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FLUID MECHANICS APPLIED TO THE STUDY OF ATMOSPHERIC CIRCULATIONS

(Research conducted in cooperation with U. S. Department of Agriculture under Bankhead-Jones Special Research Fund)

PART I

A STUDY OF FLOW PATTERNS WITH THE AID OF ISENTROPIC ANALYSIS

A. On the Maintenance of the Westerlies South of the Polar Front

BY

CARL-GUSTAF ROSSBY

B. Technique and Examples of Isentropic Analysis

BY

JEROME NAMIAS

C. Isentropic Analysis of a Case of Anticyclogenesis

BY

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CONTENTS

PREFACE AND ACKNOWLEDGMENTS

This paper constitutes Part I of a report on certain investigations which have been in progress at the Massachusetts Institute of Technology during the past few years and which have been supported in part with funds provided by the Weather Bureau of the U. S. Department of Agriculture under the Bankhead-Jones Special Research Fund. The ultimate purpose of these investigations is to develop a sound physical model of the general circulation of the atmosphere, in the hope that an improved understanding of this process eventually may furnish valuable clues as to how the time range of our present daily weather forecasts may be extended and their quality be improved.

In the past, the interpretation of the large-scale circulations of the atmosphere with the aid of the tools of classical hydrodynamics has suffered from the fact that these tools were designed for the study of thermodynamically inactive fluids, in which, furthermore, viscous or eddy stresses could be neglected. Through the work of V. Bjerknes and his students a good start has now been made towards the development of a science of hydrodynamics applicable also to thermodynamically active fluids, in which density changes are taking place as a result of non-adiabatic temperature changes. The removal of the second restriction—i.e., the development of hydrodynamic tools adapted to the study of fluids in which eddy stresses play a dominant role—has been accomplished mainly through the investigations of the Göttingen school of fluid mechanics.

As yet, no synthesis of these two modern developments has been accomplished, although it is becoming increasingly clear that such a synthesis is needed before any headway can be made with the interpretation of the behaviour of the atmosphere. There has been a tendency on the part of meteorologists to assume that the effects of eddy stresses are restricted to a layer near the ground, and that the atmosphere above this layer behaves approximately as an ideal fluid. Even fairly elementary considerations show that a real understanding of atmospheric circulations becomes absolutely impossible on the basis of this assumption.

A modest first attempt towards such a synthesis of the Norwegian and German developments will be attempted in these reports. It will be shown that the movements in the free atmosphere above the ground friction layer are affected by large-scale lateral mixing processes which produce shearing stresses acting across vertical planes, and one or two examples will be given to demonstrate that reasonable steady state solutions for the atmosphere can be obtained by taking this internal stress distribution into account.

It will be shown, moreover, that the distribution of cold sources and heat sources in the free atmosphere is at least in part controlled by the stress distribution, which regulates the location of ascending and descending movements.

The investigations here reported have been directed by the undersigned, and conducted as a collaborative undertaking by a number of persons. In addition to the authors appearing on the title page of this part of the report, Dr. C. L. Pekeris of the Massachusetts Institute of Technology, Messrs. H. Wexler, G. Grimminger and V. Starr of the Weather Bureau, Prof. A. F. Spilhaus of New York University, and Dr. Hans Ertel of the University of Berlin have made valuable contributions, mainly of a theoretical nature. Related investigations, also under the Bankhead-Jones Special Research Fund, have been in progress in the Meteorological Research Division of the Weather Bureau at Washington,

and will be reported in later publications elsewhere; the contributions of those mentioned above will be coordinated and presented in the form of a theoretical discussion of atmospheric circulations, to be published as Part II of the report.

To a very large extent the results presented below are based on studies of the upper air data analyzed as a matter of daily routine in the Meteorological Division of the Massachusetts Institute of Technology. Dr. H. C. Willett, Professor J. Holmboe and Mr. G. Lukes have carried a large portion of this work and made valuable contributions in the many discussions preceding the preparation of our report.

All of us wish to take this opportunity to publicly acknowledge our appreciation of the wholehearted support this investigation has received from the late Chief of the U. S. Weather Bureau, Dr. Willis R. Gregg, in whom our division had a sincere friend and supporter.

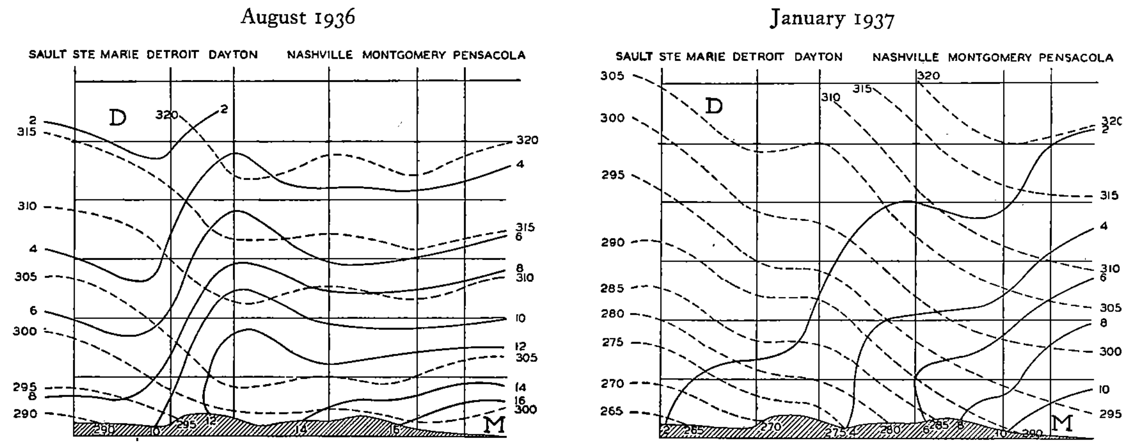
Dr. C. F. Sarle, principal economist of the Bureau of Agricultural Economics, took the initiative toward a coordination of governmental and university facilities for the purpose of getting under way a broad research program in basic meterological problems. We are greatly appreciative of his initiative, broad vision and unfailing support.

C.-G. Rossby

INTRODUCTION

In summer the principal extra-tropical front in North America is normally found somewhere in the vicinity of the Great Lakes. During this season, and apart from occasional inundations with rapidly warming polar air, the United States is covered with a blanket of tropical air and its weather is consequently to a large extent controlled by processes occurring within this air mass.

The prevailing movement in the tropical air consists in a slow drift eastward. A study of various aerological mean cross sections through the United States for the summer months reveals that during this season the temperature in the lower half of the troposphere is fairly constant throughout the greater portion of the country. Thus there are no solenoids available to generate kinetic energy, and it follows that the movements observed must derive their energy from other regions and then most likely from the north, where there is a marked concentration of solenoids around the polar front. (Figs. 1a and b.)



FIGS. 1A AND 1B.—Vertical cross sections Sault Ste. Marie-Pensacola, showing the distribution of potential temperature (broken lines) and specific humidity (full lines). Note the practically horizontal isentropic lines in the August section south of Dayton, indicating absence of solenoids in this region. The fairly uniform slope of the isentropic lines in the January section suggests a uniform distribution of solenoids over the major portion of the country.

The absence of solenoids over the greater portion of the country further suggests that this is a region where the kinetic energy of the atmosphere is undergoing incessant decay and dissipation. Such a decay must be associated with a breaking up of the individual current systems into eddies of varying diameters. The summer time movements within the tropical air over the United States are no exception to this rule. By means of a technique to be described further down in this report, it will be shown that the flow patterns in the lower half of the troposphere are characterized by the frequent formation of vortices, mostly anticyclonic, which tend to remain stagnant or drift very slowly eastward across the continent.

These slow-moving vortices are capable of bringing about frequent and thorough redistributions of the moisture in the troposphere and may thus have a profound influence on the occurrence and the distribution of summer time precipitation in the United States. For this reason and because of the light they shed on the dynamics of the westerlies south of the polar front, they have been subjected to a detailed synoptic study, the principal results of which are set forth in the first part of our report.

As a framework for the study of these vortex patterns, a brief theoretical discussion of the dynamics of the westerlies south of the polar front precedes the synoptic analysis. It is suggested that the west winds in the tropical air south of the polar front most readily can be explained as the result of lateral frictional drag from the strong west winds observed above the polar front and maintained there by direct solenoidal circulation. It is also suggested that the formation of large anticyclonic vortices is the result of the dynamic instability associated with the strong lateral shear within the westerlies. This dynamic instability has been discussed by Pekeris (1938).

The flow patterns discussed below were established with the aid of a new technique which, for the sake of brevity, has been named "isentropic analysis." In view of the newness and fruitfulness of this technique a brief summary of its development and basic principles is included in this introduction (see also Rossby and coll. 1937 a,b; Rossby 1938 c; Namias 1938 a and b.)[1]

Isentropic analysis may be defined as a method for determining free air trajectories which makes essential use of the fact that the currents in the free atmosphere, within certain fairly well-defined restrictions and over not too long periods of time, are constrained to move within and with their proper isentropic surfaces rather than in horizontal planes. This fundamental fact suggests that synoptic charts for the free atmosphere be drawn for surfaces of constant entropy rather than for constant geopotential, since charts of the first-mentioned type would enable one to follow approximately the same sheet of air from one day to the next.

The suggestion that free air weather maps be drawn for isentropic surfaces was first made by Sir Napier Shaw several years ago (Shaw 1933). Using mean summer values from various aerological stations in the Northern Hemisphere, he constructed a chart giving the distribution of isotherms on a prescribed isentropic surface. Shaw pointed out that on such a surface, isotherms, isobars and lines of constant density coincide. Using surface observations of pressure and temperature and adopting a uniform increase of entropy with elevation he also constructed a synoptic isentropic chart for the British Isles.

Shaw's suggestion never received the attention it deserved. In part this may have been due to the poor development of the aerological networks in Europe and America at that time, but it is probable that other factors contributed to retard the introduction of isentropic charts. The polar front theory had then just been accepted and there was still a general tendency to believe that the structure of the free atmosphere could be fairly well extrapolated from the observed distribution of fronts and air masses at the ground. Thus the few upper air soundings available were considered mainly as means for verifying the interpretations of the surface maps.

During the last few years the aerological network of the United States has reached a state of development which far surpasses that of any other part of the world. Daily analysis of the rich aerological material thus made available has brought out the fact that the relation between surface fronts and upper air structure is far more complex than might have been anticipated on the basis of the polar front theory. There is indeed, on many sides, an impression that the development, movement and destruction of fronts often merely reflect large-scale developments in the middle portion of the troposphere. If this point of view is correct, a method must be found to utilize the daily upper air data in such a fashion that they tell something new and essential about the free air flow patterns, not merely verify the results of our surface analyses; but, in the absence of any acceptable working hypothesis for the movements in mid-troposphere, no clue has been available as to how this additional information could be extracted from the upper air data.

Some time ago Richardson and Proctor (1925) directed the attention of meteorologists to the existence of large-scale lateral mixing processes in the free atmosphere. From a study of the lateral diffusion of volcanic dust and from the scattering of toy balloons they arrived at kinematic coefficients for the lateral diffusion varying from $2 \cdot 10^6$ to

[1] References are listed alphabetically at the end of this volume.

$1.3 \cdot 10^9$ cm² per sec. These values refer to diffusion over distances ranging from 3 to 86 km. It is reasonable to assume that the turbulent mechanism responsible for this scattering must produce an equally intensive lateral diffusion of momentum. If the above coefficients are converted into eddy viscosity, the resulting coefficients will fall between $2.5 \cdot 10^3$ and $1.6 \cdot 10^6$ grams per cm per sec.

As a result of the strong gravitational stability of the atmosphere, the eddy movements responsible for lateral diffusion must take place along isentropic surfaces rather than in strictly horizontal planes. The shearing stresses that develop from this eddy motion would naturally tend to scatter the momentum of any limited current sideways. It thus appears that one should find in the free atmosphere, when properly represented, a counterpart to the jet stream or "Freistrahl", which has been investigated both theoretically and experimentally in the Göttingen laboratories, particularly by Tollmien (1926).

In order to study the effects of this lateral mixing, we decided to investigate the air movements in individual isentropic surfaces, as suggested by Shaw, but with the important modification that we now had a dynamic model before us, namely the jet stream. To determine the intensity of the mixing in the isentropic surfaces and thus the intensity of the lateral shearing stresses, the observed distribution of water vapor content in the isentropic surface was followed from day to day. With the aid of this identifying element it was possible to establish trajectories on the isentropic surface and to make an estimate of the degree of mixing. Preliminary calculations by Grimminger (1938) have given values for the eddy diffusion coefficient between $4 \cdot 10^5$ and $5 \cdot 10^7$ grams per cm per sec. These values fall below the value of about 10^8 obtained by Defant (1921) for the atmosphere as a whole, considering the general circulation between high and low latitudes as a turbulent process. The difference is to be expected, since in Defant's scheme whole cyclones and anticyclones serve as turbulent elements, whereas we are concerned with the large-scale mixing between one individual current and its environment. On the other hand, the values found by Grimminger exceed those obtained by Richardson and Proctor, which likewise is to be expected, since Grimminger's values refer to diffusion over much larger distances than those considered by Richardson and Proctor.

After a few attempts during the winter of 1936–1937 (Osmun 1937), isentropic charts have been constructed daily since May 1937 and very little difficulty has been experienced in the attempt to maintain continuity from day to day. From a dynamic point of view, the most significant result of this work has been the discovery of the fact that, at least during the warmer season, the current systems observed on our charts show a marked tendency to break up in anticyclonic vortices of diameters varying between perhaps a few hundred and fifteen hundred miles (Rossby and coll. 1937 a and b, Wexler and Namias 1938). It is important to keep in mind that the isentropic surfaces analyzed by us normally are characterized by fairly strong westerly winds to the north. It is our belief that these anticyclonic eddies represent a mechanism for the dissipation of the kinetic energy of the west winds. A detailed discussion of this problem will be given later in the theoretical report.

The anticyclonic eddies normally occur in air masses which, on the basis of the surface map analyses, must be classified as fairly homogeneous tropical air. The discovery of these eddies, a discovery which could not easily have been made without the aid of isentropic analysis, furnishes ample evidence that the number of principal tropospheric models is not limited to air masses and fronts, as sometimes stated (Bergeron 1937).

It has been found that these eddies normally consist of one dry and one moist tongue which converge and wind up anticyclonically around each other, the converging air being removed by sinking near the center, as shown by the persistent dryness of the innermost portion of the eddy.

The existence of a summer time high level anticyclone at fixed levels in the free atmosphere over the interior of the United States was established in a valuable paper by Reed already in 1933 (Reed 1933). However, Reed's technique, which was based on the use of wind readings at fixed levels, could not disclose the complex structure of these anticyclones and did not bring out the fact that these vortices move and that several may exist simultaneously over the continent and adjacent oceans. For these and other reasons, the thermal explanation offered by Reed has been discarded in favor of a dynamic theory, which interprets these vortices as frictionally driven by the stronger westerly winds to the north.

If the two principles of isentropic motion and of intense, isentropic mixing are accepted, we must necessarily revise our conception of fronts and air mass boundaries. No reasonably permanent air mass boundary or front can intersect an isentropic surface in which intense mixing occurs. Daily vertical cross sections through the atmosphere are now drawn for potential temperature and specific humidity. The analysis of these cross sections has shown that a consistent acceptance of the above logical conclusion permits a better understanding of the distribution of water vapor in these sections, whereas cross sections of the older type, in which fronts were drawn on the basis of horizontal and vertical variations in actual temperature, sometimes have led to irreconcilable conflicts between consecutive sections.

In consequence of the arguments set forth above no fronts are entered on the isentropic charts presented below. This does not mean that sharp wind shift lines do not occur. It will be shown in the theoretical report that the mixing process itself, in conjunction with the deflecting force of the earth's rotation, must lead to the development of counter currents on both sides of a spreading current, but the wind shift lines thus created move relative to the air and cannot be classified as true air mass boundaries.

The kinetic energy of the atmosphere must be generated through solenoidal circulation and thus requires the existence of currents crossing the isentropic surfaces. In many cases the regions of such non-adiabatic sinking and rising are easily established from a study of the water vapor distribution and its interdiurnal change in a prescribed isentropic surface. It appears that regions of strong non-adiabatic ascent (warming) are concentrated to fairly narrowly confined regions in any one prescribed isentropic surface well above the ground friction layer. The cooling is probably slow and fairly widespread. If consecutive isentropic surfaces are charted for 5° intervals of potential temperature it is unlikely that radiational cooling in one day could displace an individual air particle from its original surface to the one next below. It will be shown that the location of these regions of non-adiabatic vertical motion to a large extent is controlled by the lateral frictional stresses, which cause departures from gradient flow and thus horizontal convergence and divergence. However, at present we are concerned primarily with the essentially isentropic movements associated with the development and eventual breakdown of the strong current systems observed in the free atmospheric, and for this purpose the assumption of isentropic motion is adequate.

The daily work with isentropic charts has led to the establishment of a practically important correlation between convective rainfall and the advance of moist and dry tongues in isentropic surfaces well removed from the ground. This application will be discussed below by Mr. Namias and a preliminary report on this subject has already been published (Namias 1938a).

The drifting anticyclonic eddies appear to have a definite cycle of growth and decay. The amalgamation of such a high level anticyclone with a migratory low level cold anticyclone appears to be responsible for the anticyclogenesis not infrequently observed in the eastern part of the country after inundations with rapidly subsiding polar air. A detailed discussion of this problem is presented by Dr. Simmers in the last section of this part of the report.

C.-G. Rossby

A. ON THE MAINTENANCE OF THE WESTERLIES SOUTH OF THE POLAR FRONT

BY C.-G. ROSSBY

The maintenance of the broad belt of westerly winds between the polar front and the subtropical high pressure area has never been adequately explained. There is a steady loss of momentum within this westerly current due to ground friction, and this loss must be offset through an influx of momentum from the environment. In an attempt to determine the source of this supply Jeffreys (1926) computed the gain of momentum through the northward flow within the frictional layer next to the ground. He found that on the average the momentum thus supplied to each vertical column represents a very small fraction of the loss within the same column due to the action of ground friction, and concluded that a steady west wind belt symmetrically distributed around the northern hemisphere cannot be maintained but that the west winds are reestablished from time to time through west-east pressure gradients.

In the present paper an attempt will be made to show that the required momentum most likely is supplied through lateral diffusion from the strong belt of westerlies normally found farther to the north and above the principal polar front. The maintenance of these winds above the polar front is taken care of by a transversal circulation in the same direction as the circulation acceleration caused by the solenoid distribution in the polar front itself. This maintenance has been analyzed in a preliminary study published elsewhere (Rossby 1938 b and c) and will be discussed in detail in Part II of this report. For the present it is sufficient to assume that at the latitude where the polar front reaches the ground a strong westerly wind of vertically constant velocity u_0 prevails throughout the entire atmosphere. Through lateral friction this strong west wind drags along a belt of air further to the south.

In the following analysis the y-axis points south with its origin at the point where the polar front intersects the ground. The x-axis points eastward. On the assumption that the convective acceleration term may be neglected, the equation of motion for the x-axis then takes the form

$$(1) \qquad 0 = -\rho f v + \frac{\partial}{\partial y}\left(\rho \nu \frac{\partial u}{\partial y}\right),$$

v being the southward component of motion, ρ the density, f the Coriolis' parameter and ν the kinematic eddy viscosity due to lateral mixing. It will be assumed that the west wind velocity u and the kinematic viscosity ν both are independent of elevation. Under these conditions the mass distribution is barotropic and the horizontal density variations are so small that equation (1) may be simplified and written

$$(2) \qquad 0 = -f v + \frac{\partial}{\partial y}\left(\nu \frac{\partial u}{\partial y}\right).$$

It will now be assumed that the kinematic viscosity ν is given by the expression

$$(3) \qquad \nu = -l^2 \frac{\partial u}{\partial y},$$

l being the mixing length of the lateral turbulence, assumed to be independent of y. The minus sign is needed since u decreases with increasing y. Thus

$$fv = -l^2 \frac{\partial}{\partial y}\left[\left(\frac{\partial u}{\partial y}\right)^2\right]. \tag{4}$$

This equation applies above the layer of ground friction influence. Within the latter layer there is a flow northward, the total mass transport northward per centimeter of latitude being given by the equation

$$M_{-y} = \frac{\tau_x}{f}, \tag{5}$$

τ_x representing the x-component of the total stress (τ_0) exerted by the wind per unit horizontal area at the ground. This frictional transport of air across the isobars takes place within a layer of depth K next to the ground.

The transversal motion caused by the lateral shearing stress gives rise to a mass transport southward which may be computed from (4) and has the value

$$M_y' = \int_0^\infty \rho v dz = -\frac{p_0}{fg} l^2 \frac{\partial}{\partial y}\left[\left(\frac{\partial u}{\partial y}\right)^2\right].^* \tag{6}$$

The net flow across any latitude circle must vanish. Thus

$$M_{-y} = M_y' \tag{7}$$

and consequently

$$\tau_x = -\frac{p_0}{g} l^2 \frac{\partial}{\partial y}\left[\left(\frac{\partial u}{\partial y}\right)^2\right]. \tag{8}$$

The ground stress τ_0 depends upon the wind velocity (w_a) at anemometer level (30 m above the ground) and upon the air density next to the ground, ρ_0. Thus

$$\tau_0 = \rho_0 \kappa_1^2 w_a^2, \tag{9}$$

the non-dimensional constant κ_1^2 having a value of about $25 \cdot 10^{-4}$. (Taylor 1916) From this equation one obtains

$$\tau_0 = \rho_0 \kappa_1^2 \left(\frac{w_a}{u}\right)^2 u^2 \tag{10}$$

and finally, since the stress τ_0 has the same direction as the wind at anemometer level,

$$\tau_x = \tau_0 \cos \phi_0 = \rho_0 \kappa_1^2 \left(\frac{w_a}{u}\right)^2 \cos \phi_0 \cdot u^2. \tag{11}$$

The ratio of anemometer wind speed to gradient wind speed has a value of about 0.6 (Taylor 1916) The angle ϕ_0 between surface wind direction and gradient wind direction

* The integration is extended all the way to the ground, it being assumed that lateral stresses are at work also in the ground-friction layer.

varies between a minimum of perhaps 10° at sea to a maximum of about 30° on land. For rough estimates it is sufficient to write

(12) $$\tau_x = \rho_0 \kappa^2 u^2, \qquad \kappa^2 = 9 \cdot 10^{-4}.$$

Substitution in (8) gives

(13) $$\rho_0 \kappa^2 u^2 + \frac{p_0}{g} l^2 \frac{\partial}{\partial y}\left[\left(\frac{\partial u}{\partial y}\right)^2\right] = 0$$

or

(14) $$\frac{\kappa^2}{H_0 l^2} u^2 + \frac{\partial}{\partial y}\left[\left(\frac{\partial u}{\partial y}\right)^2\right] = 0.$$

H_0 being the height of the homogeneous atmosphere and defined by the equation

(15) $$H_0 = \frac{p_0}{\rho_0 g} = \frac{RT_0}{mg} \cdot \left(\frac{R}{m} = \text{gas constant}\right)$$

In the last equation T_0 represents the air temperature at the ground.

We seek a solution of (14) which vanishes for $y = \infty$ and has the value $u = u_0$ for $y = 0$. It is easily seen that

(16) $$u = u_0 e^{-y/L},$$

the length L being given by

(17) $$L = \sqrt[3]{\frac{2H_0 l^2}{\kappa^2}}\,.$$

The distribution of u/u_0 as a function of y/L is given by the full line in Fig. ~~1~~ 2.

The southward component above the ground friction layer is obtained by substituting (16) in (4). The result is

(18) $$v = \frac{2l^2}{fL^3} u^2 = \frac{2l^2 u_0^2}{fL^3} e^{-2y/L} \equiv v_0 e^{-2y/L}$$

and, with the aid of (17),

(19) $$\frac{v}{u_0} = \frac{u_0 \kappa^2}{H_0 f} e^{-2y/L}.$$

The distribution of v/u_0 is given by the broken line in Fig. 2.

The southward flow indicated by (19) is characterized by horizontal convergence, while the northward flow in the ground friction layer is divergent. Thus a vertical flow is established, the intensity of which may be computed with the aid of the continuity requirement. One finds

(20) $$\frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0$$

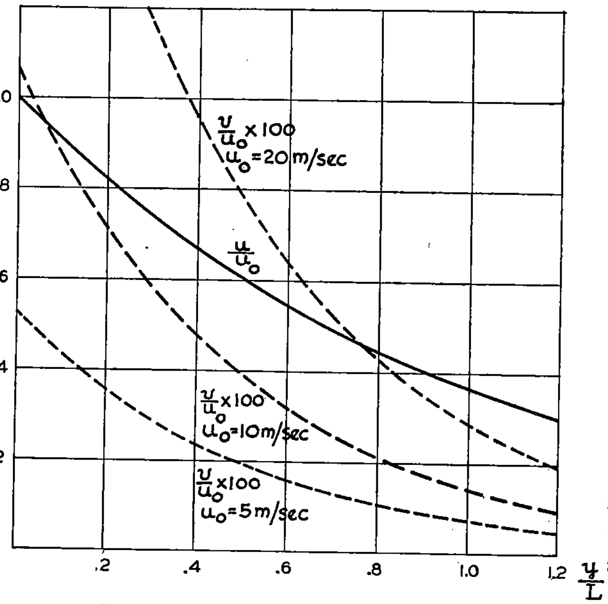


FIG. 2.—Distribution of axial and horizontal transversal velocities within the westerlies.

or, after integration,

$$\rho w = \frac{\partial}{\partial y} \int_z^\infty \rho v dz. \tag{21}$$

and finally, since v is independent of z,

$$\rho w = \frac{\partial}{\partial y} \left[\frac{p v}{g} \right]. \tag{22}$$

The pressure varies only slightly in a horizontal direction and thus

$$w = \frac{p}{\rho g} \frac{\partial v}{\partial y} = \frac{RT}{mg} \frac{\partial v}{\partial y}. \tag{23}$$

It is possible to introduce a stream function ψ for the transversal circulation. The equation of continuity is satisfied if

$$\psi = \int_z^\infty \rho v dz = \frac{p v}{g} \tag{24}$$

and

$$\rho w = \frac{\partial \psi}{\partial y}, \qquad \rho v = - \frac{\partial \psi}{\partial z}. \tag{25}$$

This transversal circulation cannot be maintained without an appropriate distribution of cold sources. Their intensity per unit mass and time, dq/dt, is easily calculated. One has

$$\rho \frac{dq}{dt} = \rho c_p \frac{T}{\theta} \frac{d\theta}{dt} = c_p \frac{T}{\theta} \left(\rho v \frac{\partial \theta}{\partial y} + \rho w \frac{\partial \theta}{\partial z} \right). \tag{26}$$

in which expression θ is the potential temperature and c_p the specific heat.

This equation may be written

$$\rho \frac{dq}{dt} = c_p \frac{T}{\theta} \frac{\partial \theta}{\partial z} [\rho w - \rho v \tan \alpha] \qquad \left(\tan \alpha = - \frac{\frac{\partial \theta}{\partial y}}{\frac{\partial \theta}{\partial z}} \right) \tag{27}$$

$$= c_p \frac{T}{\theta} \frac{\partial \theta}{\partial z} \left[\frac{\partial \psi}{\partial y} + \frac{\partial \psi}{\partial z} \tan \alpha \right]$$

$$= c_p \frac{T}{\theta} \frac{\partial \theta}{\partial z} \cdot \frac{\partial \psi}{\partial y} \left[1 - \frac{\tan \alpha}{\tan \beta} \right].$$

In this expression α represents the angle between the isentropic lines and the horizontal, positive when the isentropic lines ascend towards the south, and β the angle between the transversal stream lines and the horizontal. Under the assumed condition of constant gradient wind with elevation α is very small compared with β and (27) reduces to

$$\rho \frac{dq}{dt} = c_p \frac{T}{\theta} \frac{\partial \theta}{\partial z} \frac{\partial \psi}{\partial y} \tag{28}$$

or

$$\frac{dq}{dt} = c_p \frac{T}{\theta} \frac{\partial \theta}{\partial z} w = c_p(\gamma_0 - \gamma)w, \tag{29}$$

γ_0 and γ being the adiabatic and actual temperature lapse-rates.

For purposes of numerical evaluation of the last equation, it is sufficient to evaluate (23), which gives

$$w = \frac{RT}{mg} \frac{\partial v}{\partial y} = -2 \frac{RT}{mg} \frac{v}{L} \tag{30}$$

and consequently

$$\frac{dq}{dt} = -2c_p \frac{RT}{mg} \frac{\gamma_0 - \gamma}{L} \cdot v \,. \tag{31}$$

It is interesting to note that

$$\frac{\left|\dfrac{\partial u}{\partial y}\right|}{\left|\dfrac{\partial^2 u}{\partial y^2}\right|} = L \tag{32}$$

and thus, if one accepts the similarity hypothesis (von Kármán 1930) the mixing length l would be constant as assumed above. On the other hand, von Kármán defines the mixing length l with the aid of the equation

$$l = k_0 \frac{\left|\dfrac{\partial u}{\partial y}\right|}{\left|\dfrac{\partial^2 u}{\partial y^2}\right|} = k_0 L, \qquad k_0 = 0.38 \tag{33}$$

which in this case would lead to very large mixing lengths. Through a combination of (17) and (33) one finds, for $H = 8$ km,

$$l = \frac{2k_0^3 H_0}{\kappa^2} = 975.5 \text{ km} \tag{34}$$

$$L = \frac{2k_0^2 H_0}{\kappa^2} = 2567 \text{ km} \tag{35}$$

and for the eddy viscosity

$$\begin{aligned} \eta &= \rho k_0^2 L^2 \left|\frac{\partial u}{\partial y}\right| = \rho k_0^2 L u \\ &= \rho k_0 l u = \frac{2\rho k_0^4 H_0 u}{\kappa^2} \end{aligned} \tag{36}$$

For $y=0$ and $u_0=10$ mps. this last equation would give a maximum value of about $4.9 \cdot 10^7$ c.g.s. units for η. We shall accept the expressions (34), (35) and (36), while keeping the numerical value of k_0 open.

Returning now to the rate of cooling, it follows from (23) and (29) that

$$\frac{dq}{dt} = c_p(\gamma_0 - \gamma) H_T \frac{\partial v}{\partial y}, \tag{37}$$

H_T being the height of the homogeneous atmosphere at temperature T. One obtains from (18)

$$\frac{\partial v}{\partial y} = - \frac{4 l^2 u^2}{f L^4} \tag{38}$$

and, with the aid of (34) and (35),

$$\frac{\partial v}{\partial y} = - \frac{u^2 \kappa^4}{f k_0^2 H_0^2} \cdot \tag{39}$$

Substitution in (37) gives

$$\frac{dq}{dt} = - c_p(\gamma_0 - \gamma) \frac{\kappa^4 u^2}{f k_0^2 H_0^2} \cdot H_T \tag{40}$$

A clearer picture of the heat loss is obtained by expressing it in terms of the temperature drop that it would cause in one day, if no sinking occurred. This temperature drop ΔT is given by

$$\Delta T = - \frac{1}{c_p} \frac{dq}{dt} \cdot 24 \cdot 3600 \tag{41}$$

or

$$\Delta T = \frac{24.3600 \cdot \kappa^4}{k_0^2 f H_0^2} (\gamma_0 - \gamma) H_T u^2. \tag{42}$$

The maximum cooling occurs next to the polar front, just at the top of the frictional layer, where H_T is very nearly equal to H_0 and where the west wind has its maximum speed u_0. The cooling at this point is given by

$$\Delta T_{\max} = \frac{24.3600 \cdot \kappa^4}{k_0^2 f H_0} (\gamma_0 - \gamma) u_0^2 \tag{43}$$

and the relative value at any other point may be computed from

$$\frac{\Delta T}{\Delta T_{\max}} = \frac{H_T}{H_0} \left(\frac{u}{u_0} \right)^2 = \frac{H_T}{H_0} e^{-2y/L} = \frac{T}{T_0} e^{-2y/L}. \tag{44}$$

This result is based on the additional assumption that the temperature lapse rate γ is everywhere constant.

It is evident that there must be agreement between the dynamically prescribed and the thermodynamically possible distribution of cold sources. At first sight the theory here presented appears to violate completely this requirement since the rate of cooling according to (44) decreases rapidly to the south, in spite of the fact that the temperature distribution is practically uniform horizontally. In view of our present deplorable lack of knowledge concerning the radiation balance in the free atmosphere, it is not possible to discuss this phase of the problem quantitatively, and thus the following qualitative comments must suffice.

There must be a tendency towards a decrease southward in the net loss of heat from the free atmosphere, due to the increased absorption of radiation from the ground and of short wave solar radiation. In the northern part of the westerlies, where the transversal stream lines emanate from moderate heights, the air must contain much more moisture than further south where the transversal circulation brings down very dry air from extremely high levels, and this again would seem to further a greater heat loss to the north than to the south.

The necessary agreement between the dynamically prescribed and thermodynamically possible distribution of cold sources may, however, in part be brought about by dynamic means. If the lower isentropic surfaces just south of the polar front intersect the ground, the lateral stresses exerted along the northern edge of some of the isentropic sheets will, to some extent, be balanced by ground stresses, and these layers are then subjected to a much less intense transversal circulation than the one here computed. In this case the gradient wind distribution within the westerlies would no longer be barotropic and the solution presented above would have to be considerably modified.

It would be tempting to develop a theory for the westerlies from a prescribed distribution of cold sources. It is doubtful, however, if such a procedure would bring us very much closer to the true solution, since there can be no doubt that the actual distribution of cold sources is very largely determined by the moisture distribution, which, at least in part, must be dynamically controlled.

On the basis of von Kármán's value of $k_0=0.38$ the theory leads to values for the mixing length of about 1000 km and values for the lateral eddy viscosity of the order of magnitude which approach those obtained by Defant (1921) in his interpretation of the general circulation as a turbulent process. These values are definitely much greater than the values obtained by Grimminger (1938) for the lateral eddy diffusion coefficient in individual homogeneous currents, which vary between $4\cdot 10^5$ and $5\cdot 10^7$ c.g.s. units, corresponding to much smaller mixing lengths. Such a reduction can be accomplished by a reduction in the numerical value for k_0. If k_0 is reduced, the width of the westward belt, as measured by L, decreases. The sinking will then be concentrated to a fairly narrow zone and this again requires a much stronger rate of cooling. Assuming a value of 10 mps for u_0 and a lapse rate 0.5°C per hundred meters, the values of l, L,ΔT_{max} and η_{max} for different values of k_0 are given in Table 1a.

TABLE 1a

u_0= 10 m/sec

k_0	0.38	0.3	0.2	0.1
l km	1032	508	151	19
L km	2717	1693	752	188
ΔT_{max}	0.286°C	0.46	1.03	4.13
η_{max}	4.9×10^7	1.9×10^7	3.8×10^6	2.4×10^5

This table has been recomputed for $u_0=20$ mps. The change does not affect the values of l and L, but the rate of cooling is quadrupled and the eddy viscosity is doubled.

TABLE 1b

$u_o = 20$ m/sec

k_o	0.38	0.3	0.2	0.1
l km	1032	508	151	19
L km	2717	1693	752	188
ΔT_{max}	1.145°C	1.84	4.13	16.53
η_{max}	9.8×10^7	3.8×10^7	7.5×10^6	4.7×10^5

It is quite evident from these tables that Grimminger's values for the lateral exchange coefficient correspond to values of k_0 ranging from 0.1 to 0.3, with a reasonable mean value of about 0.2. The rate of cooling then required to maintain a steady state is of the same order of magnitude as the values computed by Möller (1935) for the rate of cooling in middle latitudes, but since their calculations are based on absorption coefficients which appear doubtful in the light of recent research, this agreement may not be of great significance. Sverdrup's (1917) values for the rate of cooling in the Azores High are free from this objection, since they are computed from the vertical temperature distribution and the distribution of vertical velocities, the latter having been computed with the aid of the equation of continuity from the observed horizontal wind distribution at different heights above sea level. Sverdrup's values fall within the range of values given in Tables 1a and 1b above, but the distribution of the cold sources established by Sverdrup does not agree with the one obtained through our simplified analysis, indicating that considerable refinement of the theory is needed.

The building up of an equilibrium state must take place gradually and coincident with the development of larger and larger anticyclonic eddies. Assuming that a strong west wind has been created above the polar front through direct solenoidal circulation and that the air south of the polar front is very nearly stagnant, it follows that the first effect of the lateral drag from the north on the air further south will be to set it in motion eastward and to throw it southward in such a fashion as to produce a dynamic (warm) high further to the south (Rossby 1937b, 1938a). The establishment of the high follows from the inability of the radiative mechanism of the atmosphere to close the transversal circulation in such a fashion as to permit the return of some of the accumulated air northward in the ground friction layer. The west wind belt must grow in size until finally a thermodynamically possible equilibrium state is reached, and the transversal circuits are completely closed. However, because of the dynamic instability of the shearing motion in the westerlies large anticyclonic eddies must form which distribute the sinking motion over a very broad area. The dynamically required rate of cooling then becomes less than the thermodynamically prescribed and more air will now be carried off northward within the ground friction layer than is accumulated at somewhat higher levels through horizontal convergence. During this entire development the speed of the west winds above the polar front will decrease as a result of the diffusion process. With the development of a strong northward movement of the moist surface air, the stage is set for a new cycle.

Figure 3 contains the stream lines (full lines) in a diagram with a log-pressure vertical scale and y/L as horizontal coordinate. It is evident from (24) and (19) that the stream lines above the frictional layer then must be straight lines. The top of the turbulent layer has been placed arbitrarily at a pressure of 850 mb and the sea level at 1000 mb, the small horizontal variation in sea level pressure being of no consequence in this connection. The stream lines in the ground friction layer are arbitrarily drawn and serve merely to indicate the return flow northward. The broken lines give the distribution of the cold sources in relative measure $\Delta T/\Delta T_{max}$.

It is evident from the slow transversal velocity values indicated in Fig. 2 that a parcel of air may complete several closed anticyclonic circuits while completing only a fraction of its transversal path. This is particularly true in summer when the polar front circulation is weaker and thus u_0 and v both reach their lowest value.

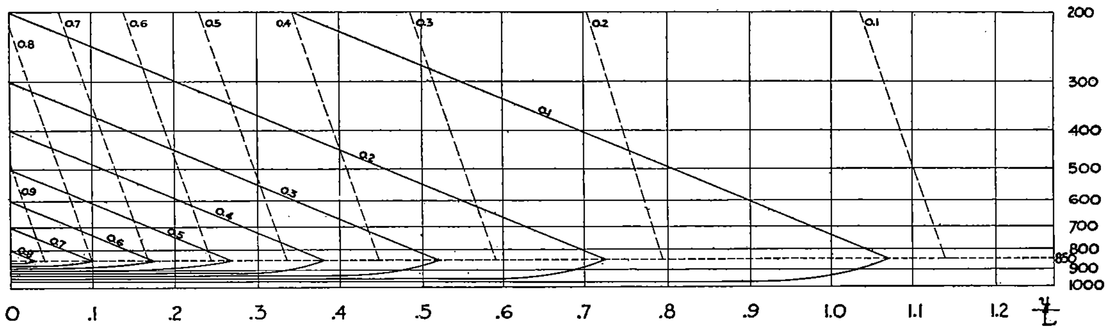


FIG. 3.—Transversal circulation in region of the westerlies, plotted against log pressure as ordinate and distance southward from polar front as abscissa. Stream lines (full lines) are drawn for intervals of 0.1 in the ratio of the stream function ψ to its value ψ_{max} at the point $p = 1000$ mb, $y = 0$ (polar front position at the ground). The broken lines give the heat loss in the same relative measure.

The low speed of the west winds, the further decrease in the speed of the transversal circulation relative to the west winds and the decrease in the intensity of the cold sources combine to make the summer season particularly well suited for the determination of flow patterns from isentropic charts.

B. TECHNIQUE AND EXAMPLES OF ISENTROPIC ANALYSIS

BY JEROME NAMIAS

I. Technique

1. *Plotting Routine*

a. *Values chosen for representation.* The principal tools of isentropic analysis are characteristic curves, isentropic cross sections and isentropic charts. The first of these tools consists of plots of specific humidity against potential temperature, one for each aerological sounding. It is used primarily for identification of vertical air columns and has been thoroughly discussed elsewhere (Rossby 1932). It is with the second and third of the tools listed above that this paper is concerned.

The fundamental assumption underlying isentropic analysis is that airlayers well removed from the ground tend to conserve their potential temperature. The validity of this assumption was clearly recognized by Shaw (1933) and led him to suggest that synoptic charts be constructed on surfaces of constant potential temperature, thus enabling one to follow a given sheet of air from chart to chart.

The fundamental difference between the isentropic charts suggested by Shaw and the ones now drawn as a daily routine at the Massachusetts Institute of Technology lies in the introduction of a second conservative element, specific humidity, to trace the movements of individual air parcels *within* the isentropic surfaces.

Evidence in support of the basic assumption of adiabatic motion is furnished by the remarkably conservative nature of some of the charcateristic curves obtained from our aerological soundings. The author (Namias 1934) has shown that subsidence inversions normally are characterized by fairly unchanging values of potential temperature at their bases and at their tops, a fact which implies adiabatic displacements. While there is much evidence of isentropic motion in an unsaturated atmosphere, it is equally well established that saturated air is capable of crossing the isentropic surfaces. Through condensation latent heat is realized and leads to an increase in the potential temperature. Thus, as is well known, displacements of saturated air are characterized by constancy of equivalent potential temperature. Indeed, inspection of characteristic curves from stations penetrating well defined warm fronts along which condensation is occurring shows that the points of maximum moisture content frequently lie along a line of constant equivalent potential temperature. Thus the assumption of isentropic motion is not strictly justified in the case of saturation.

It is unfortunate that there are but two conservative elements at our disposal for the tracing of air movements. These two elements in combination define the equivalent potential temperature. Thus the chart which might logically suggest itself for regions of saturation, that is, one drawn upon a surface of constant equivalent potential temperature is of little value in tracing air movements since we can plot upon it no conservative quantities which do not enter into the definition of the equivalent potential temperature. Moreover, above active warm fronts convection frequently leads to the establishment of saturation adiabatic lapse rates, and in these cases surfaces of constant equivalent potential temperature are transformed into layers of finite thickness. In a later section we shall discuss how such non-adiabatic motions may be recognized and taken into consideration.

In the routine of plotting isentropic charts the values of specific humidity and potential temperature at each station must be available. They may be determined graphically from the directly observed elements of the aerological soundings with the help of thermodynamic diagrams. In the United States, specific humidities at significant levels are computed at the individual aerological stations and then transmitted by code. It would be of considerable aid to isentropic analysis if this method were employed for potential temperatures as well, thereby doing away with the time-consuming process of extracting these values from each ascent.

The question arises as to which isentropic sheet should be used for the analysis. The principal guiding factor is the elevation of the sheet, which in turn depends upon the general temperature distribution. Thus the isentropic surface $\theta = 290°$[1] which has been found useful during the winter months is far too low during the warm summer months. In general, the isentropic sheet finally chosen should be high enough to be above the layer of surface effects over most of the area concerned, and at the same time low enough to show a pronounced range of specific humidity values. It is obvious that over a large area of diverse topographical and climatic features these two criteria cannot be completely satisfied. However, it has generally been possible for us to find an isentropic surface that has satisfied these conditions well enough for a reasonably sound analysis.

Suitable values of potential temperature for the individual seasons are:

Season	*Potential Temperature*
Winter	290°–295°A
Spring	295°–300°A
Summer	310°–315°A
Fall	300°–305°A

The abrupt increase from spring to summer values is due to the normally rapid increase of free air temperatures as summer convection sets in.

During periods of unusual weather it is sometimes necessary to change to a different surface for a few days, and then to return to the normal for the season. It should be pointed out, however, that such changes carry with them a certain loss of continuity—and it cannot be emphasized too strongly that continuity is the primary requirement of isentropic analysis. For this reason it is most advantageous to follow from day to day the flow patterns in a given isentropic surface, and when an abnormal period suggests change in surface, to construct an additional set of charts for a more representative surface for this particular period.

Once the proper surface has been selected it remains to obtain the values of the various meteorological elements, particularly specific humidity, on the surface. The simplest method of accomplishing this is to make use of a pseudo-adiabatic diagram. If the observed values of pressure, temperature, and relative humidity are known, a curve of temperature versus pressure may be plotted and the relative humidities indicated numerically beside the sounding. The chosen value of potential temperature may then be marked by a heavy line along the proper dry adiabat. Through interpolation between significant points of the sounding one obtains values of relative humidity at the particular isentropic surface, and from these data the specific humidity is easily determined with the help of the lines of constant (saturated) specific humidity. The height of the selected isentropic surface may be similarly determined by finding through interpolation the

[1] That is, characterized by the potential temperature 290°A.

height corresponding to the pressure at which the chosen dry adiabat cuts the observed temperature pressure curve. In the United States where the specific humidities of soundings are transmitted by code, it is a simple matter to interpolate directly.

There has also been some use made of the weight of the vertical column of air contained between two isentropic sheets, the interdiurnal changes in this value being an indication of the convergence and divergence of air. This weight is easily determined by marking in the graph another dry adiabat, differing by, say, 5° of potential temperature from the adiabat originally chosen. The weight of a vertical column of air between the corresponding surfaces is then simply the difference in pressure between the two intersections made by the dry adiabats with the temperature-pressure curve in the diagram.

We now have at hand specific humidity, height, and relative humidity at one surface of constant potential temperature, and also the weight of the air between this surface and another, let us say 5° below it. These values are then plotted at the appropriate stations on a geographical chart; the most convenient order is specific humidity, height, and relative humidity to the right of the station (from top to bottom), and to the left and below the station, the weight of air between surfaces.

With these data alone it is possible to construct lines along which the specific humidity remains constant, and also lines of constant elevation. *Such a mechanical interpretation of the data does not constitute an analysis*, for nowhere is the network of aerological stations sufficiently dense to permit a unique determination of the flow patterns on the isentropic chart. It is the purpose of the first portion of this report to suggest various important tools used in the analysis of the data from a comparatively open network of aerological stations. The more important of these tools are vertical cross sections through the atmosphere, analyzed surface weather maps, isallobaric charts, cloud and precipitation data, and upper air winds. But before proceeding with the discussion of the analytical use of these, we shall make a few remarks concerning the plotting of some additional helpful data on the isentropic chart.

Let us suppose that the isentropic surface is found above the top of the sounding. In this case it is frequently possible to obtain approximate values by extrapolation. This may be done only if the surface is not far above the top of the ascent. Furthermore, extrapolation is not permissible when there is a very steep temperature lapse rate in the uppermost layer of the ascent, since the lapse rate then very nearly follows a dry adiabat, and the desired point of intersection is difficult to determine accurately. Whenever there are indications of discontinuities just above the sounding, it is also best not to attempt an extrapolation. In normal cases, however, when the top point of the ascent is not too far removed from the fixed potential temperature surface, extrapolated values of specific humidity and elevation will be sufficiently accurate for the analysis. Some special notation (such as parentheses) should be used to show that the values so marked are extrapolated, and it is helpful to indicate the potential temperature at the uppermost level of the sounding.

When extrapolation is not indicated, there still is some helpful information in the uppermost readings of the sounding, and it is desirable to enter on the chart the specific humidity and elevation at the highest level together with the value of potential temperature of this point. For identification, these numbers may be plotted on the isentropic surface in red ink. A similar procedure may be used for certain high mountain observations, for these often throw some light on conditions in the free air when airplane observations are not available.

Clouds and precipitation forms should be entered on the chart, for they show the regions of saturation, and frequently offer clues to the direction of air flow when pilot-balloon winds are missing. We are chiefly concerned with three possibilities: (1) the clouds are above the charted isentropic surface, (2) they are below it, and (3) they penetrate the isentropic surface. It will be shown later that (1) and (3) may be attended by significant changes in the character of the surface, brought about by condensation and precipitation. When the clouds are below the sheet, their effect upon the chosen surface is generally of little significance, although even in this case valuable hints may be gained by entering the clouds in the customary international symbols.

The direction of movement of the clouds is best shown by an arrow appended to the symbol, and the amount of sky covered may be indicated by a number placed as a subscript. If the cloud is *below* the isentropic sheet with which we are concerned, this fact may be indicated by adding the letter "b" to the cloud symbol. If it is above the sheet, nothing need be appended. If clouds penetrate the isentropic surface, it is advantageous to enter beside the cloud symbol the elevations of base and top. When a cloud is reported as being somewhere within the range of the aerological sounding, yet not placed specifically, we have found it convenient to place an asterisk after the cloud symbol.

Precipitation is an important element to consider in carrying on an isentropic analysis. Precipitation forms should be entered on the isentropic chart together with the levels in which they are present. Also for this purpose international symbols are convenient.

Since the analysis of isentropic charts has for its purpose a thorough description of the air movement, it is essential that upper air winds be used to the fullest extent. At those stations where both soundings and pilot-balloon data are available the wind in the isentropic surface may be readily extracted, since the elevation of the surface is one of our computed quantities. But there are many more pilot-balloon stations than airplane or radio-sonde stations. In order to use all the available upper wind data it is first necessary to construct lines of constant elevation for the isentropic surface. This is really part of the technique of isentropic analysis, and will be discussed in BI2a.

The term "isentropic analysis" applies not only to the study of upper air charts for prescribed isentropic surfaces, but also to the interpretation of atmospheric cross sections, without which the analysis would be incomplete. Isentropic analysis is in reality a method whereby the meteorologist attempts to discover the major flow patterns of the atmosphere through successive approximations, and in these successive stages it is helpful to be able to compare the flow picture obtained from a selected surface with the picture suggested by a few cross sections.

In order to take full advantage of the cross sections it is necessary to make use of the most conservative air mass properties, potential temperature and specific humidity. The older type cross sections, in which temperature and relative humidity were used, have been found inadequate and at times actually misleading. Frequently, the level for level comparisons used in analyzing such cross sections led to confusing and inconsistent pictures of frontal structure. The chief objection to the older form of representation lies in the fact that large scale vertical motions bring about adiabatic changes which render ineffective the comparison of elements at fixed levels. A much sounder form of cross section representation is that obtained by studying the distribution of potential temperature and specific humidity. In this manner one has a method of representation similar to that suggested by Rossby in his treatment of the equivalent potential temperature diagram. The chief advantage of this type of cross section is that it presents some information concerning the moisture distribution in *several* isentropic surfaces, one of which corresponds to the particular isentropic surface for which a complete chart may be available.

Upper air winds may be entered along the station verticals in the cross sections. In working with sections which run east-west, a north wind has its shaft directed downward; an east wind has its shaft directed toward the left; and so on. In a north-south section (north to the left of the section) a north wind is represented so that the shaft points to the right; in an east wind, downward.

Clouds and precipitation forms should be entered in the cross sections in the same way as in the isentropic charts, at the proper levels.

b. *An alternate method of representing data.* In a recent paper Byers (1938) has suggested that the isentropic chart becomes more useful when lines of constant pressure (isobars) and lines of constant isentropic condensation pressure are entered on the isentropic chart instead of the constant specific humidity lines and contour lines suggested in the preceding section. The use of isobars rather than height lines has distinct advantages, since thermodynamic changes in the atmosphere are the result of changes in pressure, not elevation. In accordance with Byers' suggestion the isentropic charts now made at the Massachusetts Institute of Technology contain isobars rather than height lines. For the sake of consistency the cross sections are also plotted with pressure (on a logarithmic scale) as the vertical coördinate.

On a prescribed isentropic surface the isentropic condensation level pressure is a function of specific humidity alone. Since furthermore, for low specific humidity, small variations in the moisture content bring about large variations in the condensation level pressure, it is evident that the moisture distribution and thus the flow patterns may be adequately represented through lines of constant condensation level pressure and this method would appear to have the further advantage of permitting a more detailed analysis of dry tongues (high portions of the surface). However, this gain is to some extent fictitious, since the observed values of relative humidity often are inaccurate in cold regions.

The use of isentropic condensation pressures instead of specific humidities, has certain additional disadvantages. In the first place, as Byers points out, lateral mixing depends upon the gradient of specific humidity, not upon the gradient of the condensation pressure. A more serious objection is that the combined use of cross sections and isentropic charts, so important in defining the axes of moist and dry tongues, and the establishment of flow patterns is hampered when the quantities represented on the cross sections differ from those on the isentropic chart. In his report Byers describes a method, originally suggested by C. H. Pierce, of using condensation isotherms of potential temperature on the cross sections, but this substitution does not eliminate the criticism made above, since isentropic condensation level temperatures depend not only upon the specific humidity but also upon the potential temperature.

One of the points brought out by Byers in favour of the use of isobars and isentropic condensation isobars is that nearness to condensation may be estimated from the closeness of these two sets of lines. Thus, where an isobar intersects the isentropic condensation isobar of the same value, saturation occurs. A series of such intersections bound the area in which condensation is occurring. However, an equally suitable form of representation may be obtained where isobars and specific humidities are used. One merely affixes to each isobar in the isentropic chart the value of the saturation specific humidity (which is a function of pressure alone in a given isentropic surface) and the intersection of these maximum specific humidity lines with the observed lines of observed specific humidity defines the area of saturation. Within this area the assumption of isentropic motion does not hold.

The use of isobars rather than lines of elevation should cause little confusion. The procedure described below for the construction of height lines may equally well be applied to isobars.

2. *Analysis*

a. *Preliminary construction of contour lines.* In the preceding chapter it was stated that in order to obtain winds at all pilot-balloon stations it is necessary to construct on the isentropic chart lines along which the elevation of the isentropic surface is constant (contour lines). The purpose of these lines is, however, not solely to permit the incorporation of additional upper air winds, but they also serve a useful thermodynamic and hydrodynamical function. The number of upper air soundings available is generally insufficient to permit construction of contour lines in a purely mechanical fashion. It is often possible to construct several different patterns of such lines from the data in a single chart, and the detailed drawing of the contour lines is therefore a matter of judgment (analysis). Fortunately, however, for purposes of obtaining the wind distribution in an isentropic surface, different solutions of the pattern of contour lines will generally lead to similar results as far as the wind distribution is concerned. The reason is that currents in the free air are for the most part fairly constant in direction over vertical intervals of one to two kilometers, and that the uncertainty in the contour lines in regions where there is a reasonably close network of sounding stations falls within these limits. But this circumstance does not justify a mechanical construction of height lines, for while the wind patterns may be similar to the true pattern, there are frequently small variations in wind flow which offer important clues to the complete analysis. Moreover, the contour lines serve to indicate the slope of the isentropic surface, a most important factor in the weather processes. It is the purpose of this section to point out some of the more important aids one may use in making a first approximation to the solution of the pattern of the contour lines. First among these are the surface isallobaric charts.

It is well known that pressure changes to a large extent are the result of advection in the free air which brings about substitution of warm air for cold and vice versa. The large contributions of shallow layers of extremely cold polar air to the surface pressure changes have been emphasized by Willett (1933) and Emmons (1935). For many years forecasters have used isallobaric charts as one of their most important aids. However, it is also well known that the total pressure changes observed at the ground are in part dynamically produced, and that at times the dynamic effects may outweigh the advectional.

