ANALYSIS OF SPACE-BASED OCEAN SURFACE WIND SPEED DATA AT GLA

Stephen C. Bloom
University of Maryland
College Park, MD

Robert Atlas
Laboratory for Atmospheres
NASA/Goddard Space Flight Center
Greenbelt, MD

Summary: Different methods for assigning directions to satellite surface wind speeds have been developed and tested. The best of the methods appear to be sufficiently accurate to allow for the routine assimilation of such data in global atmospheric models.

1. INTRODUCTION

Accurate observations of surface wind velocity over the oceans are required for the determination of surface heat, moisture and momentum fluxes as well as for the study of a wide range of atmospheric and oceanic phenomena. In addition, the effectiveness of an observation is strongly affected by the analysis procedure in which it is combined with other information. The quality of a surface analysis is a combination of the quality of the observational data, the accuracy of the GCM (including the precision of the first guess, and the accuracy of the physical parameterization of surface processes), and the ability of an analysis procedure to combine properly the observations with the GCM first guess. Conventional meteorological surface observations are provided by ships and buoys. Ship winds are often of poor accuracy, have very limited regional coverage, and occur at irregular intervals in time and space. Buoys, while yielding higher quality data, have extremely sparse coverage. Thus, analyses using conventional oceanic surface data can become heavily contaminated with GCM first-guess errors in persistently data-sparse regions.

For a 96 day period in 1978, the Seasat satellite provided a new source of surface wind data with a vastly improved coverage in time and space. On board was the Seasat-A Satellite Scatterometer (SASS), which measured the radar backscatter from centimeter-scale capillary waves on the ocean's surface. An empirical relationship provided up to four possible directions with each report. Thus, before this data could be used in meteorological analyses, this ambiguity in direction needed to be resolved. At the Goddard Laboratory for Atmospheres (GLA) an objective procedure was developed for removing the directional ambiguity of SASS data. This method made use of a first guess provided by the GLA general circulation model. The GLA analysis/forecast system was then used to assimilate the 96 days of SASS observations, as well as to generate global gridded fields of ocean surface fluxes based on this data (Atlas et al., 1987).

In addition to the brief period of Seasat data, surface wind speed measurements from space are currently available from a number of satellites. Microwave instruments (such as SMMR on Nimbus-7 and SSM/I on DMSP satellites) can sense information related to the surface emissivity, from which surface wind speeds can be inferred (Wentz and Mattox, 1986). These data have the great virtue of day-to-day widespread global coverage, comparable to Seasat, in stark contrast to the nature of the ship wind data; a typical example of SSM/I data coverage for a 6 h period is shown in Fig. 1. The internal consistency and coherency of SSM/I data is evident in Fig. 2.

However, both operational and research models and data assimilation systems are in general not designed to use wind speed information alone, and these data have thus not been used except for very limited studies. Atmospheric models do not predict wind speeds directly; they require initial states which specify the full vector wind. It therefore follows that the assimilation of wind speed data requires either an extensive modification to current analysis schemes (cf. Lorenc, 1988; p. 215ff), or a methodology which assigns directions to the wind speeds before they are assimilated. The work described in this paper takes the latter approach.

In this paper, we present a variety of methods to assign directions to surface wind speed data within the context of a data assimilation process. Section 2 describes the GLA assimilation system used in this research. Section 3 describes five methods for assigning wind directions. Section 4 contains the results of evaluations of the methods, using both simulated and real data, as well as the results of some assimilation experiments using SSM/I data. Finally, Section 5 contains a summary of the work presented.

2. THE GLA DATA ASSIMILATION SYSTEM

In this study, we use a version of the GLA Assimilation System similar in many respects to the one described in Atlas et al. (1987); the major differences here involve the replacement of the Seasat dealiasing procedure with directional assignment methods, and the use of a multivariate Optimum Interpolation analysis in some of our results. As in the previous study, an assimilation cycle consists of an analysis performed every 6 hours; after each analysis, a 6 hour forecast follows, which then provides the first-guess for the next analysis. All of the conventional and satellite data within +/- 3 hours of the analysis time are used to correct the first guess. Some of the salient features of the model and the analysis are summarized in the following sections.

2.1 Forecast Model

The forecast model used in the assimilations is the GLA Fourth-Order General Circulation Model. For the results in this paper, the model had 4 deg latitude by 5

