THE NATURE AND ORIGIN OF MICROSEISMS

by

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M. Sc. Dacca University
(1946)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1954

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ABSTRACT

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Submitted to the Department of Geology and Geophysics on May 17, 1954 in partial fulfillment of the requirements for the degree of Doctor of Science.

The important literature on the study of microseisms has been historically reviewed. A detailed investigation about the nature and origin of microseisms has been made by using microseism records from Harvard and Weston observatories, the swell records from Woods Hole, Mass., Gilgo, L.I., LOng Branch, New Jersey, and the surface wave reports from the weathership 4YH located at 36°N, 70°W and the synoptic surface weather maps from Logan Airport.

In order to study the nature of microseisms 1500 clear and unsuperposed wave groups were selected covering five storms. It has been observed that in almost all the cases the waves satisfy the properties of Rayleigh wave. In about two per cent of the cases studied the waves showed the characteristics of Love wave. The later wave groups were considered to be generated by some mechanisms not related to the origin of microseisms.

By comparing the amplitudes of microseisms with those of ocean waves beating against the nearby coast it has been found that the two phenomena are not directly related to each other. Similar comparisons with the wave heights in deep water as reported from the weathership 4YH showed strong correlation between the microseisms recorded at Weston and Harvard and the swells in the deep water regions of the North Atlantic. By making spectrum analysis of microseism and wave records it has been found that the frequencies of ocean waves and the microseisms are related to each other by the ratio of 1:2 as predicted from theoretical considerations. These facts led to the conclusion that microseisms are generated by standing waves in the ocean. Detailed study of the associated weather conditions led to the following conclusions.

1. Standing waves can be generated in any of the following ways.
   (a) When a barometric depression such as in a hurricane moves over the ocean surface.
   (b) When a cold front travels over the ocean surface provided the isobars while crossing the front change directions through sufficiently large angles.
   (c) When waves from two independent sources superpose on each other such as that observed by Dinger and Fisher.

2. Coastal reflection appears to be ineffective in the mechanism for the generation of standing waves as far as the eastern coast of North America is concerned.
3. The effect of attenuation on the waves when they travel through oceanic paths seems to be much less in the nothern part of the Atlantic compared to what has been observed by Dinger and Fisher in the regions of Guam.
4. The depth of water in the generating area seems to have a significant effect on the nature of microseisms. Large amplitude microseisms are generated by standing waves in the deep water regions.

Thesis Supervisor Dr. Norman A. Haskell

CONTENTS

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to Dr. Norman A. Haskell under whose supervision the work has been done, for his many helpful suggestions and criticisms. The author feels particularly grateful to Dr. L. Don lee who not only helped by supplying the records of the Harvard Observatory but also took a great interest in the investigation itself. Grateful acknowledgement should be made to a group of people who had been kind enough to supply the materials necessary for the study. Dr. Willard J. Pierson of New York University supplied the wave records from Woods Hole, Mass., Gilgo, L. I., Long Branch, N. J. Father F.J.Donohoe, S. J. made available the records of the Weston Observatory. Mr. O. Tenenbaum of Logan Airport in Boston furnished the weather maps. The surface wave reports from the weathership 4YH were made available by Mr. E. A. Murphy of M.I.T., Department of Meteorology.

The author also wishes to express his indebtedness to Dr. S. M. Simpson, Jr. and Mr. W. P. Walsh for their many technical helps.

Introduction

Observations with sensitive instruments show that the surface of the Earth is in a constant state of vibration, the intensity of which of course varies considerably. This fever of the Earth as it may be called increases or decreases due to certain reasons not yet fully understood. We are here concerned with a particular type of Earth vibration which can be distinctly identified from all other types of oscillations on records obtained at the seismological observatories all over the world. These are natural regular ground oscillations usually known as microseisms. Their origin is neither due to large scale earth movements such as in earthquakes nor due to artificial causes such as dynamite explosions or traffic. These regular ground oscillations had long been observed by the seismologists and remained as a puzzle ever since. It is perhaps on account of their unknown reasons of their origin, they had been differently named in different countries where they were studied. The Germans have called them as "Pendulunruhes" "Mikroseismiche Unruhe" "Seismiches Bodenunruche" "Bodenunruhe", "Mikroseismiche Bewegungen", "Mikroseismische Pulsationen".

The English speaking seismologists referred to them as "Microseisms", "microseismic disturbances", "microseismic waves", "microseismic tremors", etc.

In French they were mentioned as "microseisms", "oscillations microseismes", "movement microseismique", etc.

The Japanese investigators prefered to translate them as "micro-tremors", "pulsatory oscillations", "surface tremors".

"It seems quite certain that microseisms, as such, were first studied at Florence, Italy, by the Barnabite monk, Timoteo Bertelli (1826-1905) whom Milne called the "father of systematic microseismical research". Bertelli spent three years, from 1869 to 1872, making a series of simple experiments and studying the small spontanious movement of a pendulum suspended in his cellar. Such movements had been observed some centuries before but full credit should be given to Bertelli for having made thousands of observations during this three-year period, for suggesting the causes of the tremors and for introducing two names for them, "microseismic", and "moti tromometrica", the latter from tronometer or pendulum. At the end of Nov. 1872, he arrived at the three conclusions "(1) the microseismic movements of an isolated pendulum often occur contemporaneously with distant earthquakes, (2) others occur during continued barometric depressions, and (3) the movements have a maximum in winter and a minimum in summer". (Ramirez)[83]

In Japan the problem was first discussed by Milne[73] and later by Omori[77,78]. From their observations at Tokyo they classified these pulsations as they called them, into types q, Q_1 and Q_2 according to their periods of oscillations.

At the turn of the century after the development of more refined instruments and newer techniques, the study of microseisms received an added impetus in other countries especially in Europe. A group of investigators in Gottingen stressed the importance of the study of these mysterious pulses observed on seismological records. In 1905 Wiechert[93] first presented the hypothesis that microseisms are generated by the impact of the surf against a steep coast. He compared the periods of ocean waves at the Scandinavian Coast with the simultaneously observed periods of the microseisms in Gottingen and pointed out that the most frequent period of 7.5 seconds during large microseisms may be harmonic of the free vibration of the ground (1907).[94]

Guttenberg[38] (1912) studied the different types of microseisms recorded at Gottingen. He observed that "there are microseisms with periods of 1 to 4 seconds connected with local storms, the regular microseisms with periods from about 4 to 8 seconds which show a strong correlation with the surf in Norway and the wind direction at the Norway Coast, and finally irregular motions with periods of ½ minutes and more if temperatures below freezing prevail. A more detailed discussion of the microseisms with periods 4 to 8 seconds leads to the conclusion that they are due to surf driven by strong winds against the steep coast of Norway".

He again (1921)[40] made a detailed study of the microseisms with periods from 4 to 8 seconds recorded at a large number of stations in Europe and noted that "microseisms increase and decrease simultaneously over a large part of Europe. The maximum of the microseisms occurs near the maximum of the surf". The study of the effect of location of the station on the microseisms recorded led him to conclude "small microseisms occur in general on solid rock, large microseisms at stations on recent sediments. There is no clear relationship between the depth at which the instruments are located down to 1000 meters". He again emphasized that the surf on steep coasts of Western Europe was the cause of giving rise to microseisms observed at different stations in Europe.

Gherzi[29] (1923) discussed the different types of microseisms recorded at Zi-ka-wei, Shanghai. He observed microseisms related to typhoons. He suggested that the atmospheric vibrations caused by the pumping of air due to typhoons might be the cause for generating microseisms. The periodic pressure variation of the surface of the ocean is transmitted to the bottom of the ocean by some unknown mechanism giving rise to these pulsatory motions observed on land. He[31] (1927) cited examples when no appreciable microseisms were recorded in spite of high waves existing in the ocean near by. He further observed that microseisms suddenly decreased in amplitude when a typhoon entered the coast and again increased in amplitude when it returned to the sea again.

Matuzawa[77] (1927) studied in detail the microseisms observed at Tokyo. He grouped the waves into three categories with periods (a) 2 to 4 seconds (b) 6 to 7 seconds and (c) 8 to 9 seconds and indicated that "pulsatory motions are due to the oscillations of some elastic system proper to each locality, and that they behave in different ways in accordance with the varying modes of the disturbances.

Benerjee[3] (1930) reported that a Milne-shaw seismograph installed in an underground room with constant temperature recorded microseisms only when there was rough sea conditions over a fairly large area covering the Arabian Sea or the Bay of Bengal. By studying those records he noticed three distinct types of microseisms associated with "(1) south-west monsoon (2) the storms in the Arabian Sea and the Bay of Bengal and (3) local disturbances such as pronounced land and sea breezes". The microseisms associated with the south-west monsoon were steady vibrations "having periods varying from 4 to 10 seconds, according to the strength of the air current over the sea". He also observed that "the microseisms associated with storms have periods ranging from 4 to 6 seconds and show typical irregular variations in amplitude owing to the super-position of waves of different periods arising on account of the existence of marked difference in wind velocity in the storm and the surrounding areas. They make their appearance in the seismograms as soon as a storm has formed, and disappear only after it has passed inland and ceased to affect the sea".

"During the pre-monsoon and the post-monsoon periods, when the records are almost free from monsoon microseisms, the formation and the early developments of a storm are easily recognized by the appearance of feeble microseisms of variable amplitude, which become more and more marked as the storm is fully developed. During the five years the instrument has been in operation several storms formed in the Arabian Sea and the Bay of Bengal, and all of them gave rise to microseisms of this kind from the time of their formation until they passed inland and ceased to disturb the sea".

By a mathematical analysis he tried to show that the sea waves generated by wind should produce a pressure variation at the bottom of the sea giving rise to progressive waves in the ground which should propagate as Rayleigh waves on reaching the land where the normal stress is zero. But his analysis can hardly be defended since the pressure variation due to progressive waves on the water surface dies down exponentially with depth.

For irrotational motion the solution of the hydrodynamical equations in two dimensions is given by

$$\phi = \frac{ga}{\sigma} \; \frac{\cosh k\,(y + h)}{\cosh kh} \; \cos\,(k\,x - \sigma t) \qquad (1)$$

where ϕ is the velocity potential, h, the depth of the sea bottom. x and y indicate the horizontal and vertical directions respectively of the co-ordinate axis. Y is taken positive vertically upward with the origin at the surface of the ocean.

Starting from equation (1) he then assumed $\frac{\cosh k\,(y + h)}{\cosh kh}$ to be equal to 1 for large h and tried to show the transmission of pressure variation to the bottom of the sea. This is not true because for large h

$$\frac{\cosh k\,(y + h)}{\cosh kh} = e^{ky}$$

and therefore the actual form of the equation is given by

$$\phi = \frac{ga}{\sigma}\, e^{ky} \,\cos\,(kx - \sigma t)$$

which shows that the variation of pressure diminishes exponentially with depth.

This was pointed out by Gutenberg[43] (1931) who also computed the energy transferred by the breaking of the waves against steep rocky coasts to see whether it is sufficient to generate microseism. The energy imparted to the coast by the breaking of a trachoidal wave is given by

$$E = f \frac{gLH^2 \ell}{16T} \qquad (2)$$

where L is the length of the wave of height H and of period T. ℓ is the length of the coast and f the fraction of the total energy transferred to the coast. The factor f is included to take into account the dissipation of energy by friction with the sands, etc. In order to estimate the magnitude of E he used the following values. $L = 100$ m $= 10^4$ cm, $H = 5$m $= 5.10^2$ cm $T = 8$ seconds, $\ell = 500$ km $= 5.10^7$ cm, $f = .1 = 10^{-1}$. Substituting these values in equation (2), he obtained E to be of the order of 10^{17} ergs per sec. Compared to a normal earthquake in which the energy liberated is of the order of 10^{20} to 10^{24} ergs this computed value is considerably less. He, however, argued that "we must take into consideration that in the case this energy is produced every second", which does not seem to be very reasonable for in an infinite medium energy can not store at a particular place. It is transferred away as soon as it is imparted.

By studying the microseisms recorded at Tokyo and the local meteorological conditions Wadati[90] (1935) observed that the breaking effect of high swells against rocky coasts might be the cause for generation of microseisms. He also suggested the possibility of local microseisms being generated by strong winds nearby.

Bradford[12] (1936) pointed out that the values assigned by Gutenberg in computing the magnitude of E in equation (2) was rather too large. He also showed that the waves do not always break parallel with the shore nor can they be refracted with sufficient abruptness to render the crests parallel to the sharp and complex irregularities of the shores. This will cause to decrease the energy transferred to the coast by the wave by a factor n which is of the order of .8. He computed the actual energy transferred to the coast for a wave of heights 5×10^2 cm to be of the order of 3×10^{14} ergs per second which was considerably less than what Gutenberg obtained. Lee[96] (1934) also stated "no exact explanation of how the surf sets the ground into oscillation is given, but presumably Gutenberg envisages each breaker as a tiny earthquake generating surface waves. A difficulty at once confronts such an hypothesis, for the impact of the waves would not occur simultaneously along the whole coastline affected, and consequently the agreement between the period of the microseisms and the sea waves is not explained". As regards the origin of microseisms Bradford however suggested that atmospheric pressure oscillation due to relatively rapid pumping of the air on the forward side of low pressure area transmitted to the sea bottom might be the cause. He concluded with the statement "If the microbarographs in use at present possessed greater magnification and trace speed, we should be able to see and study atmospheric oscillations with periods ranging from a fraction of a second to as much as six or seven seconds". Thus we see that microseisms eluded all the attempts made to know their real origin ~~and continued to know their real origin~~ and continued to remain in the realm of the unknown.

Krug[61] (1937) designed a set of moveable horizontal seismographs for the special study of microseisms of periods between 4 to 8 seconds. He set up the seismographs at the corners of an isosceles triangle, the two equal sides being 1400 m in length. With this special arrangement he determined the velocity and direction of approach of microseisms at Göttingen. For microseisms of periods 4 to 8 seconds he found a velocity of 1100 ± 200 m/sec. His observation of the direction of approach showed strong correlation between the barometric depression on the Norwegian Coast and the intensity of microseisms at Gottingen.

Ramirez[83] (1940) studied the microseisms observed at St. Louis by means of a special arrangement of seismometers, the so-called tripartite arrangement, particularly with respect to their travelling nature, direction of propagation, their speed, their amplitude, period variation, their wavelength, the motion of ground particles and their origin. "The following instruments have been used: four horizontal electromagnetic seismographs especially designed for recording microseisms, two microbarographs constructed with the purpose of studying the short air pressure oscillations and a special pendulum and tickler combination for marking signals on the records every six seconds. The four seismographs were arranged in the form of a network; two E-W component, one at the St. Louis University gymnasium and one 6.4 km almost due west at Washington University; and two N-S components, one at the St. Louis University gymnasium and one 6.3 km almost due south, at Maryville College. These distances were chosen because they are presumably about one-quarter of a microseismic wavelength".

"A perfect synchronization of time mark was effected from a single clock by means of leased telephone wires. The pendulum and tickler combination was used to send signals at shorter intervals than the regular one-minute clock marks and thus to increase the number of simultaneous observations."

He observed a definite relationship in the arrival time of the waves at the three stations of the network: "The troughs and crests of the waves, in the course of a storm, pass first through a certain station and then arrive at a second station and finally at a third station. This recording of the arrival of waves at one station ahead of another station is not simply a question of high percentage, for regular waves of well-defined storms it is 100 p.c."

From the difference in arrival times at the three stations he computed the velocity of the microseismic waves and found it to be of the order of 2.67 $\pm$ 0.03 km / sec.

To find their possible relationships with the atmospheric air oscillation he compared the microseisms and the micro-barometric oscillations recorded with a specially designed microbarograph for a period of more than a year. He observed "no direct relationship between the two phenomena in wave form, group form, period or duration of storms".

As to the nature of the waves constituting the microseisms he concluded that "the Rayleigh theory and the observed characteristic of microseisms seem to agree fairly well except for the motion across the direction of propagation....". These waves may be independent waves of the same type - due to refraction and reflection." The direction of propagation of the microseism can also be computed if the time intervals between the arrival of successive groups at the three corners of the tripartite station are known. The following deduction is due to Macelwane[72].

Let A, B, and C be the known angles of the triangle in Fig. 1, and let a, b, and c represent respectively the opposite sides of known length. Let us suppose a wave front of microseisms is travelling from left to right and reached A. BP and CQ are perpendiculars dropped on the wave front from the vertices B and C respectively. X indicates the angle QAC between the wave front and the side B and similarly Y indicates the angle PAB between the front and the side C. Then it can be shown

$$\cot Y = n \frac{tCA}{tBA} - R$$

$$\cot X = m \frac{tBA}{tCA} - R \qquad (3)$$

where

$n = \frac{c}{b}$ cosec A

$m = \frac{b}{c}$ sec A

R = cot A

tBA = interval between the time for the wave front to pass through B and A

tCA = interval between the time for the wave front to pass through C and A

By using this method Ramirez[83] computed the azimuth of the source from which the waves arrived at St. Louis. He observed that the direction of approach always pointed towards a strong barometric low existing in the ocean. In the case of the New England hurricane of 1938 which he very carefully studied, he observed that the direction of approach of the microseisms at St. Louis continuously pointed towards the centre of the storm as it moved up the coast and not toward the area where high surf existed. From this he concluded that "the source of microseisms is to be found not over the land, but rather out over the surface of the ocean. The amplitudes of microseisms depend only on the intensity and wide spread character of barometric lows travelling over the ocean".

Since then the problem has been extensively studied by various authors all over the world, the results of which are contained in several hundred papers. The U. S. Navy ~~Bureau of Aeronautics~~ started a research project in 1943 under the technical supervision of Father J. B. Macelwane to study the microseisms with a view to determining the possibility of using these ground vibrations for detecting, locating and tracking severe hurricanes and typhoons when they are far from land. Under its auspices several tripartite stations were established in different places both on the continent as well as on islands such as in Guntanemo Bay, Cuba, Florida, Puerto Rico, Guam, etc. The results of these investigations often led to contradictory conclusions.

Gilmore[34,37] (1946, 1948) discussed the microseisms recorded at the U. S. Navy tripartite stations in the Caribbean and the Pacific. He concluded that "(1) typhoons and hurricanes always cause an increase in the amplitude of microseisms when near enough to the recording stations. The same is true for frontal systems and extratropical lows when accompanied by sufficient wind. (2) This increase in the amplitude of the microseisms is, in the Pacific, almost directly proportional to the intensity and size of the storm and to its distance from the recording station. The same rule applies to the Caribbean area except that greatly reduced microseisms amplitudes are recorded when the meterorological condition causing them pass over very shallow water, over land or over some other type of microseismic barrier. (3) Severe storms in the Pacific can be detected as far as 1600 miles from Guam except when large island groups and major fault systems exist".

Lee[69] (1949) pointed out the danger of laying too much emphasis on the determination of bearing of the direction of approach of the microseismic wave with the help of tripartite stations as super-position of waves coming even from the same direction with some phase difference between them may yield wrong bearing unless the stations are provided with three component instruments to check the results of such determinations.

Similar difficulties have also been noted by Donn and Blaik[26] (1953) who observed that azimuths with tripartite stations with single component instruments are "obtainable with angles of error of 20 to 40 degrees".

Relatively few studies were made to know the type of wave or waves that constitute the microseismic oscillation. Lee[65] (1935) studied the relation between the phases of the horizontal and vertical displacements, and observed that the phase differences between the three components, although variable, definitely showed a predominance about a certain value which is generally expected from surface waves of Rayleigh type. Assuming that microseisms are predominantly constituted of waves of Rayleigh type, he then showed how the direction of approach of microseisms can be determined by using the records from a single station provided with three component instruments. The same method was later on applied by Kishinouye[57] (1947) and Leet (1945) to track storms over oceans with a view to examine whether microseisms originate in a restricted area such as the eye of a hurricane. Leet also reported to have identified love waves associated with micro-seismic oscillations and concluded that "vertical pressures have served as a common source for both".

By comparing the amplitude of microseisms recorded at Berkely and the strength of the surfs on near-by beaches Byerly[13] (1942) reported that the two phenomena correlate with each other " quite as well as the observations of surf strength at adjacent stations correlate with each other. During winter months the correlation coefficient between microseisms and surf becomes as high as 0.81".

Bernard[10] (1941) compared the periods of sea waves on the coast of Morocco and the microseisms at Algiers and European stations and observed that the periods of the sea waves were about twice the periods of the microseisms. Similar results were later on observed by Deacon[17] (1947) by comparing the periods of the microseisms at Kew with those of the sea waves computed by Barber and Ursell in their harmonic analysis of the waves reaching the coast. It has also been observed that the microseisms arrive from a storm much earlier than the sea waves reach the coast agreeing with the hypothesis that they are generated in the storm centre.

We have already pointed out that this theory has to face a serious theoretical difficulty because the pressure variation due to a progressive wave on the surface of water diminishes exponentially with depth. Fortunately however M. Miche[74] (1944) showed from a theoretical study of wave motion that the mean pressure on the bottom under a train of standing waves fluctuates with an amplitude proportional to the square of the height of the waves on the surface. This pressure variation at the bottom is also independent of depth and remarkably enough its frequency is twice the foundamental frequency of the waves on the surface. Longuet-Higgins noticed that this was exactly what was required to explain the facts noticed by Bernard and Deacon. A shorter proof of Miche's results due to Longuet-Higgins[70] is as follows.

The equation of a stationary wave on the surface of water is given by (Lamb 1932)

$$\eta = a \cos kx \cos \sigma t + O(a^2) \qquad (4)$$

where $\sigma^2 = gk \tanh kh$

Let us now consider a mass of water contained between the bottom $Z = -h$, the surface $Z = \eta$ and the two vertical planes $x = 0, \lambda$ where $\lambda = \frac{2\pi}{k}$. Let us also suppose that there is no flow across the vertical planes, so that the mass of water contains always the same particles. The total vertical force on the mass of water is therefore given by

$$F = \sum m \frac{d^2 z}{dt^2} = \frac{1}{g} \frac{d^2}{dt^2}\left[\text{Potential energy}\right] \qquad (5)$$

Since the horizontal forces across the vertical plane has no contribution so far F is concerned, hence we have

$$F = \lambda(P - P_o - \rho g h) \qquad (6)$$

where P is the mean pressure at the bottom P_o, the constant pressure at the free surface and $\lambda \rho g h$, a constant force exerted by gravity. Now for a stationary wave we have by neglecting the compressibility of water

$$\text{Potential energy} = \int_o^{\lambda} \tfrac{1}{2} \rho g \eta^2 dx$$

$$= \tfrac{1}{4} \lambda \rho g a^2 \cos^2 \sigma t \neq O(a^3) \qquad (7)$$

$$\text{Hence } \frac{P - P_o}{\rho} = gh - \tfrac{1}{2} a^2 \sigma^2 \cos 2\sigma t \neq O(a^3)$$

Equation (7) shows that the pressure at the bottom varies with a frequency twice the frequency of the waves on the surface and its amplitude is proportional to the square of the amplitude of the stationary waves on the surface.

On the basis of this result Longuet-Higgins[71] (1950) worked out a new theory for the generation of microseisms. He showed that interference between trains of waves of approximately the same period travelling in opposite direction may give rise to a system of stationary waves which should cause the pressure at the bottom to fluctuate in the way shown above. This interference may occur near the eye of a hurricane or due to reflection of waves against a steep coast. By a detailed analysis he also showed that the energy transferred due to this pressure variation is of the right order of magnitude to give rise to ground oscillations observed on seismological records due to microseismic storms.

Derbyshire[16] (1950) made a frequency analysis of the microseisms recorded at Kew and the wave records obtained at Perranporth and observed that the periods of the microseisms and the ocean waves approximately satisfy the 1:2 relationship as predicted by the Longuet-Higgins theory. He even showed that one can identify the microseisms coming simultaneously from different source areas by such comparisons of the periods.

Kishinouye[58] (1951) studied the microseisms recorded at Tokyo and the sea waves observed from two weatherships located at about 39.5°N, 152°E and 28.5°N, 135°E. He reported that "the periods of swells were not always twice the periods of microseisms at Tokyo during the same time".

Donn[22] (1951) presented case history analysis for four microseismic storms recorded at Palisade, N. Y. and Weston Observatory. He observed that "all the evidence from the cases studied tends to strongly oppose the importance of coastal surf, and progressive and standing waves or swell as being the mechanisms in the generation of the microseisms". He suggested that the "mechnaism of microseism origin lies in a pulsational effect in the atmosphere possibly produced as a result of instability and turbulance in cold air, and from turbulance only in the case of warm air moving at very high velocities, i.e. hurricanes". He[23] (1951) made periodogram analysis of wave records obtained off Cuttyhunk Island and the microseisms recorded at Weston. By comparing the results of this analysis he observed that "there appears to be no relationship between the period of the swell arriving at Cuttyhunk off Cape Cod and the period of microseisms recorded at nearby Weston Observatory".

Gutenberg[47] (1953) studied the microseisms with periods of about six to eight seconds recorded at stations near the Pacific Coast of North America during November and December 1951. He observed that "in Southern California the maximum amplitudes -- usually conincided with the highest breakers and waves observed in Southern California".

Dinger and Fisher[20] (1953) discussed the microseisms recorded at the Navy tripartite stations at Guam and the ocean waves observed with two pressure gages set up on the two sides of the island, one on the eastern side and the other on the western side. They noticed that high microseisms were recorded only when there were high waves on both sides of the island. When waves were high on one side of the island, there was no significant rise in the amplitude of microseisms. Although this observation gives a strong support to the Longuet-Higgins theory, their conclusion that "interfering waves generated by two independent areas of wind give rise to particularly high microseismic activity" does not seem to be consistent with facts because high microseisms were recorded at Weston and Harvard Observatories when a single cold front moved to the sea from the land or a single low pressure area travelled over the ocean surface.

Problems to be Studied

In view of the mystery that still envelopes these pulsatory ground motions and moreover for the possibility of using them in predicting weather over oceans it has been considered useful to study more systematically to understand the nature and origin of these waves. In the present study we have discussed the problem from the following aspect.

(1) Nature: It has been observed in our preceding review that relatively few studies were made to understand the nature of these pulses. Although it is generally held that they are constituted dominantly of waves of Rayleigh type, there is still some controversy as to their real nature as some authors claimed to have identified other kinds of waves such as Love waves. In the present investigation detailed study has been made for each individual group of waves which appeared distinctly on each of the three components making use of the properties of Rayleigh waves and Love waves as predicted from theoretical considerations.

(2) Origin: Of the many theories that had been proposed to explain the real origin of microseisms due to continuous study during the past half a century, the probability has been narrowed down to two. One is the surf theory held by the Gottingen school first proposed by Wichert in 1910 and ever since supported and defended by Gutenberg. According to this theory microseisms are supposed to be generated by beating of the waves against steep rocky coast. The other is the standing wave theory pro-

posed in 1950 by Longuet-Higgins which asserts that when two trains of travelling waves in water of approximately the same frequency coming from opposite directions superpose on each other, they set up a system of standing waves due to which the pressure variation at the bottom of the water column fluctuates with frequency twice the frequency of the waves on the surface thus giving rise to oscillations in the ground which are recorded on our seismological observatories. Although evidences were being observed now and then as to its validity no convincing observational data has been offered until very recently in which case also studies were made only with one set of meteorological conditions. Detailed study has yet to be made to put it on a sure basis if of course this proves to be the right one.

Since by the very nature of the problem no direct experiment under controlled conditions is possible as in other problems of physics, we shall have to depend on indirect evidences. By using those indirect evidences which we shall explain later on, we shall try to examine and see which one of the two may be the most probable or the only probably cause to give rise to microseisms.

(3) Possible uses of microseisms: We have pointed out in our previous survey that after Ramirez made his first study at St. Louis by using the so called tripartite stations, the work has been continued under the auspices of the U. S. Naval Research Laboratory in order to determine whether these tiny ground oscillations can be used to serve any big purpose such as locating the

storm centers or for tracking well defined barometric lows travelling over ocean surface. The results of this long and expensive study have not provided any definite conclusions. As has been pointed out earlier, some authors[26] observed waves coming from places as far as 40^{o} away from the eye of the hurricanes. No explanation for observing waves coming from so far separated points has been provided. The author however tried to suggest some modifications in the experimental arrangements to increase the accuracy of locating the azimuths of hurricanes. In the light of the origin of microseisms determined from our present investigation, we shall examine whether such observations of waves coming from widely separated points are expected due to the underlying causes of the origin of microseisms. Some authors have indicated the use of Rayleigh wave for determing the direction of approach of microseisms. We shall also try to examine in the present investigation how accurately we can use Rayleigh waves for the same purpose using records from a single station provided with three component instruments i.e. two horizontals and one vertical.

Materials Used

In the present investigation, the following materials were used.

(1) Microseism records from Weston and Harvard Observatories.

(2) Swell records from Woods Hole, Mass., Gilgo, L. I. and Long Branch, New Jersey obtained with the help of underwater pressure sensitive gages.

(3) Three hourly synoptic surface weather maps from U.S. meteorological station at Logan Airport.

(4) Water depth chart of the North Atlantic U.S. Naval Hydrographic office, No. 0955.

(5) Three hourly ocean surface wave reports (M.I.T. Meteorology Department) as observed from the weather ship 4YH located at 36°N, 70°W. The weather ship will often be referred to by 4YH hereafter.

Specifications of the Seismological Observatories:-

Harvard Observatory

Geodetic coordinates	42° 30' 26" North
	71° 33' 45" West
Elevation	180 meters
Lithologic foundation	Micaceous Schist

Instrument - Vertical, North-South, and East-West Benioff long and short period seismographs.

Pendulum mass - 112.7 kg

Normal Operating Constants

Instrument	To sec	Tg sec	Drum Speed
ZSP	1.0	0.2	60mm/min
NSP	1.0	0.2	60mm/min
ESP	1.0	0.2	60mm/min
ZLP	1.0	0.2	30mm/min
NLP	1.0	0.2	30mm/min
ELP	1.0	0.2	30mm/min

Weston Observatory

Geodetic Coordinates	42^{o} 23' 04.9N
	71^{O} 19' 19.5W
Elevation	60 meters
Lithologic foundation	Metavolcanic

Instruments - Vertical, North-South, and East-West Benioff long and short period seismographs

Pendulum mass 100 kg

Normal Operating constants

Instrument	To sec	Tg sec	Drum speed
ZSP	1.0	0.5	60mm/min
NSP	1.0	0.25	60mm/min
ESP	1.0	0.25	60mm/min
ZLP	1.0	30.0	30mm/min
NLP	1.0	60.0	30mm/min
ELP	1.0	60.0	30mm/min

Presentation of Data

Nature: It is generally believed that microseisms are surface waves of some kind or other for they have been observed to be able to travel hundreds of miles without appreciable loss of energy. But the question is yet unsettled whether they are constituted of purely Rayleigh waves or a combination of Rayleigh waves and Love waves as some authors reported to have identified Love waves also in microseisms. If Love waves do really exist in microseisms, should we then consider that the characteristic property of the source which generates microseisms is such as to be able to give rise to oscillations in the ground only in the horizontal direction or they appear as a secondary effect due to the propagation of microseismic waves. To understand the origin of microseisms we must know their nature thoroughly because the nature of the waves generated is intimately related to the force generating them.

Now there are two kinds of waves that propagate only on the surface of an elastic medium. One is called Rayleigh wave in which theoretically the particles in its way move in such a way that they describe ellipses in the vertical plane with their longest axis pointing upward, the motion being retrograde. The other is called the Love wave or Q wave in which the particles in its way move in the transverse direction to the direction of propagation of the wave with no vertical component. These properties can be utilised to understand the nature of the waves that constitute the microseisms. In the case of Love waves therefore we expect to observe movement only in the horizontal directions without any simultaneous displacement in the vertical direction also. Simultaneous movement of the particles both in the vertical and horizontal directions should therefore indicate waves other than Love waves. This, on the other hand, should mean that the waves are either Rayleigh waves provided they satisfy other conditions which we shall soon indicate or they are some kind of body waves.

We have noted that the particles along the path of Rayleigh waves move in an elliptic fashion with the maximum displacement being in the vertical direction. The motion of the particles is retrograde when they are at the top most point (Fig. 2a). Therefore the displacements of the particles in the horizontal and vertical directions should always maintain some definite relationship.

Fig. (2b) is a graphical representation of the displacement of the particles due to the propagation of a Rayleigh wave from East to West. The positive displacement indicating the displacement in the upward direction for the vertical component and towards the East for the horizontal component. Similarly Fig. (2c) represents the displacement for a Rayleigh wave moving from West to East. In the same way we can plot the displacements of the particles due to propagation of Rayleigh waves in the north-south direction or in some intermediate direction. Now Fig. (2b) and (2c) show that if microseisms are Rayleigh waves then we should observe maximum displacement on the horizontal component when the vertical component indicates zero displacement decreasing from positive maximum. It may be either to the east or to the west depending on the direction of approach of the waves. In the present study we have used these criteria to decide whether a particular group is constituted of Rayleigh waves or Love waves. During a storm the waves however do not come to the station separately. Several wave groups may come to the station simultaneously. We have already pointed out that simultaneous arrival of waves from different directions may throw the components completely out of phase. Hence we can not expect to observe the required relations for Rayleigh waves by measuring any and every group of waves on our record although they may be constituted of pure Rayleigh waves. Hence we shall have to choose. Since some kind of choice has to be made, the following method has been adopted.

In a particular microseismic storm each of the groups of waves on the record was carefully studied. Only those groups that appeared distinct and unsuperposed on each of the components in which they were recorded were selected and then measured to see if they satisfy the above mentioned condition required for a Rayleigh wave propagation. Particular care was also taken to see if there were any groups of waves showing displacements only in the horizontal directions. In this way fifteen hundred groups of waves were chosen covering five storms. It has been observed that excepting a few, all of them satisfy the conditions indicated above thus showing that they are Rayleigh waves. Cases were, however, observed, which showed peculiarities. In about 2 p.c. of the cases studied displacements were only in the horizontal directions indicating waves of Q type. In two cases, only the vertical component showed displacements. These later wave groups were probably due to some local causes.

Now the problem arises whether we should consider that the waves observed having the property of Love waves were also generated by the same source as all others or by some entirely different causes. Leet (1947) suggested that they were generated by the same mechanism as all others although he recognized that microseisms are generated by a vertical force. It does not seem to be very reasonable to conclude that all of them were produced by the same mechanism because if the characteristic of the source which gives rise to microseisms be such as to be able to generate oscillations in the ground having motions only in the horizontal direction, then their number would have been more numerous. Secondly, if microseisms are generated by vertical forces which we shall show later on to be very likely, it is hard to see how they can produce Love waves in the ground. Consequently they may appear on record for one of the two following reasons. Either they may originate from causes which are completely independent of the microseisms. Or they may be generated by Rayleigh waves when they pass from the ocean to the continent. Although it is not yet definitely known what happens when Rayleigh waves pass from the sea into the land, there is reason to believe that they may generate other kinds of waves when they pass major structural discontinuities. In any case they are not likely to be generated by the same mechanism as all other waves that constitute microseismic oscillation.

Origin

Procedure of Study

Although the real mechanism by which microseisms are generated is not yet known, due to continuous study during the last fifty years it has been observed that they are in some way connected with the sea waves. One group of Seismologists believe that they are generated by the breaking of the waves against steep rocky coasts while others consider that they originate from fluctuation of pressure at the bottom of the sea due to a system of standing waves on the surface formed by interference of progressive waves of approximately equal period coming from opposite directions. In order to determine which one of the two may be the most probable cause for the generation of microseisms, we have examined the problem from the following points of view.

If microseisms are generated by the beating of the surf, then the amplitude of microseisms should attain the maximum amplitude simultaneously with the highest waves breaking against the nearby coast. If on the otherhand they are generated by standing waves in the ocean, then they should be observed only when a particular type of meteorological situation exists on the ocean surface. For to have standing waves, two systems of progressive waves of approximately the same period coming from opposite directions should superpose on each other, which will call for special types of wind motion. Therefore high swells in the ocean may not always be accompanied by observations of high microseisms. Secondly, if the later mechanism in the generation of microseisms operate, then an important relationship between them should be observed i.e. the frequencies of microseisms should be twice the frequencies of ocean waves. Further if microseisms are generated by standing waves, then the depth of water in the generating area should be of considerable importance, for theoretical considerations show that if the depth of water be ($\frac{n}{2} + \frac{1}{4}$) times the wave length of compressional waves in water, the amplitude of microseisms may be increased by a factor of five due to resonance. To examine these questions we shall adopt the following methods. (1) We shall plot the amplitude of microseisms and the trace amplitude of wave heights at nearby coasts in time to see whether they reach their respective maximum at the same time. If they do, our obvious conclusion will be that microseisms are generated by the beating of the surf against the coast. If the two phenomena are found to be independent of each other, we shall examine whether the situation can be explained from the point of view of standing wave theory by studying the wind motions in different parts of the ocean and also by comparing the amplitude of microseisms with the wave heights inside the ocean as observed from the weather ship 4YH. (2) We shall make spectrum analysis of microseisms and wave records to see if their frequencies are related to each other by a ratio of 2:1 as predicted from theoretical considerations. (3) We shall also compute the direction of approach of microseisms assuming that they are Rayleigh waves to see whether they come to the station from the regions where they are expected to be generated from other considerations. (4) By comparing the nature, period and amplitude of microseisms and the depth of water in the regions where they are likely to be generated, we shall examine the effect of the depth of water on them.

Amplitude: - In order to compare the microseismic activity with the wave heights near the coast, we have indicated to plot the amplitude of microseisms and wave heights in time. Before going in to actual measurement we have to decide two important points. (1) How to measure the amplitude? If we take the absolute maximum amplitude within a certain period, it will not certainly represent the microseismic activity during the period. If on the other hand we try to take the mean of all the wave amplitudes, it will mean almost a superhuman task. Therefore we have to make some choice. Various techniques were used by different authors. In the present study the following technique was employed. The double amplitudes (from crest to trough) of all the waves within ten minutes, five minutes at the end and five minutes at the beginning of every half hour, was measured with the help of a square grid each division of which is equivalent to .89 mm. From these, five wave groups were chosen having the largest amplitude. The arithmatic mean of those five wave groups was considered to be the measure of microseismic activity during that half hour. We have used a slightly different technique in measuring the trace amplitudes of wave heights in which case we have records for only twenty to thirty minutes every four hours. Here we have chosen ten wave groups with maximum amplitude over the entire length of the record and taken the arithmatic mean. (Hereafter the term "amplitude" will refer to "double amplitude").

(2) Next question to decide in measuring the amplitude is the choice of record i.e. on which component should we measure the amplitude in order to have a fair representation of the ground motion.

In our discussion on the nature of microseisms, we noticed that they are constituted mainly of Rayleigh waves. Now the ground motion in the horizontal direction due to Rayleigh waves depends on the direction of propagation of the wave. Hence the displacement on either of the horizontal components can not be considered to represent the ground motion. The displacement in the vertical direction on the other hand is independent of the direction of propagation of the wave. Therefore the amplitude on the vertical component will be a fair representation of the ground motion as far as our problem is concerned. If one wants to be too accurate, one can convert the displacements on each of the components into ground motion and then find the vector sum to determine the actual ground motion. This will involve a tremendous amount of work without any great hope for significant gain. Since we are particularly interested in times of beginning and ending of a storm, together with the time when the intensity becomes maximum, the plot of trace amplitude on the vertical component will serve our purpose.

Spectrum analysis:

To compare the frequencies of microseisms with those of the ocean waves we must know their frequencies accurately. We may compute their periods by measuring the distances between two successive crests or troughs. Since there may be two or more groups of waves with different periods superposing on each other, this kind of measurement is very likely to give erroneous results. For that reason we have decided to make exact analysis in order to separate the different frequencies for convenience of comparison.

There are two methods for making such analysis. One is by means of machines as described by Klebba[60] (1946) and Deacon[18] (1949). Many people, however, have questioned the validity of the results of such analyses, for the spectra obtained were very irregular. The other is the statistical method developed by N. Wiener in his study of generalized harmonic analysis of time series. Here we have adopted the later method, a detailed exposition of which can be found in references (91,95). For continuity of discussion we shall briefly indicate the underlying basic principle. A sequence, discrete or continuous, which is generated in time is called a time series, and it can be represented by a function f(t). If we operate on a time series as in equation (8), for a sequence of lags τ , than the resulting function is called the auto-correlation function of f(t) i.e.

$$\phi(\tau) = \lim_{T\to\infty} \frac{1}{2} \int_{-T}^{+T} f(t)\, f(t-\tau)\, dt \qquad (8)$$

Now it has been shown (Wiener) that an auto-correlation function of a sequence or time series preserves all information regarding the frequencies of the original function and it is also an even function. Therefore the auto-correlation function of an oscillating sequence will be an oscillating function having the same frequencies as the original sequence and hence can be represented by an equation of the form

$$\phi(\tau) = 2 \int_0^{\infty} \phi(\omega) \cos(\omega\tau)\, d\omega \qquad (9)$$

where $\phi(\omega)$ is a measure of the power corresponding to frequency . The power corresponding to different frequencies can therefore be separated by using the Fourier transform formula i.e.

$$\phi(\omega_n) = \frac{1}{\pi} \int_0^{\infty} \phi(\tau) \cos(\omega_n\tau)\, d\tau \qquad (10)$$

where $\phi(\omega_n)$ is the power corresponding to frequency ω_n. Since our wave record or the seismic record is essentially a time series, we can utilize the same technique to separate the frequencies. In actual application we replaced the infinite integrals in equation (8) and (10) by sums over finite length of our record. The computational procedure followed here is essentially the same developed by Tukey[86] (1949) and Tukey and Hamming[87] (1949). The method has been beautifully summarized by Wadsworth and his associates in GEOPHYSICS (1953). For convenience the section is quoted below.

"The unnormalized auto-correlation of a group of data at equally spaced intervals of time, say x_1, x_2 -----x_n are computed by the standard formulae. The formula which Tukey prefers is given by

$$R_p = \frac{1}{N-p} \sum_{i=1}^{N-P} x_i x_{i+p} \qquad (11)$$

Here the Rp's are estimates of the unnormalized auto-correlation function at the discrete lag P and are called the sample serial product".

