On the Scales of Motion and Internal Stress Characteristics of the Hurricane

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ABSTRACT

In cumulus convective atmospheres where important energy and momentum interactions are occurring on the cumulus cloud scale (width 1 to 3 nautical miles) dynamical processes may be significantly different than middle latitude baroclinically driven circulations. This is the case especially in the intense cumulusconvective atmosphere of the hurricane. The purpose of this study is to present recent observational information of the cloud-scale and meso-scale wind fluctuations in the hurricane and to discuss their possible significance with regard to understanding the dynamics of the cumulus convective atmosphere.

Detailed investigation is made of the wind observations collected during the 1958 season by the National Hurricane Research Project (NHRP) B-50 aircraft from 28 radial penetrations in hurricanes at levels between 830 and 560 mb. Horizontal wind velocities are measured with the aid of an AN/APN-82 radio navigation instrument utilizing Doppler frequency shift. These measurements, together with the author’s (Gray, 1965) previous calculation of vertical air velocity along these same radial legs, give the complete three-dimensional cylindrical wind representation to a space resolution of approximately one-half nautical mile. From the characteristic width of the component fluctuations, space smoothing along the radial legs is performed. With certain approximations this allows determination of the three component space-smoothed (mean) and eddy winds. Computations of the turbulent Reynolds stress from these cloud-scale wind fluctuations are made. Observational evidence of the correlation of cloud-scale horizontal and vertical wind components is presented. Other aspects of the hurricane circulation are discussed.

1. Introduction

Background. A topic of increasing interest to meteorologists is the quantitative treatment of the cumulus-induced tropical storm. A number of numerical models have been proposed, but there are still major questions concerning the interpretation of the physical processes involved (Yanai, 1964). Dynamical processes occurring in cumulus-convective atmospheres may differ significantly from middle-latitude baroclinic circulations. The purpose of this study is to present observational information on the cloud-scale and meso-scale wind fluctuations in the hurricane and to interpret and discuss their significance.

Beginning in 1955, the U. S. Weather Bureau’s newly formed National Hurricane Research Project (NHRP) began instrumentation of two Air Force B-50 and one B-47 aircraft with the purpose of investigating the meteorological parameters of the hurricane and other weather systems on the meso- and micrometeorological scales. The then recent development of the Doppler radio-navigation system had greatly enhanced the opportunity for meso-scale cloud and sub-cloud observations of wind. Many investigations into the dynamics on the cloud- and meso-scales of motion could now be pursued. This paper will present and interpret the wind characteristics on the cloud- and meso-scales of motion in the lower and middle tropospheric levels of the hurricane from the above measurements.

From the determination of the horizontal wind variations, along with the other standard aircraft measurements such as radar and pressure altitude, power setting, etc., it is possible to make determinations of the mean vertical motion to a horizontal space resolution of 0.5 to 0.7 nautical miles (Gray, 1965). These calculations have previously been made along the same radial flight legs here studied. All three wind components are thus available.

Data used. This study will make use of the National Hurricane Research Project (NHRP) radial-leg flight observations collected on six flights into three hurricanes on four different days during the 1958 season. These storms and flight levels for which computations were performed are listed in Table 1.

Fig. 1 shows a typical horizontal radial-leg flight track. To obtain a complete picture of all of the data which were simultaneously available, the data were plotted with respect to time (usually one observation every two seconds) on graph rolls. Fifty to sixty nautical miles (n ml) of such data were plotted along 28 of the radial flight legs of the six flight levels of Table 1. Fig. 2 is a typical sample of a section of the plotted data.

