ICE FORMATION IN THE ATMOSPHERE

by

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Any discussion of the problem of ice formation in the atmosphere should early treat of certain fundamental processes or phenomena inherent to the changes of state from water vapor to condensed water in droplet formations and, finally, to the various forms in the solid state--- clear ice, rime, and frost. These processes or phenomena are: (1), the condensation of water vapor in the atmosphere, (2), the existence of under-cooled water in the atmosphere, and (3), the processes involved in the freezing of under-cooled droplets. These will be discussed in the above order.

Section I

The Condensation of Water Vapor in the Atmosphere

The amount of aqueous vapor that can exist in a given volume of the atmosphere depends upon the temperature. Supersaturation may be produced under laboratory conditions but is not believed to occur in the free atmosphere. If a state of saturation is said to exist, a condition of equilibrium prevails, i. e. as many molecules of water are entering the free water surface, per unit time, as are escaping to the space above. These water molecules in the space above the water surface exert an independent pressure in accordance with Dalton's Law. This is called the vapor pressure and, since the number of molecules which contribute to this pressure is dependent upon the temperature, we may say that the saturation vapor pressure is also dependent upon the temperature. It is directly proportional to the temperature. If we start with a condition of saturation and lower the temperature, we produce one of two conditions. Either we bring about supersaturation or, if suitable nuclei are present, condensation of water vapor will take place thereon and small water droplets will be formed. The natural processes by which portions of the atmosphere are cooled sufficiently to bring about condensation are: (1), cooling by mixing or through contact with a surface which itself has lost heat by radiation or is otherwise cooled; (2), spontaneous cooling by radiation; and (3), dynamical cooling by expansion.

Cooling by mixing or through contact with a cooled surface produces advective sea and land fogs.

Spontaneous cooling by radiation produces the fogs which are common on clear cool nights when the wind movement is light. This form of cooling, in conjunction with advective effects, is also responsible for the stratus clouds so frequently formed at the base of subsidence or turbulence inversions. These clouds are common around the perifery of polar air masses and semi-permanent anticyclones.

Dynamical cooling by expansion is the most effective process of all. Such cooling may be due to the convective action resulting from the heating of surface layers, producing cumulus clouds; to the convective overturning or the forcing aloft of warm air at the forward portion of the cold front type of discontinuity, producing cumulo-nimbus clouds, or by the active upglide of warm moist air over the warm front or by the lifting of cold moist air under the warm front due to the convergence of stream lines along the warm front, producing nimbus, stratus, or alto-stratus clouds. The lifting of moist air in crossing mountain ranges is also important in this respect-- the cloud types produced depending upon the stability of the air.

The cooling of portions of the atmosphere, by whatever process, will yield condensation only provided nuclei in sufficient numbers are present. Many investigations have been conducted in efforts to determine the exact nature of such nuclei. Recent discoveries have been made in this connection which prompt a radical revision of our ideas regarding the nature of these nuclei. It had formerly been believed that minute dust particles and ions of dissociated hygroscopic gases constituted the nuclei about which condensation takes place. It is true that condensation will take place about dust particles, provided other more effective nuclei are not available. The well known Aitken's "dust counter" had, for years, been used to determine the number of nuclei available in different samples of air. It has developed, however, that the "dust particles" counted by this ingenious device are not dust at all but other more effective nuclei. Indeed it has been demonstrated that no increase in the number of nuclei was observed in a sample of air that had been deliberately made dusty. Thus it is now believed that the particles counted by the Aitken device are not dust at all, but other forms of nuclei. Hence it is quite probable that the ordinary dust particles play an unimportant rôle in condensation within the atmosphere.

It has been shown that a fourfold supersaturation is required before condensation will take place on negative ions, while a sixfold supersaturation is required for condensation about positive ions. This relative effectiveness of ions of opposite charge has been misunderstood by some, leading to an erroneous conclusion that negative ions could be regarded as nuclei of condensation for the atmosphere. But since there is no reason to believe that such a degree of supersaturation exists in the atmosphere, and which has never been recorded, it appears that such ions may be definitely eliminated from consideration here.

What, then, are the effective nuclei within the atmosphere? Hygroscopic nuclei from evaporating sea-spray are, without doubt, carried into the atmosphere by turbulent and convective action. Also, more strongly hygroscopic nuclei are derived from the combustion of sulphur which is present in large quantities in coal and coke. In this connection it is interesting to note that minute particles of sodium chloride have been shown to become deliquescent and form water droplets when exposed in air with a relative humidity as low as 75 per cent. Other more strongly hygroscopic nuclei may result in condensation at still lower values of humidity. Table No.1 shows several examples of cloud formations existing at low humidities, that at Oklahoma City on April 6, 1935 being the most notable and indicating alto-cumulus clouds of 500 meters thickness in which the humidity ranged from 51 per cent at the base to 54 per cent at the top. Such observations certainly suggest that the nuclei of condensation within the atmosphere consist of such hygroscopic material.

Köhler has conducted investigations concerning the nature of atmospheric nuclei wherein samples of cloud and cloud air have been analyzed. From such ahalyses he has not only provided interesting and valuable information about the size and number of nuclei of condensation, and the size and number of cloud droplets per unit volume, but he has rather definitely shown that the formation of cloud and fog droplets are dependent upon nuclei of sodium chloride, magnesium chloride, and calcium sulphate, and, therefore, derived from sea-spray. The acceptance of the proposition that nuclei of condensation do consist very largely of these materials, with their varying degrees of solubility in water, will contribute to an understanding of the capricious behavior of water in the liquid state at low temperatures.

Köhler's measurements of the size of cloud droplets show a range in the diameter from 0.011 mm to 0.0638 mm, the average being 0.0276 mm. Many thousand such droplets could exist per cubic centimeter, the number depending upon the density of the cloud. Köhler has found that the water content of cloud (excluding water vapor) ranges from 0.12 gram per cubic meter in the less dense clouds to 1.84 grams per cubic meter in the most dense clouds. Conrad and Wegener have found maximum values approaching 5 gram per cubic meter. However, their values are based upon the assumption of 100 per cent relative humidity in clouds and, in some cases, of conditions of supersaturation, whereas Köhler, in no case, found a relative hunidity in clouds as high as 100 per cent. His values varied from 92 per cent to 97 per cent, which are in close agreement with the values listed in table No. 1. The numerous cases shown in this table wherein relative humidity values are considerably below 100 per cent in clouds show that it is decidedly unsafe to assume complete saturation in all clouds.

Initially, cloud droplets formed on nuclei of the same kind are uniform in size, soon, however, due to different rates of condensation on the droplets in various portions of the cloud, a difference in size will result. Once this condition is established, it is interesting to note that, due to the larger vapor pressure about the smaller droplets of greater convexity, these droplets will evaporate and the water vapor therefrom condense on the larger droplets. Thus the larger droplets are continuously being formed at the expense of the smaller ones. Through such processes we may expect to find cloud droplets within the atmosphere through a wide range of sizes. Droplets less than 0.025 mm in diameter are generally classified as cloud or mist. Larger droplets, ranging in size up to 5 mm, are found in various classes of rain. The larger drops, requiring for their support forces operating against the acceleration of gravity, are associated with strong vertical motions and are, therefore, confined to regions where these currents are produced. The smaller droplets, on the other hand, are found in clouds or fogs which are produced primarily by radiational cooling and hence may be expected in regions not associated with strong vertical currents.

Section II

The Existence of Under-cooled Water in the Atmosphere

It has been a matter of common laboratory experience that water could be cooled far below its normal freezing point before solidification took place. Further, that as soon as the smallest particle of the substance in the more stable phase, (ice), is introduced, the under-cooled water is immediately transformed into it. The saturation vapor pressure over water in this under-cooled stage has a higher value than over ice at the same temperature.

Thus when there is contact between this metastable phase and the stable phase the vapor of the former will diffuse toward the latter and there sublimate. This process will continue until all the under-cooled water is converted to ice.

It is also well known that a slight agitation of under-cooled water will result in its almost immediate change to the solid state. Experimental researches have been conducted for the purpose of determining the tendency of under-cooled liquids to solidify by themselves, without the introduction of any crystallized particle. It has been found that microscopic crystalline nuclei make their appearance at different parts of the liquid and then grow until all the liquid has been solidified. It appears plausible that agitation, such as referred to above, might well assist in the arrangement of these crystalline nuclei, from which point the transformation is completed.

A very important consideration in connection with the existence of under-cooler water in the atmosphere is the fact that, since the salts of evaporating sea-spray constitute the principle nuclei of condensation, each cloud droplet is in fact a salt solution. It is also well known that when a foreign substance is dissolved in a liquid, the freezing point of the solution is lower than that of the pure solvent. The solution will begin to freeze at that temparature where the vapor pressure of the solution and that of the pure solid solvent are the same. That is, where the solution is in equilibrium with the solid solvent. Only at this point can the two phases co-exist. Figure No.1 will serve to illustrate this point.

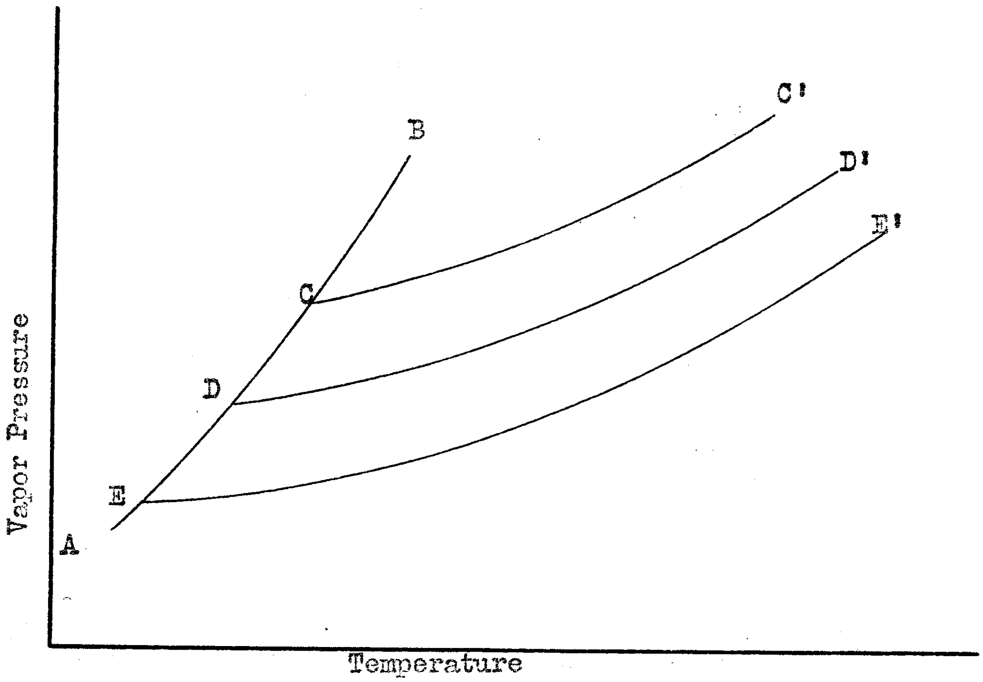

Figure No. 1

The curve A-B shows the variation of vapor pressure of the solid solvent with temperature, while the curves $C-C'$, $D-D'$, and $E-E'$ represent vapor pressure variations with temperature of solutions of three different concentrations. The temperatures shown by the points C, D, and E, where the vapor pressures of the solutions and the solid solvent coincide, are the freezing points for the three solutions. This phenomenon may be understood by considering that since the free surface of the solution must contain some molecules of the solute and therefore less molecules of the pure solvent, and since the vapor pressure of the solute is always less than the vapor pressure of the solvent, we may properly expect that as we add more of the solute, lower vapor pressures will be measured for the solution and hence the freezing point will be lowered.

