TROPOSPHERIC AND STRATOSPHERIC TEMPERATURE CHANGES ASSOCIATED WITH PRESSURE CHANGES

By J. M. Austin and R. Shapiro

Massachusetts Institute of Technology[1, 2]

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ABSTRACT

The hypothesis is investigated that there is a physical difference between the development and motion components of a surface pressure change. Temperature changes indicate that deepening and filling are accompanied by high-level heating and cooling, respectively, while the motion part of pressure changes is associated with low-level temperature variations.

1. Introduction

Many empirical studies have been conducted on the changes of temperature and density in the free atmosphere which accompany pressure changes at the earth's surface. The results of these investigations have formed the basis for theories concerning the pressure-change mechanism. The fact that no completely adequate theory yet exists stems perhaps from the failure of the empirical studies to give a unique picture of the temperature and density changes associated with pressure changes. One of the principal objectives of this paper is to report another empirical study, whose results appear to clarify certain relationships between density, temperature and pressure. With this clarification, it should be possible to draw some conclusions concerning the mechanism of pressure change.

2. Motion and development components of pressure change

When average values of the temperature changes at various levels are obtained in the vicinity of sea-level pressure falls, it is found that warming, or decrease of density with time, occurs near the earth's surface and near the tropopause. The converse holds for pressure rises. The existence of this double maximum of density change has been the principal conclusion of previous statistical studies. Malone [1] and Mironovitch [2] review such investigations. In general, it has not been possible by statistical studies to separate completely sea-level pressure falls or rises into two distinct groups, where the density change occurs near the earth's surface for one group and near the tropopause for the other group. The possibility of such a separation has been suggested by some recent research on the temperature field in the vicinity of isallobaric centers.

Austin [3] has shown that there is usually warm-air advection in the low levels over katallobaric centers and cold-air advection over anallobaric centers. This relationship between advection, as judged by the geostrophic flow, and pressure change provides an explanation of many features of the motion of isallobaric systems. For example, the katallobaric system in fig. 1 is associated with a strong advection of warm air, and consequently it should be expected to move in the direction of the low-level flow, *i.e.*, in the direction of the geostrophic wind FC. However, the isallobars show that the geostrophic field is changing so as to intensify the warm-air advection at B and to produce cold-air advection at A. This changing field of horizontal motion itself gives rise to a motion of the katallobaric center in the direction AB. Hence, it should follow that the actual motion of the pressure-change center is in a direction somewhere between the direction AB and the existing geostrophic direction FC. Synoptic studies indicate that a large percentage of isallobaric systems follow this principle. It is apparent, however, that this low-level advection of warm or cold air cannot account for the development of new isallobaric systems, nor for the intensification or weakening of existing isallobaric centers. The question then arises as to whether there is a physical difference between the part of the pressure tendency which gives rise to the motion of a pressure system and the part which causes the deepening or fill-

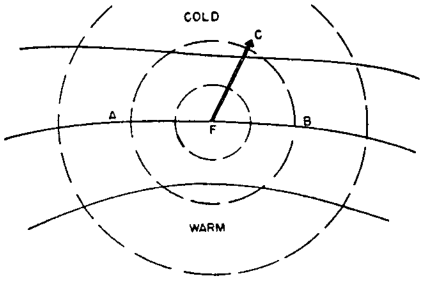

Fig. 1. A katallobaric system. Dashed lines are katallobars and solid lines are isotherms.