Probably never before have so many meteorological observations been so systematically taken on a selected

1 The author’s other paper (Gray, 1965) describes in detail the data used and results of vertical motion calculations.

2 See Monthly Weather Review for individual storm summaries.
Table 1. Flight levels of computation for 1958 storms.

<table>
<thead>
<tr>
<th>Storm</th>
<th>Date</th>
<th>Location</th>
<th>Minimum pressure (mb)</th>
<th>Maximum wind (knots)</th>
<th>Flight level (mb)</th>
<th>No. of radial legs on which computations were performed</th>
<th>Approximate no mi of computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleo</td>
<td>18 Aug.</td>
<td>27N 72W</td>
<td>970</td>
<td>90</td>
<td>810</td>
<td>5</td>
<td>250</td>
</tr>
<tr>
<td>Cleo</td>
<td>18 Aug.</td>
<td>27N 72W</td>
<td>970</td>
<td>85</td>
<td>560</td>
<td>6</td>
<td>345</td>
</tr>
<tr>
<td>Daisy</td>
<td>25 Aug.</td>
<td>30N 71W</td>
<td>990</td>
<td>65</td>
<td>830</td>
<td>5</td>
<td>300</td>
</tr>
<tr>
<td>Daisy</td>
<td>25 Aug.</td>
<td>30N 71W</td>
<td>990</td>
<td>65</td>
<td>560</td>
<td>4</td>
<td>163</td>
</tr>
<tr>
<td>Daisy</td>
<td>27 Aug.</td>
<td>34N 56W</td>
<td>940</td>
<td>120</td>
<td>620</td>
<td>5</td>
<td>217</td>
</tr>
<tr>
<td>Helene</td>
<td>26 Aug.</td>
<td>31N 77W</td>
<td>950</td>
<td>110</td>
<td>570</td>
<td>3</td>
<td>138</td>
</tr>
</tbody>
</table>

2. Characteristics of plotted wind data

Wind speeds as measured by the AN/APN-82 system verified previous knowledge of the broad-scale vortex nature of the hurricane's winds. Wind fluctuations of the order of 10 to 20 knots (kt) over distances of approximately 1 to 10 n mi were often found superimposed on this broader scale motion, however. Winds on this scale had previously never been measured. Figs. 3 and 4 illustrate typical component fluctuations. Gentry (1963) and Colón (1961) have also noted these fluctuations in their studies of NHRP flight data. These wind fluctuations were observed in both the tangential and radial wind and appeared to be on a space scale somewhat similar to that of the spacing of the strong convective clouds as shown in the patterns of the radar composite of Fig. 5. These wind fluctuations were not observed outside of the hurricane while approaching or leaving it. They were usually larger at the higher or middle tropospheric levels than at the lower levels (Fig. 6). These fluctuations showed considerable variation both along the individual flight leg, and from leg to leg on the same flight level. Great diversity of fluctuations occurred for similar mean wind speeds.

**Characteristics of the cylindrical wind components.** At middle tropospheric levels the NHRP observations show that the storm average radial component of motion varies only slightly from zero. Along individual radial legs, however, an overall average radial wind of ±10 to 20 kt may be present. The asymmetry of the broad-scale tangential wind may vary up to 40 kt. The average vertical velocity is positive (upward) by only a fraction of a knot. Within individual cumulus and cumulonimbus clouds, however, the vertical motion, upward or downward, may be greater by an order of magnitude or two (Gray, op. cit.).

**Vertical wind fluctuations.** Histogram distributions of the cumulus and cumulonimbus draft magnitudes and widths for the four middle tropospheric levels are portrayed and discussed in Gray (op. cit.). Magnitudes were 10–20 kt; widths were 1–3 n mi. These widths are designated as the half-wavelength or L/2 value of the vertical motion.

**Horizontal component fluctuations.** At places where arbitrary inspection of the wind profiles showed significant wind speed changes, a so-called ridge or trough line would be drawn and distance and velocity changes between these lines determined. No specific restriction was placed on the speed changes or distance intervals. In almost all cases significant-appearing changes occurred on distance intervals of from 1 to 10 n mi. Figs. 3 and 4 portray the typical places where choice of trough and ridge lines and half-wavelength values would be placed.

