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ABSTRACT

An experiment is in progress to verify geostationary satellite derived cloud motion wind estimates by *in situ* aircraft wind velocity measurements. One or more low-level aircraft equipped with Inertial Navigation Systems (INS) were used to define the vertical extent and horizontal motion of a cloud and to measure the ambient wind field. A high-level aircraft, also equipped with an INS, took photographs to describe the horizontal extent of the cloud field and to measure cloud motion. The aerial photographs were also used to make a positive identification in the satellite picture of the cloud observed by the low-level aircraft. To date the experiment has been conducted over the tropical oceans in the vicinity of Florida, Puerto Rico, Panama and in the Western Gulf of Mexico. A total of 60 hours have been spent tracking some 40 tropical cumulus and 5 cirrus clouds. Results for tropical cumulus clouds indicate excellent agreement between the cloud motion and the wind at cloud-base. The magnitude of the vector difference between the cloud motion and the cloud base wind is less than 1.3 m s^{-1} for 67% of the cases with track lengths of 1 hour or longer. Similarly, the one standard deviation of the vector differences between the cloud motion and the wind at sub-cloud (150m), mid-cloud, and cloud-top levels are 1.5, 3.6, and

7.0 ms^{-1}, respectively. The cirrus cloud motions agreed best with the mean wind in the cloud layer with a vector difference of about 1.6 m sec^{-1}.

1. Introduction

Many areas of the world are devoid of conventional rawinsonde data. It is fortunate that cloud motions derived from geostationary satellites can provide a method of estimating the winds at some levels in the regions where they are needed. One example is the tropical oceanic regions which are particularly data poor and where wind is the most definitive quantity for describing the atmosphere. It is a fortunate coincidence that tropical oceanic cumulus clouds are plentiful, reasonably uniformly distributed, and can be easily tracked from the satellite measurements. The second generation geostationary satellite images provide a superb tool for investigating mesoscale phenomena such as severe thunderstorms in which wind is also the definitive parameter because of the short time scale involved. Wind estimates from cloud motions are already in operational use by NOAA in their global numerical prediction model. For these reasons, it is extremely important to verify the accuracy and reliability of these estimates.

Previous evaluations of cloud tracers as wind estimators have been made by comparing them with rawinsonde measurements. Some of these studies are described by Fujita et al (1969), Hasler (1972), and Hubert and Whitney (1971). This evidence has been obtained primarily from comparisons of cloud tracers, whose height is only roughly estimated, with rawinsonde winds up to 250 km distant and up to three hours removed in time. In addition to the disadvantageous time and space separation, there are independent errors produced from the cloud motion measurements and rawinsonde wind measurements and those caused by island orographic effects. Finally, because the rawinsonde balloon is a very small object passing quickly through a layer, it may not be representative of the large scale motions. For these reasons previous evaluations of cloud motions wind estimates are not completely definitive. The comparisons between cloud motions and rawinsonde winds most likely place only an upper limit on the difference between the cloud motion and the true wind.

An improved evaluation of wind estimates from cloud motions results from performing sufficiently accurate in situ measurements of cloud motion and height as well as ambient wind velocity. Phase I of such an improved evaluation was performed and described by Hasler et al, (1975). The results show that for a small sample of cumulus clouds, the magnitude of the vector difference between the cloud base wind and the cloud motion was about 1.2 m s^{-1} while for a single cirrus cloud, the difference was 1.1 m s^{-1}. However, it is necessary to expand the size of the sample for a larger statistical base, and for varied meteo ological situations and cloud conditions.

2. Techniques

Figure 1 gives an overall view of the experimental procedures with a depiction of the aircraft flight patterns used. Low level aircraft equipped with Inertial Navigation Systems (INS) were used to define the vertical extent and development of the cloud, while simultaneously measuring the ambient wind field. Aerial photographs from a high level aircraft, also equipped with an INS, were used to measure the cloud motion. Finally the results were compared with the cloud motions derived from geostationary satellite pictures. The clouds were well enough defined so that the low-level aircraft could also be used to measure the cloud position with respect to time, thus permitting a third determination of cloud motion. All three cloud motion determinations were made by Hasler et al (1975). This paper gives the preliminary results of phase II conducted in the Southwest Caribbean and phase III conducted in the Gulf of Mexico. These results are combined with those from phase I. Only the measurements made by the low level aircraft are presented.

