A Technique for Deducing Wind Direction from Satellite Microwave Measurements of Wind Speed

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ABSTRACT

A technique is presented to deduce wind direction from satellite microwave measurements of wind speed information. The technique, based on simple Ekman boundary layer dynamics, makes use of surface pressure fields routinely analyzed at the National Meteorological Center. To demonstrate its application, a three-day sample of altimeter and scatterometer wind speed data, taken from the Seasat satellite, was used to deduce wind directions. The deduced wind vectors are presented and compared with the NMC 1000 mb wind analyses, and with the subjectively edited vector winds. It is suggested that the technique proposed in this study could be applied to the ocean surface wind speed measurements derived from a satellite altimetric mission to produce a more useful parameter, namely, the ocean surface wind vector. This technique can also be used to objectively resolve potential ambiguities in scatterometer wind directions.

1. Introduction

Global ocean surface winds are important for meteorological and oceanographic applications. One application is in the use of ocean surface winds to improve the prescription of atmospheric initial states for numerical weather prediction (Yu and McPherson, 1979). Others are the use of ocean surface winds on global wave forecast models (SWAMP Group, 1985), and large-scale ocean circulation models (Richardson and Philander, 1987). It is not feasible however, to obtain a comprehensive coverage of global ocean winds from conventional ship and buoy measurements. Wind measurements over the oceans reported by ships of opportunity and buoys represent a total of approximately 900–1000 reports per each synoptic hour of the day. This constitutes a very poor spatial density even if the measurements are distributed uniformly over the global oceans.

Satellite-borne instruments are obviously the only possible source that can provide a systematic global coverage of ocean surface winds even if they might be asynoptic in nature. If the winds derived from spaceborne techniques represent a sufficiently large set of data, and if they are provided in a timely fashion to an operational forecaster, it is possible to utilize these additional data in improving the initial representation of the atmospheric structure for numerical weather prediction. Even though a Seasat scatterometer data assimilation study (Yu and McPherson, 1984) showed only a small positive impact, it should be kept in mind that their conclusions pertained to the analysis and forecast models of the late 1970 vintage. The question of impact of ocean surface wind vectors from satellite-borne devices on the initial analyses and forecasts of the current generation models is yet to be addressed systematically. Irrespective of the answer to this question, there is no doubt that marine winds from satellites will contribute to an improvement of the sea surface wind stress prescription, an essential aspect in studies of ocean circulation and air–sea interaction problems.

Of the available microwave sensors from satellites, only scatterometer measurements can provide vector winds. However, these measurements suffer from ambiguities in wind direction, which need to be resolved. There have been techniques designed for removal of the ambiguity problem, notably those of Yu and McPherson (1984), Woiceshyn et al. (1986), and Hoffman (1982, 1984). Another active microwave wind sensor is the altimeter, which can only provide wind speed, but not its direction (Fedor and Brown, 1982; Wentz et al., 1986). Since a measurement of wind speed alone is not a very useful parameter for most of the meteorological and oceanographic applications, these altimeter wind data tend to be ignored.

The purpose of this paper is to present a technique for deducing wind direction using wind speed information from either an altimeter or a scatterometer from satellites. The technique is based on simple Ekman boundary layer dynamics with a drag coefficient representation for the surface momentum flux, together with the surface pressure analysis field routinely available at the National Meteorological Center (NMC). This procedure, which does not require any a priori specification of the surface drag coefficient, enables one to uniquely compute the wind direction from the satellite wind speed data. Such an exercise will provide a global coverage of ocean surface wind vectors from the currently available altimeter wind speed measurements taken on board the operational GEOSAT satellite. In addition, the technique suggested here will help resolve any directional ambiguities in future scatterometer wind vector measurements, should they arise.

2. Description of the technique

The method is based on Ekman boundary layer dynamics which assume a balance between the pressure gradient, Coriolis and friction forces in the atmospheric boundary layer:

$$-fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(K_m \frac{\partial u}{\partial z}\right)$$

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(K_m \frac{\partial v}{\partial z}\right) \tag{1}$$

where f is the Coriolis parameter, p is atmospheric pressure, and u and v are wind components in the east–west and north–south directions, respectively; ρ is air density, and K_m is the eddy diffusion coefficient for momentum. If we integrate (1) from $z = z_*$, (a small height of typically about 10 meters above the ocean surface), to h, top of the marine boundary layer, we have,

$$K_m \frac{\partial u}{\partial z}\bigg|_{z=z_*}^{z=h} = \int_{z_*}^{h}\left(\frac{1}{\rho}\frac{\partial p}{\partial x} - fv\right)dz$$

$$K_m \frac{\partial v}{\partial z}\bigg|_{z=z_*}^{z=h} = \int_{z_*}^{h}\left(\frac{1}{\rho}\frac{\partial p}{\partial y} + fu\right)dz.$$

We shall assume that the momentum fluxes vanish at the top of the marine boundary layer, i.e., $K_m\partial u/\partial z = K_m\partial v/\partial z = 0$ at $z = h$, and that the momentum fluxes at the low boundary, i.e., $z = z_*$, may be represented by

$$K_m \frac{\partial u}{\partial z}\bigg|_{z=z_*} = C_D|S|u; \quad K_m \frac{\partial v}{\partial z}\bigg|_{z=z_*} = C_D|S|v$$

where C_D is the surface drag coefficient, and S is wind speed, i.e., $S = (u^2 + v^2)^{1/2}$. Now, let

$$\int_{z_*}^{h}\left(\frac{1}{\rho}\frac{\partial p}{\partial x} - fv\right)dz = \hat{h}\left(\frac{1}{\rho}\frac{\partial p}{\partial x} - fv\right)_{z_*}$$

$$\int_{z_*}^{h}\left(\frac{1}{\rho}\frac{\partial p}{\partial y} + fu\right)dz = \hat{h}\left(\frac{1}{\rho}\frac{\partial p}{\partial y} + fu\right)_{z_*} \tag{2}$$

where $\hat{h}$ is defined to be an equivalent depth, and assumed to have the same value in the two equations above. Note that $\hat{h}$ represents some characteristic depth scale which, when multiplied by the surface values of the integrand, yields the total contribution of the integral on the left-hand side of Eq. (2) throughout the planetary boundary layer. Based on this assumption then, Eq. (1) may be rewritten as

$$-fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} - \hat{C}_D|S|u$$

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} - \hat{C}_D|S|v \tag{3}$$

where $\hat{C}_D = C_D/\hat{h}$ is the effective surface drag coefficient. All the quantities in Eq. (3) are evaluated at the height of $z = z_*$ above the ocean surface. It follows from (3),

$$\hat{C}_D{}^2S^4 + f^2S^2 = \left(\frac{1}{\rho}|\nabla p|\right)^2. \tag{4}$$

From (4) we note that if the surface pressure field ($\partial p/\partial x$, $\partial p/\partial y$) at the ocean surface is given, and speed S is also known, then the parameter $\hat{C}_D$ is determined. There is no need to resort to any a priori specification of the surface drag coefficient C_D, nor do we need to know the values of the so-called equivalent depth $\hat{h}$. Thus, if one is provided with the wind speed data from the altimeter or scatterometer measurements and the surface pressure field, the parameter $\hat{C}_D$ is determined from (4), and consequently the wind components (u, v) can be computed from (3).