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3 For a discussion of the accuracy and characteristics of the wind data and the other observations recorded on the aircraft, the reader is referred to the author's previous paper (Gray, op. cit.) and to papers by Hawkins et al. (1962) and Hilleary and Christensen (1957).

4 Compositing of the radar flight observations is discussed by Colón (1961).

![Fig. 1. Typical hurricane aircraft track.](image-url)
Fig. 2. Data available on most radial flight legs.

Fig. 3. Illustrating typical tangential (vθ) velocity component changes in knots along a radial leg to the west from the center of Helene at 570 mb. Vertical lines are drawn where typical trough or ridges would be chosen. The distance between trough and ridge (or vice versa) lines is defined as the half-wavelength or L/2 value of the vθ variations.

Fig. 4. Illustrating typical radial (vr) velocity component changes in knots for the same radial leg as in Fig. 3.
No attempt was made to perform spectral analysis on the wind data. It is felt that the magnitudes and characteristics of the wind variations on the 1–10 n mi scale are readily demonstrated by inspection of these component profiles and by the calculations here presented. On the average, the $v_r$ and $v_9$ variations between trough and ridge (or vice versa) were 8–12 kt at the 800 to 830 mb levels and 14–18 kt at the 560 and 620 mb levels. The distance intervals from trough to ridge (or vice versa) averaged 6–7 n mi at both levels for
TABLE 2. Distance (n mi) and velocity (kt) changes from trough to ridge (or vice versa) of horizontal wind plus draft widths and velocities along five middle tropospheric radial flight legs (from eye wall to radii of 50–60 n mi) of Daisy, 27 Aug. at 620 mb and Helene, 26 Sept. at 570 mb.*

<table>
<thead>
<tr>
<th></th>
<th>Daisy</th>
<th>Helene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td></td>
<td></td>
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<tr>
<td>Daisy</td>
<td></td>
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<tr>
<td>9.7</td>
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<td>8.9</td>
<td>3.9</td>
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<td>6.4</td>
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<td>1.7</td>
</tr>
<tr>
<td>10.6</td>
<td>5.0</td>
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</tr>
<tr>
<td>8.5</td>
<td>4.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Helene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.8</td>
<td>6.7</td>
<td>2.0</td>
</tr>
<tr>
<td>8.3</td>
<td>4.8</td>
<td>1.8</td>
</tr>
<tr>
<td>12.8</td>
<td>6.5</td>
<td>3.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tangential wind (vφ)</th>
<th>Daisy</th>
<th>Helene</th>
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<tbody>
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<td>9.5</td>
<td>6.2</td>
<td>5.1</td>
</tr>
<tr>
<td>9.0</td>
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<td>5.6</td>
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<td>10.1</td>
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<td>5.7</td>
</tr>
<tr>
<td>7.8</td>
<td>4.6</td>
<td>4.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vertical wind draft widths and velocities (w)</th>
<th>Daisy</th>
<th>Helene</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>1.3</td>
<td>1.4</td>
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<td>1.3</td>
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<tr>
<td>2.1</td>
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<td>1.0</td>
</tr>
<tr>
<td>2.1</td>
<td>1.7</td>
<td>1.2</td>
</tr>
<tr>
<td>2.0</td>
<td>1.4</td>
<td>0.7</td>
</tr>
<tr>
<td>1.3</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>1.9</td>
<td>1.3</td>
<td>0.8</td>
</tr>
</tbody>
</table>

* See Figs. 3 and 4.