The NCAR Sabreliner and the C130 and P3 from NASA were used to measure cloud heights and the ambient wind velocity. In previous studies, the vertical extent and development of the cloud were quantities which were determined poorly, if at all. In this experiment, the cloud height was determined by having the pilot adjust the aircraft altitude until the plane reached the cloud base, or top, and then read the altitude from the pressure altimeter. For the measurement of the ambient wind velocity, each aircraft was equipped with an INS platform and the standard instruments for determining true air speed such that it was able to measure the wind with an accuracy of approximately 1.4 m s^{-1} (Kelley and Zruber, 1973). If the effect of the nominal INS error of 0.5 m s^{-1} were removed, the accuracy would be about 1.3 m s^{-1}. The wind measurements were taken from one minute averages on straight and level flight legs at 150 m, cloud base, mid-cloud, and cloud top.

Discrete cloud tracers with long lifetimes were found near enough to the base of operations so that they could be tracked by the aircraft for long periods.

The location of the cloud center was done by measuring cloud entrance, center, and exit on each pass. The cloud centers were generally located by the low level aircraft within an accuracy of one km at five minute intervals. The method of computing cloud motion from these data was as follows: (1) The cloud motion direction was obtained from a least squares fit of successive cloud positions; and, (2) the cloud speed was computed from the sum of the components parallel to the least squares direction, divided by the time difference between the first and last cloud position. For a cloud track of one hour using the first and last cloud locations only, the cloud motion error due to the error in center determination of one km was 0.35 m s^{-1}. In order to estimate the error when all the cloud tracking data were used, a random error with a standard deviation of one km/$\sqrt{2}$ was added to the x and y coordinates of each cloud location. Then for the phase I measurements, the absolute value of the vector difference between the cloud velocity with and without the random error was determined 25 times for each of the 7 cloud tracks. For all 7 tracks, averaging 0.9 hours in length, the average vector difference was 0.32 m s^{-1}, so apparently there was a slight improvement in accuracy using all the tracking data, even over the shorter time interval. Combining the 0.32 m s^{-1} with the nominal drift error of 0.5 m s^{-1} gave an upper limit to the total error of 0.6 m s^{-1} for the cumulus-cloud motions measured by the low-level aircraft. The errors for cirrus clouds were somewhat higher because of their more diffuse nature.

To add the wind and cloud velocity errors, the square root of the sum of the squares was taken which gave the results of approximately 1.5 ms^{-1} if the INS errors are included, and just over 1.3 m s^{-1} if they are not. Because the ambient-wind measurement and the cloud-motion measurement are made using the same aircraft INS platform, the INS drift error is identical and is eliminated when differences are computed. Therefore, for this experiment, random differences of 1.3 m s^{-1} would be expected between the cumulus cloud motion and the ambient wind even if the clouds were perfect tracers.

3. Results

Table 1 summarizes the results of the experiment for cumulus clouds. Forty trade wind cumulus clouds were tracked at 4 different locations in the Caribbean and the Gulf of Mexico. The cumulus clouds ranged in horizontal size from 3-15 km. The cloud bases were quite uniform at about 960 mb, while most of the tops were at about 600-700 mb ranging to as high as 200 mb. The velocity of the cloud as determined by the low-level aircraft is compared with the wind at 150 m, cloud base, mid-cloud, and cloud top that is measured by the same aircraft. The 21 cases with track lengths of one hour or longer are the most indicative of the best comparison of the cloud motion and the wind, since experimental errors are minimized.

