Development and Characteristics of Free Convection in the Clear Air as Seen by Radar and Aircraft

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(Manuscript received 6 June 1973, in revised form 14 August 1973)

ABSTRACT

Observations of the development of a convective field in clear air were made simultaneously using radar and an instrumented aircraft. The growth of the field as seen by the radar was compared with the characteristics of the temperature and humidity measurements made by aircraft at various times and locations within the convective depth. Probability distributions of the temperature and mixing ratio fluctuations exhibit distinct, identifiable characteristics for different regions within the field. The altitude of the aircraft measurement, referenced to the maximum altitude of the convective field at the time of the measurement, was found to be a usable parameter in the comparison of aircraft data and in the characterization of convective field growth. Using the relative height parameter, it was found that the area covered by convective cells (modified air) varies linearly with height in the upper reaches of the convective field. The characteristics of individual cells as seen by the radar and as deduced from the aircraft measurements are also discussed.

1. Introduction

The convective process is fundamental to the transfer of heat, water vapor and momentum in the lower troposphere and, as such, has been the subject of much theoretical and experimental effort. Aircraft measurements of temperature, humidity and vertical velocity in convective activity have been reported by a number of authors (e.g., James, 1953; Vulfson, 1961; Warner and Telford, 1963, 1967; Grant, 1965; Myrup, 1967; Donelan, 1970; Lenschow, 1970; Katz, 1970). In most cases the aircraft probes were limited to the first few hundred meters in altitude or to a range of altitudes which did not include the top of the convective field. The more extensive probes extended to cloud base, ~ 1 km. Once condensation occurs, however, the physical process changes and the convective field development below cloud base may be modified in an undetermined way. Based on these aircraft data, models of the convective field were suggested by several authors (e.g., Grant, 1965; Warner and Telford, 1963, 1967; Telford, 1970).

The convective process is a dynamic process and the properties of the field and the individual cells change with both space and time. One of the basic difficulties in probing convective fields with aircraft alone is knowing where and at what stage in the development of the convective field the measurements were made. Radar observations of the convective field are of particular value in this regard. Recent experiments have shown that high-power, narrow-beam radars are capable of observing the convective process in optically clear air.

Hardy and Ottersten (1969) and Konrad (1970), for example, describe the characteristics of clear air convective fields and individual cells as seen by radar. These characteristics were then compared and interpreted in terms of the aircraft data and qualitative models from the above investigators by Konrad (1970).

This paper concerns an experiment where radar and aircraft were used simultaneously to investigate the characteristics and properties of convection in the clear air. The radar was used to locate and document the formation and development of the convective activity; based on this information, aircraft probes were then made at known, selected altitudes within the convective field to measure temperature and humidity.

2. Experiment description

The experiment was carried out on 12 June 1970, at Wallops Island, Va., using the high-power (3 MW), narrow-beam (0.4°) S-band radar at the Radar Atmospheric Research Facility (RARF). A detailed description of the radar is contained in NCAR (1969). The data reported here were taken as part of a multi-purpose, week-long experiment to study free convection arising from hydrostatic instability. Other aspects of the experiment with additional information on the radar and aircraft equipment described below are contained in Konrad and Robison (1972).

Radar observations of the convective activity began at 0700 (all times EST) in the form of Range Height and Plan Position Indicator (RHI and PPI) photographs. Sunrise was at 0438. Stepped elevation angle

PPI and stepped azimuth RHI scans were used to document the formation and development of the convective field in both space and time. The typical ring-shaped patterns on PPI and inverted U-shaped domes on RHI photographs as discussed by Konrad (1970) were observed throughout the morning. There were no haze layer or clouds throughout the period of observations. This was confirmed by pilot reports during the various runs and by the radiosonde data. Winds were westerly, 290° – 310° , and light, $<5 \text{ m sec}^{-1}$, at altitudes up to 1.2 km.

