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National Environmental Satellite Service

Convective Clouds as Tracers of Air Motion

LESTER F. HUBERT AND ANDREW TIMCHALK

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CONVECTIVE CLOUDS AS TRACERS OF AIR MOTION

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.507.362.2	Satellites
.557.3	Upper air wind variations
.576.5	Cloud movements

CONTENTS

CONVECTIVE CLOUDS AS TRACERS OF AIR MOTION

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ABSTRACT. Deviations between cumulus cloud motions (measured from sequences of satellite pictures) and wind (observed from ships during the Barbados Oceanographic and Meteorological Experiment) are analyzed to determine the magnitude and the nature of the differences between these two sources of wind data and to deduce the mechanisms responsible for the deviations.

Cloud motions [Advanced Technology Satellite (ATS) vectors] and balloon-derived winds correspond best near cloud bases, despite the fact that the cloud targets are cumuli about 2 to 3 km deep. Magnitudes of deviations were found to be 7 kt, on an average, approximately the same as those found in earlier studies of similar nature.

The principal result of this study is that a substantial part of the deviation was caused by short-term changes of the reported (rawinsonde) winds. This suggests that low-level cloud motions might correspond to synoptic scale air motion as closely as do balloon winds. Hence, a realistic assessment of "accuracy" of ATS vectors as wind observations must be made on the basis of sophisticated space- and time-smoothed analyses, not merely on the basis of deviation from individual balloon wind soundings.

1. INTRODUCTION

Cloud motions measured from geosynchronous satellite images are used as wind estimates. Validity of these estimates depends, therefore, on clouds moving with their ambient flow. Various studies have demonstrated that the correlation between cumulus cloud motions and the "observed wind" is such that the average deviation ranges from 5 to 8 kt.

Deviations result partly because of errors in measuring cloud and balloon motions. Moreover, in earlier studies, wind soundings compared with cloud motions were not simultaneous with satellite observations; thus, time changes also were a source of deviation. Another factor is land-produced disturbances. In earlier studies, soundings made from land-based equipment had to be used. The wind immediately downstream from an island might be quite different from the wind about 100 km away from the island where the cloud targets might be located. In the present study, we sought insight into these factors by using a set of data in which some of these elements were minimized [viz, ship soundings from the Barbados Oceanographic and Meteorological Experiment (BOMEX)]. (See de la Moriniere 1972.)

Another refinement of this study is that deviations between cloud motions and observed winds were computed for individual cloud layers rather than for an average cloud layer (i.e., for some comparisons, the observed winds from 600 to 1500 m near one ship might be used while, near another ship, the winds from 400 to 2500 m might be used.

Initially, the deviations between low cloud motions and balloon-observed winds at various levels were analyzed to determine whether the cloud motions corresponded closely to flow at some particular level or layer. For example, do convective clouds move with the velocity of winds at the cloud base, mid-cloud, or cloud top or with the velocity of the layer-mean winds?

Some clouds propagate by mechanisms other than horizontal advection. Wavelike motions frequently can be recognized. Nevertheless, in all likelihood, undetected waves have contributed to the deviations found between cloud motions and observed wind; but other nonadvective mechanisms may exist. We attempted, with little success, to detect the existence of a separate nonadvective component. The data only weakly suggest a shear-related mechanism.

2. DATA AND PROCEDURES

Soundings from four BOMEX ships during parts of June and July 1969 were compared with cloud motions measured from the Advanced Technology Satellite ATS 3 picture sequences. Preliminary BOMEX records, the so-called "A_0 Data," were used (de la Moriniere 1972); and the BOMEX Analysis Project assisted in eliminating some errors in this early version of the record. Soundings from a fifth ship, The Rockaway, were not used because its instruments were not capable of reliable tracking at low levels.

We measured cloud displacements over intervals of about 2.5 hr from animated ATS picture sequences displayed on the National Environmental Satellite Service (NESS) Electronic Animation System (EAS)--a closed-circuit television system that stores images on magnetic disc and displays them as time-lapse movies. An analyst selected cloud targets and marked their positions at the beginning and end of the time sequence with a cursor on the display; the coordinates of these points were punched on tape by the EAS. A computer program performed the projective geometry to convert from image coordinates to earth coordinates and printed out the ATS vectors on a Mercator Projection. Cloud motions from these maps were interpolated to ship locations and tabulated for comparison with wind soundings.

