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# SYNOPTIC STUDIES IN FOG

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THIS STUDY of fog formations at Hadley Airport was carried out during the winter of 1928–29 with the intent of finding out how far a careful scrutiny of local records might assist in explaining and forecasting local fogs. It was meant to be supplementary to a more general discussion of fog and haze formation which had appeared previously in the *Monthly Weather Review* for November, 1928. This study is based on the general fog classification set forth there. The United States Weather Bureau working charts were consulted in connection with each local fog formation appearing on the Hadley records over a period of two and a half years.

Hadley Airport is situated between New York and Philadelphia, about thirty miles from the former and sixty from the latter. It is typical as regards fog for that densely populated coastal portion of the North Atlantic States east of the Appalachians. Therefore an inquiry into the nature of the more prevalent fogs at this station should be of practical value. The station itself is situated in a broad, perfectly flat plain, with hills rising to a few hundred meters some miles to the north and northwest. The nearest water is the Raritan, which is a small river about five miles to the west. Therefore Hadley is subject to no local influences of water bodies or cold air drainage. It lies perfectly open to winds from the sea, though at a distance of some thirty miles inland. Although the period of time for which there are regular observational records at Hadley is very short, it is quite sufficient for a study which must be as limited in scope as the present one. Furthermore these records have been more completely and observantly kept by Mr. Andrus at Hadley than elsewhere in this section. Just those meteorological elements which receive especial attention at an airways station, such as visibility, cloud forms, and height of cloud base, are the very ones which require particular attention in any study of fog.

Although this discussion is in the nature of a classification and explanation of the fog formations observed at Hadley Airport, it is not based on the careful analysis of particular situations, but rather on a general survey of all fog situations from September 15, 1926 to January 1, 1929. The local records contain observations of visibility, ceiling, condensation forms, and humidity observations, as well as temperature, state of weather, barograph trace, wind direction and velocity, pilot balloon observations, and time of beginning and ending of all precipitation, fog, and haze. For the earlier part of the period the observations were more or less irregular, with only two daily humidity determinations. But during 1928, with the establishment of all-night weather service at Hadley, the relative humidity was observed at six-hour intervals, and the other elements, regularly at the end of each hour throughout the twenty-four hours. This gives an almost continuous local record, on which the passage of significant discontinuities indicated by the regular morning and evening Weather Bureau maps can be checked, and the dependence of the fog upon the air mass ascertained.

In the scrutiny of the local records from Hadley, only those situations were chosen for study and comparison with the synoptic charts in which fog was observed at the ground of such density that the horizontal visibility was reduced to 4 or less on the Weather Bureau scale, which is the same as the international scale. This means simply that prominent objects or landmarks are invisible at a distance of 2 kilometers or 1¼ miles. Thus fog was not considered when of such slight density that the visibility was recorded as 5 (from 1¼ to 2½ miles). Neither were cases of low ceiling without surface fog considered, although a low stratus cover is frequently nothing more nor less than a high fog which for one reason or another cannot settle quite to the ground. Especially is this true for a station like Hadley Airport, which is only a few miles inland. On almost any clear, warm afternoon in spring or early summer low stratus may move in from the coast, with an abrupt lowering of temperature. This is nothing other than a Monsoon Fog from the cold water. It has been evaporated in its lowest layers in passing over the heated ground. However, to keep this discussion strictly one of surface fog in the usual sense of the word, such cases were considered only if the fog eventually extended down to the ground.

In classifying the individual cases of fog formation by types, there were certain difficulties encountered which in some cases render the classification rather uncertain. In the first place, the working charts at the Weather Bureau are subjected to no careful air mass analysis whatsoever. Therefore it is frequently quite impossible to tell just what the origin of the air mass covering a certain region really is. The amount of work involved in plotting data and analyzing charts to cover an extended period of investigation, like the present one, is quite prohibitive. More precise information about the particular types of fog to be considered here can be obtained only by choosing well-marked instances of the particular type to be studied, and carrying out a careful analysis of the situation leading up to the fog formation in each particular instance. Especially should any available upper air data be utilized as fully as possible, for vertical moisture distribution depends to a large degree on mechanical and convective turbulence and consequently on lapse rates.[1] This discussion is intended rather as a general survey of all fog occurrences over an extended period of time. However, as long as each fog formation occurred in an air-mass which had been for some time within the field of observation, it was fairly easy to trace the approximate trajectory of the fog-forming air mass, without any careful analysis of the situation. The real difficulty occurred with fog-bearing winds from the sea. Vessel reports from along the North Atlantic coast were so scattered and irregular that frequently it was quite impossible even to trace approximately the isobars off the coast. It was out of the question to determine the air flow over the off-shore waters with any precision at all, yet a small variation in this flow in a region of such rapidly changing surface water temperatures is very important for fog. Therefore certain distinctions are very hard to make. Especially is this true of the distinction between Sea Fog and Monsoon Fog. Monsoon Fog at Hadley Airport and much more markedly on the outer North Atlantic coast occurs especially in late spring and summer with winds between northeast and southeast, or even south. Without a map showing the pressure distribution off the coast, it is impossible to tell whether the source of the warm air giving this fog is the warm Gulf Stream to the southeast (Sea Fog), or a warm offshore wind alo g the Middle Atlantic coast (Monsoon Fog). The indications are that it is usually the latter, so that this type of fog has been classified as Monsoon Fog rather than Sea Fog. Since this warm offshore current is usually of tropical origin (the Gulf of Mexico), this fog might also be classed as Tropical Air Fog. However, since Tropical Air Fog is the more general phenomenon due to cooling from below with increasing latitude, whereas Monsoon Fog is the result of local intensification of this process as a result of land and water surface temperature contrast, it is called Monsoon Fog in this case. It is also easy to confuse Prefrontal Fog before a warm Front, in certain cases, with this Monsoon Fog. In the very frequent case of a weak cyclone passing slowly off the coast just south of Hadley Airport, it often happens that the warm offshore current of air on the south side of the weak center of circulation is brought around on shore as an east or northeast current, cooled and foggy. The net effect may be a slowly northward moving well-marked warm front, preceded by fog, low stratus, and rain. However, such fog is usually distinguishable from real Prefrontal Fog if it is remembered that Prefrontal Fog is not an advection fog, but grows from the ground upward with very light air movement in the region of falling pressure and rain in advance of a front. It forms especially in cold air over a cold surface in winter. On the other hand, Monsoon Fog is an advection fog, occurring in spring and summer, and at a point as far inland as Hadley it usually appears first as a low stratus, moving in rapidly from the sea, which quickly lowers to the ground to give the surface Monsoon Fog.

In addition to the occurrence of surface fog, instances of dry or smoke haze were considered if the haze was especially noted as dense, and the visibility reduced to five or less. The lowest visibility ascribed to dry haze in the Hadley records was three (5/16 to 3/5 miles), but such a density occurred a number of times with rather low relative humidity. During the period of twenty-seven and a half months there were only nineteen cases of smoke haze in which the density was such that the situation was included for analysis. In a location such as that of Hadley Airport, in the midst of a densely populated industrial region, light haze is usually more or less noticeable in clear weather, as the Hadley records show.

[1]See for instance: H. B. Hutchinson, A Fog Situation in the United States During the Winter 1928–1929, M. I. T. Professional Notes, No. 3, 1929.

In the twenty-seven and a half month period considered here, there were 193 cases of fog formation at Hadley Airport, a number which is surprisingly high. (For frequency distributions see table below.)

TABLE OF FOG FREQUENCIES BY MONTHS

| Fog Type | *Jan.* (2) | *Feb.* (2) | *March* (2) | *April* (2) | *May* (2) | *June* (2) | *July* (2) | *Aug.* (2) | *Sept.* (2½) | *Oct.* (3) | *Nov.* (3) | *Dec.* (3) | *Total* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radiation | 3 | 2 | 10 | 1 | 6 | 4 | 9 | 15 | 17 | 23 | 15 | 11 | 116 |
| Monsoon | 1 | 3 | 1 | 1 | 5 | 5 | 4 | 8 | .. | 1 | .. | 5 | 34 |
| Prefrontal | 5 | 4 | 5 | 2 | 1 | .. | 2 | 1 | .. | 1 | 7 | 3 | 31 |
| Maritime | 1 | .. | .. | 1 | .. | .. | .. | .. | .. | .. | 4 | 2 | 8 |
| Front Passage | .. | .. | .. | .. | .. | 2 | 1 | .. | .. | 1 | .. | .. | 4 |
| Total | 10 | 9 | 16 | 5 | 12 | 11 | 16 | 24 | 17 | 26 | 26 | 21 | 193 |
| High Inversion Haze | 5 | 4 | 5 | 2 | 1 | .. | .. | .. | .. | .. | 1 | 5 | 19 |

In determining the number of cases of fog formation, the attempt was made to count only those instances in which a new fog actually formed, and not those in which the same fog formation simply lifted or withdrew, only to settle or return later. On a number of occasions the same formation lasted two or even three days. In 109 of the 193 cases the fog was reported as dense, which apparently indicates a visibility of two or less on the scale, or that prominent objects are invisible at half a kilometer (5/16 miles). As would be expected of a location on the eastern edge of a continent, where a predominantly continental rather than maritime climate should prevail, the majority of the fog formations were of the radiation type mostly with the surface inversion. One hundred sixteen of the 193 occurrences of fog are to be ascribed primarily to radiational cooling, 67 of them being reported as dense. However, for an east coast location there was a surprisingly large amount of Monsoon Fog. The explanation of this fact will be attempted in the detailed discussion of the Monsoon Fog cases. It further appears that while the Prefrontal Fogs are of frequent occurrence at Hadley, the front passage fogs play a minor part in effecting surface fogginess. Tropical Air fogs are entirely lacking. Warm Air fogs occur, however, in the somewhat cooler current of returning Maritime Polar Air from the Bermuda High rather than in the real tropical air from the Gulf of Mexico and the Caribbean Sea. The typical Maritime Fog does not appear at all.

Although the period of time covered in this investigation is entirely too short to expect that any statistical analysis of the results will have much significance, a few things stand out so clearly that their reality for this locality scarcely can be doubted, in particular:

1. That there is no period of the year which is really free of fog at all, though conditions seem to be best during the late spring and early summer.

2. That due to the frequency of Radiation Fog from August to November, fog frequencies are greatest during this period. However, since these fogs usually dissipate with the sunrise, they may not be as troublesome as the less frequent but more persistent winter fogs.

3. That dense smoke haze is restricted quite definitely to the months December through March.

4. That Monsoon Fog has a distinct maximum from May through August, and Prefrontal Fog from November through March.

Explanations of these facts follow in the more detailed discussion of each fog type.

# I. AIR MASS FOGS

## *A. Advection Types Due to Transport of Warm Air Over a Cold Surface*

### 1. Monsoon Fog

At Hadley Airport Monsoon Fog is exceeded only by the Radiation Fogs in frequency. In the period from September 15, 1926 to January 1, 1929, there were no less than thirty-four cases of Monsoon Fog, of which twenty-two were dense. Since Monsoon is one of the most persistent types of fog, this high frequency is especially significant. In view of the fact that the North Atlantic coast is on the eastern side of the continent, therefore enjoying actually a continental climate, and also that Hadley is situated some thirty miles from the coast, this frequent occurrence of Monsoon Fog is quite striking. The waters off the North Atlantic coast are particularly cold, due to the Labrador Current. This explains the almost constant presence of Monsoon Fog off the coast during the spring and summer, and its very frequent occurrence on the most outlying points of the coast. But it does not explain its frequency as far inland as Hadley, for no daily monsoon circulation brings the fog in so far. This fog at Hadley is not of the daily monsoon type, but rather of the irregular type brought on shore from time to time by favoring cyclonic circulation. It is a very frequent occurrence along the Atlantic coast, especially in spring and summer, to have a stagnant situation with a succession of weak disturbances passing off the coast usually over Maryland or Northern Virginia. Sometimes they hang on the New Jersey coast for twenty-four hours or more. In this situation there exists a weak quasi-stationary front between a very warm southwest air current of tropical origin on the south, and a cool foggy easterly current from the sea on the north. This is the typical circulation which invariably brings Hadley Airport fog or low stratus, and usually drizzle. The very warm tropical air flowing off the coast to the south is rapidly cooled over the cold water. It is brought around in front of each stagnating disturbance on the coast, reaching the shore first as a southeast wind which normally goes to east and northeast as the center moves off to the northeast. Apparently a movement of only a few hundred miles over the cold water is sufficient to effect this cooling and fog formation in the warm air current.

A very excellent illustration of this rather frequent situation occurred on May 18, 19, and 20, 1928 (see maps I, II, and III). In this case the same stagnant cyclone was on or just off the South Jersey coast during the entire period, and maintained a steady flow of warm air off the coast of the Carolinas and Southern Virginia, which was brought around on shore as a current of cool foggy air, first from the southeast and later from the east and northeast. The coast from Atlantic City to Boston was constantly fogbound or under low stratus, but not once did the fog reach inland to Scranton or Harrisburg. It will be noted on the maps (see nos. I, II, and III) how in the northeast a stagnant air mass of cold maritime polar air maintained its position and prevented the normal northeastward advance of the warm tropical air current and low pressure. Probably the air brought on shore in the fog zone during these days was actually a part of the tropical current, but had been so thoroughly cooled in passing over the cold offshore waters that it reappeared on the coast with the characteristics of transitional air of tropical maritime origin. It will be noted especially on the map for May 18 how the cold water of the Great Lakes has had a similar cooling effect wherever an air current moves off the water. This means practically that the warm front indicated as lying southeast of the fog zone has no significance dynamically, but merely indicates a rapid horizontal transition in surface air temperatures resulting from an abrupt change in surface water temperatures.

At Hadley Airport this period was marked by constant dense fog and low stratus, which thinned away a little each day at noon, but returned with undiminished density early in the afternoon. Every night the temperature was 55°, rising to 60, 61 and 62° successively between twelve and one o'clock on the three successive days. On the fourth day the low stratus broke away as the wind went to southwest, and warm weather returned. It is interesting to note the extreme regularity of the temperatures which prevail during the typical Monsoon Fogs at Hadley, as elsewhere along the coast. They show very clearly what the surface water temperatures are off the coast. In the middle of May the value is 53 to 55° rising to 60° early in June, 65° by the middle of July, and nearly 70° by the end of August. With low stratus and east or northeast winds these temperatures are almost invariable at Hadley, though they are probably a trifle higher than the sea temperatures, as would be expected.

It is also interesting to note how the Monsoon Fog at Hadley almost invariably appears as a low deck of stratus moving in rapidly from the east or southeast, often in clear warm weather, with an abrupt drop in temperature, especially in the spring. The cloud base rapidly lowers, and frequently drizzle or mist sets in. Winds are usually light to moderate. When the fog is reported as light, the cloud base is invariably reported at a few hundred feet; when dense, the cloud base is reported as 0. Probably this indicates only that in the less dense case the visibility in the vertical direction is a few hundred feet, rather than that there is any abrupt cloud layer at that elevation. The fact that this fog makes its first appearance at some elevation is doubtless to be explained as a result of a certain amount of heating and consequent evaporation from below in its first progress over the heated land surface.

Although this type of Monsoon Fog occurs principally from May to August (twenty-two of the thirty-four cases occur during these months), it may appear in almost any month. It is least frequent during the autumn months, only one case being found in three years during September, October, or November. This is, of course, exactly the period when the cooling of the land surface runs furthest ahead of that of the water surface. But due to the coldness of offshore waters on the North Atlantic coast, and the high temperatures which characterize air from the Gulf as it moves northeastward at any season, every other month shows at least one instance of Monsoon Fog at Hadley. There are two very persistent and excellent cases occurring in December, from December 10 to 13, 1926, and 11 to 14, 1927. In each of these cases the warm current extended as far north as Northern Virginia with temperatures over 70°, while the cold foggy air was between 45° and 50°.

Occasionally, especially in the early spring, a movement of cold air from the northeast coastal region takes place southwestward along the entire coast, bringing low stratus, some fog, and much lower temperatures especially when preceded by a distinctly warm offshore current. Such a movement brought dense fog to Hadley on April 17, 1927, with a relative humidity of only 84 per cent. However, the surface fog quickly lifted to stratus, which soon gave way to clearing, but with continued cold and northeast winds.

