A Comparison of Three Satellite-Based Methods for Estimating Surface Winds over Oceans

Donald P. Wylie, Barry B. Hinton and Kellie M. Millett[1]

Space Science and Engineering Center, University of Wisconsin-Madison, Madison, WI 53706

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ABSTRACT

The feasibility of using satellites for providing surface winds or wind stress data was explored. Three popular methods were compared using nearly colocated data to assess the accuracies of each and the coverage that each could provide. The three methods tested were 1) the use of the sun glitter reflection seen on visible images of the ocean surface; 2) the use of active microwave sensors (flown on SEASAT) which reflect microwaves off the ocean surface; and 3) the use of cloud motions as indicators of the surface winds.

Close agreement in wind speed estimates was found among the three methods. The biases were <0.6 m s^{-1} for comparisons between comparable methods of estimating surface winds (1 and 2). Cloud motion comparisons to the other methods exhibited biases of <3.0 m s^{-1}. Individual point-by-point comparisons between wind measurements had an average scatter of 2.0 m s^{-1} (rms) or less after the mean biases were removed. Atmospheric variability caused as many of the differences as the instrumental errors indicating that meaningful wind information could be obtained from all three methods.

Very detailed spacial coverage was obtained with the sun-glitter method for wind speeds. However, the coverage was restricted to a narrow band 5° of latitude wide in the tropics. SEASAT also provided good coverage for two swaths (4° longitude wide) on each side of the satellite's orbit. Gaps between the swaths and orbits (polar non-synchronous orbits) were left unsampled. Both methods required external data on the wind directions which were obtained from cloud motions. The cloud motions provided coverage over larger areas than the other two methods because of the abundance of low-level cumuli.

1. Introduction

In this paper three methods of estimating low-level winds are examined to demonstrate the quality of oceanographic information that can be obtained from satellite platforms. Two methods were developed using image data from the Geostationary Operational Environmental Satellite (GOES). SEASAT-A provided a third method using an active microwave scatterometer. All three methods have potential for being operationally used in the future.

The strengths and weaknesses of each method are discussed based on comparisons between methods using colocated data in two geographical areas. Comparisons to ship and buoy observations were made when it was possible. However, very few ship observations of acceptable quality were found (19 total on 4 days) in the areas we focused on which were in the tropics and not in any highly traveled shipping routes. The satellite methods produce 4–10 times more observations in the same areas. Therefore, most of our findings were based on comparisons between the satellite methods because of data availability.

2. The satellite methods tested

a. The sun-glitter method

Detailed observations of the sun's reflection from the ocean surface were originally made by Cox and Munk (1954) from aircraft. These studies established how the intensity and shape of the sun-glitter reflection changed with the sea state. They developed empirical relationships for measuring surface winds using photographs of the sun glitter taken from aircraft.

Their method was adapted to satellite imagery by Levanon (1971). In satellite images of the ocean the curvature of the earth modified the shape of the sun glitter pattern. The glitter area was ~4–6° of latitude or longitude wide in the satellite pictures. Over such a large area a homogenous assumption of the wind field could not be made as done by Cox and Munk. To use satellite images, wind estimates had to be made at individual points inside the glitter area.

For estimating surface wind speeds, the Cox and Munk (1954) empirical relationships require either measurements of the brightness of a point, given the sun-satellite viewing geometry, or measurements

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[1] Also Marine Studies, University of Wisconsin-Madison.

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of the width of the glitter area. Because Levanon (1971) had to work with a satellite sensor that was uncalibrated (ATS-3) he chose to measure the width of the glitter area. The brightness of one point location was measured in time using a sequence of satellite images to approximate the east–west width of the glitter area as the sun passed overhead.

In our application we were able to calibrate the satellite which greatly simplified the method. Observations of the sun and space were used to calibrate the three GOES-East spacecraft that were used in the course of this study. The procedure is described in Norton *et al.* (1980).

The shape of the glitter area is elongated in the direction of the wind as described by Cox and Munk (1954). To accurately account for this distortion, we estimated the direction of the wind at each point independent of the wind speed. The direction of the cloud motions seen on sequences of geostationary images was used to estimate the wind direction at the surface. Given this information the Cox and Munk (1954) relationships were applied to sea surface brightness measurements at any location in the glitter area where wind estimates were needed.

GOES image sequences of three pictures were displayed on the Man computer Interactive Data Access System (McIDAS) of the University of Wisconsin-Madison. Methods for measuring cloud motions on the McIDAS had been previously developed and used on an operational basis (Mosher, 1979).[2] The method for extracting wind information from the sea surface brightness also was installed into operational software on the McIDAS.

The glitter method was applicable only to wind speeds < 16 m s^{-1}. Under light winds the glitter patch was very small and very bright in the center. As the wind roughened the surface the width of the area grew while the center maximum brightness decreased. The Cox and Munk (1954) data indicated that for winds > 16 m s^{-1} the maximum glitter brightness would have been too small to distinguish from the ambient brightness of the sea surface using the GOES sensors. We thus confined our measurements to areas where the speeds were somewhat below this level.

Contamination of the sensor's field of view by small clouds (<4 km) and random sensor noise were sources of error that had to be eliminated. To avoid these problems we manually chose areas of the image displayed on the McIDAS that appeared to be mostly cloud free inside a 40 × 40 km box.

