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ON THE DESICCATION OF A CLOUD BANK BY A PROPAGATED PRESSURE WAVE [1]

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ABSTRACT

On December 6, 1949, an accelerated microbarograph in Washington, D. C., produced a unique pressure trace at the time that a peculiar cloud bank passed overhead. The rear (western) edge of this cloud bank ended very abruptly and had the appearance of an Antarctic ice barrier. A study of the synoptic conditions of the day revealed that this pressure variation was produced by an expansion-type pressure wave which travelled eastward from the Midwest and was propagated between two inversion surfaces with a speed far in excess of the wind speed in that layer. The cloud bank also travelled in this same atmospheric layer but was advected by the prevailing winds. The conclusion is reached that the pressure wave which progressively overtook the cloud bank was associated with a rapid drop of the isentropic surfaces which in turn produced the adiabatic heating necessary to desiccate the cloud partially in the Midwest and completely over Washington. Confirmation of this conclusion is found in solar radiation records.

INTRODUCTION

This study was motivated by two events which occurred simultaneously in Washington, D. C., on December 6, 1949. On the afternoon of that day a cloud bank appeared over the city. At about 1615 EST the cloud ended abruptly—like the pictures of an Antarctic ice cliff. This feature is shown in figure 1. This picture was taken facing eastward, so that the sun in the western skies brilliantly illuminated the edge of the cloud bank and showed it to be very thin. The author estimated it at the time as no more than 300–500 feet thick. This phenomenon traveled very rapidly eastward. The second phenomenon, which occurred at the same time that the western edge of the cloud bank passed overhead, was a pressure pulse which produced the barogram shown in figure 2. The microbarograph which recorded this trace is one with accelerated gears which records continuously on an attached Esterline-Angus Recorder. By expanding the time scale, finer detail in the variation of the pressure may be studied. This trace shows that with the passage of the "chopped off" portion of the cloud bank, the pressure dropped very suddenly and in a short time recovered suddenly. The simultaneity of the peculiar behavior of the cloud bank and the pressure trace suggested the possibility of some relationship between them. This study was a search for this relationship.

BAROGRAM INVESTIGATION

The history of the pressure pulse was studied through an investigation of the barograms for all the stations in the general neighborhood of Washington, D. C. Portions of these barograms are reproduced near their respective stations in figure 3. Care was taken in copying these traces to keep all the sheets oriented in exactly the same manner so that the pressure profiles of the stations and their slopes might be compared. The peculiar V-shaped pulse which was noted on the accelerated microbarograph at Washington could be traced back as far as western Pennsylvania, but not below the latitude of Washington, D. C. Furthermore, as western Pennsylvania was approached, the "first" part of the V-shaped pulse (i. e. the pressure fall) became the more pronounced while the rise diminished in amplitude. Continuing westward still

[1] Paper presented at the 109th National Meeting of the American Meteorological Society, New York City, January 30, 1951.

Figure 1.—Cloud bank over Washington, D. C., on the afternoon of December 6, 1949. The photograph was taken looking eastward from the Washington Star building by the newspaper's staff photographer, Mr. Edward Baker. The picture is reproduced here through the courtesy of the Washington Star and Mr. Baker.

farther, one notices that this pronounced fall could be followed to western Indiana. In the Ohio-Indiana area, this fall was part of an over-all, but gentler pressure fall.

Isochrones of the passage of the V-shaped pulse to the east and the marked pressure fall to the west were drawn as indicated in figure 3. For the sake of uniformity, the time of onset of the fall was chosen throughout as the time designator for the isochrone. The two significant features of this isochrone pattern are:

(1) The pressure disturbance (which hereafter shall refer to both the V-shaped pulse to the east and the pressure drop to the west) can be followed only through the northern portion of the area studied. The southern portion shows gradual prolonged falls (particularly in the west) but no indications of a disturbance such as experienced farther north.

(2) The speed of the disturbance was approximately:

43 m. p. h. during 0800–1100 EST (in Indiana)
77 m. p. h. during 1100–1400 EST (in Ohio)
77 m. p. h. during 1400–1700 EST (in southern Pennsylvania and Maryland)

It should be indicated in passing that due to current practices of pressure recording by means of barographs the isochrones can be considered accurate only to about one-half hour.

CLOUD INVESTIGATION

A study of the Surface Weather Observations (W. B. Form 1130) for the stations in the area, revealed the following progression of cloud formations. The early part of the day was characterized either by clear skies or by the presence of thin, high clouds above 20,000 feet. Later in the day, each station reported the appearance of low clouds with bases varying from 5,000–10,000 feet. Finally, and this has only incidental significance for our purposes, most of the stations reported lower overcast. Our primary concern will be with the *initial* appearance of the

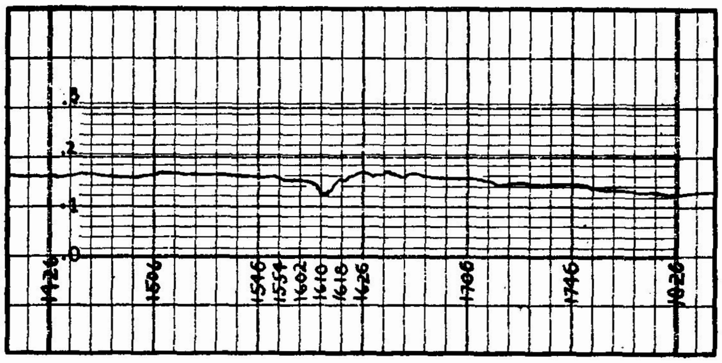

Figure 2.—Barogram, December 6, 1949, Washington, D. C.