Temperature was measured aboard the aircraft by a resistance thermometer with a 0.00035-inch diameter tungsten wire, platinum flashed. The frequency response of this instrument is 100 Hz with an accuracy of $\pm 0.2^{\circ}\text{C}$. A Lyman-alpha humidity meter was used to measure water vapor density. This instrument has an electronic response of 2 kHz but the limiting factor is the cavity flushing time estimated to be roughly half the electronic response frequency. The data were telemetered to the ground and recorded on magnetic tape.

Table 1 shows the various aircraft probes made during the morning hours. All the runs were made within the area being observed by radar. At the time of the initial soundings (runs 1–3) the convective activity as seen by the radar extended only to an altitude of 450–500 m. Thus, the atmospheric conditions in the ambient, undisturbed air above this level were also recorded.

The development of the convective activity during the morning was documented using RHI and PPI photographs. Based on these data, the altitudes of the constant level runs (runs 4–10, except 8) were chosen to be within the convective field at selected locations. The aircraft flew a “stair-step” pattern during each run which included two or more constant-altitude sections. An air speed of 50 m sec^{-1} was maintained during each straight and level portion of a run.

In addition to the aircraft measurements of temperature and humidity, data from the 0615 routine radiosonde and a special release at 1028 were also available from the National Weather Service station at Wallops Island.

TABLE 1. Aircraft probes through the convective field.

Run	Type	Test (EST)	Altitude (m)	Z/Z_{max}
1	Sounding	0806–0813	75 to 750	—
2	Sounding	0829–0834	750 to 75	—
3	Sounding	0840–0846	150 to 750	—
4	Constant level	0906–0916	457, 366, 305	0.71, 0.57, 0.48
5	Constant level	0919–0928	152, 305, 366	0.23, 0.46, 0.55
6	Constant level	0942–0953	457, 518, 580	0.63, 0.71, 0.79
7	Constant level	1002–1009	640, 701	0.79, 0.87
8	Sounding	1021:50–1528:05	915–152	—
9	Constant level	1044–1051	762, 670, 610	0.68, 0.60, 0.54
10	Constant level	1053–1101	533, 457, 305	0.44, 0.38, 0.25

FIG. 1. Growth of the convective field as determined from RHI and PPI photographs.

3. Data reduction

The height of the convective field and the field growth rate were determined using the RHI and PPI photographs. In the case of RHI pictures, the depth of convection can be measured directly. On PPI photographs, the farthest cell return at each elevation angle was measured (corresponding to the highest cell at that range). This technique was used previously and is discussed in Konrad (1970).

The aircraft measurements of temperature, pressure and water vapor density were telemetered to the ground and recorded on magnetic tape. An analog computer was used to calculate the potential temperature θ and mixing ratio α , and optical oscillograph records were made for all runs listed in Table 1. The analog data, in turn, were digitized at a 1-kHz rate and the probability

FIG. 2. Virtual potential temperature from the 0615 radiosonde at Wallops Island prior to any convective activity.

FIG. 3. Probability distributions of potential temperature θ and mixing ratio α with the corresponding oscillograph record taken from run 4 at 457 m ($Z/Z_{\max}=0.71$). Average ambient conditions from 0615 radiosonde are indicated as $\bar{\theta}$ and $\bar{\alpha}$.

density and cumulative distribution functions of θ and α were calculated using a special purpose digital computer.

4. Characteristics of the convective field and cells

a. Field height and growth rate

The growth of the convective field as determined from the RHI and PPI photographs is shown in Fig. 1. The solid line is an envelope of the data and indicates the maximum height of convection. There are two distinct linear portions with a transition between the two slopes. During the early morning hours the convective field grew rather slowly (~ 135 m hr^{-1}), while later the growth rate increased to roughly 480 m hr^{-1} . Konrad (1970), reporting on observations of convective growth rates in clear air, gives values of 270–360 m hr^{-1} . Rowland (1973) found changes in field growth rates and noted their dependence on atmospheric stability.