"The basic problem is to obtain an approximation to the spectrum from a given number m of these serial products computed from a finite time series. Frequencies ω and frequencies $2\pi + \omega$, $4\pi + \omega$ etc. are equivalent as far as the method of Tukey and Hamming is concerned. Thus the effect is to fold over the last part of the frequency scale where $\frac{2\pi}{\omega} < 2$ into that portion of the scale where $\frac{2\pi}{\omega} \geq 2$. This means of course that on the scale the distribution of frequencies will now run from - 0 to π, and we shall confine our attention to this region. By choosing discrete values of angular frequency $\omega = \frac{s\pi}{m}$ (s=0,1,2,...m), we may perform numerical integration of (10) by the trapazoindal rule and write

$$\Phi\left(\frac{s\pi}{m}\right) = L_s \qquad (12)$$

where

$$L_s = \frac{1}{\pi}\left[\tfrac{1}{2} R_o \cos o + \sum_{j=1}^{m-1} R_j \cos \frac{s\pi j}{m} + \tfrac{1}{2} R_m \cos s\pi\right] \qquad (13)$$

By letting $r_j = \frac{R_j}{R_o}$ (j = 0,1,...m) we have

$$L_s = \frac{R_o}{2}\left[1 + 2\sum_{j=1}^{m-1} r_j \cos \frac{s\pi j}{m} + r_m \cos (s\pi)\right] \qquad (14)$$

An approximate integration of $\phi(\omega)$ from $-\pi$ to π by the trapezoidal rule yields

$$\int_{-\pi}^{\pi} \phi(\omega)\, d\omega = 2\int_0^{\pi} \phi(\omega)\, d\omega \approx \frac{\pi}{m}\left[L_0 + 2\sum_1^{m-1} L_s + L_m\right] \qquad (15)$$

"Because the values of L_s are subject to systematic error, they must be smoothed in order to obtain a satisfactory estimate of the spectral density. After research into feasible smoothing techniques, Tukey and Hamming settled upon the following simple scheme. The smoothed estimate U_s of the spectral density is given by

$$U_s = .23\, L_{s-1} + .54 L_s + .23 L_{s+1}\,, \quad (s=0,1,2,\ldots m) \qquad (16)$$

Since U_0 and U_m respectively involve L_{-1} and L_{m+1}, which have not been defined, set $L_{-1} = L_1$ and $L_{m+1} = L_{m-1}$. Or what amounts to the same thing, smooth the end points thus:

$$U_0 = .54\, L_0 + .46\, L_1 \qquad (17)$$

$$U_m = .54\, L_m + .46\, L_{m-1}$$

Because of the identity

$$U_0 + 2\sum_1^{m-1} U_s + U_m = L_0 + 2\sum_1^{m-1} L_s + L_m \qquad (18)$$

We see that the smoothing process is area preserving." In our computation we have used instead of equation (11) a different formula for serial product given by

$$R_p = \frac{1}{2N+1} \sum_i^{N-P} x_i x_{i+p} \qquad (19)$$

for use of equation (11) gives negative power for some frequencies which has no physcial significance. Use of equation (19) for the serial product guarantees positive power and a smoother curve. A discussion of this can be found in reference (95) page 113. A sample auto-correlation curve for one hundred lags is shown in graph 8. It has been mentioned that in the computation we replaced the integral in equation (8) by a sum,i.e. the traces on the wave record and seismogram were approximated by displacements x_i at discrete intervals τ . Now the problem arises, how closely should we read the displacements in order that we may consider the sum a fair approximation of the integral? After careful considerations, we decided to have at least ten readings within a complete wave length i.e. between crest to crest or trough to trough. Since the drum speed of the seismograph is only 3 cm per minute, it was not possible to read so closely. We have therefore enlarged a section of the microseism records which we chose for frequency analysis four times, in order that we could have the desired number of readings within a wave length. On the enlarged record we read the amplitude of the displacements at discrete intervals with the help of a transparent square grid graduated at intervals of .89 mm.

Similar technique was also used in the case of wave records where the displacements were read with a grid in which the vertical lines were replaced by circular arcs of the same radius as that of the stylus of the brush recorder on which the records were obtained.

Directions

In our discussion on the nature of microseisms, we have seen how we can determine the quadrant in which the aximuth of the wave lies from the relative displacements on the different components. Once the quadrant is known, we can compute the direction of approach by using the formula

$$\tan \theta = \frac{A_n}{A_e} \qquad (17)$$

Where θ is the angle between the direction of approach and the N-S meridian at the station. A_n and A_e are the displacements on the N-S and E-W components respectively.

In actual computation we meet the same difficulties we mentioned in connection with our discussion on the nature of microseisms. Consequently we adopted similar technique here in this case also i.e. we have gone through all the wave groups individually and chosen only those that appeared to be unsuperposed by examining the displacements on each of the components on which they were recorded. We then measured the amplitude (double amplitude) estimating within a tenth of a millimeter. It was not considered necessary to make any correction for the sensitivities of the instruments for they are almost the same for the horizontal components of the Weston Observatory instruments.

It should be mentioned in this connection that the directions computed by this method can not be considered very accurate because of the many factors involved. It will, however, give us some idea to see whether the waves were approaching the station approximately from the right directions.

Presentation of Case History Analysis

Seven case history analysis of microseisms and photostatic copies of synoptic surface weather maps showing the meteorological conditions at the same time are presented below. Of the seven cases presented, the first five cases show the characteristic frontal microseisms and the associated meteorological conditions. Case six has been presented to show that unless some special meteorological conditions exist, microseisms are not generated although there may be high waves near the coast as well as in deep water. Case seven is a study of microseisms associated with a strong barometric low over a restricted area such as in a hurricane travelling over the ocean surface.*

Before going into the discussion of the individual cases it will be perhaps worthwhile to add some explanatory notes regarding the interpretation of the symbols on the weather maps. Isobars (lines of equal pressure) are shown by closed lines and drawn at intervals of 3 millibars by relatively finer lines. The centers of low pressure areas (cyclones) and of high pressure areas (anticyclones) are indicated by "Low" and "High". Cold fronts are shown by heavy lines with wedges pointing in the direction of motion. Warm fronts are also indicated by similar lines with blackened semicircles on the side towards which they move. Wind directions are indicated by arrows flying with the wind. Bars on the tail of the arrows show the wind speed;

Note *Copies of the maps are attached only for those times when the meteorological conditions were considered to be significant.

each full bar indicating 10-12 miles per hour and a half bar 5-6 miles per hour. The one-thousand fathom line is shown by dashed lines on the maps.

Graphs 1-7 show the amplitude of microseisms, the wave heights near the coast and at 4YH. Discontinuities in the wave height curves in graphs 3-5 are due to the fact that the records for the period were not available. Amplitude of microseisms at Harvard are not shown on the graphs because they follow very closely with those at Weston, as is shown in graph 7 as a sample case.

Case 1 December 11-13, 1952

The amplitude of microseisms at Weston, wave heights at Woods Hole and at 4YH are shown in Graph 1 which indicates a lag between the wave heights near the coast and the amplitude of microseisms. The trace amplitude of wave heights at Woods Hole reached the maximum at 21.00 h G.S.T. on December 11th when the microseisms at Weston just started to increase. The microseisms attained the maximum amplitude after about 12 hours at 09.00 h G.S.T. on the following day by which time the wave heights near Woods Hole decreased considerably. This indicates that the two phenomena are not directly related to each other. A study of wave heights at 4YH and the amplitude of microseisms indicate on the other hand that they are likely to be closely related to each other. For example they both increased almost in the same manner, reached the maximum almost simultaneously and also started to decrease almost simultaneously. Therefore if microseisms are generated by any wave action in the sea, then it is due to waves in deep water rather than the breaking of the surf against the coast. We have mentioned earlier that microseisms can be generated in deep water only when waves of equal period coming from opposite directions superpose on each other. This situation should arise when there is a rapid change in the direction of wind motion. Let us now examine the maps to see whether the development of weather conditions was such as to give rise to the proper kind of shift in the wind direction or the correlation we have observed is just a matter of chance. A brief survey of maps 1-7 will show that a cold front extending all the way over the eastern United States accompanied by a low pressure area moved from land into the ocean. At 03.30 G.S.T. Dec. 11th the cold front was roughly parallel to the coast from Florida to New York and wind with speeds between 13 to 24 miles per hour was blowing from the sea to the land. The wave records at Woods Hole show a trace amplitude of 5.5. The microseisms at Weston and Harvard about that time were at the noise level.

Six hours later the front was right on the coast near Cape Hatteras, part of the front extending into the coastal waters. Wind along the coast, north of Cape Hatteras was blowing on shore. At Nantucket wind at 13 to 18 miles per hour was blowing from S40°E. At 4YH wind at 19-24 miles per hour was blowing from S20E. Wave heights at Woods Hole and at 4YH just started to increase while the microseisms at Weston continued to be at the noise level. The condition is shown in Map 1.

Conditions nine hours later at 18.30 G.S.T. are indicated in Map 2 which shows that the part of front, south of the low moved into deep waters with the center of the low pivoting itself entirely on land near New York. North of New York the wind was still on shore. The trace amplitude of wave height at Woods Hole increased to 9.5 without causing any significant increase in the amplitude of microseisms. Wind speed at 4YH increased to 39-46 miles per hour blowing due north. The wave heights there also increased to $9\frac{1}{2}$ ft. Since wind in the deep water region was continuously blowing in one direction the waves generated were all travelling in nature.

Map 3 shows the conditions at 00.30 G.S.T. Dec. 12th. The center of the low had just moved into the water south of L. I. The part of the front south of the low which was moving rapidly eastward, had crossed the 4YH with consequent change in the wind direction there. Wind was still blowing on shore near Cape Cod where the wave heights reached the maximum. The amplitude of microseisms increased to 5.

The conditions six hours later at 06.30 G.S.T. are shown on Map 4. One end of the cold front kept pivoted at the same place while the other end rapidly moved eastward. The wave heights at Woods Hole already started to decrease, wind on opposite side of the front moving almost in opposite direction. At 4YH the wind velocity increased to 47-54 m.p.h. and it was blowing from N70W which means a shift in the direction by 130^{o} during the last 21 hours. This change in the wind direction should therefore give rise to standing waves. The amplitude of microseisms reached 8.

Map 5 shows that the front became arched as the southern portion was rapidly moving eastward. The center of the low moved north of Woods Hole where the wind had become off shore as a result of which the wave heights there diminished considerably. At 4YH wind was blowing with the same speed approximately in the same direction. The wave heights there reached the maximum and also the amplitude of microseisms at Weston.

An important point to be noticed is that as the front was arching, a section of it in deep water was slowly extending east of Boston. As a result of this the generating area of microseisms should slowly extend from south to south east, if, of course, microseisms are generated by standing waves. The aximuths computed by using equation (17) show that this was exactly the case. Although the waves continued to come from all parts of the front in deep water, the generating area continuously extended towards the north.

Another important point to be observed is that from the time the amplitude of microseisms started to increase, the part of the front in deep water was moving rapidly towards the east. Since the wind on the two sides of the front was moving almost in opposite directions or at least with a high component in opposite directions, this rapid movement of the front should be very efficient in giving rise to standing waves. Maps 4,5, and 6 which indicates the weather conditions for the period during which microseisms had the highest amplitude clearly shows this rapid movement of the front.

The conditions at 00.30 G.S.T. Dec. 13th are shown in Map 6. During the last twelve hours the center of the low was shifting towards the north while the front was continuously moving towards the east. The portion of the front which was in deep water had moved far into the ocean. The microseisms amplitude meanwhile had been decreasing continuously. It seems that the portion of the front north east of Boston, was not effective in generating microseisms probably because it was lying in the shallow water. It should be noticed that a new cold front was moving towards the coast.

Map 7 shows that the second front which was moving eastward extended into the ocean by 06.30 G.S.T. A special feature of the new front was that the winds on its two sides were blowing almost in the same direction and were not effective in giving rise to standing waves. Consequently the amplitude of microseisms continued to decrease, although the front moved into the deep water.

By examing the seismogram traces we observe that at the beginning of the storm the waves are very irregular both in amplitude and period. They did not start taking definite shape until 22.00 G.S.T. Dec. 11th when the front had moved well beyond the 1000 fathom line. The earlier waves are probably the ones generated in the shallow water. As the storm developed the waves gained in amplitude and looked like well defined pulses with uniform period. Thus we see that high amplitude microseisms strongly correlate with the rapid movement of a cold front in deep water.

Case 2 Dec. 15th to 17th, 1952

The amplitude of microseisms recorded at Weston, the trace amplitude of wave heights at Woods Hole, the wave height at 4YH are shown in graph 2. In the plot the scale factor in this case has been doubled in order to show the variations more clearly. Although the period was not one of high microseismic activities as in other cases, the case has been presented because it shows some definite characteristics which help to draw important conclusions. For example it clearly demonstrates that the microseisms at Harvard and Weston are not in any way related to the beating of the surf near the coast. During the period the trace amplitude of wave heights at Woods Hole went hardly beyond the noise level, the maximum amplitude being only 2.8. A glance at the graph will immediately make it evident that the increase or decrease of wave heights near the coast didn't affect the character of microseisms at our stations. This also clearly demonstrates the changes in the meteorological conditions that are necessary for the generation of microseisms. Let us first examine the weather conditions and the corresponding changes in the character of microseisms before going into the discussion of these important points.

On the 15th of December 1952 a cold front started to develop in the coastal waters extending from Florida to Newfoundland. During the earlier part of the day the conditions were not clearly defined. By 18.30 G.S.T. (Map 8) the condition became fully developed. A strong barometric low was formed in deep waters at about 38°N 67°W with one part of the cold front extending approximately south. The other to the north east from the center of the low. Because the front developed entirely in the deep waters the wind was off shore all along the coast. As off shore wind can not give rise to high waves near the coast, the wave heights there remained low as we find in graph 2. The wave height at 4YH at this time was 5 ft. although the wind there was blowing 32-28 m.p.h. During this period microseisms with amplitude approximately 2 were recorded at Weston. As a matter of fact these feeble microseisms were continuously coming ever since the storm in case 1 ended. They were very irregular in nature both as regards amplitude as well as period. Before we pass on to the next map it will be perhaps important to mention one important feature associated with the cold front. It should be noticed that the isobars were breaking at sharp angles as they crossed the front as a result of which wind was blowing almost in opposite directions on the two sides of the front.

Map 9 which depicts the conditions three hours later, 21.30 G.S.T. Dec. 15th, shows some small changes in the situation. During the period the center of the low slightly shifted to the north while the front south of it became straight although its general position remained more or less the same. As a result of this, the breaks in the isobars along the front became sharper. The wind direction at 4YH meanwhile changed from due north to due N70^{o}W. The nature of microseisms at Weston remained unchanged.

Conditions three hours later at 00.30 Dec. 16th are indicated in Map 10 which shows that the front had started to move rapidly towards the east with the center of the low pivoting itself at the same place. Simultaneously with the movement of the front, the amplitude of microseisms at Weston started to increase rapidly as can be seen in graph 2. This again confirms our observation in case 1. Although the wind speed at 4YH remained constant (i.e. 32-38 m.p.h.) its direction had changed to N60°W. The wave height there also increased to 11 ft. As before the wind along the coast from Florida to the Maritime provinces remained off shore.

Six hours later at 06.30 G.S.T. (Map 11) the center of the low had shifted north into the shallow water while the part of the front which was in deep water, had been continuously moving eastward. Conditions six hours later at 12.30 Dec. 16th shows the continued movement of the front. During the last twelve hours it moved about 330 nautical miles along the 40th parallel and about 450 nautical miles along the 35th parallel. Before this the movement of the front was almost insignificant. As a result of this rapid movement of the front, the wind direction in places swung through almost 180° as can be seen by comparing its directions at Sable Island in map 10 and 12. Similar shifting in the wind direction can also be observed at HKD (32°N 65°W) on the maps. During this period, the amplitude of microseisms at Weston steadily increased to its maximum. It should be noted that during the entire period the wind along the coast was off shore and naturally there could not be high waves there, as is also shown by graph 2.

By 18.30 G.S.T. (Map 13) the low had moved over to Newfoundland. The front was still moving eastward but its speed had considerably diminished. The amplitude of microseisms had started to decrease. It should be noticed that in the mean time a new front was approaching the coast from the land. It did not however, cause any change in the wind direction along the coast.

By 06.30 Dec. 17th (Map 14) the southern portion of the front which was approaching the coast, moved well into deep waters. Since the wind was blowing almost in the same direction on its two sides, nothing changed so far as microseisms were concerned due to the extension of this new front. They had been steadily decreasing in amplitude although not as rapidly as when they were increasing.

The study of the azimuths of the origin of the waves coming to the station at different time also reveals an interesting fact. We have seen that at the beginning of the storm, only a section of the front whose general direction from Weston was about S45°E had been moving and so became effective in generating microseisms. Later on, the center of the low shifted to the north and the sections of the front lying on either side of that direction started to travel. The direction of approach of the waves as computed by using Rayleigh waves shows similar sequence showing the extension of the generating area of microseisms on both sides.

To conclude we note the following facts as revealed by this case history analysis. (1) The fact that wind was continuously blowing from the land to the sea and the trace amplitude of wave heights near the coast had hardly risen beyond the noise level during the entire period of the storm completely negates any possibility of microseisms being generated by beating of the waves against the coast. (2) Existence of a barometric low or a cold front over the ocean either in deep water or in shallow water regions does not give rise to microseisms. For increase in the amplitude of microseisms did not commence until 00.30 G.S.T. Dec. 16th although the meteorological conditions became well defined by 18.30 G.S.T. Dec. 15th. (3) Rapid increase in the amplitude of microseisms as soon as the front started to move strongly suggests that the movement of the fronts or lows is the important factor in the mechanism for the generation of microseisms. Absence of similar effects when the second front was travelling shows the type of wind motion that should be associated with the cold front in order that the mechanism may be effective for the generation of microseisms. (4) It has been mentioned by Dinger and Fisher that the microseismic waves are highly attenuated over oceanic paths. This particular case does not seem to support this idea. If we consider that the nearest places from where the microseisms came to Weston during the storm were at the initial position of the front (21.30 G.S.T. Dec. 15th), then the waves must have travelled at least 475 KM before they were recorded. If the effect of attenuation would have been so strong as the authors thought it to be then the amplitude of microseisms would be much less than what has been observed.

Case 3. Feb. 8 - 11, 1953

This case covers a period of four days from Feb. 8th to Feb. 11th 1953. Actually from the point of view of our problem it represents two cases. One is from Feb. 8th through Feb. 9th during which time we had an unusually high microseismic storm accompanied by high ocean waves. The other is from Feb. 10th through Feb. 11th during which time we had high waves at 4YH with feeble microseisms recorded at Weston and Harvard. The amplitudes of microseisms, the wave height at 4YH and the trace amplitude of wave heights at Gilgo, L. I. are represented in Graph 3. The meteorological conditions for the period are shown in Maps 15 to 27. The amplitude of microseisms and the wave heights at the nearby coast could not be compared during the early part of the storm as the wave records for the period were not available. The only records for the coastal waves available for the period were from Long Branch, New Jersey. Unfortunately, this instrument was operated at such a low sensitivity that quantitative measurement of wave amplitudes would be very inaccurate. However, the record does indicate the time of the maximum wave heights, and this, together with the weather maps for the period can be used to estimate when the wave heights at Gilgo reached the maximum amplitude, since the wind direction at both the places changed almost simultaneously as can be seen in Maps 15 and 16. By doing so we observe that the wave height at Gilgo, L.I. should have reached the maximum at least 12 hours before the microseisms at Weston (maximum wave height at Long Branch was at 09.00 G.S.T., Feb. 8th). Graph 3 however, shows a strong correlation between the wave heights at 4YH and the microseisms at Weston indicating again a close relationship between them.

The amplitude curve of the microseisms in graph 3 shows a very peculiar characteristic of the storm under discussion. It rises very quickly and steadily to its maximum and drops down almost as fast as it rose although the wave heights in deep water continued to be as high as 12 ft. We shall come back to this point later on after discussing the general weather conditions.

The weather maps show that on Feb. 7th about a day prior to the beginning of the storm a stationary front had been developing almost parallel to the eastern coast of North America extending from Florida to New Brunswick several hundred miles inside the land. Towards the end of the day the cold mass of air on the western side of the front started to move towards the east and reached the coast at about 21.30 G.S.T. of the same day. During this period strong wind was blowing on shore.

At 00.30 G.S.T. February 8th (Map 15) the front was almost parallel to the coast with one low over Georgia and the other over ~~the~~ eastern ~~portion of~~ Maine. A section of the front between Cape Cod and Cape Hatteras was lying on the coastal waters. As the front moved into the coastal waters, the wind in southern New England changed direction from SE to NW. On the eastern side of the front the wind was blowing generally from south to south-east. In some places it was blowing due east. At 4YH wind was 39-46 m.p.h. from due south. The microseisms at this time were very low.

By 3.30 G.S.T. the front had moved further to the east as a result of which wind in New England became entirely off shore. By 6.30 G.S.T. it became northerly. The condition about this time shows that the southern low associated with the front became well defined while the one on the north started to move northward.

Map 16 indicates the conditions three hours later at 09.30 G.S.T. This shows that the front had moved well into the ocean but it was still in the shallow water except a small portion of it north of Cape Hatteras bulging off the shelf. The southern low was then lying slightly north of Cape Hatteras. The northern low associated with the front had meanwhile moved over to Quebec and developed an occluded front. All along the coast the wind had become off shore. This wave height near the coast should therefore start to decline as is also shown by the Long Branch wave records. Conditions six hours later (map 17) shows little change in meteorological conditions so far as the microseisms are concerned. Only the southern low associated with the front had shifted slightly to the north. A portion of the front south of the low was then extending into the deep water. The amplitude of microseisms recorded at Weston had just started to increase.

After this time the low was moving continuously towards the north while the part of the front south of the low was travelling rapidly towards the east. At 21.30 G.S.T. (map 18) the center of the low was just off the coast near Cape Cod, the part of the front south of the low being entirely in deep waters. As soon as the front crossed 4YH, the wind there immediately became westerly. Within this last six hours the amplitude of microseisms increased from 4 to 16 on our scale. This again shows, as we observed in the last two cases, that the mechanism by which microseisms are generated is related to the movement of a front on opposite sides of which the wind moves in opposite direction or with a large component in opposite direction. If we examine the isobars, we observe the same features as in the last case, i.e. they break at a sharp angle as they cross the cold front. Six hours later 03.30 G.S.T. Feb. 9th, the low was on southern Nova Scotia and became very sharp. The front was moving continuously towards the east. At 4YH wind was then blowing from N40^{o}W at 47-54 m.p.h. This indicates a change of 150^{o} in wind direction during the last 9 hours. This should therefore give rise to high standing waves and consequently of high microseisms. Graph 3 shows macimum amplitude for microseisms.

At 09.30 G.S.T. Feb. 9th (map 20) the center of the low was over the maritime provinces. The rapid movement of the front was still continued. This clearly indicates that microseisms are not generated directly under the low for in that case there would have a sharp drop in the amplitude of microseisms when the low shifted on to the land. The amplitude of microseisms at this time shows a slow average decrease. There may be two reasons for this. First due to continuous blowing of wind from one direction the amplitude of standing waves which were formed during the earlier part were being slowly suppressed. Secondly, the front was probably getting too far from the recording station. This, of course, does not suggest the attenuation of the waves of the type as mentioned by Dinger and Fisher. By 15.30 (map 21) the front reached the 55th meridian still continuing its rapid movement eastward (compare with map 20). The center of the low remained more or less stationary. Graph 3 shows a rapid decrease in the amplitude of microseisms during this period.

During the next six hours (map 22) there was little change in meteorological condition except further movement of the front. The wave height at Gilgo shows a steady decline as they should for the wind during the entire period was blowing off shore. The wave height at 4YH after a small drop again increased to 14 ft. The microseisms at Weston dropped to 6 on our scale, at which they continued for the next two days although during this time the wave height at 4YH again rose to as high as 19 ft. This has been presented to illustrate that there may be high waves in the ocean without any corresponding change in the microseisms. Maps 23 to 27 show that during the period the wind was continuously blowing in one direction. The waves generated were all travelling in nature and therefore did not give rise to any high amplitude microseisms.

Summarizing we note the following facts.

(1) As previously observed, the present case again show that microseisms are generated only when the cold fronts (we are discussing frontal microseisms) with wind moving in opposite direction on its two sides travel rapidly across the ocean surface.

(2) High amplitude microseisms are generated only when the front moves into the deep water.

(3) Microseisms are not generated under the barometric low or the cold front as we observed in the previous cases.

(4) The attenuation of microseismic waves does not seem to be excessively great over oceanic paths.

(5) Microseisms are not related to surf beating against the coast.

(6) These facts strongly suggest that they are generated by standing waves in the ocean.

Case 4, Feb. 11 - 14, 1953

Graph 4 represents the amplitudes of microseisms recorded at Weston, the wave heights at 4YH and the trace amplitudes of wave height at Gilgo, L. I. from Feb. 11th through Feb. 14th 1953. The associated meteorological conditions are shown in maps 28 to 31. Thus graphs 3 and 4 show the continuous record of microseismic and wave data for seven days beginning from Feb. 8th through Feb. 14th. We observed in case 3 that towards the end of the storm the amplitude of microseisms rapidly declined to 6 at which it remained more or less constant (on the average) for the last forty hours, although the wave heights at 4YH rose to 19 ft. for sometime. It was probably because only a small component of the waves in opposite direction was effective to cause pressure variation at the bottom. Here also we don't have the wave records from Gilgo at the beginning of the storm to compare the coastal waves with the microseisms. By using the Long Branch records and the weather maps as we did in case 3 we find that the wave heights near the coast should have reached the maximum much earlier than the microseisms at Weston.

Graph 4 shows that the wave heights at 4YH began to decrease at 09.00 G.S.T. Feb 11th and so did the microseism amplitude although not as rapidly. Both of them reached the minimum at about 06.00 G.S.T. on Feb 12th and started to increase again almost simultaneously. Increase in the wave heights at Gilgo commenced much earlier as they should because the front crossed the shore line long before it effected the wind motions at 4YH.

If we examine graph 4 and the meteorological conditions during the period concerned we notice the same relationship between the increase and decrease in the amplitude of microseisms with the movement of the cold front having the same type of wind motions associated with it.

Map 28 which depicts the condition at 12.30 G.S.T. Feb. 12th shows that a low pressure area associated with a cold front extending up to the Gulf of Mexico on the south was approaching the coast. A minor low associated with a warm front projecting towards the ocean was then lying on the Delaware Bay. Wind north of the warm front was onshore while on the south the front, it was blowing off shore. At 4YH wind was blowing 25-31 m.p.h. from S50°W. Conditions three hours later show that the fronts had shifted eastward. Along the coast the situation remained unchanged.

Three hours later, 18.30 G.S.T. (map 29) the entire warm front from Nantucket Westward changed into a cold front and joined the old one running NE - SW near Richmond, Virginia. A new low had developed just south of Nantucket where the new cold front and the warm front came together. The new front was then lying off the coast.

Three hours later, the front had moved well into deep waters between Nantucket and Cape Hatteras. The low was then just south-east of Nantucket. At 4 YH wind velocity increased to 39-46 m.p.h. with a consequent increase of wave heights there. Microseism amplitude at Weston started to show a definite upward trend at this time (graph 4).

After 00.30 Feb. 13th, the front started to move rapidly eastward with the center of the low shifting to the north. By 03.30 the front crossed the 4YH ship as a result of which the wind direction there changed to N30°W, but its velocity decreased to 19-24 m.p.h. Consequently the wave heights there dropped down to 11 ft. Microseisms about this time show a rapid increase in amplitude as we should expect from our observation in the past examples.

The position of the front at 06.30 G.S.T. Feb. 13th is shown in map 30. It was then entirely in deep water with the center of the low lying on the 65th meridian almost due east of Boston. If we examine the nature of the isobars, we again notice the same peculiarities i.e. they were breaking at a sharp angle when they crossed the front and the wind was moving at large angles on the two sides of the front.

During the next twelve hours the front moved rapidly to the southeast as can be seen by comparing with its position in map 31 which indicates the condition at 18.30 G.S.T. The amplitude of microseisms during this time had been maximum. This again shows that the depth of water also plays an important role . The large amplitude microseisms are generated when the cold fronts of particular type travel over the ocean surface in deep water regions.

Case 5. Feb. 15 - 17, 1953

During the period Feb. 15th to 17th several waves of cold air masses moved across the eastern United States. The situations were rather complex. Graph 5 represents the amplitudes of microseisms as recorded at Weston and wave heights at Gilgo, L. I. and at 4 YH. A glance at the graph at first gives the impression that microseisms at Weston agree more closely with the beating of the waves against the nearby coast rather than the waves in deep water. As a matter of fact this particular case has been presented in order to illustrate that occasions may arise when beating of the surf against a rocky coast may seem to offer a good explanation for the origin of microseisms. A closer examination of the weather condition reveals the real mechanism by which they are generated. Observation of such cases may often lead to wrong conclusions.

As we mentioned earlier that the meteorological conditions during the period were rather complex. The weather maps show that towards the beginning of the storm a cold front was extending north south ending in a center of low pressure area between the 35th and 40th parallels from which again a warm front projected eastward into the sea. This was closely followed by another cold front ending likewise into a barometric low in the higher latitudes. From this also a similar warm front was projecting towards the south east.

The conditions at 15.30 G.S.T. Feb. 15th are indicated by map 32 which shows the first low over the Chesapeak Bay with the cold front extending into the coastal waters south of Cape Hatteras. The warm front associated with the low extended up to the 67th meridian near the fortieth parallel. South of the warm front and east of the cold front wind was roughly parallel to the coast blowing from the south. On the north of the warm front wind was on shore which caused an increase in the wave height along the New England coast as is also indicated by graph 5. At that time wind was blowing from south with a speed of about 32-38 m.p.h. at 4YH where also wave height was rising rapidly. Microseisms at Weston was at the lowest during this time.

By 18.30 G.S.T. the low moved over to southern New Jersey and the front shifted to the east pivoting on its end at the center of the low. On the south of the low wind was blowing offshore while on the north it was on shore. At Nantucket it was 25-31 m.p.h. from S70°E and at 4YH, 32-38 m.p.h. from S30°E. At both these places wave amplitudes were increasing very rapidly but microseisms at Weston was still at the noise level.

The conditions at 21.30 G.S.T. Feb. 15th, when microseism amplitude at Weston was just commencing is indicated by map 33 which shows the edge of the cold air masses by two fronts. The one leading had already moved into deep waters off Cape Hatteras and the one following was lying parallel to the coast. Wind in southern New England remained on shore as before but gained in strength and it was between 39-46 m.p.h. The trace amplitude of wave height at Gilgo, L. I. became 15 ½ at this time. Wave height at 4YH rose to 19 ft. where wind was 47-54 m.p.h. blowing from due south.

By 00.30 G.S.T. Feb. 16th the two fronts coalesced into one and were moving eastward as a single front. Three hours later the low was over southern Maine. The front at this time was almost entirely off the coast except near Cape Cod. As a result the wind all along the coast became off shore. The wave height near the coast should therefore start to decline from this time. Although microseisms at Weston were increasing rapidly which they should of course do, but there was yet quite some time to reach the maximum.

Conditions three hours later at 06.30 G.S.T. are shown in map 34, which indicates that the front was moving rapidly eastward and had already crossed the 4YH. As a result of this wind at 4YH and other places in deep water had changed direction. If we are guided by our experiences from preceding cases we should expect rapid increase in the amplitude of microseisms. Graph 5 shows that the amplitudes of microseisms coming to Weston at this time were reaching the maximum. Along the coast south of central Maine where the center of the low was located at the time strong wind was blowing off shore. Conditions six hours later at 12.30 G.S.T. (map 35) show that the two fronts separated again and were moving eastward as before independently of each other. Meanwhile the center of the low shifted on to New Brunswick. Conditions afterwards followed exactly in the same way as in previous cases as can be seen in maps 36 and 37. The two fronts coalesced again and continued their movement. As the front was getting further and further out, the amplitude of microseisms slowly decreased.

If we examine the maps, we again observe that the isobars were breaking at sharp angles as they crossed the front.

Case 6, Feb. 21 - 23, 1953

Although the period under discussion does not show any significant microseimic activity, the case has been presented because it demonstrates more clearly some of the assertions we made in course of our previous discussion. In the preceding five cases we observed that microseisms have no relation with the beating of the surf against the coast. Particularly in case 2, we found that high microseisms were recorded at Weston and harvard observatories when the trace amplitude of waves at Woods Hole were hardly beyond the noise level. The present example confirms our observation by showing that the converse situation also occurs i.e. microseisms are not necessarily recorded at seismological stations although the waves breaking against the coast are of sufficiently high amplitude. We also observed in the preceding cases that microseisms are related to the rapid movement of a cold front on the ocean surface. Absence of microseisms in the present case emphasizes the significance of characteristic wind motion that must be associated with the fronts thus demonstrating more clearly the mechanism underlying the origin of microseisms.

Graph 6 shows the amplitudes of microseisms recorded at Weston, the trace amplitude of waves at Gilgo, L. I. and the wave height at 4 YH during the period from Feb. 21st through 23rd, 1953. The associated meteorological conditions are shown in maps 38 to 44.

Graph 6 shows that towards the end of Feb. 21st the trace amplitude of waves at Gilgo rose to 27 (on our scale) which indicates that the waves breaking against the coast at the time were much higher than they had been at any time we have been discussing. If microseisms were generated in the preceding cases by surf action, then we should have observed high microseisms during the period. The fact that the amplitudes of microseisms during the period was hardly beyond the noise level proves beyond all doubt that they are not generated by any surf activity.

A brief survey of the maps 38-44 shows that an intense cold front passed over the North Atlantic during the period. As a result of this the waves at 4YH rose to as high as 17½ ft. (graph 6). But the corresponding amplitude of microseisms was only six (on our scale). This shows that microseisms are not necessarily generated if a cold front travel over the ocean surface however vigorous the associated wind motion may be. Let us now examine the weather maps more closely.

Map 38 shows a barometric low located over the Great Lakes at 06.30 G.S.T. Feb. 21st with a cold front extending southward in the form of an arc coming towards the east and a warm front projecting east as far as the 66th meridian. Wind along the coast was generally from the south ranging in velocity from 8 to 24 m.p.h. It was about this time that the wave height near the coast started to increase and also the wave height at 4 YH, but not as rapidly as near the coast. Wind at the later place was 19-24 m.p.h. from S20°W. The proximity of the isobars indicates the intensity of the low and also the wind motion.

During the next nine hours (map 39) the front was moving rapidly towards the east as a result of which wind along the coast gained strength; for example at Nantucket its velocity increased to 25 to 31 m.p.h.

By 21.30 G.S.T. of the same day (map 40) the front reached the coast. It extended from New Brunswick to Florida lying almost parallel to the coast. Wind at Nantucket increased to 32-38 m.p.h. blowing from S30W. At 4YH its direction was approximately the same as at Nantucket. It is to be noticed that as the front was approaching the coast, isobars across the front was becoming more and more straight i.e. the break in the direction of the isobars as they crossed the front was diminishing. As a result the direction of wind motion was becoming more or less the same on both sides of the front.

Map (41) shows the conditions at 03.30 Feb. 22nd at which time the front moved into the coastal waters between Nova Scotia and Cape Hatteras. It should be noticed that although the front had already crossed Cape Cod, wind direction at Nantucket did not change appreciably. At 4YH the wind was blowing 39-46 m.p.h. from S80W.

Conditions six hours later (map 42) shows that the front had already moved into deep waters. At this time the wind on the two sides of the front was blowing more or less in the same direction. For example at Long Island it was N80°W and so also at 4YH.

Conditions nine hours later at 18.30 G.S.T. Feb. 22nd (Map 43) shows that the front was moving rapidly towards the east during the period. It is interesting to notice that the isobars across the front became almost straight lines in the meantime. This means that wind on the two sides of the front was moving almost in the same direction. It should be remembered that movement of such a front can not give rise to opposing waves to set up standing waves necessary for the generation of microseisms. The wind direction at 4YH was S80W, when the front was west of it. It changed to N40W after the front had shifted to the east of it. The change in the wind direction was therefore only 60°. It should also be noticed that the intervals between the isobars in this case as compared to the preceding ones were sufficiently close to showing that the intensity of the wind motion was sufficiently high to give rise to high microseisms.

Map 44 which depicts the conditions at 00.30 G.S.T. Feb. 23, 1953, shows that it was moving very rapidly during the last six hours.

Case 7. Aug. 14 - 16, 1953

All the microseismic storms we discussed so far were associated with a particular type of weather conditions i.e. a cyclonic front passing from the land into the ocean. The generating areas in those cases were too large to permit any precise location. We have studied a hurricane as an example of a localised barometric low center in which the generating area should be limited if microseisms are generated by any mechanism in which the movement of an atmospheric low over water is involved. There is however, no special reason for choosing this particular hurricane rather than any other. Another reason we had in mind for choosing a hurricane for the study of microseisms was to see whether they could be utilised for predicting the movement of a barometric low travelling over the ocean surface. If so, how accurately we can locate the position of the low by using information from a single station provided with three component instruments assuming that microseisms are pure Rayleigh waves. This requires that the positions of the low should be clearly defined so that we may know how accurate we are. The study of a hurricane will also allow us to examine more accurately whether microseisms are generated right below the eye of the hurricane or in some other part of it.

It has not been possible to compare the wave heights near the coast with the corresponding amplitudes of microseisms because the wave records for the period were not available. However, the study of the weather maps clearly indicates that the two phenomena are not related to each other.

Graph 7 is a plot of microseism amplitude at Weston and Harvard and the wave heights at 4YH. The positions of the hurricane are indicated by maps 45-51. The similarity of the amplitude curves for microseisms and waves in graph 7 especially at the beginning of the storm strongly suggest their intimate relationship. The microseisms however attained the maximum amplitude about 5 hours after the wave height at 4YH became maximum. There may be several reasons for it. First the hurricane did not pass exactly over the ship. Secondly it probably waited for the wind to change direction through sufficiently large angle at 4YH to set up standing waves. Thirdly the microseisms due to the movement of a localized low can not be correlated with the waves at one place because the generating area continuously shifts position.

The weather maps show that the hurricane with wind velocity up to 50 m.p.h. was moving on the 13th of August 1953, from the Bahamas towards Cape Hatteras where it reached at 00.30 G.S.T. on Aug. 14th. At Cape Hatteras wind was blowing on shore at 55-63 m.p.h. At 12.30 G.S.T. Aug. 14th (map 45) the eye of the hurricane was right on the coast. Wind near the center of the hurricane was about 40 m.p.h.

Six hours later at 18.30 G.S.T. (map 46) the center of the low moved into shallow waters just off the Delaware Bay. The wind velocity at 4YH increased to 39-49 m.p.h. It was about this time that microseisms commenced at Weston and Harvard.

During the next six hours (map 47) the center of the hurricane moved but very little and was still in shallow water. The wind near the center of the hurricane was extremely high. At Delaware Bay it was about 64-75 m.p.h. The wave amplitude at 4YH became maximum. The microseisms also gained in amplitude. After this the hurricane started to move and by 03.30 G.S.T. Aug. 15th it was right on the edge of the shelf south of Rhode Island.

The position of the low at 06.30 G.S.T. Aug. 15th was south of Cape Cod as shown in map 48. As a result of this movement the wind direction south of the 40th parallel swung through 180°. It was about this time that microseisms at Weston and Harvard reached the maximum and were coming directly from the south.

During the next six hours (map 49) the hurricane moved well to the east of Cape Cod. Wind in New England became either parallel to the coast or off shore. Microseisms during the period more or less had the same amplitude but they are coming at this time from South East, as well as from south which means that the generating area had extended north.

By 18.30 G.S.T. (map 50) the center of the hurricane moved on to the coast of Nova Scotia and its strength had considerably deminished. Over the deep water area south of Cape Cod where wind was blowing from east or southeast at the beginning of the day had become westerly. A new development is shown by the movement of a cold front to the coast. Microseisms at this time started to decrease.

By 00.30, Aug 16th (map 51) the front moved into shallow water but it did not change the conditions so far as microseisms were concerned. It is important to notice that due to the passage of the front wind direction did not change effectively anywhere.

Direction of Approach of the Waves

The directions of approach of the waves were computed for selected groups by using the method indicated before. The aximuths of the hurricane at different times were measured from the synoptic weather maps. The results of this computation show that the generating area continuously shifts as the eye of the hurricane continues to move, but they always come from the rear part rather then in front of it. One important fact revealed by these results is that although the generating area shifts with the center of the hurricane, waves continue to come to the station from the direction from which the hurricane had long since moved away.

This of course is exactly what we should expect if microseisms are generated by standing waves, because the waves once generated do not die down immediately. Graph 7 shows that waves as high as 14 feet continued at 4YH for more than six hours although the hurricane was continuously moving. This leads us to conclude that the most effective region for the generation of microseisms is in the rear part of the hurricane and that they are not generated right below the center of the low.

This also indicates that the location of the hurricane at a particular time can not be predicted by determing the direction of approach for just one group of waves arriving at the station. But an attempt to that end by studying the direction of approach for a number wave groups may prove successful. In order to do that we have tried the following method. The directions of approach for all the pure and unsuperposed waves were determined continuously in time. The change in the direction of arrival was considered to be the direction in which the hurricane was moving. Now to predict the location of the hurricane at a particular time, we have studied the directions of approach for all the waves that came before that time. The furthest point in the general direction of movement of the hurricane from where a wave group was identified to have come, was then considered to be the nearest point to the center of the hurricane. Table 1 shows the position of the hurricane thus determined and its actual location measured from the weather maps.

<u>Table 1</u>

Date	Time in G.S.T.	Determined Direction of the Storm Center	Actual direction of the storm center
Aug. 15, 1953	00.30	S 30.2 W	S 35 W
	06.30	S 0 E	S 20 E
	12.30	S 67.4 E	S 75 E
	18.30	S 90 E	N 77 E

Considering the inaccuracies involved in computing the directions of approach of the waves by using Rayleigh waves as mentioned earlier it appears from the results in Table 1 that use of finer methods coupled with the above technique may prove successful for locating the center of the hurricane.

Spectrum Analysis

In our case history analysis we found strong evidences of microseisms being generated by standing waves. If this is true then there must exist an important relationship between the microseisms and the ocean waves as predicted from theoretical considerations i.e. the frequency of microseisms should be twice the frequency of ocean waves. Unless this important relation is verified, all our evidences, however strong they may appear to be, will always remain inadequate.

Now the question is how shall we expect to verify this important result unless we know which group of ocean waves is responsible for the generation of a particular group of microseisms.

Since there is no means for this identification we shall have to proceed with the analysis with the assumption that the frequencies of the ocean waves remain fairly constant during a storm and consequently can hope for only approximate verification.

Before going into actual computation of spectra we had to decide one important question i.e. which part of the record we should choose for analysis. Should we choose a section of the record at the beginning of a storm or towards the end of it? Before answering this question let us go back and see what we observed in our case history analysis. There we found that on the eastern side of North America cold fronts usually form on the land and slowly travel eastward into the ocean.

The wave height near the coast becomes a maximum when the front is in the neighborhood of the coast and hence they are generated near the coast. But microseisms increase in amplitude only when the front moves into deep water. Therefore the highest waves recorded near the coast are not responsible for the generation of microseisms and consequently are not expected to have half the frequency of microseisms. As a matter of fact they do not satisfy the 1:2 frequency relationship with microseisms. Therefore for analysis we should choose a section of the wave record where the waves recorded were generated in deep water region and travelled afterwards near the coast, for they are the ones that generate microseisms. In making our choice we can use the amplitude graph very profitably. For example graph 1 shows that at 01.00 G.S.T. Dec. 12th, 1952, the wave amplitude at Woods Hole was maximum. The waves recorded at that time were obviously generated near the coast. After the front moved into deep waters the wind along the coast became off shore and the waves generated near the coast could not have been recorded there. Therefore the waves recorded after that time must have been generated well off-shore and travelled later on to the coast to be recorded there. Thus if we choose a section of the record for example at 17.00 G.S.T. of the same day we can be fairly sure that the waves recorded at that time were generated in the deep water region.