If P is the vapor pressure of the pure solvent and P' that of the solution, then

$$\frac{P-P'}{P} = \frac{n}{N}$$

where n is the number of gram molecules of the solute in N gram molecules of the solvent.

It has been discovered that the depression of the freezing point of a given solvent is constant for the addition of one gram molecule of any solute to 100 grams of the solvent. For water, this value is 18.7 degrees Centigrade. This is designated by chemists as the molecular depression of the freezing point. Thus if the concentration of a given solution is that produced by the dissolving of one gram molecule of sodium chloride in 100 grams of water we would expect the solution to have its freezing point lowered 18.7 degrees C. This rule, however, holds only for dilute solutions and it is probable that the extreme undercooling of water is due in part to the presence of other substances in solution. Köhler has said: "The small amount of other salts than sodium chloride, for very concentrated solutions, plays a not unimportant rôle. The magnesium salts on account of their great hygroscopic characteristics and the calcium salts on account of their relatively small solubilities".

The solubility of sodium chloride in water is such that the freezing point may be depressed as much as 22 degrees C. Other salts would cause depressions of the freezing point of their solutions in accordance with their molecular weights, provided ionization did not take place in solution. Indeed this relationship is used to determine the molecular weights of solutes from the expression:

$$t = E \frac{m}{M},$$

where t is the depression of the freezing point, E the molecular depression, and m the number of grams solute of molecular weight M dissolved in 100 grams of the solvent.

It is interesting to note that the lowest temperature recorded in Table No.1, at which ice was reported, was -22 degrees C. Two observations of rime are shown in this table with temperatures as low as -26 and -28. In this connection it should be pointed out that, due to the difficulty of observing the formation of rime in small quantities, it may, at times, be confused with snow or ice crystals which already represent the crystalline state and do not show the existence of under-cooled water. L.T. Samuels, in his investigation of clear ice and rime deposits, found no temperatures lower than -23 degrees C. On the other hand many reliable observations have shown the existence of water in the liquid state at much lower temperatures. Köhler has reported cloud particles in liquid form at temperatures as low as -28. Wegener, in his Greenland travels of 1912-13, found water droplets at -34.5 degrees, and W.C.Haines has reported observing fogs at Little America at temperatures of -26, -30, and -44.

Several attempts have been made to explain the existence of under-cooled water in the atmosphere and some of these have attributed the phenomenon to the increased pressure resulting from the greater vapor pressure of very small droplets of great convexity. It would require a pressure of about 150 atmospheres to lower the freezing point as much as 1 degree. This feature of increased pressure is, therefore, of little importance in accounting for the very low temperatures that have been observed. If, however, we accept the demonstrated fact that salts of evaporated sea-spray constitute the principle nuclei of condensation, we can at least provide a partial explanation of the existence of under-cooled droplets in the atmosphere. Köhler, in his paper " Zur Kondensation Des Wasserdampfes in der Atmosphäre" says: "The introduction of salt particles here makes it very clear that fluid water can and must exist in the atmosphere at very low temperatures". The full explanation seems to rest with the fact that the under-cooled droplet is not only a solution with the freezing point depressed on account of the addition of some foreign matter to the solvent, but also to the fact that the initial alignment of molecular agregates, so necessary for solidification, is being delayed.

Section III

Processes Involved in the Freezing of Under-Cooled Water on Aircraft.

In the preceding sections of this paper it has been shown that fog and cloud particles, ranging in size from 0.011 mm to 0.0638 mm in diameter, and rain drops up to 5 mm in diameter, are formed principally about nuclei of evaporating sea-spray and therefore consisting of sodium chloride, magnesium chloride, and calcium sulphate; that the larger droplets are associated with strong vertical motions and are, therefore, confined to regions where these currents are produced; that the smaller droplets may be expected in regions where radiation is the cooling process leading to condensation, or in regions where there is an absence of strong vertical motion; finally, that the explanation of the existence of under-cooled droplets rests in the fact that these small globules of water are actually salt solutions of depressed freezing point wherein the alignment of molecular agregates has been retarded and which will be prompted to solidify by any form of agitation. It is now proposed to discuss the process of the freezing of such under-cooled droplets as they are encountered by aircraft in flight.

Pilots have reported three different kinds of ice deposits encountered in flight, viz., clear ice, rime, and frost.

Clear ice is smooth and glassy in appearance, although when mixed with sleet or snow, may assume a rough appearance. It is very tenacious and has a tendency to form in a mushroom shape with its frontal area enlarged. It forms near the leading edge of the airfoil or strut and, due to the irregular shape into which it builds, results in a loss in lift and an increase in drag. It is much the most dangerous type of icing.

Rime is pure white, opaque, and granular in structure. It consists of tiny ice pellets which have little cohesion or adhesion. Rime builds into sharp-nosed deposits on leading edges and does not alter the form of the airfoil materially. Further, due to its granular structure, it is constantly being lost through vibration. This form of icing is seldom dangerous.

Frost is a light crystalline formation which never developes in such quantity as to become of much importance. It is the least dangerous of the three forms.

In order to demonstrate just what processes develop during the icing of aircraft, let it be assumed that we have water in liquid form, either as cloud, or, perhaps, falling rain, at a temperature of -8 degrees C. which, from Table No. 1, will be seen to be within the average range of temperature for clear ice formation. Also, let it be assumed that the cloud particles encountered are of the average diameter of 0.03 mm. Each droplet then consists of 1.4×10^{-8} cc. As soon as the plane strikes such a droplet, there is provided the necessary agitation and freezing begins. But not all of the droplet will freeze at once. We know that to freeze 1 cc. of water we must remove 80 calories therefrom. We also know that at the instant the droplet begins to freeze the temperature of the mixture of ice and water will immediately rise to 0 degrees C. Actually the temperature of the droplet will rise only to the freezing point of the particular solution with which we are dealing, because that is the only temperature at which ice and our solution are in equilibrium. However, since we do not know the exact concentration of the solution let us, for simplicity, assume that the temperature rises to 0 degrees C. This rise in temperature to 0 degrees can only be accomplished as a result of heat being added, while at the same time heat is being taken away from a portion of the droplet in order to bring about the freezing. Assuming that no heat is provided from without, this added heat must be removed from that portion of the droplet which freezes. Thus the rise in temperature of the mixture from -8 degrees to 0 degrees will give us a measure of the number of calories required to produce this heating, and, thereby, the fraction of the droplet which is immediately frozen on impact. In this example, since it requires 1 calorie to raise the temperature of 1 cc. through 1 degree, it will require $1.4 \times 10^{-8} \times 8$ or 11.2×10^{-8} calories. And, since it requires the expenditure of 80 calories to freeze 1 cc., we have provided the cooling sufficient to freeze $\frac{11.2 \times 10^{-8}}{80}$ cc. which represents 10 per cent of the volume of our droplet. If we should assume the droplets to have a higher initial temperature, say -4 degrees C., we would find that only 4/80 or 5 percent of the water would be frozen on impact. On the other hand, if we should assume a cloud temperature of -20 degrees C., we would find that 25 per cent of each droplet would be frozen on impact. Thus we can say that the amount of water encountered by the plane in the form of cloud particles or rain drops, and which is immediately frozen, is directly proportional to the degree of undercooling of the droplets.

If it was only that portion of the droplet which freezes on impact that concerned us, and the remaining portion was permitted to run off as water, the icing of aircraft would not be of much importance. It is because a very large part of the remaining water freezes also that the icing conditions are considered such a hazard. It is through the operation of the process of evaporation that the remaining portions of each droplet are largely turned to ice.

Let us consider, again, our origihal droplet, 10 per cent of which has been changed into ice, while the remaining 90 per cent exists as water at a temperature of 0 degrees C. Over this water at 0 degrees C. we shall have a saturation vapor pressure of 6.11 millibars, whereas the surrounding cloud air will have a saturation vapor pressure corresponding to the temperature of -8 degrees, or only 3.12 millibars. Thus evaporation will take place from the water surface just as we observed in the section on condensation that the smaller cloud droplets with higher vapor pressure evaporated and condensed on the larger droplets of lower vapor pressure. To accomplish the evaporation of 1 cc. of water it requires the addition of 600 calories. For our particular average droplet it will require $1.4 \times 10^{-8} \times 600$ or 8.4×10^{-6} calories. To freeze the remaining 90 per cent of the original droplet we need to remove 90 per cent of this amount, or $1.4 \times 10^{-8} \times 80 \times .90$ which equals 1.008×10^{-6} calories. Hence we need only to evaporate $\frac{1.008 \times 10^{-6}}{8.4 \times 10^{-6}}$ or 12 per cent of the original droplet. Thus it is clear that the process of evaporation is of first importance in any consideration of icing conditions. Under the conditions chosen for our example roughly 88 percent of the water encountered by the plane would be frozen, nearly nine tenths of which is caused by evaporation. The size of the cloud droplet has no influence on the proportion of each that is frozen either on impact or through subsequent evaporation. A particular size of droplet was used in the computation only for the purpose of making the illustration specific.

Just as it was found that the portion of each droplet frozen on impact is directly proportional to the degree of under-cooling, so is it true that the rate of evaporation of the remaining liquid portion and the total amount to be frozen will be directly proportional to the degree of under-cooling. If we start with a temperature of -20 degrees C, 25 percent of each droplet will be frozen on impact. Only one tenth of the droplet need be evaporated to freeze the remaining portion and, due to the relative great difference between the saturation vapor pressure over water at 0 degrees C. (6.11 Mb.) and that of the cloud air at -20 degrees C. (1.04 mb), this evaporation will take place about 3 times as rapidly as in the case where we assume a cloud air temperature of -8 degrees.