In Fig. 2 the virtual potential temperature is shown for the early morning (0615 EST) radiosonde. This early sounding was made prior to any convective activity and shows the atmosphere to be highly stable above the surface for several hundred meters. The stability then decreases with altitude up to roughly 1 km where it becomes essentially neutral. Now from Fig. 1 we see that while the convection was growing in the region of high stability, below 600 m or so, the growth rate was low. As the convection continued to grow in altitude, however, it encountered less stable air and the growth rate increased. Finally, around 1000 m the convection entered the region of neutral stability and the growth rate reached the higher value of 480 m hr^{-1} .

b. Fluctuation characteristics of temperature and humidity

The probability density distributions of the potential temperature and mixing ratio as measured by the aircraft during both the soundings and constant level

FIG. 4. As in Fig. 3 except for Run 6 at 457 m ($Z/Z_{\max}=0.63$).

runs were calculated as described in the previous section. In the case of the soundings (runs 1, 2, 3 and 8) the aircraft data were grouped into 60 m (200 ft) altitude increments and the resulting distribution was assigned an altitude in the center of the interval. For the constant altitude runs, the density distributions were calculated using all the data for the entire 2–3 min run at each altitude. Examples of these distributions with portions of the corresponding oscillograph records are shown in Figs. 3–5. Note that the measurements shown in the three figures were made at the same altitude but at different times and the character of the temperature and humidity data along with their density distributions are quite different. This point will be developed later along with a discussion of the $Z/Z_{\max}$ parameter. A relative time scale is included along with a distance scale based on an average aircraft air speed of 50 m sec⁻¹.

We first examine the gross properties of the convective field by considering the extremes of the distribu-

tions as a function of altitude and time. This approach is similar to that followed by Grant (1965). Fig. 6 shows the end points of the potential temperature and mixing ratio density distributions, i.e., the extremes of the fluctuations, for all runs. The top of the convective field is marked by the region of large fluctuations in both temperature and mixing ratio (shown stippled in the figure). This is the region where the cool, moist cells are found and is also the region where the typical doughnut and inverted U-shaped radar returns are found (Konrad, 1970; Rowland, 1973). The figure illustrates how this region moves up in altitude with time, progressively invading the undisturbed, ambient air above.

In the lower reaches of the convective depth the fluctuations in temperature and moisture are relatively small, as shown in the soundings (runs 1, 2, 3 and 8) and the constant level runs 5 and 10. The temperature in this region is well above that which existed prior to the convective activity. The gradient in temperature is

FIG. 5. As in Fig. 3 except for Run 10 at 457 m ($Z/Z_{\max}=0.38$).

neutral to slightly stable in this region. As the morning progresses, the surface heating continues, increasing the average temperature in this region but maintaining a constant temperature gradient. Warner and Telford (1967) have discussed average properties of the field in this region and reported similar results.

The mixing ratio plots of Fig. 6 show the upward transfer of moisture by the convective activity. Note that the mixing ratio in the region where the gradient in potential temperature is essentially neutral does not change appreciably with time, but remains constant at 12–14 gm kg⁻¹. However, at altitudes above 600 m, for example, the mixing ratio increases with time from the ambient value around 7 gm kg⁻¹, prior to the arrival of the convective air, to values as high as 12 gm kg⁻¹. This latter value is associated with air originating at the surface which rises in the convective field while retaining its original moisture content. Again this simply indicates that the cells at the top of the field are cool and moist relative to the ambient environment.

Considering the dynamic nature of the convective

process, it is apparent that the analysis of the temperature and humidity aircraft measurements cannot be made on the basis of altitude alone. The conditions at any given altitude change with time as the depth of convection increases. The data in Figs. 3–5 taken at the same altitude but different times graphically illustrates this point. As noted above, the radar photographs of the convective activity allowed the aircraft to be vectored into specific areas and altitudes so that the location of the aircraft measurements within the convective field is known for all runs. The fluctuation characteristics of temperature and humidity for the various runs are compared below in terms of the relative location of the measurements within the field. The relative altitude, $Z/Z_{\max}$, is used where Z is the altitude of the aircraft run and $Z_{\max}$ the maximum height of the convective field at the same time as the aircraft run, taken from the envelope in Fig. 1. This parameter is also listed in Table 1.

