Deriving Surface Winds from Satellite Observations of Low-Level Cloud Motions

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(Manuscript received 29 June 1984, in final form 16 March 1985)

ABSTRACT

Climatological shears between ship winds and satellite-observed, low-level cloud motions are used to derive monthly mean surface winds from satellite observations of low-level cloud drift. The derived surface winds compare well with observed surface winds from ships, moored buoys and the Seasat altimeter.

1. Introduction

The surface wind is a key parameter in air–sea interaction; therefore, determining the wind and wind stress are major components of large-scale national and international experiments in climate research such as the Equatorial Pacific Ocean Climate Studies (EPOCS) (NOAA, 1982), the Tropical Oceans–Global Atmosphere (TOGA) (WMO, 1984), and the World Ocean Circulation Experiment (WOCE) (WMO, 1984). Available observations from ships and island stations are inadequate over the tropical oceans to produce acceptable analyses on time scales from daily synoptic to monthly or even seasonal means. The few island data are seldom representative of the open ocean, and the ship observations are very sparse for a variety of reasons (Cutchin, 1983).

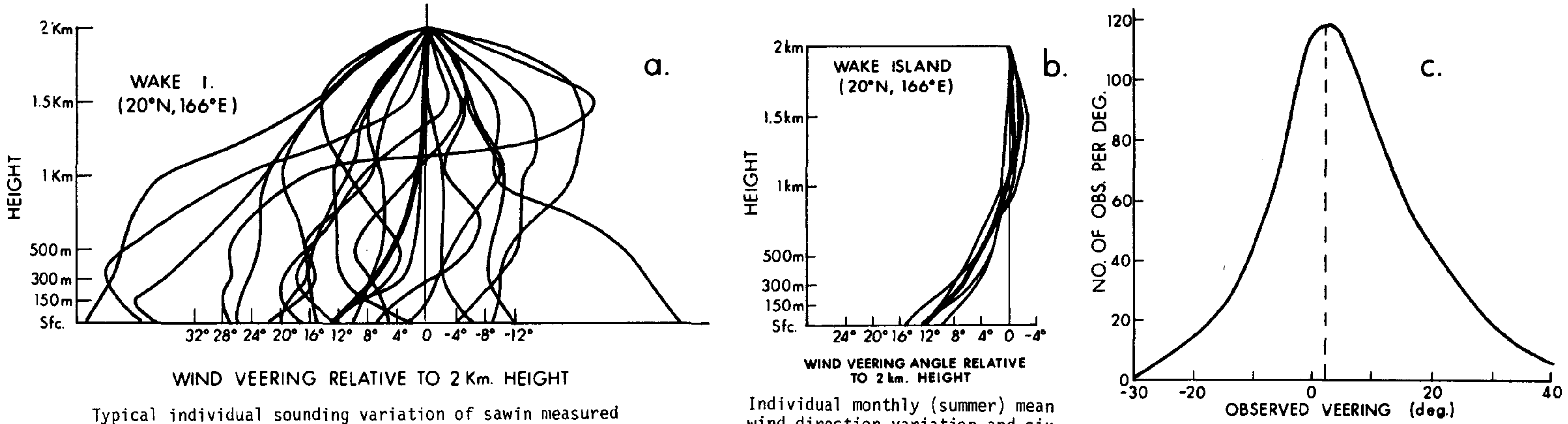
The numbers of winds obtained from geostationary satellite-observed, low-level cloud motions are a maximum over the tropical oceans; however, these winds must be reduced to the surface level for air–sea interaction studies. A method of reduction has been developed and used by Wylie and Hinton (1982) to produce surface winds during the First GARP Global Experiment (FGGE). This paper describes a method we have devised and used for reducing the GOES satellites wind data to the surface as monthly averages. The results are compared to the very limited "ground truth."

2. Background

Winds estimated from cloud motions observed by satellites have been available since the 1960s. Extensive quality evaluations (Hubert and Whitney, 1971; Bauer, 1976) have shown them comparable to rawinsonde winds. The major uncertainty in comparing with other data lies in the level assigned to the satellite-derived winds (sawins). Studies by Hubert and Whitney (1971) using colocated rawinsonde data, and Hasler *et al.* (1976, 1977, 1979) using aircraft winds, found that in trade wind cumulus, the low-level sawins agree best with the observed winds somewhere in the layer 2000–5000 feet.

The low-level sawins are the major wind data source over the tropical Pacific and Atlantic Oceans and are used routinely in the daily synoptic analysis of the 850 mb level. However, the sawins are inappropriate for use in daily analyses of the surface winds because there are insufficient auxiliary data to reduce them to the surface layer by boundary layer parameterization schemes. Halpern and Knox (1983) found that moored buoy winds were not correlated with low-level sawins on a daily time scale but became coherent after about 15 days of averaging. Extensive work by Mendenhall (1967) and Gray (1972) using thousands of rawinsonde profiles, found that winds between the surface and 2000 to 6000 feet veered randomly among individual soundings due to boundary layer turbulence. But when the soundings were averaged over time, the turbulent fluctuations cancelled and a coherent signal became apparent (Fig. 1). For a collection of soundings (Figs. 1a and 1d), veering varies at random about zero; but when the soundings are averaged, a residual signal is apparent as shown by the thick solid line in Fig. 1a and the dashed line in Fig. 1c. Monthly averaged profiles tend to be conservative in the trade wind regions as shown by the Wake Island soundings in Fig. 1b. Figure 1e shows a time series of speed shear between 250 and 1000 m for frequent soundings made at Christmas Island during the Line Island Experiment of 1967. The large variability about the average was probably even greater between the surface and 1000 m. The averaged Christmas Island wind profile for March and April 1967, which included the data of Fig. 1e, was smooth and typical of easterly trade winds (Fig. 2).

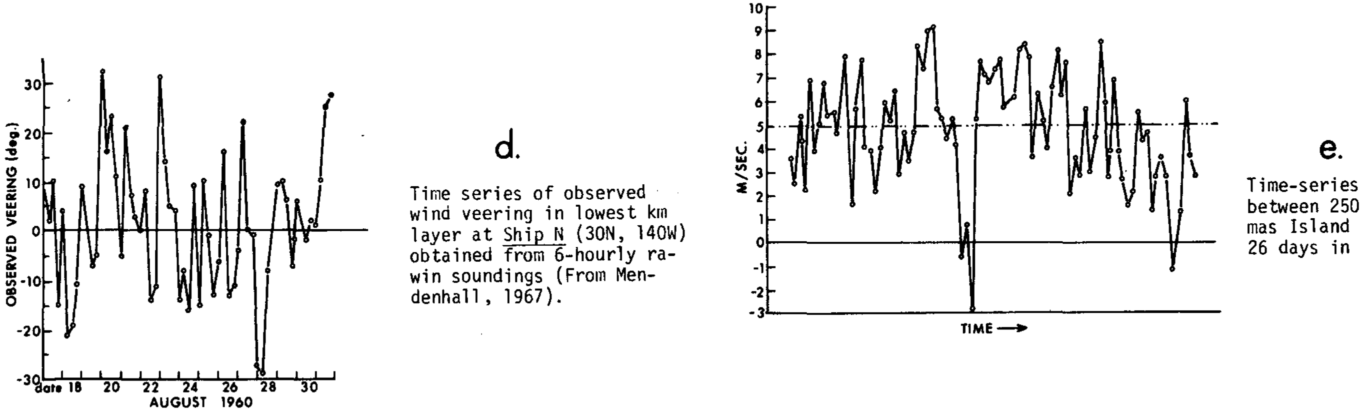
The smoothness and persistence of the monthly mean wind-veering profiles of Fig. 1b suggested that a monthly climatological profile could be used to derive monthly mean surface winds from monthly mean low-level sawins.



