Reprinted from Preprint Volume, Conference on Cloud Physics, Tucson, Ariz.
Oct. 21-24,1974. Published by Amer.
Meteor. Soc., Boston, Mass.

AIR MOTIONS AND CLOUD STRUCTURE IN A FRONTAL SYSTEM IN THE PACIFIC NORTHWEST

Peter V. Hobbs, Robert A. Houze, Jr. and Thomas J. Matejka

University of Washington
Seattle, Washington

1. INTRODUCTION

It is now widely recognized that the classical frontal models first introduced by Bjerknes (1919), do not account adequately for many aspects of frontal precipitation. During the past decade several field investigations have shown that the dynamical and precipitation processes in cyclonic storms are concentrated to a large extent on the mesoscale* (e.g. Kreitzberg, 1964; Elliott and Hovind, 1964, 1965; Browning and Harrold, 1969; Austin and Houze, 1972). The mesoscale processes in turn contain a considerable degree of cumulus-scale activity. The implications of cumulus-scale convection in mid-latitude storms for climatology and cyclone dynamics have been discussed by Houze (1973) and Tracton (1973). Recent airborne measurements on the cloud microphysical scale (e.g. Hobbs et al., 1971, 1972) have revealed that the concentrations of ice particles in frontal cloud systems are often much greater than would normally be considered favorable for precipitation growth by Bergeron's (1935) ice-crystal mechanism.

From the above studies, it is evident that in order to obtain an adequate understanding of frontal precipitation processes, field studies are required which encompass a very broad range of scales, namely, synoptic, meso, cumulus, and microphysical. The case study presented here is one of the first in which a frontal system has been examined over this entire range of scales, including the microphysical.

We have studied an occluded frontal system as it moved inland from the Pacific Ocean, across the low-lying Puget Sound Basin of Washington, and then over the Cascade Mountains. Specific objectives were (a) to describe the dynamical structure of the frontal system, (b) to diagnose the dynamical and microphysical structure of the frontal clouds, and (c) to investigate the modifications of the frontal dynamics and cloud structure as the system passed over the Cascade Range.

2. DATA

Basic data for the study obtained by our Cloud Physics Group, are aircraft, sequential rawinsonde, Doppler radar, and high-resolution raingauge observations. In addition conventional meteorological data provided by the National Weather Service, and satellite photographs were used.

Airborne measurements were obtained from the University of Washington's Douglas B-23 research aircraft. Detailed descriptions of the aircraft and its cloud physics instrumentation have been given by Hobbs et al. (1971, 1972). Only the measurements most relevant to the present case study are mentioned here.

Airborne measurements of cloud liquid water content were obtained using a Johnson-Williams meter with an effective lower threshold of 0.1 g m^{-3}. Two instruments were used to measure ice particle concentrations: a continuous Formvar particle sampler and an automatic optical ice crystal counter (Turner and Radke, 1973). The minimum-sized particles detected by the two instruments were about 0.30 and 100 μm, respectively. Other aircraft measurements included pressure, temperature, dew point, turbulence, and accurate aircraft position determination.

Rawinsondes were launched every two to three hours from North Bend, Washington, which is located near the western foothills of the Cascade Mountains. At this location the dynamical structure of the frontal system shown in Fig. 1 should not have been significantly affected by the presence of the Cascade Mountains. Under the assumptions that the system was approximately two dimensional and in a steady-state in a coordinate system moving with the front, the vertical velocity $\omega(\equiv dp/dt$ where p is pressure and t is time) was computed from mass continuity and from the conservation of wet-bulb potential temperature.

A vertically-pointing, pulsed Doppler radar was operated at Hyak, Washington, on the crest of the Cascade Range. Its characteristics are described by Weiss and Hobbs (1974).

Precipitation gauges with time scales ranging from 15 sec to 2 min were operated at ten locations. These data were supplemented by hourly precipitation amounts from eighty-two reporting gauge stations throughout Washington (NOAA, 1973).

---

*In this study, "mesoscale" refers to features having a horizontal dimension from tens to hundreds of kilometers.

