A COMPARISON OF MOISTURE FLOW PATTERNS AS SHOWN BY CONSTANT LEVEL AND ISENTROPIC CHARTS BY MEANS OF A DETAILED STUDY OF THE AEROCLOGICAL DATA DURING THE DEVELOPMENT OF THE ARMISTICE DAY STORM IN 1940.

by

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SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE from the MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1943

Signature of Author

Signature of Professor in Charge of Research

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Dear Sir:

I herewith submit a thesis entitled "A Comparison of Moisture Flow Patterns as Shown by Constant Level and Isentropic Charts by Means of a Detailed Study of the Aerological Data during the Development of the Armistice Day Storm in 1940.", in partial fulfillment of the requirements for the degree of Master of Science in the Department of Meteorology.

Respectfully,

Signature redacted

William M. Rowe  
U.S. Weather Bureau
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Chapter I.

Introduction.

There is a definite need for time saving techniques in the preparation of weather forecasts (1). In the wartime meteorological training program, little time is available for teaching the principles of isentropic analysis. Many meteorologists use isentropic charts only to follow the quasi-horizontal movements of dry and moist air currents from day to day. Others attempt to obtain an estimate of the vertical component of the air motion from these charts (2a).

It is the purpose of this paper to suggest a method by which the horizontal movements of dry and moist air currents may be followed from day to day on the constant level charts. Also, to suggest an interpretation of these charts such that an estimate of the vertical component of the air motion may be obtained, as is done from the isentropic charts. Such use of the constant level charts will save considerable time for the forecaster.

During this study, flow patterns of moisture, as shown by both the constant level and isentropic charts, were compared. Such a comparison involved a detailed study of aerological data.

Numbers in parentheses refer to the references listed at the end of this paper. Where several references are made to the same literature, small letters are used.
The development of the Armistice Day Storm, in 1940, was selected for study, as it was hoped to learn something of such developments, while studying the aerological data.

As the development of the storm represented the production of vast amounts of kinetic energy within twenty-four hours, it was decided to study these changes of energy in the atmosphere. The results of this study are presented in Chapter IV.

By using data for six consecutive days, all possibility of situations having been hand-picked to illustrate the ideas presented here, should be eliminated.
Chapter II.

Interpretations of Moisture Flow Patterns as Shown by the Constant Level Charts.

The constant level charts, usually the 10000 foot chart, have been used successfully for several years in forecasting both areas of thunderstorm activity, in Summer, and areas of precipitation and icing of aircraft, in Winter (3); these charts usually contain winds, isobars, and isotherms. Some forecasters have found values of specific humidity useful on these charts. Others have used dewpoint isotherms on the constant level charts to follow the horizontal movements of moisture (4). Recently, many contributions have been made which are expected to increase the usefulness of the constant level charts (5,6,7,8).

It is proposed in this paper to plot values of specific humidity on the constant level charts and to draw iso-lines of specific humidity in the same manner as when analysing an isentropic chart. These lines give patterns of moisture flow similar to those found on isentropic charts.

If it can be shown that the information usually obtained from an isentropic chart may be obtained from a constant level chart, analysed in this manner, much time will be saved by the forecaster, since the isentropic charts will not have to be prepared. Usually, the 10000 foot constant level chart, containing winds, isobars, and isotherms, is prepared. If so, the only additional work involved is the addition of moisture values and iso-lines. As with isentropic charts, the analysis should be substantiated with atmospheric
Moisture patterns on the 10000 foot chart are usually similar to those on the isentropic charts. This is to be expected, since the surfaces intersect approximately over the center of the United States. However, the absolute values of specific humidity do not necessarily agree, since the isentropic surface is usually above 10000 feet in the North and below this elevation in the South.

Moisture flow patterns on the constant level chart may be interpreted in several ways. Those meteorologists, who use the isentropic chart only to locate and follow the quasi-horizontal movements of moist and dry currents from day, may do so on the constant level charts with the advantage of considering flow patterns at the same elevation from day to day.

Meteorologists, who accept the assumptions of isentropic analysis (2b,9,10), may easily interpret the flow patterns on the constant level chart to obtain an estimate of either upslope or downslope motion. Usually, the air flow, as shown by the streamlines (11), on the isentropic chart has a similar pattern to the air flow, as shown by the isobars, on the 10000 foot chart. This is to be expected, since in warm air, the isentropic surface is usually below 10000 feet, and over very cold air, its elevation increases to above this height. It should be remembered that the circulation pattern is likely to extend to great elevations in warm air, and that the 10000 foot chart gives a good representation of the circulation above 10000 feet, even in cold air.
The contour lines (either the height, in meters, or the isobars) of the isentropic surface should have approximately the same pattern as the isotherms of potential temperature on the 10000 foot chart. For example, the 10000 foot (approximately, 700 millibars) contour line on the 298°A. isentropic chart should coincide with the 298°A. potential temperature isotherm on the 10000 foot chart.