Typical individual sounding variation of sawin measured wind direction in lowest 2 km layer. Soundings were taken 6 hours apart. Mean veering shown by the thick solid line (From Gray, 1972).

Individual monthly (summer) mean wind direction variation and six monthly average (heavy line). (From Gray, 1972).

Smoothed frequency distribution of veering at Johnston Island in the layer from surface to 900 mb. Sample size 3696 observations (From Mendenhall, 1967).



Time series of observed wind veering in lowest km layer at Ship N (30N, 140W) obtained from 6-hourly rawin soundings (From Mendenhall, 1967).

Time-series of wind speed shear between 250 m and 1000 m at Christmas Island for 85 soundings during 26 days in March 1967.

FIG. 1. Examples of variability of wind direction and speed in the boundary layer.

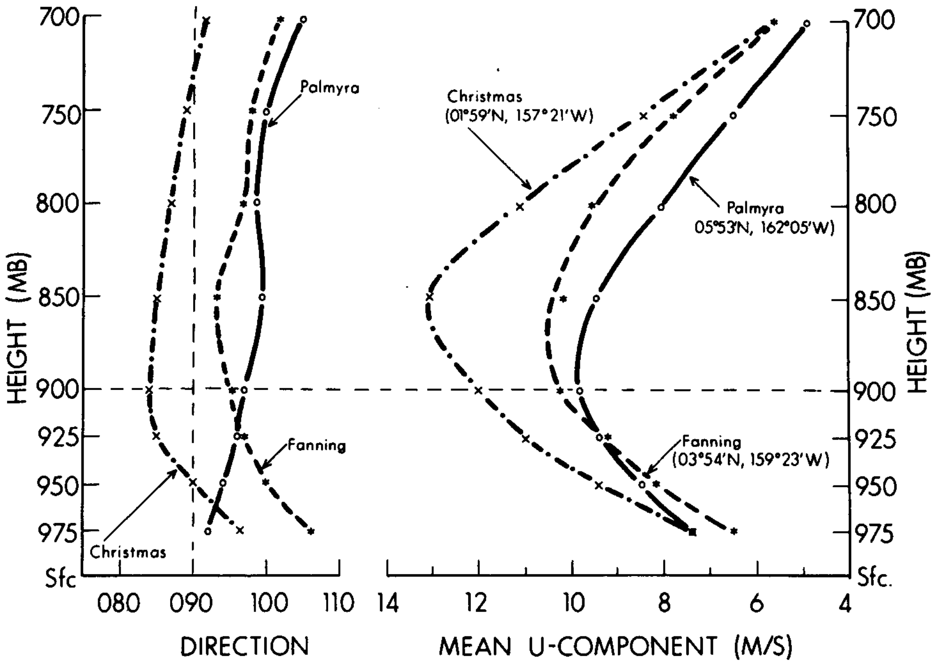


FIG. 2. Profiles of the averaged wind direction and zonal speed in the Line Islands during March and April 1967.

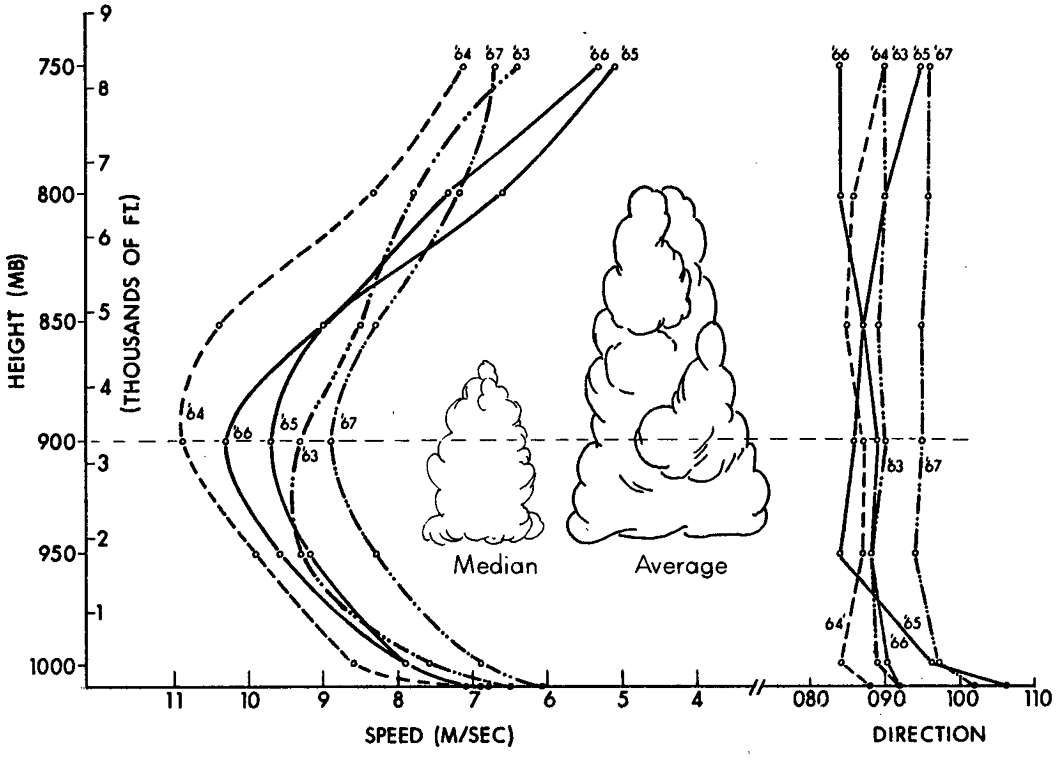


FIG. 3. Profiles of monthly averaged wind speed and direction at Johnston Island for five Julys. Sketch illustrates the average and median depth of trade wind cumulus in the Johnston area.