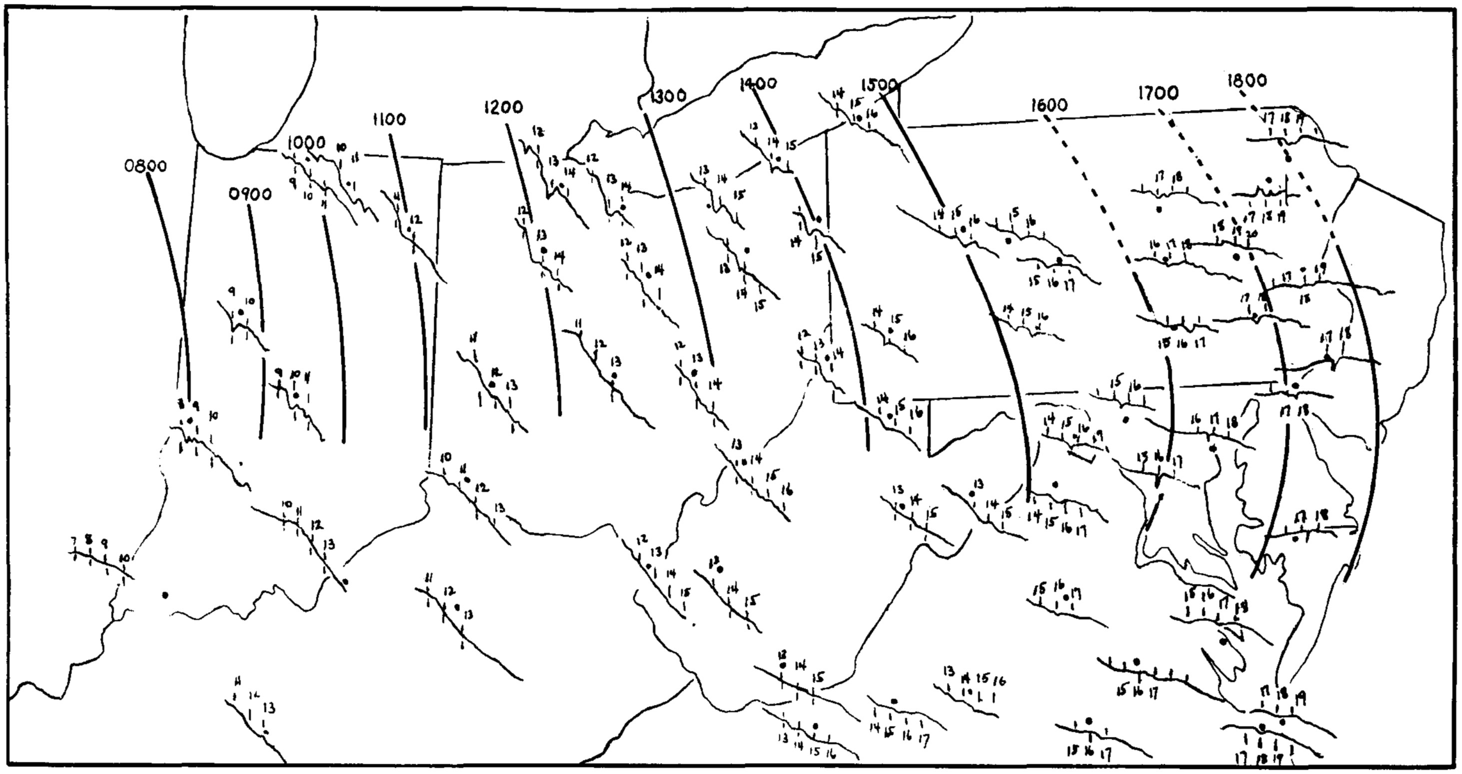

FIGURE 3.—Barograms, December 6, 1949, showing isochrones of pressure drop.