Since (2c): 
\[ \Theta \approx T + \frac{2}{c} \]

it is seen that an isotherm in degrees Centigrade on a constant level chart is approximately a potential temperature isotherm. Thus, each isotherm on a constant level chart may be considered the intersection of an isentropic surface with the surface of constant elevation. The isentropic surface slopes upward in the direction of colder temperatures on the constant level chart. Steeper slopes of the isentropic surfaces, as near frontal surfaces, are indicated by crowding of the isotherms on the constant level chart.

As an example of the interpretation of moisture flow patterns on the constant level chart, in accordance with the methods of isentropic analysis, one may consider Rule la given by Haynes (14). This rule may be rewritten, so as to apply to the constant level chart, as: If the moisture gradient is steep at the tip of the moist tongue and there is a good component of the wind toward low-

\(^\circ\) Depending on the departure of sealevel pressure from 1000 millibars, an error of sometimes 20°C. occurs. Usually, the error is 10°C., or less.
er temperatures, look for rapid spread of precipitation. The iso-
therms on the constant level chart may be regarded as intersections
of isentropic surfaces with the constant level chart. These isen-
tropes slope upward toward lower temperatures. By accepting the
assumptions of isentropic analysis, flow in these isentropes, so
long as the air does not become saturated, is implied. It follows
that when the wind has a good component normal to the isotherms
in the direction of lower temperatures, upslope motion results.

This is not necessarily so, however, as the isotherms (or the
isentropic surfaces) may be moving with the speed of, faster than,
or more slowly than the wind component normal to the isotherms on the
constant level chart (or the height lines on the isentropic chart).
In figure 1., the point $P$ may represent either an isotherm on a
constant level chart or a height line on an isentropic chart. The
arrows represent a horizontal wind from the south. Assuming that the
particle, originally at $P$, moves dry adiabatically (stays within the
isentropic surface) and that the contour lines of the isentropic
surface move horizontally northward, with a speed of less than that of

![Figure 1.](image_url)
the wind, the particle at \( P \) would move to point \( A \). This would be upslope motion. If the contour lines move northward with a velocity equal to that of the wind, the particle would move to \( B \), with only horizontal motion. If the contour lines move northward with a velocity greater than that of the wind, there would be an actual downslope motion of the particle to \( C \). In each of these cases, the particle could have moved isentropically. Furthermore, the slopes of isentropic surfaces are found to change with movement. Also, the particle may not move within the isentropic surface.
Chapter III.
Charts Prepared and Method of Analysis.

The six day period from 0100EST. November 7, through 0130EST. November 12, 1940 was chosen for this study. The 2300EST. winds aloft observations, the 0100EST. RAOBS, and the 0130EST. surface observations were regarded as being synoptic. Surface and complete winds aloft maps were prepared from these observations. The 298°A. and the 306°A. isentropic charts and the five, ten, and fourteen thousand foot constant level charts were prepared, using the RAOBS. The following seven atmospheric crossections were analysed to substantiate the analysis of the upper air charts:

1. Alaskan Stations, Sand Point, Medford, Oakland, and San Diego.
2. Bismark, Omaha, Oklahoma City, and Brownsville.
4. Portland, Lakehurst, Naval Air Station, Norfolk, Charleston, and Miami.
6. Oakland, Ely, Denver, Omaha, Joliet, Lakehurst, and the Coast Guard ship at approximately 40°N. and 60°W.

In the analysis of the upper air charts, the soundings at St. Thomas, Swan Island, and the Coast Guard ship at approximately 40°N. and 44°W. were used, although these soundings did not appear on the crossections.

Soundings taken at times other than 0100EST. were as follow:
November 7, 1940. NCOO, LP04, NASO5, HABOO, NSPOO, CLO2, PSV08, the Sebago (40.4°N, 44.1°W) 04, and the Pontchartrain (38.4°N, 59.3°W) 04.

November 8, 1940. LP04, PEV03, NC06, NR06, NSPO0, the Sebago (40.4°N, 44.3°W) 04, and the Pontchartrain (38.8°N, 59.2°W) 04.

November 9, 1940. PSV07, NASO4, PH02, NR06, LP04, NSPOO, and the Mendota (38.9°N, 59.1°W) 04.

November 10, 1940. UB02, PSV07, NSPO0, NR07, NASO5, GTO2, HABOO, the Mendota (39.0°N, 58.5°W) 04, and the Pontchartrain (40.2°N, 70.2°W) 04.

November 11, 1940. J003, NA03, LP04, NASO5, NSPO0, and PSV07.

November 12, 1940. LP04, NSPO0, and J002.

The first group of the RAOB Code is used here to indicate the station and the time of the observation.

Several soundings were missing during this period. Any data that appeared to be incorrect were checked with the original teletype message and with the ascents, plotted on pseudo-adiabatic diagrams, from the M. I. T. files.