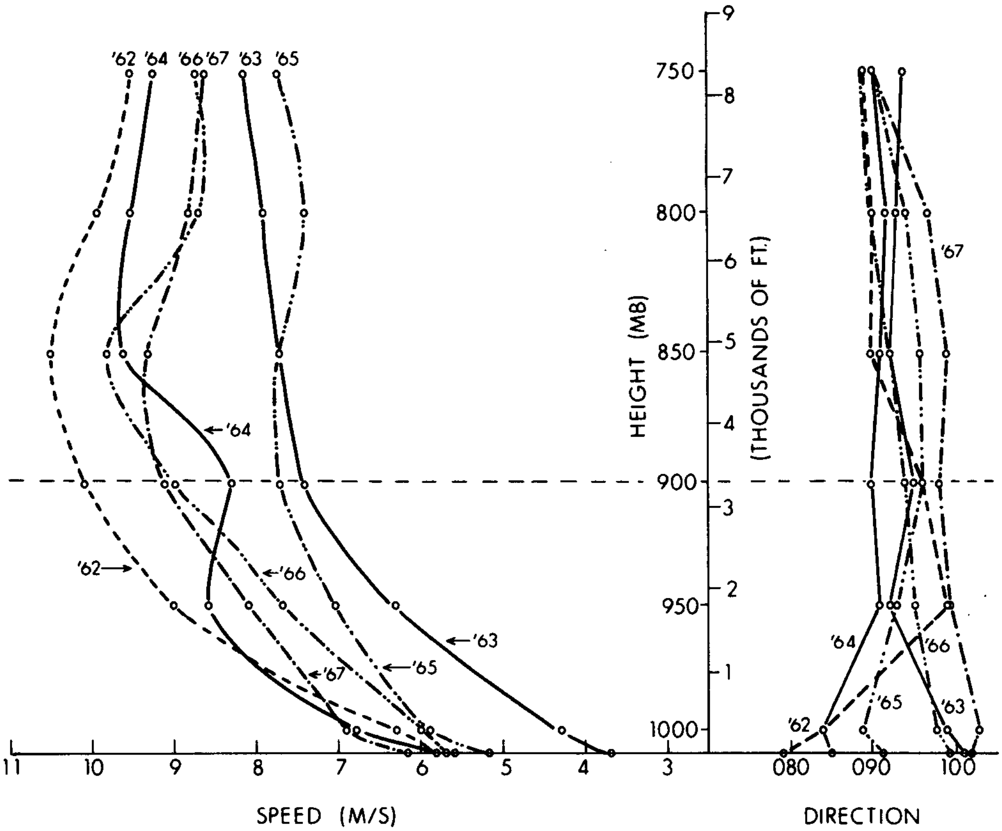


FIG. 4. Profiles of monthly averaged wind speed and direction at Canton Island for six Julys.

3. Development of the climatological shear method

a. Wind speed shear

Mendenhall and Gray dealt mainly with direction profiles in the boundary layer. We made a similar survey of the monthly mean speed profiles in the boundary layer using rawinsonde data. Sample profiles are shown in Figs. 3 and 4. These revealed that for most stations there is a characteristic monthly mean profile in which speed variability at cloud level is, in general, reflected in the surface speed. They also revealed that the profiles are region (or circulation system) dependent as well as time dependent. For example, the northeast trade wind profile at Johnston Island in July (Fig. 3) is quite different from the equatorial easterly wind profile at Canton Island in July (Fig. 4), while the Line Islands profiles in Fig. 2 differ even though the stations are only 200 km apart. This is due to the latitudinally restricted equatorial low-level jet which is strongest in late winter and early spring (Sadler and Kilonsky, 1981).

Results of the rawinsonde data surveys indicate that it was appropriate to develop and test a climatology scheme to derive surface winds from sawins on monthly time scales. The decision was reinforced by the following considerations:

1) The scheme is simple.

2) Over the eastern Pacific the climatological ship and satellite wind data are adequate for good analyses from which grid point shears between the two levels can be extracted. Despite the large differences in record period of 33 years for ship winds and eight years for sawins, the number of sawins outnumber the ship winds by almost ten to one over much of the area south of 20°N, and we consider the sawin climatology to be the superior.

b. Illustration of method

The procedure used to develop the climatology scheme is illustrated by Fig. 5 using January data. Ship winds from 1947–79, averaged for 2° latitude by 10° longitude rectangles and subjectively analyzed and manually digitized for speed and direction at 2.5° grid intersections, appear in panel A. The sawins for 1975–82, averaged over a 2.5° latitude by 5° longitude staggered grid, are shown in the center panel B. The vector difference, or climatological

