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On Pre-Frontal Precipitation Zones in the United States

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Abstract

In this paper are presented the results of detailed analyses of remarkable pre-frontal precipitation zones* during a winter season. The analyses are then compared to pre-frontal squall-line situations. Then the general aspects of pre-frontal precipitation zones are described in some detail. It is concluded that in the United States to the east of Rocky Mountains, formation of an extensive precipitation zone in a warm sector of a cyclone is a typical phenomenon. It is shown that formations of such extensive pre-frontal precipitation zones are related to regular synoptic scale disturbances aloft rather than a local mechanism which exists only very near to the ground. Roles of static stability are examined and found to be not so important for formations of such organized precipitation systems. It is also pointed out that interaction between the cold frontal surface and the precipitation system may be no more than a secondary importance.

1. Introduction

It is well-known that in the United States extensive squall-lines frequently appear ahead of cold-fronts in the surface weather charts. One of the typical examples is shown by Bergeron (1954) in which an extensive precipitation zone appeared well ahead of surface cold front whereas there was no significant weather system along it. The precipitation pattern associated with cyclone model shown in text books of meteorology.

Early investigators tried to explain this pre-frontal nature of such precipitation zones by introducing so called cold-front aloft. Holtzman (1936) and Lichtblau (1936) introduced upper cold-front in advance of the surface front to account for the precipita-

tion. The atmospheric structures considered by them were, unrealistic, in many cases, for, they considered continental polar air to exist in low levels where pre-frontal squall-lines develop. During the 1940's and early 1950's there were several other articles which related pre-frontal rain with cold front alofts. Although the upper cold frontal structure considered by various authors (Lloyd, 1942; Byers, 1944; and Fulks and Smith, 1950) were not quite the same, it appears reasonable to consider some disturbance aloft associated with pre-frontal precipitation zone.

It has been generally recognized that many squall-lines form along or near surface cold fronts and move forward to become distinct pre-frontal structure. Two essentially different mechanisms were proposed by Tepper (1950) and Newton (1950). Tepper suggested that the short-period pressure changes associated with a squall-line (*i.e.*, so-called the pressure-jump line) is a manifestation of a wave disturbance on the inversion surface, generated by transversal accelerations at the cold front. Although such wave may exist, it is difficult to relate them to pressure

* Throughout this paper the term pre-frontal precipitation zones refer to a precipitation zone located mainly in the warm-sector of a cyclone. Therefore, these systems are pre-frontal with respect to cold fronts, in some cases with respect to moisture discontinuities (dry fronts). Warm frontal rain, which may also be regarded as pre-frontal, is not considered here.

changes of the type associated with squall-lines, for, it is rather unrealistic to expect such inversion wave with the area of intense vertical circulation. Many consider that small-scale pressure disturbances associated with squall-lines are more likely to be caused by rain cooled air and dynamical effects. On the other hand Newton (1950) proposed a model which has the appealing feature of containing self-propagating mechanism. In his model the cold down-draft spreads downward over the wedge-shaped cold air beneath the cold frontal surface and advances into warm-sector air where it appears as a pre-frontal squall-line. This mechanism can be expected to operate only when the down-draft air is potentially warmer than the air in the rear of the cold front. Sasaki (1959) conducted some interesting numerical experiments on squall-line formation and obtained fields of vertical motion similar to those proposed by Newton.

All of the works concerning pre-frontal precipitation zones over the United States are, to the present authors' knowledge, squall-line cases. There has been a tendency to consider the formation and development of a zone of precipitation in the warm-sector of cyclones over North America are related to the mechanisms of squall-lines or conditions favorable for the formation of intense convective systems. However, there are cases in winter an extensive pre-frontal precipitation zone to form in the warm-sector of a well-developed cyclone over the Midwest. In these cases the larger portion of precipitation areas are of non-convective or weak convective types. It is the aim of the present paper to clarify some of the general aspects of the development and structure of precipitation zones of the pre-frontal type. Two typical cases of winter situations are described in detail and the result will be compared with typical cases of pre-frontal squall-lines.

2. Case I; The case of February 18, 1961

In the early hours of February 17, 1961 a large low-pressure area over the southern Rockies moved slowly eastward and reached Oklahoma in the evening of the day. A small low formed southwest of the Kansas

City, Mo., in advance of the old center. The new low developed rapidly while moving northeastward toward the Great Lakes region. As shown in Fig. 1, the situation represents a clear case of formation of a pre-frontal precipitation system.