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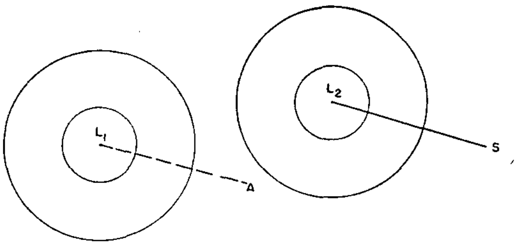

FIG. 2. 12-hr positions of an idealized cyclone.

ing of a pressure system. The advection study suggests that the motion part of a pressure fall is accompanied primarily by low-level warming. It is then postulated that the development part is accompanied by high-level warming. Such a hypothesis is also suggested by the fact that new developments in the pressure field appear to be associated with prominent changes in the tropopause height. A similar pattern could exist for pressure rises and cooling. For this reason in the present study, the pressure changes have been subdivided into their deepening and motion components before an analysis of the associated temperature and density changes is undertaken. It may be noted that this general concept of dividing pressure changes into two components is not inconsistent with the primary and secondary pressure waves discussed by Ficker [4] and Rossby [5].

To arrive at a picture of the temperature and density changes which accompany pressure changes, it is necessary in North America to utilize the twelve-hour radiosonde reports. In many instances, a twelve-hour pressure change consists of a fall and a rise, so that the accompanying temperature-change data cannot be employed to depict the behavior of the temperature field with an instantaneous pressure change. Hence, it seemed desirable to analyze only those cases of pressure fall or rise where the twelve-hour change was always in the same direction. In this respect, the present study again differs from many previous investigations.

3. Statistical results

The data for this empirical study of surface pressure changes were selected from radiosonde stations in the United States, Canada and Alaska during the period December 1947 to March 1950. The following criteria were established for the selection of cases:

1. The pressure change at the surface was of the same sign throughout the twelve-hour period.
2. The radiosonde ascents at both the beginning and the end of the twelve-hour period reached the 150-mb level, or at least terminated sufficiently close to that level so that extrapolation to 150 mb was justified.
3. Erroneous reports were eliminated through a study of analyzed charts at different levels.

The surface pressure change was divided into its deepening and motion parts by an objective technique which is illustrated by fig. 2. L_1 is a cyclone at time t_1 (the beginning of the period), and L_2 is the same cyclone at time t_2 (12 hours later). Let S be the station at which the deepening is to be computed. The point A is determined by drawing a line $\mathrm{L_1A}$ equal and parallel to $\mathrm{L_2S}$. Then the pressure at A at time t_1 minus the pressure at S at time t_2 is defined as the deepening part of the 12-hour pressure change at S. Filling is negative deepening. An identical procedure was adopted with anticyclones, to determine the deepening (pressure decrease with time) or filling (pressure increase with time) parts of a pressure rise.

A 12-hr pressure change rarely consists of a 100 per cent deepening or a 100 per cent motion. Therefore, it was decided to subdivide all the pressure changes into 6 arbitrary groups:

Group 1. *Deepening*	Cases of falling pressure, where the deepening at the station accounted for 60 per cent or more of the station pressure change.
Group 2. *Mixed*	Cases of falling pressure, where the deepening at the station accounted for less than 60 per cent but at least 15 per cent of the station pressure change.
Group 3. *Motion*	Cases of falling pressure, where the deepening at the station accounted for less than 15 per cent of the station pressure change or where the filling was less than 15 per cent of the station pressure change.
Group 11. *Filling*	Cases of rising pressure, where filling accounted for 60 per cent or more of the station pressure change.
Group 12. *Mixed*	Cases of rising pressure, where the filling at the station accounted for less than 60 per cent but more than 15 per cent of the station pressure change.
Group 13. *Motion*	Cases of rising pressure, where the filling at the station accounted for 15 per cent or less of the station pressure change or where the deepening was less than 15 per cent of the station pressure change.

Even though the majority of the cases for groups 1, 2, 3, 12 and 13 were selected from radiosonde stations in the eastern half of the United States, there was a reasonably wide scattering of stations over the North American continent. Group 11 cases were confined to data from Alaskan and North Canadian stations, since most pressure rises in middle latitudes belong to the group 12 and 13 categories. 80 per cent of all the cases occurred during the winter half of the year.