Cumulative brightness distributions were made for the area inside the selected box. The value of the lowest ⅛ of the distribution was automatically chosen by the software as the best representation of the surface brightness inside the box. This value had the highest probability of being free from cloud contamination and sensor noise.

An exception to this rule was found near the center of the glint pattern in areas of very low wind speeds (<4 m s^{-1}). Under these conditions, clouds sometimes appear dark against the bright background of the sun's reflection. These data were manually edited to remove cloud contamination. The results from this procedure were presented as wind speed magnitudes at 10 m altitude using the relationships of Cox and Munk (1954).

To test this method, a comparison of sun-glitter wind-speed estimates with moored buoy observations was made in the eastern Pacific (110°W longitude at the equator). Four research buoys were moored at this location in a diamond-shaped pattern 1° of latitude or longitude apart centered on the equator. Wind measurements were made at 3 m above the surface. Sun glitter wind estimates were made at each buoy site on seven days in March (8th, 9th, 10th, 12th, 14th, 20th and 24th) and on two days in April (28th and 30th) 1979 using one or two satellite images when the sun's reflection was closest to the buoys (2200 or 2230 GMT). The results are shown in Fig. 1.

The glitter estimated winds were 1.0 m s^{-1} higher than buoy observations, ± 1.1 m s^{-1} rms, for 32 cases. These differences were partially caused by the anemometer heights of the buoys. The Cox and Munk relationships were made for a 10 m anemometer height while the buoy data used here was taken at 3 m. If a logarithmic wind profile u with height Z for a neutral boundary layer were assumed,

$$u = \frac{u_*}{0.4} \ln(Z/Z_0), \tag{1}$$

then most of these differences could be explained. For a wind speed of 5 m s^{-1}, Amorocho and DeVries (1980) predicted a $u^* = 0.16$ m s^{-1} and $Z_0 = 3.7 \times 10^{-5}$ m. The wind speeds at 3 m would be 0.5 m s^{-1} lower than at 10 m. Thus in reality, the glitter estimates were only 0.5 m s^{-1} greater than the surface (buoy) observations, which is within the accuracies of either the buoy anemometer measurements or the Cox and Munk method.

From this comparison we concluded that the sun-glitter method was as accurate as any other data source for our comparisons if care were taken to eliminate cloud contamination.

b. The SEASAT scatterometer

SEASAT-A (Apel, 1976) flew a microwave sensor specifically designed for monitoring the surface wind or wind stress. The scatterometer (SASS) monitored the ocean surface by transmitting a microwave pulse

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[2] Mosher, F. R., 1979: Cloud drift winds from geostationary satellites. *Atmospheric Technology*, NCAR, Boulder, CO, December 1978–February 1979, 53–60.

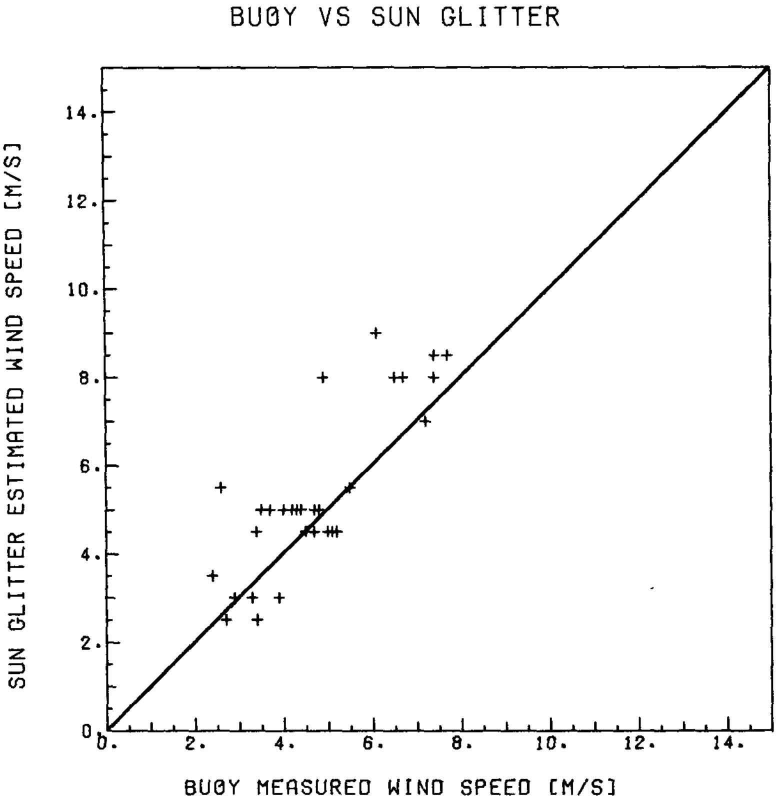

FIG. 1. A comparison of the sun glitter estimates of the surface winds to buoy measurements near 110°W longitude and the equator.

of 14.6 GHz (~2 cm) and measuring the magnitude of the returned reflection. This sensor is described by Grantham *et al.*, (1977) and Jones *et al.*, (1979).

The returned reflection came mainly from Bragg scattering off of oceanic waves of similar length (2 cm or less) with some energy from Fresnel scattering by longer waves. Based on the combined physical processes, Jones *et al.* (1979) formulated an analytical representation of the dependence of the backscatter cross section on friction velocity, (u^*) and the direction of u^* relative to the wave propagation direction. Their model contained 10 parameters whose values were determined by least-squares fit to a carefully selected set of "calibration data" or "surface truth."

