A Comparison of Low-Cloud Satellite Wind Estimates with Analyses Based on Aircraft Observations in a Disturbed Tropical Regime

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ABSTRACT

Low-level, ATS-3 satellite wind estimates are compared with values of wind direction and speed interpolated from analyses based on research aircraft observations of a synoptic tropical wave of moderate intensity on 26 July 1969 during BOMEX. The data were stratified according to whether a satellite estimate was positioned in one of three regions; namely, east or west of the wave trough or north of the disturbance center. When cloud and analysis vector magnitude deviations were computed, regional differences became apparent. These differences are attributed to the physical behavior of the cloud targets tracked under the influence of the surrounding large-scale environment.

1. Introduction

A recent two-part article by Smith *et al.* (1975) examined a low-level mesoscale cyclone embedded in a tropical wave that passed near the island of Barbados on 26 July 1969 during BOMEX. Research aircraft observations formed the primary data source of that study. Independently, these systems were investigated by Hasler (1973a) who employed satellite cloud motions only. Parts of both data sets will be compared here. Values of wind direction and speed are interpolated at the cloud estimate positions from streamline and isotach analyses, principally at 1000 and 850 mb, which appeared in the first mentioned report.

Hubert and Timchalk (1972) compared low-cloud motions with BOMEX ship rawins between 21 June and 28 July 1969. Vector deviations of cloud motions from the observed winds were computed only if the Applications Technology Satellite (ATS) vectors were within 371 km of the ship locations and the mid-periods of the ATS-3 sequences were within ±3 h of the ship observation times. For a set of 55 observation pairs, they computed a mean vector magnitude deviation of about 3.6 m s^{-1}, attributing at least half of that value to short-period changes of the balloon-observed wind. The investigators concluded that these changes were the sum of rawin error and real mesoscale variations.

The primary purpose of this article is to suggest that, in order to properly evaluate satellite wind estimates in *disturbed* tropical situations, spatial stratification of the data is required. In this study, inasmuch as the low-cloud satellite estimates were fairly uniformly distributed in space around the wave, the data are stratified according to whether an estimate lies east or west of the wave trough, or north of the disturbance center. These three regions, henceforth labeled 1, 2, and 3, respectively, form natural divisions of the synoptic wave. From the results of the investigation by Smith *et al.* (1975), at low levels, these regions were distinguished by the following general synoptic characteristics: Region 1, by convergence, upward motion, and deep convection; Region 2, by divergence, subsidence, and suppressed convection; Region 3, by a trade flow that interacted with the northwesterly moving wave.

2. Histories of the synoptic and mesoscale disturbances

The large-scale system under study had a long but not untypical history. According to Frank (1970), on 19 July 1969 it passed Dakar designated as a disturbance on the intertropical convergence zone (ITCZ). On the 26th it reached Barbados in the form of a tropical depression and on the 29th, San Andres in the Caribbean as a wave.

The mesoscale cyclone, investigated by research aircraft on 26 July north of Barbados, had a known history of about 10 h. Spiral banding of echoes on the Barbados radar during the early morning hours of 26 July first indicated that a low-level cyclonic circulation was embedded in the synoptic trough. Confirmation came from the aircraft flights which probed the mesoscale system during its phase of maximum intensity. A marked weakening of the low-level cyclonic circulation, but not the synoptic wave, is presumed to have followed within a few hours.