It should be noted that in these examples we have assumed a relative humidity of 100 per cent in the cloud air. As has been mentioned above and as can be seen from Table No.1, clouds often occur with relative humidities considerably below 100 per cent. The values noted in the table for clear ice formations range from 51 per cent to 100 per cent, with the average being about 90 per cent. Under such conditions there would exist a still greater difference in vapor pressure between that for the water on the wing and that in the free air. Hence evaporation and the resultant freezing would take place more rapidly. This consideration would seem to suggest that icing would take place more readily while flying through portions of a cloud or fog wherein the relative humidity is lower. This also explains the observed rapid formation of ice as the plane emerges from a cloud into the comparatively clear air above or below.

In a few instances ice has been reported as occurring at temperatures above freezing. This does not occur often but it is theoretically possible. Two cases of this kind are listed in

Table No.1. The explanation of this phenomenon depends upon the assumption that the relative humidity within the cloud is less than 100 per cent. A temperature of 2 degrees is about the upper limit for ice formation. If we assume an air temperature of 2 degrees C. and a relative humidity of 100 per cent, the vapor pressure of any water striking the plane will be exactly the same as that of the cloud air. Hence there will be no evaporation and no freezing. If, however, we assume the same air temperature, but now a relative humidity of 90 per cent, we would have a difference in vapor pressure of 0.705 millibar. A certain amount of evaporation would take place and a very little freezing. The temperature of the ice and water on the wing would be reduced to 0 degrees. At this point the saturation vapor pressure of the ice and water mixture would be essentially the same as that of the cloud air. Hence no further evaporation would take place. Under such conditions, therefore, ice would form very slowly because of the small difference in vapor pressure and the deposits would be small.

The formation of ice at temperatures above 0 degrees C. is also, in part, caused by the evaporation brought about by the adiabatic cooling of air in passing over the vacuous space above the airfoil.

If we assume a cloud air temperature of 0 degrees C. we see that there is no expenditure or gain of heat in bringing the water and ice mixture to a temperature of 0 degrees. But here any evaporation which may be started by encountering cloud air of less than 100 per cent relative humidity will require the expenditure of the heat of evaporation. Since to freeze 1 cc. of water we need only remove 80 calories, only 80/600 or 13.3 per cent need be evaporated. Cloud air with a temperature of 0 degrees must, therefore, be considered dangerous along with that found at lower temperatures.

Section IV

Discussion of Observational Data

Table No.1 has been prepared from a study of teletype reports of upper air soundings made in the United States during the winter of 1934-35, and in which ice formations were reported. During the early part of this period reports from the eastern portion of the country were not available, but it is believed that the data are sufficient in volume to yield representative information.

One of the most convincing features of these data is the close conformity of the regions wherein ice was encountered to the region of cloudiness. This may be seen from the following extract of Table No.1

	Avg. elev. at which formation began (meters)	Avg. elev. at which formation ended (meters)	Avg. Thickness (meters)	Clouds		
				Avg. elev. of base (meters)	Avg. elev. of top (meters)	Avg. thickness (meters)
Clear ice	2890	3362	551	2824	3251	553
Rime	3205	3768	507	3128	3695	613

It has often been claimed that both clear ice and rime are formed, at times, above and below clouds. This, of course, may happen as is suggested by the explanation offered for the formation of ice at temperatures above 0 degrees C. That is to say, that under such conditions we must have first accumulated water on the aircraft and then encounter a zone wherein the relative humidity is less than 100 per cent. This latter condition can be realized by going above or below the cloud. But here, by going above the cloud, there would be no new supply of water to be encountered and only that small portion which had adhered to the plane would be frozen. Hence under these particular conditions the danger of icing would be very small but the formation would take place very rapidly. On the other hand one might argue that flying below a cloud and in rain would continuously provide a new supply of water spreading over the plane and thereby suggest that this might be a region of dangerous icing conditions. In the region of falling rain below a cloud the temperatures will usually be too high for ice to form and the relative humidity will also remain very high so that cooling by evaporation would be a very slow process. There is only one case listed in Table No.1 where ice was encountered below the base of the cloud, this being in the report for Cheyenne, Wyoming for April 8, 1935. There are only two cases where ice was reported in regions above the cloud. The small differences in the levels of ice formation and those of cloud forms, noted in the above extract of Table No. 1, are, in most every instance, due to ice being first noted within the cloud and not at the exact level of the base. Thus it appears that the hazard of ice formation may in most cases be avoided by avoiding flight through clouds.

It is the realm of low temperatures that water exhibits its most capricious behavior. Table No.1 shows that clear ice has been observed forming at temperatures ranging from 2 to -22 degrees C., while rime has been observed at temperatures from -2 to -28 degrees C. Thus it would seem that temperature alone is not a safe criterion upon which to judge the type of ice formation to be expected. Theoretically we would expect clear ice to be formed at higher temperatures than rime because, as explained in Section III, the smaller amount the temperature is depressed below 0 degrees C., the smaller will be the portion of each droplet frozen on impact. Hence a relatively large amount is left in liquid form to spread out in the familiar mushroom shape and freeze into clear ice by subsequent evaporation. In the case of a larger depression of the temperature of under-cooled droplets we have found that a very large portion of the droplet may be frozen directly on impact. And in the case of very small droplets the speed of crystallization may be so rapid as a result of the large amount of initial freezing and the relatively small amount remaining to be frozen through evaporation, which process will be aided by the large difference in vapor pressures at the lower temperatures, that there would be little or no spreading of water, but instead the almost immediate and complete freezing of the entire small droplet. Thus with lower temperature and smaller droplets we might expect rime to form whereas with higher temperatures and larger droplets we should expect clear ice to form. The average temperature of the base of clear ice formation, as taken from Table No.1, was -6.6 degrees C., while the average temperature of the base of rime formation was -11.1 degrees C. Figure No.2 shows the percentage frequency of occurrence of clear ice and rime formations at the various temperatures.

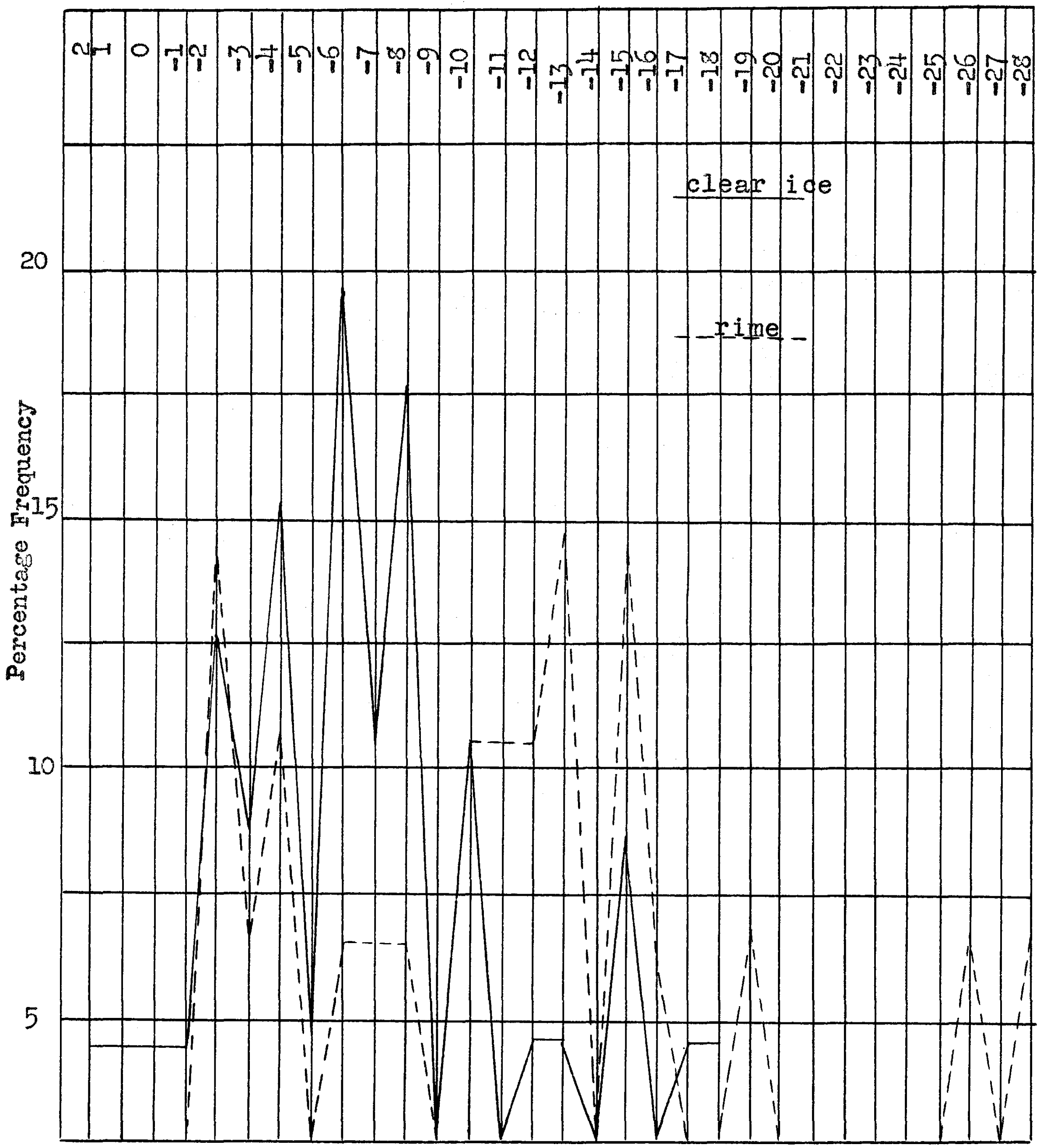

Fig. No. 2 Percentage frequencies for clear ice and rime formations at temperatures (degrees Centigrade) at which the formation began.

This shows clearly the prevalence of clear ice at the higher temperatures. Seventy-eight per cent of the clear ice observed occurred at temperatures of -8 degrees C., or higher, while only thirty-six per cent of the rime occurred in this temperature range.

No data are available showing the relative size of cloud droplets during ice deposits but it appears reasonable to assume that the smaller sized droplets are associated with rime deposits, while clear ice may be expected when larger droplets are encountered. In agreement with this we might expect rime to be encountered most often in the regions where convective action, sufficient to support the larger droplets, is absent, and clear ice to be found most often where relatively strong vertical currents, are encountered.