It should be noted that this technique can even apply at the equator where $f = 0$, although generally the results in the tropical oceans may not be as satisfactory as they are at midlatitudes. This is primarily due to the fact that the nonlinear advective terms, which are ignored in Eq. (1), become more important near the low latitudes. Further, this technique depends upon the NMC's global synoptic-scale sea level pressure analysis as an essential input for deducing wind direction. One would expect, in general, that the sea level pressure field would be more reliable and accurate in midlatitudes, where there are more surface observations and better first-guess pressure fields provided by the forecast model than in the tropics.

The above method was applied to the wind speed measurements taken from the Seasat altimetry and scatterometry. The resulting vector wind fields and difference statistics are presented in the following sections.

3. Application to Seasat altimeter and scatterometer data

a. *Directional retrieval*

Seasat, an experimental oceanographic satellite, was launched in June 1978. Unfortunately, only about three months worth of data were collected before the satellite became inoperative. These data included altimeter wind speeds and scatterometer vector winds. Recently, a set of subjectively edited scatterometer wind data was made available to us (Atlas, 1985). This dataset, hereafter referred to as "the edited dataset", was produced by using satellite imagery together with all the other available sources of surface data, including the NMC's 1000 mb wind analysis and subjectively analyzed sea level pressure fields to help select one of the four possible wind directions for each observation. This set of scatterometer data have wind vectors which are free of directional ambiguities, and thus enable us to use them for comparison with the deduced winds generated by the technique discussed here.

In this study, the Seasat altimeter and scatterometer wind speed measurements for three consecutive days were chosen to demonstrate the validity of the technique. Since the technique depends on the use of NMC's sea level pressure analysis, which applies only to synoptic-scale processes, no effort was made to resolve any subsynoptic features of the wind fields along the satellite tracks. Data from the altimeter and scatterometer wind speed measurements were taken at all points along the tracks that fall within 1½ h before and after the surface pressure analysis time. On an average, the altimeter measures ocean surface winds every second or so, thus resulting in nearly ten thousand data points for a three-hour window. In order to qualitatively display the wind vectors retrieved by the technique, it is necessary to apply an averaging procedure to obtain the satellite wind speeds on a 2.5 by 2.5 degree longitude–latitude grid. The averaging procedure is such that the weighting of each data point is inversely proportional to the distance between the data and the grid point to which the average will be assigned. Typically, about 40 data points are used to generate an average grid point value. Such an averaging procedure will undoubtedly smooth out small-scale features. However, since the external parameter in Eq. (1), namely the sea level pressure gradient, is only prescribed on a synoptic scale, the above averaging should be well justified. The total number of altimeter data points after the averaging is about 300 ($N = 276$ for 17 September, $N = 279$ for 18 September, and $N = 317$ for 19 September 1978) discussed below during the three-hour window. This is comparable to the number of surface ship reports received during the same period, thus essentially doubling the database. On the other hand, the total number of scatterometer data points after the averaging is about 700 ($N = 637$ for 17 September, $N = 701$ for 18 September, and $N = 795$ for 19 September, 1978) during the three-hour period.

The gridded wind vectors deduced from the altimeter and scatterometer wind speed data may be readily compared with the NMC's 1000 mb wind analyses and the subjectively edited winds. However, it should be kept in mind that both the edited vector winds and the NMC's 1000 mb wind analyses are not "ground truth". Ideally, one would desire to have in situ surface reports such as measurements from buoys and ships as "ground truth" for comparison with the retrieved satellite winds. However, due to lack of sufficient number of surface reports under the satellite tracks considered here, both the edited winds and the NMC's 1000 mb wind analyses are used in a three-way comparison with the deduced vector winds. It should be noted that the NMC's 1000 mb wind analyses are produced on a 2.5 by 2.5 degree longitude–latitude resolution by a multivariate optimum analysis scheme, making use of surface ship and buoy wind reports. The scales resolvable in the NMC's 1000 mb wind analyses are, therefore, synoptic in nature. Further, over the areas where there are no data reports available, such as over the Southern Hemisphere oceans, and over the tropics and higher latitudes, the analyses are merely the first guesses from the forecast models (Dey and Morone, 1985). On the other hand, the edited winds are the remotely sensed scatterometer winds with the ambiguities removed by using other auxiliary information as mentioned earlier. As such, one would expect the full set of the edited scatterometer winds to contain subsynoptic features. To use the edited scatterometer winds for comparison with the gridded satellite wind vectors deduced by the technique and the NMC's 1000 mb wind analyses, it is necessary to apply the same type of averaging procedure to the edited dataset and derive the appropriate wind fields on the 2.5 by 2.5 degree longitude–latitude grid.

Examples of vector wind retrievals by the technique from Seasat altimeter and scatterometer wind speeds are shown respectively in Figs. 1 and 2. For comparison, the corresponding NMC's 1000 mb wind analyses and the subjectively edited scatterometer vector winds are shown respectively in Figs. 3 and 4. As expected, comparison of wind vectors from altimeter wind speeds (Fig. 1) and those from scatterometer wind speeds (Fig. 2) shows that these two satellite winds retrieved by the technique are consistent and coherent with one another for all the three synoptic cases considered in this study. This is due to the fact that both of these wind fields are deduced by using the same sea level pressure analyses, and that the wind speeds from both of the sensors are comparable in accuracy. In the Joint Air–Sea Interaction (JASIN) experiment and other validation studies, the scatterometer wind speed measurements showed a 0.7 m s^{-1} high bias whereas the altimeter wind speeds showed a 0.3 m s^{-1} low bias when compared with the in situ surface ship and buoy reports (e.g., Fedor and Brown, 1982; Jones et al., 1982). This indicates that altimeter and scatterometer wind speeds are on the average within 1 m s^{-1} accuracy when compared to the surface measurements. Detailed comparison of the deduced altimeter vector winds with the deduced scatterometer winds (comparing Fig. 1a with Fig. 2a, Fig. 1b with Fig. 2b, and Fig. 1c with Fig. 2c) indicate also that overall the scatterometer vector winds are slightly stronger in wind speed than the altimeter winds, especially in midlatitudes. Further, both the retrieved satellite vector winds show discernible flow patterns, except near the tropics (latitudes between 10°N and 10°S) where the flow fields are less well organized. Comparison of the flow patterns from the deduced altimeter vector winds (Fig. 1) and scatterometer

