# THE CAUSES AND FORECASTING OF THE FOG AND STRATUS CLOUDS OF THE CALIFORNIA COASTAL REGIONS AND THE TEMPERATURE INVERSIONS ASSOCIATED WITH THEM

Thesis by

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## PREFACE

We wish to express our appreciation to Dr. Sverre Petterssen, Director of Vervarslingi Pa Vestlandet, Bergen, Norway, for his assistance and guidance in the outlining of the method of attack of this problem; Dr. Irving P. Krick of the California Institute of Technology for his most helpful assistance and suggestions; and the personnel of the Aerological Department of the Naval Air Station, San Diego, California, for their cooperation in furnishing us the necessary observational data in the most complete form.

We also wish to acknowledge the excerpt from "Some Observations on the Temperature Inversion Along the Southern California Coast" by Lieutenant Commander J. B. Anderson, U. S. Navy.

# INTRODUCTION

This research subject deals primarily with the layer of stratus clouds encountered so frequently on the southwestern coast of the United States. It is distinguished from true fog or ground fog in that it does not extend to the surface. Consequently, the condition under discussion will be referred to as existing when the sky is covered by ten-tenths (10), and breaking when the stratus amount becomes nine-tenths (9) or less.

Since it is believed that the stratus condition existing over coastal regions is primarily a convective phenomenon, we were of the opinion that the most logical results would be derived from a careful study of the relation between the height of the base of the temperature inversion and the height of the condensation level. Nevertheless, all of the elements and combinations of elements that might possibly be factors in the forecasting of stratus, in the opinion of the writers, were also studied in detail in order that no factor would be over-looked that might be of value. However, only those factors that were later found to produce positive results and are of value in practical forecasting will be discussed in detail. The others will merely be indicated by a brief statement or plate of the data plotted with a short explanation where necessary.

In order to clarify the theory previously referred to and a few of the terms used therein, with which the reader might not be familiar, a concise explanation of these might well be made here.

When a temperature-height curve of an aerological flight is plotted, the height at which the temperature ceases to decrease and commences to increase is known as the base of the temperature inversion. If this inversion is sufficiently intense all convection from below is stopped at this level, i. e., the base of the inversion appears to act as a lid. This is due to the fact that the rising air which must ascend adiabatically will find itself cooler than its surroundings at this level, and therefore cannot continue to rise.

The following excerpt taken from Lieutenant Commander Anderson's paper gives a concise explanation of the cause of the temperature inversion noted so frequently along the California coast: "This inversion is caused by the sea temperatures along the coast and exists over the land adjacent to the ocean only because the sea breeze (or prevailing west to northwest winds) keeps that area flooded with ocean air to a depth of several thousand feet. At times the hot valleys between the foothills and the high coast range, which borders Imperial Valley on the west, have a marked effect on the inversion, but, except during the time of Santa Ana winds, it is very doubtful if Imperial Valley, or any of the great valleys to the north, materially affect the atmosphere at the level of the inversion although they do have a marked influence on the atmosphere at very high levels much of the time, particularly in summer." Reference to the above paper is recommended for further information on this phase of the subject.

The condensation level is the level at which the rising air becomes saturated. If an air particle is lifted it will follow the dry adiabat to the saturation point, after which it will move along the moist adiabat. The intersection of this dry adiabat with the actual specific humidity line is the lifting condensation level (L. C. L.). When the particle is lifted to this level condensation will occur, and the base of the clouds will be at this level. If an air particle is heated it will follow the dry adiabat to the saturation point, i.e., the intersection of this dry adiabat with the actual specific humidity line, and then along the actual specific humidity curve to its intersection with the ascent curve. This second intersection is the convective condensation level (C. C. L.).

Since this formation of stratus occurs chiefly at night, and since the convective condensation level approximately coincides with the lifting condensation level at night, we have used the latter in this investigation.

The following process is believed to take place in the formation of the stratus layer:

1) Condensation first takes place at the L. C. L.

2) This cloud particle is immediately conveyed aloft by convection to the base of the inversion (B. I.).

3) This process continues until the layer of stratus has built downward from the B. I. to the L. C. L. forming a solid layer of stratus between these two boundaries.

The records studied cover the period from 6 September, 1935 to 15 November, 1935, inclusive, at San Diego, California. This season of the year is probably the most difficult period for the forecasting of stratus, due to the extremely rapid changes in the height of the base of the inversion and the height of the lifting condensation level as is exemplified in PLATE #8.

## INVESTIGATIONS YIELDING NO POSITIVE AIDS FOR FORECASTING

First we shall dispose briefly of those investigations which failed to yield positive aids in forecasting, or which were possibly included in combinations later found to give positive results.

1) PLATE #1. Time of Forming of Stratus v. s. Height of Base of Inversion gave very little if any correlation.

2) The time of forming of stratus v. s. the height of the base of the inversion for each case of a North, South, East and West wind below the base of the inversion was plotted. These plots indicated no correlation between the time of forming and the height of the base of the inversion. However, the following frequency table of the number of times stratus occurred with the different winds below the base of the inversion was obtained from this investigation:

| Direction of Wind Below Base of Inversion | Frequency Of Stratus |
|---|---|
| North | 15 |
| South | 9 |
| East | 1 |
| West | 4 |

In view of the rather light, variable, prevailing winds at San Diego, the barometric gradient, which will later be discussed, was used instead of wind direction.

3) PLATE #2. Time of Breaking of Stratus v. s. Height of Base of Inversion gave very little if any correlation.

4) The time of breaking of stratus v. s. the height of the base of the

inversion for each case of a North, South, East or West wind below the base of the inversion was likewise plotted. These indicated no correlation between the time of breaking and the height of the base of the inversion. The following frequency table was obtained:

| Direction of Wind Below Base of Inversion | Frequency of Breaking of Stratus |
|---|---|
| North | 15 |
| South | 14 |
| East | 3 |
| West | 1 |

5) The value in meters of Height of Base of Inversion minus Height of Lifting Condensation Level was plotted against time of forming of stratus. No correlation was found. However, when plotted against the time of breaking, a different result was found which will be discussed later.

6) It was definitely found that the data from the afternoon flights at about 1500 were of no value in forecasting stratus. This is obviously due to the fact that convection has been taking place during the day.

7) Numerous other combinations of elements were investigated which failed to yield any positive results.

## INVESTIGATIONS YIELDING POSITIVE AIDS FOR FORECASTING

The results of those investigations which are believed to be of value in practical forecasting will now be enumerated.

1) PLATE #3. The value in meters of Height of Base of Inversion minus Height of Lifting Condensation Level was plotted for each day at 0600, the time of the morning aerological flight. The solid black circles indicate 10

stratus. The clear circles indicate 9 or less stratus.