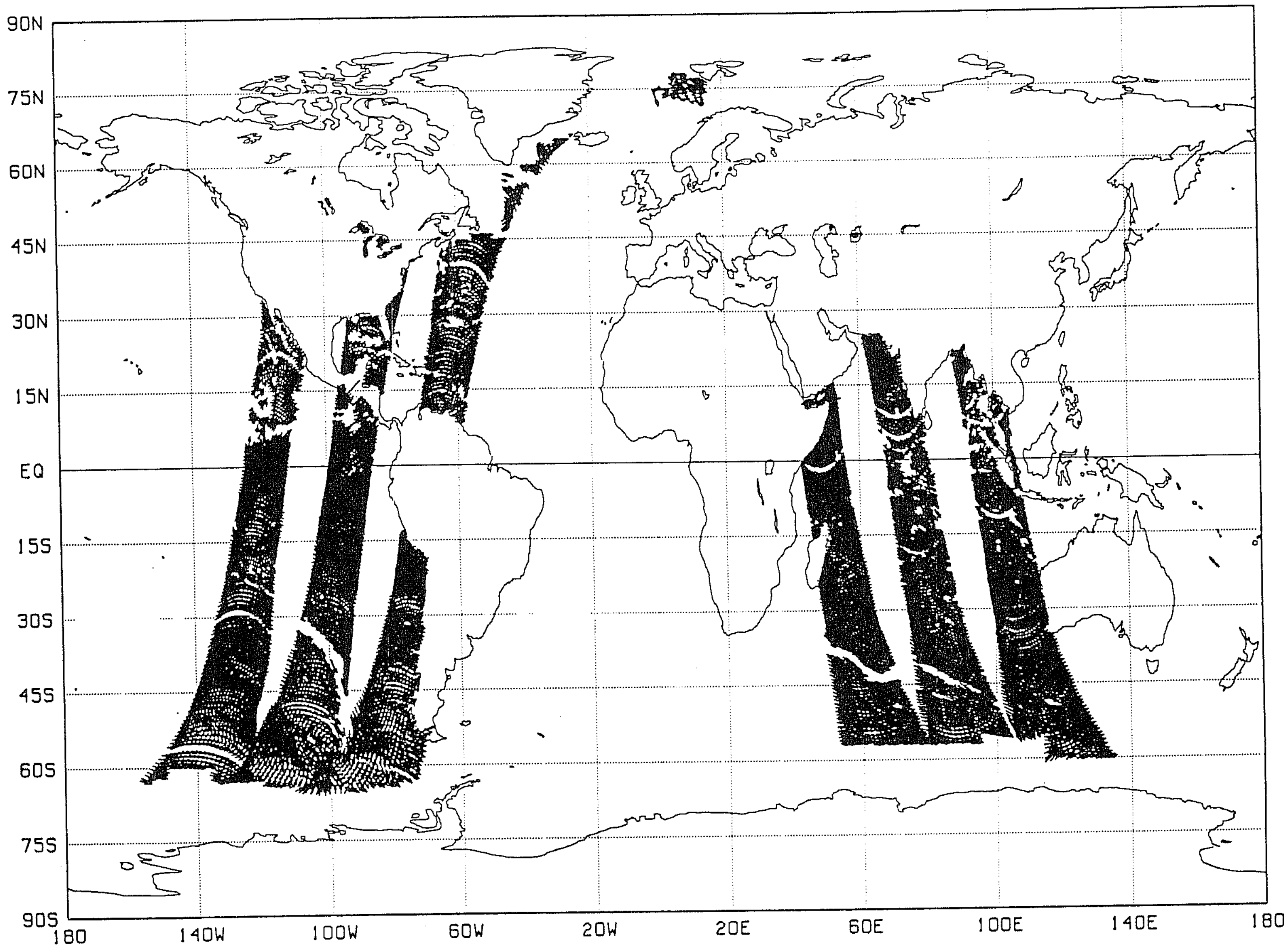

Fig. 1 EXAMPLE OF SSM/I DATA DISTRIBUTION FOR 6 HOUR PERIOD CENTERED ON 0000GMT 4 AUG. 1987

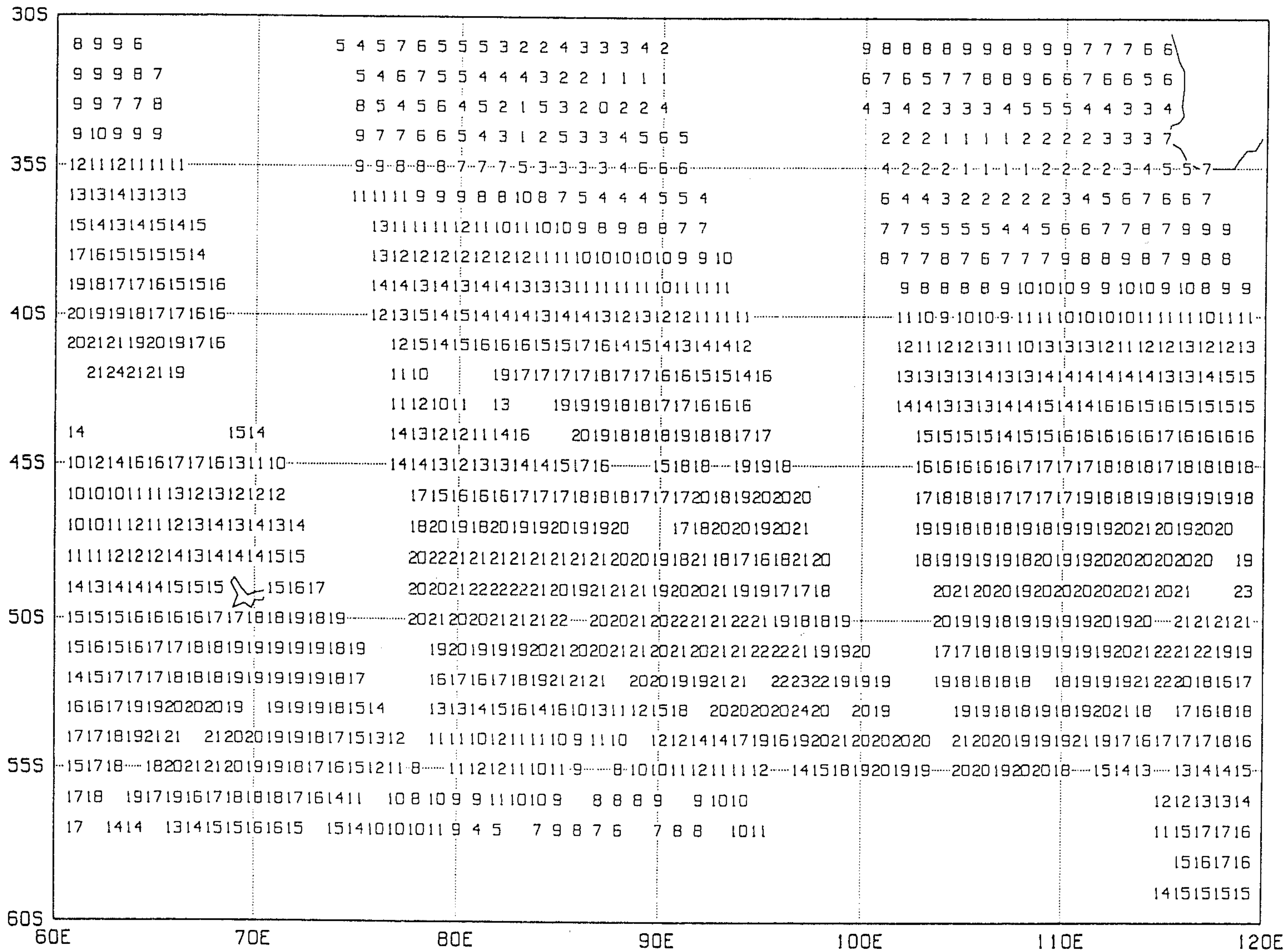

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Fig. 2 SSM/I WIND SPEEDS (M/S) SHOWING INTERNAL CONSISTENCY AND COHERENCY deg longitude horizontal resolution, and nine equally-spaced sigma layers in the vertical. The governing equations are in flux-form, and employ fourth-order accurate horizontal spatial finite differencing as well as the Matsuno (Euler-backward) scheme for time integration. Scales of motion smaller than four grid-lengths are controlled by the application of a sixteenth-order Shapiro filter every two hours during the forecast. In addition, a Fourier filter is used at high latitudes to maintain the linear stability of the model. The combination of the filtering and the Matsuno scheme's damping properties help the model to depict realistically large scale divergent motions during an assimilation process. The model also contains a full set of subgrid scale physical parameterizations: longwave and shortwave radiation, surface processes (principally bulk aerodynamic equations for surface fluxes) and convective and large-scale precipitation. Details of this model can be found in Kalnay et al. (1983).

There are many changes to the GLA GCM currently under implementation, which will likely have a strong impact on the research reported in this paper. A brief summary of the model improvements : (i) an increase in the horizontal resolution to 2 deg latitude by 2.5 deg longitude; (ii) an increase in the vertical resolution to 15 layers; (iii) a rearrangement of the sigma layers to an unequally spaced $\sin^2$ distribution, providing enhanced resolution in the boundary layer and the top of the model; (iv) a new PBL physics using either a version of Louis' (1979) scheme or a level 2.5 closure scheme developed by Helfand (1988); (v) a new longwave radiation scheme (Harshvardhan, 1987); (vi) an improved methodology for updating the model fields continuously from the effects of the parameterizations and the filters. Preliminary results indicate that these changes markedly improve the climatology of the GLA Fourth-Order GCM.