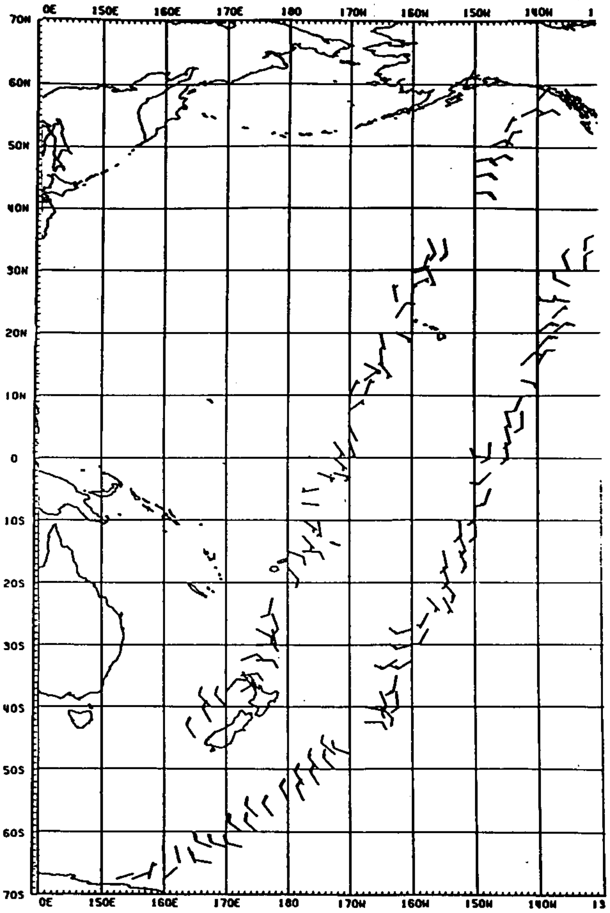

FIG. 1a. Deduced vector winds from the Seasat altimeter wind speed data for 0000 UTC 17 September 1978.

winds (Fig. 2) with those of the NMC's 1000 mb wind analyses (Fig. 3) show a good overall agreement in all regions, except in the tropics where the NMC's winds are also somewhat disorganized. The edited scatterometer winds, on the other hand, show a well-defined flow pattern over the tropics between 10°N and 10°S (Fig. 4). Elsewhere, the flow patterns discernible from the wind vectors between the NMC's 1000 mb wind analyses and the edited vector winds are generally agreeable. However, detailed comparison between the edited vectors (Fig. 4) and those of the NMC's 1000 mb winds (Fig. 3) show considerable differences. If one would regard the edited scatterometer winds as actual ocean surface wind measurements, then these differences may indicate the errors induced by the NMC analyses. This is especially true in the tropics, where the differences become substantial between the two wind fields (Compare Fig. 3 and Fig. 4). Note that the deduced wind vectors are in better agreement with those of the NMC 1000 mb analyses (compare Fig. 1 and Fig. 2 with Fig. 3), than with the subjectively edited wind vectors (compare Fig. 1 and Fig. 2 with Fig. 4). Presumably, this is due to the fact that the NMC's surface pressure field is used to deduce wind vectors from the altimeter and scatterometer wind speed measurements, and the pressure field is, of course, related to the 1000 mb analyzed wind fields. However, it should be pointed out that the height of 1000 mb is not always at the sea level, and therefore, the NMC's 1000 mb winds are not ocean surface winds.

To summarize this section, we have demonstrated that the technique proposed in this study can indeed be applied to deduce wind directions from the altimeter and scatterometer wind speed measurements. The deduced wind vectors are qualitatively comparable with the edited scatterometer winds and the NMC's 1000 mb wind analyses. In the following section, we shall show quantitatively that the technique can be truly useful in retrieving wind directions from satellite wind speeds.

b. Difference statistics

Difference statistics for vector wind deduced from the Seasat scatterometer and altimeter data with the

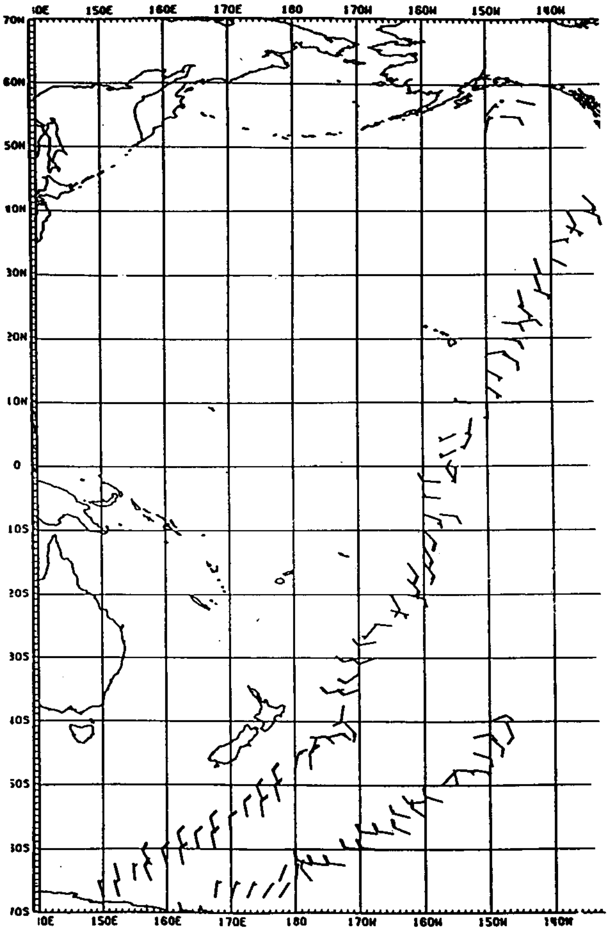

FIG. 1b. As in Fig. 1a except for 0000 UTC 18 September 1978.

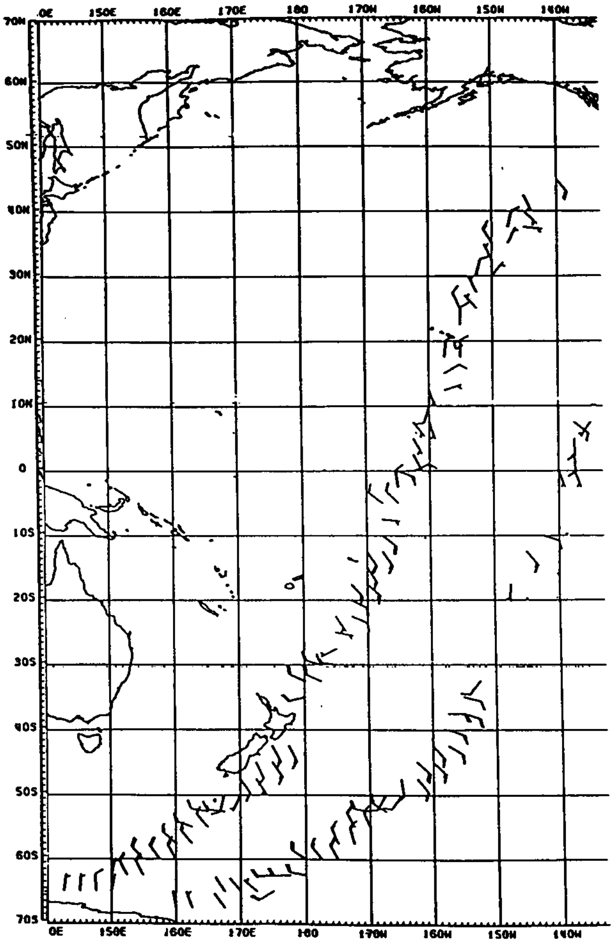

FIG. 1c. As in Fig. 1a except for 0000 UTC 19 September 1978.