Stratus never occurred with a negative value of B. I. - L. C. L., while stratus failed to occur only 5 times with a positive value of B. I. - L. C. L.

2) PLATE #4. Barometric pressure in inches at San Diego minus pressure at Yuma at time of morning aerological flight was plotted for each day. The solid black circles indicate 10 stratus. The clear circles indicate 9 or less stratus.

Stratus never occurred with a zero or negative value of this pressure difference.

3) PLATE #5. This plate is a combination of PLATE # 3 and PLATE #4.

This plate appears to show that a positive value of B. I. - L. C. L. cannot occur with a negative value of (pressure at San Diego minus pressure at Yuma).

Hence, a gradient (toward lower pressure) of barometric pressure from San Diego to Yuma is a necessary but not sufficient condition for stratus at San Diego.

A positive value of (B. I. - L. C. L.) is a necessary and sufficient condition for stratus at San Diego.

4) PLATE #6. The value in meters of Height of Base of Inversion minus Height of Lifting Condensation Level was plotted against Time of Breaking of Stratus. There obviously appears to be some correlation between the coordinates used in the construction of PLATE #6.

5) PLATE #7. is a curve of Height of Lifting Condensation Level in meters v. s. Relative Humidity at the Surface.

6) PLATE #8. is the Height of Base of Inversion and Height of Lifting Condensation Level in meters at time of morning flight, 0600 -- for each day.

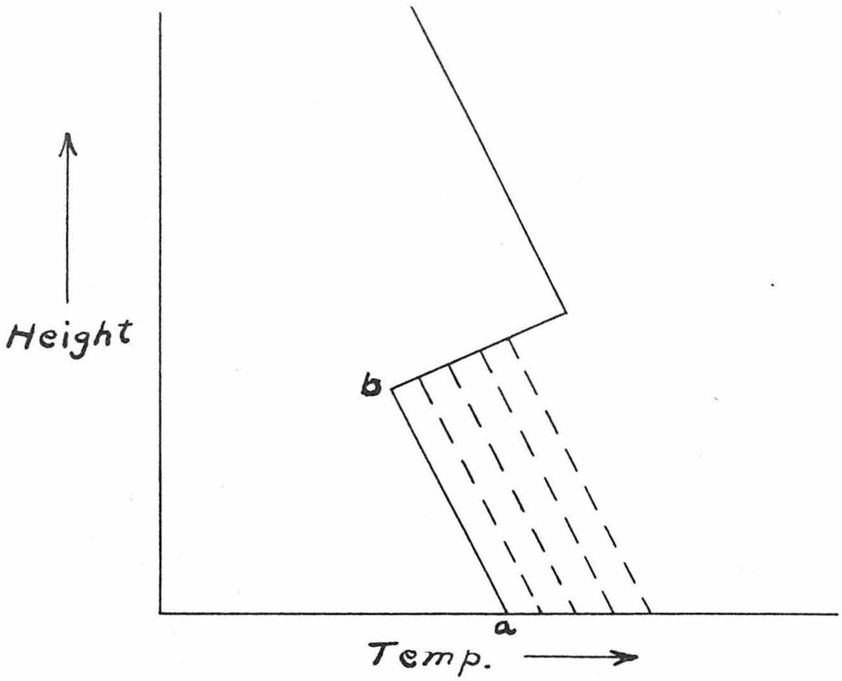
7) The following table was compiled by Dr. Petterrssen.

| Height of Base of Inversion (meters) | Diurnal Amplitude of Temperature in $^{o}F$. |
|---|---|
| 0 - 50 | $23^{o}$ |
| 50 - 100 | $17^{o}$ |
| 100 - 200 | $14^{o}$ |
| 200 - 300 | $10^{o}$ |
| 300 - 400 | $9^{o}$ |
| 400 - 500 | $7^{o}$ |
| 500 - 600 | $7^{o}$ |
| 600 - 700 | $7^{o}$ |
| 700 - 800 | $8^{o}$ |
| 800 - 900 | $1^{o}$ |

## DISCUSSION

A study of PLATES #3, #4, and #5 shows that the value of B. I. - L. C. L. must be positive for stratus to occur and that for this value to be positive, the gradient must be from San Diego to Yuma. However, it does not follow that a gradient from San Diego to Yuma is a sufficient condition for a positive value of the above quantity.

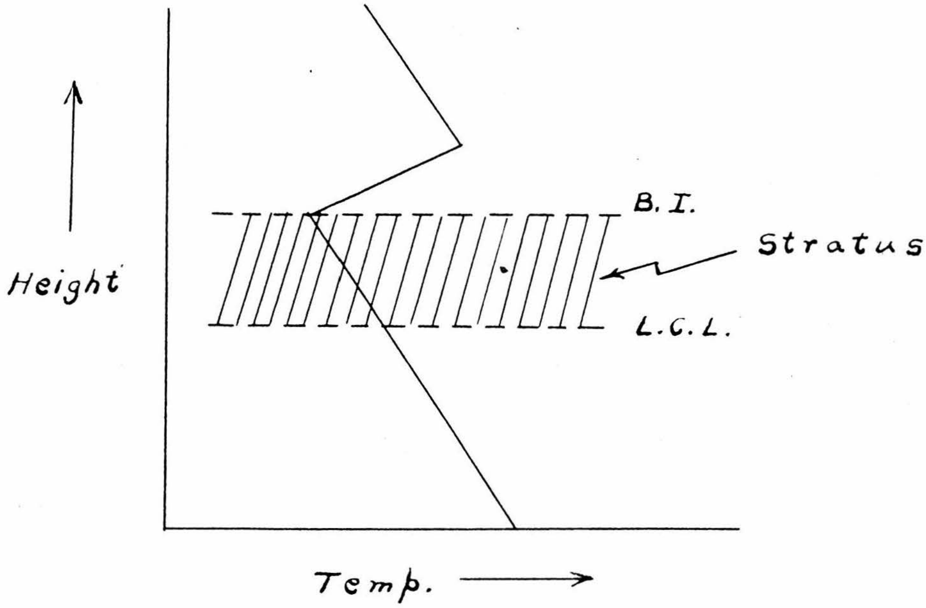
It has been an accepted fact for some time that these stratus conditions are connected with inversions. An inversion acts as a lid or resists convection taking place below it. The more intense the inversion, the more resistance it offers. Since convection is chiefly the result of heating during the day, neglecting the effect of frontal lifting etc., the following sketches show the process involved most simply.




The solid line is the original temperature-height curve. It is assumed that the curve below the B. I. is along the dry adiabat. Heating takes place during the day and convection occurs along ab. As the temperature increases, ab moves to the right, raising the inversion. If the inversion is sufficiently intense, the diurnal heating will not be sufficient to destroy it. At night we do not have this marked heating to raise the base of the inversion and the inversion acts as a lid holding the moisture laden air below it.

