 66 kv transmission lines which had been uniformly loaded with ice did not clear simultaneously. An instance was observed where the two lower conductors of one of the circuits had cleared of ice and the upper conductor was sagging about 3 feet below the middle one. Even a slight wind would have caused contact between phases. This condition did not last more than one hour. Later in the day, in the span. but in another circuit, the bottom conductor rose until the vertical separation from the conductor above it was reduced to about one foot. The total rise of conductor to normal sag was in no observed instance a sudden large movement, but rather the result of a large number of small increment rises."

A practice recommended by engineers of the Pennsylvania Water and Power Company (Sheely, et al, 1952) to aid in safeguarding lines against this dangerous condition is to increase the vertical spacing of conductors, and vary the length of crossarms in order that upper and lower level conductors be offset. Unfortunately, these practices cannot always be followed. Some types of long-distance telephone circuits must be built with relatively close spacing between the two wires constituting each pair, and on such circuits unequal loading or unloading can result in the actual freezing together of the wires, especially if a slight wind is blowing (Carr, 1949).

(2) Breakage of lines

In unusually severe storms, utility lines may have to support extremely heavy loads of ice. One week after the Michigan storm of February, 1922, a 1-foot length of telephone wire weighed 11 pounds (Seeley, 1922). In this same storm, a 3-foot length of electric conductor weighed 12 pounds with its load of ice (Lockwood, 1922). A report from Great Britain (Pattinson and Dines, 1940), states that during the storm of

January , 1940, a segment of ice-covered telegraph wire 4.5 inches long weighed 178 grams (6 oz.) which amounted to an increase of 130 times its weight without ice.

Instances of wire breakage occasioned by the sheer dead weight of ice are probably not too common, at least in the United States. Usually, one of the conditions described above has been a factor in causing the rupture, or the wind has been of sufficient force to become a factor. In many cases where ice alone appears to be responsible, it is found upon observation that the wire had been weakened previously at the point of rupture by a lightning strike or as a result of having been hit by a rifle bullet (Shealy, et al., 1952).* The minimum standards for construction put forth by the National Bureau of Standards in the "National Electrical Safety Code" (U. S. Dept. Com., 1948) are high enough, especially in the part of the country where heavy loading requirements must be followed, to enable wires to sustain all but the heaviest load without failing. Modern construction makes it possible for lines to carry well up to 1 inch of radial ice without danger (Christie and Chartier, 1943). Observations in various parts of the country have shown that even greater loads can be tolerated without serious consequences. The map in Figure 25 shows that deposits greater than 1 inch in radius may occasionally have to be supported by lines in almost all sections of the country.

f. Damage from ice and wind working in combination

(1) Effects of wind and ice

The factor of wind is one that is fully appreciated by utility engineers and has been the subject of a good deal of study. Because of the strength of design currently used in constructing utility lines and poles, wind by itself rarely is the source of damage to such facilities. An occasional tornado, hurricane, or thunderstorm may carry wind of sufficient force to harm lines and poles, but their capacity to endure extremely strong buffeting without injury is amazingly high. However, when lines are loaded with ice, even moderate winds of 10 to 15 miles an hour can create havoc in short periods of time. The angle at which the wind strikes the line is extremely important, with maximum danger when the wind is at right angles, and minimum when it is parallel to the line. Cases have been reported where, in the same storm, lines running across the wind direction were heavily damaged and those running parallel to the wind escaped injury.

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* Tremendous damage is inflicted each year on utility lines by vandals who use them for "target practice."

The combined effects of ice and wind on electric power and telephone lines are twofold (1) they increase by many times the transverse loading* upon both wires and poles, and (2) they upset the equilibrium of wires so that they become subject to violent and erratic movements.

A coating of ice on wires increases the "sail area" that the wire presents to the wind and this, of course, increases the pressure put on the wire by wind of any given speed. If a wire with a diameter of 0.20 inch is encased in a sheath of ice with a radial thickness of 0.50 inch (an amount which is not unusual in many parts of the country), the area exposed to the wind is increased by 6 times. Using the expression**

$$Wh = \frac{p\ (d + 2r)}{12}$$

in which Wh is the horizontal wind load in pounds per linear foot of line, p is the wind pressure in pounds per square foot of projected area (calculated on the basis of $p = 0.0025v^2$, where v is wind velocity in miles per hour), d is the diameter of the wire in inches, r the radial thickness of ice coating in inches and assuming a wind velocity of 40 miles per hour normal to the direction of the line, it can be shown that the increased transverse load upon the line increases from 0.07 pound per linear foot for the bare wire to 0.4 pound per linear foot for the ice-covered wire in this example. For small telephone wires, which can have a diameter as small as 0.08 inch, the proportional increase in transverse load with 0.50 radial ice covering will be even greater. Some shielding from the wind of one wire by another is afforded in the case of thick ice coats, but in determining the actual structural strength of lines (as required by the National Electrical Safety Code), no allowance is assumed for shielding and the wind load is computed on each individual wire.

(2) Role of gust velocities

The Association of American Railroads has investigated the influence of gust velocities upon lines and has decided that, although of some importance, gusts probably are not as significant as previously believed. They base this on the assumption that gusts usually have narrow fronts and therefore do not normally exert their full pressure over an entire span, and that gusts have a relatively instantaneous effect upon poles and wires; unless occurring with synchronous line vibrations, their repetive effect is less than that of the lower but constant pressure of the

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* The pressure exerted at right angles to the lines.

** Formula used by the Association of American Railroads in calculating transverse loading on lines. See their Glaze storm loading summary, 1927-28 to 1936-37.

mean wind velocity. They believe that for purposes of statistical analysis, the fastest average 5-minute wind velocity during the period ice remains on wires is better than peak gust velocity as a measure of the strongest winds lines would have to experience in a given storm.

(3) Effect of icicles on transverse loading

The Association of American Railroads also has made an effort to determine the effect of icicles on the transverse load of ice-covered lines. After a careful study of the matter they present the following conclusions:

(a) Icicle formations are, in general, very irregular and any method of computing their "sail area" necessitates assumptions which would be difficult to substantiate.

(b) The effect of wind pressure on a glaze-coated conductor with icicles present is to cause the wire to rotate so that the icicles take a position at an angle to the vertical plane and in consequence their "sail area" may be materially reduced.

(c) Wind tunnel tests carried out by other investigators show that icicles tend to produce a streamlining effect which results in decreasing the effective wind pressure on the glaze-coated conductor.

(4) Effect of transverse loading of poles

Transverse loading is even more important for poles than for wires. In fact, it is the major consideration in determining pole strengths. A heavy load of glaze alone on wires will not necessarily place an important additional stress on the ability of a pole to remain upright or resist breaking, because tension on the pole will be approximately equally divided between the lines leading up to it from each side. However, if the lines on one side break, the load is suddenly thrust upon one side of the pole with the result that it can be pulled to the ground. When one pole goes down, its immediate neighbors are subjected to the same unequal line loading, possibly causing them also to topple. Eyewitness accounts have been given of 2 to 3 miles of poles going down one after another from this effect (Lockwood, 1922). Most cases involving the failure of poles are associated with this type of situation or with an instance of excessive transverse loading. In the latter case the pole is broken or falls at an angle to the trend of the line.

(5) "Dancing" conductors

One of the most serious conditions arising from the combined effects of ice and wind on utility lines is the phenomenon of "dancing" or "galloping" conductors. It has been known to occur in the absence of ice deposits, but such cases are rare and not very well authenticated (Grimmitt, 1945). In a storm in Pennsylvania when it was noted that the amount of ice necessary to start "dancing" was rather critical, by knocking some ice off the conductor, the "dancing" would cease in that span (Zehfuss, 1945). The cause of "galloping" conductors is obscure. Probably as good an explanation as any has been given by Carr (1949):

> "Winds need not have a very high speed to cause damage to the telephone plant. Some which are steady and moderate under certain conditions will set up damaging vibrations in wires and cables. When wind blows across a suspended cylindrical material such as line wire, eddies are formed alternately near the top and bottom on the lee side of the wire. These eddies import little kicks to the wire and force it to vibrate. The frequency of such vibrations is directly proportional to the diameter of the conductor and inversely proportional to the speed of the wind."

Carr goes on to say that "dancing" is a term given to a type of wind-induced vibration in which the wire or cable vibrates only a few times each second, but with high amplitude as compared to the rapid, low-amplitude vibrations normally seen (or rather heard) on wires wherever the wind is blowing across the lines. A factor not mentioned by Carr but generally believed to contribute in initiating "dancing" is the uneven distribution of the ice load along the wire (Mironov, 1953).

"Dancing" usually involves an entire span of wire which jumps up and down as a unit. The different wires in a span may or may not dance in synchronism, and when dancing is violent it may become decidedly irregular. A given point in a dancing wire describes an elliptical path with the long axis inclined at an acute angle to the vertical, the wire in the usual 130- to 150-foot spans sometimes moving through vertical distances of as much as 4 to 6 feet.* At rare intervals another type of "dancing" may occur. Christie and Chartier (1943) describe this as "...a vertical wave or ripple with a 20 or 30 degree front about six inches high traveling from one support (pole) to the next, then reflecting and returning with no discernible change in amplitude." They add that it took approximately one second for the wave to traverse the 200-foot span, and that the conductors and arms in this section of line had failed, the pins being torn from the arms, possibly from this cause. The wire was covered with 1 1/2 inches of radial ice and a cross wind of about 15 miles per hour was blowing.

In 1949, the National Research Council of Canada sponsored a conference on galloping conductors in which a number of electrical engineers from the United States and Canada participated (Canada, 1949). It was concluded that most cases of galloping are caused by moderate winds of 10 to 25 miles per hour. Most other sources of information on the subject agree. The Pennsylvania Electric Association (Zehfuss, 1945) found dancing usually begins when wind strength decreased from strong to moderate. The principal effects of dancing are to cause wires to come in contact and tangle with each other, loosen ties and insulators, cut and chafe wires at

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* Amer. Tel. & Tel. Co., 1944

insulators, cause fatigue breaks in the span, and break and chop insulators (Am. Tel. & Tel. Co., 1944). Wire fatigue, as a result of dancing, may cause difficulty long after the storm and after all apparent damage has been corrected. On occasions, dancing is violent enough to be responsible for the failure of large steel high-voltage transmission towers.

Aerial cables also have been found to be subject to dancing, but from the infrequency with which it is experienced, it seems likely to be serious only when unusual combinations of conditions conducive to the development of dancing are encountered. Dancing of cables fatigues the suspension strand, and is known to break the wires composing the strand, but its most serious effects are the cutting and abrasion of the cable sheath and the formation of fatigue breaks in the sheath as the result of violent movement (Am. Tel. & Tel. Co., 1944). It might be noted in passing that cables are more capable than ordinary wires of withstanding glaze damage. They have been known to support the weight of broken poles and trees (Carr, 1949; Waters, Undated).

As yet no sure means to eliminate dancing have been found, although various mechanical methods of damping the motion involved have been tried (Canada, 1949).

g. Damage from trees or limbs falling on lines

One of the most common sources of trouble to utility lines during glaze storms is from trees or limbs falling across wires, causing them to break. Description of many storms indicates that the most serious damage in the storm resulted from this action (Carr, 1949; Meyer, 1938; Porter, 1953; Mau, 1953).

h. Localization of damage

Throughout many descriptions of damage inflicted on utility facilities by glaze storms runs the general theme of variation in geographical distribution of damage. In the collection of storm descriptions compiled by the Pennsylvania Electric Association, there are many references to storms in which severe damage was highly localized. Especially common in this compilation are accounts of greater damage experienced at high elevations in the mountains than lower down on the mountain sides or in the valleys. In at least one case, however, less damage was reported from the summit of a mountain, where the precipitation was in the form of snow instead of freezing rain. The varying exposure of different locations to the wind is another factor, of course, not only from the standpoint of the damaging effect of the wind, but also because increased wind velocity apparently favors the development of thicker coats of ice. This is borne out by observations that report heavier icing on wires in locations unobstructed by buildings or natural wind breaks. Zikeev (1941) states that observations made in the Soviet Union show a significant decrease of glaze on lines near forests. The same effect probably explains the finding of greater destruction in rural areas than in towns in a storm that struck southern Colorado in 1944 (Porter. 1953). An example of extreme localization of damage is given by W. Hill (1945) in a description of a storm in Great Britain in 1940. He states,

> "... near Badminton ... ice on conductors started from a junction pole and covered a distance of about 1000 yards. On other lines at the same altitude and in a similarly exposed position, radiating from the same junction pole, there was almost no ice formation. Near Brisly ice involved only a comparatively short length of line, something under a mile. From a point where the line changed direction there was no formation of ice, although the line was still in an exposed position, and for part of the distance even more exposed. In every case severe ice formation was very localized and affected only part of the line."

i. Methods of minimizing or controlling damage

There are four principal ways in which utility companies limit the serious effects of glaze storms on their operations, as discussed below.

(1) Avoiding sites known to have heavy and frequent glaze

First, to a certain degree, they avoid locating lines in places in which experience indicates glaze is frequent and heavy, and where there is a good chance of strong wind during glaze storms. Such sites cannot be avoided entirely, of course, because the lines must go to the customer no matter where he is located. However, by avoiding, where possible, notoriously dangerous locations, such as mountain and ridge tops, considerable trouble can be eliminated. A practice which could benefit companies in the northeastern states would be to choose the western rather than the eastern sides of mountains for the location of transmission lines where such a choice is possible.

(2) Avoiding trees

Trees are a special problem. Obviously they cannot always be completely avoided, so steps are taken to keep them trimmed away from lines as much as possible. In small towns and villages where old trees may be highly valued for esthetic reasons, the problem of avoiding tree damage can be aggravated. The alternative of burying lines underground is not generally economically feasible in such situations.

(3) Increasing structural strength of lines and poles

Another method of limiting ice damage is by constructing lines and poles sufficiently strong to withstand the combined effects of ice and wind in glaze storms. There is no doubt that lines could be designed which would stand up under the most severe conditions, but their construction might well put the cost of electric power and telephone service prohibitively high. Also damage could be completely avoided by burying lines underground, but again this solution must be ruled out for economic reasons, except in large cities and towns. By and large, it would appear that utilities are following sound practices in the design of their outdoor facilities. Experience has taught them that carelessness in this regard can lead to heavy financial loss.* Public relations can likewise be seriously injured by frequent or long interruptions of service.

(4) Artificial heating of lines

Another method is the artificial heating of lines through the application of increased current loads. Unfortunately, this practice cannot be carried out by telephone companies on their systems. It undoubtedly helps explain why communication lines sometimes suffer more severely than power lines from glaze.

Details of the heating procedures worked out by various power companies vary somewhat. In order to present in the discussion below a routine that would approximate the ideal, the best features have been selected from the procedures of a number of companies.

Experience has shown that prompt action is of the utmost importance in the application of heat if ice prevention and melting are to be successful, because it is easier to prevent ice accumulation than to melt the ice once it has formed, and because air temperatures sometimes drop or a heavy fall of snow occurs after the formation of glaze has ceased, thus requiring more current to raise the wire temperatures to the necessary level. Also, once the storm is well under way the transportation of work crews to switching points along the lines becomes difficult. Prompt action also means that lines will be kept out of service for shorter periods. The ideal practice, therefore, is one in which emphasis is on speed of melting, using high current values over comparatively short periods of time.

The necessity for speed calls for reliable means of forecasting glaze formations and for detecting their incipient formation. Accurate forecasting is doubly important because some time is required to set up operating conditions which will permit heat runs. A warning usually is given at least 4 hours before the onset of the ice formation. This warning is best when based on all available information, including U. S. Weather Bureau forecasts, airway weather conditions for the area, and weather observations on neighboring utility systems as well as the company's own system. In order to insure the maximum use of this information, some companies hire their own meteorologist. Others rely upon the services of a private forecasting concern.

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* During the 1920's there was at least one case of a small electric power company being forced into bankruptcy because of the financial disaster resulting from a severe glaze storm (Seely, 1922).

Once the warning has been issued, it is necessary to be alert for the first formation of any ice on the lines. Some companies rely on direct observation, stationing personnel equipped with portable radios at strategic points along the rights of way; others depend upon instrumental means to aid in detection. The most common instrument method used is based on a sleet detector developed by Langdon and Marquis (1939). The method consists of comparing the carrier's receiver-signal strength during glaze forming weather with a signal strength received when the wires were known to be clear of glaze. An accumulation of ice on the wires causes a comparatively high attenuation of the carrier signal, and the amount of attenuation is indicative of the thickness of ice on the lines. Unfortunately, there are serious disadvantages to this method that definitely limit its reliability. The detector cannot distinguish between different types of ice, and is unable to differentiate between a slight deposit of ice over an entire line and a dangerous concentration of ice within a few spans. In addition, fog may cause a change in the attenuation of the carrier signal similar to that induced by glaze. Most companies using this method supplement it with on-the-spot observers in order to be on the safe side. Where neither method is used, the first warning of actual ice formation may come in the form of a line failure.

5. An example of storm damage

As an example of the type of damage a glaze storm can inflict on utility company facilities, quotation will be made from a description prepared by E. J. Christie* and H. S. Chartier** (1943) of a severe ice storm that visited east-central New York in December, 1942. The storm, the most destructive experienced in that area to that date, started with freezing rain on December 27, reached its peak of intensity on the 30th, and was followed by snow and a long period of sub-zero temperatures. A similar but lighter storm followed on the 18th and 19th of January. The conditions described for the first storm are worse than those encountered in the usual storm but they represent what could happen in any part of the glaze belt of the United States. The affected area was a rather mountainous one that included parts of the Catskills and Adirondacks. Excerpts from the description of the storm are as follows:

"Little direct ice damage to lines occurred at elevations less than 500 feet, as up to that height the glaze did not exceed one-half inch in radial thickness. Most troubles in this belt came from falling limbs that caused short circuits on primary lines and burned them down. Interruptions were generally of not more than one or two hours duration.

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* Chief meteorologist in the New York City office of the U. S. Weather Bureau.

** Distribution engineer with the New York Power and Light Corporation of Albany, New York.

"In the second zone of elevations, between 500 and 1000 feet, glaze was from one-half to one inch in radial thickness ... Little wire fell from direct ice loading ... Many larger wires were burned off when short circuited by falling limbs ... Damage could have been somewhat lessened if all service had been discontinued, and lines killed ... Interruptions from this cause for the most part were corrected within a 72-hour period after limbs ceased to fall...

"Services were a source of great trouble ... Over 1000 services have been replaced and 500 repaired. Where two or three open wires were fastened to a rack on a building, sections of the boards were frequently torn out ...

"Real ice damage occurred at an elevation of above 1000 feet ... Glaze had accumulated to a thickness of five-eighths of an inch ... and it was practically impossible to maintain any service even though 40 men were massed on as short a line as 3,000 feet of the main street of a small town. Work on restoration was discontinued before midnight, as limbs and trees were falling so often that risk of injury to men was excessive.