At 0000 CST of the 18th (chart a), while the new development had just become a major circulation system, the precipitation were wide-spread in a disorganized manner. Note the positions of relatively heavy precipitation areas designated by letters A and B. At 0600 CST the precipitation in the warm-sector of the cyclone was still wide-spread. During the following six-hours precipitation centers A and B became aligned and a relatively narrow band of heavy precipitation was formed within the warm-sector as shown in the chart c. Toward the evening the rain area crossed the Appalachian Mountains without much change in structure. At about this time a few minor precipitation areas began to appear along the cold front, but they failed to develop. Analysis of hourly precipitation data revealed an interesting behavior of the precipitation system A which moved southeastward through very deep southwesterly current. A rough estimate was made to find the movement of the system by means of the method proposed by Newton and Fankhauser (1964) for convective storms. In this case, however, the system was much larger than those considered by them. The result was the rainstorm of this size, under the considerations of the present situation, should move almost perpendicular to the mean current of troposphere, which was actually the case.

The vertical velocities at different levels were computed by a kinematic method in the manner explained in the Appendix, and some of the results are shown in charts a and b of Fig. 2. These may be compared with the vertical velocities computed from ω -equation at the National Meteorological Center (NMC) (charts c and d). On the whole, the kinematically computed vertical velocities show a closer association with the patterns of rainfall than do the NMC velocities. The magnitude of the kinematic vertical velocity for the pre-frontal precipitation zones are considered to be reasonable

Fig. 1. Six-hour surface charts for the period 0000 to 1800 CST, 18 February 1961. Light stippling shows areas of precipitation with amounts from 0.01 to 0.25 inches in a 2-hour period centered at the times to which the charts refer. Dense stippling indicates precipitation in excess of 0.25 inch during the same period.

because evaluation of amount of precipitation from the moisture field using the same wind analyses gave a very good result in comparison with actual amount of precipitation. (Omoto, 1963). Therefore, upward velocity

obtained at the NMC for the pre-frontal system appears to be too small to account for actual precipitation intensity. It is noteworthy that the NMC method also yielded a band of upward motion field with its axis

Fig. 2. Vertical velocity at 4 km (above) and 600 mb (below) expressed in cm/sec. The data of the upper charts were computed with the aid of the method described in the appendix, and those of the lower chart are reproduced from the computations made in the National Meteorological Center.

well-ahead of surface cold front. Although the region of upward motion is far broader than actual precipitation zone, this feature may be considered in connection with formation of pre-frontal precipitation system of a

synoptic scale.

Chart a of Fig. 3 shows vertical structure of the atmosphere through the southern portion of the pre-frontal precipitation zone (including the system B) at 1800 CST. Ver-

Fig. 3. Vertical cross-sections of the pre-frontal precipitation zone along the line X-Y in chart d of Fig. 1. In the upper chart, broken lines indicate dew-point ($^{\circ}\text{C}$), and full lines with dots show the vertical velocities (cm/sec), stippling indicates frontal surface or stable layers.

tical velocity given in this chart is considered to be reasonable in regard to actual situation. The lower chart shows relative motion of air with respect to moving pre-frontal precipitation zone. The general feature is very much similar to that obtained by Newton and Newton (1959). However, the vertical velocity given in the figure is computed from the area averaged divergence for $(300 \text{ km})^2$ whereas the circulation shown by the above-mentioned investigators is based upon small-scale features associated with the squall-line. The absence of a downdraft within the rain area in this figure may not be due to

lack of local downdraft but the procedure utilized in computation of the divergence field eliminating weak local subsidence, as it is averaged over large areas where strong upward motion existed, thereby giving net convergence in low levels for the grid points.

3. Case II; The case of 4-6 December, 1960

During the late evening of 3 December 1960 a wave low appeared in the north-central New Mexico, and there was a broad precipitation area straddling the cold front which extended from the low center. As

Fig. 4 (1).

the front moved across the southern part of Rocky Mountains, precipitation area became horse-shoe shape as the rain along the frontal zone dissipated. Although pre-frontal rain was not well organized during the early morning hours on the 4th, at noon there was

a well defined precipitation zone well ahead of the cold front. The dissipation of cloud along the front* and the formation of pre-frontal precipitation zone in this case appears

* for detail see Omoto (1963).

Fig. 4 (2).

Fig. 4. Charts during the mature and dissipating stages of the pre-frontal system of Case II. The chart on the left shows the surface charts, and where broken lines are dew-point, solid lines are isobars. The chart on the left shows the 500 mb contours (solid lines) and vertical velocities at 4 km level (lines with dots, cm/sec), lines of small circles indicate shear zone at the level. In all charts light stippling indicated precipitation areas as in Fig. 1.