NMC analyses for these three synoptic cases were calculated. Let the wind speeds from any two sources be represented by S_A and S_B, and the corresponding wind vectors be (U_A, V_A), and (U_B, V_B), then the following quantities may be defined.

Mean difference in wind speed (Bias):

$$D1 = \Sigma(S_A - S_B)/N$$

Mean absolute difference in wind speed:

$$D2 = \Sigma|S_A - S_B|/N$$

Root-mean-square difference (rms) in wind speed:

$$R1 = [\Sigma(S_A - S_B)^2/N]^{1/2}$$

Rms difference in vector wind:

$$R2, R3, R4 = [\Sigma(U_A - U_B)^2/N + \Sigma(V_A - V_B)^2/N]^{1/2}$$

Two types of statistics are calculated. The first type is based on the grid-averaged data points on the 2.5 by 2.5 degree longitude–latitude grid. As explained previously, after applying the grid-averaging procedure, the satellite data sample size used in computing the difference statistics is about 700 for the scatterometer data, and about 300 for the altimeter data (e.g., the sample size, N, for each synoptic case is shown in Tables 1 and 2). Before discussing the results, it should again be remembered that both the edited scatterometer winds and the NMC's 1000 mb analyses are not the ground truth, but rather are used to set the difference statistics in the right prospective. From Table 1, one can see that, in comparison with the NMC's 1000 mb wind analyses, the scatterometer wind speeds tend to be biased high, whereas altimeter wind speeds biased low by about 1–2 m s^{-1} (e.g., D1 values in Table 1). The mean absolute wind speed differences are about 2–3 m s^{-1} (see D2 values in Table 1), and the rms difference in wind speed is about 3–4 m s^{-1} (see e.g., R1 values in Table 1). Further, the rms vector wind differences are about 5–6 m s^{-1} for the deduced scatterometer winds, and about 6–7 m s^{-1} for the deduced altimeter winds (see R2 values in Table 1).

There have been validation studies conducted during the period of July to September 1978, where the scatterometer and altimeter wind speed data were compared with the in situ surface ship and buoy wind measurements. Fedor and Brown (1982) compared Seasat

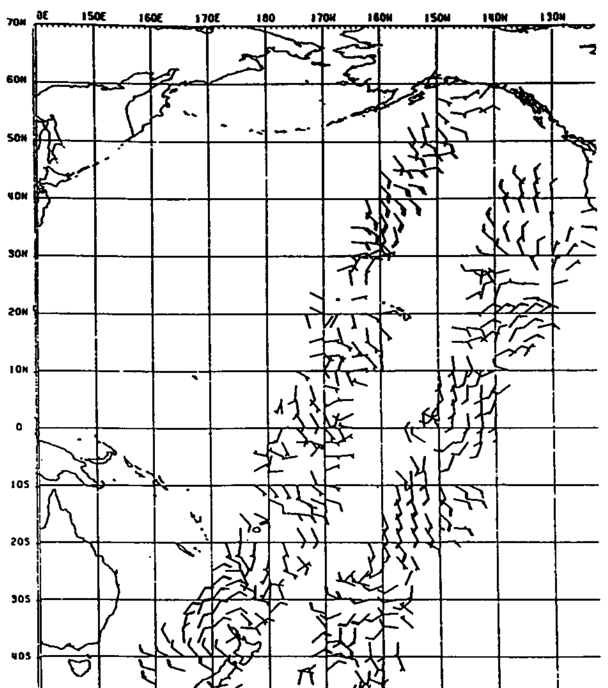

FIG. 2a. Deduced vector winds from the Seasat scatterometer wind speed data for 0000 UTC 17 September 1978.

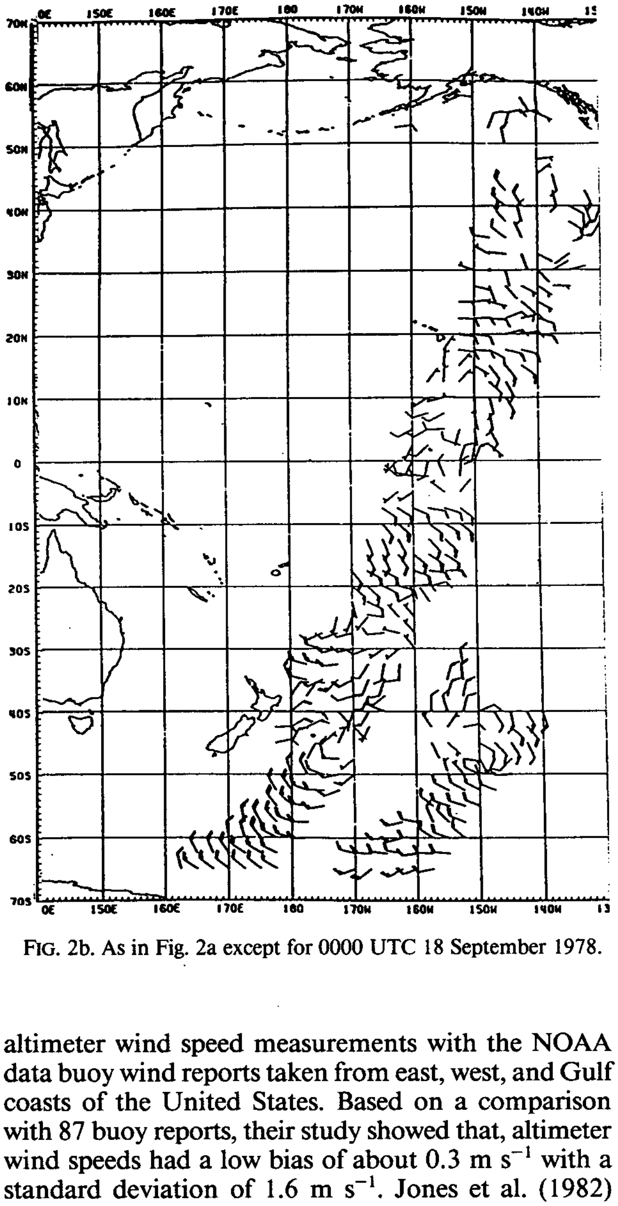

FIG. 2b. As in Fig. 2a except for 0000 UTC 18 September 1978.