In the analysis of isentropic charts it soon becomes evident that there is in most cases an association between the pattern of the height lines and the surface pressure changes. Where the surface pressure rapidly rises the isentropic surface is high, where the surface pressure falls the surface is low. In order to show this general relationship more clearly for an individual station (Fargo, North Dakota) Fig. 1 was constructed, wherein the height of the isentropic surface $\theta = 310°$ is plotted against the preceding twenty-four hour sea level pressure change for the available soundings of June and July 1937. The curve drawn by inspection through the observed points shows that in most cases rising pressure at Fargo is associated with an increase in the level of the isentropic surface. This suggests that the pressure changes observed at the surface at Fargo are in large part advective in origin, so that when a mass of cold air moves in, raising the isentropic surface, the static effect of the colder air produces a pressure rise at the ground. This relationship offers a key to the location of height lines and frequently gives indications of isentropic domes and troughs which may be beyond the geographical boundaries of the aerological network. It is equally helpful in regions where data are missing. But it must be emphasized that this relationship is not infallible—a fact which is readily seen from the great scattering of the points in Fig. 1. Moreover, it appears that this relationship, at least in summer in the United States, is confined to the northern portions of the country. To illustrate this point Fig. 2 for Nashville has been constructed. Here the coordinates are the same as those used in Fig. 1 and the period is the same, but it is obvious that no significant correlation exists. It would thus appear that in summer the contribution to

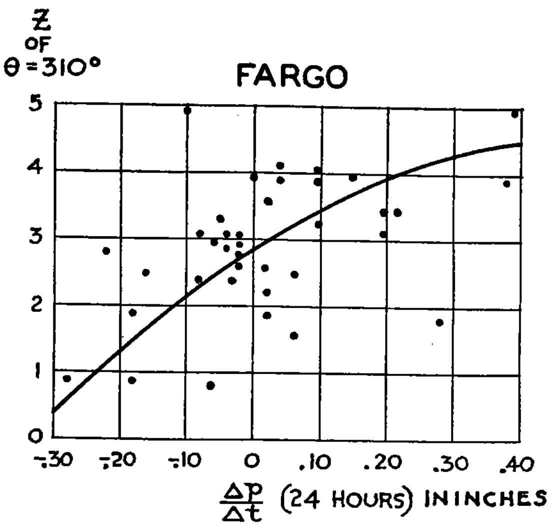


FIG. 1.—Height of the isentropic surface $\theta=310°$ as a function of the preceding twenty-four hour surface pressure change at Fargo, North Dakota, during June and July 1937.

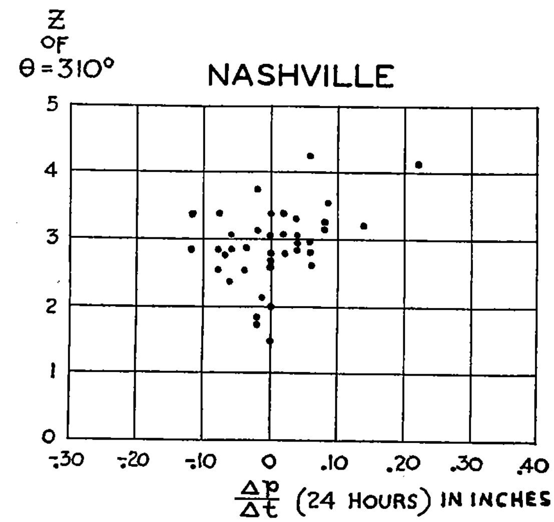


FIG. 2.—Height of the isentropic surface $\theta=310°$ and preceding twenty-four hour surface pressure changes at Nashville, Tenn. during June and July 1937.

sea level pressure changes over Nashville brought about by advection of various air masses within the lower atmosphere is no more significant than the effect of advection at higher levels or purely dynamic pressure changes. Thus the relationship between contour lines and pressure changes cannot be used in the southern section of the United States in summer. This restriction, however, is not very serious since the network of aerological stations in this area is sufficiently dense so that the contour lines there may be reasonably well defined by observations.

There is reason to believe that in winter the relationship between isentropic topography and sea level pressure change holds also in the southern sections of the United States, although only a limited amount of data have been examined. In winter the polar front is normally located much farther south than it is in summer, and the air mass changes are more pronounced and frequent in winter than they are in summer. These air mass changes are generally reflected in the surface pressure changes. In winter it is advantageous to use twelve rather than twenty-four hour pressure changes, owing to the greater rapidity of air mass movement. In summer the twelve hour pressure changes contain a large diurnal term, which does not occur in the twenty-four hour changes; thus the latter are more useful in summer. The three hour pressure changes are correspondingly helpful as an indication of the instantaneous direction of movement of the contour lines.

Fronts on the surface weather map also offer a great deal of information about the structure and pattern of the contour lines. Regions in the vicinity of well marked fronts are characterized by a "packing" of the contour lines. Since cold fronts are generally much sharper and steeper than warm fronts, this steep gradient of contour lines on the isentropic chart is usually at its maximum just behind cold fronts. Moreover, as one should expect, the contour lines usually run parallel to the surface fronts. Indeed, it appears that many well-defined fronts are characterized by constant potential temperature, and therefore the isentropic surface may be the frontal surface, or may lie nearly parallel to it in space.

The warmest air is normally found just ahead of the surface cold front. Thus the trough in the height lines is to be found in this locality, and from this line backward through the cold air the gradient of contour lines is steep.

The parallelism of contour lines with well marked cold fronts many times enables one to construct height lines in regions where there are few data. The application of this principle to frontal non-occluded wave disturbances is apparent, for here there must be a wavelike pattern in the contour lines roughly parallel to the frontal waves in the synoptic surface chart.

Sharp warm fronts show up in the height line pattern in much the same manner as cold fronts, the gradient of the lines increasing abruptly at the front while the lines remain fairly parallel to the front. There are, however, many warm fronts on the surface maps which are not associated with this simple contour line pattern above. Moreover, the surface maps frequently indicate homogeneous open warm sectors which in the isentropic charts are far from homogeneous, but rather characterized by troughs in the contour lines suggestive of fronts. Some time after their appearance in the contour line pattern, these troughs may appear in surface charts as regions of frontogenesis, suggesting that such newly formed fronts are a *result* rather than a cause of upper air activity. It thus appears that many fronts on the surface weather map are "induced" by action taking place first in the upper air and later showing up at the ground.

We may express some of the above ideas in diagrammatic form. In Fig. 3 the heavy line represents the polar front at the ground; the solid portions are cold fronts; the dotted portions, warm fronts. The light broken lines labelled z, $z+1$, etc., are contour lines of the isentropic surface. H indicates regions where the isentropic sheet is high, and L regions where it is low. Fig. 3a represents the ideal topography to be expected on the basis of the Norwegian frontal theory, while Fig. 3b shows a topography frequently observed and associated with frontogenesis within the originally apparently homogeneous tropical air mass subsequent to the appearance of the trough in the contour lines. This latter case is that of the frictionally driven anticyclonic eddy which we shall treat from the observational standpoint later on.

It is to be stressed that cross sections should be used in constructing the contour lines. It is always helpful to mark the intersection with the chosen surface of constant potential temperature in the cross sections, as this enables one to define the high and low points of the isentropic surface for these sections.

The purpose of the preliminary construction of the contour lines is to enable one to extract all the available information from the pilot-balloon wind data. It will be recalled that in our present stage of the analysis only those upper air winds are available which are made at airplane or radio-sonde stations. These winds, as well as pressure changes and fronts, help in determining the topography of the isentropic surface. Under steady state conditions the upper air winds must very nearly follow the contour lines but in individual cases the winds may flow in any direction relative to the contour lines, even though the air be constrained to remain in an isentropic surface. Indeed, it is this very

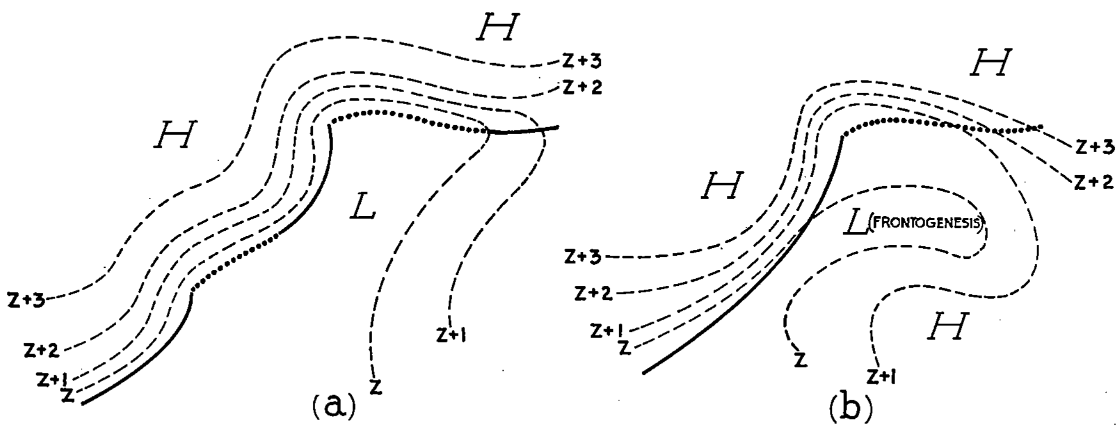


FIG. 3.—Relation of contour line pattern to surface fronts.

component of motion of the air across the height lines which is largely responsible for the weather during the winter season. Empirically it has been found that in the majority of cases the winds on individual isentropic charts are approximately parallel to the height lines. Since this condition frequently is approximated also in areas where frontal precipitation is occurring, it would appear that the upslope components associated with convergence are quite small, and thus it is not always advisable to attempt to determine the component of upslope motion from the relative orientation of wind direction and contour lines on the isentropic charts, particularly in view of the fact that the contour lines themselves may be displaced with practically the speed of the wind. It has been found empirically that whenever there is a reasonably steep gradient of contour lines the wind is directed mainly along these lines. Since the contour lines fairly nearly coincide with the isotherms in horizontal planes this result is in good agreement with that obtained by Clayton (1923) that high level clouds generally move parallel to the surface isotherms. This relationship, then, may be used in constructing the preliminary set of height lines, for we have on hand certain winds at the aerological stations. The sense of rotation of these winds is normally so that the domes and ridges of contour lines are to the left of the current flow. It should be emphasized that this rule is by no means always applicable, for the pressure distribution at any level depends not only upon the thermal distribution aloft but also upon the pressure distribution at the surface. Moreover, there is good evidence in support of the contention that there are at times sizeable components of motion across the isobars (Bjerknes and Palmén 1938).

b. *Isentropic flow patterns.* After the preliminary contour lines have been constructed and all available upper level winds entered on the isentropic chart, the stage is set for the determination of flow patterns with the aid of the lines of constant specific humidity. In order to avoid the confusion of different sets of lines, it is necessary to completely erase the preliminary contour lines. The general character of contour lines is sufficiently well remembered by the analyst to assist in the study of the moisture pattern, and the clean map encourages the careful sketching of smooth curves. The word "sketching" should be emphasized, for we are not dealing with a problem as simple as drawing sea level isobars. Because of the limited supply of aerological data, it is not possible to construct moisture lines in a mechanical fashion. The eraser will be found to be a most useful tool.

In sketching tentatively the first approximation to the flow pattern, the first principle to bear in mind is continuity of analysis. Moist or dry tongues of the preceding maps may be assumed to be carried by the general wind flow along the isentropic surface. One must consider various non-adiabatic influences in order to explain satisfactorily certain changes in the character of these tongues which are not compatible with simple advective transport. We shall treat some of the most commonly observed flow patterns shortly, but first it is advisable to mention the use of cross sections in this first approximation.

Suppose that we have sketched a moist tongue in the isentropic surface, and that the axis of this tongue runs in an east-west direction. Since the axis of this moist current may lie in the gap between aerological stations, it is impossible to establish the greatest amount of moisture (the maximum line of specific humidity) in the center of the stream from the data in a single isentropic surface. The cross sections, however, satisfy just this need, for if we choose a section which runs cross stream (in this case north-south) we can sketch in the moisture lines as they intersect not only the chosen but also the surrounding isentropic surfaces, and thus more readily interpolate the most probable moisture maximum of the current. A schematic picture of such a cross section is shown in Fig. 4, where the lines of specific humidity are drawn solidly and the surfaces of potential temperature are broken. Let us say that we are analyzing the 310° surface (the heaviest

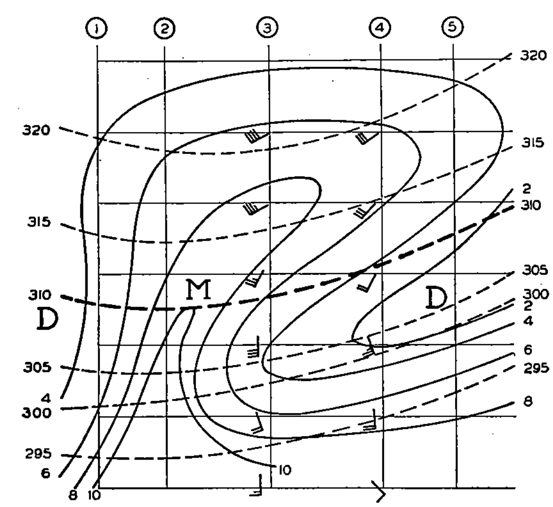


FIG. 4.—Schematic cross section through a convective area.

broken line). Then the axis of the moist current on the isentropic chart lies 1/4 the distance between stations 2 and 3, near station 2. Moreover, this cross section suggests that the 10 gram line most likely intersects the 310° surface.

In choosing cross sections it is most helpful to make use of those sections which run cross-stream. Since prevailing wind directions in the free air and in middle latitudes have a good westerly component, the north-south sections are most frequently helpful, but in summer time a section from El Paso, Texas, to Montgomery, Alabama is often found very useful.

On occasions the first approximation to the flow pattern may indicate a moist tongue between aerological stations but the analysis of the cross section cannot be strained to fit this pattern. In this case, the trial solution must be abandoned and some more consistent pattern sketched. In this manner one finally arrives at the probable solution.

The moisture lines in general tend to follow the wind directions. If this were rigidly true, however, the moisture lines would also be stream lines. But it is probable that a steady state is seldom approximated in the atmosphere, so that the parallelism of moisture lines and stream lines is only roughly true. Generally the axis of a moist or dry current coincides with the region of strongest winds, so that from this axis laterally outward there is found a diminution of both moisture and wind velocity. Advective transport from the source of moisture is undoubtedly the determining factor in this moisture pattern, although appreciable modifications are brought about through isentropic mixing.

The Norwegian meteorological school stresses the fact that no current of uniform direction can exist completely around the earth, and that the atmosphere must break up into a number of cells (V. Bjerknes and coll. 1933). Similarly, in the case of isentropic charts, it has been found that currents do not move in straight paths, but there is a pronounced tendency of the current systems to break up into large anticyclonic eddies (Rossby and coll. 1937a and b). The curvatures of large scale current systems are in the main the result of the struggle for balance between Coriolis' forces and dynamically created pressure gradients. Since the moisture distribution in the atmosphere is controlled mainly by advection, it follows that the patterns of moisture must follow closely the general patterns of the large current systems. It is evident, then, that in carrying out the analysis one must try to arrive at a moisture pattern, and consequently a flow pattern, which is compatible with the behaviour of a real fluid. Analogies between air currents and streams of water are becoming mutually helpful, and some of the flow patterns of the atmosphere have been found in the ocean (Montgomery 1938, Parr 1938). Spilhaus (1937) has made photographs of flow patterns produced by a jet of liquid flowing into a rotating tank of water which bear a striking resemblance to the patterns of the moisture lines on the isentropic chart.

The observed patterns naturally divide themselves into the two classifications, cyclonic and anticyclonic. It is generally one current that dominates the motion over a large area, and this current will be referred to as the "wake stream." Normally it is the current with the highest velocity that dominates—it may be composed of dry or moist air, and may curve cyclonically or anticyclonically. The wake stream, through lateral shearing stresses, drags along other currents in its neighborhood and sucks in air along its boundaries. Moreover, it may build up an anticyclone to its right and a counter-current to its left, as suggested by Rossby (1936). It is therefore desirable to define the wake stream on each isentropic chart, so that a consistent flow pattern can be constructed using this dominating stream as a frame.

In the daily isentropic analyses it has been found that wake streams moving southward from polar and sub-polar regions are predominantly cyclonic in their flow, while those of tropical and sub-tropical origin moving rapidly northward are anticyclonic. This applies only to fast moving currents, which appear to govern the major flow patterns. Prof. Rossby suggests that this phenomenon may be explained on the basis of the principle of conservation of absolute circulation. Thus the total absolute circulation of any isentropic fluid chain consists of a circulation relative to the earth plus the circulation of the earth itself about this chain. If there are no frictional forces and if the motion is strictly adiabatic this sum must remain constant. Thus, if an originally stationary isentropic fluid chain is displaced from equatorial to polar regions it must develop an anticyclonic sense of circulation relative to an observer on the earth in order to counterbalance the increased circulation of the earth itself around the chain as it moves northward. Similarly, a southward moving system tends to develop a cyclonic circulation.

Rossby's conclusion that the current systems observed on the isentropic charts over the United States have a pronounced tendency to break up into large anticyclonic eddies was based essentially on a study of two situations, each one involving about a week's weather. One of these (Osmun 1937) was an exceptionally steady one, there being little change in the general upper air flow patterns for several days. More recent studies indicate that such extremely steady conditions aloft are rare, yet it is surprising to note that this fundamental isentropic flow pattern, the large anticyclonic eddy, is the one most frequently observed on the daily isentropic charts. Moreover, there often are important anticyclonic eddies of a much smaller size than the one analyzed by Osmun. This is especially true in summer.

It is probable that these anticyclonic eddies are at least in part caused by lateral eddy stresses. Through such stresses super-gradient wind velocities may be produced in the environment of a current and a banking of air to the right of the motivating stream results. This banking, or piling up of air finally produces an anticyclonic eddy—a frictionally driven eddy. It is natural that these eddies should form in regions where there is the greatest anticyclonic wind shear. Parr (1936) has suggested that isentropic mixing should be most pronounced where the vertical stability is greatest. Thus it is in the layers of greatest stability that one should expect to find embryonic anticyclonic eddies. In a following section, where a detailed analysis of the synoptic situation for the period June 21–30, 1937 is presented, a pronounced anticyclonic eddy may be followed for several days. This eddy forms in the region of wind shear between a broad northerly current of dry air and, to the west, a southerly flow of moist air. The anticyclonic vortex set up in the region of wind shear creates a new distribution of moist and dry air, which, as we shall see, is of great importance for subsequent weather developments. In order to obtain a more complete picture of the character of the zone in which this particular anticyclonic eddy forms a vertical cross-section running west-east through the center of the eddy has been constructed. This is shown in Fig. 5, where for purposes of clarity the lines of constant specific humidity (given numerically to the left of the station verticals) are omitted, and dashed lines represent isotherms of potential temperature. The center of the anticyclonic eddy on the isentropic surface ($\theta=310°$, the heavy dashed line) lies between Omaha and St. Louis.

The lateral wind shear responsible for the development of this eddy appears to be more pronounced along the isentropic surfaces of the cross section than it is along any constant level. Moreover, fixed level charts on which pilot-balloon winds are plotted (not here reproduced) do not bring out the anticyclonic circulation nearly as well as the isentropic chart for $\theta=310°$. A chart constructed for the higher isentropic surface $\theta=320°$ for this day likewise shows little evidence of the circulation. Apparently, the eddy is just forming and is confined to the lower layers of air in the region of $\theta = 310°$. Comparing the lapse rate in the air layer between $\theta = 300°$ and $\theta = 310°$ with that of the layer extending from 315° to 325° one finds that the lower layer is everywhere more stable than the upper. The fact that the incipient anticyclonic eddy is found best developed in the more stable layer, would seem to lend some support to Parr's (1936) suggestion that lateral mixing is most pronounced in regions of strong vertical stability.

The heavy slanting lines in Fig. 5 bound a layer in which there is a relatively steep lapse rate. This zone becomes thicker and its lapse rate steeper as it reaches higher levels until at Cheyenne its lapse rate becomes slightly super-adiabatic. The pilot-balloon wind

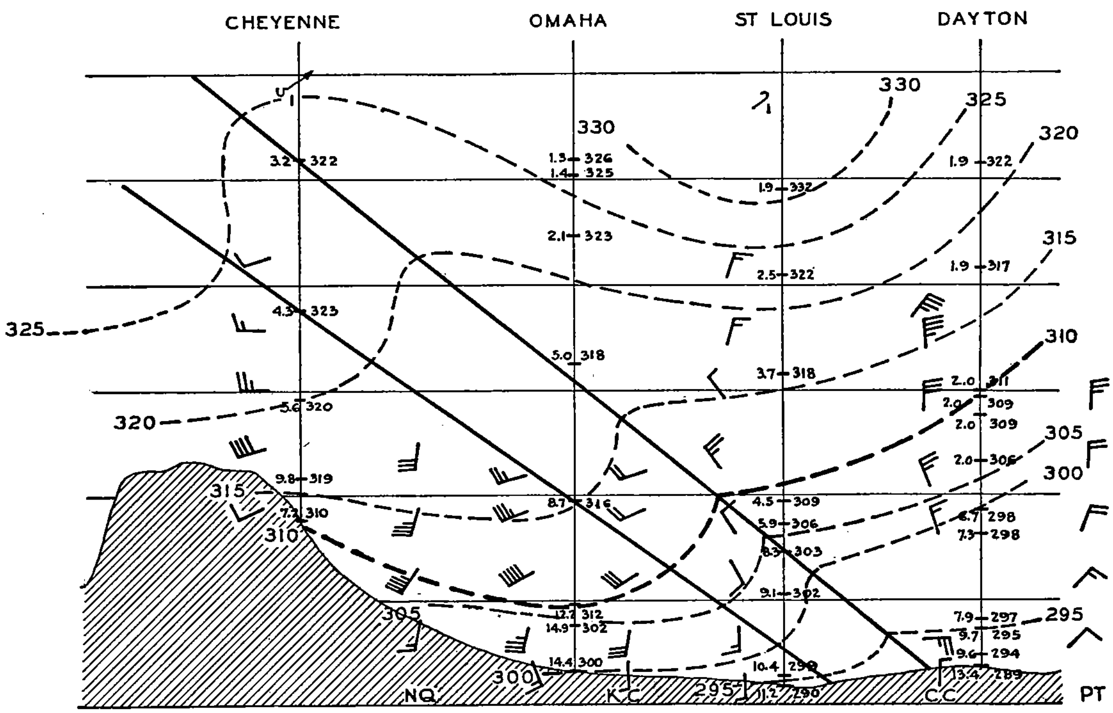


FIG. 5.—East-west cross section through an anticyclonic eddy on June 23, 1937.

observations at St. Louis suggest that this zone coincides with the layer in which the winds turn from southerly to northerly as one penetrates it from below. The zone of anticyclonic wind shift is generally considered as a ridge of high pressure, which, because of the thermal structure surrounding it, is displaced westward with increasing elevation. However, in entering the northerly current over St. Louis there is a sharp drop in moisture, and a similar decrease is found in the transition zone over Omaha. It is difficult to explain these discontinuities in moisture and lapse rate on the basis of a ridge of high pressure in which the northerly stream has curved anticyclonically around the ridge. It seems more likely that the cool and dry air at the top of the transition zone is a part of an independent northerly flow which is dragged over the warm and moist southerly stream through lateral shearing stresses exerted by the broad northerly current further to the east.

This type of transition differs from a front in that it has warmer and potentially less dense air *below* it, and thus it cannot be stable. Several cases of this nature have come to light in the daily routine of upper air analysis at the Massachusetts Institute of Technology.

The anticyclonic eddy becomes an important weather factor through its ability to bring about changes in the distribution of moisture; it is evident from the preceding discussion that it is this particular characteristic which enables one to locate the eddies on the isentropic chart. It frequently happens, however, that an eddy creates a new moisture distribution and later on dies out as a circulatory motion in the wind pattern on the isentropic surface. In this case the lines of constant specific humidity may suggest an eddy which is not borne out by the winds and which, therefore, is a result of previous history and is "fictitious" as an eddy. The important question then arises as to what are the determining factors in the life of an anticyclonic eddy.

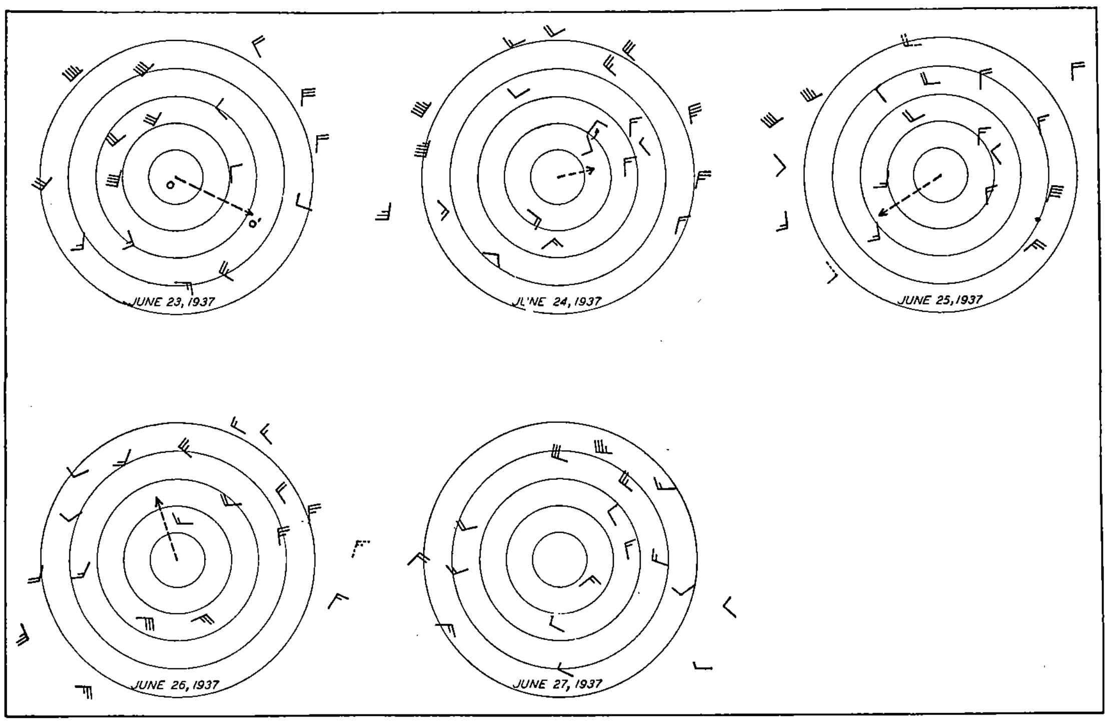


FIG. 6.—Relation between displacement of anticyclonic eddy and the distribution of tangential velocity.

In order to obtain a clue to this problem I have plotted in Fig. 6 the wind velocities observed around a well marked anticyclonic eddy which appears on the isentropic charts from June 23 to 27, 1937, and is treated in detail in BII. The center of the eddy is easily determined on the individual isentropic charts, and these centers are represented in Fig. 6 as the centers of concentric circles, the distance between two successive circles being 100 miles.

On the 27th the circulation has broken up so that at this stage one can hardly talk about an anticyclonic eddy. This disintegration can be observed setting in on the 26th where the symmetry of velocity is not as pronounced as in the first three days. Indeed, it appears from these individual diagrams that the life of the eddy may be tied up with the distribution of velocity about its center. Thus in the embryonic and developing stages of its history, from the 23rd to the 25th, the tangential velocities show an appreciable increase radially outward, while in the dying stages there is a pronounced weakening of the radial gradient of velocity. Even before these eddy profiles were plotted, Mr. H. Wexler called my attention to the fact that such eddies should tend to remain stable as long as they rotate as solids. If the angular velocity remains constant or increases radially outward, the eddy has a stronger tendency to persist than if the angular velocity decreases outward. In synoptic practice, this criterion has been found helpful.

The centers of anticyclonic eddies are not stationary but move about. There seems to be no association of the direction of migration with any of the features of the constant level charts or surface weather maps. There is, however, some indication that the direction of displacement may be associated with the velocity distribution about the eddy itself. In the figure, arrows indicate the movement of the center of the eddy with respect to its own center in the succeeding 24 hours. From the 23rd to 24th, for example, the center has moved from o to o′. In three of the four cases of displacement studied, it appears that the direction of movement of the center of the anticyclonic eddy is towards the region of lightest tangential winds or smallest radial gradient of tangential velocity. In the fourth case, from the 24th to the 25th the displacement is small and poorly defined. The preceding rule has been applied to other eddies and appears to be of some assistance. There is also some indication that the displacement of the eddy center is greater the greater the assymmetry of the tangential velocity.

The explanation of this rule of migration is probably to be found in the theory that these anticyclonic eddies are frictionally driven by the currents of higher velocity. It is reasonable to suppose that the strong winds along certain portions of the periphery of the eddy are in excess of the gradient velocity and thus subjected to an unbalanced Coriolis force directed to their right, that is, inward toward the center of the eddy. This resultant force is probably much weaker in the regions of light wind and thus the entire system is subject to a resultant force from high towards low tangential velocity and should be displaced in this direction. In fact, when marked outward wind components are observed in eddies of this type, it is usually found that these components are most marked in the region of smallest tangential velocity.

These anticyclonic eddies, then, possess both rotation and translation. Because of the lack of symmetry in their moisture distribution both elements become important when one wishes to predict the displacement of the associated moist or dry tongues.

To the north of the prevailing westerlies it is believed that there may be a series of cyclonic vortices. On occasions the westerlies are displaced far enough to the south over the United States so that cyclonic eddies are observed. The eddies are generally associated with occluded systems, most of which have reached a deep stage of development. These cyclonic vortices are only infrequently observed within the confines of our aerological network, and when they are well within the field of observation the bad weather around them makes soundings by airplane dangerous. Thus it is not surprising that we are comparatively ignorant of the characteristics of cyclonic flow patterns on the isentropic chart. It appears fairly definite, however, that in such cases the dominating current is polar air and the tropical air is cyclonically curved merely in response to the shearing stresses of the cyclonic polar current.

Isentropic analysis of the data from such a cyclone leads to a picture which fairly well agrees with the occlusion model of the Norwegian School. A schematic representation of an isentropic flow pattern from such a cyclone is shown in Fig. 7, where the surface fronts are indicated in the customary fashion in heavy lines (cold front is solid; warm front, dotted; and occluded front, alternately dotted and dashed) and the moisture lines are light and solid.

The weather phenomena surrounding both types of eddies, cyclonic and anticyclonic, largely depends upon the distribution of moisture around them. Thus, an anticyclonic eddy consisting entirely of dry air does not create zones of bad and good weather which we recognize on the surface as fronts. But the same eddy, after an ample supply of moisture has been injected into it, produces zones of active weather changes. The sources of

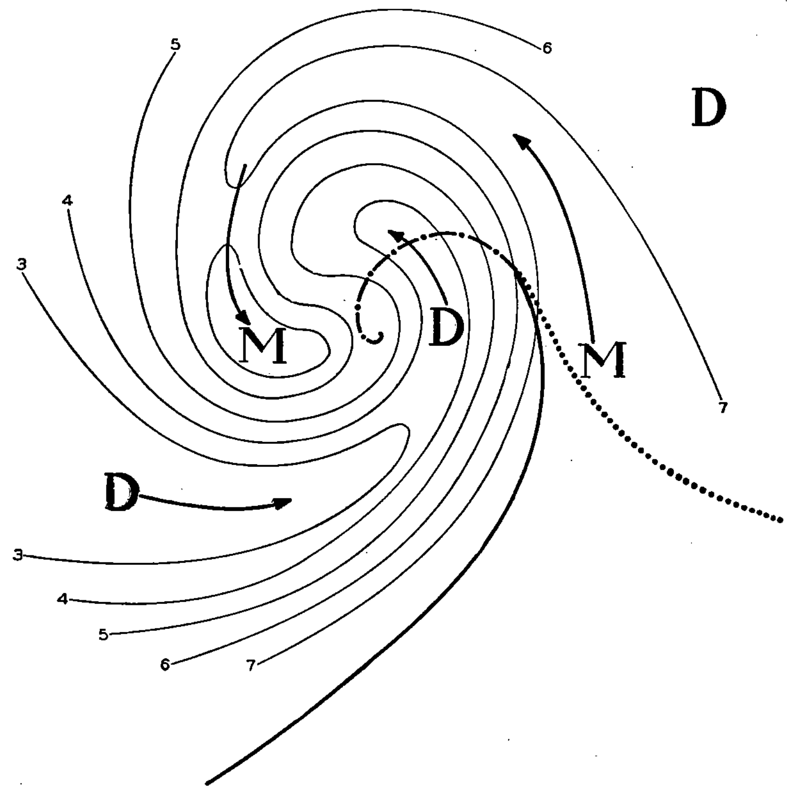


FIG. 7.—Schematic flow pattern around an occluded cyclone as indicated by the moisture lines.

moist and dry air are normally so close to one another that eddies are likely to be lacking in symmetry with regard to moisture. It is likely that the main stream of the eddy eventually makes a completely closed circuit. In this manner air currents differing in their moisture content from the main stream may be trapped in the eddy and cut off from their source region. Thus in the cyclonic eddy pictured in Fig. 7 the moist "island" is being trapped by the extensive cyclonic whirl of dry air. Similarly, an island of dry air is often trapped by a strong anticyclonic eddy composed mainly of moist air. This process, in which a portion of a current is cut off from its mother current, is perhaps best called "seclusion," a term originally applied by the Norwegians to the surrounding of the warm sector of a cyclone by polar air. But the seclusion with which we are dealing may be due to the interaction of warm and cold air or moist and dry air and moreover, may occur equally well in anticyclonic as in cyclonic eddies.

When a body of air has been trapped and appears as an island of moist or dry air on the isentropic chart, it is subjected to lateral mixing with its environment. Thus, if it is a moist island, it must gradually give up moisture to the surrounding dry air; if it is dry, it must gradually acquire more and more moisture at the expense of the moist air surrounding it. When, as sometimes happens, such a dry island in an anticyclonic eddy becomes drier, there must be non-adiabatic descent of dry air.

c. *Non-adiabatic effects.* It has been pointed out that while the movements in the free atmosphere are very nearly adiabatic over short periods of time, there are disturbing influences which tend to destroy the conservatism of potential temperature as well as of specific humidity. These non-adiabatic influences are generally of such a magnitude that they do not invalidate the flow patterns obtained from the isentropic charts but exceptions to this rule are not uncommon. There are three fundamental processes of this nature which should be considered:

1. Radiation
2. Convection
3. Condensation and evaporation.

We shall briefly discuss these processes in terms of their effect upon the elevation of a prescribed isentropic surface and upon its specific humidity distribution. In the main the effect of all three of these processes is to alter the vertical distribution of temperature so that the level of a given isentropic surface is changed. When this occurs consecutive isentropic charts no longer represent identical air particles from one day to the next. The case of radiational cooling is effectively illustrated by a diagram (Fig. 8) reproduced from a study of radiational cooling over polar regions (Wexler 1936). As the cooling proceeds the lapse rates of temperature change from a to b to c. The height of a given isentropic surface, represented by the dotted dry-adiabat in the figure, therefore increases from day to day as the cooling progresses. Since the moisture distribution normally decreases with elevation, the specific humidity observed in the isentropic surface decreases as the cooling goes on. Similar reasoning may be applied to the radiational cooling taking place at the top of a cloud. Fortunately, the rate of radiational cooling is probably small compared to other effects, so that it does not destroy the essential character of the flow pattern. This slow rate of free air cooling is indicated by the cooling curves computed by Möller (1935), which suggest that the maximum temperature change resulting from the radiative unbalance in the atmosphere hardly exceeds 1.5°C per day, corresponding under normal conditions to a maximum displacement of the isentropic surface upward of 300 m in one day. Nevertheless, it is at times necessary to introduce this factor to explain changes in moisture content or height of the isentropic surface which cannot satisfactorily be explained by advection or other causes.

The opposite effects are observed when there is radiational heating. Then the isentropic surface is lowered, and since the specific humidity at lower levels is greater than above, there appears to be an increase in moisture over the affected area of the isentropic chart. This type of non-adiabatic modification is significant near the ground, during the summer season, in continental areas.

A good example of the modifications introduced by radiative factors is afforded by a study of subsidence made by the author (Namias 1934). It was found that the potential temperature at the bases and at the tops of subsidence inversions remained fairly constant from day to day, but that there was a well marked tendency toward decreasing values of potential temperature as the inversions subsided to lower elevation. The approximate constancy of the potential temperature along the surface of subsidence lends strength to the fundamental principle of isentropic analysis. The slight lowering of the values of potential temperature as the surface of subsidence sinks must be explained by slow radiational cooling. In dealing with such situations, one may find that the specific humidity in a dry region of the isentropic surface *decreases* from day to day, although one should expect a slow increase as a result of lateral mixing with adjacent moist air within the same surface.

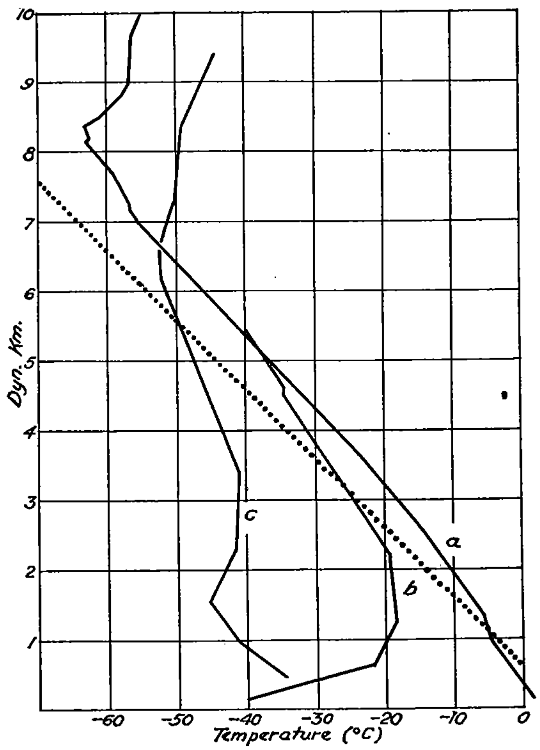


FIG. 8.—Soundings at (a) Ås, Norway, February 2, 1933, 15.11 h, (b) Fairbanks, Alaska, December 28, 1932, 9.34 h, (c) Ellendale, North Dakota, Feb. 8, 1933, 13.23 h, local time (after Wexler 1936).

The second of the processes which must be considered in maintaining continuity in the analysis of the isentropic chart is convection. The fundamental importance of this mechanism is that it serves to transport heat and moisture through the atmosphere. When the convection is brought about by thermal means, for instance through heating from below, there is a transport of moisture across the isentropic surfaces, and there is similarly a transfer of heat upward so that the isentropic surfaces are lowered. Both transfer processes lead to an increase in the moisture content of the isentropic surfaces at intermediate levels. Convection may occur at any time of the year, but is most pronounced in summer when surface heating is a maximum. It is largely for this reason that in summer the moisture supply of the isentropic chart frequently appears to be replenished over central United States.

There are many direct and indirect evidences of convection in the surface and upper air data. For example, lapse rates that approximate the dry adiabat indicate convective activity. Then again vertical convection tends to create a fairly homogeneous distribution of water vapor. A constant value of specific humidity with elevation is seldom established throughout the atmosphere, since condensation and precipitation are likely to occur before this stage is reached and thus remove some of the vapor. Moreover, a certain amount of water vapor is all the time supplied from the surface through evaporation. However, if active convection is taking place through the lowest four or five kilometers of the atmosphere, there can exist no sharp horizontal moisture discontinuities, but there must be a gradual decrease of moisture with height.

The fact that convection due to heating from below lowers the isentropic surfaces but raises the specific humidity at any fixed level makes the isentropic cross sections especially helpful in locating regions of significant convective activity. In these regions the moisture lines of the cross section bulge upward while the lines of constant potential temperature dip downward. This criterion for convective activity is not infallible, for a somewhat similar pattern of lines in the cross section prevails with the advection normal to the section of a warm and moist current between two colder air masses (a warm sector). It is usually possible, however, to differentiate between these two causes, convection on the one hand and advective transport on the other, with the aid of the upper air winds and the sea level map analysis. Moreover, in summer time convection in moist air generally leads to showers and thunderstorms, from which regions of active convective transport across the isentropic surface may be established. Indeed, if moderate thundershowers occur over an area, it is fairly certain that the convection is stirring at least 3 to 4 kilometers of air. Willett (1935) found that during all but the summer months tropical maritime air over the United States must be at least 3500 m deep in order for thunderstorms to form. This empirical finding may be an expression for the same thing, for at times it is difficult to say whether the moist air is deep because of the stirring caused by thunderstorm activity or whether the thunderstorms are formed after convergence produces a deep moist layer. At any rate there can be no doubt that thunderstorms of moderate intensity are always associated with a fairly thick layer of moist air. The regions in which such activity is taking place may therefore safely be assumed to be regions of high moisture content on the isentropic chart.

If convection takes place in a region where calm prevails both at the surface and aloft, the bulging of the moisture lines becomes a symmetrical pattern in the cross section. However, there is generally an appreciable degree of wind shear with elevation so that the moisture pumped aloft by convection may be carried far from its source by currents in the free air. Thunderstorm clouds in themselves offer a small scale picture of just this phenomenon. The high cirrus and cirro-stratus that appear in advance of the storm are carried over from the region of violent convection by the fast moving upper level wind streams. The moisture lines of the atmospheric cross sections frequently display a pattern strikingly similar to the well known "anvil" structure of the cumulo-nimbus. The scales of the two phenomena are of course greatly different; the horizontal spread of the thunderstorm anvil is generally of the order of 10 to 20 miles, while the horizontal spread of the moist air layers in the cross sections may be from 500 to 1000 miles. In individual soundings these advective moist currents show up as marked inversions of specific humidity. The "axes" of these tongues of high moisture content in the cross section (the axis being defined as a line connecting the maxima of specific humidity) frequently lie along a line of potential temperature—a fact which suggests isentropic flow. A schematic picture of the type of cross section discussed above, and frequently observed in the El Paso, Texas, to Montgomery, Alabama, cross section, is shown in Fig. 4.

If it were not for the replenishment of moisture by convective transport upward, the moist tongues of the isentropic charts would soon be robbed of their vapor through lateral mixing with the dry air flanking them on both sides. In summer time thunderstorms may truly be considered as the life blood of the moist currents.

Since we must look upon convection as one of the most important mechanisms whereby upper level sources of moisture are produced, it is of interest to note the influences of continental and maritime areas. In winter the land areas are much colder than the water surfaces, and for this reason continental air masses moving out over the sea are usually subjected to rapid heating from below. In this manner thermal convection is produced and a high level source of moisture is established. An excellent illustration of this type of convection is found in the thunderstorms formed in the Gulf of Mexico following a cold polar outbreak. In summer, however, water areas are cooler than land surfaces, so that air masses leaving the heated land are subjected to a stabilizing influence. On the other hand, maritime air currents which enter the continental areas in summer, are heated from below and the resulting convection produces upper air sources of moisture. These simple considerations may be summarized in the following manner:

The true source regions of deep moist air currents are found over maritime regions in winter, and over continental areas in summer. The analyses of daily isentropic charts at the Massachusetts Institute of Technology bear out this conclusion, and the isentropic charts constructed from seasonal means (Wexler and Namias 1938) lend further support.

We must finally consider the non-adiabatic effects of evaporation and condensation. In the case of condensation latent heat is set free, while with evaporation heat is consumed. It becomes clear, then, that in order to estimate the effects of these processes on any given isentropic surface it is necessary to know whether the condensation and precipitation is taking place above, within, or below the surface.

If the chosen isentropic surface lies above the active region, its characteristics will not be materially affected. An example is afforded by the instability snow flurries of polar continental air masses of winter. These flurries are generally formed in a shallow layer of air next to the earth's surface—a layer which is far below the representative isentropic surfaces chosen so as not to intersect the ground even in the tropical air.

Let us suppose now that condensation and precipitation set in over some region at the level of the chosen isentropic surface. Latent heat is set free and this brings about a lowering of the surface. Since the specific humidity normally increases downward it is evident that the realization of latent heat leads to increases of water vapor content in the moist tongues which cannot logically be ascribed to advective transport.

When precipitation falls from above the isentropic surface modifications in the upper air structure result from the evaporation of some or possibly all of the precipitation. Evaporation cools the air, and in this manner isentropic surfaces are brought to higher levels. If the moisture content decreases with elevation the specific humidity at the chosen isentropic surface decreases. But where precipitation is purely convective in nature, the specific humidity distribution with elevation is likely to be fairly constant, and besides, in the case of active fronts there is likely to be an increase of specific humidity through the transition zone. Thus in such cases, which appear to be in the majority, a lifting of the isentropic surface produces little change in the pattern of moisture. It appears, therefore, that the non-adiabatic effects which produce changes in the moisture distribution on an isentropic surface are chiefly convective activity and radiation. Since it appears reasonably certain that the radiational processes of the atmosphere are relatively slow, we must consider convection as the chief disturbing element in isentropic analysis.

d. *Weight of air contained between isentropic surfaces.* In the first portion of this chapter a method of representing the weight of the vertical air column between two successive isentropic surfaces was outlined. On the isentropic charts reproduced in this paper these values are shown below and to the left of the aerological stations. They represent weight of air, in millibars, between the 310° and the 305° surfaces of potential temperature. If the day to day changes of these values are plotted, and the corresponding isallobars drawn we have some indication of the regions of convergence and divergence. One should expect to find convergence to the right of fast moving currents, and divergence to the left (Rossby 1937b and 1938a). While there is some indication of this effect in our charts, it seems that the values of the weight of air between isentropic surfaces are subject to a number of disturbing effects which at times affect the temperature lapse rate much more than divergence or convergence do. For example, a cloud at the top of such a layer loses heat through radiation to space; this in turn makes the lapse rate below steeper, and the weight of air between two isentropic surfaces appears to increase. Because of these non-diabatic effects it has not yet been possible to develop a practical method of making full use of the isentropic isallobars.

Examples of such charts are reproduced in Fig. 9. The twenty-four hour isallobars are shown to the right thereof. There appears to be little relation between the two sets of charts.

II. Isentropic Analysis for the Period June 21–30, 1937

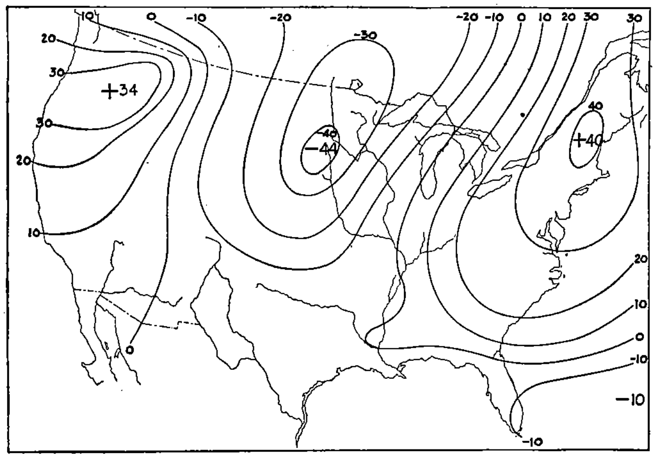
An attempt will now be made to illustrate, by means of synoptic data, some of the principles set forth in the first part of this report. In this synoptic discussion detailed descriptions have been avoided, and an effort has been made to present a bird's eye view of the principal developments during the period under consideration. The particular period selected for analysis extends from June 21 to June 30, 1937, inclusive.

1. *The Surface Weather*

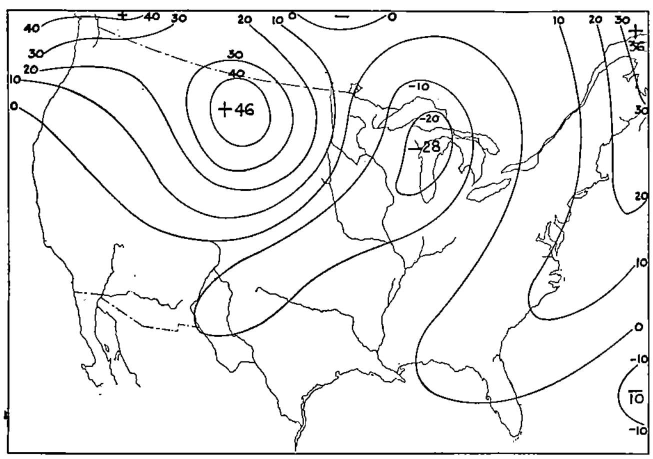
The weather over the United States during the period June 21–30, 1937, is fairly characteristic (Plates I to X) of the summer season. The frontal systems observed during this period move very slowly across the map, the horizontal pressure gradients are weak, and most precipitation appears to be of convective nature; only on the east coast and to the far north do broad frontal rain areas occasionally appear.

During this period two outbreaks of polar air occur over the eastern part of the country, and both empty into the trade winds. The first outbreak has, on the morning of June 22, reached Alabama and South Carolina. The second outbreak makes its appearance over the mountain states on the morning of the 23rd but does not reach the Gulf Coast until the 29th. These outbreaks consist originally of polar Pacific air masses, but are soon reinforced by currents from the continental region of Canada. Since the distinction between maritime and continental polar air masses over the United States in summer becomes insignificant after a short continental trajectory (Willett 1933), each one of these two polar outbreaks appears as a single, broad homogeneous current.

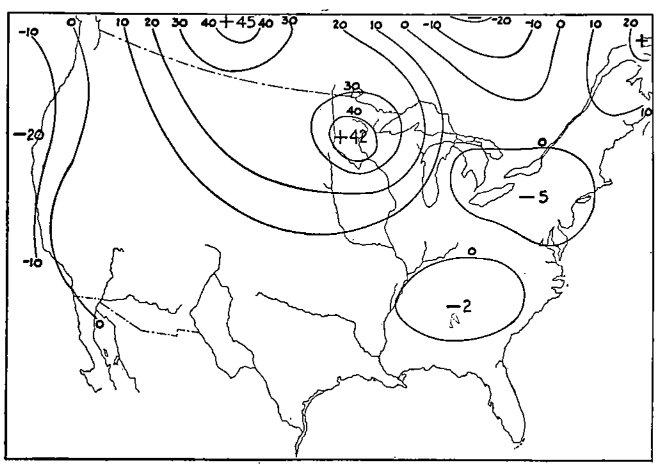
While waves form on the fronts of both these polar outbreaks, in the first instance they develop and occlude, while in the second they move as non-occluding waves, or they occlude but in the process do not deepen appreciably. Thus, during the first part of the period the polar air mass moves rapidly to the south behind a deepening wave and the anticyclone of polar air thus brought in remains over the eastern part of the country for several days. The second outbreak of polar air has difficulty in making southward progress against this anticyclone without the help of deepening wave disturbances. Moreover, the first polar outbreak is accompanied by appreciable frontal convective precipitation while the second, at least in the first stages of its history, produces very little rainfall, in spite of the fact that it is preceded by the sharper front, at least in the pressure field.



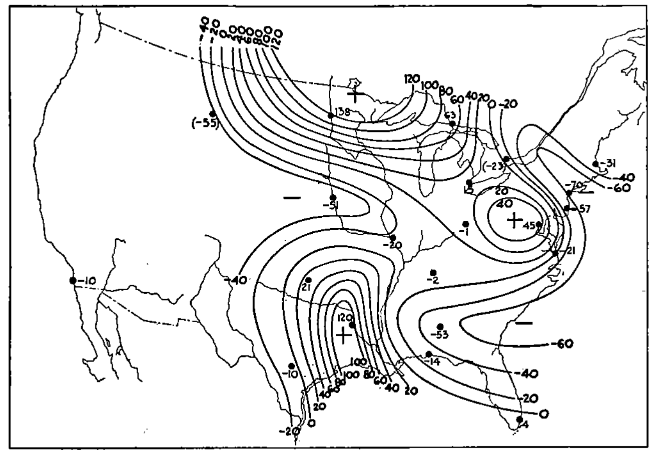
a. Surface isallobars, June 22–23, 1937.



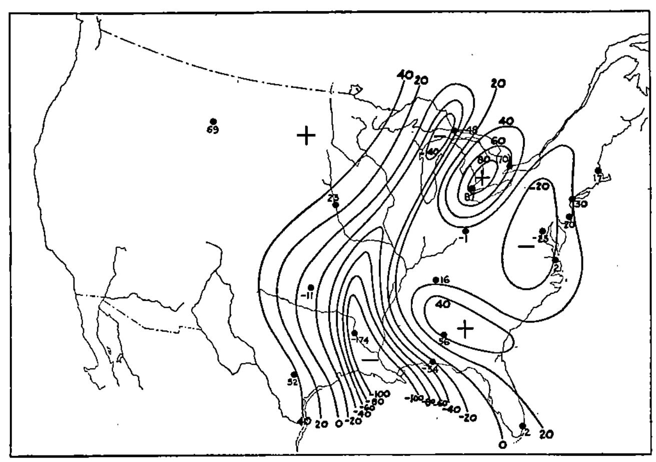
b. Surface isallobars, June 23–24, 1937.



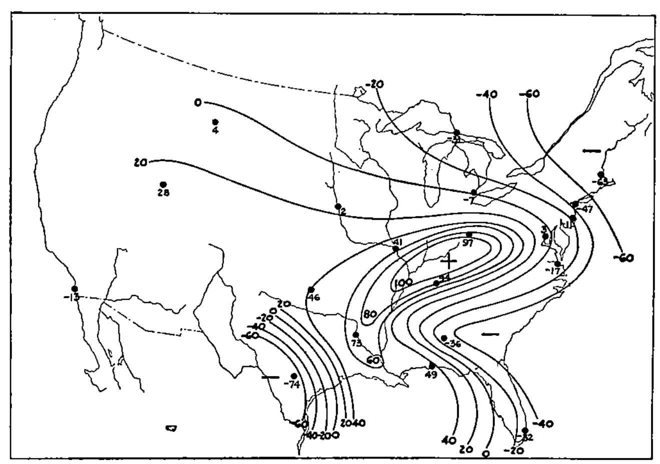
c. Surface isallobars, June 24–25, 1937.



d. Isentropic isallobars ($\theta=305°$ to $\theta=310°$) June 22–23, 1937.



e. Isentropic Isallobars ($\theta=305°$ to $\theta=310°$), June 23–24, 1937.



f. Isentropic isallobars ($\theta=305°$ to $\theta=310°$), June 24–25, 1937.

FIG. 9.—Isentropic and surface isallobars, June 22–24, 1937.

2. *General Character of Isentropic Flow Patterns*

In order to obtain a general picture of the free air structure during the period investigated we shall first describe the principal current patterns observed on the isentropic charts (Plates I to X). The first of the two outbreaks of polar air mentioned previously shows up on the isentropic charts for the first three days as an extensive area of dry air over the northern and eastern part of the country. This dry area is associated with an elevated portion of the isentropic surface and moves southeastward. The trajectory of the main body of this dry current has a cyclonic curvature. Along the southern and western boundary of this governing dry current is a narrow belt of moist air which is being dragged around the dry air in a cyclonic sense. Meanwhile, a fresh supply of moist air flows in from the northwest and coalesces with the northward-moving moist air over the middle west. Thus on the 23rd we have the simple structure pictured in Plate III, where the southern moist tongue is moving cyclonically around the dominating dry polar air, and the moist portion from the northwest and south have amalgamated into an extensive moist current that is moving northeastward, apparently up the isentropic slope. To the far west a new mass of cool and dry air is displacing the moist air and marking the advance of the second polar outbreak.

On the isentropic chart for this day there appears in the central portion of the country, a zone of pronounced wind shear and this zone extends roughly north-south. To the east thereof winds have considerable northerly components, to the west strong southerly components. The lateral shearing stresses acting along this zone produce an anticyclonic eddy which, by means of the wind and moisture distribution in the isentropic surface can be followed for several days. The circulation around the eddy tends to redistribute the moisture, so that moist air from the middle west is injected into areas previously occupied by dry air, and dry air from the east is injected into the region over which moist air lay. For a few days following the 23rd the eddy remains as a stable anticyclonic flow pattern, the dry air gradually being cut off from its eastern source and trapped by the moist air circulating around it. Meanwhile isentropic mixing reduces the gradient of specific humidity so that the dry island tends to be destroyed.

