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TECHNICAL NOTE

Assimilation Experiments With ERS-1 Winds: Part (I)-Use of Backscatter Measurements in the NCEP Spectral Statistical Analysis System

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1. Introduction

The scatterometer on board the ERS-1 satellite is an active radar designed to measure ocean surface wind speed and direction. The measurements taken by the scatterometer are normalized radar backscatters, σ^0, which are a measure of the roughness of the sea surface induced by the surface winds. The ERS-1 scatterometer has three antennas pointing at angles of 45^0, 90^0, and 135^0 degrees from the satellite direction of travel to measure a cell over the ocean surface. These three measurements of σ^0 in each cell, one from each antenna, can be used to determine ocean surface wind vectors using empirically derived transfer functions which relate wind speed and direction to the three backscatter measurements. However, the wind vectors thus derived contain directional ambiguities which preclude the use of these data in real time operational weather prediction models. With a 500 km wide swath, the ERS-1 scatterometer can provide more than 50,000 backscattered radiation measurements in a six hour window, with each observation being representative of a 50 km cell over the ocean surface. These data are routinely available at the National Meteorological Center (NMC).

Two approaches are currently being investigated in using the ERS-1 scatterometer wind data at NMC. One approach is to use the ERS-1 backscattered measurements directly in the analyses through a variational analysis scheme. This approach can apply the data globally in the atmospheric analyses without appealing to any additional correction schemes. The present study is Part (I) of this investigation which discusses results of analysis and assimilation experiments using this approach for treating the ERS-1 σ^o data. The other approach is to apply a vector retrieval algorithm to the ERS-1 backscattered measurements and then use an ambiguity removal scheme to select correct vector winds before using them in atmospheric analyses and data assimilation. The details of this selection process are described in Gemmill et al (1994). The results of assimilation and forecast experiments using the objectively derived ERS-1 vector winds from this approach are reported in Part (II) of this investigation (see Yu (1995)).

Section 2 discusses a technique based on a variational approach particularly designed for the use of the ERS-1 scatterometer σ^0 data in the NMC's Statistical Spectral Interpolation (SSI) analysis scheme (Parrish and Derber, 1992). Our technique is similar to the three-dimensional variational assimilation scheme currently under active development at ECMWF (The'paut et al, 1993). In particular, the analysis component of the assimilation system is designed to perform analyses while simultaneously retrieving the scatterometer winds and removing their attendant ambiguity problems in the wind directions. The analysis scheme minimizes the misfit to the data and other dynamical constraints as measured by a cost function.

A quality control procedure is described in Section 3, which is applied to the ERS-1 backscattered measurement data before the data are used in the analyses and data assimilation. The impact of the ERS-1 scatterometer wind data on global analyses and forecasts are addressed in Section 4, in which results of data assimilation experiments using two weeks of the ERS-1 scatterometer data in the NMC global data assimilation system are discussed. Finally, case analysis results applying the ERS-1 backscattered radiation measurements data to better resolve storm circulations are discussed in Section 5.

2. The Variational Procedure for Using σ^0 Data

The reader is referred to Parrish and Derber (1991) and Derber and Parrish (1992) for a detailed description of the operational global Spectral Statistical Analysis (SSI) scheme at NMC. The analysis scheme, briefly stated, is a three-dimensional variational problem to find a model solution, which is as close as possible in the least square sense, to observations, the six-hour forecast and a set of dynamical constraints. The misfit to the available data and the six hour forecast available at the analysis time is measured by a cost function,

$$J = \{(L(x_0)-y)^T O^{-1}(L(x_0)-y) + (x_0-x_b)^T B^{-1}(x_0-x_b)\}/2 + 0.5\, d^T D^{-1} d \qquad (1)$$

Here x_b is a background estimate of the model state x_0 at the analysis time, which is typically a six-hour forecast from a dynamic model, y is a vector of observations distributed in space at the analysis time, L is an operator which predicts the observations from the analysis variables, O is the covariance matrix of the observation and representative errors, and B is the covariance matrix of the forecast errors, d are a set of dynamical constraints, and D is covariance matrix for the dynamical constraint.