Fig. 5. Vertical cross-section of the pre-frontal precipitation at 1800 CST, December 1960. Cross-section from El Paso, Texas to Jacksonville, Fla. Along the line A-B in Fig. 4 (chart a and b). Symbols are the same as chart a of Fig. 3.

to be mainly due to orographic descending motion along the eastern slope of the Rocky Mountains. In Fig. 4 are shown further development and decay of the pre-frontal precipitation system of this case. A noteworthy feature which may be found from surface charts is the very dry air stagnating over the eastern portion of the United States. As one may notice that, at least the northern portion of the pre-frontal precipitation, which move quite rapidly southeastward, dissipated as the rain area reached the eastern edge of the low level moisture tongue. In the 500 mb charts are shown vertical motion field computed by the method described in the appendix. The computed vertical motion field show generally good correlation with respect to precipitation areas. The NMC vertical motion fields for this period were not shown here but were poor, in general, with respect to precipitation area. This failure could probably be due to weak vertical velocity associated with the precipitation systems of this case.

Fig. 6. Vertical cross-sections showing a time → charge of structure of the pre-frontal precipitation system for Case II. Cross-sections from Denver, Colo. to Tampa, Fla., along the line C-D in Fig. 4. Symbols are as in chart a of Fig. 3.

Another very interesting feature of this case is the formation of another precipitation zone along the cold front behind the pre-frontal system. The first rain area along the front appeared about at noon on the 5th. The charts e and f show the situation at 1800 CST, showing well organized precipitation band behind the cold front. This frontal precipitation developed as the pre-frontal system weakened. The weakening of the pre-frontal system seems to be started due not only to its arrival to the eastern edge of the moisture tongue but also to the formation of stronger convergence zone just behind it.

In Fig. 5 the vertical cross-section along AB of the chart a of Fig. 4 is given.* This section shows the structure of the southern end of the pre-frontal system which was expanding at this time. Please note that the stable layer became higher and then broken

* A large number of vertical cross-sections of this sort were constructed in 12 hour interval for this case. For instance, several such cross-section intersect with this particular one, the heights of inversion layers, or isolines are checked if they are consistent between charts.

in the vicinity of the pre-frontal rain. In this chart the moisture distribution corresponds well to the vertical motion field, namely relatively humid in the area of upward motion and dry in the area of subsidence. The level maximum vertical velocity was near 700 mb within the precipitation band.

The chart a through c of Fig. 6 show 12 hour change of vertical structure of the pre-frontal precipitation system along line CD of Fig. 4. The most notable feature of this series is the change of vertical motion field. When there was only developing pre-frontal system (chart a) there was only one maximum in the upward motion at about 600 mb. This maximum was risen to 450 mb or higher during the next 12 hours while to the west a new upward motion maximum appeared over the cold frontal surface. It is of importance to note that a slight downward motion appeared in the pre-frontal precipitation area at low level, suggesting the system lost the moisture supply from the low level. The chart c indicates only the strong upward motion associated with the frontal precipitation zone.

On 5th December several flight observation

Fig. 7. Vertical cross-section along the flight path showing cloud structure over the northern portion of the pre-frontal system. Heavy lines with arrowhead indicate the flight paths, cloud symbols may be inferred from their appearance. For details in definitions of these please refer to Omoto (1963).

Fig. 8. Showing the early stage of the pre-frontal system of Case III Surface charts (left) with isobars, (solid lines), isodrosotherms (broken lines) and fronts. The symbol indicates a moving discontinuity in the moisture field (dry front), and indicates a quasi-stationary discontinuity. In 500 mb charts are height contours (solid lines), isodrosotherms (broken lines) and observed winds. Stippling identifies the area of precipitation at the time indicated.

Fig. 9. Surface charts for Case IV. Symbols as in Fig. 8 (Charts a and c).

were made by the aircraft chartered by the Weather Forecasting Research Center of the University of Chicago. Number of clouds analyses were made based upon these obser-

vations and other pilots reports. Fig. 7 is one of the vertical cross-sections showing the cloud structure of the northern portion of the pre-frontal precipitation system. It may

be of interest to note that there was no cloud in the vicinity of the cold front. Significant feature of this figure is the layered type clouds associated with pre-frontal system. There was no sign of existence of deep convective clouds in the vicinity of the precipitation area.