Profiles of temperature and humidity were then analyzed to determine the base and top of the cloud layer. We tabulated winds reported at cloud

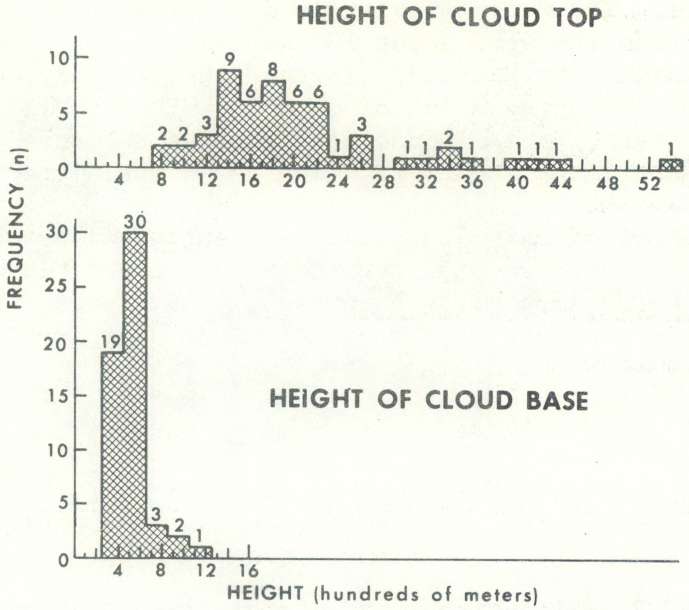

Figure 1.--Histograms of the heights of cloud bases and tops derived from ship soundings (55 cases)

base, mid-cloud, and cloud top and computed deviations between those observed winds and the ATS vectors. Cloud bases and tops were independently determined from each ship sounding. Figure 1 shows the distribution of these derived bases and tops. A smaller set of comparisons with time-averaged winds is discussed later.

Deviations of cloud motions from observed wind were computed only if:

1. At least one ATS vector was within 200 n.mi. of the ship location.

2. The mid-period of the ATS sequence was within ± 3 hr of the ship observation time.

3. The field of ATS vectors was amenable to confident interpolation to ship locations (i.e., absence of large gradients of speed and direction).

These restrictions limited the number of comparisons to 55 during the period of 21 June to 28 July 1969.

3. COMPARISON OF ATS VECTORS WITH WINDS

Figures 2, 3, and 4 and table 1 summarize deviation statistics. In each graph, distributions of deviations are shown for the three cloud levels and for a layer-mean wind. (See fig. 5 for definitions.) The lower right portion of each figure contains cumulative frequencies to facilitate level-to-level comparisons. These statistics reveal that:

1. On the basis of magnitudes of vector deviations (fig. 4), the ATS vectors correspond best to the layer-mean observed winds. However,

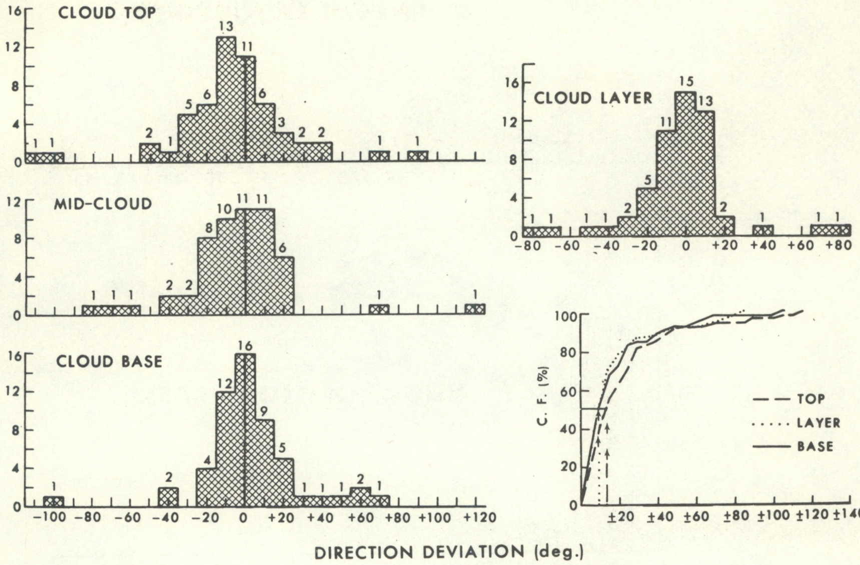

Figure 2.--Histograms and cumulative frequencies of direction deviations between ATS vectors and rawin observations (55 cases)

