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<u>IN</u> <u>SITU</u> AIRCRAFT VERIFICATION OF THE QUALITY OF SATELLITE CLOUD WINDS OVER OCEANIC REGIONS

ABSTRACT

A five year aircraft experiment to verify the quality of satellite cloud winds over oceans using <u>in</u> <u>situ</u> aircraft Inertial Navigation System wind measurements has been completed. The final results show that satellite measured cumulus cloud motions, $\vec{V}_{cloud}$, are very good estimators of the cloud base wind $\vec{V}_{CBW}$, (900 mb to 950 mb), for trade wind and subtropical high regions. The average magnitude of the vector differences between the cloud motion and the cloud base wind ranged from .9 ms^{-1} to 1.7 ms^{-1} $\left[.9\ ms^{-1} \leq \overline{|\vec{V}_{cloud} - \vec{V}_{CBW}|} \leq 1.7\ ms^{-1}\right]$. For cumulus clouds near frontal regions, the cloud motion agreed best with the mean cloud layer wind $\vec{V}_{MCLW}$ $\left[\overline{|\vec{V}_{cloud} - \vec{V}_{MCLW}|} = 2.3\ ms^{-1}\right]$. For a very limited sample, cirrus cloud motions also most closely followed the mean wind in the cloud layer $\left[\overline{|\vec{V}_{cloud} - \vec{V}_{MCLW}|} = 1.7\ ms^{-1}\right]$.

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IN SITU AIRCRAFT VERIFICATION OF THE QUALITY OF SATELLITE CLOUD WINDS OVER OCEANIC REGIONS

1. INTRODUCTION

A global system of five geosynchronous satellites is now in place. Currently it consists of the United States SMS/GOES satellites located at 75°W, 135°W and 60°E longitude; the European Meteosat at 0° longitude and the Japanese GMS at 140°E longitude. This system is likely to be permanent except that the U.S. satellite at 60°E will be replaced by the Indian Insat in 1981. One of the prime objectives of this system is to provide winds from cloud motions around the glove at low and middle latitudes for improved numerical weather forecasting. Many researchers including Fujita et al. (1969), Hasler (1972), Smith and Hasler (1976), Suchman et al. (1977), Rodgers et al. (1977) and Peslen (1977) have shown that wind fields from satellite cloud motions provide good coverage for a wide variety of atmospheric phenomena. They have also demonstrated that cloud wind analyses give reasonable descriptions of the phenomena which are consistent with accepted theories.

The American, European and Japanese meteorological agencies are providing satellite derived cloud winds at least twice a day on an operational basis.

In view of this wide use of the satellite derived cloud winds and the associated high expenditure of resources it is imperative that their quality be validated. Except for the recent research work by Rodgers et al. (1977) and Peslen (1977) and others with special short time interval images almost all satellite cloud winds for research and operations have been determined from images at 30 minute intervals, with horizontal resolutions ranging from 2 to 8 km.

According to Malkus (1949) small cumulus clouds would move at the ambient wind velocity in the absence of vertical shear of the horizontal wind. When vertical shear is present Malkus found that the cumulus cloud will move with a velocity that is primarily a function of the cloud base wind and the magnitude of the shear. However the 30 min geosynchronous satellite observation interval would not temporally resolve the individual cumulus cloud elements. Therefore with the 30 min interval the satellite is only able to follow the history of an ensemble of cumulus cells, a small mesoscale feature with a horizontal dimension of not usually less than 10 km. Wagner and Telford (1976) have concluded that the growth and decay of small cumuli are linked with the air movement at the heat and moisture source below the cloud. Thus it is reasonable to expect the satellite observed cumulus to move closest to the cloud base wind or the wind below cloud base. Hasler et al. (1976) have presented high resolution aerial photography taken as frequently as once every 7 min which show that the lifetimes of individual cells are short, but that cumulus ensembles can maintain a recognizable pattern for well over an hour.

Following the arguments of Malkus, detached passive cirrus cloud elements would be expected to move with the ambient wind in the absence of substantial vertical motion. Active cirrus clouds with upward vertical motion should, like the cumulus, have velocities which are a function of the cloud base wind and the vertical shear. For cirrus, however, cloud lifetimes can often be resolved by the 30 min satellite observations.

There are some clouds which should not have a useful relationship to the ambient flow. Orographic clouds tend to be stationary and clouds caused by gravity waves tend to move with the wave phase velocity and neither would be good estimators of the ambient wind. Studies using radar (Battan, 1973) show that cumulonimbus clouds move with a velocity which is a function of the integrated wind through most of the troposphere.