3. Equations of motion

How does one handle and incorporate these eddy or cloud-scale wind fluctuations in the framework of the equations of motion? It is evident that two characteristic flow regimes must be treated; the expected and predicted, and the unpredicted. The broad-scale general vortex current would represent the expected or predicted flow. The highly variable cloud-scale wind fluctuations would represent the unpredictable or turbulent field. The turbulent Reynolds stress equations of motion might be employed to incorporate both characteristic flow patterns. With certain manipulations and approximating assumptions, which neglect lower order terms (in general involving the earth’s curvature), the complete Reynolds stress cylindrical equations of motion applicable to hurricane motion inside radii of 100 to 150 km can be derived. Thus,

\[
\frac{d\bar{v}_r}{dt} = -f\bar{v}_θ
\]

\[
\frac{d\bar{v}_θ}{dt} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \bar{v}_r}{\partial r} \right) - \frac{\partial \bar{v}_θ}{\partial r} \frac{\partial \bar{v}_r}{\partial r} - \rho g
\]

where

\[\bar{D} = \text{altitude correction defined as the difference of pressure altitude from the standard value}\]

\[\varphi = \text{latitude of origin of coordinate system}\]

\[\Omega = \text{angular rate of rotation of earth}\]

\[f = 2\Omega \sin \varphi\]

\[k = 2\Omega \cos \varphi\]

\[p = \text{atmospheric pressure}\]

\[\rho = \text{atmospheric density}\]

\[g = \text{acceleration of gravity}\]

\[\bar{d} = \frac{\partial}{\partial t} + \bar{v}_r \frac{\partial}{\partial r} + \bar{v}_θ \frac{\partial}{\partial θ} + \bar{v}_z \frac{\partial}{\partial z}\]

Both components. There were large individual deviations from these averages, however. Table 2 lists flight leg distance fluctuations for Daisy, 27 August, at 620 mb, and Helene, 26 September, 570 mb. Other levels showed the same characteristics. This component wind fluctuations with wavelengths of 2–20 n mi will henceforth be referred to as eddy or cloud-scale fluctuations.

Resolution of wind values to 10 sec averages (0.6–0.7 n mi). The length scales associated with changes of the vertical wind velocities are the shortest. In order to resolve the vertical wind variations, a grid interval smaller than the typical draft width vertical motion scale (1–3 n mi) must be chosen. The smallest resolvable distance to which the vertical motion which could be obtained was 0.5–0.7 n mi (Gray, op. cit.). This dictated the choice of wind component space resolution. It was thus deemed advisable and convenient to average all three wind components over similar 10-sec flight time intervals. This is equivalent to a grid or space resolution interval every 0.6–0.7 n mi.
— and ′ denote the time or space determined mean and eddy wind
\( \overline{\omega} \) is the horizontal space or time average of the already determined mean and eddy wind, density and pressure.

There is no difference in the averaging interval of — and \( \overline{\omega} \), — applies to the initial determination of the mean wind and \( \overline{\omega} \) to the average of the already determined mean and eddy terms.

In averaging the wind velocity, pressure and density over appropriate space or time intervals, initial mean and deviational values are obtained from the defining equations:

\[
\begin{align*}
\overline{v_\theta} &= \overline{v_\theta} + v_\theta' \\
\overline{w} &= \overline{w} + \dot{w}' \\
\overline{p} &= \overline{p} + p' \\
\rho &= \rho + \rho'
\end{align*}
\]

where the bar and prime stand for the space or time averaged value and the deviational or eddy value, respectively.\(^5\)

4. Defining of mean and deviational winds for data sample

In most atmospheric turbulence studies the mean motion is defined with respect to time. This definition of the mean motion as one in time is not mandatory. Defining the mean with respect to space or length is also acceptable. In Reynolds' original paper (1895) developing the concept of turbulent stress, space means were used. Space means were used in this study. The selection of space or time means should be determined by the nature of the problem to be handled.

In the evaluation of atmospheric turbulence from aircraft observations, it is obviously impossible to obtain eddy deviations from time averaging at a fixed position. One must assume that over short time intervals the observations on the flight levels have been taken simultaneously. This is not too severe an assumption if the averaging is performed on overlapping space intervals of, say, 20 n mi, and it is the cloud-scale fluctuations that are dealt with. The B-50 aircraft traveled at approximately 4 n mi min\(^{-1}\). One need only assume steady state for periods of 5 min or 2/3 min on either side of a centered 20 n mi space interval to obtain mean and deviation values. Observations indicate that the individual wind fluctuations, operating primarily

\^5 In the above derivation, the eddy pressure deviations \( (p') \) stand by themselves and drop out in the space averaging. In addition, there are many terms resulting from the double and triple correlations of the turbulent density and wind components. With the compressibility of the atmosphere being quite small (i.e., \( \rho / \rho_0 < 1 \)), these terms become negligible. The density and pressure have far less percentage variation than the component winds.

in response to the convective cloud spacing, have frequency periods greater than this. The average time during which individual hurricane convective radar cell echoes can be traced is 30 min.