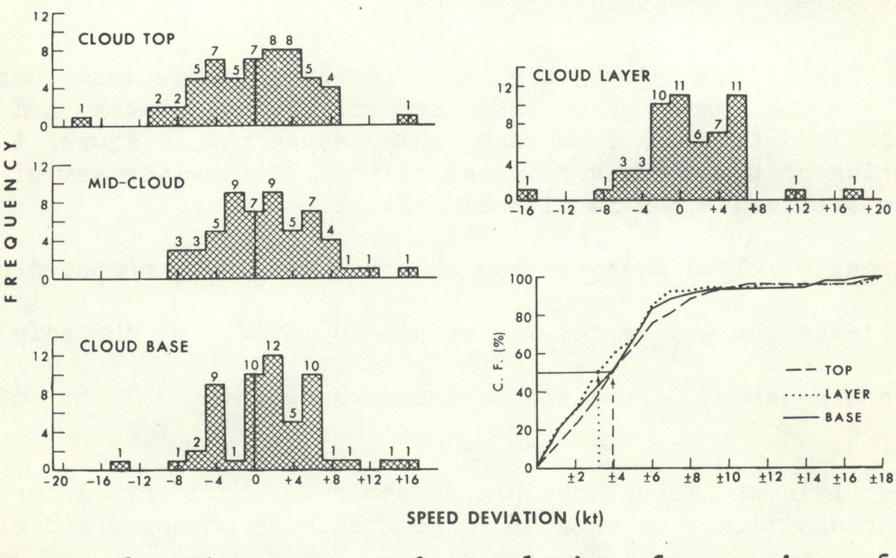

Figure 3.--Histograms and cumulative frequencies of speed deviations between ATS vectors and rawin observations (55 cases)

deviations at cloud base are not significantly larger, according to the Student's "t" test. At cloud top, the deviation is larger by 1.6 kt, a difference significant at the 1% level.

2. The better correspondence of ATS vectors to the layer-mean wind is due more to better agreement in direction than in speed (cf. figs. 2 and 3 and table 1).

3. Deviations of ATS vectors from observed winds increases with increasing altitude in the cloud layer (table 2). This worsening with altitude, however, is significant only at moderate levels of confidence.