The SASS data for the present study were derived using an algorithm similar to the Jones model by the Jet Propulation Laboratory, Pasadena, California, in August 1979. This algorithm has been modified by the SEASAT experiment team[3] to remove a bias in their wind-speed estimates. To make our results comparable to more recently produced SASS wind estimates, we have removed a mean bias of 1.3 m s^{-1} from all of our data. This correction was based on changes in the SASS algorithm made between August 1979 and December 1980[3].

The SASS results were given as a 19.5 m wind (neutral stability) because u^* data were difficult to obtain by independent methods for calibrating the SASS. This level was chosen because it is the near mean level of most ship observations. For comparisons to the sun-glitter method a height correction [Eq. (1)] of -0.3 m s^{-1} was made. Thus a total correction of -1.6 m s^{-1} was applied to the August 1979 data set. Grantham *et al.* (1977) discussed the sources and expected magnitudes of errors in the SASS wind estimates, which were mainly from system noise. When bias errors were removed, SASS was expected to give winds within ± 2 m s^{-1} or 10%.

Directional information was obtained from the fact that the returned pulse was stronger for waves aligned with crests perpendicular to the transmitting antenna direction than parallel to it, and slightly stronger in the upwind direction than the downwind direction. Theoretically, by looking at a surface patch from two different observation points (forward and aft-viewing antennai) the wind direction could be determined. However the direction of the component measured by one antenna toward or away from the satellite was seldom determined because of the uncertainty introduced by the system

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[3] W. L. Jones, NASA Langley Research Center, Hampton Roads, VA, personal communication.

TABLE 1. A summary of the relations between surface wind and winds aloft on 52 soundings from Swan Island (Station 78501, 17.4°N, 83.9°W, 11 m above MSL) from August 1978–March 1979.

	Altitude above mean sea level (m)			
	609	914	1219	1829
Mean veering: direction at altitude less the direction at the surface.	8°	15°	19°	20°
Deviation of estimate of surface direction from actual direction (deg).*	22°	24°	27°	37°
Mean speed shear: speed at altitude less speed at surface ($m\ s^{-1}$).	2.1	1.7	1.5	1.4
Deviation of estimate of surface speed from acutal speed ($m\ s^{-1}$).*	2.1	2.3	2.4	2.5

* Root-mean-squared differences between observed surface values and that predicted from the observations at the indicated altitudes using linear regressions.

For the 609 m level which is slightly above the normal cloud bases the regressions found were:

$\mathrm{Dir(sfc)} = 0.96\ \mathrm{Dir}\ (609\ \mathrm{m}) - 2.5°$

$\mathrm{Spd(sfc)} = 0.47\ \mathrm{Spd}\ (609\ \mathrm{m}) + 1.9\ \mathrm{m\ s^{-1}}$.

noise. Very often four possible directions result with the possibilities reduced to two directions (180° apart) on occasions.

To resolve these ambiguities the cloud motions measured from GOES images were used. The SEASAT wind estimates were overlayed on GOES image sequences and the SEASAT winds that were closest to the directions of the clouds were chosen as the correct solutions.

c. *Cloud motions*

Cloud motions were tracked on sequences of three GOES images taken 0.5 h apart (Mosher, 1979).[2] Displacements of the clouds were determined by correlating the digital data in a small area or box containing the clouds on successive images. The locations of the boxes were selected manually by operators viewing the images while the correlations were calculated objectively by the McIDAS. The locations of the correlation maxima were used to determine the cloud motion vectors.

Aircraft studies of the trade winds by LeMone and Pennell (1976) found little speed and direction changes on the average (less than 15° direction and 3 $m\ s^{-1}$ speed) between the cloud-level winds and the surface in the western Atlantic. Wylie and Ropelewski (1980) also found the same close relationship between the cloud level and the surface winds. This is a result of the turbulent mixing in the atmospheric boundary layer which is generally of neutral thermal stability or slightly unstable.

To test the feasibility of using cloud motions as estimates of the surface wind we inspected 52 radiosonde soundings taken at Swan Island in the Caribbean for the speed and directional shear as a function of altitude (Table 1). The cloud bases in the trades are typically reported from 500 to 600 m. We analyzed the wind shears for four of the levels reported on the soundings from 609 m to 1829 m which roughly corresponded to a range from the cloud base level to near the top of most small cumulus cloud groups.

The mean directional shear (surface to altitude) ranged from 8° at 609 m to 20° at 1829 m while the speed shear ranged from 2.1 $m\ s^{-1}$ (609) to 1.4 $m\ s^{-1}$ (1829 m). A wind-speed maximum was found in the average wind profile at the 609 m level.

Using regression equations the surface wind speeds and directions were predicted from the observations at the altitude levels on an individual sounding basis. For the 52 soundings used, the surface directions that were empirically predicted had a scatter around the observed directions (rms) that ranged from 22° using the 609 m data, to 37° using the 1829 m data. Wind-speed predictions also showed the same characteristics with height. The predicted scatter increased from 2.2 $m\ s^{-1}$ (rms) using the 609 m observations to 3.1 $m\ s^{-1}$ using the 1829 m observations. These results indicate the magnitudes of the errors that would be expected from using observations above the boundary layer to predict surface winds.