Groups 1 and 11 contain pressure-change data in the vicinity of developing pressure systems which are moving slowly, while groups 3 and 13 contain data adjacent to fast-moving pressure systems which show practically no development. Groups 2 and 12 are intermediate between the development and motion groups. This difference in motion is illustrated by the fact that the average 12-hr changes in distance between the

TABLE 1. Mean temperature changes (deg C/12 hr) per 10 mb of surface pressure change.

Group	No. of cases	Pressure layer 1000–850	850–700	700–500	500–400	400–300	300–200	200–150	1000–700	300–150
Pressure falls										
1 (deepening)	55	+0.2	+0.4	−0.2	+0.5	+1.7	+3.7	+4.1	+0.3	+3.8
2 (mixed)	105	+3.4	+1.9	+1.2	+0.9	+0.8	+0.7	+1.3	+2.7	+0.9
3 (motion)	53	+6.0	+4.3	+1.5	+0.8	+0.9	+0.5	+0.1	+5.0	+0.4
Pressure rises										
11 (filling)	22	−0.6	+1.6	+0.4	+0.3	+0.1	−5.8	−5.3	+0.5	−5.5
12 (mixed)	44	−2.8	−1.5	−1.0	−0.9	−0.7	−1.6	−0.8	−2.1	−1.3
13 (motion)	26	−6.8	−5.6	−3.6	−3.3	−2.8	+0.5	+1.4	−6.0	+0.9

cyclone center and the radiosonde station were 190 km for group 1, 380 km for group 2 and 630 km for group 3.

The changes in temperature above the earth's surface which are associated with each class of pressure change are presented in table 1. It is apparent that for pressure falls associated with cyclogenesis, the warming is generally located near the tropopause.[3] In the case of cyclones which are moving with little change in intensity, the warming with the pressure falls is located near the earth's surface. The pressure rise data show a similar distribution of cooling. The differences between the temperature changes in the 1000–700-mb layer and 300–150-mb layer within groups 1, 3, 11 and 13, and also between groups 1 and 3 and groups 11 and 13, were found to be highly significant by Student's *t*-test. The levels of significance ranged from less than 1 per cent for the 300–150-mb comparison of group 1 and group 3 to considerably less than $\frac{1}{10}$th per cent for the remaining comparisons. The mass loss or gain between standard heights is presented in table 2. These mass changes were computed from the transmitted radiosonde data by means of the formula

$$\Delta m = \frac{g}{R}\left[\frac{p_1}{\bar{T}_1}\overline{\left(\frac{\partial z}{\partial t}\right)}_1 - \frac{p_2}{\bar{T}_2}\overline{\left(\frac{\partial z}{\partial t}\right)}_2\right],$$

where Δm is the mass loss between H_1 and H_2, the average elevations of the standard pressure surfaces p_1 and p_2. $\bar{T}_1$ and $\bar{T}_2$ are the mean temperatures at H_1 and H_2, respectively, and $\overline{(\partial z/\partial t)}_1$ and $\overline{(\partial z/\partial t)}_2$ are mean changes in height of the respective pressure surfaces p_1 and p_2. Table 2 again illustrates a pronounced difference between the various groups of pressure change. The failure of the sum of the individual layers to equal exactly the surface pressure change can be attributed primarily to the number of significant figures, to the fact that the station pressure differs from 1000 mb, and to the averaging process in the formula.

A short study of horizontal advection of temperature was undertaken, as it was believed that the pressure changes in groups 3 and 13 are accompanied by low-level advection. An objective triangulation method was employed, to determine the geostrophic advection at the beginning and end of the 12-hr period. The requirement was established that a triangle of stations around and near the observing station should report upper-air data to at least 300 mb at both the beginning and end of the period. This restriction greatly reduced the number of cases, so that only the correlations presented in table 3 were undertaken. It is believed that the method of selection is one reason for the difference between the correlation coefficient for 850-mb advection and group 3 pressure changes and a similar correlation coefficient in Austin's [3] study. In the latter study, the pressure changes were selected at isallobaric maxima and minima, and they were grouped together instead of being correlated separately for falls and rises. The usual feature of local temperature changes being less than the advective changes was apparent. Obviously, vertical motion plays an important role in determining the local temperature changes.