In the next section it will be shown that the anticyclonic flow of moist air aloft is responsible for the development of what appears as "local" showers on the surface maps. An attempt will furthermore be made to show that the dry air of the eddy was primarily responsible for the lack of appreciable frontal precipitation in connection with the second polar outbreak.

During the last three days of the period the isentropic charts show the formation of another anticyclonic eddy just east of the Rockies, the development of a strong cyclonic flow pattern over the North Atlantic states.

3. *On the Relation Between Shower Activity and Isentropic Flow Patterns*

A specific application for isentropic analysis has been found in the forecasting of summer thunderstorms. The principal results of this phase of our research has been discussed in a separate report (Namias 1938a) and was based on a study of the same synoptic situation as the one here treated. A brief summary of the principal conclusions follows:

Convective showers and thunderstorms are likely to form when there is a deep layer of moist air in the lower troposphere or when moist air is transported at intermediate levels. The presence of extensive dry air above a shallow moist layer effectively prevents thunderstorm activity. In the latter case there is established within the transition zone between the dry and moist air a region of very stable temperature lapse rate or even an inversion, possibly as a result of a radiative-turbulent mechanism suggested by the author (Namias 1936). The stability of this layer hinders penetrative convection from below; cumulus clouds forming in the moist air near the surface have difficulty entering the stable layer. However, lateral mixing is probably even more inimical towards convective action in this stratum than is the stability. If, as Parr (1936) has suggested, this type of mixing is most pronounced where the vertical stability is greatest, we should expect the transition zone to be most favorable for lateral diffusion. Any current of moist air that penetrates it from below as a result of convective inertia, suffers intense horizontal mixing. Because of the dryness of the admixed air the moisture of the convective current is rapidly dissipated. Presumably summer cumulus clouds are often entirely disintegrated by this process. A similar example of horizontal mixing within stable layers can be observed in the distribution of haze and smoke through inversions; thus Willett (1928) noted that haze and smoke spread *within* the inversions rather than at their bases. The lateral dissipation of moisture out of the rising current discourages further convective activity, for it is presumably through liberation of latent heat of condensation that cumulus clouds grow to thunderstorm proportions. Furthermore, lateral mixing raises the condensation level to elevations which the rising current has insufficient momentum to reach. Clearly then, the stratification of dry air above moist air is particularly unfavorable to thunderstorm activity. Willett's empirical conclusion (1935) that over the United States tropical maritime air, from October through May at least, must be at least 3500 m deep for thunderstorms to form, lends support to the above reasoning.

When a fairly thick moist current enters at intermediate levels, any inversions existing at lower levels are destroyed and the layer from which radiation proceeds to space is raised to the top of the moist layer. This facilitates convection from below, particularly at intermediate levels where the lapse rate is steepened by cooling at the upper emission layer. Currents of moist air rising from the surface are not easily robbed of their moisture and the condensation levels are not raised to impossible heights. In this manner the latent heat of condensation may supply considerable energy to the cloud systems, and eventually this convection may reach thunderstorm proportions.

The preceding conclusions are supported by movements during the investigated period of a band of apparently local thunderstorms, the trajectory of which has been plotted in Fig. 10. The individual day by day positions on this trajectory were obtained from the twelve hourly amounts of rainfall and from the thunderstorm reports. It is fairly evident that the surface front pattern and sea level pressure distribution are incapable of suggesting an explanation for this complex but orderly trajectory. However, a rational explanation appears to be available in the slow advance at intermediate levels of a moist current which gradually curls around into an anticyclonic eddy. The trajectory of this moist current and the path of the shower activity show good agreement.

4. *Detailed Day by Day Analysis*

June 21, 1937. (Plate I)

The surface weather map shows a large warm sector of T_g air in which there have been no showers in the preceding twelve hours except in the area close to the Npp-Tg front. The temperatures and dew points within this warm sector suggest that it consists of a fairly homogeneous tropical maritime air mass. The isentropic chart reveals, however, that the structure of this warm sector aloft is far from homogeneous. A narrow stream of moist air originally from the El Paso region is rapidly flowing eastward, and is flanked on either side by extensive dry and relatively cool bodies of air. Both dry currents originally came from Canada. The nature of this distribution is shown by the two north-south cross sections. The eastern section extending from Sault Ste. Marie to Pensacola indicates that along the $\theta = 310°$ line representing the intersection with the charted isentropic surface

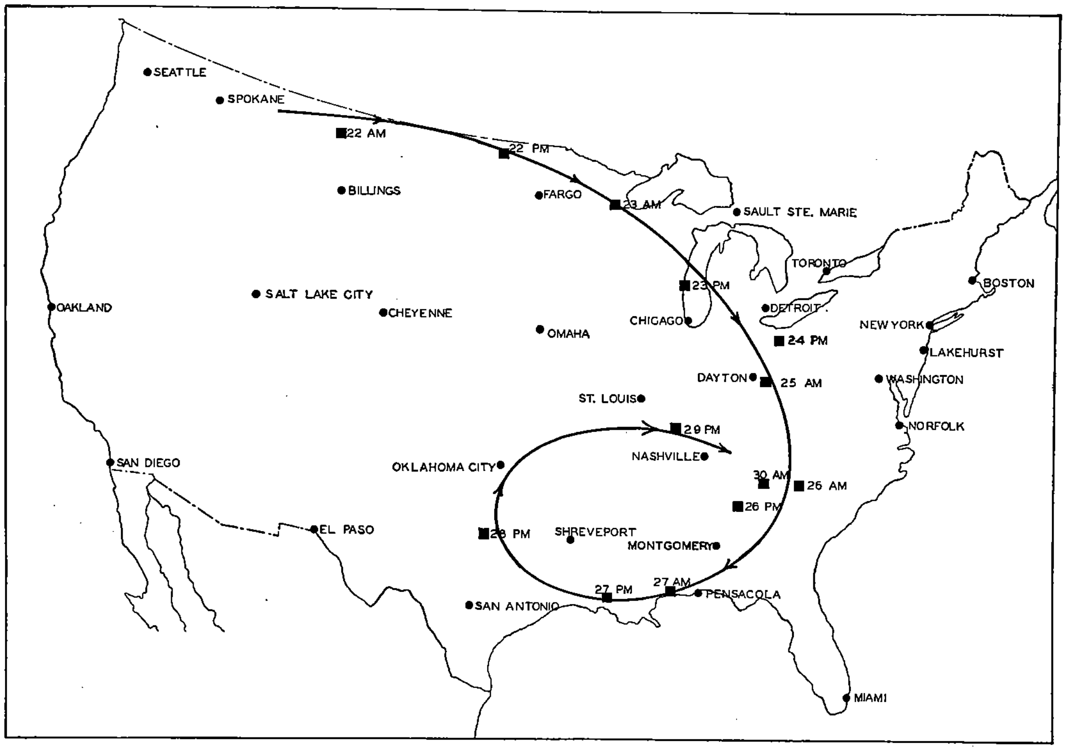


FIG. 10.—Trajectory of the center of thundershower activity associated with the anticyclonic advance of moist air aloft, June 22 to 30, 1937.

there are two moisture maxima and two minima. The dry tongues show up best at 4400 m over Sault Ste. Marie and above 2000 m over Nashville, while the moisture appears to be concentrated to the south of Pensacola and somewhere between Sault Ste. Marie and Dayton. The northern moist tongue is associated with the polar front, and the southern source appears to be essentially the result of local convection, for thunderstorms were reported during the preceding 24 hours at New Orleans. The western cross section, from Fargo to San Antonio, shows that the concentration of moisture of the main stream over this area is confined mainly to low levels. The upward bulging of moisture lines is much less pronounced than in the eastern section, and the wind distribution indicates that the frontal discontinuity is shallow, as the winds in the warm air soon shift from southerly components to northerly.

Wind velocities in the axis of the moist stream are extremely high (force 11 at Kansas City, force 9 at St. Louis). It is probable that these velocities are super-gradient and for this reason the moist tongue in this region is taking an anticyclonic trajectory. While there are few upper level wind observations in the dry and cool air to the north, it would seem that there are appreciable northerly components here. Sault Ste. Marie reports Acu clouds above the top of the sounding which are moving from the NNE. Moreover, the winds over Fargo at three km are NNW-force 12. These observations indicate a rapid displacement of the moist stream to the southward and probable domination by the cool dry tongue.

The isentropic chart also indicates that an island of moist air has been cut off from its source through inflow of dry air into the stream from both sides. The result of this process is to produce a gradual desiccation in the region where the influx of dry air is going on, and along with it a decrease of condensation and precipitation as the system moves southward.

In the Northwest we have another source of moisture, and where this moist air is forced to rise over the isentropic surface in the extreme northwest, rain is falling. This upglide process is shown by the comparison of soundings at Spokane, Salt Lake City and Billings. Though the specific humidities in the 310° surface at all three stations are not appreciably different, the relative humidities, because of the ascentional cooling, increase from 44% and 48% to 100% over Spokane.

June 22nd (Plate II)

In the east cool and dry polar air has now broken through to the south and we see from the isentropic chart that this dry air has become the dominating flow in the Atlantic states. It has a cyclonic curvature characteristic of cool polar currents moving rapidly southward. The shearing effect of this current on its environment is strikingly shown by the moisture and height lines to the south. The moist current of the 21st has apparently been severed and the moist island which on that day was located southeast of the Great Lakes is now found in the extreme north-east. A branch of the midwestern source of moisture, formerly moving anticyclonically, is now dragged around the dry and cool polar mass in a cyclonic manner. To the south the front is now producing practically no precipitation because the dry currents have cut off the supply of moisture.

The north-south cross sections offer an illuminating picture of the character of the moist and dry streams. The eastern section shows a sharp contrast from the corresponding section of the 21st. Strong northerly winds and dry air have displaced the moisture maximum of the westerlies of the 21st. The narrowness of the moist tongue resulting from the influx and mixing of adjacent dry currents is beautifully illustrated over Montgomery, where the moisture contents at levels of 3 km and above are many times those a short distance to the north and south. This cross section suggests the nature of the mechanism by which the moist tongue is cut off from its source. The cutting off process appears to be taking place chiefly at about 310°–315°. *It is just in this stratum that the vertical stability is greatest.* At Pensacola, for example, there is a layer from 2430 m to 2600 m where the potential temperature increases from 310° to 314°—an inversion of temperature. Similarly at Nashville the layer from 310° to 316° is isothermal, and at Montgomery from 307° to 312° the lapse rate is only 0.3°/100 m.

On the basis of Parr's hypothesis one should expect to observe, in this very stable zone, the maximum depletion of moisture from the moist tongue—just the phenomenon taking place in the Sault Ste. Marie-Pensacola cross section. It is probable that a similar process is responsible for the frequently observed early evening destruction of tall cumulus clouds. These clouds generally dissipate in such a manner that their tops break off from the main body presumably through lateral mixing with drier air at an intermediate level.

The Fargo-San Antonio cross section does not show a great deal of change since the preceding day, although the moisture at 3 km over Omaha has increased appreciably because of the advection of moist air from the northwest, where scattered showers and thunderstorms have occurred. The second outbreak of polar air during the period investigated has crossed the Northern Rocky Mountains and this front must be fairly steep, as indicated by the fact that the isentropic surface $\theta = 310°$ rises from 2830 m at Spokane to 4920 m at Seattle. The moisture content decreases from 9.5 g/kg to 1.3 g/kg over the same distance.

June 23rd (Plate III)

Dry polar air still dominates the eastern part of the country but along its southwestern boundary it is dragging a narrow stream of moist air eastward in a wide cyclonic arc. Along the axis of this moist tongue there have been thundershowers, and its morning position corresponds with the surface cold front.

The two moist areas located in the Middle West and Pacific Northwest on the 22nd have now merged into an extensive moist tongue whose axis runs roughly north and south. This moist tongue is beginning to show an anticyclonic curvature. The moist air responsible for the thundershowers in the northwest on the 22nd is now producing similar conditions over the area to the west of the lakes. In this case, however, the thunderstorms are caused mainly by the motion of moist air up the steep isentropic slope. The line along which the gradient of height lines begin to steepen marks the position of the warm front on the surface map—for here the temperature begins to drop sharply along a horizontal plane.

In the west, moist air is being displaced by a colder P_p air mass as indicated by the drop in specific humidity and increase in height at most of the aerological stations in this area.

Perhaps the most important thing to note in the isentropic chart for the 23rd is the zone of wind shear extending in a north-south direction and marking the boundary between the old polar air to the east and the moist and warm air to the west. This shear zone may in fact be found already on the isentropic chart for the 22nd. It is in this region we should expect the formation of frictionally driven anticyclonic eddies. Indeed, it is possible to locate an anticyclonic circulation on the isentropic chart for the 23rd with its center at the point indicated by a large asterisk. This eddy has been treated in some detail in BI2b.

The Sault Ste. Marie-Pensacola cross section brings to light the nature of the moisture and temperature distribution in a plane almost parallel to the dominating motion. The moisture forced aloft by convection west of the Great Lakes has begun to appear at upper levels over Sault Ste. Marie. Here the specific humidity rises from a minimum of 4.2 g/kg at 2360 m to a maximum of 6.8 g/kg at 3660 m. Strong northerly currents aloft are carrying this moist air rapidly southward. At Detroit, for example, alto-stratus and cirrus clouds above the top of the sounding are reported moving from the north, and at 4200 m the winds are NNW, force 9. Moreover, the influence of the moist current is already indicated at high levels over Detroit where the moisture rises from 1.4 g/kg at 3480 m to 1.8 g/kg at 5500 m, the top of the ascent.

It may be seen from the isentropic chart for this day that the specific humidity recorded at Nashville for this particular level was considered one gram too high and consequently disregarded in the construction of the moisture lines. This ascent, shown in the eastern cross section, indicates that in the region of the 310° isotherm of potential temperature there is a sharp discontinuity in moisture. It is probable that in penetrating this dry-type discontinuity the hair hygrograph did not have sufficient time to record the correct relative humidity. This type of inaccuracy of the hair hygrograph due to lag is well-known, and Spilhaus (1935) has suggested a method by which corrections may be applied in the evaluation of aerological ascents.

The Fargo-San Antonio cross section agrees with the isentropic chart, but has few noteworthy features.

June 24th (Plate IV)

The most important feature of the isentropic chart is the redistribution of moisture brought about by the anticyclonic eddy which was first noted on the chart for the day before. At Dayton, for example, the moisture content has risen from 2.0 g/kg to 9.3 g/kg since the 23rd, while dry air, injected by the anticyclonic eddy westward over the Gulf States, has caused the specific humidity at Shreveport to drop from 9.7 g/kg to 5.2 g/kg. The importance of this redistribution becomes evident if one keeps in mind the fact that advection of moist air aloft favors shower formation, dry air at upper levels prevents showers.

The eastern cross section happens to be in a favorable location since it is still very nearly parallel to the prevailing motion. It is therefore permissible to compare this section with the corresponding one for the 23rd. Currents at high levels have carried moisture far to the south so that inversions of moisture now occur at all stations in the section except Pensacola, which has not yet been reached by the moist current.

The west-east cross section extending from El Paso to Montgomery, often helpful in summer, shows the character of the dry tongue over Shreveport and the moist tongue over Montgomery. Had we chosen the 320° surface of potential temperature, it is clear that the moist tongue in the eastern part of the section would have appeared more extensive. Nevertheless, it is evident that the 310° surface gives a fairly representative flow pattern.

The polar outbreak in the northwest is associated with a steep slope of the isentropic surface, but there is very little precipitation along the sharp front. In the first place the warm air is flowing nearly parallel to the height lines of the isentropic surface and the vertical wind component must therefore be negligibly small. However, equally important is the fact that the area of high moisture indicated in the 310° chart becomes much less extensive in higher isentropic surfaces, since the southern dry tongue at these upper levels is spread out over the moist air. Therefore the condensation levels in the warm air are high and the front is not moving rapidly enough to thrust the air to these levels.

June 25th (Plate V)

The anticyclonic eddy has now carried the moist tongue far to the south, so that specific humidities at Montgomery and Pensacola have risen appreciably since the 24th. There is a tendency for this moist tongue to be cut off through the influx of dry air from the east and from the region southwest of Nashville, where the dry air of the anticyclonic eddy remains since the day before. This cutting off is illustrated by the Dayton sounding, which shows that the specific humidity has decreased 2 grams since the preceding day, evidently as the result of the sucking in of dry air from the east.

The surface weather map shows that there have been thundershowers during the preceding 24 hours along a north-south line extending from Lake Erie to a point just east of Nashville. These showers, normally considered as "local" thundershowers of the warm sector, are really associated with the moist tongue of the anticyclonic eddy. The band of activity coincides with the axis of the moist tongue in the isentropic chart for the 24th.

Strong northerly winds prevail in the easternmost dry tongue which farther south curves anticyclonically into the eddy. The dry air thus brought down over Florida prevents the formation of thundershowers over the peninsula for the next few days—a rather unusual condition in view of the fact that this region has more thundershowers than any other region in the United States (Simmers Fig. 6.).

The dry and cool air of the western polar outbreak remains in about the same position as it was on the 24th. Although thunderstorms are reported in connection with a small wave centered over Omaha, the amounts of precipitation are nowhere more than .01 inch, a fact suggesting that they are high level thunderstorms. This conclusion agrees with the statement made regarding the high condensation level of the air in the warm sector on the previous day. Most of the precipitation from these thundershowers must evaporate in layers of low relative humidity before it reaches the earth. The sounding made at Omaha on the morning of the 25th, shown in Fig. 11, illustrates this condition. The uniform steep lapse rate above the ground inversion, the gradual rise of relative humidity to saturation at the top, and the slow decrease of specific humidity upward—all these phenomena are characteristic of convection in a relatively dry current. The rain observed falling from the clouds at the top of the ascent is rapidly evaporating into the dry air through which it must fall. The cooling produced by evaporation of this precipitation helps to maintain a steep lapse rate.

The Sault Ste. Marie-Pensacola cross section does not offer as clear a picture of the motion as it did on the two preceding days because it is no longer parallel to the motion. A comparison with the isentropic chart indicates that the section alternatingly cuts through fringes of moist and dry tongues. By comparing the soundings over Montgomery and Pensacola with those of the 24th, one clearly sees the inflow of moist air aloft. The drier air at Dayton between 3 to 4 km comes from the eastern cell. The deep layer of moist air at Sault Ste. Marie and Detroit is largely the result of convective stirring, and favors heavy shower activity.

The El Paso-Montgomery cross section is similar to the corresponding section for the 24th except that the two moist tongues over Montgomery and El Paso have become more pronounced. The air above Shreveport at 3060 m has a relative humidity of only 16%. It is of interest to note that both Acu and Ast clouds reported in the Montgomery sounding are moving from the NNE, agreeing with the motion suggested by the anticyclonic eddy on the isentropic chart.

June 26th (Plate VI)

The general features of the isentropic chart are much the same as on the 25th, with the anticyclonic eddy dominating the flow pattern in the south. A dry portion of the eddy has now been completely cut off from the eastern dry cell where it originated. The dry and cool air over the northwest is now showing signs of activity, and its uplifting action has been strong enough to produce thunderstorms of moderate intensity behind the advancing surface front. The Fargo-San Antonio cross section gives a good picture of the vertical structure of the air masses and the frontal zone in this region. The moist air at Omaha has deepened appreciably, and the air mass contrast is well shown by the steep slope of the isotherms of potential temperature in the northern portion of the section.

The eastern cross section brings out the character of the dry island between Nashville and Montgomery. The section suggests that the axis of the moist current of the eddy must be located south of Pensacola.

On the coast of New England rain has set in. On the basis of the surface maps this precipitation would normally be ascribed to a wave disturbance moving in towards the coast from the south or southeast. The available ship observations in the Atlantic for this period are inadequate to definitely establish the existence of this wave. It is also possible that the rain area has moved in from the northeast. This movement is suggested in the isentropic charts by strong N and NNE currents in the dry air over the northeast portion of the country on the 25th and 26th. Moreover, on the 25th rain fell over Nova Scotia and the rain appeared to move southwestward. From the isentropic charts, one would say that moist air was dragged in from the east and northeast by the sucking action of the dominating northerly stream of dry air, in much the same fashion as Rossby (1936) showed the Gulf Stream to enlarge owing to admixture with water from its environment. In the Norwegian terminology this disturbance would perhaps be classified as a retrograde depression (Bjerknes and Giblett 1924).

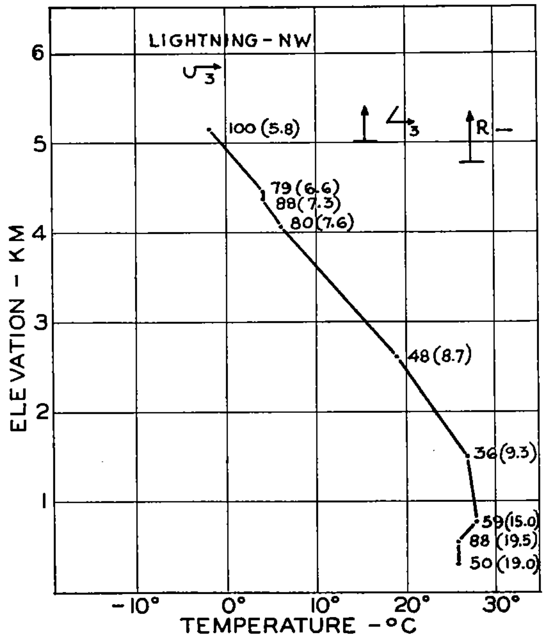


FIG. 11.—Upper air conditions during a high level thundershower at 4 a.m. over Omaha, June 25, 1937.

June 27th (Plate VII)

The sea level map shows that the polar air has advanced a few hundred miles southward and eastward but the shower activity has largely ceased. No explanation for this is available on the surface map but the isentropic chart suggests that the moist tongue with which the front is associated now is being destroyed through lateral mixing with drier air masses to both sides. The thunderstorms a few hundred miles in advance of the front in the southeast are associated with the continued advection of moist air from the north around the anticyclonic eddy.

The Fargo-San Antonio cross section shows the displacement of the moist tongue to the south since the previous day and also an increase in the height of the isentropic surfaces to the north owing to the advection of polar air.

The El Paso-Pensacola section is particularly noteworthy for it cuts across the dry portion of the anticyclonic eddy. Without this cross section it would have been very difficult to locate the axes of the moist and dry tongues. Merely using the values of the isentropic chart as a guide to drawing the moisture lines one might argue that the moist tongue lies between San Antonio and El Paso rather than in the position indicated. However, it is not possible to analyze the El Paso-Pensacola cross section so as to be reasonably consistent with this interpretation. Moreover, the sounding made on the morning of the 27th at San Diego shows an increase of specific humidity from 3.4 to 3.9 g/kg from 4030 to 4900 m, showing the westward advance of the moist tongue. On the evening of the 27th San Diego reports Acu clouds moving from the SE, and at 2 o'clock in the morning a thunderstorm occurred—a comparatively rare phenomenon for southern California. Even stations in the desert, for example Yuma, Arizona, reported showers following the influx of the moist tongue. These observed facts could not readily be explained if the axis of the moist tongue had been placed between San Antonio and El Paso.

June 28th (Plate VIII)

The isentropic chart shows that the second polar air outbreak now has reached the Atlantic Seacoast, and, like the first outbreak, has a cyclonic curvature. Indeed, the entire flow over eastern United States is governed by this cyclonic flow pattern.

The anticyclonic eddy is now breaking down but the moisture distribution it has created still persists in the southern part of the country although contrasts are diminishing as a result of strong lateral mixing. The moist tongue far to the south continues to move eastward and is invading Texas. The influence of this tongue during the following 24 hours is manifested by severe thundershowers over Texas, inland from the Gulf coast.

Returning to the dominating polar air current, it appears to have caused the moist current to move around cyclonically and into the area south and west of New England. Thus at New York the specific humidity is 10.2 g/kg at the 310° surface, while at Boston it is only 3.2 g/kg and at Washington, 5.1 g/kg. The forced ascent of this moist air along the isentropic surface produces a continuous band of rain throughout New York State and southward to Virginia. The surface maps indicate that this belt of rain later moves in a NNE direction, which agrees with the circulation suggested by the isentropic chart.

The eastern cross section bears out the isentropic analysis by showing the dry and cool tongues to the north and south of Montgomery. From this section it is obvious that any isentropic surface above the surface layers would show the same general flow pattern.

The Fargo-San Antonio cross section also agrees with the isentropic chart. The globule of moist air between Omaha and Oklahoma is probably best explained as the advance portion of the moist current to the west.

In the area between Fargo, Omaha, Salt Lake City, and Billings an anticyclonic eddy is forming in the shear zone between the northerlies of the polar flow and the moist southerly current. The moist globule at about 4 km between Omaha and Oklahoma also suggests this eddy.

June 29th (Plate IX)

The cyclonically flowing polar air has carried the moist tongue far to the south and east, and the remaining dry air from the first polar outbreak has completely lost its identity through mixing with moister air currents. The moist tongue far to the south is nicely verified by the Sault Ste. Marie-Pensacola cross section. Otherwise, we have in this section an extensive mass of cool, dry polar air.

In the west the anticyclonic eddy between the northerly dry current and the southerly moist stream appears more well-defined in the wind circulation than it did on the preceding day. On the isentropic chart an island of moist air is indicated as having broken off from its supply of moisture to the west. The upper wind indications seem to point to this conclusion, and the surface maps show that an area of precipitation and thundershowers has moved southward over Iowa during the night of the 28th. While the mechanism of this shedding of a moist island is not clear, it is possible that it is associated with convective activity that serves to pump to upper levels the moisture from lower layers. This convection may be set off by radiational cooling from layers of moisture at high levels. Already in the Fargo-San Antonio cross section for the 28th we saw the moist current at the level of about 4 km entering from the west between Oklahoma and Omaha. It is possible that the outgoing radiation from this high level source of moisture may be responsible for initiating the convection resulting in nocturnal thundershowers over Iowa. The island of moisture, once established, moves on with the dominating flow in which it finds itself entrapped. Unfortunately there are no upper air winds in the region of this moist island, but a few cloud observations show Acu moving from the NW and W. Apparently the moisture has been carried into the cyclonic circulation around the polar outbreak. This contention is further substantiated by the fact that from the 29th to the 30th showers and a number of thundershowers break out in a band extending roughly in a SW-NE region from western Tennessee to southern New England. It is interesting to note that a front is entered on the surface maps in the region in which showers occur on the night of the 29th, although there is no evidence for this front on the morning map. It would appear from the isentropic analysis that convection in the moist air *preceded* the formation of the front at the surface.

In the far west it is raining. This precipitation is undoubtedly associated with the moist tongue first observed entering the region between El Paso and San Diego on the 27th. Cases of rain of a similar nature have been described by Reed (1933).

June 30th (Plate X)

The moist island from the middle west has been caught in the fast moving cyclonic circulation around the dome of the height lines and carried far to the northeast, so that it appears to be centered south of New England. The western anticyclonic eddy is well developed in the wind circulation and also the pattern of moisture lines. This pattern is substantiated by the Fargo-San Antonio cross section in which a moist tongue appears just north of Omaha at about 3 km. Penetrating this level we note that the winds shift from N at 2400 m to NNW at 3000 m, then back to N at 3600 m. There can be no doubt that the moist air comes from the western source. The well marked dry tongue over Oklahoma is now rapidly circulating around the eddy. Tangential components of the winds are strongest on the east side and weakest on the SW side of the eddy. This dissymmetry indicates that the center of rotation will move in a southwesterly direction. There is evidence in the isentropic chart for July 1st (not reproduced) that this direction was followed. Another anticyclonic eddy is indicated as forming over the Gulf of Mexico.

It is significant that these eddies are not even remotely suggested by the surface weather map.

III. Summary

The free atmosphere may be considered to consist of an infinite number of superimposed isentropic sheets of infinitesimal thickness and constant potential temperature. As long as the movements of the air take place adiabatically, each such layer retains its identity from one day to the next.

The use of upper air data in synoptic analysis becomes particularly effective when the free air structure is described with reference to these infinitesimal isentropic sheets or surfaces. Upper air analysis based on this method of representation has been named isentropic analysis. With a network of aerological stations as dense as over the United States it is possible to carry on an uninterrupted day to day isentropic analysis, but the process would be greatly facilitated and the results would gain in reliability if the number of aerological stations were appreciably increased and if soundings were made every twelve instead of every twenty-four hours.

The method of isentropic analysis described in this report has been developed chiefly through the daily study of upper air data at the Massachusetts Institute of Technology. It has been found that isentropic charts cannot be constructed in a purely mechanical fashion but that the best results are obtained when coordinated use is made of isentropic charts, cross sections and surface weather data. By a process of successive approximations it is then normally possible to obtain a satisfactory solution of the free air flow pattern. The individual steps in this process are:

1. For each airplane or radio-sonde station, the values of the various meteorological elements (including the wind) at one or several representative isentropic levels are computed and plotted on ordinary weather base maps.
2. A first approximation to the pattern of contour lines for these isentropic surfaces is sketched, taking into consideration the indications furnished by the sea level weather and isallobaric charts.
3. Upper air winds from all other stations are entered on the isentropic charts with the aid of the elevations obtained from the preliminary contour lines.
4. The preliminary contour lines are erased.
5. Lines of constant specific humidity on the isentropic charts and on the cross sections are sketched so that by mutual adjustment a flow pattern is obtained which maintains reasonable continuity with the isentropic analysis for the preceding day.
6. The final flow pattern of moisture and contour lines is constructed.

The flow patterns studied thus far appear to be established and governed by fast-moving air currents. For the most part these patterns have consisted of anticyclonic eddies of widely varying dimensions, although cases of cyclonic eddies are by no means rare. The eddies are generally asymmetrical in their distribution of moisture. Thus moist or dry bodies of air are frequently trapped near the center but are likely to lose their identity through isentropic mixing with the environment. There is some evidence that this type of mixing is most pronounced in regions of greatest (vertical) stability. The life history of an eddy appears to be determined largely by the distribution of wind velocity around it.

There are important non-adiabatic effects which tend to obscure the continuity of isentropic analysis, and of these convection is the most disturbing. However, it is generally possible to locate and to evaluate qualitatively the effects of convection as well as the less disrupting effects of radiation, condensation and evaporation.

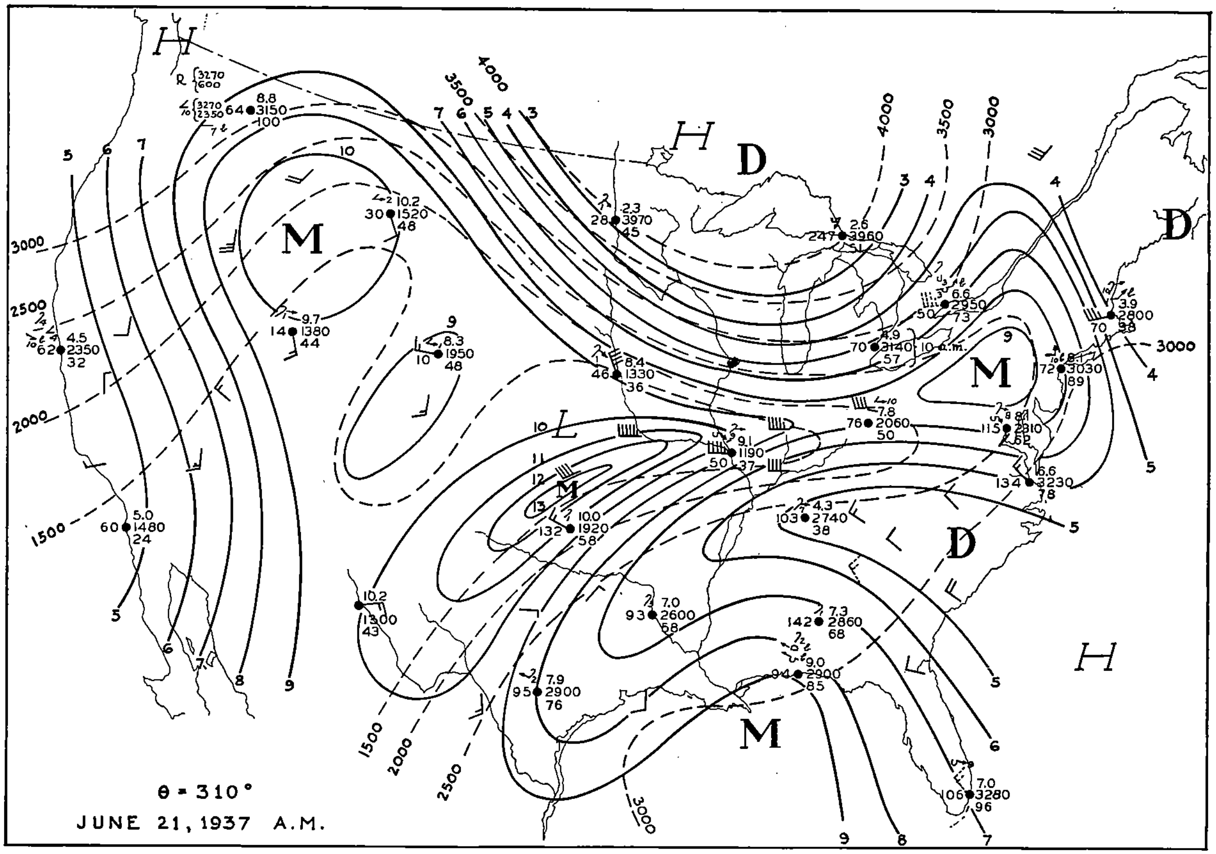
The isentropic analysis for the period June 21–30, 1937, has been presented to illustrate the practical use of the method in daily routine, and to bring to light examples of phenomena discussed in the first portion of the report.

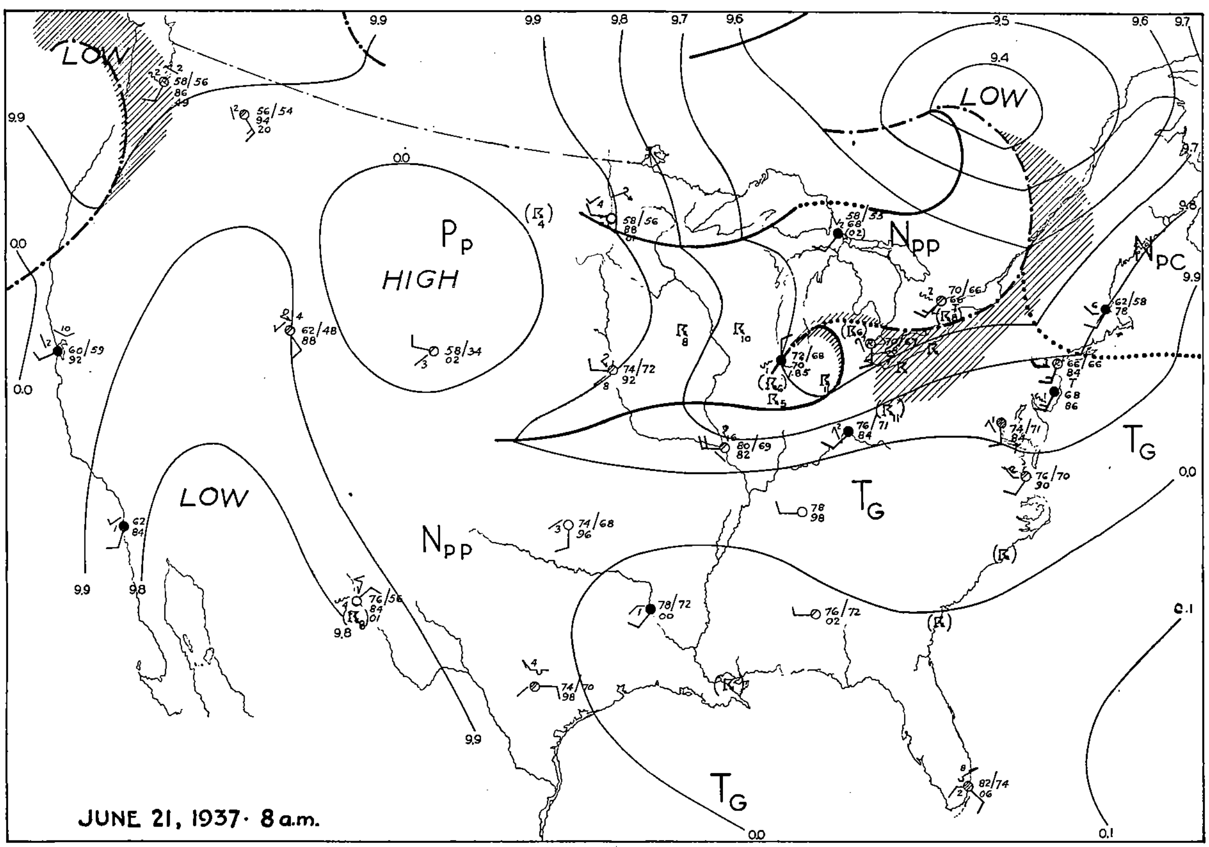
IV. Plates

Surface weather maps. Cold fronts are indicated by heavy solid lines, warm fronts by dotted lines, and occluded fronts by alternately dashed and dotted lines. The hatching indicates areas where precipitation is falling at the time of observation. Air mass symbols are those customarily in use in the United States. Surface observations at or near aerological stations (circles) are entered in the customary manner. To the right of the circles from top to bottom: temperature and dew point (°F), pressure, and precipitation. Winds are indicated by arrows, the numbers of half barbs corresponding to Beaufort numbers of force. To the left of the station are the clouds in international symbols, and the pressure characteristic and change in the preceding three hours. Thunderstorms occurring in the preceding 24 hours are indicated by the international symbol, and a subscript shows the time of occurrence. Those enclosed in parentheses took place in the first twelve hours of the preceding 24 hour period, those not enclosed within the last twelve hours.

Isentropic charts. Solid lines are lines of specific humidity while dotted lines are lines of elevation (in meters) of the chosen surface above sea level. "M" signifies the center of a moist tongue, "D" the center of a dry tongue. "H" and "L" are entered at the crests and troughs of the isentropic sheet. The numbers to the right of the aerological stations are, in the order listed, the specific humidity, the elevation, and the relative humidity at the given isentropic sheet. To the left of the station is entered the weight, in millibars, of the layer bounded by the 305° and 310° surfaces of potential temperature. The change from day to day in these values offers indications of convergence and divergence. Winds at the isentropic surface are shown by arrows, the number of half-barbs being roughly equivalent to Beaufort numbers of the scale of wind force. Clouds are indicated by the international cloud symbols. Subscripts give the amount of cloud and arrows the direction of movement. If the letter "b" appears following the symbol the clouds are below the isentropic sheet, if elevations are given the clouds penetrate the sheet, and if nothing is appended they are above it. An asterisk (*) indicates that the clouds are within the range of the sounding, yet no height was recorded.

Vertical cross sections. The evenly spaced horizontal lines represent full kilometers of height. Solid lines are drawn for specific humidity, dashed lines for potential temperature. The humidities in the individual soundings are entered to the left and the potential temperatures to the right of the vertical. The method of indicating wind direction is described on page 22. Clouds are indicated by the international symbols; those above the soundings are either above the top of the ascent, or, if accompanied by an asterisk, within the levels penetrated by the sounding but not placed specifically. Here again "M" stands for moist, "D" for dry.


θ = 310°
JUNE 21, 1937 A.M.
M
D
H


JUNE 21, 1937 · 8 a.m.
LOW
HIGH
P_P
N_{PP}
N_{PC}
T_G

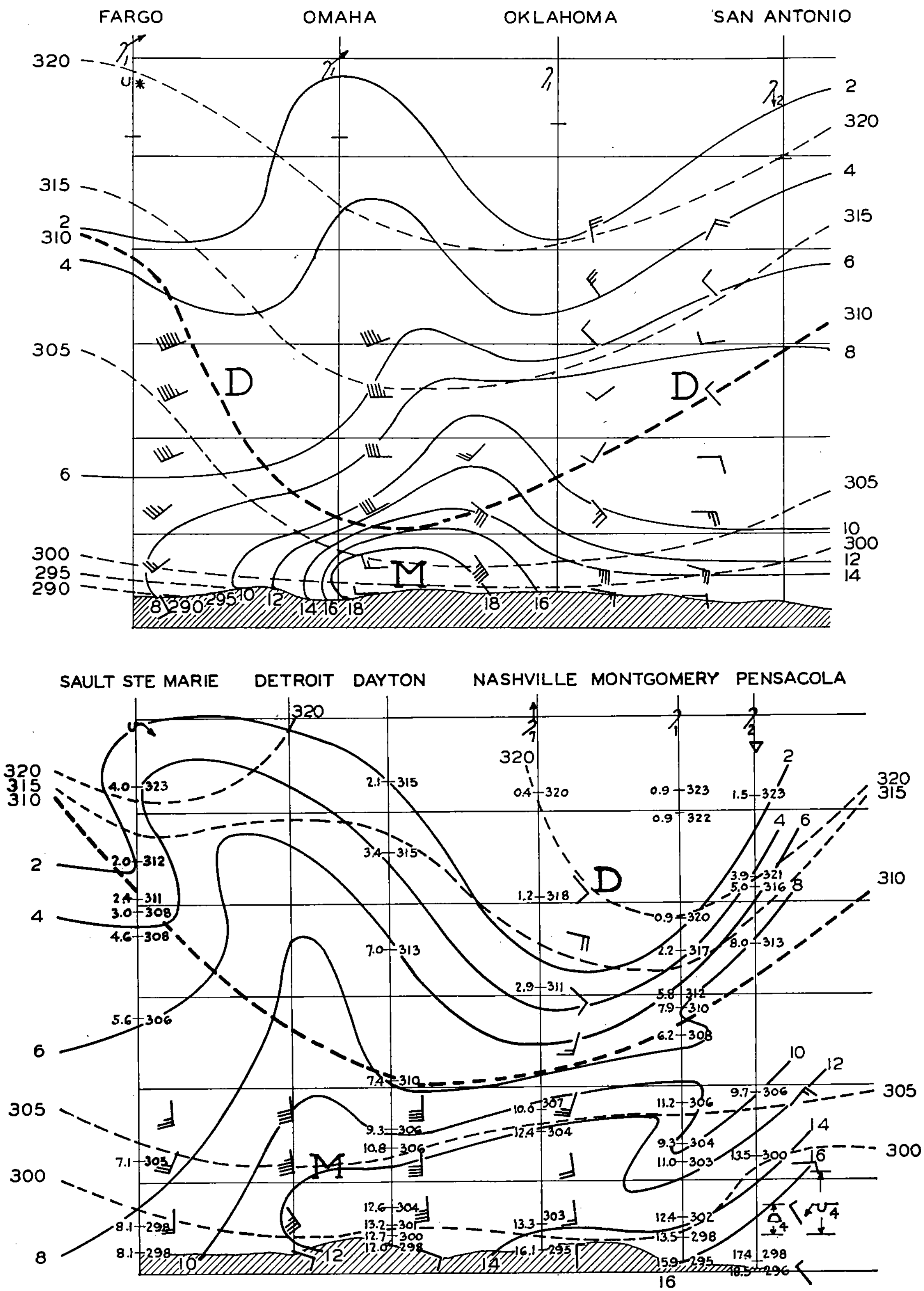
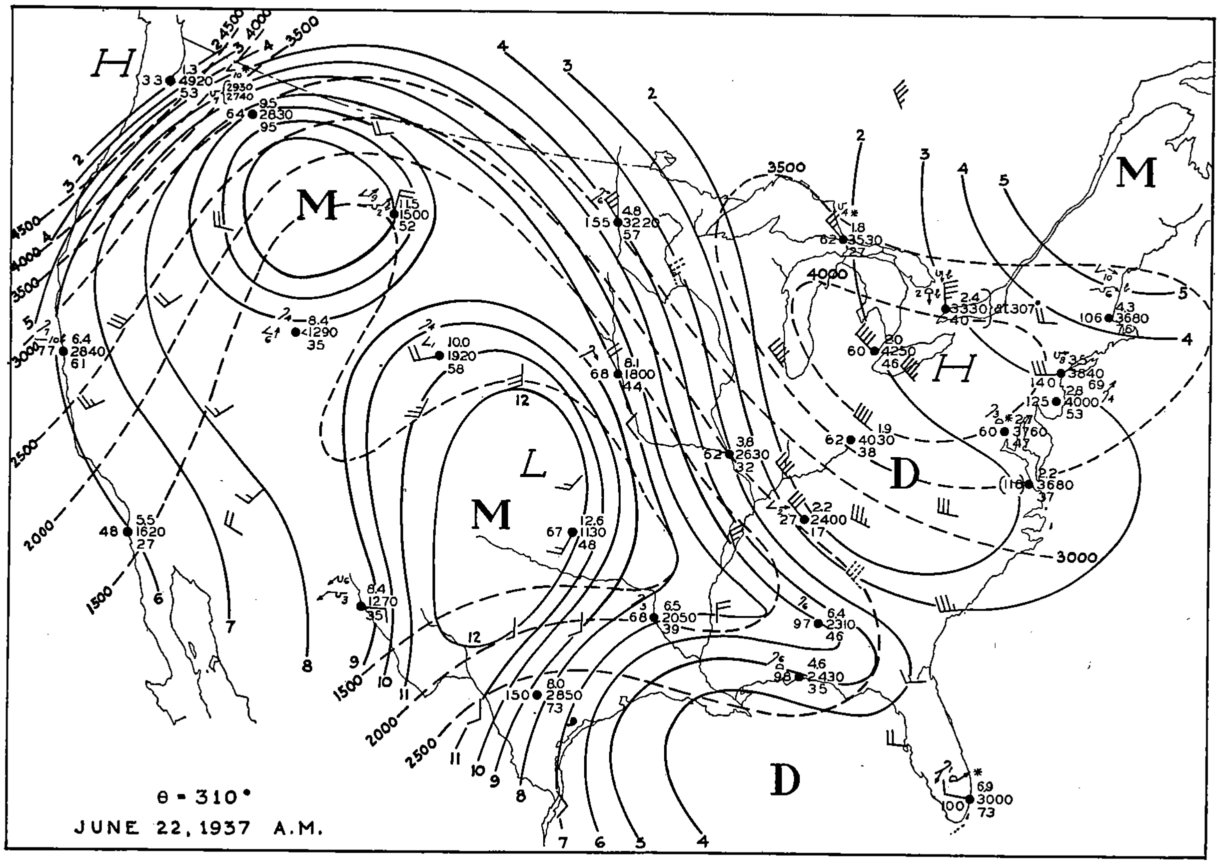

FARGO
OMAHA
OKLAHOMA
SAN ANTONIO
D
D
M
SAULT STE MARIE
DETROIT
DAYTON
NASHVILLE
MONTGOMERY
PENSACOLA
D
M

PLATE I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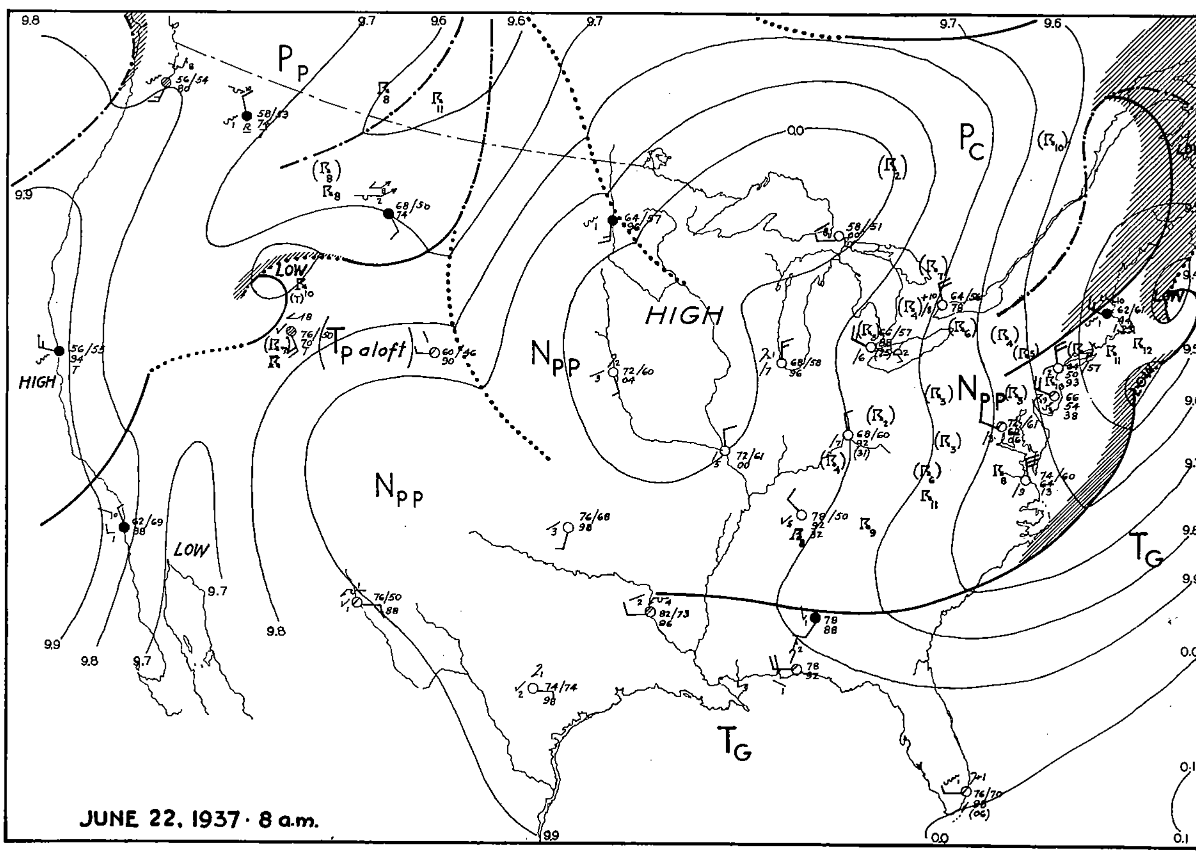
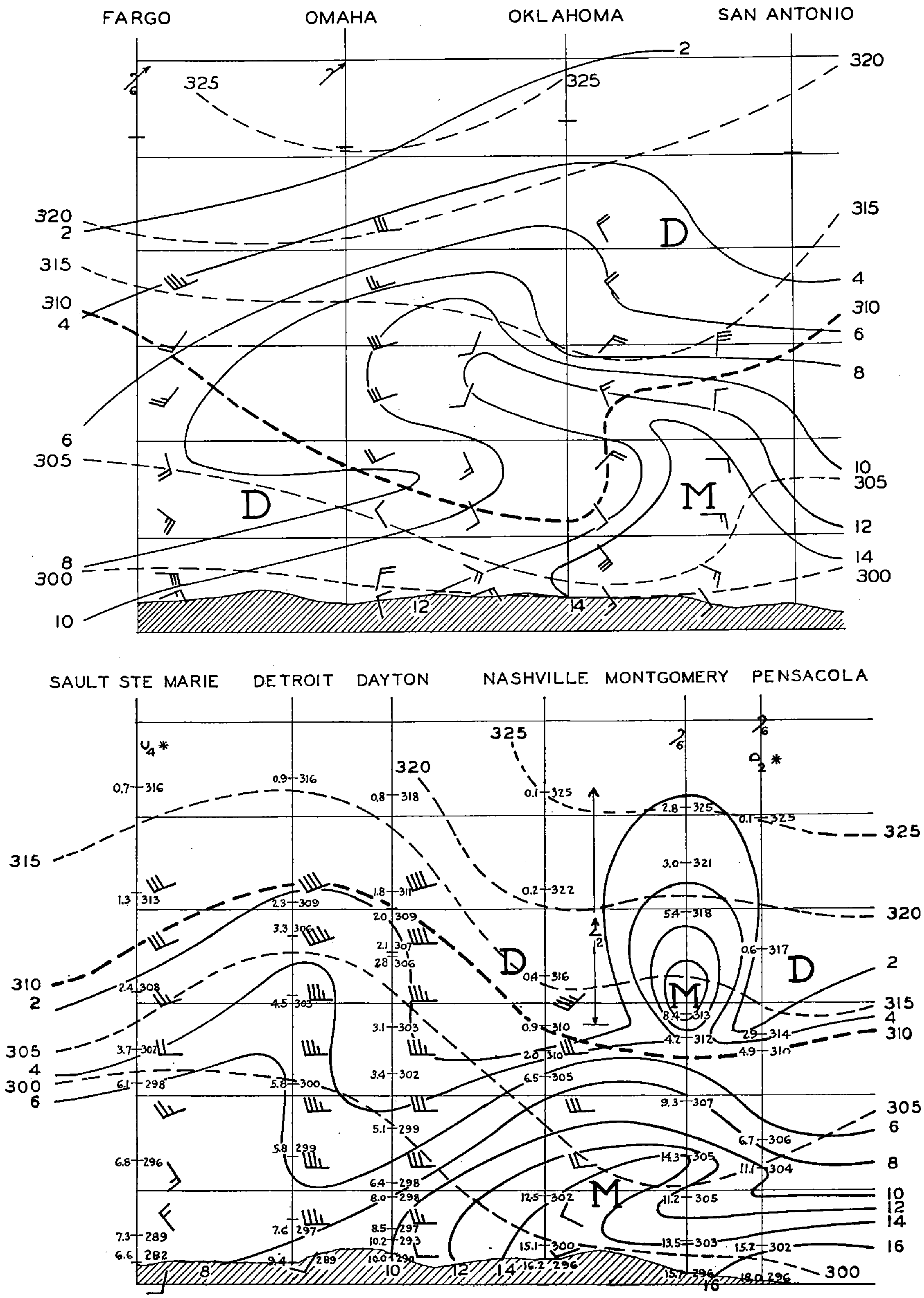
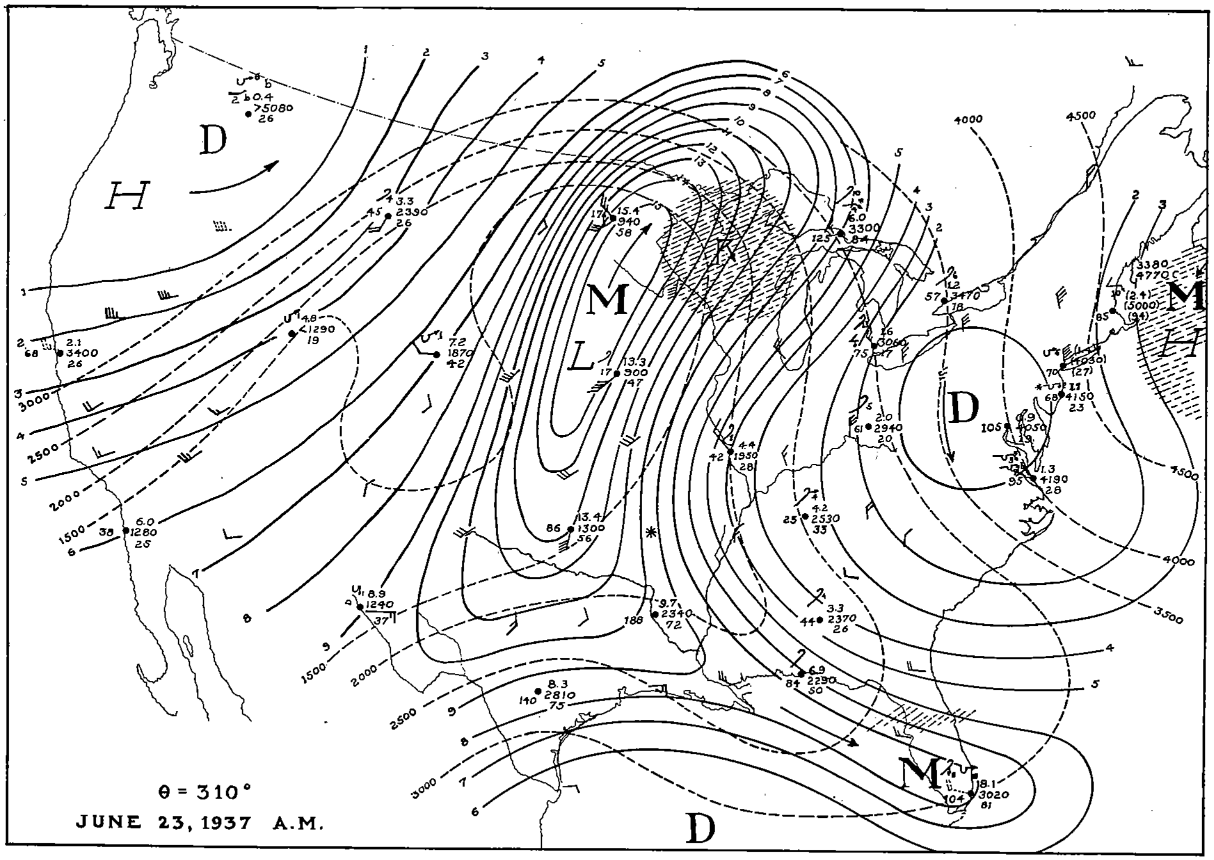
JUNE 22, 1937 A.M.