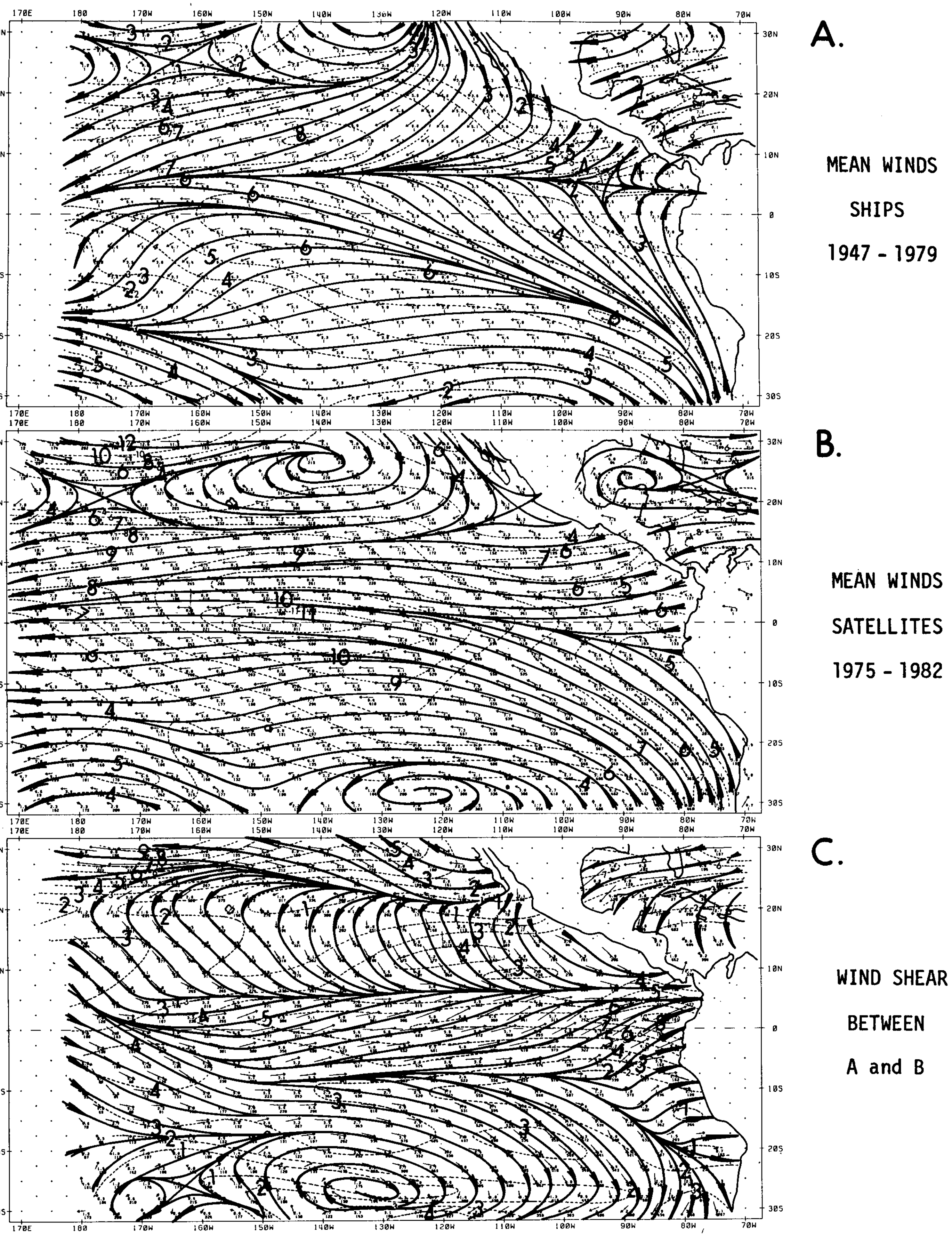


FIG. 5. January long-term mean (A) ship winds and (B) sawins; (C) vertical wind shear between the two data sets.

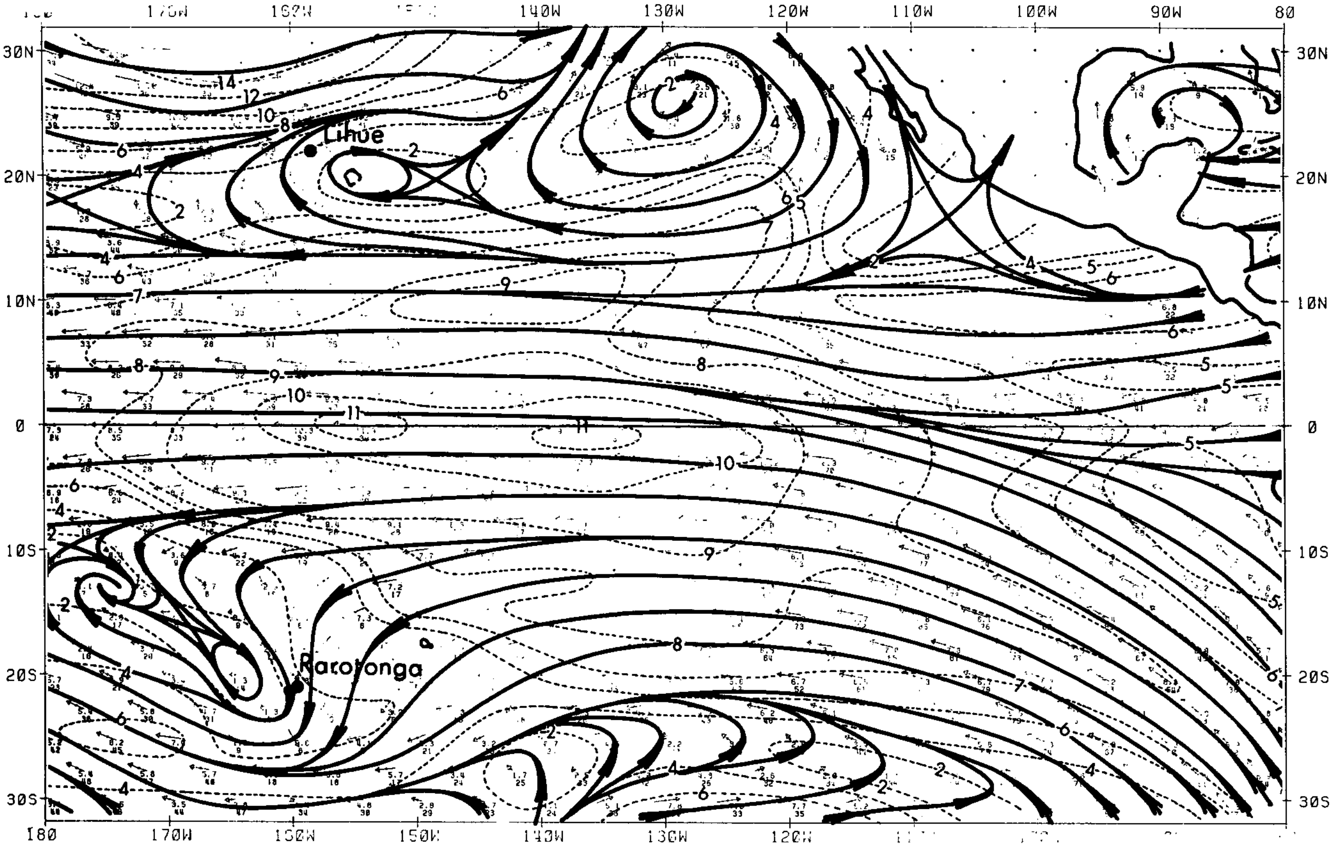


FIG. 6. Analysis of the averaged sawins for January 1980.

shear, between the ship winds (A) and sawins (B) at grid points are shown in panel C. The climatological shears are then added to individual monthly averaged sawins to derive individual monthly mean surface winds. For example, the January shear field of panel C was added to the January 1980 observed sawins (Fig. 6) to derive the January 1980 surface winds of Fig. 7. In other words, the scheme assumes that *monthly mean circulation anomalies observed at the low-cloud level reflect corresponding anomalies at the surface;* i.e., the sawin anomaly field of Fig. 8 is incorporated in the surface wind field of Fig. 7.

4. Evaluation of the scheme

During initial analyses of the monthly averaged sawins, the sawin anomalies and the derived surface winds, subjective quality checks are made whenever possible, particularly in regions of large departures from the long-term mean. For example, the two most obvious differences between the derived surface winds of Fig. 7 and the climatological ship winds of Fig. 5a are the deep trough in the midlatitude Northern Hemisphere westerlies which shifted the subtropical ridge southward to the Hawaiian Islands and the more intense Southern Hemisphere monsoon trough lying across 180° and southeastward through the Cook Islands. At Lihue and Honolulu, on the two most northern of the principal Hawaiian Islands, mean west-southwest surface winds of 1–2 m s^{-1} were observed. Raratonga, in the Cook Islands at 21°S, 160°W, was located near the monsoon trough and in the anomalous tropical westerly flow or the wet side of the trough. The island received 590 mm of rain, more than twice the normal amount. Such gross subjective evaluations of flow patterns are the only checks available over much of the area.