To use the σ^0 data in the analysis, a new observation cost function J_{scat} is added to J. Assuming that the ERS-1 scatterometer observation errors are uncorrelated in space, the scatterometer cost function J_{scat} takes the form,

$$J_{scat} = \tfrac{1}{2} \{ (\sigma^0_{model} - \sigma^0_{obs})^2 / (K_p \sigma^0_{obs})^2 \} \qquad (2)$$

Here σ^0_{model} is calculated by a transfer function dependent on the satellite's aspect and incidence angles, and the NMC model wind speed and direction at the ocean surface, and $\sigma^0_{obs}$is the measurement given by the scatterometer. $K_p \sigma^0_{obs}$ represents the observational standard errors, which in principle should account for several error sources including communication noise, radar equation and model function uncertainties and representative errors. Further, they essentially determine the weights to assign to the ERS-1 scatterometer measurements data. However, these errors are difficult to determine, and subject to a great uncertainty. The sensitivity of the analysis results to the choice of K_p will be discussed later in the paper.

The analysis procedure then is to find a model state, x_0, such that the sum of the two cost functions J and J_{scat} from equations (1) and (2) is a global minimum. A variational technique based on a nonlinear version of the Spectral Statistical Interpolation scheme (Parrish and Derber, 1992) has been developed at NMC to find the global minimum. The minimization procedure is accomplished using a nonlinear conjugate gradient algorithm (see e.g., Gill et al, 1981). The step size estimation is performed by assuming a guess step size, assuming a quadratic function, find the minimum of the quadratic and then repeating the process. The transformation from the analysis variables to the observations (L) is linear for all types of observations used in the system except for the SSM/I wind speeds and ERS-1 scatterometer data. Because of this, the step size estimation for all components is exact except the contribution from these two data sources. Despite this, it appears that some improvement in the system could be made by improving the step size estimation.

The ERS-1 scatterometer data are expressed in terms of normalized backscatters cross section in units of decibels (db). The error characteristics associated with this type of data are quite different from those of the conventional surface wind observations from ships or buoys. However, since the data are to be used directly in the atmospheric analyses, it is important that a quality control procedure be designed to eliminate erroneous data in this type of observations. Further, the error characteristics associated with the data are important because they determine the weights to be assigned to these observations when they are used together with other types of conventional data in the variational analyses described in Section 2.

In an early attempt to design a quality control procedure for the ERS-1 wind data, Yu et al (1993) investigated the error characteristics of the backscattered radiation measurements for the three antenna beams. For a synoptic case analysis, they calculated the difference between model values (using the NMC 10 meters ocean surface wind field in the CMOD2 transfer function) and the observed backscatter measurements for each antenna beam at every data point. The error characteristics of the ERS-1 wind data were investigated by inspecting the differences between observed and model values which were calculated by varying the u and v -component of the NMC's 10 meter wind values at each data point. As expected, the minimum values of the total cost function (equation (2)) and the RMS differences between observed and model calculated values occur near the NMC 10 meter wind analyses. A large bias of greater than 3 db between the observed and model calculated backscatters values for each antenna beam exists corresponding to an error of about 2.5 m/sec in the u and v components from the NMC 10 meter wind analyses. Based on these characteristics, Yu et al (1993) designed a quality control procedure based on a certain threshold value of the differences between σ^o (model) and σ^o (obs).

