Wind conditions in situations of patternform and non-patternform cumulus convection

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ABSTRACT

Comparisons were made between the wind and wind shear profiles pertaining to patternform (clouds in rows) and non-patternform cumulus convection. No unique or consistent differences were found. The directional correspondence of the cumulus rows and wind was also investigated. The rows were found to be most frequently oriented about 3° to the left of the surface wind and about 15° to the left of the wind at the cloud base level.

1. Introduction

This paper describes an investigation of the wind fields associated with two different types of cumulus cloud situations where, on the one hand, the cumuli occurred with distinct patternform organization, in the form of cloud rows, and where, on the other hand, the cumuli had no definite patternform. Other studies are also described which sought to establish the directional correspondence of the cloud rows with the surface and cloud base level winds.

Photoreconnaissance data obtained over the Florida peninsula during the months of August and September 1957 were employed in these investigations. These data consisted of trimetrigon aerial photographs which showed the Florida cumulus populations (over most of the total surface area of the peninsula) at approximate two-hour intervals during 19 separate days of observation. The wind data employed in conjunction with these photographic data were obtained from the conventional rawin and pibal reports of the Florida stations.

2. General comments about the Florida cumulus populations of common, widespread occurrence

The details of the initiation and development of the cumulus populations over the Florida peninsula, as observed during the 19 day period of this 1957 study, have been reported elsewhere (PLANK, 1960 and 1965). No attempt will be made herein to summarize these observations except as they relate to the two population types of the most frequent and widespread occurrence over the peninsula.

The first of these population types was the patternform type, wherein the cumuli occurred in distinct, regularly-spaced rows, with the cumulus elements along the rows being definitely separated from one another. Examples of these populations are shown in Fig. 1. Such populations have been observed and reported previously, e.g., by MALKUS & RONNIE (1959), KUETTNER (1959), SCHUETZ & FRITZ (1961) and CONNOVER (1964). Malkus and Ronnie referred to them as "cloud rows" while the other authors called them "cloud streets". Herein we will follow the former designation, believing it to be the more descriptive term when referring to cumulus lines of relatively tight spacing.

These row-type, patternform populations were observed very commonly over the Florida peninsula during the days of the 1957 study. They were observed at all daytime hours between 0830 EST, the customary time of the first formation of the cumuli, until 1700 EST, when the observations terminated. However, they were observed most frequently, and had the greatest area coverage over the peninsula, during the early morning hours and in the middle to late afternoon. They were relatively infrequent during the mid-day period. Thus, there was a general diurnal cycle in which the cumulus rows, initially present in large numbers at the beginning of the convection, gradually