"Glaze continued to build until evening of the 29th, at which time it varied from one to three inches in radial thickness. Lines were crushed from the weight of ice. Highways were so badly filled with broken trees, poles, and wires that state and other road employees used not only saws and axes but even large snow plows in an attempt to keep the roads open for travel.

"This situation was followed by eight inches of snow, lowered temperatures, and a wind of 25 miles per hour. No melting occurred for more than two weeks and 30 degrees below zero was recorded.

"... interruptions to service lasted from a few hours to as much as 17 days.

"Typical of the worst damage was a 30-mile section of rural line about 1500 feet in elevation where there was not a single span of usable line ... Wires had a kidney-shaped section of ice on the tops and sides one and a half inches or more in thickness, and below was a series of icicles from six to eight inches in length so close together as to form a solid sheet. This loading exceeded three pounds per foot in weight.

"Complete reconstruction was required in these areas... De-icing conductors was a major operation. Those that fell early in the storm were frozen in a two-inch layer of ice and had to be broken out, in some cases with a pickax. All had to have ice shattered foot by foot with hammers or heavy clubs.

"Early in the storm with only slightly over 1 1/4 inches of ice radially, eight A-frame towers fell, presumably from breaking of all conductors in one span. Another case of A-frame failure on 100-kv line occurred during the second storm, that of the 18th of January, when five failed with dancing conductors after several trip-outs and one burn-off ...

"A wood-pole H-frame 110-kv line connecting with another utility system was in the area with the heaviest ice loading, and 47 of the structures built with 55-foot class-A poles collapsed ...The wire was number 4/0 copper, and in some instances the ice had a radial thickness of over three inches. This, together with the sheet of icicles, gave a maximum weight of 14 pounds to the lineal foot. Ice loading exceeded seven pounds per foot for several miles. Failures were progressive and continued on more than one day.

"A light 22-kv single-circuit stub-end line feeding one village and rural lines was nearly ruined, having five out of seven miles on the ground with 90 poles broken. Its restoration required 3 1/2 days.

"After the rain stopped in both storms, there were numerous cases of dancing conductors, both on transmission and distribution ..."

k. Summary

The outside facilities, such as lines and poles, of utility companies are especially vulnerable to damage by glaze stores, with breakage of wires being the most common type of damage suffered. Wires are damaged in three ways: (1) ice load acting alone; (2) ice load and wind working in combination, (3) ice-broken trees and limbs falling across lines.

Considerable uncertainty exists concerning the thickness of ice deposited on a utility wire by a given quantity of supercooled precipitation. No theoretical relationship has ever been established between the two and efforts to do so empirically have likewise failed. Certainly, considerable supercooled rain or drizzle flows off wires before freezing, with the amount thus lost increasing with an increase in ambient air temperature, drop size, rate of precipitation, and probably wind speed. Ice is seldom completely uniform in its development around utility lines, but this seems to be of little significance in inducing damage, except insofar as it may contribute to the occurrence of the phenomenon known as "dancing" conductors. Considerable weight may be added to lines in the form of icicles, but the Association of American Railroad study concludes they play only a minor role in causing damage. There apparently is no significant relationship between wire diameter and radial ice thickness, nor in the accumulation of ice on line versus dead conductors, and telephone versus electric power lines.

Damage from weight of ice alone is more commonly due to unequal loading than to sheer dead weight of ice. Ice and wind working together generate the most dangerous conditions for lines, by increasing by many times the pressure exerted at right angles to the lines or upsetting the equilibrium of wires so they become subject to violent and erratic movements. Corona loss, while infrequent, is the chief electrical effect of glaze on utility lines.

Four principal courses are open to utility companies in attempting to limit the damage to their installations by glaze storms: (1) avoid placing lines in locations subject to heavy and frequent glaze or strong winds; (2) avoid trees; (3) increase structural strength of lines and poles; (4) heat lines artificially during glaze storms.

2. Buildings

The writer was able to discover in the literature only two references to the damage of buildings from an excessive load of glaze. During the great storm of February 21-23, 1922 in Michigan (Seely, 1922), the roofs of many buildings were caved in by ice that accumulated to weights of 16 to 20 pounds per square foot. A combination glaze and sleet storm in December, 1956 (Baldwin, 1956) that deposited 1 to 4 inches of ice and sleet in Oklahoma caused the collapse of an airport hangar and damage to 15 small planes.

In an effort to determine the amount of glaze that would form on the top and sides of unheated buildings, observers participating in the special Weather Bureau observations taken for this project during the winters of 1953-54 were asked to measure the thickness of ice forming on the top and sides of the instrument shelter. In 74 cases where these measurements were taken, the maximum amount of ice deposited on both top and sides was one inch. This thickness was observed only once. In general, the amount of ice forming on top of the shelter was approximately the same as on other types of nearby surfaces (bare ground, concrete, and bituminous highway or sidewalks). Considering only cases where more than a trace of ice was reported on either the top of the shelter or one of the other surfaces, the thickness of ice on the shelter top was equal to the maximum thickness on the other surfaces in 33 out of 56 cases. In 10 cases there was less ice on the shelter top than on at least one of the other surfaces, and in 13 cases there was more ice on the shelter top than on any of the other surfaces. In 6 of these 13 cases there was no ice or only a trace on the other surfaces, while a measurable amount accumulated on the shelter top. For example, at Fort Smith, Ark., on February 4, 1955, 0.3 to 0.4 inch of glaze formed on the instrument shelter, but none on the ground or on macadam and concrete surfaces adjacent to the ground. An almost identical case occurred at Richmond, Va., on January 22, 1955. These cases probably can be explained by the small amount of heat stored in the wood of the instrument shelters compared with the ground, bituminous and concrete surfaces. Instrument shelters, of course, are painted white to reflect the maximum amount of insolation; therefore, they should not be taken as typical of all unheated buildings.

Of the 74 cases in which ice formed on the instrument shelters 19 reported only a trace on both the top and the side of maximum accumulation. In the remaining 55 cases, the thickness was the same on both top and side 27 times, thicker on the top 24 times, and thicker on the side 4 times. Where the accumulation was greater on the top, the following ratios were observed between top and side thicknesses (counting only the 20 cases where more than a trace was observed on both top and side): 3 to 1, 3 cases; 2 to 1, 10 cases; 3 to 2, 6 cases; 4 to 3, 1 case.

3. Highway transportation

a. Sources of information

There is a scarcity of information concerning the frequency, thickness, and duration of glaze on roads and highways. A thorough search of the literature, both domestic and foreign, revealed only two papers (Weil, 1937-1938; Ekstrom, 1941) of scientific value: and only one of these contained observational data.

With the hope that unpublished data might be uncovered, all individuals and agencies in the United States who might conceivably have an interest in this problem were contacted by the writer. These included, to list only a few, the American Automobile Association, the Highway Research Board of the National Research Council, the American Road Builder's Association, the Calcium Chloride Institute, the National Safety Council, and the General Drafting Company (makers of road maps). All were most cooperative in attempting to locate information, both by searching their own files and by suggesting other possible sources, but these efforts produced no data and only a meager amount of information. No one in this country, apparently, has set out systematically to observe the action of glaze on highways and its influence on transportation.

On the recommendation of the American Association of State Highway Officials, a letter of inquiry was dispatched to the state highway engineers of all states except Florida. Replies of varying length and value were received, largely consisting of impressions formed by these individuals as a result of their experience in trying to maintain ice-free roads in wintertime in their states*. In no case was the information based on systematic observations.

One other source of information concerning ice on highways is the "Storm Data and Unusual Weather Phenomena" of the U. S. Weather Bureau**. As described earlier, these notes vary tremendously in the quality and

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* See Appendix A for a summary of this material

** See paragraph 1 a (1), Part I

quantity of information presented. Generally, however, they mention the nature of the ice formation, the degree to which traffic is impeded, and any serious accidents that might have occurred due to the slipperiness of roads. Seldom do they include definite statements as to the thickness and duration of ice.

One aspect of the problem of ice on highways that has been thoroughly investigated is the question of control. A large number of papers dealing with methods of removing or limiting ice formation of road surfaces have been published in the scientific journals of the United States, Canada, and Europe. A complete collection of this type of material can be found in the library of the Bureau of Public Roads in Washington, D. C. The question of the effect of highway ice on vehicle traction has also been rather thoroughly studied, primarily by the Highway Research Board of the National Research Council. Data from one of their test series will be presented later.

b. Types of ice

The problem of studying ice on highways is complicated by the fact that there are several processes by which ice can be formed on road surfaces, most of which produce radically different forms of ice with different densities, coefficients of friction, and the like. True glaze, the primary concern of this report, is just one of several types of ice that can form on highways and become a menace to the smooth flow of transportation.

(1) True glaze

Of all the various types of ice which form on highways, true glaze in most respects presents the greatest menace to transportation. It forms a dense, smooth, and tenacious sheet of ice possessing such a low coefficient of friction that vehicles at times find very little traction. This is particularly true when the temperature is near 32°F. and the ice is wet (see Fig. 44). Bauer (1952) found the coefficient of friction of rubber tires on dry ice to be 0.3 (as compared with 0.7 on dry pavement) and for wet ice to be 0.05. Wehner (1949) found the coefficient on ice varied from 0.2 to 0.05. These figures are not constants since they vary with air temperature, type of rubber tires, and kind of pavement, but other investigations under different conditions indicate they are essentially correct.

Because of the hardness and smoothness of glaze, ordinary round-link chains are not always helpful, especially in improving braking on passenger cars and light trucks (see Fig. 45). However, contrary to popular opinion, they are a decided improvement over ordinary or even special winter-tread tires (Moyer, 1947). The best aid to traction consists of the so-called premium chains, which are equipped with sharp points capable of cutting into the ice (Moyer, 1947). Even these do not necessarily give light vehicles sufficient traction to negotiate moderately steep grades when ice conditions are particularly bad. Heavy trucks equipped with such chains should be able to move on the worst glaze ice, but only with great caution.

The hardness and smoothness of glaze are responsible for still another handicap to the maintenance of traffic flow, in that abrasives applied to the ice surface to improve traction may not do so to any great degree because they are knocked off the road by passing traffic, leaving the ice as slippery as it was before application. One way to combat this problem is to use abrasives with small particle sizes or abrasives treated with chemicals. In Germany, coarse sand is applied to hard, packed snow and fine sand to glaze (Roulet, 1953). Field studies conducted in New York State in 1948 (Amberg and Williams, 1948) show: (1) that fine particles of rock salt tend to melt ice and snow more rapidly than coarse particles; (2) coarse particles are slower to act but tend to penetrate to greater thicknesses once they are ground into the ice; (3) a mixture of particle sizes may be warrented for general use. Probably one of the most suitable materials is boiler ash (composed of particles ranging in size from dust to 0.75 inch), treated with one of the chloride chemicals.

With the exception of a blizzard or very heavy fall of snow, a glaze storm will paralyze highway transportation faster and more completely than any other type of storm. Numerous accounts have been printed in newspapers of glaze storms which brought nearly all traffic to a halt for varying lengths of time and the "Storm Data and Unusual Weather Phenomena" also contain many references to such instances. Harlin (1952) gives a vivid description of almost complete paralysis of traffic in Tennessee and other parts of the South during the storm of February, 1951. In central Tennessee, traffic was stalled for 3 to 5 days. This was one of the worst storms ever to hit this section of the country, thus the conditions described are more severe than ordinary.

Because of its general short duration, true glaze usually does not impede traffic for any protracted period of time. Except for the unusually severe storm such as the one described above, complete or nearly complete paralysis of traffic usually will not last for more than a few hours. However, broken trees and utility poles may block some streets and roads for many days, especially in rural areas where the need for clearance is less urgent. Although no statistics of glaze duration on highways and streets actually traveled are available, data for utility wires and data collected through the special weather Bureau observations for this project, suggest that in almost all storms the ice begins to break up and disappear within 12 to 24 hours (see Table XV).

(2) Snow glaze

Of greater importance than true glaze because of its considerably higher frequency of occurrence, is what might be called "snow glaze". This originally falls as snow and at first does not seriously hamper automobile and truck traffic. The coefficient of friction of newly fallen snow on highway surfaces, even after some compaction, is sufficiently high to permit passage of most vehicles if caution is used. Steep grades may pose a problem, but even these sometimes may be negotiated if the vehicle is equipped with snow-tread tires or chains and the driver is experienced in winter driving.

However, changes frequently occur in such a snow layer to make it comparable to glaze in density and slipperiness. These changes can be brought about in two ways, frequently in combination. First, there is compaction from the weight of passing vehicles. If traffic is heavy enough, it takes but a short time to compress a layer of snow into a sheet of nearly solid ice. Added to the factor of weight is the heat generated by the friction of tires on the snow. This causes the snow crystals to melt, and when refreezing takes place, as it does almost immediately if the air temperature is below freezing, dense, amorphous ice will form. Road intersections and bridge and hill approaches, where cars are likely to be stalled or stopped temporarily and must spin their wheels to gain momentum, are particularly prone to the formation of hard, slick ice from this frictional effect.

Second, a layer of snow frequently is changed into a sheet of solid ice when snow thaws during the afternoon when air temperature rises above 32°F. and then freezes at night. Ice formed in this manner is often almost identical to true glaze in composition; that is, it is solid and amorphous in nature with few vesicles to make it friable. However, it does not form as rapidly as true glaze and its formation can be anticipated through the presence of the snow cover; consequently, precautionary measures, such as the application of abrasives and chemicals, can usually be taken before conditions become too dangerous.

(3) Ice from flooding streams or roadside seepage

Another form of ice which resembles glaze is formed when water from flooding streams or roadside seepage flows onto a road surface and then freezes because of a drop in temperature. Ice of this type can be exceedingly dangerous because it is usually limited to a few spots along a road and unless ample warning of its possible existence is given, it may cause the motorist to meet with sudden and unexpected disaster.

(4) Glaze and rime from fog

Closely related to true glaze is ice formed when heavy fog, which may or may not be supercooled, passes over cold highway surfaces. Ice resulting from such a situation is probably more apt to resemble rime than glaze, but if the fog is heavy and the drops unusually large, the drops may coalesce before they freeze, to give a sheet of hard, amorphous ice. The temperature of the raindrop, however, is probably more critical than its size as a factor in determining which type of ice will form. If the drops are supercooled, freezing certainly will take place more rapidly than if they are not, and this would mean a greater likelihood of rime than glaze. The temperature of the pavement surface also plays a role in determining whether glaze or rime forms; the colder the surface, the higher the probability of rime.

Where rime ice results from such a process, traffic conditions are in some respects as hazardous as if the deposit were glaze. Rime formed in this manner may exist on a road only in spots and the motorist who unexpectedly hits one of these spots may find the results just as disastrous as if the ice were glaze. Nevertheless, rime does not present the same overall menace as glaze because it is generally more limited in areal occurrence than true glaze, being found mostly in mountainous regions, and there for the most part only locally, and because it is more readily broken loose from pavement surfaces by traffic.

In mountainous regions, rime can reach considerable thickness and its slipperiness, combined with steep grades and sharp curves, can bring all traffic to a halt. Roads through high passes in the western United States are frequently covered with thick coats of rime that render travel all but impossible.

(5) Rime and hoarfrost from sublimation

Ice can also form on road surfaces when they are below freezing and the air above the road contains no fog layer but has a high humidity. In this situation the dewpoint of the air is the factor in determining which type of ice will be formed. When the dewpoint is just above 32°F. rime or even glaze ice will result; when it is below 32°F., hoarfrost most likely will form. In either case, the lower the temperature of the surface and the higher the specific humidity of the air, the greater the chance of appreciable amounts of ice. Ice resulting from such a situation is encountered most commonly along sea coasts and the margins of such large inland bodies of water as the Great Lakes, but it also is sometimes observed on roads near small lakes and ponds. According to Ekstrom (1941) it is a fairly common phenomenon on roads that run along the south coast of Sweden. It can create conditions of great danger and make travel difficult, but it seldom has a paralyzing and long-lasting effect. When hoarfrost forms, it usually is very thin and is easily worn off by traffic, but under certain conditions it can re-form almost immediately, resulting in a continuous hazard where traffic is not heavy.

c. Relation of glaze on wires to highway conditions

(1) Scarcity of information

By studying available statistics on the frequency, thickness, and duration of glaze on electric utility and telephone wires, can one arrive at valid conclusions concerning characteristics of glaze on roadways? A satisfactory answer to this question would require simultaneous observations of glaze on the two different types of surfaces. An attempt was made to collect a small amount of such evidence in the special glaze observations the Weather Bureau conducted during the winters of 1953-54 and 1954-55. Unfortunately, it was impossible for the observers, except in one or two storms, to do more than merely report on which of the surfaces the ice lasted longer.

A small number of incidental remarks and observations dealing with the comparison between highways and wires have been encountered in the literature, and with these as a basis, plus the small amount of Weather Bureau data mentioned above, an attempt is made here to outline the positive and negative aspects of such a comparison.

(2) Special Weather Bureau observations

Based on the Weather Bureau observations mentioned above, it seems likely there is little difference in the duration of glaze on highway and wire surfaces. Of 17 observations in which the difference was noted, the time of melting on the two surfaces was reported as being the same in 10 cases, and 6 hours or less in 6 of the other 7 cases. In 3 instances the ice melted on the ground before it did on the wires - the time differential being 2 hours, 1 1/2 hours, and "unspecified", respectively. The remaining four observations reported the ice on wires melting first. The time difference in three of these was small (1, 2, and 4 to 6 hours); in the fourth instance it was rather large, with spots of ice reported on macadam and concrete surfaces for one week after all ice had disappeared from wires.

The same set of data shows virtually no difference in the thickness of ice on the two surfaces, with 20 of 21 observations reporting the same on both. However, whereas the observers were able to make measurements of ice thickness on highway surfaces, they had to estimate the thickness on wires.

(3) Comparability of highway and wire data

A variety of factors combine to determine which surface receives the greater thickness of ice and which retains ice longer. Of paramount importance are the relative temperatures of the surfaces when glaze begins to form. Again, the only way to determine these absolutely would be to have the results of a large number of simultaneous observations of temperatures on each surface under different weather conditions. In the absence of such data, is it possible to draw conclusions as to what this temperature relationship might be? Pointing out a few of the factors affecting the relationship whould make it clear that this is almost impossible. In the first place, wires are certainly much more sensitive to changes in air temperature than any material used for roadways. The specific heat of the metals used in electric utility and telephone wires is much lower than either bituminous, concrete, or aggregate road surfaces; therefore, a smaller change in air temperature is necessary to bring about a given rise or fall in temperature of wire surfaces than is required to achieve the same change in the temperature of highway surfaces. Wire surfaces also are more likely to react quickly to changes in air temperature because of their greater exposure to the wind; when wind velocity at ground level is near zero, it can be quite strong several feet above the ground at wire level. Wire surfaces, in contrast to road surfaces, have no reservoir of heat to aid in resisting temperature drops. When the temperature of a road top begins to fall, it will be inhibited, sometimes to a large degree, by a flow of heat from below;* the volume of this flow depends upon the amount of heat stored beneath the roadway and the conductivity of the subsurface and pavement materials. In many cases it undoubtedly is sufficient to play a significant role in melting the surface ice. Similarly, when an excess of heat is added to a road surface as a result of increased air temperature or strong solar radiation, some of the heat will be transported downward, thus subtracting from the amount which goes toward increasing the temperature of the surface. But this does not happen to the same degree in wires because the total mass of material through which the added heat can be spread is much smaller; therefore, if equal amounts of heat are added, the wire surface will experience the greater increase in temperature. Road materials, of course, are not the best conductors of heat, but because the mass of a wire is small compared with the possible mass of a pavement through which the heat is likely to be spread, even in the face of low conductivity it is not believed that this would completely offset the effect described above. A similar influence derives from the fact that road surfaces generally contain more moisture than do wires, and therefore a larger part of the heat striking roads is used in the process of evaporating water from their surfaces than is used in evaporating water from wires. Heat expended in this manner cannot contribute to an increase of the temperature of the surface from which evaporation is taking place.