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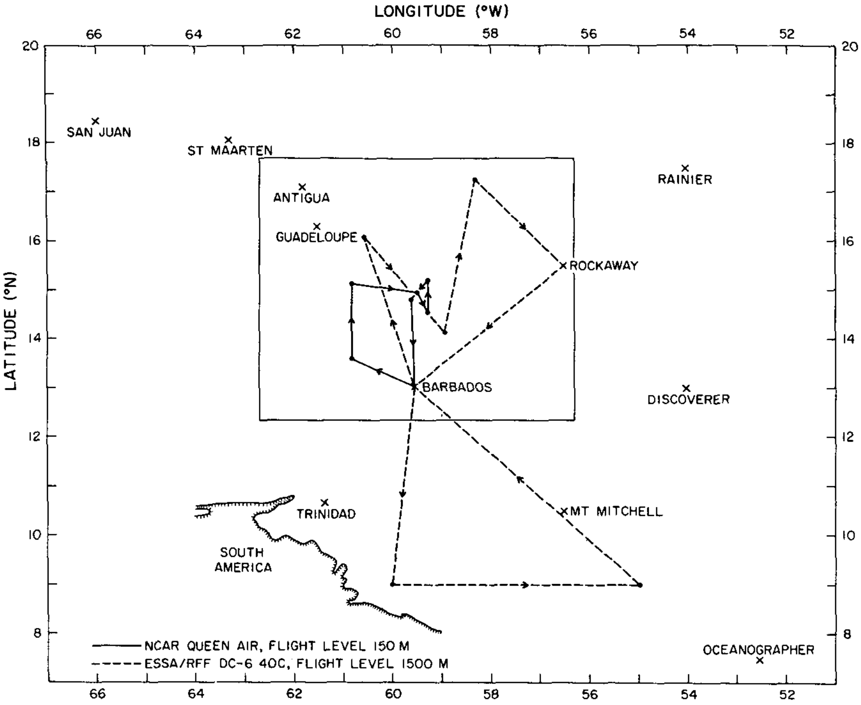

FIG. 1. BOMEX rawinsonde network 26 July 1969 with Queen Air and DC-6 flight tracks.

3. Data

a. Analysis area

Fig. 1 shows the BOMEX rawinsonde network in operation on 26 July 1969 with the flight patterns of the research aircraft[3] flying at 150 and 1500 m (1000 and 850 mb). The inner $5\frac{1}{3}^\circ$ by $6\frac{1}{3}^\circ$ rectangle defines the area where the satellite low-cloud wind estimates and the analysis data will be compared.

b. Accuracy of satellite observations

The ATS-3 spin-scan cloud camera produces a high-resolution photograph every 25 min. A sequence of seven ATS-3 pictures for the 3 h time interval, 1300 to 1600 GMT, were made into a film loop from which cloud displacements were measured.

Random and systematic cloud motion errors due to the navigation of points on the satellite picture to corresponding locations on the earth's surface were estimated. Navigation involves relating the x, y coordinate system of the picture to the spherical coordinate system of the earth and includes the effects of the satellite position. The random error in the cloud motion was found to have a standard deviation of 0.5 m s^{-1} in speed and 2.5° in direction. Near primary landmarks in the area of interest the systematic error was usually close to zero but seldom greater than 1 m s^{-1}. Near secondary landmarks, those located some distance away from the primaries, the systematic error was seldom greater than 1.5 m s^{-1}. The vector magnitude error in low-cloud tracking is estimated to have a standard deviation of 1.5 m s^{-1}.

c. Accuracy of analyses based on aircraft observations

The data sampling rate of both the Queen Air and the DC-6 was 1 s^{-1}. Averages over a period of 60 s eliminated high-frequency random errors.

The DC-6 carried the APN-82 as its standard Doppler navigation and wind computing system. Using a wind speed of 10 m s^{-1}, the approximate average speed of both satellite estimates and aircraft winds in the comparison area (Fig. 1), the accuracy tolerance for the wind computing system is ±7.9° and ±1.5 m s^{-1}, for wind direction and speed, respectively (Friedman *et al.*, 1970). While no similar Doppler wind system accuracy estimate is available for the Queen Air, experience has shown that for wind speeds of at least 5 m s^{-1} mean-value differences are less than 1 m s^{-1} in wind speed and 10° in direction. The vector magnitude error of the analyses is estimated to have a standard deviation of 1.8 m s^{-1}.

d. Assessment criterion

A basis is needed to determine when the deviations of the cloud motions from the analyzed winds are greater than expected as a result of the errors in each

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[3] The Queen Air was operated by the National Center for Atmospheric Research (NCAR) and the DC-6 by the Environmental Science Services Administration (ESSA), now the National Oceanic and Atmospheric Administration (NOAA).

data set. Expressed in terms of standard deviation, the error estimates of the satellite and analysis data sets were found to be 1.5 and 1.8 m s^{-1}, respectively. A standard deviation of 2.3 m s^{-1} is the result of combining the two (the square root of the sum of the squares of the error estimates).

If most vector deviations in a region are less than 2.3 m s^{-1}, the cloud motions are indistinguishable from the analyzed winds. If, however, they *systematically* exceed 2.3 m s^{-1}, the implication is strong that the aircraft and satellite are not measuring the same motion fields.