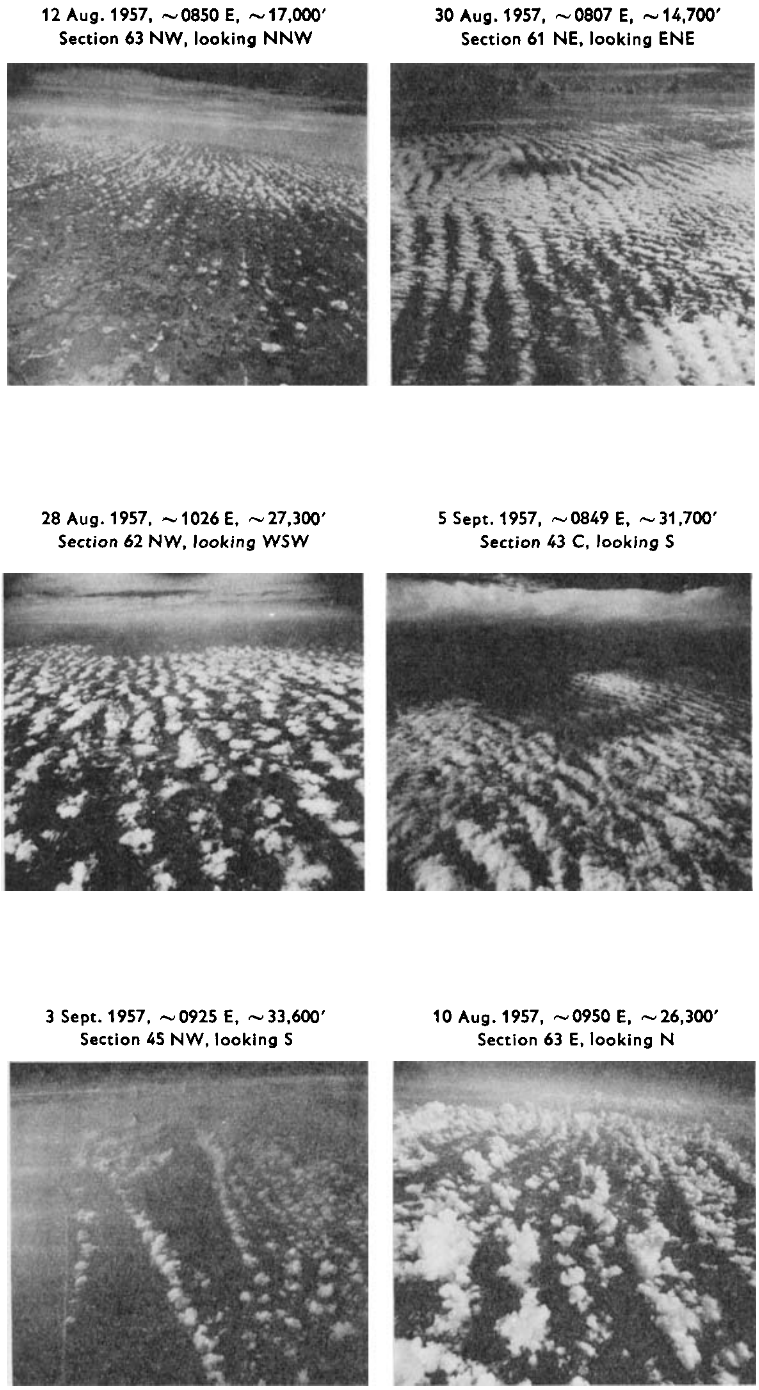


FIG. 1. Examples of Florida cumulus populations of the patternform (cloud row) type. The dates and times of the photography and the aircraft flight altitudes are indicated above the photographs. The sections that are referenced, which identify the sites of the photography, are shown in Fig. 2.

"disappeared", with the development of the convection during the mid-morning, and then "reappeared" again, in the afternoon, after the time of the maximum surface temperatures. Frequently these time changes in the patternform state of the populations occurred more or less simultaneously over vast areas of the peninsula which encompassed both the regions of the interior and the coasts. Another interesting observation was that the spacing of the cumulus rows, when these rows were present over any sustained period, increased markedly with time, from spacings of some 1000–1500 feet at the time of the first initiation of the clouds, to as much as 10,000–15,000 feet in the late afternoon.

The particular regions of the peninsula over which these row populations existed on the different study days (during the general period 0830–1100 EST) are indicated in Fig. 3. The dashed lines on the maps of this figure show the places of occurrence and the contours of the lines indicate the orientation of the rows. The dates and time periods of the observations are as indicated above the maps. The other drafted information contained in this figure will be explained presently.

The second of the two population types of frequent, widespread occurrence over the peninsula we will refer to merely as the "non-patternform" type. These populations contained cumuli which, although they had a regular visual appearance, didn't have any obvious patternform. Two examples of such populations are illustrated in Fig. 4. It is seen that the clouds comprising the populations were cumuli of the "fair weather" and/or "congestus" types. These populations are the ones most commonly observed throughout the world and conventionally reported.

With reference to Fig. 3, it may be stated that the regions where no dashed lines are shown on the maps were regions where cumulus populations of this non-patternform type prevailed generally during the indicated time periods. Thus, as can be seen, it was common and customary, during these morning observational periods, for the two different population types to coexist over the peninsula at any given time. They occurred adjacent to, or interspered within, one another.

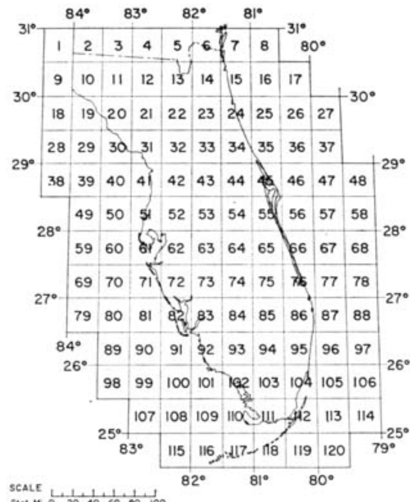


Fig. 2. Florida sectional map.

3. Investigation of the wind and wind shear profiles associated with the two population types

To investigate the wind fields associated with these two population types, the aerial photographs of the 1957 study were first inspected and the particular cumulus populations, which existed over or near the four upper-air stations of the peninsula (Jacksonville, Tampa, Cape Kennedy and Miami), were classified as being either of the patternform type or of the non-patternform type. These photographs were obtained during the first photoreconnaissance subsequent to the time of the initiation of the cumuli. In general, they pertained to the time period 0830–1100 EST. Patternform populations were found to exist over the different stations in 30 instances; non-patternform populations in 46 instances. Then, once this classification had been completed, the 0700 EST rawin observations and the 1300 EST pibal observations of the Florida stations, for the days of the photoreconnaissance, were assembled and plotted, in profile form. Additionally, the vector shear of the wind was computed and plotted.