The magnitude of the vector difference between the aircraft-measured cloud motion and the cloud-base wind is less than 1.3 m s^{-1} for 67% of the cases with track lengths over one hour as shown in Table 1. This excellent agreement is just about what would be expected from the error analysis if the clouds were perfect tracers. While it cannot be concluded that the clouds are perfect tracers, this is evidence for establishing the upper limit on the difference between the cloud motion and the cloud base wind. The magnitude of the vector difference at the 150m sub-cloud level (1.5 m s^{-1}) is almost the same as that at cloud base. It is also apparent from Table 1 that the wind at higher levels in the cloud did not compare as well with the cloud motion. For 67% of the cases, the mid-cloud and cloud top wind vectors differed in magnitude from the cloud motion by 3.6 m s^{-1} and 7.0 m s^{-1}, respectively. There is little evidence that the clouds move at a speed or direction systematically different from the wind at cloud base. On the average, the cloud speed is 0.2 m s^{-1} greater than the cloud base wind speed and the cloud moves 0.8° to the left of the wind. Since these differences are much less than the instrumental error, the systematic bias of the wind estimate is considered to be negligible.

Table 2 summarizes the results of the experiment for cirrus clouds. A small sample of 5 cirrus clouds with altitudes of 8.5 to 12.8 km have been tracked. The first case study was obtained over the eastern Gulf of Mexico and the remaining four cases were northeast of Panama in the Caribbean. The velocity of the clouds as determined by successive in situ position measurements, is compared with the wind at cloud base, mid-cloud, cloud top and with the mean wind for the cloud layer. The cirrus clouds are less discrete and therefore more difficult to track accurately with aircraft than the cumulus cloud.

The magnitude of the vector difference between the cirrus cloud velocity and the mean wind of the cloud layer is about 1.6 m s^{-1}. It is felt that the major source of error is the difficulty in locating the position of the cloud. The differences for cloud base, mid-cloud and cloud top of 2.2 m s^{-1}, 2.0 m s^{-1} and 2.8 m s^{-1}, respectively, were slightly greater than the mean wind difference, but give no significant information as to variation with height. The cirrus cloud speed averages 0.2 m s^{-1} greater than the mean wind in the cloud layer and the cloud moves 2.6° to the right of the wind on the average. Again since these differences were far less than the instrumental error, the systematic bias of the wind estimate is considered to be negligible.

4. Conclusions

This data set indicates that there is excellent agreement between cloud motion and the ambient wind for tropical oceanic cumulus clouds and cirrus clouds. Trade wind regime cumulus clouds were found to move within 1.3 m s^{-1} of the wind at cloud base, while isolated cirrus clouds moved within about 1.6 m s^{-1} of the mean wind in the cloud layer. Any systematic bias of the cloud-motion wind estimates was found to be negligible.

The error analysis shows that if the cumulus clouds were perfect tracers, there should be a difference of about 1.3 m s^{-1}. Therefore, an upper limit has been established for the difference between the motion of trade wind cumulus clouds and the ambient wind which is much smaller than those previously found.

For cirrus clouds, the difference found is also far smaller than those established in previous comparisons.

In conclusion, this experiment has provided evidence that cloud-motion wind estimates can have sufficient accuracy to be used to make the sensitive divergence, vorticity, and vertical motion calculations necessary to describe the dynamics of the atmosphere.

5. Future Work

The primary direction of further work is to continue to increase the sample size, especially for cirrus clouds. Data must be obtained under varying weather regimes, in particular for disturbed weather conditions including storms. Measurements are needed for different geographical regions. For example, comparisons are needed at higher latitudes and over land. Also, data are needed for additional cloud types. It is necessary to positively identify the aircraft tracked clouds in the satellite pictures. Future experiments must attempt to check the representativeness of the cloud-motion wind estimate over longer time intervals. One planned method is to compare the cloud motion with the motion of constant level balloons. If possible, this will be done by launching the balloons from an aircraft in close proximity to the clouds, for a true in situ verification. Since constant level balloons approach the characteristics of perfect tracers, this is the one possibility of achieving a significant improvement in accuracy of the experiments. Further analysis in progress includes the measurement of cloud top heights from the stereo aerial photographs. These data are being compared with cloud heights derived from SMS visible and infrared measurements. Infrared radiometer data will be obtained by the high-level aircraft in future experiments. These data will be used to investigate techniques for measuring cloud heights using present and future geostationary satellite data systems.