2.2 Objective Analysis

Two different objective analysis systems have been used in parts of the work reported here. Preliminary results were obtained using a Successive Corrections Method (SCM), a system in use for several years at GLA (Baker, 1983). Later results were obtained using a multivariate Optimum Interpolation analysis (OI; see Baker et al., 1987). In its current form, the GLA OI analysis consists of three broad subsystems: surface analysis, upper-air analysis, and moisture analysis. The upper-air and moisture analyses are three-dimensional, using a vertical correlation function to allow off-level information to affect an analysis. Both the surface and upper-air analyses are multivariate. The upper-air analysis uses a Geostrophic balance to relate forecast wind and geopotential height error statistics; the surface analysis uses an Ekman balance (Geostrophic + surface drag) to relate surface wind and surface pressure error statistics. Although the analyses have been performed at 6 hour intervals, the capability exists to perform them at more frequent intervals, eg. 3 hour intervals, or even every model time step ("continuous" assimilation).

3. DIRECTION ASSIGNMENT METHODS

This work is an extension of previous efforts at GLA (Baker et al., 1984; Atlas et al., 1987) to remove the directional ambiguity in Seasat Scatterometer (SASS) winds. The objective here is to develop and test methods which utilize information from observations, model first guess, and approximate balance relations which can assign directions to surface wind speeds in an objective and practical manner. The five methods discussed in this paper range in complexity from a fairly simplistic direct assignment to a fairly involved general balance approach. Other methodologies, such as using a nonlinear objective analysis (Lorenc, 1988), or using a variational approach (cf. Hoffman, 1982 and 1984), are being examined for future efforts in this area.