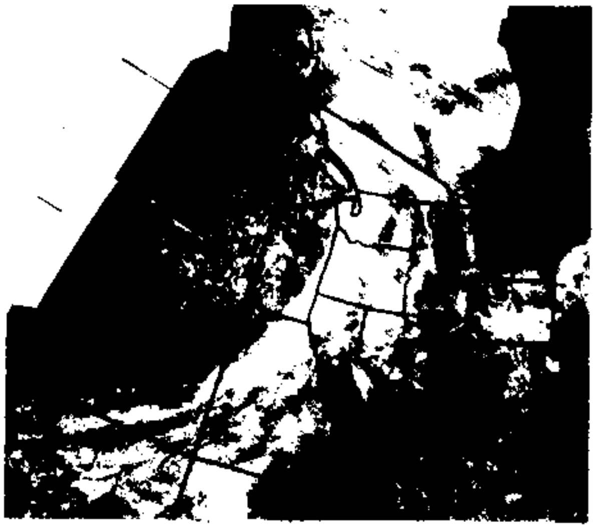

Figure 1. Satellite photograph showing occluded frontal system over North Pacific and western coast of North America at 1000 PST, March 16, 1973.

3. FRONTAL STRUCTURE

The occluded frontal system shown in Fig. 1 moved into western Washington from the Pacific at approximately 0600 PST on March 16, 1973, and progressed across the state during the remainder of the day at a speed of approximately 20 kt.

The frontal structure is represented in Fig. 2 by the vertical cross section of wet-bulb potential temperature (θ_w). The primary occluded front was located at the leading edge of the approaching cold air mass which was bounded by a strong gradient of θ_w and had a characteristic dome shape. The front was accompanied by a relatively strong horizontal temperature gradient at all levels and by a sharp surface pressure trough.

The pre-frontal air masses were less sharply defined than the cold air mass. The warm-frontal surface aloft and ahead of the occlusion was marked only by a zone where the θ_w isotherms were weakly packed.

Besides the basic frontal patterns, the following mesoscale features are seen in Fig. 2:

(a) A wavy pattern in the weakly-packed θ_w isotherms ahead of the major front.

(b) Mesoscale warm tongues behind the main front (dotted lines in Fig. 2).

(c) A pronounced tongue of low θ_w air just ahead of the main front (bounded by dot-dash line in Fig. 2).

(d) A strong, closed maximum of θ_w near the surface position of the primary front.

Similar mesoscale features in occluded fronts have been noted by Kreitzberg (1964), Elliott and Hovind (1965), Kreitzberg and Brown (1970), and Browning et al. (1973).

Feature (d) listed above appears to be accounted for by a low-level southerly flow of warm, moist air (which would be a flow into the page in Fig. 2). Southerly surface winds of 10-15 kt were consistently found in the high-θ_w tongue. This low-level, high-θ_w flow appears to have been considerably narrower than the "conveyor belt" described by Browning (1971) and Harrold (1973) or the low-level, high-θ_w flows described by Elliott and Hovind (1965) and Browning and Pardoe (1973). Diurnal heating may have slightly enhanced the low level maximum of θ_w seen in Fig. 2 (it was observed at the rawinsonde station at 1030 hr local time), however the high-θ_w tongue cannot be fully accounted for in this way since the maximum was observed in both temperature and dew point, and it was tracked inland from the Washington coast where it was observed before sunrise.

4. CLOUD DYNAMICS

The pre-frontal zone of the front depicted in Figs. 1 and 2 is generally quite dry and the precipitating clouds are first encountered in a narrow mesoscale band aligned along the primary front itself.

Fig. 3 is a composite diagram showing the frontal position, regions of potential instability, streamlines relative to the front deduced from the observed horizontal winds and conservation of θ_w, the cloud and precipitation patterns observed visually from the aircraft, and the low-level precipitation zone detected by raingauge measurements at the rawinsonde site. The clouds were positioned horizontally over the rawinsonde station according to the aircraft's position relative to the analyzed frontal position. A vertical adjustment was made to account for differences in terrain height between the rawinsonde station and the aircraft location. Apart from these adjustments, the sketches are presented exactly as they were made in-flight.

It appears from Fig. 3 that the frontal cloud band was operating as an organized mesoscale convective system similar to those described by Newton (1963) and Zipser (1969). These systems have horizontal scales of 50-100 km and have the common property that their dynamical structures are organized in such a way that they are perpetuated in a quasi-steady manner for several hours. The potential instability of the frontal cloud shown in Fig. 3 was continually replenished by the low-level, high-θ_w flow and continually released by frontal lifting.