### 2. Sea Fog

There was not a single instance of fog at Hadley Airport during the period studied which could be shown conclusively to be a case of real Sea Fog. It is quite possible that this conclusion is correct, that real Sea Fog is not brought on shore on that part of the North Atlantic coast. That is quite in accord with the fact that compared to Monsoon Fog, which is of necessity a coastal phenomenon, Sea Fog is essentially a phenomenon of the open sea, and only exceptionally brought on shore. The only distinction between these two types of fog is that Sea Fog is the result of the cooling of air moving from warmer to colder water surfaces, while Monsoon Fog is the result of the cooling of air moving from warm land to cold water surfaces. However, in the particular case of the North Atlantic coast, conditions are such that it is quite conceivable that Sea Fog should be brought on shore occasionally. Just off the shore there flows the cold Labrador Current, while farther to the south and southeast there flows the warm current which has its source in the Gulf of Mexico. Hence any long prevailing wind from the south or southeast will bring warm maritime air across the colder coastal waters and eventually on the North Atlantic coast, as the same kind of cool foggy air that characterizes Monsoon Fog. The fog would have exactly the same characteristic temperature, and appear first as the same low stratus moving in from the coast. As was pointed out above, observational data off the coast are so scanty that in quite a number of cases classed as Monsoon Fog it was quite impossible to show just what the origin of the foggy air mass really was. It is at least quite possible that occasionally the air was brought northward in a warm southerly current from the South Atlantic, in the region of the Bermuda High. It will be shown later that air brought eastward and northward from this source over the South Atlantic States is much readier to give fog than the warmer tropical air brought up from the Caribbean Sea and the Gulf of Mexico. A possible explanation of this fact is to be found in the fact that the Bermuda High is normally a region of old Maritime Polar Air, or better, Maritime Transitional Air, while the warmer air of more southerly source is real Tropical Air. However, since the Monsoon Fogs nearly always occur with marked outflow of real Tropical Air over the Middle Atlantic coast, and can frequently be shown to belong to the same air current, it seems probable that unless the air source can be proved to be maritime, it is better to assume that it is Tropical Air from the southwest rather than warm Maritime Air from the south or southeast.

### 3. Tropical Air Fog

Real Tropical Air Fogs were found to be completely missing at Hadley Airport in the period studied. There were a few cases of fog in a warm air current of southerly origin, but these cases are to be kept quite distinct from real Tropical Air Fog. On every occasion they occurred in an air current whose source was the Bermuda High. Such a current consists of maritime polar air which initially moved southward over the Atlantic in the region of Bermuda, was later deflected to the west and passed over Florida and the Gulf region from the east or southeast, and finally moved northward and northeastward as a warm air current. Such an air flow is very productive of fog along the Gulf Coast and in the Southeastern States, occasionally extending northward to Northern New England. But such an air current is not to be confused with the true Tropical Air whose origin is the Gulf of Mexico and the Caribbean Sea, where it has remained until thoroughly warmed. It is really returning maritime polar air, or transitional air, so that the fog belongs to the maritime type, to be considered later. The characteristic surface temperatures of this transitional air as it moves northward run from 10° to 20° F. colder than real tropical air. Such an air mass is subject to an amount of surface cooling by night and with progress inland which is entirely absent in the true Tropical Air current. This matter will be considered in more detail later, but at this point it must be emphasized that though a transitional air current reaches northerly latitudes as a distinctly warm air mass it has not at all the warmth nor condensation phenomena of a tropical air current in the same region, but it has a much greater tendency to produce fog, at least in the Eastern United States.

It was pointed out in the previous discussion[1] of the rather frequent occurrence of a typical Tropical Air fog formation over Northern Europe that probably in the United States this formation would be found much less prominent. The results at Hadley Airport justify this conclusion to a surprising extent. Probably the reasons for the non-occurrence of real Tropical Air Fog at Hadley are threefold:

1. The comparatively southerly latitude of the station. Tropical Air currents reaching the northwestern coast of Europe, usually from the southwest, and especially the British Isles and Norway, have undergone much greater latitudinal displacements than have Tropical Air currents from the Gulf of Mexico upon reaching Hadley Airport, at latitude 40° N. Consequently much less cooling of the lower strata of the air mass has occurred in the second case, for this cooling takes place through contact with the cold undersurface and turbulent mixing. Therefore the condensation forms, fog, stratus and drizzle, are less characteristic of the Tropical Air current over the Eastern United States, and the current is normally warmer than a similar current over Northwestern Europe. These characteristic differences are further intensified by

2. The continental character of the trajectory of the usual Tropical Air mass which reaches Hadley Airport. It was pointed out that general fog formation rarely takes place in a Tropical Air current over Northwestern Europe except as the current has been cooled by passing northward over the sea, or over snow-covered ground. The cooling is not usually sufficient to produce fog when the air mass trajectory indicates passage over the continent. Now at Hadley Airport any Tropical Air mass coming directly from the Gulf of Mexico must have passed northwestward over the Eastern United States. Such an air current invariably shows high temperatures throughout its northward journey. At Hadley it is characterized by a surface temperature of about 55° to 60° F. in winter, over the Southeastern States by temperatures from 60° to 70°. This very warm air seldom shows fog, but rather partly overcast skies, usually some strato-cumulus and some higher clouds. Furthermore, it seldom happens that such a current is exposed to a real snow cover, for it is of necessity preceded by rather warm air since only with a very persistent air flow from the south can air masses from the Gulf penetrate so far to the north. Undoubtedly if the current once reaches regions of unmelted snow, cooling and fog quickly occur. But as is explained under point (3) below, such an air mass very seldom reaches snow-covered regions in the United States as a surface current. Perhaps the period studied here is not typical, in that every winter period covered by the investigation was unusually free from snow in the Eastern United States. It may well be that during a season of heavy snowfall along the Middle Atlantic coast real Tropical Air Fogs do occur. The readiness with which cooling over a cold water surface effects fog formation in the Tropical Air mass is shown by the regularity with which fog occurs in one of these very warm currents which passes off the

[1] *Monthly Weather Review*, November, 1928, p. 444.

Middle Atlantic coast and returns cool and foggy on the North Atlantic coast. These fogs have been classed as Monsoon Fogs, because it is usually the continental heating of the air mass which is responsible for them, but on the few occasions when they occur in winter it is always in a current of real Tropical Air. In that case the air current passing on shore shows a surface temperature of 45° to 50° F., which is just the temperature which characterizes maritime Tropical Air at Bergen approaching from the southwest, the foggy type. Such a low temperature is reached so much further south on the North Atlantic coast because the water is abnormally cold here for the latitude.

3. The marked infrequency of real Tropical Air at Hadley Airport. A careful investigation of the maps in conjunction with the Hadley observational material shows that in winter it is very unusual for the Tropical Air current to appear at the surface in this region, that is, from New Jersey northward between the Appalachians and the coast. The Appalachian Mountains are responsible for this. There are two characteristic movements of the Tropical Air current from the Gulf over the Eastern States, neither one of which results in the transport of the Tropical Air mass to the North Atlantic coastal region at the ground. Of course, the Tropical Air usually moves northward as the open warm sector of a northeastward moving cyclonic disturbance whose center is on the boundary between the warm current and the colder air to the west and north. Now in winter such disturbances together with the Tropical Air current tend to move definitely on one side or the other of the mountains, as they come north. If they pass eastward, they almost invariably move off the Middle Atlantic coast, and northward just off the coast. In such situations Hatteras usually gets the real Tropical Air, Norfolk gets it perhaps on half the occasions, Richmond perhaps a quarter, and Atlantic City very seldom. In other words, if the Tropical Air current is passing northeastward east of the mountains, Hadley almost never comes into the warm sector. On the other hand, when the warm current passes northward west of the mountains, the center of the disturbance usually passes over the lake region into Ontario. In this case the Appalachian Mountains act as a very real barrier to the eastward movement of the Tropical Air current at the ground. It frequently happens that Elkins, Parkersburg and Pittsburgh are in the tropical air, while Harrisburg and even Richmond and Lynchburg are as much as 15° to 20° F. colder. Very often a surface layer of cold air in the lee of the mountains remains till the passage of the cold front, the warm air being unable to penetrate to the ground before occlusion takes place. As far north as Harrisburg and Hadley this is quite the normal development. Such a situation very frequently gives dense fog in the cold surface air which is characteristic Prefrontal Fog before a warm front. Ideal instances of this effect of the mountains in shielding the coastal region from the Tropical Air current are shown on the map of March 21, 1927, for 8 a.m., and for January 16, 1928, 8 p.m. (see maps IV–VIII). In neither case did the warm air make its presence detectable at the ground at Hadley Airport during the following hours.

It will be noticed how in the maps for both March 20, 8 p.m. and March 21, 8 a.m. (maps VII and VIII) Pittsburgh lay at the northern extremity of two successive warm sectors, and how on both maps the cold air extends southward east of the mountains. Only the passage of the cold front from the west displaced this stagnant cold air with its Prefrontal Fog which lay in the lee of the mountains. The maps from January 16, 8 a.m. to January 17, 8 a.m. (maps IV, V and VI) show an even more marked instance of the rapid northeastward advance of a warm air current which reached to Lake Erie west of the Appalachians, but which was not indicated at the ground north of Virginia east of the mountains. Cases of this type are quite frequent. On the second series of maps the formation of an extensive fog belt over the Southeastern States will be noted. This fog is of the Maritime type to be discussed presently, the air mass in which it occurs being old Maritime Polar Air which has been warmed over the warm sea off the South Atlantic coast, and cooled at night in its lowest levels on moving inland.

It is very seldom that the center of the northward moving disturbance passes over the mountains in such a way as to bring Hadley into the warm sector. Even in the situation characteristic of the spring and early summer, which brings the Monsoon Fog to Hadley, when a stagnant cold air mass and anticyclone lies over the Canadian Maritime Provinces and weak lows pass slowly eastward at the boundary of the cold air mass and a warm Tropical Air current to the south, these lows always pass to the south of Hadley. (See maps for May 18, 19 and 20, 1928, No. I, II and III.) This station gets the warm air only occasionally after it has passed around over the sea to the east of the low center, and become cooled and foggy. On the other hand, the rather warm current of returning Maritime Polar Air from the Bermuda High is frequently brought northward as a south or southeast wind over all the coastal region east of the Appalachians. It may also invade the central portions of the country by way of the Gulf of Mexico, occasionally causing very extensive fog as will appear presently. (See maps IV and VI, also IX–XII.)

### 4. Tropical Air Haze

In the discussion[1] of Tropical Air Haze over Western Europe it was pointed out that the characteristic poor visibility of Tropical Air apart from the condensation phenomena is due to dust which has permeated the air mass throughout at the source, in the Azores High. The origin of the dust is probably the Sahara and other arid regions in Northern Africa. It was suggested that this haze characteristic is probably much less prominent in Tropical Air over the United States. The observations at Hadley fully verify this. Of the nineteen instances at Hadley of haze reported especially dense, sixteen of them occurred from December to March and not one from June through October. Furthermore, every occurrence was with a cold, stagnant, anticyclonic situation. In other words, it is only the inversion smoke haze which becomes dense enough in the North Atlantic coastal region to get special mention. However, light haze was rather frequently reported during the summer, especially during periods of prevailing hot southwest winds. This haze is doubtless due to dust carried up by insolationally maintained convection over the hot dry inland regions in summer. But the very striking haze or opalescence which characterizes real Tropical Air at Bergen is not evident even in continentally heated Tropical Air in the Eastern United States. This must be attributed to the absence of any such extensive source of dry dust as the Sahara Desert in Northern Africa. Tropical Air currents originating over the Gulf of Mexico or even over the arid southwest in summer are not subject to the same thorough permeation by dust at their source as are Tropical Air masses originating over Northern Africa or the Azores High.

## *B. Advection Types Due to the Transport of Cold Air Over a Warm Surface*

### 1. Arctic Sea Smoke

### 2. Early Morning Autumn Steam Mists over Lakes, Rivers, etc.

The location of Hadley Airport is such as to render either of these fogs quite out of the question. The Sea Smoke occurs only in the Arctic, or near Arctic regions, where extremely cold air moves over open water. Similarly the absence of any local water bodies and the flatness of the surrounding country at Hadley make the steam mists which appear in Autumn in the early morning over relatively low-lying water surfaces quite impossible.

## *C. Radiation Fogs and Haze*

### 1. Ground Fog and High Inversion Fog

The majority of the fog formations at Hadley Airport during the period studied (116 out of 193 instances) were of the radiation type. Furthermore, with two or three *possible* exceptions, they were of the Ground Fog type, that is, they appeared first at the ground, and as they deepened and thickened they remained densest at the ground. Here also then must be found the base of the temperature inversion which always characterizes the formation of a radiation fog. A High Fog, on the other hand, is one which grows down to the ground from an upper inversion, having its greatest density at the upper inversion. A full discussion of these two types appears in the first part of this paper, but the distinction is briefly restated here because in ordinary aviation meteorology parlance the term Ground Fog has quite a different significance. It is simply a fog of comparatively slight vertical extent. When thirty-five of the one hundred sixteen Radiation Fog formations are characterized in the Hadley records as Ground Fog, that usually means simply that the sky overhead is clearly visible to an observer on the ground. However, it is quite evident that a real Ground Fog may grow to such a depth that the sky and even the sun are totally obscured. This frequently happens. Furthermore, when such a fog begins to lift, it frequently rises from the ground as a dense low stratus, which gradually dissolves and breaks in patches, showing clear sky and sunshine between. This does not make a real High Fog of the formation at all, for the lifting of the fog from the ground is merely the initial stage of the fog dissipation. Probably it is the result of the first heating of the ground air layers by the rising sun.

[1] *Monthly Weather Review,* November, 1928, p. 443.

The fact that no good instances of High Inversion Fog were observed at Hadley is not at all surprising. It was pointed out in the former discussion[1] of the nature of this fog that it could scarcely be expected to occur in the Eastern United States, for the development of this type of fog to a maximum requires a long persistent stagnant anticyclonic condition with sinking of the cold air mass and marked subsidence inversion formation. Furthermore, the sinking cold air mass must be Maritime Polar Air, otherwise the humidity content is too low to give the real dense and continuous High Inversion Fog. It was pointed out that in the Eastern United States almost invariably on the rare occasions when a cold air mass remains stationary for any length of time the source of the cold air is the Canadian Northwest, hence it is of the dry Continental Polar Air type. Such an air mass usually forms a very large upper inversion with generally clear skies and almost complete calm. The inversion always is quickly marked as the upper level of a layer of smoke haze which may become gradually quite dense and persist for days. But there is too little moisture in the air to give more than at most scattered local fog rarely persisting all day. The month of December, 1928, was marked to an unusual degree in the Eastern United States by this type of development. From December 2–5, 8–14 and 22–27 inclusive, were periods of real stationary growing anticyclones in the Appalachian Region. At Hadley Airport these periods were characteristically hazy, dry and clear and calm. The relative humidity increased gradually during each development from day to day, finally giving ground fog in the morning. Only in the second case did anything approaching real High Inversion Fog develop. In that case a cyclone almost stationary off Hatteras for several days brought inland a considerable amount of Maritime Polar Air into the dry continental polar air mass especially over the Southern Appalachian region. In this region there resulted a partial development of High Inversion Fog appearing at many stations either as surface fog or low stratus, which persisted almost undiminished throughout the day. During the earlier stages of this development dense smoke was reported from a number of widely scattered stations, including Chattanooga, Evansville, Columbus and Pittsburgh. This proves conclusively the existence of a widespread subsidence inversion. There was an increasing amount of fog and low cloud reported, especially in the morning, as the situation persisted. It appeared at scattered points from the Gulf coast to the Northern Lake region, and eastward to the Atlantic. The development was initiated by an outflow of Canadian Polar Air during December 7, 8 and 9, and was terminated about December 14 by the gradual encroachment of a deepening disturbance from the southwest. The morning maps of December 11 and 12 show the nature of the situation (see maps XIII and XIV). The development of this southwestern disturbance is indicated on these maps by the increasing rain area in the southwest and middle west, and the general overrunning by warm air aloft is indicated by the southwesterly direction of the upper clouds.

This is the only period in which the fog occurring at Hadley may be classified as High Inversion rather than Ground Fog, though even in this case it is not so clearly the characteristic form as it is further south. It is possible that there were other instances of High Inversion Fog at Hadley which appeared only as stratus, not reaching the ground as surface fog. But since cases only of surface fog are considered here, they would not come within the range of this study. The remainder of this discussion of Radiation Fog at Hadley, therefore, is concerned entirely with Ground Fog.