4. Discussion

Before the statistical results may be utilized in discussing the problem of the mechanism of pressure change, it is necessary to consider some aspects of the method for classifying data. The cases in groups 1 and 11 must be expected to show some of the features of the cases in groups 3 and 13, since they contain pres-

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[3] The average pressure at the tropopause was 215 mb for pressure falls and 285 mb for pressure rises. The tropopause was defined as the lowest level in the upper atmosphere where the lapse rate of temperature decreased to and remained less than 4 C/km.

TABLE 2. Mass changes (mb/12 hr) between standard heights for each class of station pressure change. H_{1000}, H_{850} ... H_{150} are the mean heights of the 1000, 850 ... 150-mb pressure surfaces.

Group	Atmospheric layer H_{1000}–H_{850}	H_{850}–H_{700}	H_{700}–H_{500}	H_{500}–H_{400}	H_{400}–H_{300}	H_{300}–H_{200}	H_{200}–H_{150}	H_{150}–∞	Average surface change
1	−1.7	−1.1	−1.2	−1.0	−1.1	−1.7	−0.7	+0.4	−8.3
2	−2.9	−2.1	−1.6	−0.6	−0.7	−0.7	−0.6	−0.2	−9.1
3	−3.6	−2.9	−1.7	−0.6	−0.5	−0.4	−0.1	−0.1	−9.5
11	+1.0	+0.8	+1.1	+0.7	+0.6	+2.4	+0.8	−0.3	+7.2
12	+3.8	+2.5	+2.3	+0.9	+1.1	+0.5	+0.1	−0.1	+10.4
13	+5.2	+3.8	+3.1	+1.0	+0.6	−0.8	−0.7	−0.7	+10.2

TABLE 3. Linear correlations between surface pressure change and horizontal advection.

	Group 1			Group 3		
Advection level	No. of pairs	r	Significance level	No. of pairs	r	Significance level
850 mb	20	−0.40	<10%	19	−0.61	<1%
300 mb	20	−0.58	< 1%	19	−0.03	none

sure changes which include a small motion component. The presence of this component may explain the minor low-level warming and cooling in groups 1 and 11, respectively, as well as the advection correlation for the 850-mb layer in group 1. Hence, it cannot be concluded that a pure development pressure tendency is necessarily associated with low-level heating or cooling. Moreover, the 12-hr period required that the cases in groups 1 and 11 be selected in the vicinity of existing pressure systems, rather than in regions where the development was just commencing. Hence, the statistical data may not give a true picture of the temperature field and its changes in the vicinity of an initial development. For example, it should not be expected that the 300- or 200-mb charts will clearly show warm-air advection directly above an incipient region of pressure fall. Despite the significance tests, it cannot be concluded definitely that all motion parts of pressure falls are associated with low-level heating or that all development parts are accompanied by high-level heating. Since the eastern portion of the North American continent is primarily a region of young cyclones, this study does not include all types of pressure systems and, therefore, the question remains as to whether the results would be duplicated in a more extensive study. The observation of pressure fall with the development of the thermal low is at least one exception to the group 1 case. Likewise, there may be a class of pressure falls associated with the motion of a cyclone which are accompanied by high-level heating.

The following conclusions may then be drawn concerning the majority of the pressure changes which occur over North America:

1. There is a physical basis for separating a pressure change into two components, namely, one part associated with the intensification of a pressure system and a second part associated with the motion of a pressure system.

2. The motion part of a pressure change is accompanied by low-level warming in the case of pressure falls and cooling with pressure rises. Furthermore, these low-level temperature changes are intimately connected with horizontal advection.