In this paper we have further investigated this procedure by using a large set of collocated buoy and ERS-1 observations during the months of December 1994 and February 1995. To be consistent with the operational usage of the satellite data, the time window is chosen to be +/- 3 hours and space separation is less than 1 degree for the collocated buoy and ERS-1 data. Three model values of backscattered radiation, one for each antenna beam, are calculated for every collocated buoy report using CMOD4 as the transfer function (see Appendix 1). It should be noted that the reason CMOD4 transfer function was chosen in place of CMOD2 for this study was due to the fact that CMOD4 was recently selected as ESA operational wind retrieval algorithm. Further, it has been shown that winds retrieved using CMOD4 have the lowest bias and RMS errors when compared to the collocated buoy winds (Gemmill et al, 1994) . These model-calculated values represent the true measurements if one assumes that the buoy winds are the ground truth and the CMOD4 transfer function has no model errors. These model calculated values are then compared with the ERS-1 backscattered measurements to calculate the difference statistics of bias, absolute bias, and RMS differences for each antenna beam. In addition, the values of the total cost function (equation (2) in Section 2), and the cost function per each data point can be calculated.

Detailed inspection of the difference statistics shows that bias, absolute bias and RMS values are quite comparable for both the fore beam and aft beams, with the mid beam showing only slightly smaller values of these difference statistics. This finding allows us to investigate the mean difference statistics for the three antenna beams as a whole, without having to deal with each individual antenna beam separately for the quality control procedure to be designed. Table 1 shows the mean difference statistics (averaged over the three antenna beams) according to four different buoy wind speed ranges and for three different quality control threshold values. One can see from Table 1 that when all the data are used, there are very large absolute bias differences between the model calculated and ERS-1 scatterometer measured backscattered values with a very large RMS difference for the buoy wind speed of less than 5 m/sec. Moreover, values of the total cost function are also very large when compared to those calculated from the other wind speed ranges. The difference statistics and the associated values of the cost functions are relatively small and of comparable values for the other three wind speed categories.

Three threshold values of 12 db, 10 db and 8 db for quality control are investigated. If the difference between the observed ERS-1 backscattered measurements and model calculated values for each antenna beam is greater than the threshold value, the data were not used in the calculation of the difference statistics. From Table 1 one can see that when a threshold value of 12 db is imposed to quality control the data, about 12% of the total data points are eliminated, and the statistics of absolute bias, RMS differences, and the value of cost function are reduced substantially in the buoy wind speed category of 0-5 m/sec. For the buoy wind speed category of 5-10 m/sec, less than 0.3% of total number of data points are excluded, and the difference statistics are not significantly affected. For the other two wind speed categories, (ie., 10-15 m/sec and great than 15 m/sec), the data points and statistics are not affected at all. Similarly, when the threshold values are decreased to 10 db and 8 db, there are about 15% and 19% respectively of the total data points are eliminated, and the absolute bias and RMS differences are further reduced in the wind speed category of 0 - 5 m/sec; but for the other two wind speed categories, the data points and the difference statistics are not much affected.

The results discussed above suggest that when the wind speed is weak, i.e., less than 5 m/sec, the ERS-1 backscattered measurements are subject to errors, and thus the data may not be very useful for the analyses. This category of ERS-1 scatterometer data will be effectively quality controlled by applying any of the three threshold values discussed above. Further, since the value of J_{scat} cost function is substantially reduced when a quality control threshold value (see Table 1) is applied to the data, one may increase the weights (or reducing the error level) assigned to the ERS-1 scatterometer sigma data in the analyses. For these reasons, a number of sensitivity analysis experiments were performed by applying different threshold values (from 12 db to 8 db) for quality control, and by varying different error levels (from $K_p = 0.4* K_{po}$ to $K_p=0.2* K_{po}$ in equation (2), where K_{po} is the observed error level) for the ERS-1 scatterometer wind data. The results show that the analyses are sensitive to the choice of error level, with $K_p=0.2 * K_{po}$ giving the best analysis results. However, the results are not very sensitive to the choice of the quality control threshold values. Therefore, for the following discussions, only results with a threshold value of qc= 12 db for quality control and an error level of $K_p=0.2 * K_{po}$ were selected for the use of ERS-1 scatterometer backscattered measurements in analyses and data assimilation experiments will be presented.