The fact that stands out most strikingly, in a general survey of the data covering the rather numerous instances of Radiation Fog occurring during the period of this study, is the extremely variable nature of the prevailing conditions which may lead to the formation of the fog. It is almost impossible to pick out any similarities in the conditions preceding the appearance of the fog in even a majority of the cases, apart from the fact that the sky must be at least partly clear. In general, in classifying the fogs in the first place, any fog which formed with skies not more than partly overcast during the cooler part of the day in the absence of any appreciable solar heating was classed as a Radiation Fog. But the similarities in the conditions end there, apart from the fact that when the fog formation actually begins the humidity must be high. Usually one associates the appearance of Radiation Fog with clear cool autumn mornings and warm, rather dry days with a large diurnal temperature variation, probably well above 20°F. As a matter of fact, not half of the Radiation Fogs at Hadley conform to this type. Out of one hundred sixteen cases of Radiation Fog, only forty-eight showed a minimum temperature as much as 20° F. colder than the maximum on the previous day. These cases where marked radiational cooling

[1] *Monthly Weather Review*, November, 1928, p. 449.

occurs are especially characteristic of the period August through November, and also March, with the result that there is an appreciable maximum frequency of Radiation Fog during the autumn months. On the other hand, Radiation Fog occurs in every month in the year, with wind velocities ranging from calm up to twelve miles per hour, and on nights when at 7 p.m. the humidity ranged from 46 per cent to 100 per cent. The decisive factors in Radiation Fog formation are (1) radiational cooling of the air above the ground, (2) relative humidity of this air, and (3) the air movement, or wind. Now it at once becomes evident that at Hadley no general formulation of the probability of Radiation Fog formation in terms of these quantities can be expected to prove very satisfactory, for they are too variable. However, if observations were taken with the object of forecasting Radiation Fog in mind, they could be made infinitely more valuable for purposes of direct comparison if conditions were observed one hour after sunset every evening instead of at seven o'clock or any other definite time. At seven o'clock in winter the sun has been two hours below the horizon, much cooling from the ground by radiation has occurred, and therefore a large increase in relative humidity from the daytime values. In summer the sun is still shining at seven o'clock, and very little radiational cooling and humidity increase is likely to have occurred. Therefore observations at the same fixed time have an altogether different significance at different seasons as far as Radiation Fog is concerned. Unfortunately in the Hadley Airport records humidity readings are to be found only for the fixed times, 7 p.m., 1 a.m., 7 a.m. and 1 p.m. The lowest value of the relative humidity at 7 p.m. to be followed by the formation of Radiation Fog was 46 per cent, and was observed in July, as might be expected. The temperature on that particular night fell 23° F. after the seven o'clock observation. That explains how the relative humidity was brought up to saturation values. There were several other occasions on which a relative humidity of less than 50 per cent at 7 p.m. was followed before morning by Radiation Fog.

If observations of humidity, radiational cooling, and wind were taken at a regular length of time after sunset, probably quite a precise formulation of the conditions normally resulting in the formation of Radiation Fog could be effected, for the mutual interdependence of the three factors mentioned above is very evident even without comparable observations. The amount of radiational cooling which takes place during the night turns out to be surprisingly dependent on the moisture content of the air just above the ground, as the theory would lead one to expect. Since the radiational cooling increases with a decreasing moisture content, it follows that these two factors alone will not determine at all precisely the probability of the appearance of Radiation Fog before morning. But the wind velocity makes the problem more precise, for a very small prevailing wind greatly reduces the radiational cooling of the lowest air layers. Therefore if it is clear and dry, just a little wind is certain to prevent the appearance of fog, for it checks the extreme radiational cooling necessary to effect saturation. That is why fog very seldom occurs at Hadley on the first night after the outbreak of a cold dry Canadian Polar Air mass from the northwest. There is always sufficient wind to prevent extreme surface cooling, which otherwise would probably take place in the very dry air. On the other hand, when the northwest winds are very light, and the clearing follows immediately on cold front rain, it sometimes happens that the humidity is high enough to give fog, which usually appears within an hour or two of the clearing, if it appears at all. There were some half dozen cases of such fog at Hadley, but it never lasts long, usually disappearing before morning if the northwest wind persists at all.

As mentioned above, the majority of the Radiation Fogs at Hadley were characterized by rather high relative humidity at the evening observation, and a comparatively small amount of radiational cooling during the night. Such formations occur throughout the year, and may in general be divided into four groups, dependent upon the source of the moisture, whose significance will be briefly explained:

1. Those in a southerly current of returning old Maritime Polar Air.
2. Those in air brought directly into Hadley from the coast.
3. Those summer formations occurring in a hot, moist air mass characterized by instability showers.
4. Those following on a clearing immediately after rain.

(1) Probably the most frequent origin of the air mass in which Radiation Fog occurs at Hadley is the anticyclone moving off the coast. In this situation the return flow of old Polar Air, often old Maritime Polar Air returning from the South Atlantic, brings a steady flow of moist air northward over cooler

surface. Local radiational cooling is very quick to effect fog formation in such an air current. The moisture content of such air is usually so great that not much further cooling is necessary to produce fog. Hence Radiation Fogs belonging in this group at Hadley are characterized by a rather high initial relative humidity, a rather small radiational cooling, and usually an appreciable air movement or wind, prevailingly southerly. It was already pointed out in the discussion of Tropical Air Fog how readily such an air current becomes the bearer of an Advection Fog. With Radiation Fog of this type the wind at Hadley may in extreme cases be as high as ten to twelve miles per hour, though that is exceptional. In the majority of cases the winds are very light, seldom averaging as high as four miles per hour. It must be remembered also that the anemometer is exposed above the roof of a large hangar, at an appreciable elevation above the ground. Probably fog formation in a moist current of any such velocity as ten miles per hour is the result of radiational cooling of the entire air mass directly to space, rather than of ground cooling. The frequency of low strato cumulus clouds in such situations indicates the same thing.

(2) A considerably less frequent source of the moist air, which on slight radiational cooling gives fog at Hadley, is from the North Atlantic coast. It sometimes happens that the gradual withdrawal from the coast south of Hadley of a weak disturbance which has been bringing inland a moist, cloudy, cool air current from the North Atlantic is followed by clearing and almost perfect calm. When this happens, which is not very often, a prompt appearance of Radiation Fog at Hadley can be counted on.

(3) The occurrence of early morning Radiation Fog at Hadley during the hottest summer weather is surprisingly frequent. It is characteristic of the warm, moist conditions which are extremely unpleasant in summer, and are associated with daily convectional thunder showers. The radiational cooling on nights of this kind is very slight, due to the great moisture content of the air. However, for the same reason, very slight cooling is sufficient to produce considerable supersaturation. Therefore fog forms very readily in the early morning, even though it is very warm. This same situation is admirably suited to give Monsoon Fog immediately off the coast, over the much cooler ocean surface. Therefore when this type of Radiation Fog appears at Hadley and other inland places, points on the outer coast, such as Nantucket and Highland Light, are usually having continuous Monsoon Fog, day and night.

(4) Naturally whenever a clearing with light winds occurs shortly after the air has been saturated by falling rain, Radiation Fog may appear without delay, first in patches in the low-lying sections, and rapidly spreading and thickening. This is a very frequent process leading to the formation of such fog, for there seems to be a tendency for clearing to take place about sunset. If it remains calm, dense fog is almost certain to persist throughout the night. What frequently happens, however, is that the clearing is followed later by increasing westerly winds of much drier air. The fog may appear and last a few hours, only to be followed by an early dissipation. It is apparently a frequent occurrence to have a light prefrontal rain, when the front occurs in a flat trough without any marked wind discontinuity, followed by a frontal clearing. In other words, frequently the clearing takes place in the very center of the low pressure trough, with no wind at all. This is very favorable for fog formation, for besides the radiational cooling the air has been freshly saturated and is being subjected to a certain amount of adiabatic cooling by expansion. It is in this kind of situation that the least radiational cooling usually takes place before fog appears.

There is one striking difference to be noted between Ground Fogs as they occur in Europe and as they occur on our North Atlantic coast. That has to do with the local intensification of such fogs in the immediate vicinity of the large industrial centers. In Europe all observational data shows conclusively a very great increase in frequency and persistency of Radiation Fog in the big cities. This has been treated by different observers for London, Paris, Hamburg, Sofia, and many other cities. Hann shows how in the environs of London the hours of fogginess decrease as one gets further from the center of the city. Yet at Hadley Airport much more dense fog is reported than from the neighboring large cities of Philadelphia and New York. The difference is striking. While Hadley Airport reported sixty-seven cases of dense Radiation Fog, sixteen of which were dense at the time of the eight o'clock morning observation, New York reported fog at only six a.m. observations; Philadelphia at four. This is to be explained in part by several facts, probably:

1. At an airport fog receives a very particular attention which it does not get at an ordinary Weather Bureau station.

2. The Weather Bureaus in the large cities are usually located on the roofs of skyscrapers, above the shallower fogs.

3. In a region as crowded with industrial cities as that around Hadley, probably the density of hygroscopic nuclei is almost equally great throughout the region.

4. Due to the high elevation of the stations above ground and the heating effect of the city, there is no chance for local radiational cooling to take place in New York or Philadelphia as it does over the fields at Hadley. That this is a very real fact is shown by a comparison of minimum temperatures at Hadley and at the two city stations. On clear, calm nights, on which the radiational cooling is large, the average difference between the minimum temperature recorded at Hadley and in the two cities was as much as 12° to 14° F. Extreme cases run up to 20°F. These were nights on which Radiation Fog occurred at Hadley, which probably checked the development of a still greater difference. On more humid nights, when the cooling at Hadley is less, the difference runs about 6° F., while on the humid nights which are characterized by a persistent air movement the difference falls to 2° or even 0° F. The thing that is difficult to explain here is why the large European cities do not show the same temperature contrast between city and outlying territory. This is probably due in part to the absence of skyscrapers and the less crowded development of the European metropolises. At any rate, the fact remains that fog is more frequent, dense and persistent in the big city in Europe, and the temperatures as low or lower than in the less foggy environs of the city.

### 2. High Inversion Haze

It was pointed out in the discussion of High Inversion Fog that, although the formation of surfaces of subsidence over the Eastern United States rarely leads to the formation of the fog, it invariably leads to the appearance of layers of dry smoke haze at the inversion. This is the typical High Inversion Haze which may become dense enough to be a menace to flying, by obscuring the pilot's view of landmarks on the ground. The greatest density of such haze observed at Hadley was such as to reduce the visibility to three. Such a density occurred a number of times.

Since this haze always accompanies marked upper inversions, it is characteristic only of the winter season when radiational cooling from below permits of the continued existence and growth of such inversions. The fact that of the nineteen cases of haze observed at Hadley of sufficient density to merit discussion in this paper, every one occurred as an instance of this formation between the months of November and May proves that this is the only type of dry haze which is of any significance for aviation in this region. The month of December, 1928, gives the best examples to be found in the United States of widespread and continuous subsidence inversions with persistent smoke haze. Day after day at Hadley was described as clear, calm and hazy or very hazy. The condition "smoky" appeared on the weather map at a number of stations during this period. (See maps for December 11 and 12, 8 a.m., Nos. XIII and XIV.)

Since Hadley Airport is located in the center of an extensive industrial region, smoke haze may and does occur with light winds of almost any direction, but the densest haze occurs with an east northeast wind, which brings the smoke from the New York sector. Mr. Andrus states that the pilots report that at times with clear weather and light east northeast winds the smoke region may be seen from above as a great cone-shaped drifting cloud, New York and Newark at the base, and pointing in the direction of the wind drift. Probably the most frequent dense smoke haze at Hadley is of this nature, a cloud drifting with the prevailing light winds at the subsidence inversion, that is, drifting in the inversion layer.

## *D. Maritime Fog*

In the previous discussion of the theoretical aspects of Maritime Fog,[1] it was pointed out that this formation may be of two distinct kinds. The most characteristic formation occurs soon after the movement inland of a fresh Maritime Polar Air mass as a result of its high relative humidity and the rapid cooling which always takes place in the lower levels of such a mass under those circumstances. The second kind is that which occurs in a rather warm northward moving current of transitional Maritime Polar Air. Such an air mass during its earlier history has acquired a high moisture content in the

[1] See *Monthly Weather Review*, November, 1928, p. 451.

course of active shower convection while moving southward over warmer water. As a returning current it again becomes cooled from below, stable and with very high relative humidity in the lower levels. Such a current becomes ideally suited to the formation of fog of the nature of a Tropical Air fog. Actually the fog formation occurs much more readily than in a Tropical Air current, due to the fact that cooling of the lower levels of the current occurs much more quickly than in the case of the Tropical Air. This may be explained as a result of the considerably lower temperatures and smaller moisture content in the upper levels of the current.

The first type of Maritime Fog is limited in the United States almost exclusively to the inland Pacific Coast region, west of the mountains. Along the Atlantic Coast, and therefore at Hadley Airport, it does not occur, simply because there is no real movement of fresh Maritime Polar Air masses inland from the North Atlantic. The large anticyclonic formations over the Eastern United States occur always in Continental Polar Air from the interior of the continent. It sometimes happens along the coast that northeast winds bring a certain amount of Maritime Polar Air some distance inland, but that is not at all in the nature of a real air mass movement inland, for the sojourn of such air over water has usually been too short to render it truly maritime. Furthermore, it usually takes place in advance of an approaching cyclone, in the prefrontal region of falling pressure and warm front rain. Hence the fog that normally occurs in this situation is in the nature of a warm front Prefrontal Fog, and is classified as such. Maritime Fog of this first type occurs in fresh Maritime Polar Air masses of marked convectional activity passing from a warm water surface to a cold land surface. The only extensive movements of North Atlantic air inland are those which occasionally occur in the spring when the water surface is relatively cold and the air masses stable, which is a very different situation.

The point was made in the discussion of Radiation Fog that frequently at Hadley the high humidity which favors the formation of a Radiation Fog on a clear night is to be attributed to a preceding northeast or east wind from the coast, especially on the north side of a cyclone passing northeastward off the coast and followed by clearing. To this extent the maritime influence may play a part in the formation of local Radiation Fog at Hadley, but such fog is not at all the extensive deep formation which is true Maritime Fog, moving with the air mass as an advection fog.

The second kind of Maritime Fog is of much greater significance in the Eastern United States. It appeared in the analysis of Radiation Fog at Hadley Airport that the most frequent occurrence of Radiation Fog (see p. 11) is in the return flow of transitional Maritime Polar Air behind an extensive anticyclone moving off the coast. Usually at Hadley such a situation gives only a local morning Radiation Fog. But sometimes a very extensive formation of Maritime Fog which persists for days may occur in such a current. The densest, most extensive, and most persistent fogs which occur in the Eastern United States are usually of this type. Over the Southern Appalachian region an extensive Maritime Fog frequently occurs when at Hadley there is only the local Radiation Fog. (See maps IV and VI.) It is always the most extensive and persistent return flow of transitional Maritime Polar Air which gives the very widespread and dense Maritime Fog formations that extend northward beyond Hadley.

Although these most extreme cases of Maritime Fog are rather infrequent, the development in every instance is so identically the same, so striking, and of such practical importance in the forecasting of fog in the Eastern United States that a rather detailed description of a particular case seems to be in order here. An excellent case is that from December 28–31, 1927. (See maps IX–XII.) For more than a week preceding the fog, a steady flow of Polar Air southward over the Atlantic had been taking place, as shown best by the observations from Bermuda. The result was a very extensive development of the Bermuda High, which maintained a steady flow of air eastward and northward from the South Atlantic over the Gulf of Mexico and the Southeastern States. A stationary trough of low pressure in the far west brought this transitional Maritime Polar Air current northward over the whole United States east of the Mississippi. For many days this situation was nearly stationary, so that the transitional Maritime Polar Air, cooled and very moist in the lowest levels, invaded the entire Eastern United States. The fog first appeared along the Gulf Coast and in the Middle West on December 28. It appeared progressively eastward and northward on the following days, so that by the morning of December 30, forty Weather Bureau stations in the Eastern United States from the Gulf of Mexico to Northern Maine reported dense fog. This entire air current was warm, but appreciably cooler than if it had originated as Tropical

Air from the Gulf of Mexico. It was also characterized by greater cooling during the night than Tropical Air so that the fog appeared especially marked on the morning maps. However, both general fog and low stratus were present both morning and evening. The deepening and eastward advance of the low pressure trough over the far West resulted in a strengthening of the southerly current, and a general inflow of real Tropical Air from the Southern Gulf of Mexico over the Eastern United States. The northward advance of this Tropical Air current was marked by clearing and warmer, with total dissipation of the Maritime Fog. At Hadley Airport dense fog was present from 8 p.m. of December 29 to 10 a.m. of December 31, without a real let-up. The fog was brought to an end by the advance of the warmer Tropical Air. Snow on the ground always favors such a fog at Hadley, but in this particular instance the ground was bare.

It is noticeable in this situation that at first there is no abrupt transition from the cooler Maritime Polar Air to the warmer Tropical Air. On the map of December 30, 8 a.m., fog appears along the Gulf Coast in what is probably the foremost portion, somewhat cooled, of the warmer air current. But as this current advances northward under the influence of the deepening disturbances to the west, the temperature contrast between the Maritime Polar Air and the displacing Tropical Air current becomes more marked. At the same time the appearance of fog is limited strictly to the cooler air mass. The conservatism of the high temperature of the Tropical Air current when moving northward over a land surface is always striking, and serves as a distinguishing mark in contrast to the readiness with which cooling takes place in the Maritime Polar or Transitional Air current.

