4. Where motion of a dense portion has occurred, its center of gravity has always moved towards the ground.

5. The contours of lowest M value (100 mg m^{-3}) have stayed at a reasonably constant height over the period of a sequence, while below them, a contour of higher M value may have fallen through a considerable distance.

6. The detailed vertical pattern of a shower changes rapidly with time, and may change out of all recognition in as little as five minutes.

D. Future plans. A considerable set of film records was obtained during the summer of 1947. Work is proceeding on their analysis according to the general method described here. More specific attention is being given to mass movement within the showers and to correlation of the 'kinematics' with the physical mechanisms involved.

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EXPERIMENTAL VERIFICATION OF ENTRAINMENT OF AIR INTO CUMULUS

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During the summer and fall of 1947, a group of four meteorologists from the University of Chicago, including the writers, engaged in a study of typhoons and other weather phenomena of the tropical Pacific Ocean. The study was carried out under the sponsorship of the Office of Naval Research. Project headquarters were located at Fleet Weather Central, Guam.

It was decided during the planning of the project to install a number of special aircraft weather instruments in weather reconnaissance aircraft for the purpose of making detailed aerological ascents and cross sections in selected weather situations. It should be possible to obtain detailed information about the mechanisms of low-latitude disturbances in this way; in particular, the ascents might uncover some interesting facts concerning the process of convection.

Since the measurement problems involved were of a micrometeorological character, the conventional weather-reconnaissance instrument, the wet- and dry-bulb psychrometer, was much too slow in response to serve adequately. Accordingly, fine-wire thermocouples were chosen to effect the measurement of temperature. One thermocouple was designed to be mounted on a strut below the nose of the aircraft so as to be completely exposed to the free flow of air and water. The other was mounted in a specially constructed housing, pictured in cross section in fig. 1 and shown mounted under the nose of the aircraft in fig. 2. The housing was constructed to allow free circulation of air about the thermojunction while deflecting the water droplets. In this manner the temperature of the air might be determined without errors due to contact of the thermocouple with large drops falling from a colder region higher in the cloud.

Because of the uselessness of the wet-bulb thermometer under rapidly varying humidity conditions, moisture measurements were made by means of an electronic dewpoint hygrometer developed in the Instrument Laboratory of the Department of Meteorology of the University of Chicago.[1] A portable lightweight model capable of being powered from the aircraft electrical system was designed and constructed especially for the project.

The voltages developed by the hygrometer thermocouple and those mounted outside the aircraft were measured and recorded on a Brown strip-chart Potentiometer Recorder. The couples were connected sequentially to the recorder terminals by means of a solenoid-actuated rotary stepping switch impulsed by a cam-driven microswitch in series with the solenoid and the direct-current aircraft supply. The cam was mounted directly on the shaft of one of the gears in the paper-drive mechanism of the Brown Recorder and was arranged to close the microswitch for one-half second every five seconds. Thus the output of each thermocouple was recorded for five seconds. For convenience in studying the record, one couple was switched in twice in succession during each sequence.

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[1] University of Chicago, Department of Meteorology, "On the development of instruments for accurate pressure, temperature, and humidity measurements in the upper atmosphere." Final progress report for the period April 1, 1946, to June 30, 1947 (mimeographed).

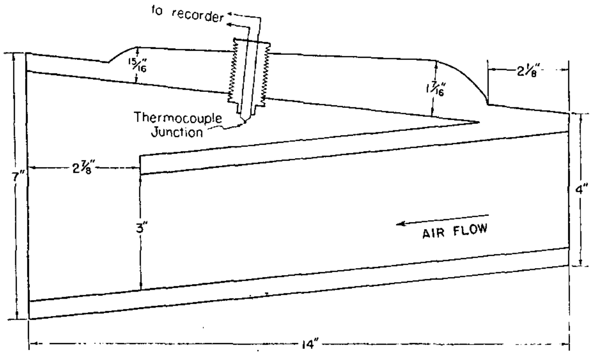

FIG. 1. Cross section of thermocouple housing.

Each variable was therefore recorded during at least one five-second period out of each 20 seconds.

These instruments were installed in a PB4Y-2M four-engined reconnaissance aircraft provided by Meteorological Squadron One (VPM-1) of the United States Pacific Fleet, based at the Naval Air Station, Agana, Guam. Initial flights were carried out for the purpose of calibrating the thermocouples for dynamic (air-speed) corrections. A correction table was calculated from the results of these flights and applied to all subsequent data.

For various reasons, it was impossible to carry out as extensive a series of special flights as was originally intended. In addition, both the aircraft and the Brown Recorder were frequently inactive due to breakdowns or normal maintenance checks. As a result, only six flights were actually carried out during September and October 1947. Five of these consisted of a series of traverses through selected cumulonimbus clouds over the open sea, three of which were completely successful and are discussed in this paper.