Six hour winds aloft maps of the five, ten, and fourteen thousand levels were prepared for the entire period. Analysed 0730EST and 1930EST surface maps were available in the M. I. T. files, and analysed surface maps, at six hour intervals, were available for reference at the Boston Airport Station of the Weather Bureau.

It was considered convenient to use specific humidity values on all upper air charts, since exact agreement of these charts with the crosssections was required. It will be remembered that iso-
lines of specific humidity on the isentropic chart are also iso-
lines of condensation pressure (10) and may be evaluated from the
pseudo-adiabatic diagram (Fig.2). However, iso-lines of specific
humidity on the constant level chart are only approximately dew-
point isotherms. The difference is small, since the dewpoint varies
little within the range of pressures found on a constant level chart.
The dewpoint may be obtained accurately from the pseudo-adiabatic
diagram (Fig.2) by using the pressure and specific humidity values
on the constant level chart. Very little error is introduced by
assuming standard atmospheric conditions.

Values of the acceleration potential (usually called the
stream function), pressure, specific humidity, and saturated
specific humidity were plotted on the isentropic charts. The twenty-
four hour change of both pressure and specific humidity were plotted.
The winds aloft were plotted, using the isobars to determine the
approximate elevation of the isentropic surface.

The winds aloft, pressure, temperature, and specific humidity
values were plotted on the constant level charts. The twenty-four
hour changes of pressure, temperature, and specific humidity were
also plotted. No element indicative of the relative humidity was
plotted, since the dewpoint may readily be obtained from the
pseudo-adiabatic diagram (Fig.2).

Height, temperature, relative humidity, and specific humidity
values were plotted for each significant point of the soundings on
crossection paper having pressure on a logarithmic vertical scale.
The winds aloft were plotted for stations between the RAOB stations,
as well as for the RAOB stations. These additional winds were found very useful in the analysis.

All charts, including the crossections, were prepared on a horizontal scale of one to ten million. The base maps included both Point Barrow and Swan Island. The figures in this paper include only the United States and a small portion of Canada.

Isobars were drawn at three millibar intervals on the surface charts and at five millibar intervals on the constant level charts. Streamlines, on the isentropic charts, were drawn at intervals of 0.5 unit (or, $0.5 \times 10^7$ ergs/gram).

At this time, values of the Shear Stability Ratio Vector (15) were not being transmitted on the teletype circuits and, therefore, were not used in drawing the isobars on the isentropic charts. Likewise, the shear vector, as defined by Fletcher (8), was not used in drawing the isotherms on the constant level charts. However, the direction of the thermal wind was qualitatively considered in drawing both the isotherms on the constant level charts and the isobars on the isentropic charts. The M. I. T. method of checking the direction of the Shear Stability Ratio Vector (16) was used for this.

Due to the paucity of winds aloft observations, reaching 10000 feet, during the latter part of the period, the three hour pressure (7) tendencies were not computed.

As the figures reproduced in this paper were reduced in size by hand, much data have been omitted in the interest of clarity. The surface maps contain only isobars at six millibar intervals, precipi-
tation areas, and fronts. The reader should consult complete surface maps, if available. The symbols used here for fronts are those given by Petterssen (17a). Values of the streamlines, or isobars, have been omitted, as have the twenty-four hour changes, on the upper air charts.

Since this paper is primarily concerned with moisture flow patterns, the 5000 foot charts do not extend west of Denver, although the chart for 0100 EST. November 7, 1940 is reproduced in full.

Figures 7 through 12e are numbered so that the number refers to the date in November 1940; no small letter, the surface map; a, the 5000 foot chart; b, the 10000 foot chart; c, the 14000 foot chart; d, the 2980A. isentropic chart; and e, the 3060A. isentropic chart. This numbering system should save much repetition of dates. For example, the 0100 EST. 10000 foot constant level chart on November 11, 1940 may be referred to as simply Fig. 11b.

It was found that the use of seven, instead of the usual three, crossections made the analysis more difficult. It is hoped that the use of nearly all the soundings on crossections increased the accuracy of the analysis. Usually, surface fronts do not appear very marked aloft. To avoid arguments as to their exact positions, the intersections of frontal surfaces with the constant level and isentropic surfaces (17b) are not indicated on the figures reproduced here.

To clarify the upper air charts reproduced here, areas of less than 2.0 g./kg. specific humidity have been shaded in blue, areas of more than 6.0 g./kg. specific humidity have been shaded in red, and areas of saturated air are not indicated.
Chapter IV.

Energy Changes.

The potential energy of an air column of unit crosssection is given by:

$$ P.E. = \int_{z}^{z_m} \rho g \, dz $$

4.00

Substituting from the hydrostatic equation, this becomes:

$$ P.E. = \int_{z}^{z_m} \rho g \, dz = \frac{z_m}{g} (P_i - P_L) $$

4.01

where $z_m$ is the height of the center of gravity of the air column.