4. Data Assimilation Experiments

The NMC T62 global data assimilation system, details of which were given in Kanamitsu (1989) and Kanamitsu et al (1992), was used to investigate the impact of the ERS-1 σ^{o} data on analyses and forecasts. Basically, the assimilation system consists of a forecast model and an analysis scheme. The forecast model is a global spectral forecast model of triangular truncation of 62 waves for the horizontal spectral resolution. In the vertical it has 28 sigma layers for the vertical grid resolution. The forecast model includes identical parameterization of such physical processes as convection, precipitation, radiation, and boundary layer physics as those employed in the NMC operational forecast T126 model. The assimilation experiment is proceeded by a six hour forward integration of the forecast model, starting from the beginning of the data assimilation period, to produce first guess fields of winds (u,v), temperatures (T), and specific humidity (q). The observations within a +/ - 3 hour window are then used to update the first guess fields and complete the analyses. This process of a six hour model forecast followed by an analysis update is repeated four times a day, once every six hour interval, until the end of the total assimilation period.

To assess the impact of the ERS-1 σ^{o} data on analyses and forecasts, two assimilation experiments were conducted for a two week period, starting 0000UTC, August 27, 1994 and ended on 0000UTC, September 9, 1994. The first experiment, Exp.A (or the control run), used only the observations routinely available at the NMC operational global data base in the analyses. In the second experiment, Exp.B, the ERS-1 scatterometer σ^{o} data were included in the analyses, in addition to all of the other types of global observation data used in the control run. For both experiments, a 120-hour forecast was initiated once a day at 0000UTC cycle, resulting in a total of 14 cases of 24-hour to 120-hour forecasts during the two weeks assimilation period. To compute the anomaly correlations and forecast errors for the two forecast experiments, the NMC operational T126 GDAS analyses were treated as the verifying analyses.

The mean anomaly correlations of the 1000 mb and 500 mb heights fields for the 14 cases of forecasts are shown in Tables 2a and 2b, respectively for Exp.A, (the control run), and the Exp. B (including the ERS-1 σ° data in the assimilation experiment). Comparing the results in Table 2a and Table 2b, one can see that the anomaly correlation differences between the two forecasts are very small. Although the anomaly correlations from Exp. B on the whole (except at 1000 mb over the Southern Hemisphere) seem slightly better than those from Exp.A, the improvement is certainly not statistically significant. Similarly, very small differences are found when the mean bias and RMS errors for the 1000 mb and 500 mb forecasts between the two experiments are compared (e.g., comparing results in Table 3a with those Table 3b).

However, examination of the anomaly correlations between the two forecasts for the 14 cases reveals a great variability in the scores on a case by case basis. The total number of "winning" anomaly correlations between the two experiments for the 14 cases of forecasts are shown in Table 4. From the results on a case by case basis, one can see that Exp. B has more forecasts with higher anomaly correlations than Exp. A. In particular, there are more cases of improvements in the forecasts for Exp.B at the 1000 mb and 500 mb levels over the Northern Hemisphere. Over the Southern Hemisphere, the improvements for Exp.B are not as noticeable. These results suggest that on a case by case basis the ERS-1 σ° data do have some small positive impact on the forecasts during this period.

The RMS vector wind errors at 250 mb and 850 mb for the two experiments are calculated in Table 5. One can see that except for the Northern Hemisphere 850 mb, RMS vector wind errors for Exp. B are slightly smaller than Exp.A suggesting that use of ERS-1 σ° wind data leads to some small positive impact for all forecast hours up to five days over both Northern and Southern Hemispheres. Over the Northern Hemisphere at 850 mb, it should be noted that differences of the

RMS vector wind errors between the two experiments are so small that they are virtually the same.