The boundary-layer wind shear has commonly been observed to change in different weather situations and geographical areas. Therefore, we have not applied any corrections to the cloud-motion data based on the Swan Island statistics. Instead, we will use our comparisons of cloud-motions to the surface-wind estimates of SEASAT and the sun-glitter method to show the differences in the boundary-layer wind shears that were observed in two different geographical areas.

Studies of the accuracies of using trade wind cumulus clouds as wind indicators were made by Hasler *et al.*, (1976, 1979). They found that the cloud groups tracked on satellite images moved at the speeds of their bases and that they approximated the base-level winds within 1.9 $m\ s^{-1}$. This indicates that the surface winds could be reasonably estimated using cloud motions if the boundary-layer shear is removed.

3. The locations of the comparisons

All three methods were compared in two geographical areas: the eastern Pacific off the coast of Columbia, South America, and the Atlantic northeast of Brazil. Both areas were in the tropics because of the restrictions of the sun glitter method (see Table 2).

TABLE 2. The basic characteristics of the areas used for the comparisons.

	Pacific	Atlantic
Bounds		
Latitude	2°S–6°N	4–19°N
Longitude	80–99°W	39–55°W
Range of cloud-motion speeds	3–10 m s^{-1}	3–15 m s^{-1}
Range of surface wind speeds (glitter method)	2–8 m s^{-1}	3–10 m s^{-1}
Range of air-sea temperature difference (ship reports)	−1 to −5°C	−8 to +7°C

Two days were studied in each area. One SEASAT oribt per day was chosen for the comparisons. All SEASAT orbits used passed through the areas within 3 h of the time of passage of the sun glitter. GOES images also were selected to coincide with the passage of the sun glitter.

In the Pacific comparisons with two ship observations indicated that the atmospheric boundary layer was unstable with reported air temperatures of 1–5°C colder than the water on both days. The exact magnitude of the temperature difference was difficult to assess because a 5°C air-sea temperature difference is not realistic over the ocean. However, consistently unstable conditions for this area were found in the climatological analysis of Hastenrath and Lamb (1977).[4]

Shallow cumulus cells were found in the Pacific area (see figure 2). The cells were organized into patterns roughly similar to the mesoscale cells observed in unstable regions by Agee *et al.* (1973). Cloud tops were below 850 mb on both days as indicated from their temperatures found on the infrared images. North of 5°N latitude deep cumulonimbus clouds developed in the southerly flow. (Cirrus from the southern edges of the Cb's are visible in Fig. 2.) All wind data were taken south of the Cb cells.

In the Atlantic both stable and unstable boundary-layer conditions were reported by the merchant ships. However, ships in close proximity to each other often disagreed on the air-sea temperatures and the stability of the boundary layer. Hastenrath and Lamb (1977)[4] found unstable conditions over most of the area except near the Brazilian coast. The satellite images contained mainly cumulus groups which are commonly found in the tropical regions of the world. Thus, we felt the Atlantic area was typical of most tropical regions and the temperature stratification was probably neutral in the locations of most of our observations.

A line of cumulonimbus cells was present at 10°N latitude (Fig. 3). Both north and south of the Cb cells scattered trade wind cumulus groups were found. The tops of the trade wind cumulus were usually below 800 mb.

4. Comparisons of surface wind-speed estimates

The wind estimates were grouped into pairs for the comparisons. All cloud vectors, SEASAT vectors, or glitter vectors within 1° latitute and longitude were averaged. One sun-glitter estimate was made in the area of each SEASAT vector or cloud. Because small cloud contamination presented a

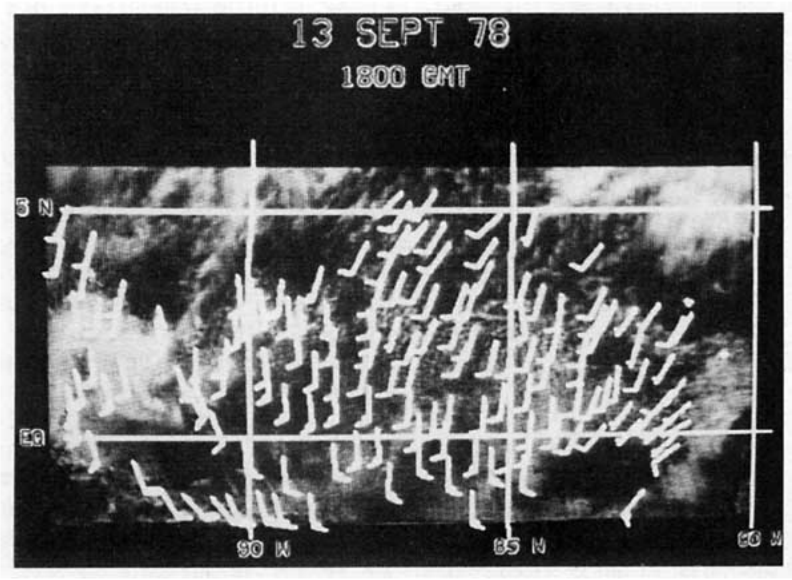

FIG. 2. An example of the cloud motion coverage in the Pacific region of study, 13 September 1978.

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[4] Hastenrath, S., and P. J. Lamb, 1977: *Climate Atlas of the Tropical Atlantic and Eastern Pacific Oceans*. University of Wisconsin Press, 116 pp.