## II. FRONTAL FOGS

### *A. Prefrontal Fogs*

The study of the Hadley Airport data shows that, at least as far as that locality is concerned, the Prefrontal Fogs are the only group of the Frontal as opposed to Air Mass Fogs which have any real significance. However, this group is of very frequent occurrence at Hadley, being exceeded only by Radiation Fog and Monsoon Fog. In the period studied there were no less than thirty cases of Prefrontal Fog at Hadley Airport. Twenty-one of these, including all the densest and most persistent fogs, occurred before a warm front. Of the others, five occurred before an occluded front and four before a cold front. It is evident that of the Prefrontal Fogs those occurring before warm fronts are of much the most importance.

The formation of the Prefrontal Fog is really due to two things: (1) the saturation of the cold air mass in advance of the warm front or occluded front by the falling frontal precipitation, and (2) the adiabatic cooling of this mass as a result of the prefrontal pressure decrease. Both of these factors are most effective before the warm front of a vigorous cyclonic development. Therefore the Prefrontal Fogs are most marked before warm fronts, and during the season of greatest cyclonic activity. This explains the predominance of the warm front type at Hadley, and furthermore the greater frequency of these fogs during the winter months. Of the thirty fog formations at Hadley classified as Prefrontal Fogs, twenty-four of them occurred during the five months of November through March. It also explains the fact that the best Prefrontal Fog formations occur in well marked zones immediately before the passage of the warm front, but entirely in the preceding cold air mass. Good illustrations of such well marked zones in the region of Hadley Airport are to be found on maps for December 18 and 19, 1929. (See maps XV–XVIII.)

It will be noticed in the case of this well-marked almost stationary warm front that the region of the fog formation was directly in advance of the front where there occurred a steady fall of pressure, and that this area was generally characterized by considerable precipitation, although not always lying entirely within the rain zone at the hour of observation. Another good instance of Prefrontal Fog is shown on the maps of March 20, 1927, 8 p.m. and March 21, 8 a.m. (See maps VII and VIII.) In this case also the front is nearly stationary, but the pressure falling in advance of it. Such a condition is most favorable for the thorough saturation of the shallow cold air layer lying in advance of and beneath the warm front. The local records at Hadley show that almost invariably the shift of wind and rising temperature which mark the warm front passage also terminate abruptly the fog. With the passage of a cold front or occluded front it is the arrival of more rapidly moving, unstable, turbulent air which quickly appears both colder and drier than the preceding foggy air mass that ends the fog. However, it frequently happens that the appearance of typical pre-warm front fog at Hadley is not followed by the arrival of the warm sector of the disturbance at all. Very often the open warm sector passes off the coast south of Hadley, so that the station remains in the cold air, the winds backing from east through north to northwest. However, the large local pressure decrease and the prefrontal rain are both marked at Hadley in such cases. This is the characteristic development of affairs when the center of the disturbance passes northeastward east of the Appalachians, as was pointed out in explaining the rare occurrence of real Tropical Air at Hadley in the winter time. The fog usually ends in such cases as the wind goes to north and northwest and freshens. This is the way in which the fog situation of December 18–19, 1929 was concluded. (See maps XV-XVIII.) The disturbance passed off the coast just south of Hadley, which never came into the warm sector.

The other most characteristic development, when the warm front disturbance passes northward west of the Appalachians, is that in which the warm sector remains open far to the north, even to the Great Lakes west of the mountains, until the passage of the cold front. This situation is ideal for the long persistence of the densest Prefrontal Fogs. The thin cold air sheet is kept continuously saturated by the passing through it of warmer rain and the steadily falling pressure, and it keeps its position long after it would naturally have been cleared out by the Tropical Air current. Typical instances of this are furnished by the maps for March 20, 1927, 8 p.m. and March 21, 8 a.m. and January 16–17, 1928. (See maps IV–VIII.) In the former case there was a well marked Prefrontal Fog belt in the cold air, in the latter case Hadley had fog, though no general fog zone appeared on the map. In neither case did Hadley come into the warm sector at all.

Probably one reason why Prefrontal Fogs, especially before warm fronts, are of such frequent occurrence in the North Atlantic coast region is due to the fact that very frequently the retreating cold air mass is Maritime Polar Air. Sometimes it is a return current of rather warm Maritime Polar Air from the southeast. The great fog-forming capacity of this air has already been considered at length under Maritime Polar Air fogs. Thus a very little addition of moisture by rain and cooling by expansion should be sufficient to cause the formation of fog in such a current. Sometimes also the prefrontal cold air is Maritime Polar Air which is brought in by northeast winds directly from the North Atlantic. Such air is colder than the other, but also very humid and quick to give fog. In the case that this air was formerly a warmer current from the south, cooled over the cold waters on the North Atlantic coast, it may have Sea Fog or Monsoon Fog already formed in it. In this case the prefrontal northeast winds bring on shore a ready formed fog. This is the normal situation in the late spring and summer time. In that season cyclonic movements and developments are slow, the prefrontal influences are greatly decreased, while the Monsoon Fog conditions are constantly present. Hence in summer the ideal Monsoon Fog situation is very similar to the Prefrontal Fog situation in winter. And even in winter when there has been an unusually warm southerly current blowing over the North Atlantic the typical prefrontal easterly winds may bring Monsoon Fog on shore. It was pointed out that Monsoon Fog was found at Hadley for every month except the autumn months. However, if complete observational data is at hand, it should not be difficult to distinguish these fogs, for Monsoon Fog is an advection fog, being brought inland from a distance, and normally appearing first above the ground as a low stratus. The Prefrontal Fogs, on the other hand, are formed locally with very light wind, appearing first as a ground fog in low-lying places and growing upwards. Usually they develop only during a period of falling rain, normally the warm front rain.

There was nothing of importance about the occluded front and cold front prefrontal fogs which occurred at Hadley. They were much less frequent, less dense, and less persistent than the pre-warm front fogs. Prefrontal fogs are less pronounced over Northern Europe than on the North Atlantic coast of the United States. Probably this is because the prefrontal cold air mass in Europe is normally a very dry cold current of continental polar air, whereas on the Eastern coast of the United States it is likely to be quite maritime in nature.

### *B. Front Passage Fogs*

Front Passage Fogs, as might be expected, are of negligible importance at Hadley Airport. There were but four cases of fog at Hadley during the period studied which might be classed as fogs of this type. Of those four fogs, three were light, and the classification of all four is somewhat doubtful. Furthermore they were all of brief duration, as such a fog must be by its very nature. The three light fogs occurred in summer, in every case when the front passage was preceded two or three hours by a prefrontal thundershower. In each case the front passage was indicated by the wind shift and change to cooler in a flat shallow depression. Preceding the thundershower the weather was always fair, very warm, and humid. This was followed by the thundershower and cooler air, the weather remaining calm, overcast, and relatively cool till the front passage. This meant probably a stable lapse rate and evaporation from the warm moist ground, so that the air became practically saturated. The front passage was in each case represented by lowering stratus to an elevation of 150 or 200 feet, when light fog was reported. Shortly afterwards the fog and very low stratus cover vanished with the appearance of a moderate cool northwest wind of gradually decreasing humidity. The fog at the front passage and the very low cloud base quite possibly were caused by mixing of the two air masses rather than the sinking of the real frontal cloud system to the ground.

The one case of a dense Front Passage Fog occurred in October with the passage of a warm front, and may have been an instance of the real frontal cloud system resting on the ground. The warm front was preceded by the normal warm front rain, and low stratus decreasing from 300 feet to 0 feet elevation with the approach of the front. The passage of the front was followed by clearing and warmer, with high clouds only.

It would be expected that at Hadley Airport the passage of a frontal cloud deck very close to the ground must be an exceedingly rare occurrence. But this is what constitutes a real Front Passage Fog. In the discussion of these fogs it was pointed out that they are really migrating low cloud systems, and appear very rarely as a surface fog except at stations situated at a high elevation and in an exposed place. A west coast station at a high elevation might expect very frequently to be enveloped in the frontal cloud system, which reaches its lowest elevation at the front passage, and therefore to have surface fog. But at Hadley Airport the conditions are very different. It is an east coast station very little above sea level, and with considerably higher elevations to the west, the direction from which the majority of fronts approach. It follows from this that Hadley is very unlikely to be enveloped in any low frontal cloud deck. And since this discussion of fogs covers only surface fogs, it is quite clear why so few front passage fogs were found at Hadley. Presumably the migrating low cloud systems are of very frequent occurrence there.

This completes the discussion of the fogs occurring at Hadley Airport during the period investigated. It is quite evident that a satisfactory and complete classification and explanation of the fogs found there, as at any other station, can be made only with much more complete observational data, including carefully analyzed maps with local upper air observations for particular situations. Any general discussion such as the present is of necessity indefinite and unsatisfactory. However, it shows that in general the same principles are applicable in explaining and forecasting fogs in the United States as in Europe, although there are many locally variable factors which must receive especial consideration. This is always true of local fog forecasting.

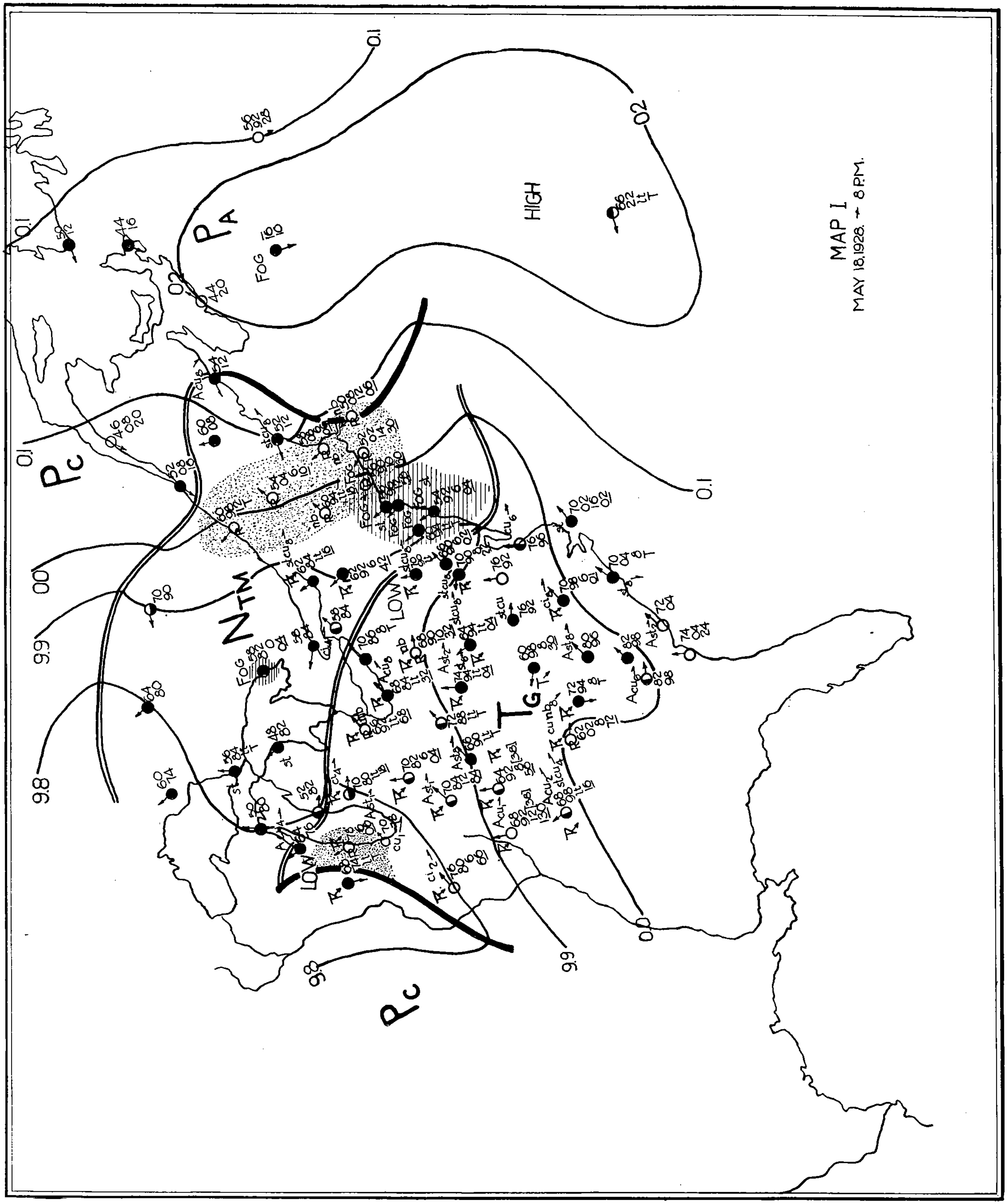
## EXPLANATION OF MAPS

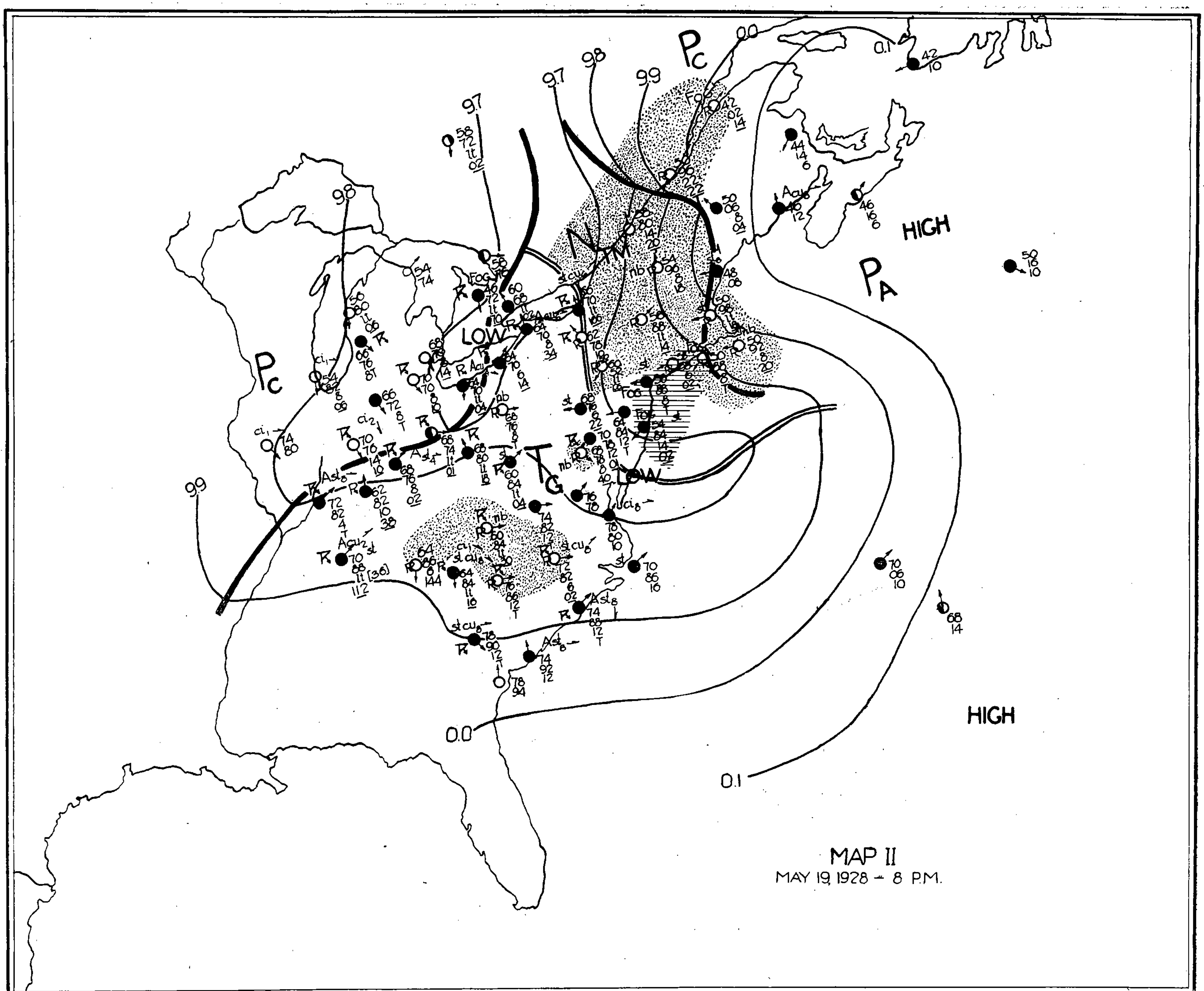
1. Entering of the data: The data entered on the maps at each station indicates the complete material at hand for that station with the exception of Hadley Airport. The material is taken directly from the United States Weather Bureau working charts. Within the circle at each station is entered the state of weather at time of observation, as clear ○, partly cloudy ◐, cloudy ●, rain RↃ, or snow SↃ. The arrow drawn from the circle indicates surface wind direction. Of the column of figures placed close to each station, the uppermost gives the temperature to the nearest even degree Fahrenheit, the next one gives the barometer reading reduced to sea level to the nearest even hundredth of an inch (the number of whole inches is omitted), and the third and fourth figures, when present, give the wind velocity in miles per hour, and twelve hour precipitation in hundredths of an inch. The letter "T" indicates a trace. The pressure change for the two hours previous to the observation, when amounting to four one-hundredths of an inch or more, is indicated by a figure written a little apart from the others and is preceded by a plus or minus sign according to the tendency. Cloud forms are entered in the standard abbreviations, the amount of each form in tenths of the sky overcast being indicated by a subscript. The direction of movement of each cloud form is indicated by a small detached arrow.