5. Comparisons of Synoptic Case Analyses

The results from of the previous section on data assimilation experiments suggest that routine assimilation and forecast experiments may not show significant differences between the control and the assimilation runs. The impact of ERS-1 winds may be more significant in selected synoptic situations where the satellite has provided data over the regions that were not covered by conventional observations. In this section, two synoptic storm cases, one over the Northern Hemispheric oceans and the other in the Southern Hemisphere, were selected for the comparison between the analyses which use the ERS-1 scatterometer backscattered radiation data and those which exclude the data in the analyses. For this analysis which uses the ERS-1 sigma data, the rate of convergence of the NL SSI scheme with respect to the J_{scat} cost function, and its sensitivity to the error levels assigned to the ERS-1 data are closely examined. In comparing the low level wind circulation patterns, the differences between the two analyses are particularly emphasized, because they give an indication about the impact of the data on the analyses.

The first synoptic case chosen for the analysis comparison was April 27, 0600 UTC, 1993. During the six-hour window, there were two swaths of ERS-1 scatterometer wind data passing through a cyclonic system with its center located near 155 west longitude and 50 north latitude over the west coast of the United States (see Figure 1). The wind analyses at the lowest level of the NMC global weather prediction model (about 40 meters above the oceans) for Exp.A , the control run (excluding the use of ERS-1 data), and for Exp.B (with the use of the ERS-1 σ° data are shown respectively in Figures 2a and 2b. The differences between the two analyses are shown in Figure 3. One can see from Figure 3 that the inclusion of the ERS-1 sigma data results in a wind difference of about 4 m/sec in the analyses over three areas of the ocean surface. These three areas , one near the storm center where 4m/s change represents about 20% of storm center wind speeds, one directly south of the storm, and the other near the San Francisco Bay of California, correspond to the two passes of the ERS-1 satellite swaths.

The above results were based on the analysis experiment where the weights assigned to the ERS-1 σ^o data was set to be $K_p = 0.2 * K_{po}$. It should be pointed out that when the weights were reduced to $K_p=0.4 * K_{po}$, the analysis results show that the inclusion of the ERS-1 σ^o data produces a similar difference pattern but with a smaller wind difference of about 3 m/sec (not shown) when compared to the control run. Moreover, the rate of convergence in the conjugate gradient iteration solution of the NL SSI analysis scheme decreases from $J_{scat}/J_{scato} = 0.1$ for $K_p = 0.2$ to $J_{scat}/J_{scato} = 0.2$ for $K_p=0.4$, where J_{scato} is the value of ERS-1 cost function at the initial time, and J_{scat} is the cost function at the end of 100 iterations. Further decrease in the weighs assigned to the σ^0 data leads to even smaller difference of less than 1 m/sec between the two analyses (not shown) . On the other hand, when the weights are further increased from $K_p = 0.2$ to $K_p=0.1$, differences of greater than 10 m/sec are found between the two analyses for this case study. However, the scheme becomes somewhat unstable for some other case analyses, probably because of the step size estimation.

The second synoptic case chosen for the analysis comparison was May 2, UTC, 1994. During the six-hour window centered at this analysis time, there were two swaths of ERS-1 scatterometer wind data passing through a well developed cyclonic pressure circulation centered at a location between 150 and 155 east longitudes and between 50 and 50 south latitudes south east of Tasmania in the Southern Hemisphere (see Fig.4). This low pressure center is also well identified in the NCAA-12 visible imagery (see Fig.5), which serves as a ground truth for the assessment of analyses results. For this synoptic case, the NMC surface wind analyses failed to depict a closed circulation center when compared to the satellite imagery. It is therefore of particular interest to see if the additional ERS-1 sigma observations will improve the low level wind analyses in better defining the center of the storm circulation.