Since there is no satisfactory "ground truth" analysis of ship winds for a single month, we were forced to compare the derived surface winds with isolated averaged ship and buoy winds, and Seasat altimeter winds. Moored buoy winds are perhaps the best of these, but they are restricted to a few points. Ship winds are very "noisy." Wylie *et al.* (1983), using 1563 pairs of colocated ships (within 110 km and 18 hours), found a root-mean-square difference of 3 m s^{-1} in speed and 42° in direction. Time averaging decreases the noise, but unfortunately very few 2

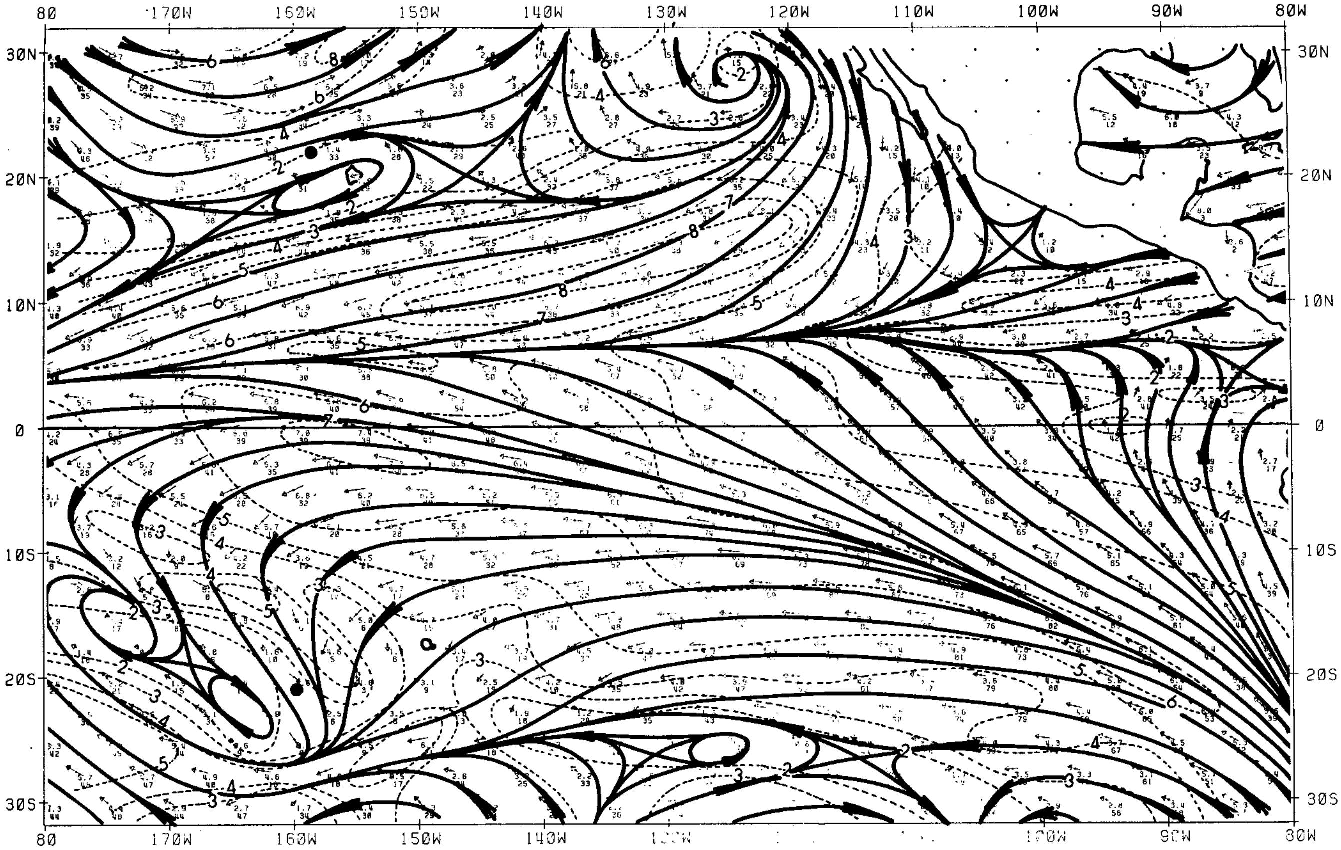


FIG. 7. Analysis of January 1980 surface winds produced by the climatological shear method using the observations of Fig. 6.

× 10° rectangles in the tropics contain even ten observations per month. In general, the correspondence between ship winds and derived surface winds improves with more ship observations. This improved correspondence is encouraging since it implies that much of the difference between the two may be due to the quality of ship observations.

For final analyses we plot the monthly averaged ship winds and the derived surface winds on the same chart. Figure 9 is an example for November 1977. There is very good correspondence between the position and intensity of the circulation systems as defined by both data sets. For example, there is good agreement on: 1) the position of the wind confluence line associated with the convergence zone extending from 10°N in the eastern Pacific to 7.5°N at 160°W, as well as with the relatively weak winds in the zone; 2) the turning of the wind from southerly to westerly in the equatorial eastern Pacific between the equator and the confluence zone; 3) the anticyclonic turning of the winds through the ridge off the Mexican coast, as well as light winds in the ridge; 4) the northeast trades in the Gulf of Mexico and light variable winds in the northwestern section of the Gulf; 5) the northeast trades south and east of Hawaii. Note the obviously poor ship data at 12.5°N, 125°W even though there are 29 observations in the rectangle. These data passed the "toss" criteria of the North Pacific Experiment (NORPAX) data center from which we obtained the averaged data.

The buoy winds along 150°W were available for November and December 1977 and January 1978 and are plotted in Fig. 10 along with the observed ship winds and derived surface winds along 145°W and 155°W. The buoy data show that the convergence zone (dashed line) moved southward and that the winds increased with time. The derived surface winds are in good agreement with this movement and the increase in winds, although they average about 1 m s^{-1} greater than the buoy winds. The derived surface winds resemble the buoy winds more than do the ship winds.

The scheme can be tested along the 10° longitudinal strip centered on 85°W, and north of the equator where the number of ship winds ranges from more than 50 per month near 10°N to about 10 near the