So far in this discussion we have been assuming that the same amount of heat would be applied to both types of surfaces. This, of course, would not often hold true under natural situations. A tremendous difference in air temperatures can and does exist between the layers of air near the ground and those at the elevation of utility wires. The time of day, and the state of the sky, ground cover, and wind are important elements in determining the magnitude and direction of this difference. Variations in incoming solar radiation also affect the amount of heat received by the surfaces. Although this normally should be the same for both, the fact that road surfaces are more often shaded by trees, high embankments, and the like than

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* Very few cases would ever be encountered in which, in the middle latitudes during winter, the flow of heat would be in the reverse direction, especially when the surface temperature is low enough to permit ice formation.

are wires, would tend to make radiation larger on the average for the latter. The albedo of the various surfaces also influences the amount of heat they receive. Assuming that all surfaces receive the same amount of solar radiation, dark-colored bituminous would absorb more heat than light-colored concrete and a conductor insulated with a dark material would absorb more than a light-colored bare aluminum conductor.

It should be evident, especially when it is remembered the various factors work together in a complex and everchanging manner, that it would be unrealistic in the absence of actual data to make assumptions concerning the temperature conditions of road and wire surfaces. Air temperatures, taken in an instrument shelter approximately five feet above the ground (or above the roof of a building), certainly could not be applied directly to either.

Even if the considerations just discussed are completely ignored, it is doubtful whether the same thickness of ice would form on wires as on highways. In many storms a certain percentage of the freezing rain that strikes wires will drop or be blown off before it freezes. Some rain could likewise be expected to run off a sloping highway surface, but it is believed that this would be small in comparison to the amount lost by wires.

Some of the conditions discussed above would affect the length of time ice lasted once it had formed. The movement of heat from sub-surface to surface layers in a road and the lack of such a heat supply in wires would tend to shorten the period of duration of ice on roads as compared with wires; on the other hand, the greater exposure of ice on wires to the wind would tend to increase the loss of ice by evaporation on these surfaces more than on roads. Where glaze is highly transparent, the color of the surfaces would also exercise considerable influence on the duration of the ice.

In spite of all the foregoing, it is believed that for purposes of general comparison, the electric utility and telephone data for glaze on wires can be applied to highways, or for that matter, to any type of surface. For instance, a map of the United States showing the broad areal distribution of glaze frequency and thickness, based on these data, would, it seems, be almost equally as valid for highway surfaces as for wires. This comparison probably would apply more closely to frequency than to either thickness or duration. Specific or detailed comparisons, on the other hand, would not be warranted.

d. Behavior of glaze on different surfaces

There is general agreement among Highway maintenance men and traffic engineers that glaze will not last as long on macadam as on concrete roads, although the quantity of objective data on the subject is limited. A small number of observations of the relative performance of ice on the two highway substances was made during the winters of 1953-54 and 1954-55 by the U.S. Weather Bureau, and somewhat similar observations were made at several points in southern Germany in the winter of 1936-37. Both sources indicate that there is probably not as much difference between the two materials as engineers believe.

(1) Special weather bureau observations

The Weather Bureau observations show (if such a small number of observations can be used as the basis for legitimate conclusions), that the tendency is for ice to clear more rapidly from macadam, although the differences in time are not great. Of 17 observations, melting took place earlier 14 times on macadam and only twice on concrete; in one instance the time was the same for both surfaces. On at least one of the occasions where the ice melted first on macadam, it did so despite the fact that the air temperature was below 32°F. and the sky was cloudy (February 19, 1955, at Topeka, Kans.) thus testifying to the high capacity of this type of pavement for heat absorption and storage. There had been a period of sunshine before the glaze formed, during which the macadam was no doubt warmed more than the concrete because of the former's darker color. None of these observations stated exactly what the difference in melting time was and only one mentioned it at all, with a brief statement to the effect that the ice melted first off bituminous surfaces and shortly after, off cement.

(2) Study made in Germany

The report of observations taken during the winter of 1936-37 in southern Germany (Weil, 1938) indicates results similar to those just described. Since this report is the only one discovered in which actual planned observations were taken of the duration of ice on highway surfaces, it is considered of such value that a rather lengthy synopsis of it is presented below.

"In the fall of 1936, plans were made to inquire, during the following winter, into the origin of glaze and to observe the tendency toward ice cover of various street pavings. Experience had shown that many streets were subject to considerable glaze at some points, while other streets seldom came under its influence, and also that there was a difference in the pavings as regards their tendency toward glaze formation ... Only cases involving glaze, formed as a result of rain or dew precipitation, were to be observed, solidly packed and frozen snow not being considered.

"At each site there were two or more different types of paving that joined or ran parallel to each other. The sites were picked in such a manner that the pavings to be compared were subjected to the same external atmospheric conditions, i.e., similarly exposed to sun and shade.

The pavings observed consisted of concrete, of Granitpflaster and Asphaltpflaster*, and of asphalt and tar pavings of different combination.

"On a highway ... consisting of concrete and Asphaltfeinbeton running parallel to each other, the thaw process was observed on three different days. In fog, rain, and sun, both pavings became ice-free at the same time.

" ... with joining Granitgrosspflaster and concrete, the former, during cloudy skies preceded by limited sunshine, became ice-free approximately 1/2 hour before the concrete.

"On the Reichstrasse ..., ice on asphalt melted after Granitpflaster. Under solar radiation asphalt became ice-free first.

"Observations on two days at the same site in Landhaus, ...Granitkleinpflaster by sunlight became ice-free before the Teertränkdecke. The difference in time was very small on one of the occasions, and more than 1/2 hour on the other. On two additional days, both pavings, once by sunlight and once by rain, became ice-free at the same time.

"At a short distance from the above-mentioned site, the following sequence was observed in the thawing of the pavings:

On two different days during rain:
Basaltpflaster - Granitpflaster - tar pavings
tar pavings - Basaltpflaster - Granitpflaster

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* The approximate English meaning of these terms is as follows:

German	English
Asphaltfeinbeton	asphalt (fine-grained) mixed with concrete
Asphaltpflaster	asphalt paving stones
Basaltpflaster	basalt paving stones
Granitpflaster	granite paving stones
Granitgrosspflaster	large paving stones of granite
Granitkleinpflaster	small paving stones of granite
Teertränkdecke	tar surface

On three different days during sunshine:
Basalt - tar - granite
basalt - granite - tar
tar - basalt - granite

During fog:

granite - basalt - tar

"The difference in time between the melting on the individual pavings varied, often up to one hour. For one of these formations the beginning of the glaze accumulation was witnessed during a light rain. The order in which the glaze appeared on the surfaces was tar - basalt - granite. The same sequence held for the thaw.

"Observations taken at the other sites also showed a variation in sequence and time of thawing for identical groups of pavement types under similar weather conditions.

"Traffic has a marked influence on the removal of glaze. After reaching the point of thaw, the ice loses its ability to adhere to the bottom, shattering along the tracks of vehicles, and becoming exposed to the air. It thus disappears essentially faster on more frequented roads. Snow chains also hasten the thawing process.

"To summarize briefly the results of the observation, it becomes evident that none of the pavements studied is adapted to retaining glaze for any great length of time. By sunlight, the dark pavings seem to thaw earlier, whereas concrete retains the ice for the longest period. The time difference in the thawing process of the various pavings is not particularly great. Rough surfaces proved to be advantageous as they lend themselves more rapidly to the thawing process than smooth surfaces.

"It could be concluded from the varied behavior of the pavings studied during sunlight, air temperatures, or rain, that besides the absorption of warmth through radiation and air temperature, particularly that quantity of heat beneath the surface and also the conductivity of the street play an important part in the formation of ice and its duration.

"If one is clear as to the origin of glaze: (1) at temperatures in the street paving below 0° (centigrade) by fog and rain or by hoarfrost; or (2) at road temperatures above 0° and by supercooled rain and fog or by hoarfrost, then the differences in the results during the freezing process can be explained. At road temperatures below 0° and rain with temperatures little above zero, asphalt paving freezes first, presuming however, that the warming up of the bottom layer does not take effect at first.

"In the thawing process, the following relationship was observed, assuming that the ground warmth is brought about by the heat conductivity of the street pavings. During cloudiness, the stone pavements thaw first, since the earth temperature reaches the surface quicker than through asphalt; by sunlight, the asphalt paving thaws first, because the absorption is greater and the heat conductivity smaller than that of stone pavings.

"In considering all these suppositions, it should be noted that by a small increase in either one of the influences, the result can be reversed.

"That, in general, the dark pavings yielded more favorable results, i.e., showed less glaze than concrete, can be explained by the fact that in clear weather that is observed frequently before periods of frost, the dark pavings absorb more warmth through radiation.

"To reflect on these observations, none of the common street pavings is to be preferred as far as ice prevention is concerned, since, depending on the weather conditions, any of them can be the first on which glaze will form or the last on which it will melt."

(3) Bituminous vs concrete

State highway officials who commented by letter on the relative merits of bituminous and concrete surfaces were by and large fairly definite in their assertions that bituminous roads usually shed ice more rapidly than concrete roads. Most of them also believe that ice is slower to form on bituminous roads. Fourteen out of 16 agree that the darker surfaces of bituminous and related surface materials absorb more heat from the sun and thus become free of ice sooner than the lighter colored cement surfaces. Typical of their remarks is the following, from Kansas (Siler, 1953):

"While we have gathered no specific data it is very apparent that icing conditions are of longer duration on concrete pavements than on blacktop."

The reply from Connecticut (G.A. Hill, 1953) expresses the belief there is a difference in the duration of ice on the different types of surfaces, not because of any quality differences, but because in Connecticut the concrete highways carry the heaviest traffic. An interesting point: the letter from Wisconsin (Hughes, 1953) describes a more rapid "shelling" or breaking loose of ice during periods of extremely low temperature (-15°F. to -20°F.) from concrete surfaces than from bituminous surfaces.

(4) Non-paved roads

Virtually no information was obtained on the performance of ice on non-paved roads. The South Dakota State Highway Commission (Ihli, 1953) reports that they have experienced little trouble with ice on gravel surfaces except where snow has become compacted as a result of thawing and freezing during fair weather, or under traffic; the Virginia Department of Highways states they have discovered ice will form on an open aggregate surface more quickly than on a densely graded aggregate surface. Some light might be shed on this aspect of the glaze problem by examining the special glaze observations taken by the Weather Bureau for this project. Simultaneous observations were taken of glaze thickness on bare ground, and on concrete and bituminous pavements. Undoubtedly, the bare ground and graveled road surfaces are not absolutely comparable because of differences in heat conductivity and porosity. Nevertheless, it should be possible to get some idea of actual conditions by substituting the ground observations for observations one would like to have taken on non-paved roads. The results show that in 23 of 41 cases* the ice reached, at its maximum, the same thickness on all three surfaces. Ten times it was thickest on the ground, and 3 times it was thicker on concrete than on either the ground or bituminous. On 5 occasions, ice was reported on the ground when none formed on either concrete or bituminous; 22 cases where duration was observed on the ground and on at least one of the pavement surfaces, ice melted last on the ground in 12 cases. Nine times glaze lasted longer on concrete than on the ground, but in only one case did it last longer on bituminous than on the ground.

e. Effect of ice on traffic flow

Many of the state highway officials who responded to the request for information commented on the frequency and severity of ice on roads in their states and its effects on transportation. No attempt has been made to incorporate this material in a unified discussion. Both the actual conditions of ice and snow and also the approach to the problem of keeping traffic on the move vary greatly from state to state. Furthermore, there is no uniformity in the quantity or in the point of view of the information furnished. Consequently, it has been decided to abstract pertinent material from 29 letters and list it alphabetically by states. This information may be found in appendix A.

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* Those were omitted in which the thickest measurement on any surface was only a trace.

f. Summary of methods used to combat glaze

It might be pertinent to summarize the methods employed to prevent or combat glaze on highways. Economically feasible means of preventing glaze formation on highways have not been devised as yet. The installation and operation of heated streets, either by buried electric wires or steam pipes, are too expensive, though it can be applied profitably to bridges and ramps (Paxson, 1951; Wall, 1949; Anon, 1954; Anon, 1952: Anon, 1953). Electrically operated radiant heat lamps have been tried experimentally, but also are too expensive except for critical locations such as bridge approaches (Ziegler, 1950). Numerous attempts have been made to develop a chemical which, when sprayed on streets, would prevent the development of glaze permanently. Recently, it seemed such a chemical had been produced in Germany (Kloss, 1953), but tests in this country proved this not to be the case (Breuning, 1953).

Because of the failure of all these efforts, only the customary methods of combating glaze remain, such as spreading abrasives and chemicals (primarily the chlorides). The organization of road maintenance personnel should be so geared as to be capable of going into immediate action. Speed of execution of remedial measures is paramount. A system which makes detailed weather reports available to the dispatching officials is essential. Probably the best discussion of the problem of combating ice on highways is in the Highway Research Board's "Reccommended Practice for Snow Removal and Treatment of Icy Pavements" (Highway Research Board, 1954).

g. Glaze as a factor in accidents

Investigations have shown that despite the greatly reduced volume of traffic on highways during winter, accidents (as measured by the ratio of the death rate to mileage traveled) increase, particularly in the northern half of the United States. Special studies by the Committee on Winter Driving Hazards of the National Safety Council (Moyer, 1947) show that in those states most subject to ice and snow, the mileage death rate is from [illegible] to 53 per cent higher during winter than summer. The major hazards responsible for this increased accident rate were found to be inadequate traction and reduced visibility.

(1) Role of glaze in reducing visibility

Among the factors responsible for reduced visibility in winter driving, the icing of vehicle windows by glaze ranks prominently. However, since true glaze seldom occurs at extremely low temperatures, standard defrosting equipment that utilizes engine heat should be more than adequate to keep windows free of ice. It is conceivable that in an unusually severe storm, where ice forms at a rapid rate, an ordinary defrosting unit would not do the job.

(2) Role of glaze in reducing traction

In general, poor traction ranks higher as a hazard than poor visibility, though in many cases the two work together. A special study made by the National Safety Council in cooperation with personnel of four typical snowbelt states (Connecticut, Indiana, Minnesota, and Wisconsin), shows that approximately two-thirds of the total number of traffic accidents during the three winter months occur on snow or icy surfaces, varying from a low of 47 percent in Indiana to a high of 83 percent in Minnesota.* In an earlier study of accident reports from seven states in the snow belt, it was found that of all accidents involving skidding, fewer than 1 percent occur on dry pavements, 18 percent on wet pavements, and 80 percent on pavements covered with ice and snow.

There is a common belief that because of the general slowing down of traffic under bad road conditions, few serious accidents will occur although minor accidents may increase greatly There may be some truth in this, although the writer is aware of no statistics that support it.

h. Tests of the National Safety Council

During the winters of 1945-46 and 1946-47, the National Safety Council conducted exhaustive tests of the braking, skidding, and traction of passenger cars and trucks on lake ice, road ice, packed snow, and on dry concrete pavements (Moyer, 1947).

Most of the ice tests were made on frozen lakes, and although this type of ice is not identical with glaze on roads, it is believed they resemble one another closely enough to be comparable for test purposes. In a few instances where tests were conducted on highway ice, it was found that the results correlated closely with those of the tests on lake ice.

The tests reveal that ice is an extremely variable and unpredictable substance, making the performance of vehicles on ice subject to equally great variation. Factors affecting the slipperiness of ice, such as air temperature, wetness or dryness of the ice, sunny or cloudy weather, granular structure of the ice, and the like, are found to have more influence on traction than the type of vehicle, size of load, type of tires, state of tire pressure, and the method of braking used. For example, the braking distance for a passenger car traveling 20 miles per hour ranges from 107 to 238 feet on ice. For a loaded 5-ton truck, the corresponding braking distances are 116 to 306 feet.

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* Nation-wide statistics for the entire year, compiled by the Travelers Insurance Company, show only a small percentage (less than 5 percent) of both fatal and non-fatal accidents as having occurred on snow or ice-covered roads (Travelers Insurance Co., 1954).

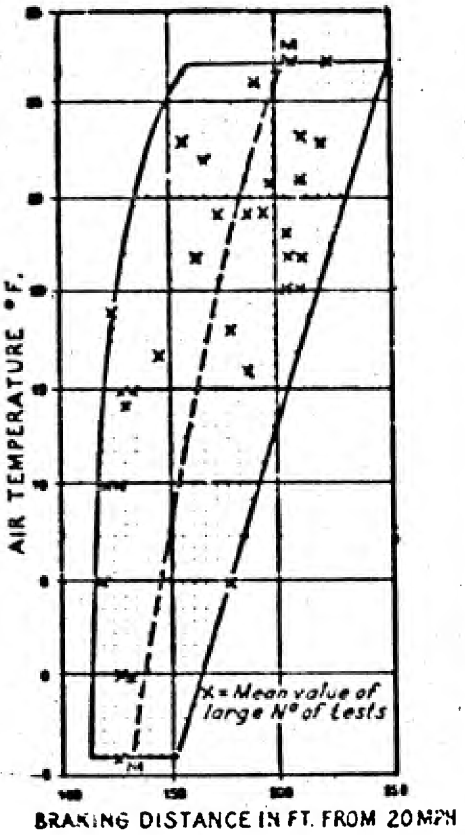

Figure 44. Relationship between braking distance of a passenger car traveling 20 mph and air temperature. After Moyer (1947).

(1) <u>Air temperature as a factor in slipperiness.</u>

It has been found that one of the most important factors affecting the slipperiness of ice is its temperature.* The results of a large number of test runs, all made with the same passenger car equipped with standard tires, have been summarized in Figure 44. This diagram shows that, though there is a wide range in braking distance at any one temperature, indicating that there are many factors other than temperature which influence the slipperiness of ice, there is nonetheless a definite tendency for traction to deteriorate as the temperature increases. The mean values of the variation found at the different temperatures (the dashed line M-M in Figure 44) show that ice tends to be about twice as slippery at 20°F. as at -4°F. The worst condition is at 32°F. when the ice is wet, the water serving as a lubricant making the ice very slick. Since approximately 75 percent of all glaze seems to form at free air temperatures as high or higher than 25°F.** (see par. 2a(2)), it is apparent that glaze ice presents one of the most dangerous road hazards a driver can expect to encounter.