Systematic deviations greater than the criterion may arise for a number of reasons. As examples, the proper comparison of height level, if one exists, is unknown, or the cloud target may for physical reasons move differently from the wind. In a thorough treatment of problems related to satellite-tracked cumulus, Fujita *et al.* (1975) emphasized errors as a result of the last mentioned possibility.

e. *Study limitations*

There are two basic limitations inherent in this study. First, there is no direct evidence of cloud height,[4] nor cloud base, of the satellite observations. Therefore, an attempt will be made to find a *level of best fit*, a concept of Hubert and Whitney (1971), by comparing the low-cloud estimates with analyses at 1000 and 850 mb and an interpolated level[5], 950 mb, which may be interpreted as a cloud-base wind level at about 575–600 m.

The second limitation concerns the different times represented by the satellite and aircraft observations. The time of all satellite observations was 1430 GMT, the mid-time of the 1300–1600 GMT period over which the estimates were made. The time of the analyses was 1600 GMT, the time when all research aircraft made their closest approaches to the low-level vortex center. For the 24 h period prior to 1200 GMT 26 July, the synoptic wave was estimated to have been moving at a speed of 6.2 m s^{-1} on a heading of 310°. During the period 1300–1700 GMT 26 July, the embedded cyclonic system took a more northerly heading, approximately 330° at 8.2 m s^{-1}.

In order to account for the translation of the vortex and trough between 1430 and 1600 GMT, henceforth called *system translation*, the satellite wind estimates were displaced (44.3 km) along the heading of the low-level vortex during the period 1300–1700 GMT. But first, effects due to not considering and then considering system translation are examined.

4. Results

a. *Superposition of satellite estimates on 850 mb analysis*

Figs. 2 and 3, *without* and *with* system translation, respectively, show streamline and isotach (kt) analyses at the 850 mb level on which 30 low-cloud satellite estimates have been superimposed. The DC-6 aircraft observations represent 60 s averages plotted at consecutive 5 min positions. The analyses, however, are based on original plots of 60 s averages. Near the disturbance center a few of these 1 min observations have been entered in order to provide a better definition of the flow. Triangles placed near the observations identify half-hourly (GMT) positions of the aircraft.

Rawinsonde observations in these figures are for 1200 GMT.

The satellite winds are distinguished by arrowheads. Numerals of wind direction and speed (dddff) in degrees and knots are plotted below the satellite observations, and for convenient reference each vector carries an identification number. Satellite winds Nos. 1–10 are in Region 1, Nos. 11–20 in Region 2, and Nos. 21–30 in Region 3.

The main effect of system translation (compare Figs. 2 and 3) is reflected by satellite winds Nos. 13, 17, and 19. With system translation (Fig. 3) these vectors became more compatible with the analyzed flow field. Further comment on the effects of system translation will be made in the next section concerning the mean vector deviation computations.

An examination of Fig. 3 north of the disturbance center (Region 3) reveals excellent agreement in wind direction and speed between the satellite winds and the analysis. West of the trough (Region 2) agreement in direction is also excellent but satellite wind speeds were faster. East of the trough (Region 1) agreement in both direction and speed is poor. Satellite winds Nos. 3 and 4 in Region 1 are inconsistent—even with a flow field solely determined by the satellite winds. It can be demonstrated that they are also unrepresentative of the flow below 850 mb, and in fact correlate best with a flow between 700 and 500 mb. They will not be included in any of the vector deviation computations.

b. *Vector magnitude deviations*

Vector deviations at the cloud estimate positions were computed for the three analysis levels, without and with translation, and regional means obtained. The result for the 850 mb level was 5.8, 6.2, and 1.9 m s^{-1} for Regions 1, 2, and 3, respectively, *without* system translation, and 5.5, 3.0, and 2.1 m s^{-1} *with* system translation. The mean vector deviations of Regions 1 and 3 were not changed significantly by system translation and the reduction in the mean vector deviation of Region 2 was primarily the result of three estimates, Nos. 13, 17, and 19, representing observations on the mesoscale, which were shifted from positions east of the trough

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[4] In certain parts of the comparison area (Fig. 1), from aircraft motion picture photography and radar range-height measurements, information is available on cloud height but not corresponding to a particular cloud target.

[5] For convenience, the 1000, 950, and 850 mb levels will all be called "analysis levels." The 950 mb level was obtained through the use of a vertical interpolation program described in the article by Smith *et al.* (1975).