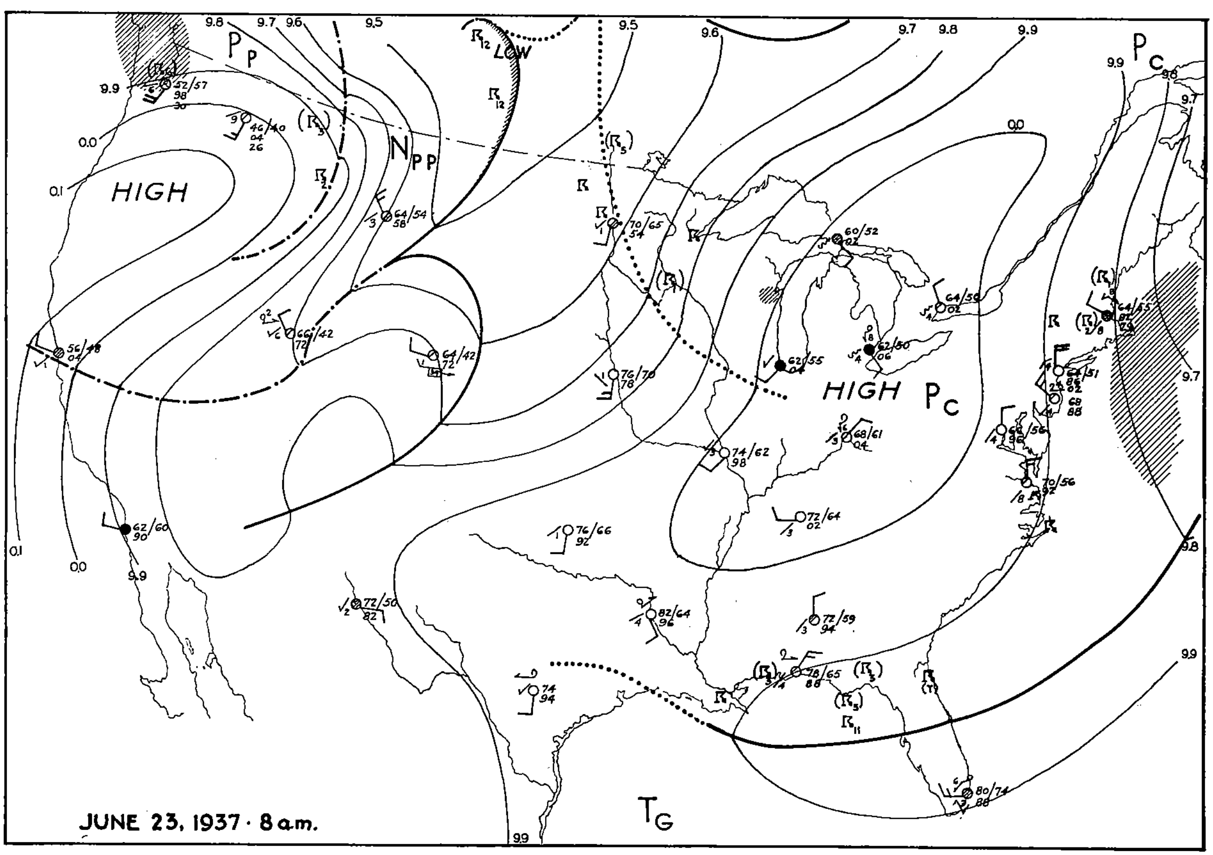

JUNE 22, 1937 · 8 a.m.

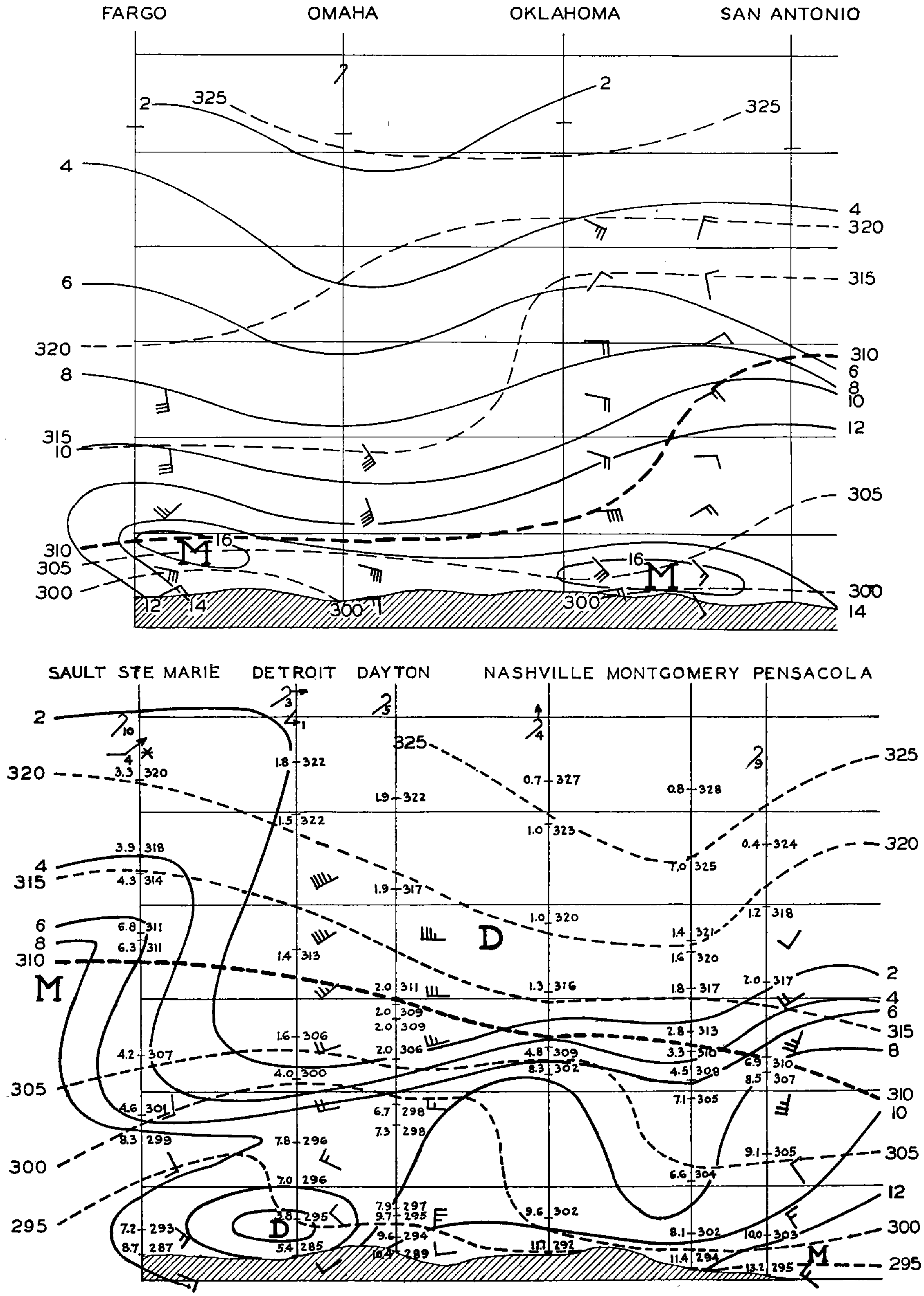


FARGO
OMAHA
OKLAHOMA
SAN ANTONIO
SAULT STE MARIE
DETROIT
DAYTON
NASHVILLE
MONTGOMERY
PENSACOLA

PLATE II

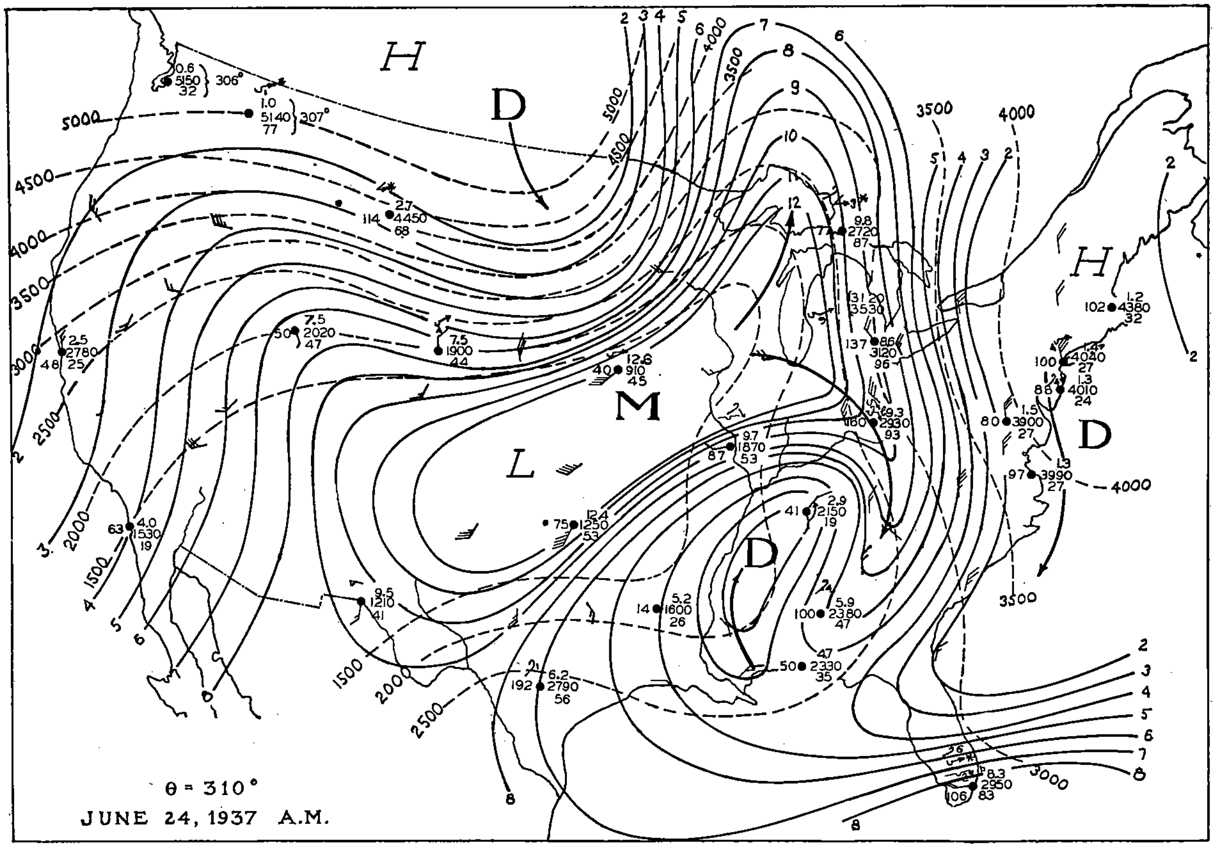

D
H
M
L
D
M
H
M
D
θ = 310°
JUNE 23, 1937 A.M.

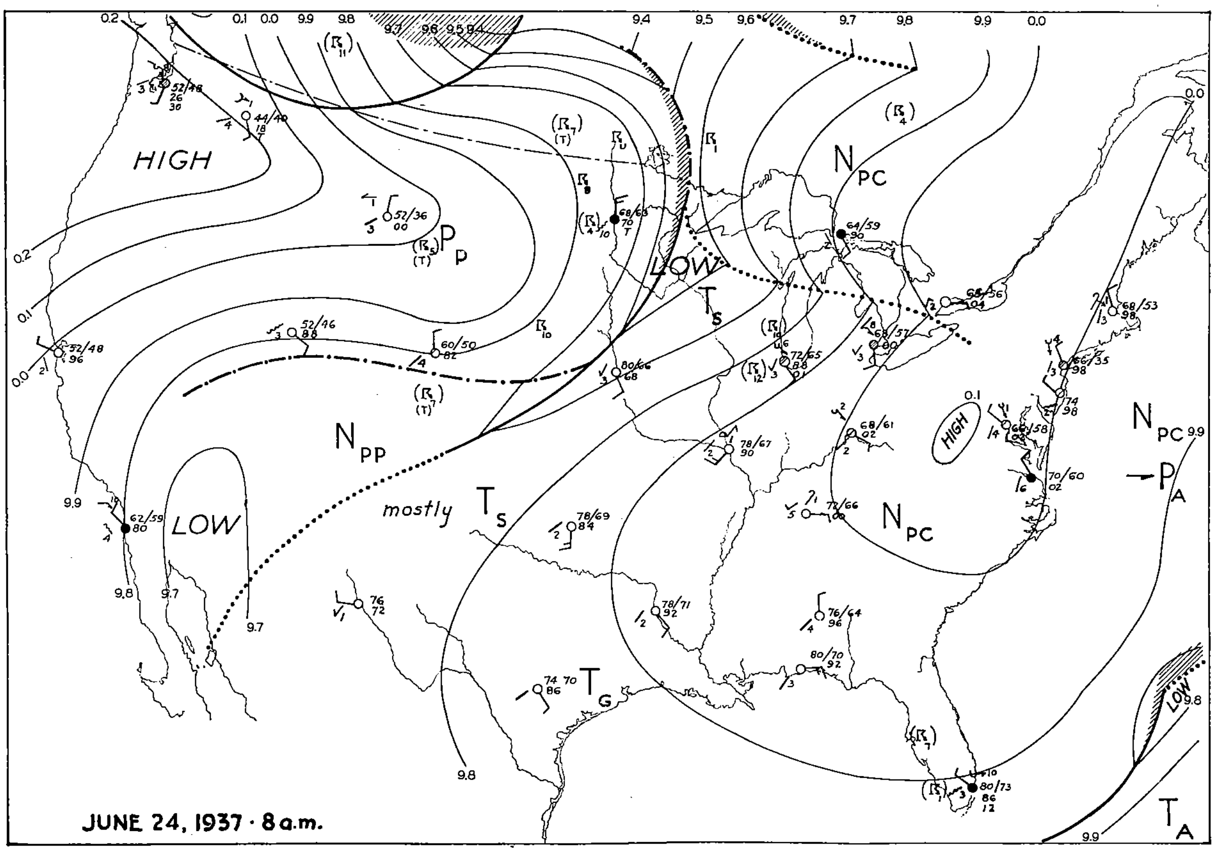

P P
N PP
LOW
HIGH
HIGH P C
P C
T G
JUNE 23, 1937 · 8 a.m.



FARGO
OMAHA
OKLAHOMA
SAN ANTONIO
SAULT STE MARIE
DETROIT
DAYTON
NASHVILLE
MONTGOMERY
PENSACOLA

PLATE III


H
D
M
L
D
H
D
θ = 310°
JUNE 24, 1937 A.M.


HIGH
LOW
LOW
HIGH
LOW
Npc
Npp
mostly Ts
Ts
Tg
Pp
Pa
Ta
JUNE 24, 1937 · 8 a.m.

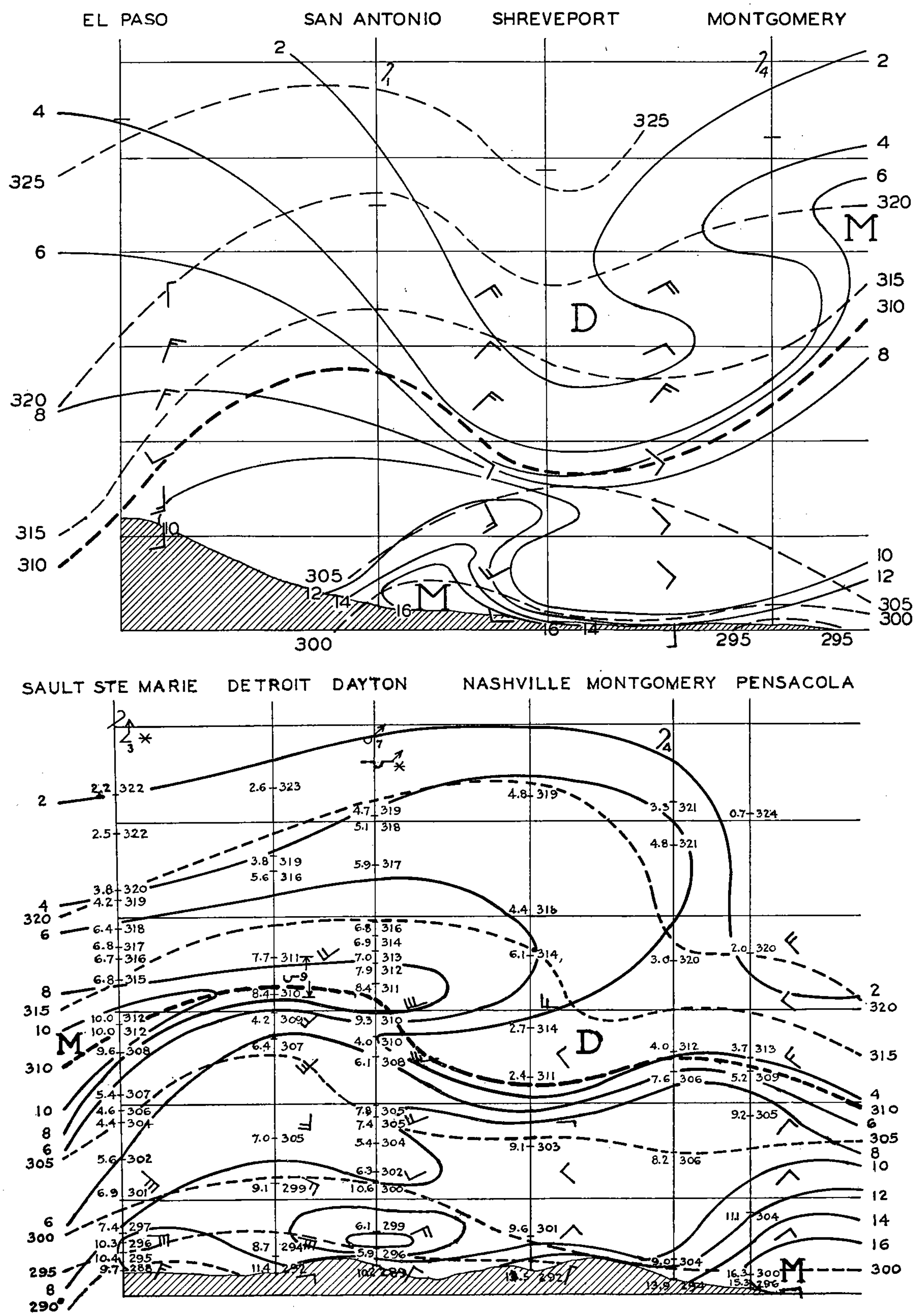
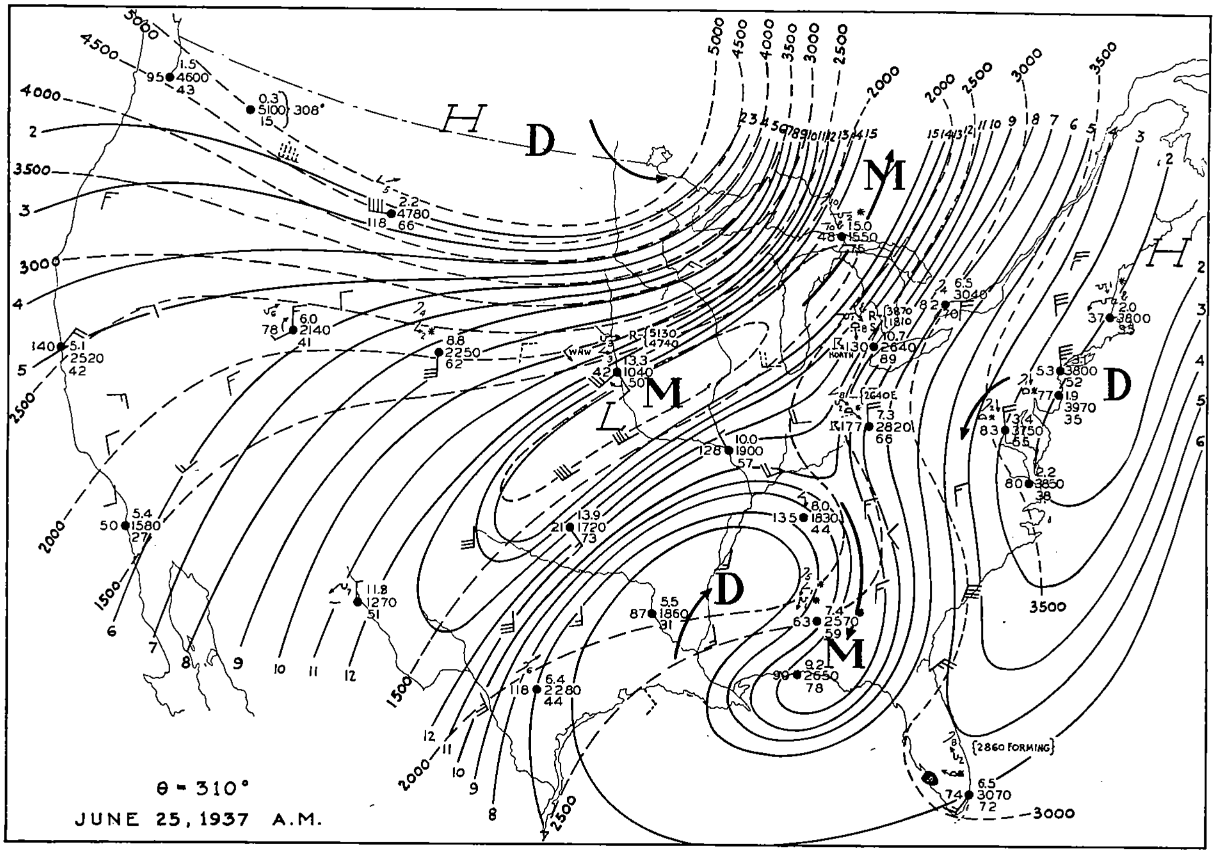
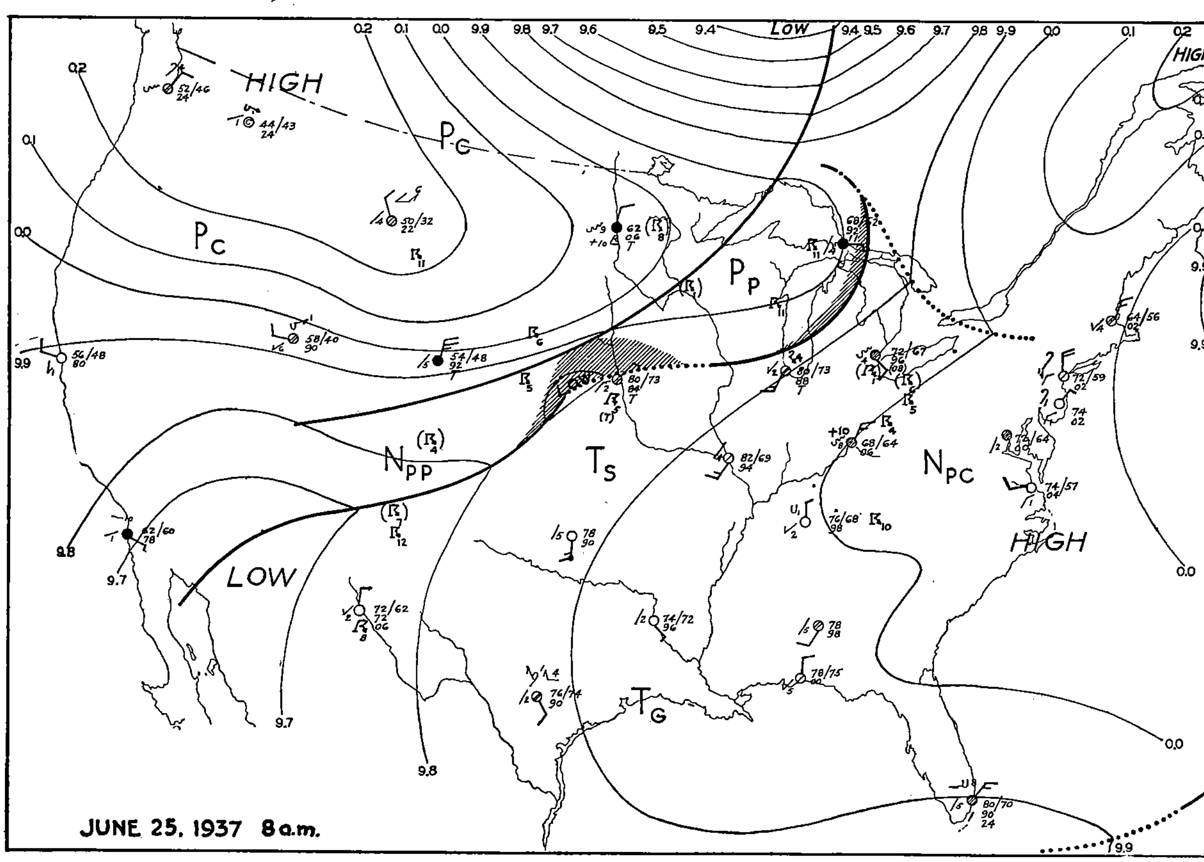

EL PASO
SAN ANTONIO
SHREVEPORT
MONTGOMERY
SAULT STE MARIE
DETROIT
DAYTON
NASHVILLE
MONTGOMERY
PENSACOLA

PLATE IV


θ = 310°
JUNE 25, 1937 A.M.
H
D
M
M
L
D
M
D
H
(2860 FORMING)


HIGH
LOW
P_C
P_C
P_P
N_{PP}
T_S
N_{PC}
HIGH
HIGH
LOW
T_G
JUNE 25, 1937 8 a.m.

NAMIAS

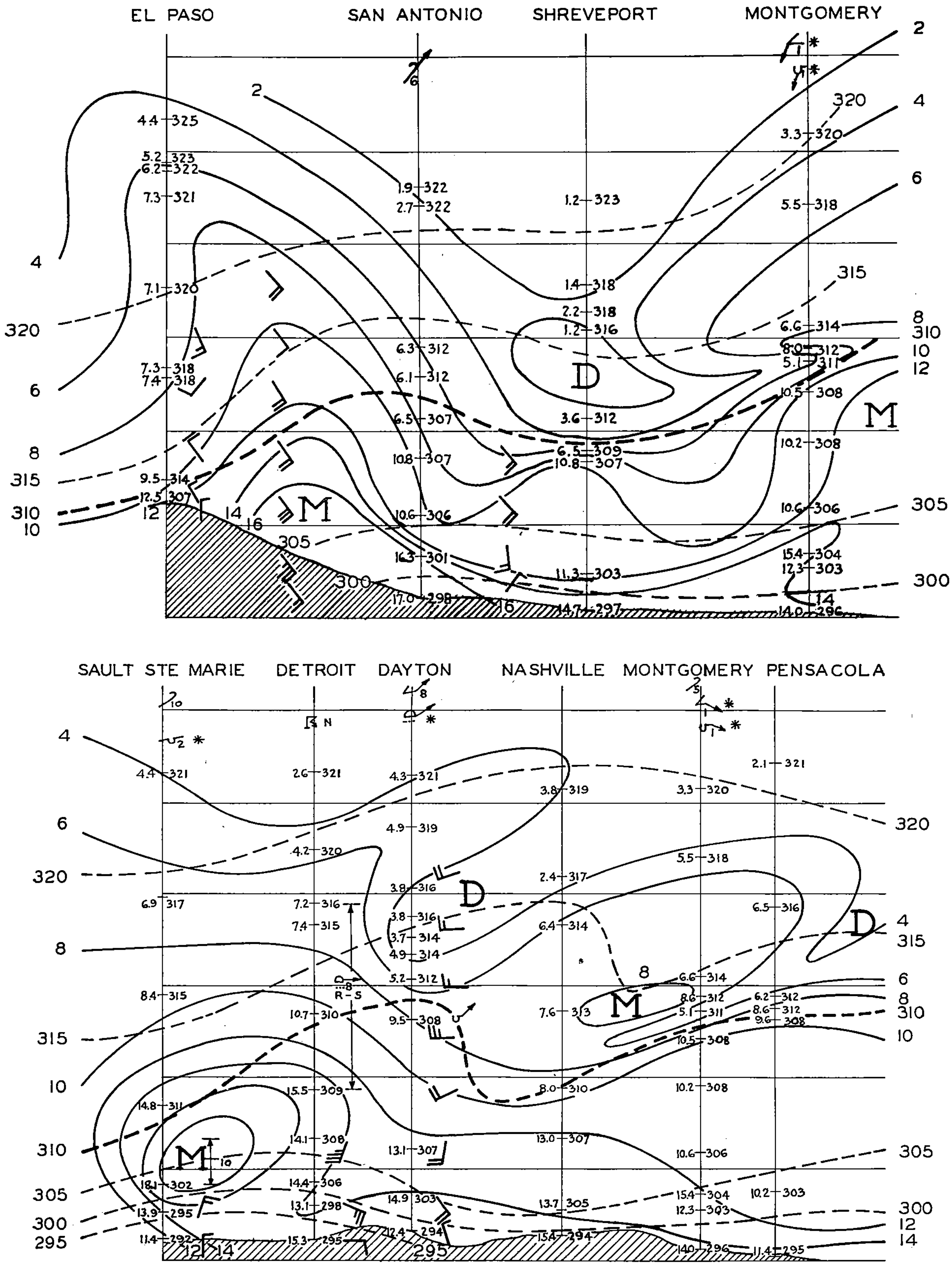
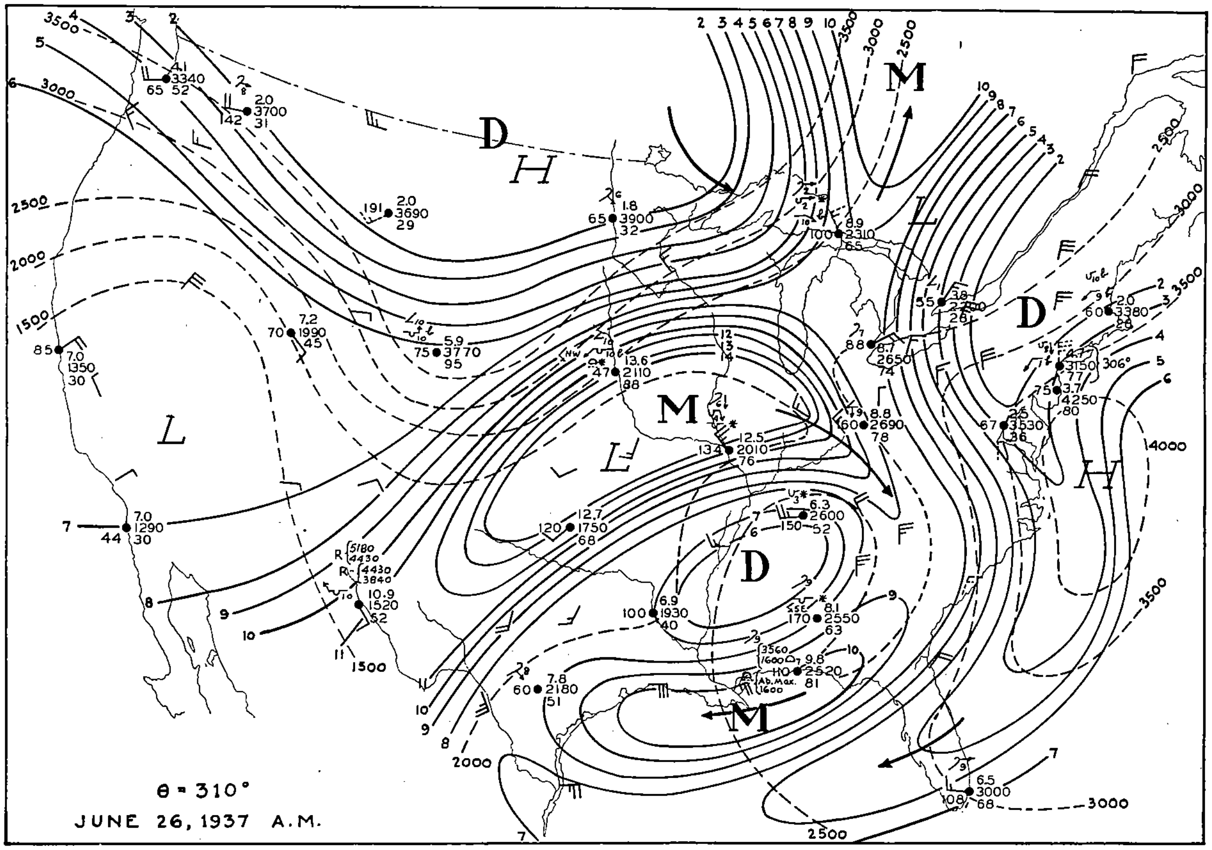
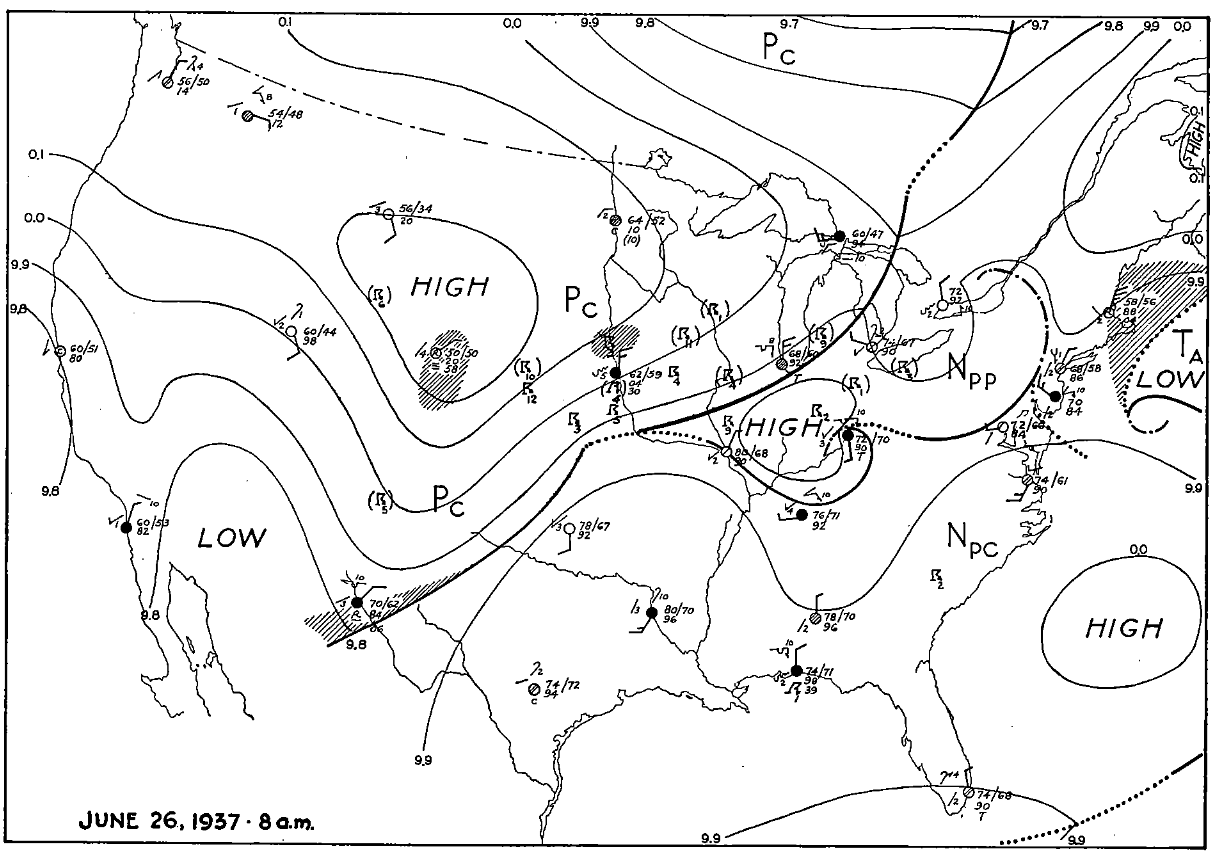

EL PASO
SAN ANTONIO
SHREVEPORT
MONTGOMERY
SAULT STE MARIE
DETROIT
DAYTON
NASHVILLE
MONTGOMERY
PENSACOLA

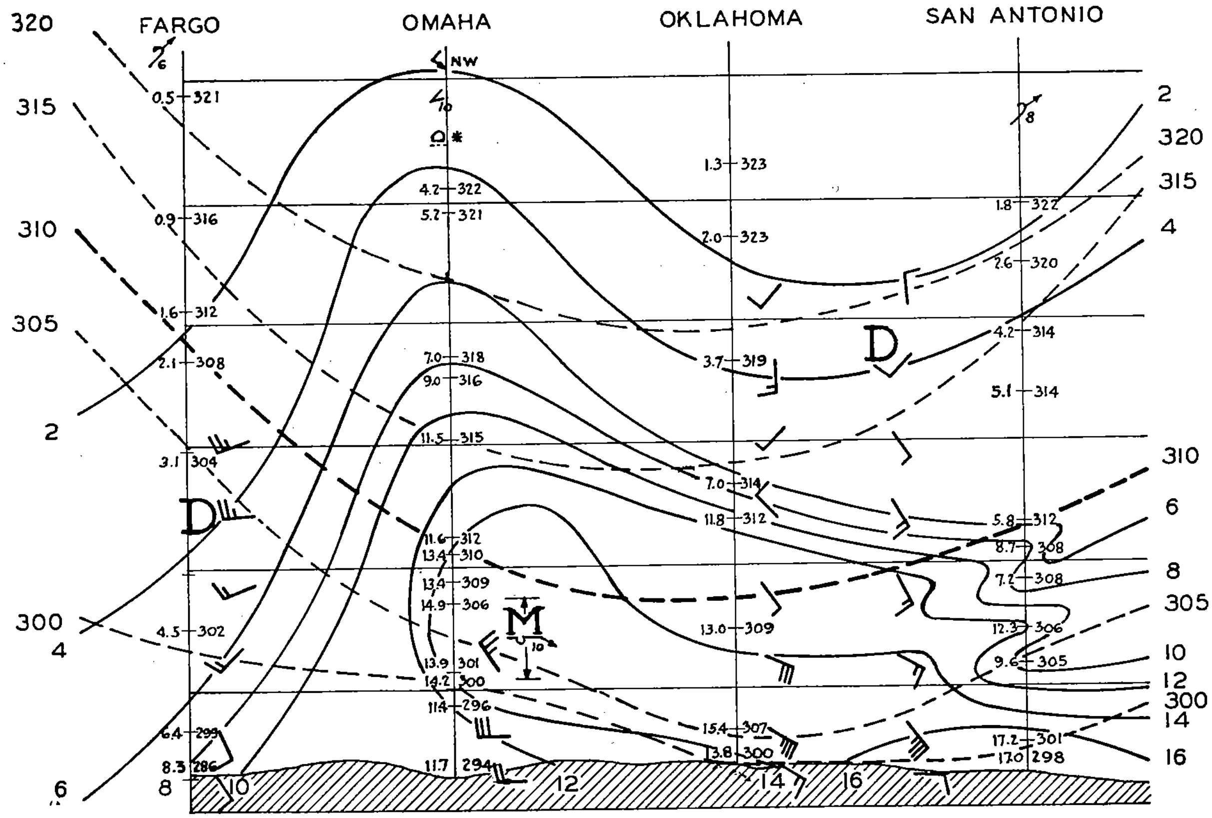
PLATE V



θ = 310°
JUNE 26, 1937 A.M.
D
H
M
L
D
M
L
L
D
H
M



JUNE 26, 1937 · 8 a.m.
HIGH
Pc
Pc
Pc
LOW
HIGH
Npp
Npc
HIGH
TA
LOW
HIGH


FARGO
OMAHA
OKLAHOMA
SAN ANTONIO

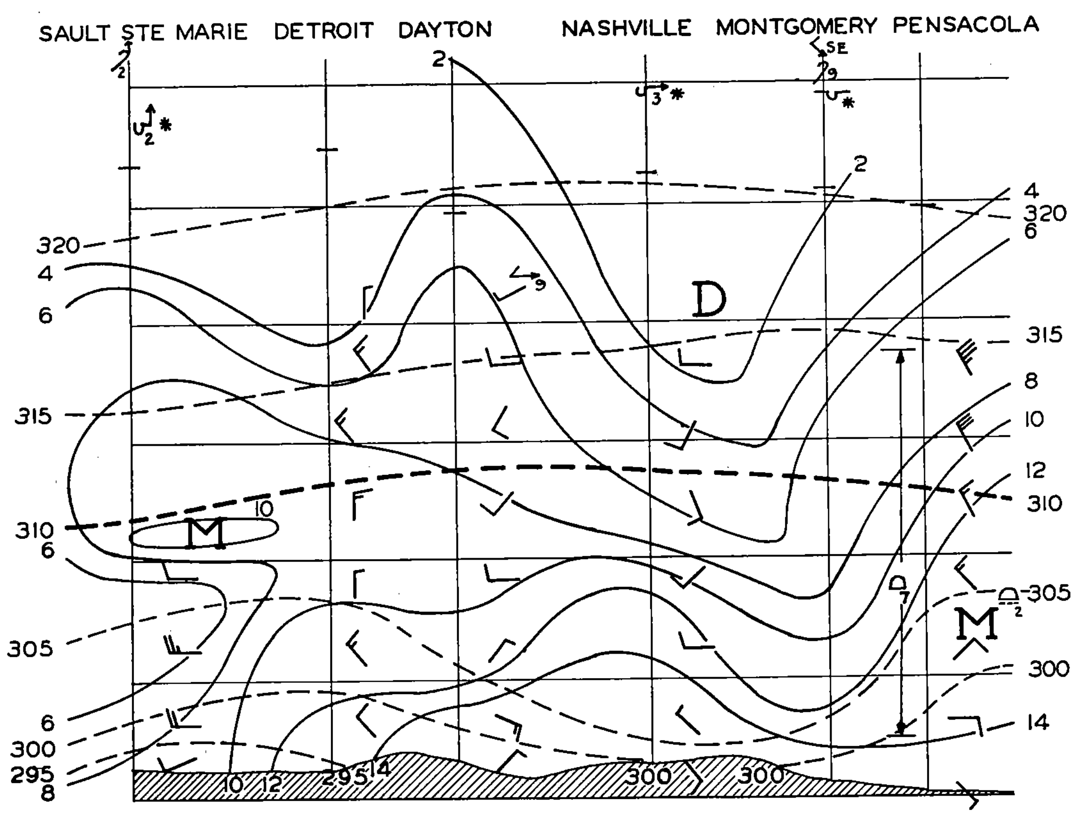
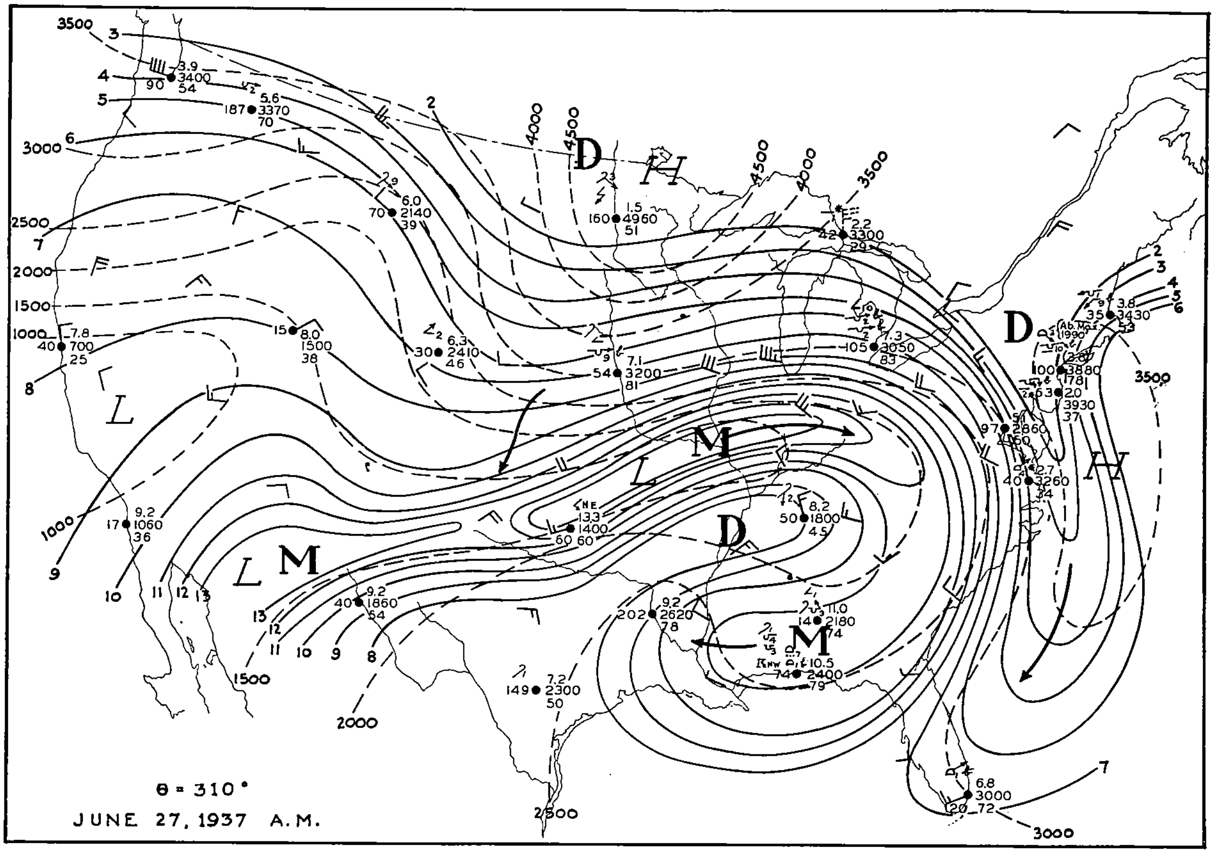
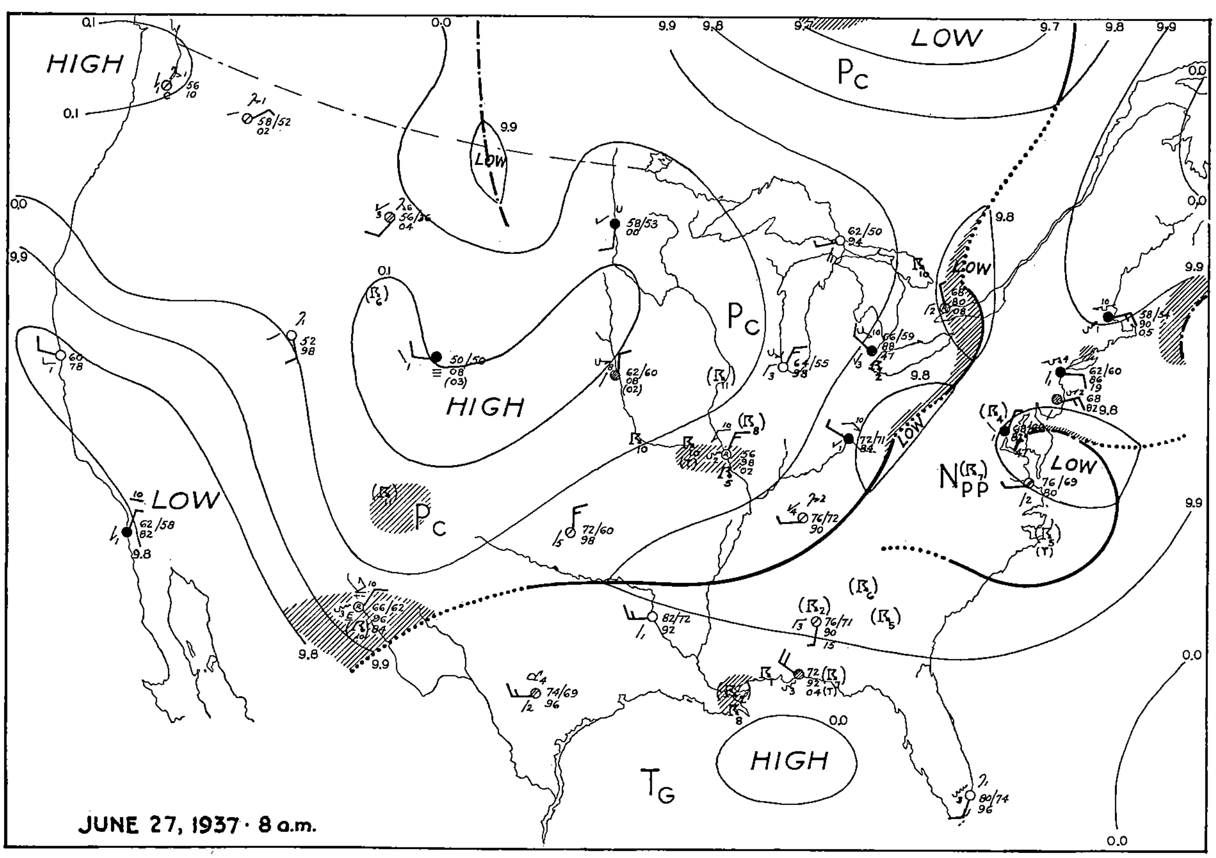

SAULT STE MARIE
DETROIT
DAYTON
NASHVILLE
MONTGOMERY
PENSACOLA

PLATE VI


θ = 310°
JUNE 27, 1937 A.M.