The occurrence of a mesoscale downdraft in the precipitating region of the cloud shown in Fig. 3 is characteristic of organized convective systems (e.g. Browning, 1965; Zipser, 1969). The vertical velocities in Fig. 3, however, were calculated from the conservation of θ_w. Those obtained from mass continuity in two dimensions indicated that the boundary between lifting and sinking below 800 mb may have been located about one hour later than shown in Fig. 3.

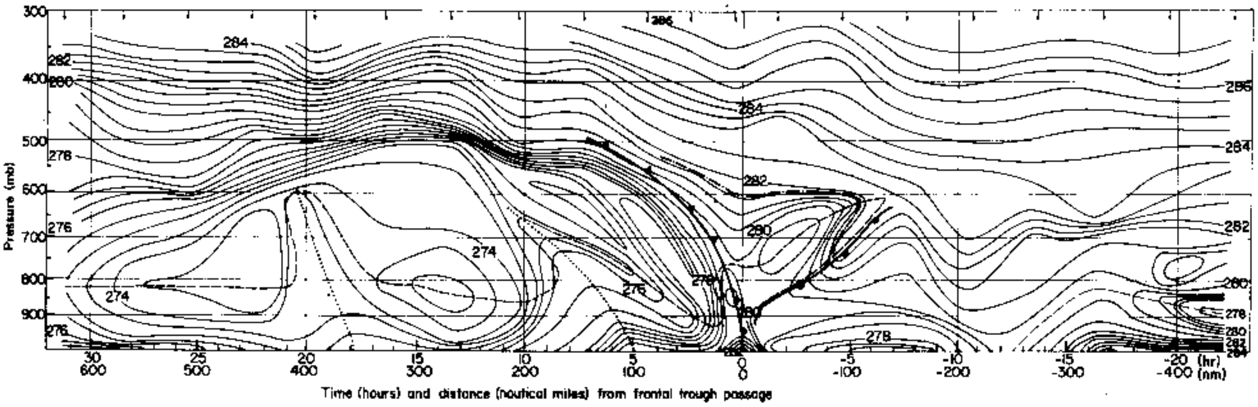

Figure 2. Vertical cross section of wet-bulb potential temperature. Isotherms are drawn for every 0.5°K. Region enclosed by dashed line is potentially unstable. Arrows indicate sounding times.

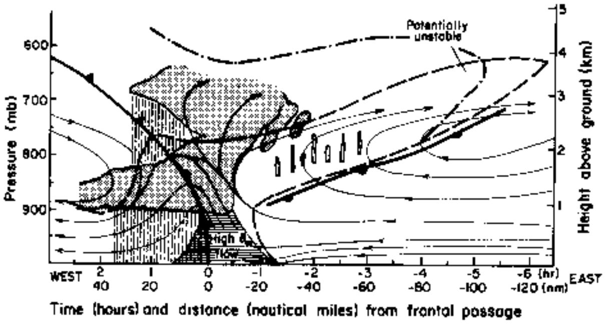

Figure 3. Composite west-east cross section through front. Airflow relative to front (←——), region of potential instability (— — —), cloud configuration (▨), precipitation (|||||||), and high-θ_w flow from south (═══).

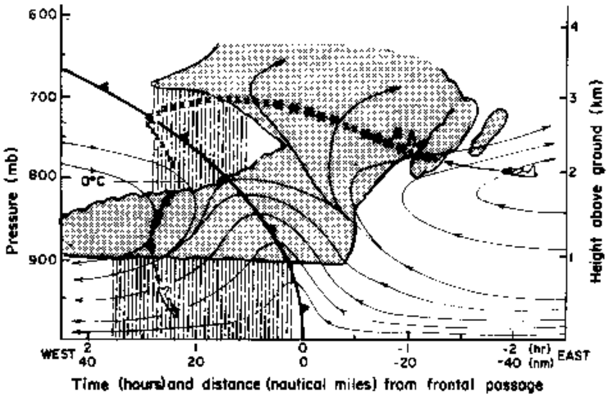

Figure 4. Cloud microphysical measurements in relation to frontal structure over Puget Sound Basin and windward slope of Cascade Range. Cloud liquid water content: • 0.1 to 0.2 gm^{-3}, ● >0.2 g m^{-3}; ice particle concentrations by conservative count: × <15ℓ$^{-1}$, ✱ 15 to 30ℓ$^{-1}$, ⊗ >30ℓ$^{-1}$. Other symbols are the same as in Fig. 3.