Before going into the discussion of the results, we want to point out one important point regarding the interpretation of the results of our computation. In our analysis we have computed the power for discrete frequencies. Therefore the frequency for which our computed value show the maximum power may not coincide with the actual frequency in which the maximum power in the record is contained. We can however decide whether the true maximum should be at a greater or lower frequency by considering the power contained at two neighboring frequencies i.e. the true maximum must lie between the two frequencies for which our computed results show the highest values and therefore our limit of accuracy will lie within half the frequency difference between any two consecutive points (the frequency difference between any two consecutive points is ~~the same in the~~ same in each case).

The results of our computation are shown in graphs 9-12. In drawing the curve no smoothing process has been adopted except at the maximum. The frequencies at the maximum are given in table 2 which shows that the ratios of the frequencies of ocean waves to the frequencies of microseisms lie between .48 to .514. Considering the many uncertainties as we mentioned earlier, the results of our analysis clearly indicate that microseisms and ocean waves do have the frequency relationship as predicted from theoretical considerations.

It will be probably important to point out one important fact as revealed by our analysis. For example the power spectrum of microseisms in graph 9 shows three distinct maxima at frequencies .21, .247, and at .313. Similarly the wave spectrum shows three maxima at frequencies .105, .11 and .081. Corresponding to the frequencies .105 and .11 we have the microseism frequencies .21 and .247 respectively. But there is no frequency in the ocean waves which can correspond to the frequency .313 in microseisms and vice versa. Should this therefore mean that the standing wave theory is not correct? The answer is no. For all the waves recorded near the coast certainly do not come from the generating area of microseisms. Secondly microseisms recorded at a station may come from different places and the waves from all the places may not reach the coast. Consequently we can not expect to be able to identify frequencies in the wave spectrum corresponding to all the frequencies in the microseisms. This therefore should not make us apprehensive about the validity of the theory. As a matter of fact this is probably one of the reasons why the attempts previously made to verify this frequency relationship between the microseisms and ocean waves by rough measurements failed.

In order to compare the periods of ocean waves as reported from 4YH with those of microseisms, we computed the mean periods of microseisms by using the following method. About the time for which the periods of the ocean waves were reported, we selected all the well formed wave groups on the microseism records within thirty minutes and measured the period for each group by usual method and then took the mean. The results are shown in table 3. Here also we observe that during significant periods two times the periods of microseisms fall well within limit of the periods of ocean waves as reported from the ship. This together with the results of our analysis proves it beyond doubt that the frequencies of microseisms and ocean waves are related to each other in the ratio as predicted from the theory.

Table 2

Record	Time	Frequency at the maximum 1	2	3	Frequency of waves/ Frequency of Microseisms
Microseism (Weston)	20.00 GST Dec 12, 1952	.21 ± .005	.247 ± .005	.313 ± .005	.5, .445
Waves Woods Hole	21.00 GST Dec 12,1952	.105 ± .0023	.11 ± .0023	.081 ± .0023	
Microseism (Weston)		.1963			.498
Waves (Geilgo)	13.00 GST Feb ,1953	.097 ± .0025			
Microseism (Weston)	17.00 GST	.2187 ± .0056	.264 ± .0056		
Waves (Geilgo)	17.00 GST Feb 13, 1953	.1125 ± .0025	.085		.514
Microseism (Weston)	16.30 GST Feb 16,1953	.185 ± .0056	.241 ± .0056	.28 ± .0056	.49 .48
Waves (Geilgo)	17.00 GST Feb 16, 1953	.09 ± .0025	.115 ± .0025		

Table 3

Date	Time in G.S.T.	Mean Period of Microseisms in Sec.	Period of Ocean Waves at 4YH in Sec.
Dec 11	15.00	3.4	7-9
	18.00	3	7-9
	21.00	3.5	7-9
Dec 12	00.00	3.8	7-9
	03.00	3.8	7-9
	06.00	4.	7-9
	09.00	4.3	9-11
	12.00	4.2	9-11
	15.00	4.5	9-11
	18.00	4.6	9-11
	21.00	4.3	9-11
Dec 13	00.00	4.	9-11
	03.00	4.2	9-11
	06.00	4.3	9-11
	09.00	4.5	9-11
Dec 16	00.00	3.6	7-9
	03.00	3.5	7-9
	06.00	3.8	7-9
	09.00	3.8	
	12.00	4.2	7-9
	15.00	4	7-9
	18.00	4.4	7-9
	21.00	4	
Dec 17	00.00	4.1	7-9
	03.00	4	11-13
	06.00	3.8	7-9
	09.00	4	7-9
	12.00	4	7-9

Table 3 (cont.)

Date	Time in G.S.T.	Mean Period of Microseism in Sec.	Period of Ocean Waves at 4YH in Sec.
Feb 8	15.00	3.3	9-11
	18.00	3.8	7-9
	21.00	4	7-9
Feb 9	00.00	4.2	5-7
	03.00	4.4	7-9
	06.00	4.6	7-9
	09.00	4.5	7-9
	12.00	4.7	7-9
	15.00		
	00.00	3.3	7-9
Feb 13			
	12.00	3.9	7-9
	15.00	4	7-9
	18.00	4.2	7-9
	21.00	3.8	7-9
Feb 14	00.00	3.8	7-9
	03.00	3.75	7-9
	09.00	3.8	7-9
	12.00	3.6	7-9
Feb 15	21.00	3.4	7-9
Feb 16	04.00	3.5	11-13
	03.00	3.8	11-13
	06.00	3.8	11-13
	09.00	4.3	11-13
	12.00	4.5	9-11
	15.00	4.7	
	18.00	4.5	7-9
	21.00	4.5	7-9
Feb 17	00.00	4.9	11-13
	03.00	4.7	9-11
	06.00	4.6	9-11
	09.00	4.6	9-11

Table 3 (cont.)

Date	Time in G.S.T.	Mean Period of Microseisms in Sec.	Period of Ocean Waves at 4YH in Sec.
Aug 14	15.00	3.4	5-7
	18.00	3.4	5-7
	21.00	3.6	5-7
Aug 15	00.00	3.7	5-7
	03.00	3.6	5-7
	06.00	3.4	5-7
	09.00	3.5	5-7
	12.00	3.3	5-7
	15.00	3.4	5-7
	18.00	3.6	5-7
	21.00	3.4	5-7
Aug 16	00.00	3.4	5-7
	03.00	3.5	5-7
	06.00	3.2	5-7
	09.00	3	5-7
	12.00	3.1	5-7

Discussion

In our case history analysis we have seen that the waves near the coast become maximum when the cold fronts are in the neighborhood expecially on the coast. They gradually decline in amplitude when the fronts move into the ocean. The amplitude of microseisms on the otherhand does not start to increase until the fronts move into deep water. As a result the microseisms usually attain the maximum amplitude after the waves near the coast become maximum. Particularly we have observed in case 2 that high microseisms were recorded at Weston and Harvard although the trace amplitude of waves at the nearby coast hardly rose beyond the noise level. Finally no significant increase in the amplitude of microseisms was observed on the 21st Feb., 1953, although the waves breaking against the nearby coast during the period were higher than at any time we have studied. These prove beyond doubt that microseisms are not generated by the beating of the surf against rocky coasts.

The amplitude graphs (1-7) show on the otherhand strong correlations between the microseisms recorded at Weston and Harvard with the waves in the deep water regions of the North Atlantic. Secondly high microseisms were recorded only when due to rapid movement of the fronts, there was sufficient change in the direction of wind to give rise to opposing waves necessary for the generation of standing waves. These together with the fact that the frequencies of ocean waves are related to those of microseisms by the ratio 1:2 as we saw from the results of our analysis and also by comparing the periods of microseisms with those of ocean waves as reported from the Weathership 4YH strongly suggest that microseisms are generated by standing waves in the ocean.

Besides demonstrating the origin of microseisms the present investigation reveals some important facts about the actual mechanism by which they are generated. These are as follows:

(1) As regards the actual mechanism by which standing waves can be generated two possibilities were suggested by Longuet-Higgins. (i) They may be generated by the superposition of waves reflected from the coast with those travelling towards the coast. (ii) They may also be generated near the center of the hurricane where wind may possible move in opposite directions.

Now if the first mechanism be effective, we should observe large microseisms when high waves strike against the coast. The fact that microseisms do not begin to increase in amplitude until the front moves into deep water clearly indicates that the coastal reflection is not a very effective mechanism for the generation of standing waves at least not of sufficiently high amplitude to produce microseisms so far as the Eastern Coast of North America is concerned. Longuet-Higgins realized the ineffectiveness of this mechanism and stated "that the largest microseisms are probably due to wave interference in mid-ocean, although coastal reflexion may be a more common cause of smaller amplitude microseisms". In regions of steep rocky coasts such as Norway, coastal reflexion may be effective in the generation of microseisms.

In our discussion on locating the center of hurricane by using Rayleigh waves we saw that microseisms usually come from the rear part of the hurricane. Secondly they continue to come from the directions from which the hurricane had moved away long time ago. These together with the fact that microseisms gain in amplitude only when the center of the low moves rapidly over the ocean surface rather than when it is stationary indicate that the most effective region for the generation of standing waves is at the rear of the hurricane rather than at the center of it. The actual mechanism may be as follows:

The winds at the two ends of a diameter through the center of the hurricane move in opposite directions. For example in a hurricane travelling from south to north, the wind on the northern part moves from east to west while on the southern side it moves from west to east. When the hurricane moves rapidly, the wind direction at a place changes direction through 180° thus giving rise to standing waves.

The second mechanism by which standing waves can be generated as revealed in the present study is by the rapid movement of a cold front if the isobars while crossing the front change direction by sufficiently large angles.

The third mechanism is by the superposition of waves coming from two independent sources as observed by Dinger and Fisher.

2. Mere existence of a cold front or a barometric low is not sufficient for the generation of microsisms. For example in case 2 we observed that microseisms did not commence to increase

in amplitude until 00.30 G.S.T. Dec. 16th although the weather conditions become well defined by 18.30 G.S.T. of the preceding day. We also observed in case 6 that there was no significant increase in the amplitude of microseisms during the period Feb. 21st to Feb. 23rd, 1953, although an intense cold front swept over the North Atlantic. These clearly indicate that microseisms are not generated right under a cold front or a barometric depression as suggested by some authors. They also negate the air-water coupling mechanism for the generation of microseisms as suggested by Donn[21].

3. It has been pointed out that in intense microseimic storms, the amplitude of microseisms decays much faster than in the case of ordinary storms. The amplitude of microseisms generally depends on two factors (a) effective change in the wind direction as the cold front travels over the ocean surface. (b) the intensity of the wind. In general the intense microseismic storms are usually accompanied by high wind velocity. On account of this strong wind, waves coming from opposite direction are quickly suppressed. As a result, the amplitude of microseisms in such cases drops down rapidly.

4. We have seen that microseisms decrease in amplitude as the fronts recede from the recording station. This is probably due to the attenuation of the waves as they travel through underwater paths. But the effect of attenuation on the waves on the northern side of the Atlantic does not seem to be so strong as was observed in Guam by Dinger and Fisher who re-

ported to have recorded microseisms coming from distances of only a few hours wave-travel from the station.

5. It has been mentioned that at the beginning of a storm, the microseisms are usually low in amplitude and very irregular in character at which times the fronts are usually on the shelf or at the edge of it. As the fronts move into the deep water regions where the depth of water is more uniform, the microseisms increase in amplitude and look like regular pulses. This shows that the depth of water in the generating area has a significant effect on the nature of microseisms. The microseisms generated in the shallow water regions where the depth is very variable, have a wide frequency range. As a result of superposition of waves of diverse frequencies, the traces appear highly irregular. When the fronts move into regions of more uniform depth, microseisms of some favored frequencies predominate due to the effect of resonance. Consequently there will be a shrinkage in the frequency band. Further the resonating waves should be of lower frequency because of increased depth. These are clearly revealed by the spectrum of microseisms in graphs 9-12 as was also observed by Donn[21]. More detailed analysis should however be made before we can make any definite conclusion about it.

CONCLUSIONS

1. Microseisms are constituted of Rayleigh waves. Waves having the characteristics of Love waves that appear on record may be due to independent causes or are generated by Rayleigh waves when they pass from the ocean on to the continent.

2. The present investigation completely negates the possibility of microseisms being generated by breaking of surf against the rocky coast.

3. Microseisms are generated by standing waves in the ocean formed by superposition of two systems of progressive waves of approximately the same periods coming from opposite direction.

4. Standing waves can be generated by any of the following ways.

   (a) When a barometric depression such as in a hurricane moves over the ocean surface

   (b) When a cold front travels over the ocean surface provided isobars while crossing the front change direction through a sufficiently large angle.

   (c) When waves from two independent sources superpose on each other as that observed by Dinger and Fisher.

5. Coastal reflection appears to be ineffective in the mechanism for the generation of standing waves so far as the eastern coast of North America is concerned.

6. The most effective region for the generation of microseisms is at the wake of the hurricane or a cold front when they travel over the ocean surface rather than directly below them.

7. The effect of attenuation on the waves when they travel through underwater paths seems to be much less on the northern

part of the Atlantic compared to what has been observed by Dinger and Fisher in the regions of Guam.

8. The depth of water in the generating area seems to have a significant effect on the nature of microseisms. Large amplitude microseisms are generated by standing waves in the deep water region.

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BIOGRAPHICAL NOTE

Born at Bagadana in the district of Noakhali, Eastern Pakistan on the 1st of September 1924. Passed the Matriculation Examination in 1940 from Mangalkandi H. E. School. Passed the Intermediate of Science Examination held under the auspices of Calcutta University in 1942 from Chittagong Government College. Entered the Dacca University the same year and obtained the degree of Bachelor of Science with Honours in Physics in 1945. On the following year obtained the M.Sc. degree in Physics from the same University. Served under the Government of East Bengal as a lecturer in Physics from 1947 to 1950. Was studying Geophysics in M.I.T. ever since.

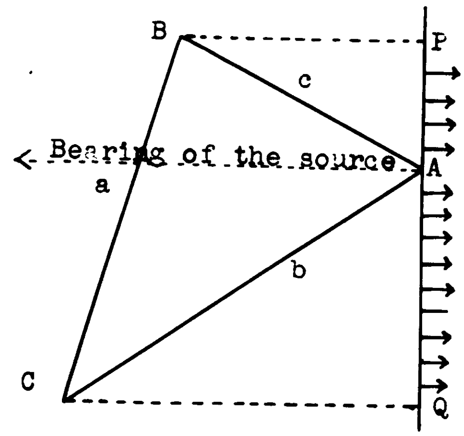

B
P
c
Bearing of the source
A
a
b
C
Q

Fig. 1

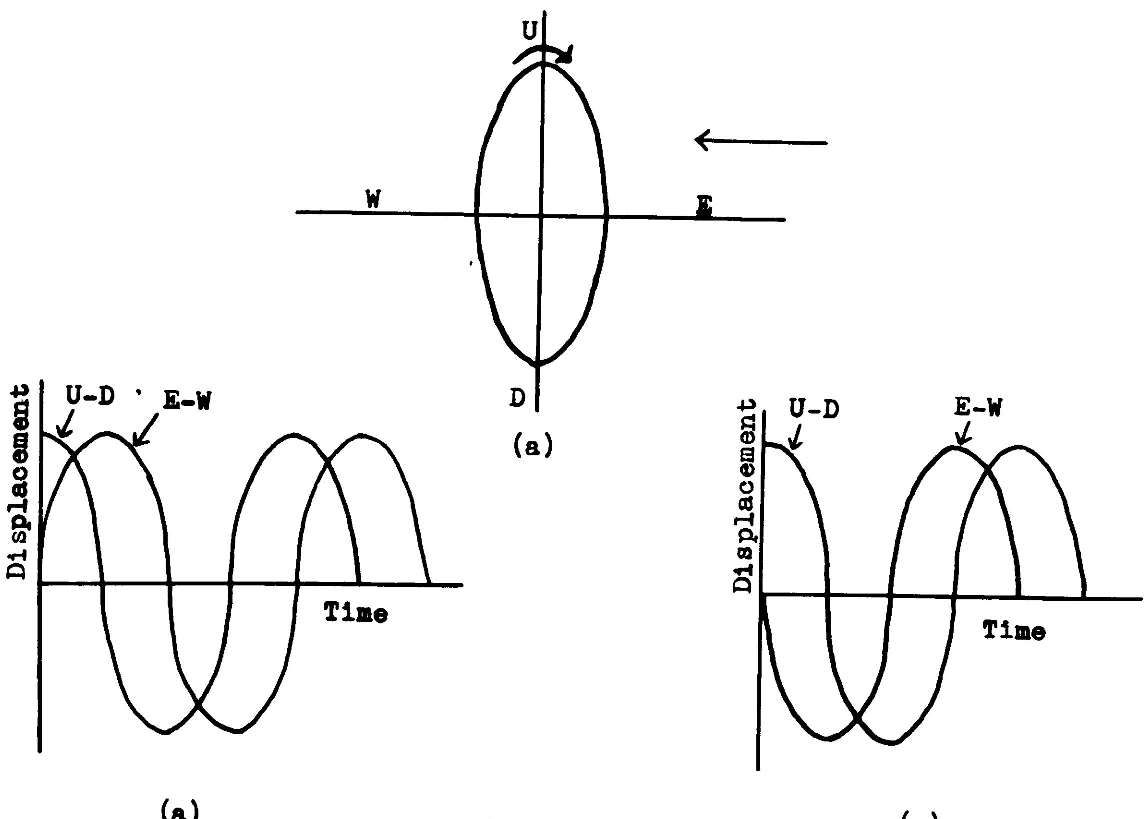
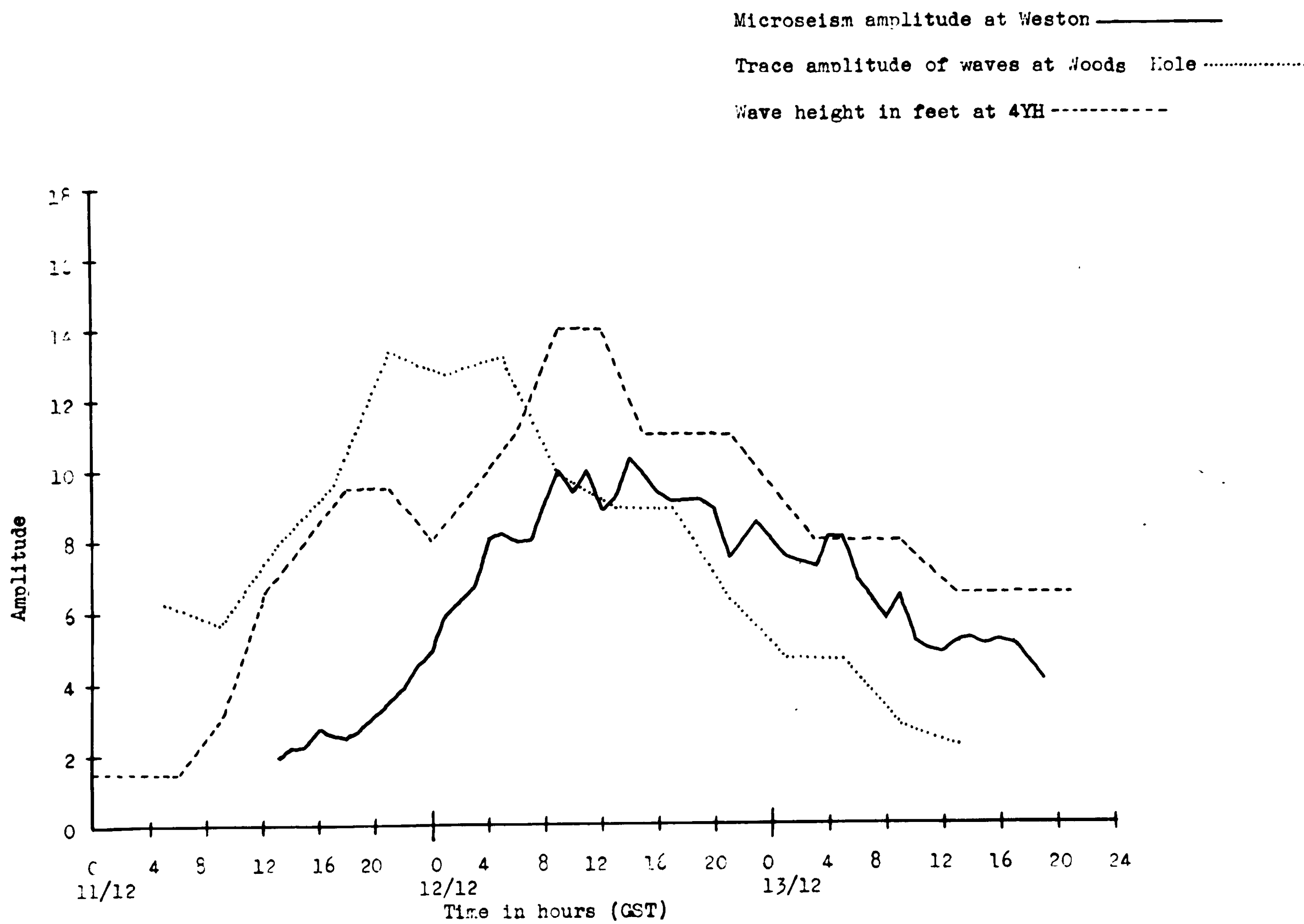
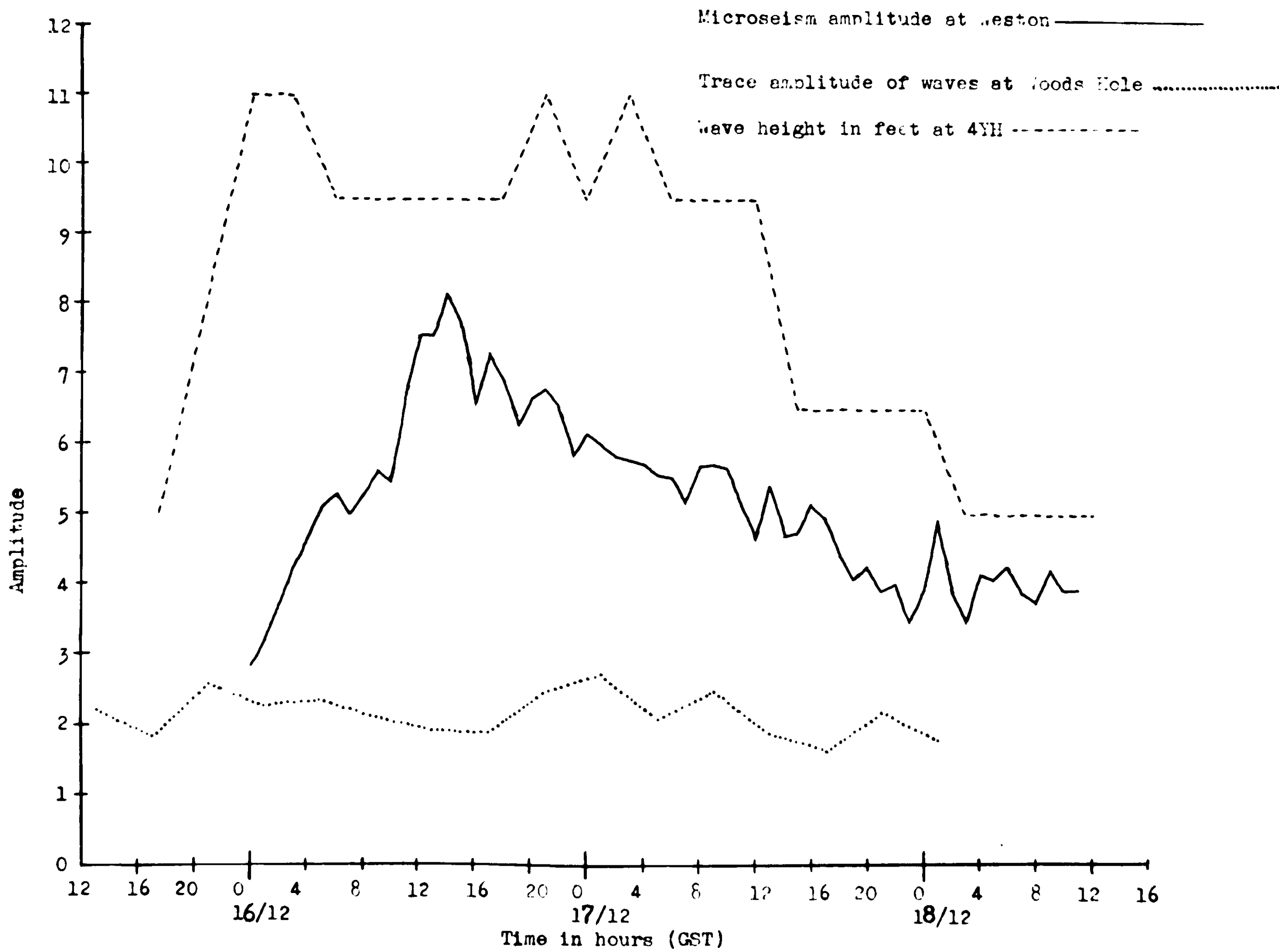

U
W
E
D
(a)
Displacement
U-D
E-W
Time
(a)
Displacement
U-D
E-W
Time
(c)

Fig. 2

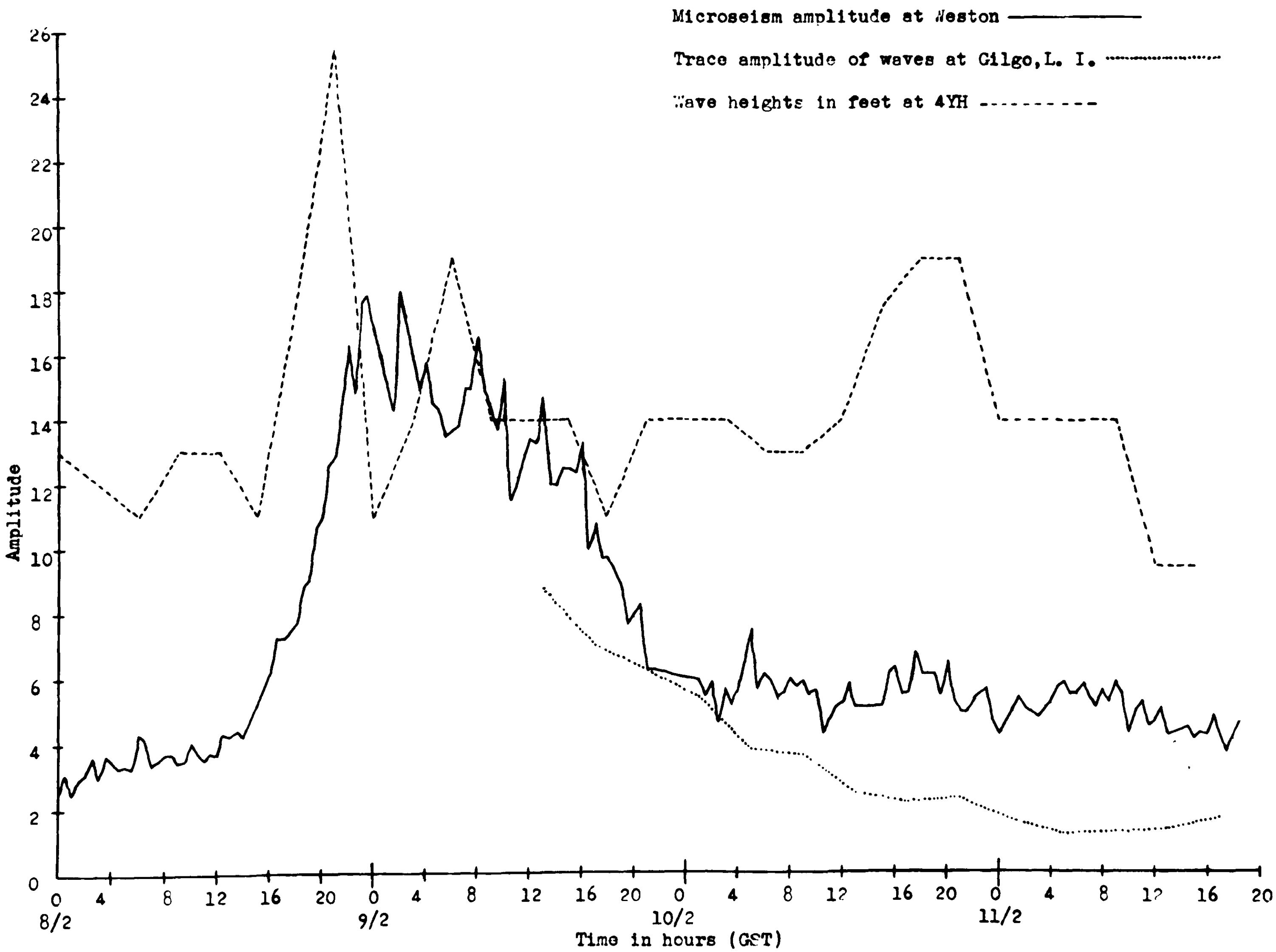


Microseism amplitude at Weston
Trace amplitude of waves at Woods Hole
Wave height in feet at 4YH
Amplitude
0
2
4
6
8
10
12
0
4
8
12
16
20
0
4
8
12
16
20
0
4
8
12
16
20
24
11/12
12/12
13/12
Time in hours (GST)

Graph 1.

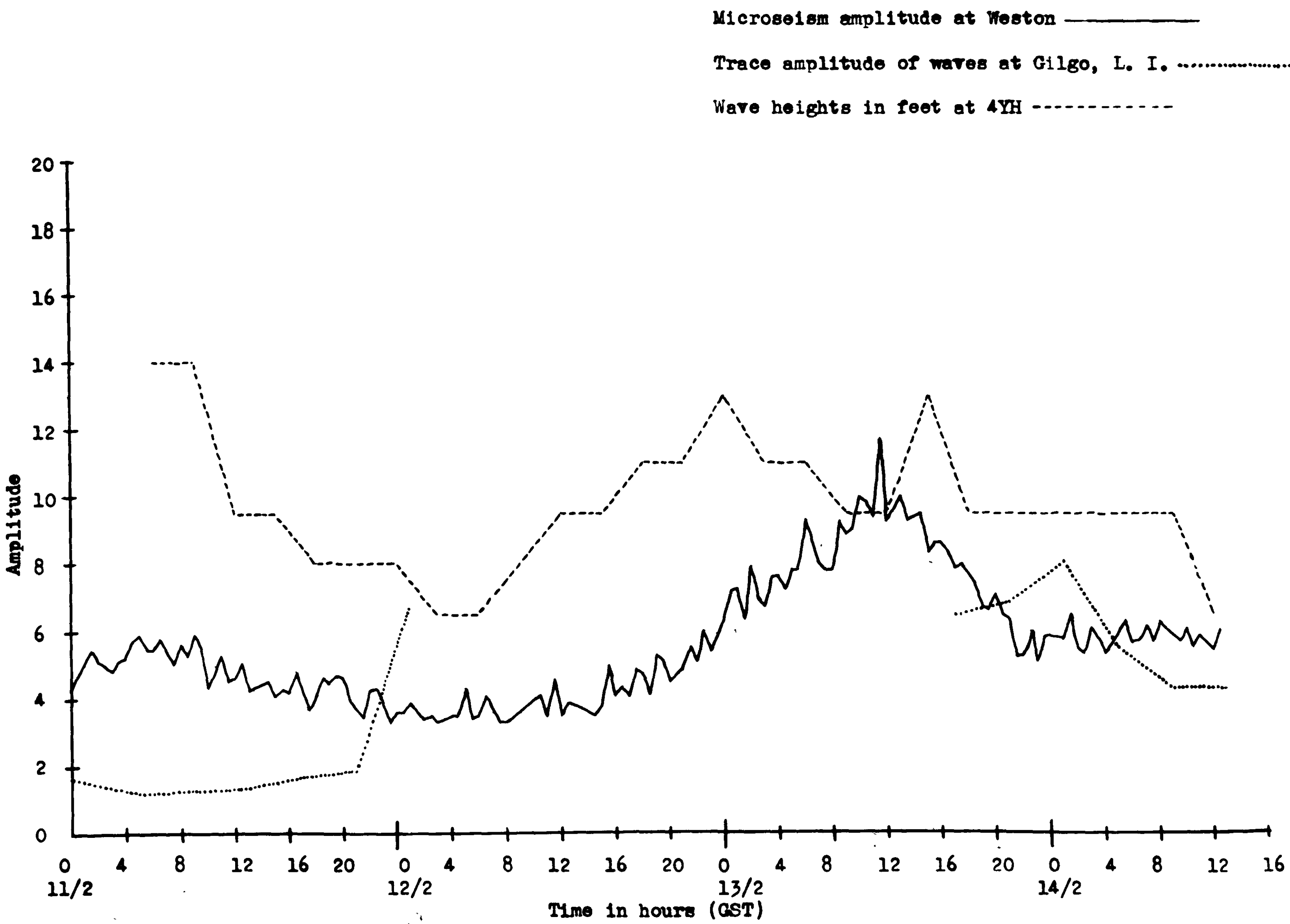

Microseism amplitude at Weston
Trace amplitude of waves at Woods Hole
Wave height in feet at 4YH
Amplitude
0
1
2
3
4
5
6
7
8
9
10
11
12
12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16
16/12
17/12
18/12
Time in hours (GST)

Graph 2.

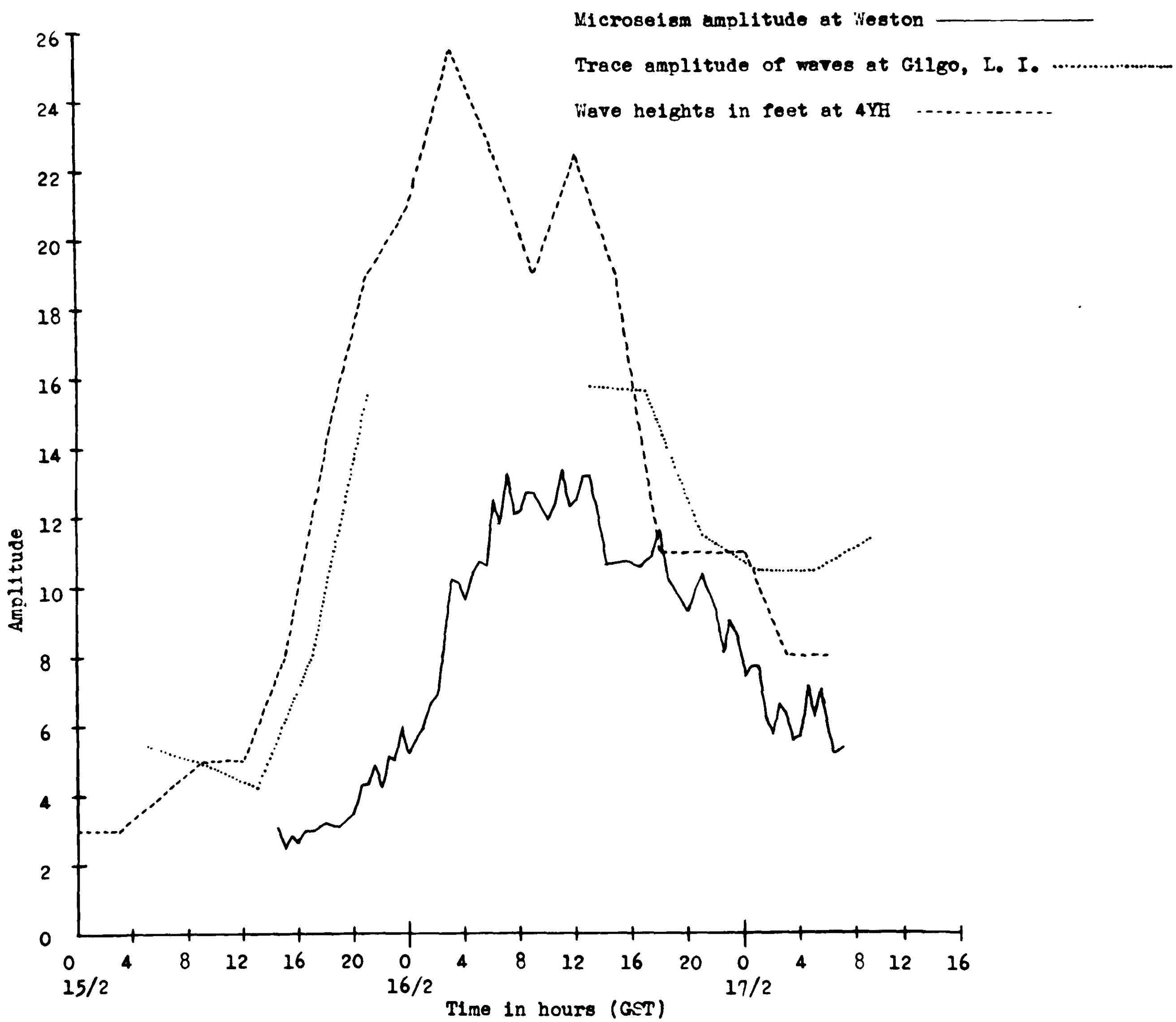


Microseism amplitude at Weston
Trace amplitude of waves at Gilgo, L. I.
Wave heights in feet at 4YH
Amplitude
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20
8/2
9/2
10/2
11/2
Time in hours (GST)

Graph 3.

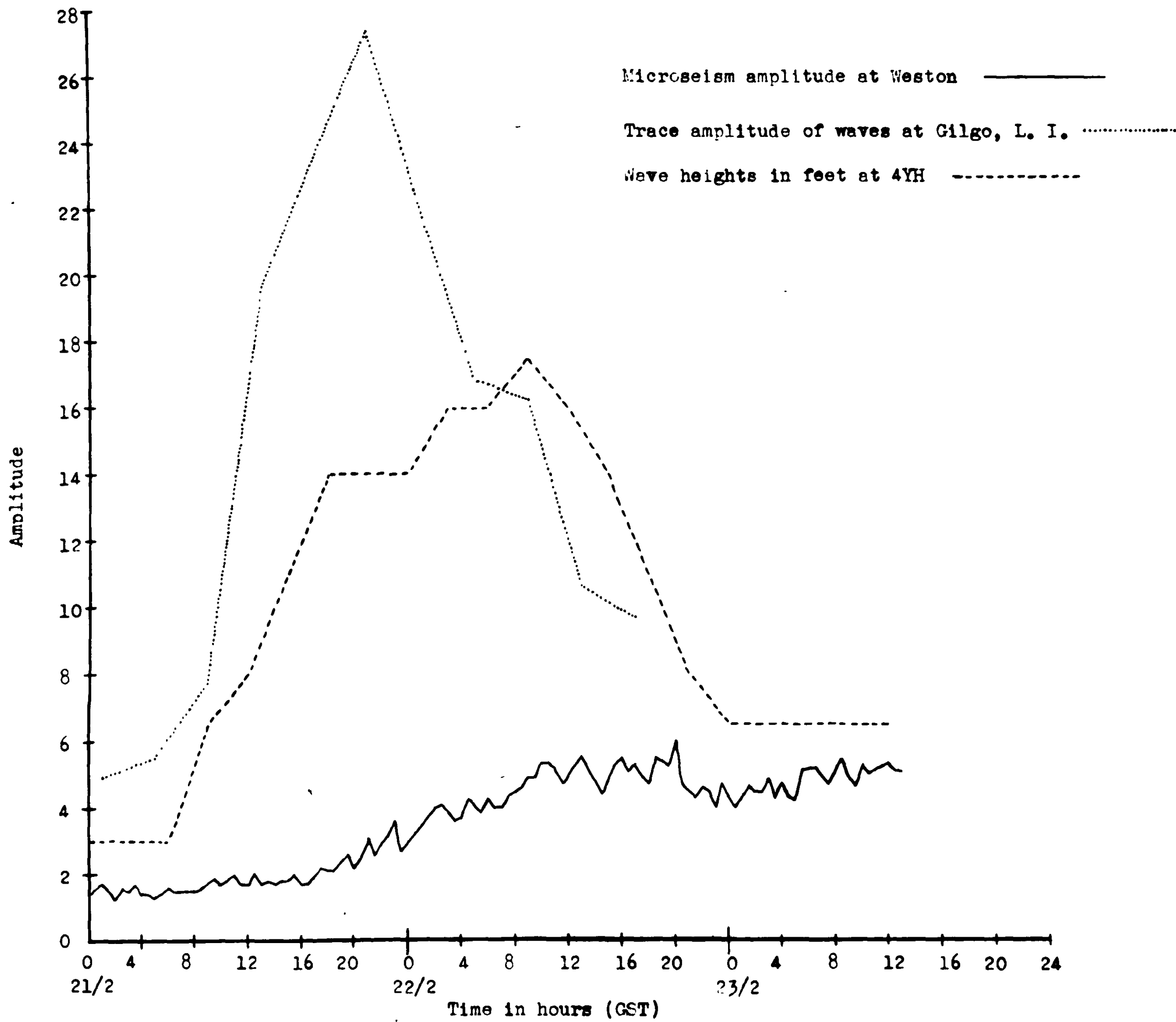

Microseism amplitude at Weston
Trace amplitude of waves at Gilgo, L. I.
Wave heights in feet at 4YH
20
18
16
14
12
10
8
6
4
2
0
Amplitude
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16
11/2
12/2
13/2
14/2
Time in hours (GST)

Graph 4.