It is misleading to attempt to show any correlation between the existence of icing conditions and the various types of clouds. This results from the difficulty of definitely classifying the clouds under all conditions, as well as the fact that flights are seldom made through certain kinds of clouds. For example, any curve showing the percentage frequencies for both clear ice and rime formations in the various cloud forms will show pronounced high frequency for A.St. clouds and pronounced low frequency for Cu. clouds. The high frequency recorded for A.St. will undoubtedly be largely due to the fact that this type is a formless cloud which may often be reported when the observer has not been in position to observe the true form. The spreading top of the Cu.Nb.or the base of a wide-spread layer of thick A.Cu. clouds may often quite reasonably be mistaken for A.St. clouds. On the other hand, the very nature of Cu. clouds, being considerably separated one from another, makes it almost always possible for the pilot to avoid flying through such clouds. Hence we find very few reports of icing conditions in Cu. clouds. Providing temperatures are appropriate, there is no reason to say that any one type of cloud will yield icing conditions more often than another. We can only state that the type of ice encountered will be governed by the degree of turbulence or vertical motion associated with the cloud forms. Thus we should expect clear ice to be associated with those clouds wherein considerable vertical motion is encountered and rime to be found most often in clouds wherein there is the absence of any considerable vertical motion.

A large number of characteristic curves were plotted for soundings in which ice was reported. These curves were studied in connection with the synoptic weather maps which agreed in time nearest to that of the sounding. The following relations were discovered:

1. Clear ice occurs in unstable air or in a cloud which has been developed by instability just below the ice level and which has, through momentum, carried through a short distance into stable air.
2. Clear ice occurs where considerable turbulence prevails.
3. Rime occurs in stable air and where little or no turbulence prevails.

Figures Nos. 3 to 17 show the synoptic maps and the characteristic curves for a number of the observations listed in Table No.1.

Figure No. 3 shows a situation on November 25, 1934 where clear ice was reported at Spokane, Wash. The map shows Spokane to be in $_{4}Pp_{1}$ air a short distance behind a cold front type occlusion. While the upper wind data are not shown the pressure distribution indicates that fairly high upper winds from the W or WNW, with resulting turbulence, must have prevailed. Further, the lifting of this air, which has had a four day trajectory over a water area and is therefore very moist, as it passes over the occluded front and the mountain ranges may be expected to result in developing considerable instability. The characteristic curve shows both instability and turbulence. Clear ice was encountered in A.Cu. clouds in potentially unstable air between 2750 meters and 3000 meters.

Figure No.4, for November 29, 1934, shows much the same condition at Spokane as in the preceding case, except that a lesser degree of turbulence,due to smaller values of upper wind speeds, will prevail. Clear ice was reported in A.Cu. clouds between 2430 meters and 2800 meters. Here the characteristic curve shows the ice to have formed in air that is practically in equilibrium but which is immediately above an unstable stratum.

Rime was reported at Billings, Mont. on December 6, 1934. Both the synoptic map and the characteristic curve of Figure No.5 show this sounding to have been made in stable air throughout. Note that the winds at upper levels are nearly parallel to the mountains and therefore can not be expected to produce much turbulence. It should be noted also that the rime was reported in St. clouds between 1700 meters and 1900 meters. St. clouds are distinctly lacking in any vertical motion, which condition we have observed is favorable for the formation of rime.

Figure No. 6 shows the conditions prevailing when clear ice was observed in a sounding made at North Island, California on December 8, 1934. This is a case where ice was observed in a zone where stable conditions prevailed, but where unstable conditions are shown below. Extreme turbulence was reported between 2800 meters and 4200 meters. Ice was encountered between 3700 meters and 4200 meters.

Figure No. 7 shows the conditions prevailing when clear ice was observed at Spokane, Washington on December 13, 1934. Note that this ice was observed in stable air, but air which was well mixed through turbulence. This ice was reported in A.St. clouds between 2500 meters and 2820 meters.

Clear ice was reported in a sounding made at Spokane on December 25, 1934. Figure No. 8 shows that the ice formed in stable air which was immediately above a zone of potentially unstable air. Also the characteristic curve shows that considerable turbulence prevailed, as might be expected from the strong pressure gradient and the general orientation of the isobars.

Figure No. 9 shows the conditions for soundings made at Spokane, Washington and Murfreesboro, Tennessee on January 27, 1935. Clear ice was observed in over-running Rpp air at Spokane in a zone which was in equilibrium and above a turbulent stratum of 1380 meters thickness which latter was potentially unstable. Rain was observed falling during this sounding between 3700 meters and 5110 meters. Rime was observed at Murfreesboro in stable Pc air. It is interesting to nate that on this date clear ice formed at Spokane at a temperature of-10 degrees C. while rime formed in the stable air at Murfreesboro at a temperature of -8 degrees C. , thus showing that the degree of stability or instability of the air is a better criterion of the type of ice to be expected than is the temperature alone.

Figure No. 10 shows another condition for clear ice formation at Spokane on February 21, 1935. The characteristic curve shows the ice forming in absolutely unstable air which appeared well mixed by turbulence.

Rime was reported in the sounding made at Selfridge Field, Michigan on February 28, 1935. Figure No.11 shows this formation to have occurred in stable Pc air.

Figure No. 12 shows the condition prevailing when ice was encountered on March 17, 1935 at Spokane, Fargo and Selfridge Field. Clear ice was found in unstable air at Spokane, while rime was observed at Fargo and at Selfridge Field in stable Pc air.

Figure No. 13 shows the conditions on March 19, 1935 when clear ice was reported at Spokane, North Island and Murfreesboro. The characteristic curve for the Spokane sounding shows clear ice forming in an unstable zone. In this case the cloud type noted was St.Cu. which had formed below a subsidence inversion and had carried through the base of the inversion for 100 meters, thus accounting for the ice observed in the stable stratum just above the inversion. Rime was observed at North Island in stable air. Clear ice was observed at

Murfrees boro in a thick stratum of unstable over-running Tg air.

Figure No. 14 shows the condition at Oklahoma City on March 21, 1935 when clear ice was reported. The characteristice curve shows the ice to have formed in a stable stratum but that this air was immediately above a deep zone of very unstable Tg air. Clouds were encountered during this sounding at 3360 meters and the plane was still within the cloud at 5020 meters wheh the descent was started. Clouds of such thickness show clearly evidence of considerable vertical motion.

Figure No. 15 shows the condition for clear ice formation at Cheyenne on April 1, 1935. The characteristic curve shows the ice forming in an unstable stratum.

Figure No. 16 shows the condition for clear ice formation at Murfreesboro on April 11, 1935. The characteristic curve shows clearly that the formation occurred in very unstable Tg air. Turbulence was reported between 1350 meters and 4670 meters. Ice was encountered at 3450 meters.

Figure No. 17 shows the conditions prevailing at Murfreesboro on April 12, 1935. In this case we observe that stable P_{c8} air now occupies this area and rime, as is to be expected, is the type of icing observed.

In summary the following may be said:

1. Icing conditions may be expected in any form of cloud wherein the temperature is 2 degrees C. or below.

2. The danger of icing conditions in regions above or below cloud forms is not great.

3. a. Clear ice will predominate at temperatures of

-8 degrees C. or above.

b. Clear ice may be expected in clouds, with appropriate temperatures, where we have vertical currents strong enough to support the larger cloud droplets. These conditions may be expected where we have:

(1) Convective action resulting from the heat- of surface layers.

(2) Convective overturning or the forcing aloft of warm air at the forward portion of the cold front.

(3) Active upglide of warm moist air over a warm front.

(4) The lifting of cold moist air under the warm front due to the convergence of stream lines along the warm front.

(5) The lifting of unstable air over mountain ranges.

(6) All of these conditions will be shown on the θ_E diagram as being within a layer of unstable air or, if in a stable layer, this latter will be immediately above an unstable zone.

5. a Rime will predominate at temperatures below -8 degrees C.

b Rime may be expected in clouds, with appropriate temperatures, wherein vertical currents are not strong enough to support the larger droplets.

c The θ_E diagrams will indicate stable conditions within the zone of rime formation.