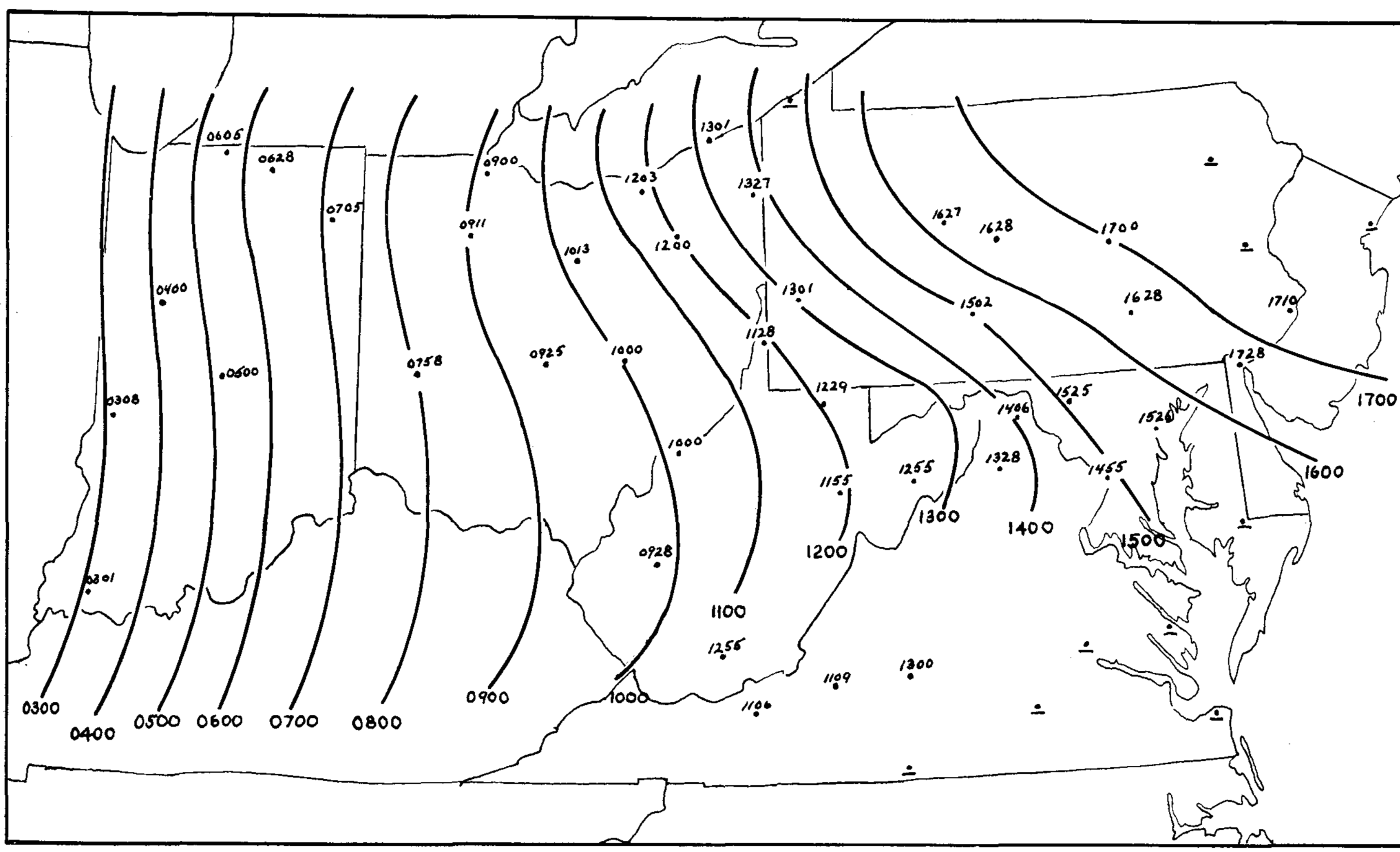

FIGURE 4.—Isochrone pattern for time of arrival of low cloud bank.

low cloud deck. The time of this initial appearance was plotted on a map and again isochrones were drawn (fig. 4). The principal features of this isochrone pattern are:

(1) The isochrone pattern indicates a uniform progression of the onset of the cloud bank in a general west to east direction.

(2) The average speed of the isochrones is approximately:

40 m. p. h. between 0500 and 0800 EST (in eastern Indiana)

50 m. p. h. between 0800 and 1100 EST (in central Ohio)

35 m. p. h. between 1100 and 1400 EST (in western Pennsylvania and western Maryland)

35 m. p. h. between 1400 and 1700 EST (in south central Pennsylvania and eastern Maryland)

Again, it should be kept in mind that weather observation practices cannot permit the consideration of the positions of these isochrones accurate to more than about one-half hour.

COMPARISON OF ISOCHRONE PATTERNS

A comparison of the pressure disturbance isochrone pattern with the onset of the cloud deck isochrone pattern shown in figures 3 and 4 reveals:

(1) East of Indiana the leading edge of the cloud bank travelled significantly more slowly than the pressure disturbance.

(2) The leading edge of the cloud bank preceded the pressure disturbance in time over most of the area.

(3) The pressure disturbance, travelling faster than the leading edge of the cloud bank, overtook the latter across a line roughly bisecting the State of Pennsylvania from the northwest corner to the southeast corner.

HOURLY SYNOPTIC MAPS

From the transmitted teletype data it was possible to plot hourly synoptic maps and analyze them. Four such maps drawn for 2-hourly intervals beginning with 1030 EST are shown in figure 5. The main synoptic feature on these maps is an open wave moving slowly through central Iowa and northern Illinois. The associated warm front stretches generally southeastward from the center of the wave. To the east, there is a pressure ridge which is also moving eastward. The position of the leading edge of the cloud bank is given by a line of open circles while the position of the pressure pulse is given by a thick line.

As may be expected, the leading edge of the lower cloud bank seems to coincide with the limit of the circulation around the wave. We may then attribute the cloudiness