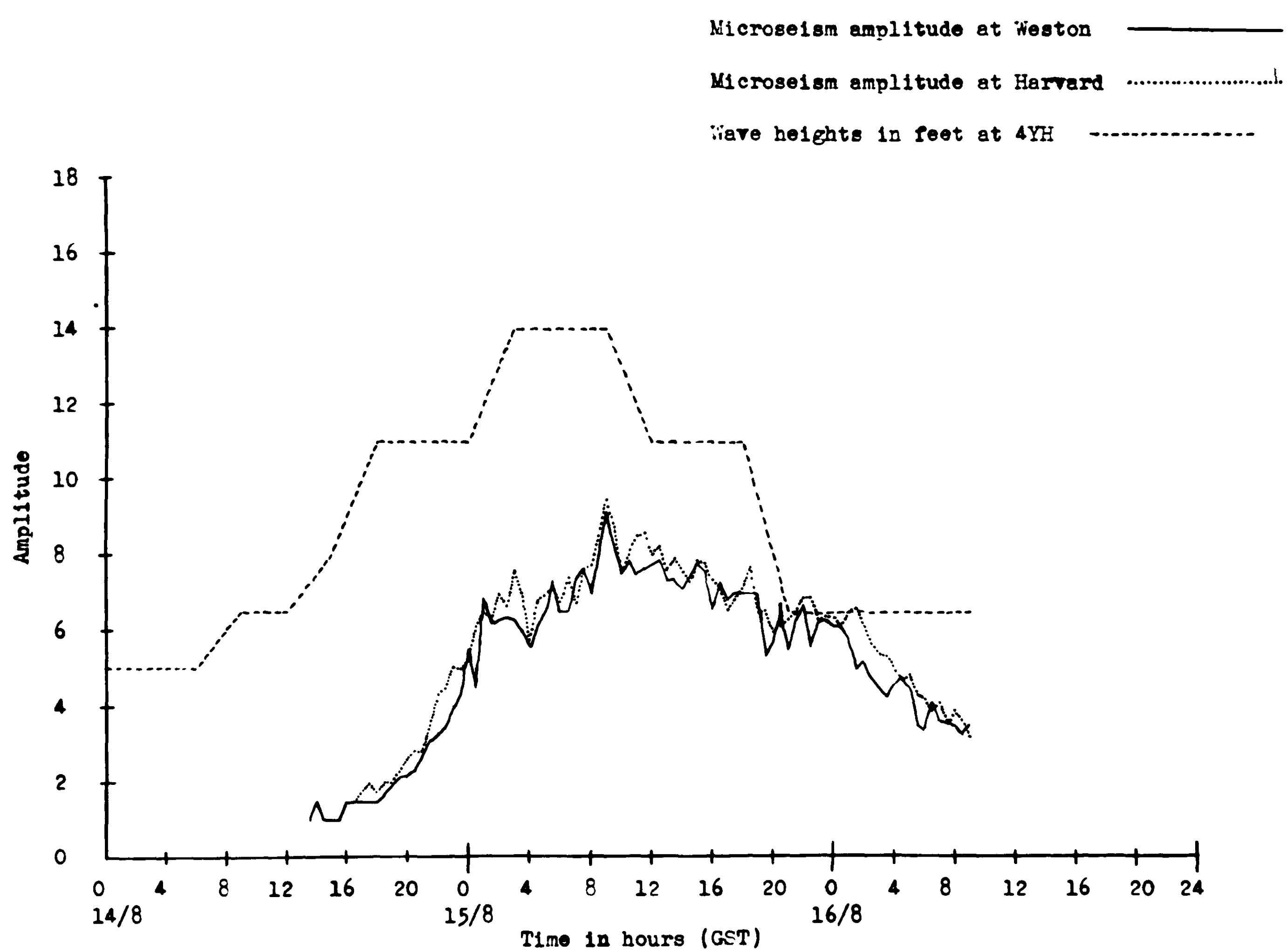


Microseism amplitude at Weston
Trace amplitude of waves at Gilgo, L. I.
Wave heights in feet at 4YH
Amplitude
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16
15/2
16/2
17/2
Time in hours (GST)

Graph 5.

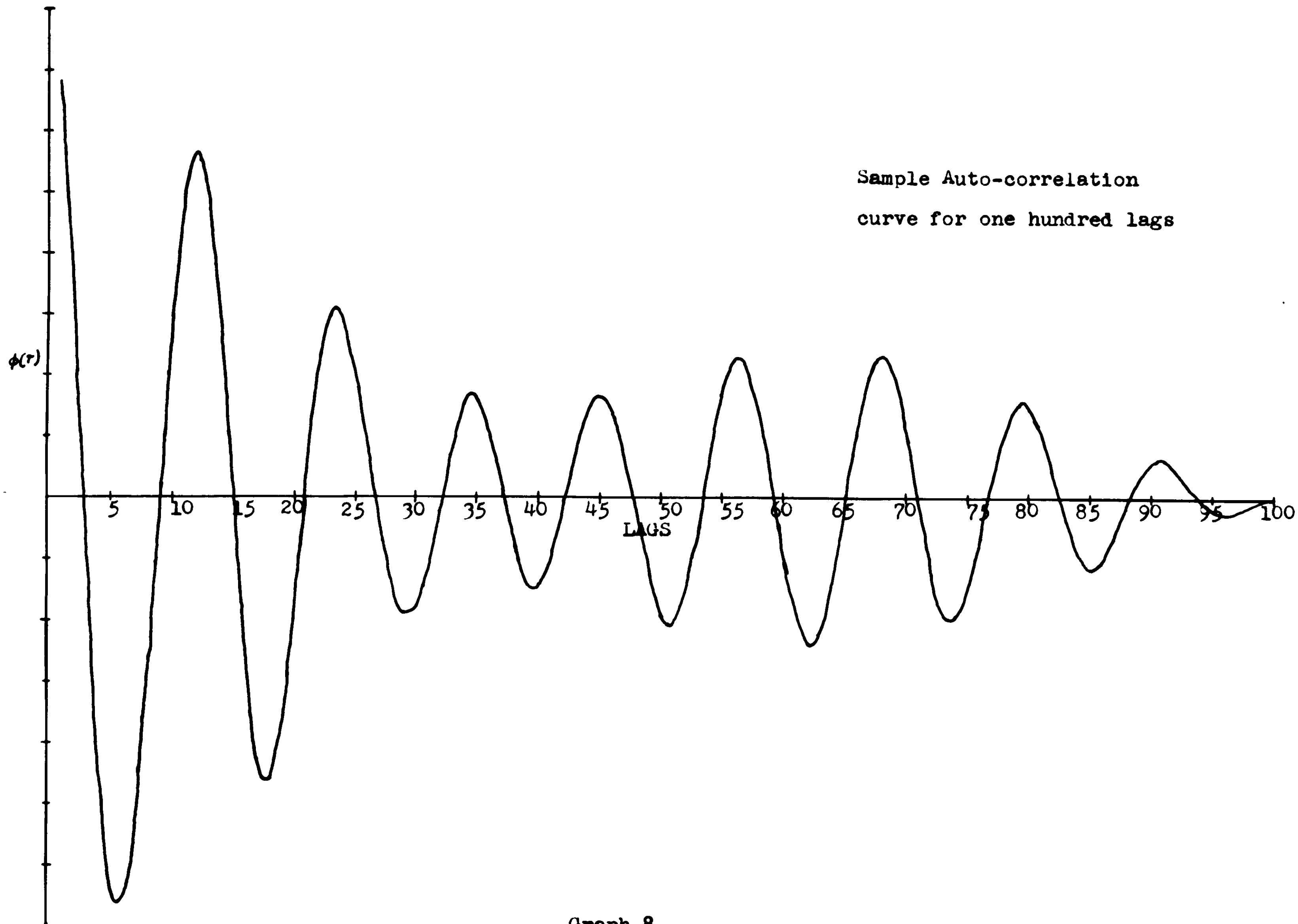

Microseism amplitude at Weston
Trace amplitude of waves at Gilgo, L. I.
Wave heights in feet at 4YH
Amplitude
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 24
21/2
22/2
23/2
Time in hours (GST)

Graph 6.



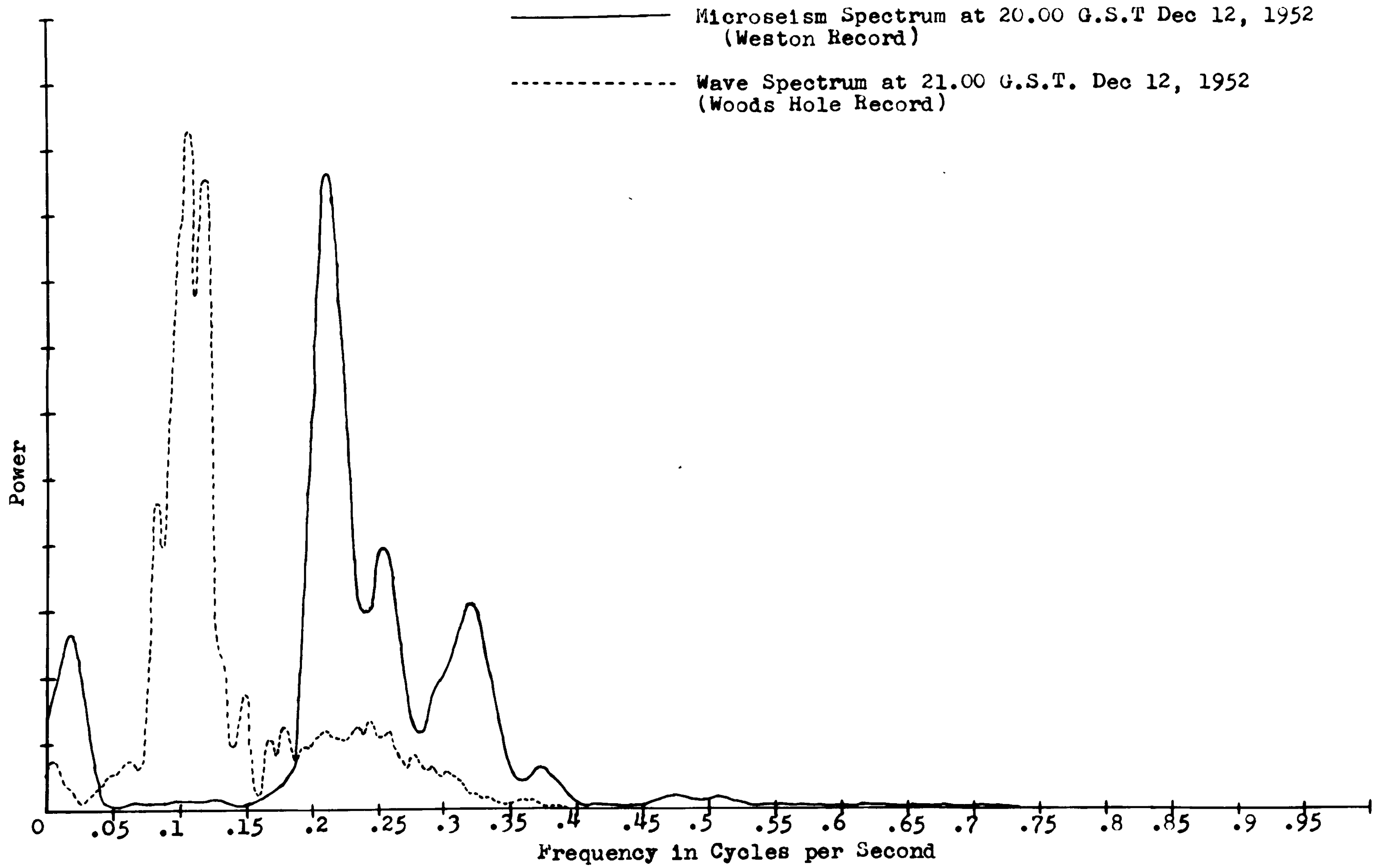
Microseism amplitude at Weston
Microseism amplitude at Harvard
Wave heights in feet at 4YH
Amplitude
0
2
4
6
8
10
12
14
16
18
0 4 8 12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 24
14/8
15/8
16/8
Time in hours (GST)

Graph 7.

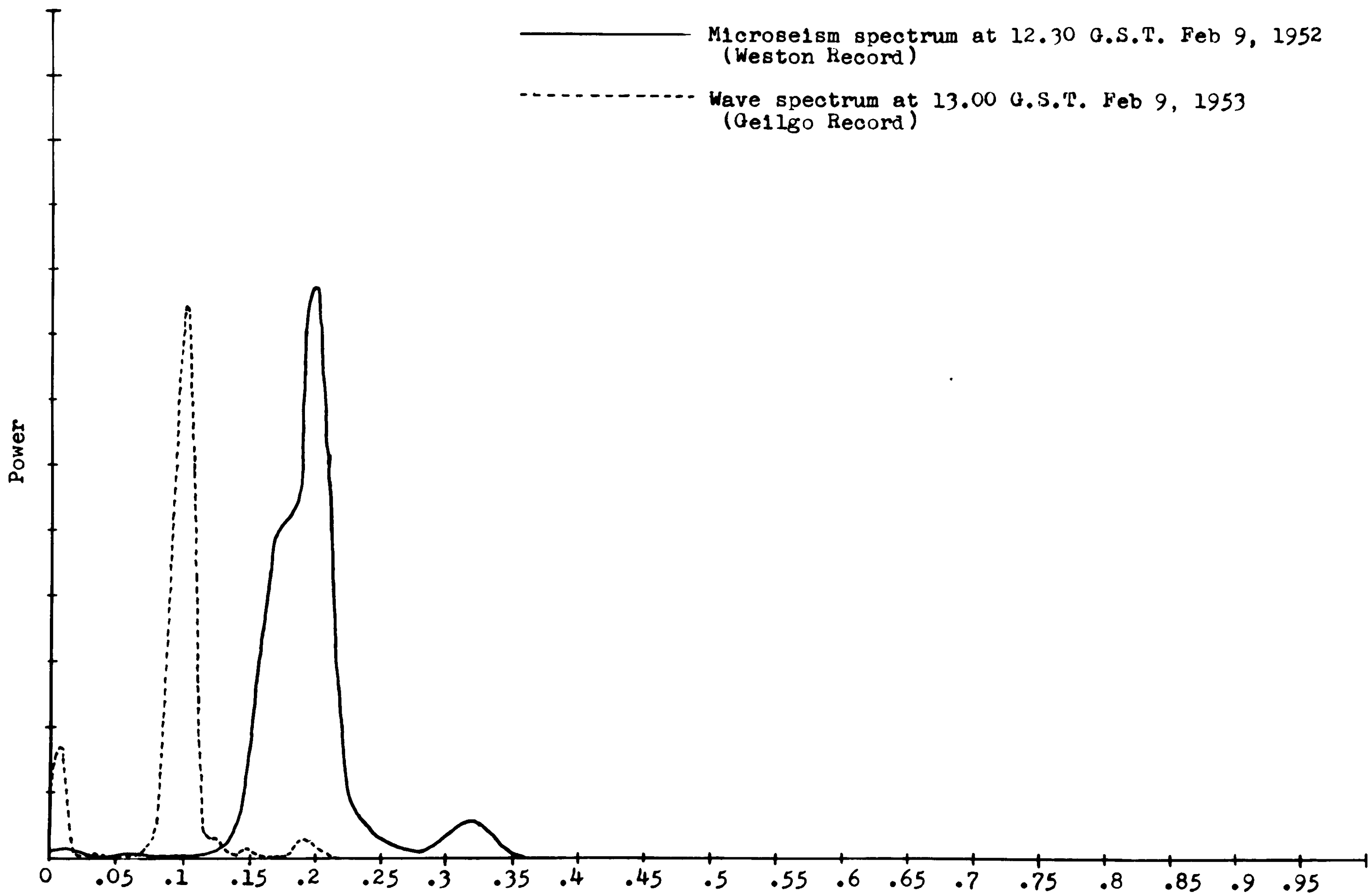


Sample Auto-correlation
curve for one hundred lags

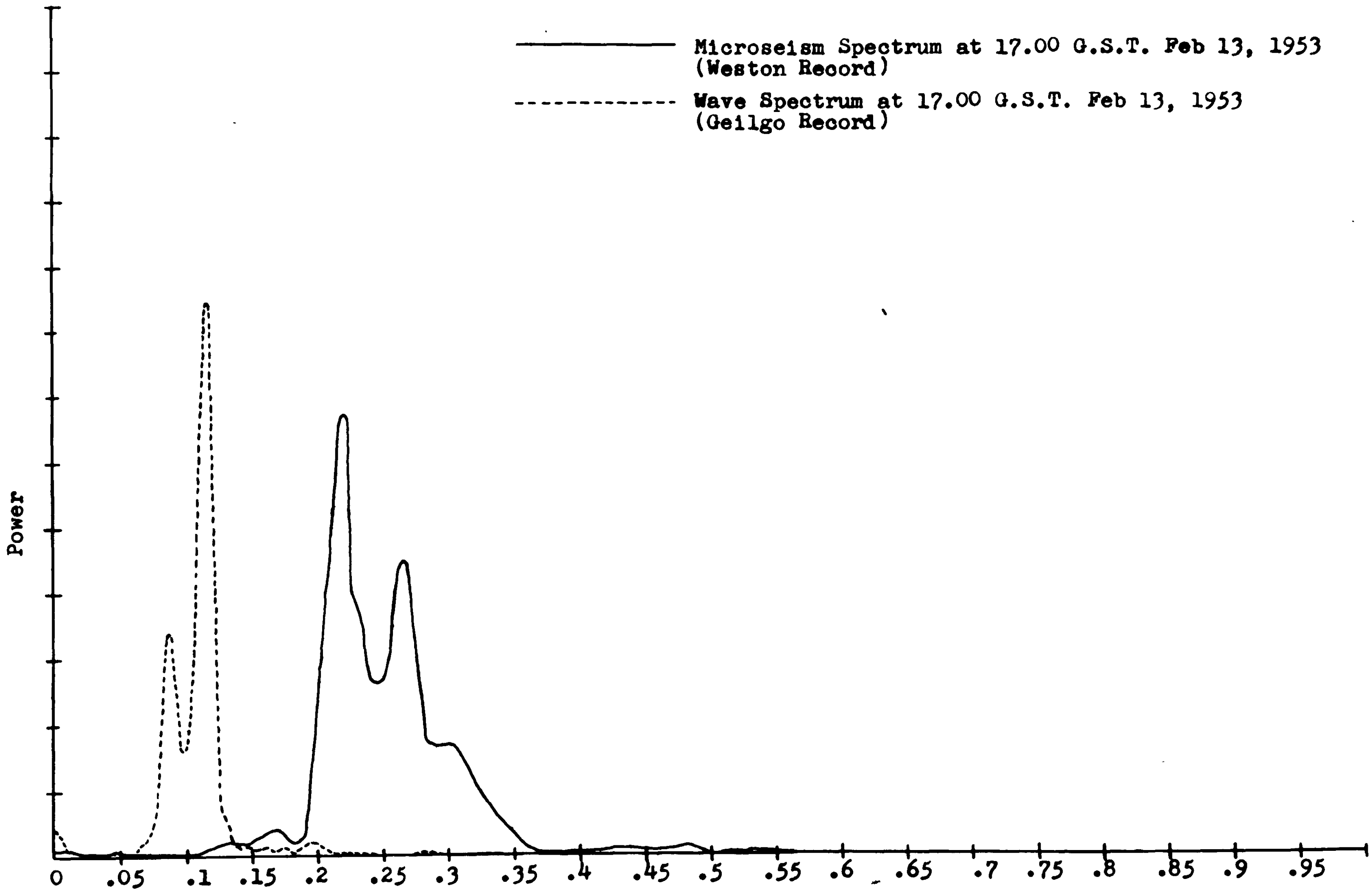
Graph 8


Microseism Spectrum at 20.00 G.S.T Dec 12, 1952
(Weston Record)
Wave Spectrum at 21.00 G.S.T. Dec 12, 1952
(Woods Hole Record)
Power
0
.05
.1
.15
.2
.25
.3
.35
.4
.45
.5
.55
.6
.65
.7
.75
.8
.85
.9
.95
Frequency in Cycles per Second

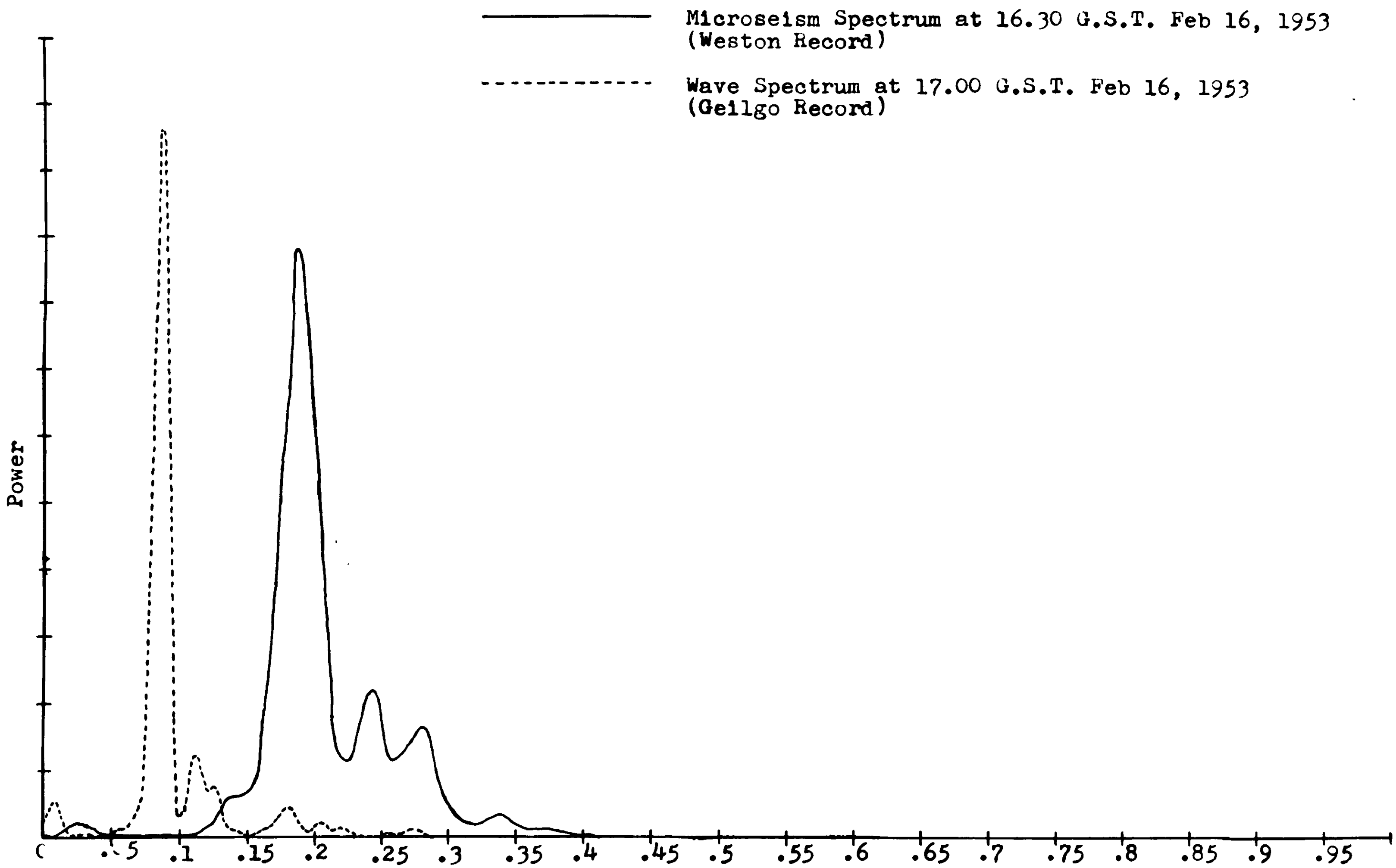
Graph 9


Microseism spectrum at 12.30 G.S.T. Feb 9, 1952
(Weston Record)
Wave spectrum at 13.00 G.S.T. Feb 9, 1953
(Geilgo Record)
Power
0
.05
.1
.15
.2
.25
.3
.35
.4
.45
.5
.55
.6
.65
.7
.75
.8
.85
.9
.95

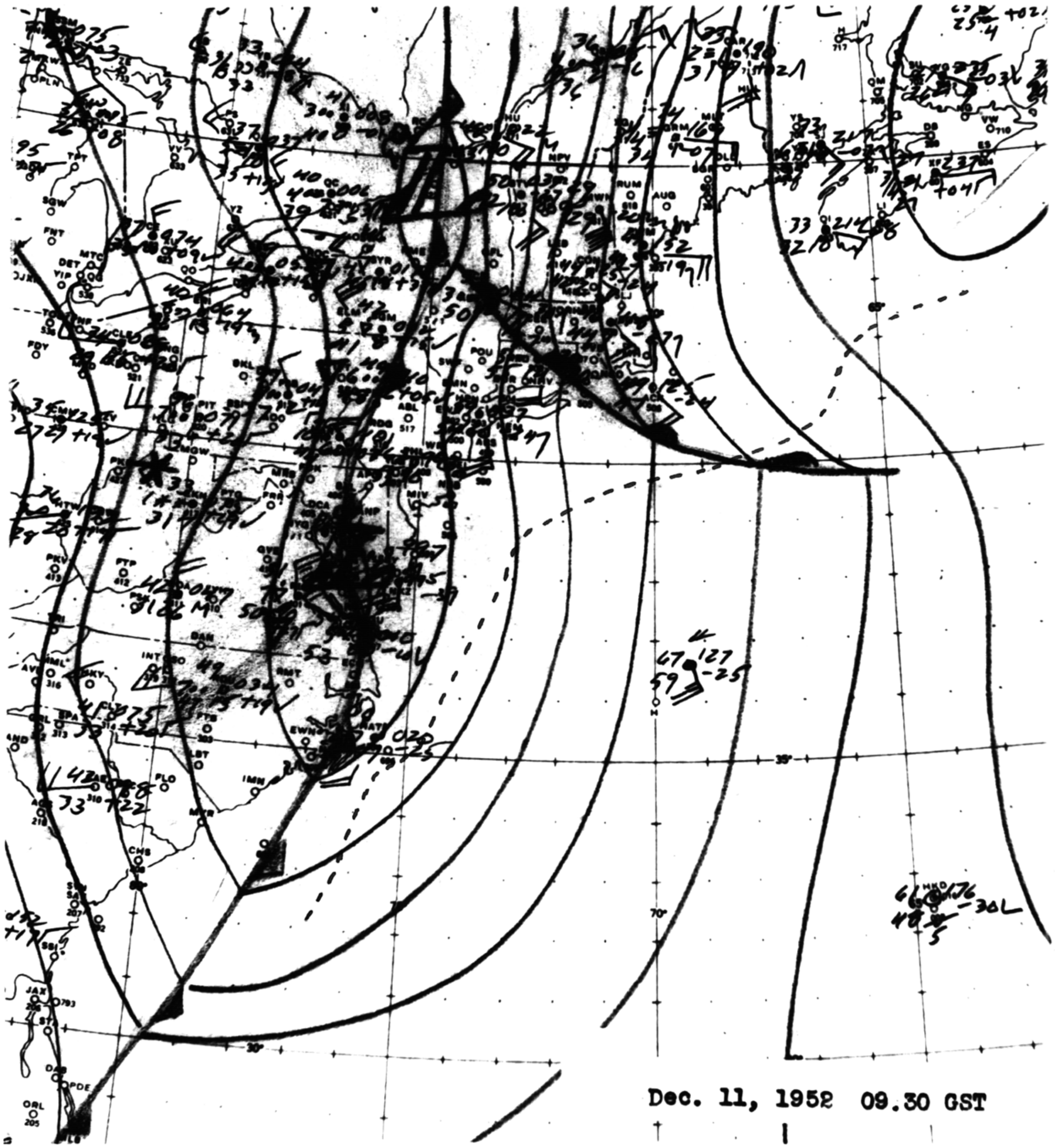
Graph 10


Microseism Spectrum at 17.00 G.S.T. Feb 13, 1953
(Weston Record)
Wave Spectrum at 17.00 G.S.T. Feb 13, 1953
(Geilgo Record)
Power
0
.05
.1
.15
.2
.25
.3
.35
.4
.45
.5
.55
.6
.65
.7
.75
.8
.85
.9
.95

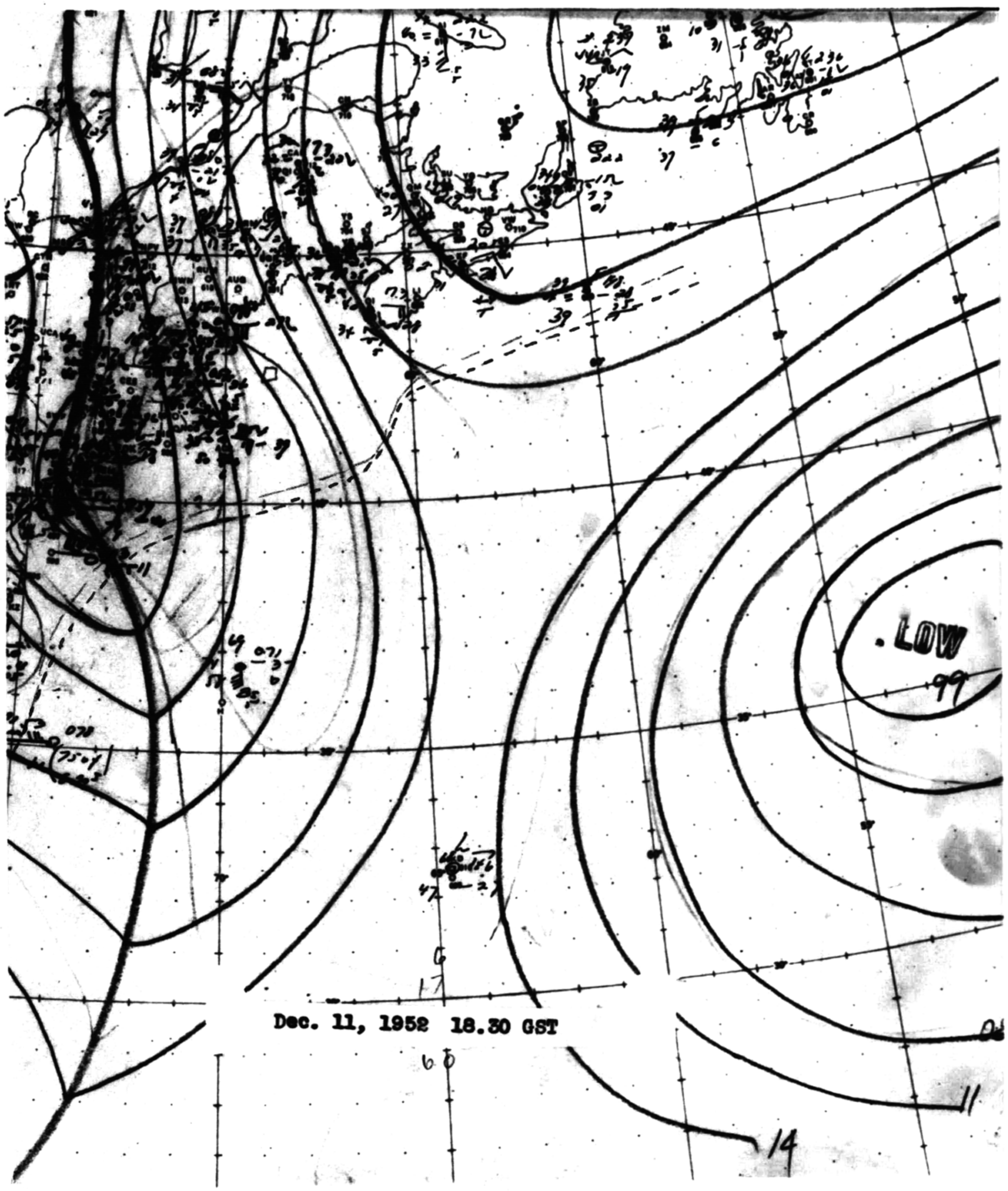
Graph 11


Microseism Spectrum at 16.30 G.S.T. Feb 16, 1953
(Weston Record)
Wave Spectrum at 17.00 G.S.T. Feb 16, 1953
(Geilgo Record)
Power
0
.05
.1
.15
.2
.25
.3
.35
.4
.45
.5
.55
.6
.65
.7
.75
.8
.85
.9
.95
Frequency in Cycles per Second

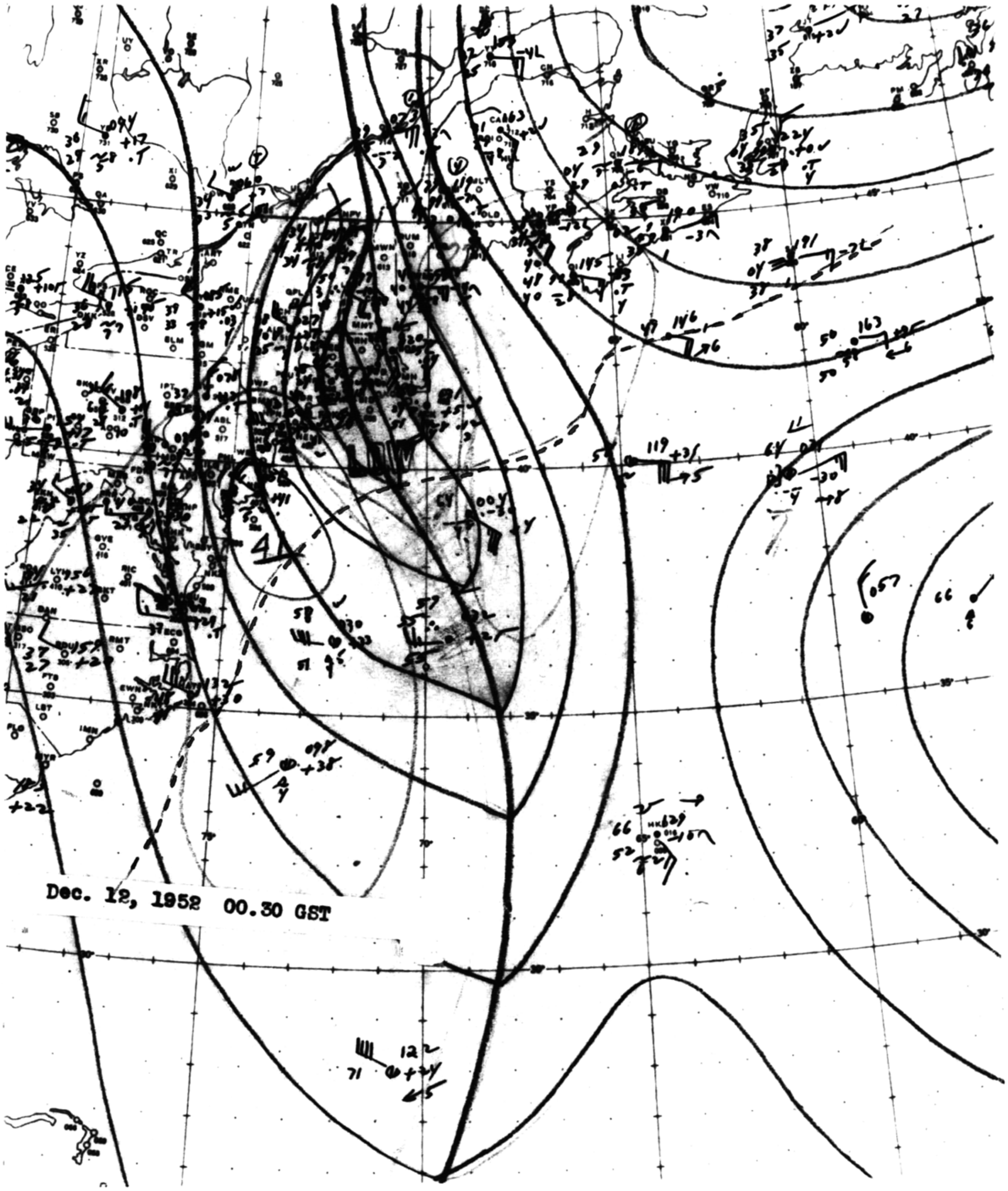
Graph 12



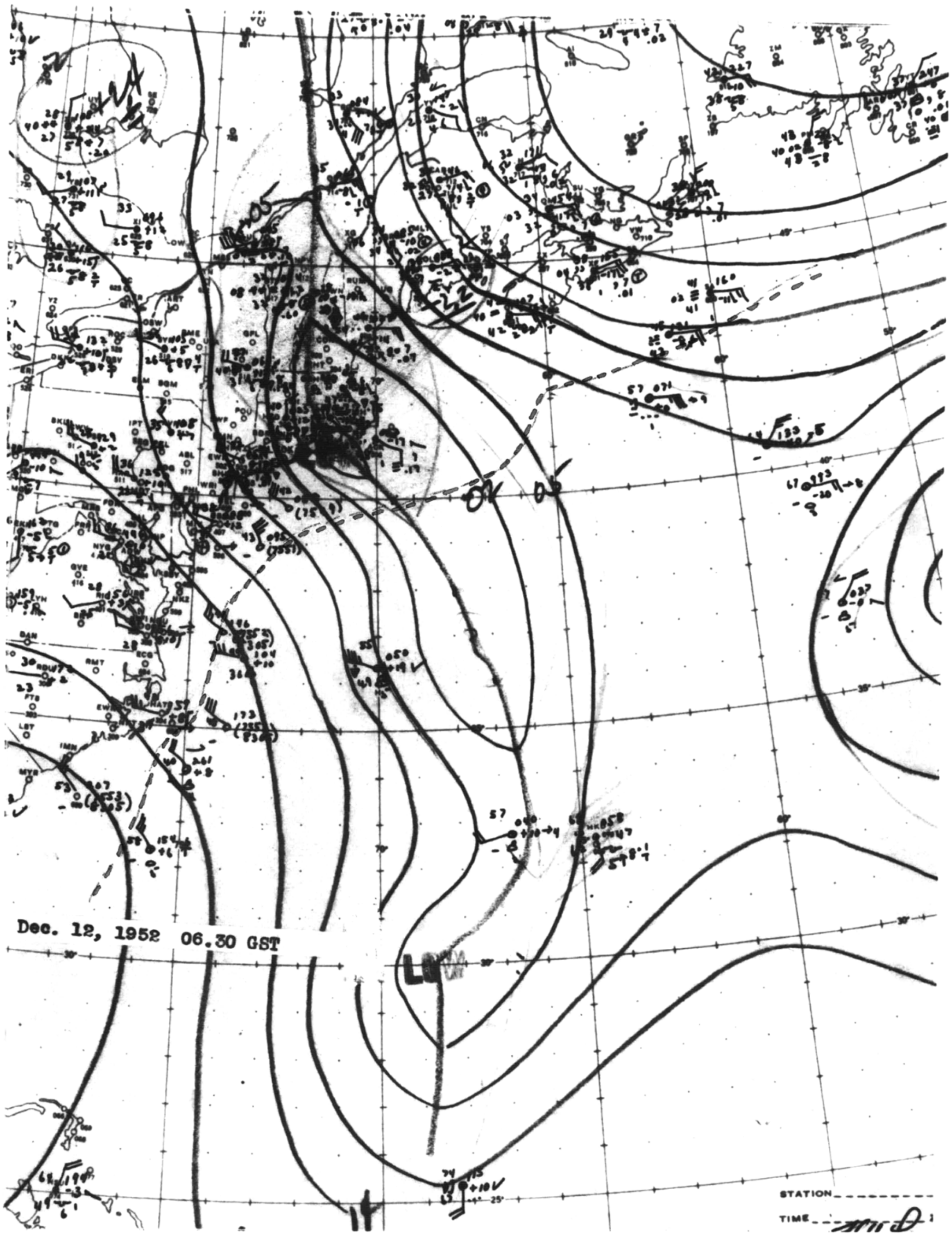
Map 1.



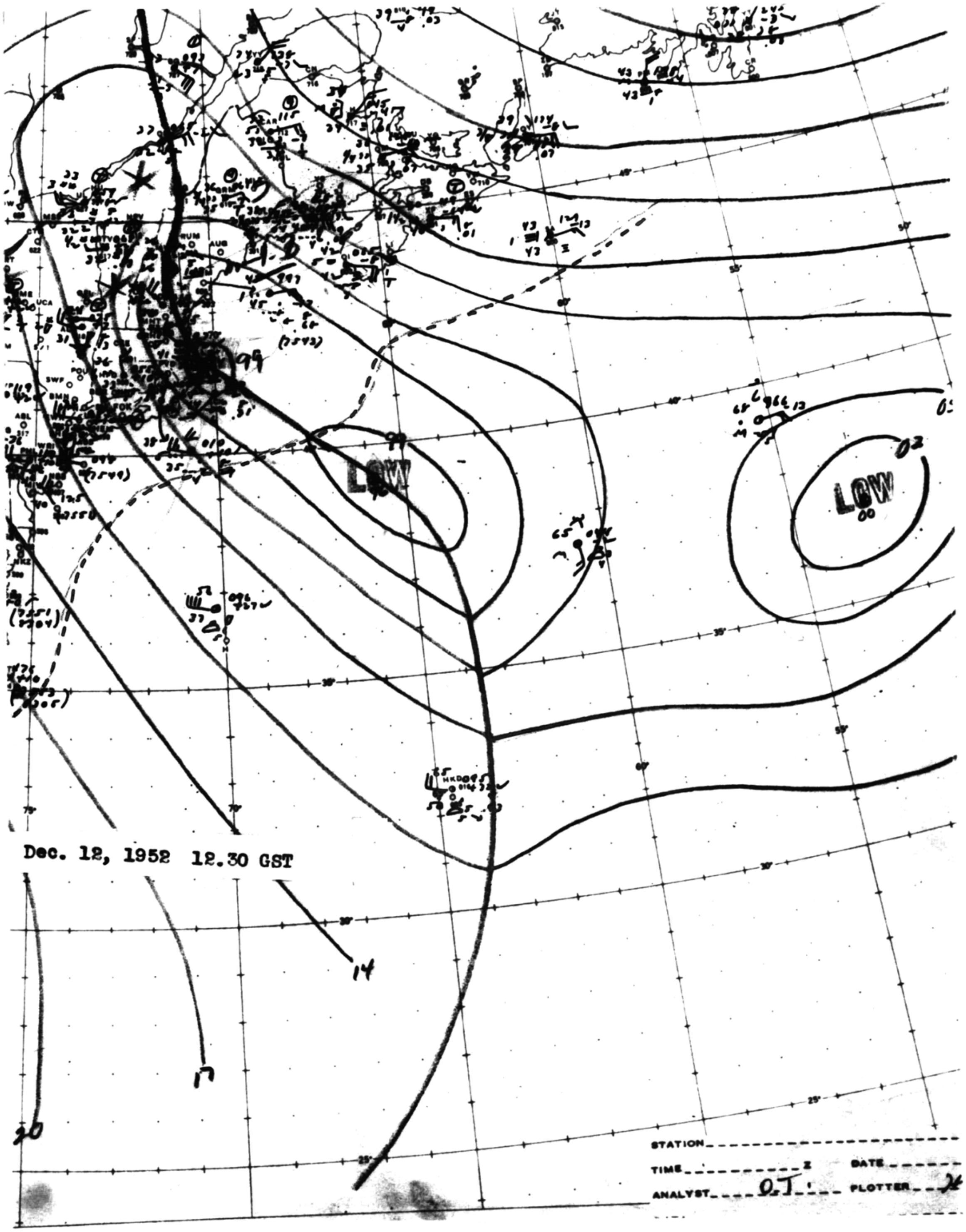
Map 2.



Map 3.