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TABLE NO. 1

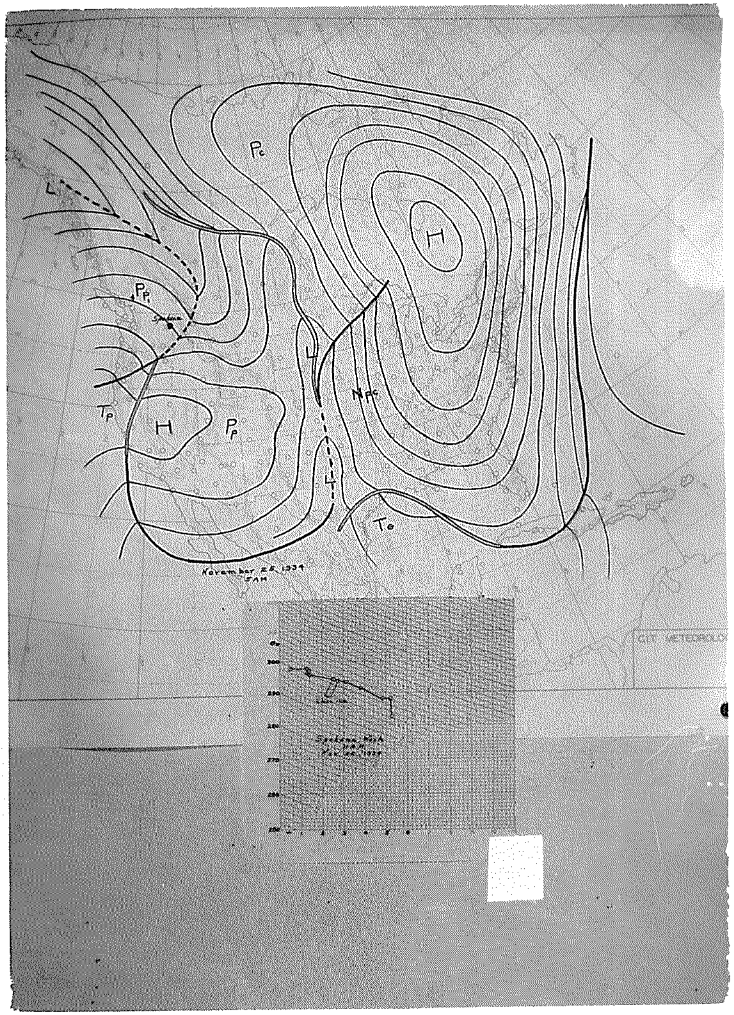
Date	Place	Type of Air	Ice Level Base	Ice Level Top	Clouds Kind	Clouds Base	Clouds Top	Temperature Base	Temperature Top	Relative Humidity Base	Relative Humidity Top
					C l e a r I c e						
11-25-34	Spokane	4 Pp1	2750	3000	A.Cu.	2750	3000	-6	-8	79	94
11-29-34	Spokane	3 Pp1	2430	2800	A.Cu.	2430	2800	-6	-9	86	91
12- 8-34	North Island	Pc	3700	4200	A.St.	3290	----	0	-3	--	--
12-13-34	Spokane	RPp	2500	2820	A.St.	2500	2820	-7	-9	94	97
12-16-34	Omaha	Pp	880	1140	St.Cu.	880	1140	-2	-4	90	96
12-25-34	Spokane	Pc	2110	2300	St.Cu.	2110	2300	-8	-9	86	88
1-19-35	Omaha	Pc&RPp	1040	1740	St.Cu.	1040	1740	-12	-4	89	100
1-23-35	Billings	RPc	3280	----	A.St.	3280	----	-7	--	80	--
1-27-35	Spokane	RPp	4300	----	A.St.	4300	----	-10	-16	89	88
2- 7-35	Fargo	RPc	1000	1560	St.	1000	1560	-8	-11	90	94
2-18-35	Spokane	Pb	4370	----	A.Cu.	4370	----	-16	-16	--	81
2-21-35	Spokane	4 Pp1	2420	2540	A.Cu.	2420	2540	-6	-7	89	76
3- 2-35	Fargo	Pc1	740	930	St.	520	930	-6	-6	94	88
3- 4-35	Fargo	Pc4	3550	3700	A.St.	3360	3700	-3	-4	99	98
3- 4-35	Spokane	1 Pp1	3550	3930	A.Cu.	3550	3930	-19	-22	89	90
3- 4-35	Oklahoma City	Tg	3720	----	A.St.	3720	----	-6	--	--	--
3- 5-35	Maxwell Field	Tg	4120	4280	A.St.	2940	4280	-4	-6	96	80
3- 9-35	Maxwell Field	2RPp4	3530	----	A.St.	3020	----	-2	--	100	--
3-10-35	Spokane	2Pp1	4780	4860	A.Cu.	4780	4860	-18	-19	94	96
3-12-35	Spokane	2RPp1	3500	----	A.St.	3500	----	-8	-12	85	--
3-13-35	Billings	4RPp3	3480	4940	A.St.	3480	4940	-4	-10	94	--
3-17-35	Spokane	2Pp1	2460	3220	Cu.	2460	3220	-8	-14	--	76
3-19-35	Norfolk	2Pc1	Ice formed above cloud		St.Cu.	860	2380	--	--	--	--
3-19-35	Selfridge Fld.	Tg	2870	----	A.St.	2870	----	-4	--	99	--
3-19-35	Murfreesboro	Tg	2980	3870	A.Cu.	----	----	1	-6	100	100
3-19-35	Spokane	Pp	1320	1880	St.Cu.	1320	1880	-4	-7	92	100
3-20-35	Spokane	2Pp1	1580	----	St.Cu.	1580	1730	-8	--	92	--
3-21-35	Oklahoma City	Tg	3400	----	A.St.	3360	----	-2	--	64	--

TABLE NO.1(continued)

Date	Place	Type of Air	Ice Level Base	Ice Level Top	Clouds Kind	Clouds Base	Clouds Top	Temperature Base	Temperature Top	Relative Humidity Base	Relative Humidity Top
					C l e a r I c e						
3-22-35	Murfreesboro	Tg	5050	----	A.St.	4770	----	-10	-11	98	98
3-23-35	Spokane	Pp	1990	2440	St.Cu.	1990	2440	-6	-9	85	96
3-28-35	Spokane	RPp	2670	2990	A.St.	2670	2990	-5	-8	--	100
3-31-35	Mitchel Field	1Ta	3230	3950	A.Cu.	3230	3950	-4	-8	86	95
3-31-35	Selfridge Fld.	2RPc2	2260	2670	St.Cu.	2260	2670	-2	-2	--	100
4- 1-35	Mitchel Field	Ta	3820	----	A.St.	3700	----	-6	--	98	---
4- 1-35	Cheyenne	3Pp3	3240	4860	St.Cu.	3240	4860	-7	-20	78	86
4- 3-35	Washington	Ta	2680	----	A.St.	1760	----	--	--	--	--
4- 5-35	Fargo	Pc	1970	2140	St.	1840	2140	-13	-14	87	80
4- 6-35	Fargo	Pcl	2220	2450	St.	1890	----	-10	-12	97	97
4- 8-35	Cheyenne	9Pp4	3290	----	A.St.	4610	----	-3	-17	51	86
			(sleet and snow 3290 m to 5310m)								
4-11-35	Murfreesboro	Tg	3450	4230	St.Cu.	1350	3840	-1	-6	72	52
4-12-35	Spokane	2Pp1	3760	3950	A.Cu.	3760	3950	-8	-10	85	87
					R i m e						
11-26-34	Spokane	4Pp1	3470	3560	A.Cu.	3470	3560	-15	-16	93	96
12- 6-34	Billings	Pc4	1700	1900	St.	1700	1900	-2	-3	--	98
1-16-35	Oklahoma City	Tg	4940	----	A.St.	4920	----	-10	--	--	--
1-27-35	Murfreesboro	Pc3	1730	2040	St.Cu.	1850	2040	-8	-8	98	100
1-31-35	Selfridge Fld.	Pp	2770	3190	A.St.	2770	3190	-12	-15	--	99
2-28-35	Selfridge Fld.	Pc	1760	2260	St.Cu.	1760	2260	-15	-16	94	92
3- 3-35	Spokane	1Pp	4130	4640	A.Cu.	4130	4640	-12	-16	72	51
3- 3-35	Cheyenne	1RPp3	2250	2460	St.	2250	2460	-2	-3	94	93
3- 4-35	Spokane	2Pp1	4860	----	A.St.	4860	----	-28	--	76	--
3- 6-35	Omaha	Tg	2520	3070	St.Cu.	2520	3070	-4	-8	88	96
3-11-35	Billings	2Pp2	4000	4240	A.St.	4000	4240	-13	-15	--	98
3-16-35	Cheyenne	1Pp2	5120	----	A.St.	5120	----	-26	--	79	--
3-17-35	Fargo	RPc	1490	1610	St.Cu.	1350	1950	-10	-10	88	90
3-17-35	Selfridge Fld.	Pc2	710	1220	St.Cu.	710	1220	-4	-7	94	100

TABLE NO.1(continued)

		Type of	Ice Level			Clouds		Tempera-ture		Relative Humidity	
Date	Place	Air	Base	Top	Kind	Base	Top	Base	Top	Base	Top
					Rime						
3-19-35	Omaha	Pc	4700	----	A.St.	4700	----	-15	-18	60	88
3-19-35	North Island	Pp	3970	----	A.Cu.	3910	----	-13	--	--	--
3-21-35	Sunnyvale	Pp	2320	2440	Cu.(side of cloud)			-11	-13	83	90
3-21-35	Spokane	Pp	3200	3250	St.Cu.	3200	----	-19	-20	--	75
3-27-35	Omaha	Pc2	2900	4020	St.Cu.	2900	----	-7	-10	94	95
3-31-35	Cheyenne	Pp	4090	----	A.St.	4090	----	-13	--	80	--
4- 5-25	Selfridge Fld.	Tg2	3420	3600	A.St.	3340	3600	--	-9	--	100
4- 6-35	Murfreesboro	Tg	4730	----	St.	2990	----	-11	--	96	--
4- 6-35	Oklahoma City	Pp	4950	----	A.Cu.	4950	----	-16	-20	51	54
4- 7-35	Omaha	Pc3	1520	4790	St.	620	4790	-2	-19	98	82
4-12-35	Murfreesboro	Pc8	2420	2690	A.St.	2420	2690	-6	-6	100	86



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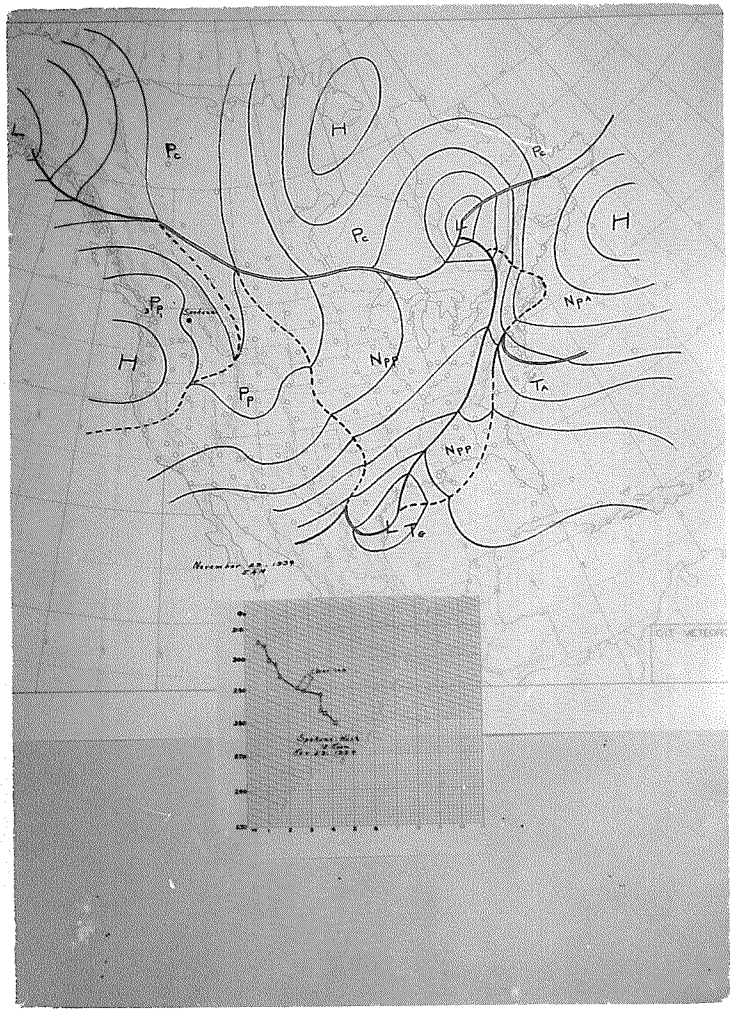