altimeter wind speed measurements with the NOAA data buoy wind reports taken from east, west, and Gulf coasts of the United States. Based on a comparison with 87 buoy reports, their study showed that, altimeter wind speeds had a low bias of about 0.3 m s^{-1} with a standard deviation of 1.6 m s^{-1}. Jones et al. (1982) compared scatterometer winds with surface ship and buoy reports taken in the JASIN experiment. They showed that scatterometer wind speeds were about 0.7 m s^{-1} high biased with a standard deviation of about 2.5 m s^{-1}. Further, they showed that scatterometer wind directions, after subjectively removing the ambiguities, had a mean difference of about 4 deg with a standard deviation of 25 deg when compared with the surface reports. The total number of scatterometer wind data used in their comparison was about 1159. In the studies of Yu et al. (1985) and Gemmill et al. (1987), a systematic comparison between the NMC 1000 mb analyzed winds and buoy winds was carried out for a 30-day period. Based on a total of about 10 000 data points, the results of these comparisons show that the rms wind speed differences between the two are of the order of 4 m s^{-1} and rms vector wind differences are of the order of 5–6 m s^{-1}. These differences arise possibly due to several sources. The NMC analysis represents large-scale flow characteristics and the 1000 mb surface is not at the buoy level in general. Further, these differences are a result of not only the differences in the implicit space and time scales of representation in each dataset, but also due to the necessarily inadequate data that has gone into producing the NMC analyses. Presumably, the contribution from the latter deficiency to the overall errors can be reduced by adding more data of a quality comparable to the available conventional measurements to the analysis.

If the wind speeds measured by the microwave altimeter and scatterometer are close to buoy wind speeds as shown in the validation studies, the rms wind speed differences reported here between satellite sensor measurements and the NMC analyses are consistent with those found between buoys and the NMC analyses reported by Yu et al. (1985) and Gemmill et al. (1987). Since the vector wind differences are nearly the same between buoys and the NMC 1000 mb wind analyses on the one hand, and the present vector retrievals from altimeter and scatterometer wind speeds and the NMC 1000 mb wind analyses on the other, it appears that

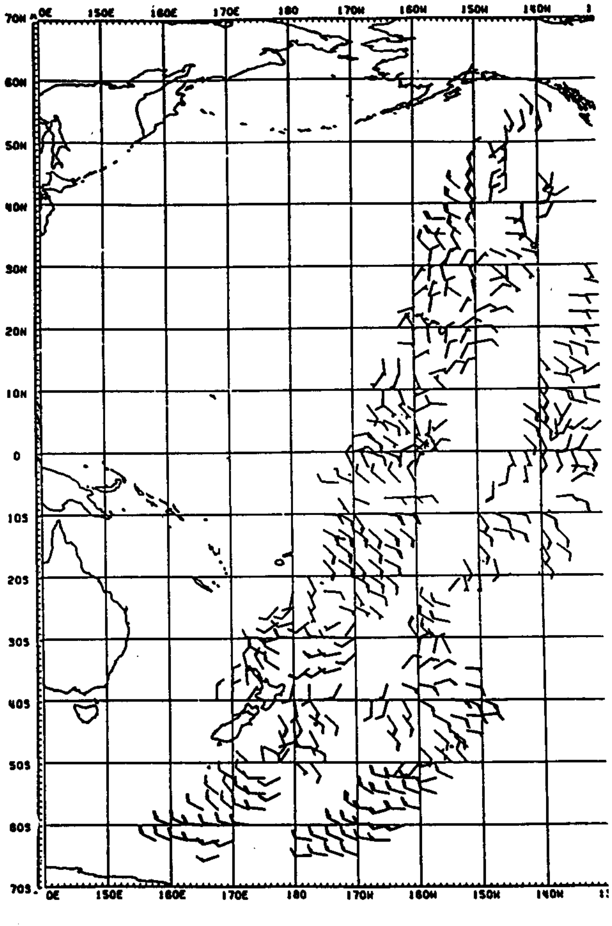

FIG. 2c. As in Fig. 2a except for 0000 UTC 19 September 1978.

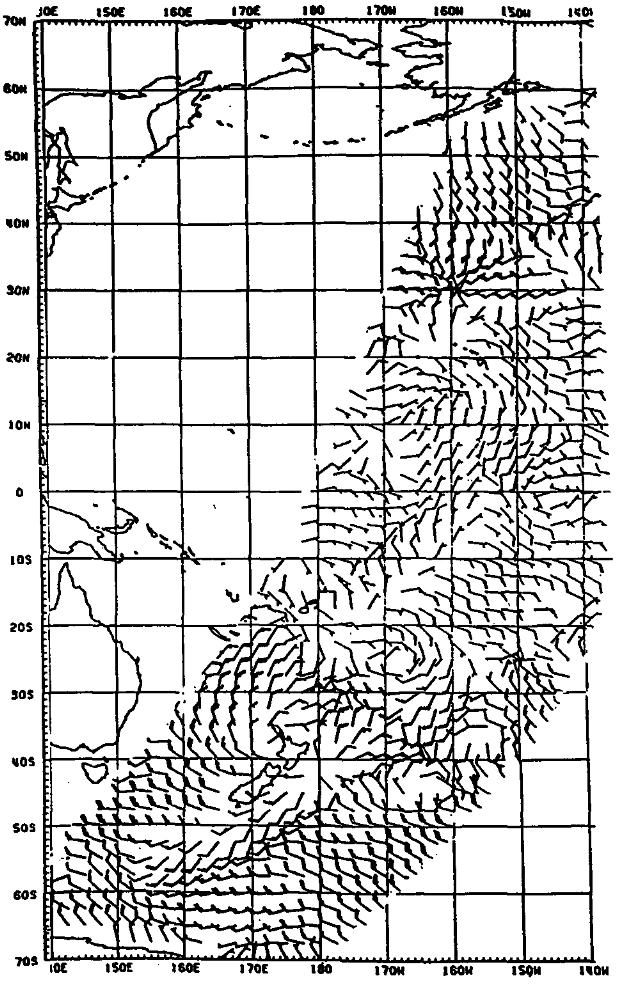

FIG. 3a. The NMC 1000 mb vector winds from multivariate optimum interpolation analysis for 0000 UTC 17 September 1978.

the technique proposed here provides vector winds from satellite wind speed measurements with an accuracy comparable to buoy measurements.

The subjectively edited scatterometer dataset enables us to compute two additional statistics i.e., the rms vector wind difference between the deduced winds and the edited scatterometer winds (*R*3), and the rms vector winds differences between the edited scatterometer winds and the NMC's 1000 mb wind analyses (*R*4). These statistics are not available for altimeter data, since the orbits for scatterometer and altimeter are different, and it is considered improper to interpolate the altimeter data points to the scatterometer locations. From the rms difference statistics for wind speeds and vector winds shown in Table 1, we observe that *R*2 values are smaller than *R*3, and *R*3 values are smaller than *R*4. This indicates that among the three-way comparisons, the difference between the deduced vector winds and the NMC's 1000 mb winds are the smallest. These three rms difference statistics are further subjected to a Chi-Square test for the hypothesis that they are not significantly different from one another at 95% significance level. The test results show that *R*2 is significantly different from *R*3 and *R*4, but *R*3 is not significantly different from *R*4, for all the three synoptic cases discussed in this study. Thus, one may conclude, based on the rms vector wind difference statistics, that the deduced vector winds are better than the edited winds if one uses the NMC's 1000 mb wind analyses as the basis for comparison. Further, the deduced vector winds are at least as good as the NMC 1000 mb vector winds if one uses the edited vector winds as the basis for comparison.