The occurrence of a thunderstorm at any station during the twelve hours previous to the observation is indicated by the usual symbol, and whenever present a subscript on this symbol gives the time of beginning, a.m. or p.m., of the thunder. The abbreviations R.B. or S.B. written near a station indicate that rain began or snow began immediately after the observation, and R.E. or S.E. the cessation of rain or snow immediately after the observation. Regions where precipitation is falling at the observation are indicated by a fine dotted shading, while regions where fog prevailed at the observation are indicated by a horizontal light line shading. The word Fog is entered at every station reporting fog at the observation, and unless otherwise specified this entry always indicates dense fog.

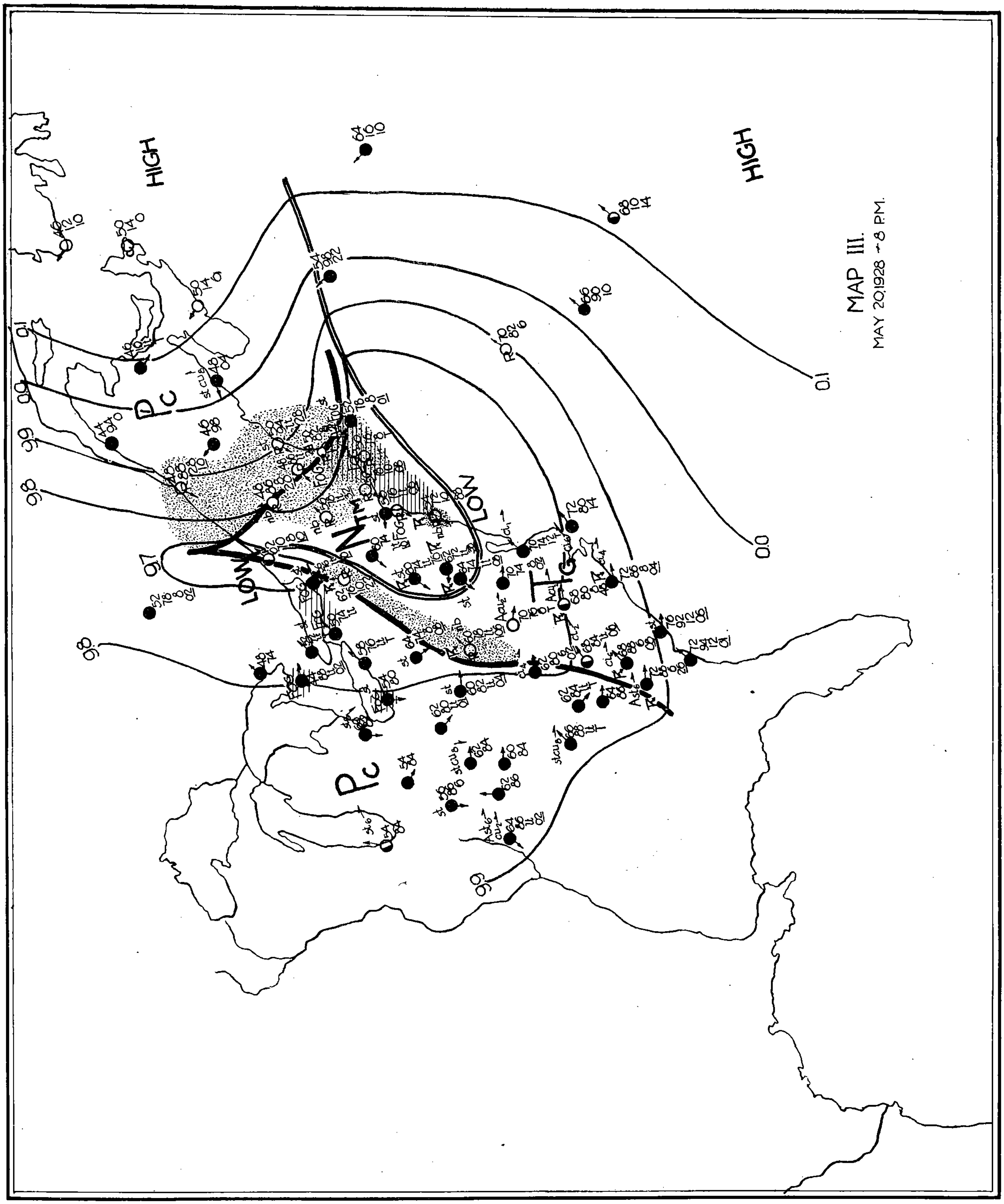
2. Air Mass symbols: The principal air mass groups are the tropical, indicated by "T," the polar, indicated by "P" and the transitional, indicated by N. The symbols $T_g$ and $T_a$ indicate tropical air masses from the Gulf and Caribbean, and the South Atlantic regions respectively. They are both warm and moist masses, normally only conditionally stable, owing to their high moisture content. (Conditional stability indicates a lapse rate between the dry and the saturation adiabatic.) $T_g$ air is slightly warmer and moister than $T_a$ air. The symbol $P_c$ indicates polar air of continental (North Canadian) origin. It is normally in winter extremely dry, very cold and very stable, at least until its properties are modified in its movement southward. In summer the only one of these properties which may still be taken as characteristic of $P_c$ air is its dryness. The symbols $P_a$ and $P_p$ apply to polar air masses from the Pacific and North Atlantic Ocean, respectively. They have normally received heat and moisture from the relatively warm water surfaces, hence in winter are characteristically unstable and showery. In summer they are distinctly cool and stable, sometimes foggy. It should be noted, also, that $P_p$ air masses which have passed eastward over the Rockies and other western mountains lose the greater part of their moisture in this process and become rather dry and variable in temperature. The transitional symbol N is applied to air masses which have lost their distinctive initial characteristics. $N_{pc}$ and $N_{pm}$ apply to air masses, initially $P_c$ and $P_a$ (polar maritime) which have moved far to the south, been considerably warmed or otherwise modified, and perhaps appear as a northward moving current. The symbol $N_{tm}$ applies to an air mass initially $T_g$ or $T_a$ (Tropical maritime) which has moved far to the north and been much cooled in its lower layers, hence normally showing either fog or low stratus clouds.

3. Designation of Fronts: The fronts, or boundaries between air masses, are indicated by heavy lines, in contrast to the light continuous lines which represent the isobars for each tenth of an inch. Cold fronts (cold air advancing and displacing warm air at the ground) are indicated by heavy continuous lines. Warm fronts (warm air advancing and overrunning cold air at the ground) are indicated by continuous double lines. Occluded fronts (trough of minimum pressure at the ground where warm air displaced by cold air at the ground lies at a minimum elevation above the ground) are indicated by heavy broken lines.

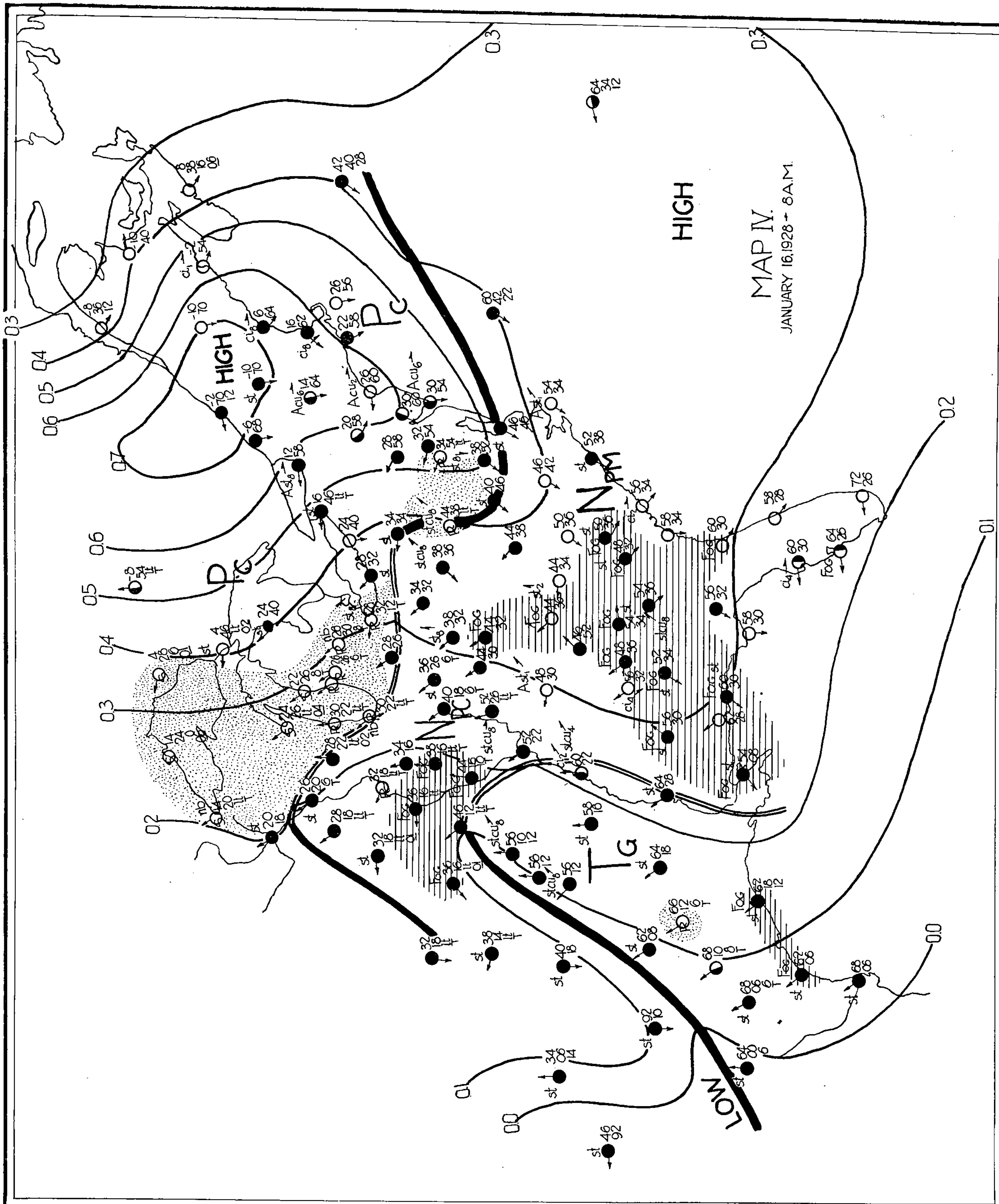

MAP I
MAY 18, 1928. — 8 P.M.
HIGH
LOW
LOW
FOG

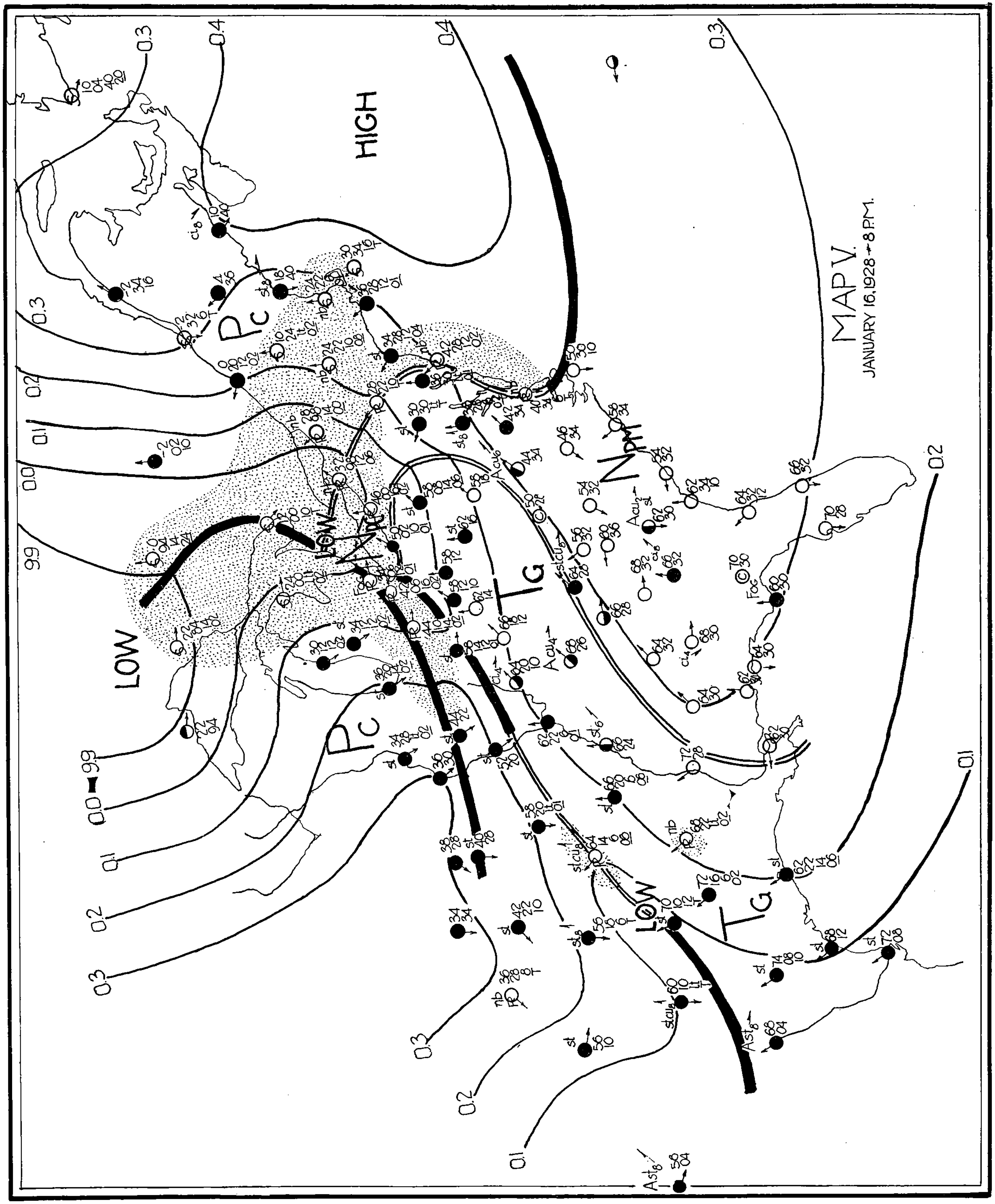



MAP II
MAY 19, 1928 - 8 P.M.