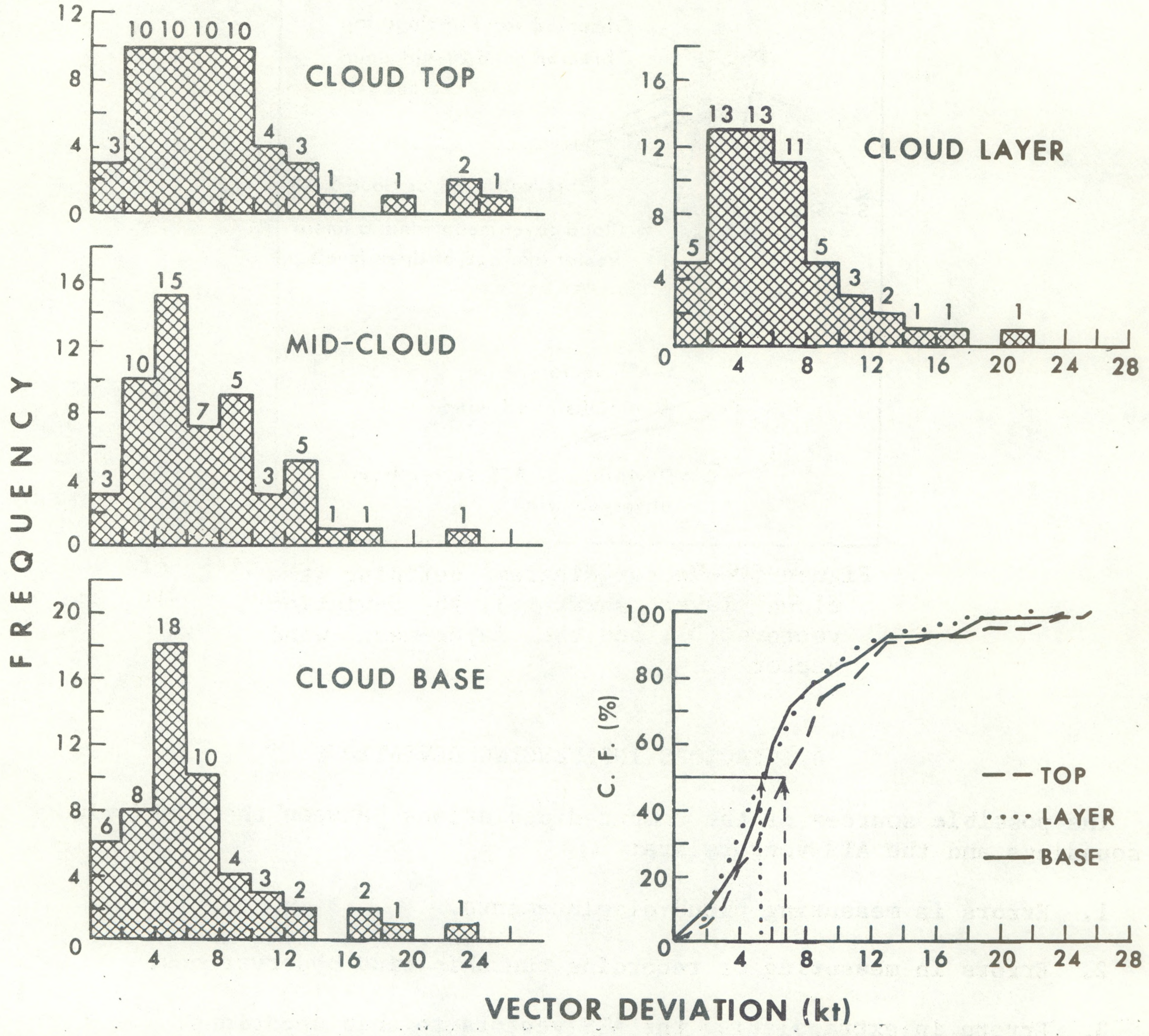

Figure 4.--Histograms and cumulative frequencies of vector deviations between ATS vectors and rawin observations (55 cases)

Table 1.--Mean deviations between ATS vectors and balloon-observed wind at three levels and for cloud layer-mean and mean wind speed (55 cases)

Level	Mean wind speed (kt)	Mean absolute deviations: Vector (kt)	Mean absolute deviations: Direction (deg.)	Mean absolute deviations: Speed (kt)	Algebraic mean deviations: Direction (deg.)	Algebraic mean deviations: Speed (kt)
Cloud base	16.6	6.62	17	4.23	+2	+1.38
Mid-cloud	16.8	7.15	19	4.25	-3	+1.16
Cloud top	17.8	7.96	22	4.50	-7	+0.08
Layer-mean	16.7	6.34	17	3.85	-3	+1.18
ATS vector	17.9					

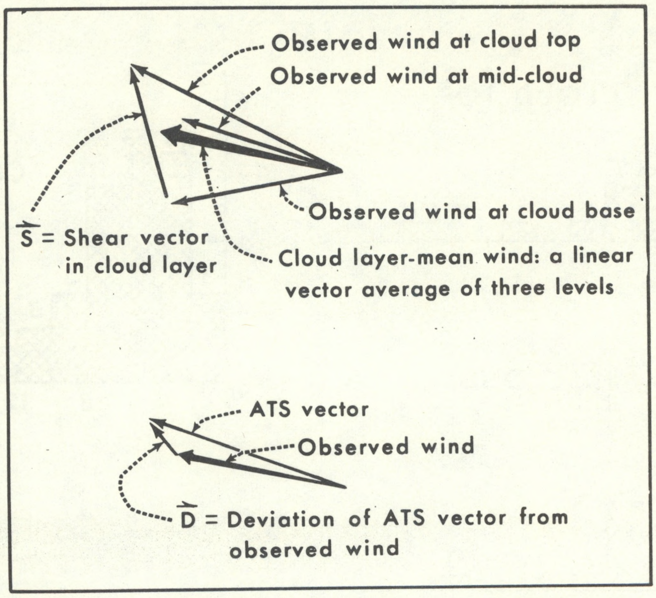

Figure 5.--Vector diagram defining the cloud layer shear ($\vec{S}$), the deviation vectors ($\vec{D}$), and the layer-mean wind vector

4. FACTORS INFLUENCING DEVIATIONS

The possible sources of the computed deviations between the BOMEX wind soundings and the ATS vectors are:

1. Errors in measuring cloud displacements.

2. Errors in measuring or recording the ship wind observations.

3. Errors in extrapolating the ATS vectors to ship locations.

4. Errors in deducing the correct cloud base and top.

5. Discrepancies between balloon motion and cloud motion brought about by their different time and space scales.

6. Dynamic (nonadvective) motion of the cloud groups due to their convective and mesoscale circulations.

The first two sources of error have been discussed elsewhere (Hubert and Whitney 1971). Certainly, the combination of those factors contribute a few knots to the average deviations.