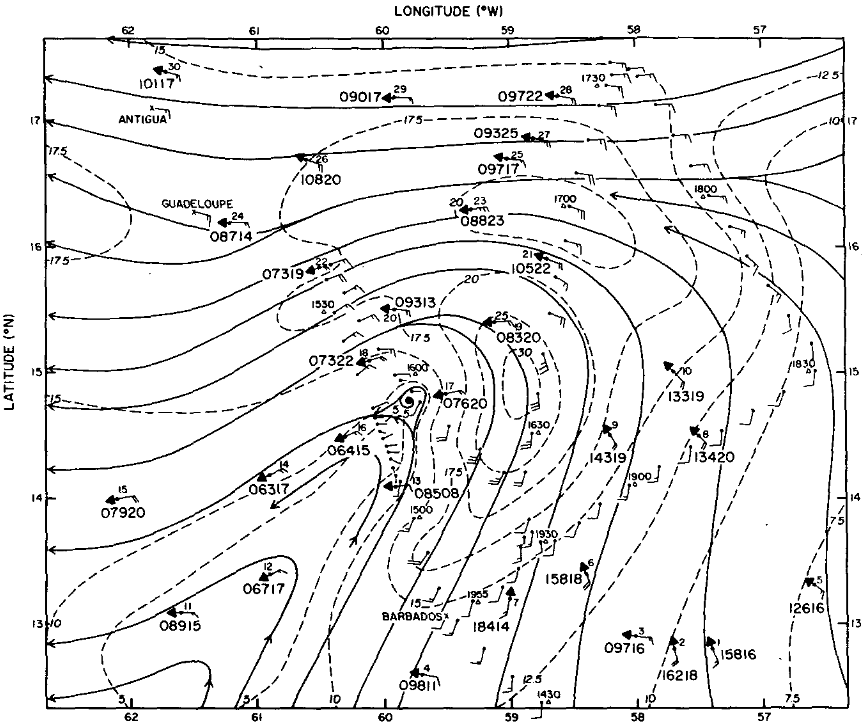

FIG. 2. Superposition of satellite cloud vectors (arrow-headed symbols) on 850 mb streamline and isotach analyses (kt) *without* system translation (see text for explanation).

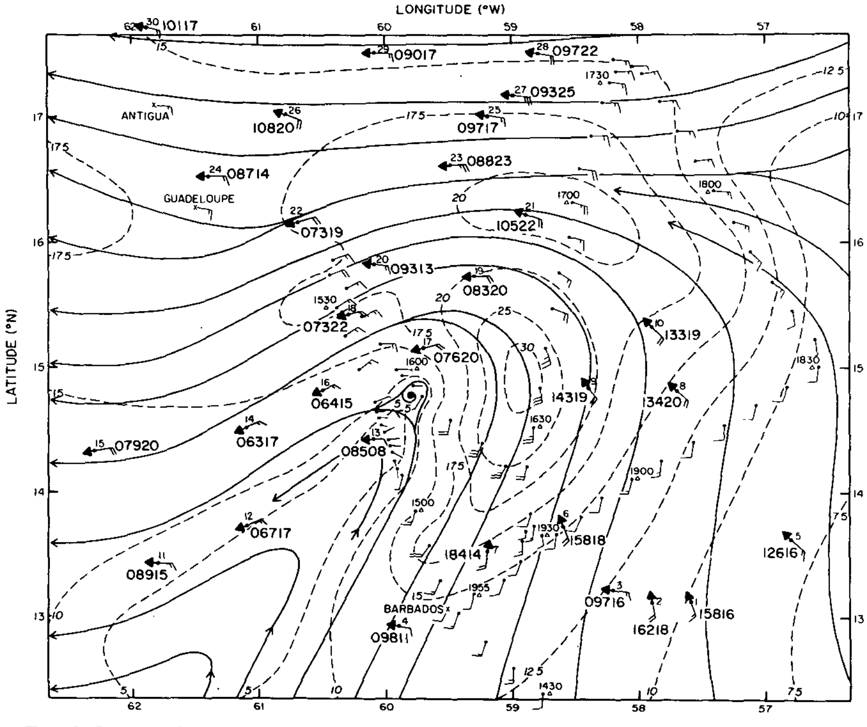

FIG. 3. Superposition of satellite cloud vectors (arrow-headed symbols) on 850 mb streamline and isotach analyses (kt) *with* system translation. See text and compare with Fig. 2 to note the northwestward displacement of the satellite estimates.

to the west of it. A similar effect was noted at the two other analysis levels. All further reference to vector deviation computations reflect system translation.