JUNE 27, 1937 · 8 a.m.
HIGH
LOW
Pc
Tg

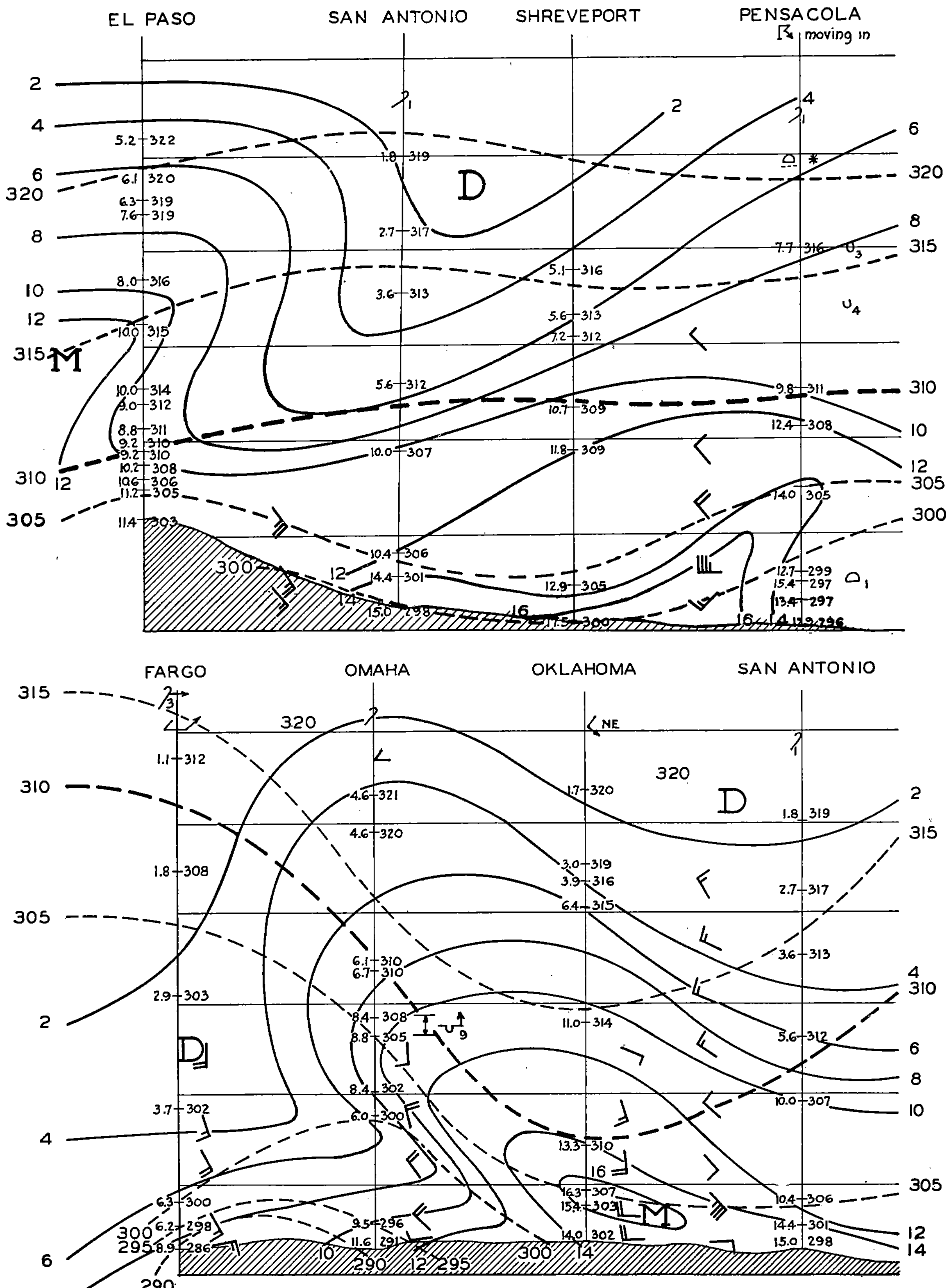
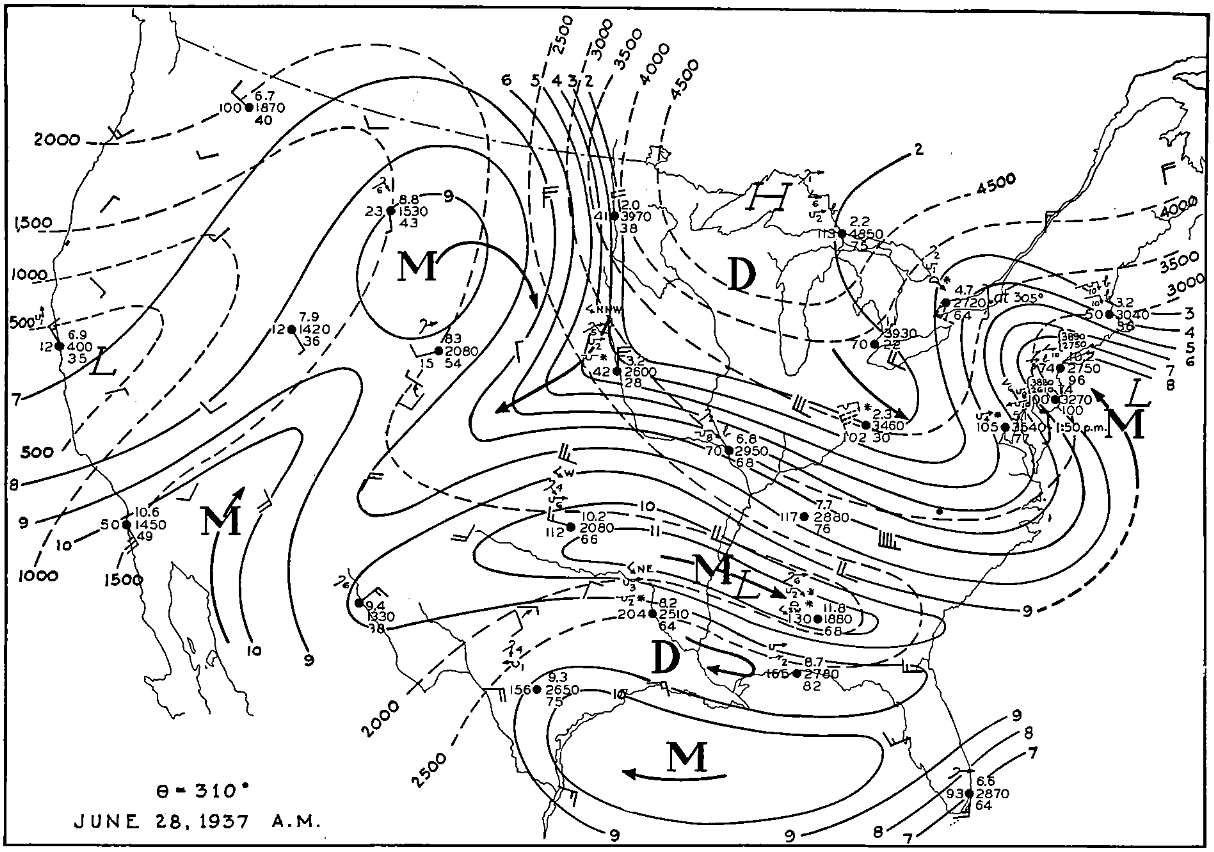
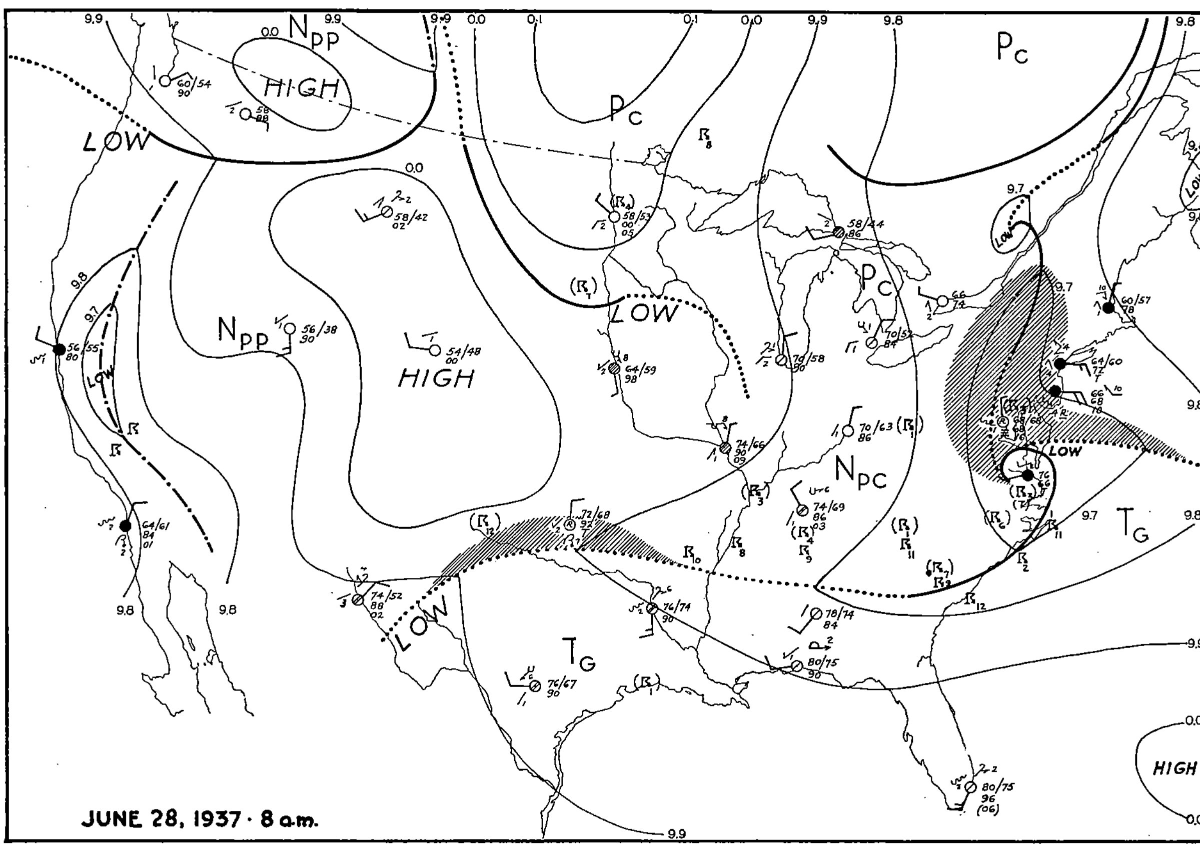
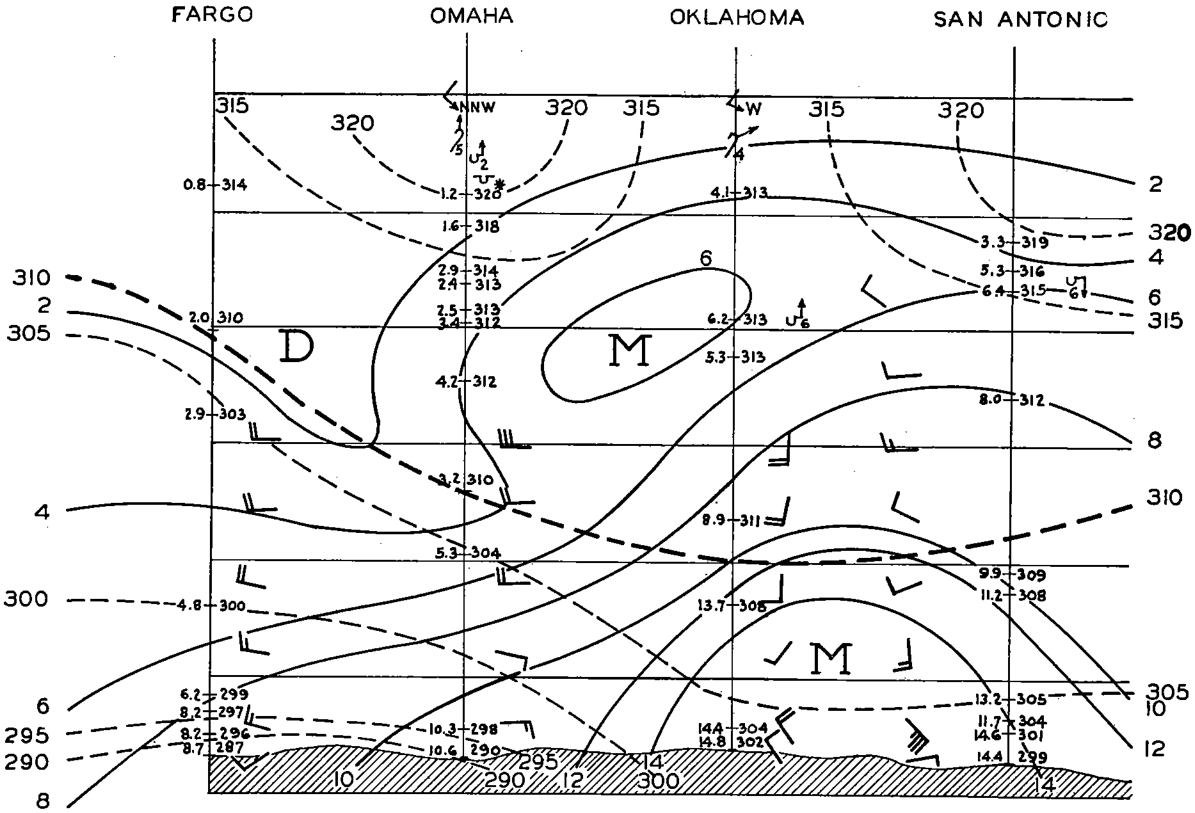

EL PASO
SAN ANTONIO
SHREVEPORT
PENSACOLA
moving in
FARGO
OMAHA
OKLAHOMA
SAN ANTONIO

PLATE VII


θ = 310°
JUNE 28, 1937 A.M.


JUNE 28, 1937 · 8 a.m.


FARGO
OMAHA
OKLAHOMA
SAN ANTONIO

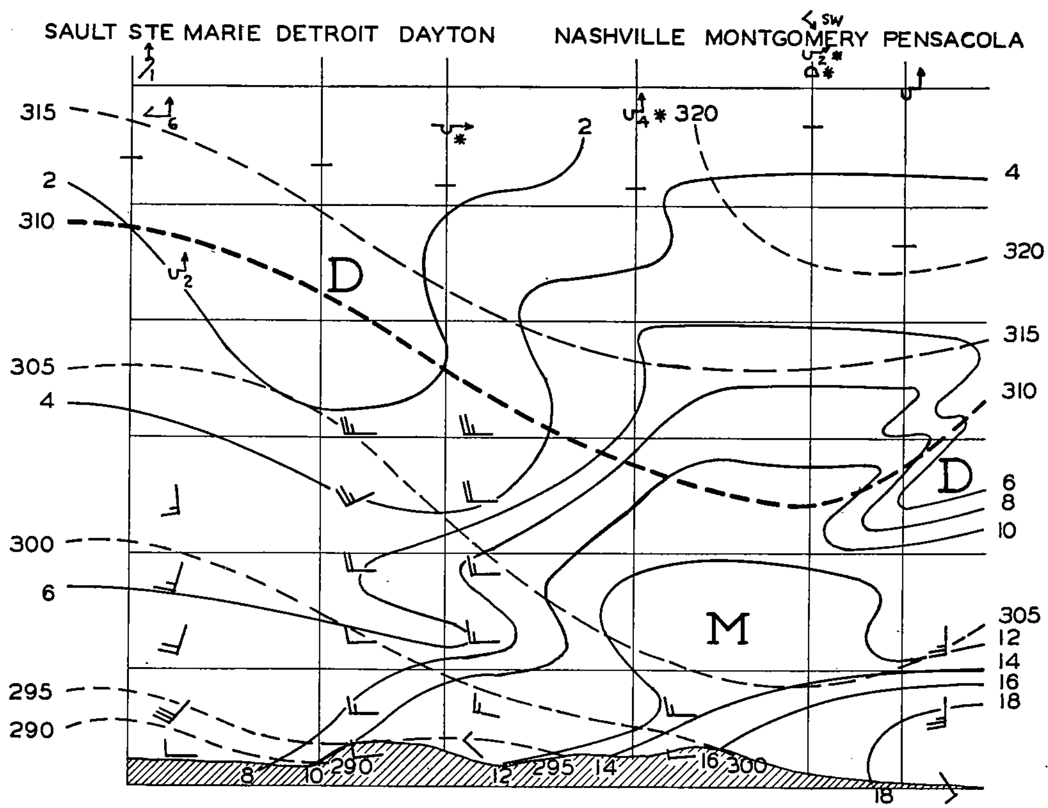
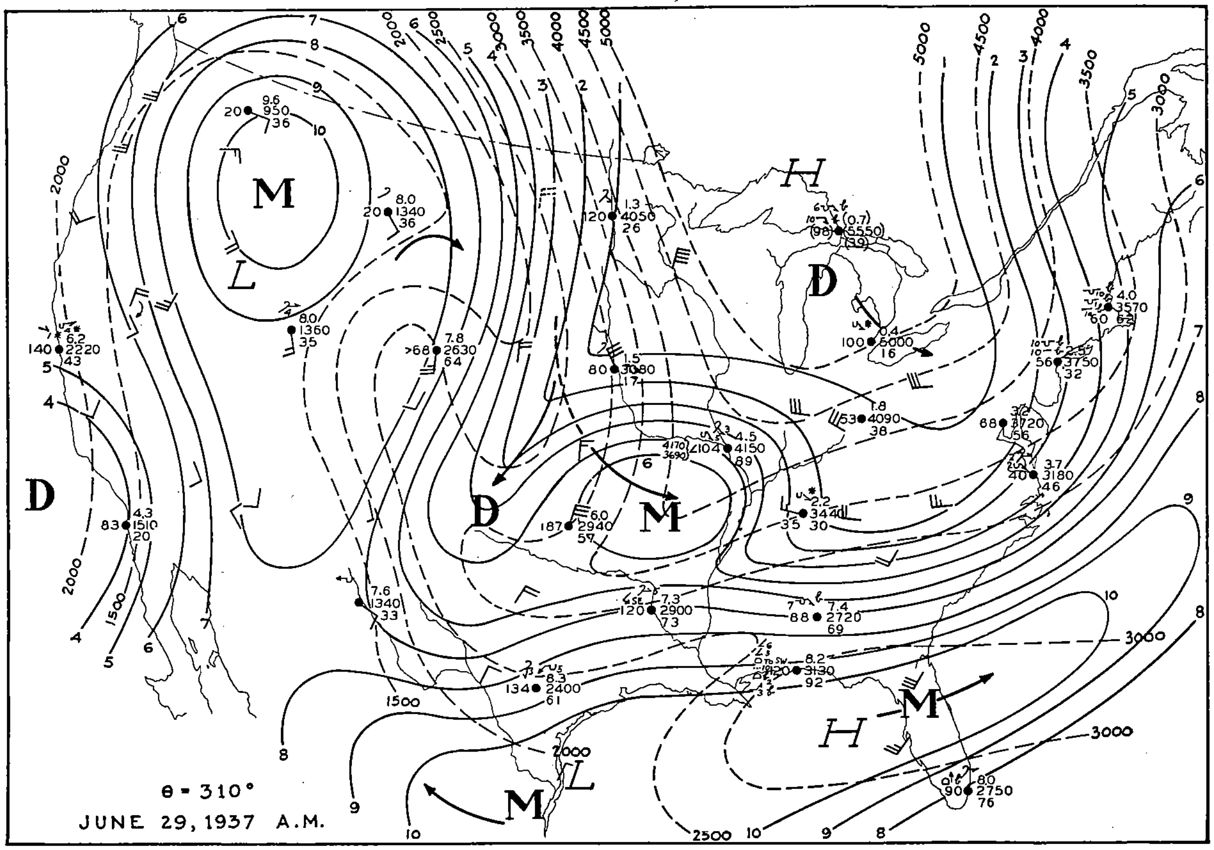
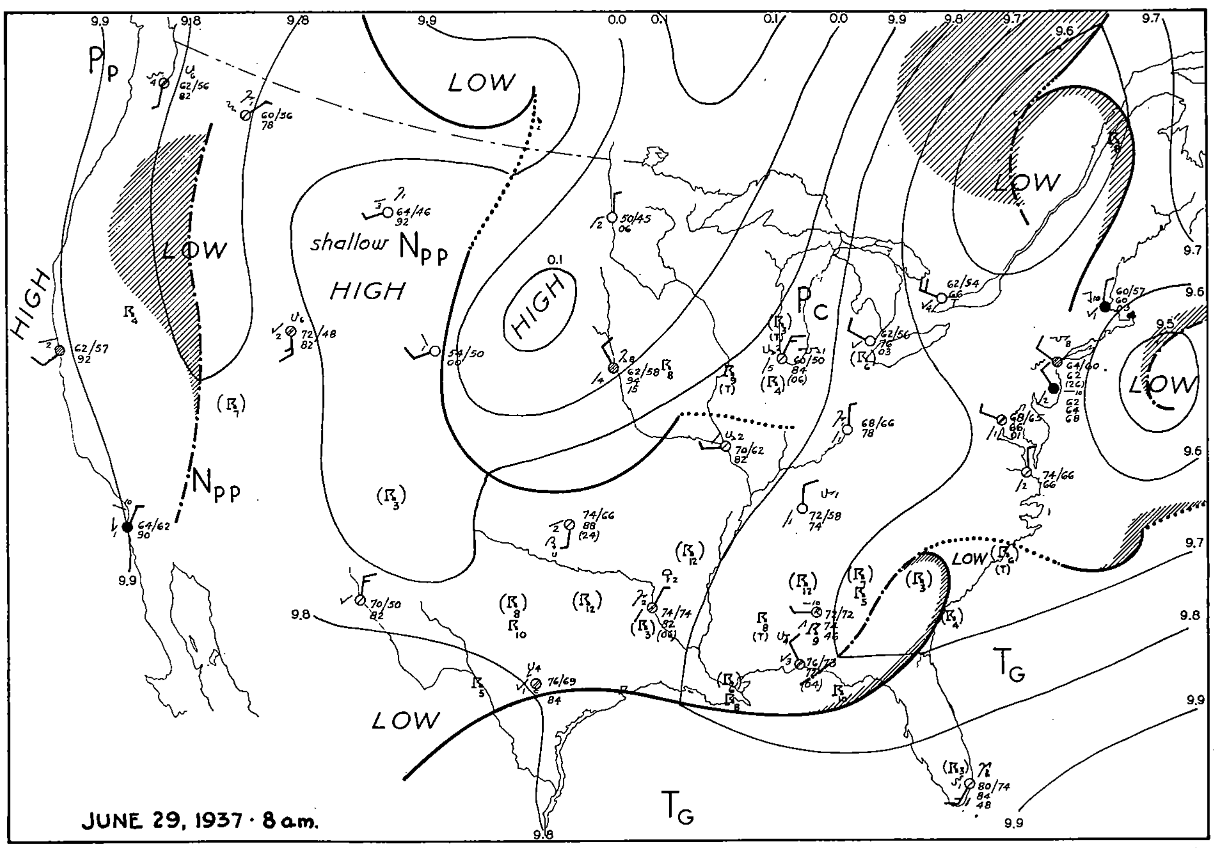

SAULT STE MARIE
DETROIT
DAYTON
NASHVILLE
MONTGOMERY
PENSACOLA

PLATE VIII


θ = 310°
JUNE 29, 1937 A.M.
M
L
D
H
M
D
M
D
H
M
L


LOW
HIGH
LOW
shallow N_{PP}
HIGH
N_{PP}
P_P
P_C
LOW
LOW
LOW
LOW
T_G
T_G
JUNE 29, 1937 · 8 a.m.

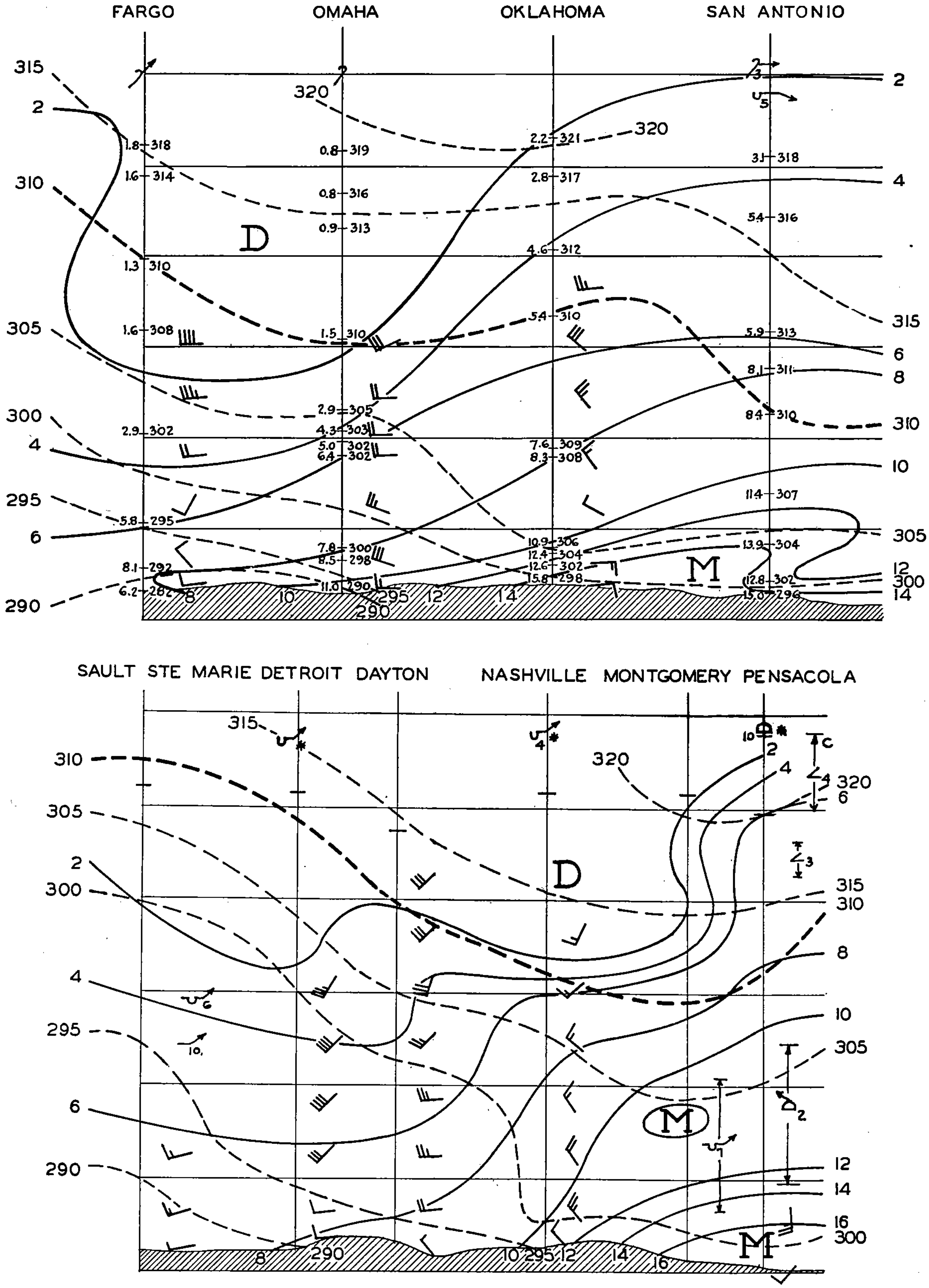
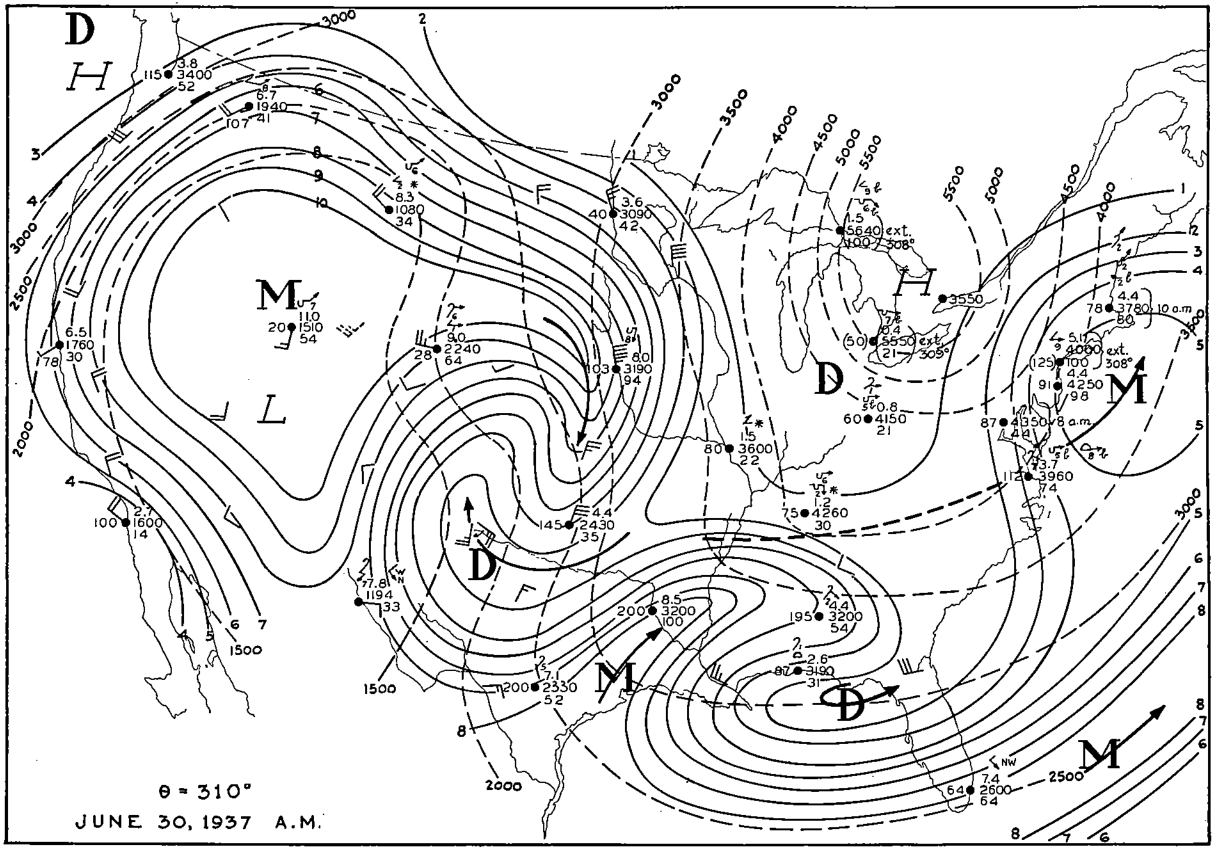

FARGO
OMAHA
OKLAHOMA
SAN ANTONIO
SAULT STE MARIE
DETROIT
DAYTON
NASHVILLE
MONTGOMERY
PENSACOLA

PLATE IX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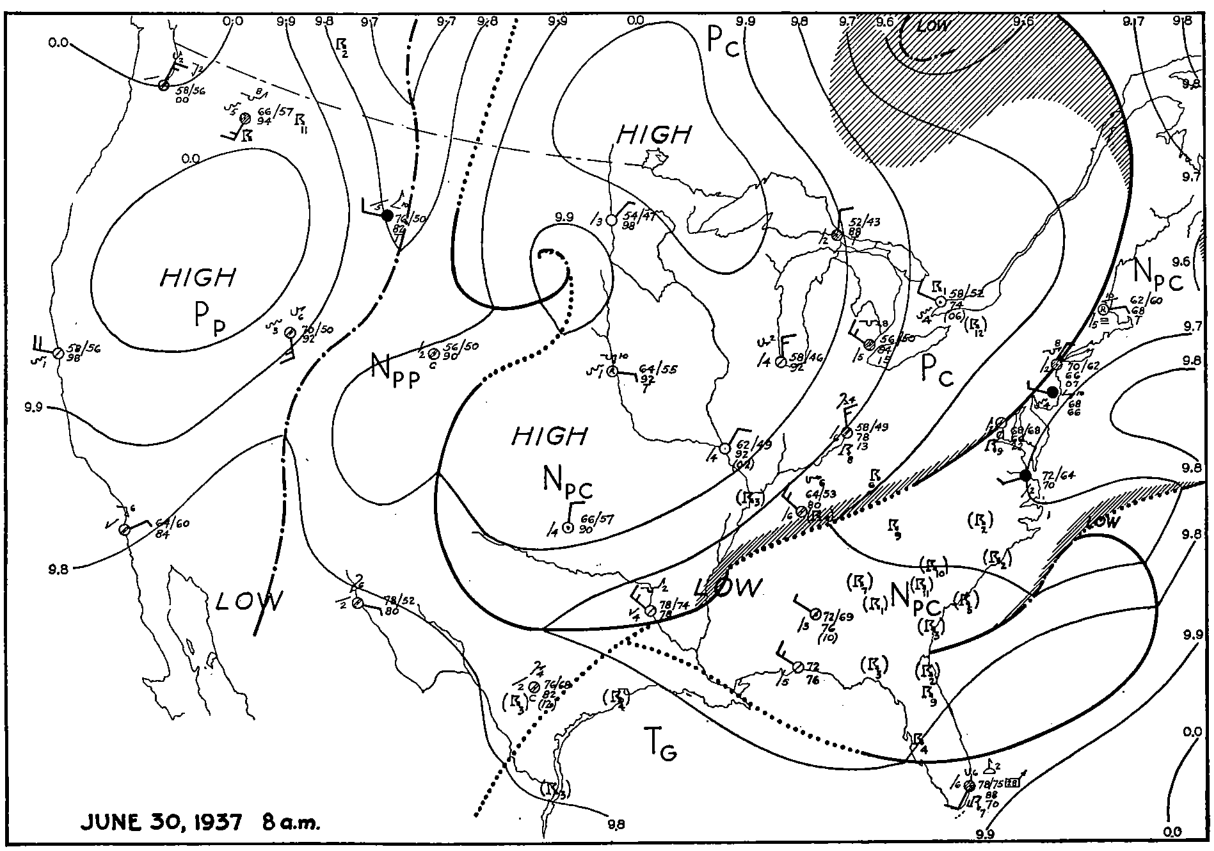
JUNE 30, 1937 A.M.


HIGH
LOW
JUNE 30, 1937 8 a.m.

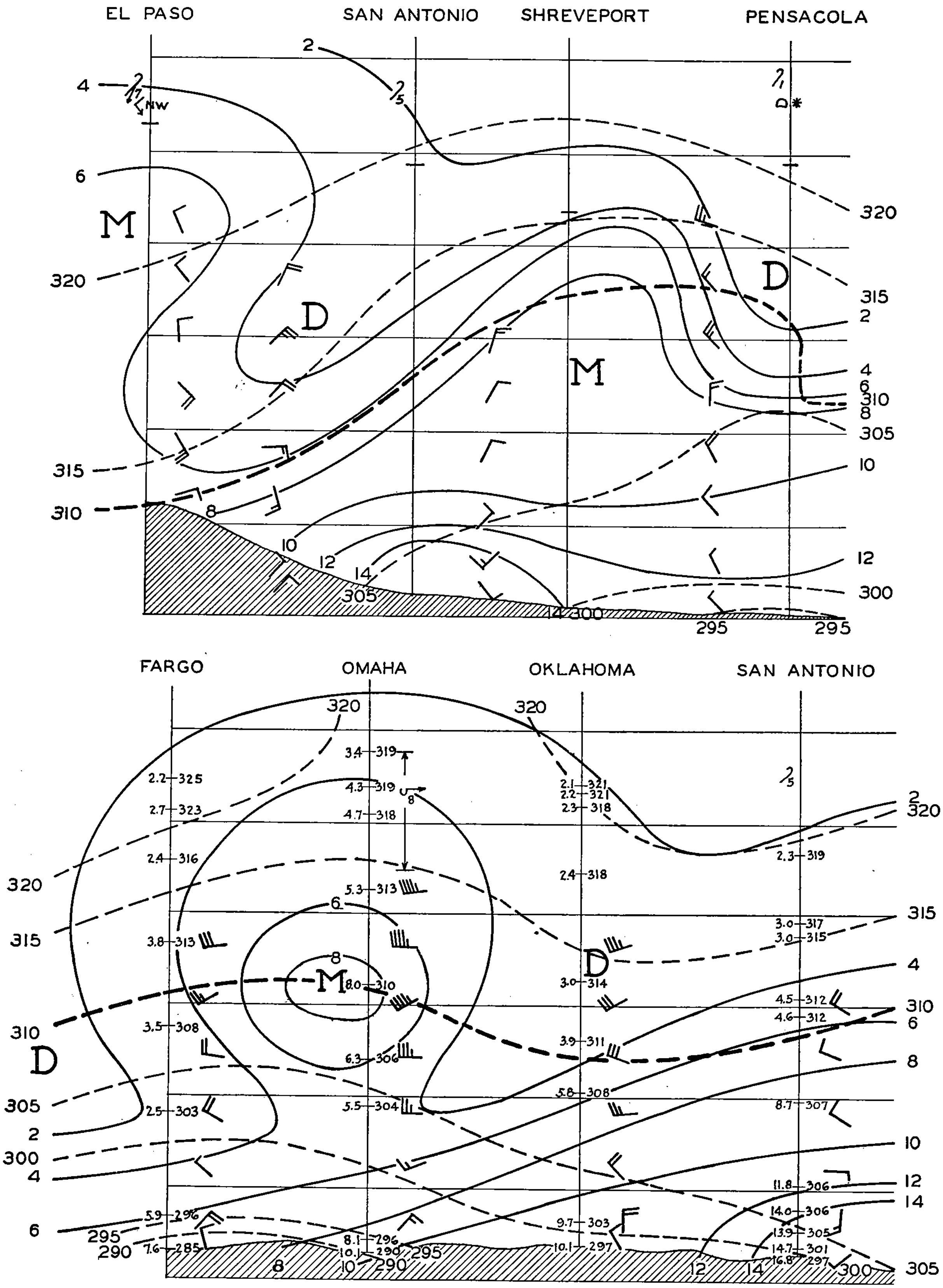

EL PASO
SAN ANTONIO
SHREVEPORT
PENSACOLA
M
D
D
M
320
315
310
305
300
295
FARGO
OMAHA
OKLAHOMA
SAN ANTONIO
M
D
D
320
315
310
305
300
295
290

Plate X

C. ISENTROPIC ANALYSIS OF A CASE OF ANTICYCLOGENESIS

BY RITCHIE G. SIMMERS

I. Introduction

Anticyclones are usually broadly classified into two groups, "cold" and "warm," distinguished by relatively low or relatively high temperatures respectively in the air comprising their lower layers. The extremes of the two types are represented by the cold anticyclones formed over snow covered regions in high latitudes and the warm anticyclones of the subtropics. In a true cold anticyclone, on the one hand, the dense surface air causes the pressure to decrease rapidly with height and within a relatively short distance above the ground the area of high pressure is replaced by one of low pressure—i.e., a cold anticyclone is confined to the lower layers and has a cyclone located above it. In a warm anticyclone, on the other hand, the decrease of pressure with height is more gradual and the area of high pressure may continue even into the stratosphere. When applied to anticyclones, then, "cold" and "warm" are synonomous with "low level" and "high level."

The anticyclones occurring most frequently in the United States are those which form over northern Canada, subsequently migrate south and southeastward in the rear of cold waves, and finally disappear in the vicinity of Bermuda. In their initial stages these anticyclones most definitely belong to the cold category, but as they travel southward the pool of cold surface air which is responsible for the high pressure spreads out horizontally and, in the absence of new supplies from the north, the layer which it occupies must necessarily become thinner. The contribution of this cold air to the ground pressure must then become progressively smaller, and a cold anticyclone might therefore well be expected to decrease in intensity as it migrates. It is found, however, that many increase in intensity during a portion of their travel southwards, this phenomenon being termed "anticyclogenesis."

Obviously the seat of the processes leading to the anticyclogenesis must be in levels above the surface layer. Increased ground pressure implies an increase of mass of the overlying air and this can be brought about in only two ways, viz: (a) by replacement with air of a higher density, and (b) by convergence, with consequent piling up of air over the area. But this is about as far as our knowledge goes. In what combination the two factors occur, at what levels, at what times and at what intensity they act is still unknown, and without the knowledge which can be obtained only by actual observations any theoretical treatment must remain rather in the nature of guesswork. The primary aim of this investigation, then, has been to provide some such observational data by means of a detailed study of upper air conditions in one individual case of anticyclogenesis and to provide a structural picture which may serve as a guide in the formulation of the corresponding dynamic problem.

The particular anticyclone chosen for study took nine days to move from northern Canada to Bermuda, marked anticyclogenesis occurring on two of the days. During this period the anticyclone also changed from a cold to a warm type and, since knowledge of this transition is as meagre as that of anticyclogenesis, the investigation has been extended to cover all nine days.

Such an investigation demands a great number of upper air observations, and it is only in recent years that there has been a really close network of meteorograph and pilot balloon stations. Dearth of adequate data, however, is not necessarily the sole reason for our paucity of knowledge of anticyclones. Failure to analyze to the best advantage what information there has been available has quite possibly retarded advance. For many years the standard practice in representation of conditions in the free atmosphere has been by means of maps at fixed horizontal levels, but for the study of day to day developments such maps are not really appropriate. Except during condensation or evaporation the processes in the free atmosphere are approximately adiabatic so that air movements will take place along surfaces of equal entropy rather than along those of equal geopotential. The natural method of representation of such movements, then, is by means of maps constructed in isentropic and not horizontal surfaces. This conception was first introduced by Shaw (1933), was revived and improved by Rossby (Rossby and coll. 1937 a and b) and has been applied for over a year to the routine daily analysis of weather maps at M. I. T. The experience gained thereby has already demonstrated the effectiveness of isentropic charts in throwing into sharp relief the flow patterns in the atmosphere and the very definite advantages they possess over the usual combinations of vertical cross sections and horizontal upper level maps. They have, then, been chosen for use in the present investigations. As this is one of the first attempts to apply the newly evolved technique of isentropic analysis in the detailed study of one definite weather situation—as distinct from the necessarily more hurried application in routine daily analyses—it constitutes, quite apart from the study of anticyclogenesis, a more or less rigorous test both of the usefulness of the method and of the validity of the underlying assumptions of isentropic flow. It can be said immediately that the method has stood up well to the test, it having been possible to carry through by means of isentropic charts a systematic and consistent analysis with good continuity through the entire period of nine days.

It was stated earlier that anticyclogenesis is due either to an increase in density or to convergence. Density increases can be quite adequately accounted for by radiational cooling in situ or by the advection of cold air, though in cases of rapid anticyclogenesis the former effect is probably insignificant, but until recently there have been no really convincing explanations of the mechanism of convergence. Recently, however, Professor Rossby has been able to analyze, in particularly simple cases, the mechanics of the adjustment of the pressure distribution to a changing velocity distribution (Rossby, 1937 b and 1938 a). The analysis shows that the inflow of momentum into a previously stagnant portion of the atmosphere produces a banking of the atmosphere to the right (on the northern hemisphere) and the magnitude of the resulting anticyclogenesis is, for certain simple cases, predictable. In addition it has been possible to show that even dynamically balanced currents under the influence of large scale lateral mixing develop cross-isobar wind components such that there is convergence (pressure rise) along the right hand side of the current. There should, then, be a tendency towards a dynamic piling up of air to the right of all currents, and one of the purposes of the present study has been to see if there is observational evidence of such banking and to provide a guide for the development of an adequate dynamic model of anticyclogenesis.

Excellent reviews of the known facts about anticyclones and unsolved problems connected with them are given by Brooks (1932) and Brunt (1934), while some of the more recent contributions in this field are those of Palmén (1933, 1935), Douglas (1935), Wexler (1936, 1937), J. Bjerknes (1937), Stüve (1937), and Haurwitz and Turnbull

(1938). The dynamically produced temperature changes in the stratosphere above cyclones and anticyclones have been treated by Rossby in a recent article (1937 a).

II. The Synoptic Situation

1. *General Features*

The meteorological situation chosen for detailed examination is that for the period May 18–26th, 1936, during which an extensive and fairly intense anticyclone of the "Alberta" type (Bowie and Weightman 1917) moved southeastwards across the United States. This anticyclone first appeared within the station network on the 16th p. m., the successive positions of the centre until the 27th, together with the values of highest pressure, being given in Fig. 1. Owing to the sparseness of observing points in the far north and over the ocean the positions and values of the highest pressure at the beginning and towards the end of the period are necessarily only approximate.

From the point of view of being nearer to the centre of the network of aerological stations, an anticyclone with a path some distance to the west of that chosen would have been preferable. As the period from which a choice could be made was limited to only a few months there were, however, few cases of anticyclogenesis available. In the first place, it is only since the middle of 1934 that there has been a sufficiently large number of aerological stations to permit an adequate isentropic analysis, while the period available was further limited by leaving out of consideration cases occurring in either summer or winter—the former season because the surface pressure systems are then usually ill defined, and the latter because the specific humidities in polar continental air are then so low that their variations, on which isentropic analysis is based, are likely to be too small to be used with confidence. In the winter, too, the winds, are in general, very strong and consequently, in the 24 hour interval between aerological observations the situations alter so much that it is difficult to obtain continuity in analyses.

Returning to the consideration of Fig. 1, it appears that between the 17th and 18th the anticyclone increased considerably in area, while during the 18th a second centre developed and subsequently moved roughly parallel to and slightly east of the original centre until it lost its separate identity on the 23rd. With the exception of the evening of the 19th, when there was a temporary decrease of intensity in the original centre, the pressures in both remained about equal. The track of this second center is also shown in Fig. 1.

From the pressures given in Fig. 1 it is seen that in general the morning maxima are greater than those of the evening, their diurnal variation being particularly marked on the 19th and 21st when there is a large diurnal variation of temperature. In Fig. 2 is shown the variation of the highest pressure at 8 a.m. each day, the afternoon values being omitted to avoid complicating the curve with the diurnal variations. After a sharp rise between the 16th and 17th, the pressure remains fairly constant for three days and then, from the 20th to 21st, when the system is centered over the Great Lakes region, there is very rapid and marked anticyclogenesis, the maximum pressure increasing more than two tenths inch (6 mb) in the 24 hours. This intensification is maintained for a day and the maximum pressure then decreases fairly rapidly for two days and later more gradually. Despite this decrease in intensity the anticyclone remains stable and can still be identified on the 28th, i.e., twelve days after its formation and eight days after the peak of its development.

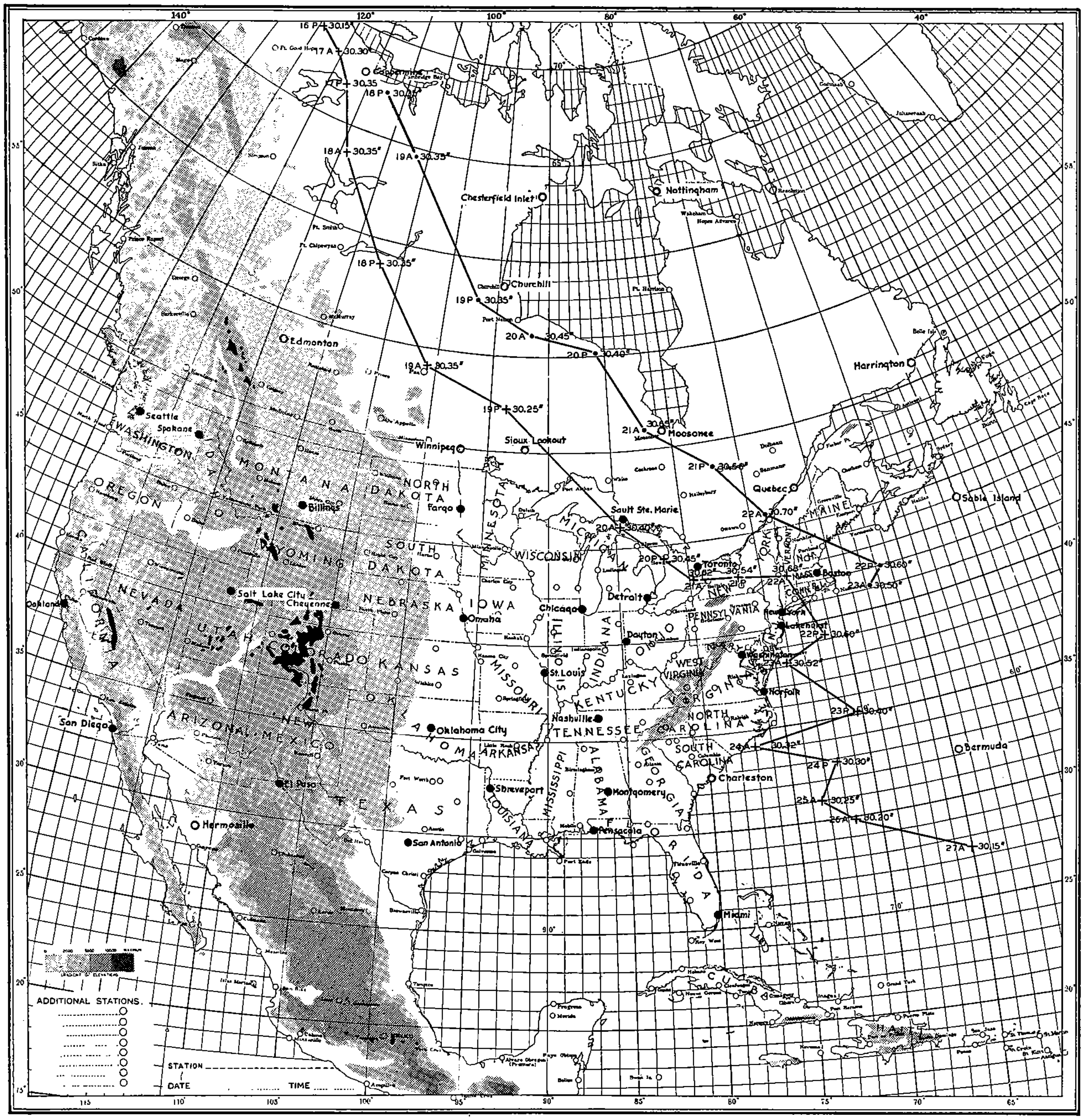


FIG. 1.—Paths of centres of highest pressure during the period May 16–27, 1936.

As a forerunner of the anticyclone there is a cold front which on the 18th runs roughly WSW-ENE some 200 miles south of a line joining Churchill to Edmonton and which advances southeastwards at about 600 miles a day till the 20th, when it becomes more or less stationary between Nashville and Pensacola. Behind this rapidly moving cold front there is typical dry and cold polar continental air. Between the 20th and 21st, i.e., coincident with the anticyclogenesis, this air mass type commences to lose its *Pc* characteristics over the Detroit-Dayton area, becoming both warmer and more moist. This increase of temperature and specific humidity continues progressively from day to day for

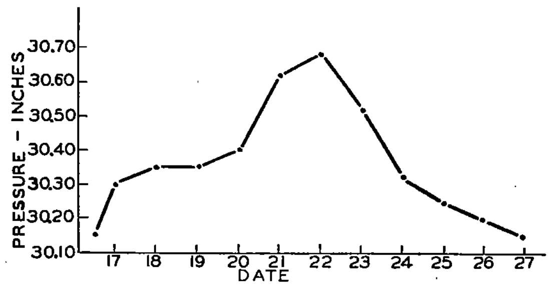


FIG. 2.—Maximum 8 a.m. sea level pressure during the period May 16–27, 1936.

most of the remainder of the period. Further to the south, however, the increase does not take place, Nashville remaining dry and not increasing much in temperature. The Detroit-Pensacola cross sections for the 21st–26th show this reversal of the normal N-S moisture gradient very clearly. The persistence of this kernel or island of subsiding dry air at Nashville, fed spasmodically by new supplies from the north and east, is one of the principal features of the situation and seems to be one of the contributory causes of the stability of the anticyclone.

2. *Data Available*

There was a wealth of meteorological information available during the period, that used comprising the following:

(1) Daily surface synoptic maps for 8 a.m. and 8 p.m. (Times throughout are Eastern Standard—i.e., 75th meridian west.) These maps are those prepared during the period at Massachusetts Institute of Technology supplemented by numerous observations obtained subsequently from various sources. Copies of the analyses together with a limited number of the individual station reports are given in Plates Ia–IXa.

(2) Records of Pilot Balloon ascensions for about 110 stations. Of these about 90 are from stations in continental U. S. A. and the remainder from ships, and neighboring stations in Canada, Bermuda, Mexico and the West Indies. For the majority of the U. S. A. stations two ascents a day (5 a.m. and 5 p.m.) were made, those in the morning being limited to a height of 4270 m (14,000 ft) while those in the afternoon were continued in each case until the balloon was lost from view.

(3) Records of the daily airplane meteorograph flights from Toronto, Canada, and twenty-two stations in the United States. With the aid of these data four vertical cross sections for each day showing the distribution of potential temperature and specific humidity have been constructed. These cross sections were for the profiles Fargo-San

Antonio, Detroit-Pensacola, Seattle-Washington, D. C., and El Paso-Boston, the more important ones being included in Plates I b,c,d–IX b,c,d.

It should be noted that the airplane, pilot balloon and surface observations are not synchronous but are for 4 a.m., 5 a.m. and 8 a.m. E.S.T. respectively. As, for various reasons, the airplane observations are in a number of cases made later than the standard hour of 4 a.m., the actual times for each ascent are given on the cross sections.

A most gratifying aspect of this investigation is the completeness of the data throughout the entire period. Thanks to the normally clear skies accompanying anticyclonic conditions there are relatively few gaps in the pilot balloon ascents, while of the twenty-three airplane stations the fewest reporting on any one day is nineteen, if we exclude the 24th which is a Sunday, and the average for the period twenty-one. As a result it has been possible to follow very satisfactorily almost everything occurring in the lower troposphere and much in the upper. This is in marked contrast to studies of depressions, in which the extensive areas of cloud and precipitation preclude pilot balloon and airplane ascents and perforce leave to conjecture much that goes on in the free atmosphere.

3. *Detailed Description*

In this section the individual surface charts are discussed, the greatest attention being paid to the eastern portion of the United States where the anticyclone was located most of the period. The maps referred to are given in Plates I–IX and XXIV. The Fargo relative humidities from the 23rd–26th and the Lakehurst temperatures on the 24th are definitely incorrect. On almost every day the Mitchell Field (New York) temperatures and relative humidities seem too high when compared with neighboring stations, while the same elements appear doubtful also at Toronto where they are based on readings made from wet and dry bulb thermometers. The Norfolk temperatures seem to be suspiciously low at times but have been accepted as correct.

It will be seen that no fronts have been entered on the cross sections. This does not mean any disbelief on the part of the author in the existence of such discontinuities. When the investigation was commenced one of the aims was to emphasize any relationship that may exist between the distribution of potential temperature and specific humidity, and it was thought that the inclusion of fronts on the cross sections, by increasing the number of lines thereon, might tend to obscure any such relationship. The present opinion of the author is, however, that fronts could be included with advantage but there has been no time available to make the requisite alterations.

May 18th. For from two to three weeks prior to the formation of the anticyclone which we are to discuss, there had been located over central Canada a semi-permanent area of high pressure, along the western and southern borders of which a series of disturbances from the Aleutians had passed southeastwards towards the Great Lakes. Connected with these disturbances there had been intermittent outbreaks of polar continental air apparently originating somewhere in the vicinity or to the north of Coppermine. The anticyclone centered over Bermuda on the 18th is the remains of one of these outbreaks, which started from the far north on the 12th, and the southern boundary of which passed Detroit as a cold front on the 15th. On its western side the air now has characteristics approaching those of *Tg*. In this area the structure has been discussed by Holzman (1936), the interesting feature of the situation being that the upper front marks the advance of *Tg* as a cold front.

Of the other two main anticyclones, that over the Rockies is comprised of air of maritime origin which advanced over the western Canadian coast about latitude 45° during the 15th, while that in northwestern Canada is the one which later undergoes the anticyclogenesis. The history of this latter anticyclone can be traced back to the 16th, between the evening of which and the following morning the pressure at Coppermine rose from 30.04″ to 30.30″. The weather conditions at Coppermine on the evening of the 16th, wind north force 4 and temperature 14°F indicate that this pressure increase is associated with an outbreak of Arctic air from the north, but this outbreak is almost immediately reinforced by a strong easterly current round an occluded centre which on the 16th p.m. is over Churchill and on the 18th is north of Quebec. The forward edge of these combined currents, which are being taken as of *Pc* air, is indicated on the 18th by the fast moving cold front lying about two hundred miles south of Edmonton and Churchill. Though not apparent on the a.m. map there are winds of force 6 and 7 behind this front.

May 19th. The front separating *Pp* and *Tg* has moved east and south since yesterday. Part of the *Pp* air mass over the Gulf has been very greatly modified and the front has all but lost its significance. At Pensacola the only evidence of its passage is the direction of the surface wind and a very slight decrease of moisture in the lowest layer. The precipitation recorded at Pensacola and Montgomery is the result of thunderstorms on the afternoon of the 18th. At both these stations (the Montgomery ascent is at noon instead of 4 a.m.) the air from the ground up is indistinguishable from *Tg*, the *Npp* classification on the surface map being retained purely for historical reasons. Otherwise, however, the stations to the rear of this *Npp-Tg* front, Nashville, Shreveport, Oklahoma, Omaha, St. Louis, Dayton and Detroit, all have typically dry *Pp* air except in the surface layers. At 4 km the specific humidity at Nashville, which is representative of the other stations in the *Pp* area, is about 1.5 g/kg contrasted with about 6 g/kg at the same level at Montgomery.

Since yesterday the main *Pc* anticyclone has advanced southwards, the cold front accompanying it having maintained its rapid movement and caught up with a rather ill-defined cold front farther to the south. Over Lake Huron a wave, either induced by the disturbance farther to the east on the *Pp-Tg* front or the remains of the occlusion which yesterday was near Winnipeg, is developing on this combined front. At least on its southern edge, if not farther north, this *Pc* outbreak is still very shallow, at Fargo probably extending up to only 1700 m. Above this level the potential temperatures have remained sensibly constant since yesterday, while below there has been a decrease of about 4°A. The steep lapse rates as indicated by the wide spacing of the isentropes in the air above 1500 m at Fargo suggest that this air is *Pp* and this conclusion is supported by the wind directions. At Bismark, North Dakota, the easterly winds of the first 1500 m change by 2500 m to almost due west. Though the *Pc* cold front continues its southward movement during the day there seems to be little increase in the depth of the *Pc* at Fargo, the pilot balloon ascent there at 5 p.m. showing a change in wind direction from northeast to west-northwest between 1200 m and 1800 m. As the depth of the *Pc* at Fargo would have been expected to increase there has probably been considerable spreading out of the *Pc* air in the lower layers, and this will account for the fact mentioned earlier that on the evening of the 19th there is a decrease in intensity of the more southern of the two centres of the main anticyclone.

The wind changes just discussed indicate that over North Dakota and also probably over a much wider area to the northeast there is a reversal of pressure gradient between the ground and 2000 m, so, in the absence of aerological observations north of Fargo, we can use this evidence for the conclusion that the anticyclone north of Winnipeg is of the true "cold" type, the high pressure area at the surface rapidly giving way to a low pressure area aloft. The distribution of surface temperatures—up to 40°F colder on the east than on the west side of the anticyclone—indicates that in all probability the centre of this upper level low pressure area is displaced to the east of the centre of the underlying anticyclone.

May 20th. Commencing first with the frontal and air mass distributions to the south of the main *Pc* front, it is seen that the western portion of the front separating the *Npp* and *Tg* air has now been entirely dissipated while the portion which was represented as a very weak cold front over the eastern Gulf has returned northwards as a warm front now extending from eastern Texas to Georgia. Oklahoma, and to a lesser extent Shreveport, are still in the *Npp* air but farther to the west this air mass has been modified by an advance from the south of moist tropical air which may be either *Tg* or *Tp* but which has been designated as *Tg*. The vertical cross-sections for Fargo-San Antonio and Seattle-Washington show the presence of this *Tg* current and from them it can be seen how the *Pp* is being modified from below by ground influences and from above by the *Tg* current. Simultaneously with this advance of the *Tg* air the *Pc* cold front in the region between Omaha and Billings has been checked and it is now returning northwards as a warm front.

Over the ocean to the east of Florida there has been placed on today's map a warm front separating *Ta* from *Tg* air. Except for the winds there is little to justify the introduction of this front, the main purpose of including it in the analysis being to emphasize the presence in the vicinity of Haiti of a weak but extensive tropical disturbance which is giving strong easterly winds and rain over a wide area south and southwest of Bermuda. This disturbance persists in about the same position and at about the same intensity for four days and is the spring prototype of the summer hurricanes of the West Indies. On the 21st there are indications of a second but not so important disturbance just south of Cuba and the two combine to give very strong easterly winds over Florida until the 24th, the strength of the winds progressively increasing through the steepening of the pressure gradient brought about by the approach of the *Pc* anticyclone.