The internal energy of the air column is given by:

$$ I.E. = \int_{z}^{z_m} \frac{C_v}{T} \rho \, dz $$

4.10

Substituting from the hydrostatic equation and neglecting variations of the acceleration of gravity with altitude, this becomes:

$$ I.E. = \frac{C_v}{\gamma} \int_{P_i}^{P_m} \frac{dP}{P} = \frac{C_v}{\gamma} T_m (P_i - P_L) $$

4.11

where $T_m$ is the mean temperature of the air column.

The energy due to water vapor in the air column, which we will call latent energy, is given by:

$$ L.E. = \int_{z}^{z_m} J_L \rho \, dz $$

4.20

Substituting from the hydrostatic equation and neglecting variations of the latent heat of condensation ($L$) and of the latent heat of fusion is not taken into account here.
acceleration of gravity, this becomes:

\[ L.E. = J \frac{L}{2} q_m (P_1 - P_2) \]

where \( q_m \) is the mean specific humidity of the air column.

The kinetic energy of the air column is given by:

\[ K.E. = \int \frac{1}{g} \frac{P}{P_2} v^2 \, d \xi = \frac{P_m}{g} \frac{v_m^2}{g} (z_2 - z_1) \]

or, substituting from the hydrostatic equation, this becomes:

\[ K.E. = \frac{1}{2g} \int P v^2 \, dP = \frac{v_m^2}{2} \frac{P_1 - P_2}{g} \]

where the subscripts "m" indicate a suitable mean value for the air column. It may be found more convenient to substitute from the geostrophic wind equation to obtain an expression for the kinetic energy.

Values of potential, internal, and latent energy were computed for each sounding on November 7, 1940. The air columns between the significant points of the soundings were considered. This procedure permitted the use of arithmetical means for the suitable means found in the equations (\( z_m \) was taken as the height of the mean pressure between the significant points of the soundings\(^\circ\)). Values were combined for the air columns from five to ten and from ten to fourteen thousand feet.

Values of potential, internal, and latent energy were also computed from the data on the constant level charts, using arithmetical means, except for \( z_m \). Values of \( z_m \) were computed graphically on Weather Bureau Form 1154, Pressure-Altitude Chart, using the arithmetical mean temperature.

\(^\circ\) It was found that the arithmetical mean could not be used for \( z_m \), without error, when the significant points were not closely spaced.
Values obtained by the two methods were compared. It was hoped that values of potential and internal energy could be computed, within a close degree of approximation, from the data on the constant level charts. As was expected, the values of latent energy did not agree at all and the values of internal energy agreed quite well. Unexpectedly, the values of potential energy computed by the two methods showed considerable variation.

By considering a hypothetical air column, between five and fourteen thousand feet, and assuming reasonable values for the quantities in the equations, approximate values for potential, internal, latent, and kinetic energy were obtained. Reasonable errors of measurement and twenty-four hour changes were then assumed and the values of potential, internal, latent, and kinetic energy computed. Except in a few cases of latent and kinetic energy, the errors of measurement were found to be as great as, or greater than, the assumed reasonable changes.

Both the total values and net changes of latent energy were found to be small as compared with those of potential and internal energy. However, values of latent energy were found to have a much larger percentual change from day to day. Computation of latent energy can be made only by considering every significant point of

\[ P.E. \approx 7 \times 10^4, \quad I.E. \approx 5 \times 10^5, \quad L.E. \approx 10^3, \quad \text{and} \quad K.E. \approx 120 \text{ kJ/m}^2, \]

when \((P_1-P_2)=25 \text{ ob.}, \quad T_m=270^\circ \text{ A.}, \quad q_m=0.002 \text{ ton/ton}, \quad C_v=71.5 \text{ m}^2/\text{sec}^2\text{degree}, \quad L=600 \text{ cal./g.}, \quad v_m=2800 \text{ m.}, \quad (x_2-x_1)=2700 \text{ m.}, \quad \text{mean density}=0.9 \times 10^{-3} \text{ ton/m}^3, \quad \text{and} \quad v_m=10 \text{ m/sec.} \]
each sounding and the precipitation that has fallen from the air columns. For these reasons, latent energy will not be discussed further, although the changes in this form of energy are by no means thought to be unimportant.

Any net loss of potential or internal energy by an air column may be considered to result in an increase of kinetic energy within the air column, although this is not strictly so. The kinetic energy is dissipated through friction (16). Further discussion will be confined to the daily changes of potential and internal energy.

The potential energy of an air column of unit crosssection between five and ten thousand feet is given by:

\[ P.E. = \gamma_m (P_s - P_o) \quad \text{and} \quad P.E. = \gamma_m' (P_s' - P_o') \]

where the primes refer to the values twenty-four hours later and the subscripts refer to the levels.