The vector winds at the lowest model level from the analysis which includes ERS-1 scatterometer wind data are shown in Figure 6b. They should be compared with the analyses which were generated without the use of the ERS-1 scatterometer wind data (i.e., the control run). This is shown in Figure 6a. One can see from comparing Fig. 6a with Fig. 6b that the analysis with the inclusion of the ERS-1 sigma data shows a better defined circulation for the storm center than the control run. The increase in the cyclonic circulation contributed by the addition of the ERS-1 σ^0 data is clearly shown in the vector wind differences between the two analyses (see Figure 7). Close inspection of the two analyses and their differences reveals that there are areas of large vector wind (about 20 m/sec) differences between the two analyses, and these differences occurred near the center of the storm over the passes of the two satellite swaths. Further, it should be noted that the magnitudes of these large vector wind differences are comparable to those reported in Part(II) of this study by Yu (1995), in which the NMC reprocessed ERS-1 vector winds are used in the analyses. These results are rather impressive, suggesting that the nonlinear SSI analysis scheme used in this study can effectively make use of the ERS-1 σ^0 data information to improve the analyses.

6. Summary

This paper discusses some results of the impact on analyses and assimilation experiments of using ERS-1 scatterometer backscattered radiation measurements (σ^o) data in the NMC global data assimilation system. A variational analysis procedure designed for the use of the σ^o data in atmospheric analyses is described. The procedure is a nonlinear version of the NMC's operational spectral statistical analysis scheme, which can use σ^o data directly in the atmospheric analyses through a transfer function (CMOD4). A quality control procedure is described which is based on certain threshold values of the difference between σ^0 calculated by the model and the observed σ^0 values. The model values are calculated by using a large set of collocated buoy (10 meter) winds at ERS-1 satellite data observation locations. It was found that imposing a threshold value of 12 db to quality control the σ^o data is desirable. The quality control procedure was applied to the ERS-1 σ data before they are used in the atmospheric analyses and data assimilation experiments.

The impact of the ERS-1 σ° data on forecasts is investigated by conducting two assimilation experiments, one including the σ° observations, the other excluding the data, in a total of two weeks of data assimilation period. Totally 14 cases of forecasts were initiated at the 0000UTC cycle of every day during the assimilation period. The NMC operational T126 GDAS analyses were used to calculate forecast anomaly correlations as well as bias and RMS height and vector wind errors. Based on the mean statistics from the 14 cases of forecasts, very small differences were found in anomaly correlations as well as bias and RMS statistics between the two forecasts. However, based on anomaly correlations calculated on a case by case basis, it is found that the ERS-1 data do show a small positive impact on the forecasts from 24 hours to 120 hours, the improvement being most noticeable over the Northern Hemisphere.

The ERS-1 σ° data were used in two synoptic storm cases analyses, one over the Northern Hemisphere, and the other over the Southern Hemispheric oceans. Careful inspection of the results from the analyses which include the σ° data show that the variational scheme does converge properly. Results of comparison from two synoptic case analyses show that inclusion of the ERS-1 σ° data in the analyses leads to improvements in better identifying the low level storm center wind circulations. It is found that inclusion of the ERS-1 σ° data can lead to a change of from about 5 m/sec to as large as 20 m/sec in vector wind differences near the centers of storm circulations.

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Table 1. ERS-1 scatterometer backscattered measurements and buoy match up difference statistics. Absolute bias (ABS), and Root Mean Squared (RMS) differences are in units of decibels (db). The total cost function per data point, Jscat, is nondimensional.

Buoy Wind Speed		0-5 m/s	5-10 m/s	10-15 m/s	> 15 m/s
All data	N	14141	40082	12836	2428
	ABS	4.93	1.45	1.30	1.19
	RMS	9.72	2.17	1.82	1.62
	Jscat	2.14	0.48	0.46	0.41
Qc = 12 db	N	12388	39870	12835	2428
	ABS	2.49	1.41	1.30	1.19
	RMS	3.41	2.04	1.82	1.62
	Jscat	1.15	0.47	0.46	0.41
Qc = 10 db	N	11996	39574	12806	2428
	ABS	2.29	1.35	1.31	1.19
	RMS	3.07	1.91	1.78	1.62
	Jscat	0.76	0.45	0.43	0.41
Qc = 8 db	N	11404	39106	12726	2428
	ABS	2.04	1.29	1.25	1.19
	RMS	2.69	1.77	1.71	1.62
	Jscat	0.50	0.40	0.39	0.41

Table 2a. Mean anomaly correlations of forecasts for two weeks of data assimilation (Aug 27, UTC to Sep 9, UTC, 1994) for Exp.A (the control run), based on a total of 14 cases of forecasts.