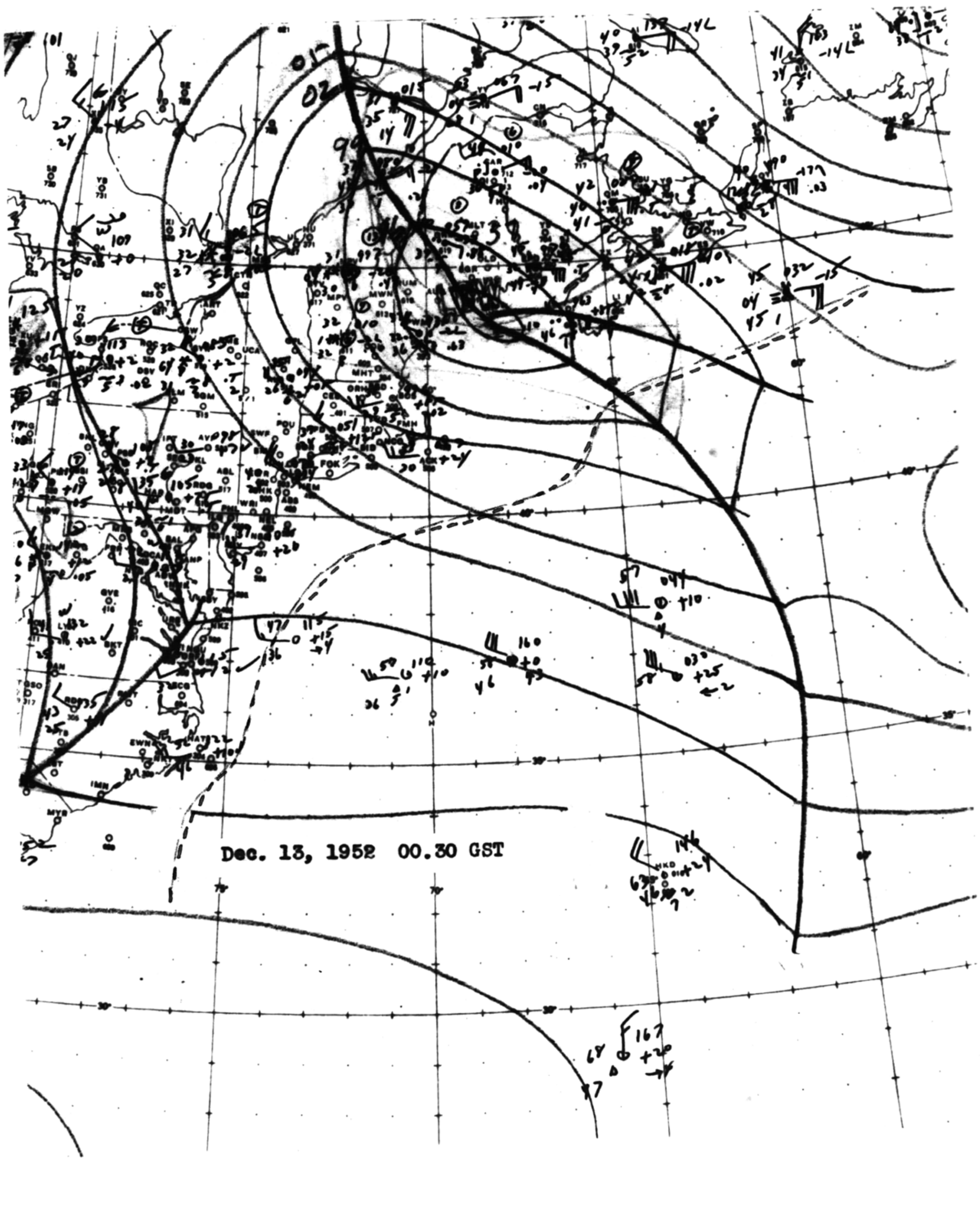


Map 4.



LOW
LOW
Dec. 12, 1952 12.30 GST
14
17
20
STATION
TIME
DATE
ANALYST
PLOTTER

Map 5.



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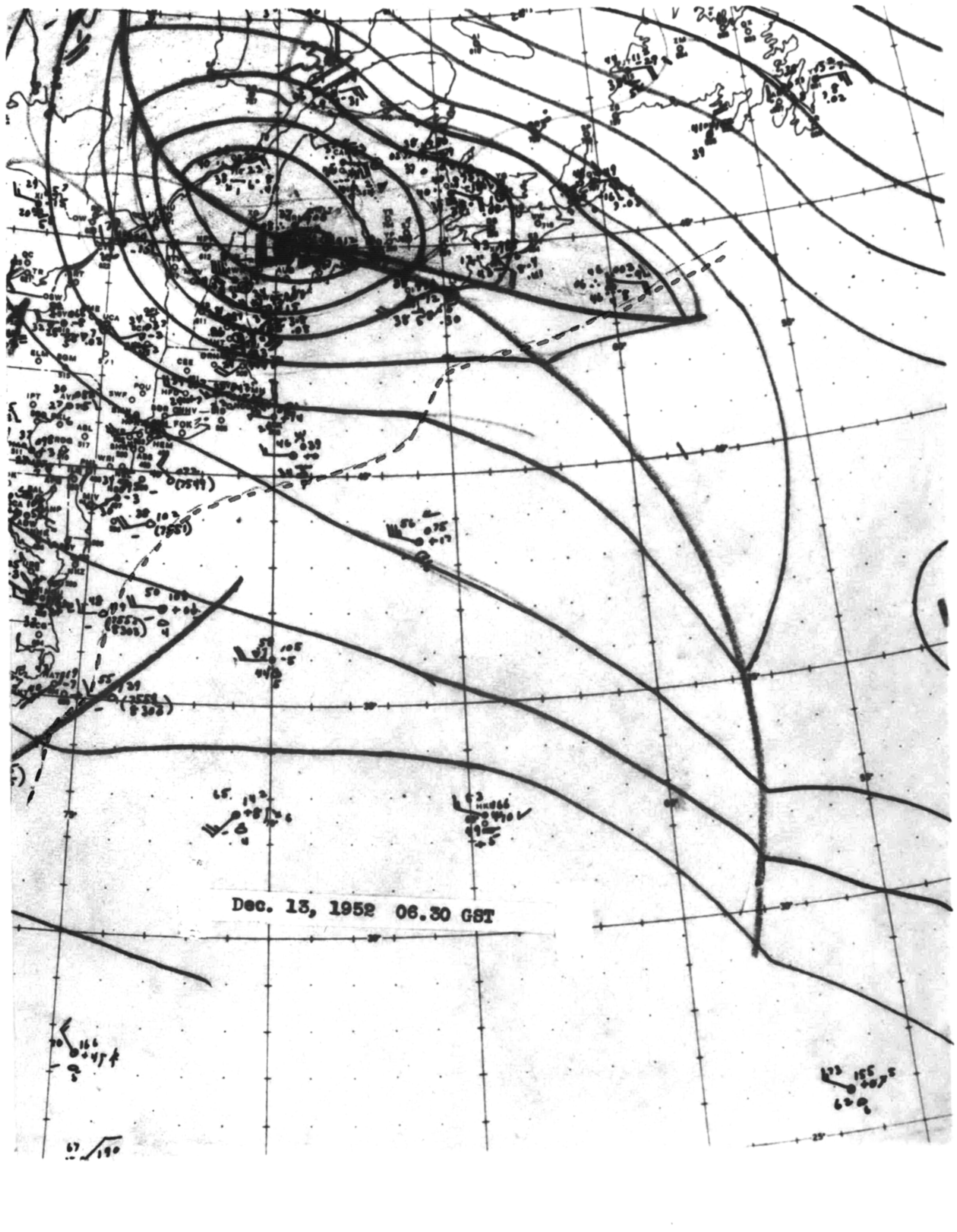
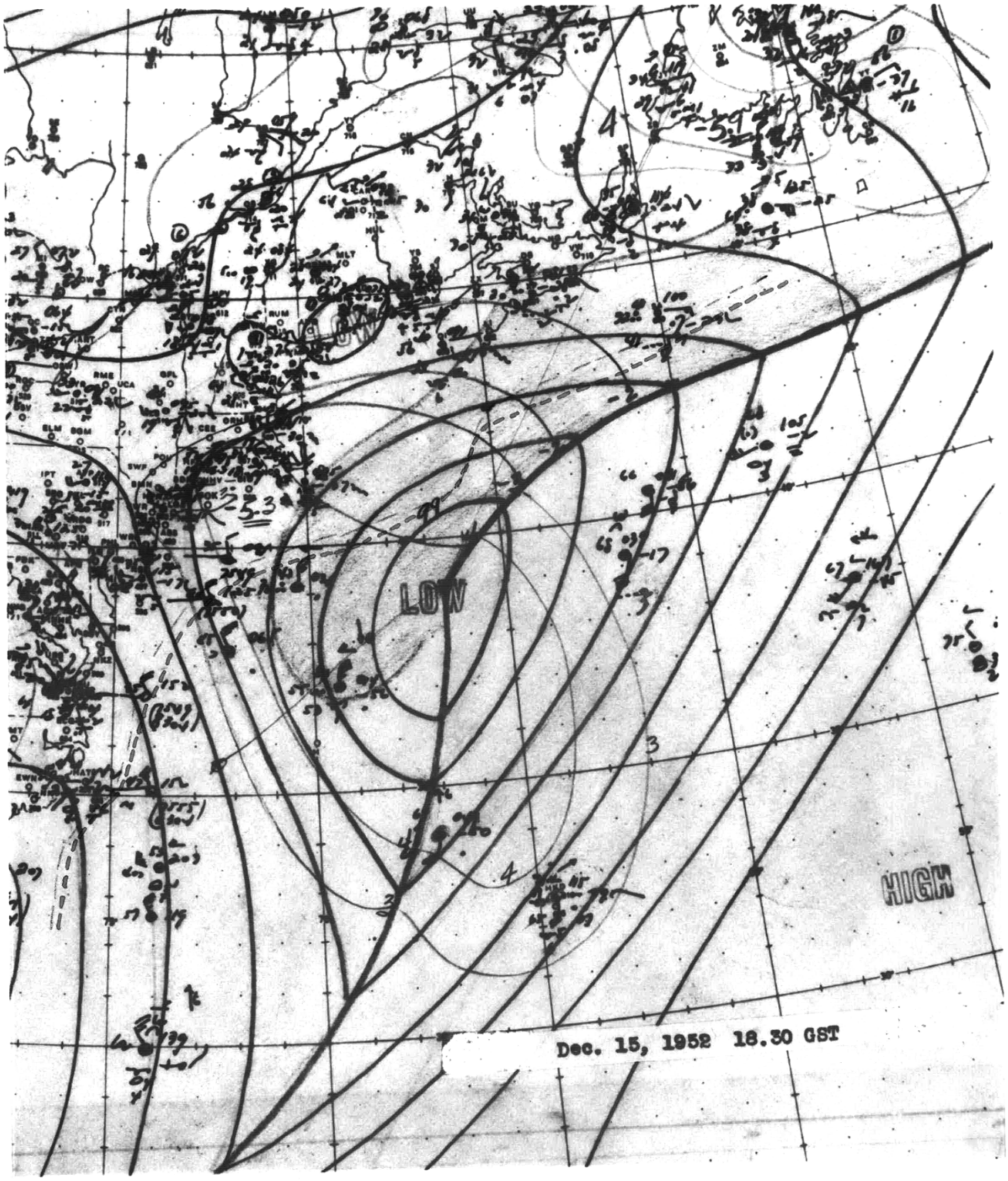
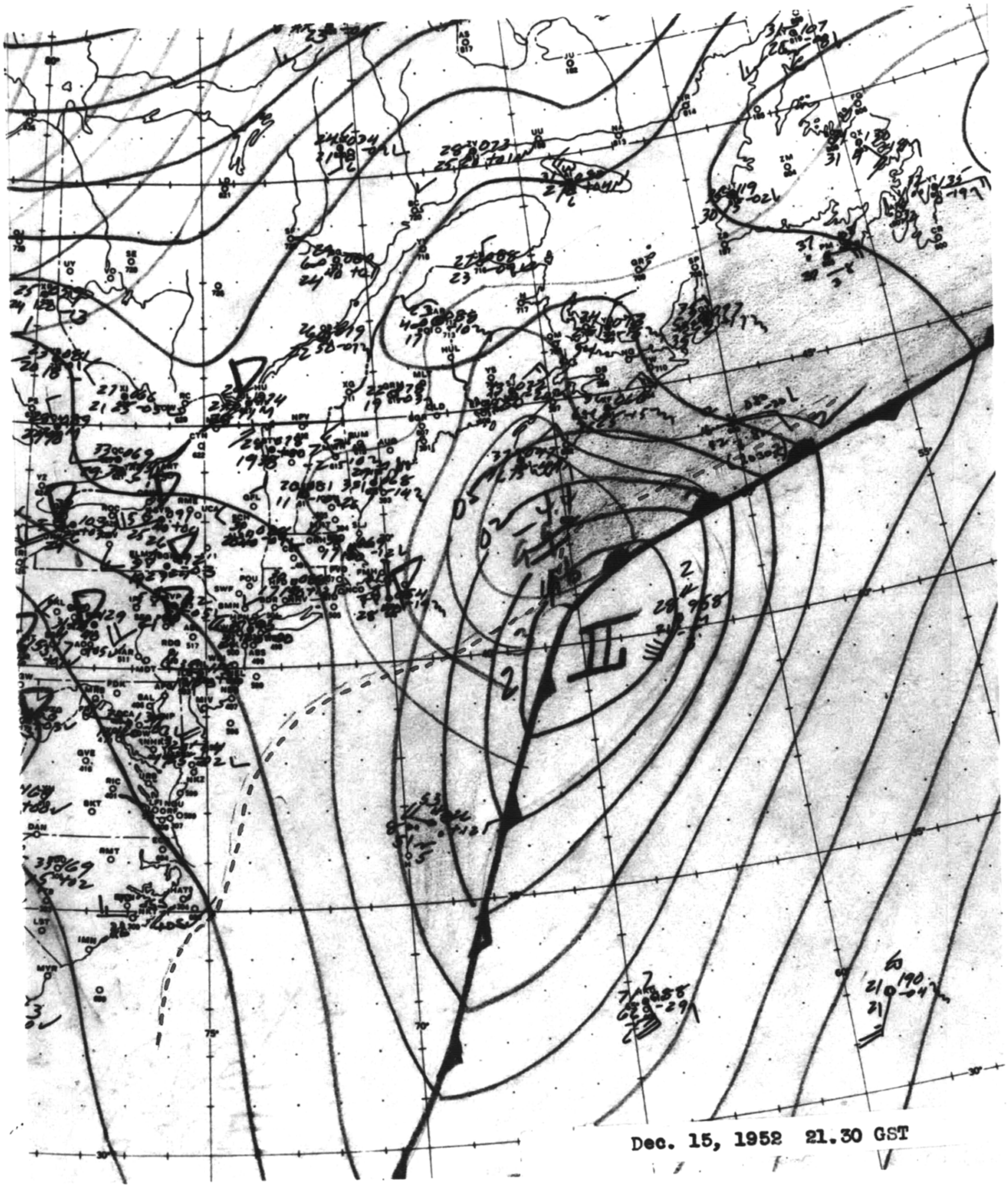


Map 7.



Map 8.



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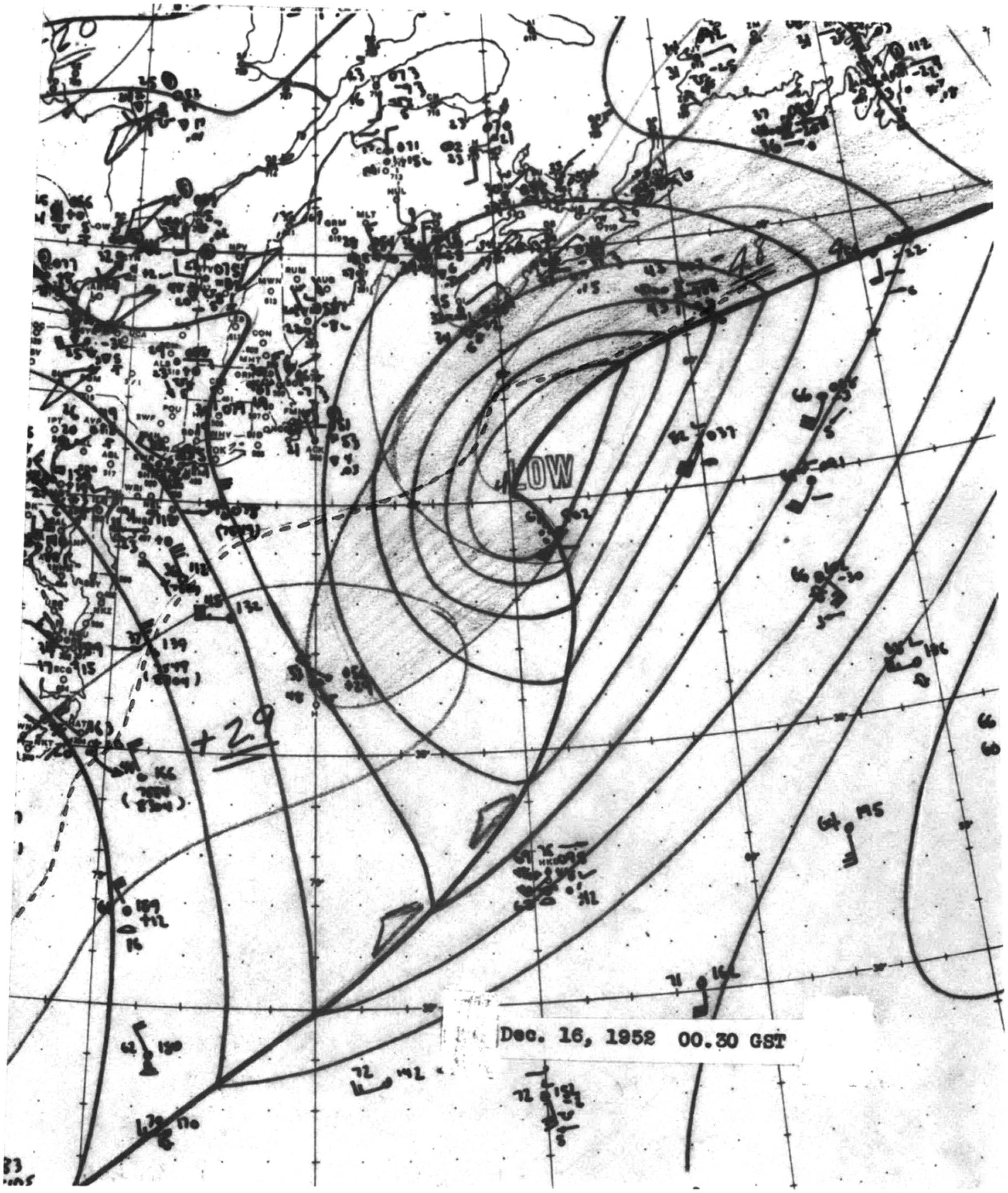

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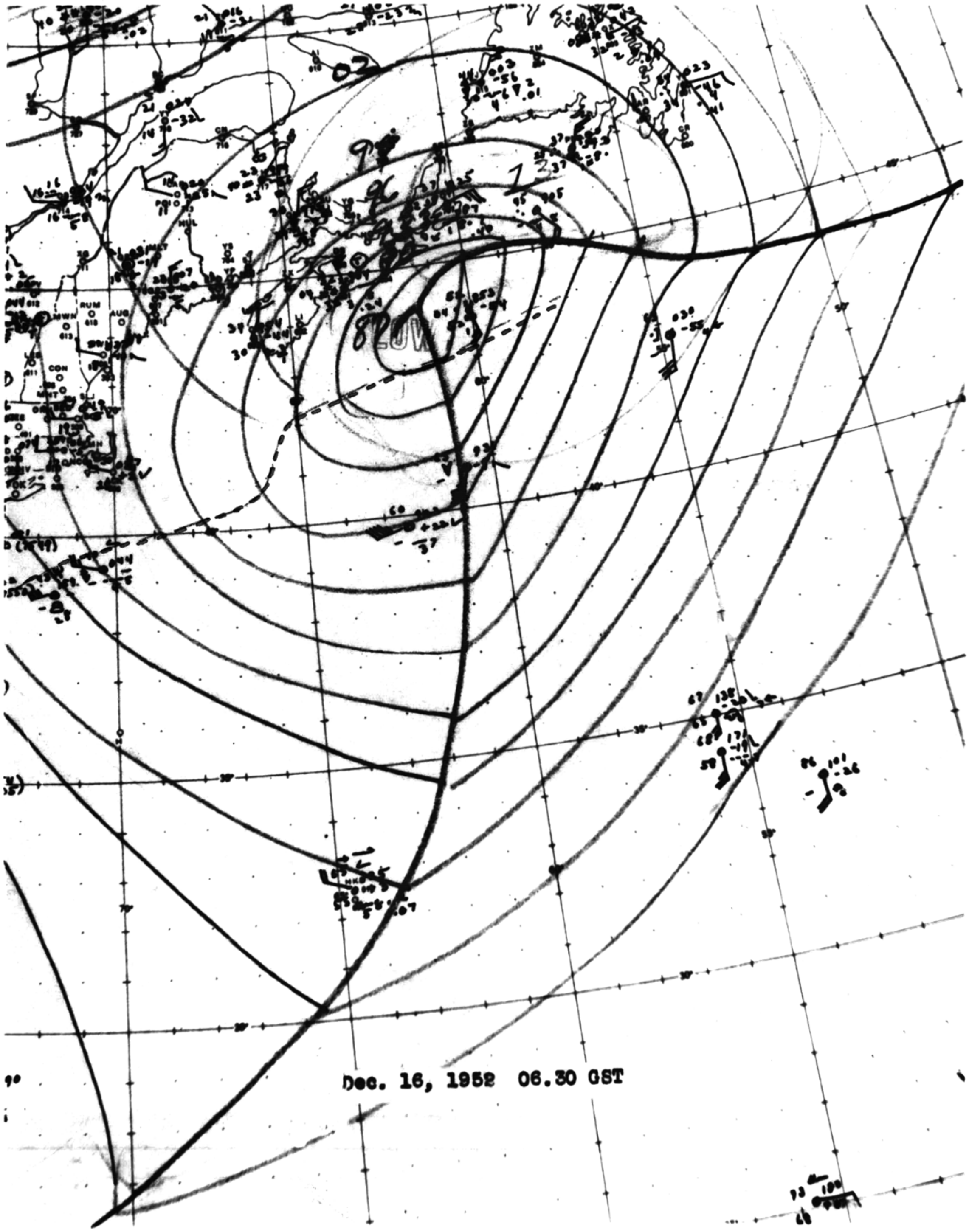
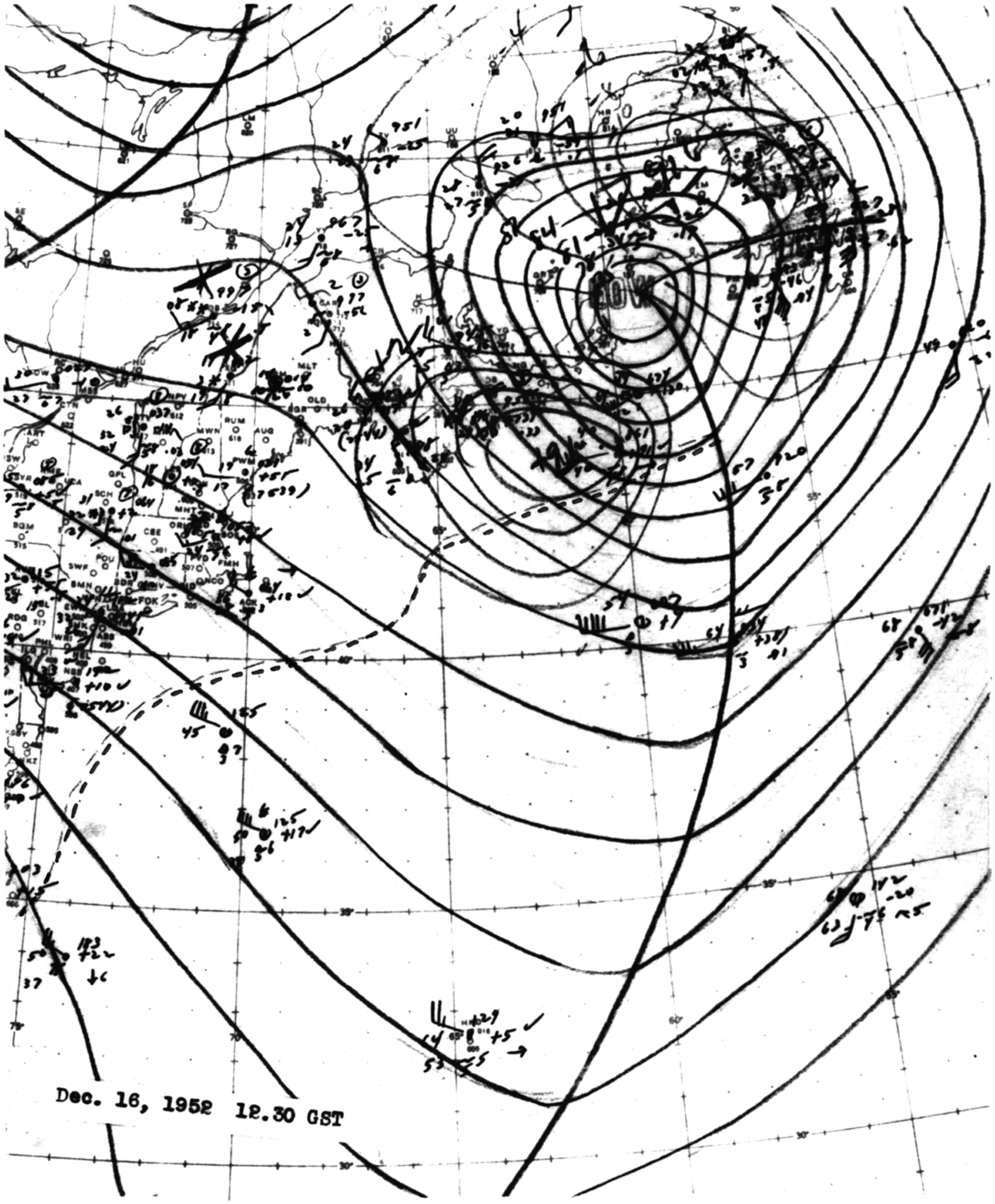
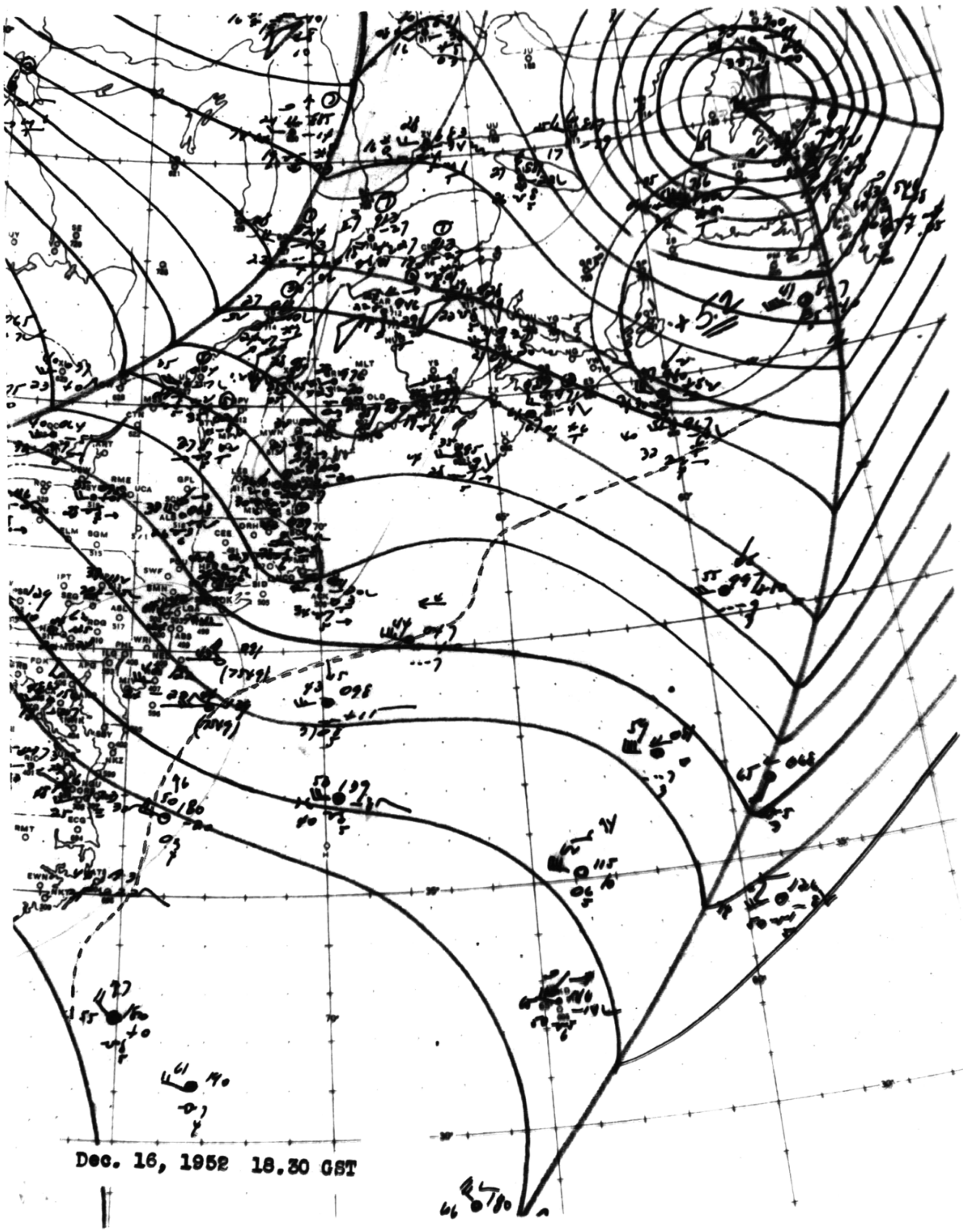


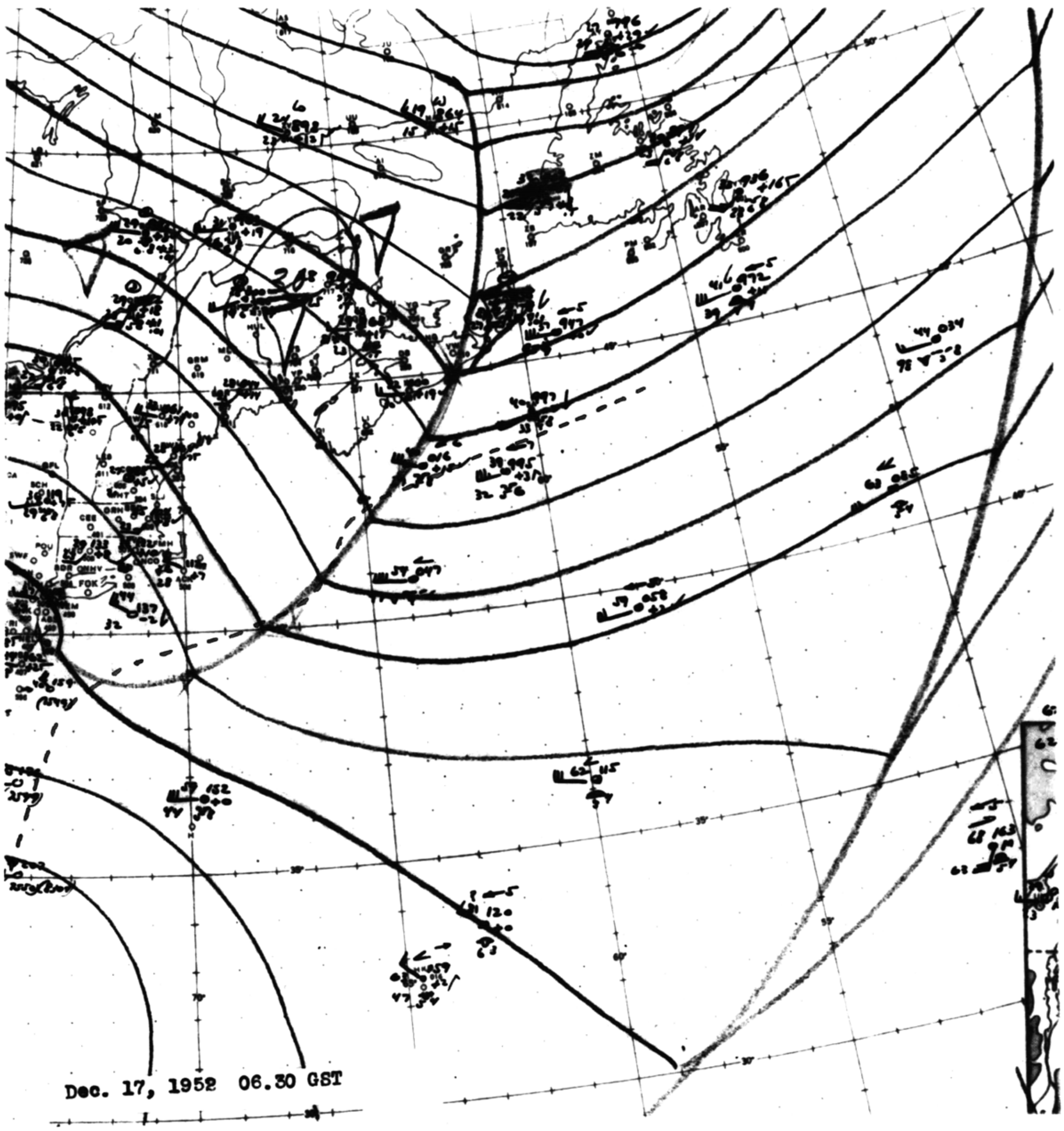
Map 11.



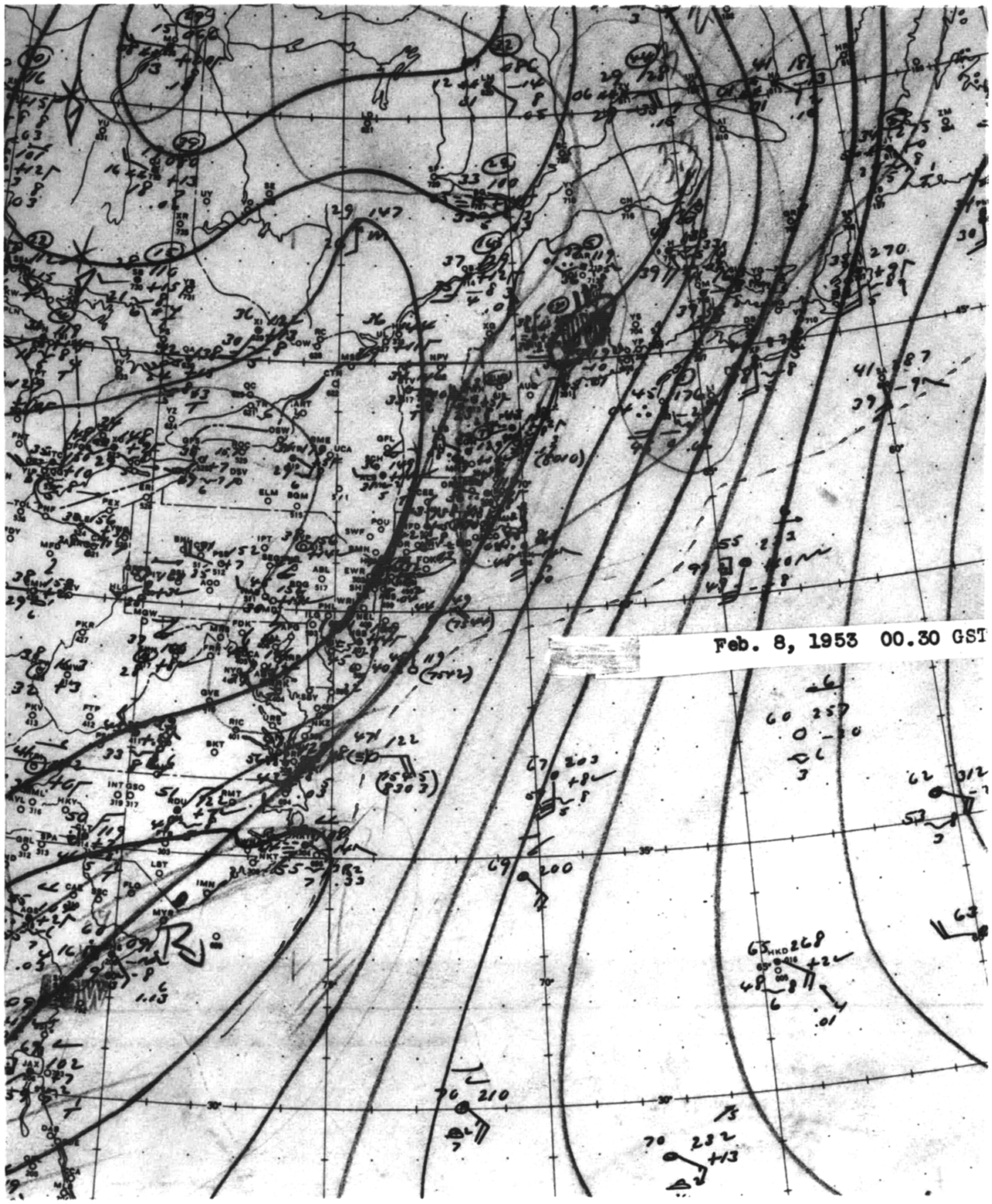
Map 12.



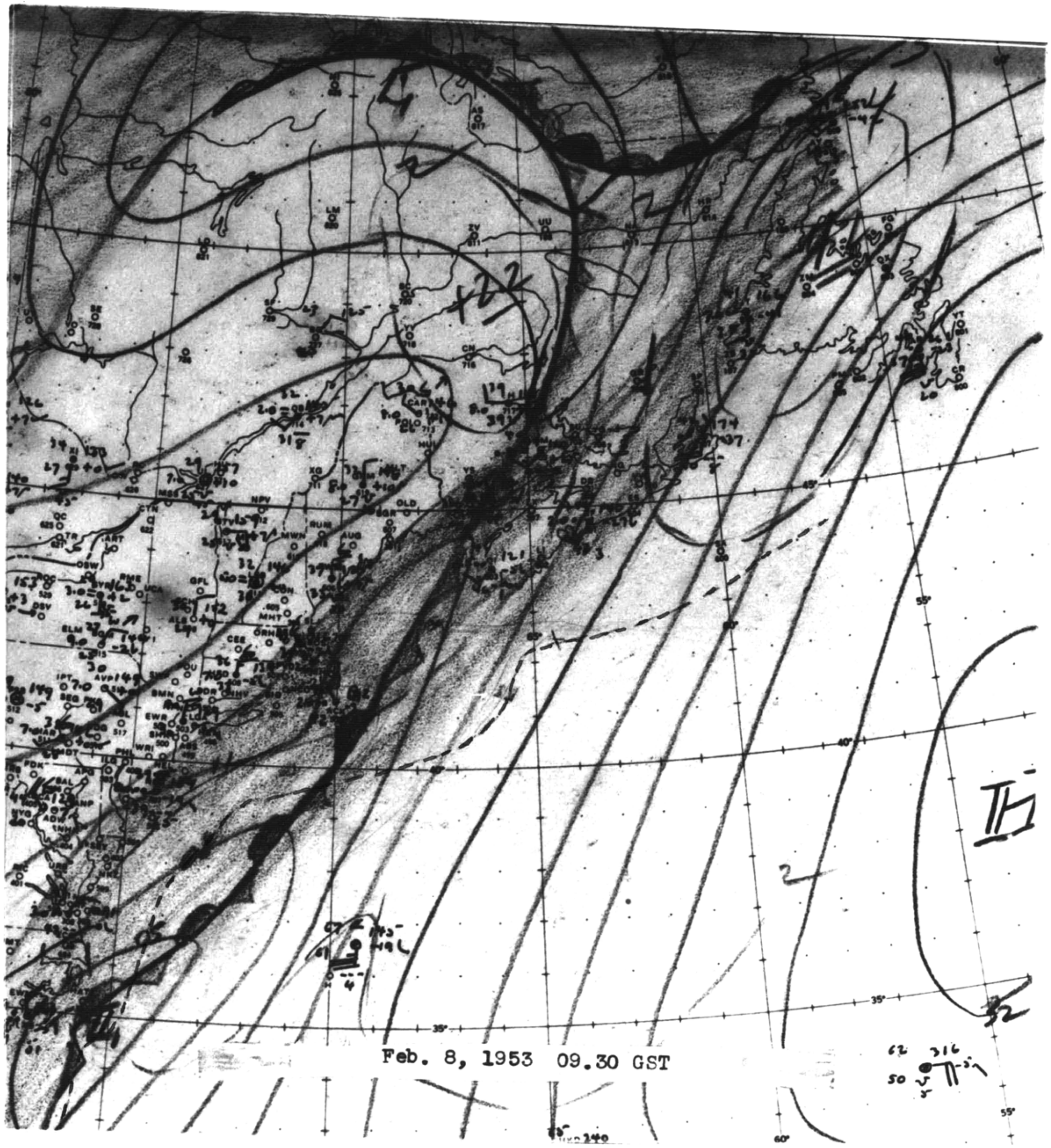
Map 13.



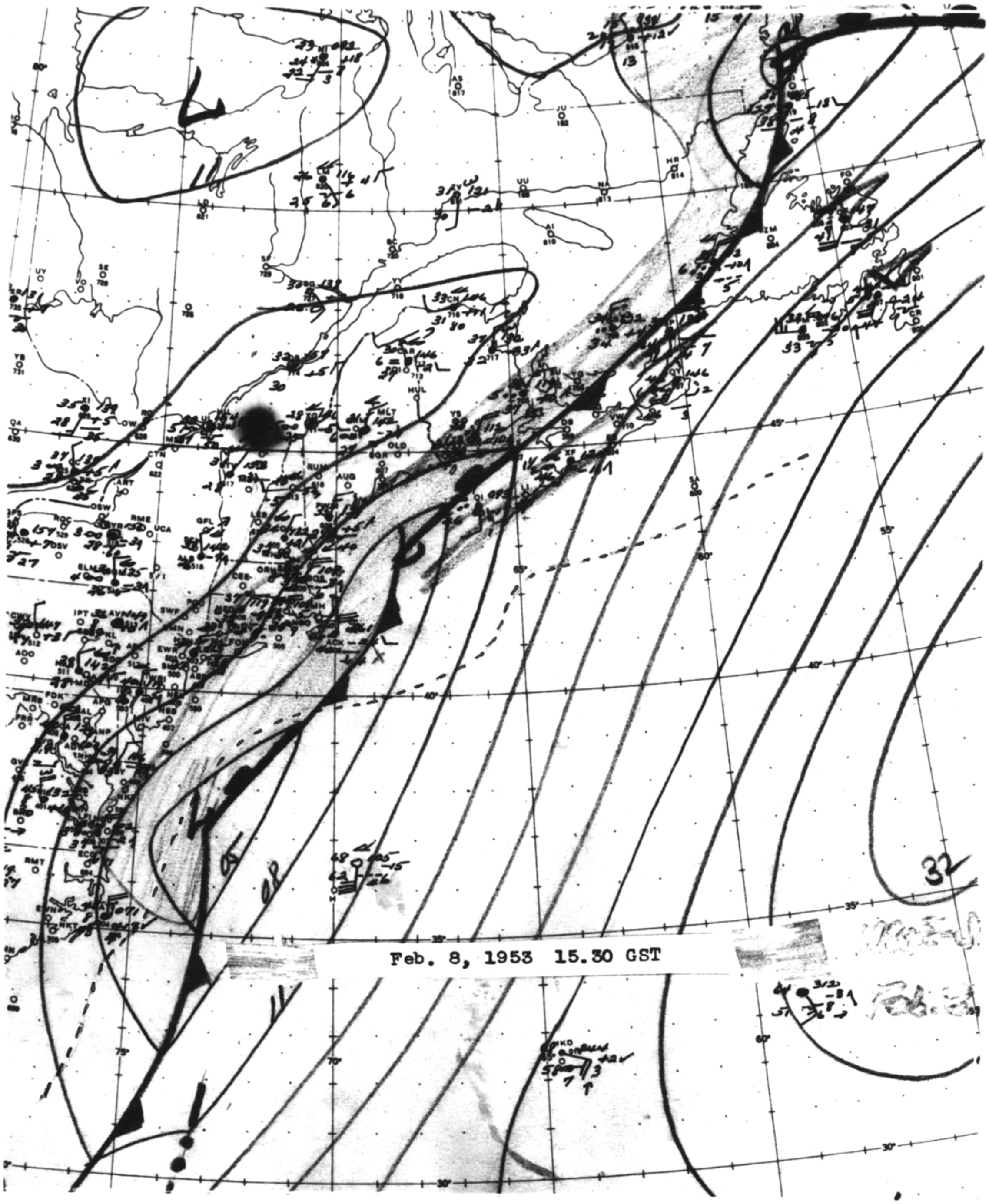
Map 14.