Satellite cloud motions vs. wind evaluations using rawinsondes have been performed by Fujita et al. (1969), Hubert and Whitney (1971), Hasler (1972), Fujita et al. (1975), Bauer (1976), Suchman and Martin (1976) and Hubert (1976). Hubert's latest study best characterizes this type of evaluation. He finds that for low cloud motions derived from the NOAA/NESS operational system the median magnitude of the vector difference from 900 mb rawinsonde winds is 2.6 ms^{-1} while 68% of the differences are less than 4.0 ms^{-1}. For cirrus cloud motions the median magnitude of the vector difference from rawinsonde winds at the assigned level is 5.7 ms^{-1} and 68% of the differences are less than 8.0 ms^{-1}. This type of comparison is limited by large time and space differences between the observations. In Hubert's work, for example, the time differences are up to 3 hrs, and the horizontal space differences are up to 300 km. Errors in height assignment, particularly for cirrus clouds, are likely to account for a large portion of the differences.

Telford and Wagner (1974) and Wagner and Telford (1976) have done limited comparisons of aircraft measured cloud motions with in situ aircraft winds overland. For three cumulus clouds Wagner and Telford's data show that the magnitude of the vector difference between the cloud motion and the wind below cloud base was about 1.0 ms^{-1}.

The technique used in this study was a comparison of cloud motions measured by satellite and aircraft with aircraft wind measurements that were coincident in time and space (Hasler et al. 1976, 1977). The results from the five year experiment are for undisturbed to moderately disturbed oceanic weather regimes. The experiment was conducted in 5 phases where a total of 77 cloud motion measurements were compared with the ambient winds. The preliminary results from the first 3 phases have been reported by Hasler et al. (1976, 1977). The locations and meteorological conditions of the five phases of the experiment are summarized in Figure 1 and Table 1. In Phase I, a small sample of cumulus clouds (6) and one cirrus cloud were tracked by the NCAR Sabreliner in December 1972 in the northwest Caribbean under conditions of moderate winds and vertical wind shear.

Phase II of the experiment was flown in April 1974 in the southwest Caribbean near Panama. Nineteen low-level clouds were tracked by the NASA C-130 and NCAR Sabreliner under moderate trade wind conditions while four additional cirrus clouds were tracked by the Sabreliner. Phase III was conducted in July 1974 in the Gulf of Mexico under light wind and shear conditions where 15 low clouds were tracked. Phase IV was accomplished in Jan.-Feb. 1976 in the northwestern Atlantic during high wind frontal weather situations near Bermuda which resulted in 25 additional cloud tracking cases. Phase V of the experiment tracked 11 more clouds during February 1977 in the northeastern Atlantic under the high wind suppressed convection conditions in the Azores subtropical high.

TABLE 1. Dates, locations and conditions for the five phases of an experiment for the *in situ* verification of cloud winds

Phase	Date	Location	Weather regime	Average low level wind speed
I	December 1972	N.W. Caribbean	Trade Wind	Moderate 12 ms^{-1}
II	April 1974	S.W. Caribbean	Trade Wind	Moderate 10 ms^{-1}
III	July 1974	Gulf of Mexico	Trade Wind	Light 5 ms^{-1}
IV	Jan.-Feb. 1976	N.W. Atlantic	Frontal	High 17 ms^{-1}
V	February 1977	N.E. Atlantic	Subtropical High	High 17 ms^{-1}

The DMSP high resolution (600m) visible satellite image in Figure 2 shows typical good cumulus cloud wind tracers in the phase II tracking area north of Panama.

2. TECHNIQUES

The basic objective of the experiment is to measure cloud motions from geosynchronous satellite image sequences and to simultaneously determine the wind field of the cloud environment with an aircraft. It was necessary to find isolated clouds with no overcast above, fix their positions as a function of time and measure the wind at the cloud top, mid cloud, cloud base, and for low level cumulus clouds, in the sub-cloud layer (150 m). Cloud positions and wind measurements were made for at least 30 min and up to 2.5 hrs for each cloud. The wind measurements were derived from the Inertial Navigation System (INS) of the aircraft. At each level a straight constant altitude flight line was made through the cloud with at least two minutes in the clear air on each side. This was repeated on a reverse heading so that bias errors originating from air speed, ground speed, heading, track and angle of sideslip could be corrected. Grossman (1977) provides a procedure for this correction.

The Grossman technique involves the application of derived wind component equations which assume wind field homogeneity and negligible error in aircraft heading. The uncorrected wind measurements are employed to obtain the component biases along the longitudinal and lateral axes of the aircraft. These biases are then applied to the uncorrected wind in order to arrive at a corrected wind. In this investigation, recorded in-flight wind data were available along the entire length of the aircraft track from the end of a turn, through a cloud, to the beginning of a new turn and a reverse track along approximately the same path. The wind data from cloud exit to the beginning of a turn were averaged to provide an average wind for one leg and the wind data from the end of a turn to cloud entry were averaged for the average wind of the second leg. These average winds, when employed with the bias component equations, permitted the computation of component bias corrections. The resultant combination of corrected and measured wind was utilized as the in situ cloud level wind for the comparisons with cloud motions. Cloud positions were determined at intervals of 5 to 10 minutes using the latitude and longitude given by the aircraft INS as shown in the example in Figure 3. These positions were used to compute the cloud motion and to locate the cloud in the satellite images. Further details on the experimental procedure using the aircraft are given by Hasler et al. (1976, 1977).