The appropriate smoothing interval was determined from the statistics of the wind component fluctuations as described in Section 2. The widths of the vertical drafts ranged from 1/4 to 4 n mi. Smoothing intervals of 10 n mi or greater would thus be a few length units greater than the characteristic vertical motion widths.

Distances from trough to ridge (or vice versa) of the radial and tangential wind fluctuations averaged approximately 6 n mi. Average wavelengths would then be 12 n mi. Maximum half-wavelengths on all radial legs were approximately 10 n mi while minimum half-wavelengths averaged 2 to 3 n mi. Radial and tangential wavelengths thus varied from just a few n mi up to and occasionally in excess of 20 n mi.

To apply the Reynolds criteria, an absolute minimum requirement would be that the average smoothing intervals be at least as large as the maximum wavelength of the fluctuations under consideration. In this case the area of a minimum smoothing interval would have to be at least \((20 \text{ n mi})^2\). A larger smoothing interval could be chosen, but important variations of the basic flow pattern with radius and tangential direction might then be obscured, especially near the storm's center.

It is necessary that a smoothing interval be chosen which best accommodates both the wind fluctuations which are of the random or unpredictable mode, and those which are characteristic of the broader, more basic current. In the attempt to satisfy both requirements, it was deemed advisable to use a space smoothing interval of \((20 \text{ n mi})^2\). It was at or a little below this area size that further increase of the space smoothing interval yielded little or no change of the eddy wind.

In general the smoothing interval should be a large number of space or time units larger than the characteristic eddy size. For this evaluation the smoothing interval was chosen between one and three length units larger than the characteristic horizontal eddy wavelength. This will be sufficient for accurate eddy wind representation if terms of the type involving the product of eddy wind and gradient of the mean wind \( (i.e., v_\theta \frac{\partial \overline{v}_\theta}{\partial r}) \) and mean wind times the gradient of eddy wind \( (i.e., \overline{v}_\theta \frac{\partial v_\theta}{\partial r}) \) approach zero over the smoothing interval as required by turbulent criterion. Calculation of these terms showed them to be of insignificant magnitude.

Definition of mean and eddy wind. The mean or space-smoothed winds will be denoted with a superscript bar (\(^\cdot\)). In theory all wind values in the \((20 \text{ n mi})^2\) box are averaged. This is then considered as the mean flow at the center of the \((20 \text{ n mi})^2\) box. The
difference between the (20 n mi)$^2$ space-smoothed wind and the 10-sec or (0.6 n mi)$^2$ average wind at the center of the box will be defined as the eddy wind. The shaded rectangular-shaped area of Fig. 7 shows the area over which the space smoothing should be performed.

In practice the wind smoothing and consequent determination of eddy winds could only be made directly along the radial flight leg. Thus,

\[
v' = \left( \frac{10 \text{ sec or } 0.6 \text{ n mi average}}{\text{wind}} \right) - \bar{v} = \left( \frac{290 \text{ sec or } 20 \text{ n mi average}}{\text{wind straddling 10 sec}} \right).
\]

Fig. 8 demonstrates how the 20 n mi mean and eddy wind would be determined along a radial leg. All computations of eddy wind were made only along the radial legs.

It is sufficient to use the 10-sec average (or 0.6 n mi) averaged wind for the eddy, if the smaller resolution components on scales below 0.6 n mi are primarily uncorrelated. This is felt to be a realistic assumption in the middle tropospheric levels above the surface boundary layer. To perform the intended computations it was necessary to make this assumption at the middle levels (see footnote 6).