The maximum fluctuation in potential temperature and mixing ratio using the end points of the probability

FIG. 6. Extremes in the fluctuations of temperature and mixing ratio taken from probability distributions.

density distributions for the constant altitude runs are shown in Figs. 7 and 8 as a function of the parameter $Z/Z_{\max}$. The trend in both parameters is toward higher fluctuations in the upper reaches of the field, i.e., higher $Z/Z_{\max}$. This trend, however, is only applicable to the top of the field where the ascending patches are cool and moist with negative buoyancy. Most of the previous aircraft probes were made low in the convective field, within or just above the superadiabatic layer, where the cells are warm and moist. The temperature fluctuations in this region, just above ground level, decrease with altitude until they become too small to identify as recognizable entities. Above this region, where the present measurements were made, the temperature pulses again become large and identifiable but are now negative, i.e., the cells are cooler than the environment.

Grant (1965) and Konrad (1970) discuss this reversal in the cell temperature characteristics with altitude.

Although the data in Figs. 7 and 8 exhibit a definite trend of increasing fluctuations with $Z/Z_{\max}$, there is considerable scatter. One possible explanation for this scatter may be the effect of atmospheric stability. In Fig. 9, we show graphically the initial temperature conditions at a time t_0 prior to any convective activity. The initial lapse rate varies with altitude, being more stable at the lower altitudes. This situation is similar to that shown in Fig. 2. At time t_1 the convection has grown to an altitude $Z_{\max 1}$ and by time t_2 , to an altitude $Z_{\max 2}$. Only the bounds or extremes of the temperature fluctuations are shown, similar to Fig. 6. As the convective elements overshoot the level of equal temperature and the level of zero buoyancy, they

FIG. 7. Maximum variation in temperature taken from the probability distributions with relative location in convective depth.

become cooler than the ambient unmodified air. This region is shown stippled in the figure. Now consider the measurements of the fluctuations in temperature made at altitudes Z_1 and Z_2 , which corresponded to the same value of $Z/Z_{\max}$ but at different times. The fluctuations ΔT when the top of the convection was still in the

FIG. 8. As in Fig. 7 except for mixing ratio.

region of high stability (time t_1) will be larger than those measured later when the field top is in a region of lower stability (time t_2). There is some evidence in the present data that the earlier runs at a given $Z/Z_{\max}$ have larger fluctuations in temperature than those taken later at a higher altitude, but the data are not conclusive on this point. In any event, stability must have an effect so that the parameter $Z/Z_{\max}$ represents only a partial non-dimensional description of the convective field.

We now consider the detailed characteristics of the probability density distribution. Again we find that the shape of the distribution is directly related to the position within the convective field where the data were taken. At the top of the field, the cells and unmodified ambient air are well defined and the distributions exhibit two disjoint peaks. An example in this region is shown in Fig. 3. The mean of one peak coincided with the mean of temperature and moisture of the ambient air taken from the early aircraft and radiosonde soundings while the other peak is that of the convective elements. The width or standard deviation of the individual peaks will be discussed separately below. This two-disjoint-peak characteristic of the density distributions occurs in the region where $Z/Z_{\max}$ is greater than about 0.7 and is referred to as the "well-defined" region.

In the lower reaches of the convective field where the $Z/Z_{\max}$ is less than 0.5, the density distributions have a single peak which is narrow and symmetrical. An example is shown in Fig. 5. This is the region discussed earlier where the temperature gradient is neutral to slightly stable and the air is well mixed.

Finally, there is a transition region between the well-defined region of high fluctuations and the well-mixed regions in the lower reaches of the field. An example of the distributions in this region is shown in Fig. 4. The distributions in both temperature and moisture are wide and usually exhibit two non-disjoint peaks.

FIG. 9. Schematic of convective development for various atmospheric stabilities.

Neither peak, however, coincides with that for the ambient unmodified air. This would indicate that the air has been somewhat modified by mixing with the convective air but has not reached the well mixed state.