The Lifting Condensation Level can be used because at night the L. C. L. and Convective Condensation Level are practically the same and the stratus usually forms at night. During the day, the C. C. L. would have to be used.

It should again be pointed out that stratus over coastal regions, and coastal regions only, is a convective phenomenon while further inland the phenomenon is practically a radiation process.




If the cooling or other causes at night are sufficient to bring the condensation level below the B. I., stratus must result. The stratus first forms at the condensation level and is conveyed upward by convection where it is stopped at the base of the inversion. This process continues until the complete layer of stratus between B. I. and L. C. L. is formed.

PLATE #5 shows that a gradient from San Diego to Yuma is necessary for the value of B. I. - L. C. L. to be positive. A plausible explanation of this is that the onshore gradient is necessary to furnish the required transport of moisture from the ocean to lower the condensation level below the base of the inversion.

PLATE #7 was computed to show the relationship between the height of the L. C. L. and the relative humidity, and also to furnish a rapid and simple means of ascertaining the L. C. L. Obviously, this curve can also be used to obtain the lift necessary to saturate a particle of air used in shower and thunder shower forecasting. After plotting this curve, it was checked against numerous lift computations and was found to agree well within the required limits of accuracy.

In order to forecast whether or not stratus will occur, the problem is now to forecast the sign of (B. I. - L. C. L.) and the direction of the gradient.

It was found that in more than 80 per cent of the cases studied, the sign of (B. I. - L. C. L.) and the direction of the gradient could be forecast from the morning flight at San Diego combined with the surface pressures and tendencies at San Diego and Yuma in order to forecast whether or not stratus would occur within the following 24 hours. It is strongly believed that this per-centage could be greatly increased by the forecaster actually being present in order to observe the synoptic situation and follow the barometric tendency, etc. For example, if the synoptic situation will be such that high winds will occur during the forecast period, it is obvious that stratus cannot form.

A study of PLATE #8 shows that in spite of the extremely rapid variations in the height of the base of the inversion and the height of the lifting condensation level, the two curves tend to parallel each other after intersecting Thus a curve of the values of (B. I. - L. C. L.) would not show such radical changes as the two elements plotted separately.

PLATE #6 evidently shows some correlation between the time of breaking and the value of (B. I. - L. C. L.). In other words, the thicker the layer of stratus the later it will break. This is true simply because there is a greater water content to absorb terrestrial radiation.

However, it is not believed that any curve of (B. I. - L. C. L.) v. s. Time could be plotted that would be of any practical use in forecasting the exact time of breaking of the stratus. There are too many factors entering into the problem to permit any simple relationship giving the exact time of breaking or forming. This is in all probability due to the fact that the stratus condition on the west coast is a combination of radiation, convection and advection, rather than simply a radiation fog or an advection fog.

However, PLATE #6 does give some measure of the relative times of breaking. The greater the value of (B. I. - L. C. L.), the later the stratus will break. In order to dissipate the stratus, short wave radiation from the sun must travel through this layer of stratus, be transformed at the earth's surface into long wave radiation, which in turn is radiated by the earth as long wave radiation. It is this long wave terrestrial radiation from the earth which the water vapor absorbs and not the sun's short wave radiation. Hence, it is the energy from the earth that dissipates the stratus. Of the sun's incident radiation, about 75 per cent is reflected by the stratus layer so that after other smaller losses only about 10 to 15 per cent of the original sun's radiation is available after the transfer into long wave radiation for the dissipation of the stratus.

There is also another very important factor that must not be over-looked. That is, the intensity of the inversion. The lower layers of the stratus dissolve first and the top of the layer does not raise appreciably if there is a strong inversion. As soon as a hole through the layer occurs, the cloud deck breaks very rapidly in the case of a strong inversion. But, with a weak inversion, the cloud layer rises as convection is set up and the top of this cloud layer rises and may not break entirely throughout the entire day. If instability exists, the stratus layer may break and then form a cumulus cloud layer. In general, then, the stronger the inversion, the sooner it will break. The weaker the inversion, the later it will break.

In case no aerological flight data is available to determine the height of the base of the inversion, the table showing the variations in height of the base of the inversion with the diurnal amplitude of temperature might be used as an indication of the height of the base of the inversion.

## GROUND FOG

A few words might be said concerning the ground fog, as it does not appear to be different from ground fog occurring in other parts of the United States. The conditions necessary for its formation are: the base of the inversion at the ground, or at least an isothermal lapse rate extending to the surface combined with light winds and sufficient moisture content of the air near the surface so that radiational cooling at night will lower the air temperature to its dew point, and thus form a fog. A possible means of determining the time of forming is to plot curves of the air temperature and dew point. By careful extrapolating determine the time at which the two curves intersect. This point will be the approximate time of forming. Ground fogs break shortly after sunrise so that no problem of importance is involved in forecasting the time of breaking, except near the coast where fog on water may drift in and out along the shoreline.

There is one important exception to the above discussion, and that is the true advection fog that may and does occur occasionally. A dense fog bank lies off the caost and is carried in to the coast by the on shore movement of air. It is believed that this type can only be treated by a very careful consideration of the synoptic situation with due consideration to probable future changes in the synoptic situation. A cold front approaching the west coast is a favorable condition for inducing a prefrontal fog.

## CONCLUSIONS

The stratus conditions occurring on the West Coast can be forecast with at least a fair degree of accuracy. The procedure to forecast whether or not stratus will occur is suggested as follows:

1. At the time of the morning aerological flight determine the value of (Height of Base of Inversion - Height of Lifting Condensation Level). Use PLATE #7 to determine Height of Lifting Condensation Level.

2. From the value of the pressures and tendencies at San Diego and Yuma, determine the probable gradient twelve hours later.

3. If the value of (B. I. - L. C. L.) is positive and the gradient will be toward Yuma, stratus should be forecast for San Diego, unless some radical change in the synoptic situation is expected, such as a strong frontal passage or high winds.

4. If the gradient will be toward San Diego, stratus will not occur.

It is quite obvious that the synoptic situation cannot be disregarded in any fog or stratus forecast.

It is believed that the following general statements can logically be made:

1. The greater the positive value of (B. I. - L. C. L.), the later the stratus will break.

2. The greater the positive value of (B. I. - L. C. L.) and the higher the base of the inversion, the later the stratus will form.