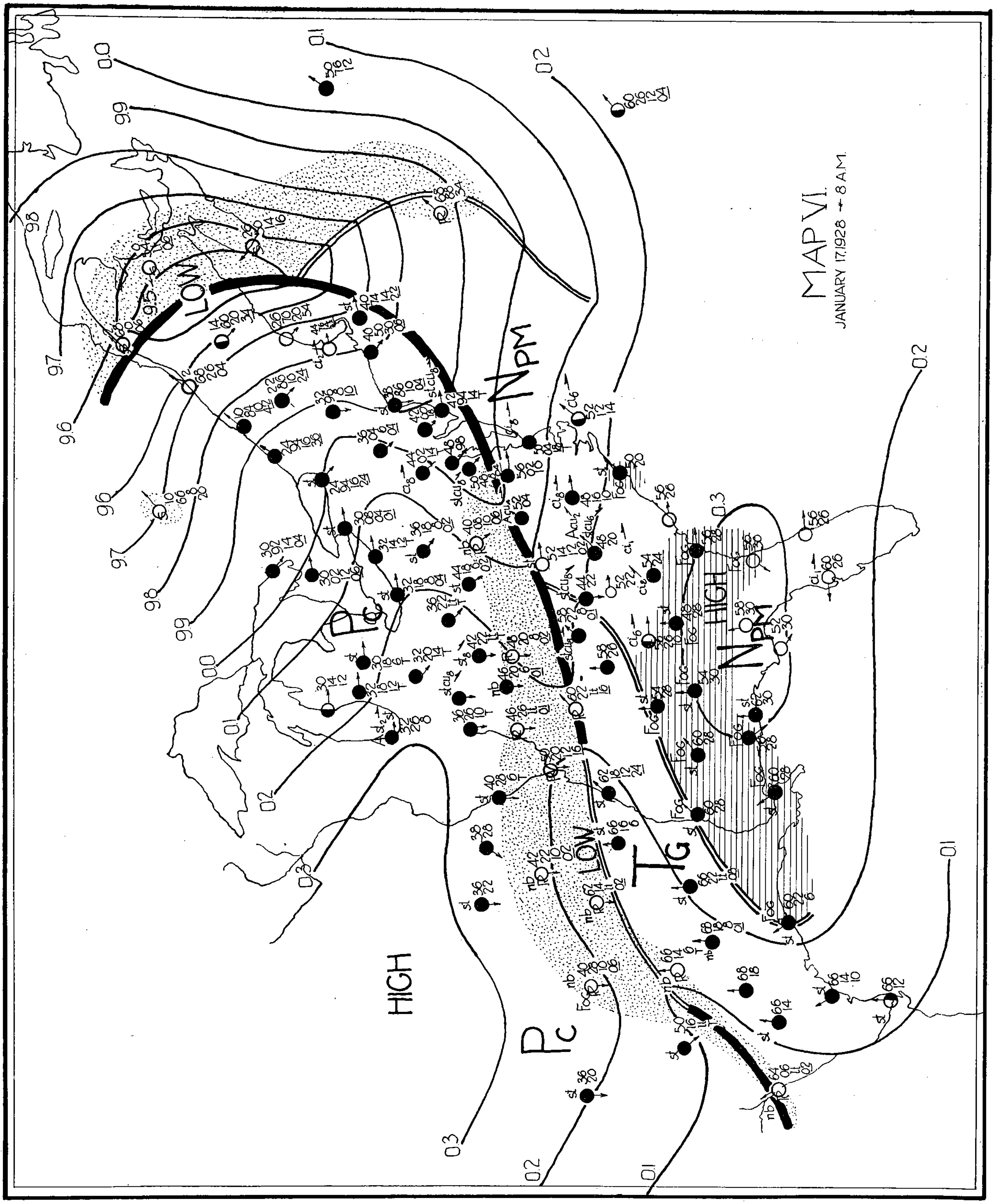


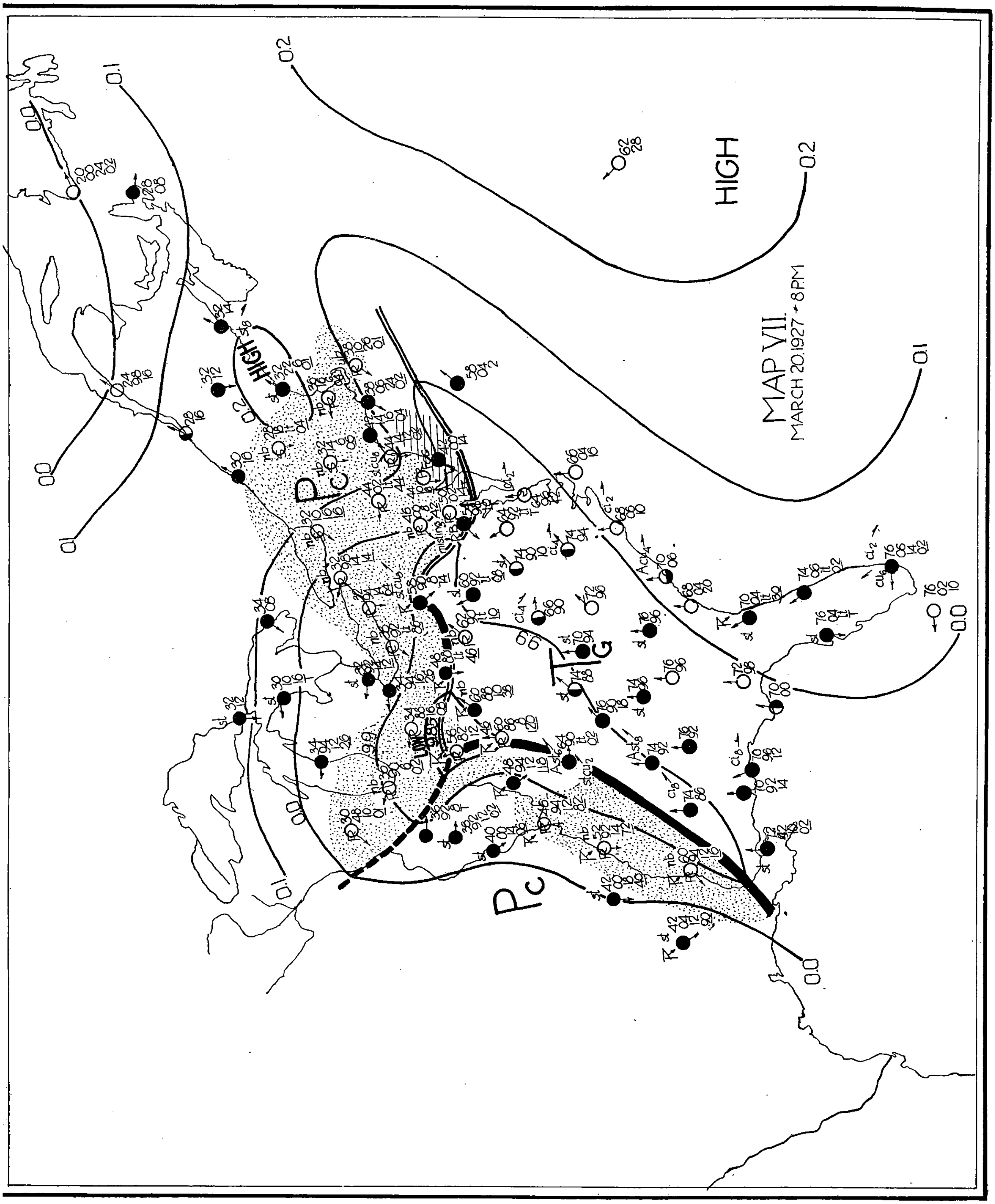
MAP III.
MAY 20, 1928 — 8 P.M.
HIGH
HIGH
LOW
LOW
Pc
Pc
FOG

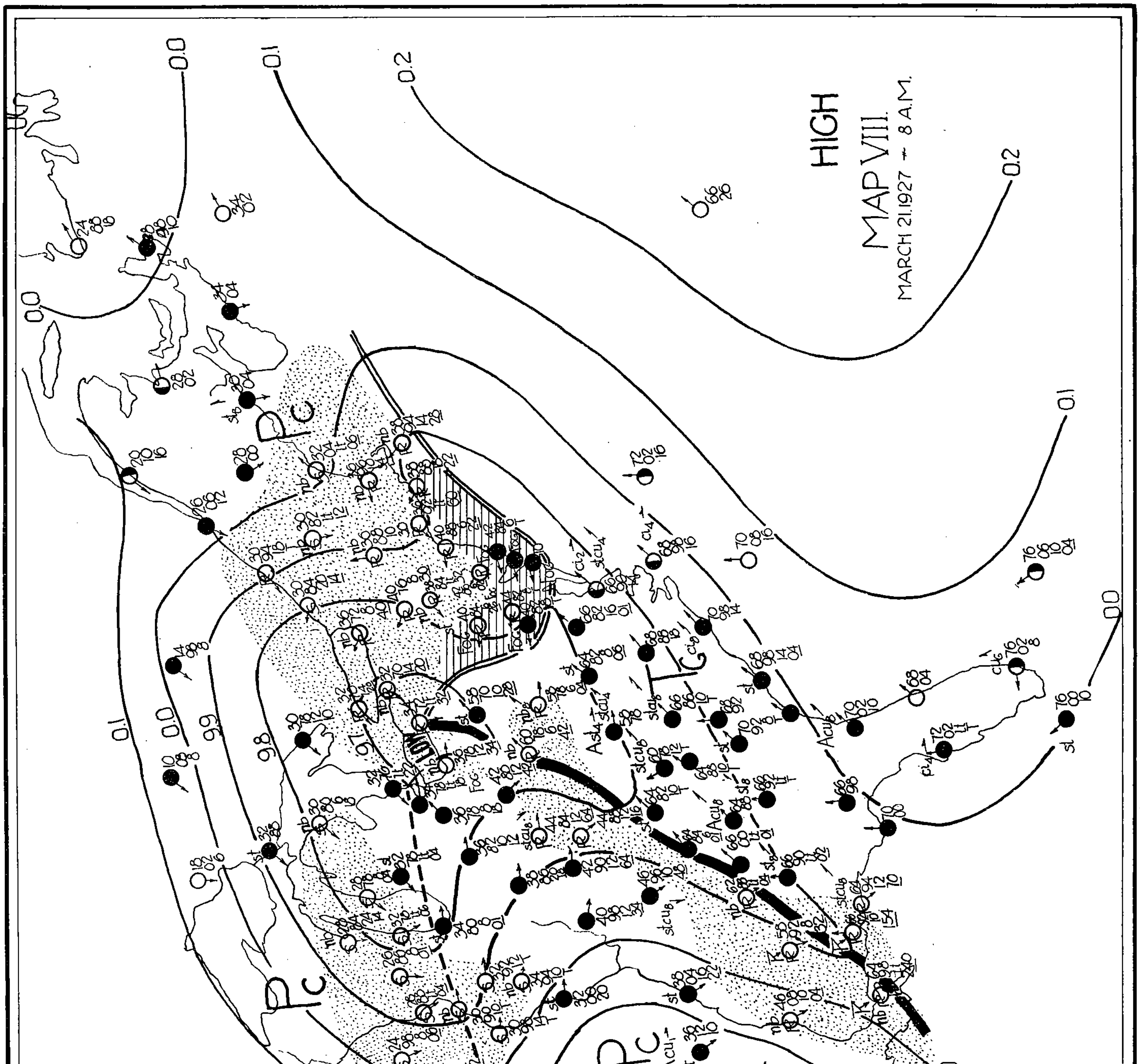

MAP IV.
JANUARY 16, 1928 - 8 A.M.
HIGH
HIGH
LOW

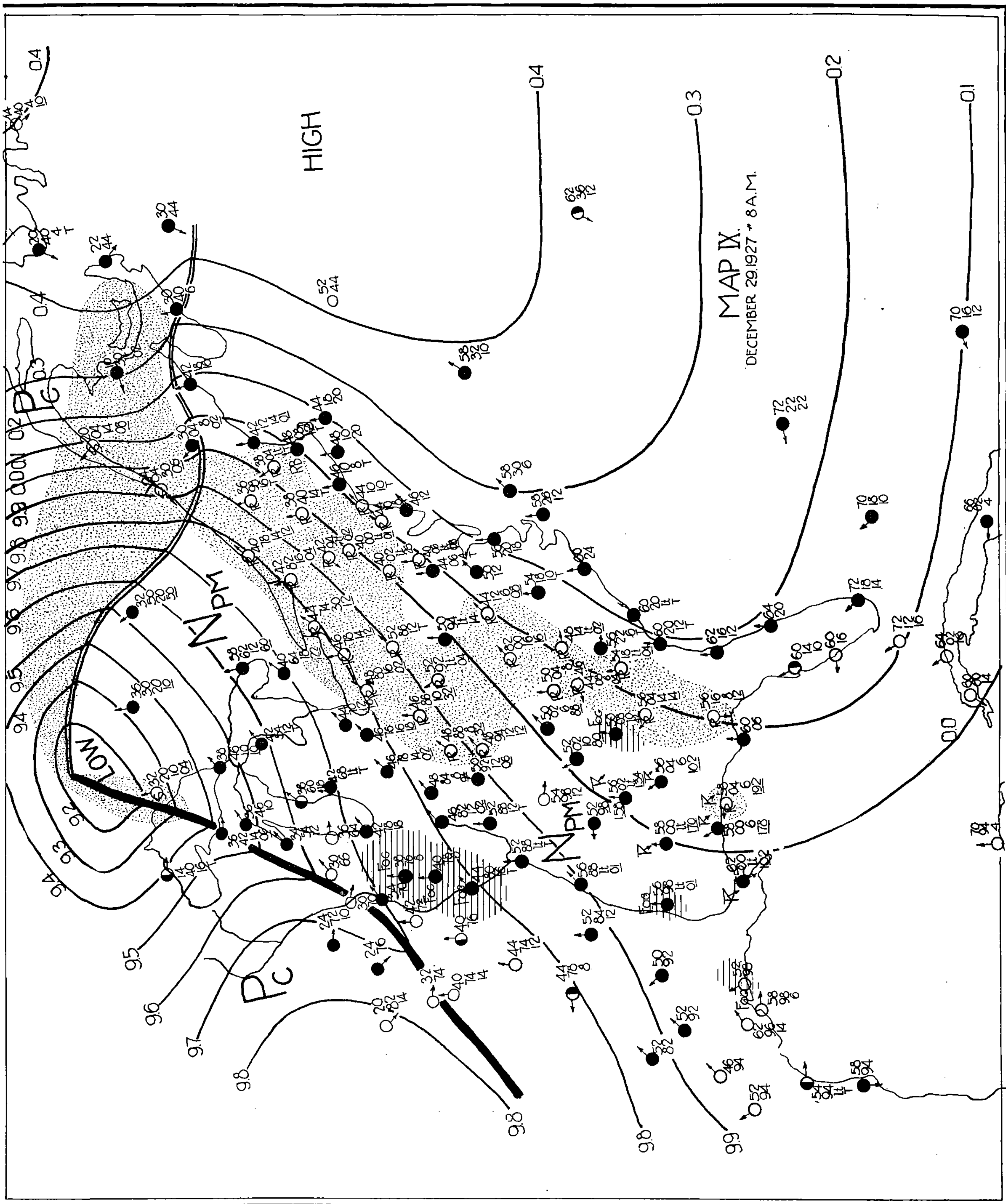


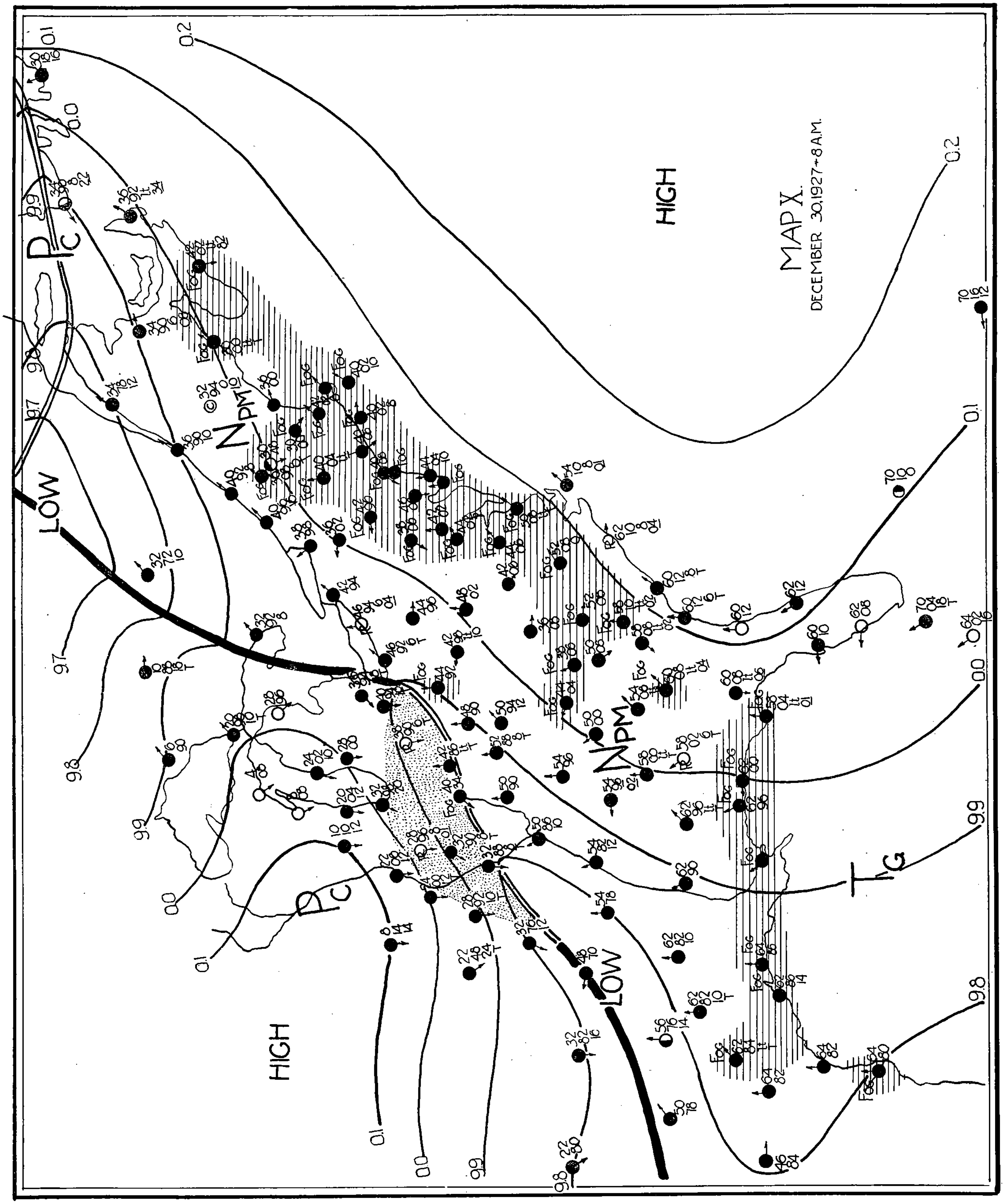

MAP V.
JANUARY 16, 1928 → 8 P.M.