Though the presence of the tropical disturbance is not apparent until the 20th, it has undoubtedly been developing for some days and probably its presence accounts for such an abnormal depth of the moist current at Pensacola and Montgomery. Between the 18th and 21st the specific humidity at these stations ranges around 4 g/kg at the 5 km level. In layers below 5 km the specific humidity is not unusually high, the feature of the vertical structure being the apparent upward spread of moisture. If we accept the hypothesis that the moisture richness at high levels is associated with the presence of the tropical disturbance we see what an important role one of these can play in the weather of the southern United States even when its centre is far distant. Tropical disturbances are usually considered as of relatively small horizontal dimensions, yet in this case Montgomery, which is almost 1500 miles from the centre, is experiencing the effects. However it is brought about, through convection consequent on condensation or by dynamic processes, the effect of the tropical cyclone is that of a pump which raises the moist surface air to high levels where it spreads out over a wide area.

Coming now to the discussion of the anticyclone, we see that the cold front associated with it has continued its rapid advance and that *Pc* or *Npc* covers the greater part of eastern and central United States. Even well behind the cold front, however, the *Pc* is still in a relatively shallow layer. At Detroit the top is at 2.0 km. Below this level there have been decreases since yesterday in potential temperatures of about 10°A while above there have been slight increases. The upper layer is evidently the same *Pp* as that above Fargo yesterday and the same vertical structure is present, viz. stability in the lower 2 km and then large lapse rates. At other stations the height, h, of the top of the *Pc* can be identified, either by the means adopted for Detroit or from the temperature and moisture discontinuities, as follows:

TABLE I

STATION	h	θ_b	θ_a	θ
	m	°A	°A	°A
Nashville	400	286	298	292
Dayton	1300	288	292	290
Detroit	2500	286	293	290
Toronto	3000*			294
Washington	1400	293	298	294
Boston	1300	289	291	290

* Approximate values.

The surface map, then, gives a rather misleading impression of the atmospheric structure to the north of the cold front. From it one would infer that there is a great amount of *Pc* air covering the United States, whereas in reality there is comparatively little—it covers a wide horizontal area but is in only a shallow surface layer with a deep superincumbent layer of *Pp*. The Seattle-Washington and El Paso-Boston cross sections show this *Pp* as a dry layer extending from Omaha eastwards to well out over the Atlantic Ocean, the dryness accounting for the almost entire absence of precipitation accompanying the advance of the *Pc* cold front.

During the 24 hours since 8 a.m. yesterday subsidence appears to have been very active in the *Pp* air. Of the stations which are in it on both days, Toronto, Detroit and Dayton have had increases of potential temperature of 2°–3°A at fixed levels, while at Nashville the increase from 400 m up to 5000 m averages 6°A.

In Table I are given, in addition to the heights, the potential temperatures at the top, θ_a, of the inversion marking the boundary between the *Pc* and *Pp* air masses (i.e., at height h) and at the next significant point below, θ_b. As the points θ_b are at varying distances below the corresponding points θ_a there are given in the last column the estimated potential temperatures, θ, which the *Pc* air would have if it extended up to the height h. θ, then, is the potential temperature that would prevail on the lower side of the boundary between *Pc* and *Pp* if the inversion zone between the two air masses was sharpened into a line. The relation between θ_a, θ_b and θ can be better seen from the accompanying temperature-height diagram (Fig. 3). *ABCD* represents the conditions actually prevailing while *E* is the point which would be reached if the lapse rate in *AB* continued unchanged up to the height, h, of the top of the inversion. θ_a, θ_b, and θ are, then, the potential temperatures correspondong to *C*, *B* and *E* respectively.

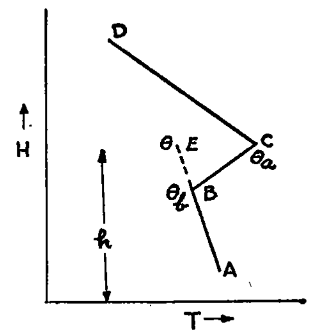


FIG. 3.—Graphical representation of method used in estimating potential temperature θ at base of idealized inversion.

There is a very small variation of the individual values of θ from the mean value of 292°, the upper boundary of the *Pc* air mass following very closely an isentropic surface.

May 21st. Between the 20th and 21st the development of the situation is straightforward except for the marked anticyclogenesis which has taken place. Both the centres, one of which is now over Toronto and the other near Moosonee, experience about identical intensifications, viz. slightly more than .2 inch in 24 hours. Though the anticyclogenesis will be discussed in more detail in a later chapter, it can be pointed out now that advection of cold polar air near the ground surface is not the entire cause. The depth of the *Pc* air mass at Detroit has decreased in the 24 hours from 2 km to 1900 m, while the potential temperatures at fixed levels within it have increased about 5°A, both of which effects decrease the contribution of the *Pc* layer to the surface pressure. At Toronto the change has been similar to that at Detroit but further east just the opposite has occurred, e.g. at Boston there has been an increase in depth and a decrease of about 6°A in potential temperature.

By the same procedure as that adopted in drawing up Table 1 above, data relative to the upper surface of the *Pc* current on the 21st have been extracted and are given in Table 2.

TABLE 2

Station	h	θ_b	θ_a	θ
	m	°A	°A	°A
Nashville	500	288	298	**
Dayton	1000	292	294	292
Detroit	1900	291	294	292
Toronto	2200			292*
Washington	1700	293	296	295
Lakehurst	1800	288	294	291
Boston	2300	288	292	292

* Approximate.
** Too close to ground for reliable estimation.

In this table there are two features which seem worthy of comment. In the first place the top of the *Pc* air still follows the same isentropic surface as yesterday, and in the second, at all the stations except Nashville and Boston there has been a decrease in the depth of the *Pc* air whereas the surface map would lead one to expect an increase.

Examination of the cross sections shows an entirely different vertical structure above the *Pc* air from that of yesterday, the deep overlying layer of dry *Pp* air having now given place at Detroit, Dayton and Lakehurst to a more moist current from the west.

There are some further features of the situation of the 21st that warrant discussion but there is such an essential similarity between the surface maps of the 21st and 22nd that they will be considered along with the corresponding features on the latter day.

May 22nd. Turning first to the frontal systems, it is seen that the main *Pc* cold front, which on both the 19th and 20th advanced about 500–600 miles, has made practically no farther southward progress in the succeeding two days. From northwest of Bermuda to Mississippi it is now classed as a stationary front, its forward movement checked no doubt by the strong circulation about the tropical disturbance near Haiti.

The *Ta-Tg* warm front of the 20th has been dropped from today's analysis, and the various fronts over the southern United States are considered as merged into one warm front extending westward from the stationary front. To the north of this warm front there is a very much stronger southerly current than would be suspected from the surface conditions. At the ground the maximum wind force reported over the plain states is four and this at only a few stations, yet at 2000 feet there are southerlies of forces nine and ten. This belt of strong upper winds extends from the Rocky Mountain region eastward to about Nashville and between latitudes 30° and 45°N. On its eastern edge the air is mostly *Npc* but becomes progressively moister to the west. The slope of the warm front surface running northward from Texas is very slight, while the *Tg* air ahead of the position of the warm front at the ground is gradually working downwards. Consequently there is no warm front rain. The location of the tropical air aloft can, however, be traced by the distribution of the thunderstorms which have occurred in a broad belt from Texas northwards to as far as Sioux Lookout and Winnipeg. Over the remainder of the anticyclone there have been negligible amounts of precipitation.

There is an important contrast between the changes which have occurred at Boston and at stations to the west during the 24 hours from the 21st–22nd. Whereas at Detroit the surface *Pc* air has almost lost its identity (a decrease in thickness of the *Pc* layer from 1900 m to 1000 m and an increase in potential temperature of 5°A) at Boston the *Pc* layer has become more prominent (an increase in thickness from 2500 m to 2800 m and a decrease of potential temperature at 2200 m of 7°A). The top of the *Pc* at Boston still coincides with the 292°A potential temperature surface.

Accompanying this temperature change at Boston there has been a marked upper wind change from west on the 21st to almost due north on the 22nd. In the light of these changes it seems not unreasonable to infer that there has been a fresh outbreak of polar continental air to the east of Boston. It has not been possible to detect any secondary cold front on the surface maps but there is support given to the supposition of the occurrence of a fresh *Pc* outbreak by the fact that during the 22nd the cold front to the north of Bermuda renews its southward movement after remaining almost stationary for two days.

May 23rd. The Shreveport, Montgomery and Pensacola airplane ascents of the 23rd lend further support to the conclusion regarding the new *Pc* current (which as a result of its trajectory over the sea is now represented as *Pa*) as at all three stations there is on the 23rd a strong invasion from the east of dry air. This invasion is much more noticeable aloft than at the surface, Pensacola having a specific humidity of only 3.8 g/kg at 2.5 km compared with a value of 8.9 g/kg on the 22nd. At the ground this renewed activity has been indicated as an advance west and south as a cold front of that portion of the stationary front which yesterday lay over the southern states. At higher levels, however, the drying out of the air at Pensacola has been accompanied by increases of potential temperature, so the surface cold front probably changes to a warm front aloft.

In making the vertical cross section analyses it has been very difficult throughout the whole period to make Pensacola, and to a lesser extent San Antonio, tie in naturally with the other southern stations, the reason being that at both there is extremely marked stratification of moisture. As an example of this the Pensacola ascent for the 22nd can be cited, successive values of q being:

700 m	13.5 g/kg
1250	9.2
1300	11.2
1900	7.1
2500	8.9
3400	4.6
4000	6.0

While the moisture has been decreasing on the southern side of the anticyclone just the opposite has been taking place on the northern. Boston yesterday had very low values of specific humidity, 1.7 g/kg at 1200 m and correspondingly dry above, whereas today there has been a rapid increase of moisture right up to the top of the airplane ascent. Together with this there have been increases in potential temperature, the maximum being 13°A at 2300 m. This moist current, which comes in with a northwest wind, is obviously associated with the moist current which yesterday was over the plain states and which today is giving the precipitation in the region to the north of the Great Lakes.

Up until today the northern portion of the anticyclone seems to have been mainly dry but the moisture at Boston and the extension of the rain area eastward almost to Newfoundland show that any northern dry air source must by now be almost completely cut off. It was to the *Pc* air that the anticyclone was originally due so it is not surprising that it has today begun to decay, the maximum pressure at the centre having decreased 0.2 inch in the last 24 hours.

May 24th. The major axis of the anticyclone now runs roughly east and west, having since the 20th made a steady clockwise rotation from its initial orientation of NNW-SSE to that of E-W.

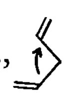
The invasion from the East of dry *Pa* (now entered as *Npa*) has continued and has displaced the moist air over the western side of the anticyclone as far west even as Oklahoma. This invasion, together with the advance from the west of a large current of Polar Pacific air, has resulted in the cutting off of the moist current up the western side of the high. Judging from the manner in which the rain area over Kansas remains almost constant in position for three days, it may in part be orographical and produced by the forced ascent of moist air from the Gulf.

The structure of the anticyclone can best be seen today by reference to the Detroit-Pensacola cross section which shows the presence of a large area of dry air over Nashville with higher moisture both to north and south.

May 25th and 26th. Despite the facts that the anticyclone has been moving to the eastward and that the supply of dry air from the north has been cut off since the 23rd the vertical structure in the Detroit-Pensacola section has remained substantially the same as on the 23rd and 24th. The dry central core of the high seems to resist remarkably effectively the influences of the moist currents to the north and south.

III. The 305° Isentropic Charts

1. *Day by Day Discussion*

The detailed isentropic charts for the 305°A surface are given in Plates X–XVIII. Plotting and analysing procedure conforms in the main with that described elsewhere in this report (vide BI). In cases where the airplane ascents have been commenced more than three hours after the scheduled time of 4 a.m. 75th meridian time the actual times of take off are given alongside the stations. Changes in wind direction at or near the 305° surface are indicated by the inclusion of the wind directions for the areas on each side of the surface with a small curved arrow indicating the direction of change with increasing height—e.g.,  represents a change from SW 4 below the isentropic surface to NW 4 above.

In areas where there are no aerological ascents the height of the isentropic sheet has had to be estimated. At Hermosillo, Mexico, the height has been taken as approximately the mean of those of San Diego and El Paso, while at Bermuda a constant height of 2440 m (8000 ft.) has been assumed throughout and at all the West Indian stations one of 1830 m (6000 ft.).

Except over the Rocky Mountain area the 305° surface is throughout the whole period high enough to be considered as lying above the layer of surface turbulence. It is for this reason plus the fact that for the most of the time it lies below the maximum elevation of the airplane ascents that the 305° surface has been chosen for the main analysis. Isentropic charts both above and below (at 295°, 300°, 310° and 315°A) have also been made but not in the detail of the 305°. These will be discussed in the next chapter.

May 18th. The flow pattern for the first day is comparatively complicated but seems well substantiated by the observations. Except near El Paso the surface is everywhere above the turbulent layer. The main features consist of a broad dry cold current, 1, and two anticyclonic eddies, one over Texas and the other off the Atlantic seaboard. In the former eddy the dry tongue, 2, cuts the ground but its presence appears to be definitely established by the fact that the air column above El Paso is dry all the way up, the maximum specific humidity of 6.5 g/kg at 1400 m (200 m above ground) being lower than in any portion of the first 2000 m at Oklahoma and 3000 m at San Antonio. The easterly (and at 8 a.m. northwesterly) surface wind at El Paso is only local, the true direction as given by the pilot balloons being southwest. The separation of the moist current in this eddy into two portions, 3a and 3b, seems at first sight to be rather artificial but has been made in order to account for a moist tongue over Cheyenne on the 19th. 3b is only shallow today, the layer of southerly winds at Cheyenne being only 1 km deep, but by tomorrow it has doubled its depth. For similar reasons of continuity the dry tongue, 4, is represented as having specific humidities of less than 3 g/kg, such low values being probable in view of the fact that, despite a strong moist current close by to the left, q at Norfolk on the 19th is only 4.6 g/kg.

Although the axis of the moist current in the eastern eddy is shown as being cut off in the vicinity of Nashville, this is of little significance since the Detroit-Pensacola cross section shows the dry current causing the division to be quite thin. Both above and below the 305° level the moist current, 5, is continuous from the Gulf of Mexico to New York.

At the ground the current over New England has a cyclonic curvature continuing northward towards the low pressure centre associated with the occlusion over Labrador, yet at the 305° surface the corresponding current, 5, has been given anticyclonic curvature. There are various indications to support this analysis: the upper wind at Bermuda is north; 5 has anticyclonic curvature further upstream and there is little reason for this curvature to change; if 5 has cyclonic curvature rain would be expected in the Newfoundland area whereas only one station reports precipitation; and, finally, we know from experience that in the temperate latitudes of North America currents have a pronounced tendency towards anticyclonic rotation.

May 19th. There has been a relatively straightforward development since yesterday, the same general pattern of a broad dry current and two anticyclonic eddies having persisted. In the western eddy tongue 2 is considered as having been wiped out while 3a and 3b have combined to give 3. This eddy has drawn into its sphere of influence a portion of the cold current to the North, a branch, 1b, of which now constitutes the dry tongue of the eddy. There has been marked downslope motion in 1b which does not occur in the companion branch, 1a. 1a has been carried well toward the southeast to account for the north to northwest upper winds which cover all Georgia and part of Florida by 5 p.m. Judging from its greater coldness, as indicated by the height of the 305° surface at Detroit, branch 1c has probably come much more directly from the north than either 1a or 1b. It does not appear, however, to be directly connected with the surface cold front which at 8 a.m. is still northwest of Detroit.

In the eastern eddy the locations of the tongues are almost identical with those of yesterday. On the eastern edge of the eddy, however, there has been a definite change, the winds at Bermuda having changed from north to southeast. 5b is now in about the same position as was occupied by the forward part of 5 yesterday, but has decreased in anticyclonic curvature, in fact it could possibly be given a cyclonic curvature. The rain and cloud areas associated with the occluded centre over Maine suggest that the moist current, if not at the 305° level, at least in lower levels has cyclonic curvature.

At Seattle the airplane ascent was not made until midday, by which time a cold front had passed. The analysis, however, has been made to simulate the conditions at 4 a.m. with the cold front still to the west. Unlike the majority of the moist tongues, 6 is given on the 18th, 19th and 20th with cyclonic rotation. There is a difference, however, between this tongue and the others. It is quite close to the ground whereas the others are comparatively high. The fact that above warm front surfaces there is a progressive increase in anticyclonic vorticity with increasing height is well known (J. Bjerknes 1932, p. 28), so at higher levels 6 probably has not such strong cyclonic rotation.

May 20th. The eastern eddy has now disappeared completely. During the day yesterday 1a reached as far south as northern Florida but since then has been pushed back by the moist current 9 associated with the tropical disturbance over Haiti. As yet 9 has made only small headway, the specific humidity at Pensacola still being low. From the wind distribution the axis of 9 should be entered some distance north of its present position but has been placed where it is because the height of the 305° surface over Georgia and Tennessee seems to have been lowered by non-adiabatic processes—either condensation or insolation—into a layer of stronger easterly winds than prevail at the level (2400 m approx.) at which the 305° surface would be if there were no such non-conservative disturbing influences.

Now larger than before but with weaker circulation, the western eddy has preserved its identity. Tongue 1b has divided into two branches, one extending down over Brownsville and the other remaining as an inert island of dry warm air over the Arkansas region. A further thrust to the south of the main cold current is being made by 1d.

Moist tongue 3 is now indicated as divided into two portions, 3c and 3d, the latter being introduced to account for the moist current at Fargo on the 21st. It is interesting to note that through subsidence, 1b is now warmer level for level than the tropical air of 3c. This is best seen at Omaha in the Fargo-San Antonio cross section, there being super-adiabatic lapse rates at the moisture inversion between 2000 m and 2500 m. From the contours of the isentropic surface it is seen that 3c is ascending fairly rapidly and this is evidenced by the deep layer of Acu between 2900–4400 m at Omaha. Severe turbulence is reported as occurring in the cloud layer in which the lapse rate follows the saturated adiabatic. As a result there is a spread upwards of moisture and the tongue is becoming thicker.

On the isentropic chart there is not much direct evidence for the existence of 3c in the position indicated, an existence which would hardly be suspected from the surface map.

There are, however, other indications which warrant giving the tongue a curve to the eastward instead of running it north or northwest towards the low pressure area north of Billings. In the first place, if the strong moist southerly current over Kansas continued northward, rain would be expected to be falling in the Fargo-Winnipeg area, whereas these stations report clear skies. More positive evidence are the reports of Ast, Acu, and Stcu moving from the west at a number of stations in Minnesota, Wisconsin and Michigan. Subsequent developments confirm the presence of 3c as placed: Detroit on the 21st has increasing moisture in a westerly current while during the day on the 20th there is light precipitation in a triangular area bounded by Fargo, Omaha and Detroit—i.e., directly under the moist tongue in question.

May 21st. Though it follows on fairly well from yesterday's chart, today's analysis has been the most difficult of the whole period and as given has one obvious weakness—viz. the criss-cross of dry and moist currents in the Great Lakes Region. What is considered as having happened is that 3c has temporarily cut through 1d which in turn has divided the moist current into 3c and 3e. It is rather difficult to conceive how one current can cut through another somewhat in the manner of a projectile, but experience shows that something of the sort occurs rather frequently and without assuming some such process in this instance it is very difficult to account for the presence of the moist area over New Jersey and the dry area over Virginia and Maryland.

In a number of other features the development from the 20th–21st seems rather forced, but what are considered adequate explanations can be given in each case. Tongue 9 has made a much more rapid advance than the winds justify, but it is not intended to be inferred that the air which yesterday was over Florida has already reached Kansas. Today's 9 is a combination of yesterday's and a moist current originating over the Gulf of Mexico. The dry current 7 over Arizona, despite moderate winds, has made no appreciable advance. In this case the 305° surface cuts the ground at a number of places and it appears that the current is continuously being broken up. The final feature is the low level of the isentropic surface and the high value of specific humidity over Fargo. In its advance northward 3d appears to have gained instead of lost moisture by lateral mixing. The cause of the increase is that there has been addition of heat to the tongue, thereby resulting in a displacement downwards of the 305° surface into a stratum of higher specific humidity. The non-adiabatic heating of the layer can probably be explained as the result of insolation during the previous day when the tongue was over the eastern slopes of the Rocky Mountains and fairly close to the land surface.

An interesting point is that despite the great increase in moisture at Fargo, Omaha is still comparatively dry. This is due to the continued presence of the island of dry air which yesterday was indicated as 1b. Such islands, as is demonstrated later in the case of a much larger one over Nashville, seem in some manner to remain stable and to be less affected by lateral mixing than moist currents.[1] In order to keep the flow pattern as simple as possible, 1b has been dropped out in today's analysis, but it is still present and can be considered as the forward position of 1d.

On the 20th tongue 1b seems to be quite separated from 1d, yet today the two have amalgamated in the eddy over Indiana and Ohio. The presence of the eddy of 1b seems to have exerted an influence on 1d and sucked it into its circulation. As has already been mentioned, just the same occurred between the 18th and 19th when 1b itself was drawn

[1] This persistence may also to some extent be the result of radiational cooling in the centre of the dry island.

into the vortex over Texas. This process is reminiscent of the theory of Fújiwhara (1923, 1931, 1937) in which he states that there exists a tendency for two vortices of the same sense of rotation to amalgamate and increase in intensity. As evidence in support of his theory, which is in direct contradiction to the teachings of ordinary hydrodynamics, he cites the results of experiments on liquid vortices and examples of the amalgamation and intensification of cyclones. In the two cases occurring in the present investigation the situation is not quite analogous to Fujiwhara's in that we do not have two fully developed vortices but one anticyclonic eddy and one approaching current, which, though not in the form of an eddy, has at least anticyclonic vorticity. If this effect is real and can be confirmed in other situations, it has an obvious value in forecasting from isentropic charts.

May 22nd. Today the complicating but not really important moist tongues over the Great Lakes and New York have all but disappeared and the flow pattern is now in the form of a single large anticyclonic eddy. In this eddy there appear to be two distinct dry tongues. That nearer the center, 1d, is considered to be formed of *Pp* air from the west, while the other, 10, as pointed out in the discussion of the surface map for the 22nd, is fresh *Pc* air from over the Labrador area. In between the two are the remains of 3e.

In constructing the contour lines the height of 2800 m at Dayton has been considered as too low, the increase of 1000 m in the height of the 305° surface at St. Louis in 24 hours being taken as justification for running a crest of the isentropic surface along the path of 1d. Between Toronto and St. Louis, then, this tongue exhibits very little subsidence—much less than in the other dry tongues from the north. With the arrival of 10 there is a very marked change in the wind at Bermuda, the southeasterlies of the past three days giving place to northerlies which continue until the 25th.

In the lower levels over Florida there are exceptionally strong easterly winds (force 9 at Tampa at 1000 m) and the 5 p.m. winds suggest that the current continues up to the level of the 305° surface. Moist tongue 9 is therefore considered to extend at least as far east as Florida and then to continue in a wide arc to beyond Sault Ste. Marie. Judging, however, by the light variable winds over Cuba the current is very sharply limited along its southern edge. Throughout almost the entire period the wind conditions over the West Indies are unrelated to the main anticyclonic circulations over the continent. Whereas over the southern United States there is in general a deep easterly current, further to the south the layer of easterly winds is relatively shallow giving way to westerlies usually by 3000 m and on occasions before 2000 m. At this time of the year the easterlies over Cuba would normally be expected to extend to great heights, but in this case the presence of the tropical disturbance has upset the usual wind regime.

9 is now a very broad and powerful current and is so dominant over the northern mountain states that it is dragging along with it the dry tongue 8 which yesterday had northwest winds but now, except in the remnant over Utah, has southwest. (Denver and Cheyenne have southwest winds a short distance above the 305° surface.) Although being dragged along by its more vigorous neighbour, 8 has caused a rise in the 305° surface at Fargo from 1500 m to 3090 m.

The numbering of the various tongues has been stopped at 10 and started again from 2, the first of the new series being a dry current over western Canada.

A not very prominent but none the less a very important feature of today's 305° chart is that near the centre of the main eddy the circulation, as shown by the winds at Pittsburgh, Cleveland, Detroit, and Columbus, is definitely cyclonic instead of being anticyclonic as one might have expected. Now this very area of cyclonic winds is quite close to the centre of the anticyclone and we have the apparently anomalous situation of an anticyclonic pressure distribution giving cyclonic circulation. The same reverse motion is discernible in the surface winds in the 8 a.m. map but in that case it might be argued that the effect is caused by Lake Ontario. The 305° isentropic surface, however, is over 3000 m above the ground which seems much too high a level for any land-water effect to reach.

Professor Rossby has pointed out that this cyclonic circulation is in accord with the theory for dynamic anticyclogenesis. His argument is substantially as follows, being a qualitative extension to the case of circular flow of his recent discussion of the mutual adjustment of the pressure and velocity distributions in a linear current (Rossby 1937c). Assume that the horizontal ring of air represented schematically in Fig. 4 has acquired an anticyclonic rotation as a result of lateral frictional drive from a strong current somewhere along its periphery. In the absence of a completely balancing pressure gradient the ring thus set in motion will converge as a result of the Coriolis' forces associated with the frictionally acquired rotation. The centre of the eddy, unaffected by frictional forces, will likewise be forced to converge, and in so doing it acquires a cyclonic rotation. Whether or not this cyclonic circulation shows up on the maps depends on whether it is sufficient to cancel out the already existing anticyclonic rotation or the anticyclonic rotation transferred inward by lateral mixing. The important result, however, is that in extreme cases it is theoretically possible to have an anticyclone with cyclonic rotation near the centre and the wind distribution of May 22nd appears to supply an example of such a situation. It is admitted that the cyclonic eddy does not show up at other isentropic surfaces, but in them there is at least a weakening of the anticyclonic rotation. The period from the 20th to the 22nd is one of rapid anticyclogenesis (see Fig. 2), which would seem to make the suggested explanation more plausible.

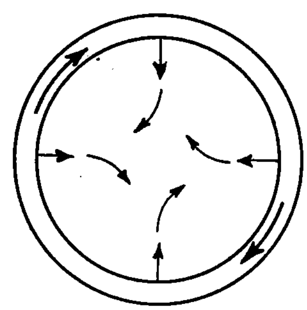


FIG. 4.—Sketch of dynamic anticyclogenesis and the generation of cyclonic core. See text.

In an investigation, the results of which are not yet published, Spilhaus has detected evidence of a similar nature. In his work, however, he did not have winds to indicate the presence of the cyclonic rotation but based his conclusions solely on the distribution of the stream function for an isentropic surface (Montgomery, 1937) on a day when there was a well marked anticyclonic eddy. The importance of the present case lies in the fact that, by corroborating the discovery by Spilhaus, it increases considerably the probability that the effect is real and not merely chance, and gives very satisfactory confirmation of the correctness of theoretical expectation.

It may be wondered why a similar structure is not found in the anticyclonic eddies on other days in the period from May 18 to 26th. Such could, however, hardly be expected. Lateral friction from the surrounding air with anticyclonic rotation should all the time be tending to destroy any cyclonic circulation which may develop in the large eddy, so there is very remote probability of a reverse circulation enjoying anything but a very brief existence.

May 23rd. In tongue 10 there must have been a great deal of downward motion. When it was over the Canadian Maritime Provinces it probably was at an elevation of 5000 m yet its average height about two days later over southern United States is in the vicinity of 2000 m. All the decrease may not be due to subsidence, some probably being due to the addition of heat through convection and condensation along its path over the ocean. That there has been considerable convection is suggested by the distribution of moisture across the tongue. In the presence of lateral mixing alone there should be in any transverse section of the current an increase of moisture outward from the axis, yet St. Louis, Nashville, Montgomery and Pensacola show the moisture distribution to be uniform, suggesting that the effects of lateral mixing have been offset by additions of moisture through vertical mixing.

The anticyclonic eddy has now become an almost symmetrical vortex of truly tremendous dimensions, the horizontal diameter being between 2500 and 3000 miles. Though on the 305° chart there are no wind reports along the axes of the main currents 9 and 10, there is evidence that in both the winds reach a force of at least nine or ten Beaufort. At Omaha the top of the pilot balloon ascent is at 2000 m with wind SW force 10, while at 5 p.m. Chicago and Detroit have SW 9 and WSW 9 respectively at 2500 m. In Florida the Tampa 5 a.m. pilot balloon ascent reached only 1400 m, at which level, the wind was E 9, but the 5 p.m. ascent went to 3000 m with easterly winds of force 8 and 9 all the way up. Thus in addition to being very strong the currents in both main tongues are quite deep so they must possess very large amounts of kinetic energy.

If we accept the fact that the winds along the axes of the main tongues are about force 10, it is seen that there is slightly less than a linear increase of velocity with increase of distance from the centre of the vortex—i.e., the whole system is rotating almost as a solid. It follows that this eddy should be fairly stable (see page 32), and this is borne out by its subsequent history.

However the apparent persistence of the eddy is not solely due to its kinematic stability. It has been seen how on the 19th–21st the subsiding mass of dry air of tongue 1b was able to withstand the effects of lateral mixing from the strong moist currents on its sides, and now a similar process on a much larger scale is going on in 1d. An island of subsiding dry air has formed east of Nashville and remains as the centre of the eddy at least until the 26th and perhaps longer. From these two cases it seems that a subsiding dry core favours the prolongation of the life of an eddy. At least two distinct processes appear to contribute to this persistence of the dry core.

(a) In the central portion of the eddy the winds are light and, as this reduces the lateral mixing, the rate of diffusion of moisture inwards from the periphery is decreased. However, even though the lateral mixing may be reduced, it always acts in the one direction, that of increasing the moisture in the dry core. If there is no replenishment of dry air, there should be a gradual increase of specific humidity in the central portion of the eddy. The charts of the 23rd and 24th both indicate that the supply of dry air is cut off by moist tongue 9, so between these two days, increases in moisture in the dry kernel should be expected. There are, however, definite *decreases* in specific humidity over the entire area to the south of St. Louis and Boston—i.e., over the dry core—and this trend continues also on the 25th. These decreases show more clearly on the 310° and 315° charts than on those of 305°.

(b) To explain these moisture decreases in the isentropic surfaces radiation must be taken into account. Over the central portion of the eddy the air is dry and the skies practically cloudless, so there should be a loss of heat from the air itself by radiation. This is a non-adiabatic process and is equivalent to a sinking of the air downward through the isentropic surfaces. As the specific humidity normally decreases upwards this apparent sinking will tend to reduce the moisture at any fixed isentropic surface and may thus account for the changes taking place from the 23rd–25th. Radiational heat losses should cause an increase in elevation in the constant potential temperature surfaces, but inspection shows that there has been a steady decrease in height of both 310° and 315° surfaces over the dry portion of the eddy. This can be readily explained as due to subsidence, the effects of which have been great enough to more than offset those of the radiational cooling.

May 24th. With the moisture distribution so symmetrical round the centre of the eddy, it is impossible today to dintinguish any definite axis of motion of the dry tongue. 10d has, then, been entered rather arbitrarily merely to indicate the previous history of the mass of relatively dry air west of the vortex centre. This tongue and 2a (*Pp* air associated with a cold front which crossed British Columbia on the 19th) have now cut off 9 and 9a from their moist source to the south, and the easterly current 3 over the Gulf of Mexico is being deflected westward instead of following its normal path to the northeast.

Conditions over the northwestern states call for some comment. Since yesterday Billings and Spokane have had increases in moisture and decreases of the height of the 305° surface, suggesting an invasion of a moist current. The winds over the whole area, however, have been quite light and variable and rule out the possibility of such an invasion. What appears to have happened is that the surfaces have been lowered through radiational warming, the moisture changes being accounted for by the normal increase downwards of specific humidity. Similar stagnant conditions continue to the 26th, by which time the 305° isentropic surface is quite close to the ground. The upper air has evidently been heated directly by radiation in situ and not indirectly through surface heating and convection. If the latter had been the case one would expect progressive spreading upwards of heat and moisture, but from day to day the specific humidity distributions at Billings and Spokane remain remarkably constant, the only changes being the steady increase in temperature. This addition of heat by radiation is in direct contrast to the loss which has been shown to take place over the eastern eddy, the difference in effect in the two cases being due partly to the presence of the mountains in the west and partly to different vertical distributions of moisture in the two air masses.

May 25th. The decrease of height and increase in moisture of the 305° surface at Cheyenne, immediately east of the mountains appears to be due to advection of the warm moist tongue 4. Since the 305° surface is close to the ground the winds are rather irregular, but at somewhat higher levels there have been south and southeasterly winds during the last 24 hours along the track of 4. This current appears insignificant on the chart, but is really of some importance as its presence helps to account for the active wave disturbance which develops during the 25th and 26th on the front formed over Montana on the 24th.

From the surface synoptic map for 8 a.m. a rather natural forecast would be for an extension northwards of the rain area which covers southeastern Texas; the isentropic chart, however, shows that such a forecast would be likely to fail as the moist tongue 3 is very definitely curving cyclonically instead of anticyclonically. On the 26th we see the value of the isentropic analysis: the rain area over Texas is still small while to the west El Paso has had rain and Phoenix, Arizona, a station with a normal May rainfall of only 0.1 inch, reports a thunderstorm.

In the main eddy the development since yesterday has been quite straightforward and calls for little discussion. Boston has had a decrease both in specific humidity and in height of the 305° surface, and must therefore be at the edge of a polar current in which there has been a great deal of downflow. By tomorrow it is within the body of the dry air, the height of the isentropic surface having increased from 2580 m to 3970 m with little decrease in specific humidity. At Dayton the moist current is being underrun by a cold front, this resulting in forced ascent of the moist air and the formation of a deep turbulent layer of Ast in which the lapse rate is the saturation adiabatic. Both the general flow patterns and the surface situation today bear a strong resemblance to those of the 18th, and it will be seen that the developments in the succeeding twenty-four hours in each case, though not proceeding at the same speed, are on the whole very similar.

May 26th. Considering the flat pressure distribution at sea level the eddy is still surprisingly well developed, and judging by the anticyclonic curvature of 2c it is still able to attract new currents into its circulation. On the 27th the system is too far to the east for us to tell if the addition of 2d has intensified the vortex, but even if not, the amalgamation has probably at least lengthened its life.

Over the southeastern part of the country there is today a distinct change in the air currents. For the past few days the currents over Florida have almost all been from directions close to east and have been considered as having recently come from the north. Now, however, the Florida winds are more southerly and the air, instead of having its origin in the north, is coming from the subtropics. Pensacola is already showing the effects of this change and by the 27th Montgomery also is affected. Nashville on the 27th is still dry at the 305° level, but this is caused by a new invasion of dry air from the west and is probably not a portion of the dry island which has prevailed during the last few days.

2. *General Features*

Viewing the situation now as a whole instead of by the individual days the principal features appear to be:

(1) It has been possible to carry on a systematic analysis by means of the isentropic charts.

(2) Good continuity from day to day has been maintained without resort to either improbable current velocities or undue modifications of air mass properties.

(3) The most outstanding feature of the flow patterns has been the persistence of a single slowly moving anticyclonic eddy composed of two distinct currents, one moist and one dry.

(4) The central portion of the eddy remains dry, being maintained partly by three successive injections of polar air and partly by radiational cooling. Two of the dry tongues, 1b and 1d, are off-shoots from the right hand side of a strong westerly current to the north, while the third, 10, appears to be a main parent current from the north which curves anticyclonically over the eastern Atlantic and enters the eddy from the east.

(5) The eddy follows a cycle of growth and decay, increasing in both size and intensity to a maximum on the 22nd and 23rd and then slowly decreasing. As far as can be told, the degree of development is approximately unchanged from the 22nd to the 23rd, whereas the sea level pressure in the centre of the anticyclone has a well marked maximum on the former day.

(6) The eddy moves with fairly constant velocity along a curved path, the successive positions of the centre of the eddy being indicated by crosses in Fig. 5. Included in the

same figure for comparison are the corresponding positions (dots) of the centre of the sea level anticyclone. Discussion of the relation between the two paths will be given in a later chapter.

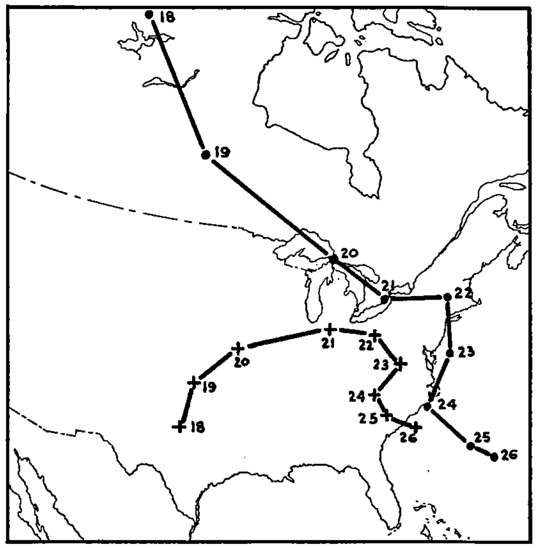


FIG. 5.—Paths of centre of eddy on 305°A surface (+) and of surface anticyclone (•), May 18th–26th, 1936.

(7) The dry currents of polar origin all exhibit marked subsidence, whereas the moist currents in travelling to higher latitudes have a tendency to move horizontally.

IV. VERTICAL STRUCTURE OF THE FLOW PATTERNS

In order to study the vertical structure of the circulation, isentropic charts have been prepared for potential temperatures 285°, 295°, 300°, 310° and 315°A. Space does not permit the reproduction of them all and, in fact, there is little need to do so as they bear a marked similarity to the 305° charts. In Plate XIX are given those for 310°. In order to be able to obtain a bird's eye view of the development during the period all nine 310° maps have been included on one page. With the consequent reduction in size of the individual charts it has not been possible to include complete analyses such as those made for 305°. The relative humidities, clouds, heights, and isopleths of specific humidity have all been omitted while the moist and dry tongues are indicated by full and open line arrows respectively.

For the 315° surface some idea of the circulation can be obtained from Plate XXII in which arrows indicating the axes of the various currents have been superimposed on charts of the isallobars at 5000 m. The flow pattern on these charts are for the end of each 24 hour isallobaric period viz. for the eight days May 19th–26th.

1. *The 300°, 310° and 315° Isentropic Charts*

These are the most important series of charts as surfaces with lower values of potential temperature intersect the ground while those with higher values are frequently above the top of the airplane and pilot balloon ascents.

The outstanding feature of these and the 305° charts is the fact that the flow patterns at all four levels are essentially similar. Except in a few cases, discussed later, any current appearing on one chart can be identified in much the same position on each of the other three. Both in size and in shape the main eddy is repeated in the successively higher isentropic surfaces with a slight tilt of the axis to the westward.

Rough overall averages for the heights of the lowest surface, 300°, and the highest, 315°, are 1500 m and 5000 m respectively, the mean pressure difference between the two being around 300 mb. As the similarity of flow pattern probably continues above and below the two extreme surfaces analyzed, we are safe in assuming that throughout the nine days investigated at least half the atmospheric mass above the United States followed the same general flow pattern. This conservatism with height is of great importance for routine daily analyses as it means that, in order to give a fairly representative flow pattern, one map, provided a suitable value of potential temperature is chosen, should normally be quite sufficient, although exceptions to this rule are known to occur.

May 18th. Mention has already been made in Chapter II of the discussion by Holzman (1936) of the vertical structure over the Appalachian area, and on the surface map for the 18th an upper level cold front has been included to conform with his analysis. According to Holzman the upper front marks the forward edge of a *Ta* air mass advancing northeastward as a cold front on to *Ts*. Under both the *Ts* and *Ta* are shallow surface layers of modified polar air. The isentropic charts, however, show that there is little evidence to warrant the inclusion of this cold front. Instead of having *Ts* aloft to the east of the front there is most decidedly a moist current, 5, which appears to be practically continuous right back to the Gulf of Mexico. The advance of a line of high level thunderstorms which Holzman associates with the upper air cold front may in part be the result of the gradual dissipation through mixing of the narrow dry stratum (tongue 4) which the Detroit-Pensacola cross section shows to be present at about 305° between Montgomery and Nashville and which prior to its dissipation, has been able to suppress the development of thunderstorms.

The above comment has been given not so much for the purpose of pointing out disagreement with Holzman's interpretation, as for the purpose of providing a convenient illustration of how misleading horizontal maps can be in representing atmospheric structure and movements. Level for level comparisons show that at the latitude of Dayton the air to the west of the Appalachians is moister than that to the east, and it was presumably on this evidence that the distinction between *Ts* to the east and *Ta* to the west was drawn yet the isentropic surfaces, sloping as they do downward to the east, indicate just the opposite to be the case, Lakehurst having higher specific humidity than Dayton for all values of potential temperature.

May 19th. The upper wind maps today show a very broad and deep south to southwest current over almost the entire western half of the country, and at first sight one would perhaps expect this to be uniform in structure. It consists, however, of three distinct tongues—two (3 and 6) moist and one (7) dry. It is 7 which is of most interest, as it is the only dry tongue discussed so far with a definite source region to the south, all the others having been of polar origin. Being of tropical origin 7 can, therefore, be considered as belonging to the true *Ts* classification, as distinct from the very much more numerous warm dry currents which it has been the practice to call *Ts* but which Namias (1938 a p. 6) states are in reality currents of subsided polar air, and therefore could be more rationally designated by the abbreviation *Ps*.

Subsequent to the 19th, 7 has a different history at different levels. On the evidence afforded by the afternoon high level pilot balloon ascents which show a continuation of southwesterly winds across Minnesota on the 21st, it has been retained as a main current on the 315° map for the 22nd. At the 305° and 310° levels, however, 7 never progresses much beyond Cheyenne, where it is cut off by a second dry tongue, 8, and by 3, the latter of which is more dominant in the lower levels than higher up.

May 20th. As there are no airplane stations between Spokane and San Diego there is no direct evidence to justify the introduction of a moist current, 8a, distinct from 8, the latter of which is most definitely dry. Along the path of 8a there is admittedly very little cloud, but nevertheless it has been classed as a moist tongue on the strength of its high specific humidity at the 315° level when it reaches El Paso on the 23rd and 24th. On both these days the lapse rates below the 315° level at El Paso are too stable to permit the moisture to have been carried up by convection.

May 21st. Tongue 9 at the 315° surface is placed north of Miami, but, must then be very narrow, as the Miami wind is from west of north. This small width is scarcely consistent with the relatively large size which the current supposedly possesses on the 22nd, so in all probability it is supplemented by another southerly current over the Gulf of Mexico and to the west of Miami.

May 23rd. 2a marks the commencement of a new thrust of dry air southeastward and is considered as being associated with the short surface cold front running through Winnipeg, Fargo and Cheyenne. The isentropic charts put 2a some distance ahead of the surface cold front but this may be due to incorrect placing of the latter. The surface indications are so indefinite that the surface front could perhaps be made coincident with the old cold front separating *Npp* from *Tg*, but it has been kept to the rear to give a reasonable advance from its position on the 22nd.

Over the Middle Atlantic coast the arrows 1d today are not meant to indicate air trajectories but merely the source of the dry air. This dry air which is attributed to the 1d of the 22nd extends well to the southwest, Shreveport having lower specific humidities than can be accounted for by 10.

May 24th. On both the 24th and 25th the flow patterns over Mexico, New Mexico and Colorado change radically with elevation, the moist tongues of the 300°, 305°, and 310° charts not being present at the 315° surface. The difference shows up more clearly in the 5 p.m. upper air maps, on which the analysis has in this case been partly based, El Paso having a change in wind direction from southeast to northwest between 2500 and 3500 m on both the 23rd and 24th.

May 25th. Over North Dakota today we have an apparent case of a warm current undercutting a colder one. In the past 24 hours the 300° surface at Fargo has decreased in height from 3220 m to 800 m and the strong southwest winds today in this isentropic sheet indicate that the warm and moist tongue 5 has advanced into the region. At higher levels there has been no corresponding change—the 305° surface at Fargo has dropped only from 3820 m to 3520 m while the wind at St. Paul is from the north. Over Fargo the cold current 2a still prevails at the 305° surface and we have the phenomenon of a warm current cutting in underneath a cold.

2. *Circulation Above the 315° Surface*

So far it has been shown that the circulation is essentially the same everywhere between the 300° and 315° levels, i.e., in the layer lying between approximately the 1500 m and 5000 m levels. There still remains to be described the circulation above and below these levels. The airplane ascents, as a rule, do not reach much above the 315° surface, so it is impossible to construct isentropic charts for higher values of potential temperature. If, however, as a first approximation we assume the high θ-surfaces to be horizontal, a fair idea of the circulation in the upper atmosphere can be obtained from the upper winds alone. It is well known that with increasing elevation there is a pronounced tendency for winds to become more westerly so it is not to be expected that the flow patterns in the upper levels should be as complex as those found in the lower. Small eddies, then, should become less distinct and less frequent with increasing height.

Too few of the 5 a.m. pilot balloon ascents attain sufficient height to indicate adequately the character of the circulation above the 315° level, so for the following discussion the more numerous high level ascents made at 5 p.m. have been used. On most days these suffice to give a fair indication of the general flow up to about 10 km.

The first result arising from an examination of the upper air maps is that the major currents of the 315° surface continue up to the 10,000 m level, i.e., the circulation of the upper half of the troposphere is essentially the same as that of most of the lower half. (By "most of the lower half" is meant the layer between the 300° and 315° surfaces—the changes below the 300° surface will be discussed in the next section.)

The second feature of the upper level circulation is the gradual growth upwards of the main anticyclonic eddy. On the 18th it is more pronounced in the 305° than in the 310° isentropic surface and is very much weakened in the 315°, which lies below 5000 m. On the 19th the anticyclonic eddy can be faintly detected over Arkansas at 6 km, and on the 20th is still in about the same position. By the 21st there is a well developed anticyclonic circulation at 6 km with a weaker one probably reaching one or two kilometers higher. On the 22nd the eddy, now over Tennessee, exists up to 10 km but, as indicated by a wind change at Nashville from northeast to northwest between 10 and 11 km, does not reach the latter level. Throughout almost the entire troposphere we now have a well marked closed circulation with strong easterly winds along its southern edge. On the 23rd the eddy over the middle Atlantic States reaches at least to 12 km (SE wind at Greensboro at this level) and can even be detected from the directions of motion of the cirrus clouds. After the 23rd the high level observations are rather scanty over the area where the eddy would be expected to be present, but what observations there are suggest that there is a progressive decrease in the elevation to which the anticyclonic circulation extends. It no longer reaches the cirrus level and by the 26th has probably lowered to about 6 or 7 km.

3. *Circulation Below the 300° Surface*

For much of the period and over most of the country the circulation pattern of the 305° surface extends to quite close to the ground. In the northeast part of the United States, however, from the 19th to the 22nd, i.e., following the invasion of cold air in the rear of the main cold front, this is not the case. It has been pointed out earlier that the top of the *Pc* air mass coincides with the 292° surface, and it is at this surface that the change in flow pattern occurs. On the 20th at 285° there are strong northeast winds in the surface *Pc* air over the Ohio area, whereas in the overlying *Pp* air at 295°, where the flow is similar to that at 305°, the winds are northwest. Though not so marked as on the 20th, there is still a distinct difference between the 285° and 295° circulations on the 21st, Boston having a northwest wind of force 5 in the *Pc* air and west, force 10, in the *Pp* air; while at Detroit there is a change from east to west with increasing elevation.

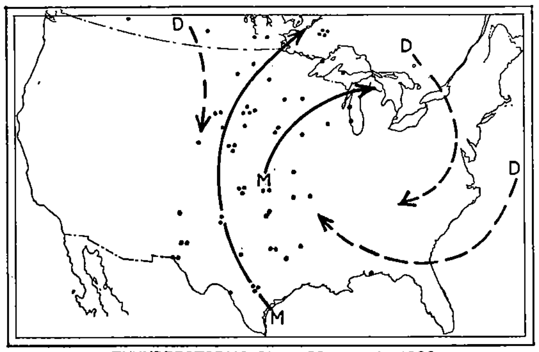
Summarizing the main results of this chapter we have:

(1) Over most of the country the flow patterns are conservative from the ground up to high levels.

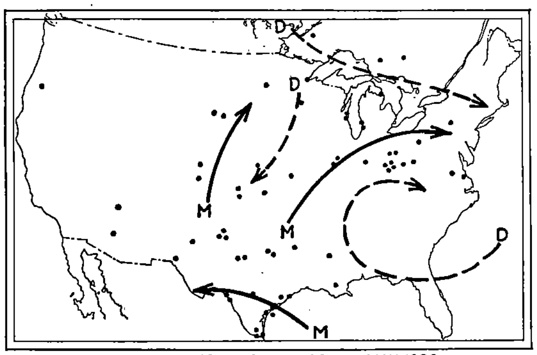
(2) This conservatism does not hold in the northeastern states on the 20th and 21st when the fresh *Pc* air covers this area. In this case the flow patterns, and also the features of the pressure field, change within the first two kilometers, the anticyclonic circulation of the lower levels being replaced by a broad northwesterly current.

(3) The principal eddy has a well marked variation in vertical extent. On the 18th it has a depth of about 5 km, increasing to at least 12 km by the 23rd and then apparently gradually dying away. On the days of its maximum depth it has also its greatest horizontal dimensions and greatest intensity.

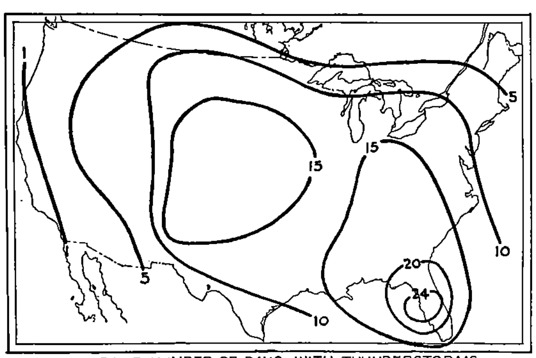
(4) In the free atmosphere currents tend to assume anticyclonic curvature. In moist currents in particular, however, this curvature becomes weaker with decreasing elevation and, on approaching the ground, may even change to cyclonic.



THUNDERSTORMS 21a.m.-23p.m. MAY 1936



THUNDERSTORMS 24a.m.-26p.m. MAY 1936



AVERAGE NUMBER OF DAYS WITH THUNDERSTORMS MAY—JUNE 1904-1933

FIG. 6a.—Thunderstorms 21 a.m.–23 p.m. May 1936.
FIG. 6b.—Thunderstorms 24 a.m.–26 p.m. May 1936.
FIG. 6c.—Average number of days with thunderstorms May–June 1904–1933.

V. Relationship Between Flow Patterns and the Distribution of Thunderstorms

Examination of the maps of distribution of cloud and precipitation (not reproduced) shows that the connection between the flow patterns and the areas of *continuous* precipitation is only slight. Most of the rain occurs on the northern side of the moist tongues, but so many factors other than the mere presence of moisture enter into determining whether there will or will not be continuous precipitation that the flow patterns by themselves do not provide a very useful guide.

The distribution of thunderstorms, however, follow the flow patterns much more closely than does that of continuous precipitation. If what occurs in this nine day period can be accepted as representative, the mere presence of a moist tongue, irrespective of whether or not it is flowing up-slope, is sufficient to give thunderstorms, while in dry tongues they are entirely suppressed. How well these relationships hold is brought out in Fig. 6a and 6b. From a scrutiny of the 8 a.m. and 8 p.m. synoptic maps each report of "thunderstorm in the past 12 hours" has been noted and indicated by a dot. Fig. 6a covers the six synoptic maps May 21 a.m.–May 23 p.m., and Fig. 6b refers to the succeeding six maps. The full and dashed lines M and D represent the mean positions of the moist and dry tongues respectively of the 305° isentropic sheet for each of the three day periods. As the change in flow pattern from day to day is very gradual the variations from the mean are quite small, and the positions of the moist and dry tongues can be taken as practically constant during each three day interval. There is, however, some overlapping in the patterns in the case of the dry tongue running south-southwest from Minnesota on Fig. 6b, the thunderstorms along its path being, in consequence, not due to it but to moist tongues which are not permanent enough to show up in the mean.

Namias (1938 a) has already brought out by means of isentropic analysis the importance of moist air for the development of thunderstorms, and the manner in which dry tongues are able to suppress them. Namias' conclusions are strikingly brought out by Figs. 6a and 6b. In all six days not a single thunderstorm is reported over the southeastern portion of the country, an area which, as can be seen from Fig. 6c (adapted from Alexander 1935) is normally the centre of maximum thunderstorm activity at this time of the year. The three reports north of the Great Lakes in Fig. 6b apparently provide an exception to the rule of no thunderstorms along dry tongues. All three, however, are of frontal origin.

The high correlation found between the flow patterns and the distribution of thunderstorms suggests that the isentropic chart should be a useful tool in the forecasting of summer precipitation.

VI. Anticyclogenesis and the Transition of the Anticyclone from Cold to Warm Type

1. *Transition*

In this particular instance there has been no such thing as a "transition" from one type to the other. The anticyclone of the last half of the period is not a direct development from the cold polar anticyclone of the 18th, but is the result of the amalgamation of this with the initially quite unrelated warm type anticyclone which on the 18th was located over Texas. As shown by the tracks in Fig. 5 (p. 91) the two systems approach one another on the 18th, 19th and 20th and then merge. The cold Canadian anticyclone continues at its original low level merely cutting in underneath its Texas companion. From the 21st onwards, then, the surface high pressure is the resultant of the contributions of the two systems, and its centre does not necessarily coincide with that of either component. With increasing age the shallow surface layer of air constituting the cold anticyclone spreads horizontally and so gives a steadily decreasing contribution to the surface pressure.

Thus we see that the final warm anticyclone is directly descended from the Texas anticyclone and not from the Canadian. In the latter there has been no transition from cold to warm type—all it has done has been to move southwards, temporarily intensify the anticyclone from Texas, and then decay.

The process in four successive stages is indicated in a schematic form in Fig. 7. C is the Canadian surface system and T that from Texas. The latter is arbitrarily assumed to remain constant in size and intensity, while the former increases in area, the relative contribution of C to the sea level pressure being indicated by the number of plus signs. The heavy full line represents the resultant of the two systems—i.e., the pressure which would be observed at the ground.

Though so artificially simplified, such a scheme fits in well with many of the observed facts. First of all it accounts for the rotation of the axis of the surface high pressure from N-S to E-W. It also explains qualitatively the surface pressure changes. Between stages b and c, when the two systems merge, there should be anticyclogenesis, while later, as C continues spreading horizontally, there should be a gradual decrease in intensity, just as

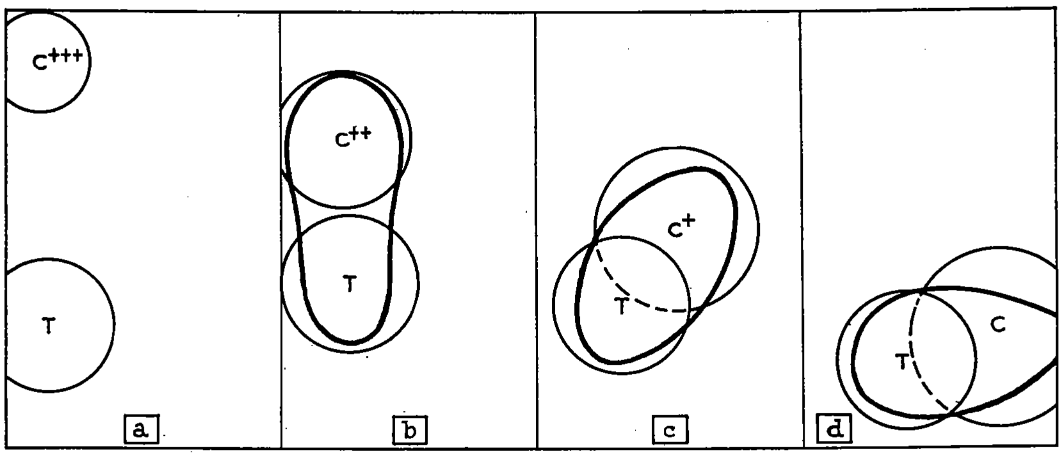


FIG. 7.—Amalgamation of warm (T) and cold (C) anticyclones.

is found to occur. As the influence of C becomes weaker the centre of T should tend to coincide with that of the surface anticyclone, but according to Fig. 5 this apparently does not happen, the path of the 305° eddy being indicated as running almost parallel to that of the centre of maximum sea level pressure from the 21st–26th. In all probability, however, the two do actually approach one another. Since they fall outside the station network the true positions of the centre of the eddy on the 24th–26th cannot be determined, and they are quite possibly farther to the east than those given—i.e., closer to the centre of the sea level high pressure.