3. The larger the diurnal amplitude of temperature, the lower is the base of the inversion.

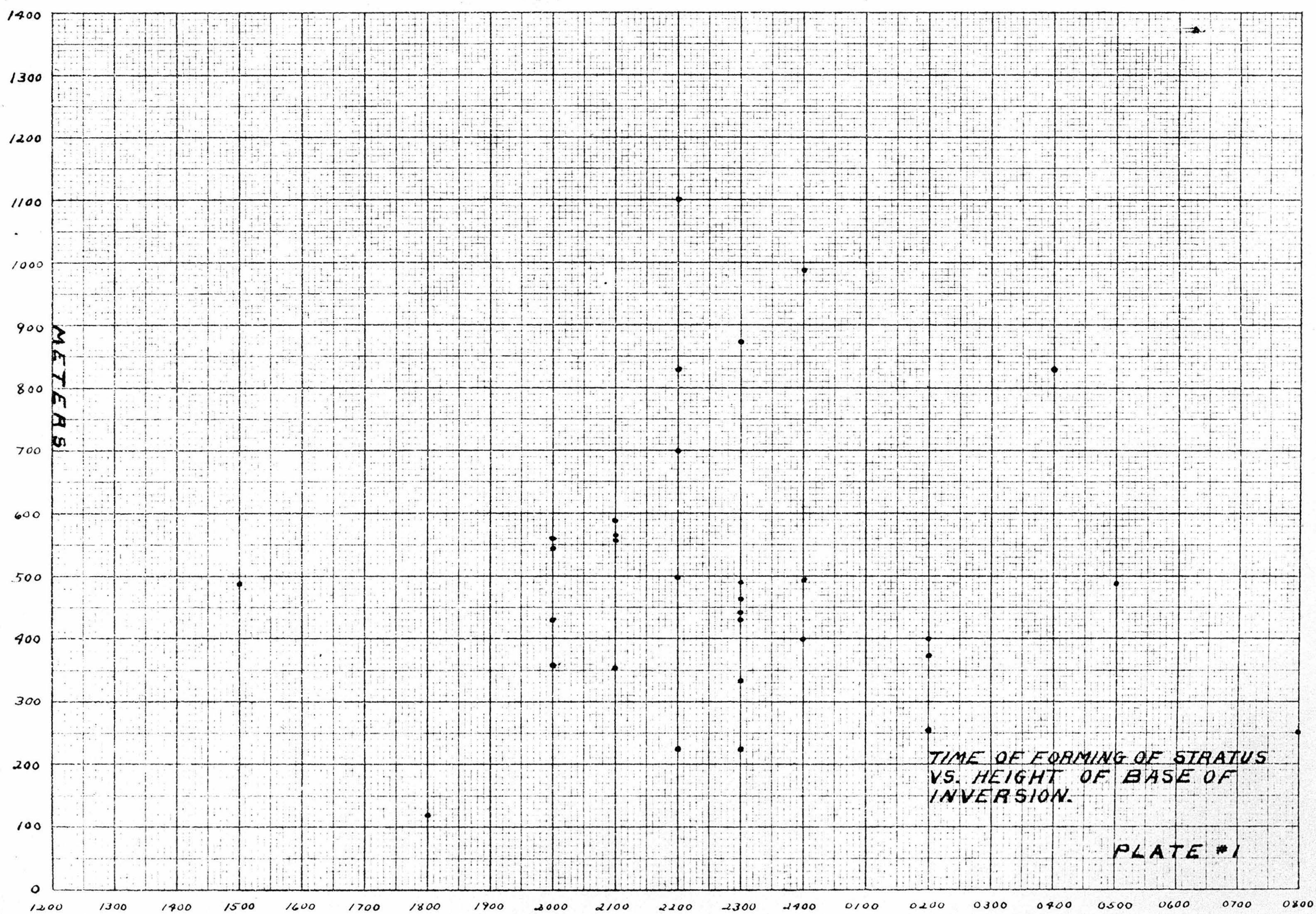
4. The more intense the inversion, the earlier the stratus will break.

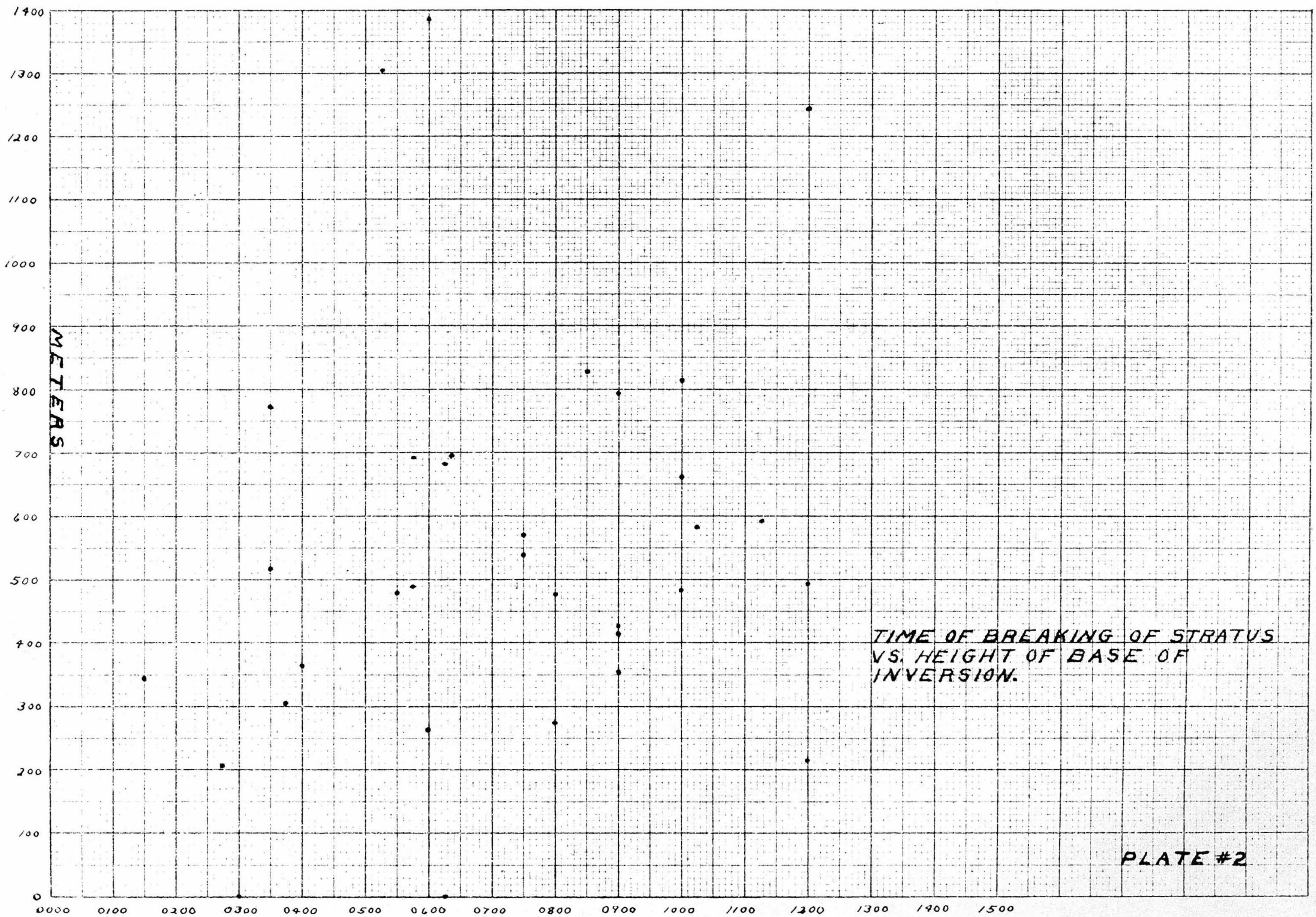
5. The weaker the inversion, the later the stratus will break.