No appreciable part of the deviations were produced by the third factor, interpolating to ship locations. A plot of deviations versus distance of interpolation (not shown) revealed a lack of correlation between those variables--less than 0.1. For that reason, we did not pursue the study of this effect.

Table 2.--Mean vector magnitude of time changes of ship wind soundings

Time increment	Wind observation levels			
	Cloud base	Mid-cloud	Cloud top	Cloud layer-mean
1.5 hr	4.2 kt	5.0 kt	4.4 kt	3.1 kt
(No.)	(19)	(19)	(19)	(19)
3 hr	3.7 kt	3.7 kt	6.1 kt	3.4 kt
(No.)	(24)	(24)	(24)	(24)
6 hr	5.6 kt	5.5 kt	5.0 kt	4.0 kt
(No.)	(17)	(17)	(16)	(16)

Incorrect derivation of cloud base and top, the fourth factor, contributed to computed deviation; the magnitude of this effect cannot be determined. Error arises because the depth of the moist layer bearing the cloud might be somewhat different from the depth of the moist layer measured by ship. Moreover, deduction of the base and top was not always clear. In those cases, best estimates were made by analyzing the ship cloud observations and soundings made a few hours earlier or later. Although it was not possible to eliminate questionable samples on any objective basis, the effect of this factor is in our opinion of secondary importance--an opinion based on the absence of any relationship between depth of the layer and the computed deviation.

Scale discrepancies, the fifth factor, is important because the volume of air that contains a group of cumuli is very much greater than the volume that carries along a sounding balloon. Likewise, the 2.5-hr displacement of cloud groups is the consequence of motion on a time scale quite different from the scale that displaces a rising balloon during a few-minute time interval. These scale effects are shown by the frequent soundings made during the BOMEX.

During an early part of this comparison period, soundings were made at 1.5-hr intervals; later, the more usual interval was 3 hr. With those soundings made near the times of the ATS sequences, time changes of vector magnitude were computed over time increments of 1.5, 3, and 6 hr. The results are summarized in table 2.

In general, time changes are of the same magnitude over all three time increments. This attests to their small scale, for changes attributable to synoptic patterns (e.g., trough passage) would produce larger changes over longer time intervals. Comparison between 6- and 1.5-hr changes suggests that large-scale changes affecting our deviation statistics are less than 1 kt, but that short term changes are a major contribution (i.e., observed winds deviate 3 to 6 kt over a 2.5-hr interval). It follows that a single wind estimate made for the 2.5-hr interval must necessarily deviate by a few knots from the balloon soundings.

Table 3.--Median vector magnitude of deviations from individual wind soundings and from time-averaged soundings (39 cases)

Cloud level	Median deviations from individual soundings (kt)	Median deviations from time-average soundings (kt)	Change* (kt)
Base	5.4	5.3	+0.1
Mid-Level	6.5	6.2	+0.3
Top	6.6	6.2	+0.4
Layer-mean	5.3	5.8	-0.5

*The plus sign indicates improvement; the minus indicates deterioration.

In an effort to compute deviations between cloud motions and winds that were more nearly matched in scale, deviations were computed from time-averaged winds. Time-averaged winds were derived by using the same cloud levels previously deduced and vectorially averaging all observations occurring during the period from 2.5 hr before the beginning of the ATS sequence to 2.5 hr after the end of the sequence. Lack of two soundings in that period and missing data reduced the original 55 cases to 39.

By using this smaller sample, deviation statistics were again computed, first from the individual soundings and then from the time-averaged soundings. With a single exception (table 3), deviations were slightly smaller from the time-averaged soundings than from the individual soundings.

Changes of vector deviations listed in the last column of table 3 show that only minor improvement was achieved by this attempt to match time scales. Similar small improvements were also evident in the deviations of speed and direction. Such small improvement, in view of the earlier evidence of short-period time variations, suggests that the observations available for time averaging were inadequate to yield representative, valid time-smoothing.