The satellite cloud motions were measured for the 1972 N.W. Caribbean case (Phase I) by techniques described by Hasler et al. (1976). For the 1974, 1976, 1977 phases, measurements were made from sequences of digital SMS/GOES images on the Atmospheric and Oceanographic Information Processing System (AOIPS) at the Goddard Space Flight Center (GSFC). Descriptions of the AOIPS hardware and software systems are given by Billingsley (1976). Cloud motions were determined on AOIPS from image sequences of at least 60 minutes with a partial or complete overlap in time with the aircraft observations. In most cases there was little doubt that the cloud tracked by the satellite and the aircraft were the same. In a few cases due to high level overcast or confusion caused by nearby clouds, a similar cloud within 25 km of the aircraft location was used. According to procedures developed by Hasler and Rodgers (1977) satellite cloud velocity errors of 0.5 ms^{-1} would be expected using an image sequence of 60 min with 1 km resolution SMS/GOES images on AOIPS. The aircraft wind measurements are accurate to 1.4 ms^{-1} (Kelly and Zruber, 1973). Therefore adding the expected error in the satellite measured cloud velocity to the expected aircraft wind error in a root mean square sense the expected measurement error is 1.5 ms^{-1}. The error in the aircraft measured cloud velocities is .6 ms^{-1} (Hasler et al. 1976) so the root mean square sum is also approximately 1.5 ms^{-1} for aircraft cloud velocity vs. aircraft wind comparisons. Adding the expected aircraft cloud velocity error, 0.6 ms^{-1}, to the expected satellite cloud velocity error, 0.5 ms^{-1}, in the same manner yields a total expected measurement error of 0.8 ms^{-1} for comparisons.

3. RESULTS

Aircraft measured cloud motions vs. winds. In Table 2 the final results for all five phases of the experiment are presented. For low level cumulus in moderate trade winds (average cloud speed of 8.7 ms^{-1}) and high wind speed (average cloud speed of 17.8 ms^{-1}) subtropical high regimes, the cloud motions agree best with the winds at cloud base $\left[1.5\ ms^{-1} < \overline{|\vec{V}_{cloud} - \vec{V}_{CBW}|} < 1.8\ ms^{-1}\right]$. Both the average magnitude of the vector difference $\left[\overline{|\vec{V}_{cloud} - \vec{V}_{wind}|}\right]$ and the difference within which two-thirds of each sample were contained $\left[\overline{|\vec{V}_{cloud} - \vec{V}_{wind}|}_{67\%}\right]$ are presented. For low level cumulus in high speed wind regimes near fronts the cloud motions are closest to the mean wind in the cloud layer $\left[\overline{|\vec{V}_{cloud} - \vec{V}_{MCLW}|} = 2.5\ ms^{-1}\right]$. Surprisingly the relationship was the same for the relatively deep convective region ahead of the front and the suppressed convection behind it.

For the few cirrus cases that were tracked in the subtropics, Table 2 shows that the cloud motion agreed best with the mean wind in the cloud layer $\left[\overline{|\vec{V}_{cloud} - \vec{V}_{MCLW}|} = 1.7\ ms^{-1}\right]$, but the agreement at any of the three levels is not significantly different.

Satellite measured cloud motions vs. winds. Table 3 shows cloud motion vs. ambient wind comparisons where the cloud motions were measured from sequences of geosynchronous satellite visible images on AOIPS. The satellite cloud winds vs. aircraft wind comparisons in Table 3 give

TABLE 2. Cloud motion vs. wind*

Cloud type	Oceanic weather regimes	Date	Location	Number of cloud tracks	Ave. cloud speed (ms^{-1})	$\overline{\lvert\vec{V}_{cloud}-\vec{V}_{wind}\rvert} / \lvert\vec{V}_{cloud}-\vec{V}_{wind}\rvert_{67\%}$** ($ms^{-1}$)				
						150m	Cloud base	Mid cloud	Cloud top	Mean in cloud layer
Low level cumulus	Trade wind	Dec 72 Apr 74 Jul 74	N.W. Caribbean S.W. Caribbean G. of Mexico	40	8.7	1.6/1.9	1.5/1.5	2.9/3.4	6.2/6.8	2.8/3.2
	Subtropical high	Feb 77	N.E. Atlantic	6	17.8	3.5/3.7	1.8/1.9	5.4/4.6	9.6/9.1	5.1/4.8
	Frontal	Feb 76	N.W. Atlantic	18	15.3	3.6/3.8	3.2/3.8	2.8/3.3	5.6/6.9	2.5/2.9
Cirrus	Subtropics	Dec 72 Apr 74	W. Caribbean	5	11.0	–	2.2/1.7	2.0/1.8	2.9/2.2	1.7/2.0

*All measurements made in-situ by aircraft equipped with Inertial Navigation Systems

**$\lvert\vec{V}_{cloud}-\vec{V}_{wind}\rvert_{67\%}$ means that 2/3 of the differences have this value or less

TABLE 3. Satellite cloud winds vs. in situ aircraft measurements* for oceanic cumulus clouds