Directional difference statistics calculated for scatterometer and altimeter wind data on the 2.5 by 2.5 degree longitude–latitude grid are presented in Table 2. As was done previously for wind speeds and vector winds, three directional statistics are calculated, i.e., mean difference, mean absolute difference, and rms difference in wind directions. From Table 2 one sees that there exists a very small bias of less than 10 degrees in wind direction among the three-way comparison of

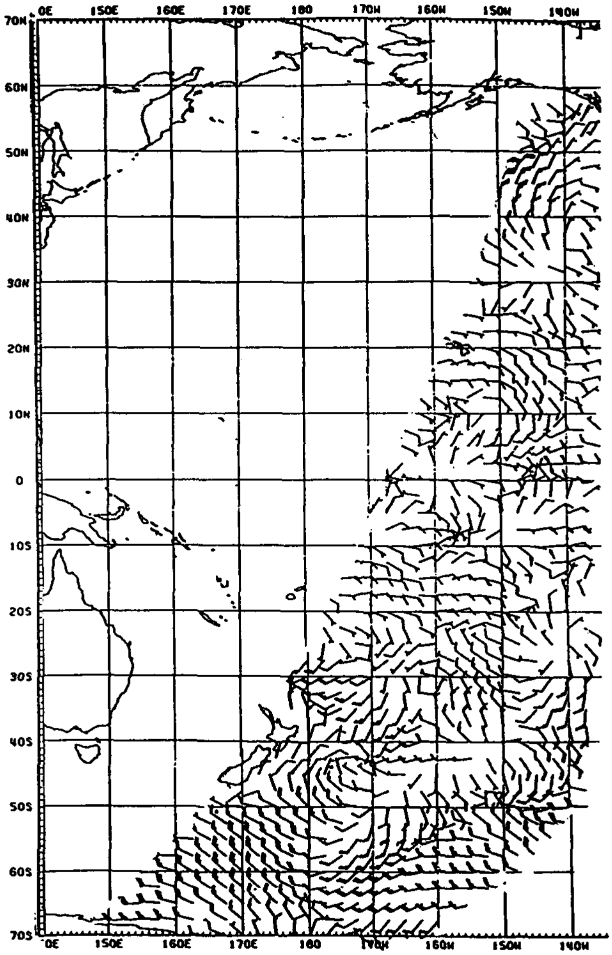

FIG. 3b. As in Fig. 3a except for 0000 UTC 18 September 1978.

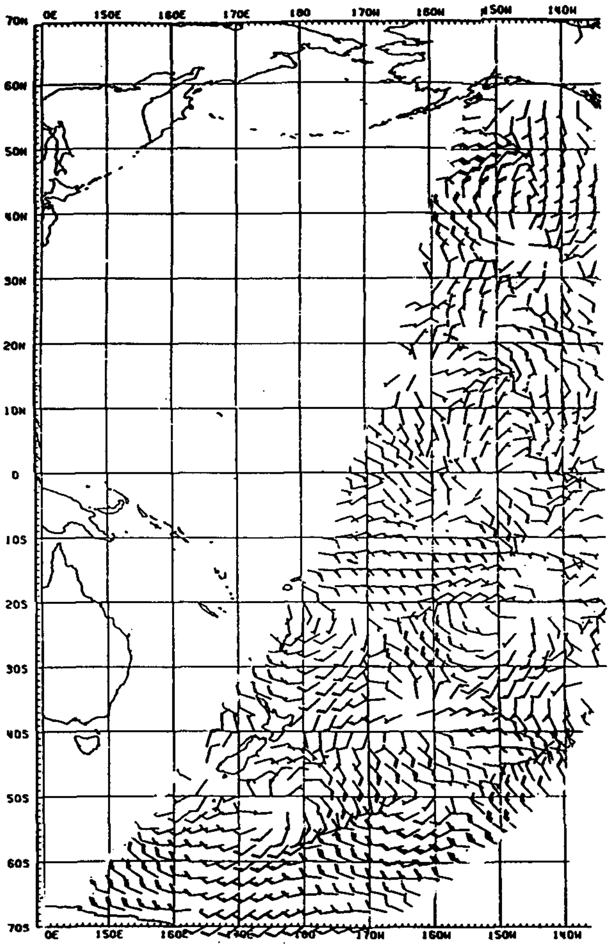

FIG. 3c. As in Fig. 3a except for 0000 UTC 19 September 1978.

the directional difference statistics, i.e., between the NMC 1000 mb wind direction and deduced wind direction, between deduced wind direction and the edited wind direction, and between the NMC 1000 mb wind direction and the edited wind direction (e.g., see mean difference statistics in Table 2). The bias statistics show that the deduced wind directions are in best agreement with the manually edited wind directions because the bias between these two is the smallest. However, due to the small variability of the difference statistics in wind directions among the three way comparison shown in Table 2, it is considered improper to attach a significance test to the bias values discussed here, and other types of statistics to be followed.

The mean absolute differences in wind direction are about 40 deg for the three-way comparison (see Table 2). The fact that these absolute differences are of the same magnitude suggests that the deduced wind directions are at least as good as those from the edited winds and the NMC's 1000 mb wind analyses. The 40 deg in wind-direction difference statistics should be compared with those reported in Gemmill et al. (1987), in which the NMC 1000 mb wind direction error is about 35 deg when compared with buoy reports. Judging from the fact that in the original Seasat scatterometer instrument design, a directional error of ±20 deg is specified (Jones et al., 1982), a 40 deg directional difference for the retrieval technique reported here may be considered credible. The rms directional difference values among the three-way comparison are about 50 deg (see Table 2) for both scatterometer and altimeter data. It should be noted that Jones et al. (1982) reported a rms directional error of about 25 deg when the Seasat scatterometer wind data were compared with in situ buoy reports during the JASIN experiment. Gemmill et al. (1987) reports a rms directional error of about 40 deg when the NMC 1000 mb winds are compared with the buoy reports.