When these wind and wind shear profiles for the two population types were intercompared, no unique or characteristic features of the wind field could be discovered that clearly differentiated the two. Much effort was devoted to such comparisons but it was found that both types

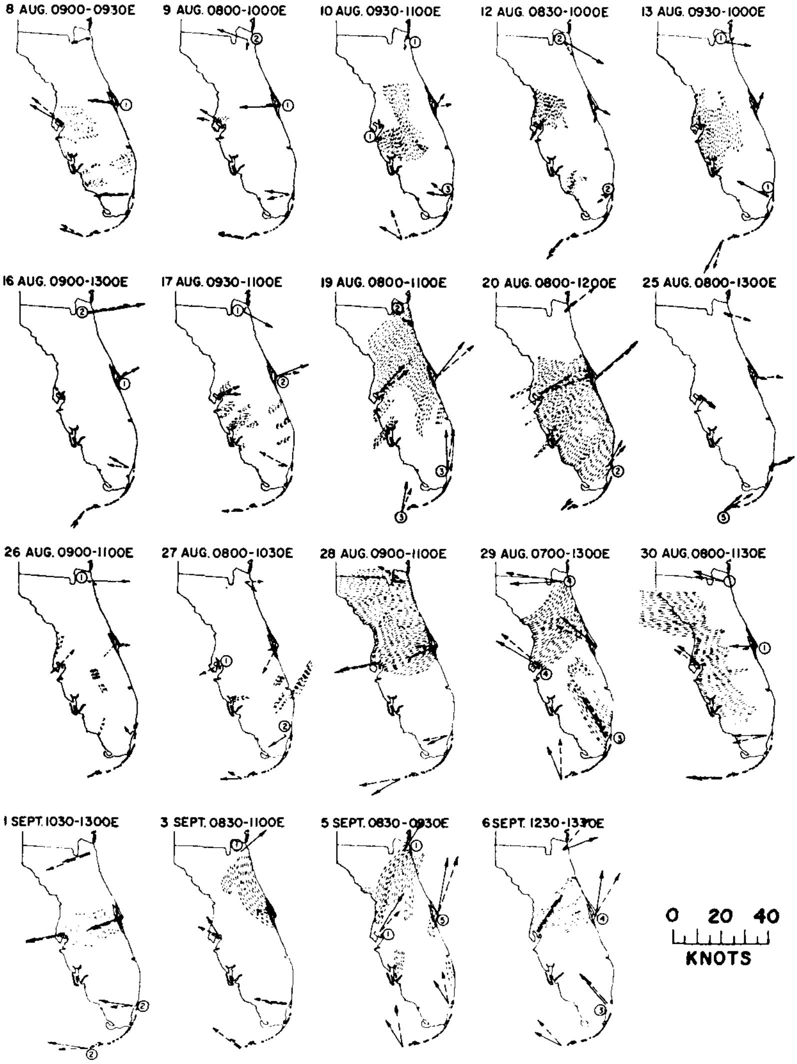


FIG. 3. Regions of cumulus row occurrence over the Florida peninsula as observed during 19 morning periods of photoreconnaissance in August and September 1957. The dates and particular time periods of the observations are indicated above the maps. The dashed lines show the regions of cumulus row occurrence and indicate the orientation of the rows. The winds at the 2000 foot level are shown by the solid vectors, those at the 5000 foot level by the dashed vectors. The other information contained in this figure is explained in the text.

of populations occurred on days and times of large and small wind speed, on days and times of large and small shear, and on days and times when the wind profile had appreciable curvature, and when it did not.

The photographs and associated wind profiles shown in Fig. 5 illustrate this point. The photographs at the left show three situations of patternform convection. The profiles of wind speed for the situations, obtained from the 0700 EST rawins for the stations nearest the convection (not more than 20 miles away in these particular cases) are the heavy solid curves. The profiles of the total shear, i.e., of the magnitude of the vector shear, are the fine solid curves. The profiles of the "speed shear", which ignores the directional component of the total shear, are the fine dashed curves. The dates and times of the photographs, and the aircraft flight altitudes, are noted immediately above the pictures. The aircraft positions at the time are specified by the sectional notations, which refer to the map shown in Fig. 2. Also indicated in these diagrams, immediately to the right of the drafted wind profiles, are the cloud base altitudes, the maximum cloud top altitudes (pointed out by the arrows) and the "average", or "typical", altitudes attained by the visually most-predominant cumuli of the populations (indicated by the vertical extent of the sketched clouds).