3.1 Method 1 - Assign First Guess Directions

In this approach, the 6-hour model forecast winds are interpolated to the wind speed data locations; the directions of the resultant winds are then assigned to the wind speed observations. The new wind vectors are then assimilated in a regular analysis. Since the model does not forecast surface winds directly, a method has been developed whereby the winds from the bottom layer of the model (roughly representative of winds at 945 mb) are used to infer values of the surface winds (i.e. the level at which the surface wind observations are made; for example, ship winds at 19.5 m). We estimate the winds at the top of the surface layer (50 m), using momentum flux-matching arguments; the surface winds are then obtained by an interpolation procedure described in Geleyn (1988).

This method clearly places a heavy reliance on the quality of the GCM forecast. In areas where the model is in serious error, incorrect directions would be assigned to the wind speed observations.

3.2 Method 2 - Assign Analyzed Wind Directions

This is a multi-pass approach. The first step involves performing a surface analysis incorporating all conventional (buoys, ships) data. Then one proceeds as in Method 1, only now analyzed winds are interpolated instead of first-guess winds. There is less reliance placed on the quality of the GCM forecast in this case, although this method devolves to Method 1 in regions with very sparse conventional data.

3.3 Method 3 - Use Surface Pressures with a Balance Relation

This method is largely the one presented in Yu (1987); it assumes an Ekman balance relation between surface pressure gradients and surface winds. Briefly, the method works as follows. First, perform a conventional surface pressure analysis, similar in approach to Method 2. Next, estimate a value of the surface drag, C_D, by combining the observed wind speeds and the gradients of the analyzed surface pressure with an Ekman balance relation:

$$f\hat{k} \times \vec{v} + C_D S\vec{v} + \frac{1}{\rho}\vec{\nabla}P = 0 \qquad (1)$$

to obtain the following equation:

$$C_D^2 S^4 = \frac{1}{\rho^2}\left|\vec{\nabla}P\right|^2 - f^2 S^2 \qquad (2)$$

where S = wind speed, ρ = density, and f = Coriolis parameter. Finally, use the estimated drag from (2) in (1) to obtain estimates of the surface wind components.

Once the wind components have been obtained, they can then be assimilated along with the rest of the conventional data in the same manner as the previous two methods.

Unlike Methods 1 and 2, Method 3 concentrates on the mass field (surface pressure) and a balance relation to obtain the desired directions. Any flaws in the underlying assumptions of the balance relation will be transferred directly to the assigned directions. For example, Ekman balance is probably not really applicable in the tropics; other terms in the momentum equation (advection, time-tendency) could play important roles in the overall tropical wind balance. In middle latitudes where there are regions of strong curvature in the flow, a gradient-wind type of modification to the Ekman balance may be needed to model adequately the wind balance. Eq. 2 also shows that Method 3 may have a problem with very low wind speeds; note the possibility of an inconsistency on the right side (i.e. the chance that the analyzed pressure gradients may be insufficient to balance the Coriolis force). Method 5 (below) attempts to address some of these concerns.

3.4 Method 4 - A Combined Approach

We attempted to combine the relative strengths of Methods 2 and 3. In Method 4, we apply Method 2 everywhere except for data-sparse regions in higher latitudes which have wind speed observations greater than 3-5 m s^{-1}; in those latter areas, we apply Method 3.

3.5 Method 5 - Use a General Balance

As mentioned in Section 3.3, Method 5 attempts to relax some of the assumptions made in Method 3. Consider the horizontal momentum equation in the following form:

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} + f\hat{k} \times \vec{v} + C_D S \vec{v} = -\frac{1}{\rho}\vec{\nabla}P \tag{3}$$

where $S = |\mathbf{V}|$, $\mathbf{V} = S \cos\gamma\, \mathbf{i} + S \sin\gamma\, \mathbf{j}$, and γ defines the wind direction relative to the x-axis; C_D is the drag coefficient and f is the Coriolis parameter. If we take the scalar product of $\mathbf{V}$ with (3) and then divide out S, we then obtain a "speed" equation for the surface wind:

$$\frac{\partial S}{\partial t} + (\vec{v} \cdot \vec{\nabla})S + C_D S^2 = -\frac{1}{\rho}\left(\frac{\vec{v}}{S}\right) \cdot \vec{\nabla}P \tag{4}$$

Note that we have ignored vertical advection in obtaining (4). We can express the advection and pressure terms in (4) as follows:

$$\vec{v} \cdot \vec{\nabla}S = S\frac{\partial S}{\partial x}\cos\gamma + S\frac{\partial S}{\partial y}\sin\gamma \tag{5a}$$

$$\frac{1}{\rho}\left(\frac{\vec{v}}{S}\right) \cdot \vec{\nabla}P = \frac{1}{\rho}\frac{\partial P}{\partial x}\cos\gamma + \frac{1}{\rho}\frac{\partial P}{\partial y}\sin\gamma \tag{5b}$$