The second type of statistics is based on vector retrievals calculated at individual data points along the satellite tracks instead of at the 2.5 by 2.5 degree grid points discussed above. To deduce vector winds from

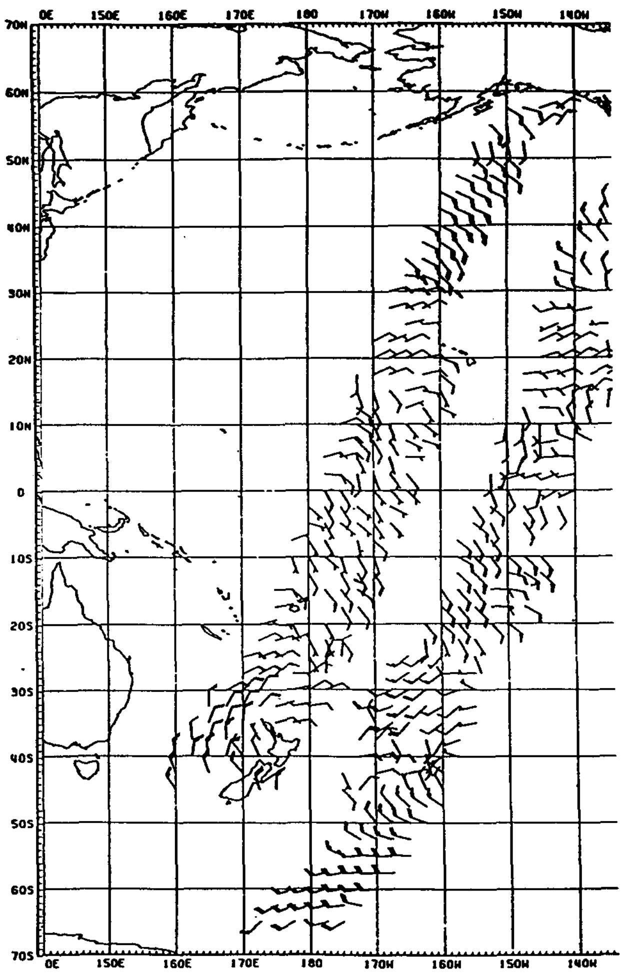

FIG. 4a. The subjectively edited scatterometer vector winds for 0000 UTC 17 September 1978.

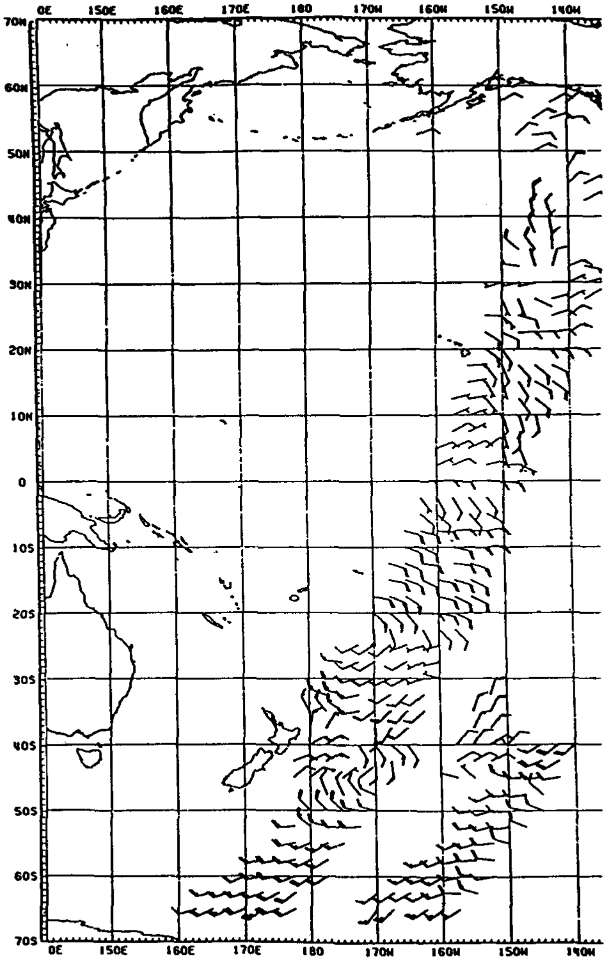

FIG. 4b. As in Fig. 4a except for 0000 UTC 18 September 1978.

the given scatterometer and altimeter wind speed measurements at these individual data points along the satellite tracks, we bilinearly interpolate the NMC's surface pressure analyses from the 2.5 by 2.5 longitude–latitude grid to the data locations. In computing the difference statistics, the same bilinear interpolation procedure was applied to the NMC 1000 mb wind analyses to obtain the values along the satellite tracks. These difference statistics are shown in Tables 3 and 4 for wind speeds and wind directions, respectively. These results are consistent with those discussed previously in Tables 1 and 2 for the difference statistics from the wind speed data interpolated to the 2.5 by 2.5 degree longitude–latitude grid. Detailed inspection of the difference statistics for along the satellite tracks, shown in Tables 3 and 4, leads to the same observation that the deduced vector winds from the altimeter and scatterometer wind speed data are at least as good as the edited vector winds and the NMC 1000 mb wind analyses. From Tables 3 and 4, we see that the difference statistics are slightly reduced for the along track data locations as compared to those calculated for the 2.5 by 2.5 degree longitude–latitude grid points. However, these reductions are very small indeed (e.g., comparing values in Table 3 with those in Table 1, and Table 4 with Table 2). As discussed previously, applying the grid-averaging procedure will undoubtedly lead to smoothing the subsynoptic features associated with the altimeter and scatterometer wind data. However, for the purpose of resolving large-scale synoptic features, it may be practical to use the grid-averaged altimeter and scatterometer wind data for inclusion in the initial analyses for numerical weather prediction.

Although these results are based on only a limited number of retrieval experiments, it is clear that from the objective difference statistics discussed in this section, the technique has a potential application to future altimeter and scatterometer wind speed data for deducing wind direction information. In particular, considering the enormous effort that was required to derive the subjectively edited Seasat scatterometer wind vectors, it is obvious that the simple procedure used here certainly has an advantage in resolving the directional ambiguities in a very efficient manner, while yielding

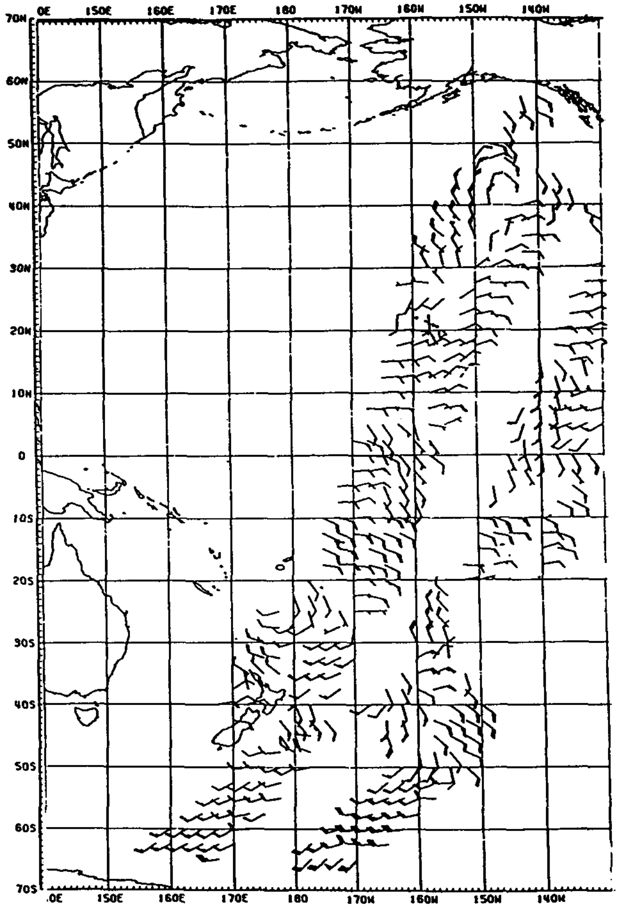

FIG. 4c. As in Fig. 4a except for 0000 UTC 19 September 1978.