Weather regimes	Date	Location	Number of cloud tracks	Ave. cloud speed (ms^{-1})	$\overline{\lvert \vec{V}_{cloud} - \vec{V}_{wind} \rvert} / \lvert \vec{V}_{cloud} - \vec{V}_{wind} \rvert_{67\%}$** ($ms^{-1}$)				
					150m	Cloud base	Mid cloud	Cloud top	Mean in cloud layer
Trade wind	Dec 72	N.W. Caribbean	6	12.2	—	0.9/1.2	3.2/3.0	5.2/6.0	2.1/3.4
Trade wind	Jul 74	G. of Mexico	10	5.3	1.4/1.7	1.7/1.8	3.4/2.9	5.4/5.4	2.2/3.0
Subtropical	Feb 77	N.E. Atlantic	7	19.0	4.3/4.1	1.7/1.8	4.8/4.3	10.7/11.5	4.8/5.3
Frontal	Feb 76	N.W. Atlantic	19	15.7	4.1/4.2	3.6/4.0	3.0/3.0	5.3/7.8	2.3/2.5

*Aircraft wind measurements made using Inertial Navigation Systems

**$\lvert \vec{V}_{cloud} - \vec{V}_{wind} \rvert_{67\%}$ means that 2/3 of the differences have this value or less the same general results as those in Table 2. However satellite data were not available for the 1974 southwest Caribbean cumulus and cirrus cases. For trade wind and subtropical high cumulus clouds, the motions agree best with the winds at cloud base or below $\left[.9 \text{ msec}^{-1} < |\overline{\vec{V}_{cloud}-\vec{V}_{CBW}}| < 1.7 \text{ ms}^{-1}\right]$. The cumulus cloud motions near fronts again were closest to the mean wind in the cloud layer $\left[|\overline{\vec{V}_{cloud}-\vec{V}_{MCLW}}| = 2.3 \text{ ms}^{-1}\right]$.

Satellite vs aircraft cloud motions. Figure 3 shows a comparison of an aircraft cloud track with a satellite cloud track where an isolated well defined cloud was tracked over nearly identical 2 hr periods of time by both systems. For this case the magnitude of the vector difference was $|\overline{\vec{V}_{cloud_S}-\vec{V}_{cloud_A}}| = 0.3 \text{ ms}^{-1}$. For the cases where aircraft and satellites tracked the same clouds the average differences were $|\overline{\vec{V}_{cloud_S}-\vec{V}_{cloud_A}}| = 1.4, 1.8, 1.5$ and 1.6 ms^{-1} for the 5, 16, 4 and 10 clouds tracked in the N.W. Caribbean, Gulf of Mexico, N.W. Atlantic, and N.E. Atlantic respectively. These differences are about twice as large as the $.8 \text{ ms}^{-1}$ expected error which was calculated in the previous section. This indicates that some clouds must not have been properly identified in the satellite pictures or/and measurement errors were larger than anticipated in some cases.

Bias errors. Table 4 gives the satellite cloud wind (satellite cloud motion) bias errors with respect to the cloud base wind and also the mean wind in the cloud layer (cloud layer wind). For the cloud wind biases with respect to the cloud base wind, all speed biases are 1 ms^{-1} or less. Direction biases are also small for the trade wind N.W. Caribbean case and the subtropical high cases. For the Gulf of Mexico trade wind case the 5.0° systematic direction bias error contributes only slightly to the mean magnitude of the vector difference $\left[|\overline{\vec{V}_{cloud}-\vec{V}_{CBW}}| = 1.7 \text{ ms}^{-1}, \text{ from Table 3}\right]$ because of the low average wind speed of 5.3 ms^{-1}. For the frontal case a nearly identical direction bias error of 5.1° contributes much more to the large vector difference $\left[|\overline{\vec{V}_{cloud}-\vec{V}_{CBW}}| = 3.6 \text{ ms}^{-1}\right]$ because of the high average wind speed of 16.2 ms^{-1}. The cloud wind bias errors with respect to the mean wind in the cloud layer are small only for the frontal case (-1.0 ms^{-1} in speed and $-1.3°$ in direction). Because of the high average wind speed in the frontal case the small direction bias error contributes substantially to the vector difference of $|\overline{\vec{V}_{cloud}-\vec{V}_{MCLW}}| = 2.3 \text{ ms}^{-1}$ between the