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Table 1

WIND ESTIMATES FROM CLOUD MOTIONS:
PHASES I, II AND III OF AN IN SITU AIRCRAFT VERIFICATION EXPERIMENT
RESULTS - TROPICAL OCEANIC CUMULUS CLOUDS

DATE	LOCATION	AIRCRAFT	NUMBER OF CLOUD TRACKS	SYSTEMATIC BIAS: AVE CLOUD SPEED ($m\ sec^{-1}$)	SYSTEMATIC BIAS: AVE WIND SPEED AT CLOUD BASE (m	SYSTEMATIC BIAS: Δ SPEED ($m\ sec^{-1}$)	SYSTEMATIC BIAS: DIRECTION (CLOUD - CB WIND) (degree)	$\lvert \vec{V}_{CLOUD} - \vec{V}_{WIND} \rvert$ SPEED ($m\ sec^{-1}$): 150 m	CLOUD BASE	MID CLOUD	CLOUD TOP
DEC 72	N. W. CARIBBEAN	NCAR SABRELINER	6	12.5	12.9	-0.4	1.0		1.2	3.4	5.5
APR 74	S. W. CARIBBEAN	NCAR SABRELINER	10	10.7	10.4	0.3	-2.1	1.9	1.5	2.7	7.0
APR 74	S. W. CARIBBEAN	NASA C130	9	10.0	9.2	0.8	3.4	1.6	1.8	2.8	6.8
JUL 74	GULF OF MEXICO	NASA P3	15	5.1	5.1	0.0	-3.1	1.6	1.4	3.1	5.4
			40 TOTAL								
		TOTAL SAMPLE MEAN		8.7	8.5	0.2	-0.8	1.6	1.5	3.0	6.2
		STANDARD DEVIATION		3.6	3.6			.8	.8	1.2	2.5
		NUMBER OF CASES WITH TRACK LENGTH OF ONE HOUR OR LONGER						13	21	18	17
		MEAN						1.3	1.2	3.1	6.1
		STANDARD DEVIATION						0.6	0.6	1.4	2.5
		67% OF CASES WITH THIS DIFFERENCE OR LESS						1.5	1.3	3.6	7.0

Table 2

WIND ESTIMATES FROM CLOUD MOTIONS:
PHASE II OF AN IN SITU AIRCRAFT VERIFICATION EXPERIMENT PUERTO RICO AND PANAMA C. Z.
RESULTS - CIRRUS CLOUDS

DATE	TRACK LENGTH (hr)	WIND VELOCITY FOR: CLOUD VELOCITY DIR (deg)	CLOUD VELOCITY SPD (m sec⁻¹)	CLOUD LAYER MEAN DIR (deg)	CLOUD LAYER MEAN SPD (m sec⁻¹)	CLOUD BASE DIR (deg)	CLOUD BASE SPD (m sec⁻¹)	MID CLOUD DIR (deg)	MID CLOUD SPD (m sec⁻¹)	CLOUD TOP DIR (deg)	CLOUD TOP SPD (m sec⁻¹)	ESTIMATED CLOUD TOP (10^3 m)	$\lvert\vec{V}_{CLOUD} - \vec{V}_{WIND}\rvert$ SPEED (m sec⁻¹) MEAN	CB	MC	CT
DEC. 5, 1972	0.5	265	20.5	261	20.6	262	20.6	261	20.6	261	20.6	8.5	1.4	1.1	1.4	1.4
APR. 15, 1974	1.7	242	8.9	234	10.4	247	10.4	235	11.6	217	9.7	12.1	2.0	1.7	3.0	4.1
APR. 16, 1974	1.6	218	10.0	217	10.2	218	9.8	213	8.5	220	12.2	12.8	0.2	0.2	1.8	2.2
APR. 18, 1974	2.2	253	8.1	238	8.2	234	9.9	232	8.7	251	6.8	11.3	2.2	3.5	3.1	1.3
APR. 18, 1974	1.0	175	7.6	190	8.8	211	6.8	181	7.6	185	12.5	12.1	2.4	4.5	0.8	5.2
TOTAL SAMPLE MEAN			11.0		11.6								1.6	2.2	2.0	2.8
STANDARD DEVIATION			5.4		5.1								0.9	1.8	1.0	1.1