5. CLOUD MICROPHYSICS

In Fig. 4, the cloud dynamics serve as a framework for examining the cloud microstructure. It is seen that at the aircraft's flight level the main body of the frontal cloud was composed primarily of ice particles, except near the base of the high-level convective clouds at the forward edge of the main cloud mass and in the lower precipitating deck of the frontal cloud behind the front.

The concentrations of ice particles along the upper flight path in Fig. 4 were quite high. At point B, the ice particle concentration was 10 times greater than the ice nucleus concentration expected at the cloud top temperature. It should be noted that the concentrations of ice shown in this figure are extremely conservative since they are obtained by counting only regularly shaped ice particles which were replicated intact and fragmented ice "blotches" (each counted as one ice particle) but ignoring isolated fragments. Ice particle to ice nucleus ratios as high as 10^6 are obtained using a more realistic counting technique described by Hobbs et al. (1972) and the flight-level cloud temperature. It is noted that even in the regions of maximum ice particle concentrations, rimed particles and frozen drops were observed.

Anomalously high ice particle concentrations such as those observed in the frontal cloud band in this study have been observed frequently in both convective and stratiform clouds (for a review see Hobbs, 1973), however, no physical process has yet been described which adequately accounts for them. It has been noted, however, that anomalously high ice particle concentrations do not appear to be found in clouds which have existed for less than about ten minutes. This time scale is consistent with the frontal cloud portrayed in Fig. 4. This cloud system, because of its apparent quasi-steady nature could have existed for several hours before it was penetrated by the aircraft. According to the computed vertical velocities and streamlines, individual rising cloud parcels would have been in-cloud for an hour or more before passing through most of the points along the flight path of the aircraft. Thus, it appears that there would have been ample time for high ice concentrations to develop in parcels rising to the aircraft flight level.

6. OROGRAPHIC EFFECTS

To investigate the modification of the frontal cloud system as it passed over the Cascade Mountain Range, which runs north-south through central Washington, hourly precipitation amounts from the eighty-two NOAA gauge stations throughout the state were plotted as a function of their position relative to the moving front and to the crest of the Cascade Range. The coordinate system used is shown in Fig. 5. Various horizontal strips of the plot are associated with particular orographic regions, while various vertical strips may be identified with regions of the frontal system. The analysis of the precipitation data in this coordinate system is shown in Fig. 6.

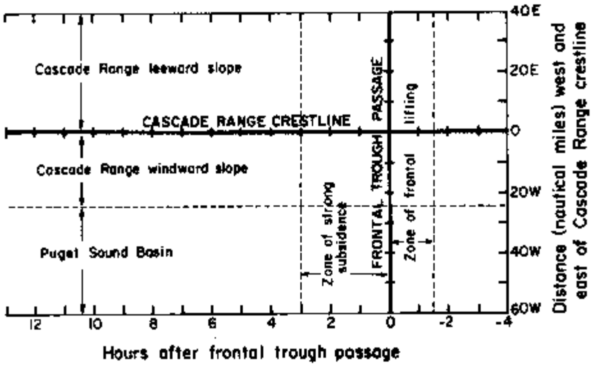

Figure 5. Coordinate system used to separate orographic and frontal effects.

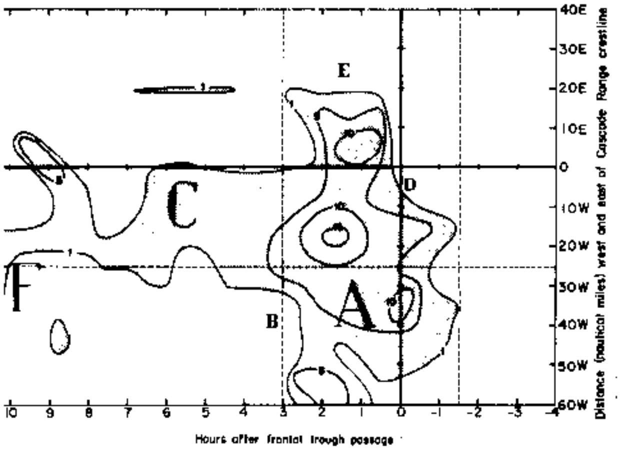

Figure 6. Average hourly precipitation rates (in units of 10^{-2} inches hr^{-1}) with respect to time from frontal trough passage and distance from the Cascade Range crestline.