Once a suitable cloud was selected, flight procedure consisted in traversing the cloud several times first at or near the 15,000-ft (pressure-altitude) level, which was the highest level at which the aircraft could operate for longer periods. The plane then descended at some distance from the cloud to about 12,500 ft for the next set of traverses, and this process was continued until the base of the cloud was reached. In one case, traverses were also made at 1000 ft (with cloud base at 1800 ft) and at approximately 25 ft above the sea surface. Each traverse was made at as constant a value of pressure-altitude and air speed as the turbulence inside the cloud would permit.

The time needed to complete the traverses consumed from 90 minutes to two hours. Since clouds rarely persist in steady state for such a long time, the measurements necessarily covered all stages of cloud development.

Evaluation of the data obtained from the flights led to the interesting but somewhat negative conclusion that it was not possible to measure the temperature inside the cloud to any greater accuracy than about ±2C. The exposed thermocouple indication always dropped from one to four degrees below the temperature outside the cloud during a traverse. Furthermore, the magnitude of this drop correlated very well with the observed density of liquid water striking the airplane. Such falls in temperature could be ascribed exclusively to colder raindrops falling from aloft, and to downdrafts [2], except that the falls also took place during traverses in the very tops of the clouds. This discovery caused considerable concern, although it has since been explained satisfactorily by Dr. Irving Langmuir, in a General Electric Company intramural report, in the following manner: The air, being compressible, is warmed dry-adiabatically due to the partial stagnation at the measuring element; it is this warming that is corrected for by the use of the dynamic air-speed correction. The water drops, however, are nearly incompressible and therefore do not undergo the adiabatic warming. If we apply this explanation to the present situation, we may conclude that when the aircraft moves through a mixture of air and liquid water, the measuring element is exposed to contact with the warmed air and the unwarmed water in very rapid succession. Thus the average temperature, given by the measuring element, will apparently be lowered if the full dynamic heating correction is applied in such circumstances. In order to apply the proper correction, it would be necessary to employ a dynamic heating factor which is a function of the instantaneous density of liquid water in the vicinity of the measuring element.

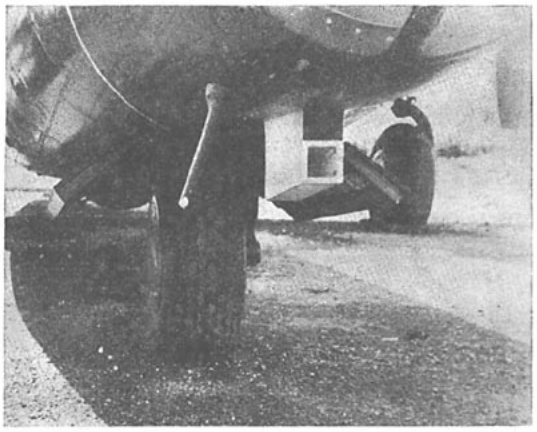

FIG. 2. Installation of thermocouples on aircraft.

The indications of the housed couple were likewise not without ambiguity. It became apparent that the housing acquired a coating of water during a prolonged traverse and thus tended to operate as a wet-bulb for a short time after leaving the cloud. Because the air velocity in the neighborhood of the measuring element was reduced to a low value by the housing, the possi-

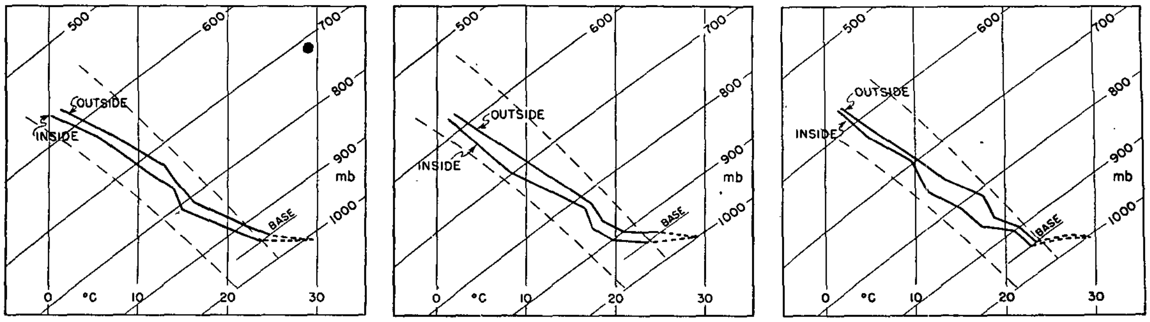

FIG. 3. Tephigrams: morning ascent (left), afternoon ascent (center), night ascent (right).

bility of evaporation cooling of adiabatically warmed air around the couple could not be ignored. A certain amount of confusion thus existed as to the magnitude of the dynamic correction factor to be applied to the housed couple when in saturated air containing liquid water. If evaporation into the warmed air took place rapidly enough, it would be necessary to apply a moist-adiabatic rather than a dry-adiabatic correction. It seems probable that some evaporation did occur, but it was not possible to ascertain whether this evaporation took place to such an extent as to completely saturate the air around the couple before it was replaced with a fresh supply of warmed compressed air. Thus the magnitude of the proper airspeed correction to the measuring element in the housing was somewhat indeterminate.