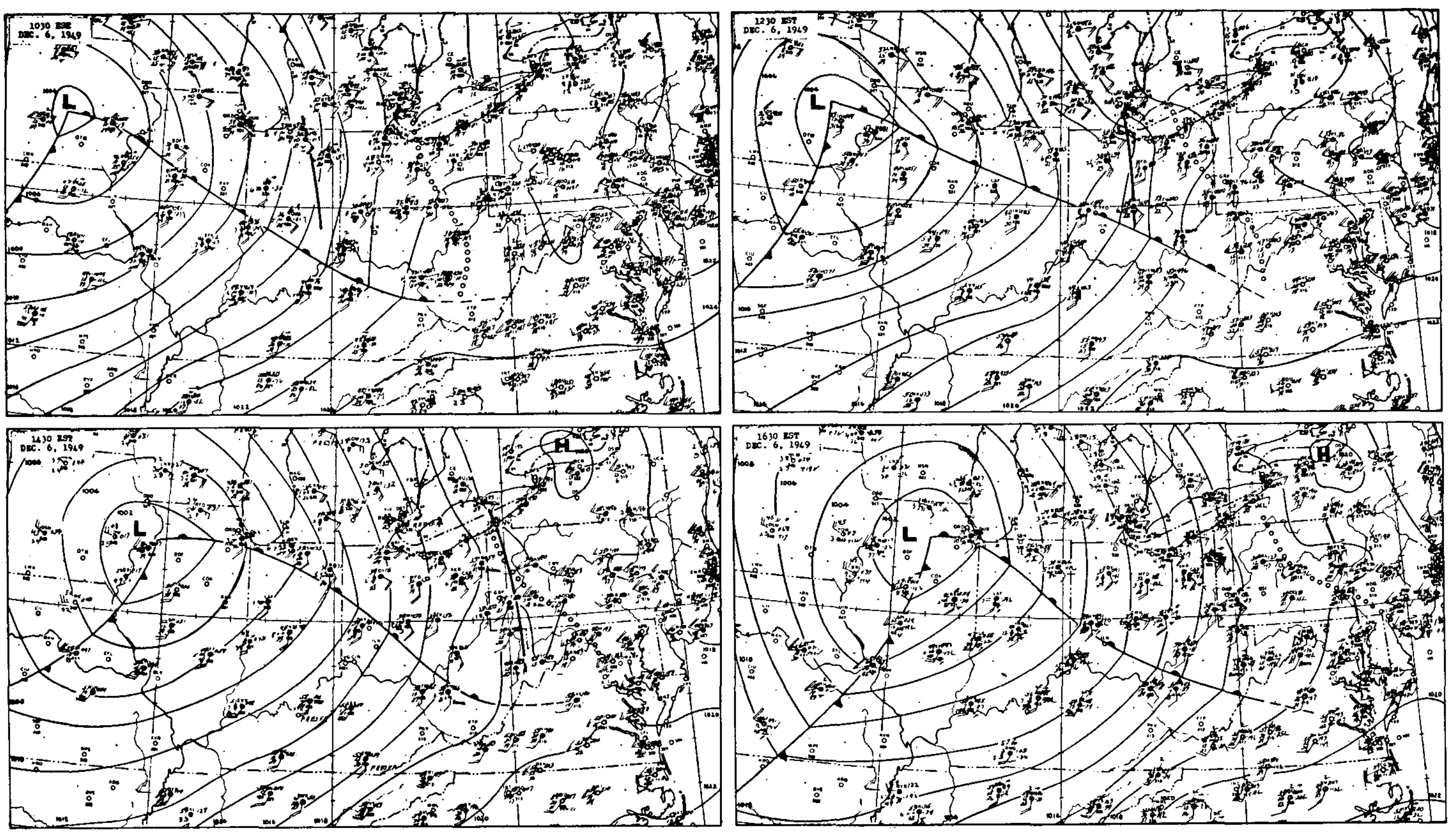

FIGURE 5.—Surface synoptic maps for 1030, 1230, 1430, and 1630 EST, December 6, 1949. Synoptic position of leading edge of cloud bank is indicated by line of open circles and the synoptic position of the pressure pulse by a thick solid line.

to overrunning or convergence which precedes a cyclone. On the other hand, the period of relatively clear skies may be associated with the anticyclonic circulation around the ridge.

The hourly synoptic maps graphically illustrate how the pressure disturbance travelled *through* the surface system. As the disturbance travelled away from the circulation around the wave and closer to the region dominated by the pressure ridge, its character changed from a pressure drop to a V-shaped pulse as identified in Pennsylvania, Maryland, and Washington, D. C. An explanation for this relationship will be given in a subsequent section.

It should be noted that throughout, the surface position of the warm front designates the southern limit for the pressure pulse isochrones.

WINDS ALOFT

It is, of course, of considerable importance to investigate whether or not advective processes could account for the propagation of either the pressure disturbance, the cloud bank movement, or both. Table 1, the wind data for 1000 EST and 1600 EST, shows that winds below 3 km. could have advected the cloud bank but not the pressure disturbance, while above 3 km. the winds were strong enough to have advected either or both. However, evidence will be presented in the next section to indicate that *the disturbance was probably propagated below 3 km.* and as such could not have been the result of an advective process.

CROSS SECTION

From the atmospheric soundings taken at Joliet, Toledo, Pittsburgh, and Washington, it was possible to construct a vertical cross section through the atmosphere for the time 1000 EST (fig. 6). At this time the pressure pulse was in a position indicated by the arrow and the leading edge of the lower cloud bank in the position indicated by the upright triangle. The wind data for Fort Wayne, Toledo, Columbus, Akron, Elkins, and Washington were superposed on the section. The winds were rotated in the plotting to conform to the orientation of the cross section. The important features of the cross section are:

(1) Isentropes: Above 4 km. the isentropic surfaces are pretty much horizontal and the atmosphere in this region represents quasi-horizontal homogeneity. Below 4 km. and east of Toledo the same situation prevails. The isentropic surfaces are again roughly horizontal. However, between the Toledo and Joliet soundings there is a marked change in the isentropic surfaces below 4 km. Interpreting this space cross section as reflecting the changes that would appear on a time cross section we may conclude that the potential temperatures indicate that subsequent warming has taken place. It should be noted that the isentropic surfaces were drawn to represent extremely rapid dropping of the isentropic surfaces in the area of the pressure pulse only, rather than a gradual descent from the values at Toledo to the values at Joliet. The reason for this analysis will be clear later.

(2) Inversions: The thick vertical lines represent elevations for which the soundings showed inversions of tem-