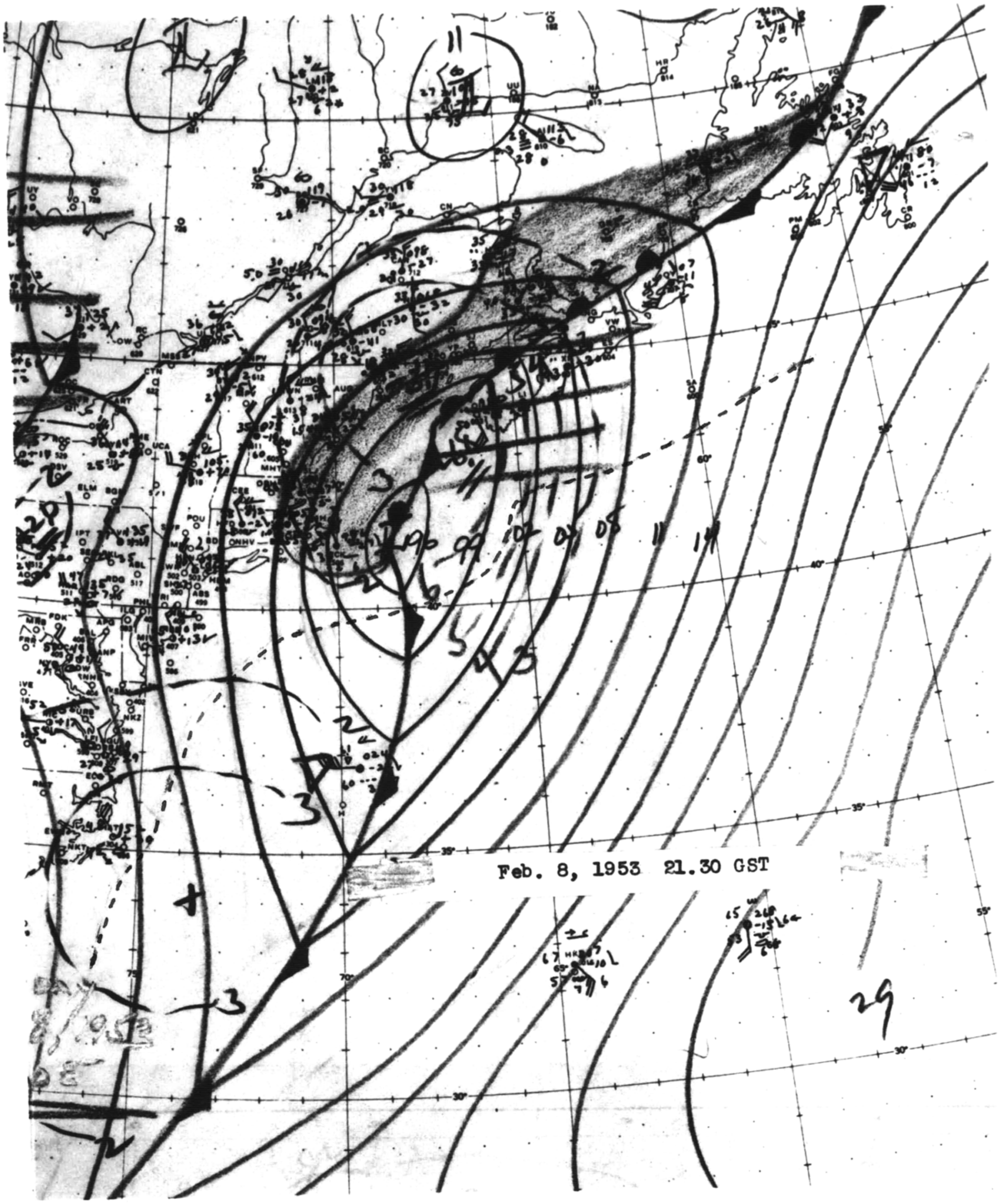
Map 15.



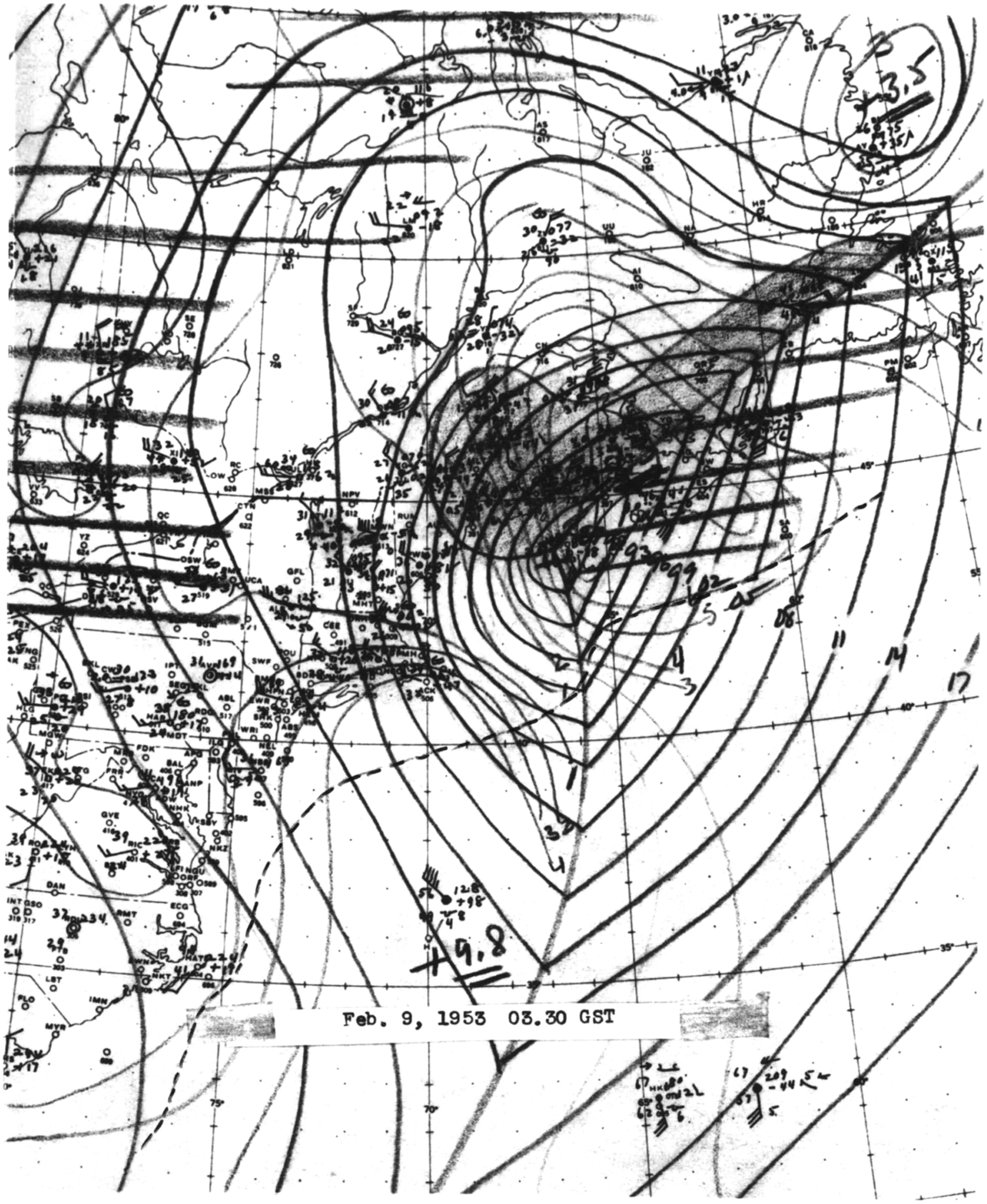
Map 16.



Map 17



Map 18.



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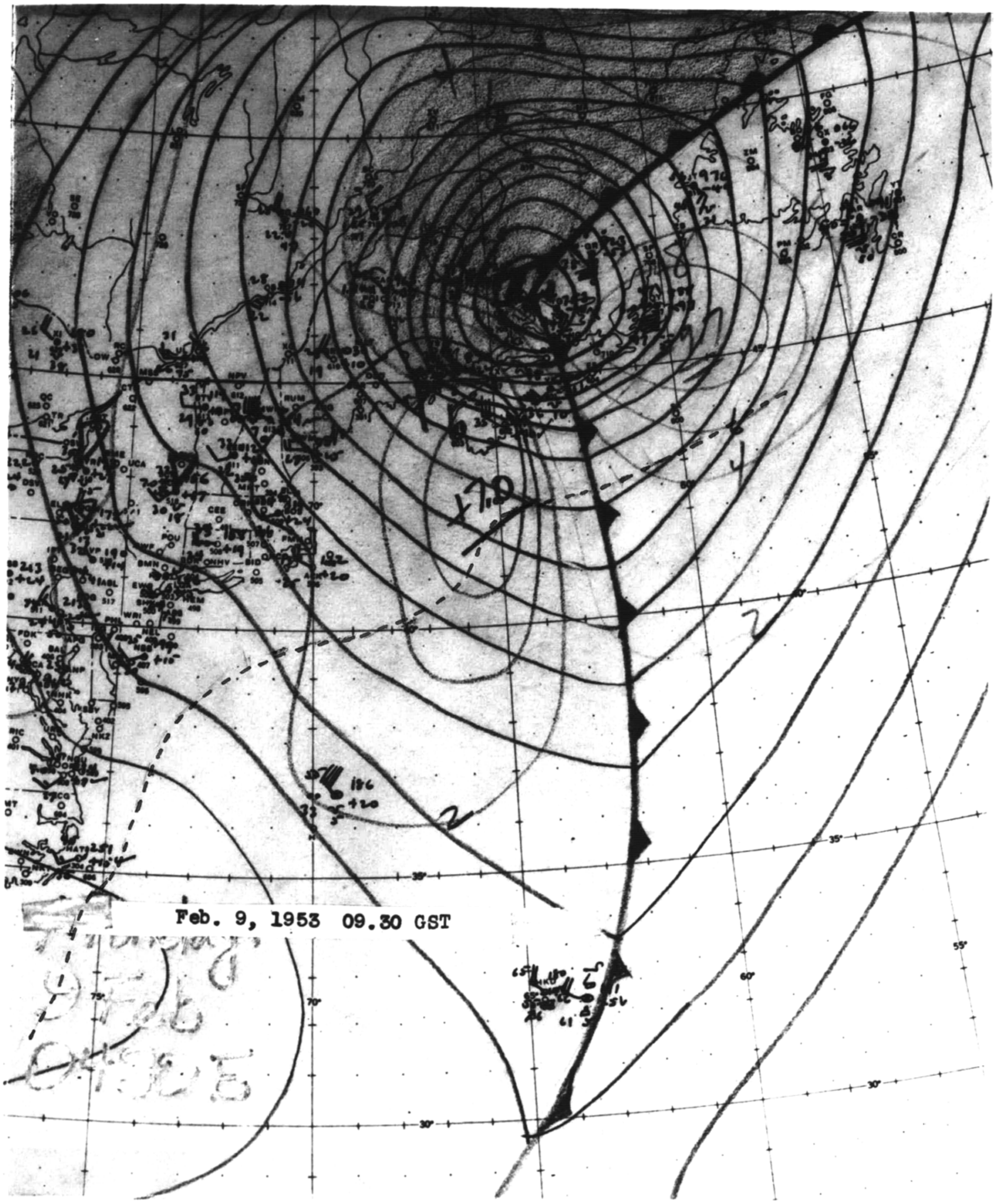

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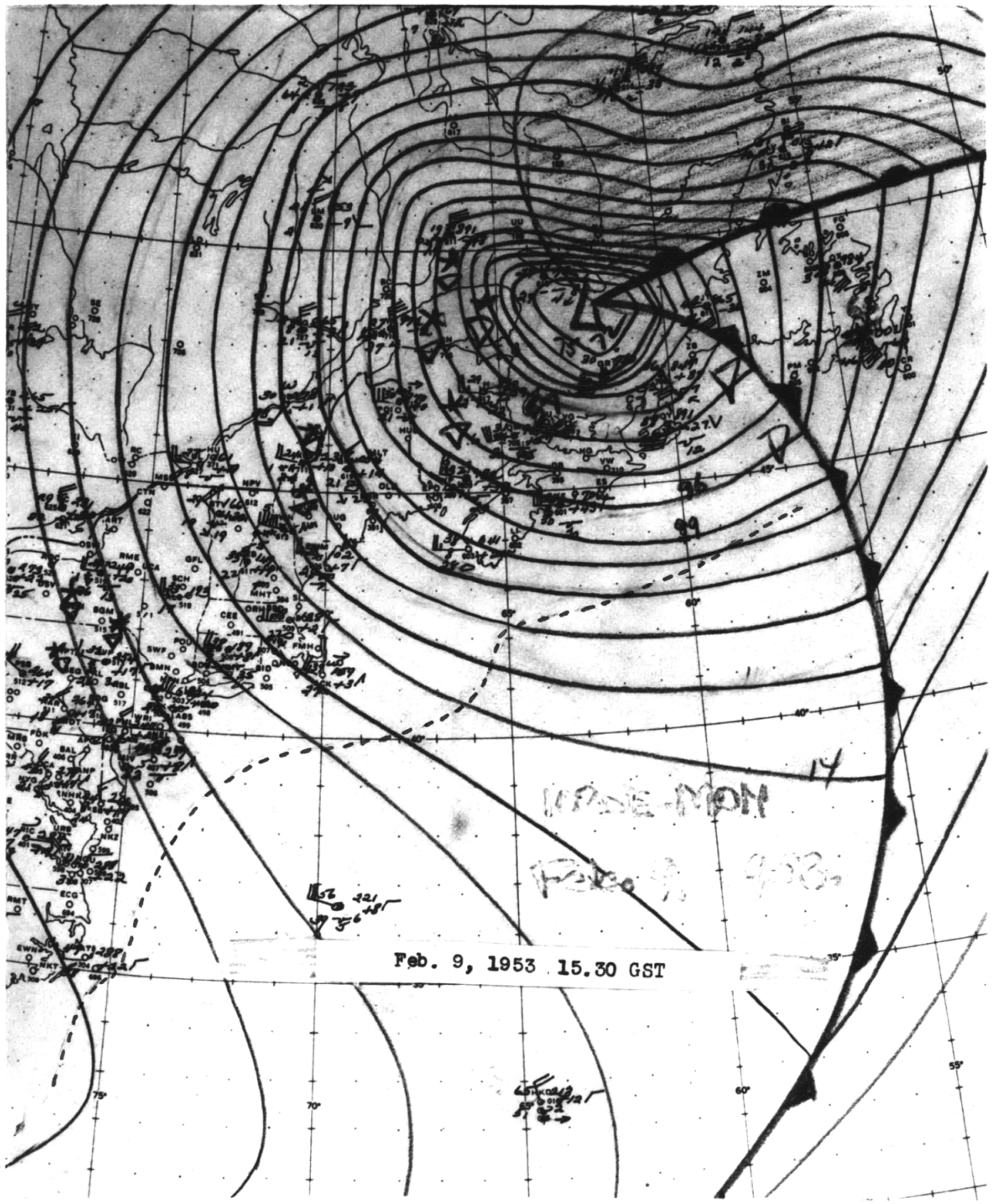

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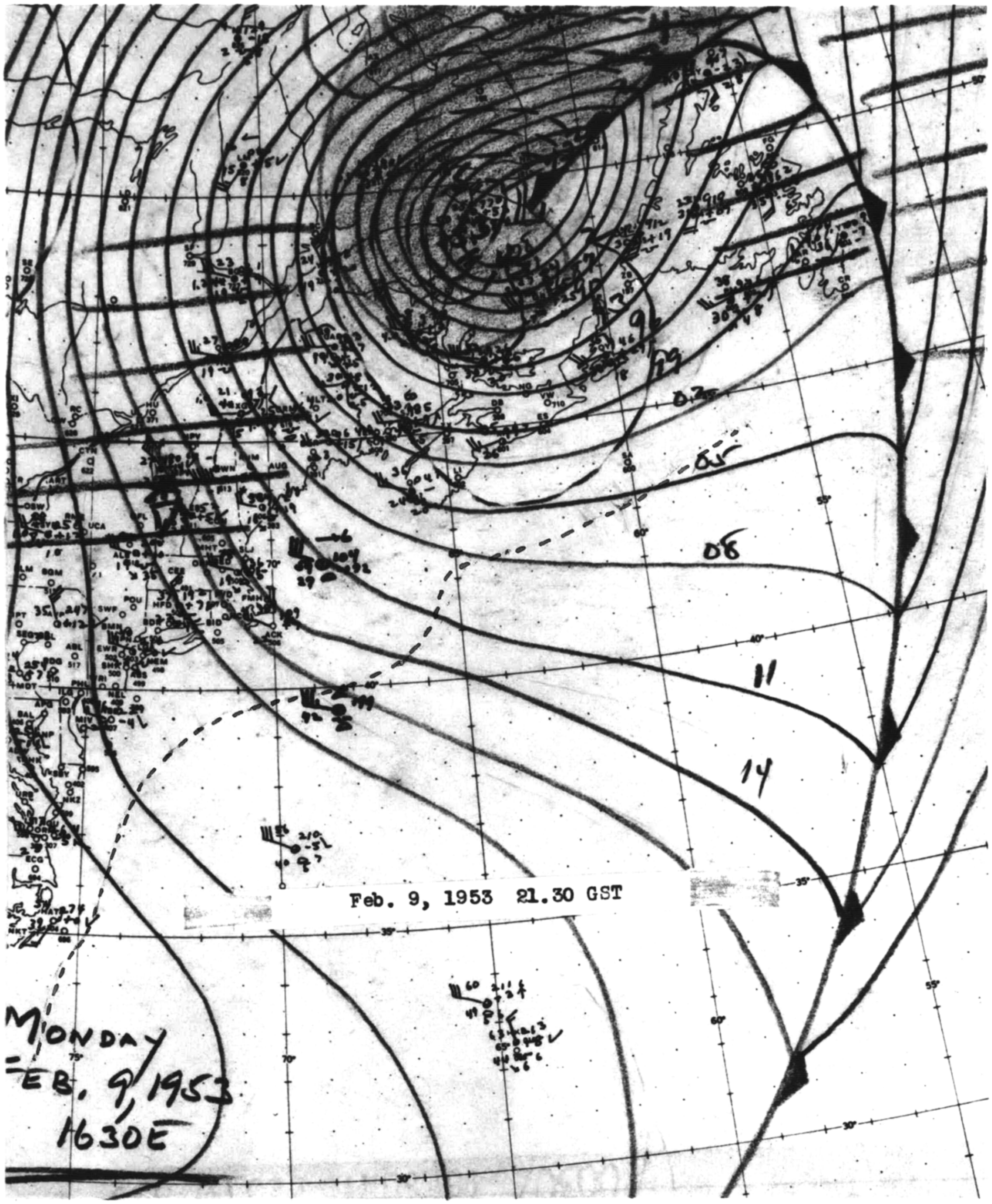

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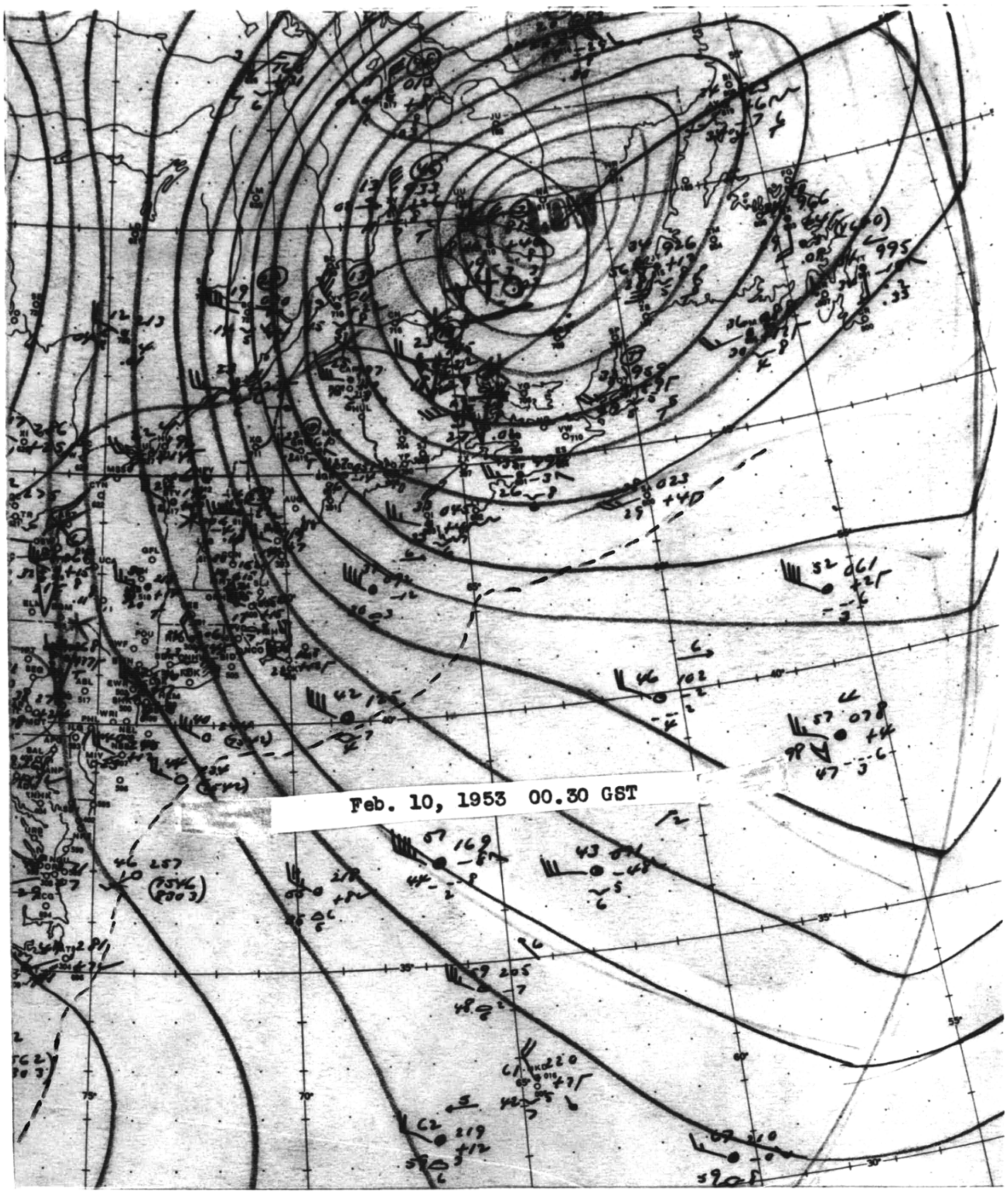

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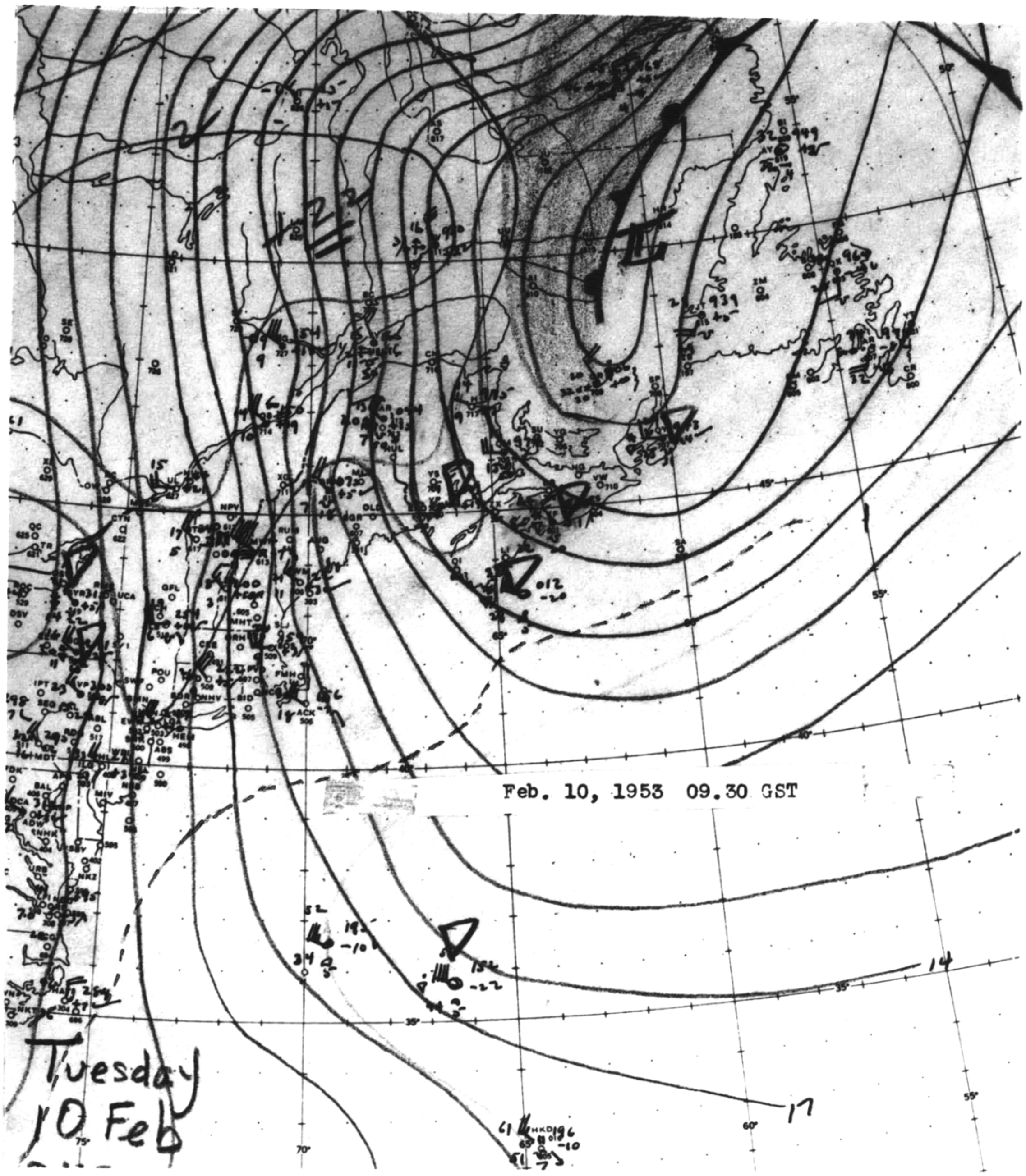

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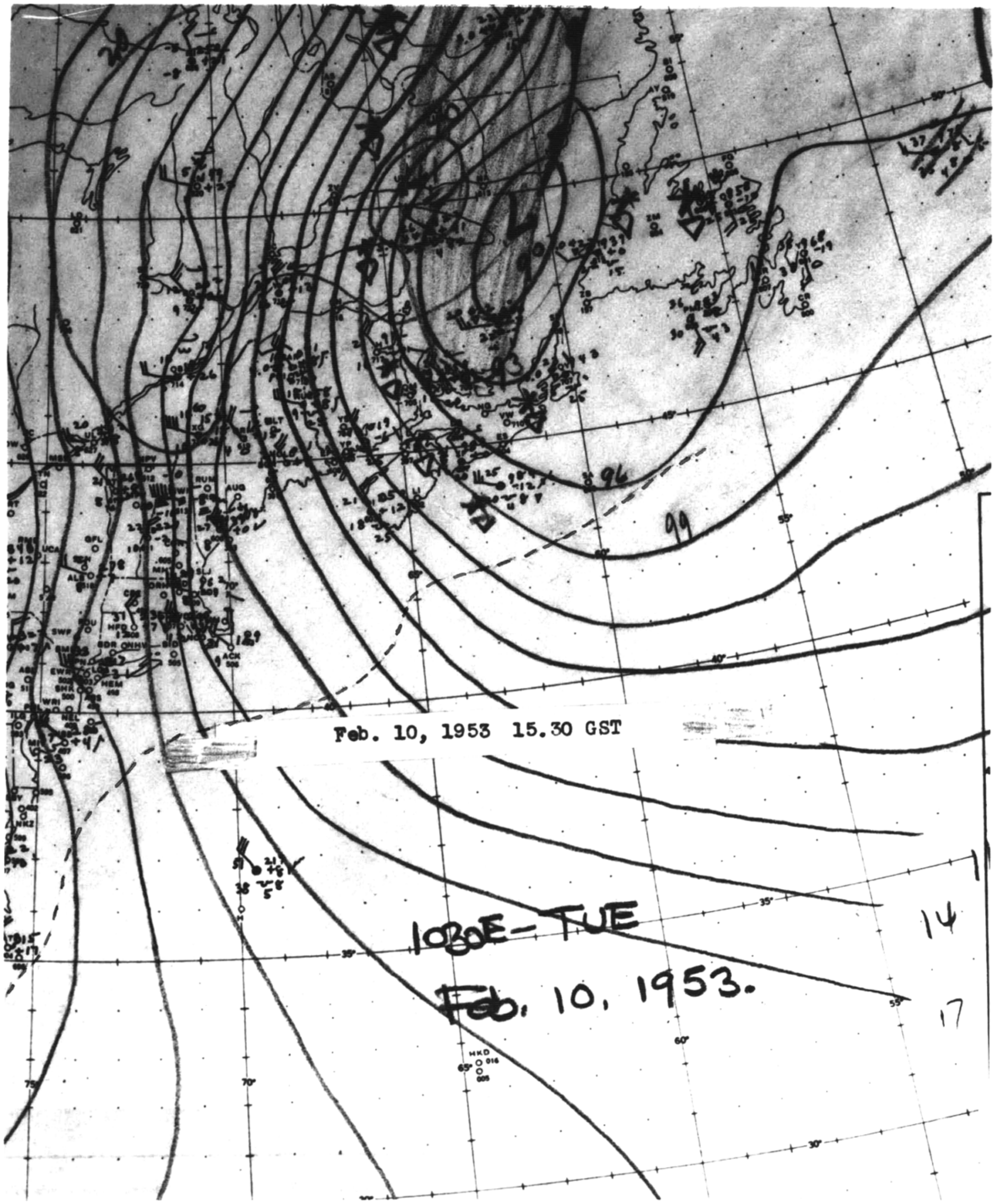
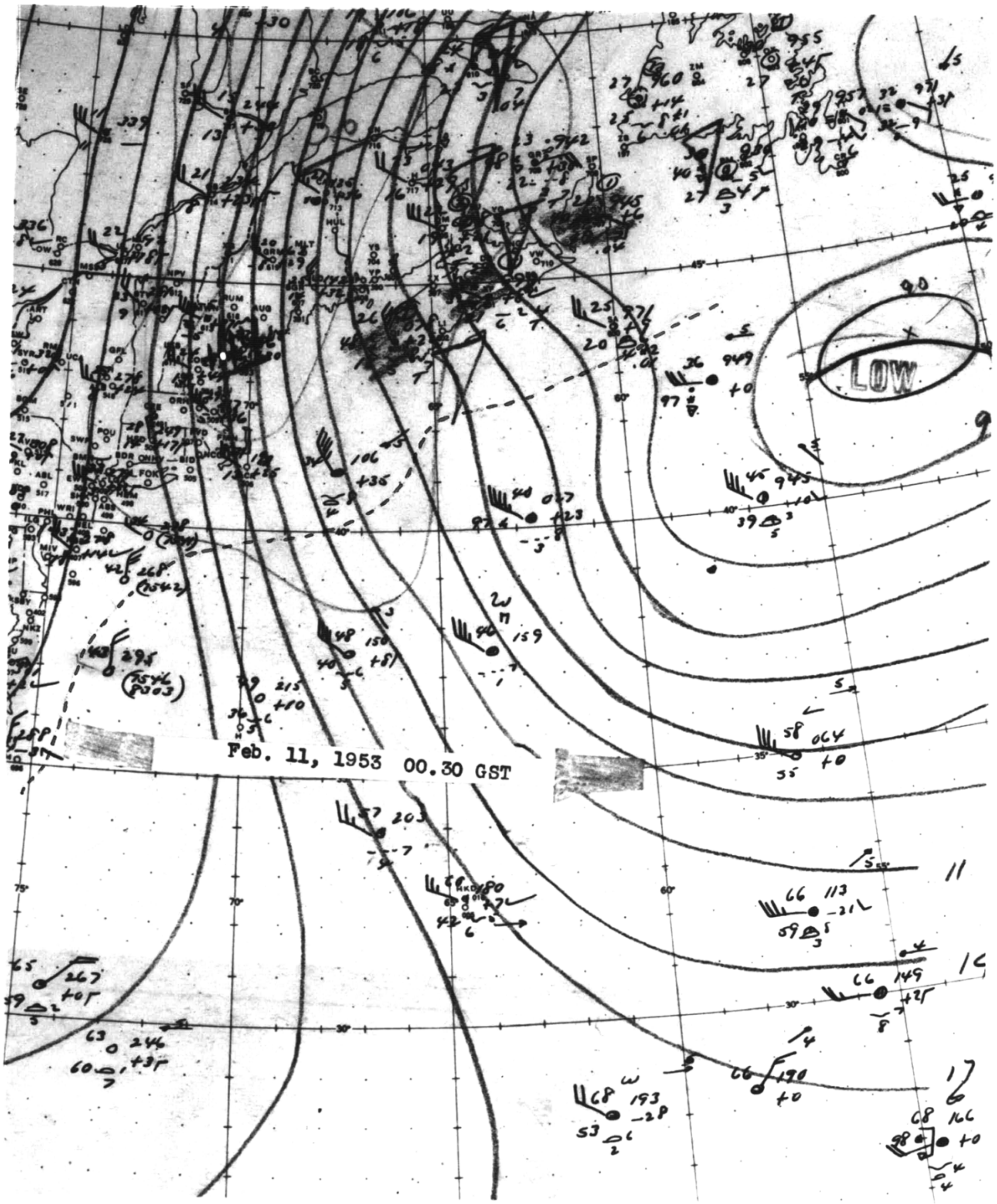
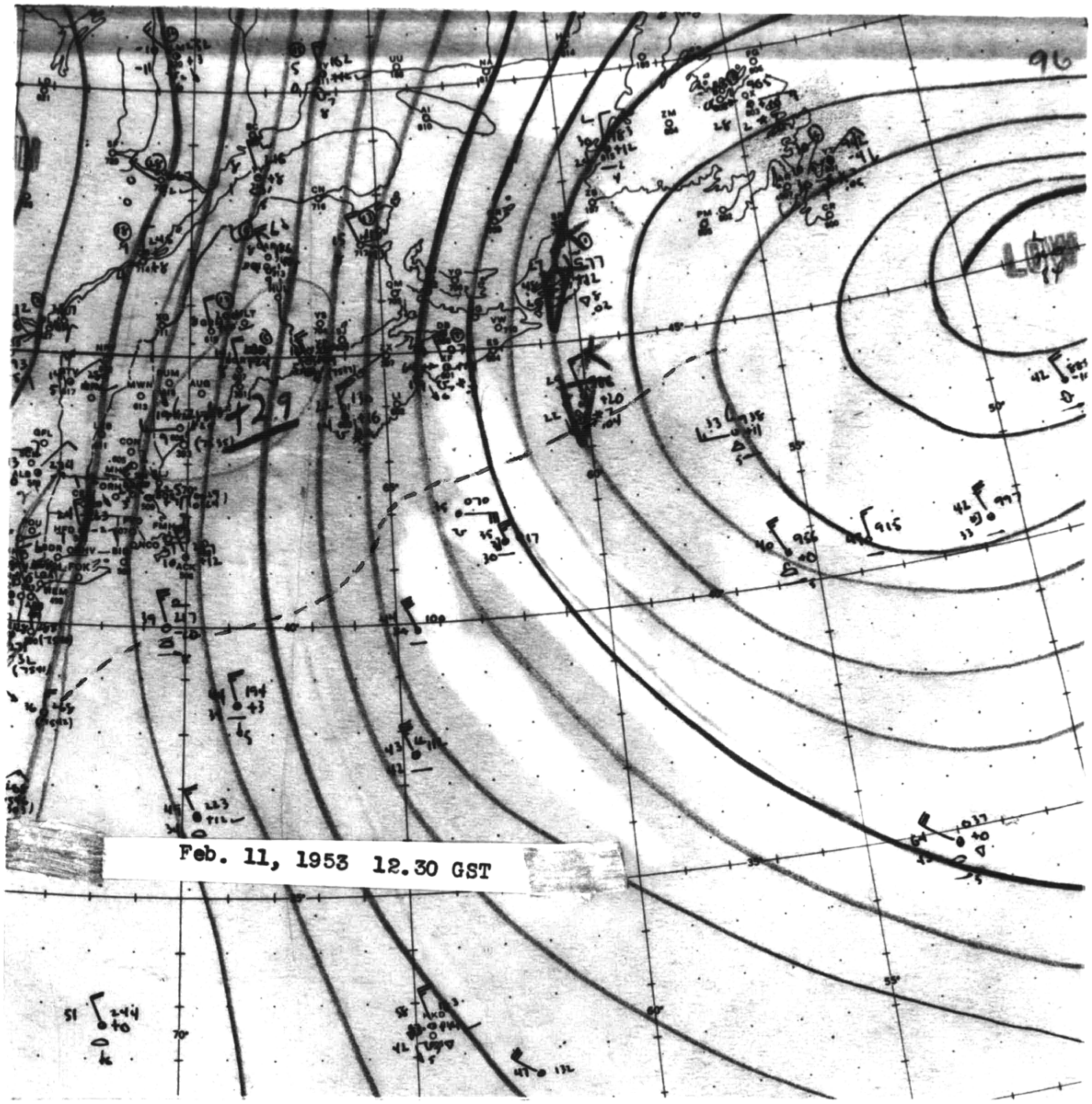


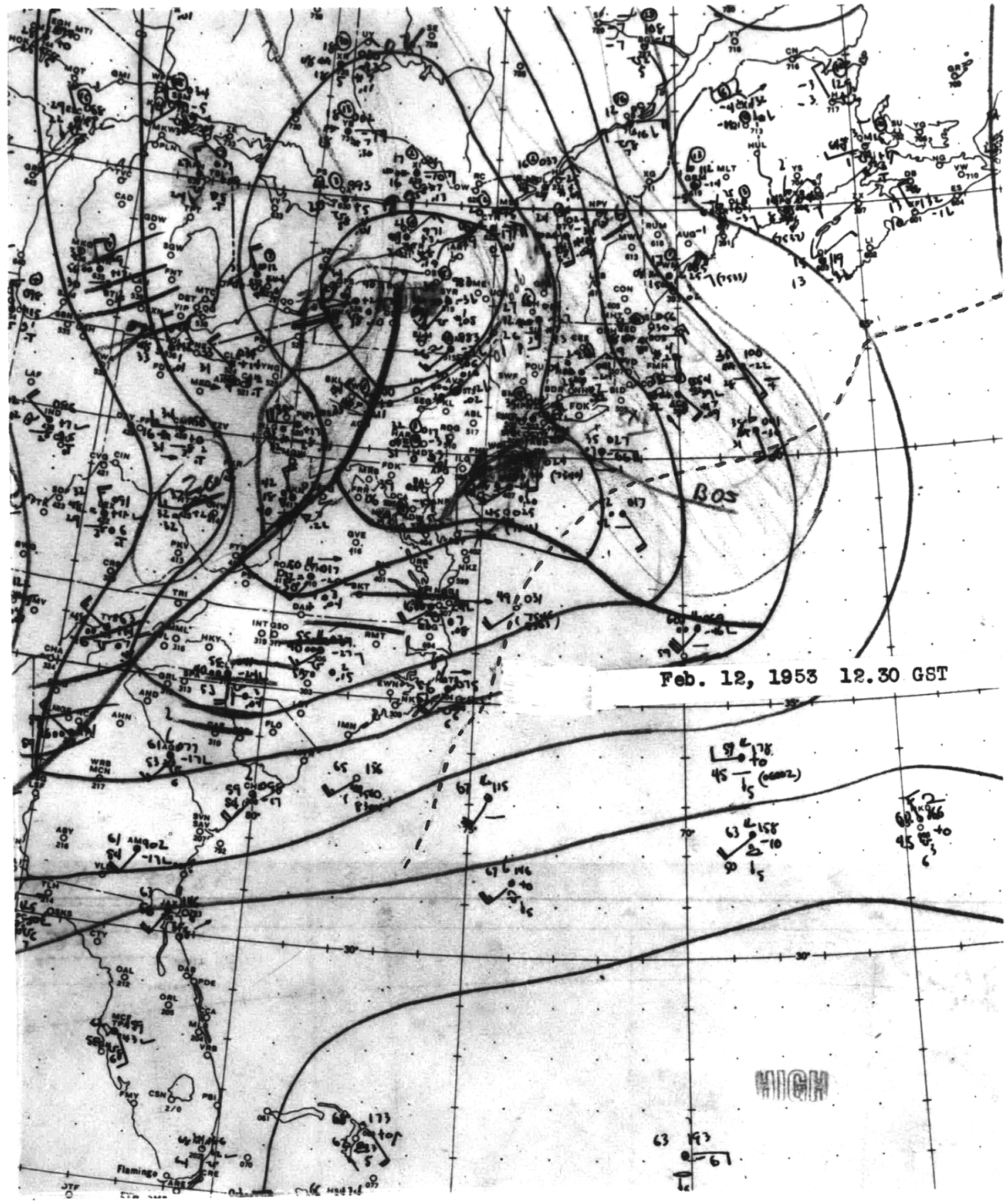
Map 25.