This indeterminacy is regrettable insofar as the interpretation of the data with regard to the convection mechanism is concerned. The temperature given by the housed couple (with dry-adiabatic correction), if accepted, would require the conclusion that the clouds were always colder (at all levels up to 15,000 ft) than their surroundings. This in turn would indicate that the clouds were actually denser than their sursurroundings, since the water-vapor difference between the outside and inside of a cloud is small. Therefore the widespread tropical convection could not be free convection, accompanied by a release of energy, but would be forced convection, driven by the kinetic energy of the circulation. If, on the other hand, a moist-adiabatic correction were applied to the data, the clouds would always possess a higher virtual temperature and so be less dense than their surroundings, thus affirming the principle of free convection. Because of this uncertainty in the magnitude of the dynamic correction, no conclusions as to the absolute density inside the cloud are justified. In view of this restriction, and because the isolines of temperature and potential temperature on thermodynamic diagrams are calculated in terms of actual temperature, we will use actual temperature rather than virtual temperature as a basis for the following discussion.

In spite of the uncertainty in the absolute temperatures inside the clouds, it is possible to gain one piece of information concerning the convection process from the data. Fig. 3 presents the temperature data from the three most successful flights, plotted on tephigrams. The temperature inside the cloud as shown in these figures, is the arithmetic mean of all the indications given by the housed couple while actually inside the cloud. In view of the difficulties of measurement and correction of the temperatures inside the clouds, we feel that the arithmetic mean of the temperatures obtained in traverses at a given level is a better basis for discussion than any single temperature measurement which we might select as 'representative.' For the same reasons we will draw no conclusions regarding horizontal temperature gradients within the clouds.

The outside temperature is the mean of the indications of the exposed couple obtained while flying at constant pressure altitude and air speed outside the cloud. The exposed couple was used to obtain the outside temperature because it was observed to dry off within a few seconds after emergence from the cloud, whereas the housed couple behaved as a wet-bulb for periods up to a minute after a severe wetting.

Inspection of the tephigrams shows remarkable uniformity of all ascents, in spite of varying radiational conditions. Clearly, the lapse rate within the clouds is in all three cases more unstable than the moist adiabatic, and absolute instability must therefore prevail within the clouds. It is evident that if the moist-adiabatic airspeed correction were applied to the data inside the clouds the effect would be to steepen the lapse rates, since the difference between the wet- and dry-adiabatic corrections is greater at higher temperatures. Likewise, the use of virtual rather than actual temperatures would tend to steepen the lapse rates, since the virtual temperature correction is also greater at higher temperatures. It can be seen that the soundings as plotted show the *maximum* possible stability of the lapse rates inside the clouds, and that a more refined knowledge of the proper airspeed correction factors would tend only to decrease this stability.

Standard treatments of convection assume that a cumulus cloud is composed entirely of air that has risen adiabatically from the vicinity of the surface. Such adiabatic ascent precludes the possibility of mixing between ascending current and surroundings, and it demands a moist-adiabatic lapse rate within the cloud. The present observations which show that the lapse rate in cumulus is greater than moist adiabatic demonstrate that this hypothesis is not tenable, as also indicated by soundings taken by Wyman and Woodcock.[2]

As pointed out elsewhere [4; 3] radiosonde and pilot-balloon observations show that in a large-scale sense the organized convection zones of low latitudes, excepting tropical storms, are denser than their surroundings. This would not be possible if convection followed the process conventionally described. It is necessary to introduce large-scale mixing, in order to explain the pressure configurations and flow patterns observed aloft [5]. Stommel [7] and Austin [1] showed that horizontal mixing—entrainment of outside air into cumuli—explains lapse rates inside cumuli as observed by Wyman and Woodcock. FIG. 3 fully substantiates their deductions to the extent that the present data can be utilized. Thus, as regards both individual cumuli and large-scale convection zones, mixing processes can no longer be ignored in theories of convection.

Because of the importance of the mixing process, it is very difficult to build up an air column formed entirely of surface air. Therefore the energy necessary for such ascent cannot be sought in microscopic density differences between converging airmasses. Nevertheless, observations inside tropical storms do show [6] that in the final state these disturbances are composed of air funnelled upward from the surface layers. Employment of more complex dynamic considerations thus is necessary for attempts to explain inception and growth of tropical storms.

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