The vector deviation for each observation pair by region at the 1000, 950, and 850 mb levels is listed in Table 1. An asterisk indicates those observations which meet the assessment criterion of less than or equal to 2.3 m s^{-1}. The levels of best fit are the 950 mb level for Region 1, 850 mb for Region 2, and the 1000 mb level for Region 3.

TABLE 1. Vector magnitude deviations (m s^{-1}) between satellite low-cloud estimates and analyses by region (with system translation).

Vector No.	1000 mb	950 mb	850 mb
Region 1			
1	3.4	4.0	3.9
2	3.6	4.7	4.6
5	6.6	7.0	6.7
6	3.9	6.1	5.6
7	2.9	2.5	2.9
8	4.6	3.7	7.7
9	2.6	2.2*	8.3
10	4.7	1.6*	4.4
Mean	4.0	4.0	5.5
Standard deviation	1.3	1.9	1.9
Region 2			
11	4.2	5.1	4.3
12	6.4	5.7	6.2
13	5.2	4.9	2.1*
14	4.6	3.5	2.1*
15	4.7	3.7	3.8
16	5.0	4.2	0.7*
17	0.0*	0.7	2.2
18	2.9	3.4	3.4
19	4.8	4.0	1.3*
20	4.2	5.4	4.1
Mean	4.2	4.1	3.0
Standard deviation	1.7	1.4	1.6
Region 3			
21	0.2*	1.3	1.4
22	0.0*	1.1	0.7
23	2.5	0.3*	2.1
24	2.6	2.2	1.2*
25	1.1	2.5	1.2
26	1.0*	3.0	2.9
27	3.6	3.3	4.2
28	3.7	4.1	4.4
29	3.2	1.8	1.5*
30	1.0*	2.1	1.3
Mean	1.9	2.2	2.1
Standard deviation	1.4	1.1	1.3

The premise of this article, namely that there are important differences among the mean regional vector deviations to warrant stratification of the data, is evidenced in Table 1. The mean vector deviation for Region 3 is approximately half the value of either Region 1 or 2. The disparity between mean deviations comparing levels of best fit, 950 and 850 mb, of Regions 1 and 2, respectively, is not as great, 4.0 vs 3.0.

c. Physical causes of observed cloud target movements

In Region 3, the trade flow area north of the disturbance center, there was little vertical shear in the layer 1000–850 mb, averaging about 0.5 m s^{-1} in speed and less than 10° in direction. Conceivably, the satellite estimates in this region could be used to represent any level from 1000 to 850 mb. Perhaps, trade flow in the north Atlantic southward to its maximum at about 15°N can be so represented, but at lower latitudes this is probably not the case.

For a small area in Region 2 there is some direct evidence concerning how the cloud targets moved. The 16 mm nose camera photography on the DC-6 indicated the type and extent of cloud lines encountered by the aircraft on its northwestward traverse (see Figs. 1 and 3). After it crossed the wave trough, the aircraft passed through a series of cloud lines at intervals of about 30 km. The lines extended lengthwise an estimated 25 km and were about 6 km in width. The lines, oriented almost perpendicular to the flight track, had tops to about 3000 m shearing to the right. Approximately 40 min earlier the NCAR Queen Air was also in this vicinity. On its anticyclonic course around the disturbance, the aircraft made a short surveillance climb to about 1150 m, made a 90° turn toward the mesoscale cyclonic center, and then descended to its normal flight altitude of 150 m. Ascent and descent rates were about 130 m min^{-1}. Fig. 4 shows the ascent and descent paths of the Queen Air in relation to the satellite estimates in this part of Region 2. Hodographs of these two soundings were prepared as shown in Fig. 5. Points at the 850 and 700 mb levels (1500 and 3000 m) were interpolated from the analyses corresponding to an average position during ascent and descent. Also plotted in this figure are the Region 2 satellite vectors.