TABLE 1.—*Winds aloft (mph) at 1000 EST and 1600 EST, December 6, 1949*

Station \ Altitude	Surf.	500	1000	1500	2000	2500	3000	4000	5000	6000	7000	8000	9000 meters
	1000 EST												
Evansville, Ind	SSW 16	SW 40	WSW 63	WSW 58	WSW 56								
Fort Wayne, Ind	SE 11	SE 31	S 36	SW 29	WSW 36	WSW 43							
Indianapolis, Ind	SSE 13	SSW 29	SW 34	SW 36	WSW 43								
Akron, Ohio	S 5	S 7	W 11	W 22	W 36	WNW 45	W 45	W 81	WNW 96				
Cincinnati, Ohio	SSE 9	SSW 27	WSW 36	WSW 36	WSW 43								
Columbus, Ohio	SSE 5	SSE 18	SW 18	W 27	W 34	W 43							
Toledo, Ohio	SE 9	SE 13	SSW 20	SW 20	W 31	W 38	W 38						
Curwensville, Pa	NW 13		WNW 31	WNW 40	WNW 49	WNW 56	WNW 63						
Harrisburg, Pa	W 16	WNW 22	WNW 22	WNW 20									
Philadelphia, Pa	WNW 18	W 16	NW 29	WNW 43	WNW 58	NW 67	NW 74						
Elkins, W. Va	WSW 9		W 13	WNW 31	WNW 45	WNW 47	WNW 67	WNW 76	W 90	WNW 87	WNW 105		
Norfolk, Va	WNW 11	W 31	W 20	NW 25	NW 40	NW 50	NW 60	WNW 72					
Richmond, Va	W 9	WSW 22	W 16	WNW 22	NW 44	NW 58	WNW 67	WNW 81	WNW 98	WNW 116	WNW 119	WNW 98	WNW 154
Roanoke, Va	WSW 9	WSW 9	WNW 16	WNW 36	WNW 50	WNW 56	WNW 54	WNW 74	WNW 81	WNW 81	WNW 85	WNW 87	WNW 87
Washington, D. C	WSW 16	W 18	WNW 27	WNW 49	NW 56	NW 56	NW 67	WNW 78	WNW 107	WNW 114	WNW 112		
	1600 EST												
Evansville, Ind	SSW 18	SSW 43	SW 45										
Fort Wayne, Ind													
Indianapolis, Ind	S 11	SW 34											
Akron, Ohio	SE 9	SE 18	S 29	SW 9	SW 27								
Cincinnati, Ohio	SSW 25	SSW 38	SW 54	SW 56									
Columbus, Ohio													
Toledo, Ohio	ESE 20	SE 29											
Curwensville, Pa	SW 7		WSW 5	WNW 18	WNW 40	WNW 49	WNW 60						
Harrisburg, Pa	WSW 5	W 9	W 16	WNW 34	WNW 49	WNW 52	WNW 52	W 87	W 87	W 90			
Philadelphia, Pa	WNW 9	WNW 20	W 25	WNW 36	WNW 47	WNW 49							
Elkins, W. Va	S 5		SW 18	WSW 38	W 47	W 49							
Norfolk, Va	WSW 9	WSW 20	WSW 20	WNW 31	NW 38	WNW 47							
Richmond, Va	SW 5	SW 9	WSW 13	W 27	WNW 63	WNW 60	W 58	W 65					
Roanoke, Va	SW 9	SW 16	SW 22	WSW 29	W 38	W 47	W 56						
Washington, D. C	WSW 2	SW 11	WSW 20	WNW 34	WNW 49	WNW 55							

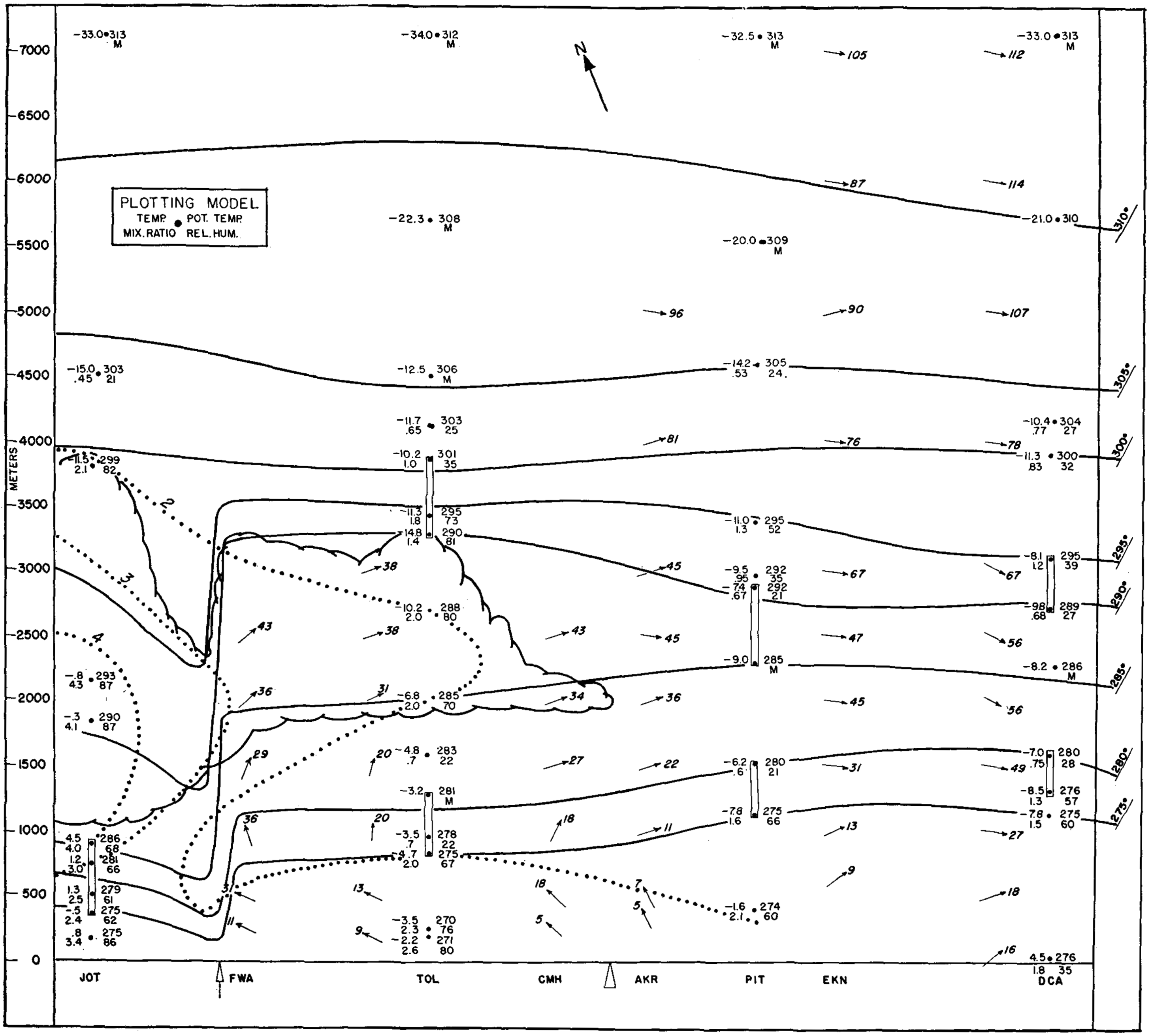

Figure 6.—Atmospheric cross section, Joliet—Washington, 1000 EST, December 6, 1949. Solid lines are isentropes (° A), dotted lines are lines of equal mixing ratio (gm./kg.), upright rectangles are temperature inversions. Along the bottom of the chart, arrow represents location of pressure pulse and upright triangle the leading edge of the cloud bank. The winds (in m. p. h.) are plotted with reference to the directional arrow in the top center. JOT=Joliet, FWA=Fort Wayne, TOL=Toledo, CMH=Columbus, AKR=Akron, PIT=Pittsburgh, EKN=Elkins, DCA=Washington.