TABLE 1. Wind speed and vector wind difference statistics calculated for the Seasat scatterometer and altimeter data gridded at 2.5 by 2.5 deg longitude-latitude points (units: m s^{-1}).

Scatterometer*	00Z 17 Sep (N = 637)	00Z 18 Sep (N = 701)	00Z 19 Sep (N = 795)
$D1$	1.385	1.763	2.181
$D2$	2.706	3.220	3.349
$R1$	3.591	4.340	4.219
$R2$	5.772	5.855	5.776
$R3$	6.174	7.030	6.470
$R4$	6.596	7.394	6.521
Altimeter*	(N = 276)	(N = 279)	(N = 317)
$D1$	−0.481	−1.378	−1.336
$D2$	2.658	3.541	3.728
$R1$	3.275	4.520	4.716
$R2$	6.413	7.309	7.225

* Remarks $D1$: Mean difference between scatterometer (altimeter) wind speed and the NMC 1000 mb wind speed. $D2$: Mean absolute difference between scatterometer (altimeter) wind speed and the NMC 1000 mb wind speed. $R1$: Rms difference between scatterometer (altimeter) wind speed and the NMC 1000 mb wind speed. $R2$: Rms difference between deduced vector wind from scatterometer (altimeter) wind speed and the NMC 1000 mb vector wind. $R3$: Rms difference between deduced vector wind and the subjectively edited vector wind for scatterometer data. $R4$: Rms difference between the NMC 1000 mb vector wind and the subjectively edited vector wind for scatterometer data.

TABLE 3. Wind speed and vector wind difference statistics calculated for the Seasat scatterometer and altimeter data points along the satellite tracks (units: m s^{-1}).

Scatterometer*	00Z 17 Sep (N = 3000)	00Z 18 Sep (N = 3188)	00Z 19 Sep (N = 3821)
$D1$	1.502	1.808	2.373
$D2$	2.631	3.096	3.394
$R1$	3.505	3.989	4.248
$R2$	5.530	5.588	5.464
$R3$	6.014	6.667	6.310
$R4$	6.340	6.940	6.390
Altimeter*	(N = 7776)	(N = 7662)	(N = 8826)
$D1$	−1.103	−1.440	−1.260
$D2$	2.434	2.840	3.199
$R1$	3.198	3.883	4.470
$R2$	6.213	6.643	6.989

* Remarks $D1$: Mean difference between scatterometer (altimeter) wind speed and the NMC 1000 mb wind speed. $D2$: Mean absolute difference between scatterometer (altimeter) wind speed and the NMC 1000 mb wind speed. $R1$: Rms difference between scatterometer (altimeter) wind speed and the NMC 1000 mb wind speed. $R2$: Rms difference between deduced vector wind from scatterometer (altimeter) wind speed data and the NMC 1000 mb vector wind. $R3$: Rms difference between deduced vector wind from scatterometer wind speed data and the subjectively edited scatterometer vector wind. $R4$: Rms difference between the NMC 1000 mb vector wind and the subjectively edited scatterometer vector wind.

results that have the same accuracy as the subjectively edited winds for large-scale atmospheric processes.

4. Summary

A technique based on simple Ekman boundary layer dynamics has been presented and applied to deduce wind directions from either altimeter or scatterometer wind speed information. The deduced wind directions compare well with the NMC 1000 mb wind analyses as well as with those of subjectively edited vector winds. The statistics show that the differences between deduced wind vectors from satellite wind speeds and the NMC analyzed winds are approximately the same as those between buoys and the NMC analyzed winds. This suggests that the vector fields deduced from wind speed measurements of an altimeter would appear to provide data with an accuracy comparable to a buoy measurement. It further suggests that the technique

TABLE 2. Directional statistics (units: degrees) calculated for the Seasat scatterometer and altimeter data gridded at 2.5 by 2.5 deg longitude-latitude points. Winds speeds less than 5 m s^{-1} are not used in the calculation of the directional difference statistics.

Scatterometer	00Z 17 Sep (N = 486)	00Z 18 Sep (N = 589)	00Z 19 Sep (N = 683)
Σ(NMC − deduced)/N	−5.4	−2.9	−0.5
Σ(deduced − edited)/N	−0.8	1.8	−0.3
Σ(NMC − edited)/N	−7.6	−2.3	−5.1
Σ|NMC − deduced|/N	36.9	32.4	37.1
Σ|deduced − edited|/N	35.9	38.0	39.9
Σ|NMC − edited|/N	37.9	35.7	37.1
Rms(NMC − deduced)	49.6	44.2	51.2
Rms(deduced − edited)	49.6	51.9	53.9
Rms(NMC − edited)	52.1	48.0	51.9
Altimeter	(N = 180)	(N = 182)	(N = 205)
Σ(NMC − deduced)/N	−5.2	−11.4	−10.4
Σ|NMC − deduced|/N	35.9	40.0	40.3
Rms(NMC − deduced)	45.0	50.1	50.9

TABLE 4. Directional statistics (units: degrees) calculated for the Seasat scatterometer and altimeter data points along the satellite tracks. Wind speeds less than 5 m s^{-1} are not used in the calculation of the directional statistics.

Scatterometer	00Z 17 Sep (N = 2227)	00Z 18 Sep (N = 2612)	00Z 19 Sep (N = 3171)
Σ(NMC − deduced)/N	−5.0	−3.4	1.1
Σ(deduced − edited)/N	−2.5	−0.2	−2.9
Σ(NMC − edited)/N	−7.5	−4.7	−4.4
Σ|NMC − deduced|/N	37.5	32.0	35.6
Σ|Deduced − edited|/N	36.9	36.4	38.9
Σ|NMC − edited|/N	39.7	35.5	34.4
Rms(NMC − deduced)	50.8	44.6	49.5
Rms(deduced − edited)	51.4	49.9	53.4
Rms(NMC − edited)	55.0	47.6	48.7
Altimeter	(N = 4765)	(N = 4794)	(N = 5531)
Σ(NMC − deduced)/N	−8.8	−13.6	−9.4
Σ|NMC − deduced|/N	36.5	37.6	37.9
Rms (NMC − deduced)	45.6	49.2	49.9

could be applied now to the GEOSAT altimeter wind speed data to increase the observational data base available for numerical weather prediction. This technique can also be used to objectively resolve any ambiguities in scatterometer wind directions.

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