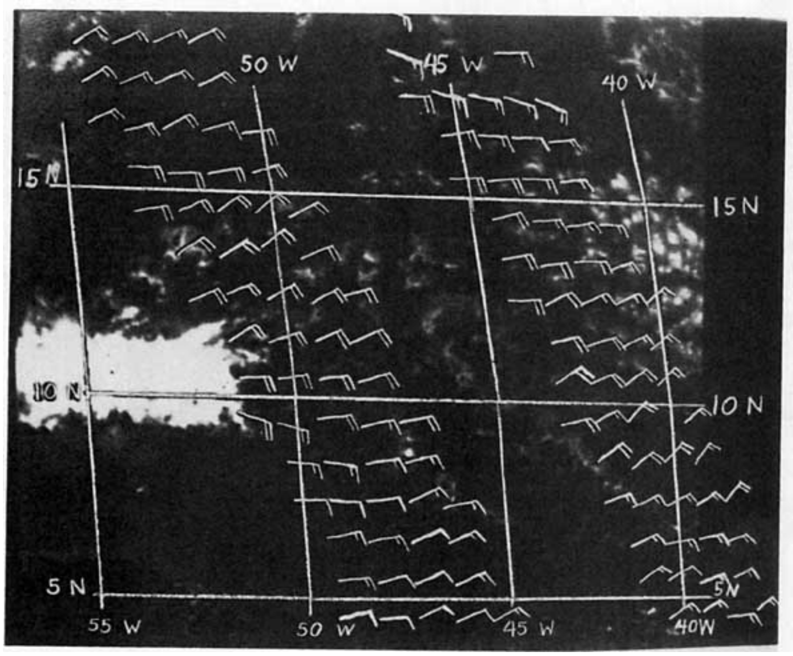

FIG. 3. An example of the SEASAT wind coverage in the Atlantic region of study, 16 July 1978. The vectors shown were selected from four possible directions based on the cloud motions.

problem in obtaining valid glitter data we chose to select mostly clear areas for the glitter measurements. This limited the number of vector pairs obtained. SEASAT data were readily obtained in areas of cloud cover and thus many cloud-SEASAT pairs were compared. No adjustments were made to the cloud motions for boundary-layer wind shear.

TABLE 3. Average differences between colocated wind-vector pairs (m s^{-1}) within 1° of latitude or longitude of each other. The number of paired vectors is given in parentheses.

Date	Location	Clouds* − Sun glitter	SEASAT − Sun glitter	Clouds* − SEASAT
16 Jul 78	Atlantic	3.0 (12)	0.6 (13)	0.8 (148)
17 Jul 78	Atlantic	2.2 (38)	−0.2 (33)	2.2 (116)
13 Sep 78	Pacific	−0.9 (17)	0.3 (24)	−0.8 (43)
16 Sep 78	Pacific	0.8 (12)	−0.2 (11)	0.5 (8)
Both Atlantic				9.7° (264)
Both Pacific				−3.3° (51)

* Corrections for wind shear in the boundary layer have not been applied.

The averages of each type of vector in the pairs indicated the biases between the different methods were small (Table 3). Scatter plots for these comparisons are shown in Figs. 4, 5 and 6. Cloud motions were faster than the glitter estimates (3.0 and 2.2 m s^{-1}) in the Atlantic area on the average. This indicated only slightly larger wind shears than found in the Swan Island radiosonde data. Comparisons of cloud motions to buoy observations by Halpern (1978, 1979) in other areas also have shown very similar results.

In the Pacific the cloud motions were not faster than the glitter wind estimates. The comparisons averaged −0.9 and 0.8 m s^{-1} on the two days studied. This was possibly a result of strong mixing in the atmospheric boundary layer which has commonly been found under cellular convection (Agee *et al.*, 1973).

SEASAT wind estimates averaged very close to the glitter estimates ranging from being 0.6 m s^{-1} higher to −0.2 m s^{-1} lower for the different days studied. This was expected because they are similar methods. The cloud motion measurements were usually faster than the SEASAT wind estimates in the Atlantic comparisons (0.8 and 2.2 m s^{-1}), but were nearly the same in the Pacific comparisons (−0.8 and 0.5 m s^{-1}) which again illustrated the different below cloud wind shears that were found in the two areas.