perature. It should be noted that from Toledo and eastward there are two distinct inversion surfaces; the lower at approximately 1,000 m. and the upper one at approximately 2,000–3,000 m. The lower inversion was associated with the warm front to the south. At Joliet, only the lower inversion is present and it has lowered between 300 and 500 m. The upper inversion has been almost eliminated undoubtedly due to the warming that has been discussed above. (A remnant of the upper inversion may still be found over Joliet at 2 km.)

(3) Moisture and clouds: The cloud bank has been drawn in the regions where the relative humidity was greater than 70 percent. It should be noted that the cloud bank appears to travel in between the two inversion layers. At the point where the isentropic surfaces were drawn to dip down very sharply, the cloud pattern was drawn in a manner to conform with this adiabatic heating. Similarly, the isentropic surfaces were lifted over Joliet which reported higher humidities. This feature will be discussed in greater detail in the subsequent sections.

(4) Winds: Below the lower inversion the winds are predominately easterly. Between the two inversions they change to westerly and are of the same speed as the speed of propagation of the cloud bank. Above the second inversion the winds are very strong, but here nothing seems to be happening. It is of particular interest that the winds over Fort Wayne, below the lower inversion are much faster (easterlies) than the winds at Toledo, Columbus, or Akron.

EASTERLY WIND COMPONENTS

This increase in the easterly wind component may be seen in figure 7. Here the reported winds at various stations have been broken down into their components and the *easterly* component plotted with respect to position of the passage of the pressure pulse. It can be seen that there are definite indications of an increase in the easterly wind component associated with the passage of the pressure pulse. The wind values plotted are not continuous but represent discrete wind observations taken at relatively long-period intervals. Continuous records might have indicated this behavior much more clearly.

HYDRAULIC EXPERIMENT

In setting up a hypothesis to explain the phenomena described above, it will be helpful first to consider the following laboratory experiment (fig. 8 A, B, C). Water is made to flow in a trough (60 by 6 by 2 inches) from right to left. By adjusting the opening at the left a constant level of water is maintained (fig. 8A). (The size of the opening is controlled by sliding a plate up or down.) The plate is suddenly raised (fig. 8B) allowing the water to accelerate to the left. This produces a depression of the water surface which *travels to the right.* The plate is suddenly lowered (fig. 8C) to its original position and the water which has been accelerating piles up and raises the water surface. This elevation of the water surface also *travels to the right* behind the depression.

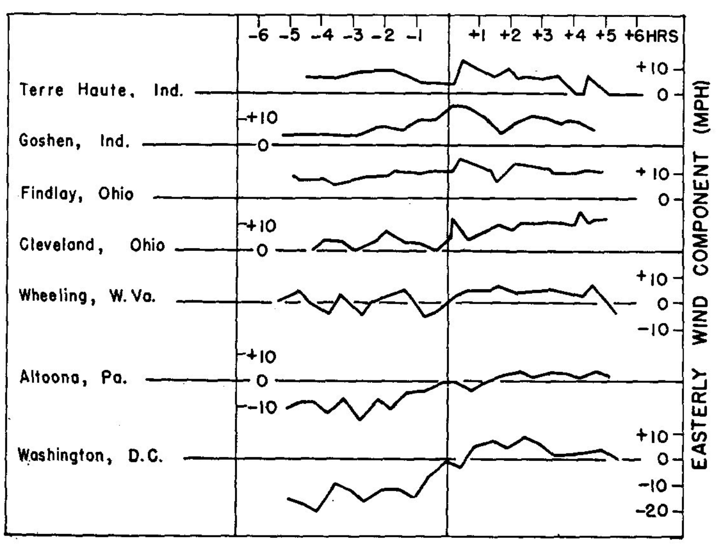

FIGURE 7.—Easterly wind component (m.p.h.) in relation to the passage of the pressure pulse.