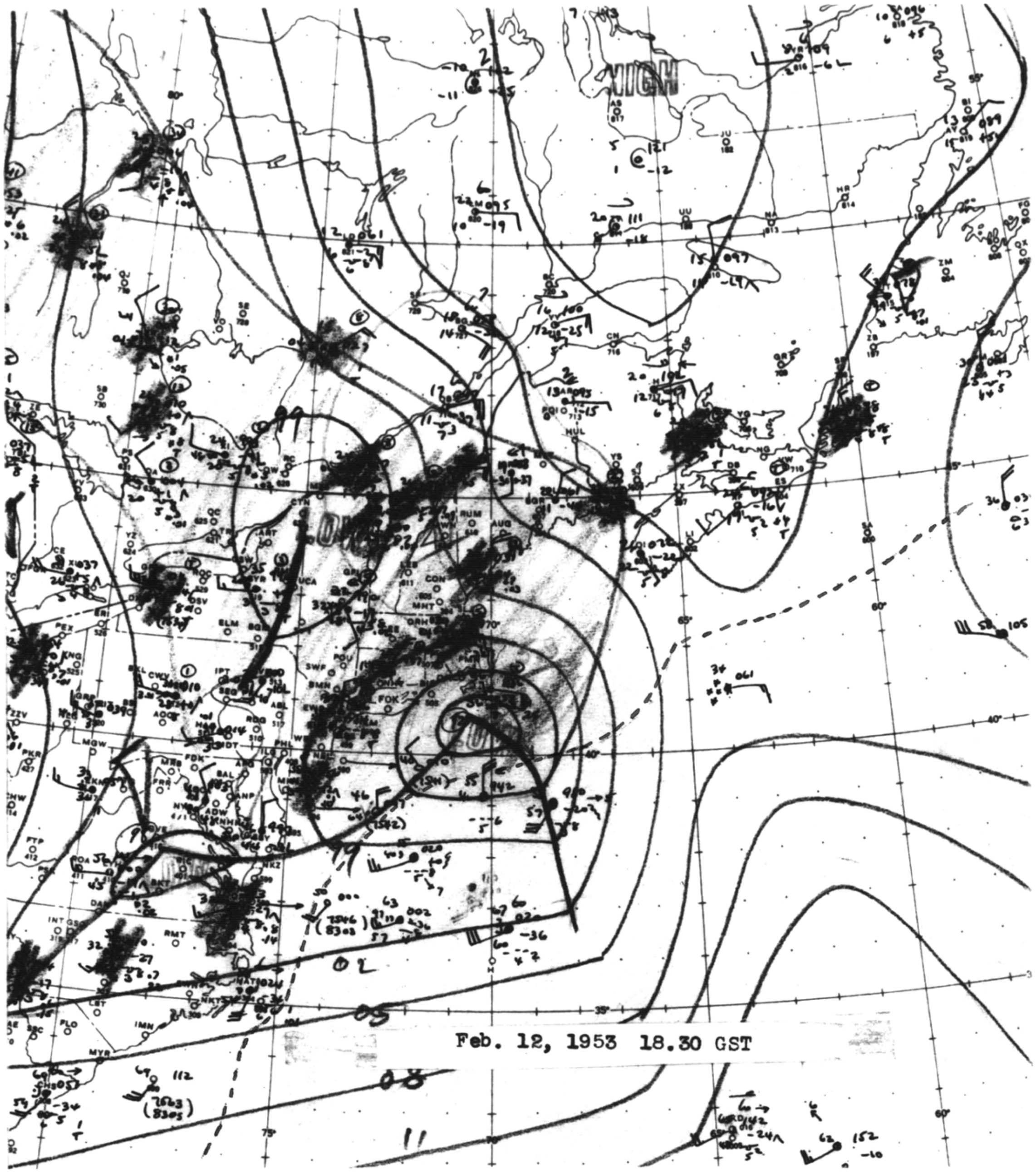
Map 26.



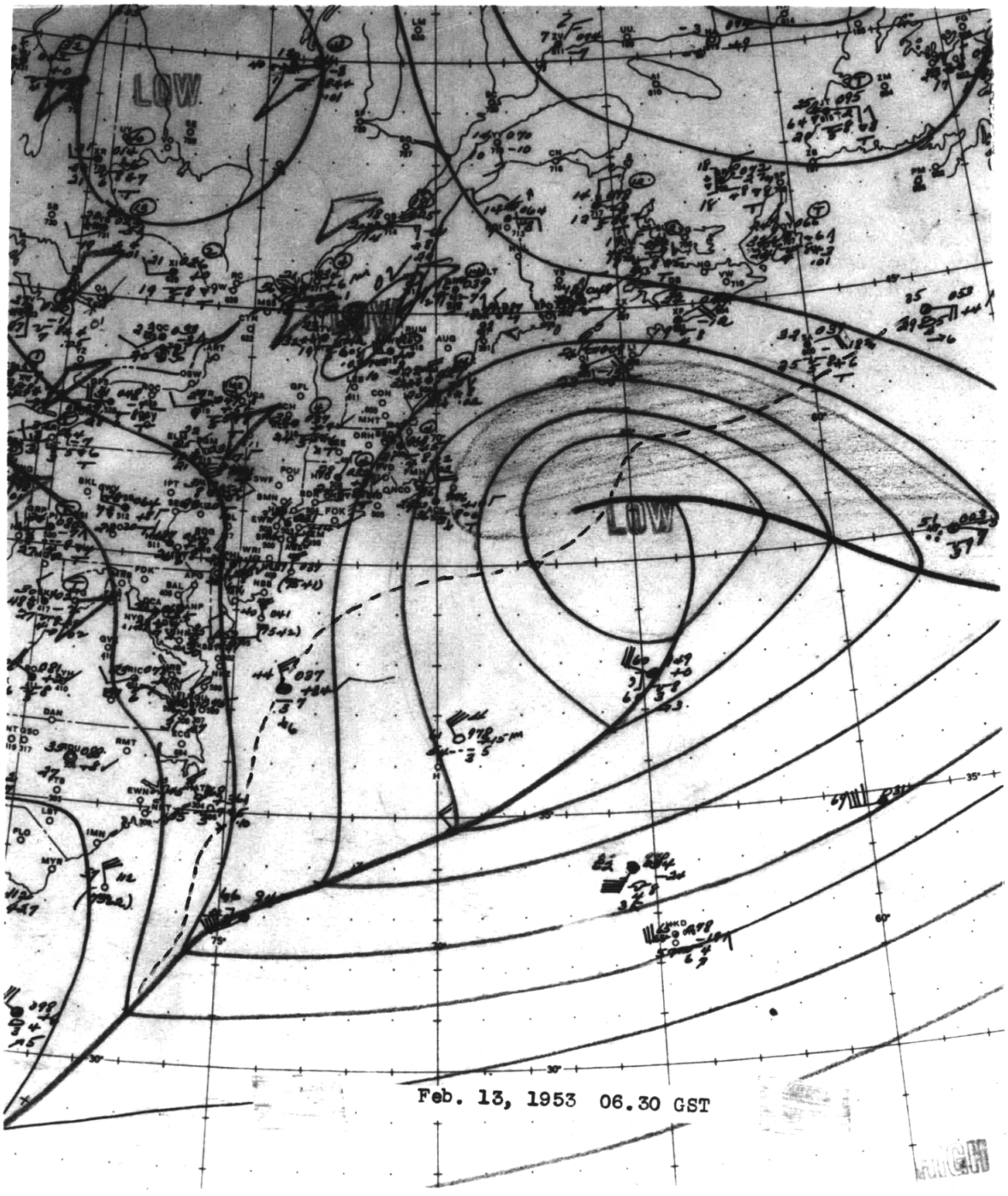
Map 27.



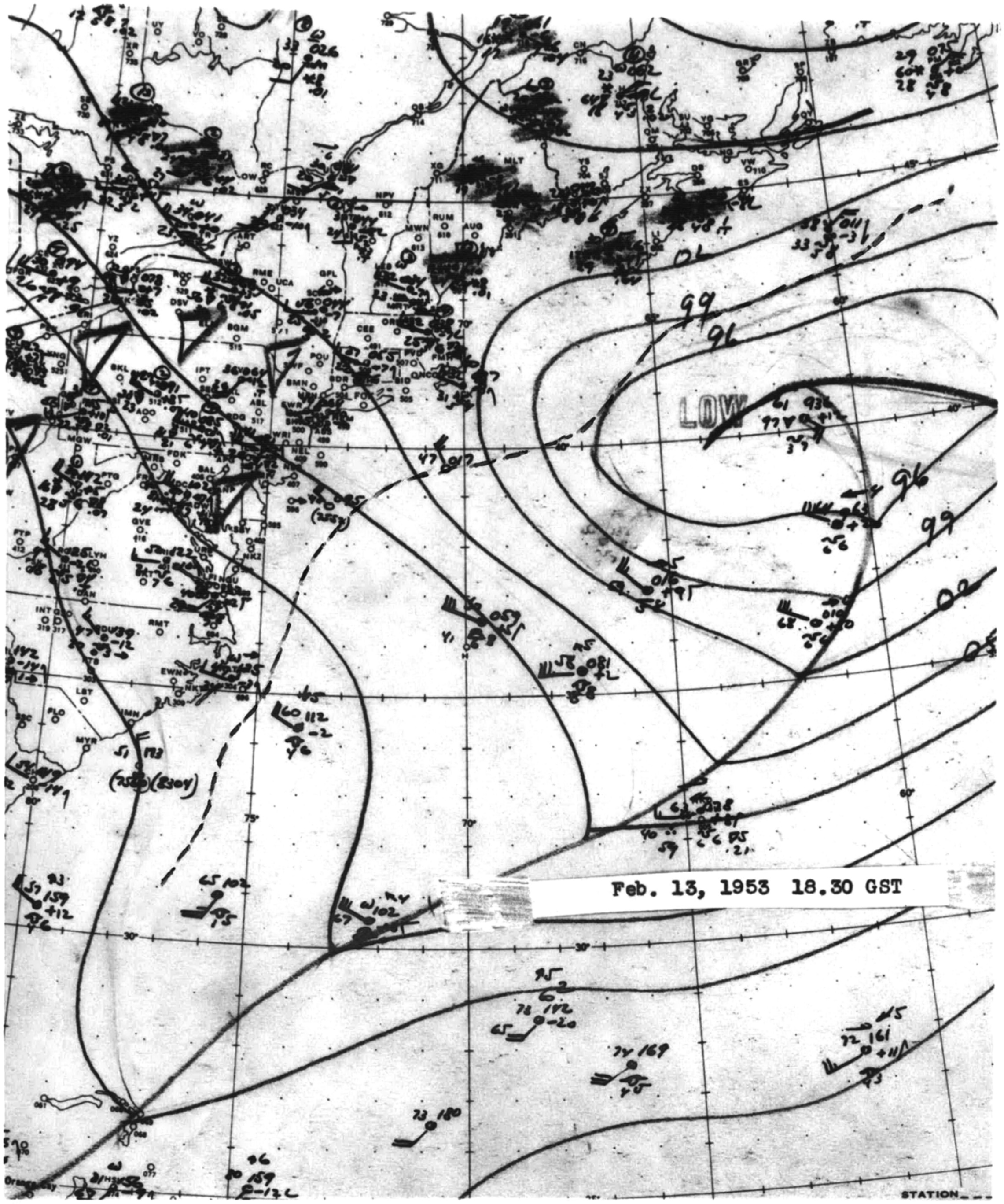
Map 28.



Map 29.



Map 30.



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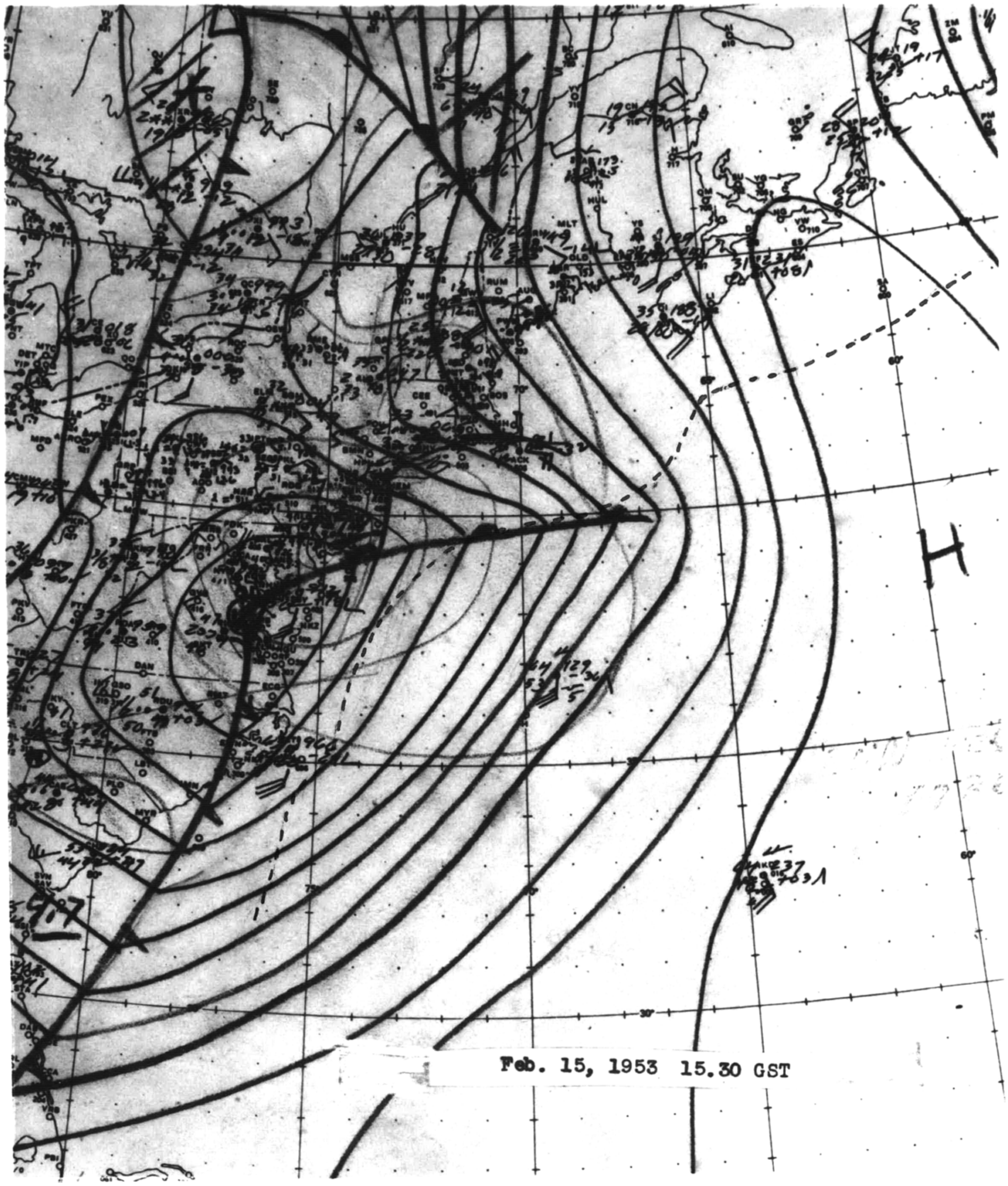
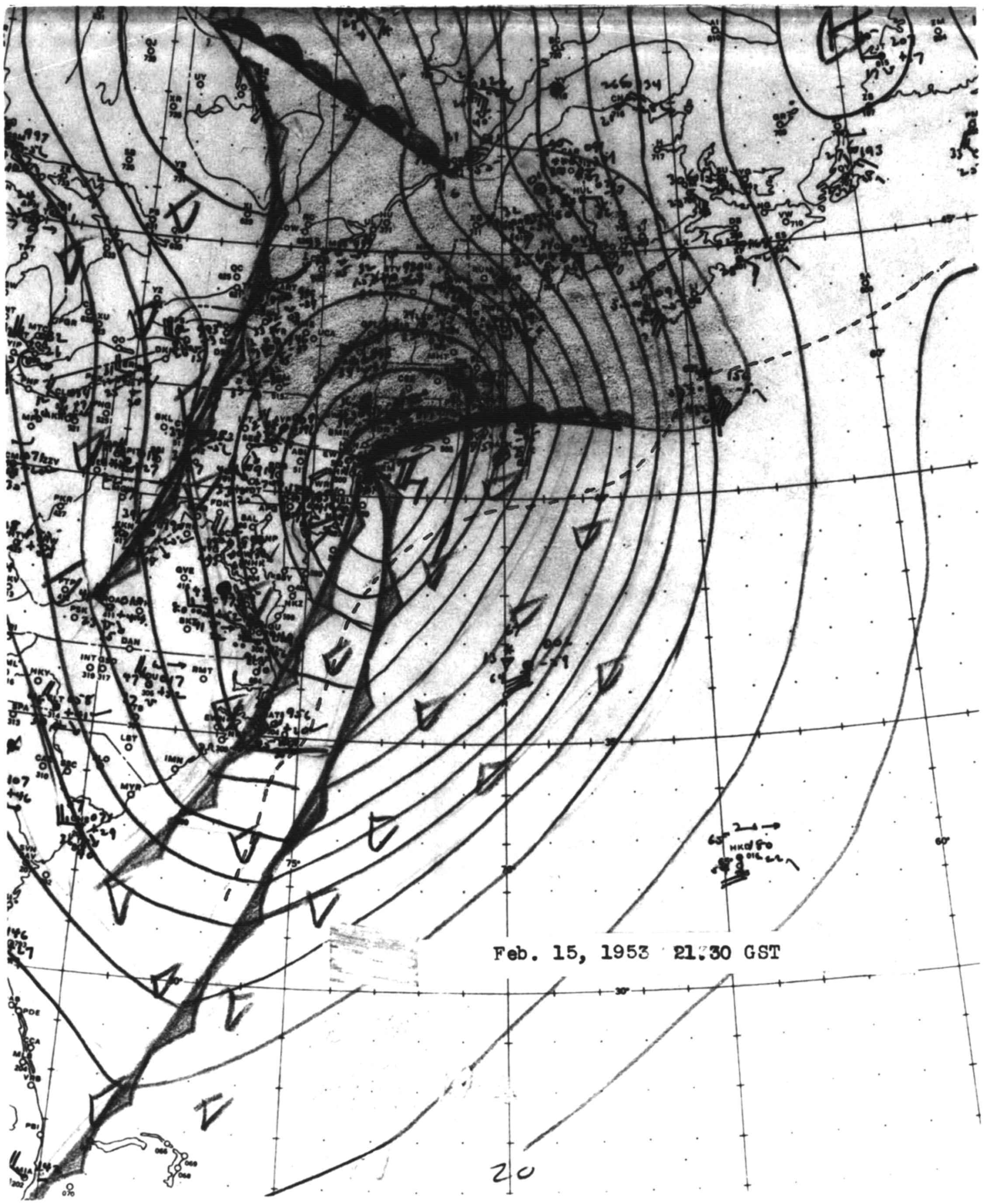
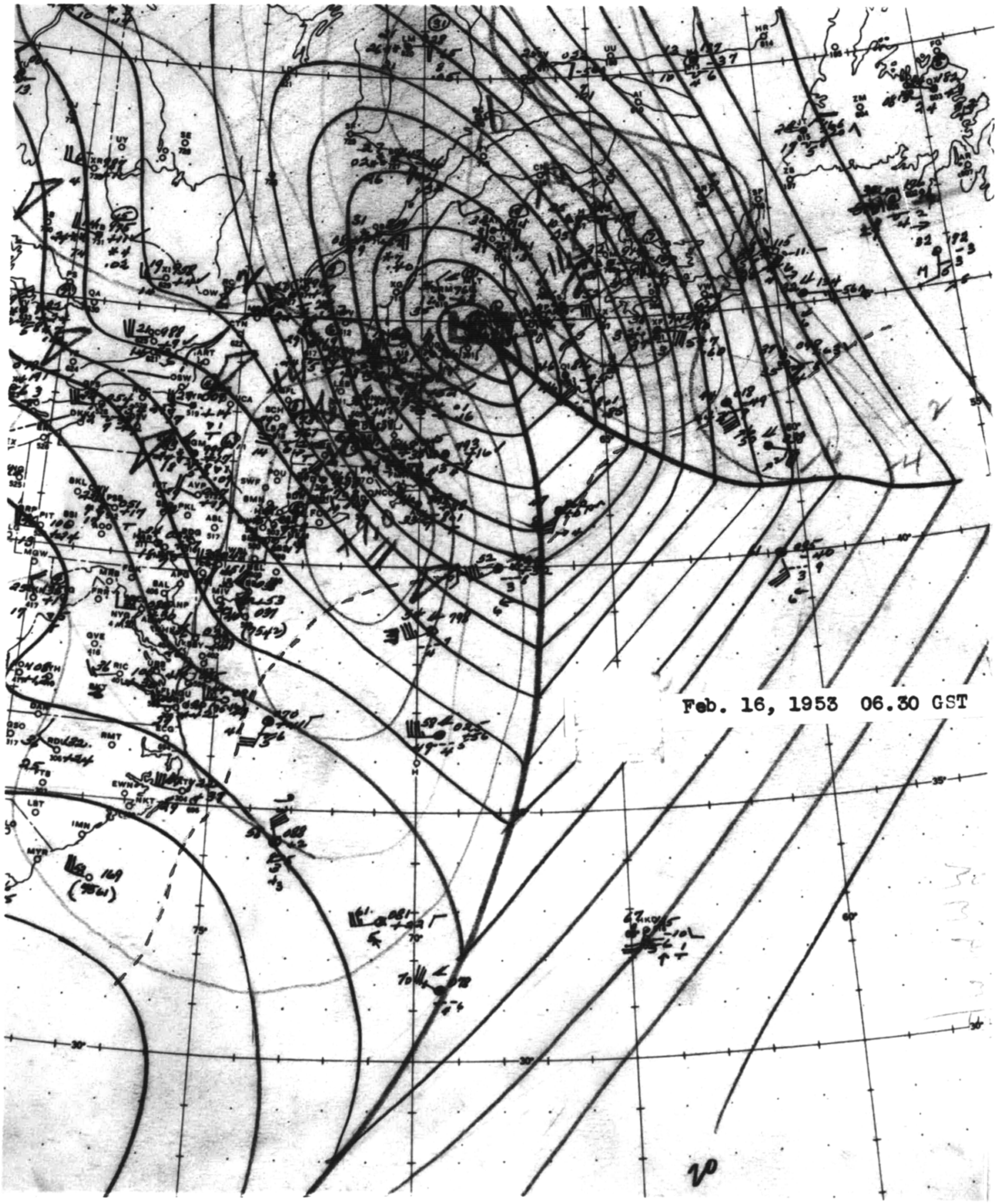


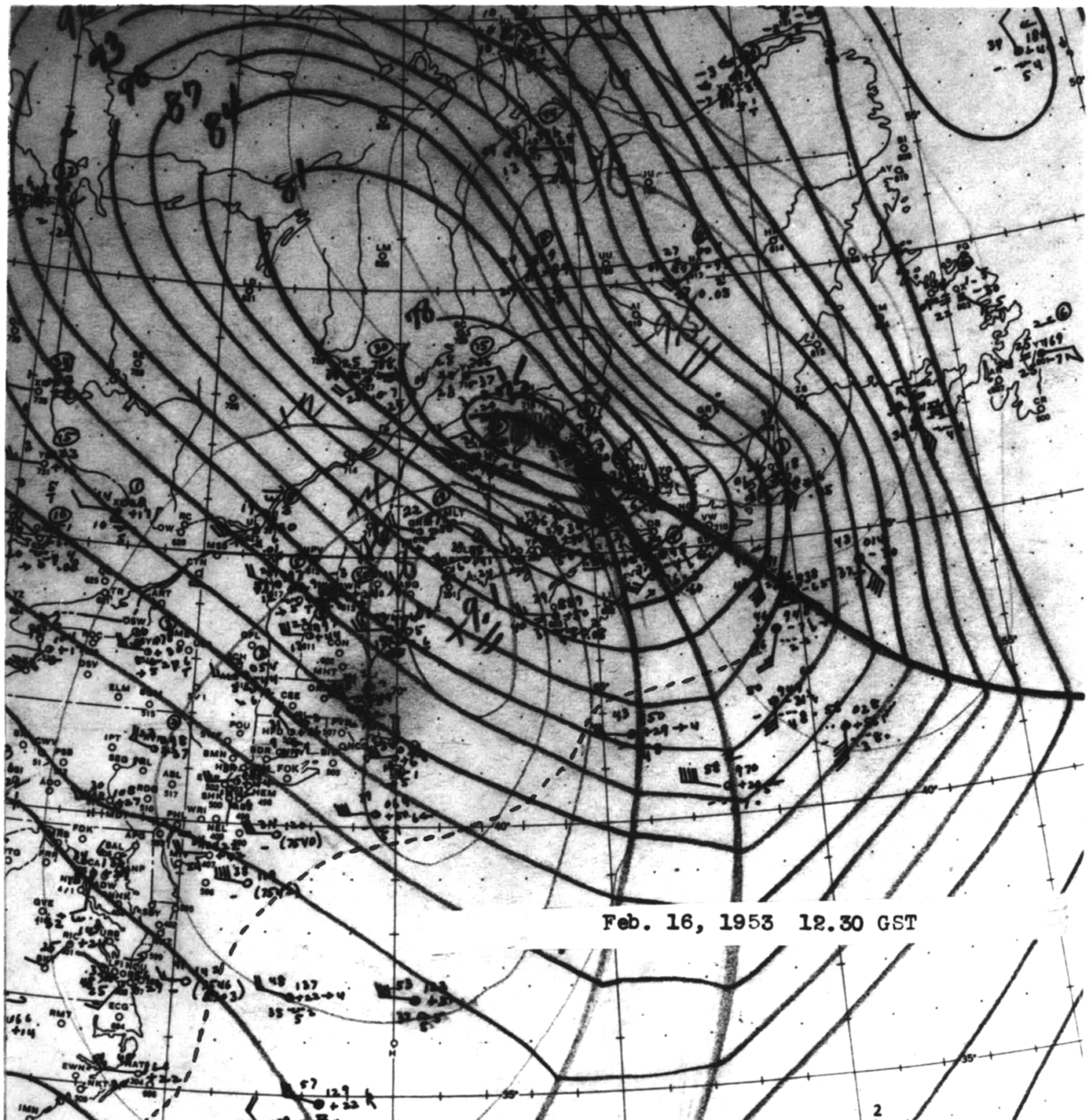
Map 32.



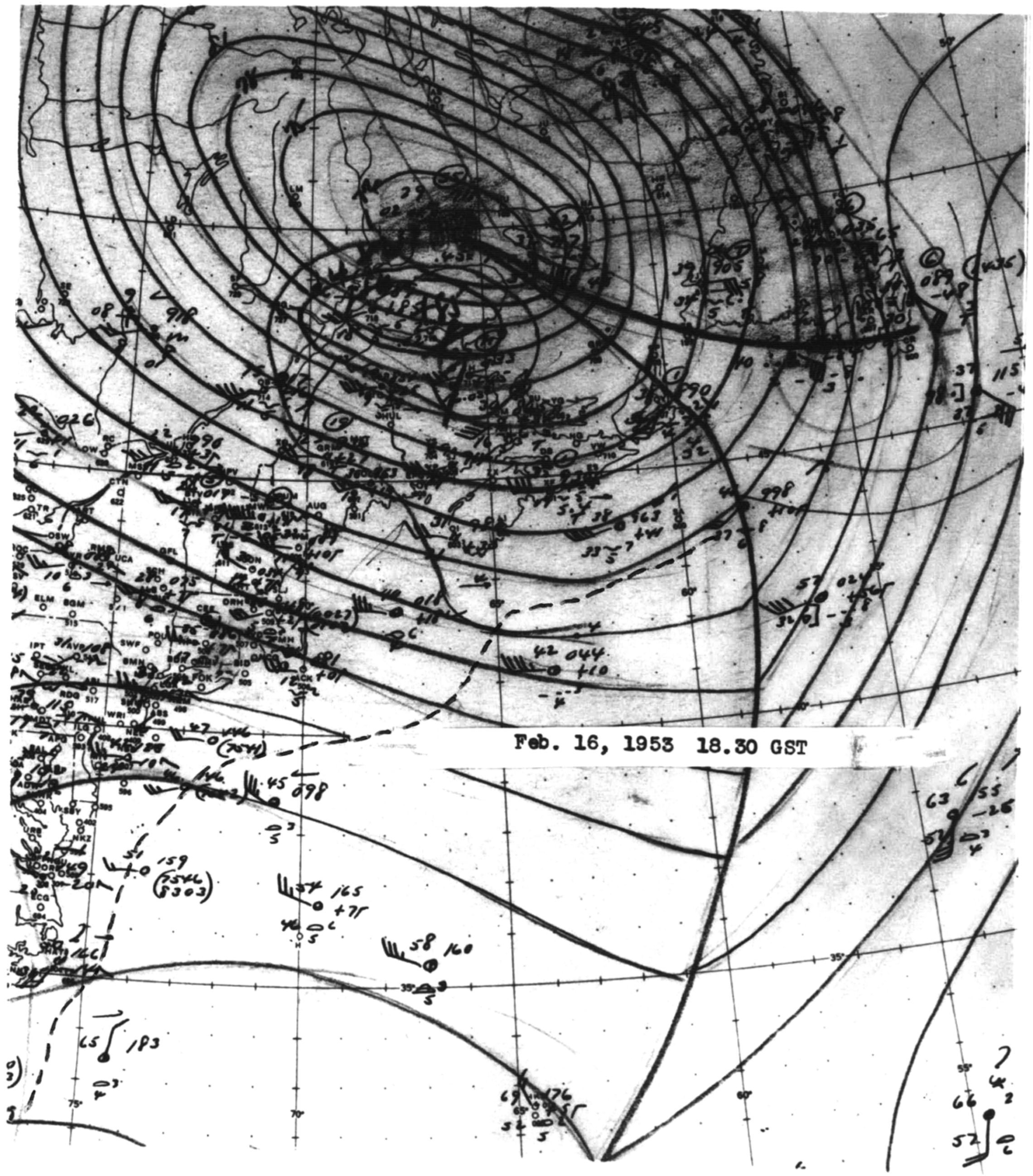
Map 33.



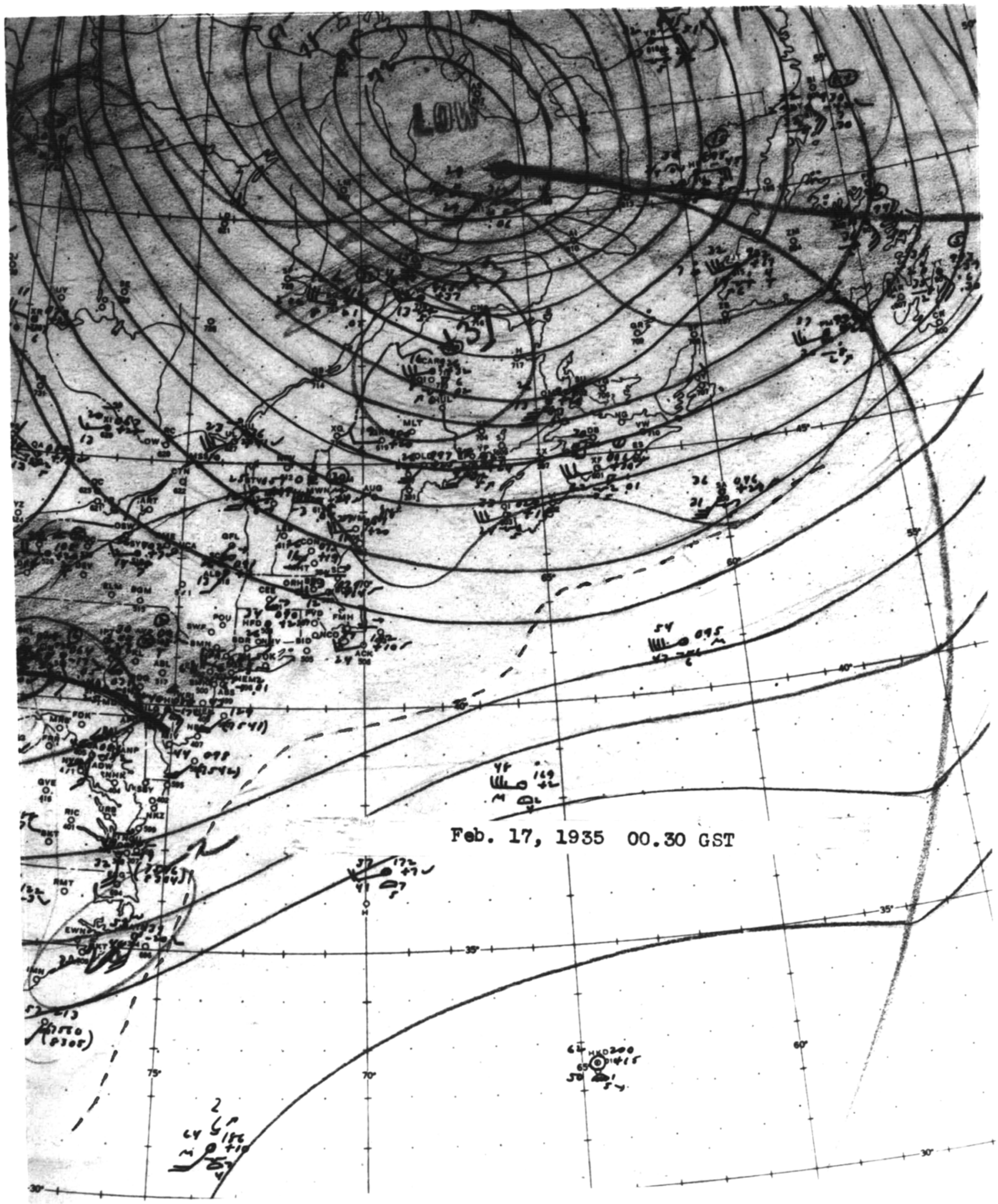
Map 34.



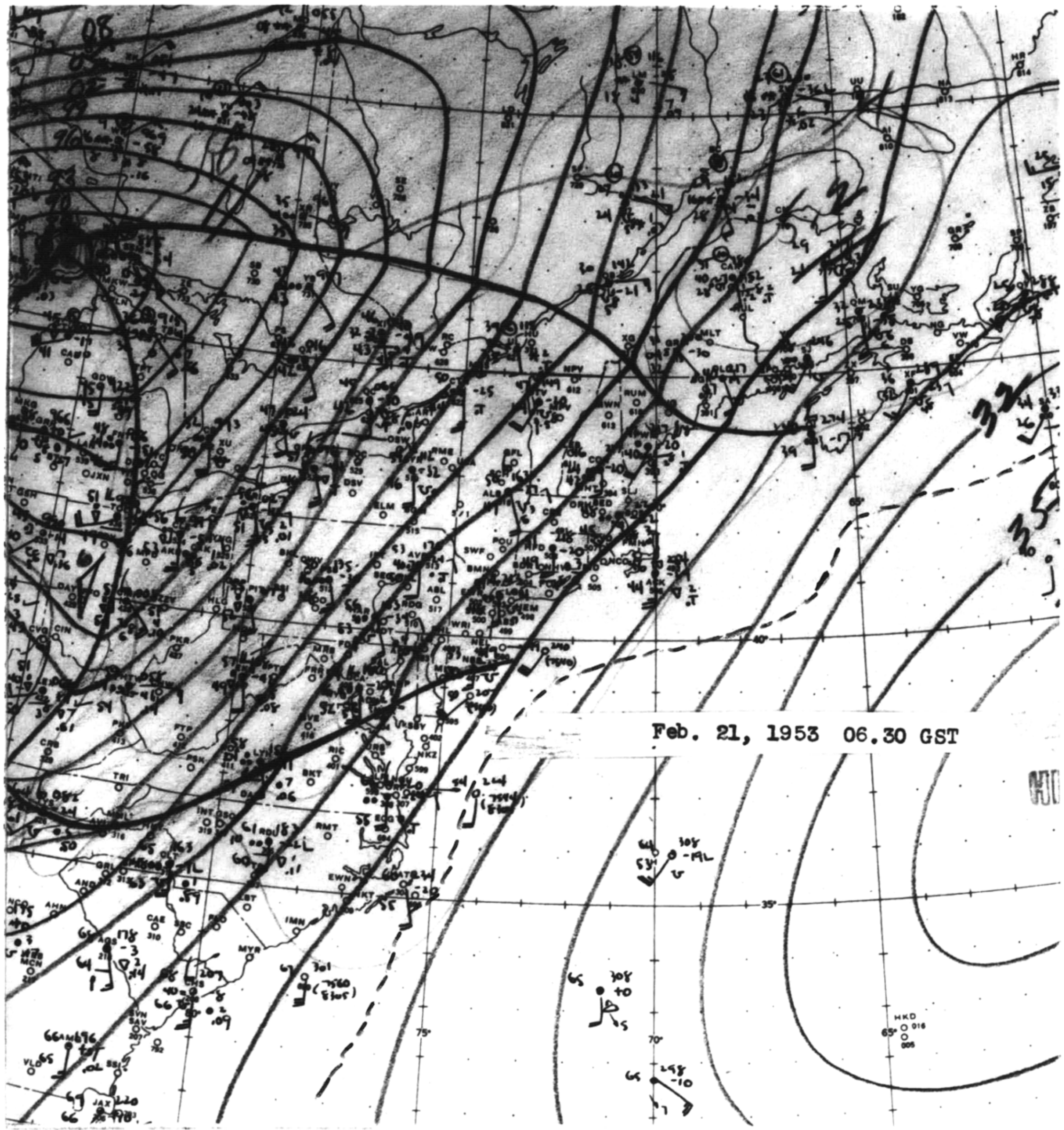
Map 35.



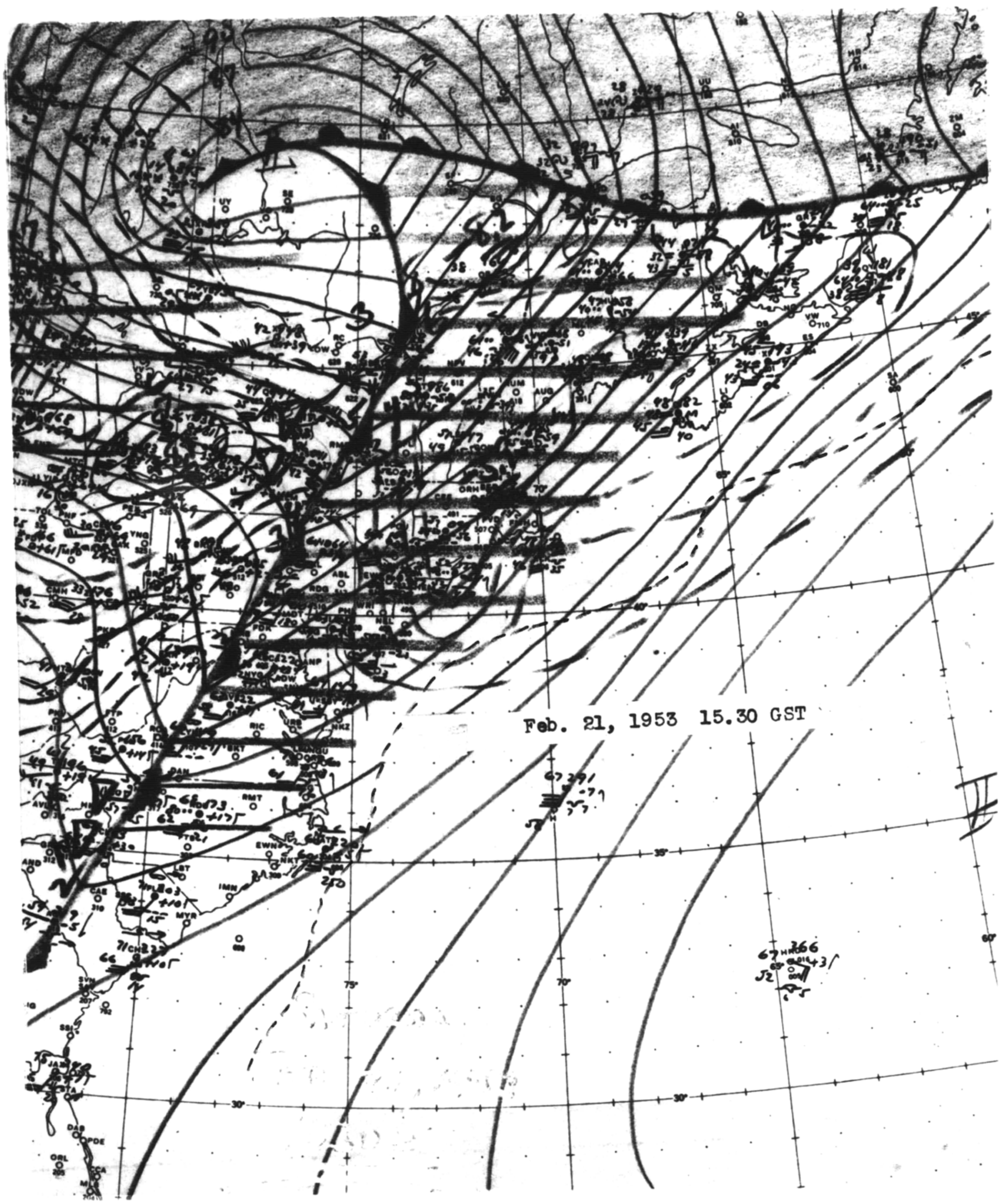
Map 36.



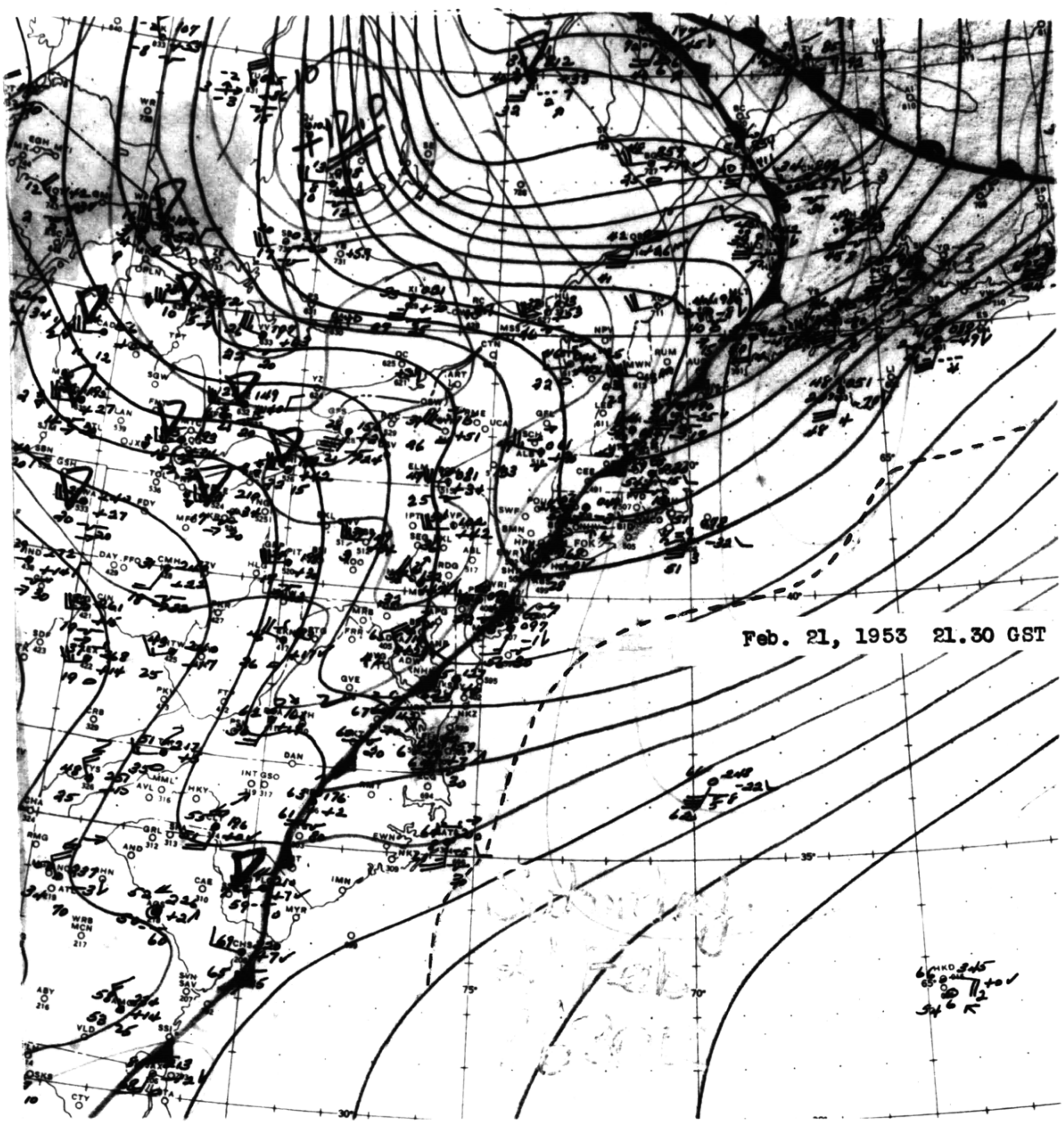
Map 37.