Though the actual trajectories of the air are best shown on the isentropic charts and it has been from them that the above model of the development has been evolved, the pressure changes associated with this model are well demonstrated on the upper level pressure maps (Plates XX and XXI). The motion of the T anticyclone is best represented on the 3000 m map where it is seen to move (as does the eddy in the 295°–315° isentropic charts) in an anticyclonically curved path commencing over Texas on the 18th and finishing up off the Atlantic coast on the 26th. For the time being we shall omit consideration of the increase in intensity which occurs in this system. The wind directions above 3000 m in the northern portion of the United States—west and northwest throughout the entire period—indicate that at least until the 22nd no air at these levels can have moved southward from the Canadian high. At the 1000 m surface, however, we have evidence of such southward transport. At this level there is an area of high pressure corresponding to T, but on the 20th and 21st this area is elongated northwards (Fig. 8) because of the top of the high pressure of the cold anticyclone. There is no such elongation at 3000 m. For the 1000 m level this corresponds to stage *B* of Fig. 7. At the ground the same stage is represented, but not so well, by the highs over Kansas and just north of Winnipeg on the 19th.

On page 78 it was shown how on the 19th the changes in wind at Bismarck from easterly in the surface layers to westerly above 1500 m indicated that the main anticyclone was then of the true cold type with an area of low pressure above it. This system does not move southwards en bloc; the cold surface layer separates from the upper air and, as indicated by the *Pc* cold front, moves rapidly southwards in a shallow stratum only about 2 km. deep. The upper system, however, makes relatively little southerly progress, the southern boundary of the region of strong westerly winds above 2000 m remaining in approximately the same position on the 19th, 20th, and 21st—viz., roughly along a line running from Chicago to New York. It is this evidence that has led to the conclusion that the process is not that of a transition from cold low level into a warm high level anticyclone, but is a double process: the gradual dissipation of the low cold anticyclone, and its amalgamation with an already existing warm anticyclone.

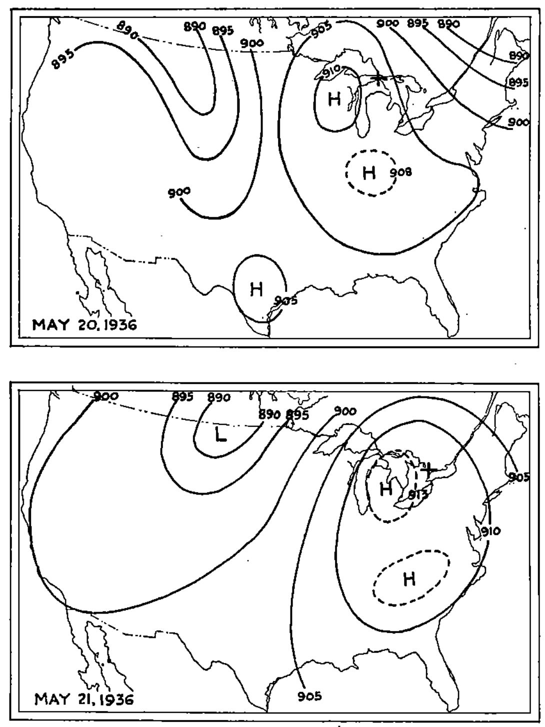


FIG. 8.—1000 m isobars (millibars) + indicates position of the center of the surface anticyclone.

Up till the 21st, then, there have been three main currents associated with the two anticyclones. These are: (1) The various southerly warm currents from low latitudes, (2) The strong westerlies to the north, and (3) The shallow northerly current of *Pc* air. The *T* anticyclone has been maintained by currents in the first group plus offshoots (tongues 1b and 1d) from the southern side of the westerlies, these offshoots having been characterized by marked subsidence. The northerly current has brought high pressure with it but is rapidly becoming of less importance.

In stating that the Canadian anticyclone remains a low level system throughout its whole history, it seems that no account is being taken of the important polar current, which is represented by tongue 10 on the isentropic charts, and which by the time it enters into the anticyclonic eddy is most decidedly not confined to a shallow layer. The air in 10, however, is not considered to be a part of that which originally comprised the Canadian anticyclone and so does not enter into the question of the transition. Though there are no upper air observations to prove it, this current probably is of maritime origin, traveling from the northern Atlantic round the deep low pressure centre, which on the 21st is located over Labrador. When 10 enters the eddy over the southeastern portion of the United States any subsidence which may have been taking place in it earlier has ceased, and from the 23rd to the 26th the potential temperature surfaces remain almost unchanged in height. This is in marked contrast to the rapid subsidence in tongues 1b and 1d.

2. *Anticyclogenesis*

The anticyclogenesis occurs when the two anticyclones, the high level one from the south and the low level one from the north, meet. To a large extent, then, it is the result of the advection of air masses of different temperatures. Pure thermal-advective processes, however, do not appear sufficient to explain all the pressure changes which occur. Consider, for instance, the pressure changes at the 5000 m level in the twenty-four hour period from the 20th–21st, the first of the two days on which the most marked anticyclogenesis occurred at the ground. These changes are shown in Plate XXII. The heavy lines are the flow patterns of the 315° isentropic surface at the close of each 24 hour interval. Over the Great Lakes area there have been pressure rises at 5000 m of about 8 mb. Since the pressure at this level (550 mb) is roughly half of the sea level pressure, the change in weight of the layer originally above the 5000 m level amounts to almost 16 mb. The upper winds indicate that a southwesterly current at least 9–10 km in depth, of subtropical origin, has invaded the area, replacing the original polar air from the northwest. Palmén has shown that the maximum temperature difference between maritime polar and subtropical currents over Europe in winter occurs between 4–7 km, so it is reasonable to assume that in the present instance the southwesterly current is the warmer. This means that the layer 5–10 km gives a negative contribution to the change of mass above the 5000 m level, necessitating an increase above the 10 km level of at least 20 mb. It is putting too great a burden on advection above 10 km to ask it to account for this entire increase. If only advection acts, and no piling up of air, the increase of 20 mb requires a temperature decrease of about 15°A throughout the stratosphere. This in turn, for a normal temperature distribution, requires a transport of air from south to north through fifteen degrees of latitude at the very least. The cirrus observations, however, preclude the possibility of such a large latitudinal displacement, so all the pressure change cannot be attributed to advection. A similar situation holds also on the 21st–22nd over the northeastern portion of the country.

Some process or processes other than advection must in these two cases have been operating to bring about the piling up of air. That on the 20th–21st may be due to the bodily lifting of the whole upper layers by the *Pc* wedge. As, however, the *Pc* does not increase in depth after the 21st this cannot account for the large area of positive pressure tendencies at 5000 m in the eastern United States on the 22nd. So even after taking into account advection and bodily uplift, there is still a residual increase of mass. There must, then, have been very appreciable convergence of air into this area. This can have taken place either above or below the 5000 m level, the effect of the latter being to push up the overlying air and so to increase the pressure at a fixed level.

In the past most emphasis has been placed on advection as the source of pressure changes in the free atmosphere, the reason being that there has been no established mechanism to cause convergence or divergence. These two phenomena require non-gradient winds and until recently there was no force known which could bring about departure from gradient flow in the layers above those affected by ground friction. Rossby, however has demonstrated that there is such a force present, viz: the shearing stress resulting from large scale horizontal mixing, and that it causes a banking to the right hand side of all northern hemisphere currents. In the case in question such banking very nicely explains the residual mass increase above 5000 m. As shown by the flow patterns and winds, the area of large positive isallobars, in which advection and lifting by *Pc* cannot account for all the pressure rise, is located between and to the right of two broad and deep currents—the southwesterly to the west and the northwesterly to the east.

The anticyclogenesis at the ground is thus the net result of two quite separate processes. These are: (1) Advection, causing the amalgamation of the Canadian and Texas anticyclones.

(2) The banking along the right hand side of the currents taking part in the circulation.

Banking is a continuous process, so anticyclogenesis (and cyclogenesis, its converse on the left side of all currents) must be taking place at all times in the atmosphere. On the other hand, the amalgamation of the two anticyclones may largely be a random effect resulting from the intersection of their trajectories.

Without more extensive aerological data—e.g., meteorograph and pilot balloon observations from higher levels than those available—it is impossible to tell how great is each effect, but the indications are that the banking is by no means negligible.

If the 5000 m isallobaric maps for the whole period are examined it is seen that in the majority of cases the currents have areas of rising pressure to their right and of falling to their left. This association is doubtless partly due to advection but, if that were the only factor, the axes of the currents would tend to coincide with the axes of maximum pressure change, whereas there is a pronounced tendency for the current axes to coincide with the isopleths of zero pressure change.

Though considered to be fairly conclusive the above evidence for banking due to lateral mixing is very indirect. There is, however, a direct method of detecting convergence by means of isentropic surfaces. If all motion between any two isentropic sheets is adiabatic the total mass of air between the two should remain constant. Lateral mixing causes a redistribution of this mass, the areas of convergence being areas of increased mass, or bulging apart of the isentropic sheets. From an examination of the time and space variations of the mass between two surfaces, then, it should be possible to detect the presence or absence of convergence.

In Plate XXIII are given the pressure-differences in millibars between the 295° and 310° surfaces on the 19th, 20th, and 21st, and between the 300°–315° surfaces on the remaining days, the change in layer being necessary to avoid getting above the top of the airplane ascents in the former set, and getting too close to the ground in the latter. In interpreting these charts two things need to be kept in mind: (a) Non-adiabatic processes can disturb the relative position of the upper and lower surfaces. (b) In most of the troposphere the pressure difference for any particular layer decreases to the north. This is a result of the relative constancy of lapse rates throughout the atmosphere which tends to make the distance between layers constant, and, as the layers slope upwards to the north, the pressure-difference there must be less.

On each day the mean position of the centre of the anticyclonic eddy on the 305° and 310° isentropic charts is marked by a cross. Throughout the whole period the eddy centre is associated with an area of maximum pressure-difference—a very important result indicating that convergence takes place in the middle layers of an anticyclone. The eddy centre and the maximum pressure-difference should not necessarily coincide, the latter being probably displaced towards the currents of subtropical origin. If the processes were truly adiabatic, the convergence should cause a progressive increase in the pressure-difference in the centre of the anticyclone, but no such increase is apparent. This does not imply that convergence is not occurring, but results from the masking influence of divergence caused by ground friction in the lowest portion of the isentropic stratum. By choosing a higher-valued potential temperature surface for the lower boundary of the stratum this difficulty could be overcome. This was tried but the layer was thereby reduced from a potential temperature interval of 15° to one of 10°, and it was found that non-adiabatic effects then destroyed the simplicity of the picture.

As there is no reason to suppose that in going from the 300°–315° layer to higher layers there should be any change of effect, it is considered very probable that convergence occurs right to the top of an anticyclone—with, of course, a shallow layer of divergence close to the ground. In layers well removed from surface turbulence we should expect then to get a steady increase with time in the pressure-difference in an area with anticyclonic circulation. The result of this should be the growth upwards of such a circulation, just as was found to occur in the situation investigated and is shown by the anticyclogenesis which occurs in the centres of high pressure on the 3000 m and 5000 m maps, and which cannot be attributed to advection of cold polar air.

This conception of convergence and divergence resulting from isentropic mixing is of the greatest significance as it affords the possibility of transferring to the troposphere some of the control of the atmospheric processes usually attributed to motion in the stratosphere. It is generally accepted that the pressure distribution at the tropopause determines to a large extent that at the ground. According to the older thermal-advective theories, the pressure at the tropopause is determined in turn by the advection in the stratosphere. This advection then has been considered by many to be the "primary" controlling factor for circulation in the troposphere, the resultant circulation in which has been termed "secondary." It is obvious, however, that the effects of convergence and divergence in the troposphere must be reflected in the overlying atmosphere, and such convergence and divergence must therefore exercise a measure of control over the pressure at the tropopause. In this respect the motion of the air in the troposphere, which causes the convergence and divergence, is the "primary" controlling factor. Though advection in the stratosphere admittedly is of importance, it seems only natural to expect that the troposphere, which contains most of the mass of the atmsophere should be of greater importance in determining the atmospheric motion.

VII. Summary

This investigation has been a practical study of the conditions existing in the free air during a case of marked intensification of an anticyclone, the data used being the extremely extensive pilot balloon and airplane meteorograph records available over the United States of America. The study covers a period of nine days, May 18th–26th, 1936, during which an anticyclone moved from Northern Canada in a southeasterly direction to south of Bermuda. On two of the days there was rapid anticyclogenesis. At the beginning of the period the Canadian anticyclone was definitely of the "cold" type while that over Bermuda at the end of the period was of the "warm" type.

The chief conclusions are:

(1) It has been demonstrated that over a period of nine days it has been possible to carry out a systematic and consistent analysis of upper air conditions by means of isentropic charts.

(2) The flow patterns on the isentropic charts for a series of values of potential temperature indicate that in the area considered the circulation was substantially the same at all levels throughout the lower half of the atmosphere.

(3) The major feature of the flow patterns is a large slowly moving anticyclonic eddy which

(a) consisted of two main currents, one moist and one dry.

(b) moved during the period in an anticyclonically curved path from Texas over Ohio to east of Florida.

(c) and passed through a definite cycle of growth and decay both in horizontal and in vertical extent.

(4) Though the sea level pressure changes suggested a gradual transition from the cold anticyclone of the initial stages to the warm anticyclone of the final stages this was found not to have occurred, the final warm system being directly descended from an older high level anticyclone which was present over Texas at the beginning of the period. The cold Canadian anticyclone which began on the 18th as a low level surface system remained as such merely progressively spreading out laterally and dissipating as it moved southwards. There is no observational evidence to support the view that it grew upwards to form the final warm anticyclone and it seems probable that the frequently referred to "transition from cold to warm type anticyclone" is a very rare meteorological phenomenon.

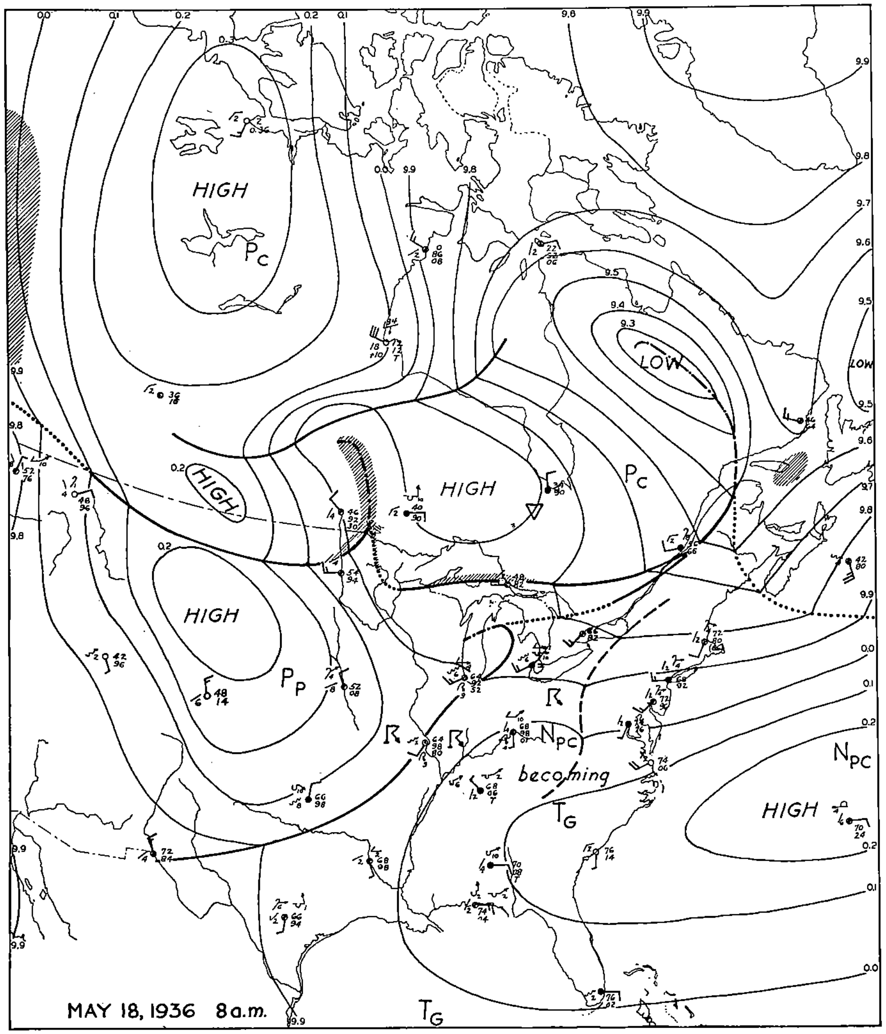
(5) The anticyclogenesis was the outcome of two distinct causes:—(a) The coincidence and amalgamation of two separate migratory anticyclones, the one a cold low level system from Northern Canada and the other a warm high level system originating over Texas. (b) Convergence of air into and piling up of air over the area covered by the anticyclone.

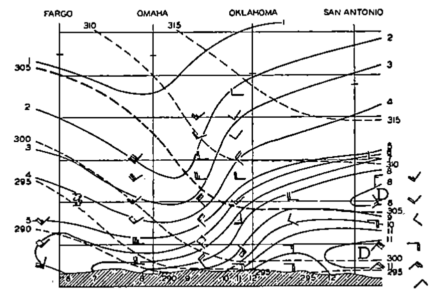
(6) It has been shown that the convergence of "dynamic anticyclogenesis" can be adequately explained on the basis of Rossby's theory of the banking of air on the right hand side of all northern hemisphere air currents having wind velocities in excess of the gradient wind value.

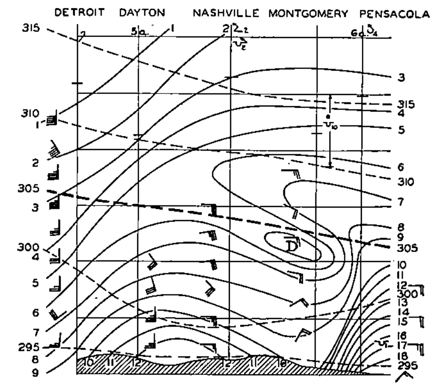
(7) A relationship has been found between the flow patterns of the isentropic charts and the distribution of non-frontal thunderstorms the latter being quite suppressed along the dry tongues.

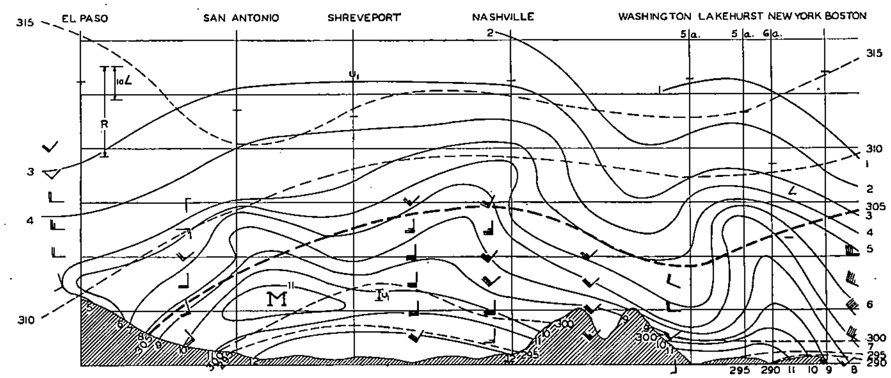
VIII. Plates

For an explanation of the symbols used in the Plates, see B IV, page 51.



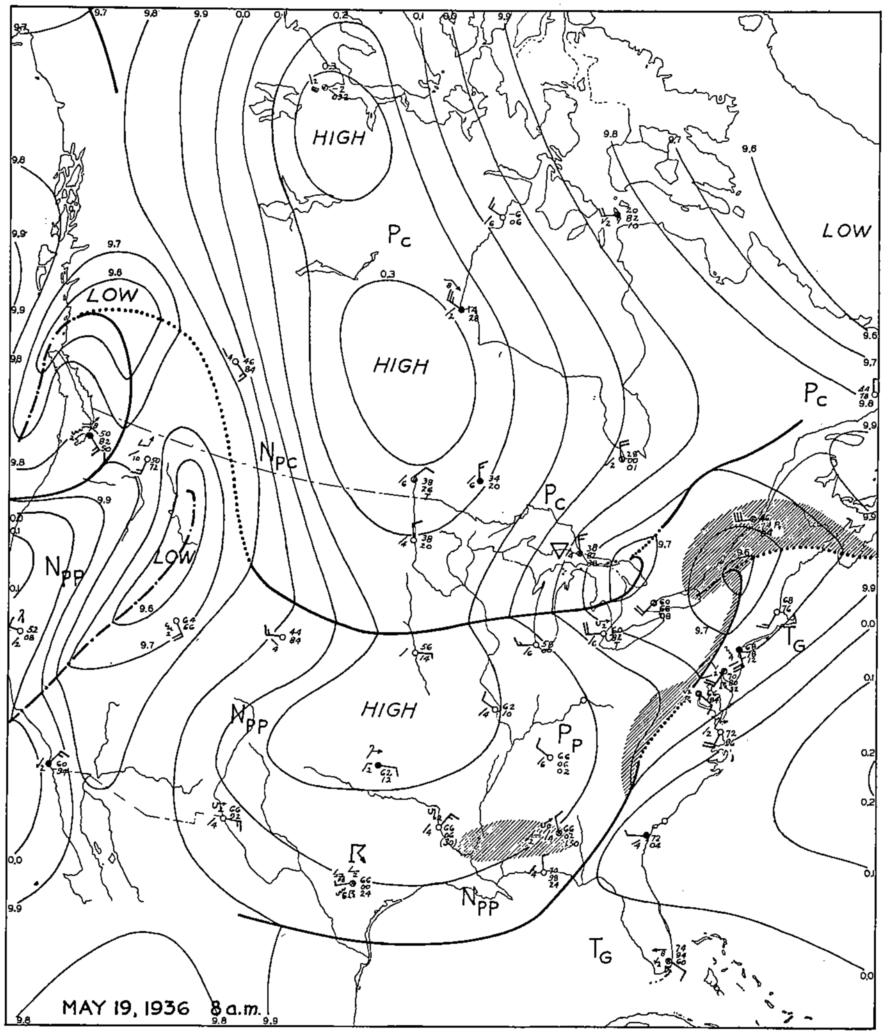






Simmers

Plate I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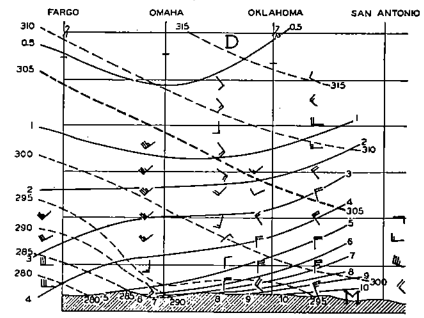
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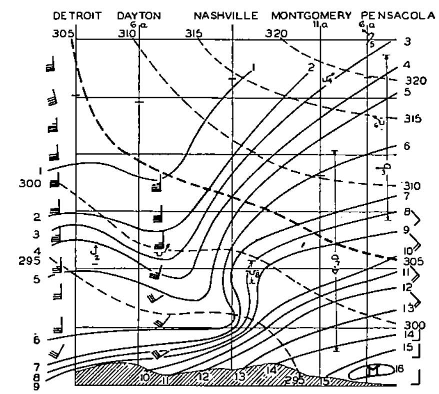
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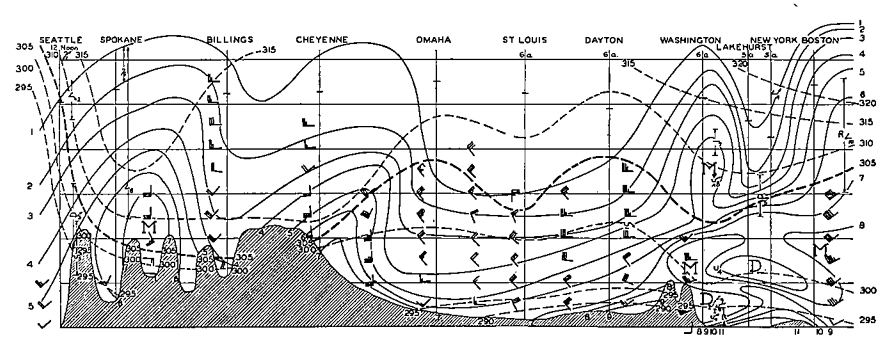
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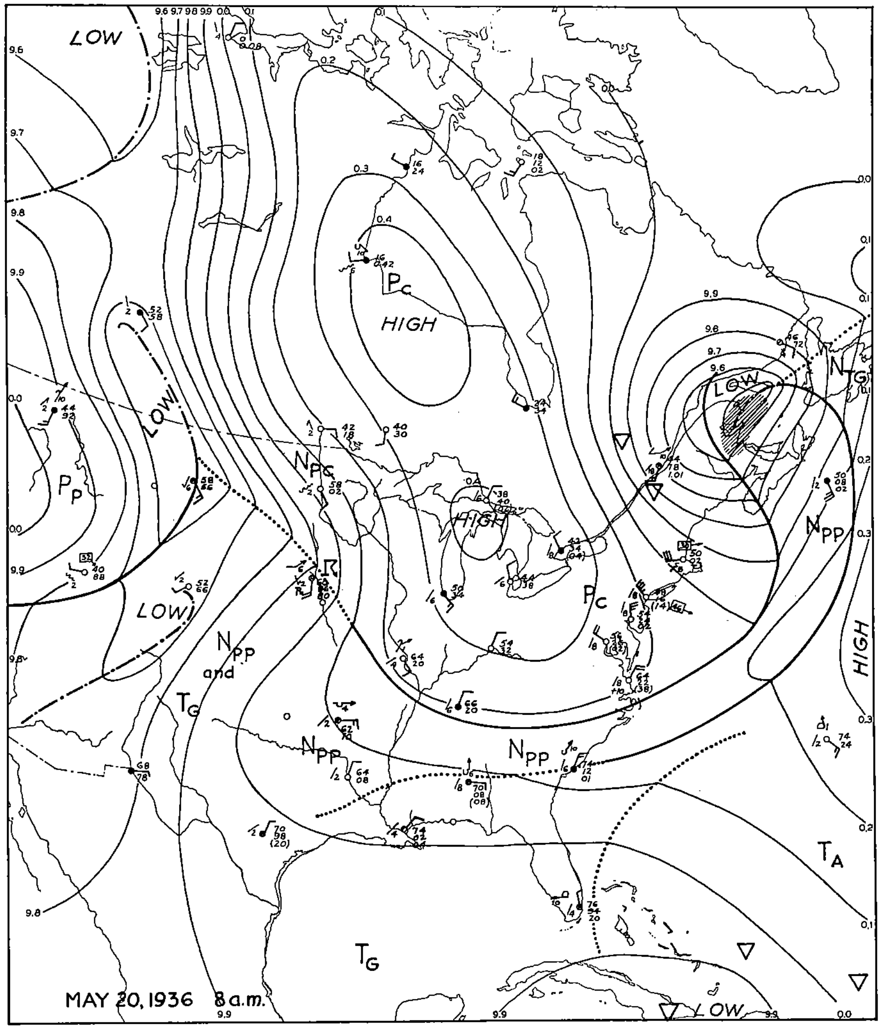
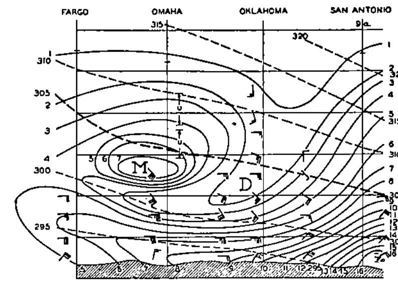
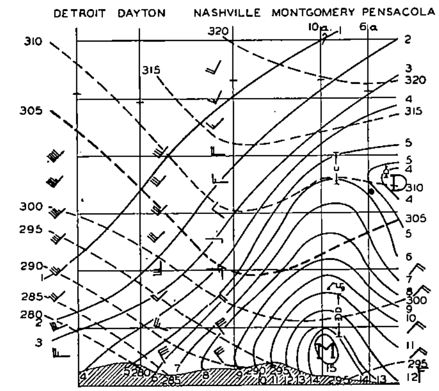
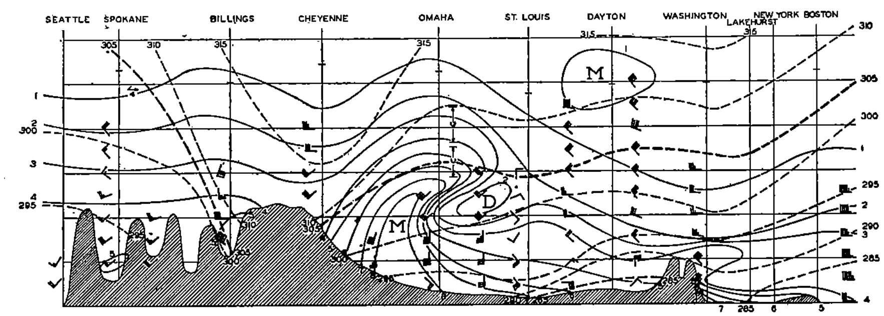


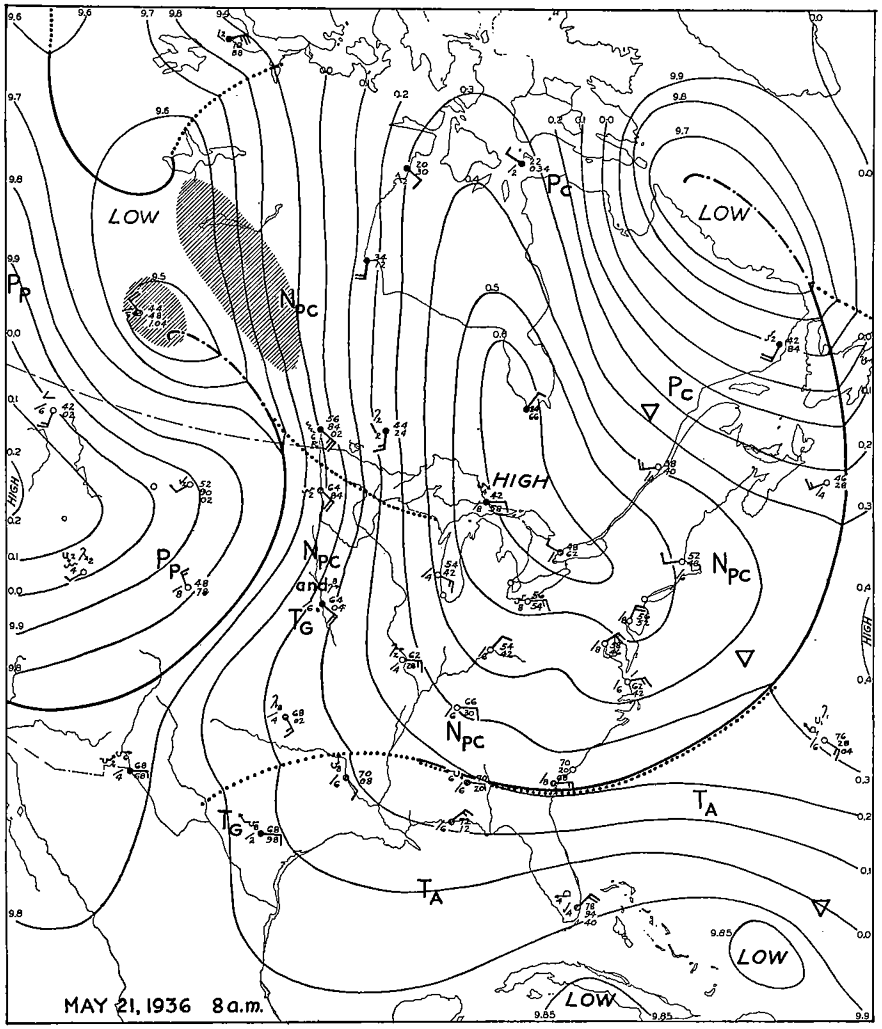


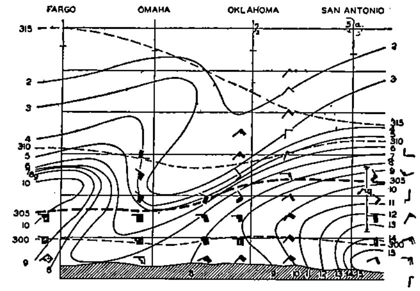


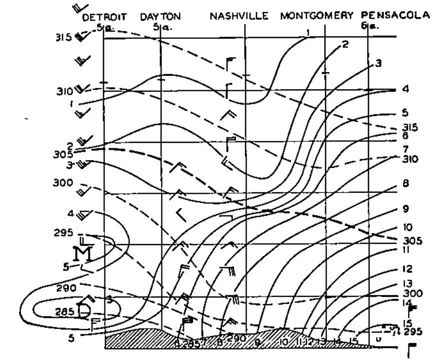


SIMMERS

PLATE III







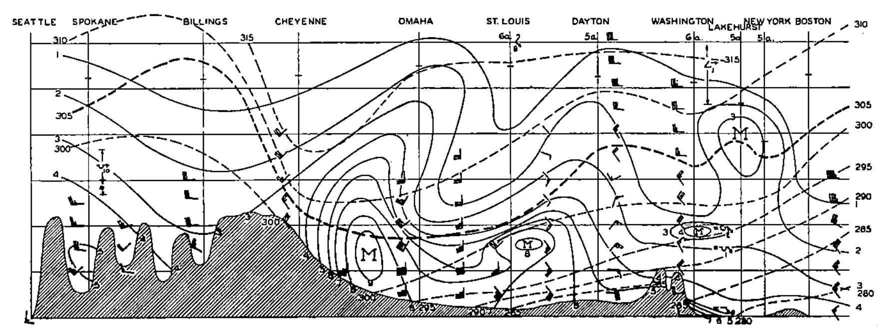


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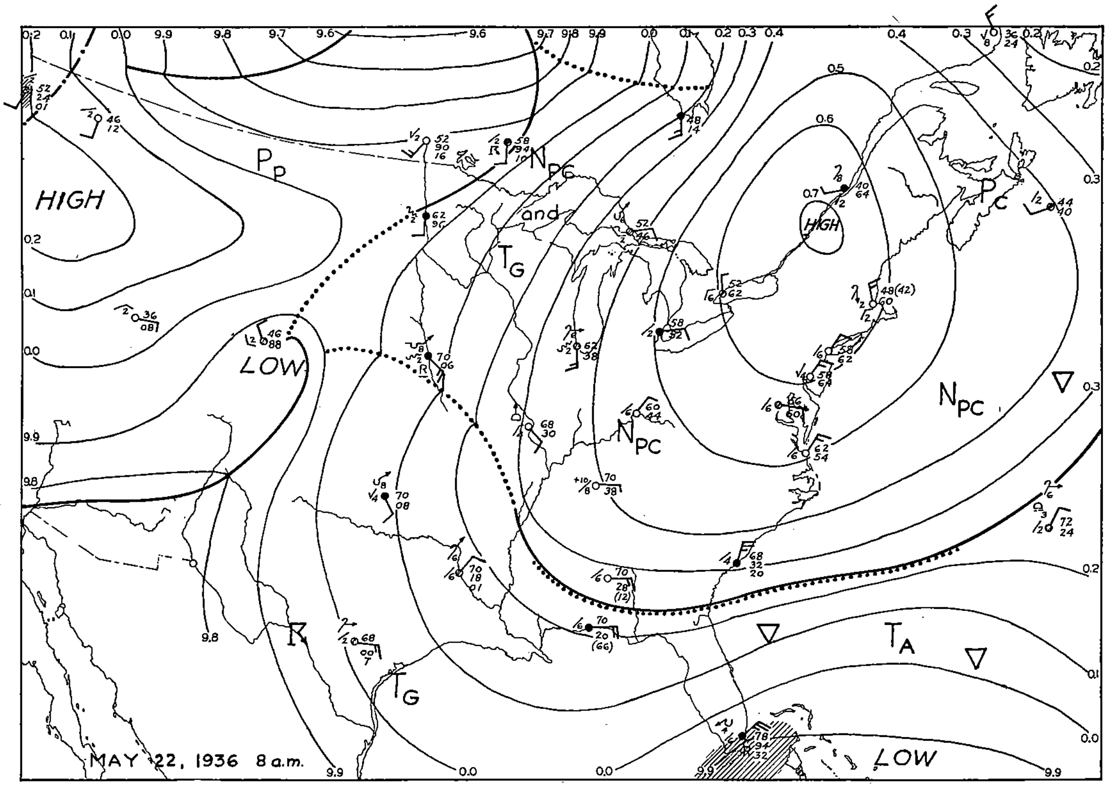
PLATE IV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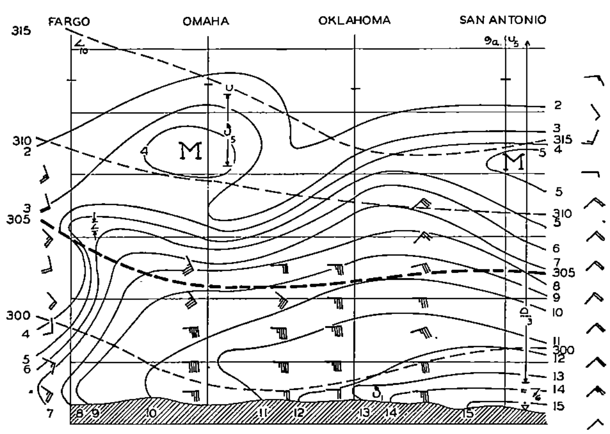
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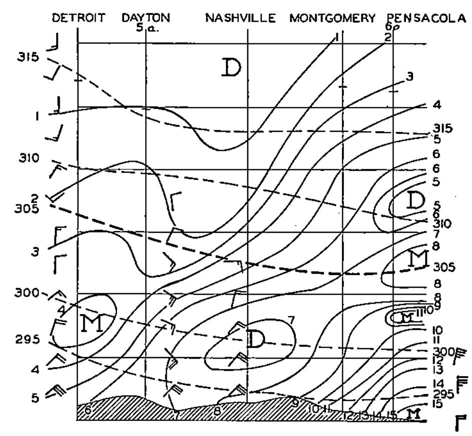
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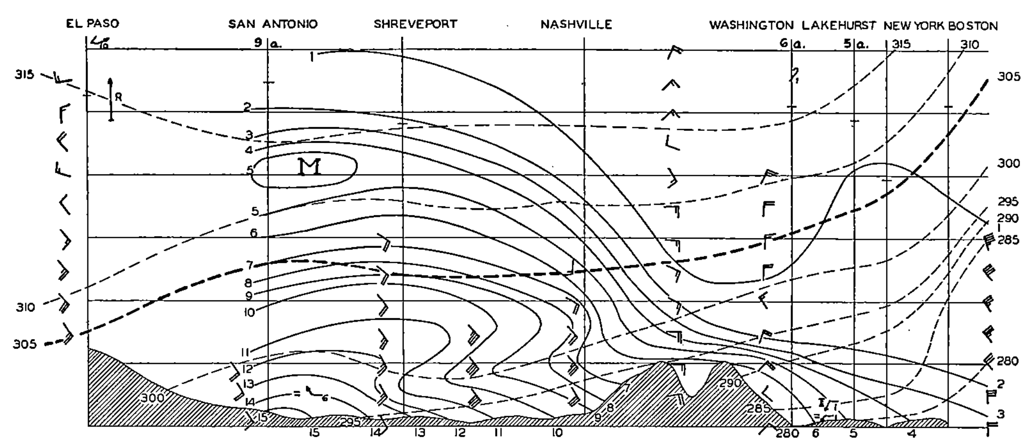
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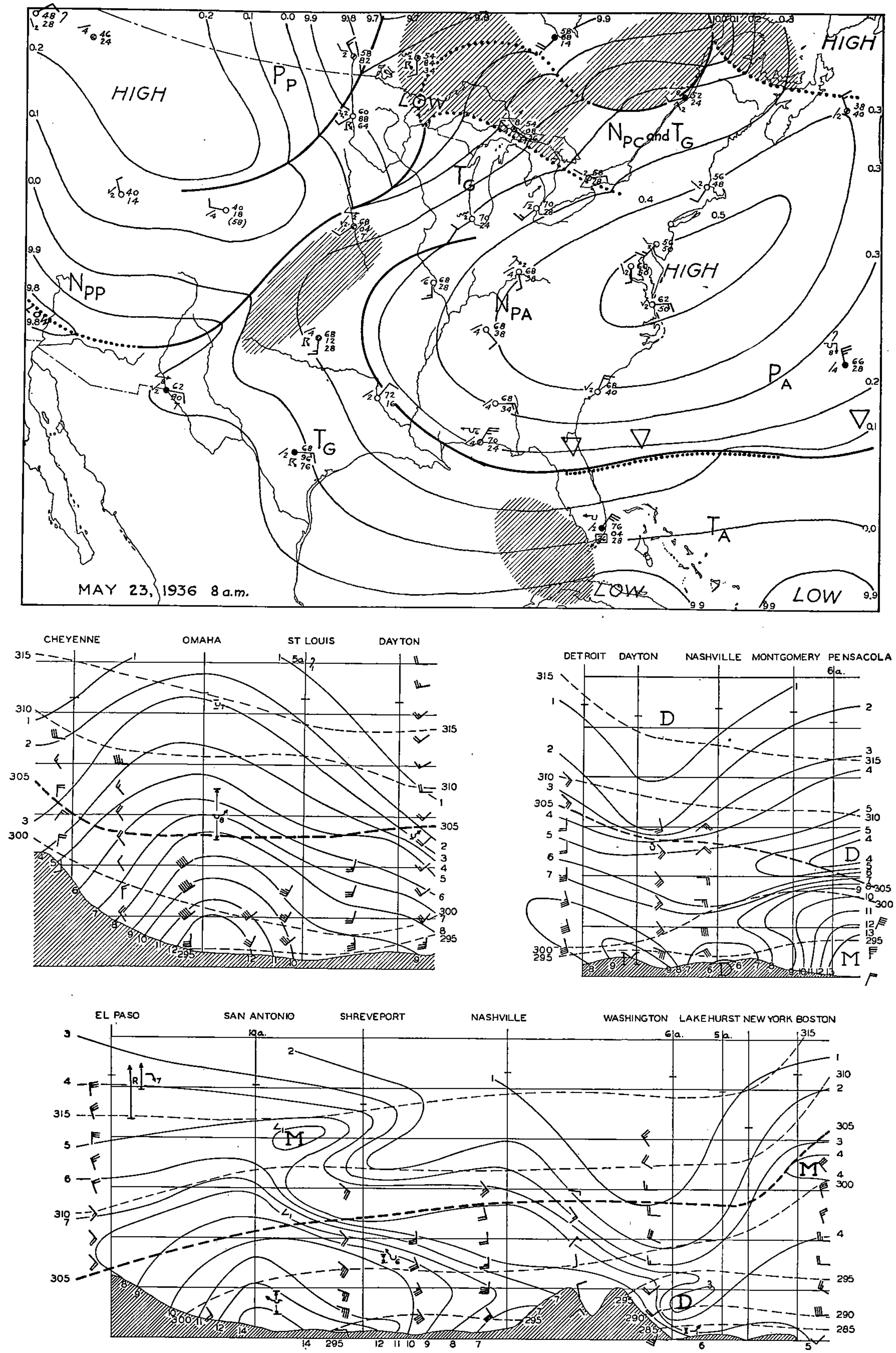

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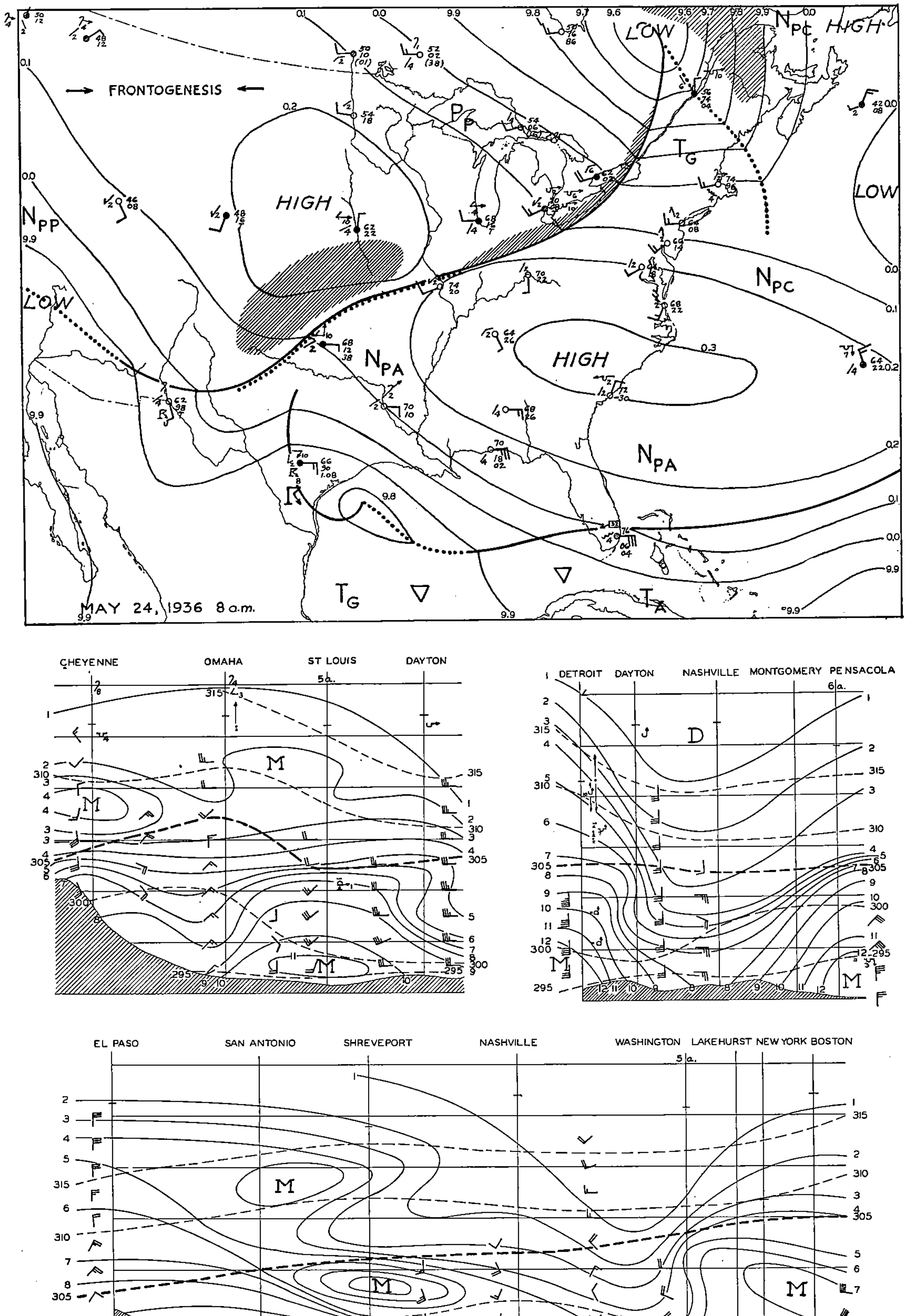
PLATE VI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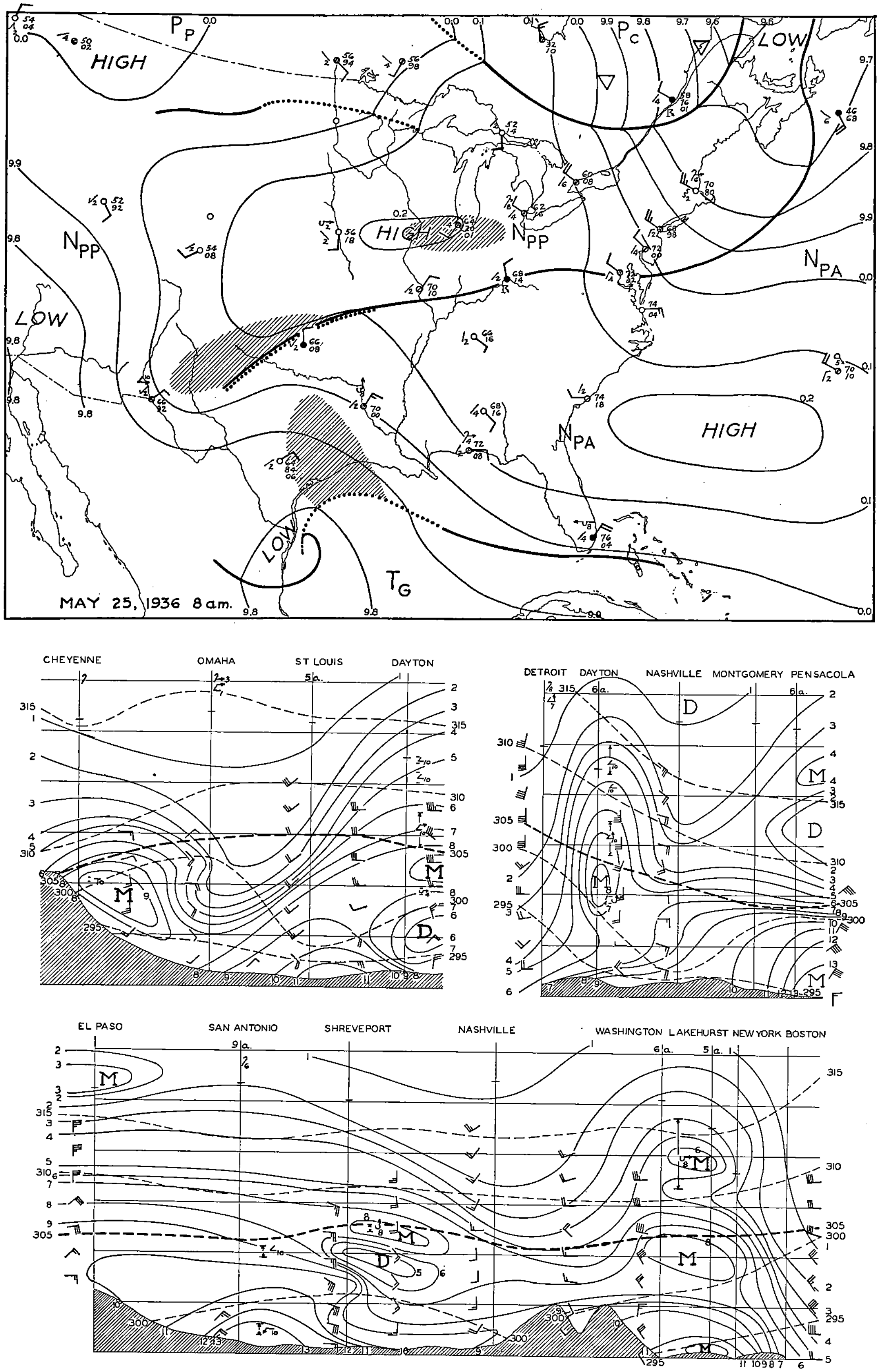

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WASHINGTON
LAKEHURST
NEW YORK
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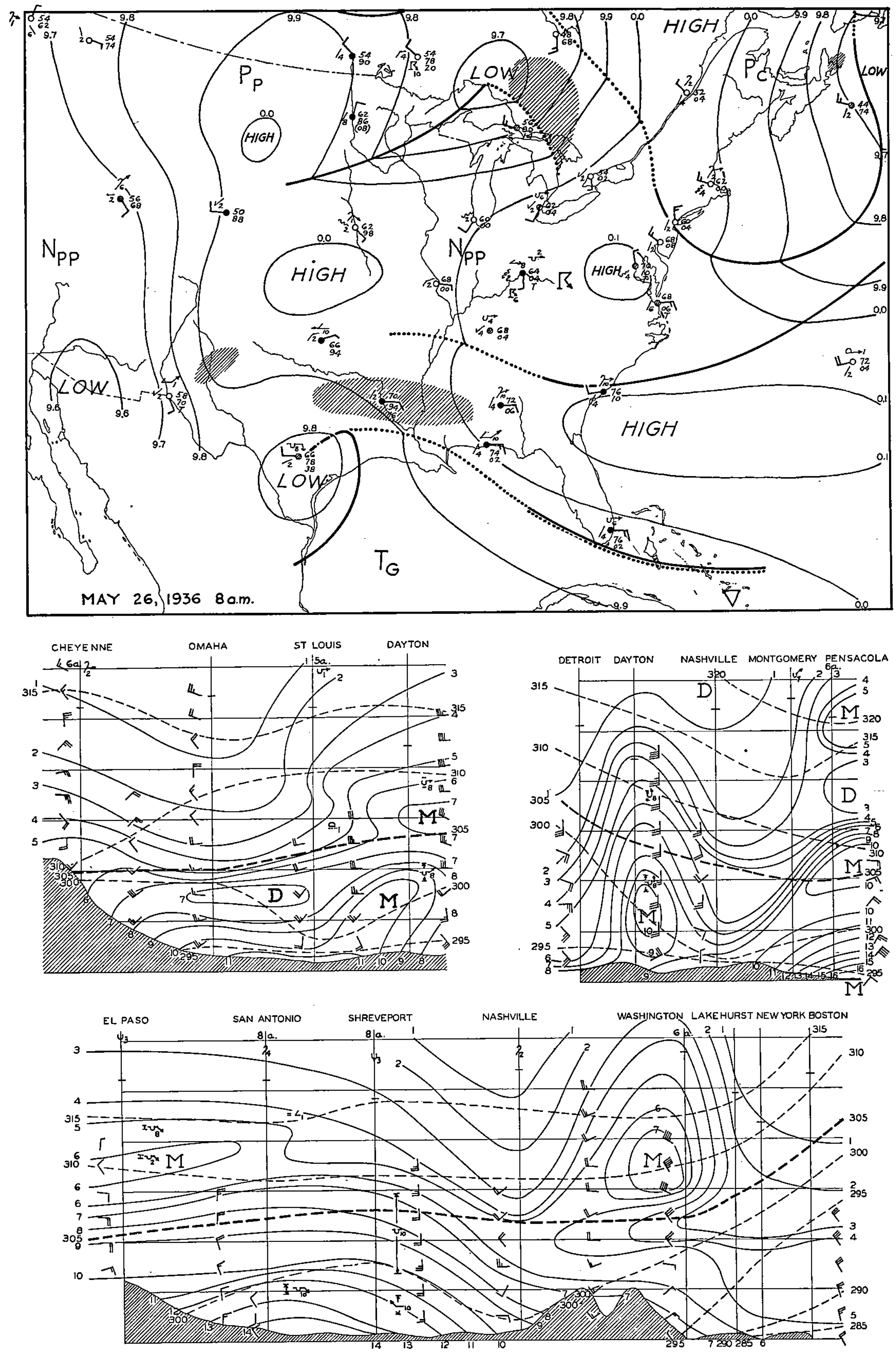
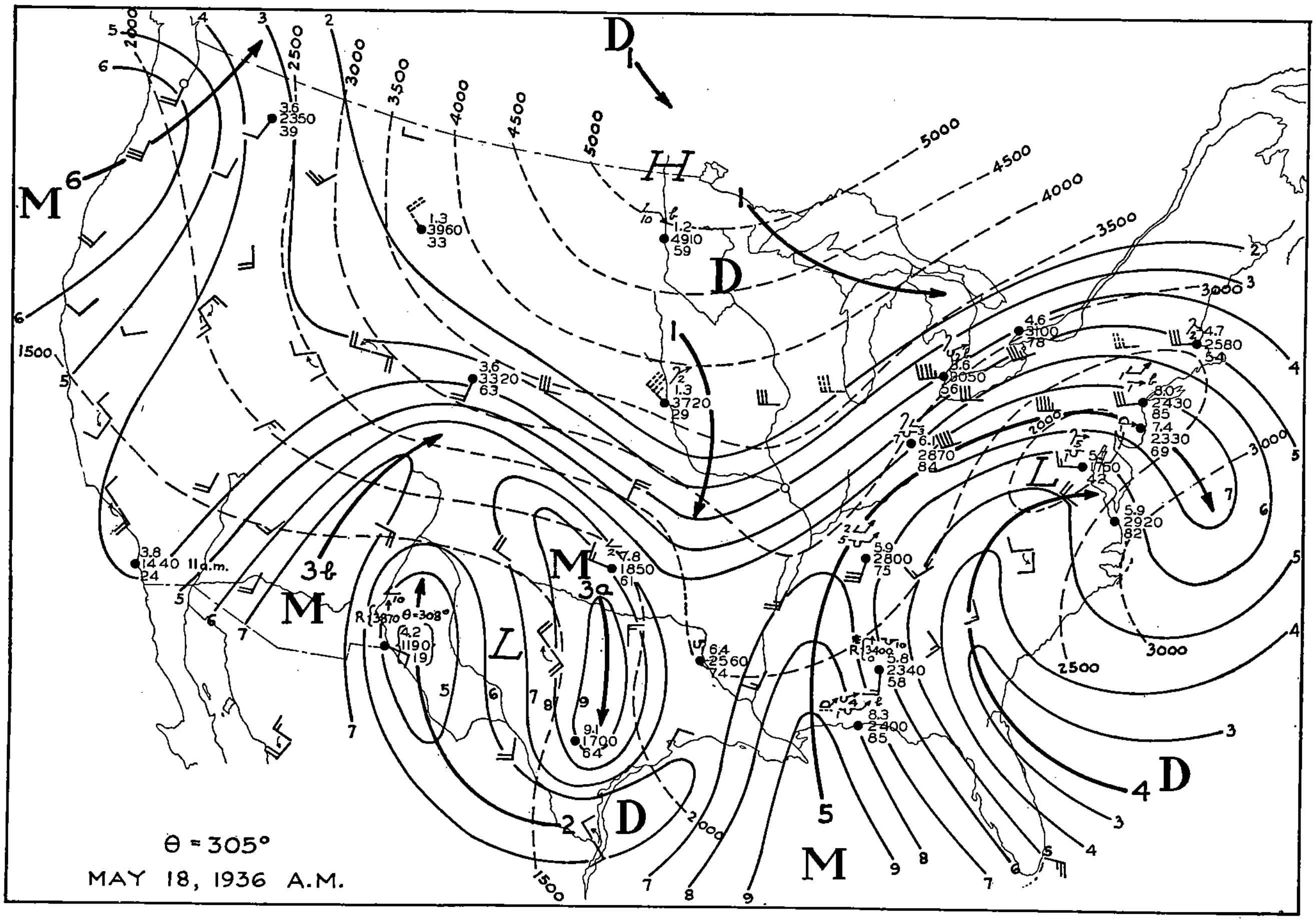