Putting (5a,b) into (4) and grouping the direction terms, we then have the following speed relation:

$$-\left[\frac{\partial S}{\partial t} + C_D S^2\right] = \cos\gamma\left[S\frac{\partial S}{\partial x} + \frac{1}{\rho}\frac{\partial P}{\partial x}\right] + \sin\gamma\left(S\frac{\partial S}{\partial y} + \frac{1}{\rho}\frac{\partial P}{\partial y}\right) \tag{6}$$

Equation (6) is of the form

$$\mathbf{A}\cos\gamma + \mathbf{B}\sin\gamma = \mathbf{C}$$

with the solution

$$\gamma = \pm\cos^{-1}(\mathbf{C}/\mathbf{D}) + \tan^{-1}(\mathbf{B}/\mathbf{A})$$
$$\mathbf{D} = (\mathbf{A}^2 + \mathbf{B}^2)^{1/2} \tag{7}$$

where the "+" sign is used in the Northern Hemisphere and the "-" sign is used in

TABLE 1. GLOBAL DIRECTIONAL ERROR (IN DEGREES) AFTER ANALYSIS OF SIMULATED DATA

METHOD	0-5m/s	5-10 m/s	10-15 m/s	15-20 m/s	ALL SPEEDS
1	41.8	18.8	18.0	24.9	27.2
2	35.0	16.1	17.3	23.1	23.3
3	62.3	30.8	17.4	9.0	40.1
4	35.0	14.9	12.2	6.3	21.8
6	33.8	15.0	14.4	20.4	21.9
number:	532	681	218	15	1446

TABLE 2. GLOBAL DIRECTIONAL DIFFERENCES BETWEEN DIRECTIONAL ASSIGNMENT METHODS AND OBJECTIVELY DEALIASED SASS WINDS (7 -11 SEPTEMBER 1978)

Method	0-5m/s	5-10 m/s	10-15 m/s	15-20 m/s	>20m/s	ALL
2	33.1	26.3	22.7	24.2	32.0	26.2
6	33.5	25.0	22.0	23.7	28.4	25.3
number:	14454	43397	28878	7830	1221	95780

TABLE 3. COLLOCATION STATISTICS:

SSM/I (METHOD 2) VS INDEPENDENT BUOYS

	MEAN ABSOLUTE ERROR	BIAS
WIND SPEED:	1.9 m/s	0.3 m/s
DIRECTION:	28.4 deg.	6.7 deg

number of collocations: 296

the Southern Hemisphere. If the time-tendency in **C** and the speed advection terms in **A** and **B** are dropped, then the direction γ in (7) can be shown to be identical to the direction obtained using Method 3. Our approach here is to use first-guess estimates for the drag and time-tendency terms in **C**, obtain the pressure-gradients terms in **A** and **B** in a manner analogous to Method 2, and estimate the speed advection terms in **A** and **B** from the data. The last step is accomplished by performing a univariate speed analysis; this should result in realistic estimates of the surface speed gradients in the areas of dense SSM/I coverage.

3.6 Method 6 - Use a Variational Analysis Method (VAM)

This method differs substantially from the previous five in that it combines the direction assignment and subsequent analysis steps. It employs a formalism which incorporates constraints on smoothness, closeness of fit to a first guess, and dynamical balance. VAM's can account for both the accuracy of the data (through the use of metric weights describing the fit of the analysis to the data) and the level of confidence to be ascribed to the applied constraints (through the use of "weak" constraints; Sasaki, 1970). For this study, we use an algorithm based on the VAM developed by Hoffman (1982, 1984) for the objective dealiasing of Seasat data.

4. RESULTS

The evaluation of the relative utility of the directional assignment methods is performed using both simulated data (where the "correct" direction is known) and real data. The simulation experiments use a reference atmosphere ("nature run") generated from the European Centre for Medium Range Forecasts (ECMWF) 1.875 deg resolution gridpoint model. This nature run was used to generate simulated conventional and space-based data, including satellite surface wind velocity measurements similar to SASS, as well as to verify the directional assignment.

For each observation type to be simulated, the nature run's gridpoint values were interpolated to corresponding real data locations to ensure realistic data coverage. The wind directions for the simulated SASS data were then withheld, and directions were assigned using the GLA analysis/forecast system with the methods described in section 3. (see Atlas et al., 1985 for a more complete description of the simulation methodology)

Table 1 presents a summary of the relative accuracy of five of the direction assignment methods. Method 5 is in the final stages of implementation at the time of this writing. As expected, the use of conventional data in method 2 improves the direction assignment over that of method 1; method 3 performs poorest at low wind speeds (especially in the Tropics) but it is significantly more accurate than either method 1 or 2 at high wind speeds (primarily in high latitude regions of the Southern Hemisphere, where little or no conventional data are