TABLE 4. Satellite cloud wind systematic bias errors for oceanic cumulus clouds

Weather regimes	Location	Satellite cloud motion vs. cloud base wind					Satellite cloud motion vs. cloud layer wind				
		Number of cloud tracks	$\overline{V}_{cloud}$ (ms^{-1})	$\overline{V}_{CBW}$ (ms^{-1})	Systematic bias (cloud-CBW)		Number of cloud tracks	$\overline{V}_{cloud}$ (ms^{-1})	$\overline{V}_{MCLW}$ (ms^{-1})	Systematic bias (cloud-MCLW)	
					Speed (ms^{-1})	Direction (deg.)				Speed (ms^{-1})	Direction (deg.)
Trade wind	N.W. Caribbean	6	12.2	12.3	-0.1	0.5	4	12.6	10.8	1.8	-8.2
	G. of Mexico	10	5.3	5.3	0.0	5.0	10	5.3	3.9	1.3	14.8
Subtropical high	N.E. Atlantic	7	19.0	18.0	1.0	1.6	7	19.0	23.0	-4.0	3.7
Frontal	N.W. Atlantic	19	15.7	16.2	-0.5	5.1	19	15.7	16.7	-1.0	-1.3

cloud wind and the cloud layer wind. In the frontal case the cloud wind does not agree with the mean wind in the cloud layer as well as the cloud winds for the other phases agree with the cloud base winds (see Table 3). Therefore the effect of systematic bias error removal was evaluated for this case. From Table 5 it is evident that systematic error removal results in only a very small improvement in the average magnitude of the vectors difference for the mean in the cloud layer, from 2.3 ms^{-1} to 2.2 ms^{-1}. However the removal of large systematic differences in direction would give improvements of 4.1 to 2.6 ms^{-1} and 3.6 to 2.9 ms^{-1} for the 150 m and cloud base levels respectively. Therefore if the cloud winds are used to estimate the mean wind in the cloud layer there would be little purpose in removing systematic errors; but for cloud base or sub-cloud layer wind estimation, removal of the bias errors would be advantageous.

It was also determined that the magnitude of the vector difference between cloud motion and the cloud base wind is not highly correlated to either the wind speed or the vertical shear for the trade wind and subtropical high cases.

Cloud wind height assignment. Satellite cloud winds for oceanic trade wind and subtropical high regions may be assigned to the cloud base altitude. There is no reliable way of measuring cloud base height from geosynchronous satellites so the best method for low level cloud wind height assignment is to use climatology, or surface reports where available. Cloud base altitude statistics for the entire experiment are given in Table 6. The average low level cloud base altitude for the experiment was 936 mb with a standard deviation of only 19 mb. There was a tendency for the low latitude cloud bases to be lower, $\sim \bar{h}$ = 940 mb, and more uniform, $\sim \sigma_h$ = 10 mb, than the higher latitude bases ($\sim \bar{h}$ = 930 mb, $\sim \sigma_h$ = 25 mb). However the total range of the low level cloud bases was only from 977 to 898 mb. Since the low level cumulus cloud bases are very uniform in altitude, assignment of the cloud winds to 950 mb or 900 mb should be sufficiently accurate for most applications.

In frontal regions cumulus cloud winds may be assigned to the middle of the cloud layer. This can be done by measuring the cloud top altitude by the Mosher's combined infrared and visible

TABLE 5. Satellite cloud winds vs. in situ aircraft winds, systematic bias error removed*
Western Atlantic (32°N) Jan-Feb 1976

	150m	Cloud base	Mid cloud	Cloud top	Mean in cloud layer
Before removal of systematic differences $\overline{\lvert \vec{V}_{cloud} - \vec{V}_{wind} \rvert}$ (ms^{-1})	4.1	3.6	3.0	5.3	2.3
Systematic speed differences ΔS (ms^{-1})	-1.2	.5	.8	2.5	1.0
Systematic direction difference ΔD (deg)	-8.1	-5.1	3.5	6.5	1.3
Systematic differences removed $\overline{\lvert \vec{V}_{cloud} - \vec{V}_{wind} \rvert}$ (ms^{-1})	2.6	2.9	2.9	4.8	2.2

*Statistics are based on 19 cases.

method (Suomi, 1975) or stereo techniques (Minzner et al., 1978, and Hasler et al., 1979) and using the cloud base of ~930 mb from Table 6 to calculate the mid-cloud level.

Cirrus cloud winds should be also assigned to the mid-cloud level. Great care must be taken not to underestimate the altitude of the cirrus cloud tops from infrared measurements, but stereo heights show considerable promise for eliminating this problem. It may be best to assign cirrus cloud winds to the cloud top altitude, because the data show little difference between the various levels and it is difficult to make a good estimate of the cloud base height.

4. SUMMARY AND CONCLUSIONS

For oceanic trade wind cumulus and cumulus in oceanic subtropical high regions, satellite cloud motions estimate the wind at cloud base at approximately the limit of the instrumental accuracy possible from this experiment $\left[.9\ ms^{-1} \leqslant \overline{\lvert \vec{V}_{cloud} - \vec{V}_{CBW} \rvert} \leqslant 1.7\ ms^{-1}\right]$ with no significant bias errors. For oceanic cumulus clouds near fronts, agreement is best with the mean wind in the cloud layer $\left[\overline{\lvert \vec{V}_{cloud} - \vec{V}_{MCLW} \rvert} = 2.3\ ms^{-1}\right]$. The differences are larger in this case, but removal of

TABLE 6. Cloud base and cloud top height statistics based on 64 cumulus and 5 cirrus clouds