SIMMERS PLATE IX



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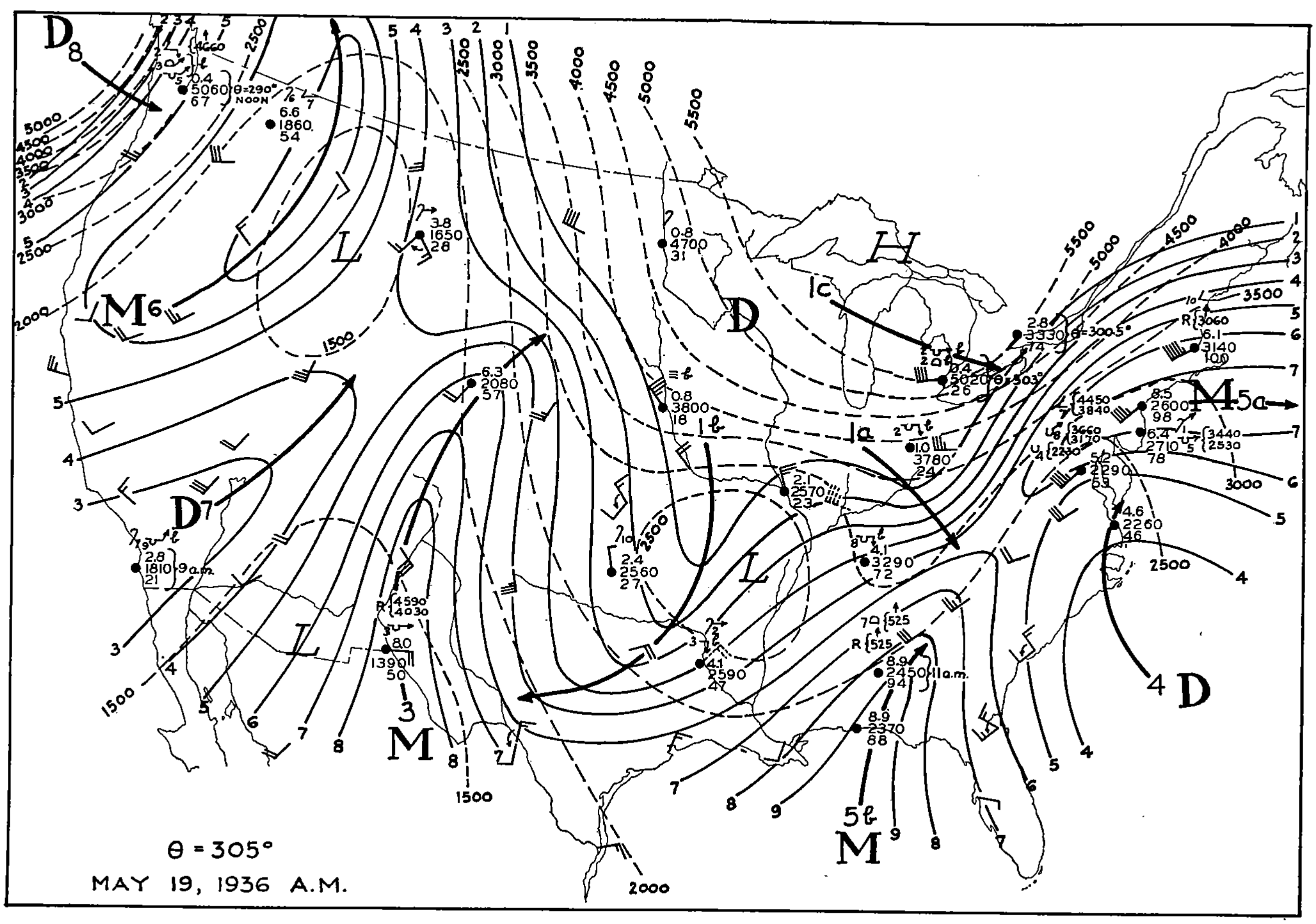

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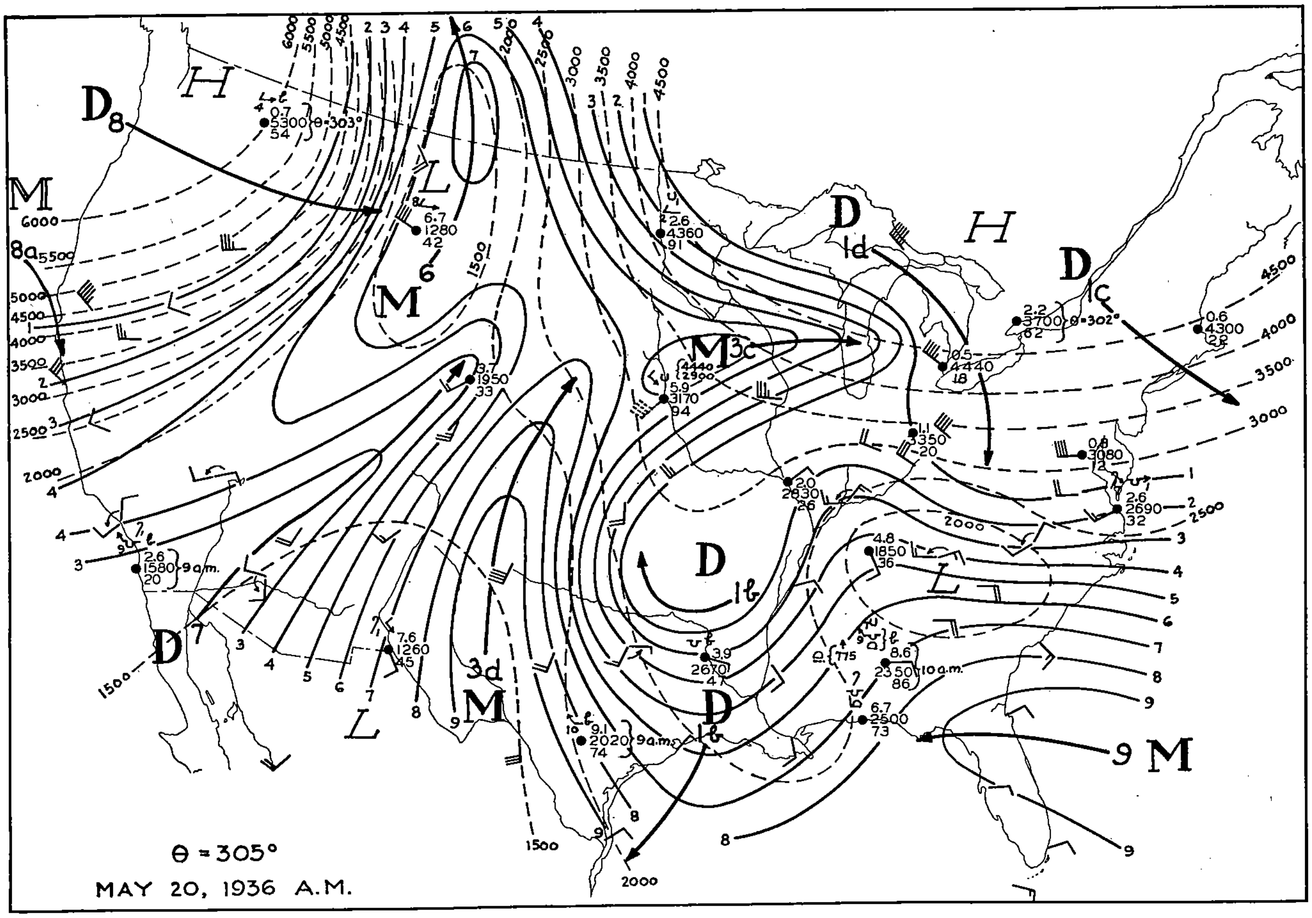
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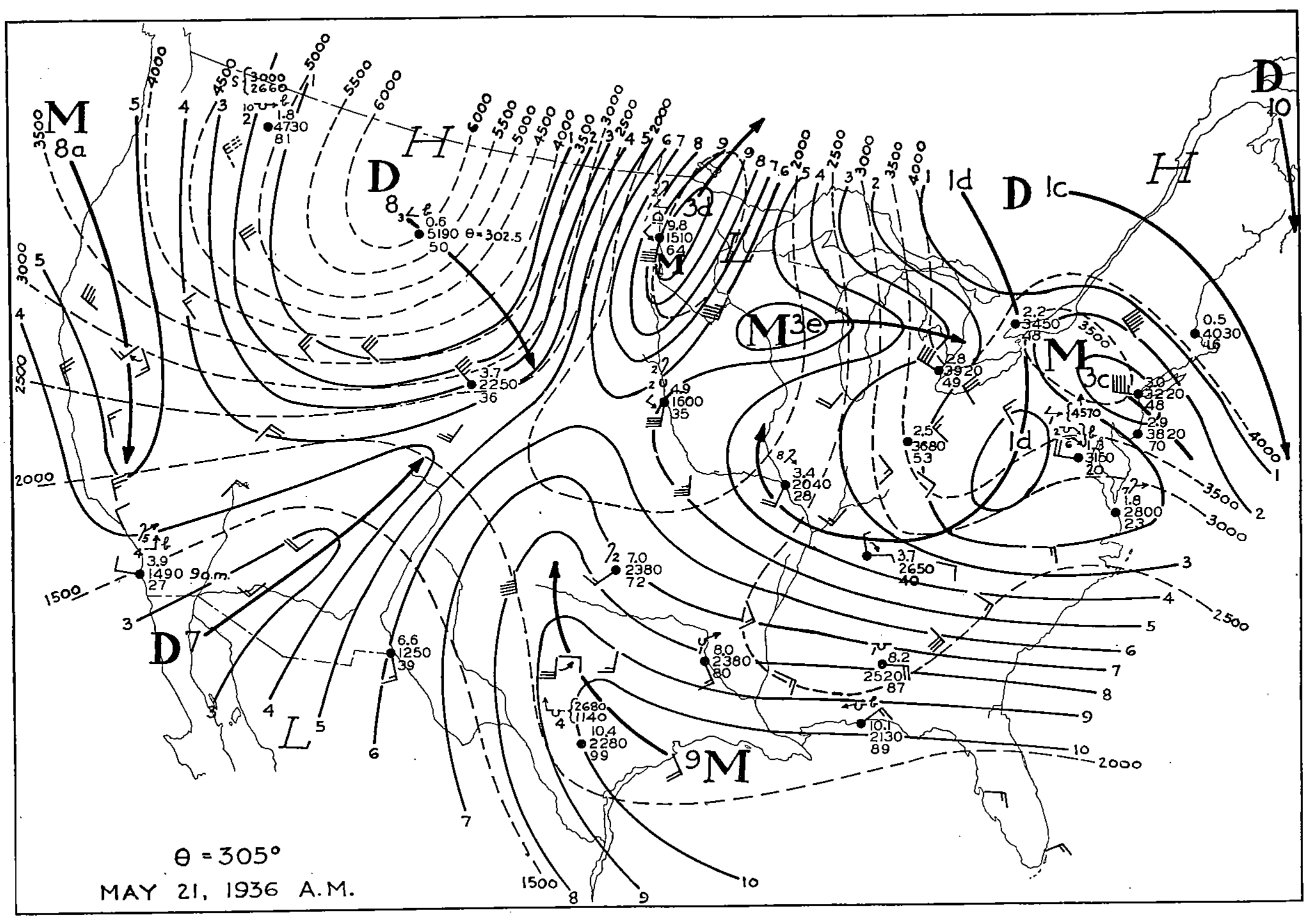
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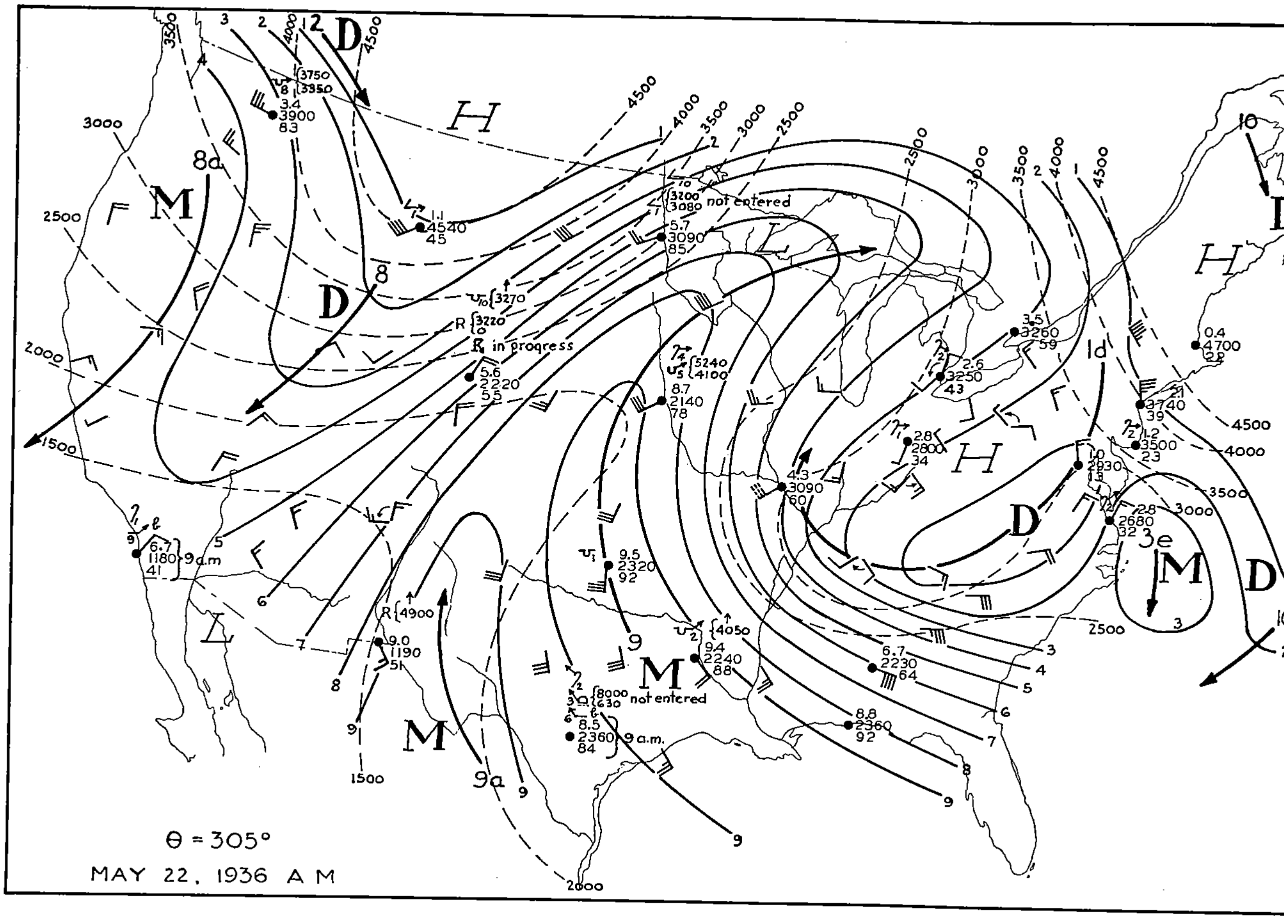
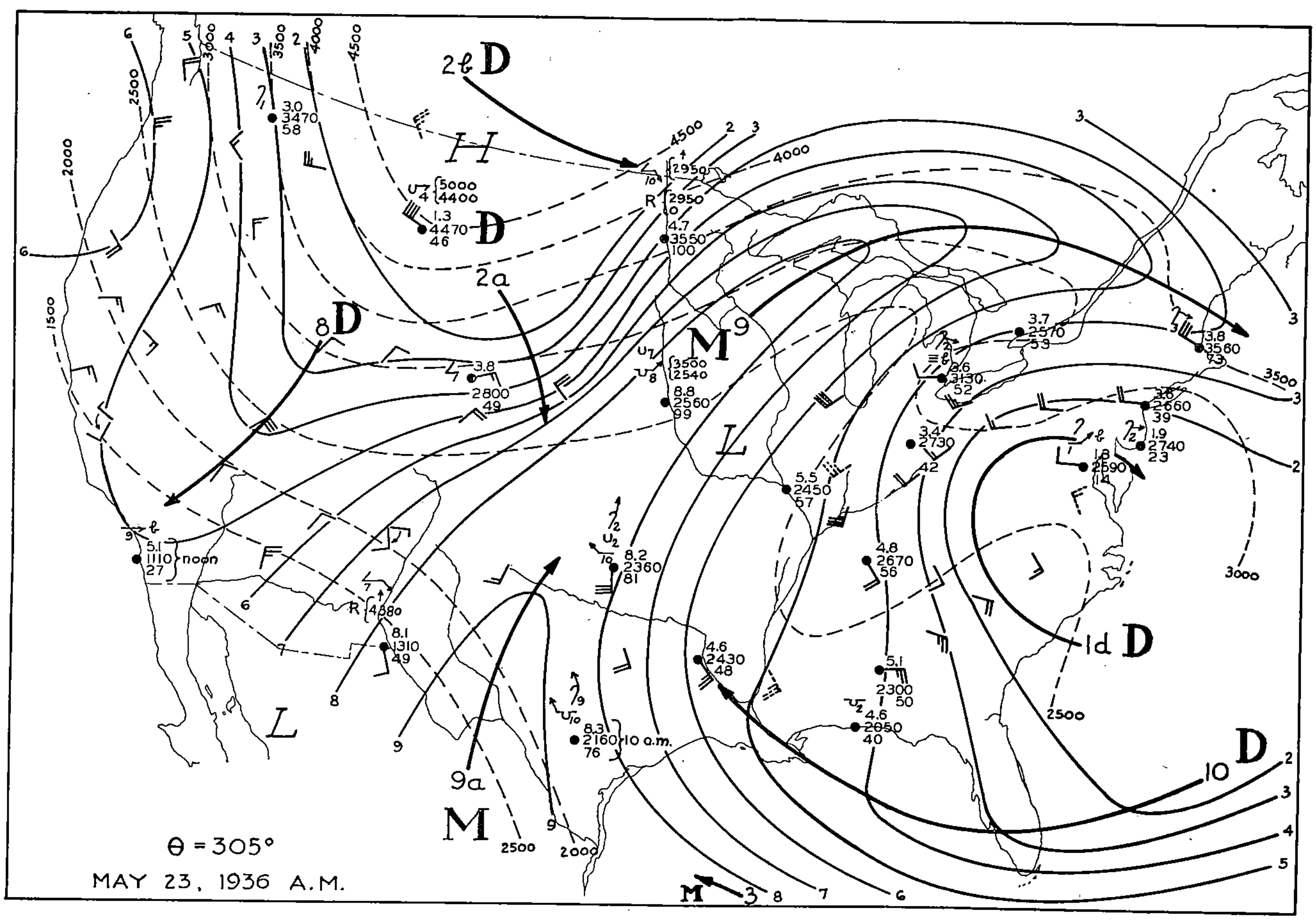
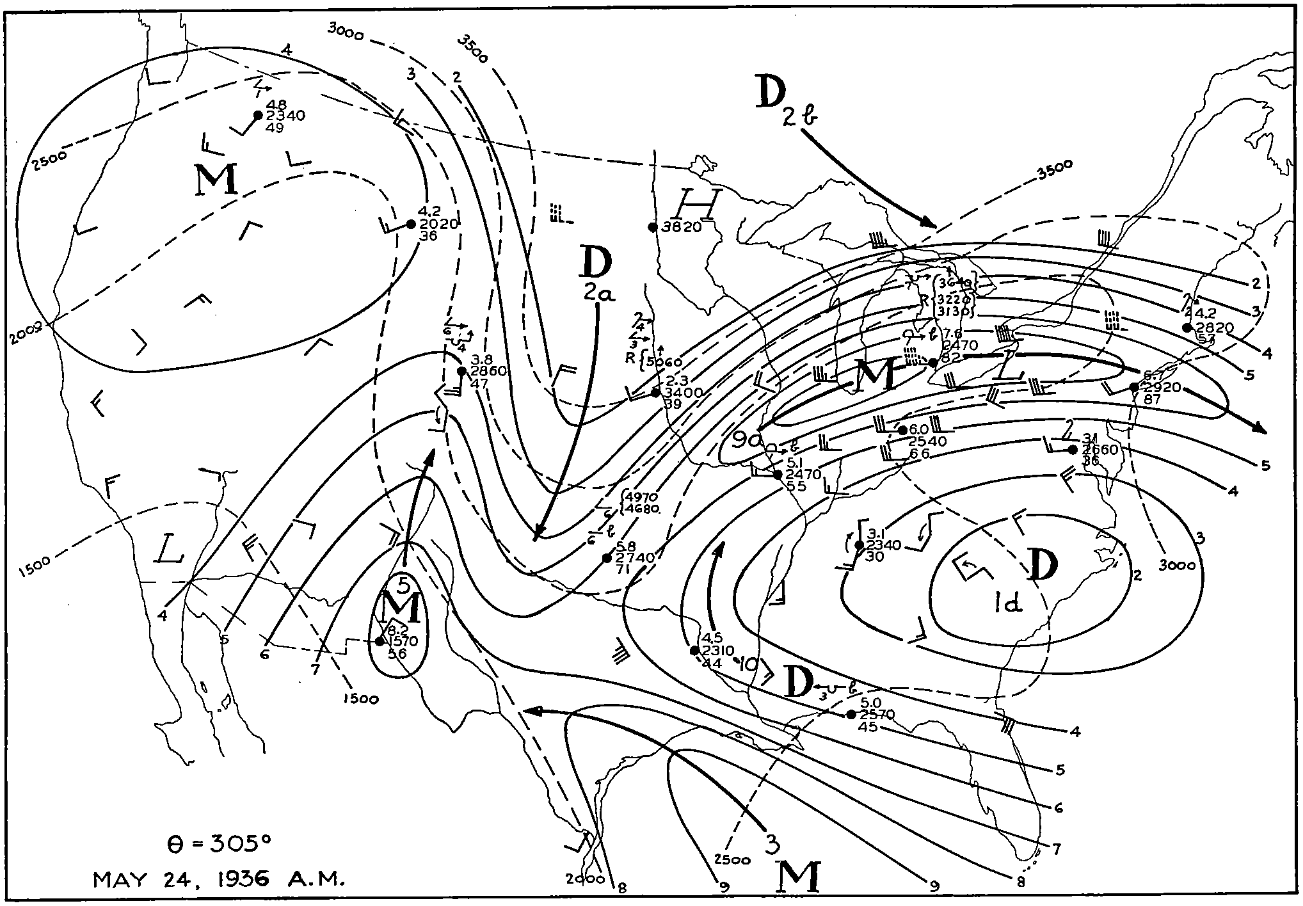




SIMMERS

PLATES XIV AND XV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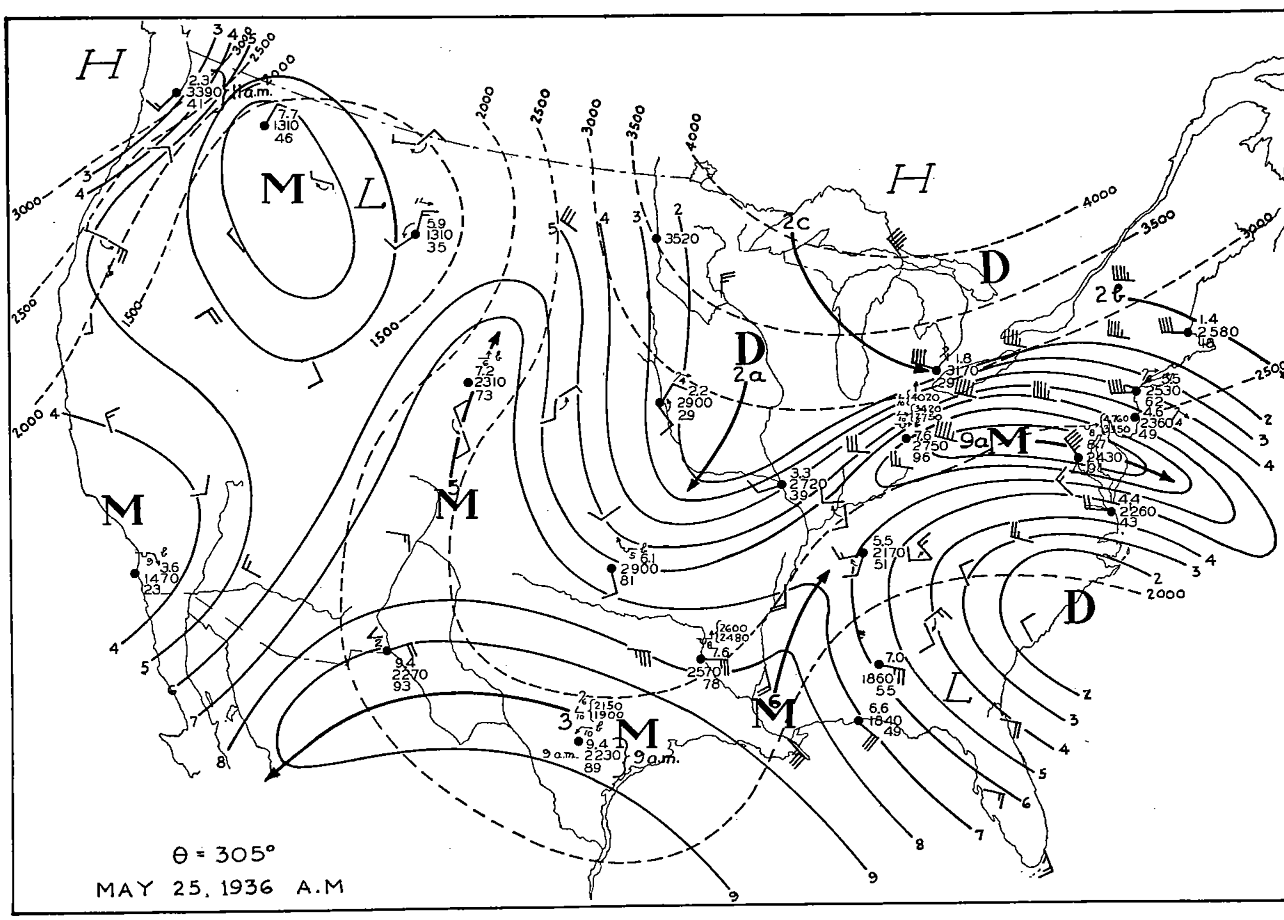
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MAY 25, 1936 A.M

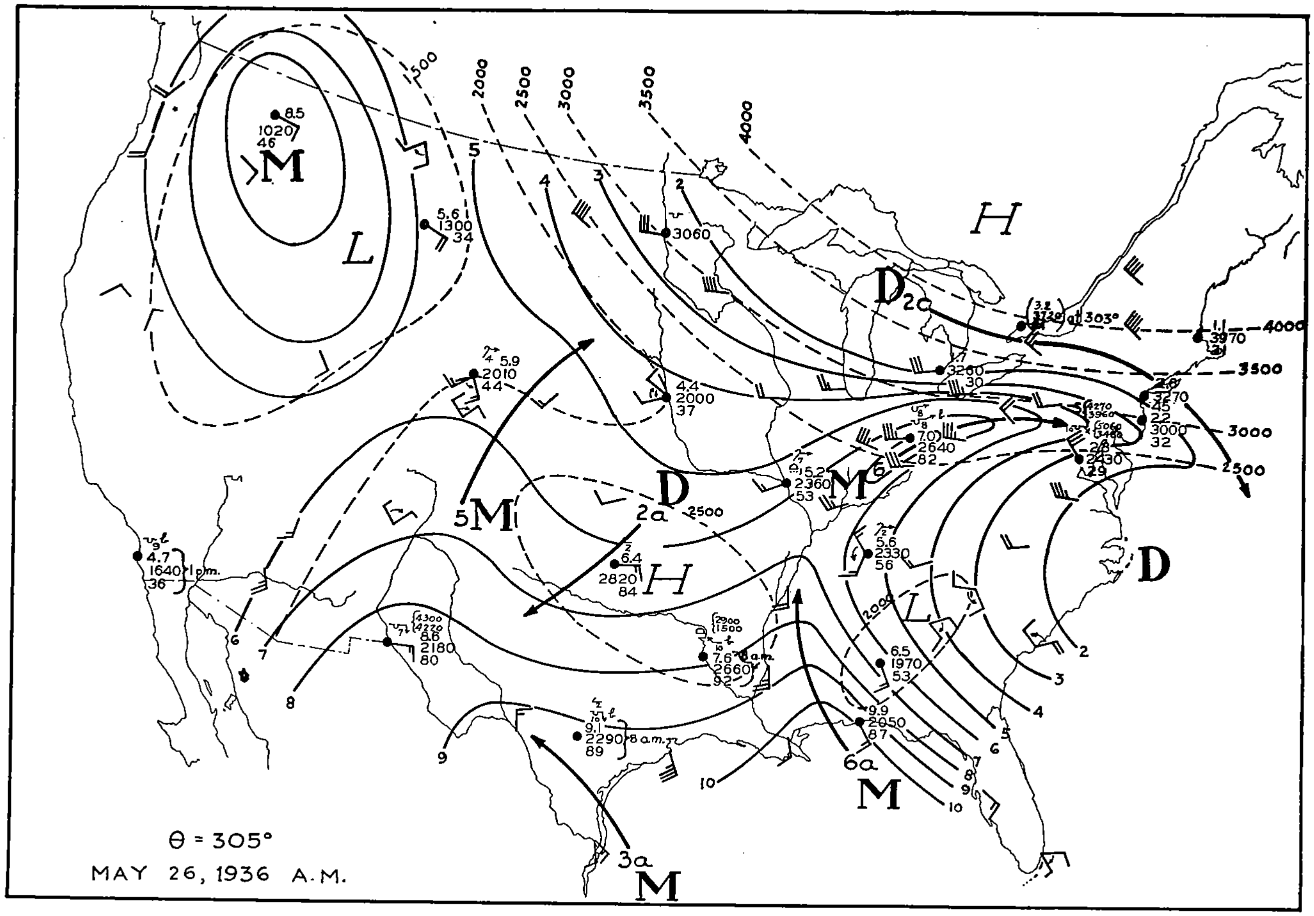

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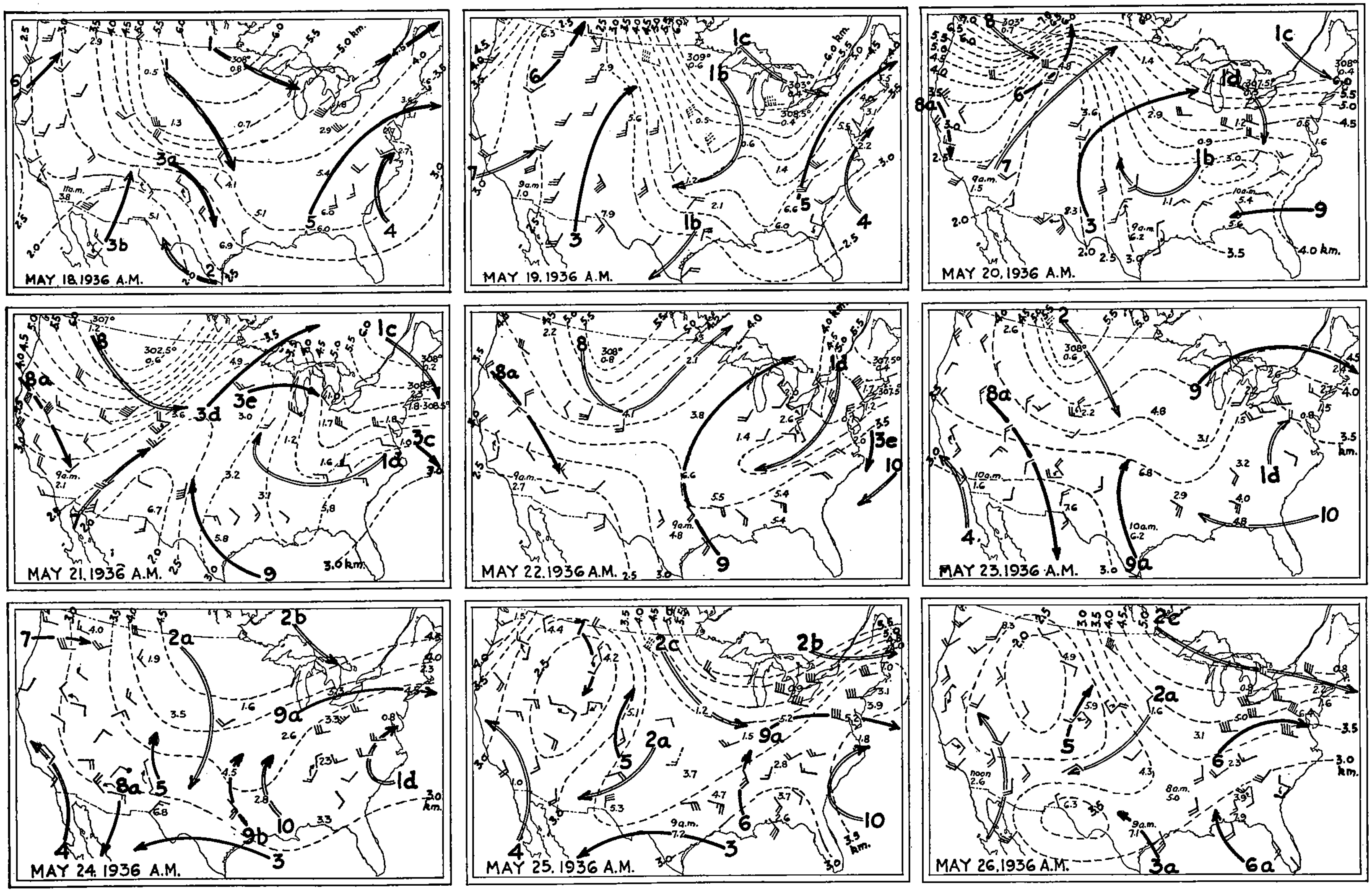
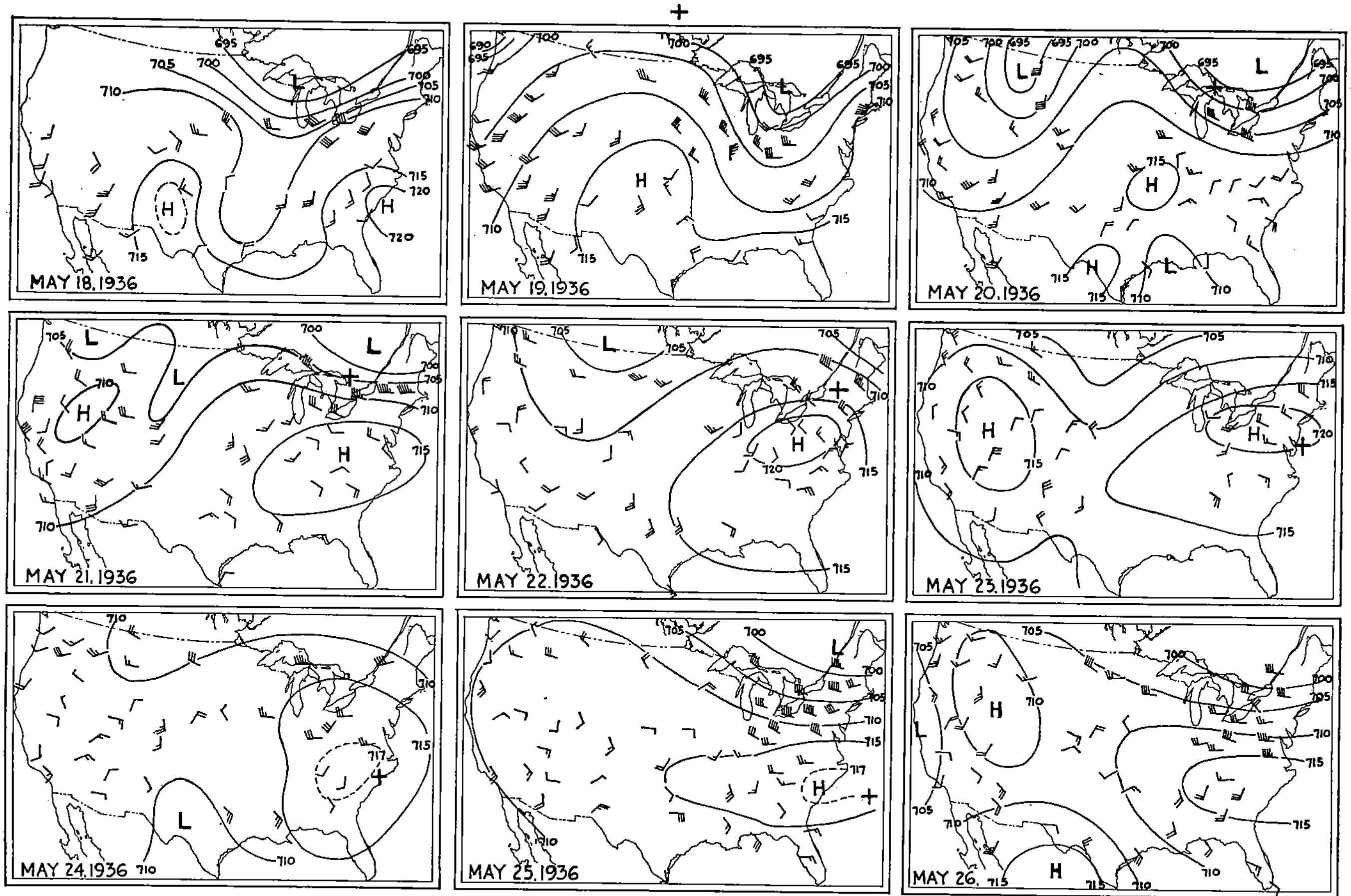
Plate XVIII



SIMMERS

PLATE XIX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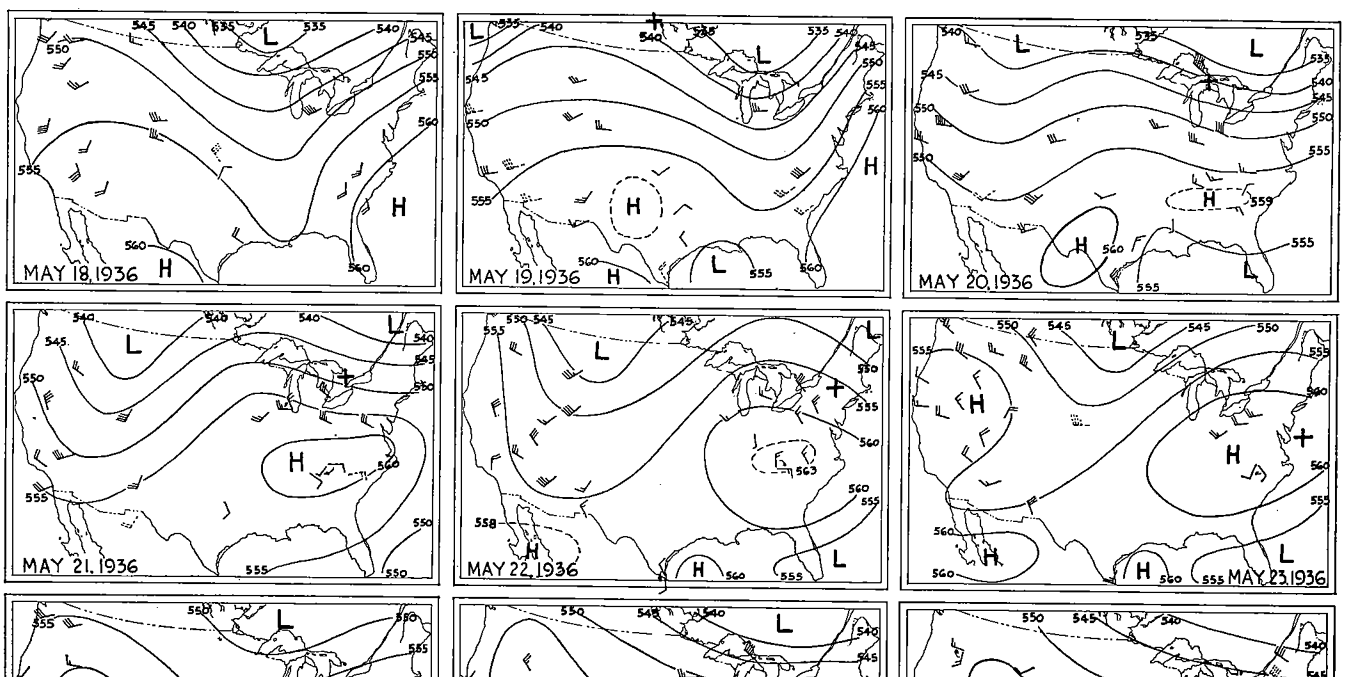
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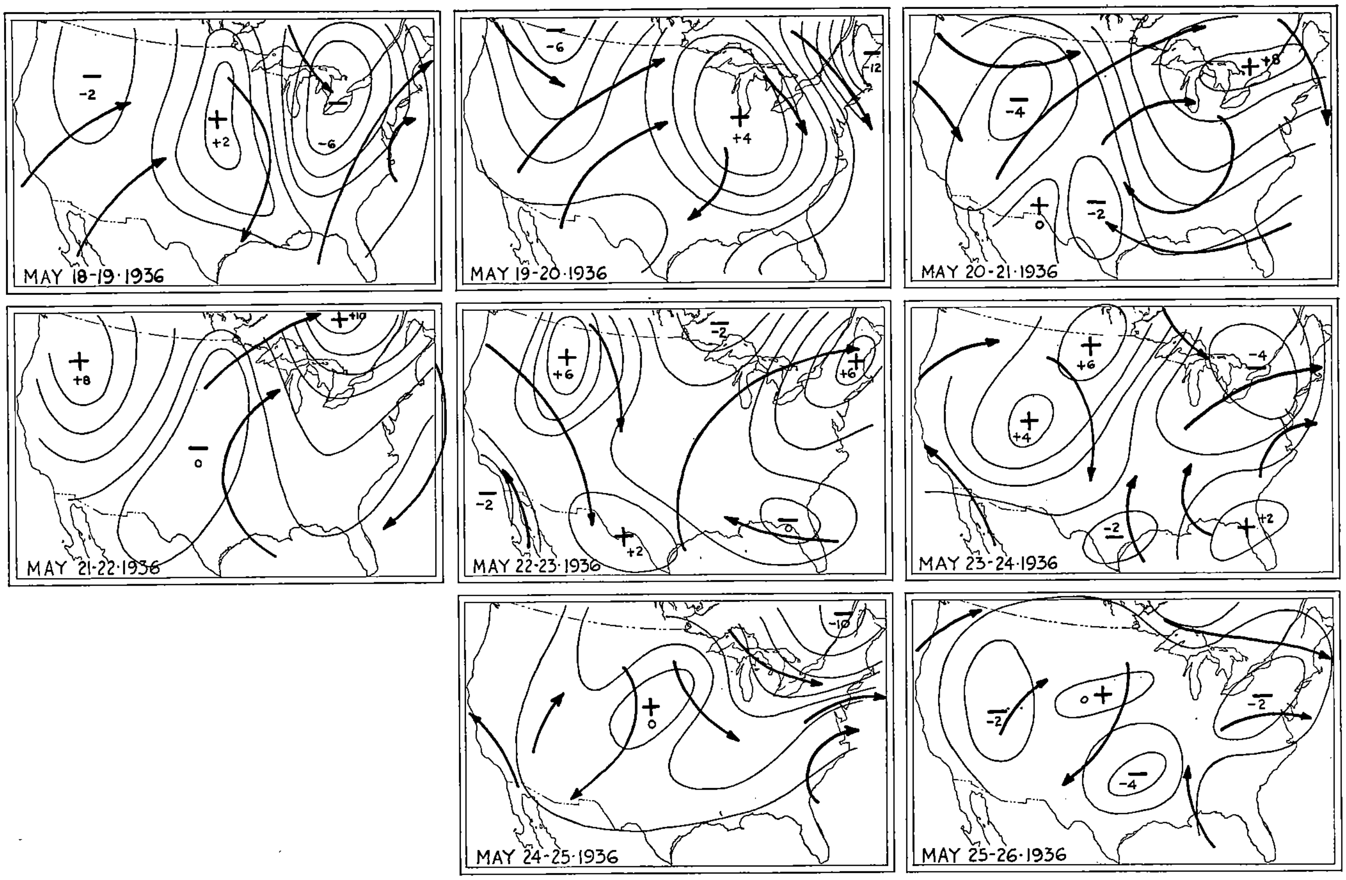
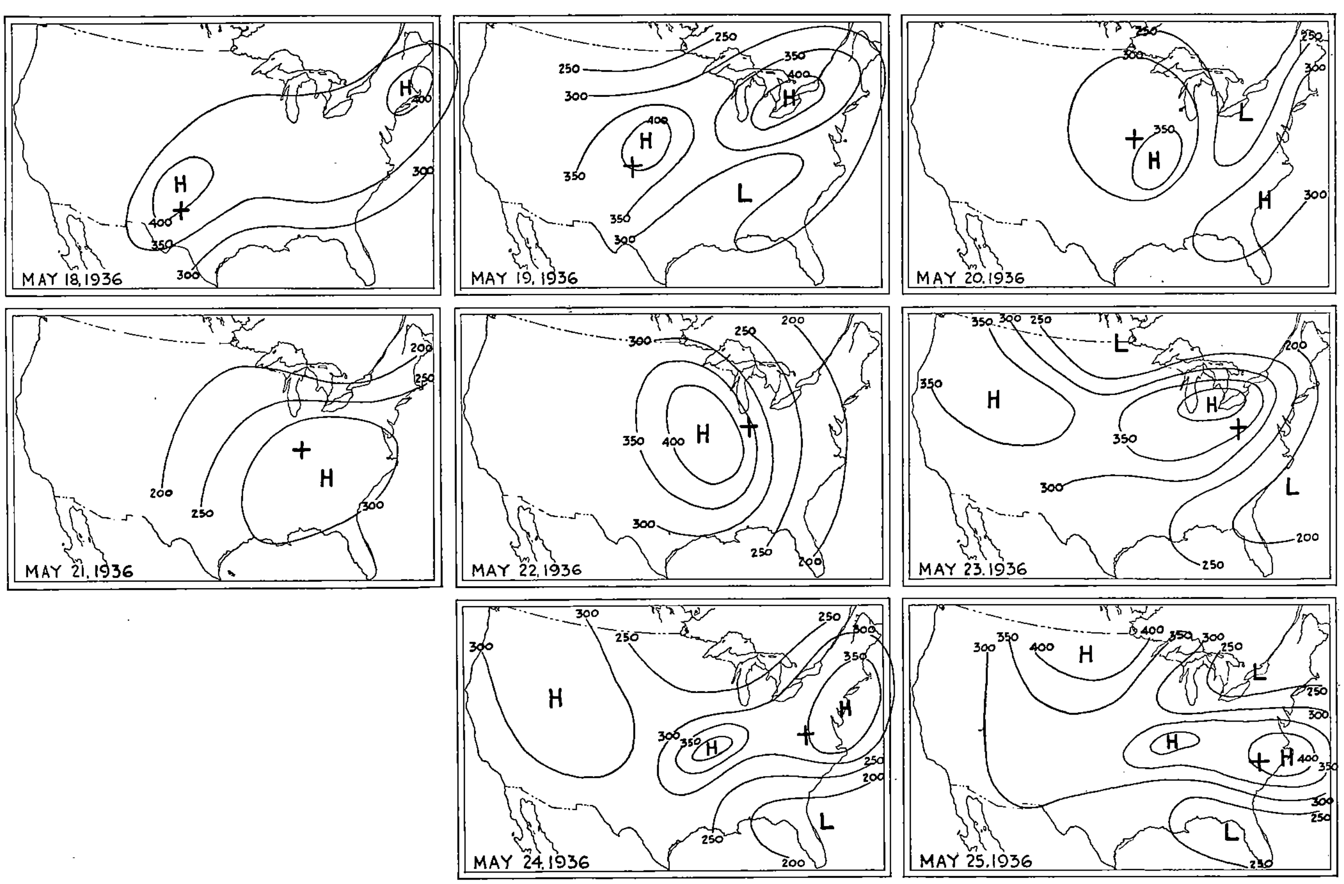
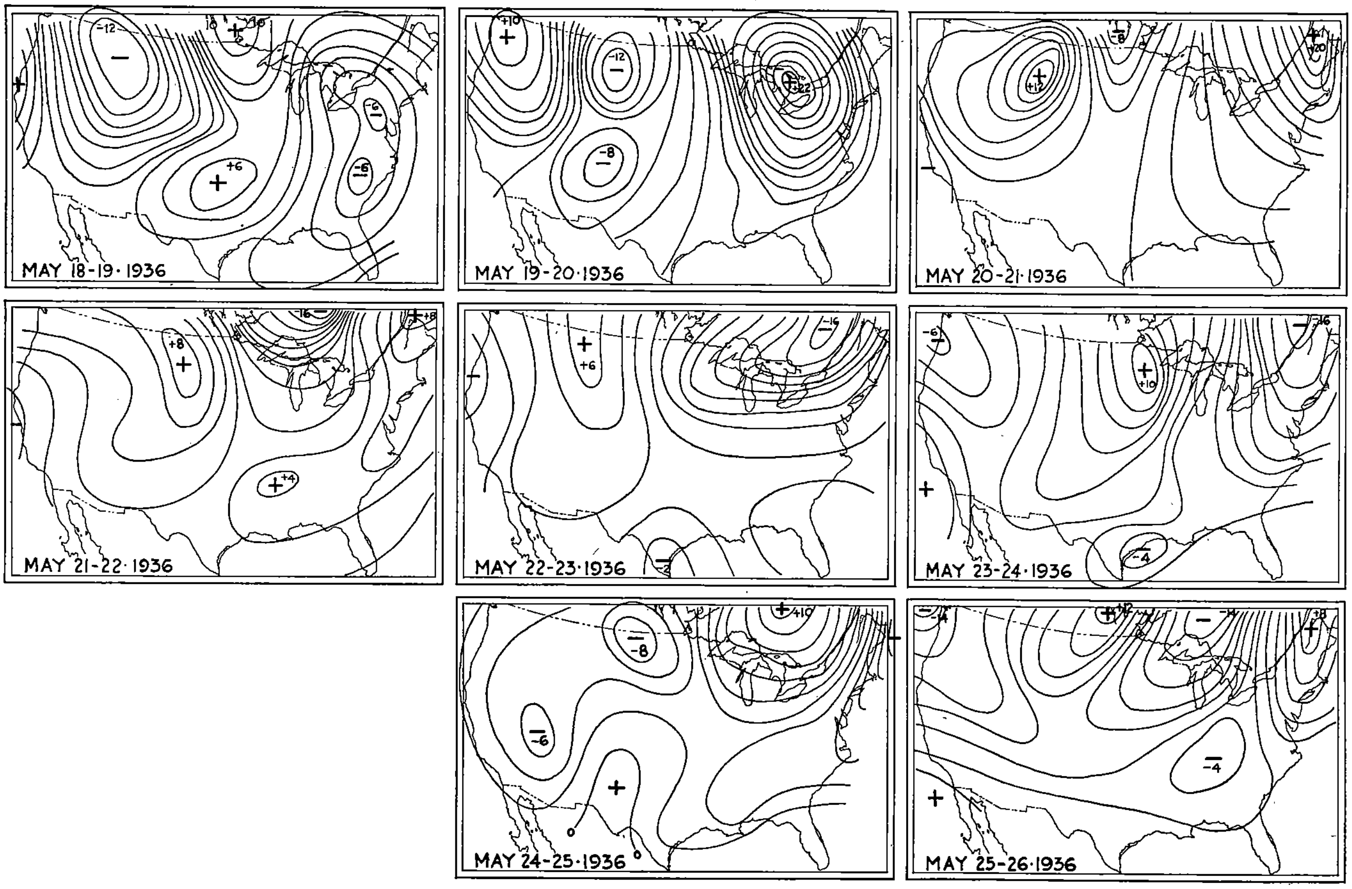




SIMMERS

PLATES XXII AND XXIII



SIMMERS

PLATE XXIV

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