The wind situations in the two cases illustrated at the top of this figure are roughly comparable in that both are situations of relatively small wind speed and small shear. Yet, in the one case the cumuli are distinctively organized in rows, in the other the cumuli have no obvious patternform. The wind situations of the two cases illustrated in the middle are also roughly comparable; the wind speeds are moderate; the low-level shear is rather large. But again we have a case of cumulus rows and one of no rows. Likewise, the two situations at the bottom are comparable (both profiles evidencing appreciable curvature), one with rows, one without. It is seen that there is little in the profiles of this figure that offers any definite basis for differentiating the situations. It may be stated that, at least as concerns the wind and wind shear parameters, this was also true of the other 70 of the situations that were studied in this comparative manner.

3 Sept. 1957, 0935 E, 34,500′
Section 52 E, looking S

29 Aug. 1957, 1250 E, 15,100′
Section 73 C, looking WSW

FIG. 4. Examples of Florida cumulus populations of the non-patternform type. The dates, times and sites of the photography and the aircraft flight altitudes are indicated above the photographs. The sections referenced are shown in Fig. 2.

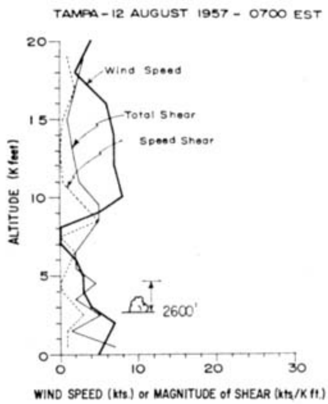
4. Profile curvature

KUETTNER (1959) studied various of the cloud street (cloud row) situations of the Boston area and elsewhere. He found that the wind profile in virtually all of these situations had appreciable negative curvature, of the order of -1×10^{-10} to -1×10^{-7} ($\text{cm}^{-1}\,\text{sec}^{-1}$). Moreover, the wind speeds in such situations were usually larger than normal. For Boston, he cited a 15 knot surface wind speed average for the street situations as opposed to a 9 knot average for the 60 year climatological mean.

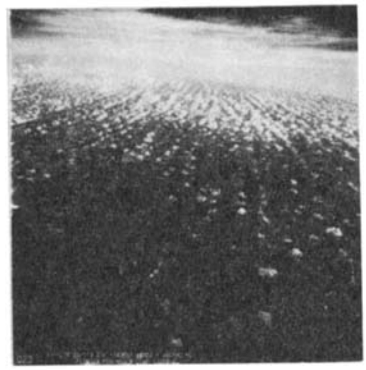
A wind profile has negative curvature when a maxima of wind speed occurs somewhere above the ground level.[1] Negative curvature may also occur in other ways, but this is the usual situation. According to Kuettner, this profile, and the associated cloud streets, result from the heating of a cold current of air which flows across a warm ground surface. Specifically, his statement was that "the profile owes its existence to a frictional wind increase with height in its lower portion, and to a thermal wind decrease with height in the upper portion, while the almost two-dimensional uniformity of the wind direction follows from the cold air advection of the low-level flow which gains heat during its progress".

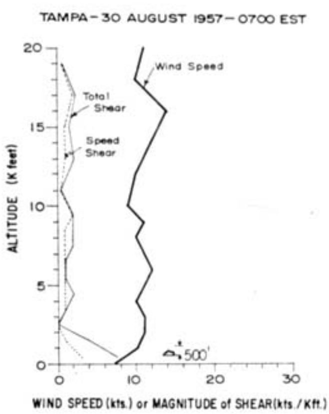
With this general process in mind, Kuettner also postulated, from an extension of the basic theory of LORD RAYLEIGH (1916), that cloud streets, which paralleled the wind, should theo-

[1] A tangential-normal coordinate system is assumed here with the direction of the wind speed maxima defining the tangential direction.