4. Squall-line cases

Three squall-line cases are analyzed to compare with the winter situations. One of the situations occurred during the period 1st through 3rd May, 1958 (Case III). In this case pre-frontal type precipitation system developed east of a slow moving dry front extending north-northeast through south-southwest over the southern part of the Great Plains. The most interesting feature of this case is the appearance of a well-defined weak trough aloft, (see Fig. 8). The importance of such upper air disturbance will be discussed in some more detail in the next section. The squall-line of the Case IV formed behind the pre-frontal system of above-mentioned case. In Fig. 9 surface charts for this situation are given, please note that the dry front changed into the cold front. An interesting finding related to this case is the role of static stability in the formation and development of pre-frontal precipitation zone. Detailed discussion concerning this point is given in the next section. Analyses were made for another squall-line situation which occurred 25–27 April 1957 (Case V). In this case the cold front not only caught up the pre-frontal precipitation system which is similar to case II, but also moved ahead of rather stationary precipitation zone. Thus forming a post-frontal precipitation zone.

5. General aspects of pre-frontal precipitation zone

Relation to general synoptic situation

The early stage of development of pre-frontal precipitation systems has been found to occur in a variety of synoptic situation. In Case I (weak convective except southern extremity of the zone) the northern part of the rain band first appeared in the cold air in the rear of the cyclone center, while the southern part of the band developed in the

warm-sector, in Case II (weak convective) and IV (intense convective) the first outbreak of rain took place at a pre-existing cold front. In cases III and V the early development took place near dry front. And in the latter of these cases a cold front swept forward from the northwest so that the developed precipitation system became aligned in advance of a cold front. As in all of these cases the rain area moved forward to become entirely pre-frontal during the early stage.

One of the common features for the very early stage of developments of the system is that they start from areas of thunderstorms. This feature is especially interesting for case I, in which the precipitation system denoted as A formed northwest of the deepening cyclone center in mid-winter.

Another common feature among the cases during the early stage is the first appearance of pre-frontal precipitation system along the western border of a low level moisture tongue. In particular this is true of the

Fig. 10. Schematic illustrations showing the growth of the precipitation zone associated with the stretching low-level moisture tongue, based upon computations for the situation of Case III. Dash-dot lines indicate the axes of zone of upward motion.

northern extension of such tongues. Computation made for Case III indicated that these extension result mainly from horizontal advection of moisture laden air at low levels. The conditions have been generalized into the model shown in Fig. 10. Development of this type indicates that the northward extension of the precipitation zone is mainly due to an increased supply of moisture in low levels in regions where other conditions for formation of rain may already be favorable.

In all cases the first development of a pre-frontal precipitation system took place under the forward side of an advancing major pressure trough in the upper troposphere, thus within the area of southwesterly flow in the middle troposphere. In four out the five cases, the remaining is Case IV, detailed analyses revealed the existence of weak disturbances in the form of minor troughs or shear zones in the vicinity of the pre-frontal precipitation zones. In these cases the disturbances appear more conspicuously in the wind field than in the height field, indicating appreciable ageostrophic wind component. For all cases wherein this feature was seen, the shear zone seemed most distinct at about the 600 mb surface. Such shear zone were found during the early stage or even before the formation of the precipitation systems, and they became less distinct near the mature stage of the precipitation system. In temperature field, although very weak in appearance, it gives the region of relatively cold air, probably for this reason early investigators considered cold front aloft near pre-frontal precipitation zones.

Remembering that at least the major portion of the precipitation zone were situated to the southeast of anticyclonic side of the high level jetstream, when small troughs of this sort appear in the region, and move with the approximate velocity of wind near the middle troposphere, the conditions just ahead of this trough would be favorable to formation of a precipitation system. We may infer from consideration of vorticity and wind fields associated with this trough that the conditions just east of this trough favor the formation of a precipitation system. The vorticity equation may be written,

$$D \approx - (V - C) \frac{1}{Q} \cdot \nabla Q$$

where C is the velocity of the vorticity field, V is the wind velocity, D is the horizontal divergence, and Q is absolute vorticity. In general there is a tendency that

$|V \cdot \nabla Q| < |C \cdot \nabla Q|$ in the lower troposphere, and

$|V \cdot \nabla Q| > |C \cdot \nabla Q|$ in the upper troposphere.

Such a domination would result in low level convergence and high level divergence in the region of the forward side of the trough.