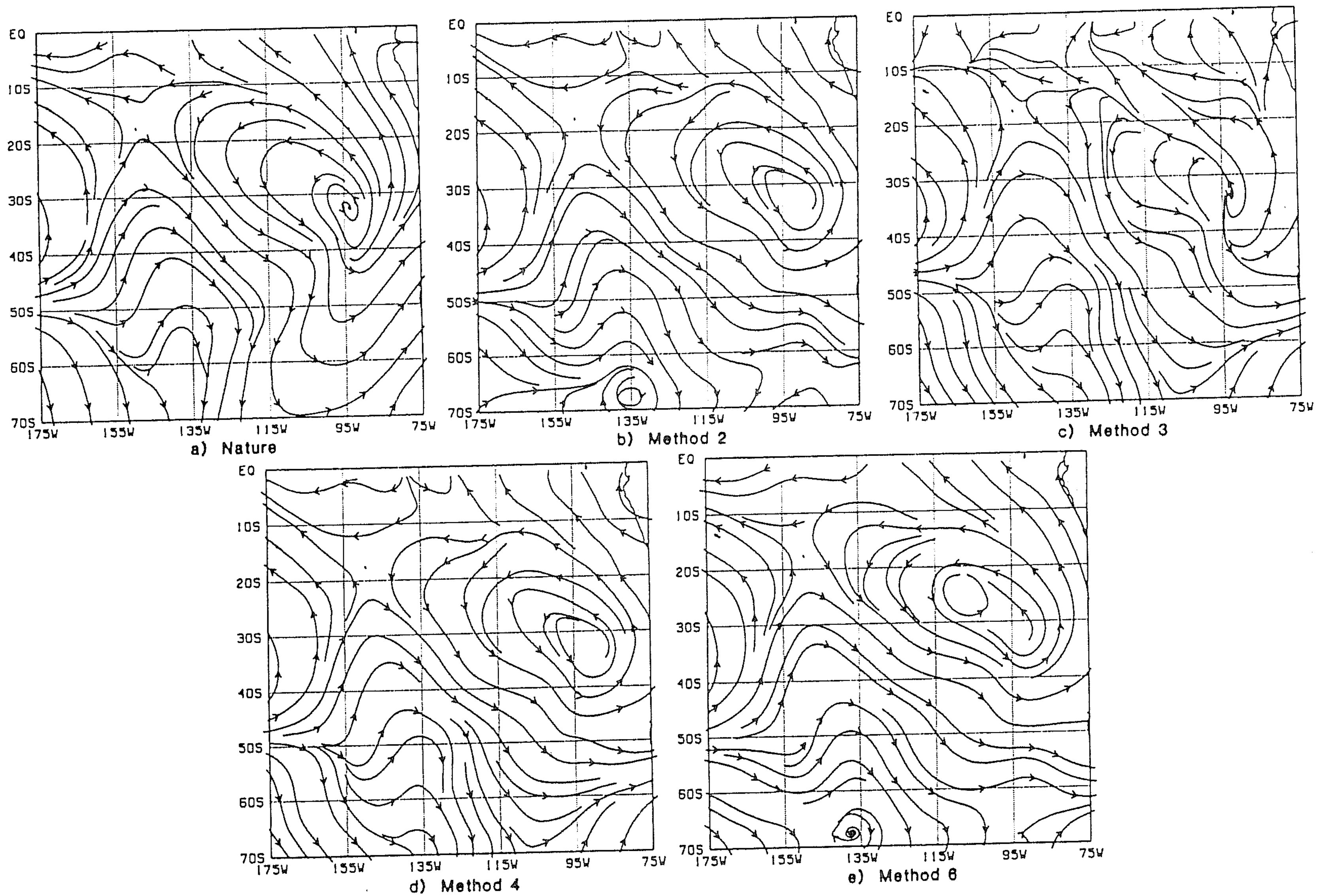


Fig.3 Surface wind streamlines for (a) the nature run, (b) method 2, (c) method 3, (d) method 4 and (e) method 6.

available and the model first guess is the poorest). Method 4, combining the best aspects of methods 2 and 3, is identical to method 2 at the lowest wind speeds, and it provides the best results at moderate to high wind speeds. Finally, method 6 is comparable to method 4 in giving the best overall results; however it is much worse than methods 3 and 4 at high wind speeds, where errors in directional assignment are probably most important.