The scatter of these wind estimates was within

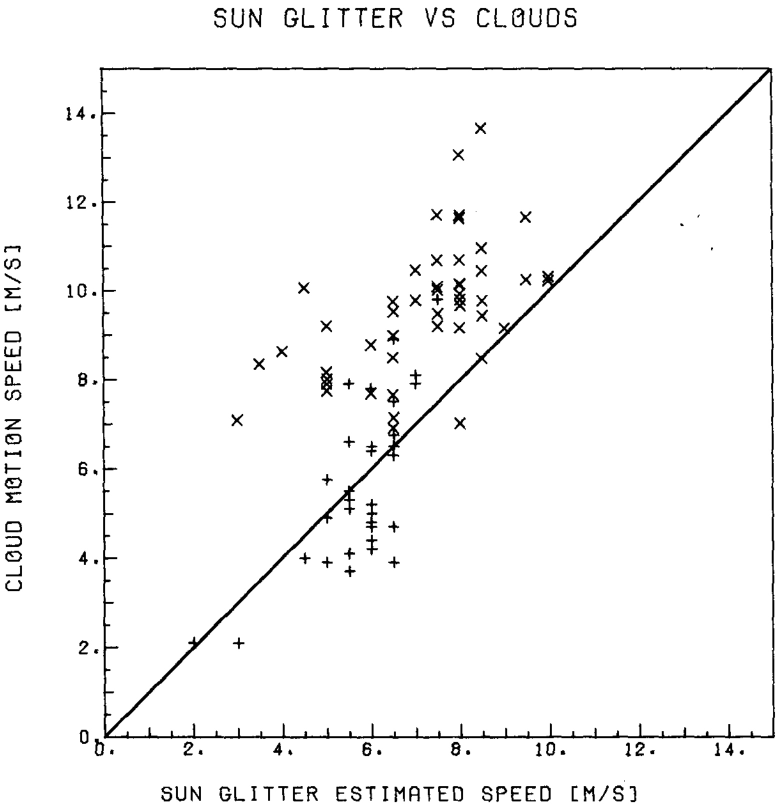

FIG. 4. The comparison of cloud motions to the sun glitter surface wind estimates: (+) Pacific area, (×) Atlantic area.

that found by comparisons of cloud motions to radiosonde observations or radiosondes to neighboring radiosondes. Hubert and Thomasell (1979)[5] and Bauer (1976) compared cloud motions to radiosondes and found disagreements of 4 m s^{-1} (rms). They estimated that the spacial variability of the wind field in the atmosphere caused a 2–3 m s^{-1} difference by itself. Our data averaged 0.6–1.9 m s^{-1} (Table 4, Figs. 4, 5 and 6) which was less than the atmospheric variability estimates. This was probably a result of using only one type of cloud, tropical cumulus, and confining our comparison to only data that were in close proximity (1° of separation).

The correlations found between the different wind estimates were reasonably good as indicated by Figs. 4, 5 and 6. The correlation coefficients found for these comparisons were as follows: cloud-glitter 0.6, clouds-SEASAT 0.7, and glitter-SEASAT 0.6.

Comparisons of cloud motions and SEASAT winds to ship reports also were made in the Atlantic area (Table 5). For the two days studied the ship reports indicated cloud motions were only 1.4 m s^{-1} faster than the ship reports while the SEASAT speeds were 2.6 m s^{-1} faster. This differs slightly from the comparisons of both methods to the sun glitter method shown in Table 3. However, because of the small number of ships available (19) and the large scatter of the ship comparisons we have less faith in the ship related comparisons.

5. Comparisons of wind-direction estimates

To assess the ability of each method to provide wind-direction information we compared cloud motions to the edited SEASAT data (Tables 3 and 4) and also each satellite method to the few ships found in the areas studied (Table 5). Comparisons were not made to the buoys discussed in Section 2a because few cloud tracers were found close to the buoys on the days studied and SEASAT was not operating during this period.

In general, we found close agreement between the cloud directions and the SEASAT vectors on the average (−3.3° and 9.7° of boundary-layer veering) as expected from our editing process which removed the worst cases (three total out of 267 in the Atlantic). The Pacific data indicated little direc-

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[5] Hubert, L. F., and A. Thomasell Jr., 1979: Error characteristics of satellite-derived winds. NOAA Tech. Rep. NESS 79, 35 pp.

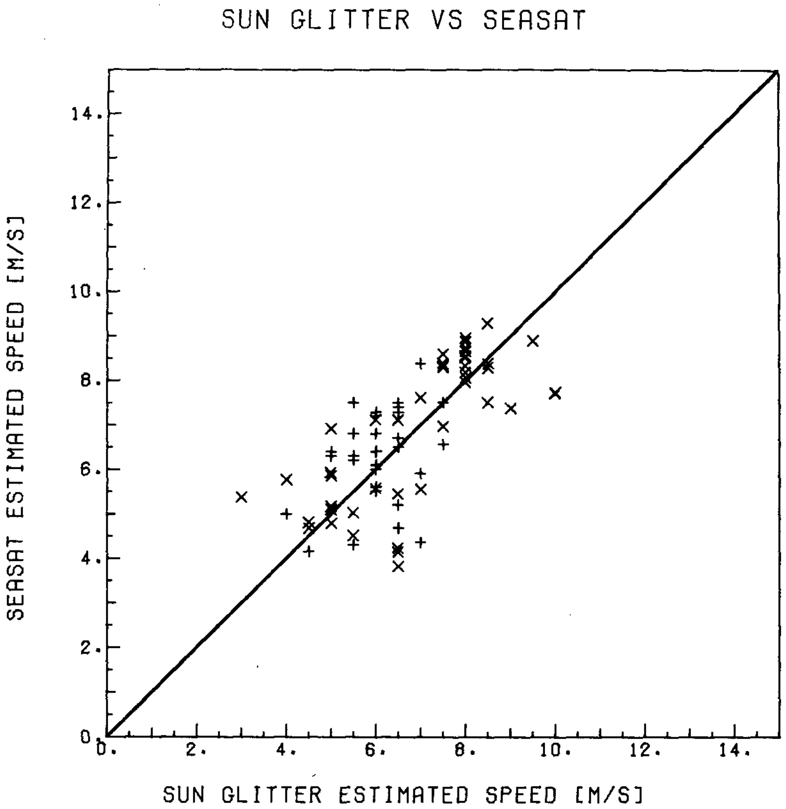

FIG. 5. The comparison of SEASAT wind estimates to the sun glitter wind estimates: (+) Pacific, (×) Atlantic.

tional shear (−3.3° average) which was a result of the unstable boundary layer present and the lower altitudes of the clouds that were found. In the Atlantic directional relationships of wind veering were found for a large majority of comparisons made. Satellite comparisons with ship observations in the Atlantic also found similar veering conditions averaging 16° for the cloud-ship data and 10° for the SEASAT-ship data. The rms scatter per paired comparison was ~16° for cloud-SEASAT, 13° for SEASAT-ships, and 22° for clouds-ships.