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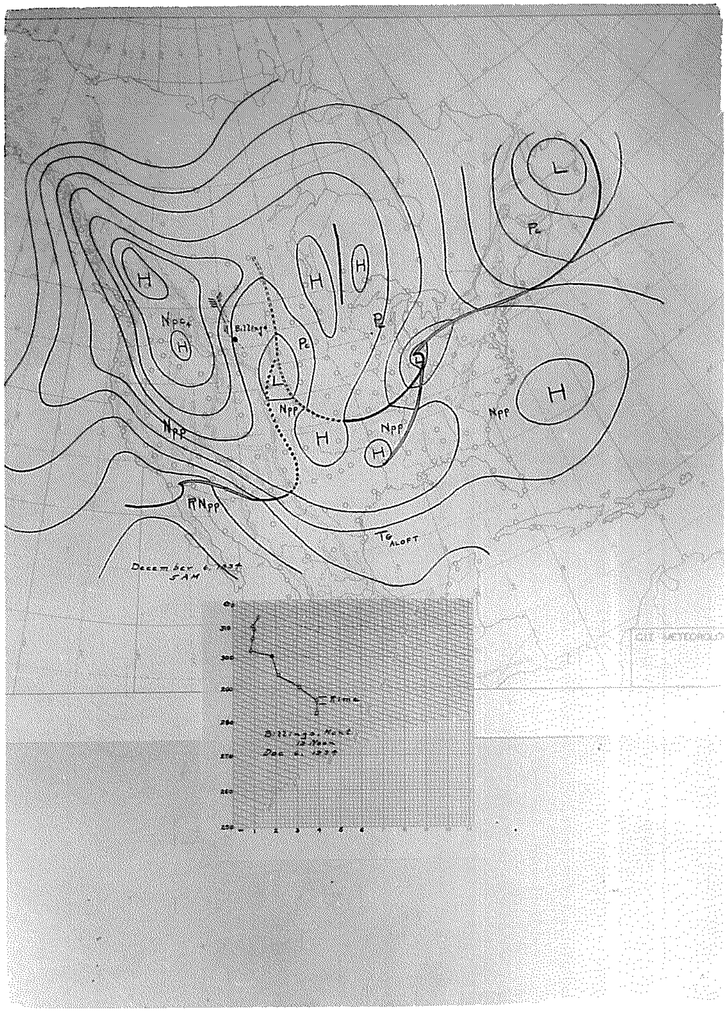

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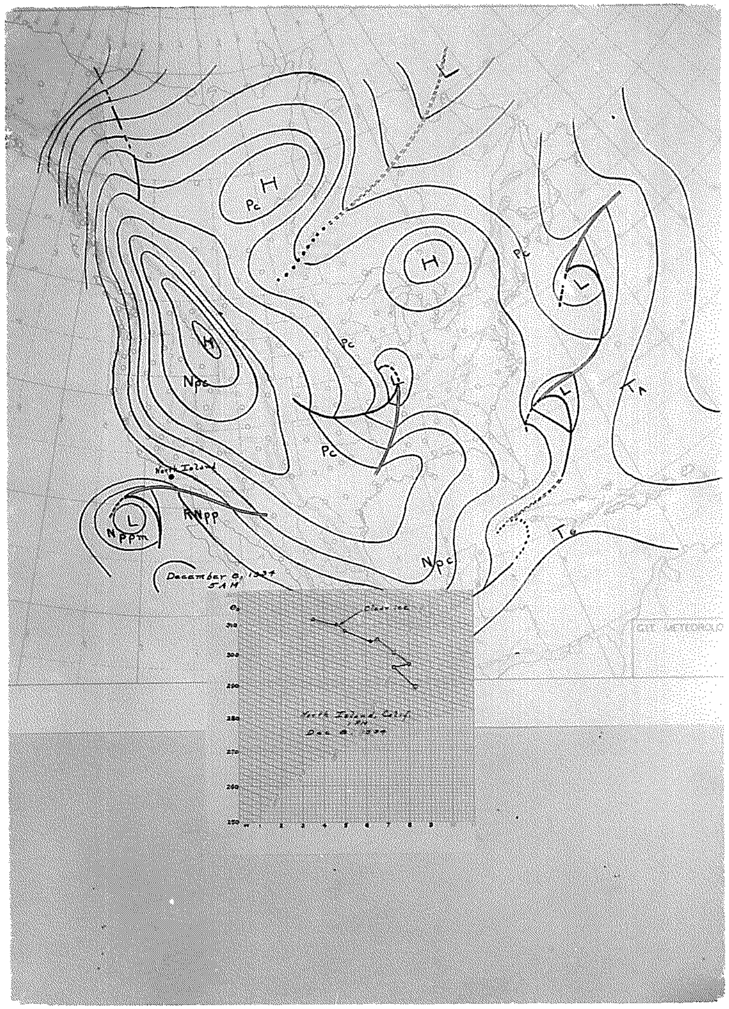

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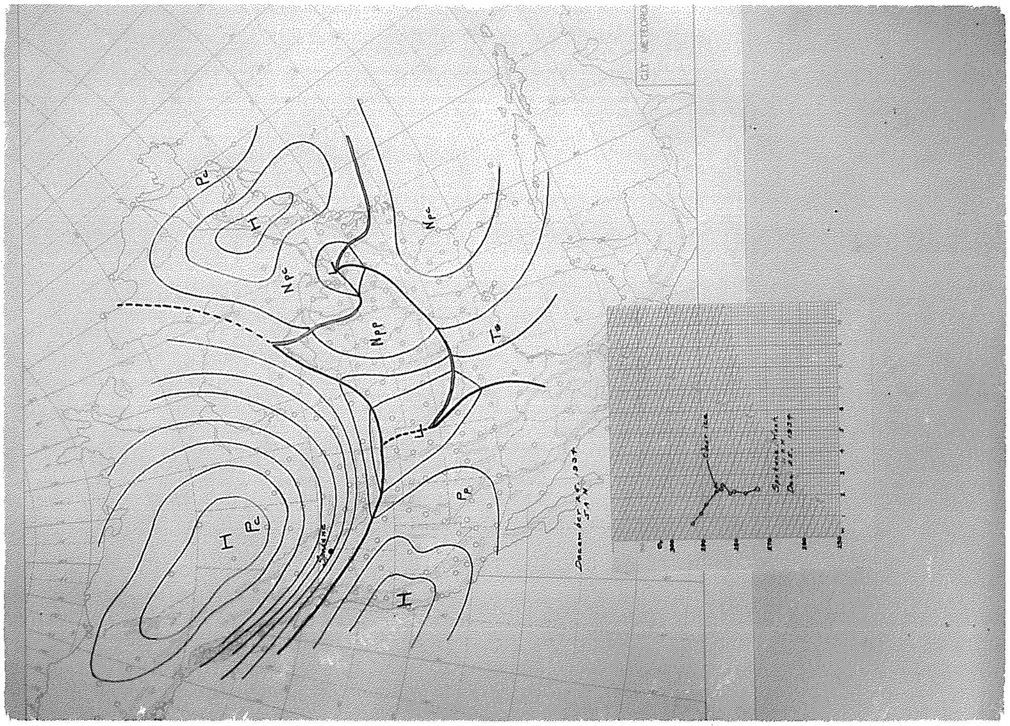

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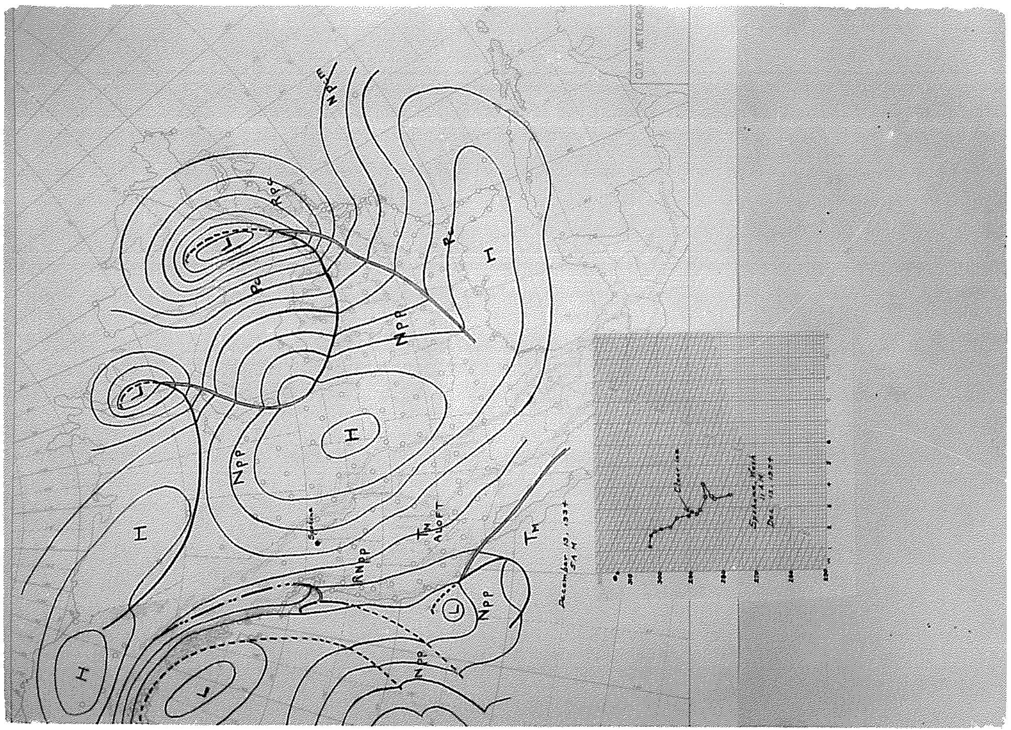