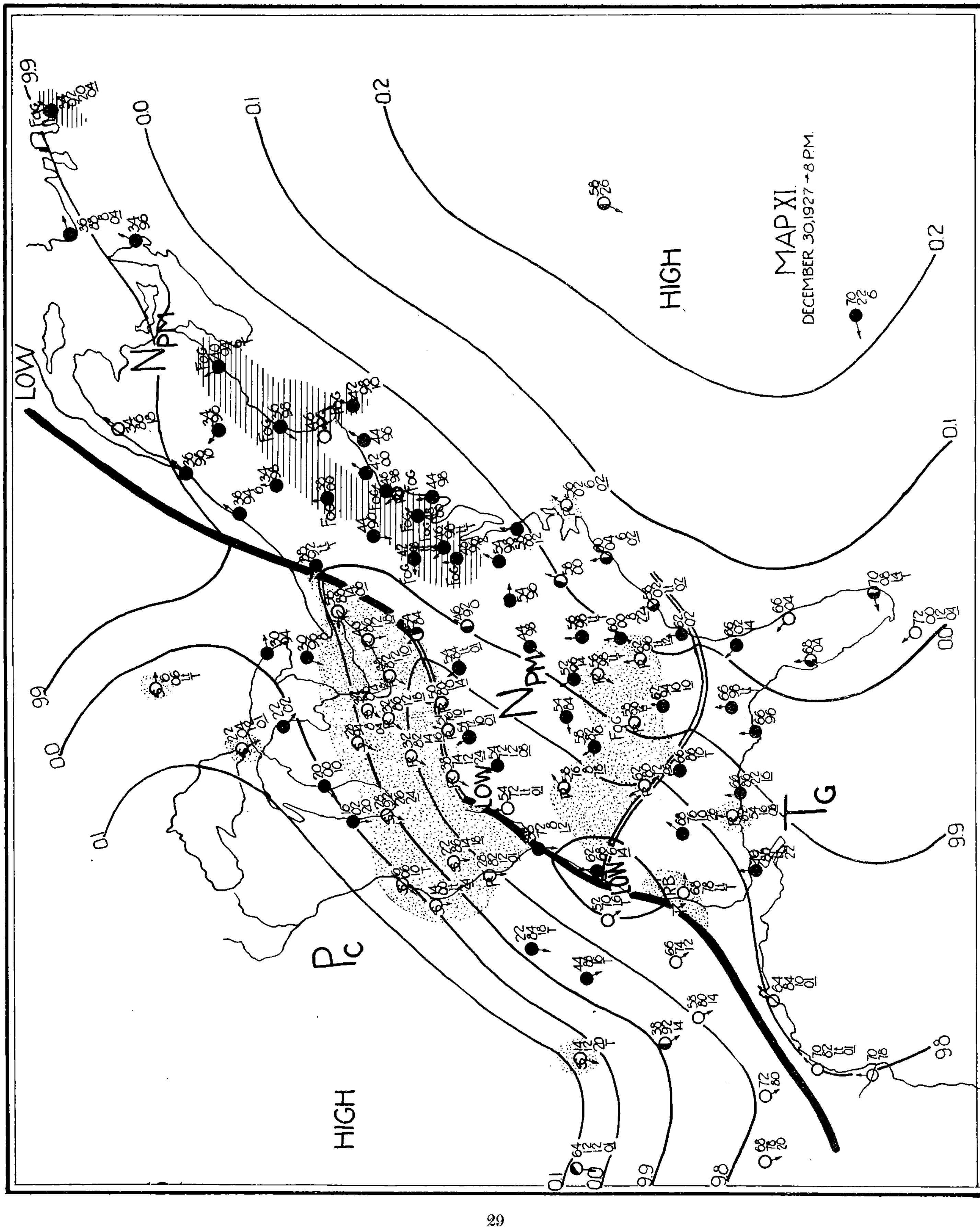

MAP VI.
JANUARY 17, 1928 — 8 AM.
HIGH
LOW
HIGH
LOW
HIGH
NPM
NPM
TG

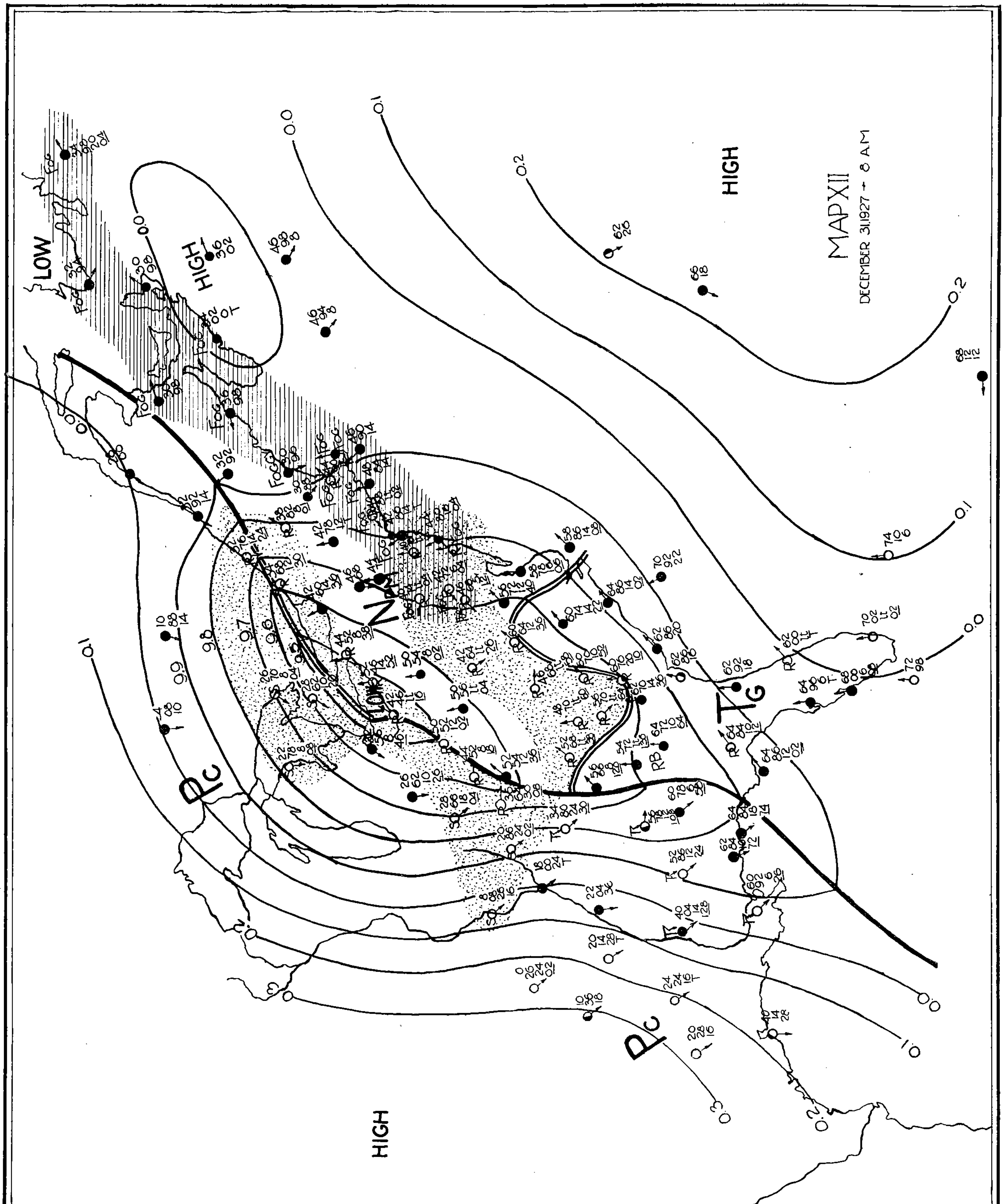

MAP VII.
MARCH 20, 1927 - 8 PM
HIGH
LOW

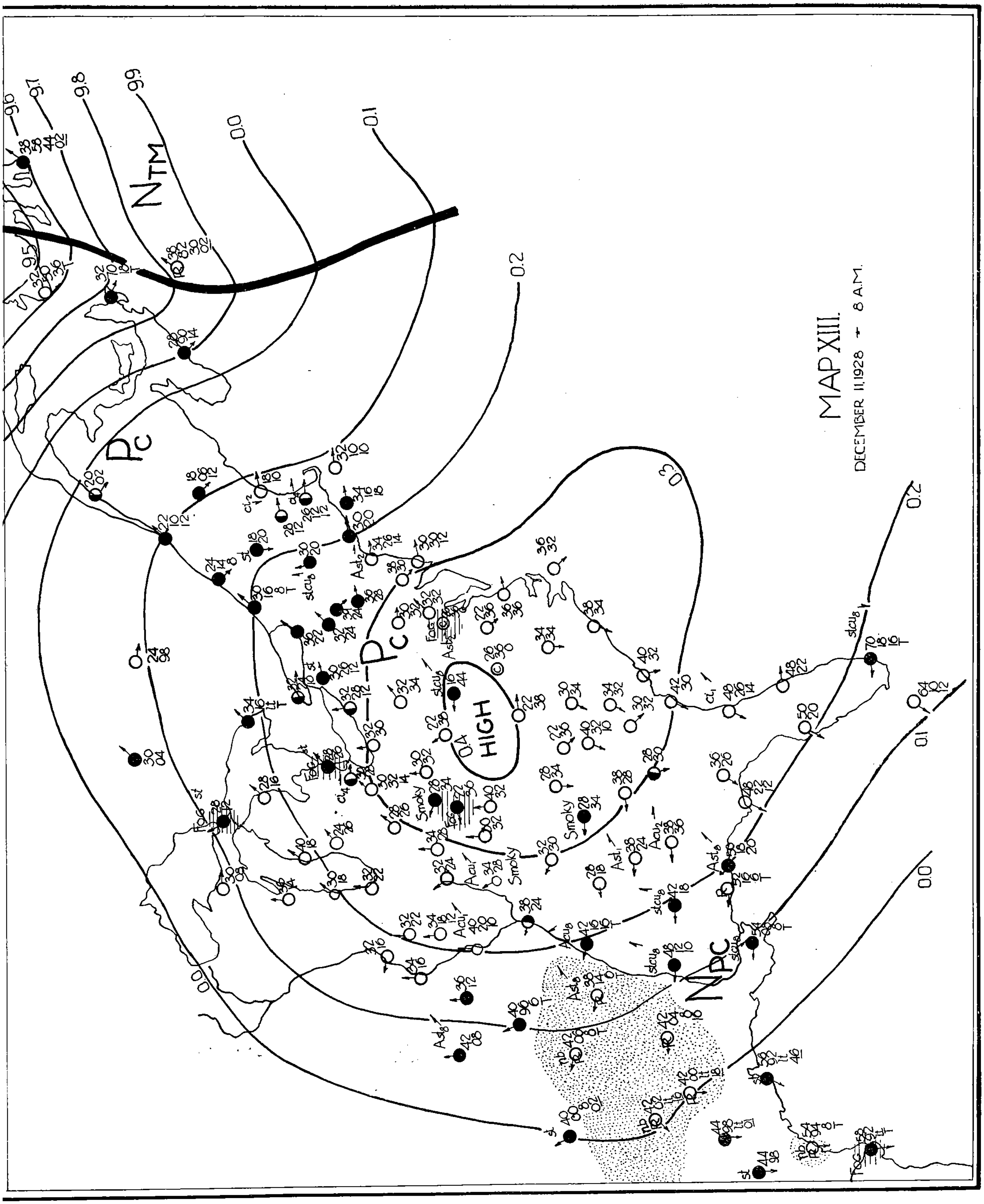

HIGH
MAP VIII
MARCH 21.1927 — 8 A.M.
LOW

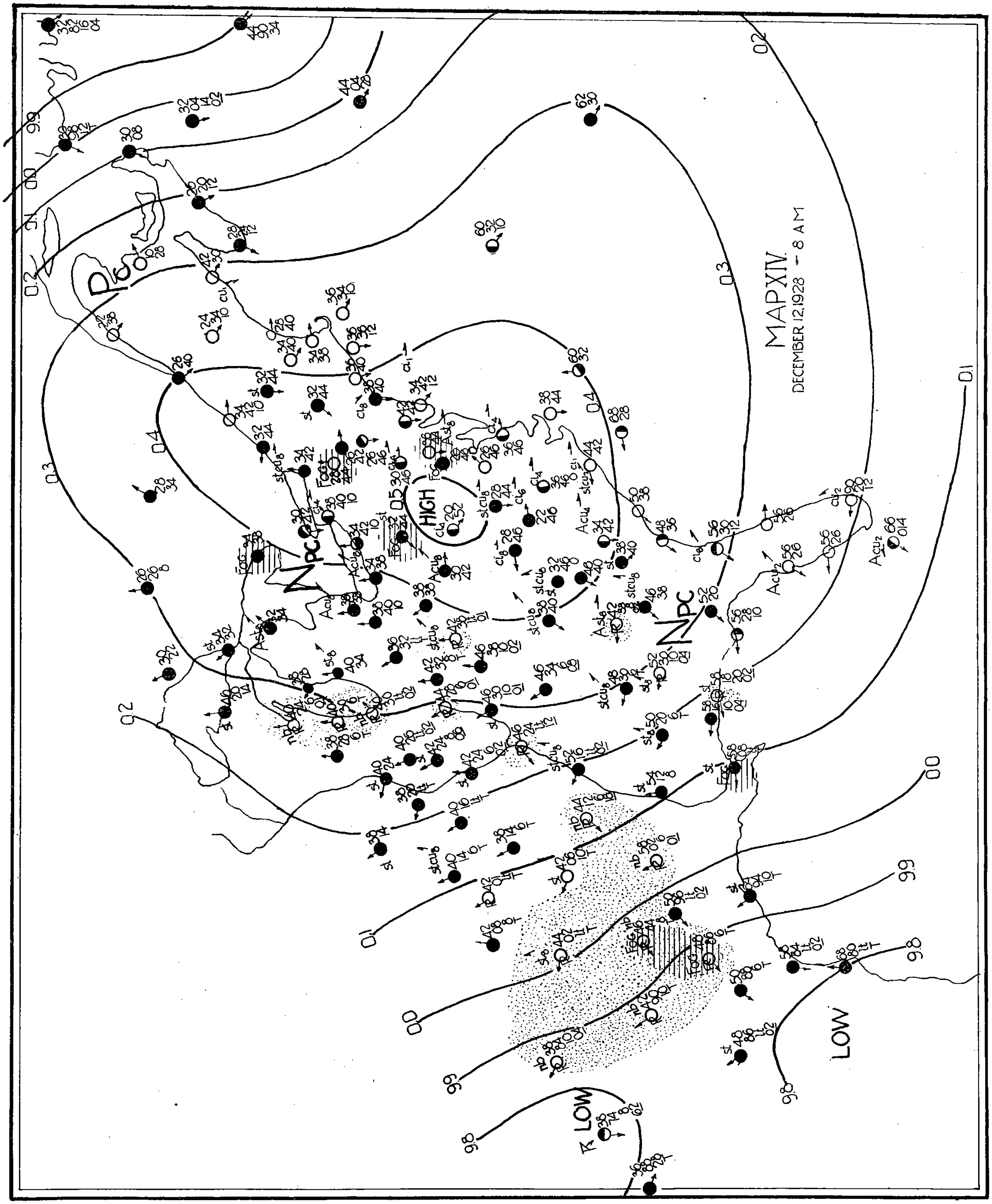

MAP IX.
DECEMBER 29, 1927 — 8 A.M.
HIGH
LOW

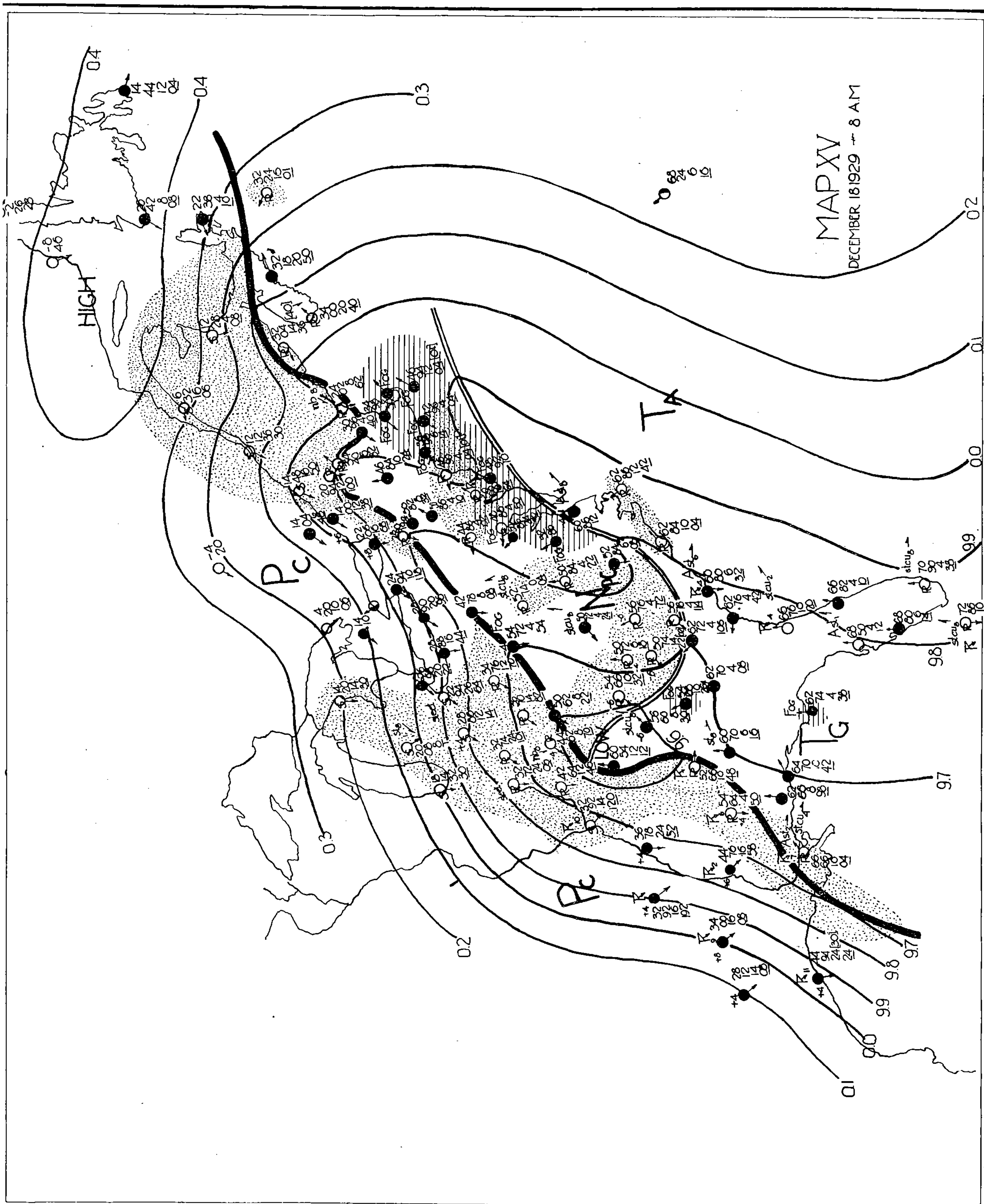

MAP X.
DECEMBER 30,1927—8 A.M.
HIGH
LOW
HIGH
LOW

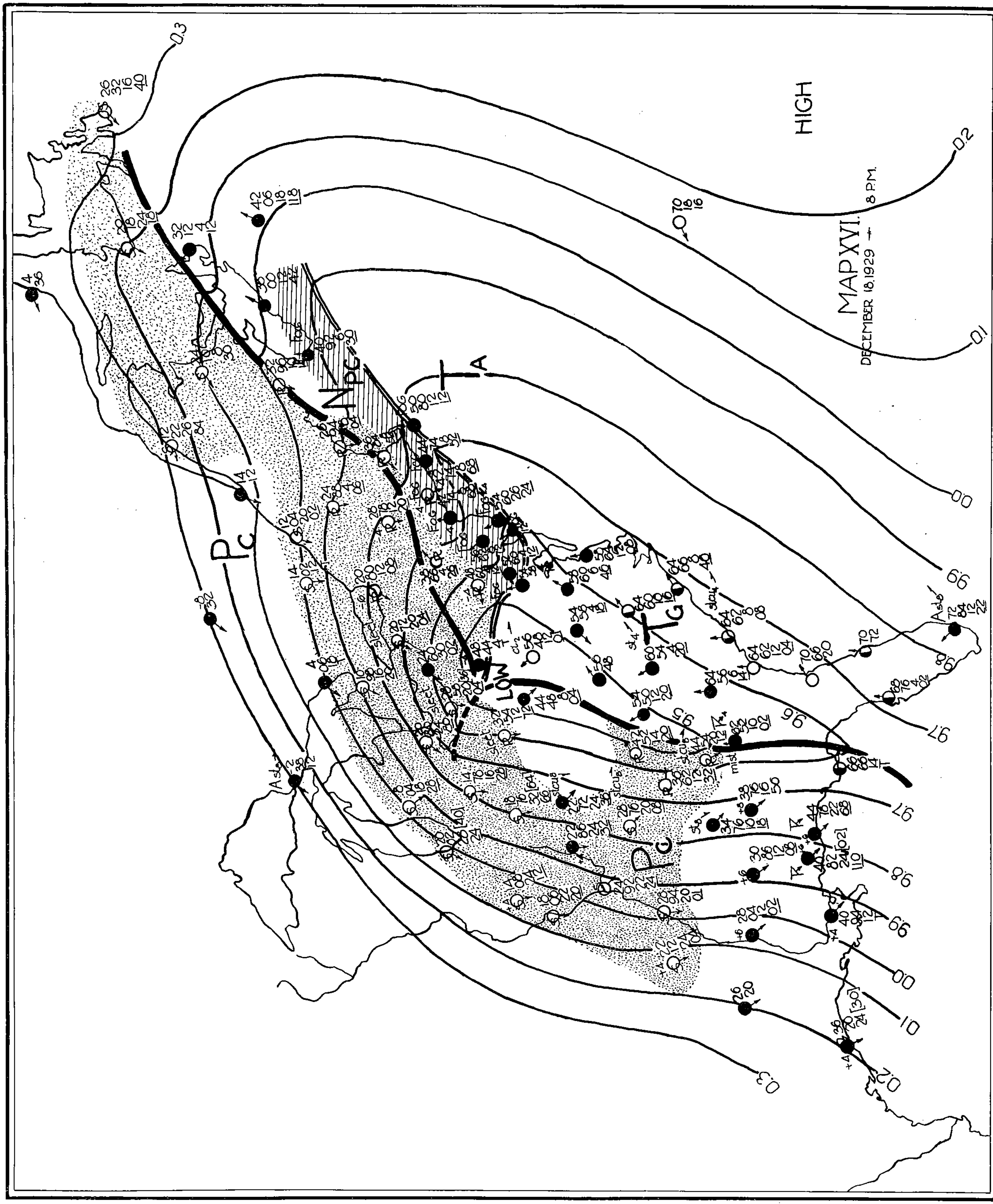

MAP XI.
DECEMBER 30, 1927 – 8 P.M.
HIGH
LOW
HIGH
LOW
$P_c$
$N_{PM}$
$N_{PM}$
$T_G$
FOG

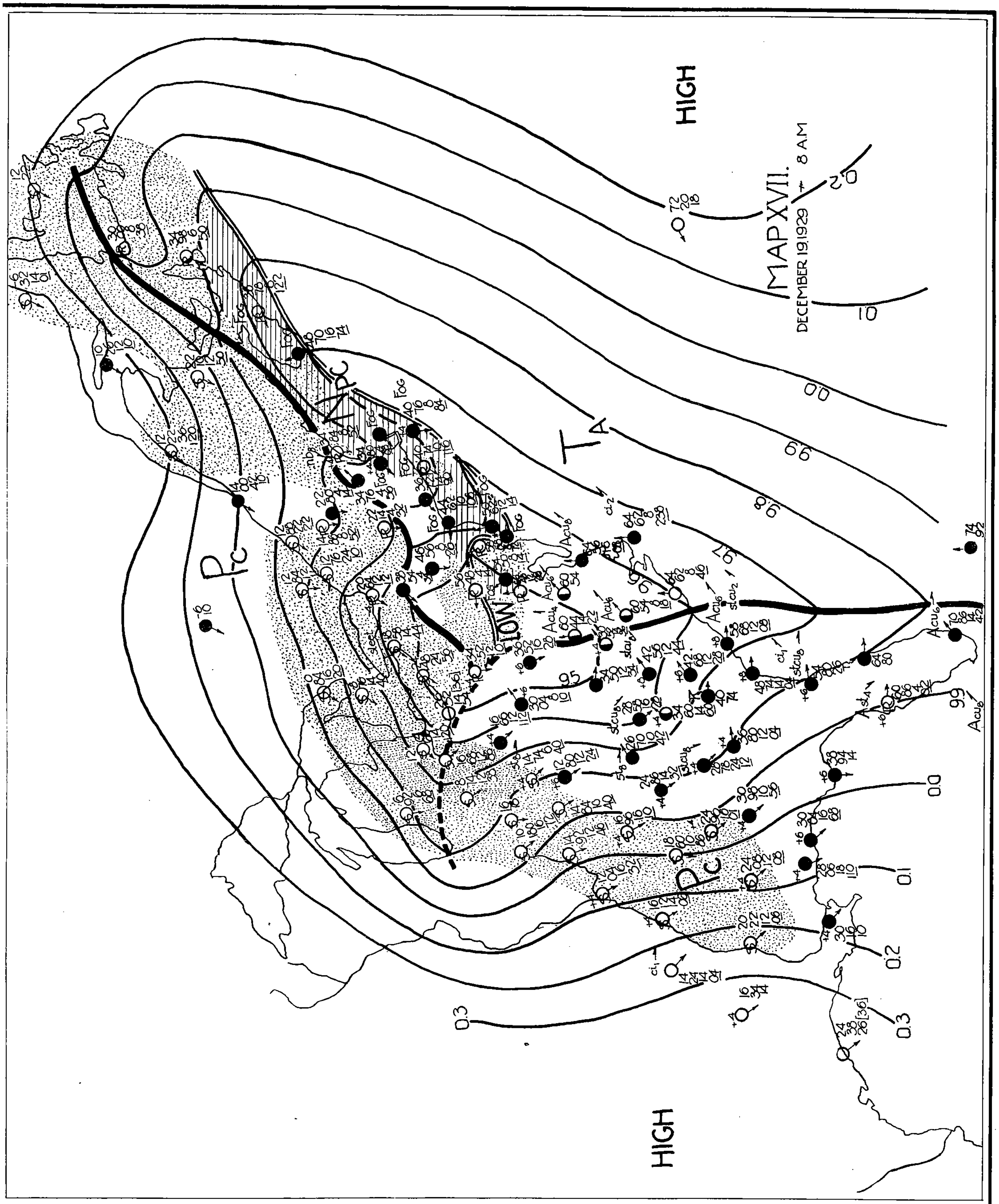

MAP XII
DECEMBER 31, 1927 — 8 A.M.
HIGH
LOW
HIGH
HIGH

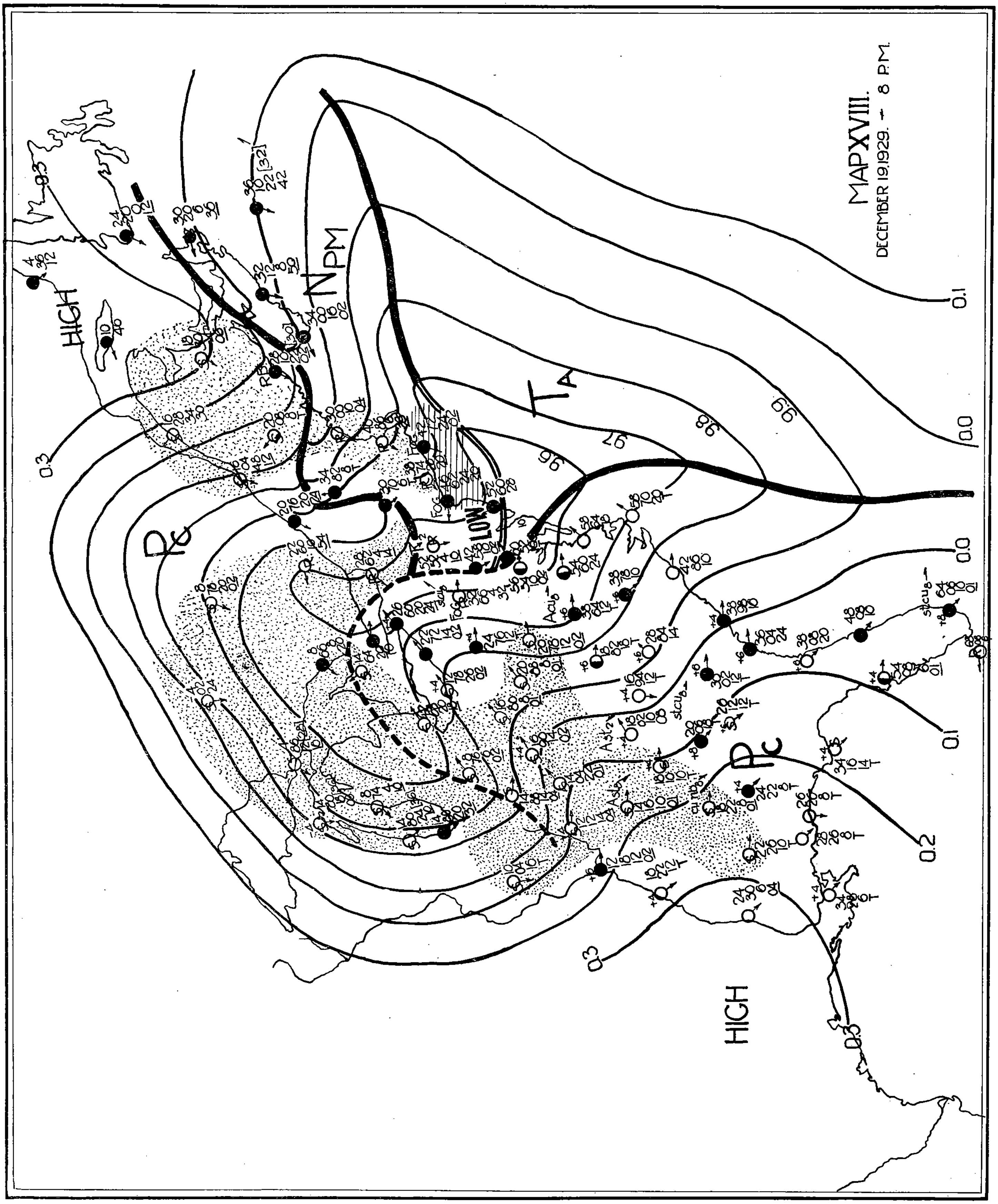

MAP XIII.
DECEMBER 11, 1928 — 8 A.M.
HIGH
0.4
$N_{TM}$
$P_C$
$N_{PC}$


MAP XIV
DECEMBER 12, 1928 — 8 AM
HIGH
LOW
LOW


MAP XV
DECEMBER 18 1929 — 8 AM
HIGH
LOW


MAP XVI.
DECEMBER 18, 1929 — 8 P.M.
HIGH
LOW


MAP XVII.
DECEMBER 19, 1929 8 A.M.
HIGH
HIGH
LOW
TA
NPC
PC
PC


MAP XVIII.
DECEMBER 19, 1929. — 8 P.M.
HIGH
LOW
HIGH

## PUBLICATIONS BY THE METEOROLOGICAL COURSE

*Meteorological Papers*

Vol. I, 1. H. C. Willett: Synoptic Studies in Fog.

*Professional Notes* (mimeographed)

No. 1. C. M. Alvord and H. C. Smith: The Tephigram, Its Theory and Practical Use in Weather Forecasting.

No. 2. C. G. Rossby: First Annual Report of the Meteorological Course of the Massachusetts Institute of Technology.

No. 3. H. B. Hutchinson: A Fog Situation in the United States During the Winter 1928–1929.