Values of \( \gamma_m \) for the five to ten thousand foot interval, computed graphically, for all the soundings in the United States on November 7, 1940, ranged from 2248 to 2273 meters. These values were determined using the mean virtual temperature of the air columns, as found by the equal area method from soundings plotted on pseudo-adiabatic diagrams. It appears reasonable that the twenty-four hour change in \( \gamma_m \) over a station should be less than the total range of this value over the entire country on a single day. Since the computed values of \( \gamma_m \) are considered correct to within ten meters and, since a variation of twenty-three meters from an assumed mean value of 2260 meters would result in only a 1.0% error, it appears reason-
able to assume a constant value of 2260 meters for \( \bar{z} \).

Then:

\[
P.E.' - P.E. = \bar{z}'(p'_s - p'_o) - \bar{z}(p_s - p_o)
\]

since, from the preceding paragraph,

\[
\bar{z} = \bar{z}' = 2260 \text{ meters},
\]

this becomes:

\[
P.E.' - P.E. = 2260 \left[ (p'_s - p'_o) - (p_s - p_o) \right]
\]

Likewise, for the interval from ten to fourteen thousand feet on November 7, 1940, extreme values of \( \bar{z} \) were 3618 and 3653 meters. A mean value of 3635 meters was assumed. As above:

\[
P.E.' - P.E. = 3635 \left[ (p'_s - p'_o) - (p_s - p_o) \right]
\]

Thus, the twenty-four hour change of potential energy between two levels in an air column over a station is given by the difference of the twenty-four hour pressure changes at those levels. Since the twenty-four hour pressure changes are usually plotted on the constant level charts, the twenty-four hour changes of potential energy may be evaluated quickly and easily.

According to Haurwitz (18), a simple relation exists between the potential and internal energy of an air column.

\[
P.E. = - P_h h + (\lambda - 1) I.E.
\]

where

\[
\lambda = \frac{C_p}{C_v} = 1.405
\]

or

\[
I.E. = 2.47 \left( P.E. + h P_h \right)
\]

where \( h \) is the height of the air column and \( P_h \) is the pressure at the top of the air column.

The twenty-four hour change of internal energy is given by:
where the primes refer to the values twenty-four hours later. For
the air column between five and ten thousand feet,

\[ IE' - IE = 2.47 \left[ (PE' - PE) + h \left( P_n' - P_n \right) \right] \tag{4.14} \]

and for the air column between ten and fourteen thousand feet,

\[ IE' - IE = 2.47 \left[ (PE' - PE) + 1524 \left( P_n' - P_n \right) \right] \tag{4.15} \]

By substitution from 4.03 and 4.04 for the changes in potential
energy, these become:

\[ IE' - IE = 5282 \left( P_s' - P_s \right) - 736 \left( P_0' - P_0 \right) \tag{4.17} \]

for the air column between five and ten thousand feet, and:

\[ IE' - IE = 9023 \left( P_o' - P_o \right) - 5968 \left( P_w' - P_w \right) \tag{4.18} \]

for the air column between ten and fourteen thousand feet.

As the potential energy change above, the twenty-four hour
change of internal energy over a station may be computed from the
twenty-four pressure changes on the constant level charts.

The twenty-four hour changes of potential and internal energy
over the radiosonde stations were computed. Equations 4.03, 4.04,
4.15 and 4.16 were used. The air columns from sealevel to five
thousand feet were not considered in order to avoid computation of
values in the surface frictional layer and beneath the surface of
the earth.

The potential and internal changes for the air columns from
five to fourteen thousand feet were plotted on base maps. Iso-lines
of the twenty-four hour changes of potential and internal energy
were drawn at intervals of one thousand kilojoules per square meter.
The greatest changes of potential and internal energy occurred on November 11 and 12 (Figs. 13 through 22). A comparison with the surface and upper air charts (Figs. 11 through 12) will show that the winds were highest on these days. It might be concluded that the large loss of internal energy in the neighborhood of the low pressure center (Figs. 20, 21, 22) resulted in a gain of kinetic energy and a corresponding increase of wind velocity. Since these charts (Figs. 13 through 22) represent the energy changes over the stations, rather than the changes in moving air columns, conclusions based on these charts must be reached cautiously.

From study of the potential energy changes (Figs. 13 through 17), it appears that these changes indicate primarily the advection of either colder or warmer air over the stations. Conversion of potential energy into kinetic energy could account for the negative areas, but it seems that the large positive areas (Figs. 16, 17) can be explained only by the advection of colder air. It should be remembered that the potential energy of an air column depends on the pressure difference between two levels (Equation 4.01). Since this pressure difference determines the mean density (approximately, the mean temperature also) of the air column, advection of colder air over a station results in an increase of potential energy.