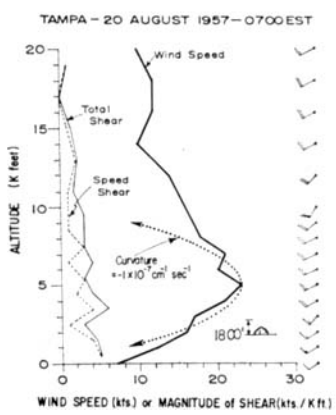


12 Aug. 1957, ~0850 EST, 17,000'
Section 63 NW, looking NNW





30 Aug. 1957, 0807 EST, 14,700'
Section 61 NE, looking ENE



20 Aug. 1957, 0937 EST, 36,900'
Section 53 SE, looking N

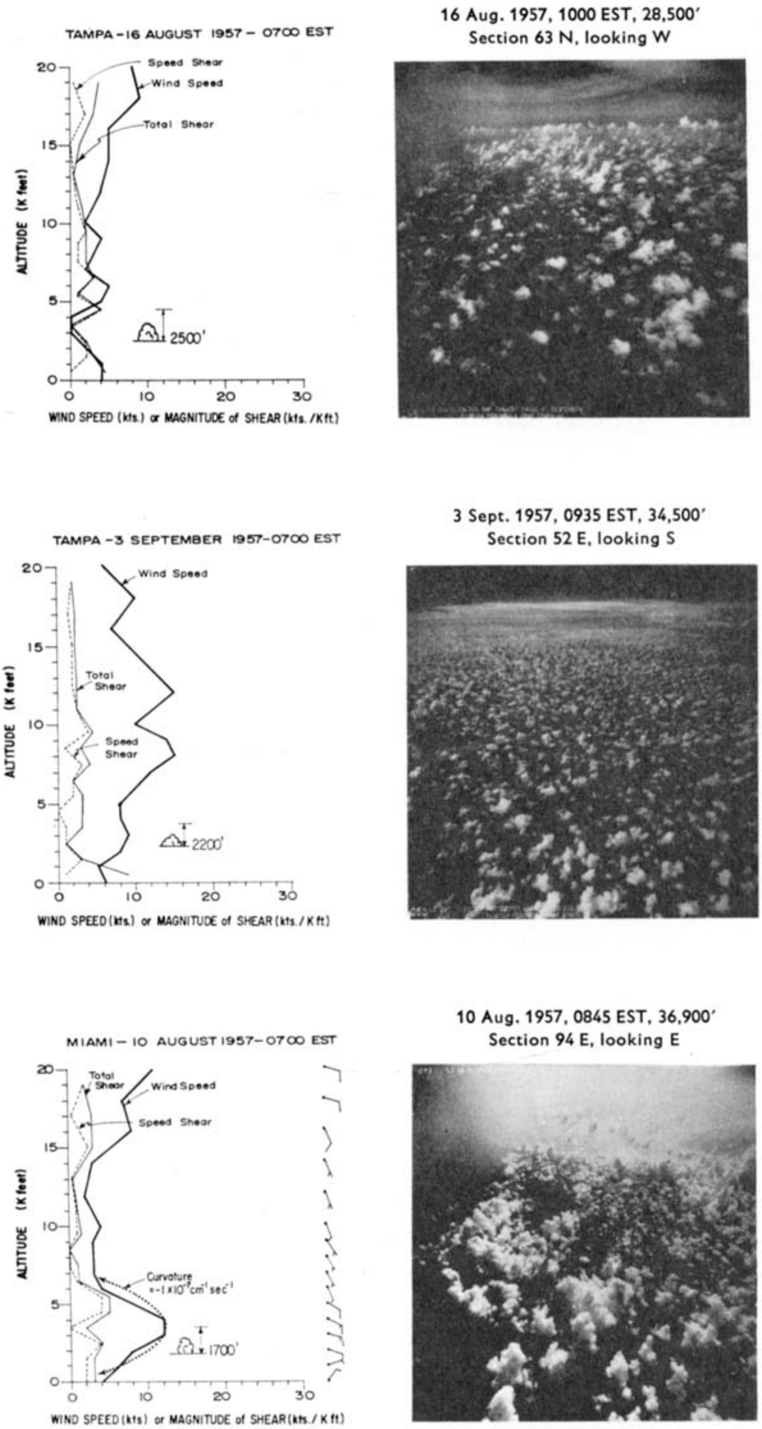


FIG. 5. Comparisons of the wind and wind shear profiles in situations of patternform and non-patternform cumulus convection. See text for discussion of these diagrams.

retically occur when the profile curvature exceeded the particular "critical value" -1×10^{-7} cm^{-1} sec^{-1} (approximately). This critical curvature is indicated, in Fig. 5, by the dotted lines shown superimposed over the wind speed profiles of the bottom diagrams.

To test these criteria of Kuettner in the present investigation, the curvature of the wind profile was determined for each of the upper-wind observations of the four Florida stations. This was done both for the 0700 EST rawin ascents and for the 1300 EST pibal ascents as well. Profiles having curvature in excess of the critical were identified and noted. There were many such instances, comprising approximately 30 per cent of the total profiles.

In reporting the results of these tests, we will first reference the two situations illustrated in the bottom diagrams of Fig. 5. It is seen, in the situation at the left, that the actual wind profile has "less curvature" than the critical and yet, contrary to hypothesis, cumulus rows are present. In the situation at the right, the curvature approximates the critical but the cumulus clouds are without pattern, again contrary to hypothesis. Moreover, it may be pointed out that the Kuettner criteria also fail to be verified in the other patternform situations of this figure.