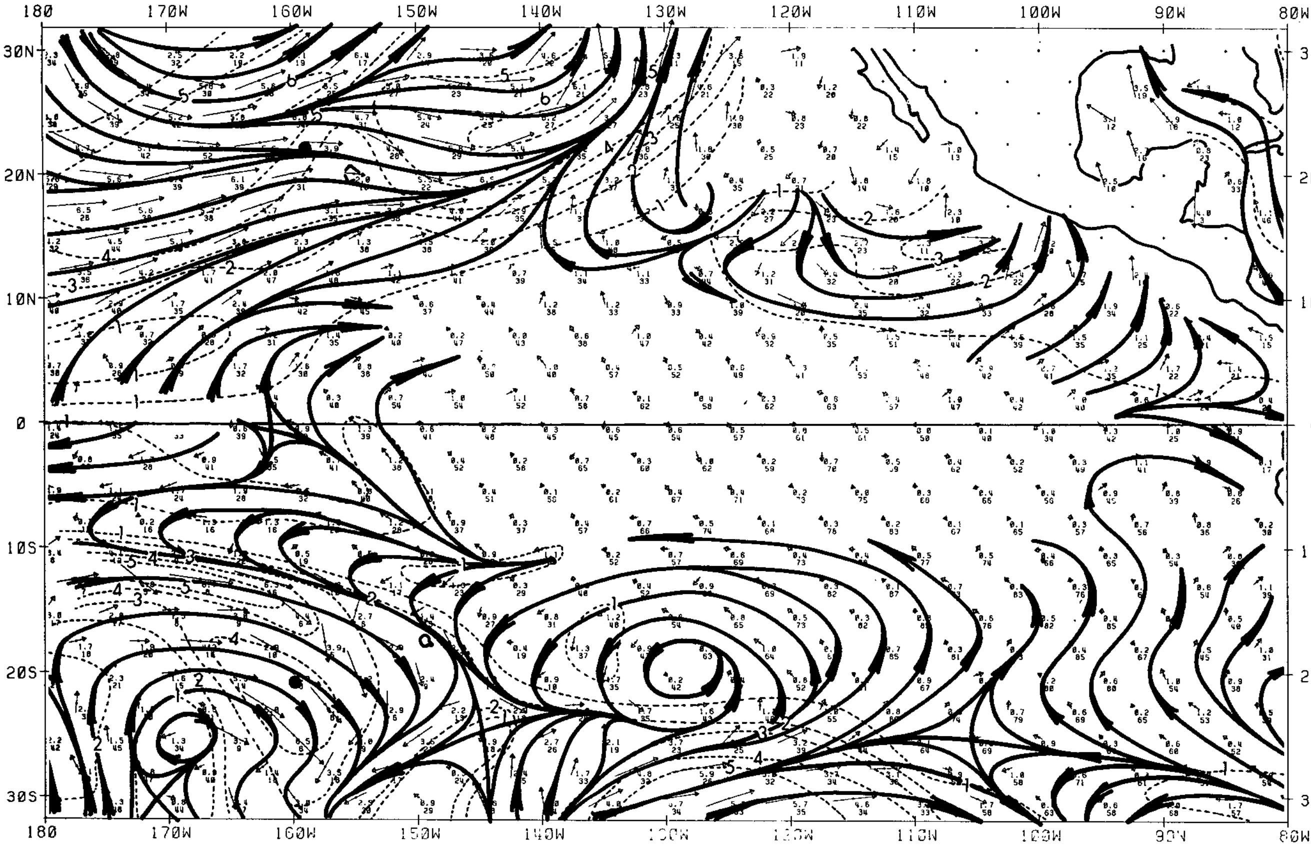


FIG. 8. Anomaly of the January 1980 sawins in Fig. 6 from the long-term mean of Fig. 5B. Analyzed only where organized and greater than 1 m s^{-1}.

equator. This is a region of extreme shear in both direction and speed between the surface and sawin levels (see Fig. 5c). In Fig. 11 ship winds and derived surface winds along this corridor are compared for the same three months as in Fig. 10. Associated with the southward movement of the convergence zone from November to January were: 1) increasing northeast winds north of the zone at 10–12°N; 2) decreasing southerly and southwesterly winds south of the zone from the equator northward; 3) broadening of the area of light and variable winds in the zone. These features are present in both data sets. Grid point data correspondence between the two sets is very good overall and excellent in the northern portions where the largest number of ship observations occurs.

Chelton and O'Brien (1982) compared three months of surface winds obtained from the Seasat microwave altimeter with the available ship data. Figure 12 shows their analyses of the three-month (July–September) averaged *scalar* wind speeds and our analysis of the derived surface resultant *vector* speed for the midmonth of August. We did not process our data for scalar speeds nor seasonal averages; however, the scalar and vector speeds are roughly comparable in areas of high steadiness. The areas of climatological steadiness greater than 90 percent are enclosed by the heavy dashed line on Fig. 12a and include the northeast trades around Hawaii and a major portion of the southeast trades including the equatorial zone. The Seasat winds and derived surface winds are remarkably similar in pattern and speed within the high steadiness areas. Note for instance the max–min–max pattern of 8, 5, and 7 m s^{-1} in the eastern Pacific, centered on 100°W from the core of the southeast trades across the equatorial minimum to a secondary maximum near 5°N; an isolated 7 m s^{-1} maximum near 5°S, between 140 and 150°W; the decrease of the northeast trade speed in the lee of the Hawaiian Islands. The correspondence is much better than that between the ship wind and the Seasat wind analyses. In the ship wind analysis, the core of the southeast trades is displaced some 2000 km westward; the equatorial minimum is not pronounced nor is the Hawaiian lee side minimum present.

Table 1 compares derived surface winds with Halpern's buoy winds in the equatorial Pacific. Tests