It is seen from Fig. 6 that the heaviest rainfall is consistently found within 1-2 hr behind the surface frontal trough (letter B). This behavior is consistent with that depicted in the vertical cross section shown in Fig. 3. The frontal rainband is seen to have ended abruptly 3 hrs after the trough passage while the system was in the Puget Sound Basin (letter B, Fig. 6) however on the windward slope of the Cascade Range (letter C), post-frontal orographic precipitation continued for over 10 hrs.

It is evident from Fig. 6 that the largest precipitation rates over the Cascade Range were found within the frontal zone (which extends from -1.5 to +3.0 hr after the frontal trough passage). The precipitation amounts in the frontal zone indicate that the frontal rainfall was enhanced slightly as the system moved over the Cascade Range. The amounts over the mountains exceeded those in the Puget Sound Basin by about a factor of two. This amount of enhancement indicates that both frontal dynamics and orography played important roles in the precipitation process with neither one overwhelming the other.

A particularly interesting orographic effect is that the frontal precipitation began later relative to the frontal trough, on the windward slope of the Cascade Range than in the Puget Sound Basin (letter D in Fig. 6). Winds in the cloud layer had westerly components and orographic enhancement of the frontal lifting might have been expected to lead to an earlier onset of precipitation on the windward slopes.

The delay in the onset of precipitation in the mountains is attributed to orographic interference with the low-level flow which served as the source of moisture and instability for the frontal clouds. It is well known that precipitation is generally less on the leeward sides of mountain ranges due to the loss of condensate on the windward slope, however, the data of this study indicate that the precipitation in frontal clouds may be inhibited <u>before</u> the system passes over a mountain range.

The precipitation pattern in Fig. 6 agrees well with the cloud configurations and microphysical properties observed from the aircraft. The delay in the leading edge of the frontal cloud band relative to the front as the system moved across the Cascade Range is seen in the aircraft data by comparing Figs. 5, 7 and 8. As the frontal clouds moved over the leeward slope of the range (Figs. 7 and 8), the rear edge of the frontal cloud band became indistinguishable from orographic clouds forming on the windward slope.

The airborne measurements of cloud liquid water content and ice particle concentration are summarized in Fig. 9 which shows the patterns of these quantities encountered at flight levels ranging from 2-4-3.0 km above sea level. The coordinate system in Fig. 9 is the same as in Figs. 5 and 6 and the flight legs numbered 2, 3 and 4 are the same as those shown in vertical cross section in Figs. 4, 7 and 8 respectively. The general cloud pattern shown by Fig. 9 is very

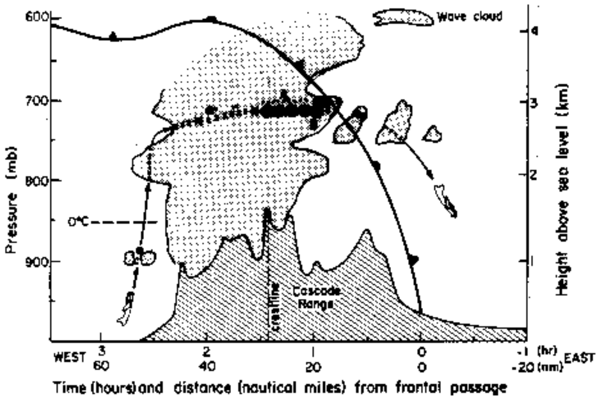

Figure 7. Frontal clouds passing over crest of Cascade Range. Symbols same as in Fig. 4.

consistent with the surface precipitation pattern in Fig. 6. The leading edge of the frontal cloud is again seen to have been increasingly delayed relative to the front as the system crossed the Cascade Range (letter C in Fig. 9).

The trend in the microphysical quantities measured from the aircraft was very similar in all of the flights through the frontal cloud band as it passed over the Cascade Range. In Fig. 9 it is seen that moderate liquid water contents and low ice concentrations consistently appeared in a relatively narrow zone at the leading edge of the frontal band. However, the main body of the cloud consisted almost entirely of ice in high particle concentrations. The largest ice particle concentrations were found immediately behind the zone of maximum liquid water content. This pattern continued as the front crossed the mountains, even though the leading edge of the frontal band receded behind the front.