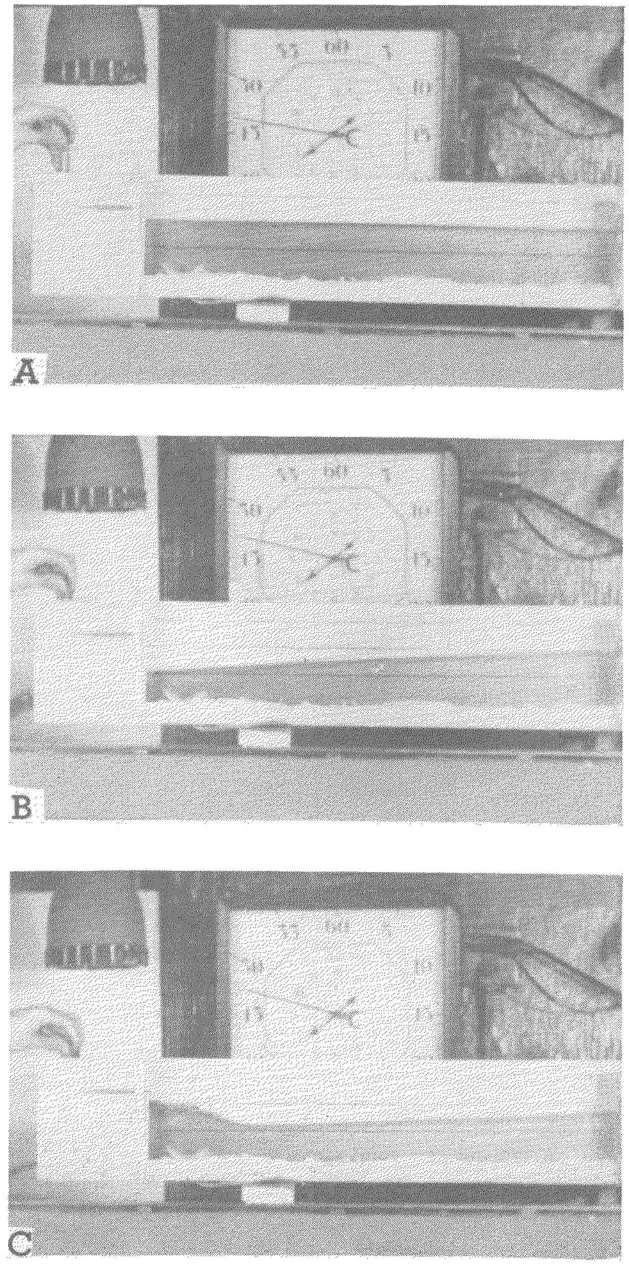

FIGURE 8.—Hydraulic experiment. (A) Steady state conditions; the water is flowing from right to left and the level of the water is maintained constant. (B) The plate at the left is lifted producing a drop of the water surface. The wave moves to the right. (C) The plate at the left is lowered to its original position producing an elevation of the water surface. This wave also moves to the right. (The bottom surface of the trough is perfectly smooth. The apparent roughness is due to paint along the edge of the glass.)

By analogy to gas flow, we may refer to the traveling depression of the water surface as an expansion type wave and the subsequent elevation of the water surface as a compression type wave. It is emphasized that *both the expansion and the compression type waves* travel in a direction opposite to that of the flow of the water.

THE HYPOTHESIS

Freeman [2] has indicated the conditions under which the flow of air under an inversion surface may be considered analogous to the flow of water in an open channel. In this analogy, the inversion surface corresponds to the free surface of the water, and variations of the height of the inversion surface behave in a manner similar to water waves. In particular, waves on the inversion surface would be propagated independent of the flow of the air particles themselves.

We postulate then, that some mechanism accelerated the air below the warm frontal inversion. As in the case of the water in the laboratory experiment the inversion surface dropped suddenly, producing an expansion-type wave which moved eastward. The second phase of the pressure pulse is associated with the compression-type wave produced as the accelerating air is slowed down by convergence with the air ahead of it. It would be expected from hydrostatic reasoning alone, that the expansion-type wave would be reflected as a pressure drop at the surface and the compression-type as a pressure rise. This combination of pressure fall followed by a pressure rise when superposed on a falling pressure field would produce the type of trace characteristic of the Midwest. When this pulse reached the flat pressure area in the East it appeared primarily as a V-shaped pulse.

Now, associated with the rapid fall of the inversion surface there would be rapid heating and consequent desiccation of part or all of the cloud. We should then expect that when the pressure wave traverses an area where the cloud is relatively thick that its power to desiccate the cloud completely would be less than in those places where the cloud was relatively thin.

Returning to figure 1 which shows the picture of the cloud bank over Washington, we may state that the pressure wave had just caught up to the cloud and because the cloud was very thin, the pressure wave was able to desiccate the cloud completely.

SOLAR RADIATION

While the physical interpretation given above explains the peculiar phenomenon that passed Washington, D. C. on December 6, 1949, it also raises the obvious question, did this phenomenon happen only at Washington or did it occur elsewhere? The answer is that the basic phenomenon did occur elsewhere but on a different scale. The evidence for this statement lies in solar radiation data.

We shall assume here that sudden changes in transmission are probably caused by sudden changes in the thickness of the intervening cloud layer. While it is conceded that changes in transmission may also be caused by changes in the water content and/or drop size in the cloud layer, it will be safe to assume that the sudden changes in transmission that will be shown were probably caused by decrease in thickness of the cloud layer.

[2] J. C. Freeman, Jr., "An Analogy Between Equatorial Easterlies and Supersonic Gas Flow", *Journal of Meteorology*, vol. 5, No. 4, August 1948, pp. 138–146.

Figure 9 shows the radiation traces from Indianapolis, Columbus, Put-in-Bay, Cleveland, and Washington. For comparison the radiation trace for a relatively clear day at each station is shown by the dashed line.

The general feature of all these traces is that they contain two significant points. The first is a decrease in radiation and the second is a very sharp increase in radiation. Some of the time scales are in Solar Time and so a conversion to Eastern Standard Time is required. This conversion factor is shown where required. The time of occurrence of each of the two significant features from each trace was recorded and compared with the isochrone pattern for the onset of the low cloud bank and the passage of the pressure pulse. This comparison is shown in table 2. The two columns refer to the time of decrease in radiation and the time of sudden increase in radiation. The numbers in parentheses refer to the time that the lower cloud bank appeared over the station as reported on the Surface Weather Observation Sheet. The numbers in brackets refer to the time of the passage of the pressure pulse over the station as recorded on the microbarograph trace.

Considering the errors that may arise in reading the traces, the difference in location of the instruments at any one city, and the possible lack of accurate time considerations in taking observations, the agreement in the time values is remarkable. We may safely associate the decrease in radiation with the onset of the cloud bank and the sudden increase in radiation with the passage of the pressure pulse.