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* This has been confirmed independently by a number of investigators. Wilkinson (1953), for example, shows that the friction of rubber on ice increases as the temperature decreases from 0°C to -30°C and then decreases with a further drop in temperature.

** This temperature is only applicable to the period of glaze formation and not to the period between the cessation of formation and the beginning of melting. Nevertheless, it is doubtful if a similar figure for the last-mentioned period would vary very much from this. Often it would be higher than 32°F., thus further validating the statement about glaze being an extreme hazard.

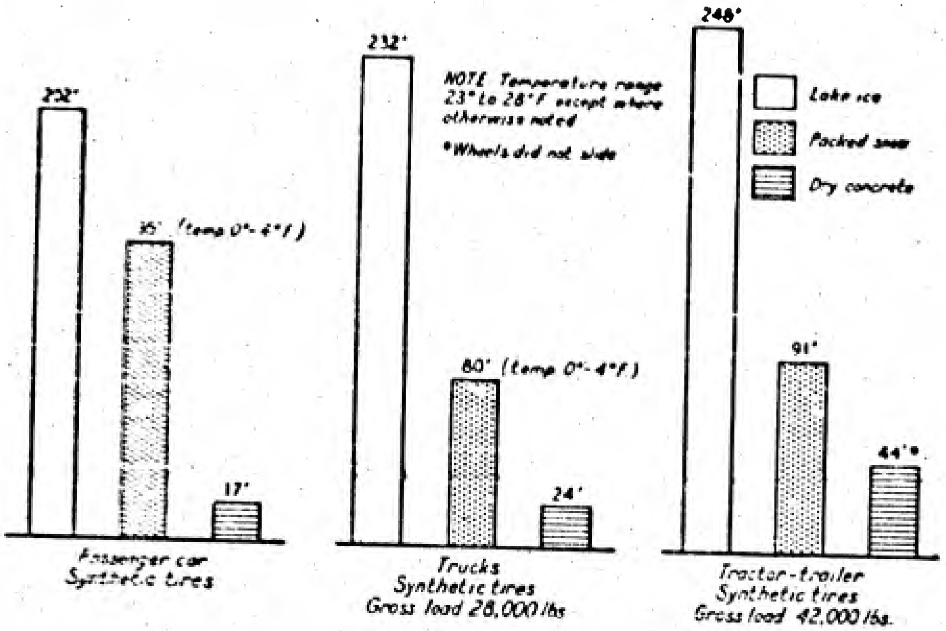

Figure 45. Comparative braking distances of various types of vehicles traveling 20 mph on lake ice, packed snow, and dry concrete. After Moyer (1947).

(2) Performance of vehicles in braking tests

Braking tests indicate that average stopping distances for trucks and passenger cars are about ten times longer at 20 miles per hour on glaze ice than on dry concrete and from two to three times longer on glaze ice than on packed snow (see Fig. 45). The braking distance varies from a low value of 13 to 17 feet for passenger cars on dry concrete to high values of 232 to 248 feet for tractor-trailer combinations on glaze ice. These tests were all made at temperatures of 28°F. or less. At 32°F. large trucks were found to require more than 300 feet in which to stop. This distance is highly significant when one remembers that the trucks were traveling only 20 miles per hour. Many drivers of heavy vehicles assume they are justified in driving at relatively high speeds on ice and packed snow. The above tests seem to invalidate this. In fact, if the large amount of damage which a heavy vehicle can inflict upon itself and others when out of control is considered with the longer braking distances required, it would appear that trucks should be operated at lower speeds than passenger cars in the interest of greater safety.

(3) Performance of tire chains in braking tests

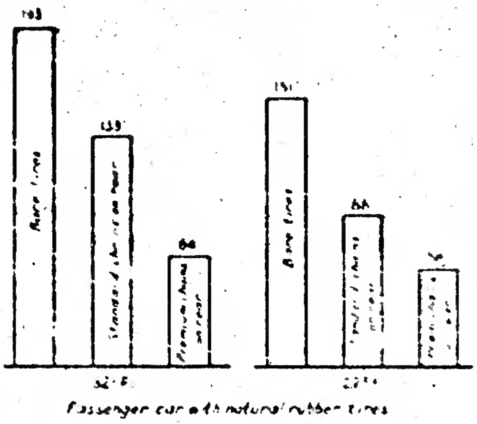

Figure 46. Braking distance of a passenger car traveling 20 mph. Note the longer distances at the higher air temperatures. After Moyer (1947).

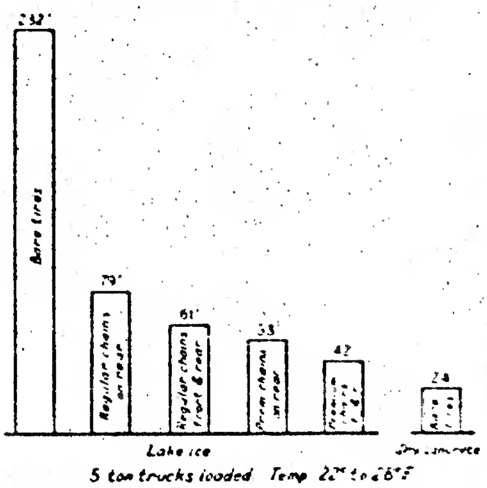

Figure 47. Braking distances of a 5-ton truck traveling 20 mph, on lake ice and dry concrete. After Moyer (1947).

The effect of tire chains in reducing braking distances is shown in Figures 46 and 47. It is obvious from these charts that chains, especially premium chains, equipped with sharply pointed lugs capable of cutting into the snow, greatly reduce the hazard of travel on icy roads. Chains seem to be more effective for trucks than for passenger cars, probably because of the greater weight which causes chains to dig deeper into the ice. For every type of vehicle best results are obtained when chains equipped with sharp lugs are used on all four wheels.

(4) "Pumping" vs. sudden application of brakes

The above braking tests were conducted with brakes locked from sudden application. "Pumping" the brakes reduces braking distances as much as 20 percent. Because of the increased steering control possible through "pumping" (sudden application of brakes will often cause a car to go into a dangerous skid or even spin out of control), this method of braking is recommended by the National Safety Council for all drivers. It is particularly essential for tractor-trailer vehicles which will frequently "jack-knife" in a serious skid when brakes are applied suddenly.

3. Summary

Data concerning the performance of glaze on highway surfaces and the effect of ice on transportation are almost totally lacking. An evaluation is further handicapped by the fact that glaze is just one of several types of ice that forms on road surfaces. During the winters of 1953-54 and 1954-55 an attempt was made, with the cooperation of the U.S. Weather Bureau, to collect data that would be of value in analyzing glaze thickness and duration on different highways. The measurements, although low, indicate no significant differences between concrete and bituminous surfaces, although melting apparently occurs earlier in some cases on bituminous. A study made in Germany reaches the same conclusion. The possibility of applying performance data for glaze in utility wires to highway surfaces is examined and rejected except for purposes of general comparison.

Information received from State Highway officials concerning the frequency and severity of ice on roads in their states and practices followed in keeping traffic on the move during glaze storms is presented (see Appendix). The only effective methods employed involve the prompt application of chemicals and abrasives. Tests to develop measures that prevent ice formation altogether have either failed or proved too expensive for widespread use.

Winter driving tests by the National Safety Council reveal that glaze is slipperiest when air temperature is near 32°F. Braking tests indicate the average stopping distances for trucks and passenger cars traveling 20 miles per hour are 10 times longer on glaze than on dry concrete and from 2 to 3 times longer on glaze than on packed snow. Chains improve traction and braking considerably, particularly for trucks.

4. Cross-country movement of vehicles

Something should be said about the effect of glaze on cross-country movement of vehicles. It is the writer's opinion that in most situations of this type any vehicle adapted for non-highway operation will usually not be hindered by a sheet of glaze ice. However, this will depend to a large extent on whether the ground under the ice is frozen solid. If the ground is unfrozen or only slightly frozen, the weight of most vehicles will cause them to break through the ice deposited by most storms. Even where the ground is frozen, frost heave may make it possible for vehicles to crack the ice and find better traction on the ground beneath. Tracked vehicles will, of course, perform better than those equipped with wheels and encounter difficulty only in climbing steep slopes where the ice is of unusual thickness and the ground beneath is frozen solid. Movement through wooded country might be extremely difficult after some storms, because of the broken limbs and downed trees littering the forest floor. Such a condition could continue to exist for long periods after a storm. During a storm the tangled mass of ice-coated shrubs and bent trees might present an almost impenetrable barrier. An example of this in England is described by Cave (1940).

5. Railroad transportation

Under a U.S. Air Force research contract, Professor William W. Hay of the University of Illinois has carried out a thorough investigation of the effect of glaze storms on railroad transportation. Because this study is of such high quality and also because it can be readily obtained from the ASTIA* library service, it was deemed unnecessary for the writer to undertake an independent search for material on this subject. Professor Hay's report is divided into three principal sections: (1) "General Effects of Ice Storms on Railroad Operations," in which he discusses the effect on labor, motive power and rolling stock, roadway facilities, terminal facilities, and repair and maintenance facilities; (2) "Detailed Effects of Ice Storms on Railroad Operations," in which the effect on signals, electric traction, communications, train operations, and methods of repair and recovery are discussed; and (3) "Examples of the Effect of Ice Storms on Railroad Operations," in which he describes the impact of two rather severe storms on rail transportation in the upper and lower Mississippi Valley. Detailed data concerning train delays, repair costs, and the like for these two storms are given in an appendix.

With the permission of Professor Hay, parts of his summary and all of his conclusions are given here.

"Summary:

1. Minor effects of ice storms include hazardous working conditions, frozen switches, loss of contact on third rail and catenary contact conductors, frozen coal and water facilities, and frozen turntables.

2. Major effects of ice storms are loss of communication and signal systems.

    a. Damage results from breaking of ice-laden wires, and poles, and from falling branches and trees.
    b. Loss of signals delays but does not stop train movements.
    c. Minor signal failures involve slight delays but no change in operating methods.
    d. Major signal failures require (in the United States) a change to use of train order and/or manual block rules, a dependable but slower system of moving trains.

3. Loss of communications has the most serious effect on railroad operation.

    a. All communications --- telephone, telegraph, teletype, and inductive telephone---are usually lost near the storm center.

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*Armed Services Technical Information Agency, Arlington 12, Va.

b. Rail operations are badly disrupted---passengers, perishables, or other preference trains experience an average delay of one to four hours; dead or low-grade freight trains are sometimes annulled entirely until dispatcher circuits are restored (2 to 10 days); branch line service may sometimes be discontinued for the same period, but more often the simpler systems of signaling and train operation permit normal movement of branch line trains even when the main line is in serious difficulties.

"Conclusions:

1. Ice storms do not halt railroad operations.

2. On a modern railroad loss of communications and signals will cause delays of 2 to 14 hours for passenger, perishable, or other preference or necessary trains; in some isolated cases, dead freight is delayed for 2 to 14 days.

3. On-schedule train operation can be restored in 2 to 14 days (upon restoration of dispatcher's circuits).

4. Normal communications can be restored in 14 to 30 days; full rehabilitation in 30 to 90 days.

5. The simpler the system of signaling and communication the less effect will an ice storm have on railroad operation.

6. The effect of ice storms is most serious in areas where they are least likely to occur, i.e., in areas where emergency equipment and materials, trained personnel, and supervisory experience have not been developed by this type of emergency.

7. Terminals are normally not badly affected by ice storms. Lines are usually carried in cables or underground conduits and are therefore less susceptible to storm damage."

6. Pedestrians

Glaze in many cases does not present as great a hazard to pedestrians as it does to vehicles. Much depends upon the type of surface on which the ice has formed. Concrete sidewalk surfaces and practically any paved road surface when covered with a coat of smooth glaze can be slippery to the point of making it extremely difficult and hazardous to walk. Worn cobbled pavements are especially dangerous. Streets and highways that slope steeply from center to road edge can present such an obstacle that many pedestrians will be unable to cross from one side to the other without considerable risk. The writer witnessed an example of this during a glaze storm in Lincoln, Nebraska. Fortunately, the traction on all such surfaces usually can be improved so that walking becomes relatively easy, merely by sprinkling cinders, sand, or one of the chloride salts on the ice. These remedies work best when the temperature is in the neighborhood of 32°F., that is, when the ice is slipperiest. When the air temperature is extremely low, cinders and sand may merely slide on the ice without "digging in" when stepped on. In this situation, one of the salts (preferably calcium chloride) gives better results. Where such surfaces have not been treated properly, the prudent walker can often improve his footing by taking to the grass or soil surface at the side of the roadway or sidewalk.

In many instances, glaze does not hinder movement by foot across open fields. If the ground underneath the ice is not frozen solid or if the ice forms on grass, the layer of ice deposited by almost all storms crumbles under a person's weight, and walking is not difficult. The same results are often encountered even where the ground is frozen, since frost heave causes thin layers of the soil surface to expand and bulge upward to form numerous vesicles or air pockets that collapse when stepped on.

An item included in the special Weather Bureau observations of glaze during the winters of 1953-54 and 1954-55 was designed to test the validity of the assumption that foot movement across open ground is not always impeded by glaze. The observers participating in this program noted whether ice on grass surfaces crumbled when walked on. The results show that in 44 cases the ice crumbled and in 12 remained firm under the weight of the observers. In 31 cases they were unable to report what happened.

The Metropolitan Life Insurance Company (1940) presents data concerning fatal falls on sidewalks and streets among policyholders 14 years and older. It showed that out of 300 such deaths which could be classified as to cause, 114 or 38 per cent were due to slipping on ice or snow. The next highest category, falls due to excessive intoxication, showed only 47 deaths or 15.7 per cent of the total.

In concluding this section, it should be pointed out that walking in a forest soon after a heavy glaze storm can be dangerous. In his description of the January, 1940, storm in England, Cave (1940) states: "It was dangerous to be in the forest for two days owing to the crashing of boughs and the falling of lumps of ice."

7. Trees

a. Importance of Glaze in the Ecology of Forests

In the United States, glaze storms are one of the principal agents of damage to forest, orchard, and shade trees. Even in those areas of the country where glaze is only an occasional phenomenon, it may be a factor of major ecological importance because of the tremendous damage that can be left in the wake of the infrequent but heavy storms that visit the region. In the glaze belt, where occurrences of glaze of moderate and heavy intensity are known almost every winter, it stands high among the leading natural hazards to healthy tree growth, ranking with such other scourges as fire, disease, and insects. According to Dow (1952), of 228 glaze storms recorded by the Weather Bureau as having occurred east of the Great Plains between the years 1923 to 1936 inclusive, a total of 158 (69 per cent) inflicted heavy damage to timber. The fact that glaze damage is one of the chief propagators of conditions favorable to the action of the other common scourges mentioned, further increases its importance as a forest menace.

The great significance of glaze damage in the ecology of forest trees has been pointed out by a number of individuals. For example, Abell (1934), writes:

> "No doubt injury from ice will help explain many of the deformed stands on slopes and ridges which formerly have been explained on other bases, such as site quality, growth habit, and drought. Ice storms may also help to account for windshake and the large amount of wormy and diseased timber of middle age found throughout certain sections."

A more specific observation is made by Ashe (1918), who states that "...over certain sections (of the Massanutten and Shenandoah Mountains of Virginia), the general appearance of the forest seems to indicate that practically all of it has been injured by ice during some period of its existence." C.F. Brooks (1938) points out, "Trees in snowy northern New England are often more shapely than those of the southern New England states because the latter are more subject to ice damage."

b. Weight and Thickness of Glaze

(1) Weight of glaze

The load that trees may be called upon to support during a severe storm can be truly colossal. Brooks and Howe (1921) estimate the weight of ice deposited on a large evergreen tree, 50 feet high and approximately 20 feet wide, by the Massachusetts storm of 1921, to be in the neighborhood of 50 tons. In a storm that struck Buffalo, N.Y., in December, 1929 (Spencer, 1929) several tips of branches from an elm tree weighed 2 1/2 pounds before the ice was melted; after melting they weighed 3 ounces. This is a ratio of slightly over 13 to 1 for the weight of ice to the weight of wood. For a diagram of the ice which accumulated on a forsythia branch during this storm, see Figure 48 below.

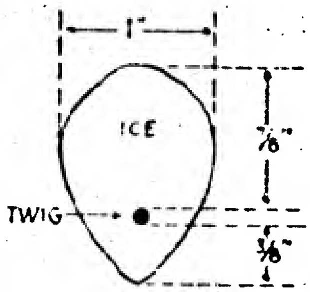

Figure 48. Accumulation of glaze on a forsythia twig. After a drawing in Spencer (1929).

Similar ratios have been obtained in other storms. Abell (1934) found that branches may be required to carry more than 15 times their weight, and Root (1924), Lockwood (1922), and Seeley (1922), report that twig weight increased 15, 16 and 32 times, respectively. Rogers (1923) discovered in one storm a considerable range in the ratio of ice weight to twig weight, with a variation from 132 to 1 for the American elm, and 5 to 1 for the white oak. However, such high ratios as the former unquestionably would not be maintained over an entire tree because in the case of larger branches one would not find as great an increase in ice load as in branch weight. An example of this relationship is given by Pattinson and Dines (1940):

Weight (Gms)		
Twig Alone	Ice Formed	Ratio
0.70	24.30	34.7
1.25	21.75	17.4
27.00	146.00	5.4

(2) Thickness of glaze

As for the thickness of ice that might build up on trees during severe storms, one of the most extreme cases ever reported in the United States occurred during the Michigan storm of 1922 where ice 5 to 6 inches thick was reported on tree twigs (this undoubtedly refers to diameter, not radius) in the worst area of the storm (Buttrick, 1922). This ice did not begin to melt for nearly a week after the storm.

In this same storm the average thickness of ice on twigs was 2 1/2 inches. Another very heavy deposit was found in a storm that struck central New York State, in which the radial thickness was between 1 1/4 and 2 1/2 inches throughout most of the storm area, and in some locations was more than 3 inches (Spaulding and Bratton, 1946). In the Buffalo storm referred to above, the ice grew, during 48 hours of almost continuous freezing rain, to a depth of 1 to 1 1/4 inches on all exposed surfaces and remained there without melting for four days. Unusual thicknesses are frequently encountered on trees in the Columbia River gorge of the western United States, but because the storms almost always occur when strong winds are blowing down the gorge from the east, the ice builds up mostly on one side of the trees. Describing this particular situation, Lawrence (undated) says: "A glaze storm may continue for 24 hours or more, with east-west velocities between 25 and 30 miles per hour, while branches and twigs on the east and northeast sides of a fir crown may become covered with ice coating as much as 3 or 4 inches thick." All of these examples are, of course, exceptional.

Lemon (undated) has commented on the thickness of ice needed to bring about damage to trees in New York State.