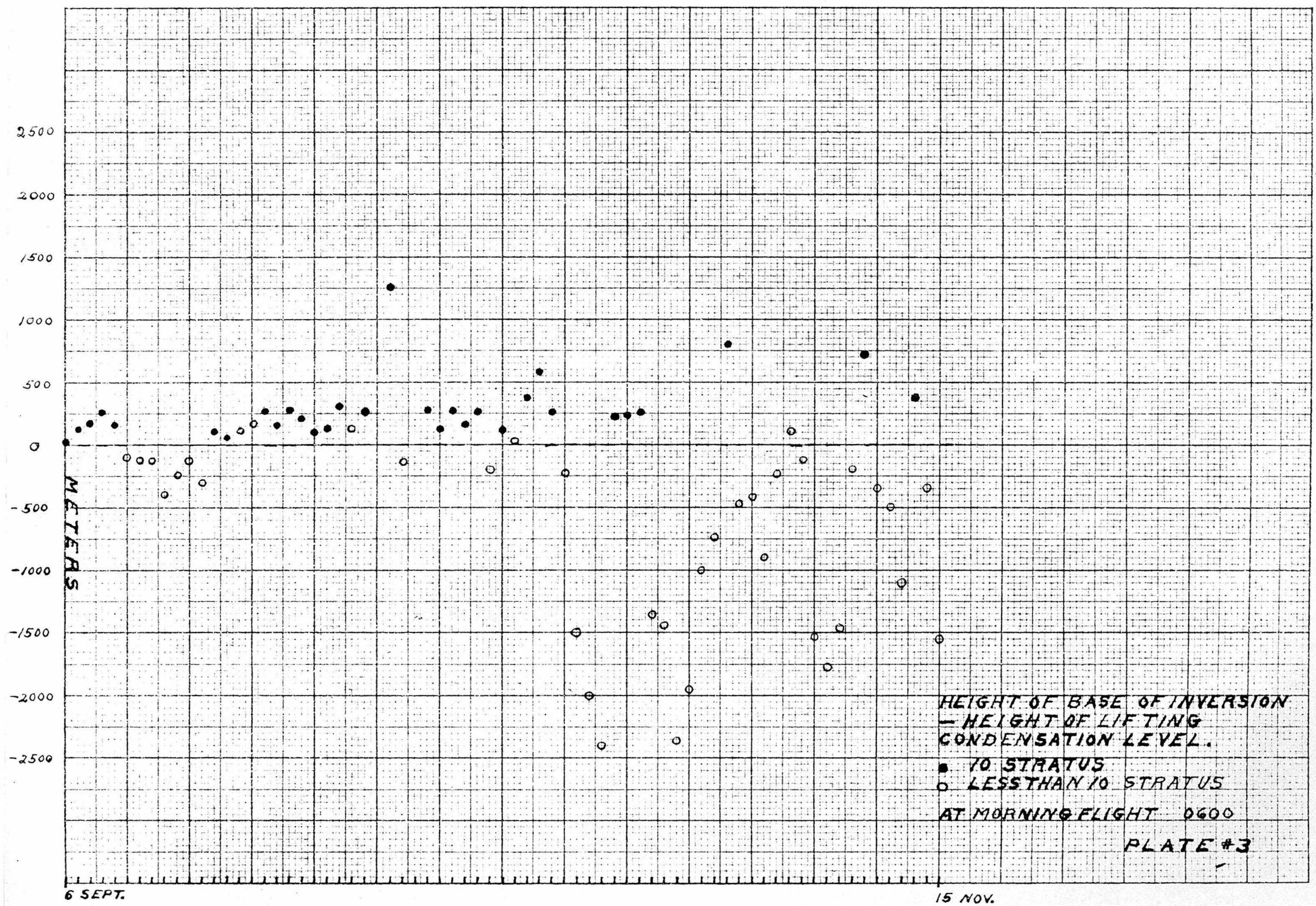
6. A layer of high clouds will retard the formation of stratus.