Table 2.—*Times of sudden decrease and increase in solar radiation. Figures in parentheses refer to time of arrival of the cloud bank and figures in brackets to time of passage of pressure pulse*

	Time (EST)			
	Decrease		Increase	
Indianapolis, Ind.	----	(0500)	0922	[0920]
Columbus, Ohio	0914	(0925)	1148	[1215]
Put-in-Bay, Ohio	0947	(1000)	1240	[1230]
Cleveland, Ohio	*1200	(1203)	1315	[1320]
Washington, D. C.	1455	(1455)	1602	[1610]

*The fluctuations in radiation at Cleveland, beginning with 0950 are related to a few scattered Cu. which were reported on the Surface Weather Observations Form beginning at 0900. These clouds were reported under "Remarks." Lower clouds were not reported under "Sky Conditions" until 1203 and this entry was undoubtedly associated with the continuous decrease in radiation beginning at 1200. Surface Weather Observations Forms are not available for Put-in-Bay so that it is not possible to determine whether the fluctuating transmission after 0947 was due to scattered clouds at the leading edge of the cloud bank or scattered clouds unrelated to the cloud bank. The records from Toledo seem to indicate 0900 as the time when the leading edge of the cloud bank moved in at Toledo. It is for this reason that 0947 was chosen as appropriate for Put-in-Bay.

CONCLUSION

We conclude from the evidence presented in this study that a pressure wave consisting of a pressure drop followed

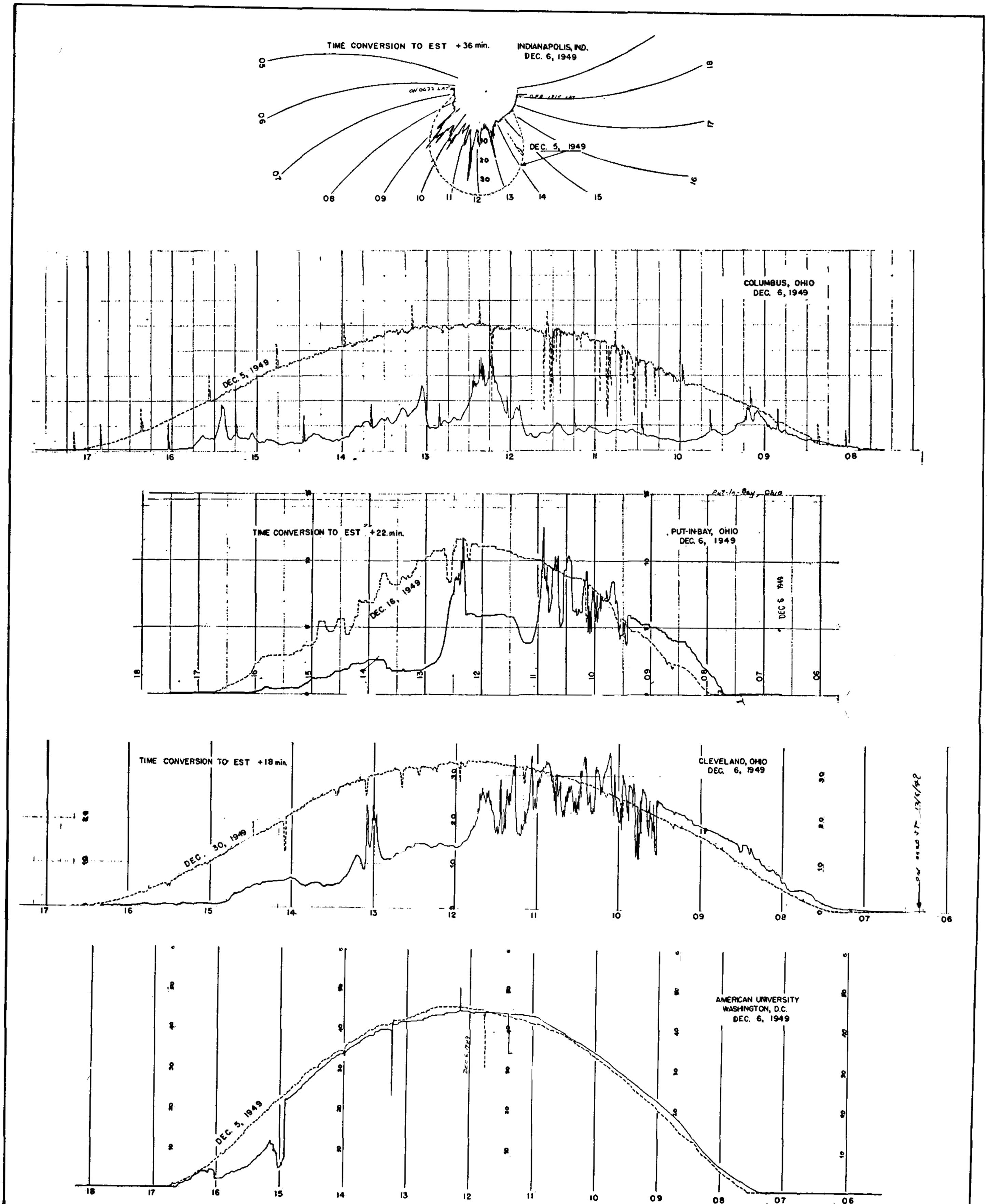

Figure 9.—Radiation traces for Washington, D. C., Cleveland, Ohio, Put-in-Bay, Ohio, Columbus, Ohio, and Indianapolis, Ind., December 6, 1949. A relatively clear-day radiation trace is indicated by the dashed line.

by a pressure rise, was propagated on the warm frontal surface with a speed far in excess of the winds in the lower layers. This wave was produced by sudden acceleration in the winds below the frontal surface. The pressure drop which is but an indication of the sudden fall in the isentropic surface was associated with a partial (in the Midwest) and total (over Washington) desiccation of the cloud layer. We leave unanswered the question: what is the mechanism that produced the sudden acceleration of the winds below the inversion surface?