Cloud type	Weather regimes	Location	Cloud bases (mb)				Cloud tops (mb)			
			Mean height ($\bar{h}$)	Standard deviation (σ_h)	Minimum height ($h_{min.}$)	Maximum height ($h_{max.}$)	Mean height ($\bar{h}$)	Standard deviation (σ_h)	Minimum height ($h_{min.}$)	Maximum height ($h_{max.}$)
Low level cumulus	Trade winds	N.W. Caribbean	946	11.5	960	930	721	55.6	810	205
		S.W. Caribbean	943	7.5	956	932	671	86.6	797	565
		G. of Mexico	939	5.8	942	925	492	134.4	753	301
	Subtropical high	N.E. Atlantic	927	27.1	974	901	753	110.7	901	558
	Frontal (N.W. Atlantic)	Pre frontal	938	23.1	977	898	613	96.8	736	416
		Post frontal	915	15.5	944	898	757	38.9	827	716
		Combined frontal	931	23.6	977	898	659	102.7	827	416
	Combined low level		936	19.0	977	898			901	205
Cirrus		W. Caribbean	275	62.2	345	197	219	64.4	331	171

systematic errors produces no significant improvement. For high level cirrus cloud motions measured by aircraft, the comparison agreement is also best with the mean wind in the cloud layer $\left[\overline{|\vec{V}_{cloud} - \vec{V}_{MCLW}|} = 1.7 \text{ ms}^{-1} \right]$, but is not significantly better than the agreement with the cloud base or top wind. It is concluded that for most equatorial through mid latitude ocean areas of the world, satellite cloud motions can be used to estimate the low level (cloud base) winds with high accuracy. There is not reliable method yet demonstrated of estimating cloud base altitudes from geosynchronous satellite orbit, but low level cumulus cloud bases are very uniform in height and can be determined within a few tens of mb from climatology and/or from relatively widely spaced surface station reports. The 64 cumulus clouds measured in this experiment had an average cloud base height of $\overline{h}$ = 936 mb with a standard deviation of only σ_h = 19 mb.

In frontal regions cumulus cloud top altitudes should be determined from infrared or stereo measurements and the cloud wind assigned to the mid cloud level. Cirrus cloud winds should also be assigned to the mid cloud level if it can be determined, but assignment to the cloud top level is probably satisfactory.

Satellite cloud motions can be excellent estimators of the wind for carefully selected tracers which are not affected by gravity waves or orography. Proper height assignment of the cloud winds is also extremely important and has probably contributed most to poor wind estimation in the past (e.g., the case of thin cirrus cloud motions assigned to too low a level).

5. FUTURE WORK

It is still necessary to obtain more data for cumulus clouds in other oceans, over land and under disturbed conditions to more fully assess cloud motion wind relationships. The sample size for cirrus clouds needs to be increased and comparisons made in high wind shear situations (e.g., jet streams). There is potential for better comparisons with rawinsondes if geosynchronous satellite stereo observations become available in regions where cloud winds can be measured coincidently in time and space with the rawinsondes. In the immediate future the experiment will concentrate on *in situ* aircraft verification under disturbed conditions, particularly over land for the antecedent conditions for severe local storms.

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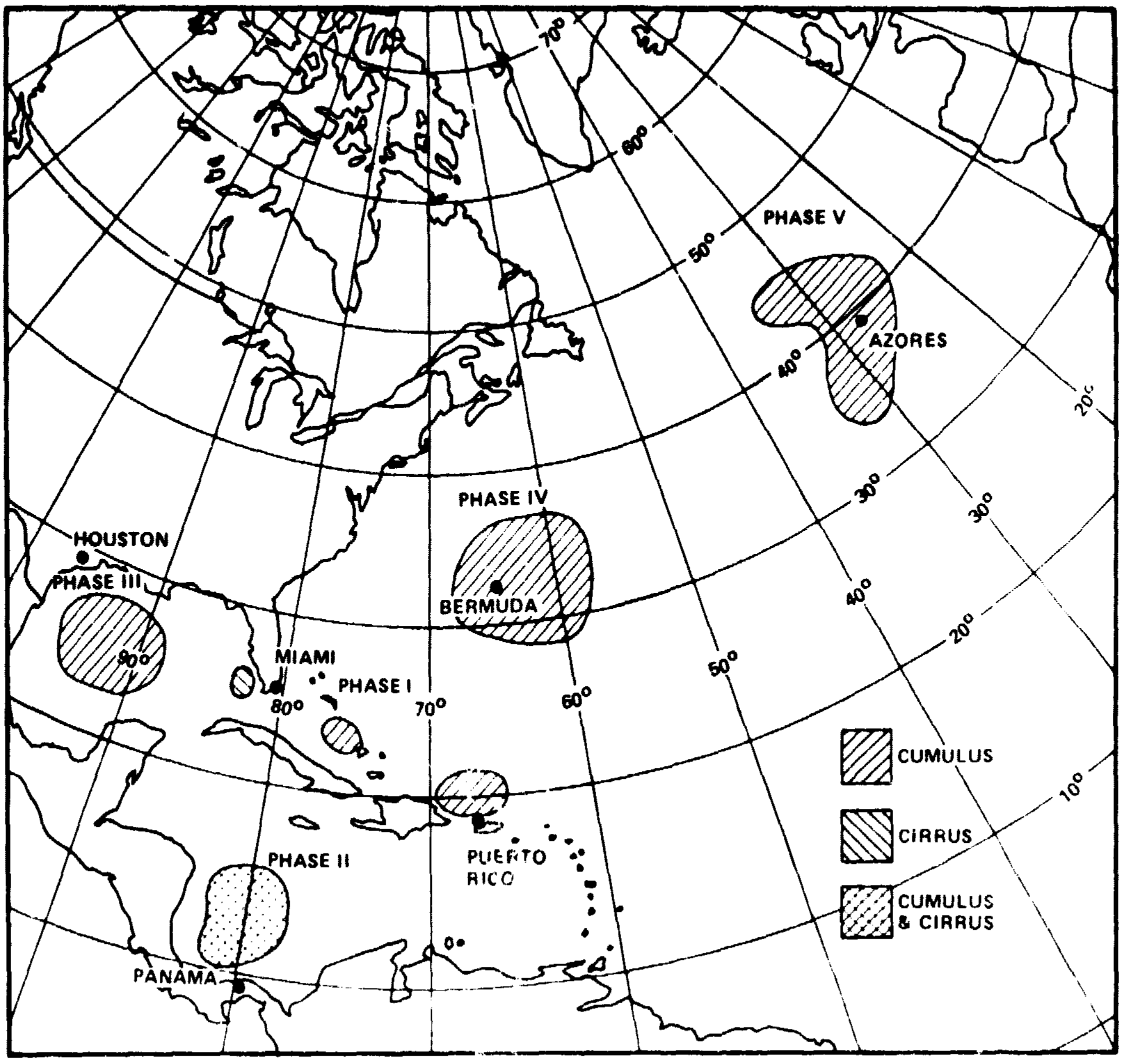