Δ SPEED = 0.6 m sec^{-1} Δ DIRECTION = 2.6°

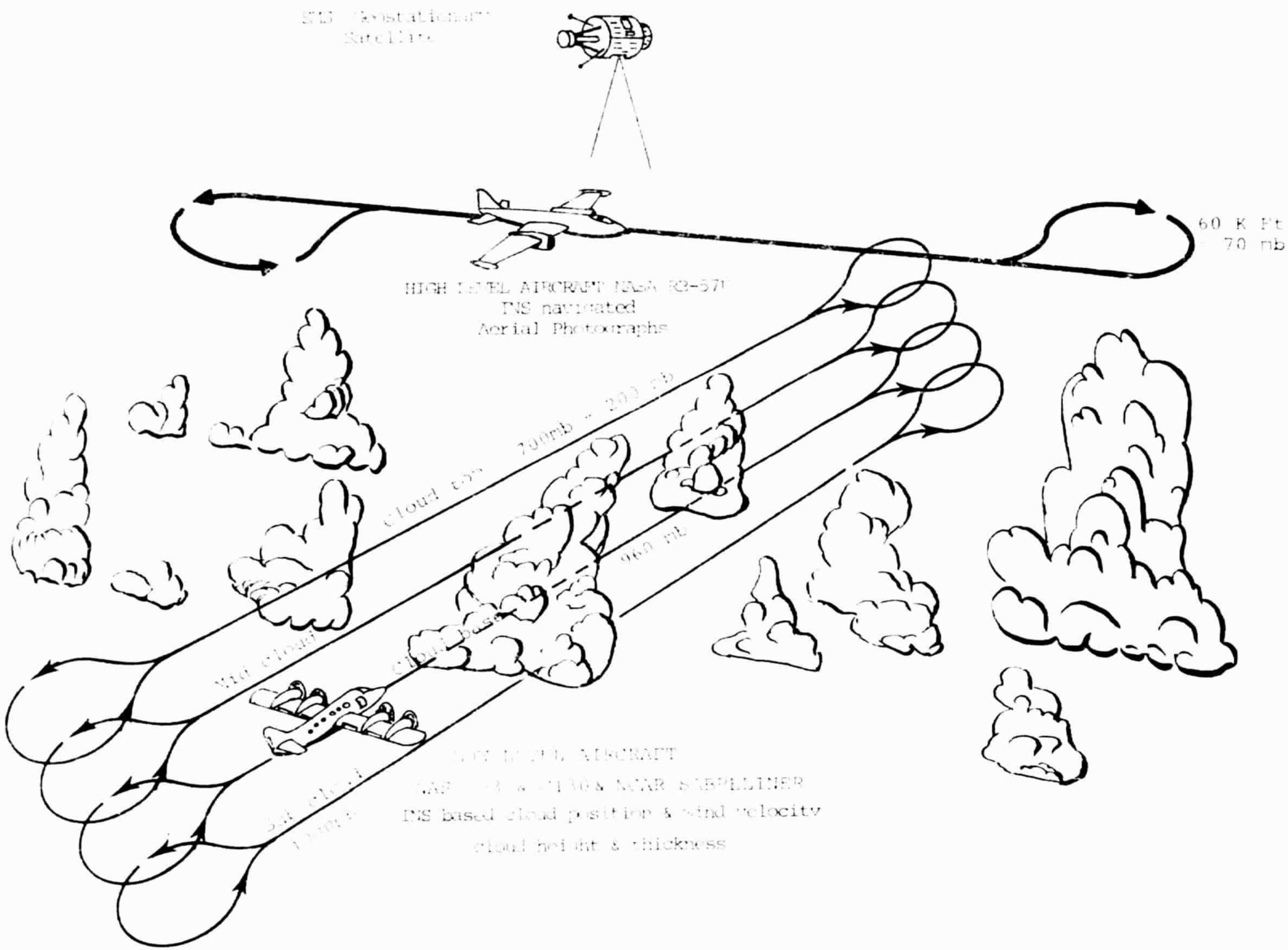

Figure 1. Overall View of Experiment Featuring Aircraft Flight Patterns