The results shown here were better than the cloud-buoy comparison reported by Halpern (1979) because we inspected the satellite-derived wind-field patterns and eliminated one ship report because of obvious error.

6. Areal coverage

An example of the areal coverage that was obtained from all three methods is shown in Figs. 7 and 8 for the Pacific area. Very dense coverage was obtained. Each sensor identified features in the wind field which were unique. They will be discussed individually.

a. Cloud motions

Cloud-motion data produced very smooth flow fields. Southerly winds were found which curved to the northeast near the deep cumulonimbus cells (Cb).

b. SEASAT

When the SEASAT data were added, more details were observed. A shift in the wind direction from southerly to southwesterly was analyzed southwest of the Cb cells. The wind shift analysis was made assuming that a convergent flow into the Cb cells was the most reasonable flow pattern when the SEASAT directional choices deviated from cloud motions. The cloud motions also indicated this directional change but in a more gradual manner. A similar directional shift is evident north of the Cb cells in the Atlantic shown in Fig. 2.

c. Sun glitter

North of the Gallapagos Islands, bright patches were evident on the GOES images (Fig. 8). These patches indicated very low sea states downwind of

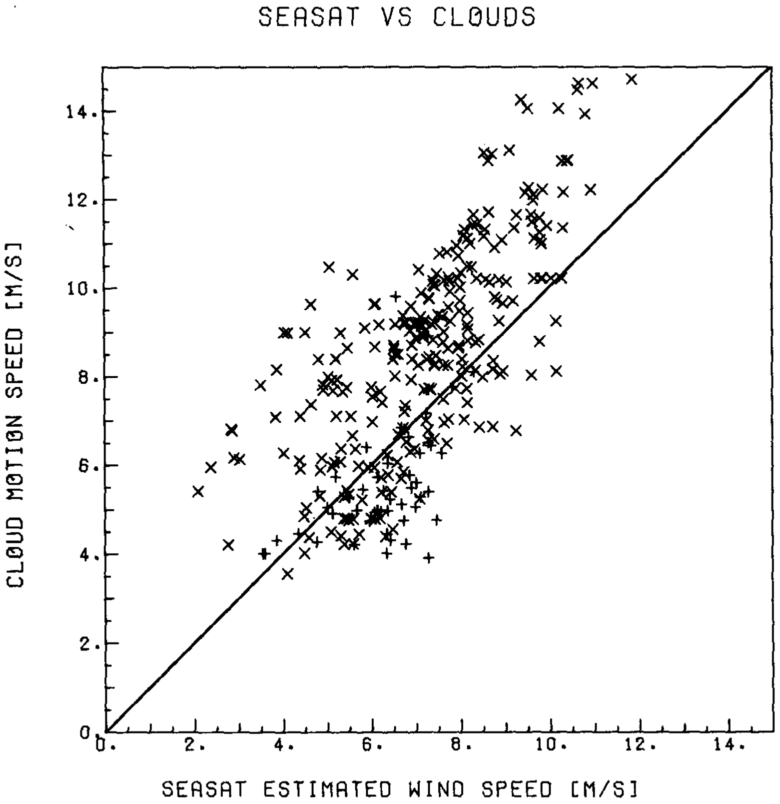

FIG. 6. The comparison of cloud motions to SEASAT wind estimates: (+) Pacific area, (×) Atlantic area.

the major islands. These areas were very dark until the center of the glitter pattern approached. At that time they became very bright. This was expected under low wind conditions because the Cox and Munk relationships predicted a very small and very bright sun-glitter area for low sea states. Under higher wind conditions the surface brightnesses exhibited smaller changes in time because of the wider distribution of the glitter (more reflections from inclined wave surfaces).

In some of the wake regions behind the islands the winds were <5 kt (3 m s^{-1}) because of the blocking of islands. These calm spots have been commonly observed in other island areas. A calm area near one Cb system also was found on an image not used for these comparisons. These GOES data illustrate that very fine detail can be obtained on the stress from the sun glitter.

7. Conclusions

In general, it was found that all three methods could be combined for making detailed data sets because the biases between the methods were small. The preferential sensor would be the SEASAT scatterometer because it was capable of providing data at all latitudes and did not depend on cloud coverage.

TABLE 4. The rms deviations (m s^{-1}) of the vector pair differences, i.e., the scatter of one measurement about the other using colocated vector pairs.

Date	Clouds − Sun glitter	SEASAT − Sun glitter	Clouds − SEASAT
16 Jul 78	±1.4	±0.7	±1.9
17 Jul 78	1.5	1.2	1.2
13 Sep 78	0.6	0.9	0.9
16 Sep 78	1.3	1.3	1.3
Atlantic			15.8°
Pacific			14.2°

TABLE 5. The average differences and scatter between satellite surface wind estimates and merchant ships reports on 16 and 17 July 1978, in the Atlantic area. The scatter (rms deviations) between ship and satellite observations are indicated by ±.