Figure 1. Location for the five phases of an experiment for the in situ verification of satellite cloud winds using aircraft.

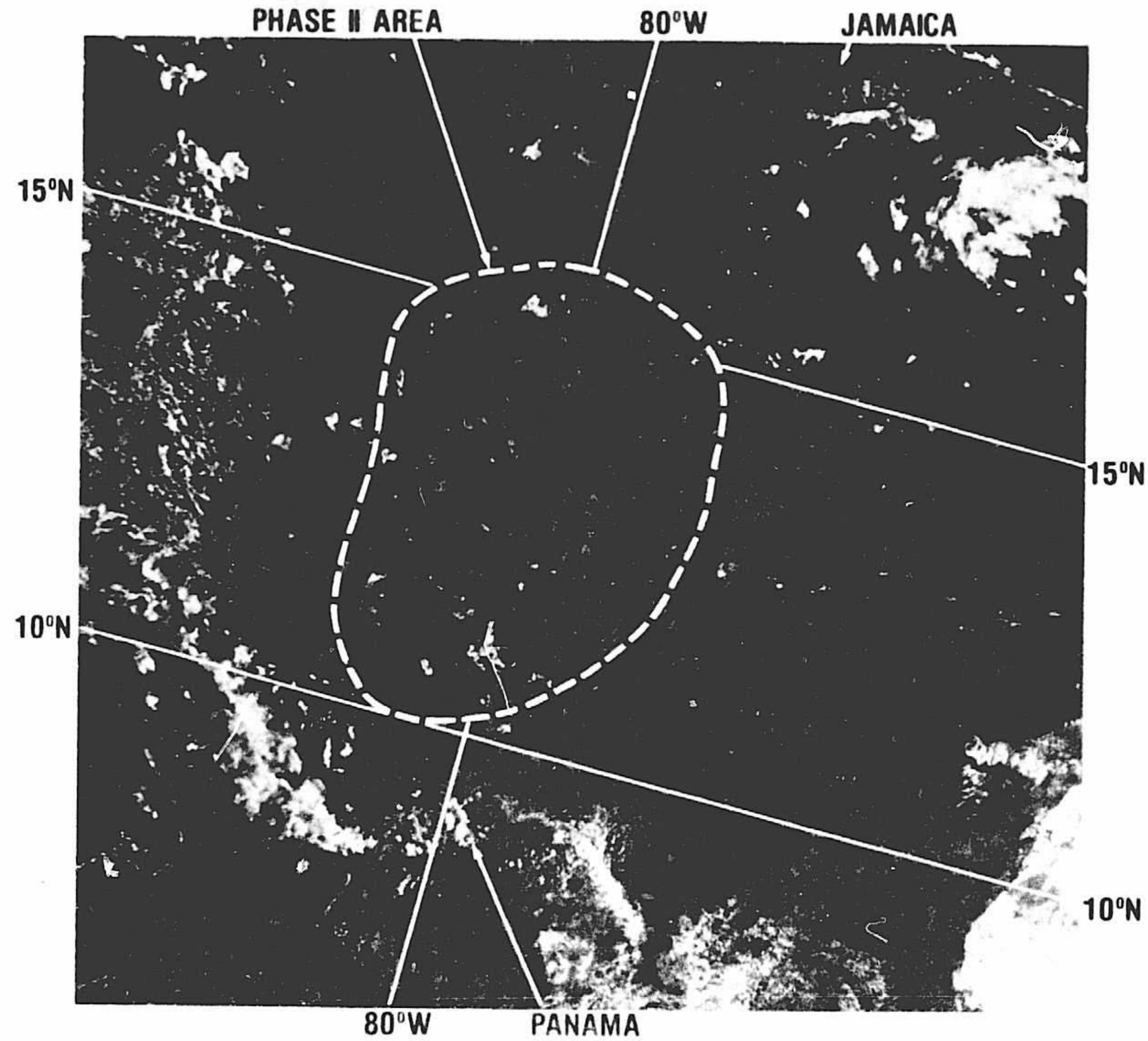

Figure 2. High resolution visible DMSP satellite photo of the southwest Caribbean for 16:16 GMT, April 11, 