Similar reasoning may be applied to the changes of internal energy (Figs. 19 through 22). However, there are only losses of internal energy in regions of very high winds. The large gains of internal energy, such as occurred over the eastern part of the

also depends on the mean temperature.
country on November 9, 10, and 11 (Figs. 19, 20, 21), appear to be associated with the high pressure area and its attendant light winds. Part of this increase of internal energy may have been due to advection; but, as the high pressure was becoming warmer during this period, it is thought that a larger part of this increase was due to changes occurring within the high pressure area. With an increase of wind velocities in this area (Figs. 11, 12), the twenty-four hour changes of internal energy became negative (Figs. 21, 22). It seems the loss of internal energy should result in an increase of potential energy, the loss of which increases the kinetic energy of the system.

At present, no definite conclusions are attempted from these energy change charts. Many subjects for further study suggest themselves. By computing the three hour (or instantaneous) barometric tendencies at different levels in the atmosphere from the winds aloft observations (7), the rates of change of potential and internal energy can be obtained from the equations in this chapter. Since the winds aloft observations are taken at six hour intervals, such determinations may be found useful in forecasting.

As the method used in computing these energy changes is based on the use of the differences of small differences, determinations made here can be regarded only as approximations.
Chapter V.  

Development of the Armistice Day Storm in 1940.

As the low pressure center, west of Seattle, began to fill (Figs. 7, 8, 9), the trough aloft continued to move eastward (Figs. 7b, 8b, 9b). An occluded front associated with this trough underwent frontolysis, after passing Denver (Figs. 8, 9, 10). As this trough aloft moved inland, waves were induced on the stationary front through Wyoming and western Montana, but it was not until November 10 that the air mass contrast became marked enough for strong cyclogenesis to take place (Figs. 7, 8, 9, 10).

The increasing temperature and moisture gradients (Figs. 8b, 8c, 9b, 9c, 10b, 10c) indicated an increasing amount of energy available for the production of kinetic energy. This increase of air mass contrast is thought to have been aided by the circulation accompanying the trough aloft, mentioned above. There was very dry air behind this trough. A small shallow wave development, on the front south of Brownsville, strengthened the air mass contrast by feeding warm moist air into the Mississippi Valley. As the cyclonic circulation, centered over Colorado, increased (Fig. 10), the cold front, associated with the wave over southern Arkansas, was swept northward and became a section of the warm front extending from Missouri to Florida (Fig. 11).

At 0130 EST, November 11, 1940 (Fig. 11), the low pressure was centered just west of Kansas City. There was unusually cold and very dry air behind the surface cold fronts and warm moist air over the eastern part of the country. This inflow of warm moist air was al-
ready shown by the constant level charts, when the low pressure was centered over Colorado (Figs. 10a, 10b, 10c). That the air mass contrast extended to high levels is shown by the 14000 foot charts (Figs. 10c, 11c).

During the eighteen hours from 0130 EST. to 1930 EST. on November 11, the center deepened about 27 millibars and moved about 675 miles, to just west of Houghton, Michigan. During this time much damage was done by high winds, heavy precipitation, and a cold wave behind the surface cold fronts (19, 20). The high wind velocities are apparent from an inspection of the isobars on the surface map (Fig. 12) and of the streamlines on the upper air charts (Figs. 12a, 12b, 12c, 12d, 12e).

It is believed that the rapid deepening (cyclogenesis) was due to the great amounts of energy available for conversion into kinetic energy, as is shown by the unusual temperature and moisture contrast between the air masses present. These contrasts extended to high levels. As there was heavy precipitation over large areas (19), considerable amounts of latent energy were released. With the colder air under-running the warmer air, and thus lowering the center of gravity of the entire system, large amounts of potential energy must have been released. From figures 21 and 22, it was seen that large losses of internal energy occurred.

It has been noted, in similar cases of rapid movement accompanied by deepening, that the motion was retarded when the moisture

\# A more complete description of this storm is given by this reference.

\@ Chapter IV.
supply was cut off. It is thought that further study of this point would be valuable. Such cases show that considerations of deepening and movement should not be combined. Forecasting rules state that a deepening low usually moves slowly (17c), but many exceptions to this rule occur.
Chapter VI.

Comparison of Flow Patterns as Shown by Isentropic and Constant Level Charts.

In the analysis of both the isentropic and constant level charts, it was thought advisable to carefully consider the data and to avoid any exaggeration of the moisture flow patterns. For example; the 1.0 and 2.0 g/kg specific humidity iso-lines on figures 7b and 7d could have been drawn around northwest of New England to fit the precipitation area in eastern Canada (Fig. 7), but this would have been done without data and would not have agreed too well with the Sebago and Pontchartrain soundings (see page 9).

From a consideration of the isentropic charts (Figs. 7d,7e), it must be concluded that the saturated air, resulting in the precipitation in southeastern Canada (Fig. 7), was at some elevation beneath the isentropic surfaces. But, at what elevation?