> "When ice deposits reach ¼ to ½ inch in thickness there is conspicuous breakage in trees and shrubs. At first it is confined to faulty limbs and dead branches and more or less natural pruning. Strong winds, of course, increase the breakage by glaze. In the usual case ice of ½ to 1 inch thickness will cause very serious breakage. The enormous weight of such a burden brings down many healthy branches and may affect young, vigorous, well-formed trees as well as mature ones."

(3) Weight of glaze and snow combined

In many storms, not only must the trees bear their load of ice, but also an additional load of snow deposited after the cessation of glaze formation. This weight may amount to almost as much as that resulting from the ice. In the Buffalo storm cited above, for example, the glaze was followed by 8 inches of snow. Assuming the glaze had a specific gravity of approximately 0.8 - 0.9, and that 8 inches of snow is equal to 0.8 inch of water, there would have been very little difference in the weight of ice and snow.

c. Examples of Damage to Trees

The result of the heavy loads described above can be catastrophic. One of the most graphic descriptions of what happens to trees when they are subject to a glaze storm of more than usual intensity is given by Buttrick (1922) in his account of the Michigan storm of 1922.

> "Hardly an uninjured tree remains in the whole storm zone. Some of the towns look from a distance as though they had been under heavy shell fire, so badly are their street trees riddled and broken. In the woods the damage is on the scale of that caused by great forest fires and tornadoes. It will require 25 years at least for the trees and forests of the stricken area completely to recover. In young woods the enormous weight of ice bent trees less than 8 inches in diameter double so that their tops lay on the ground. Many of them snapped at the point of greatest strain, others simply cracked, still others were apparently uninjured but may not be able to straighten up after having been bent over so long. Trees in woods where the stand averaged 8 to 12 inches in diameter lost practically all their branches and remain standing as bare poles or were broken off a short distance below the crown. In the big timber the smaller branches were sheared off so completely that the trees remain standing as gaunt skeletons. The litter of fallen branches on the ground is so great that it is difficult to walk through it. It resembles logging slash."

Other accounts describing equally appalling conditions are common. Burnham (1922) in writing of the famous Massachusetts storm of 1921, states that the Worcester Parks and Recreation Department estimated between 7500 and 8000 trees were destroyed outright, while another 5000 to 7000 were so mutilated they would die within a few years because of a weakened resistance to insects and disease. In storms of such extreme severity even the largest and strongest of trees can be felled. Vanderpool (1929) writes of trees 10-12 inches in diameter being broken off clean. Williamson (1934) tells of trees 18 inches in diameter being split, and White (1944) describes a storm in which trees as large as 24 inches in diameter were broken off or uprooted.

d. Areal Extent of Damage

As in the case of damage to utilities, the areal extent of damage inflicted on trees by any one glaze storm may be local in nature or may spread over hundreds or even thousands of square miles. A storm damaging an area only 1 1/2 miles long and confined to the top of a small mountain occurred near Connellsville, Pa. in 1936 (Zehfuss, 1945). On the other hand, a 1944 Texas storm (White, 1944) damaged trees over an area of 8 million acres of approximately 12,500 square miles, and in 1940 a storm severely injured trees in a broad belt along the Atlantic seaboard from Pennsylvania to Boston (Deuber, 1940). Most instances of damage, probably 85-90 per cent, are restricted to rather limited areas, generally extending across no more than 2 or 3 average-size counties. Even where an occasional storm inflicts punishment on the trees of several states, a really heavy toll is taken only in those generally rather limited parts of the damaged area where ice thickness and/or wind velocities reach relatively high intensities. In fact, in most storms, except the most severe where ice accumulates almost everywhere over a large area in thicknesses capable of sweeping down everything, damage is very spotty. The storm described by Buttrick (1922) is of this type.

e. Geographic and Climatic Factors in Damage

(1) Wind

In a large number of storms in which trees are damaged, the wind plays an important role. Positions with an aspect favoring strong winds and located in an area where glaze is fairly common will, of course, be subjected repeatedly to severe damage. Trees in such sites may become considerably deformed (but not entirely from glaze damage, since wind alone, and wind and snow combined, also can be very destructive). Mountain top and water or wind gap exposures in the northern and central Appalachians are typical of this type of location. An outstanding case is the Columbia River Gorge of the western United States. Another situation favorable to repeated damage is found on windward slopes in regions where the wind has a pronounced tendency to blow from a given direction during glaze storms. This exists in the central and northern Appalachians where north and northeast slopes are more apt to face the wind during these storms than slopes oriented in other directions.

Buttrick (1922), investigating damage caused by an unusually heavy storm that hit Michigan, reported that despite the fact ice thicknesses were great and heavy damage was general, small trees in protected locations escaped with only a few broken branches. He also observed that open woods suffered more than dense ones. However, he believed this was because the trees in open stands were unable to give each other mutual support. This might be a factor, but probably of greater significance is the fact that trees in open stands are much less sheltered from the wind. C. F. Brooks (1941) found greater damage in interstream upland surfaces in the High Plains region, due to stronger winds there than in the valleys. Deuber (1940) gives an example of a storm where, although ice load was the primary cause of injury to trees, high winds greatly intensified damage in some areas. An excellent study of the effect of exposed and protected sites on tree damage was conducted by J. F. Reed (1939) after a heavy storm hit Amarillo, Tex., on February 16, 1938. The results of his survey, which concerned only elm trees, are shown in Table VIII. The data in this table establish definitely the importance of exposure to the wind. Trees on the north side of east-west running streets were nearer protective buildings (the storm had north to northeast winds), than those on the south side. Likewise, trees on the east side of a north-south street had more protection than those on the west. Trees less than 18 feet in height were much better shielded from the wind than taller trees, and as the table shows, suffered considerably less damage on the north and east sides of the street than on the south and west. In the case of trees more than 18 feet in height, most of whose crowns extended above the tops of buildings, no shielding effect because of location on the lee side of a wind shelter resulted. In fact, curiously enough, these taller trees suffered greater damage on the north and east sides of the streets than on the south and west.

TABLE VIII

EFFECT OF LOCATION ON DAMAGE TO ELM TREES DURING GLAZE
STORM OF FEBRUARY 16, 1939 IN AMARILLO, TEXAS*
(in % of trees damaged)

	Small Trees (<7 ft. high)		Medium Trees (7-18 ft. high)		Large Trees (>18 ft. high)	
Side of Street on which located	No. Obs.	% Dam.	No. Obs.	% Dam.	No. Obs.	% Dam.
North	76	14.5	128	28.8	32	71.9
South	21	61.9	54	50.0	46	50.0
East	25	0.0	90	15.6	9	67.0
West	38	31.6	96	52.1	96	32.3

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* J. F. Reed (1939)

Still another way in which the wind can have an influence is in causing more ice to be deposited on the windward sides of trees than on the leeward sides. Lockwood (1922) reports an occurrence in Wisconsin where the ice accumulation was almost entirely on one side (the windward) of trees; such a situation can be dangerous because of the imbalance of weight. It seems likely it could bring about the toppling of trees in severe cases, and at the least would produce misshaped crowns. In the Columbia River Gorge, where the ice is concentrated on the east sides of trees in almost every storm, this imbalance is a leading factor in causing permanent crown deformation – a serious matter having more than mere esthetic significance. Lemon (1956) points out that an unbalanced crown " ... ill fits a tree to withstand future stresses in nature such as wind storms or the weight of glaze or snow."

(2) Altitude

Almost all references in which varying altitude is mentioned as an important factor in glaze damage to trees indicate that in hilly and mountainous terrain of moderate relief, damage is greater at the higher elevations. One of the best documented descriptions, by C. F. Brooks (1925) concerns a storm in eastern Massachusetts in which the hill tops were covered with ice and the trees suffered considerable damage, while the lowlands were ice free. Ashe (1918), Pierce (1933), Gustafson (1938), Downs (1938), and Zehfuss (1945), all of whom describe storms in the Appalachian region, similarly found damage greater at higher elevations. The results of Downs' observations are summarized in Table IX. The Pennsylvania Electric Association found there were only about one-half as many storms in the Susquehanna and Schuylkill valleys as at higher locations in the mountains, and that storms depositing ice with a thickness of one-half inch or more were frequently experienced at the higher elevations, but not at the lower. Lockwood (1922), reporting on the severe storm of February, 1922, in Wisconsin, states that apple trees suffered much more damage on the ridges than in the valleys. Brooks found essentially the same was true on the High Plains of the western United States, pointing out that there was definitely less damage in valleys than on interstream areas. However, this relationship between increasing elevation and increasing ice damage to trees does not always hold true.

TABLE IX

GLAZE DAMAGE BY ELEVATION IN SECOND GROWTH STANDS IN THE KANE EXPERIMENTAL FOREST, ELK COUNTY, PA.*

Elevation (ft)	Trees (no.)	% of Trees	
		Damaged	Severely Damaged
1700-1800	1,916	2.3	1.3
1800-1900	3,128	12.1	7.8
1900-2000	10,885	22.1	17.3
2100-2200	6,606	30.4	25.2

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* Downs (1938)

Rhoades (1918), in a paper dealing with a glaze storm in the mountains of North Carolina, observes that the severity of the storm was felt alike on the hills and along the stream valleys. Under some circumstances the reverse of this elevation-damage relationship is encountered, with trees located in more sheltered locations in valleys and depressions suffering greater damage than those at higher, more exposed sites. Abell (1934) reports an example of this during a 1932 storm in the southern Appalachians. It is interesting to note that during some storms the vertical distribution of temperature may be such that ice damage to trees is limited to a rather narrow zone on the side of a mountain, with the upper and lower elevations escaping entirely (Ashe, 1918). This damage zone may have an altitudinal range of only a few hundred feet, yet in an occasional storm it may extend for many miles laterally along the side of the mountain.

(3) Latitude

Another fact of importance with regard to intensity of glaze damage with elevation is the influence of latitude. One might reasonably expect that to get into an area where one would encounter evidence in the forest of repeated glaze damage, it would be necessary to go farther above sea level in the southern Appalachians than in the middle and northern sections of those mountains. In other words, an effect similar to that of the gradual increase in the elevation above sea level of the timber line from high to low latitude should exist. Brooks placed great weight on this supposition in the preparation of the icing map for Putnam. Even in a single storm, particularly one with a considerable north-south extent, the latitudinal influence might be observed. Evidence for this is given by Downs (1938). In describing the March, 1936, storm in the mountains of Pennsylvania and New York, he says: "Serious damage did not begin until 1900 feet and above in northwestern Pennsylvania, but in New York damage was general above 1000 feet and in some places even reported below 600 feet."

(4) Water bodies

Another location factor is situation with respect to unfrozen bodies of water. Brooks (1925) describes a case in Massachusetts in which in the vicinity of a small lake at an elevation where ice was generally heavy there was no ice on trees for a few tens of yards from the water. Downs (1938) notes that sizeable bodies of water, such as Lake Ontario and the Finger Lakes of New York State, appear to cause a decrease in glaze damage in their vicinity. He reports that during the storm of March 17-19, 1936, woodlots within a mile of Seneca and Cayuga Lakes in New York were injured much less than those farther away.

(5) Ground cover

Downs (1938) points out the possible significance of another microclimatic influence - the condition of the surface of the ground. He states that in the 1936 storm just mentioned, north and east slopes suffered heavier damage than south and west slopes. He attributes this to the possibility that "... snow on the north and east slopes and bare ground on the south and west created local climatic conditions favoring greater deposition of ice." This may be true; such a condition could undoubtedly bring about the situation he describes in storms where there was little or no wind and the temperature was extremely close to the critical point for glaze formation.

f. Non-Geographic Factors Determining Resistance to Damage

(1) Varying resistance among trees.

Although of great consequence, the factors discussed above are probably no more important than certain other factors which have

TABLE X

ESTIMATES OF RESISTANCE OF TREES TO GLAZE DAMAGE*

Species	Sources of Estimates		
	Strong	Moderate	Weak
Conifers in general	Dow, Buttrick, Deuber, Reed		
Eastern hemlock	Abell, Downs, Dolgow	Lemon	
Spruce in general	Downs, Deuber		
Red spruce	Lemon		
White cedar	Downs, Croxton		
Northern red cedar		Lemon, Croxton	
Eastern white pine	Abell, Downs, Kienholz	Croxton, Lemon	Deuber, Spaulding
Norway pine	Downs	Spaulding	
Scotch pine	Kienholz		
Red pine	Kienholz		
Jack pine			Kienholz
Longleaf pine	Boggess	McKellar	
Slash pine		McKellar	
Loblolly pine	McKellar	Boggess	
Virginia pine			Dow
Poplars in general	Reed		Deuber, Croxton, Gooch Burnham
Yellow poplar	Dow, Downs	Lemon	Burnham, Buttrick
Lombardy poplar	Buttrick		
Caroline poplar			Buttrick
Maples in general	Reed		Gooch, Burnham
Sugar maple	Downs	Dow, Deuber, Croxton, Lemon	Buttrick, Spaulding
Red maple		Downs, Buttrick	Dow, Abell, Deuber
Silver maple		Buttrick	Dow, Deuber, Croxton
Norway maple	Deuber		
Oaks in general	Burnham	Deuber	
White oak	Croxton	Dow, Abell, Buttrick	
Northern red oak		Lemon	
Black oak		Dow, Abell, Buttrick	
Scarlet oak		Buttrick	Abell, Dow

TABLE X (Cont.)

Species	Strong	Moderate	Weak
Miscellaneous species			
Sweet birch		Dow, Downs	Deuber
Yellow birch		Dow, Downs	Deuber
Gray birch		Lemon	
Blueleaf birch			Croxton
Black locust	Reed	Croxton, Downs	Abell, Dow
Hickory in general	Dow, Downs		
Shagbark hickory	Lemon		
Sycamore	Dow, Downs, Reed		
Catalpa	Dow, Deuber, Reed, Croxton		
Ailanthus	Dow, Croxton		
Beech	Buttrick	Dow, Downs, Lemon	Spaulding
Ash	Reed, Burnham		
White ash	Lemon, Downs, Buttrick	Dow, Buttrick	Spaulding
Cucumbertree		Dow	
Black gum		Dow	
Basswood			Dow, Downs, Buttrick Spaulding, Lemon
Aspen			Dow, Downs, Buttrick, Lemon
Willow			Dow, Downs, Deuber
Black cherry			Dow, Downs
Chestnut		Croxton	Dow
American elm		Downs	Dow, Buttrick, Reed, Croxton Gooch, Burnham, Lemon
Slippery elm			Lemon
Box elder			Dow
Eastern cottonwood			Rogers, Lemon
Hackberry	Reed		
Black walnut	Croxton		
Butternut			Lemon

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* Based on observations by a number of individuals; for identification of sources see bibliography

nothing to do with geographical location or climate. This second group, which can cause one tree to be almost totally destroyed while another beside it escapes, is based on the great variation in resistance to ice damage found among different species of trees and also among individual trees of a single species.

Much evidence has been gathered to show that this varying reaction of trees to glaze and wind damage is, in part, the result of differences in inherent characteristics, such as wood strength, elasticity, and habits of growth. These characteristics can be important in determining the type of injury experienced by trees of a given species and in determining the degree and rapidity of recovery from severe damage. However, all trees having a certain characteristic will not necessarily react in the same way to the stresses of a heavy load of ice, even where seemingly glaring weaknesses exist. For example, one might suppose that all trees with weak, brittle wood would be among the hardest hit by glaze storms, but such is not the case. Some actually stand up quite well to rather heavy loads of ice as a result of the greater importance of some other special quality. A case in point is the ailanthus which, despite its extremely weak and brittle wood, has been little damaged in storms where supposedly more rugged trees have suffered heavily (see Table X).

(2) Resistance of conifers

(a) Conifers vs. deciduous trees

Probably the greatest contrast due to the nature of the species is that found between conifers on the one hand and virtually all broadleaf deciduous trees on the other. When subjected to the same ice conditions, conifers almost invariably fare better than deciduous trees. Buttrick (1922), Downs (1938), Reed (1937), and Deuber (1940), all found this to be true. However, on occasion the reverse can occur. For instance, in a storm that struck the Piedmont plateau between Atlanta, Ga., and Washington, D. C., Gooch (1943) found that while all species suffered quite severe punishment, the heaviest damage was inflicted upon the younger pine stands; Young (1928) reports a case where in a Michigan plantation composed of both hardwood and coniferous species, Scotch and Austrian pines were the only trees severly injured by glaze. A very severe Connecticut storm (Kienholz, 1941) also resulted in greater damage to the coniferous species than to the deciduous. Whether any special circumstances were responsible for these deviations from the general rule is not known.

As for the factors responsible for the normally greater resistance of conifers, Downs (1938) lists the comparative resilience of their branches, the fact that they generally have smaller upper crowns and thus do not become top-heavy from having the weight of ice concentrated in the upper levels of the tree, and the fact that their branching habits are better adapted mechanically to resist weight on their crowns. In connection with the last point, Metcalfe (1949) states that accumulations of ice on horizontal branches, such as those of conifers, soon change from a bending to a pulling load that is carried well, as long as the weight is symmetrically distributed. Several investigators, among them Haufe (1935), who studied the effects of a heavy coating of ice that remained on the trees in the Ore Mountains for four weeks, show that trees with long, symmetrical crowns generally do better than trees with short, one-sided crowns. This is probably another plus factor on the side of conifers because they are more apt to meet the first requirement than non-conifers. Windirsch (1936), on the other hand, discovered that trees with cylindrical crowns, suffered less bole injury than those with conical crowns, a fact that seems to work to the detriment of at least some conifers.

It appears that conifers, as a class, have more flexible stems or trunks than deciduous trees, thus allowing them to tolerate a greater amount of bending before the stem splits or breaks completely. However, this flexibility decreases rapidly with an increase in tree age so that only relatively young trees are able to stand much bending of the trunk without snapping. Furthermore, many deciduous species, such as the willow, aspen, hickory, and birch have very supple stems when they are young. An account is given of a storm in England in which silver birches up to 20 or 30 feet in height were bent until the tops were resting on the ground, and yet they recovered when the ice fell from the branches (Pattinson and Dines, 1940).* Young conifers may also recover from such an experience, but more often such extreme bending, even though causing no fracturing of the trunk, will result in the loss of the trees (Boggess and McMillan, 1954).

A storm in which conifers suffered virtually no damage while a large percentage of the deciduous trees present were devastated is described by Buttrick (1922). "They (the conifers) became coated with a layer of ice over the entire outside of the tree, but the interior escaped so that the total weight upon them was less than in the case of the hardwoods where every individual tree was coated." He goes on to say that had there been strong winds associated with the storm, the picture would have been quite different, with the conifers taking more punishment than the deciduous because of the solid wall of resistance they would have presented the wind.

Another advantage of conifers has been pointed out by Metcalfe (1949). He states that dense, low-branched evergreens may develop icicles downward from branch to branch and finally to the ground in such a way that all are safely supported by an ice structure.

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* Lemon (undated) states, "Almost any young stand of even-aged, spindly trees will 'lodge' like grain under heavy ice or snow."