The cloud liquid water content measured near the leading edge of the clouds occurred on each flight leg in cumuliform clouds (Figs. 4, 7 and 8). From their appearance and from the presence of liquid water, those clouds were evidently quite young. The aircraft encountered more turbulence in those regions than in the rest of the frontal cloud.

The largest cloud liquid water contents and ice particle concentrations recorded in the frontal band (region A of Fig. 9) occurred when the band was over the Cascade Mountains. This fact apparently reflects the coincidence of frontal and orographic lifting. It is noted, however, that the largest ice particle concentration recorded at flight level (position E in Fig. 9) exceeded the largest value recorded in the frontal band over the Puget Sound Basin by only about a factor of five. It is therefore concluded that high ice particle concentrations (as discussed in sec. 5) were characteristic of the frontal cloud band before its dynamical structure was influenced by the Cascade Range.

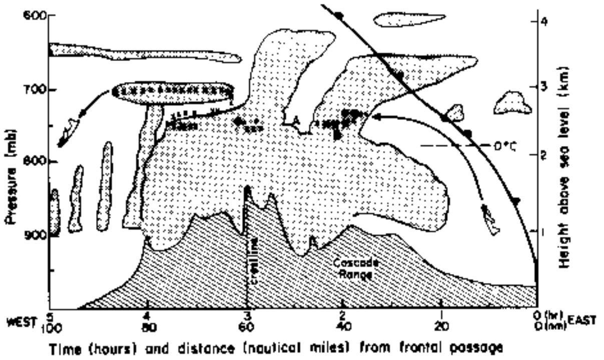

Figure 8. Frontal clouds passing over leeward slope of Cascade Range. Symbols same as in Fig. 4.

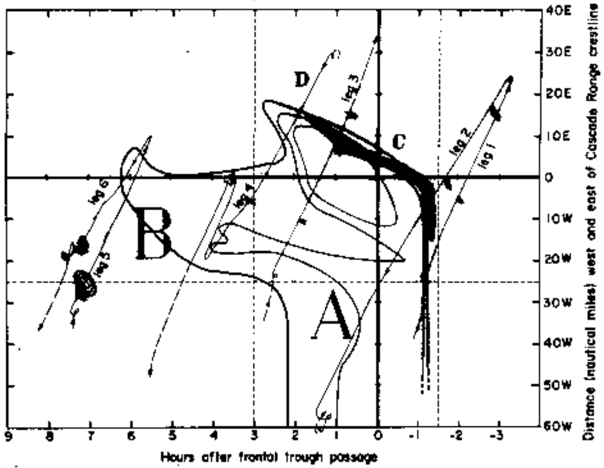

Figure 9. Airborne cloud microphysical measurements in relation to frontal trough passage and the Cascade Range crestline. Cloud liquid water content (▨ 0.1 to 0.2 g m^{-3}*, ■ >0.2 g* m^{-3}*) and ice particle concentrations as determined by conservative count (<15*ℓ^{-1}*, 15 to 30*ℓ^{-1}*, >30*ℓ^{-1}*; heaviest contour marks edge of measured ice field). Path of aircraft from 2.4 to 3.0 km elevation is indicated by (——→) and at lower elevations by (←– – →).*

7. CONCLUSIONS

This case study is the first in a series now being undertaken at the University of Washington to increase our understanding of the dynamics and microphysics of frontal clouds. It has provided a detailed examination of a mesoscale frontal cloud band associated with a West-coast occlusion. The dynamics of the cloud band appear to be similar to those of a quasi-steady, organized convective system. The inferred dynamical structure has provided a basic framework for interpretation of airborne cloud microphysical measurements which showed that the mesoscale precipitation band was characterized by high concentrations of ice particles. Analysis of hourly precipitation data, composited in relation to topography and frontal structure, and aircraft cloud observations have indicated that both frontal and orographic lifting played significant roles in the precipitation processes of the frontal system as it passed over the Cascade Range. These data indicate that the topography of the mountain range interfered with the frontal cloud dynamics by effectively cutting off the low-level moisture source of the cloud band before it reached the leeward slope of the range.

ACKNOWLEDGMENTS

This research was supported by Grants GI-31759 and GA-40806, from the Weather Modification Program, RANN, and the Meteorology Program of the Atmospheric Sciences Section of NSF, respectively.