These are merely several particular examples: however, they are indicative of the frequent failure of the criteria when it was applied to the Florida cumulus situations. Actually, when all of the data were considered, and when the instances of the occurrence or non-occurrence of a critically-curved wind profile (at 0700 EST) were compared with the instances of the occurrence or non-occurrence of patternform cumulus convection over or near the station sites, it was found that

(*a*) cumulus cloud rows occurred in conjunction with wind profiles having greater than critical curvature in 11 instances,
(*b*) cumulus cloud rows occurred in the absence of critically curved profiles in 19 instances,
(*c*) non-patternform cumulus populations occurred in conjunction with critically curved profiles in 31 instances,
(*d*) non-patternform cumulus populations occurred in the absence of critically curved profiles in 15 instances.

These cases of coincidence and non-coincidence are illustrated in a qualitative fashion in Fig. 3. As mentioned previously, the regions shown by the dashed lines on these maps indicate the places where patternform populations occurred; the other regions being occupied generally by non-patternform populations. Now it may be additionally noted that circles, with numbers inscribed, have been drafted next to certain of the stations. These circles indicate the existence of a critically-curved wind profile over the station at the 0700 EST observational time. The numbers tell the altitude (in thousands of feet) of the wind speed maxima. Also drafted on these maps, but not yet mentioned, are the station wind vectors for the 2000 foot level (the solid vectors) and for the 5000 foot level (the dashed vectors). The wind speed scale is at the lower right. In certain cases these vectors were not drafted, either because the winds at the stations were light and variable (less than 3 knots) or because their inclusion would have confused other of the drafted information.

These maps illustrate the instances wherein the critically-curved profiles coexisted, or failed to coexist, with the patternform cumulus populations. They also illustrate something of the directional correspondence between the cumulus rows and the upper winds. We will discuss this subject specifically in the subsequent section.

As noted earlier, the first photoreconnaissance over the station sites, on which the judgement of the patternform state of the cumulus populations was based, was made during the general period 0830–1100 EST. This was considerably later than the 0700 EST observational time of the wind data discussed above. Thus, since it was conceivable that a critically-curved wind profile might have developed later than 0700 EST and that this might have been responsible for certain of the cumulus row situations, the cloud and wind data were intercompared once again and the instances were recorded when cumulus cloud rows occurred in conjunction with critically-curved profiles *which existed either at the 0700 EST, or at the 1300 EST, observational times.* With this relaxation of the criteria of correspondence, it was established that

(*e*) cumulus rows coexisted with critically curved profiles (present either at 0700 EST or at 1300 EST) in 19 instances, (*f*) cumulus rows occurred in the absence of critically curved profiles (either at 0700 EST or at 1300 EST) in 11 instances.

There were no changes in the figures for the non-patternform populations (over those cited in (*c*) and (*d*) above).

The fact that the number of coincidental occurrences of cumulus rows with critically-curved profiles increased with the inclusion of the 1300 EST wind observations is suggestive that the curvature might have been influential in certain cases. However, if we reason thus, we are then at a loss to explain why, within the total data, the critically-curved profile was found to coexist so very frequently, in fact most frequently, with the cumulus populations of the non-patternform type. The question is left open here; but some general comments are made in the summary.

Two other findings relating to the Kuettner hypothesis should also be noted before leaving this section. First, as can be seen from Fig. 3, the patternform populations over the Florida peninsula tended to be generally most pronounced and extensive on the days of the largest wind speeds.[1] This is in accord with Kuettner's finding of a wind speed dependence in his cloud street situations. Second, the Florida wind profiles (those with curvature) usually evidenced very little directional shearing of the wind. This too corresponded to Kuettner's findings, and hypothesis, that the wind profile in cloud street situations is, and should be, essentially two-dimensional.

5. The directional correspondence of the cumulus rows with the surface and cloud base level winds

As an adjunct to the investigations just described, other studies were additionally conducted to establish the directional correspondence of the cumulus rows with the winds at the surface level and at the cloud base level. In these studies, 85 particular "photographic samples" of the patternform type populations were selected from among the total photoreconnaissance data. These samples were selected to be typical and representative of the various patternform populations observed on the different days and hours. Also, they were selected for regions of the peninsula which had uniform surface characteristics and which were well removed from the coastal areas of the peninsula and from the vicinity of any of the inland lakes. The cumulus cloud rows shown in these samples were especially well defined and their directional orientation was apparent and could be determined without question.

The dates, times and locations of these 85 samples will not be specifically noted here. Actually, there is little point, since the results to be reported are of a statistical nature.

Photogrammetric measurements were performed on each of these population samples to establish the orientation of the cumulus rows. Then, utilizing the surface wind reports of the nearest airways stations, for the observing hour closest to the times of the samples, the angular departures of the row orientations from the surface wind directions were determined. Likewise, the departures were determined for the winds at the cloud base level. These base level winds were interpolated winds, which were obtained from temporal and spatial interpolations of the basic rawin and pibal data to match the particular times and locations of the individual population samples. The base altitudes of the cumuli in each of the samples were known, with fair precision, from photogrammetric measurements performed on the aerial photographs. Hence, there were no problems of selecting the proper wind levels.