It is essential to note that the magnitude of Q is relatively small in the region on the anticyclonic shear side of the jet stream. Consequently the magnitude of divergence may be large enough to produce a precipitation system even though a trough is feeble in appearance, with only a weak disturbance of the vorticity field. It may be for this reason that especially when weak troughs are near large amplitude systems it is difficult to define the disturbance. This is one of the reasons why it was not possible to identify the weak trough aloft for the case IV, in which case the squall-line was situated near a very strong south-southwesterly flow in the middle troposphere. Careful examination of the wind field suggested the existence of a zone of secondary vorticity maximum just behind the precipitation system.

Remembering the NMC vertical velocity field for Case I, for example, gave a broad zone of upward motion mainly ahead of the surface cold front when there was a pre-frontal precipitation zone, we may consider effects of such a trough may appear even in the large scale analyses. Since these troughs move with the wind in the middle troposphere, roughly, it is in accordance with the well known observations that the pre-frontal squall-line move faster than surface fronts.

Whether or not the precipitation system appears as a continuous belt or consists of aligned elements is, perhaps, immaterial since irregularities in vertical motion and moisture distribution may result in a patchy arrangement. Actually many investigators have found extensive pre-frontal precipitation zone consisted from several mesosystems (*e.g.*

Brown, 1958). A line arrangement of the precipitation area was present in all cases and is considered to be predominant feature. It is found that even in the case of a continuous precipitation zone, it may be considered as an aligned mesosystem since detailed analyses reveal several maxima of precipitation within the zone. It is noteworthy that in all cases the axis of the developed pre-frontal precipitation system was almost a straight line while the front often exhibited appreciable curvature. This feature is also in favor of relating the system with weak trough alofts, for, they also show similar characteristics.

In only two of the cases (one winter situation and another early summer situation) was the entire life history examined. In the other cases it was possible to infer the later stages from examination of the 6-hourly charts routinely produced by the U.S. Weather Bureau. In all cases except Case V, the pre-frontal precipitation system appeared to lose their vigor and dissipated as they approached quasi-stationary anticyclone of the subtropical type. In the later development of Case V a cold front swept forward, overtook the pre-frontal precipitation system and continued to pass it, with the result that a post-frontal precipitation zone could be identified before it died out.

It is noteworthy that in all cases, except the Case II, the dissipation of precipitation zones took place in a region of abundant moisture in low levels. Although it is very difficult to express explicitly, dissipation of pre-frontal precipitation, in most of cases, are caused by subsidence associated with the subtropical high over the south-eastern States or the adjacent Atlantic Coast.

Effect of Static Stability

The relationship between a pre-frontal precipitation and static stability was studied in detail for the situation given in Case IV. For other cases only the Showalter Index was used to find the static stability of the atmosphere. In each case the pre-frontal precipitation zone developed in the relatively unstable region corresponding to the tongue of moist air at low levels. However, the magnitude of instability varies one case to the others. In the Cases I and II, the index

values ranged from 0 to 50°C in the precipitation area and it ranged for -6 to 0°C over the moist tongue for the Cases III and IV. It may be more adequate to consider that the intensity of convective activity alone can be related to the stability of the atmosphere and whether or not pre-frontal precipitation zone from is related to other factors.

In Fig. 11 are shown stability condition for 1800 CST on the 3rd and 4th May 1959. Charts a and c show the Showalter Index and isodrosotherms (isolines of dew-point) of the 850 mb level, and charts b and d show the distribution of a new stability index which is introduced to overcome some of the shortcoming in the Showalter Index. The new Index is similar to the Showalter Index except that refers to three overlapping layers. These have their bases at 50, 150, and 250 mb above the ground, in order to equalize the influences from the ground at various station. Then from these bases the air assumed to be lifted 300 mb, in the same manner as in the computation of the Showalter Index, and the difference between the temperature of the parcels and the observed values are obtained for each of these air particles. These values are averaged to give the final values. By this method air mass characteristics over the stations are considered in more detail than just taking values of at two levels. As shown in these figures, for the cases investigated, the patterns of these indices are the very similar and neither of the indices gave an indication of the development from scattered showers to an organized squall-line. Please note that the positions of fronts, and moisture distribution are also very similar for these two time. It will be informative to mention that the condition in charts a and b corresponding to the last stage of the pre-frontal system of Case III (for example, a shower area near Chicago, Ill.), and those in charts c and d corresponds to the mature stage of Case IV. The similarity of these two indices is discouraging rather than encouraging considering the amount of work required to obtain the new index. However, a study of many more cases will be necessary before one may conclude that these two indices generally give the same patterns.