REFERENCES

Austin, P. M., and R. A. Houze, Jr., 1972: Analysis of the structure of precipitation patterns in New England. J. Appl. Meteor., 11, 926-935.

Bergeron, T., 1935: On the physics of cloud and precipitation. Proc. 5th Assembly U.G.G.I. Lisbon, 2, 156.

Bjerknes, J., 1919: On the structure of moving cyclones. Geofys. Publ., Vol. 1, No. 2, 8 pp.

Browning, K., 1965: A family outbreak of severe local storms -- A comprehensive study of the storms in Oklahoma on 26 May 1963, Part I. Special Report No. 32, AFCRL-65-695(1), 346 pp.

__________, 1971: Radar measurements of air motion near fronts, Part 2: Some categories of frontal air motion. Weather, 26, 320-340.

__________, M. E. Hardman, T. W. Harrold, and C. W. Pardoe, 1973: The structure of rainbands within a mid-latitude depression. Quart. J. Roy. Meteor. Soc., 99, 215-231.

__________, and T. W. Harrold, 1969: Air motion and precipitation growth in a wave depression. Quart. J. Roy. Meteor. Soc., 95, 288-309.

__________, and C. W. Pardoe, 1973: Structure of low-level jet streams ahead of mid-latitude cold fronts. Quart. J. Roy. Meteor. Soc., 99, 619-638.

Elliott, R. D., and E. L. Hovind, 1964: On convection bands within Pacific coast storms and their relation to storm structure. J. Appl. Meteor., 3, 143-154.

__________, and __________, 1965: Heat, water, and vorticity balance in frontal zones. J. Appl. Meteor., 4, 196-211.

Harrold, T. W., 1973: Mechanisms influencing the distribution of precipitation within baroclinic disturbances. Quart. J. Roy. Meteor. Soc., 99, 232-251.

Hobbs, P. V., 1973: Anomalously high ice particle concentrations in clouds. Invited review paper, Eighth International Conf. on Nucleation, Leningrad, September, 1973 (in press).

__________, L. F. Radke, A. B. Fraser, J. D. Locatelli, C. E. Robertson, D. G. Atkinson, R. J. Farber, R. R. Weiss, and R. C. Easter, 1971: Studies of winter cyclonic storms over the Cascade Mountains (1970-71). Contributions from the Cloud Physics Group, Research Report VI, University of Washington (Seattle), 306 pp.

__________, __________, J. D. Locatelli, D. G. Atkinson, C. E. Robertson, R. R. Weiss, F. M. Turner, and R. R. Brown, 1972: Field observations and theoretical studies of clouds and precipitation over the Cascade Mountains and their modification by artificial seeding (1971-72). Contributions from the Cloud Physics Group, Research Report VII, University of Washington (Seattle), 293 pp.

Houze, R. A., Jr., 1973: A climatological study of vertical transports by cumulus-scale convection. J. Atmos. Sci., 30, 1112-1123.

Kreitzberg, C. W., 1964: The Structure of Occlusions as Determined from Serial Ascents and Vertically-directed Radar. Research Report, AFCRL-64-26, Meteorology Laboratory Project 8641, Air Force Cambridge Research Laboratories, L.G. Hanscom Field, Mass., 121 pp.

__________, and H. A. Brown, 1970: Mesoscale weather systems within an occlusion. J. Appl. Meteor., 9, 417-432.

Newton, C. W., 1963: Dynamics of severe convective storms. Meteor. Monogr., 5, No. 27, 33-58.

NOAA (U.S. Dept. of Commerce, NOAA, Environmental Data Service), 1973: Hourly Precipitation Data--Washington, 23, no. 3.

Tracton, M. S., 1973: The role of cumulus convection in the development of extratropical cyclones, Mon. Wea. Rev., 101, 573-593.

Turner, F. M., and L. F. Radke, 1973: The design and evaluation of an airborne optical ice particle counter. J. Appl. Meteor., 12, 1309-1318.

Weiss, R. R., and P. V. Hobbs, 1974: The use of a vertically pointing pulsed Doppler radar in cloud physics and weather modification studies. (Submitted for publication).

Zipser, E. J., 1969: The role of organized unsaturated convective downdrafts in the structure and rapid decay of an equatorial disturbance. J. Appl. Meteor., 8, 799-814.