(b) Variation among conifers

Among conifers themselves there is evidence of variation in the degree to which individual species are able to withstand glaze storms, but they probably vary less in this regard than deciduous trees. This relatively small variation among conifers appears to be especially true in storms of light and moderate intensity. (A storm of moderate intensity is, in the opinion of this writer, one with ice less than 1/2-inch thick and with an absence of strong winds. Such storms, of course, make up by far the greatest number of all glaze storms.)

Consequently, it is as a result of prolonged and heavy storms that we find descriptions of some conifers suffering greatly while others are little damaged. McKellar (1942) found that as a consequence of a severe glaze storm lasting several days in an area of pine plantations in Georgia, the final net loss (as determined by the number of broken-stemmed, badly bent, and uprooted trees) was 24 percent for long-leaf pine, 29 percent for slash pine, and only 4 percent for loblolly. He gives as the probable reason for the greater damage to the first two their denser, more uniform foliage, which appeared to be responsible for the accumulation of a greater ice load than on the sparse-foliaged loblolly.

After the severe southern Illinois storm of January, 1952, Boggess and McMillan (1954) found that where the same conditions had existed during the storm, loblolly suffered considerably less than shortleaf pine. Croxton (1939) also encountered a variation in the degree of damage to different conifer species, in this case as the result of an unusually severe storm that visited parts of Missouri and Illinois. The results of his investigation show the following percentages in his category for "badly broken conifers": northern white pine, 55; eastern red cedar, 26; northern white cedar, 7; white spruce, 5. Deuber (1940) reports that conifers fared better than deciduous trees in heavy storms along the Atlantic coast, but while spruce withstood the ice remarkably well, plantations of white pine about 25 years of age were badly injured by the terminal shoots snapping off from 4 feet to 6 feet below the bud. These conditions somewhat parallel those resulting from a storm in 1942 that severely damaged the forests in Otsego and Herkimer Counties, New York, described in a paper by Spaulding and Bratton (1946):

> "Mature white pine was badly injured with tops completely removed or branches partially broken out. Damage to hemlock was of such a minor character as to be considered negligible. In plantations, red Scotch and white pines lost leaders, laterals and in some cases entire tops, or the trees were pressed down into a horizontal position by the weight of the ice. Norway spruce and European larch apparently suffered less than the pines."

One more account on this subject worth noting is Kienholz' (1941) description of conditions found in Connecticut pine plantations after a very destructive storm.

"Scotch pine, white pine, and red pine in mixture with jack pine or in pure stands nearby were but slightly injured. (The jack pine was devastated.) Scotch pine was broken in a number of cases (17 percent), white pine had an occasional top broken out or a limb torn off, while red pine was seldom damaged beyond breaking the current year's leader. In one case where a few jack pines were scattered through a red pine plantation, the jack pine was nearly all snapped off and the red pine was undamaged."

All investigators, however, have not encountered in conifers the variations in resistance described above. Buttrick (1922), for instance, found "...no special difference in the degree of injury to evergreens of different species..." in the severe Michigan storm he studied. In this same storm there was considerable range in the amount of damage experienced by the deciduous species. Buttrick did discover, as a result of studying this storm, that factors other than those associated with the nature of the species can have a great deal to do with determining which particular coniferous tree is damaged and also the nature of the damage to individual trees:

"In the woods the evergreen suffered most in the class of trees from six to ten inches in diameter. These were occasionally broken off somewhere midway in their height. Smaller ones were bent over but will probably straighten up in time to escape damage. Larger ones frequently had their entire tip broken out. Very large evergreens suffered scarcely at all. In the open, evergreens of all sizes, since their crowns extended rather close to the ground or were small and open, escaped practically uninjured."

(c) Conclusions regarding resistance of conifers

In summary, the following generalizations can be made concerning the behavior of coniferous trees during glaze storms, remembering, of course, that the data are rather meager for firm conclusions in the case of some species:

1 Conifers are generally more resistant to mechanical damage than deciduous species (see Table X).

2 In most storms, there will probably be a relatively small range in the degree of injury suffered by different specimens in the conifer community.

3 The spruces, cedars, and hemlocks seem to be the most resistant conifers, while the pines show a range from strong resistance for Scotch, red, and loblolly, to weak for jack and possibly slash and longleaf. White pine has stood up well in some heavy storms, moderately well in others, and poorly in still others.

(3) Resistance of Deciduous Trees

To make similar generalizations about the behavior of deciduous trees is considerably more difficult, primarily because the information available on them is much more conflicting. There are, however, many points of agreement to be found among the many studies that have been made on this aspect of the ecology of the deciduous trees of North America and an attempt will be made to summarize these.

(a) Wide range in resistance among deciduous species

Several conclusions concerning the deciduous species as a class have already been touched upon. One of these has to do with the wide range in ability to endure the stresses of glaze storms encountered among their different species.* A glance at Table X should suffice to illustrate this point. Certain species, such as elm and basswood, are listed only in the weak category, while others, notably catalpa and sycamore, are found solely in the strong column. The factors responsible for this differentiation appear to be complex and are not always agreed upon by the authorities. It should be noted, as in the case of conifers, that data are too meager on many species for strong conclusions to be made.

(b) Tree size and configuration

Tree height and crown size and configuration, however, must definitely be classed as having some significance. In this connection, Buttrick (1922) reports:

"The damage to individual trees standing in the open was in proportion to their height and the extent of their crowns. Tall and wide-crowned trees (that is, with wide, spreading branches) suffered most severely. Low-crowned trees with few large limbs, least ... Shade trees suffered in proportion to their size, location, and kind. Small ones in protected locations escaped with only a few broken branches, middle-aged ones generally had their lower branches bent completely down to the ground and often cracked but seldom broken off. The upper branches were broken or twisted off and often the crowns were entirely broken out. Large trees generally had their branches entirely shorn off." Downs (1938) also discovered that the degree of damage was largely governed by the tree size and crown class. According to his account, damage increases proportionally to tree and crown size. He found large, spreading crowns to be particularly dangerous.

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* Although he found some variations among deciduous species in New York, Lemon (undated) generalized, "Most of the dominants of the deciduous forest climax seem to suffer about the same."

Reed (1939) found that when trees of the same height but different crown width grow on completely exposed sites, the extent of the damage varies with the width of the crown. Sixty-two trees with an average crown width of 10 feet were 41 percent damaged, but 57 trees whose crown width averaged 6 feet suffered only 26 percent. Dow (1952) similarly reports that large crown size increases a tree's danger of receiving serious damage, and as have several others, he found that lop-sided or misshapen crowns have the same effect. Deuber (1940) gives as a partial explanation for the extremely resistant quality of Norway maples the compactness of their crowns. De Bele (1935) and Spaulding and Bratton (1946) also found crown form and size to be significant. Obviously, a small, compact, symmetrical crown is better designed to withstand mechanical strain. The limbs are usually shorter and thicker and the symmetry means that the ice load is distributed evenly over the tree and that there are no weakly supported limbs projecting at odd angles. Trees with V-shaped forks (the American elm, for example), are prone to splitting at these forks in heavy storms (Metcalfe, 1949).

Lemon (undated) has the following to say about the role of crown configuration.

"Much as it would be desirable to associate susceptibility with crown forms ... it seems impracticable to do so. If it is possible to design an ideal form, it would seem that a very straight and strong central trunk with small, flexible and perhaps drooping side branches might be resistant to glaze damage. Spruce (<u>Picea</u> spp.), Balsam (<u>Abies Balsamea</u>) or <u>Liriodendron</u> approach this pattern. As it happens, these three types are generally glaze damage resistant.."

Related to the factor of height is a tree's relative position in the woodland association in which it grows. Tall trees that extend above the canopy level are especially subject to damage. Gustafson (1938), De Bele (1935), Curtis (1935), Downs (1938), and Boggess and McMillan (1954) all found this to be true. Supporting this theory is a fact pointed out by Downs (1938) concerning the black cherry, a species commonly found in the early successions on abandoned fields. Because it grows very fast during youth, it rises above the other invaders, thus making itself liable to injury.* Another point Downs makes is that in any forest association the overstory has a greater tendency to be damaged than the understory. The reasons for the greater damage to trees extending above the general canopy level is probably due to their greater exposure to the full

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* Somewhat related to this is the fact observed by Lemon (undated) that in New York some trees belonging to early stages of the succession are subject to severe glaze damage. He believes "Their greater susceptibility simply assists the replacement process by which succession advances and may slightly accelerate succession."

onslaught of the wind and the fact that they may on occasion accumulate heavier loads of ice. Geiger (1950), in studying a close pine stand averaging 15 meters (49 ft.) in height, found that when the wind speed below the canopy level was approximately 4 miles per hour, speeds above the canopy were nearly 10 miles per hour. The fact that trees, rising above the canopy, would average a greater volume of freezing precipitation over their entire surface would explain the greater ice loads. However, the difference in ice loads would probably be much smaller than the difference in the wind velocities. In fact, there may even be occasions where the reverse is true, that is to say, more ice in the canopy than on trees that rise above it. Such a situation may be brought about when there is a strong wind and freezing rain of moderate or heavy intensity which was supercooled only slightly below 32°F. In this case a large percentage of the precipitation might be blown off the more exposed tree surfaces before it had a chance to solidify, only to freeze after falling to the sheltered surfaces within the canopy. Differences in air temperature can exist between the canopy and the zone immediately above it, but just what they would be under conditions of cloudy skies and precipitation is not known. Probably they would be too slight to have any significance in causing a differentiation in ice formation.

(4) Age

As is brought out in Table XI, age is another factor that seems to have considerable significance; damage is more severe in forest stands of old growth than in stands of young growth (Buttrick, 1922; Gustafson, 1938; Moses, 1929; Spaulding and Bratton, 1946). For one thing, old growth is much more likely to have been weakened by decay (Downs, 1938). In storms where mature trees may have their trunks snapped by the great weight of ice they are forced to endure, many young trees, too flexible to break, escape total destruction by bending to the ground. This can have serious consequences, as has been mentioned before, but at least the victims have a chance for recovery. However, in unusually heavy storms age alone, like any other small factor, probably is of little importance. Rhoades (1918) cites an instance of this in which, particularly in spots where the ice was thickest, "... young trees with flexible branches suffered as severely as did old trees of stiffened fiber." In the severe Texas storm of 1944 (White, 1944), damage actually was greatest to young trees, and the same condition is reported by Kienholz (1941) for the Connecticut storm in 1940. Both of these cases, however, apply to pine trees growing in cultivated plantations where special conditions could possible affect the results.

(5) Strength and flexibility of wood

The difference in strength and flexibility usually found between old and young trees also exists among trees of different species. In general, species with brittle wood may be expected to suffer more than those with wood of more strength and pliancy (Buttrick, 1922; Rogers, 1923; Vorreiter, 1937). Buttrick (1922) especially, places emphasis on

TABLE XI

GLAZE DAMAGE BY AGE CLASSES IN THE KANE EXPERIMENTAL FOREST, ELK COUNTY, PA.*

Age Class	No. of Trees**	% of Trees Damaged	% of Trees Severely Damaged
Young growth (10 to 20 yr.)	5,337	7.1	6.1
Second growth (21 to 40 yr.)	22,535	21.5	16.9
Old growth (culled)	675	39.4	29.0

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* Downs (1938)

** Based on a 2.6 percent sample of 1,675 acres

brittleness as a factor of paramount importance in the Michigan storm he studied, stating that among trees of the same size and development stage and among deciduous trees of different species, injury seemed to be greatest in the soft and brittle-wooded species. He found, for instance, that aspens and poplars are harmed a great deal more than oaks and ashes. Similar results are noted by Deuber (1940), who observes that oaks, by virtue of their strength of wood, are less damaged than elms and maples. A somewhat different picture is given by Ashe (1918) for conditions in the southern Appalachains, where tough-wooded species such as oaks and hickories frequently have the entire upper portions of their crowns destroyed by the breaking of their central stems. In the case of poplar, linn, cucumber, chestnut, and some other species having comparatively brittle wood, breakage is limited to the larger branches, thus effecting less deformation of the crown.

(6) Fineness of branching as a factor in resistance

Some observers (Croxton, 1939; Deuber, 1940; Rogers, 1922) have encountered heavy injury in finely-branched species, suggesting that the amount of surface presented by the branches as focal points for ice accumulation is of considerable importance. Lemon (undated) reports that the "amount of ice carried is roughly proportional to the surface area of the tree in winter condition." Croxton (1939) warns, however, that the data on some of these species are so limited no definite conclusion is warranted. Nevertheless, the idea probably contains some validity, because, otherwise, it is difficult to explain the high resistance of such extremely soft and brittle-wooded species as ailanthus and catalpa. The twigs of both of these trees are thick and few in number when compared to those of other species, notably elm.

(7) Decay

As has been suggested earlier, the amount of decay and insect damage in a tree has a major influence on the amount of injury from ice, with old trees suffering more in this regard than young trees. Buttrick (1922), to cite only one reference, reports that the most severe damage is experienced by trees with decay in their trunks or larger branches, such trees generally being completely broken apart and ruined.

Another aspect of the decay problem is that wounds resulting from breakage in a glaze storm are one of the principal avenues of entry for insects and other destructive organisms. In fact, the greatest damage from many storms comes not from immediate mechanical breakage, but from decay organisms entering the tree as a result of that breakage. The effects of the decay may not be felt until years later when the tree again is subjected to some severe strain. Deuber comes to this conclusion at studying the effects of a storm that struck the north Atlantic coast in March, 1940. He also concludes that glaze damage in the eastern United States greatly enhanced the spreading of Dutch elm disease. Rhoades (1918) found that one year after a severe storm struck the southern Appalachians, the southern bark beetle invaded the area and destroyed a large number of the pines. Entomologists attribute an outbreak during 1936 and 1937 of the southern pine beetle in trees of the piedmont of the south Atlantic coastal states to the favorable environmental factors created for their existence by the ice storm of 1934 (Gooch, 1943). Campbell and Davidson (1940) discovered that two years after a glaze storm in the Allegheny section of Pennsylvania, practically all the top wounds in black cherry and sugar maple were infected by white-rot fungi. Campbell (1937) writes authoritatively on this subject as follows:

"The different tree species making up the northern deciduous forests vary considerably in their resistance to decay. For this reason injuries which would create but a slight decay hazard in one species might cause a relatively high decay hazard in another ...

"Top injuries, especially those not involving the main stem or large branches, usually present a low decay hazard for all tree species. Top injuries in which large main branches are broken, especially if the wood is much stattered at the injured area, offer a high decay hazard in some species, and less in others. Large trunk injuries caused by the splitting of forked stems and the breaking of large lower branches involving the main stem offer a high decay hazard in all species. The splitting of forked stems is particularly hazardous because of the large wounds which heal slowly."

Among the species he studied, Campbell found that the black cherry was very resistant to decay coming from moderate breakage and that the same was true of the sugar maple. Wounds in sugar maple resulting from a 10-year-old storm had healed without infection on all but the largest branches. On the other hand, red maple apparently offered little resistance to decay. Trees 45 years old, with top damage 10 years old, contained considerable decay. Beeches also were found to have been greatly affected by decay as a result of glaze storm injury.

Spaulding and Bratton (1946) present somewhat conflicting evidence. They examined after a lapse of 2 1/2 years, the reaction of sugar maple, beech, white ash, and basswood to heavy top damage inflicted by a severe glaze storm. The white ash and basswood made good recovery, even when stripped of all branches, because of rapid development of sprout growth and because of their thick, rough bark, which apparently prevented dying of the bark on the trunk and subsequent infection there by the deadly sap-rot fungi. Beech sprouted somewhat less vigorously, but new growth was adequate to prevent infection of the main stem except in a few instances. Sugar maple sprouted even less and as a result suffered very heavily from decay.

(3) The ecological factor

There is yet another type of injury imposed on forest trees by glaze storms. This is physiological damage resulting from the abrupt change in the environment of the surviving trees following severe storms. Campbell (1937) sums up this aspect of the problem by saying:

> "It is not supposed that the decay hazard will be the chief factor causing deterioration of ice-damage hardwood stands, as physiological changes caused by reduction of the crown-root ratio, opening of the stand, change in water content of the top soil, and the opportunities for sun scald, may also be important. Trees weakened by any of these agencies may become more susceptible to root fungi as well as a host of parasitic but non-decaying leaf and twig fungi."

g. Methods of preventing damage

To conclude this section dealing with glaze damage to trees, it might be worthwhile to list certain measures recommended by Downs (1938) for the long-range prevention of glaze damage to forests in the eastern United States.

(1) Remove holdovers. Their large-spreading crowns make them highly susceptible to glaze damage; and when they come down they do much damage to the smaller trees around them.

(2) Reduce the proportion of susceptible species. A larger percentage of conifers should be encouraged on sites subject to glaze damage.

(3) Preserve an even canopy. Fast-growing species which in youth tend to grow fast and to project above the general canopy level are especially subject to damage.

(4) Use group silviculture for species of widely different growth habits. Large spreading crowns are prevented when species of similar growth rate are reproduced in groups.

(5) Modify local silviculture with elevation and aspect. For example, at higher elevations and on northerly aspects, sugar maple and hemlock should be encouraged at the expense of black cherry.

h. Summary

Glaze ranks high among the natural hazards to forest and shade trees of the eastern United States. The combined effects of great ice weight, estimated up to 50 tons for an individual tree in some storms, and wind often are sufficient to sheer off large branches or bring about complete destruction of trees. Most sections of the country's eastern forests bear the scars of past storms.

Damage in any one storm may be local in nature or may spread over millions of acres. Because of strong microclimatic influence, damage often is extremely spotty in areal distribution. Exposure to wind, differences in altitute and ground cover, and proximity to unfrozen bodies of water are important in determining the extent of damage.

Considerable variation in resistance to ice damage is found among different species and among individual trees within species. Conifers for example, tend to tolerate heavier ice loads without damage than do deciduous species. Among deciduous trees there is a wide range of resistance from the easily damaged American elm to the hardy catalpa. Among the factors apparently contributing to this variation are tree size and configuration, strength and flexibility of wood, and fineness of branching. Age and the amount of decay and insect damage suffered by a tree can also be important factors. In addition, wounds suffered in a glaze storm may allow entry of insects and other destructive organisms which will cause the slow destruction of the affected trees. Glaze damage has been suspected of aiding the spread of Dutch elm disease along the Atlantic seaboard.

8. Animals and Field Crops

The slippery condition created by glaze can become a danger to the safety of farm animals. In addition, the thick coat of ice on the ground can make it impossible for grazing animals to obtain the feed underneath. After a series of glaze storms in Iowa (Reed, 1937), the surface of the ground provided such poor footing that farmers fastened burlap bags on the horses' hoofs to enable them to walk, and many dragged their cattle with the aid of tractors to feed lots and shelter. Some animals were without feed and water for 48 hours. Many farm animals were killed or injured by falls on steep icy slopes. As a result of a storm that struck Texas (Tannehill, 1929), many cattle along the Gulf coast died from the combined effects of low temperatures and heavy sleet and snow.