Fig. 11. Showing patterns of convective stability at 1800 CST, May 3 and 4, 1959. Solid lines indicate stability in terms of the Showalter Index (Charts a and c) and the proposed index (charts b and d). Conventional symbols for fronts and weather are used. In charts a and c, hatching indicated areas where the dew-point at 850 mb exceeds 10°C, and in charts b and c widely spaced horizontal lines indicate clear sky. Note that despite of rather quasi-stationary nature of fronts and 850 mb moisture patterns, the area of clear weather moved southeast appreciably.

It is important to note that some thunderstorm areas within the very unstable air mass on May 3, 1959, dissipated without forming an extensive system. This gives rather unfavorable support for any hypothesis that a self-developing nature could be an essential for the formation of an extensive pre-frontal precipitation system. It would be safe to consider that the degree of static instability only represents the intensity of convective activity, if some disturbance initiates a vertical circulation. It appears likely that the formation, expansion, and dissipation of pre-frontal precipitation systems are essentially depend upon dynamical processes which appear to be related to some properties of the currents of the middle and lower troposphere.

Vertical structures

The cross-section analyses for these five cases are compared with a view to extracting common features, and the result is shown in Fig. 12. Here the significant front has been indicated as a cold front. In many cases it may be discontinuity in the moisture

field of the type referred to earlier as dry fronts, in which cases the slope will be much steeper than that of a cold front. The deep cloud identified by X in the model represents a large mass of continuous cloud or multiple-layer clouds in non-convective precipitation portion and it will consist of clusters of cumulus or cumulonimbus in convective portion of pre-frontal precipitation zones. However, the outward appearance of the system as a whole will not be materially affected.

Often, stable layers of relatively small horizontal extent develop in the middle troposphere as indicated by A and C in the figure. One often finds a layer of altostratus or altocumulus related to the stable layers.

The vertical circulation associated with the pre-frontal precipitation zone is shown schematically in the model. The arrows intended to show the predominant features of the motions relative to the moving system, and the model is intended to represent average rather than extreme conditions. Normally there is a weak convergence and a rather shallow layers of cloud near the

Fig. 12. A model showing the vertical structure of a generalized pre-frontal precipitation zone. Stippling indicates inversions or stable layers. Cloud symbols are schematic. Heavy lines with arrows indicate general flow pattern relative to the pre-frontal system.

cold front or in the rear of the precipitation system. Four stable layers are indicated in the diagram but all of them are rarely present at one time. Usually only one stable layer (A or B) exists in the rear of the precipitation, in addition to the inversion indicated as the cold front. The inversion layer indicated by A was present in the Cases I, III, and V. In the Cases I and II the stable layers B was found in cross sections. In the Cases I and II the stable layers correspond to B were so extensive that they surmounted to cold frontal surface in places.

On many occasions one finds two stable layers on the forward side of the precipitation system. The inversion denoted by C (Fig. 12) is normally weak and of small horizontal extent, there, it is sometimes difficult to detect, in the analysis using regular radiosonde observational network. The inversion at D usually represents the border between moisture laden tropical air at low levels and dry air which has taken part in anticyclonic systems in the subtropical belt. The inversion layer usually shows increasing height toward the precipitation area and ends where the strong upward motion begins.

Other features which may be related to pre-frontal precipitation zones

A) A formation of cold frontal precipitation system behind a pre-frontal rain area does not appear to be an unusual phenomenon. In four out of five cases such secondary formation was observed. For the remaining case (Case IV) the detailed analysis did not cover the last stage of the system so that no conclusive statement could be made in this respect. Actually the pre-frontal precipitation of this case started as a secondary formation behind the rain area of Case III. In three cases, Case I, III and V, new precipitation system developed as the old pre-frontal system dissipated, or else the old system weakened and merged with the new one. Only one occasion, the secondary system remained very weak and lasted only a short time, dissipating before the pre-frontal system became very weak (Case I).

There is a clear distinction in wind and pressure field in the surface charts between cases when frontal precipitation systems did and did not develop. In all cases when the

secondary system developed, this occurred along the portion of cold fronts in inverted trough. The secondary precipitation systems which did not develop further, formed near the cold front in normal V-shaped troughs.

Fig. 13 illustrates the situation to explain how such a difference in flow pattern near the ground is related to future development of precipitation formed along the cold front. When the cold front is in an inverted trough the maritime tropical air flows directly toward the front and glides up the frontal surface. In this case, the circulation around the frontal surface may be similar to a warm front in the classical model. The reason the front is called a cold front here is that the boundary moves toward the warm air mass.