Forecast Hours	N. H. 1000 mb	N. H. 500 mb	S. H. 1000 mb	S. H. 500 mb
24	.9585	.9762	.9350	.9600
48	.9026	.9365	.8814	.9110
72	.8221	.8761	.8219	.8520
96	.7362	.7953	.7714	.7927
120	.6323	.6913	.6819	.7260

Table 2b. Same as Table 2a except for Exp. B (i.e., including ERS-1 σ° data).

Forecast Hours	N. H. 1000 mb	N. H. 500 mb	S. H. 1000 mb	S. H. 500 mb
24	.9591	.9763	.9293	.9606
48	.9026	.9363	.8805	.9114
72	.8225	.8763	.8236	.8522
96	.7348	.7962	.7705	.7941
120	.6316	.6938	.6745	.7227

Table 3a. Mean Bias and RMS height errors (meters) of model forecasts for Exp. A (the control run) based on a total of 14 cases of forecasts.

Fcst Hrs	N.H. 1000mb		N.H. 500mb		S.H. 1000mb		S.H. 500 mb	
	Bias	RMS	Bias	RMS	Bias	RMS	Bias	RMS
24	-.61	15.2	-2.67	15.8	-.95	31.4	-4.93	29.8
48	-.53	22.5	-5.09	25.7	0.03	42.0	-7.57	44.7
72	-.72	29.7	-7.29	35.7	0.33	51.6	-9.94	58.5
96	-.61	35.3	-8.80	45.6	-.25	59.2	-13.0	71.2
120	-.58	41.6	-9.37	55.4	-.28	68.6	-15.3	83.5

Table 3b. Mean Bias and RMS height errors (meters) of forecasts for Exp. B (including ERS-1 scatterometer σ° data) based on a total of 14 cases of forecasts.

Fcst Hrs	N.H. 1000mb		N.H. 500 mb		S.H: 1000mb		S.H. 500 mb	
	Bias	RMS	Bias	RMS	Bias	RMS	Bias	RMS
24	-.57	15.1	-2.69	15.7	-1.13	32.9	-4.70	29.7
48	-.48	22.5	-5.16	25.7	-0.23	42.3	-7.27	44.7
72	-.63	29.7	-7.34	35.6	0.18	51.5	-9.46	58.4
96	-.53	35.4	-8.90	45.4	-.39	59.1	-12.4	70.8
120	-.53	41.7	-9.57	55.1	-.27	69.3	-14.6	83.7

Table 4. Total number of cases with higher anomaly correlations in the forecasts between Exp.A (the control run) and Exp. B (including ERS-1 σ^o data in the assimilation) on a case by case basis for the whole ensemble of 14 forecasts.

	N. H. Anomaly Correlations				S.H. Anomaly Correlations			
Fcst Hours	1000 mb		500 mb		1000 mb		500 mb	
	Exp.A (w/o)	Exp.B (with)	Exp.A (W/o)	Exp.B (with)	Exp.A (w/o)	Exp.B (With)	Exp.A (w/o)	Exp.B (with)
24	3	11	7	7	7	7	7	7
48	6	8	7	7	7	7	7	7
72	6	8	5	9	5	9	6	8
96	6	8	5	9	7	7	3	11
120	5	9	3	11	12	2	7	7

Table 5. RMS vector wind errors (m/sec) at 850 mb and 250 mb for Exp.A (The control run) and Exp. B (including ERS-1 scatterometer σ^o wind data)