Lenschow (1970) observed that the cumulative probability distribution of air temperature, averaged over a number of aircraft runs, could be represented by two separate normal distributions—one distribution being characteristic of the fluctuations in the ambient air and the other characteristic of modified or cellular air. The present data were examined in a similar manner. In the well-defined region, where the two peaks in the density distribution are disjoint, the normal representation was quite reasonable. In the transition region, however, where two peaks are distinguishable but are not disjoint, the fit was somewhat more difficult. Finally, in the well-mixed region, the probability is well represented by a single normal distribution. The standard deviations of these fitted normal distributions to temperature and mixing ratio are shown in Figs. 10 and 11, respectively. In the well-defined region, the values for the ambient unmodified air are identified separately. As noted above, in the lower regions the air has been modified to such an extent that ambient unmodified air no longer exists. The figure indicates that the temperature and humidity fluctuations of the cellular air at the top of the convective field are typically 3–4 times larger than those for the ambient unmodified air. This result is similar to that of Lenschow (1970). Donelan (1970) presents standard deviations of temperature and humidity as a function of altitude which are considerably smaller than those reported here. However, his data are for altitudes well below those of the present study. Further, the top of the convective field for his data is not known so the relative location of his measurements cannot be determined.

FIG. 10. Standard deviation of fitted distributions to potential temperature variations. Open circles identify ambient unmodified air.

FIG. 11. As in Fig. 10 except for mixing ratio.

c. Area occupied by convective elements

One of the parameters of interest to fluid dynamicists in the modeling of convective fields is the percent of area occupied by the convective cells. In the well-defined region where ambient and cellular air are identifiable, this percentage may be obtained directly from the cumulative distributions of temperature and humidity. That is, the cumulative probability at points β_a and β_θ which separate the two peaks in the density distributions in Fig. 3, is also the percent of the aircraft path occupied by cells (or conversely, by ambient air).

This approach is equivalent to that of Vulfson and others who examine the oscillograph traces and add up the time that the aircraft is in ambient air and in cellular air. The present method is somewhat simpler, less time consuming, and less subjective. Note that in either approach the assumption must be made that the percentages derived from a one-dimensional line measurement are representative of the two-dimensional area percentages.

FIG. 12. Area occupied by cells as a function of altitude. Solid points are based on temperature distributions and open on mixing ratio.

FIG. 13. Area occupied by cells in terms of relative location within convective depth. Solid and open symbols as in Fig. 12.

Fig. 12 shows the area occupied by cellular air for all runs in the well-defined region as determined using the cumulative probability curves for both temperature and humidity. The data for runs 6 and 7 are more complete in terms of altitude coverage and indicate a linear variation with altitude. Based on this, the data for runs 4 and 9 were also extended as straight lines. Note the close similarity in the percent of area determined using the cumulative distributions for either temperature and humidity (solid vs open symbols).

By extending the linear curves in Fig. 12 to zero percentage, i.e., no cellular air, the altitude of the top of the field can be estimated. Also included on the figure are the maximum heights of the field during those runs taken from Fig. 1. The estimated heights from the extrapolation are 80–90% of the measured heights from the RHI's and PPI's. This is not surprising since the heights taken from Fig. 1 represent the maximum cell height for all the photographs taken at a particular time (i.e., the envelope of all the radar data), while the extrapolated heights in Fig. 11 are for data taken along a single aircraft run.