Considering the constant level charts (Figs. 7a,7b,7c), it is seen that the respective temperatures and dewpoints at Portland (from Fig. 2) are approximately: -5°C, -5°C, -11°C, and -13°C, and -18°C, and -22°C. (Actual and saturated values of specific humidity, from figure 2, might just as well have been considered.) Even though Portland is reporting clear skies, it is seen that the air at 5000 feet is nearly saturated. Since the air becomes colder northwest of Portland, while there is not a very rapid decrease of dewpoint in this direction (as shown by the weak specific humidity
gradients on figures 7a, 7b, and 7c); it may be concluded that the air over this precipitation area is possibly saturated as high as 10000 feet. To the airway forecaster, it is apparent that a flight over the precipitation area could probably be made at 10000 feet and could certainly be made at 14000 feet. The temperatures at the higher level would not be favorable for icing of the aircraft. Should such a flight have been made at 10000 feet, the pilot would have been instructed to climb, should icing be encountered.

When used with surface maps, a set of analysed constant level charts give a better picture of conditions at the levels in which the forecaster is interested than do the isentropic charts.

It is hoped that the reader will compare the moisture flow patterns on the constant level and isentropic charts with the precipitation areas on the surface maps throughout the period (Figs. 7 through 12a). For this reason, all the upper air charts have been reproduced here. If complete surface maps are available, much additional information may be obtained from the cloud forms and their heights.

A comparison of the figures reproduced here shows that upslope or downslope motion of the air currents may be estimated from the constant level charts with the same degree of accuracy as from the isentropic charts. The constant level charts have a distinct advantage in that motions at significant levels are being considered.

It is thought that the position of the 0°C. isotherm should be considered, when using either the isentropic or constant level charts for precipitation forecasting. According to Bergeron (17d), coexist-

6 See Chapter II.
enec of water droplets and ice crystals in the cloud is necessary for great amounts of precipitation to form. This means that most precipitation is formed at temperatures slightly below freezing. From figure 2, it is seen that the isentropic surfaces used in this study cross the 0°C. isotherm at about 740 and 675 millibars (or, at about 8000 and 11000 feet) respectively. It is thought that a better idea of the distribution of the 0°C. isotherm in the atmosphere is obtained from the constant level charts than from the isentropic charts.

During the study associated with the five-day forecasting project, it was found that, for precipitation forecasting, the presence of moisture on the prognostic five-day mean isentropic chart "is best used where the isentropic surface is expected to lie between 600 and 800 millibars" (21a). This is the pressure interval in which the commonly used isentropic surfaces cross the 0°C. isotherm (Fig.2). Since the 10000 foot chart lies midway of this pressure interval, it could be expected that the moisture patterns shown on a five-day mean (or daily) 10000 foot chart should correlate well with precipitation areas, especially in the neighborhood of the 0°C. isotherm on the constant level chart.

Upon correlating precipitation areas with the moisture supply, as shown by isentropic charts, Smith found less correlation in the northern sections of the United States, east of the Rockies, than in other sections (21b). This has been explained by the isentropic surfaces, over these sections, being above elevations at
which precipitation is usually formed. It is suggested here, as a topic for future study, that the moisture supply, as shown by the mean 10000 foot charts, be correlated with precipitation areas (or anomalies) in a manner similar to that used by Smith. It is felt that the correlation coefficients would be much higher than those obtained by Smith, since the 10000 foot chart is more nearly at a significant level than were the isentropic surfaces, used by Smith.

Since the O°C. isotherm is usually at a lower level in the northern than in the southern sections of our country, it is thought that the moisture patterns on the 5000 foot chart should be considered, especially in Winter, when making precipitation forecasts for northern sections. Likewise, the moisture patterns on the 15000 or 20000 foot charts may be found useful, in the South, in Summer. If only one of the constant level charts is prepared, it is thought that the 10000 foot is the most useful. If the forecaster has access to three or more analysed constant level charts, the distribution of both moisture and the O°C. isotherm may be clearly seen.

There are objections to analysis of the moisture patterns on constant level charts, as advocated in this paper. It is claimed that there is no physical basis for assuming horizontal, rather than isentropic motion. As was pointed out in Chapter II., the moisture flow patterns on the constant level charts may be interpreted assuming either isentropic or quasi-horizontal motion. It is believed that neither of these interpretations can be strictly followed.

Another objection to the use of moisture flow patterns on the constant level charts is that the same air particles are not being
considered from day to day. It is believed that the advantages of dealing with changes at significant levels far outweigh any disadvantages the constant level charts have in this respect. According to Schuknacht (22), moisture flow in the free atmosphere is not an isentropic process and does not take place in isentropic surfaces. It is believed that a more detailed study of the actual movements of air currents in the free atmosphere should be made.