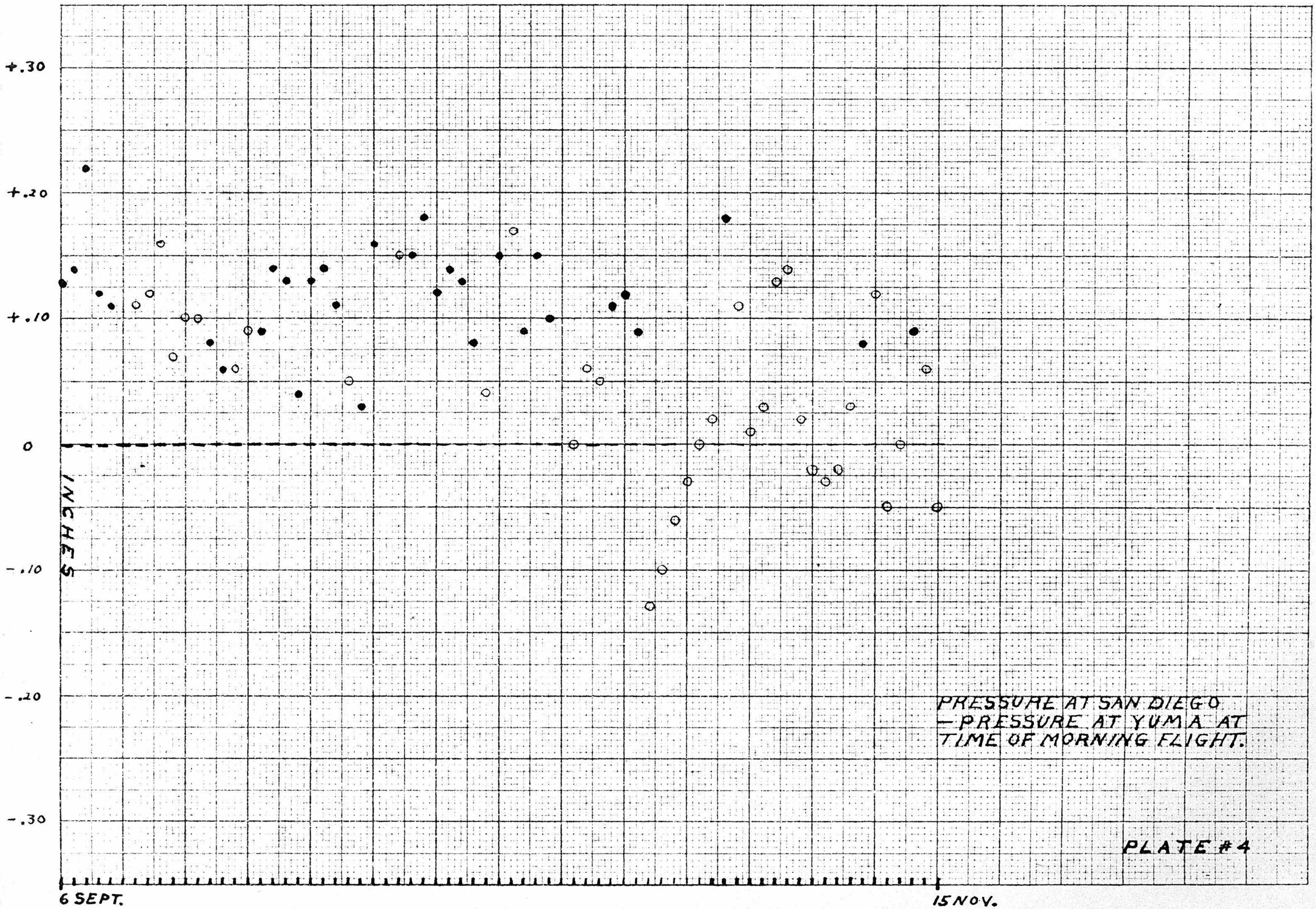
It is very seriously doubted if any simple fixed means of forecasting fog or stratus, such as a formula similar to the formula for the movement of pressure centers will ever be developed, because of the large number of factors involved. If some element or elements should be determined that are as representative for fog or stratus as pressure and tendencies are for the computation of pressure center movements, it might be possible to develop such a formula, but this appears to be rather improbable.

We are of the opinion that a continuation of the research method followed in this investigation, covering a much longer period of time, would reveal much greater correlation between some of the elements investigated.


TIME OF FORMING OF STRATUS
VS. HEIGHT OF BASE OF
INVERSION.
PLATE #1
METERS
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 0100 0200 0300 0400 0500 0600 0700 0800


TIME OF BREAKING OF STRATUS
VS. HEIGHT OF BASE OF
INVERSION.
PLATE #2
METERS
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0000
0100
0200
0300
0400
0500
0600
0700
0800
0900
1000
1100
1200
1300
1400
1500


2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
METERS
6 SEPT.
15 NOV.
HEIGHT OF BASE OF INVERSION
— HEIGHT OF LIFTING
CONDENSATION LEVEL.
● 10 STRATUS
○ LESSTHAN 10 STRATUS
AT MORNING FLIGHT 0600
PLATE #3


+.30
+.20
+.10
0
-.10
-.20
-.30
INCHES
6 SEPT.
15 NOV.
PRESSURE AT SAN DIEGO
—PRESSURE AT YUMA AT
TIME OF MORNING FLIGHT.
PLATE #4