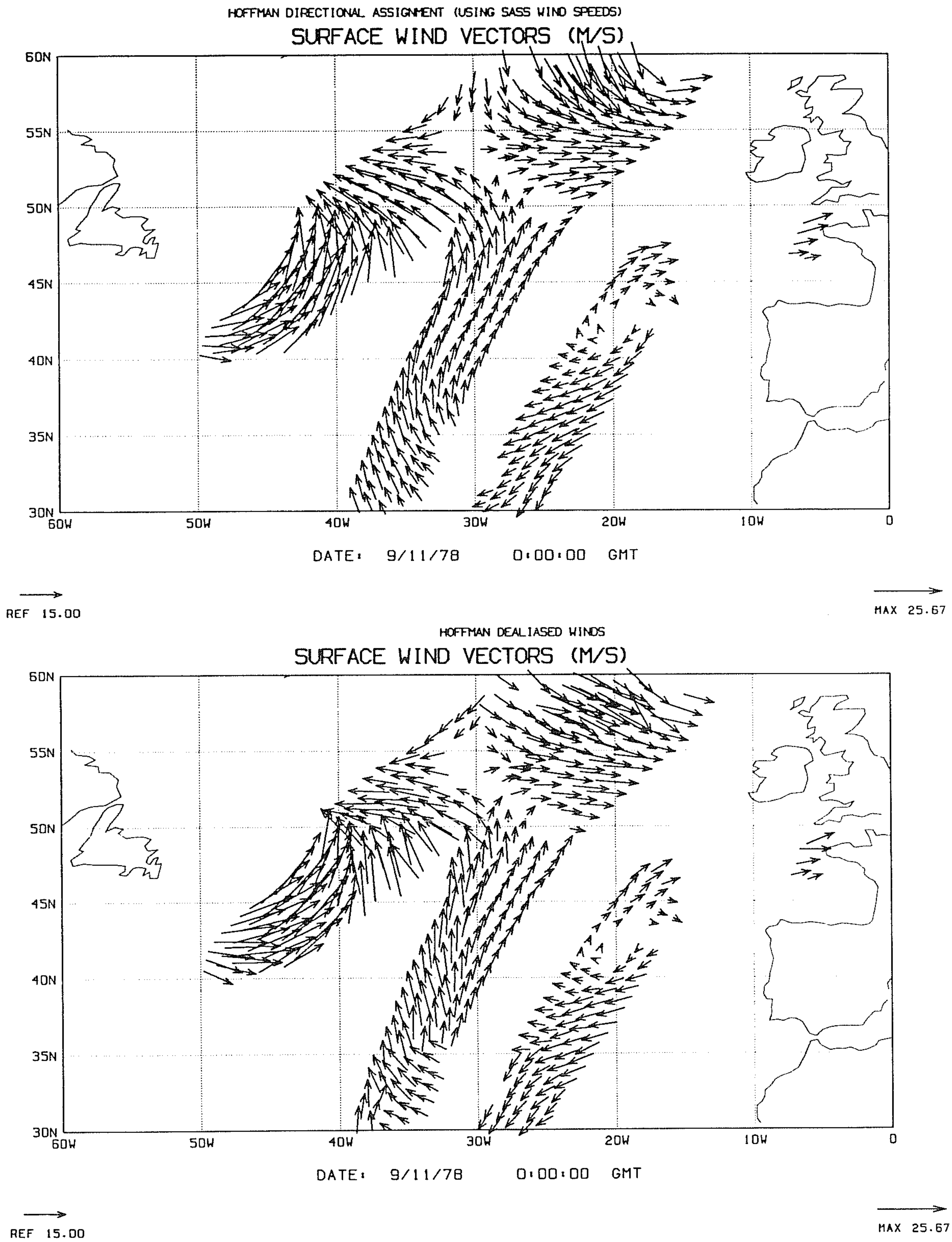
Some of these differences are illustrated in Fig. 3, which shows the streamlines of the surface wind for a portion of the South Pacific for the nature run and for methods 2,3,4 and 6. Comparison of these figures shows large directional errors associated with method 3 in the Tropics and with methods 2 and 6 in the high latitudes of the Southern Hemisphere, as well as the improvements with method 4 in these regions.

In a further evaluation of the accuracy of the directional assignment methods, we applied them to "real" Seasat and SSM/I data. In the case of the Seasat data, the objectively determined SASS wind directions were withheld and new directions (without incorporating any of the SASS directional information) were assigned to the SASS speeds. Table 2 shows the directional differences between winds with assigned directions and objectively dealiased (using the GLA objective dealiasing system) winds; for this comparison, only methods 2 and 6 are shown. In general, the new directions and the original SASS directions differed by less than 30 degrees, with the largest discrepancies occurring at the lowest wind speeds. An alternate way to view this result is shown in Fig. 4, which compares assigned winds against objectively dealiased (this time using the Hoffman, 1984 method) winds at one analysis time. The two sets of wind vectors are strikingly similar; the differences between them are due to the extra information contained in the direction (i.e. the aliases) sensed by the scatterometer instrument. Table 2 indicates that satellite wind speed data with the directions assigned should be moderately useful in data-sparse regions but that accurate scatterometer data should represent a considerable further improvement in those areas.

In the case of SSM/I data, we have performed a limited (5 day) assimilation experiment to evaluate the direction assignment (using only method 2 to date) and the impact of the resultant SSM/I winds on the gridded global analyses. The accuracy of the direction assignment was evaluated by comparing assigned SSM/I directions with an independent set of collocated buoys. During the 5 day period, 296 collocations were made in both the Tropics and Extratropics. Table 3 summarizes the results of this experiment: an average error of 28 degrees, in good agreement with the simulation results, as well as the Seasat results, for method 2.

The impact of SSM/I winds on GLA assimilation winds was assessed by comparing analyses generated with and without the SSM/I data. Fig. 5 shows the impact of SSM/I (after a single analysis) on the GLA 1000 mb wind fields. As can be seen from the figure, large coherent differences result from the inclusion of SSM/I data, particularly in the Southern Hemisphere.