Both hodographs are similar in profile, except that during descent wind speeds were appreciably higher as the aircraft approached the cyclonic center. It should be noted that wind speeds decreased markedly above 950 m. The two cloud estimates, because of their closest proximity, that can be compared with the ascent and descent hodographs are Nos. 14 and 18, respectively. Both cloud targets moved to the right of and with speeds appropriate to a mean layer wind between 550 and 950 m. A tentative explanation for the rightward movement of the cloud targets with respect to the mean layer wind follows.

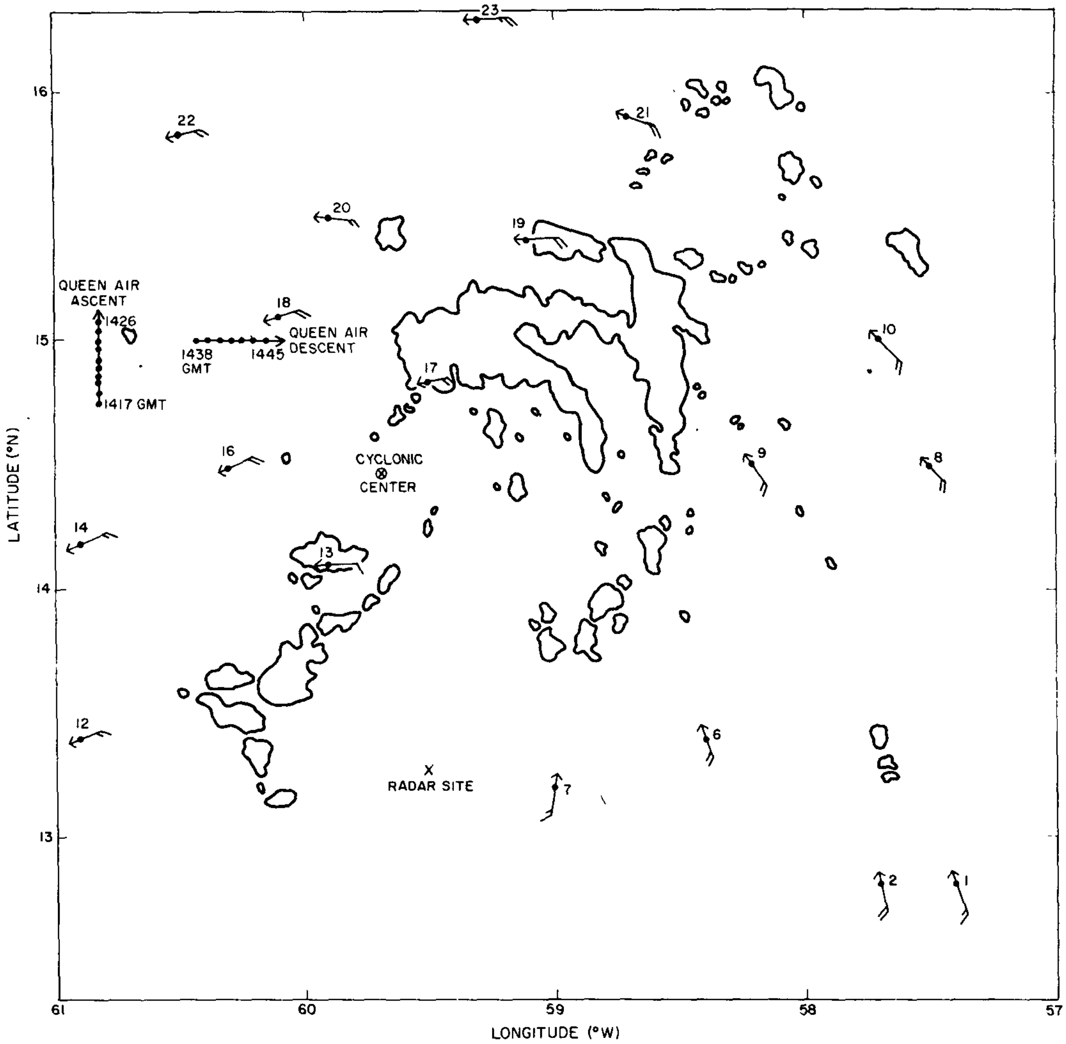

FIG. 4. Barbados radar display at 1427 GMT, selected low-cloud satellite estimates at 1430 GMT, and the positions of the Queen Air during its 1417-1426 GMT ascent and 1438–1445 GMT descent soundings, respectively.