It was also necessary to assume that the component 20 n mi mean winds along the radial leg segments are representative of the mean winds 10 n mi in the tangential direction on either side of the radial segment.

5. Results

Determination of 10-sec (=0.6 n mi) space-averaged values of the three wind components were made along the 28 radial-leg penetrations of the six flight levels as shown in Table 1. From these values, mean- and eddy-wind components were determined with the 20 n mi smoothing scheme as discussed in the previous section. Table 3 lists individual radial-leg maximum, average, and minimum computed 10-sec average eddy-wind products and resulting stress for five legs of Daisy, 27 Aug. at 620 mb and for three radial flight legs of Helene at 570 mb. These statistics are based on data from the eye wall to radii of 50–60 n mi. These data are typical of the other flight levels.

The eddy winds showed no systematic component-magnitude difference. Maximum and minimum values
of the eddy components were within the range of ±10–20 kt.

Leg maxima and averages of the eddy wind squares \((\nu'\nu', \nu'\nu', \nu'\nu')\) showed considerable variation from leg to leg (as did the amount and intensity of the cumulus convective cloud flown through). Great variation was also observed between individual legs in the average values of the eddy-wind products \((w'\nu', w'\nu', w'\nu')\). The absolute magnitude of the eddy-wind products (and consequent internal atmospheric stress) was generally larger at the middle (=600 mb) than at the lower (=800 mb) levels. The highest computed leg averages of \(\rho w'\nu', \rho w'\nu', \rho w'\nu'\) were, respectively, 24, 35 and 62 dyne cm\(^{-2}\), corresponding to correlations of eddy components of 0.67, 0.43 and 0.51. This correlation of the eddy components was also quite variable. Leg-average values of \(w'\nu'\) tended to be both positive and negative while values of \(w'\nu'\) and \(\nu'\nu'\), especially \(w'\nu'\), were usually positive. The higher correlations of \(w'\nu'\nu'\) were always positive indicating upward transport of momentum, as would be required by the decrease of mean wind speed with height in a convective atmosphere. In the majority of cases the leg-average correlation of the component eddies was not very high, but the correlations need be only 0.3–0.5 to render significant internal stress.

If horizontal and vertical eddies of the magnitudes here presented are significantly correlated in an area covered with 5 to 10 per cent deep cumulus convection, then average mid-tropospheric maximum stress values of 20 to 30 dyne cm\(^{-2}\) appear to be reasonable.

Representativeness of results. Undoubtedly in many cases, the computed eddy winds and stress values were not representative of the actual values. Only if representative cloud samples (particularly Cb clouds) within each (20 n mi\(^2\)) smoothing area were traversed could representative individual results be obtained. As the cumulonimbus make up only a small fraction (0–20 per cent) of the individual quadrant areas from eye wall to 60 n mi radius, it is felt that in only a minority of cases were individual representative radial-leg stress values obtained. Radial flight tracks might have been just within or without the deep convective clouds. For this reason the eddy-wind data collected along the individual flight legs may only be qualitatively repre-

sentative of the eddy winds in the area adjacent to the flight leg.\(^7\)

These sampling deficiencies make it necessary to interpret the data only in a statistical sense. Nevertheless, it is felt that insight into the primary physical mechanism of the free atmospheric stress and its approximate magnitudes and variability are correctly portrayed.

Other features of eddy wind and stress values. In general, the eddy wind variations appear to be related to the number and intensity of cumulonimbus clouds traversed and to some degree, to the storm quadrant flown through. There is large variation in the magnitude and correlation of individual eddy wind components between the various radial legs. On some legs the correlation of two of the eddy-wind components was as high as 0.67. On other legs there was little, if any, overall leg correlation. The eddy components showed both positive and negative correlation, indicating that the gradients of stress or frictional accelerations may be directed in either the positive or negative sense along the coordinate directions. The cloud-scale wind fluctuations can then be such as to produce stress values and consequent gradients of stress or frictional acceleration which act both with or against the mean wind. These cloud-scale wind fluctuations may then act either to dissipate or to generate kinetic energy. In the majority of cases, however, the cloud-scale wind correlations were such as to cause dissipation of kinetic energy.