Fig. 4 COMPARISON OF DIRECTIONAL ASSIGNMENT VS. DEALIASING OF REAL SEASAT SCATTEROMETER DATA USING METHOD 6



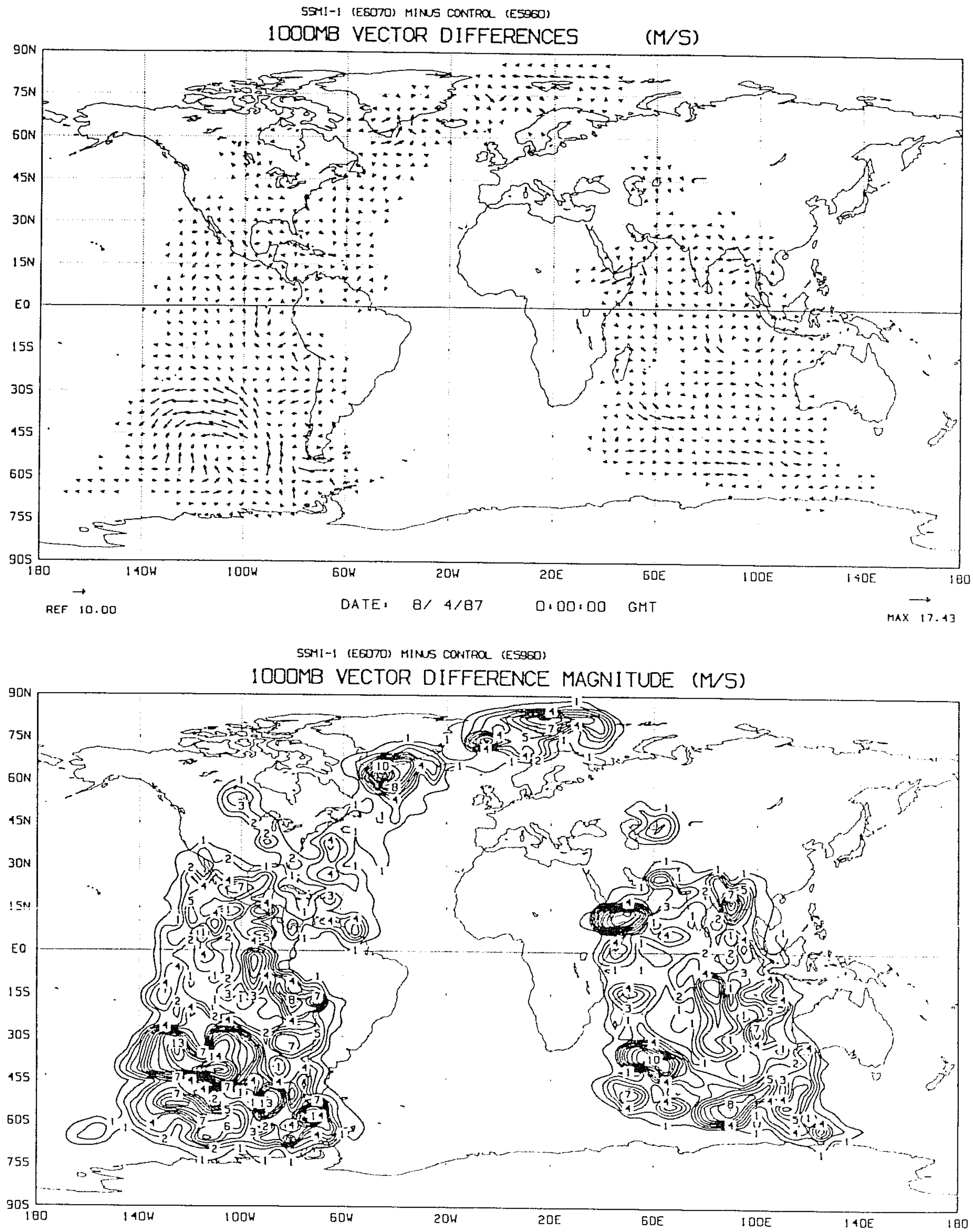


Fig. 5 IMPACT OF SSMI DATA ON GLA ANALYSIS FOR 4 AUG. 1987

5. CONCLUSIONS

Different methods for assigning direction to satellite surface wind speeds have been developed and tested. The best of the methods appear to be sufficiently accurate to allow for the routine assimilation of such data using global atmospheric models. Three modes of verification of the direction assignment methods have been used in this study: check against simulated winds, check against objectively dealiased Seasat winds, and a check using SSM/I data against collocated buoys. All of the verifications yielded consistent results, indicating that the best of the current methods have global error differences (for all speeds) in the range of 20 to 30 degrees. Work is currently underway to complete the implementation and testing of method 5, to implement fully all the methods using the GLA OI analysis system, to test the methods using the updated GLA forecast model, and to perform more experiments with method 6 to find the optimal set of weights which give the best direction assignment. Preliminary experiments indicate a substantial impact of SSM/I winds on gridded global analyses, but further assimilation experiments and numerical forecasts from these assimilations will be required to assess adequately the nature of this impact.

6. ACKNOWLEDGEMENTS

The authors would like to thank G. Brin, J. Ardizzone, C. Caruso and J. Terry for their excellent computing and technical support for this work, and F. Wentz for providing the SSM/I data used in this study. Funding was provided by NASA Headquarters and by the NSCAT project.

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