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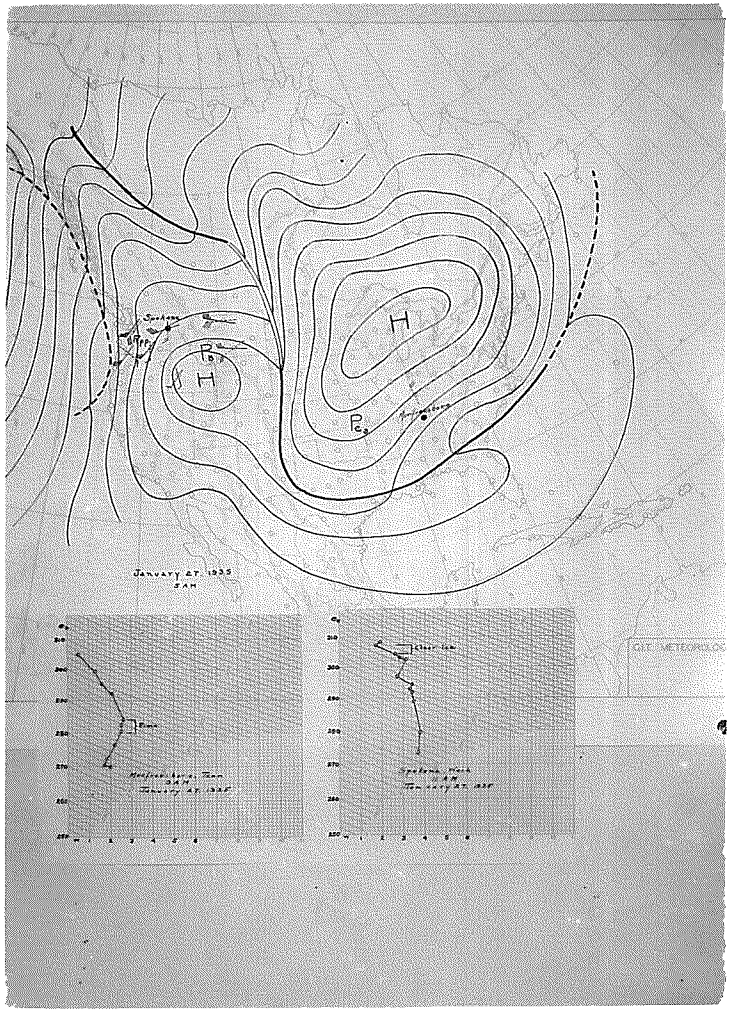

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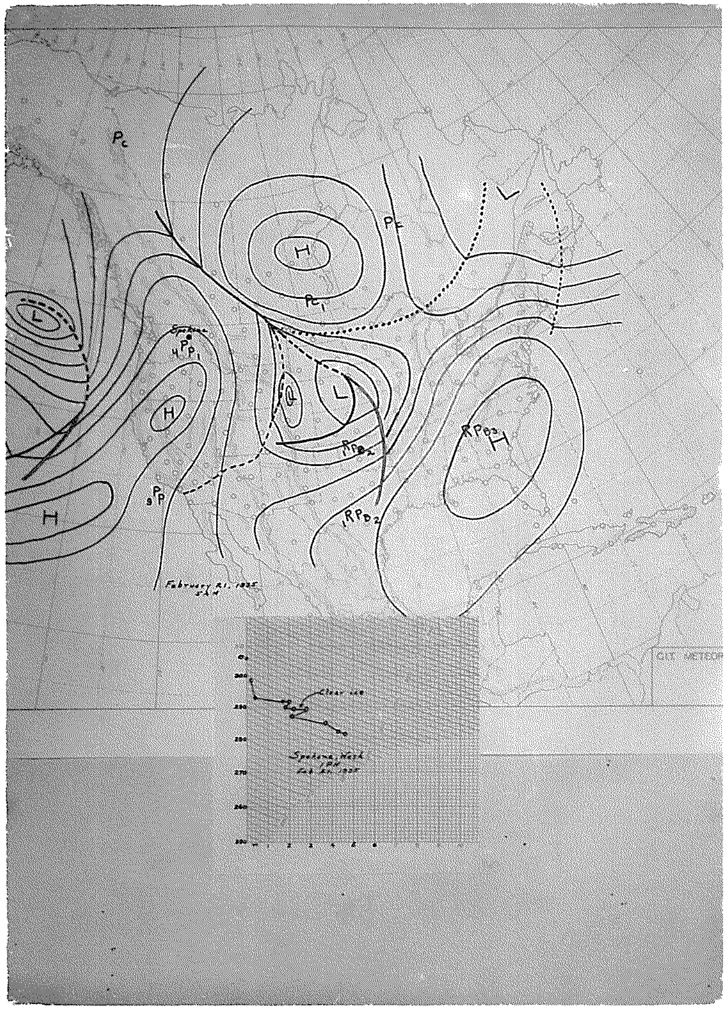

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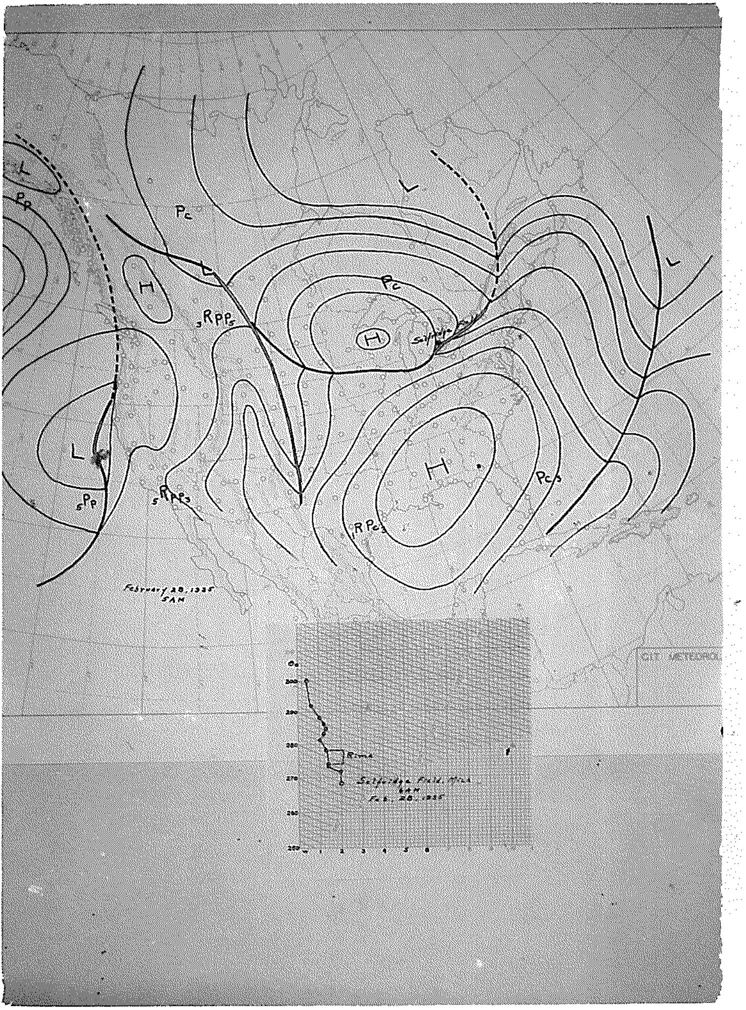

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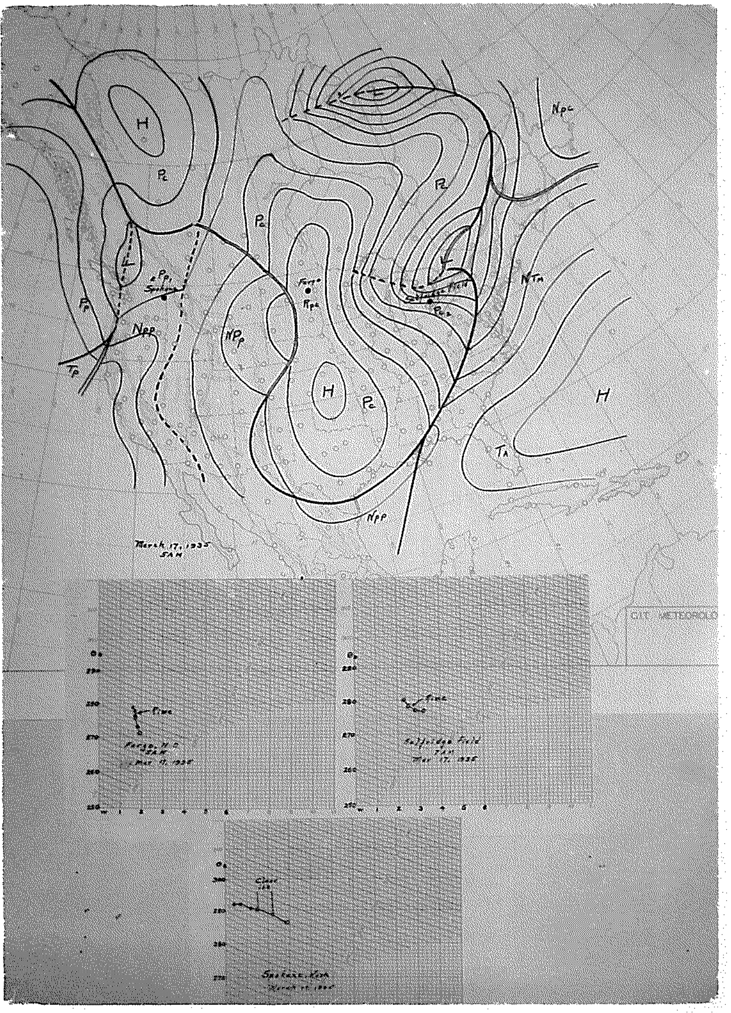

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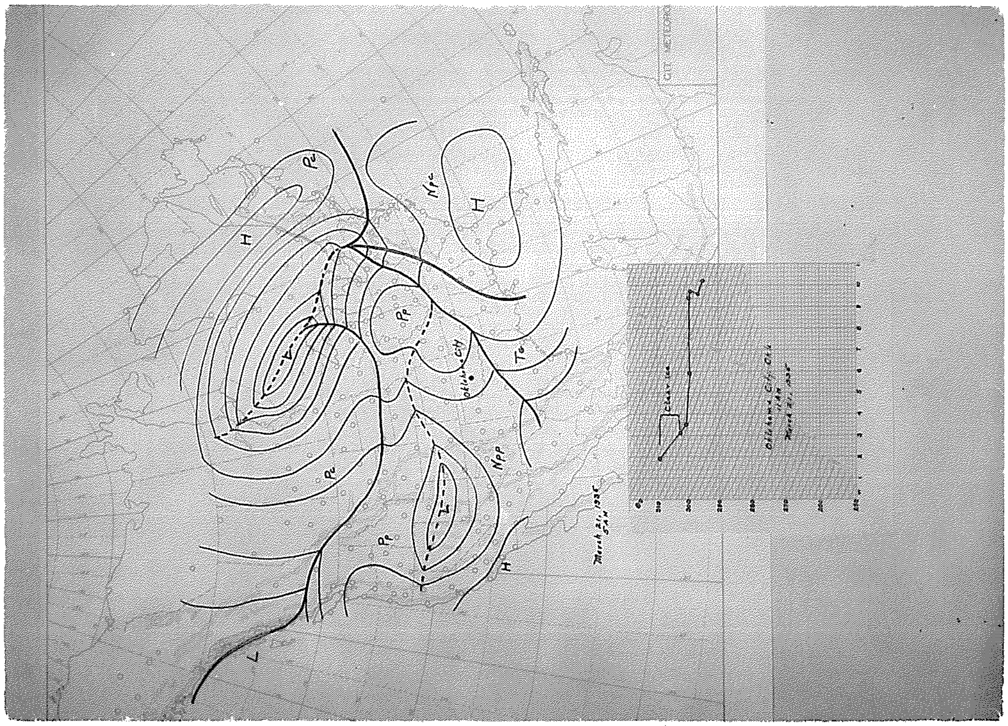