Fig. 13. Illustrating the difference in flow pattern near the ground between an inverted trough and an ordinary V-shaped trough situation. In the figure are: isobars (thin solid line), stream-lines for tropical maritime air (heavy solid lines), those for polar continental air (heavy broken lines) and cold fronts.

It is known, however, fronts in such cases move very slowly. On the other hand, when the front is in a V-shaped trough the supply of moisture toward the frontal zone will be weaker, especially when there is pre-frontal precipitation zones.

B) A feature of considerable interest is a tendency for the precipitation system as a whole to assume a horse-shoe shaped configuration with the pre-frontal system as one of the branches. Such a precipitation pattern is shown in the classical model when a cyclone is well occluded. In the United States, precipitation patterns of this type appear in association with cyclones during the developing stages. In such cases one often finds an area of clear or nearly clear sky extending from the southwest of the vicinity of the cyclone center as noted by Pattersen and his collaborators (1963).

6. Discussions

When there is a pre-frontal precipitation zone, we generally find dry air to the rear and moisture-laden unstable air ahead of a cold front east of the Rocky Mountains. Although moist air ahead of the front is one of the necessary conditions for formation of precipitation systems within a warm sector, classical concept of structure of cyclone, especially of role of fronts in relation to vertical motion field fail to explain this phenomenon. When the air mass in the warm sector is moist and unstable one expects from the Norwegian model scattered heavy showers within the warm sector in addition to cold frontal rain (*e.g.* Pettersen, 1940). It is probably more adequate to consider some disturbance aloft rather than those at the ground level as a cause of such a well organized precipitation system in the warm sector of cyclones. In fact, some of the behaviors of the pre-frontal precipitation zones are difficult to understand from conditions which exist only in the extreme lower part of the troposphere, say within 100 mb from the ground. The weak troughs or shear zones found in the cases given in this report might be such disturbances. As mentioned in the foregoing section conditions associated with such disturbances are suitable for explaining some of the characteristics of pre-

frontal precipitation systems, which are difficult to explain from conditions given by surface analyses alone.

The shear zones found in the cases given in the paper seemed to exist during the very early stage of development of the precipitation zones, and became less distinct as the precipitation systems approached the mature stage. However, there is a case study (Fujita, 1962) showing a weak trough formed concurrently with the development of a squall-mesosystem. At the present time the knowledge concerning such weak disturbances aloft is meager. More case studies using a considerably improved upper air observation network, both in density and frequency of observations, are needed to establish firm evidence of the existence of such weak upper air disturbances. Furthermore, it will also be important to demonstrate numerically how an extensive zone of precipitation will affect the height and wind fields in the middle troposphere.

It is found that the role of static stability of the atmosphere may not be very important for the formation and development of pre-frontal precipitation zones. One may notice that the expansion of rain area of the case presented in this paper are difficult to explain from the self-developing or self-expanding nature expected from convective systems.

It has been stated that the existence of such an extensive pre-frontal precipitation is one of the unique features frequently seen on weather maps of the United States. In fact, to the present investigators' knowledge, nowhere else in the world can such extensive pre-frontal precipitation zones be found. Ramaswamy (1956) has shown large-scale convective precipitation in the southeast sector of a low in Northern India, however, the precipitation area was diffuse and did not form a narrow zone. Osawa (1958) and Ushijima (1960) presented case studies of pre-frontal squall lines in western Japan. For both cases the scale of the precipitation system was so small and close to the cold fronts that only a very detailed analyses could identify the pre-frontal nature of the precipitation system. In the United States, pre-frontal precipitation zones are clearly seen

in charts showing regular synoptic scale disturbances.

The existence of extensive pre-frontal precipitation zones over the United States can also be attributed to topographical and climatological features of the region. As one of the climatological features which itself is not independent of topography, we can consider the existence of the large warm sectors associated with cyclones over the United States. Topographically one can mention the gentle but extensive downward slope east of the Rocky Mountains. Were this plains region mountainous, the formation of well-defined precipitation system could not be expected, for, orographically induced vertical motions over such regions would be very complicated and would not permit the existence of an organized precipitation system. Although it is not possible to state explicitly, the eastward lowering of the ground probably plays an important role in the formation of such pre-frontal precipitation system, giving an effect of intensifying downward motion along the cold frontal surface.