Nearly all dissipation of kinetic energy occurs along the tangential direction. The predominant correlation of the vertical and tangential eddies at the middle levels is positive, however, showing that the frictional acceleration term, \(-\frac{\partial \rho w'\nu'}{\partial z}\), acts against the mean wind below the level of maximum stress. Above the level of maximum stress this term acts to generate kinetic energy. The vertical transport of momentum continually acts to suppress vertical shear of the horizontal mean wind.

Comparison of vertical to horizontal gradients of stress. It is a significant feature of the earth's atmospheric system that its vertical to horizontal ratio is so small. As a consequence of the fact that the component eddy winds have similar 10–20 kt fluctuations, the terms \((\rho \nu'^2, \rho \nu'\nu', \rho \nu'\nu', \rho \nu'\nu', \rho \nu'\nu'\nu')\) are all of the same approximate magnitude. Gradient components of these terms must also be of equal magnitude. However, it should be apparent that for application of the equations of motion on horizontal surfaces, the horizontal

\(^7\) It should be remembered that the eddy product values should be summed over (20 n mi\(^2\)) areas (10 n mi in the tangential direction on either side of the radial-flight legs). The measured eddy winds here portrayed, however, are only those obtained directly along the radial legs. The averaged eddy-wind products along the radial leg may then not necessarily be closely representative of the average eddy-wind product in the (20 n mi\(^2\)) area straddling the radial leg. The radial average is very nearly representative of the mean wind of the surrounding area, however.
gradients of these terms are of much smaller importance than the vertical-gradient terms. The stress terms $\rho \omega' v'$, $\rho \omega' v_g'$ and $\rho v'_r v'_q$ change their sign many times, and their gradients tend to cancel over horizontal distances larger than the eddy-wind wavelengths. This need not take place in the vertical, however. An accumulated vertical gradient of stress of one sign can act across the horizontal surfaces on which the equations of motion are applied, as consistently different mean and eddy winds may be present on each horizontal surface. In addition, the distance intervals between the varying values of stress are much smaller in the vertical than the horizontal. Only within the eye or within the eye-wall cloud can horizontal gradients of $\rho \omega' v'$, $\rho \omega' v_g'$ and $\rho v'_r v'_q$ become of comparable magnitude with the vertical gradients.

6. Comparisons with other observations

In a detailed observational study of hurricane Daisy (1958), making use of the same NHRP flight data, Colón (1961) has shown similar horizontal wind fluctuations.

Gentry's (1963) detailed study of hurricane rainbands using NHRP flight data also gives documentation of horizontal wind fluctuations on the scales here observed. These fluctuations extend both along and normal to the rainbands. Gentry found much greater fluctuations of wind within the rainbands than outside of them.

Senn et al. (1959), Senn et al. (1960), and Senn et al. (1962) have presented extensive evidence of radar-echo movement in hurricanes. They have made special studies from land-based radar of the movement of echoes in storms Helene and Daisy of 1958 and have shown many cases of differences of echo movement from measured wind components surrounding the echo. In many instances this difference would amount to as much as 20–30 kt at middle levels, and 30–40 kt at upper tropospheric levels as portrayed in Fig. 9. Other recent studies have observed or inferred large horizontal wind changes in convective clouds (McLean, 1961; Fujita, 1962; Newton, 1963).
7. Discussion

In cumulus convective atmospheres, represented most markedly in the earth’s hurricanes and typhoons, relatively large values of free atmospheric stress (and consequent frictional acceleration and kinetic-energy dissipation) may be produced by nonlinear interactions brought about by the correlation of cloud-scale horizontal and vertical wind eddies. This paper has attempted to emphasize the magnitude of these cloud-scale wind fluctuations and to show that the component fluctuations may be correlated. It has also attempted to demonstrate how these wind variations may be treated as wind eddies from the Reynolds stress point of view. In other atmospheric wind systems where a much weaker intensity of cumulus convection is present, similar, but much weaker, free atmospheric stress and frictional accelerations may also exist, and play a significant role in organizing and altering the flow features of longer time periods characteristic of the synoptic scale.