Wild animals naturally suffer in the same way as domestic animals. Birds in particular feel the cruel effect of a heavy glaze storm. Cave (1940) has commented on this in describing the January, 1940, storm in England:

> "The effect on bird and animal life must have been disastrous. In the press was an account of birds with their feet frozen to branches ... pheasants could not fly as their wings were frozen ... a moorhen was found with its feathers so frozen that it could be caught quite easily ... starlings were seen eating members of their own species."

Little information is available regarding glaze damage to field crops. A large number of persons have investigated the effect on crop plants of an ice sheet formed by the refreezing of melted snow, but so far as the present writer is aware, no one has dealt exclusively with glaze. Klages (1942) states: "If the ice layer (glaze) remains long enough, winter wheat or other winter annual plants may be damaged by suffocation." However, the question which remains unanswered is whether glaze remains on the ground long enough to cause suffocation. On occasion it probably does. Lockwood (1922) reports that as a result of the storm of February 21 to 23, 1922, in the Great Lakes area, winter grains and grasses were smothered by the heavy coating of glaze on fields and meadows.

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(all 1953)

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BURCH, J.S.
Engineer of Statistics and Planning, State Highway and Public Works Commission, North Carolina (Oct. 16).

CHURCH, J.B.
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COVERT, GEORGE S.
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CROUSE, W.J.
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GRAY, H.G.
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GREEN, D.C.
State Highway Engineer, Texas Highway Dept. (Oct. 20).

HARRIS, H.H.
Maintenance Engineer, Dept of Highways, Commonwealth of Virginia. (Oct. 19).

HILL, G.A.
State Highway Commissioner, State Highway Dept., Connecticut. (Oct. 26).

HOLLAND, R.J.
District Engineer, Arizona Highway Dept. (Oct. 19).

HUGHES, O.J.
Secretary, Highway Commission, State of Wisconsin. (Oct. 29).

HUMMEL, C.A.
Vice President, Interstate Power Co., Dubuque, Iowa. (Sep. 3).

IHLI, Leo A.
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ROOT, W.H.
Maintenance Engineer, State Highway Commission, Iowa (Sep 16).

ROSENSTONE, E.A.
Director, Dept. of Public Works and Buildings, State of Illinois. (Nov 27).

ROTHROCK, C.A.
State Planning Engineer, State Road Commission of West Virginia. (Oct 20).

SARGENT, H.E.
Chief Engineer, Dept. of Highways, State of Vermont. (Oct 20).

SHERARD, T.
Administrative Asst., State Highway Commission, Wyoming Highway Dept. (Nov 4).

SILER, L.J.
Engineer of Maintenance, State Highway Commission of Kansas. (Oct 23).

SUVERKUP, A.N.
Executive Asst. to the Governor, State of Nevada. (Nov 2).

ZANSKAS, A.S.
Engineer, Otter Tail Power Company, Fergus Falls, Minnesota. (Nov 19).

APPENDIX A

Excerpts from letters from State Highway Officials

During the course of the study, a letter was written to each State requesting information concerning the frequency and severity of glaze on their roads and its effect on transportation. Pertinent material has been taken from 29 replies and is presented below. Bibliographic references apply to the second section of the bibliography.

Arizona (Holland, 1953)

> "In the southern part of Arizona we experience no adverse ice or snow conditions. Highways 70 and 60 across the state are clear of any ice condition except for an occasional short storm in December or January. This is true of Highway 60 from Superior to the Colorado River.
>
> "U.S. Highway 60 from Springerville to Superior has ice and snow conditions at times each winter which slows movement of traffic slightly (never is closed by snow). U.S. Highway 66 from Gallup to Kingman has approximately the same conditions as above described covering Highway 60.
>
> "We are able to keep all main arteries and communications and transportation open except for an occasional exceptional storm which may happen one year in ten; and then traffic is slowed down considerably; however, highways still are kept open.
>
> "In the higher elevations of this state, 6,500 to 8,000 feet, we spread sand and common volcanic cinders to control ice and snow on the pavement. The black cinders also add a little heat increment,* and the grinding under traffic gives us a breakup."

Arkansas (A.E. Johnson, 1952)

> ". . . icing is not the serious problem in this state that it is in the states farther north."

Connecticut (Hill, 1953)

> "Ice storms caused by freezing rain are a very serious winter maintenance problem in this state. Freezing rain will cause the pavements to ice over in a matter of minutes

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* The author apparently means the heat is added as a result of absorption by the black cinders of solar radiation.

and cause very hazardous driving conditions. Normally, this type of storm lasts from 1-3 hours. Temperatures usually rise and even though the rain continues, the ice starts melting. The exception is when the storm starts late in the day and continues throughout the night with temperatures remaining below freezing. Snow-packed pavements are not quite as slippery, but the frozen snow usually remains on the pavement for a longer period of time - from 24 to 48 hours. We have from 20 to 25 storms each winter, about equally divided between the two types of storms described above.

"We quite often get a variety of conditions during the same storm. For example, rain along the shore; freezing rain and icy pavements through the central part of the state; and snow on the higher elevations in the northern part of the state.

"Traffic tie-ups are usually of short duration and are invariably caused by motorists attempting to negotiate icy or snow-packed hills without the use of chains.

"We have a personnel of 1600 men available to combat our winter storms, operating 430 snow-plowing and sanding trucks. These trucks operate out of 100 strategically located garages. In addition we hire about 70 trucks with operators from contractors or trucking companies. Our men are on 24-hour call and report whenever called day or night. There are two Federal Government Weather Bureaus in this state and arrangements are made with them to give us three special weather forecasts daily during the winter season. In addition we arrange with the New Jersey Highway Department to give us advance information for storms coming up the Coast. We use sand and chlorides during the storms on steep grades, sharp curves, and heavy traffic highways."

Delaware (McWilliams, 1953)

"We do have a considerable amount of storms that cause icing of roads in this area, but they are usually short in duration, generally not exceeding 2 or 3 days before the sun and water conditions remove the ice from the road. We do carry out an ice control problem with the use of both chemicals and sand.

"One important transportation artery across the Delaware River is the Delaware Memorial Bridge which ices up before the rest of the highway system in Delaware, due to its elevation.* We use special precautions on the bridge in order to keep traffic moving over it. The period of icing on the bridge is also relatively short, one or two days will usually take care of the problem."

District of Columbia (J.N. Robertson, 1953)

"In the District of Columbia, such icing as does develop is generally from sleet or freezing rain. Once in a while, melting snow may freeze during a sudden drop in temperature. Temperatures do not remain below freezing for any extended periods and the major portion of such ice and snow, as may be present, is generally no longer than one or two days in duration."

Idaho (Miller, 1953)

"In northern Idaho we have more frequent storms and longer periods of overcast skies which result at times in ice staying on the roadway for longer periods than in the southern part of the state."

Illinois (Rosenstone, 1953)

"We know from years of past experience that snowstorms, ice formations and freezing rains temporarily reduce traffic on Illinois highways. Communications in the form of mail deliveries to small towns by trucks and to rural residents by mail carriers are also delayed for hours and sometimes days at a time.

"Documented reports on which calculated percentage of traffic before, during, and after the storms can be figured are rare. Traffic counts at one location 1 1/2 miles north of Edwardsville and U.S. Route 66 during normal weather and during snow and ice period are available and probably are representative throughout the state.

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*The greater exposure of the bridge to cold air on the bottom as well as on the top, and the absence of a flow of heat from sub-surface layers of the ground to the surface of the bridge, are probably much more important than elevation.

24-hour manual count, fair weather, Feb., 1950	4,560
add traffic increase, 1951 over 1950-7%	319
Equivalent fair weather traffic, 1951	4,879
Manual 24-hour traffic count, snow and ice period 1951	3,074
Daily traffic reduction due to snow and ice	1,805

"It is probable that essential transportation proceeds at a reduced speed without the high percentage of volume reduction that occurs for the nonessential traffic. Trucks that carry milk, bread, and groceries to the smaller towns manage to get through if the roads are passable. Nonperishable items that are not in daily use may be delayed, but total volume over a time period of 2 or 3 weeks would not be reduced. The men, and probably some of the women, who must travel some miles to reach their work also generally get to their destinations, but late. The traffic going to picture shows, athletic events, social visits, club meetings, school attendance, shopping trips . . . is greatly reduced during the snow and ice periods. A serious situation does sometimes develop in interference with the emergency movements of fire trucks and ambulances when roads are slippery with ice or blocked snow.

"The 385 miles of north-to-south length of this state passes through different mean winter temperature ranges that run 0°F. to above freezing on the same day, accompanied by clear ice on pavements formed by ZR, and mists and paper-thin icy surfaces resulting from freezing fogs. Many of these last formations occur before daylight and are melted off before 10:00 a.m. when temperatures rise above freezing, but they do seriously affect early morning traffic schedules. Clear ice from freezing rain may remain from a day to more than one week and occasionally several weeks. It slows traffic speeds to about 25 miles per hour, but volume movements gradually increase as drivers gain confidence. Accidents after the first 24 hours seem to decrease.

"One problem yet unsolved is that of traffic blockades caused by improperly equipped trucks and passenger cars that are so frequently caught out on roads by the unexpected snows and ice formations. Two or three inches of rough ice or packed snow can stall heavily loaded trucks when wheels spin tractionless in depressions in the ice. Many of these carry no chains or abrasives. Saturated earth shoulders will not carry the weight of the traffic; consequently, as additional cars or trucks arrive, they too must stop and in turn become stalled when their warm tires melt depressions in the ice. Frequently, snowplows, trucks with load of abrasives and tow trucks are caught helplessly in long lines of stalled traffic, tempers get short and considerable time and police assistance is required to get the lines moving again."

Iowa (Root, 1953)

"We have no specific data on the effect of these storms on our transportation, except we do know some of our roads become temporarily blocked thus stopping transportation, and in other cases the going becomes so hazardous the amount of transportation is cut down."

Kansas (Siler, 1953)

"The traffic counts do show a material decrease in traffic during inclement weather, but the reports do not show in detail whether the weather conditions were snow storms, icing conditions, or other hazardous weather conditions. We do know, of course, that icing conditions reduce traffic but in this state these icing conditions are not usually of long duration. In many cases a severe icing condition may develop during the night and continue into the daylight hours but may clear up during the afternoon."

Kentucky (Crouse, 1953)

"Occasionally we do have ice storms and freezing rain, usually about the last of November and again near the first of March. Icy spells are of short duration and traffic is not tied up for more than a few hours, as we start applying salt or calcium chloride or cinders and sand as soon as these conditions arise."

Louisiana (Covert, 1953)

"Louisiana is very fortunate in that we very rarely have any serious icing conditions on the highways. . ."

Maine (Church, 1953)

"In general we are bothered a great deal during the winter months by this problem in all sections of the state, except in northern Aroostook county. In that area the storms are usually dry snow, and high winds clean the road surface before the snow packs and forms ice. In all other parts of the state we have severe ice conditions caused by sleet storms and packed snow. As a chemical we use rock salt applied either during the storm or directly after it. Numerous power graders are used to clear away the resulting slush. This generally is accomplished within a period of two to five hours."

Massachusetts (Gray, 1953)

> "Inasmuch as the policy of this Department (Department of Public Works), in its responsibility for the maintenance of the State Highway System, involves bare winter pavements as promptly as possible, icing does not constitute a major problem in the movement of highway transportation.
>
> "Our procedure involves the extensive use of chlorides both in abrasives and by means of straight applications at the beginning of storm conditions. This results generally in the maintenance of bare pavements shortly after the termination of the storm with rare exceptions.
>
> "When approximately two inches of snow have fallen and immediately prior to the start of plowing operations or at the beginning of sleet storms, a straight application of sodium chloride at an average rate of 800 pounds per mile is made by means of mechanical chloride spreaders. This creates, subject to existing temperature conditions, a film of chloride solution on the pavement surface which generally eliminates the accumulation of snow or ice packs. Our average storm temperatures in this state range from 25°F. to 32°F. thus making such a diluted chloride solution effective. It has been found that this procedure, supplemented with the application of abrasives on grades and at intersections during and immediately following storms, has largely eliminated interruption of the movement of highway transportation. We do, however, advocate the use of skid chains on all vehicles during storms."

Missouri (Acuff, 1953)

> "Missouri is located on the border between the ice and rain belts, with the result that winter conditions are extremely variable in both geographic and temperature sense. After snow or ice storms the temperature remains below freezing from a day to several weeks. Storms of long duration are the exception rather than the rule in a large part of the state.
>
> "Icing conditions certainly cause some delays in highway transportation. Complete traffic tie-ups due to severe storms are infrequent and are generally confined to rather small areas and for short periods of time.

Montana Bawden, 1953)

> "When we have ice storms and freezing rains which cover a

considerable area, we give first attention to sanding the hills and curves. It has been our experience that the ice formed on the road on these occasions generally breaks off and melts within a few hours. Occasionally, it may last for several days in which event we sand the tangents affected."

Nebraska (McMeekin, 1953)

"Ice storms and freezing rains are fairly common in Nebraska and the duration of ice on the highway usually does not exceed three or four days."

Nevada (Suverkrup, 1953)

"Nevada has had many miles of its highways ice up over night and within a few hours after the sun appears, the ice will be melted."

New Hampshire (L. F. Johnson, 1953)

"Previous to 1942 combating ice or snow residue on our highways was by the spreading of abrasives. The result was that for days after such storms traveling was hazardous and naturally reacted adversely on the economics of highway transportation. Starting in 1942, after some experimentation in previous years, a method of ice and packed snow prevention by the use of sodium chloride was put into practice. This has resulted in providing bare, dry pavements within a few hours after the cessation of a storm. Occasionally with plunging temperatures following a storm, conditions remain poor for a day or so, but, in general, clearing is reasonably rapid. This method of ice prevention keeps the snow in a mealy condition during the storm which not only allows complete removal by plowing but also provides for better traction for motor vehicles traveling at reasonable speed.

"Highway users, over the last decade through this method, have enjoyed continual use of the State Highways even during the height of storms. One adverse effect has resulted in that some motorists have come to expect safe driving at full speed at all times, forgetting the past, and are quick to blame the Department for accidents that are a result of excessive speed for existing conditions."

New Jersey (Muir, 1953)

"It has been found that ice forms on bridges and viaducts under certain atmospheric conditions when there is no formation of ice on pavements laid on the ground. Our experience, furthermore, indicates that roadways which are not shaded by heavy cut slopes, by the presence of woods or trees, etc., do not form ice as quickly, nor does the ice remain as long as is the case where there is a deep cut or shading of the pavement surface by woods and other closely spaced trees along the highway.

"It is our judgment that any icy condition on a highway is a definite hazard to traffic and interferes with normal highway traffic, in spite of the most complete application of materials for the removal of the ice or the skid-proofing of the surface. It is absolutely necessary, therefore, that, for safety, the speed of traffic be reduced to only a fraction of normal speeds. It is our considered opinion that neither special winter tires nor chains are very effective on hard, glassy ice."

New York (Ostrander 1953)

"Icy pavements can and frequently do stop all movement. The degree of trouble varies from a few minutes' interruption to perhaps one or more days. The danger of storm to traffic is great and is aggravated by the quickness of the development of icy conditions over wide areas. This, coupled with the lack of realization on the part of many drivers of the dangers inherent in winter driving results in many serious traffic accidents despite the very best efforts of patrol crews."

North Carolina (Burch, 1953)

"Of course, we are blessed in this State with having relatively little ice to contend with, as compared to the majority of the States in the Nation. Normally, we can expect perhaps one half dozen ice storms in our mountainous regions in the western 15 percent of the State. In the remaining 85 percent of the State, we rarely have more than one or two sleet storms during a winter, and these are usually of only one or two days' duration. There are many winters during which the entire coastal area of the State has no ice whatever.

"During ice storms, bridges and other structures supporting a highway represent the critical features in terms of transportation. A bridge deck or overpass floor is exposed to the cold air from the bottom as well as the top, and falling moisture will form an ice layer on the floor of such structures when there may be no ice formation on the highways themselves, where the pavement is in contact with the warmer sub-grade.

"Especially in the mountains, ice will form on the shaded north side of a cut much quicker, and will last much longer than when the highway is exposed to the sun either before, during, or after the fall of moisture.

"Unfortunately, a large per cent of drivers do not understand the inherent dangers outlined above; and, when sleet forms over a wide area, it is impossible for our forces to do protection work at all key points at the same time. Therefore, each sleet storm results in a number of accidents which could only be prevented by common sense operation on the part of motor vehicle drivers."

South Carolina (McMillan, 1953)

"The northwestern part of this state, reaching into mountains, has frequent ice conditions during the winter, but the southern tip, 212 miles farther south, has freezing conditions very rarely. Taking the state as a whole, it is reasonable to say that highway transportation is adversely affected by infrequent freezes and that the damage done is out of all proportion to the severity of the freeze because the drivers are not skilled in handling vehicles on glazed roads and do not usually carry proper equipment.

"It is often that bridges and overheads will freeze over while the adjacent road is in normal condition. This creates a hazardous trap for the unwary driver. We also have trouble from the melting and refreezing of snow."

South Dakota (Protheroe, 1953)

"This Department has not experienced much trouble with ice on gravel surfaces except where snow has become compacted as a result of thawing and freezing during fair weather conditions, and under traffic."

Texas (Greer, 1953)

"Most of the state is relatively free of this problem, with the Panhandle area the only one in which snow and icing are frequent, and the northern half of the State only subject to a few ice storms or freezing rains each year."

Vermont (Sargent, 1953)

"During the past ten years we have been using rock salt for the clearance of ice and thin layers of snow from our pavements. This has been so satisfactory that we very seldom have a lasting ice condition."

Virginia (Harris, 1953)

"In Virginia, icing conditions are rather infrequent and the average motorist and many truckers are not equipped to cope with such conditions; therefore, if and when ice forms on the pavement, traffic movement is seriously retarded."

West Virginia (Rothrock, 1953)

"Snow and ice on highways constitutes one of West Virginia's greatest, and, sometimes one of our most expensive problems. The first effect of an ice storm is to paralyze all motor vehicle movement.

"Our experience is that ice will first accumulate on bridge floors, because there is no heat stored under them. Beginning of icy conditions on bridges is generally the signal for the maintenance crews to prepare for action."

Wisconsin (Hughes, 1953)

"It has been observed that when icy conditions have arrived during the night, traffic may be reduced in volume temporarily for a few hours due to the deferment of trips in the day, since the motorist is by experience aware that sanding, etc. by our maintenance forces and the action of other traffic will improve conditions rapidly. It would be our opinion that it has been generally unnecessary for motorists to seek other means of transportation except possibly in cases of extreme emergency."

Wyoming (Sherard, 1953)

"We have very little icy conditions on our State highways in Wyoming. This is due to the fact that we seldom have rain at freezing temperatures, but rather have snow generally with accompanying winds which tend to keep the road surfaces clear. Other factors which minimize the hazards resulting from ice are the comparatively short duration of our storms and the high incidence of sunshine during the winter months. Even at freezing temperatures the reflection from the sun's rays during the daytime tends to soften the ice and it is splashed from the road surface by traffic."