1974. Typical low level cloud tracers which were tracked in the experiment. The phase II cloud tracking area north of Panama is marked.

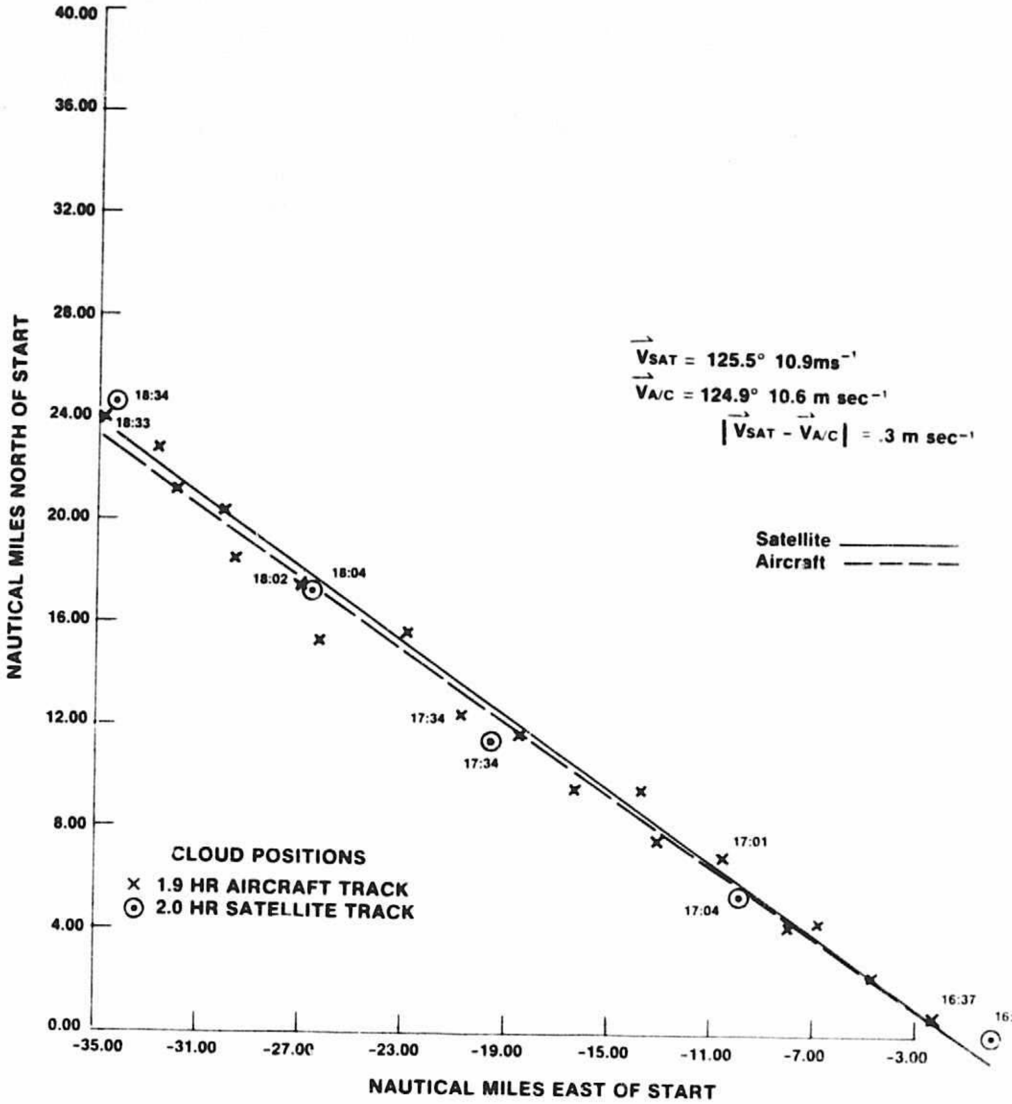

Figure 3. Satellite vs. aircraft cloud tracking. Northwest Atlantic (31°N. 67°W) January, 1976.