The results of these studies are illustrated in Figs. 6 and 7. The two histograms in Fig. 6 show the frequencies of occurrence of angular departures (positive and negative) of the row orientations from the surface wind directions. The total data have been split in halves, based on the wind speed. Thus, the histogram at the left pertains to situations with surface wind speeds less than 9 knots; that at the right pertains to situations with speeds greater than 9 knots. The winds were calm at one station during one of the observational hours; hence only 84 of the total 85 cases are included in these histograms.

It is seen that the departures were smaller, with the rows being more closely aligned with the surface wind direction, in the situations of the larger wind speeds. There were a few in-

[1] However, this wind speed dependence, although generally apparent, was not found in the comparisons of the individual station observations. This was noted previously but should be reiterated here.

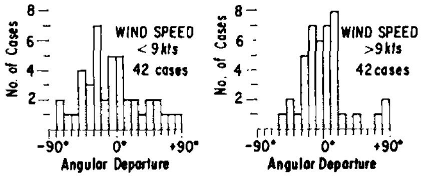


FIG. 6. Departures of the cumulus row orientations from the surface wind directions. The histogram at left shows the departures for wind speeds less than 9 knots; that at the right shows the departures for speeds greater than 9 knots.

stances when the rows were oriented normal to the winds, or at large oblique angles, but generally they were aligned within $-30°$ to $+20°$. On the average, within this modal region, the rows departed from the winds by about $-3°$. In contrast to this, the departures in the situations of the smaller wind speeds were much larger and there were numerous instances when the rows were oriented normal to the winds, or at angles exceeding $\pm 45°$. The distribution of the departures was continuous, and broader, at these smaller wind speeds and the modal region was less sharply defined. On the average, for the distribution as a whole, the mean departure was $-5.2°$.

The histograms in Fig. 7 illustrate the departure distributions for the winds at the cloud base level. As in the case of the surface winds, the data were divided in halves based on the wind speed; the histogram at the left is for speeds less than 10 knots; that at the right is for speeds greater than 10 knots. It is seen that the latter histogram is sharply peaked at $-15°$, indicating that the cumulus rows, in these large wind speed situations, were most frequently

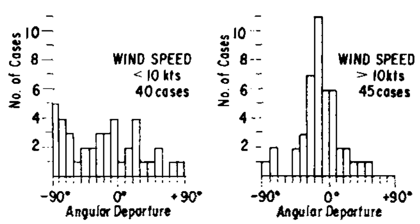


FIG. 7. Departures of the cumulus row orientations from the wind directions (interpolated) at the cloud base level. The histogram at right shows the departures for wind speeds less than 10 knots; that at the right shows the departures for speeds greater than 10 knots.

oriented about 15° to the left of the wind direction at the cloud base level. The distribution of the departures here is rather narrow, with very few of the rows evidencing departures exceeding $\pm 45°$. On the other hand, the histogram for the smaller wind speeds, at the left, reveals a general broad distribution of departures, with many minor peaks. Hence, the rows in these situations were commonly oriented at virtually all angles to the cloud base wind. However, the distribution does evidence a somewhat bi-modal character suggesting preferential departures at about $-5°$ (rows and wind in near alignment) and at about $-85°$ (rows lying nearly normal to the wind).

These findings, it is of interest to note, are relatively similar to the laboratory findings reported by PHILLIPS & WALKER (1932), GRAHAM (1933) and AVSEC (1937 and 1939). These investigators observed, in Bénardtype experiments wherein a fluid layer was translated across a heated lower surface, that banded cells, which were oriented normal to the flow, occurred when the fluid layer was translated at very small speeds. Then, at translational speeds somewhat greater, these banded cells tended to become oriented at various oblique angles to the flow. Finally, at a particular larger speed, and for all speeds exceeding this, the banded cells became aligned with the flow. The histograms of Figs. 6 and 7 show that the cumulus cloud rows of the Florida peninsula also evidenced certain of these same general characteristics.

It is of additional interest to note the correspondence between one of the findings herein and one reported by FALLER (1963, 1964 and 1965). Faller conducted experiments employing a large circular tank containing a fairly deep layer of water. The tank was rotated and the water was caused to circulate at a speed usually slow compared to the basic speed of the driving rotation. Faller, using a dye tracing agent, found that frictionally produced roll vortices, which he suggested were similar to the "large eddies" described by TOWNSEND (1956), occurred immediately above the lower surface, within the turbulent boundary layer, under certain unstable combinations of flow speed, Reynolds number and layer depth. For combinations of these parameters that might be anticipated in the atmosphere, Faller found that these parallel rolls (bands) were oriented between 10° and 17° to the left of the gradient flow. The average was

14.5°. Experiments essentially analogous to these of Faller were also carried out by Gregory, Stuart & Walker (1955). They found an average angular relationship of 14.0°. These results correspond very well with the finding herein that the Florida cumulus rows, with the larger wind speeds, were most often oriented about 15° left of the wind at the cloud base level (which, for Florida, usually lies close to the gradient level).