One of the unique features of wave cyclones over the United States, is the existence of a clear tongue extending forward from behind the cold front into the warm sector. This feature appears to be related to the existence of the pre-frontal systems. Therefore, in future studies it will probably be necessary to consider pre-frontal system as a part of the internal structure of cyclones, rather than just relating the system to the cold fronts behind them. In fact, it is very difficult to consider direct influence of the cold frontal surface on such a precipitation area some 300 km or more further away from it. Finally, considering overall features of vertical motion fields associated with cyclones and behavior of precipitation systems, it may be necessary reconsider the mechanism of so-called the frontal precipitation.

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Appendix

Computation of vertical velocity

A kinematic method is used to compute vertical velocity, in which vertical velocity w at a level k , (superscripts) may be obtained for the expression, derived from the continuity equation ;

$$\tilde{w}^{(k)} = \frac{\tilde{\rho}^{(k-1)}}{\tilde{\rho}^{(k)}} \tilde{w}^{(k-1)} - \frac{\tilde{\rho}^{(k)}}{\tilde{\rho}^{(k)}} \bar{D}_{(k)} \Delta z \quad (1)$$

where ρ the density, D the horizontal divergence Δz the thickness of the layer. Subscript k refers to the k -th layer, which lies between k -1th and k -th levels, $k=0$ at the ground. Bar designate the quantity refers to the mean for the layer, curled-bar designate the area averaged value. The ratios $\tilde{\rho}_{(k)}/\tilde{\rho}^{(k)}$ and $\tilde{\rho}^{(k-1)}/\tilde{\rho}^{(k)}$ found to be approximately constant with height and place, and for the computed cases, Case I and Case II, these are 1.06 and 1.12 respectively. Using the grid shown in Fig. 14, horizontal layer mean divergence is computed from the expression

$$\bar{D}_{i,j} = \frac{\bar{u}_{i+1,j} - \bar{u}_{i-1,j} + \bar{v}_{i,j+1} - \bar{v}_{i,j-1}}{\Delta s} \quad (2)$$

where $\bar{}$ and $\bar{}$ designate averages along x -axis and y -axis respectively, which are actually computed by taking weighted averages,

$$\left. \begin{aligned} \bar{}_{i,j} &= \frac{()_{i-1,j} + 2()_{i,j} + ()_{i+1,j}}{4} \\ \bar{}_{i,j} &= \frac{()_{i,j+1} + 2()_{i,j} + ()_{i,j-1}}{4} \end{aligned} \right\} \quad (3)$$

Fig. 14. Rectangular grid used for computation by finite difference method.

The values of u and v are determined at each grid point from analyses of wind fields. In eq. (2) Δs designates twice of the grid distance and taken as 300 km and 200 km for the Case I and Case II, respectively. The computation of vertical velocity proceed upward from the lowest layer. An expression given below is used to take the effect of sloping ground into account.

$$\tilde{w}_{i,j}^{(1)} = \frac{(\bar{u}h^*)_{i+1,j} - (\bar{u}h^*)_{i-1,j} + (\bar{v}h^*)_{i,j+1} - (\bar{v}h^*)_{i,j-1}}{\Delta s} \quad (4)$$

In deriving this expression (See Fig. 15) effects of variation of the density of air was neglected, for, the error caused by this

Fig. 15. Showing how the vertical velocity at the lowest level may be obtained where the ground is sloping.

simplification is less than 5% which is insignificant considering the accuracy of analysis of wind field.

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米国における前線の前方の降雨帯について

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米国ロッキー山脈以東においてスコールラインが寒冷前線の前方に発達する事はよく知られている。このような降雨分布は現在の殆どの気象学教科書に採用されている低気圧内の天気分布のモデルとかなり異なるので、スコールラインが前線の前方に発達する機構に関する種々の研究がなされている。

しかし冬期においても帯状降雨域が発達した低気圧の温域に屢々現われる事はあまり知られていない。この論文には冬期の二つの典型的な例についての詳細な解析の結果を示した。特に注目される点としては冬期の例では問題にする降雨域が強い対流性の部分は少なく弱い対流性とか又は非対流性の部分がかなり大きい事である。

従って降雨帯が前線の前方に発達する理由をスコールラインの特性と結びつけると云う今までの考え方に大きな疑問が持たれる。又解析例にも示したように降雨帯と寒冷前線との間隔が 300 km もある場合もあり、これ等 2 者の相互作用の重要性にも疑問が持たれる。詳細な解析の結果この種の雨域が発達する時には 700 mb—500 mb の間に弱いトラフが現われる事が見付けられ、この種の擾乱が前線の前方の降雨帯の発達に関係があると見る事が妥当と思われる。その他降雨帯に関連した垂直流の分布及び大気の安定度の問題などについても論じた。