Type	Cloud − ship	SEASAT − ship
Speed (m s^{-1})	1.4 ± 3.3	2.6 ± 2.1
Direction (deg)	16 ± 22	10 ± 13
Number of observations	12	7

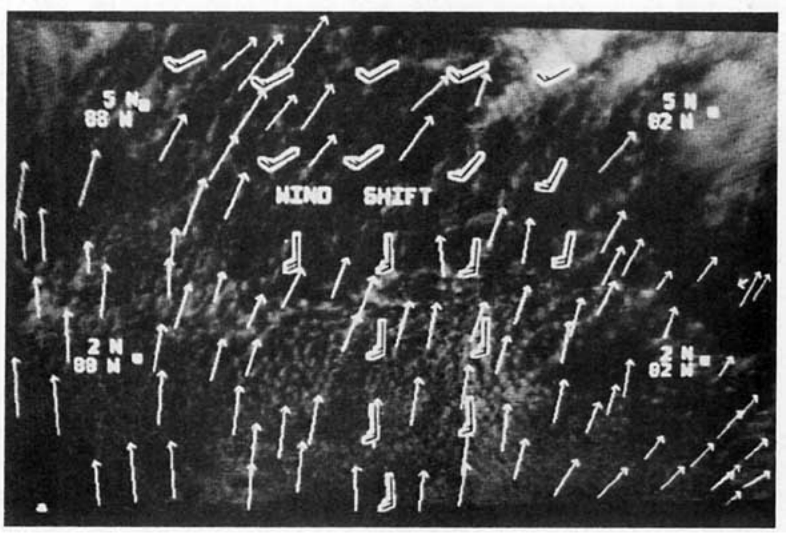

FIG. 7. An example of the wind directional detail contained in the SEASAT data (flags) as compared to cloud motions (arrows). The wind shift area reported by the SEASAT data is labeled.

However, this sensor required data on the general wind direction from an external source. We found that cloud motions could easily provide this information.

In the tropics the polar orbiting SEASAT left gaps between orbits that were equal in size to the swaths covered by the scatterometer. For daily coverage of the tropics other data such as cloud motions or ship reports will be needed to fill in these areas. This could be important for the monitoring of transient storm systems that produce intense wind patterns that deviate from climatological means.

The scatterometer will not be flown again until the next generation of satellites, the NOSS series which will not be launched until 1985 or later. Until that time cloud motions could be used to estimate the surface winds, providing the characteristics of the clouds used as tracers are identified and known.

We have shown that two different cloud fields had two different relationships to the surface wind

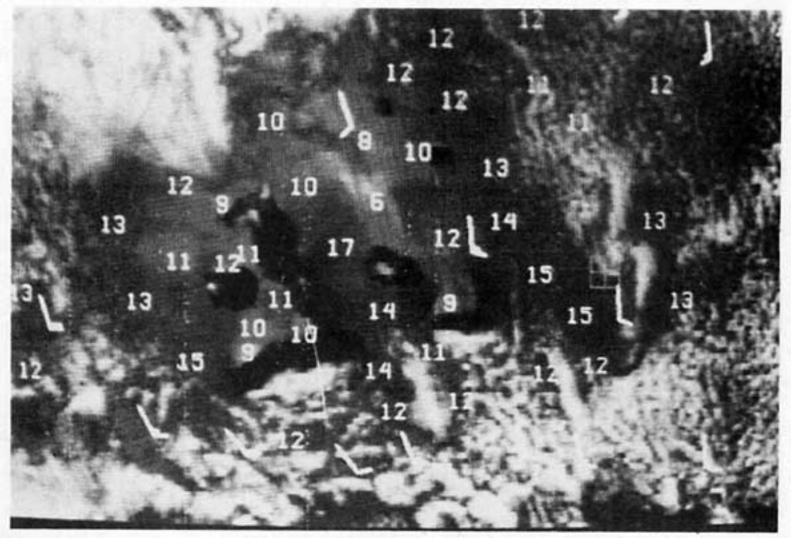

FIG. 8. An example of the detailed wind-speed coverage provided by the sun glitter method in the region of the Gallapagos Islands. Glitter speeds (kt) are indicated numerically. Cloud motions are indicated by the flags. The spot area sampled on the image for the glitter reflection was approximately the same size as the numbers shown and the glitter sample areas were centered on the upper left corner of the numbers.

fields, the Atlantic area versus the Pacific area. Similar differences were found between the tropics and clouds around frontal systems in higher latitudes by Hasler *et al.* (1976, 1979). It is evident that different categories of clouds (trade cumulus, cellular cumulus, etc.) should be studied along with the different characteristics of different geographical areas so that the best possible information can be extracted from the cloud-motion data. Studies of higher wind-speed regimes also are needed for both scatterometer and cloud-motion data.

For more detailed information the sun glitter method can be used. This method is restricted to the tropics but it can provide higher spacial details in coastal areas and around islands where wind fields are very complicated. It also has one advantage over other methods of estimating stress which is shared with the cloud motion measurements—it can be applied to archives of existing operational satellites.

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