In Region 2 the 1000 mb relative storm inflow[6] was from the north and northwest. In relation to the northeast- to southwest-directed cloud lines as photographed by the DC-6 nose camera, this implies that new clouds built on their north sides. Assuming that the clouds moved in the direction of the lines, the lines and clouds propagated north or northwestward opposite to the relative inflow direction. This is consistent with the observed rightward movement of targets Nos. 14 and 18 relative to the aircraft winds.

The poorest correlation between satellite estimates and the analyses was obtained in Region 1, east of the trough. Relative storm inflow at 1000 mb in this region was from the west and southwest. Analogous, but opposite, to the cloud propagation suggested in Region 2, a leftward movement of cloud targets relative to an observed wind is indicated. Clearly, from Table 1, there is difficulty in assigning a "level of best fit" in this region. Here, a directional shear from 1000 to 850 mb, the wind veering and the speed decreasing with height, averaged about 30°, or about three times the other two regional values.

Finally, in addition to the hodographs previously discussed, Fig. 4 shows the Barbados radar at 1427 GMT and the low-cloud satellite estimates at 1430 GMT. The radar presentation is instantaneous. However, as before, the satellite estimates represent 3 h averages but are positioned without system translation. At least for direction of movement, since the satellite vectors are approximately parallel to the radar bands, a close relationship between cloud targets and corresponding radar echoes may exist.

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[6] See Fig. 10 in Smith *et al.* (1975, Part 1).

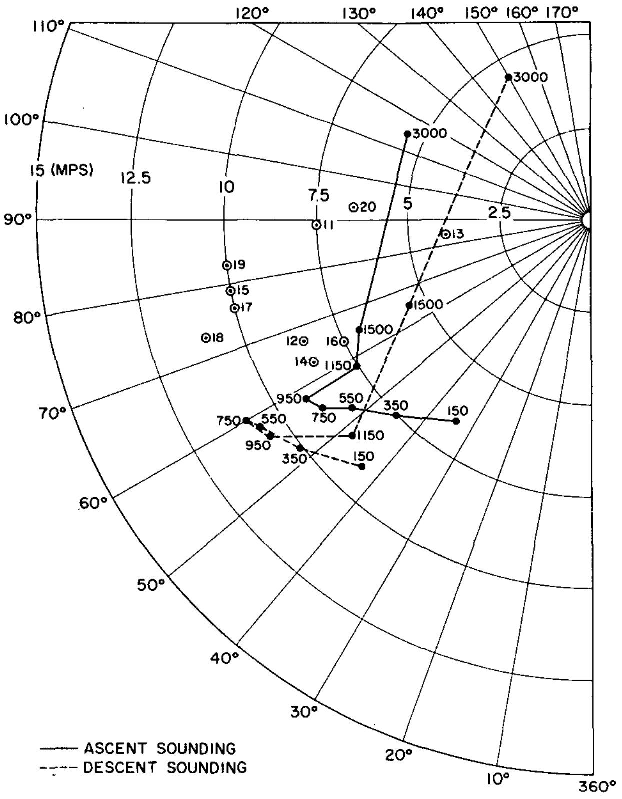

FIG. 5. Hodographs (m s^{-1}) of Queen Air ascent and descent soundings. See text and Fig. 4.

5. Concluding remarks

Regional vector magnitude deviations in this study were found to differ to the extent of suggesting that environmental factors peculiar to the regions influenced the movement of the cloud targets. If this should be always true, then evaluation of satellite estimates used to describe the low-level flow in a synoptic tropical wave should be determined on a regional basis.

Specially designed experiments involving instrumented aircraft with the purpose of directly comparing winds with satellite motions have been carried out in *undisturbed* tropical conditions (Hasler, 1973b; Hasler and Shenk, 1975; Hasler *et al.*, 1976). For *small* samples of cumulus targets obtained in this way, the mean vector magnitude deviation between the cloud motion and the aircraft wind at cloud base was about 1.3 m s^{-1} standard deviation.

These "ground truth," more aptly "air truth," experiments have in their favor the removal of uncertainties regarding cloud height and type as well as those introduced by large space and time differences that frequently arise when the attempt is made to compare satellite motions with conventional wind data. It is recommended that further "air truth" experiments be planned to investigate important features of a tropical wave in relation to satellite cloud motion, e.g., the wind shear in each region, the velocity of cloud propagation, and particularly in Region 1, the active convection region, the relationships among aircraft winds, radar echoes, and cloud motions.

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