5. CONVECTIVE CLOUDS: PASSIVE OR DYNAMIC TRACERS?

Perhaps our computed deviations are not entirely accounted for by errors and shortcomings of the data discussed up to this point. Perhaps the displacements of clouds were different from the displacements of balloons because their respective behavior was different in a (vertical) shearing flow. In this section, we report our search for evidence that such a dynamic component of motion might exist.

An aspect of scale disparity somewhat different from that already discussed must be considered here. The observing and the data reduction system limit spatial resolution of images we use for measuring cloud motion. The spin scan camera scans the earth with lines about 5 km wide; but if cloud motions are measured from projected movie sequences or on a television display, the actual resolution is considerably degraded. With the additional effect of limited dynamic range, effective resolution is perhaps down to 10 km.

Only rarely is the cloud target of that minimum resolved size; typical targets range upward from 15 to 20 km. Hence, cloud groups 15 km or greater in size are tracked for 2.5 hr to obtain ATS vectors. Clearly, these are not the individual cumulus cells that are about 50 times smaller and have a life cycle on the order of half an hour.

Malkus (1954) studied isolated large trade cumuli that existed for more than an hour and concluded, ". . . . a . . . large cloud seems to imply the aggregate of several small . . . clouds and the precedence . . . of earlier clouds in the same locality."

What, then, are the cloud targets we track? The film loops offer persuasive evidence that these targets are the upward motion branches of mesoscale cells which persist for hours with little change in shape or in their relation to each other. The most reasonable explanation of persistent cloud patterns is that the upward motions of mesoscale cells control the locations of a succession of cumuli. As one cloud decays, its successor develops where the upward motion of the mesoscale circulation exists, while clouds are inhibited in regions of mesoscale subsidence. Cellular patterns of this type are typical over oceans (Hubert 1966). Such cells might interact with a shearing flow to produce a component of motion.

To investigate this possibility, we hypothesized that a dynamic motion component is produced by interaction of the mesoscale circulation with vertical shear of the carrying flow. If such an interaction produces significant motion, it might be revealed by a relationship between the observed deviations of the cloud targets from the wind flow and the shear in the cloud layer. We arrayed the data to reveal this relationship. In addition, we subdivided the sample by types of shear.

Mendenhall (1967) investigated the effect of thermal wind and vertical stability and found that both influenced vertical shear. Because stability and thermal effects may also influence the size and vigor of mesoscale cells, we first separated our cases into three types of shear. The polar diagram, figure 6, displays the distribution of shear vectors relative to the layer-mean wind. Direction of the mean wind is held fixed in that diagram with the end points of the cloud-layer shear scattered about the head of the mean wind vector. The total wind change in the cloud layer is shown, regardless of the cloud thickness. The radial distances are therefore knots, not knots per unit thickness.

Only 35 points appear; four of the 39 cases discussed earlier were removed because the magnitude of the shear vector was less than 2 kt. Our purpose here was to seek a relationship between the deviations and shear; hence, the nonshear cases could not be so used.

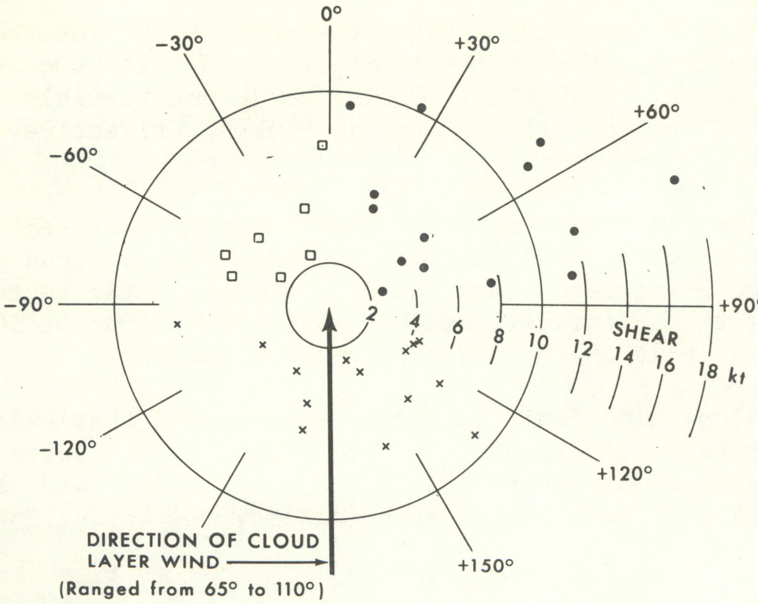

Figure 6.--Wind shear in the cloud layer relative to the direction of layer-mean wind (35 cases). Circles represent the wind increased and veered; squares, wind increased and backed; crosses, wind decreased with height.