The percent area covered by cellular air as a function of the relative location within the depth of the convective field, $Z/Z_{\max}$, is shown in Fig. 13. In this case, the extrapolated altitude of the top of the field from Fig. 11 at zero percentage was used as the $Z_{\max}$ and not the value of the envelope from Fig. 1. When nondimensionalized in this manner, the data display a remarkable consistency considering that the measurements were made at a variety of times and altitude. It should be remembered, however, that the above analysis applies only to the top-most region of the convective field where unmodified ambient air and cellular air are identifiable. It does not apply in the lower regions of the field where the analysis criteria are not applicable. This point is illustrated in Fig. 12 by the fact that the curve shows 100% of the area covered by cells at a normalized altitude around 0.6. That is, all the air in the lower 60% of the convective field depth has been completely modified and no original ambient air exists at these levels;

d. Characteristics of individual cells

As mentioned above, the unmodified and cellular air were easily identified based on the temperature and humidity measurements made during the initial soundings and on the early morning radiosonde data. Fig. 14 is an example of the data in the well-defined region taken from run 6. These data as well as those from other runs made in the well-defined region were examined to determine whether the individual cells at a given level had similar or distinctive characteristics. For example, is the air in the center of the "top hat" region quiet or disturbed? Do all the cells at a given level and time have similar properties, such as mean values and standard deviations in the fluctuations?

The data for each run in the well-defined region were subdivided into short segments of ambient and cellular air as illustrated in Fig. 14. The symbols $\bar{\theta}$ and $\bar{\alpha}$ indicate the average temperature and mixing ratio at 518 m altitude taken from the early aircraft and radiosonde soundings. The probability density distribution for each subsection was calculated as described earlier. As one might expect, the distributions for the ambient regions were similar in terms of both mean and variance, to those discussed earlier where all the data at a given altitude were used. In the case of the distributions for the individual cell segments, however, a large variation in both the mean and variance was found from one cell to another. This is not surprising when one examines the temperature and mixing ratio traces for the various convective parcels in Figs. 3 and 14.

The interior of the cells is quite disturbed. Only rarely do we find a "quiet" area within the cell such as at times 75–78 sec and around 150 sec in Fig. 14. The large cells appear to be made up of an aggregate of smaller parcels. These may be the result of entrainment or they may be small parcels which originated at the ground but retained their identity as they became organized into the larger entity. In Fig. 3 we find a group of small elements from 65–85 sec where the temperature and mixing ratio return to essentially the ambient level between the individual elements. Such a characteristic may indicate entrainment, i.e., ambient air at that level is being mixed in. In Fig. 14, however, the temperature and mixing ratio fluctuations within the large cells rarely return to ambient conditions.

It does not appear that the cells at a given level within the convective depth have common characteristics. A wide range of cells from newly arrived, small cells to older, larger cells with relatively well-mixed interiors are found. That is, cells in various stages of their individual development are observed.

The sizes of the modified air parcels also vary considerably at a given altitude. In Fig. 14, for example, the cell diameters range from roughly 400 to 1200 m. This size is consistent with the observations by Konrad

FIG. 14. Potential temperature and mixing ratio in the well-defined region at 518 m ($Z/Z_{\max}=0.71$), run 6. Cellular or modified air is indicated by c while ambient air is indicated by a. Symbols $\bar{\theta}$ and $\bar{\alpha}$ denote average ambient conditions from 0615 radiosonde.

(1970) where he examined the sizes of cells at a given altitude based on their radar patterns.

5. Conclusions

Distinct regions within the convective depth are identifiable based on the characteristics of the probability density distributions for temperature and mixing ratio. Just above the surface the distributions exhibit a single peak, while at the top of the field they have two distinct and disjoint peaks corresponding to modified cellular air and ambient air at that level. Separating these two regions is a transition zone where the distributions are wide with two non-disjoint peaks. The relative altitude $Z/Z_{\max}$ provides a basis for the comparison of cell characteristics at various altitudes within the field at different times. Fluctuations in temperature and

mixing ratio generally increase with increasing $Z/Z_{\max}$. At the top of the field, in the well-defined region, the cells are cool and moist relative to their surroundings. The area occupied by cellular or modified air decreases linearly with $Z/Z_{\max}$ in the well-defined region.

Acknowledgments. The authors wish to thank J. Howard and the personnel of the RARF radar facility for their cooperation during the experiment as well as F. Klein and J. Rowland who took the aircraft measurements. This research has been supported by the Air Force Cambridge Research Laboratories and by the National Aeronautics and Space Administration, Wallops Station.

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