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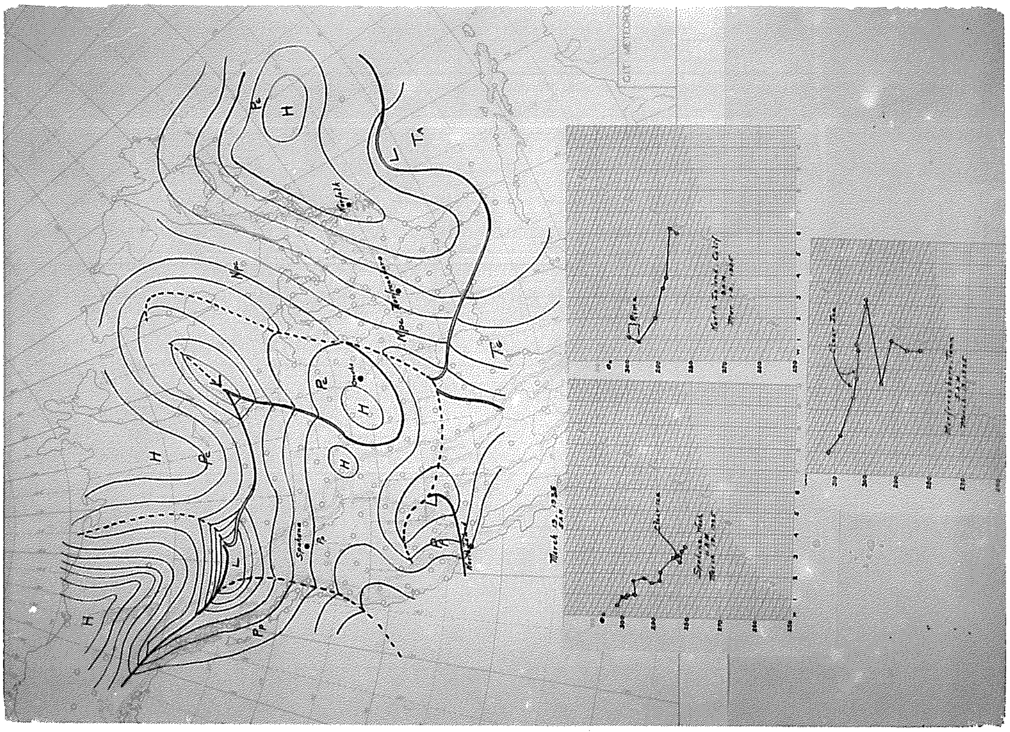

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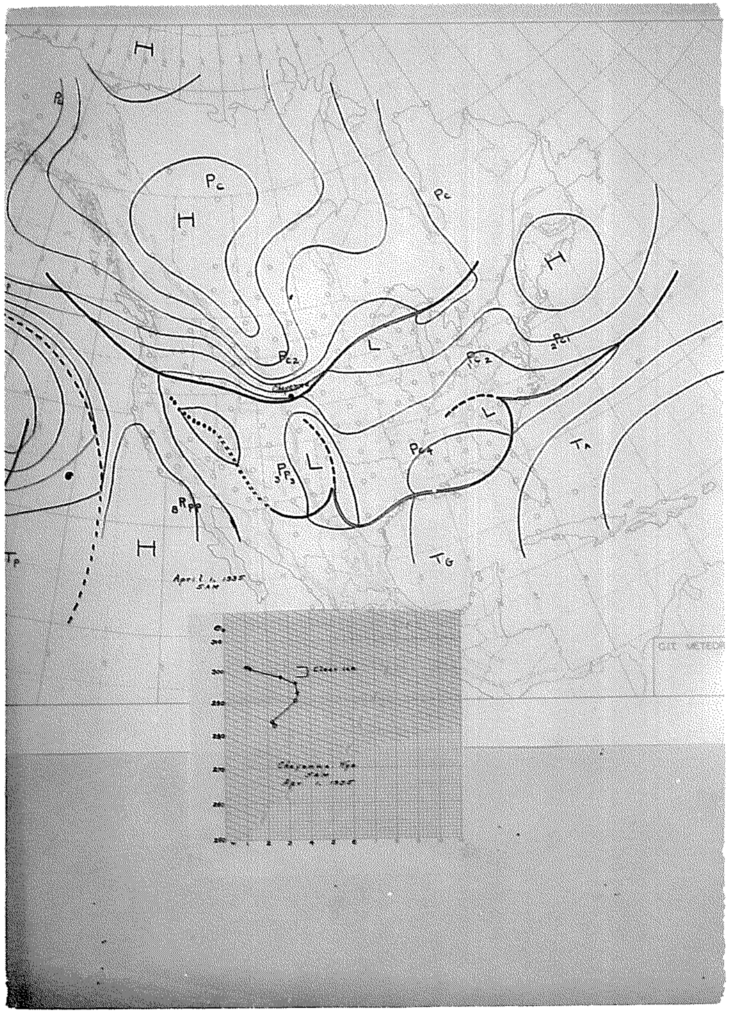

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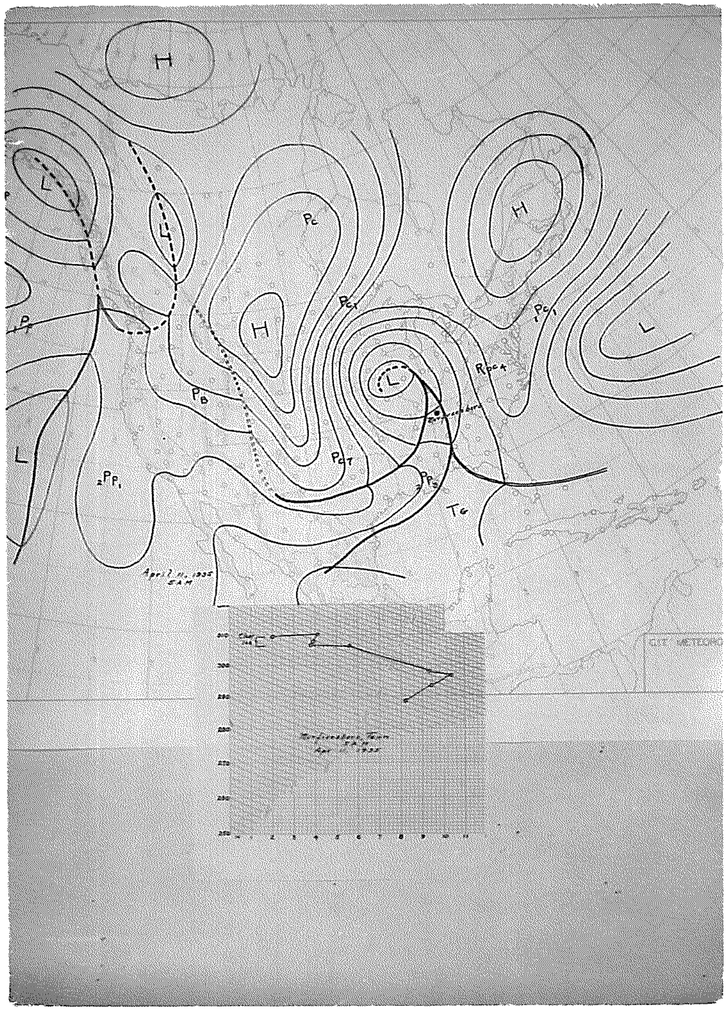

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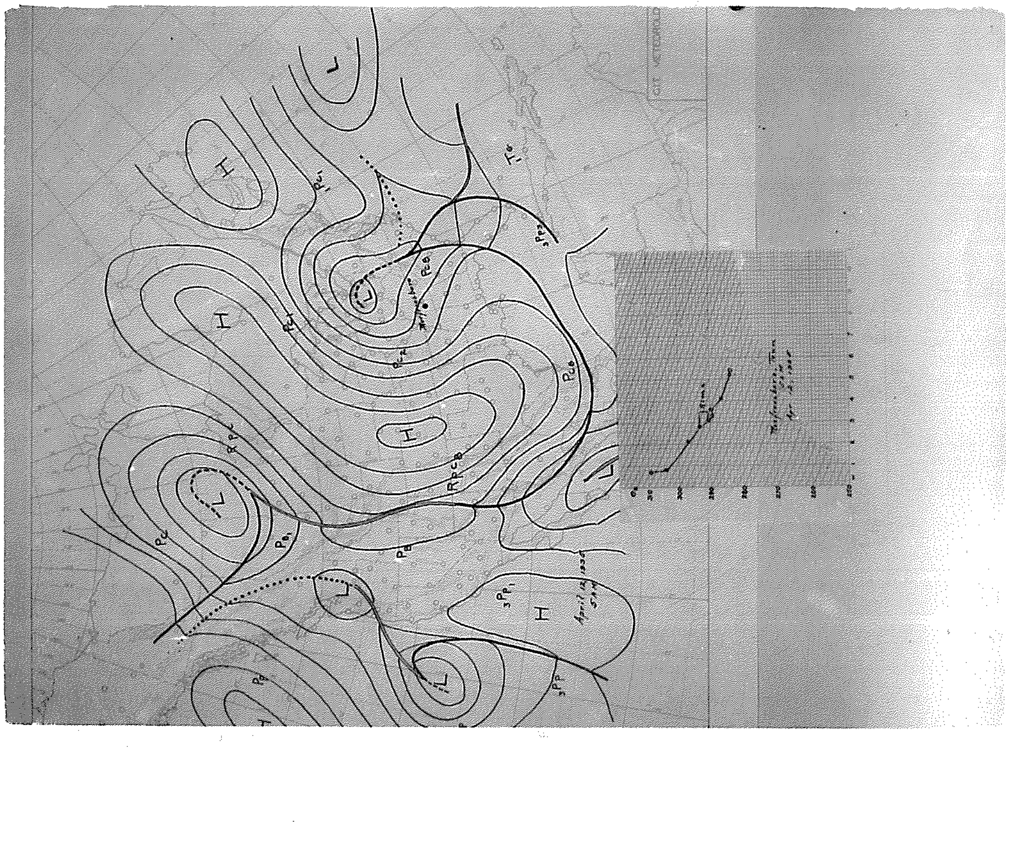

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