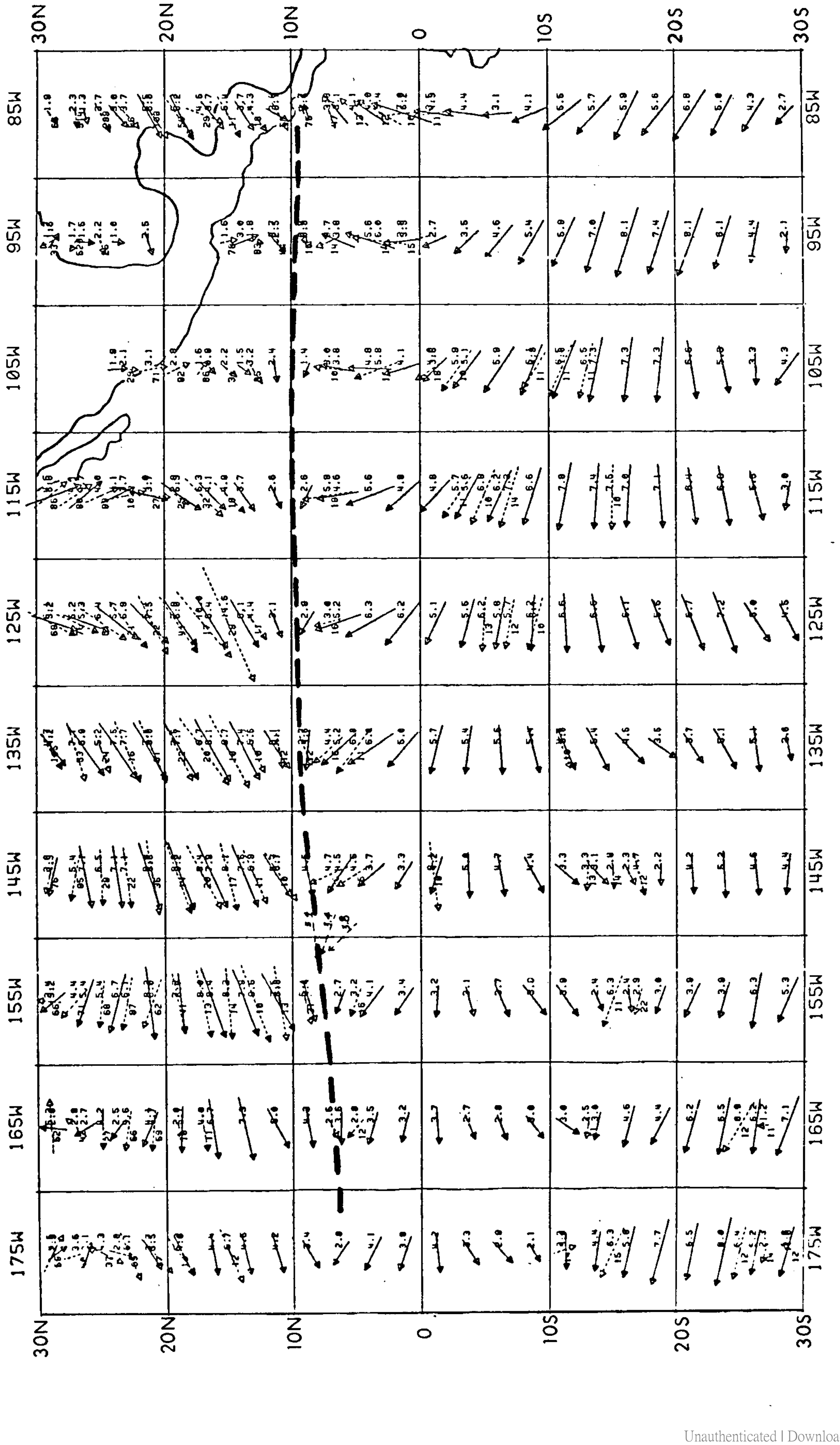


FIG. 9. November 1977 mean surface winds from satellites, ships and buoys. Derived surface winds on 2.5 by 10° grid are solid shaft arrows. Ship winds on 2 × 10° grid are dashed shaft arrows, and the number of observations are ≥10 and plotted to the left. The moored buoy winds at 6, 7 and 8°N along 150 W are from Halpern (1979). Lengths of all arrows are proportional to speed.

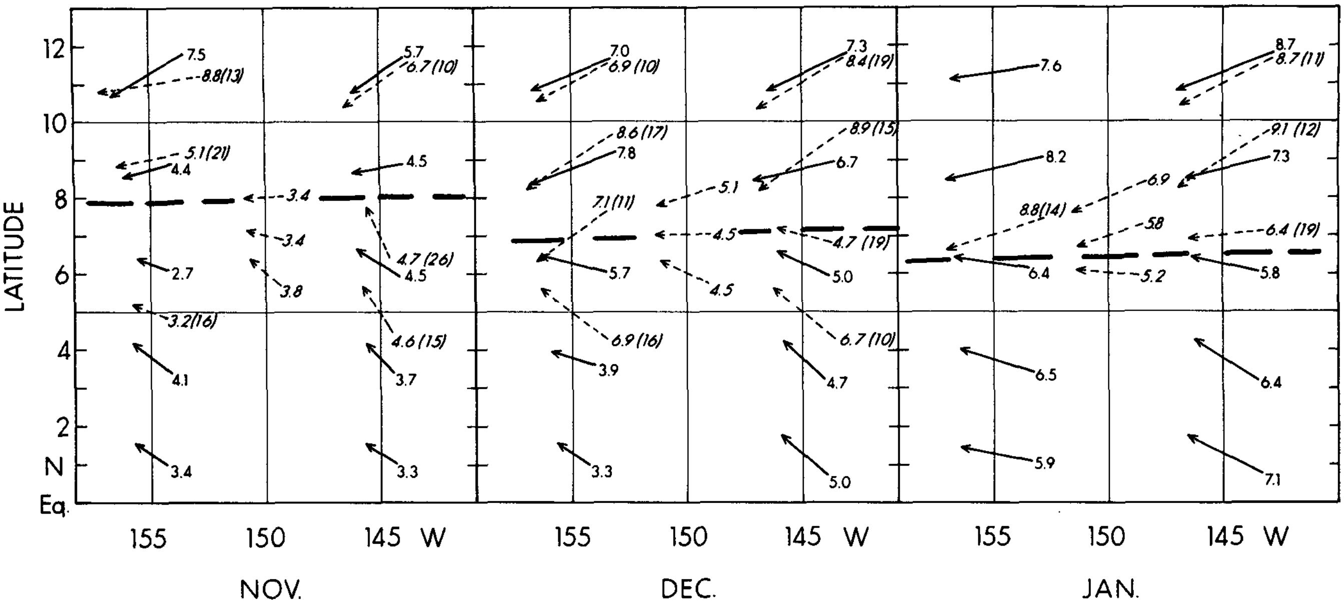


FIG. 10. November and December 1977 and January 1978 mean surface winds derived from sawins, ships and moored buoys. Grids and plotting are as in Fig. 9. Number of ship observations shown in parentheses. Wind confluence line is the horizontal dashed line.

indicate that buoy winds are accurate to within 1 m s^{-1} and 20° (Halpern, 1978). The agreement between the two data sets is surprisingly good. In only two of the 16 months did the wind speeds differ by more than 1 m s^{-1}. In February 1980, the derived surface wind speed was 1.1 m s^{-1} less than the single buoy, while in June 1979 it exceeded the wind speed of adjacent buoys of 1.2 and 2.5 m s^{-1}. Attesting to the quality (or stability) of the buoy winds, their speeds differed by only 0.1–0.3 m s^{-1} except for the month of June.

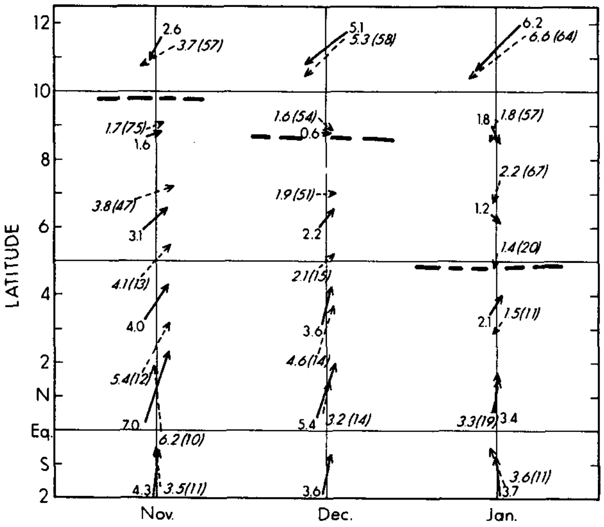


FIG. 11. Comparison of monthly mean ships and derived surface winds in the 10° strip between 80 and 90°W for the months of November and December 1977 and January 1978. The numbers of ship observations are in parentheses.