The reason for this preferred angular relationship between rows and wind undoubtedly lies in the fact that the circulations associated with the rows extend well downward into the planetary boundary layer where there is a systematic frictional flow toward low pressure.

6. Summary discussion

In the several investigations reported herein, conventional rawin, pibal and surface wind data were employed in comparisons with photoreconnaissance data showing cumulus populations over the Florida peninsula. The objectives of these comparisons were (1) to determine the kinematic differences between convective situations where the cumuli were organized in rows, and where they were not, and (2) to establish the directional correspondence between the cloud rows and the wind.

In the first of these investigations, no definite, consistent differences were discovered, in any of the wind parameters, that would differentiate the separate situations. There was some suggestion that the curvature of the wind profile might have been influential to the cloud patterning in certain cases. However, within the total data, the curvature criteria suggested by Kuettner (1959) actually failed to predict the correct patternform state of the populations more often than it was successful.

In the second of the investigations, the results were more positive. The cloud rows and wind were found to be most closely aligned at the larger wind speeds, the rows lying about 3° to the left of the surface wind and about 15° to the left of the wind at the cloud base level. At the smaller wind speeds, however, the rows and wind were found to be variably oriented, with the rows, in numerous instances, lying normal to the winds, or at departure angles exceeding ±45°. The similarity of these behavior characteristics to certain ones observed in the laboratory was noted.

With regard to the first of these investigations, it is utterly inconceivable that kinematic differences did not, in actual fact, exist between the patternform and non-patternform situations. Therefore, the indefinite results herein suggest either that the basic wind data employed were inadequate to resolve the differences or that the temporal and spatial discrepancies between the times and sites of the separate wind and photoreconnaissance observations were too large to permit meaningful comparisons of these data. Thus, it would appear that the investigative failures could be attributed specifically to one or more of the following possibilities:

(*a*) that the rawin and pibal measurements lacked the accuracy and resolution required to detect the differences,

(*b*) that the time scale of the important kinematic events associated with the cumulus convection was too short to permit valid comparisons between separate sets of data obtained several hours apart,

(*c*) that the wind measurements were nonrepresentative of the particular cumulus situations because the sites of the separate observations were removed by a few miles, or tens of miles, from one another.

(*d*) that no measurements of the thermal structure of the lower atmosphere were made at the local sites. (The 0700 E raobs of the Florida stations were inspected but these showed no obvious correlations.)

Because of these rather obvious deficiencies in the 1957 data, a more specific and refined program of wind observations in Florida cumulus situations was carried out in August 1963, near Melbourne. In this program, slow-ascending pilot balloons, tracked by double theodolites, were released successively into fields of developing cumuli (at approximate 20 minute intervals) while at the same time these fields were being photographed from aloft by a U-2 aircraft. About 100 such releases were made, on 10 separate days.

These double-theodolite data are presently being reduced by computer and are being related to the cloud fields shown in the aerial photographs. The balloon trajectories, and the winds along the trajectories, are being established relative to the individual cumuli of the fields, and to the pattern features. This study will be reported later but it may be mentioned that the preliminary results show that the wind profiles in the sub-cloud layer were extremely variable with time, from early morning to noon, across the 20 minute balloon release intervals. The profiles also varied considerably depending on whether the balloons rose into or near a cloud, or through the clear-air regions between clouds. These results were not unexpected; but the magnitude of the variations (the winds varied as much as $\pm 50°$ in direction and ± 3 m/sec in speed on certain of the days was suprisingly large.

Cumulus rows existed on two of the days, the clouds on the other days being generally of the non-patternform type. Again, as in the 1957 study, there were no obvious, consistent differences between the wind profiles of the separate situations. Any such differences as might have existed between the fields of mean wind flow were effectively masked by the large convective perturbations that were superimposed on the fields, and by the substantial temporal modifications of the fields with the progressing convection.

Whether any differences will be discovered later in this study, when the winds and clouds are compared on a case by case basis, remains to be seen. However, it is apparent, even at the moment, that any investigation of the kinematics of patternform convection, if it is to yield definitive results, will require accurate, high-resolution wind data which are obtained synoptically with detailed observations of the clouds. Moreover, the analyses of these data must be accomplished with considerable care and precision.

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