The vertical gradients of the stress terms often make a significant contribution within the equations of motion and must usually be included, but their magnitudes relative to the other terms are highly variable, as is the cumulus convection. The functional representation of friction proportional to $\nu \nabla^2 \bar{z}$, where $\bar{z}$ is the mean wind, and $\nu$ is an assumed eddy-viscosity coefficient, is not often a valid relationship at individual grid points. Quite variable convective patterns may be present within similar regimes of mean wind. Parameterization of convection in terms of the broad-scale flow may only be possible by collective treatment of the entire vortex flow.

A paradox of the cumulus-convective atmosphere is the dual role in which the cumulus clouds act to both transfer momentum and produce horizontal temperature gradient. The vertical transport of momentum by the correlation of horizontal and vertical winds in the cumulus continually acts to suppress vertical shear of the horizontal wind. At the same time, the cumulus-produced condensation heating and its diffusion throughout the vortex acts to increase the horizontal temperature gradient and the vertical shear of the horizontal wind through the thermal wind relationship. The continuously observed small vertical shear of the horizontal winds below 400 mb in the hurricane (Hawkins, 1963) attests to the dominant effectiveness of the cumulus clouds in suppressing vertical wind shear in spite of the simultaneous existence of large horizontal temperature gradients. These large cloud-scale momentum exchanges may be the primary mechanism by which the cumulus clouds act to intensify and maintain the large scale vortex flow. In this way the condensation heat produced by the cumulus does not remain within the cumulus to continue their unlimited group but is more quickly diffused to the surroundings to maintain or intensify the larger system.

The implications of this paper on the importance of cloud-scale momentum transports are in agreement with Riehl and Malkus’s (1958, 1961) so called “hot tower” hypothesis, whereby the majority of vertical heat transport is accomplished within deep cumulus up- and downrafts. In this paper, the emphasis has been on the associated vertical transport of horizontal momentum by the deep cumulus up- and downrafts. In this regard the processes for the primary vertical transfer of heat and momentum are envisaged to be identical.

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APPENDIX

Accuracy of winds in data sample

The calculations given in this paper are felt to be closely representative of wind conditions occurring at middle and lower tropospheric levels and at radii between 10 and 60 n mi in the moderate hurricane. Hilleary and Christensen (1957), Hawkins et al. (1962), and Gray (1965) have discussed the accuracy of the winds measured with the aid of the AN/APN-82 system. The reader is referred to these articles for information on the wind values used.

There is evidence which points to the basic reliability of the AN/APN-82 system used in the wind measurement. In all but a few cases the winds appear to be reasonable. The magnitude and characteristics of the wind fluctuations are much like those of the airspeed changes. Navigation corrections after many hours of flight were usually within a few nautical miles on the 1958 flights. The wind fluctuations were not observed outside of the hurricane when the aircraft were flying to or leaving the storms. This discussion is meant to refer only to the winds measured with the NHREP B-50 aircraft during the 1958 flights.

It is not denied that some observational deficiencies may be present, but the questions that have been discussed are thought to be of enough basic importance that it was felt well worthwhile to present and discuss the above findings. The possible observational shortcomings are not felt to be of significant magnitude to alter the conclusions. It is hoped that this study, in
addition to stimulating meteorological discussion of the cloud-scale wind fluctuations, will also stimulate a greater interest in further developing and testing of the Doppler radio-navigation system as a wind-measuring device.

REFERENCES