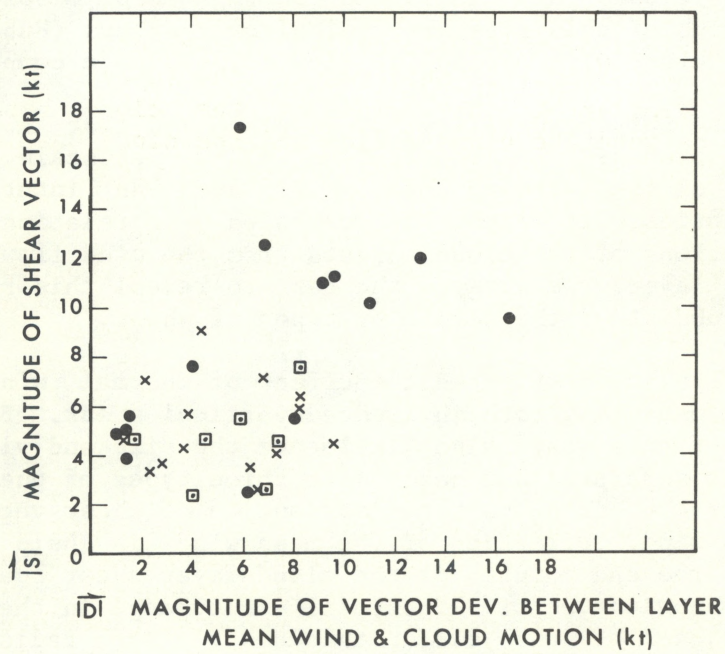

Figure 7.--Magnitude of the cloud layer shear versus the magnitude of the vector deviation between the ATS vector and the layer-mean wind (35 cases). The symbols are the same as those in figure 6.

As shown by figure 7, the deviations are positively but weakly correlated with the shear vectors in the cloud layer. On the basis of our hypothesis, the direction of the shear vector should also bear a relationship to the direction of the motion component. We plotted the direction of deviation vectors relative to the direction of the shear vectors (not shown), seeking some such association. None was found. Hence, the evidence available here does not support the hypothesis that there is a dynamic component of motion related to the vertical shear vector.

The weak correlation shown between the magnitude of shear and the magnitude of deviation merely suggests that the greater the vertical shear, the greater is the likelihood of larger deviations between cloud and balloon motions. The mechanism responsible for this tendency is unknown.

6. SUMMARY AND CONCLUSIONS

Comparisons of low cloud motions with the BOMEX ship soundings yield average vector deviations of about 7 kt. At least half of this deviation appears to be caused by short-period changes of the balloon-observed wind. This result points out the limitation in assessing the "accuracy" of ATS wind estimates by a straightforward comparison with standard balloon soundings. "Ground Truth" winds for such assessment might be derived from space and time smoothing. It was shown that a simple time-smoothing over a few hours is inadequate.

The motions of convective clouds measured from ATS sequences probably are due to the motions of mesoscale cells. These motions correspond best to the cloud layer-mean flow. In this sample, the layer-mean wind was found to be quite similar to the wind at the cloud base. Hence, the correspondence between the cloud motion and the cloud-base wind was about the same as the correspondence to the layer-mean wind.

We failed to detect the effect of a nonadvective mechanism (associated with a vertical shear vector) for moving clouds. A weak correlation exists between the magnitude of shear and the magnitude of cloud motion deviation; but no relationship was found between the direction of those vectors. If such a dynamic component of motion exists, it is too small to be detected with this small sample of this type of data.

The principal result of this study is that a significant part of the deviations between ATS vectors and wind observations was found to be due to the short-term changes associated with rawinsonde reports. These reported changes are the sum of rawin error and real mesoscale variations. This is "noise" that can be eliminated by analysis procedures, such as that leading up to numerical forecasting. The ATS vectors, therefore, may correspond better to the desired synoptic field of motion than do the individual balloon winds. Hence, the value of ATS vectors to synoptic analysis is not truly represented by deviations from individual balloon reports. The real deviations between ATS vectors and air flow must be assessed by a much more sophisticated method--perhaps by incorporating these data into a numerical analysis scheme with appropriate dynamic constraints.

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