APPENDIX B

Miscellaneous Tables

TABLE XII

FRONTS AND AIR MASSES ASSOCIATED WITH FREEZING RAIN, 1939-1948*
(at 12 U.S. stations)

Air Masses		Type of Front**	Source of Wave
Cold	Warm		
		Caribou, Me.	
cp,12; cp→mP,15; mP,2	mT,24; cP→mT,3	0,14; W,7; C,2; 0-C,1; W-0,1; W-C,1; N.F.,2	E.Can.,1; S.Atl.,1; E.Gulf,2; Tex.,6; Cent.,3; Colo.,3; N.Rocky,3: Alb.,3 N.Pac.,2; S.Pac.,2
		Providence, R.I.	
cP,12; cP→mP,14	MT,23; cP→mT,3	0,7; W,12; C,3; W-0,3	S.Atl.,3; E.Gulf,4; Tex.,5; Cent.,2; Colo.,3; N.Rocky,2; Alt.,1; N.Pac.,2
		Washington, D.C.	
cP,16	mT,15	0,3; W,11; W-0,1	S.Atl.,2; E.Gulf,4; Tex.,6; Colo.,2
		Atlanta, Ga.	
cP,11	mT,11	W,8; C,2; W-C,1	E.Gulf,2; Tex.,6; N.Pac.,1

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* Freezing rain data obtained from U.S. Weather Bureau.

** 0 - Occlusion
W - Warm
C - Cold
S - Stationary
0-C - Occlusion followed by Cold
N.F. - No front

TABLE XII (cont)

Air Masses Cold	 Warm	Type of Front	Source of Wave
		Cleveland, O.	
cP,28	mT,17; cP,1; cP→mT,2; Pac.mP,2	0,12; W,7; C,5; N.F.,1	S.Atl.,1; Tex.,9; Cent.,1; Colo.,4; N.Rocky,2; Alb.,4; N.Pac.,2
		Sault Ste. Marie, Mich.*	
cP,5	mT,2; Pac.mP,2; mT or cP,1	0,3; W,1; W and O aloft,1	Cent.,2; Alb.,2
		St. Cloud, Minn.*	
cP,6	mT,4; Pac.mP,1	W,4; S,1	Tex.,1; Cent.,1; N.Pac.2
		Milwaukee, Wis.*	
cP,11	mT,7; Pac.mP,3	0,6; W,4; N.F.,1	Tex.,2; Colo.,1; N.Rocky,1; Alb.,2; N.Pac.2
		Springfield, Ill.*	
cP,13	mT,9; cP→mT,2; mP or mT, 1	0,1; W,6; C,3; C-W,1; N.F.,1	E.Gulf,1; Tex.,3: Colo.1; Alb.,1; N.Pac.,3

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* Maps analyzed only for periods, Jan.-May, 1939, and Sept.-Dec., 1945
See Footnote at beginning of Table, for explanation of letters.

TABLE XII (cont)

Air Masses Cold	Air Masses Warm	Type of Front	Source of Wave
		Bismarck, N.D.	
cP,27	mP or Polar Basin, 18; mT,4	0,7; W,5; C,4; S,8; N.F.,3; C aloft,1	Tex.,1; Colo.,2; Alb.,3; N.Pac.,9
		Oklahoma City, Okla.	
cP,21	mT,15; mP,3; cP→mT,3	0.2; W,4; C,14; W aloft,1; S+W,2; C-W,1; S,1	Tex.,3; N.Rocky,1; N.Pac.,2
		Spokane, Wash.	
Polar Basin, 4; cP,3	mP,7	0,3; W,2; N.F.,2	N.Pac.,5

See footnote at beginning of this table for explanation of letters.

NOTE: AIR MASS CLASSIFICATION (Winter season)

cP	Continental polar: cold, dry air mass with source region in northern North America.
mP	Maritime polar: cool, moist air mass with source region in North Pacific or North Atlantic ocean.
mT	Maritime tropical: warm, moist air mass with source region in southern North Atlantic ocean or Gulf of Mexico.
cP mP	Continental polar partially modified in lower layers to maritime polar due to passage over ocean.
cP mT	Continental polar partially modified in lower layers to maritime tropical due to passage over ocean.
k,w	When added to above symbols indicate the air mass is colder (k) or warmer (w) than the surface over which it is passing.

TABLE XIII

FRONTS AND AIR MASSES ASSOCIATED WITH GLAZE FORMATION* IN UNITED STATES (1929-1937)

Station	Date	Radius of Ice**	Air Masses		Type of Front	Source of Wave or Front
			Cold	Warm		
Northeast						
New Haven, Conn.	12-13-29	.26	cP→mP	cP→mT	W	Colo.
" " "	1-12-30	.20	cP→mP	cP	W	S. Pacific
" " "	1-18-30	.20	cP→mP	mT	W	S. Atlantic
" " "	2-9-31	.12	cP→mP	mT	W	Colo.
" " "	12-12-32	.26	cP→mP	mT	O	E. Gulf
" " "	12-29-34	.09	cP→mP	mT	W	S. Atlantic
" " "	1-20-35	.26	cP→mP	mT	W	E. Gulf
W. Barrington, R.I.	1-10-32	.45	cP→mP	mT	O	Tex. Gulf
Chester, N.J.	12-13-29	T	cP→mP	mT	W	Colo.
" " "	12-24-29	.70	cP	mT	W or O	E. Gulf
" " "	2-26-3[illegible]	T	cP	mT	S (W)	Colo.
" " "	2-4-3[illegible]	.26	cP→mP	mT	W	N. Pacific
" " "	2-26-3[illegible]	.26	cP→mP or cP	mT	W or O	Colo.
" " "	3-19-33	.39	cP→mP	mT	W	Colo.
" " "	3-20-33	.39	cP→mP	mT	W	Colo.
" " "	1-5-34	.34	cP→mP	mT	W	S. Atlantic
" " "	1-18-36	.39	cP→mP	mT	W	Tex.
" " "	2-4-36	.33	cP→mP	mT	W	E. Gulf
" " "	2-14-36	.34	cP	mT	O	E. Gulf
" " "	1-7-37	.26	cP→mP	mT	W	S. Atlantic
" " "	1-24-37	.33	cP→mP	mT	W	Tex.
" " "	3-16-37	.51	cP→mP	mT	W	E. Gulf
Canton, N.Y.	12-13-29	.07	cP	mT	W	Central
" " "	12-20-29	.10	cP or cP→mP	mT	O	Tex.
" " "	1-14-30	.10	cP	mT	W	Central
" " "	3-17-30	.15	cP	mT	W	N. Rocky
" " "	3-25-30	.20	cP	cP or mT	W	Central

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* Based on ice thickness data obtained from Association of American Railroads (undated)

** On wire having .104-inch diameter.

T = trace

TABLE XIII (cont)

Station	Date	Radius of Ice	Air Masses Cold	Air Masses Warm	Type of Front	Source of Wave or Front
Canton, N.Y.	1-24-32	.15	cP	mT	O	Colo.
" " "	4-3-32	[illegible]	cP	mT	W or C	Colo.
" " "	3-8-33	.19	cP	mT	O	Colo.
Buffalo, N.Y.	12-8-29	.13	cP	cP	W	Colo.
East Ithaca, N.Y.	3-20-33	-	cP→mP	mT	W	N. Pacific
" " " "	3-18-36	.23	cP	mT	W	Tex.
Erie, Pa.	12-12-29	.08	cP	mT	W	Colo.
" "	1-9-30	.20	cP	mT	C	Colo.
" "	3-18-30	.10	cP	mT	W or O	Central
" "	3-25-30	.10	cP	mT	W	Central
Southeast						
Richmond, Va.	2-4-36	.23	cP→mT	mT	W	E. Gulf
Elkins, W. Va.	2-5-30	T	cP	mT	O	Tex.
Columbia, S.C.	12-17-30	.14	cP	mT	W	E. Gulf
" " "	12-17-32	.20	cP	mT	O	Tex. Gulf
" " "	12-29-35	.33	[illegible]	mT	W	S. Atlantic
" " "	2-7-36	.20	cP	mT	W	E. Gulf
Birmingham, Ala.	2-22-29	.07	cP	mT	W	Yucatan
" "	12-16-32	.20	cP	mT	W	Tex. Gulf
Great Lakes and Upper Mississippi Valley:						
Toledo, O.	1-8-30	.17	cP	mT	C	-
Escanaba, Mich.	2-25-30	.33	cP	mT	W	-
" "	3-4-35	.08	cP	cP	W	N. Pacific
Madison, Wis. (vic.)	12-28-34	T	cP	cP	W	Colo.
" " "	1-16-35	T	cP	mT	W	Colo.
" " "	3-16-35	.10	cP	mT	C	-
Milwaukee, Wis.	3-20-33	.20	cP	mT	O	Colo.
Peoria, Ill.	1-7-30	.08	cP	cP→mT	C	-
" "	2-8-35	.18	cP	mT	W	Tex.
Gurnee, Ill.	2-7-31	.17	cP	mT	W	Colo.
" "	3-2-32	.23	cP	mT	W	-
" "	3-20-33	.53	cP	mT	W	Colo.
" "	1-20-37	.04	cP	mT	W	-
Indianapolis, Ind.	3-7-31	-	cP	mT	O	Alberta
" "	1-9-37	.10	cP	mT	C	-
" "	1-22-37	.14	cP	mT	W	Tex.

TABLE XIII (cont)

Station	Date	Radius of Ice	Air Masses		Type of Front	Source of Wave or Front
			Cold	Warm		
Springfield, Ill.	2-4-32	.08	cP	mT	W	N. Pacific
" "	12-24-34	T	cP	mT	W	-
" "	1-18-36	T	cP	mT	W	Tex.
Davenport, Ia.	3-20-33	.20	cP	mT	W	Colo.
" "	1-7-37	.33	cP	mT	W	Tex.
Keokuk, Ia.	2-8-35	.20	cP	mT	W	Tex.
" "	1-7-37	.53	cP	mT	W	Tex.
Northern Great Plains:						
Sioux City, Ia.	11-23-31	-	cP	mT	W	Tex.
Pierre, S.D.	12-10-29	.17	cP	mP	S	-
Birdwood, Neb.	11-19-30	.20	cP	mT	W	S. Pacific
Southern Great Plains:						
Springfield, Mo.	2-26-34	.10	cP	mT	W	-
Dodge City, Kan.	1-30-37	.33	cP	mT	C(aloft)	-
Oklahoma City, Okla.	1-5-34	-	cP	mT	O	Tex.
" " "	1-20-35	.27	cP	mT	C	-
Pacific Northwest:						
Troutdale, Ore.	1-29-30	.05	-	mP	None	-
" "	12-30-32	.30	-	mP	W	N. of Hawaii at 35° Lat.

TABLE XIV

TOTAL NUMBER OF DAYS WITH FREEZING PRECIPITATION IN UNITED STATES (1939-1948)

(Data: U.S. Weather Bureau)

Station	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Caribou, Me.		2	17	18	16	15	8	6	2	84
Eastport, Me.			1	3	12	11	5			32
Portland, Me.			1	27	24	20	12	2		86
Concord, N.H.			2	24	29	23	16	1		95
Burlington, Vt.			3	20	14	12	12	3		64
Pittsfield, Mass.			5	26	32	26	22	4		115
Providence, R.I.			2	11	23	18	6			60
Trenton, N.J.				6	28	13	7			54
Rochester, N.Y.			1	22	23	17	12			75
Binghampton, N.Y.				19	19	5	9	1		53
Williamsport, Pa.[1]			2	23	18	14	7	1		65
Allentown, Pa.[2]			3	22	18	14	7	1		84
Harrisburg, Pa.			1	16	16	13	14			60
Washington, D.C.			1	16	17	5	9			48
Roanoke, Va.			1	23	24	11	12			71
Richmond, Va.				11	15	8	6			40
Petersburg, W. Va.[3]				13	7	7	2			29
Parkersburg, W. Va.			1	8	7	6	5			27
Raleigh, N.C.				10	17	11	2			40
Wilmington, N.C.				2	9	2				13
Asheville, N.C.				9	6	4	2			21
Augusta, Ga.				6	10	2	1			19
Atlanta, Ga.				11	11	4	1			27
Albany, Ga.[3]			(No freezing precipitation reported)							
Birmingham, Ala.				1	8	1	1			11
Nashville, Tenn.				3	6	2				11
Memphis, Tenn.				3	11	6	3			23
Lexington, Ky.				13	14	12	7			46
Youngstown, O.[3]			1	21	27	14	7	1		71
Cleveland, O.			2	24	31	34	12	1		104
Dayton, O.			3	21	35	28	10			97
Lansing, Mich.			3	24	42	34	22	2		127
Alpena, Mich.				7	3		4			14
Escanaba, Mich.				6	10	9	10	5		40
Sault Ste. Marie, Mich.			3	15	23	18	15	1		75
South Bend, Ind.			4	24	36	30	14			108
Terre Haute, Ind.				12	15	9	3			39
Evansville, Ind.				14	8	4	2			28

TABLE XIV (cont)

Station	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Springfield, Ill.			3	21	17	18	9			68
Milwaukee, Wis.			3	21	14	18	23			79
St. Cloud, Minn.		2	10	35	25	26	19	1		118
Rochester, Minn.[4]			12	23	14	10	8	2	1	70
Dubuque, Iowa			1	13	6	7	[illegible]			[illegible]
Des Moines, Iowa			9	35	20	15	12			91
Burlington, Iowa			4	25	[illegible]	[illegible]	14			81
Columbia, Mo.			3	24	15	17	10			69
Springfield, Mo.			8	32	19	23	17			99
Fort Smith, Ark.				5	3	6				14
Little Rock, Ark.				5	4	5	2			16
Texarkana, Ark.				5	15	8	1			29
Jackson, Miss.				2	15	1	3			21
Baton Rouge, La.[6]					8					8
Houston, Tex.				1	5	1	1			8
San Antonio, Tex.					8	3	1			12
Waco, Tex.				2	15	5	1			23
San Angelo, Tex.[7]				3	6	4	4			17
Wichita Falls, Tex.				8	10	7	4			29
Amarillo, Tex.		1	7	26	10	24	10	7		85
El Paso, Tex.					1					1
Oklahoma City, Okla.			[illegible]	[illegible]	16	24	8			74
Wichita, Kan.			6	[illegible]	[illegible]	23	12			[illegible]
Dodge City, Kan.			8	25	20	22	[illegible]	4		95
Goodland, Kan.[4]	2		8	14	5	16	20	5		70
Concordia, Kan.			1	9	9	3	7			29
Norfolk, Neb.[8]			2	10	3	6	6			27
North Platte, Neb.			6	17	21	13	[illegible]	2		84
Valentine, Neb.			5	1	3		5	1		15
Rapid City, S.D.		1	13	4	2	8	21	5		[illegible]
Huron, S.D.			11	12	10	[illegible]	9	2		54
Fargo, N.D.[2]		1	32	39	32	24	23	7	1	[illegible]
Devils Lake, N.D.		4	6	5	7	1	6	[illegible]		[illegible]
Bismarck, N.D.		1	19	21	19	12	12	5		[illegible]
Williston, N.D.		1	8	3	1	4	3			20
Havre, Mont.			1		1					2
Billings, Mont.		2	6	4	3	7	6	2		30
Missoula, Mont.		1	13	16	11	3	1			45
Lander, Wyo.[4]		1	1	1		1			1	5
Cheyenne, Wyo.	1	3	1	3	1	12	9	8	3	41
Grand Junction, Col.						2	2			4
Pueblo, Col.			[illegible]	3	4	11	2	2		[illegible]

TABLE XIV (cont.)

Station	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Albuquerque, N.M.							2			2
Roswell, N.M.				5	3	4				12
Boise, Idaho			2	5	8	1	1			17
Salt Lake City, Utah				2	1					3
Winslow, Ariz				2	1					3
Ely, Nev.			2	5	1					8
Spokane, Wash.			7	10	16	4				37
Stampede Pass, Wash.		2	14	16	11	9	6			58
Seattle, Wash				2	1					3
Troutdale, Ore.			2	2	2					6
Eugene, Ore.				3	15					18
Medford, Ore.				3	1					4
Red Bluff, Cal.			(No freezing precipitation reported)							
Blue Canyon, Cal.			1	7	5	1	2	1		17
Fresno, Cal.			(No freezing precipitation reported)							

Footnotes indicate all or parts of records missing for years listed below:

1) 1939, [illegible]
2) 1939
3) 1939-41
4) 1943
5) 1939-42
6) 1939, 1942-45
7) 1939, 1940, 1944
8) 1939-45
9) 1939-41, 1943, 1945

TABLE XV

MEAN DURATION OF GLAZE ON UTILITY WIRES IN U.S. (Hours)*

	October		November		December		January		February		March		April		Year	
	Cases	Mean	Cases	Mean	Cases	Mean	Cases	Mean	Cases	Mean	Cases	Mean	Cases	Mean	Cases	Mean
Alabama					2	36			1	6					3	26
Colorado	1	38					1	17	2	11	1	6	1	5	6	15
Connecticut					5	12	8	12	2	21	2	17			17	13
Georgia					3	54									3	54
Idaho					1	19	1	52	1	9					3	27
Illinois			2	11	6	49	10	29	8	34	8	31			34	33
Indiana			1	11	4	29	5	46	2	31	8	34			20	35
Iowa	1	14	2	112	6	45	10	33	1	21	4	29			24	41
Kansas			1	70	4	48	7	60	4	42					16	53
Kentucky					2	46	1	11			1	[illegible]			4	28
Maine							2	35							2	35
Massachusetts					9	20	9	18	3	15	2	40			23	20
Michigan			3	22	6	26	5	20	6	39	7	22			27	26
Minnesota			3	20	3	45	5	41	1	44	1	27			13	36
Missouri					2	38	6	20	4	41	2	40			14	32
Montana			1	17	1	23									2	20
Nebraska					1	11	1	15			1	17			3	14
New Jersey					5	21	3	9	6	23	4	22			18	20
New York			1	56	9	32	13	25	4	18	7	44	1	65	35	32
North Carolina			1	25	3	34	1	9	3	12					8	21
Ohio					3	31	6	35	1	36	7	34			17	34
Oklahoma							7	50	1	33	1	18			9	44
Oregon									1	14					1	14
Rhode Island					2	17									2	17
South Carolina			1	10	5	28	1	15	3	22					10	23
Tennessee					3	70	1	77	2	19					6	54
Vermont							1	24							1	24
Virginia					2	9	4	18							6	15
Texas			1	34	1	65	3	77	2	45					7	60
Washington					1	21									1	21
Wisconsin					6	42	8	27	2	34	7	20	2	16	25	28
Total	2	26	17	35	95	34	119	31	60	28	63	29	4	25	360	31

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* Data: Edison Electrical Institute, 1928-29 to 1936-37