It should be kept in mind that much time will be saved, if the constant level charts are analysed in the manner suggested here, instead of preparing the isentropic charts.
Chapter VII.
Mean Lapse Rate and Thick-Thin Charts.

Charts of the temperature differences between the constant levels were prepared. Since these charts represent the mean lapse rate in the layer considered, unstable and stable areas are easily located. These charts were consistent with conditions as shown by the surface maps. Only the most interesting of these charts is reproduced here (Fig. 3). The areas marked "Stable" and "Unstable" are relatively so. The area of instability from Brownsville to Joliet is especially interesting, since thunderstorms occurred within the southern part of this area (Fig. 11), and a tornado occurred in western Tennessee on this date.

Since the information obtained from these charts may be deduced from inspection of the surface and constant level charts, it is thought not worthwhile to prepare them. If the soundings, plotted on pseudo-adiabatic (or any other thermodynamic) diagrams, are available, preparation of these charts is considered a waste of time.

It has been suggested that charts of the pressure difference between two isentropic surfaces be used to indicate areas of stable or unstable lapse rate (10). Studying a wintertime thunderstorm situation, Lenahan (23) found thick-thin charts of this pressure difference and the changes of this pressure difference indicative of convergence or divergence within the layer between the isentropic surfaces. Assuming isentropic motion, there is convergence within
the layer, when the pressure difference between the isentropic surfaces increases.

Thick-thin charts were prepared for each day of the period studied. Similar charts, using the height difference (in meters) between the isentropic surfaces, were also prepared. That these charts give different patterns is readily seen from a comparison of the data at Great Falls and San Diego (North Island) on November 7, 1940 (Figs. 4, 5). The chart for November 12, 1940 (Fig. 6) shows an area of relatively unstable air over the surface cold front in the eastern part of the country (Fig. 12). Areas of convergence are indicated over Miami, across the northern boundary of the country, and in the Southwest. These charts did not always show such good agreement with the surface maps.

Perhaps the use of changes over the stations, rather than in moving air columns, during a period of such rapid movements was not a fair test of the usefulness of these charts. If the changes in moving air columns are considered, much time must be spent in computing the trajectories, which may not be the same for both the tops and bottoms of the air columns. It is concluded that these charts are of more use for teaching and study purposes than for forecasting purposes. The determination of convergence or divergence appears more feasible by other methods (24).
References to Literature


   (a) Relation of Isentropic Flow to Precipitation. page 150.
   (b) Basis for the Analysis. page 136.
   (c) Technique of Analysis. page 141.
   (d) The Processes Which Tend to Disrupt the Continuity of Isentropic Analysis. page 155.


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   (a) Chapter XI, page 445.
   (b) Chapter XI, Figs. 246 and 247, pages 484 and 485.
   (c) Chapter X, Rule 31, page 437.
   (d) Chapter I, page 44.


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Willett, H.C., and Others, Report of the Five-Day Forecasting Procedure, Verification and Research as Conducted between July 1940 and August 1941. Massachusetts Institute of Technology, 1941.

(a) page 36.

(b) page 80.


(1) Abscissae are temperatures in °C.
(2) Ordinates are the 0.288 powers of the pressures in millibars.
(3) Sloping, straight lines in brown are dry adiabats, i.e., lines of constant potential temperature. These are drawn for every two degrees absolute.
(4) Broken, overprinted curves are pseudo-adiabats. Figures thereon are equivalent potential temperatures (°A).
(5) Unbroken, overprinted curves are lines of constant saturation mixing ratio, giving water vapor contents, in grams of water vapor per kilogram of dry air, required for saturation at the indicated temperatures and pressures.
(6) The latter two sets of curves are computed under the assumption that for all temperatures, including those below 0°C, saturation is with respect to a flat surface of liquid water.
Fig. 3

Nov. 11, 1940
TEMPERATURE DIFFERENCE
5000 TO 10000 FEET.
Fig. 6.

Nov 12, 1940 0100 EST
THICK-THIN CHART

ΔP Θ = 298° 24 HR CHANGES ----
Θ = 306°
Fig. 7d.

Nov. 7, 1940.
0100 EST
θ = 298°
Fig. 8d.

NOV. 8, 1940.
0100 EST.
θ = 298°
Fig. 9b.
Fig. 10.

Nov. 10, 1940.
0130 EST.
Fig. 11b.
Nov. 12, 1940
0100 EST
$\theta = 298^\circ$

Fig. 12d.
Nov. 12, 1940
0100 EST.
$\Theta = 306^\circ$ Fig. 12 e.
Fig. 14.

24 hr. P.E. change Kj/m²
5000'-1400'
Nov. 9, 1940.
Fig. 18. 24-hour Antennal Capacity Change 5000 ft./2000 kVa.

November 8, 1940.
24-hour Potential Energy Change
5000'-14000'
kg/m²
Nov. 10, 1940. Fig. 20.