3. The intensification part is associated with high-level warming with pressure falls and cooling with pressure rises.

It is apparent that additional statistical studies and detailed studies of particular situations are necessary, to generalize further on the relationships between pressure, temperature and density changes.

On occasions, theories of the pressure-change mechanism have been based upon the observed temperature distribution and its time variation in the centers of cyclones and anticyclones. Hess [6] and Vederman [7] have presented some empirical facts on the density changes over the centers of deepening and filling cyclones. It is emphasized that the results of these studies should not be compared with the empirical data which are presented in this paper. The fundamental difference between the two approaches may be illustrated by a consideration of the following equations:

$$\text{(a)} \quad \frac{\partial p}{\partial t_0} = \int_0^\infty \frac{\partial \rho}{\partial t} g\, dz,$$

$$\text{(a}'\text{)} \quad \frac{\delta p}{\delta t_0} - \mathbf{c} \cdot \nabla p_0 = \int_0^\infty \frac{\partial \rho}{\partial t} g\, dz,$$

$$\text{(b)} \quad \frac{\delta p}{\delta t_0} = \int_0^\infty \frac{\delta \rho}{\delta t} g\, dz,$$

$$\text{(b}'\text{)} \quad \frac{\delta p}{\delta t_0} = \int_0^\infty \left(\frac{\partial \rho}{\partial t} + \mathbf{c} \cdot \nabla \rho \right) g\, dz,$$

where ρ is the density, g is the acceleration of gravity, $\delta/\delta t$ denotes time differentiation in a moving coordinate system and $\mathbf{c}$ is the velocity of the coordinate system, which is considered to be moving with the pressure system. The current paper discusses the left- and right-hand sides of equation (a′). Local changes in density ($\partial\rho/\partial t$) and temperature are compared with local pressure changes for three classes of $\partial p/\partial t$, namely, a group where $\delta p/\delta t$ is the major part of $\partial p/\partial t$ (deepening), another where $\delta p/\delta t \approx 0$ (motion) and an intermediate group. On the other hand, Hess and Vederman present data on the time variation of the air-density distribution in a column which is always located at the center of a cyclone. In other words, these data prescribe values of $\delta\rho/\delta t$ in equation (b). Equation (b′) shows that such density variations ($\delta\rho/\delta t$) in a moving coordinate system cannot readily be compared with the local density variations ($\partial\rho/\partial t$) discussed in this paper. The term $\mathbf{c} \cdot \nabla\rho$ must make a significant contribution to $\delta\rho/\delta t$. For example, the fact that many deepening cyclones are observed to move across the isopycnics is a pertinent factor for any interpretation of the density change presented by Hess and Vederman. This same term $\mathbf{c} \cdot \nabla\rho$ makes it difficult to discuss the contribution of particular processes, such as horizontal advection, to the pressure change of equation (b). Since the usual meteorological observations and charts are not readily suited for a study of the causes of $\delta p/\delta t$, no attempt has been made to accumulate information on this quantity.

5. The pressure-change process

The temperature changes which have been presented in this study are the result of the pressure-change process. However, they do not lead directly to an explanation of the process, since temperature changes can occur at one level as a consequence of processes operating at lower or higher levels. Nevertheless, it would appear that the motion part of most pressure tendencies can be attributed to the circulation of the pressure system in a field of temperature contrast. For example, the circulation of the cyclone must produce pressure falls ahead of (warm-air advection) and pressure rises behind (cold-air advection) the center of the cyclone, and thereby gives the pressure changes which move the cyclone across the low-level temperature gradient. It does not follow, however, that the low-level air-mass contrast is not also important for the development part of the pressure tendency, even though the heating occurs at high levels. The fact that most cyclones move as they develop suggests that the air-mass contrast is an important part of the development pattern. These concepts and others which are suggested by this study must await further investigation before more definite hypotheses may be advanced as to the mechanism of pressure change.

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