5. Summary

Tests of our method—using monthly climatological shears to derive surface winds from satellite observed cloud motions over the eastern Pacific—have been encouraging. The derived surface winds are comparable in quality to those from ships, buoys, and Seasat. However, it should be cautioned that this and other methods are based on large assumptions concerning shear through the boundary layer. This method assumes that the grid-point wind shear profiles associated with circulation systems (northeast and southeast trades, monsoon westerlies, etc.) on the monthly climatological time scale are appropriate for the individual monthly time scale such that a monthly anomaly observed by the sawins is also present at the surface. The method should not be valid for rare occasions such as the extremely low Southern Oscillation regime of 1982–83, when the normal tropical easterly regime was replaced by a near-equatorial westerly regime in the central and eastern Pacific. The method of Wylie and Hinton (1982), which is based on concurrent ship and satellite colocated data, requires averaging over very large areas and time periods (seasons) to have sufficient ship data to obtain

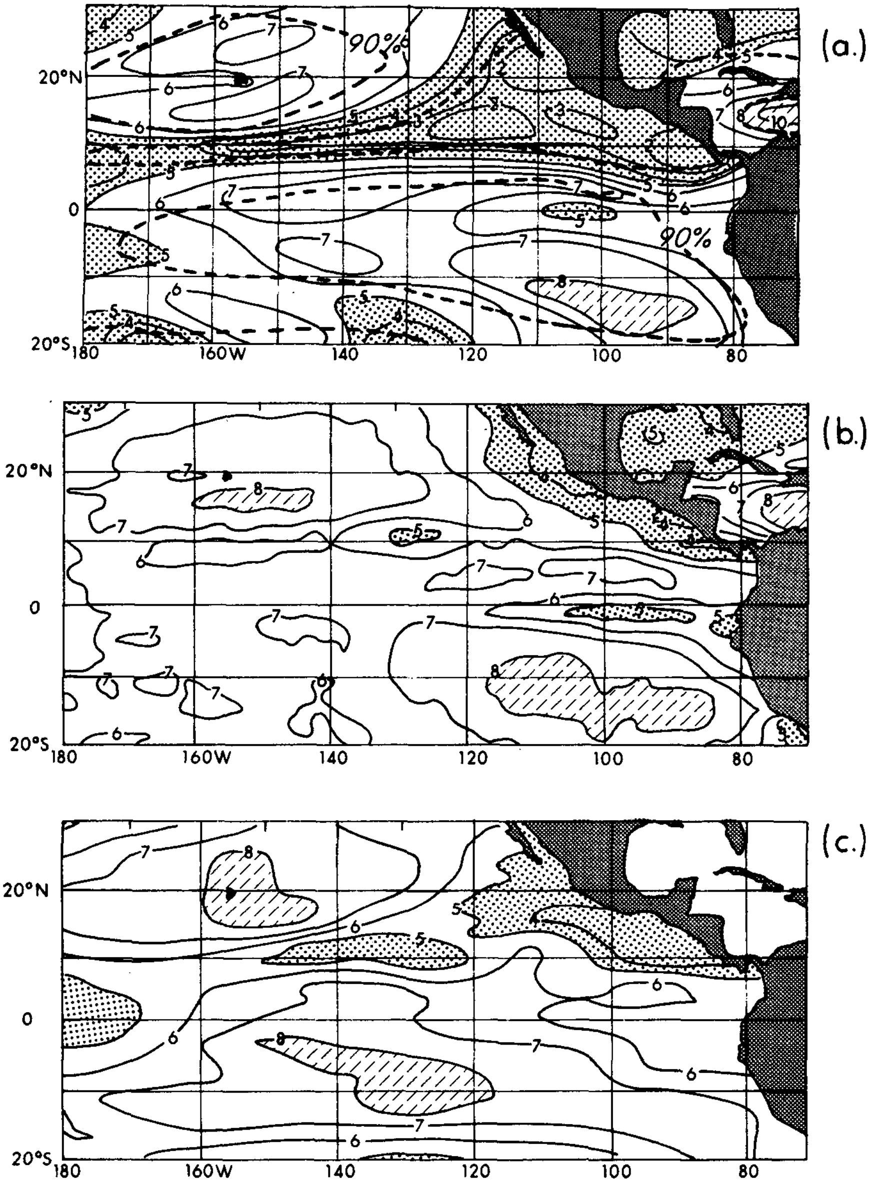


FIG. 12. Analyses of surface winds. (a) August 1978 averaged vector speed derived form GOES satellite; (b) July–September 1978 averaged scalar speed form Seasat satellite altimeter; (c) July–September 1978 averaged scalar speed from ships. Climatological wind steadiness of 50 and 90 percent shown on (a); (b) and (c) from Chelton and O'Brien (1982).

TABLE 1a. Comparison of satellite surface winds and buoy winds: Equator and 110°W.*

	Buoy		Satellite	
Date (1979)	Direction (deg)	Speed (m s^{-1})	Direction (deg)	Speed (m s^{-1})
February	145	3.3	138	3.0
March	123	2.9	135	2.4
April	122	2.8	120	2.8

*Average difference: direction = 7°; speed = 0.3 m s^{-1}.

an averaged shear value. The one shear value is then applied to all of the observed sawins within that large area and time period. This assumption of constant shear over large areas and time periods can be quite serious as indicated by the analysis of Fig. 5c which shows that the shear has large variations over short space scales and is circulation system dependent rather than fixed geographical area dependent. The two methods have not been compared using independent data.

TABLE 1b. Comparison at satellite surface winds and buoy winds: Equator and 152 and 153°W.*

	Buoy 152°W		Buoy 153°W		Satellite	
Date (1979–80)	Direction (deg)	Speed (m s^{-1})	Direction (deg)	Speed (m s^{-1})	Direction (deg)	Speed (m s^{-1})
May	84	4.2	81	4.0	100	4.5
June	92	5.4	93	4.1	102	6.6
July	98	4.4	99	4.3	97	5.0
August	109	4.5	106	4.6	112	4.8
September	114	5.3	107	5.4	117	5.1
October	102	5.3			119	4.5
November	94	6.6			97	6.2
December	91	5.8			93	5.1
January	92	6.5			95	6.6
February	92	6.3			90	5.2
March	90	5.4	102	5.7	90	5.3
April	84	4.6	92	4.9	90	4.1
May	86	4.4	99	4.3	91	4.6

*Average difference: direction = 5°; speed = 0.5 m s^{-1}.

Acknowledgments. We are grateful to Arnold Hori and Mark Lander for data processing and analysis support, to Louis Oda for drafting the figures, and to Mrs. S. Arita for typing the manuscript.

The work was supported by the National Science Foundation under Grant OCE-80-18186 and National Oceanic and Atmospheric Administration under Contract NA80RAH00002.

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