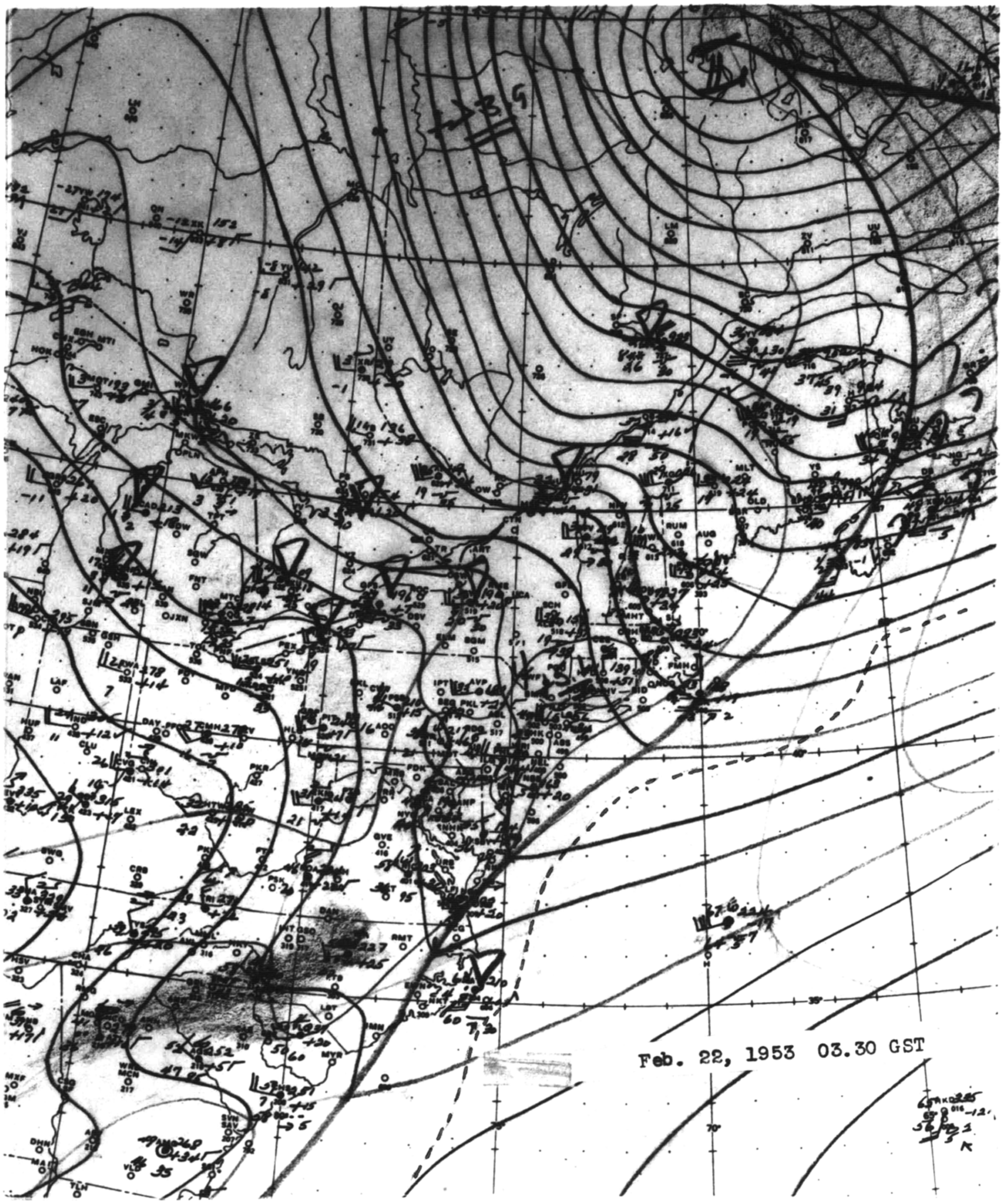
Map 38.



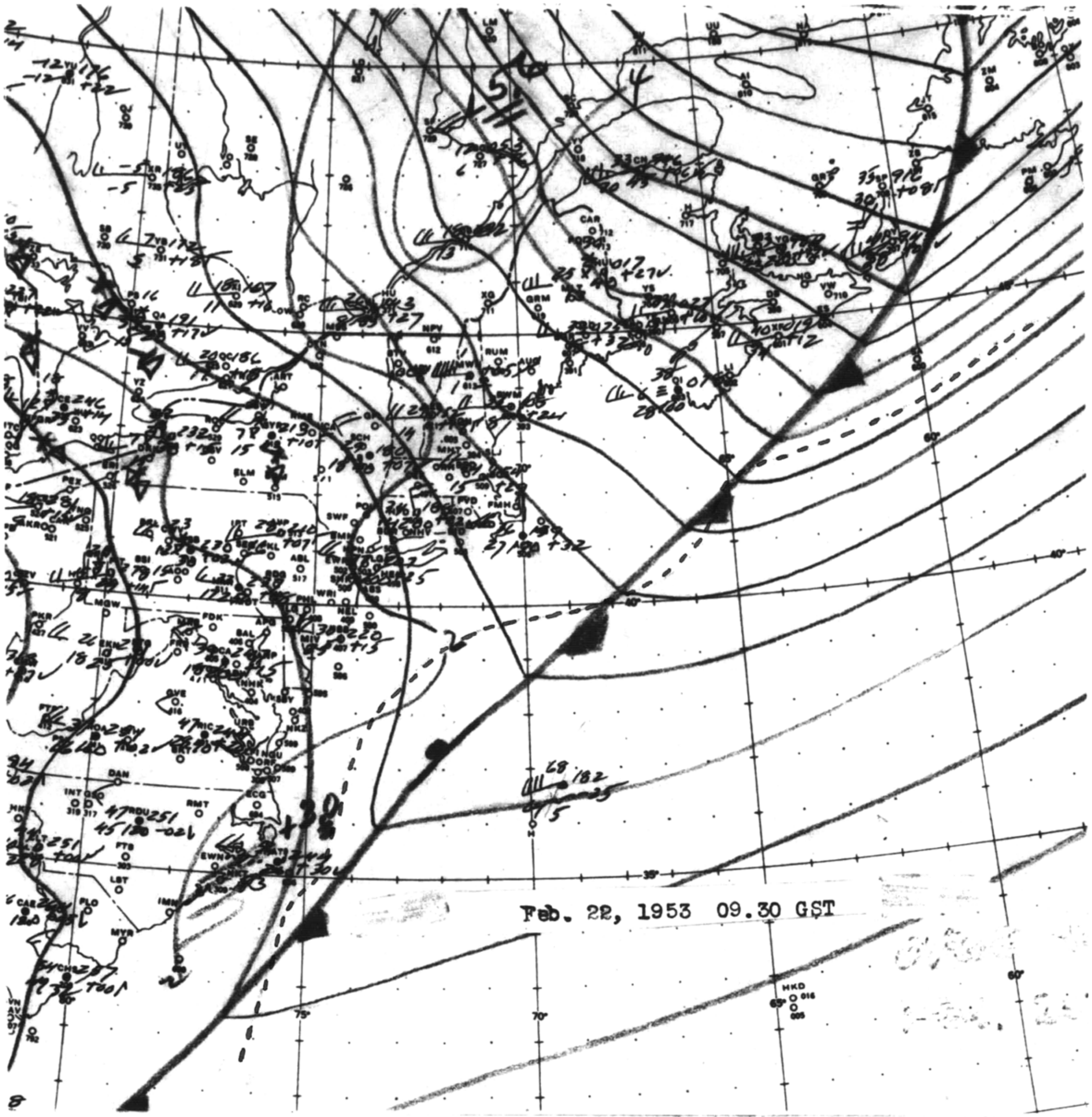
Map 39.



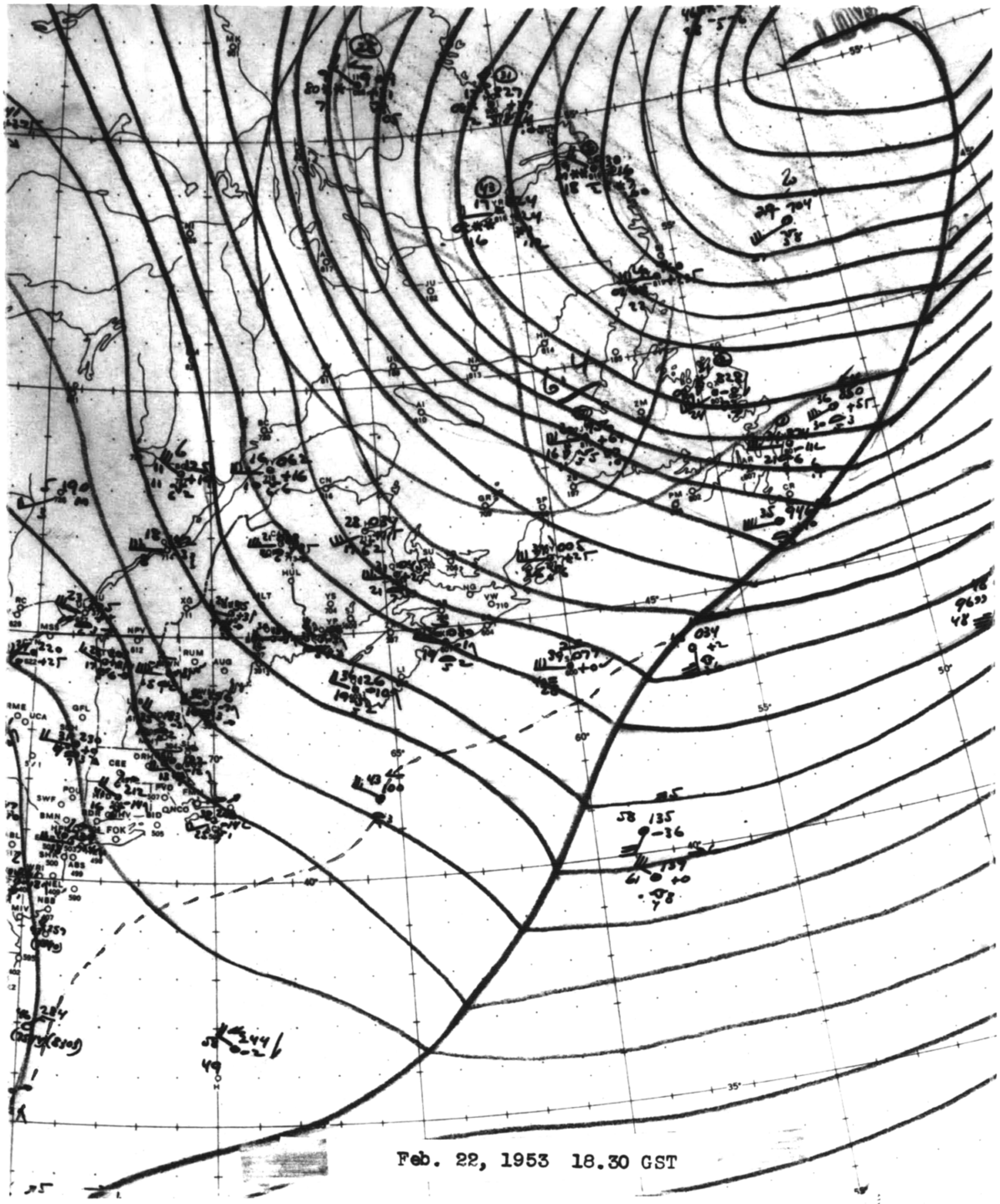
Map 40.



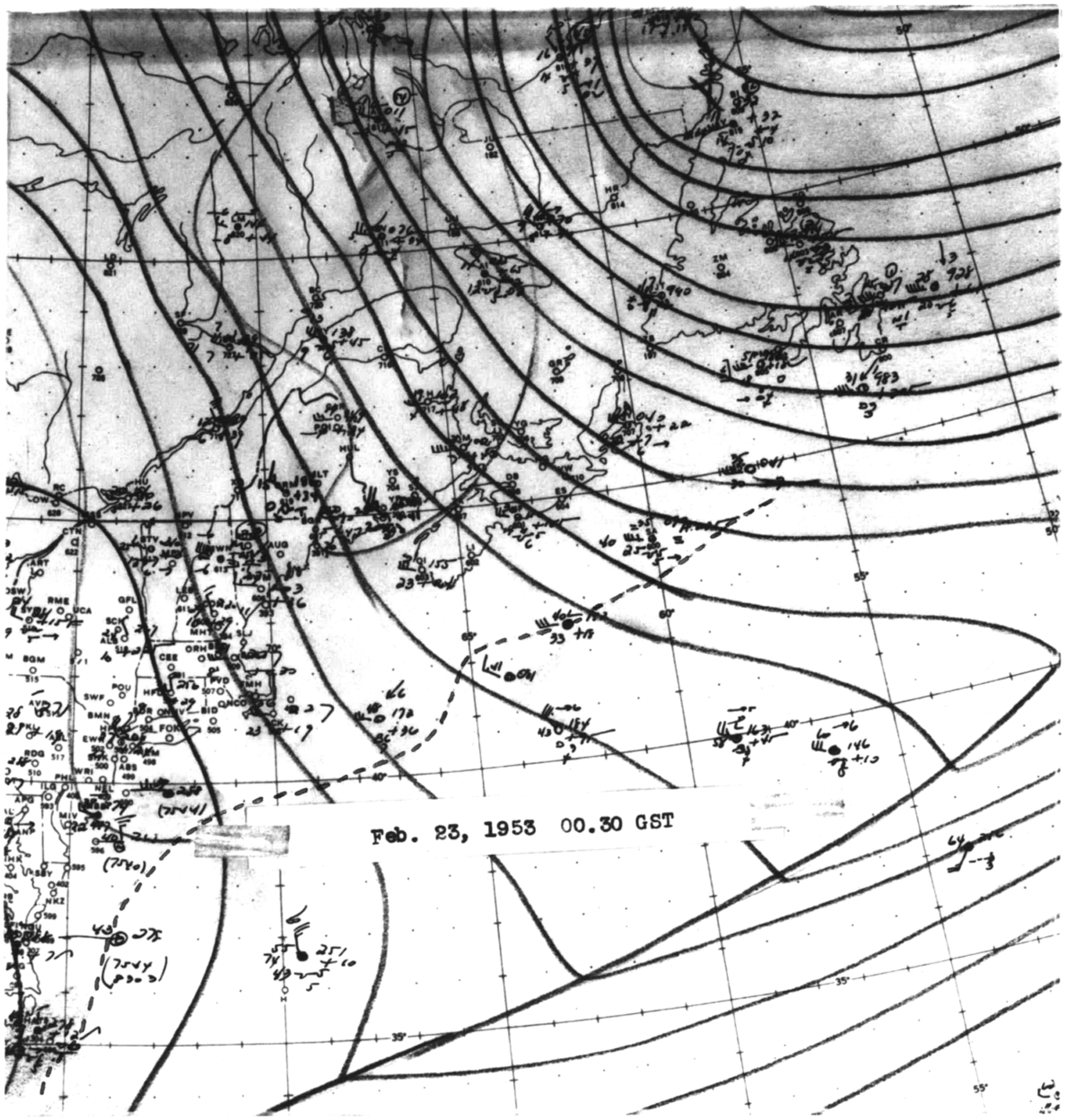
Map 41.



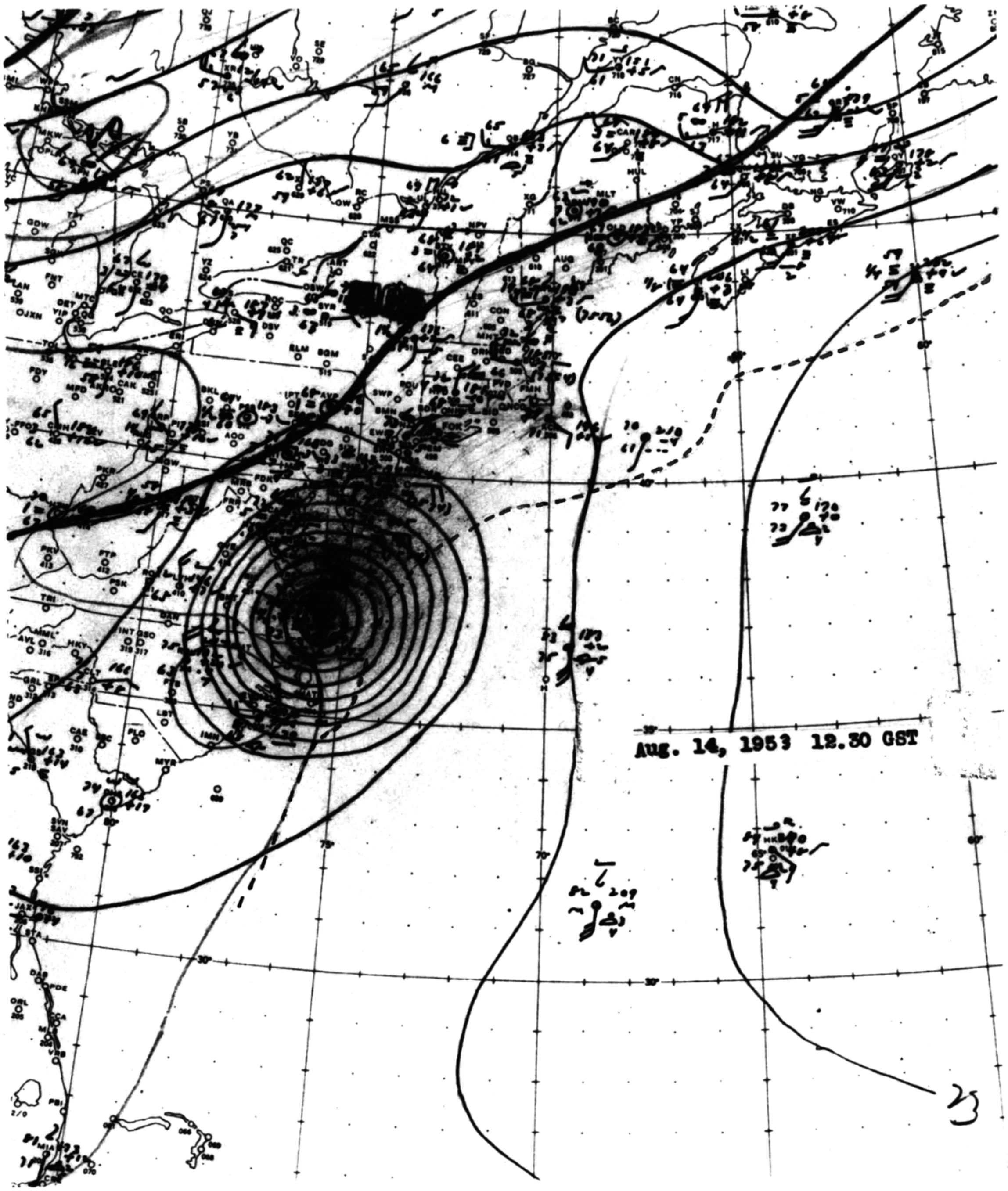
Map 42.



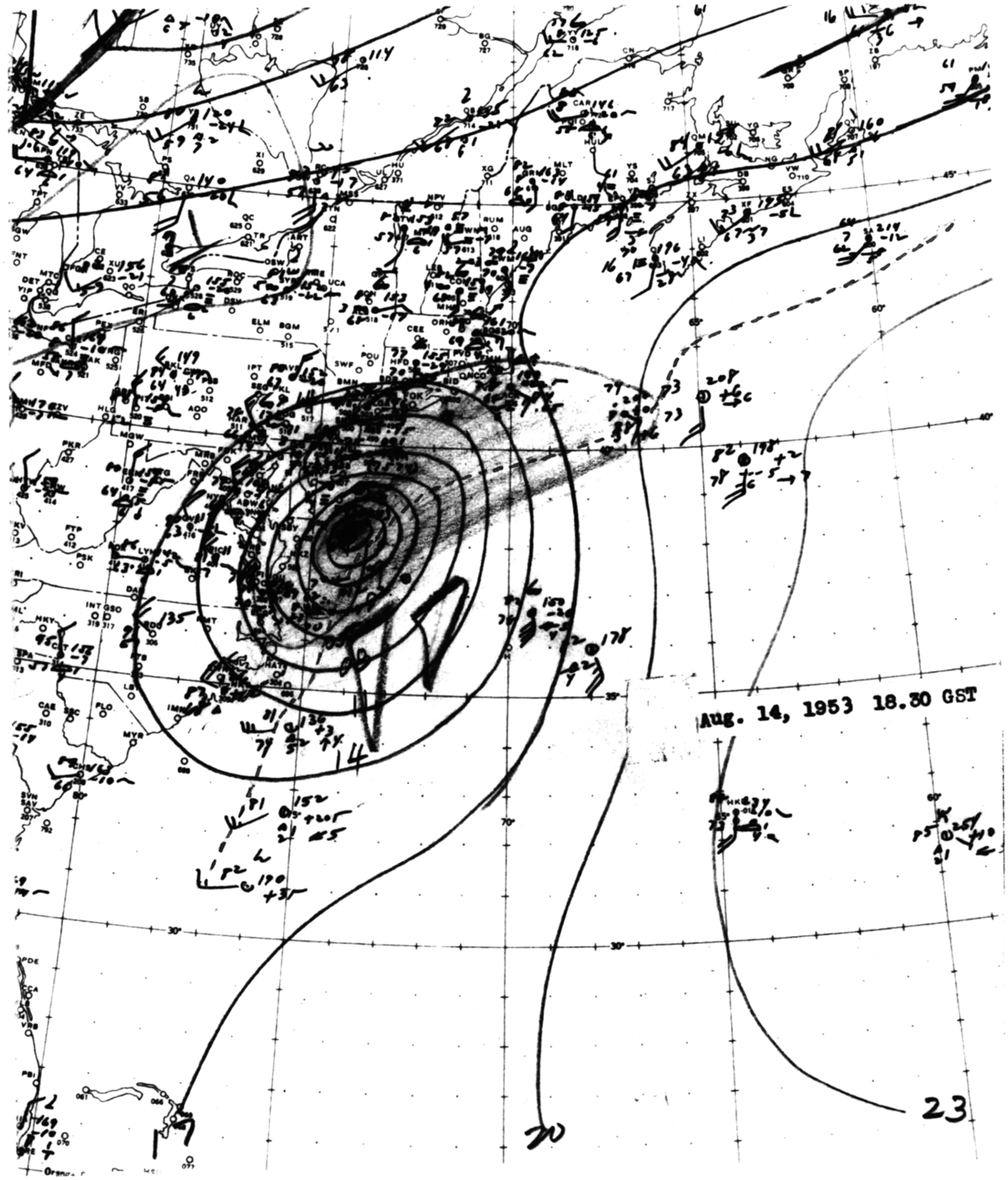
Map 43.



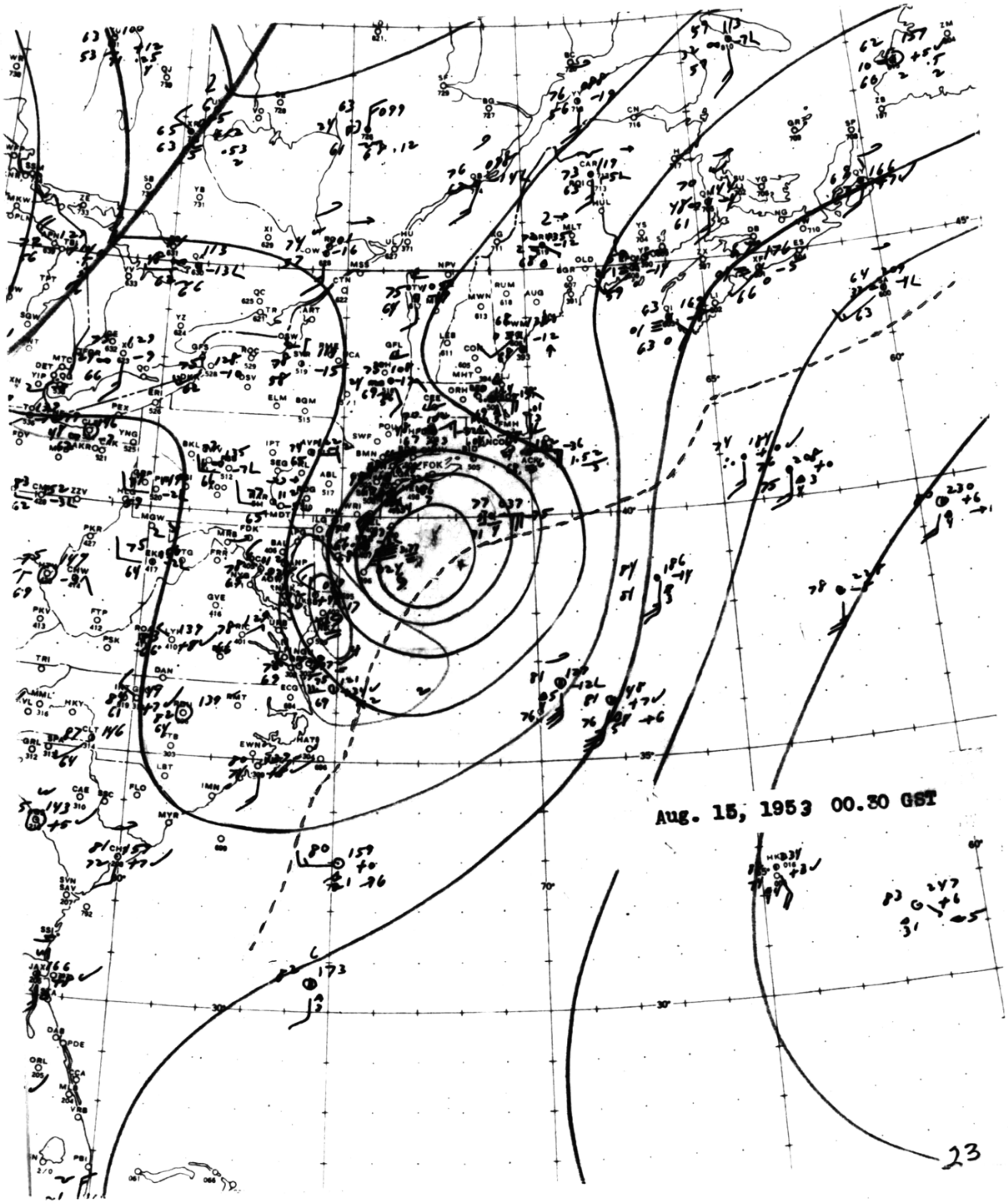
Map 44.



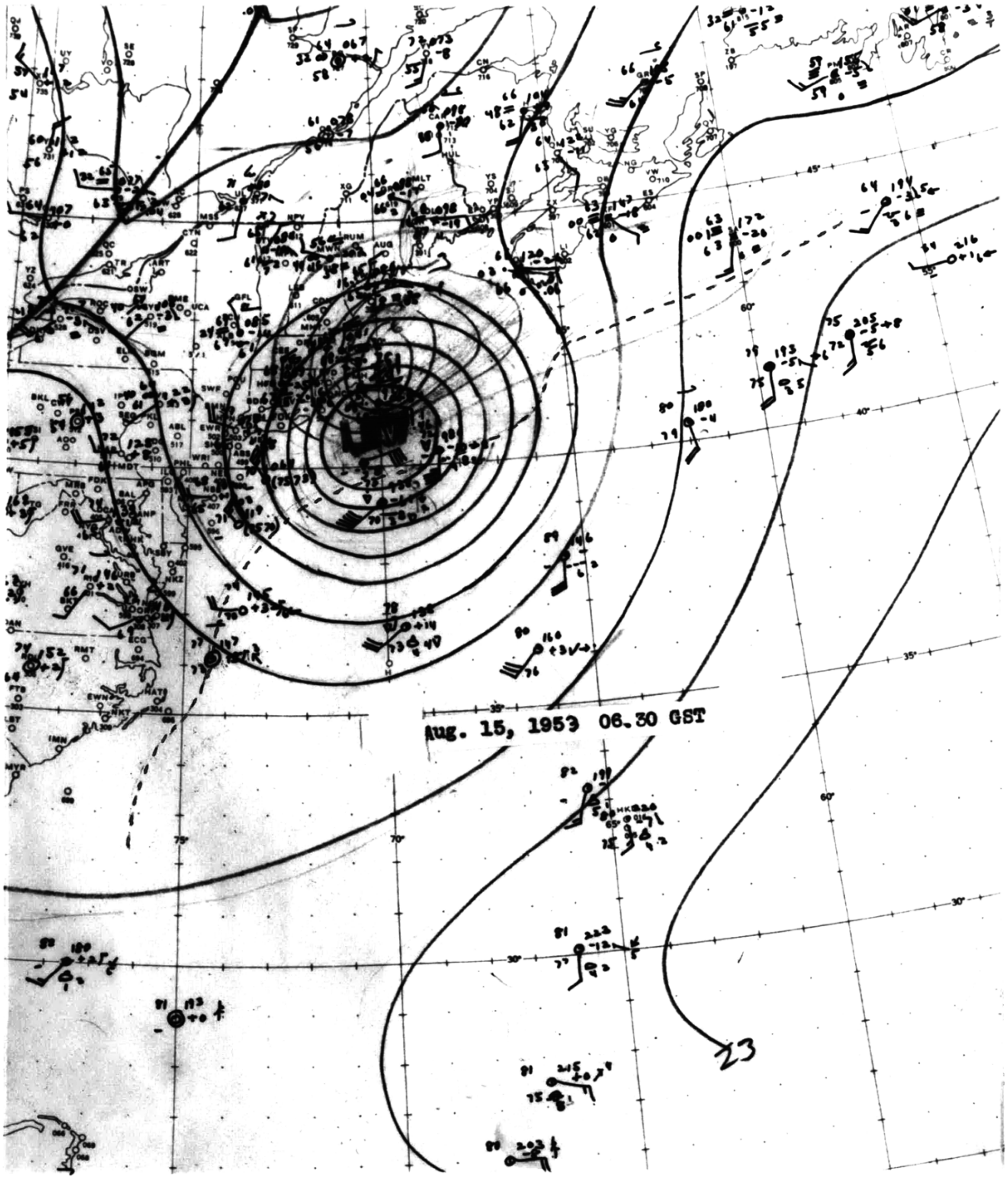
Map 45.



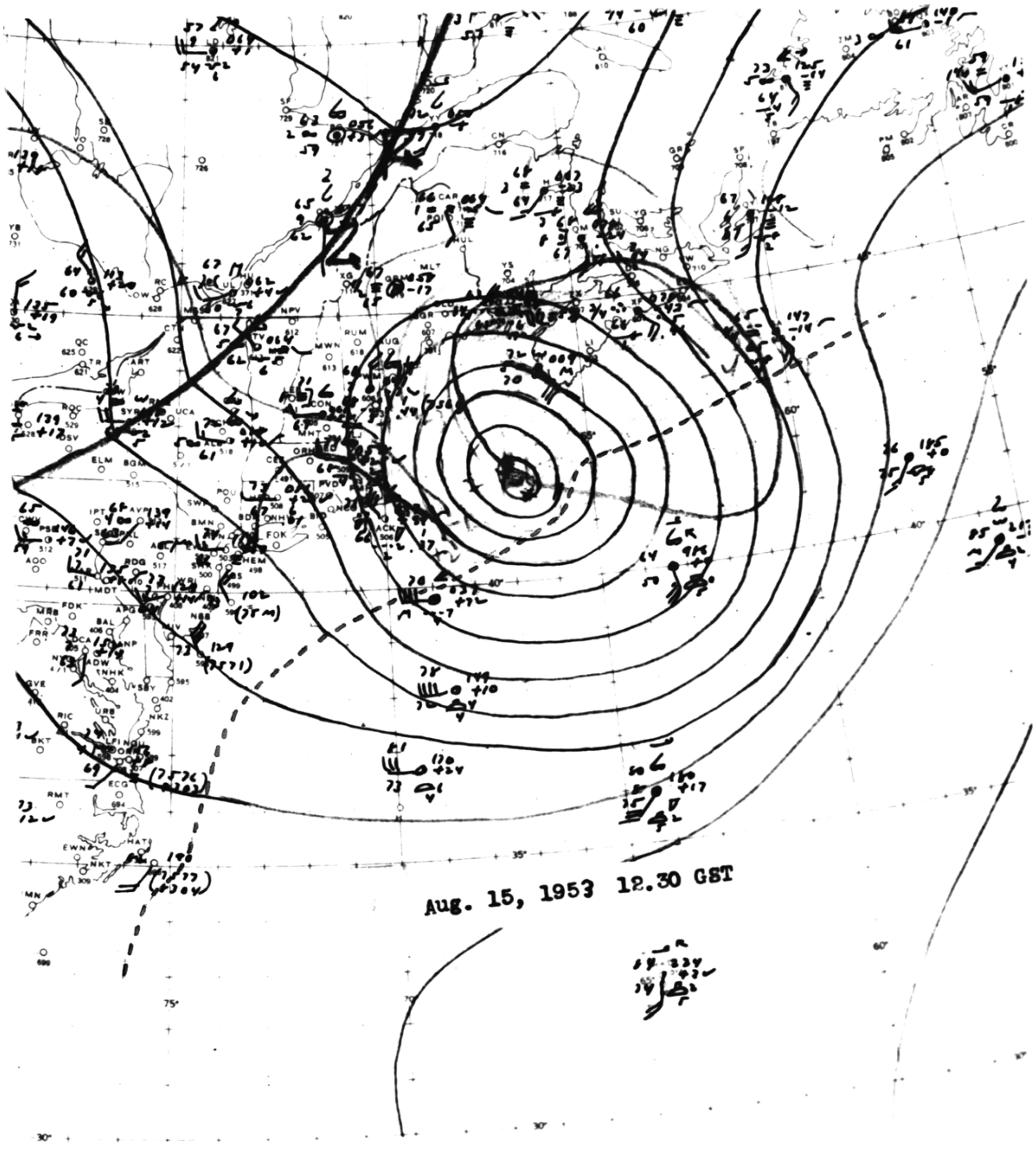
Map 46.



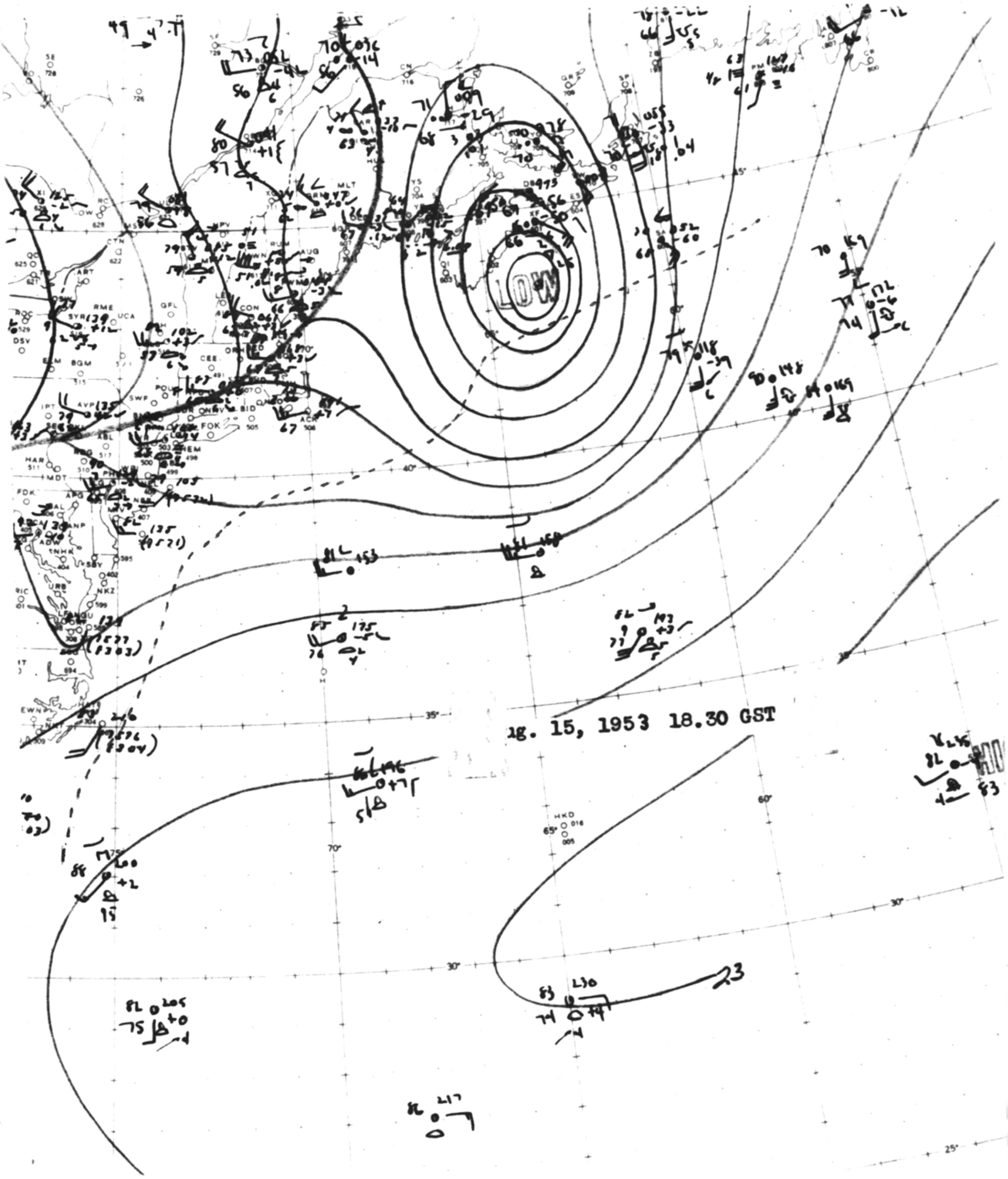
Map 47.



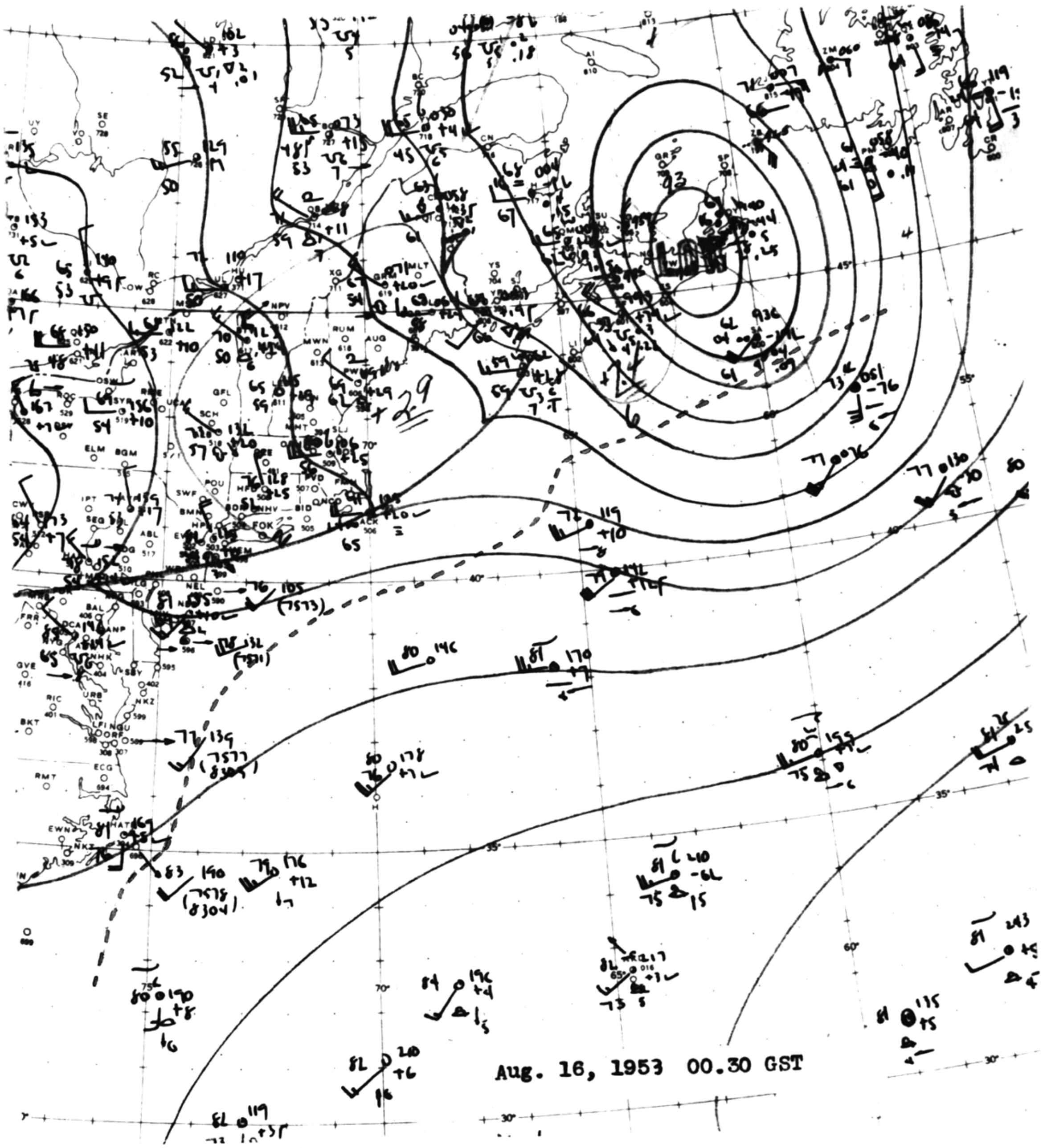
Map 48.



Map 49.



Map 50.



Map 51.