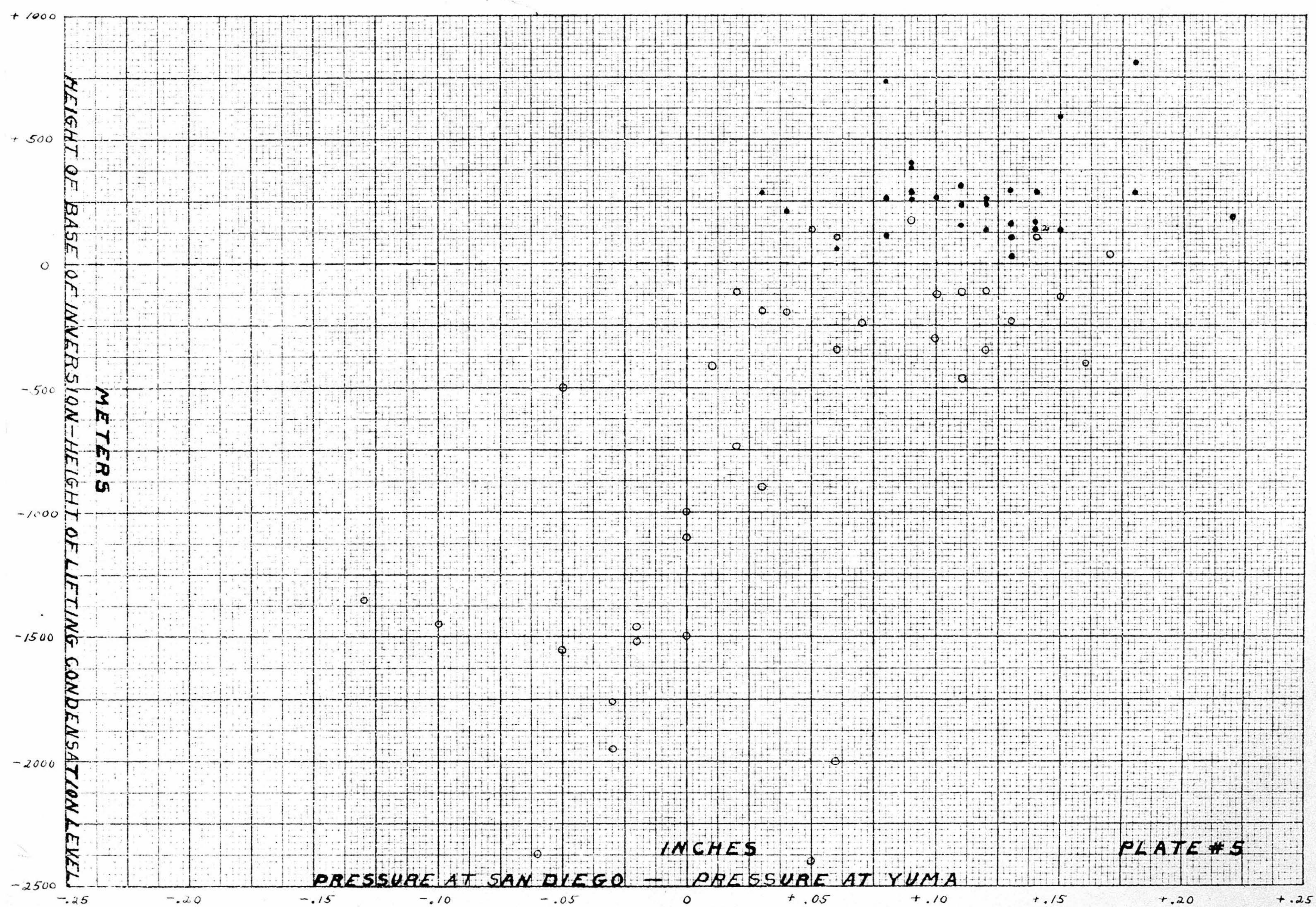
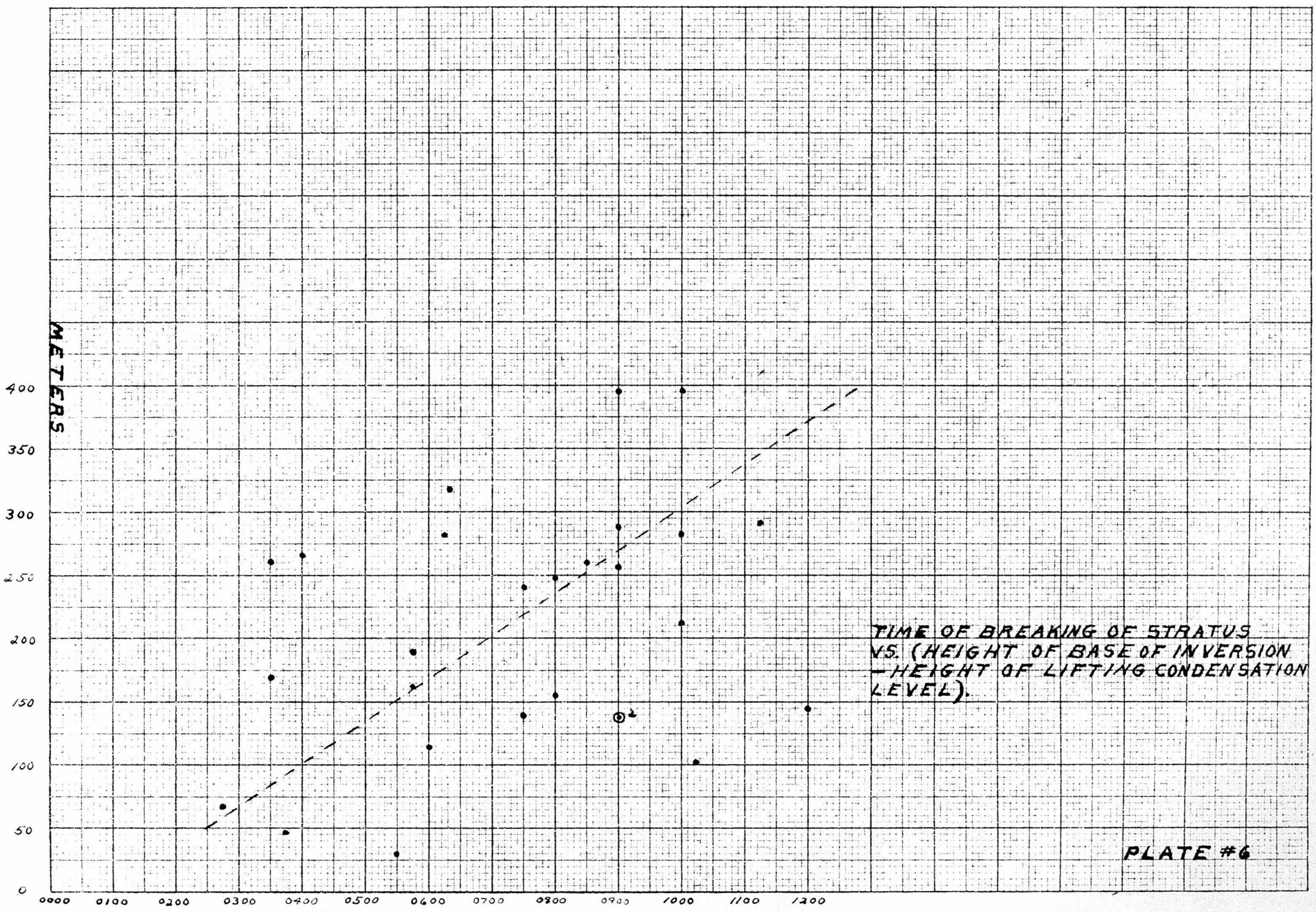
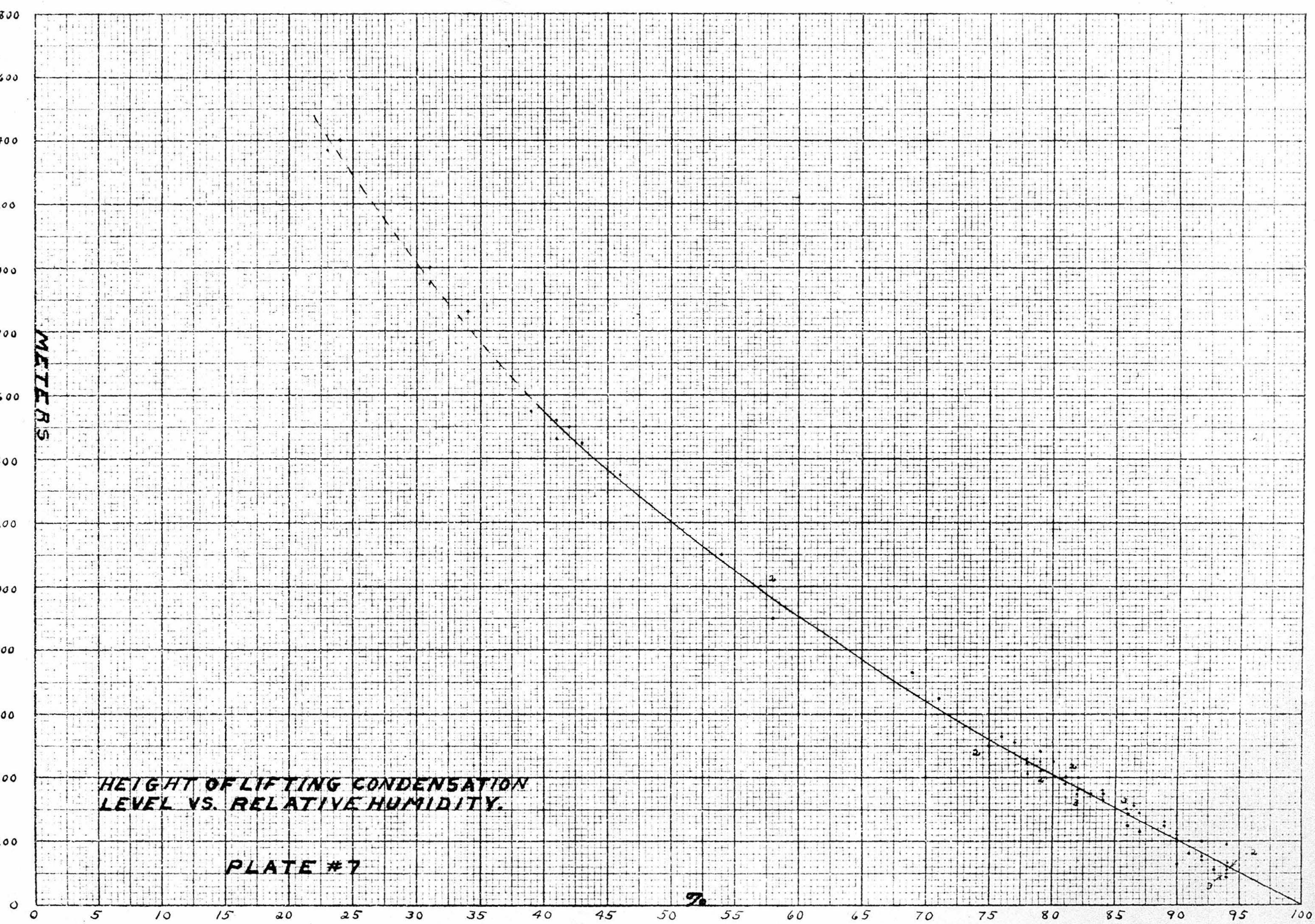
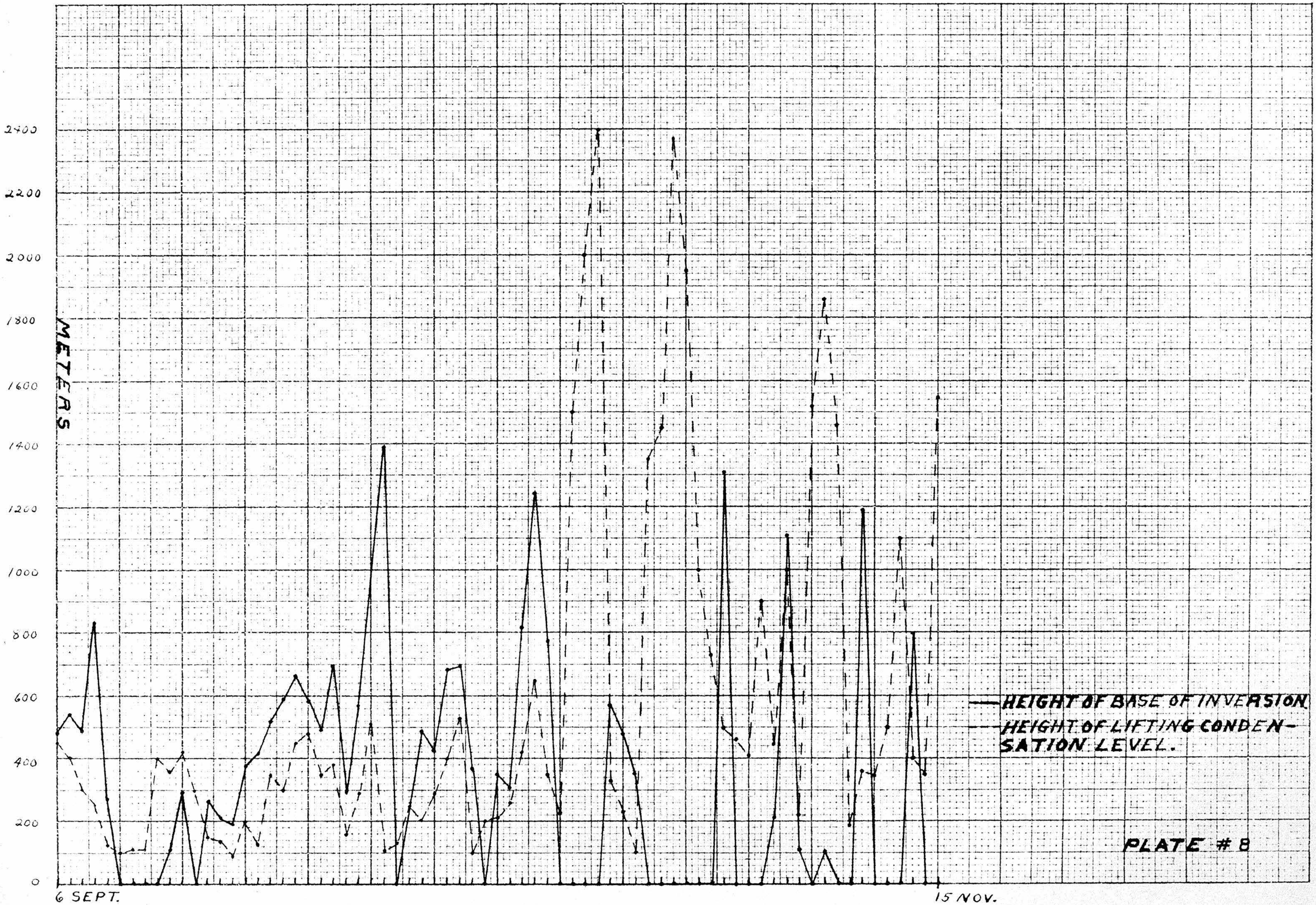


PLATE #5
METERS
HEIGHT OF BASE OF INVERSION—HEIGHT OF LIFTING CONDENSATION LEVEL
INCHES
PRESSURE AT SAN DIEGO — PRESSURE AT YUMA
+1000
+500
0
-500
-1000
-1500
-2000
-2500
-.25
-.20
-.15
-.10
-.05
0
+.05
+.10
+.15
+.20
+.25


METERS
400
350
300
250
200
150
100
50
0
0000
0100
0200
0300
0400
0500
0600
0700
0800
0900
1000
1100
1200
TIME OF BREAKING OF STRATUS
VS. (HEIGHT OF BASE OF INVERSION
-HEIGHT OF LIFTING CONDENSATION
LEVEL).
PLATE #6

KEUFFEL & ESSER CO., N.Y. NO. 359-11
20 × 20 to the inch.




METERS
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6 SEPT.
15 NOV.
—HEIGHT OF BASE OF INVERSION
--HEIGHT OF LIFTING CONDEN-
SATION LEVEL.
PLATE #8