Fcst Hours	Northern Hemisphere				Southern Hemisphere			
	850 mb		250 mb		850 mb		250 mb	
	Exp.A (w/o)	Exp.B (with)	Exp.A (w/o)	Exp.B (with)	Exp.A (w/o)	Exp.B (with)	Exp.A (w/o)	Exp.B (with)
24	3.46	3.46	5.78	5.77	5.04	5.04	7.12	7.10
48	4.49	4.50	8.45	8.44	6.62	6.60	9.85	9.81
72	5.44	5.45	10.95	10.93	7.94	7.90	12.57	12.54
96	6.29	6.29	13.45	13.41	8.73	8.73	14.91	14.88
120	7.09	7.08	15.50	15.46	9.66	9.78	16.87	16.98

Appendix 1. The CMOD4 Model Transfer Function

$$\sigma^o_{lin} = b_0.(1 + b_1 \cos\phi + b_3 \tanh b_2 . \cos 2\phi)^{1.6}$$

where:

$$b_0 = b_r.10^{\alpha+\gamma.\mathcal{F}^1(V+\beta)}$$

and

$$\mathcal{F}^1(y) = \begin{cases} 0 & \text{if } y \leq 0 \\ 10 \log y & \text{if } 0 < y \leq 5 \\ \sqrt{y}/3.2 & \text{if } y > 5 \end{cases}$$

and $\alpha, \beta, \gamma, b_1, b_2$ and b_3 are expanded as Legendre polynomials to a total of 18 coefficients. b_r is a residual correction factor to b_0, and is given as a look-up table as a function of incidence angle.

$$\begin{aligned}
\alpha &= c_1 P_0 + c_2 P_1 + c_3 P_2 \\
\gamma &= c_4 P_0 + c_5 P_1 + c_6 P_2 \\
\beta &= c_7 P_0 + c_8 P_1 + c_9 P_2 \\
b_1 &= c_{10} P_0 + c_{11} . V + (c_{12} P_0 + c_{13} . V) . \mathcal{F}^2(x) \\
b_2 &= c_{14} P_0 + c_{15} . (1 + P_1) . V \\
b_3 &= 0.42(1 + c_{16}(c_{17} + x)(c_{18} + V)) \\
b_r &= LUT(\theta) \\
\mathcal{F}^2(x) &= \tanh\{-2.5(x + 0.35)\} - 0.61(x + 0.35)
\end{aligned}$$

where the Legendre polynomals in x are:

$P_0 = 1$ $\quad$ $P_1 = x$ $\quad$ $P_2 = (3x^2 - 1)/2$ $\quad$ with $x = (\theta - 40)/25$

V is the wind speed in ms^{-1}, ϕ the relative wind direction in degrees and θ the incidence angle in degrees.

CMOD6 Coefficients.

Model:		CMOD6_E1
α	c_1	-2.301523
	c_2	-1.632686
	c_3	0.761210
γ	c_4	1.156619
	c_5	0.595955
	c_6	-0.293819
β	c_7	-1.015244
	c_8	0.342175
	c_9	-0.500786
b_1	c_{10}	0.014430
	c_{11}	0.002484
	c_{12}	0.074450
	c_{13}	0.004023
b_2	c_{14}	0.148810
	c_{15}	0.089286
b_3	c_{16}	-0.006667
	c_{17}	3.000000
	c_{18}	-10.00000

Residual Factors for CMOD6_E1

θ^o	b_r	θ^o	b_r	θ^o	b_r
16	1.075	31	0.927	46	1.054
17	1.075	32	0.923	47	1.053
18	1.075	33	0.930	48	1.052
19	1.072	34	0.937	49	1.047
20	1.069	35	0.944	50	1.038
21	1.066	36	0.955	51	1.028
22	1.056	37	0.967	52	1.016
23	1.030	38	0.978	53	1.002
24	1.004	39	0.988	54	0.989
25	0.979	40	0.998	55	0.965
26	0.967	41	1.009	56	0.941
27	0.958	42	1.021	57	0.929
28	0.949	43	1.033	58	0.929
29	0.941	44	1.042	59	0.929
30	0.934	45	1.050	60	0.929

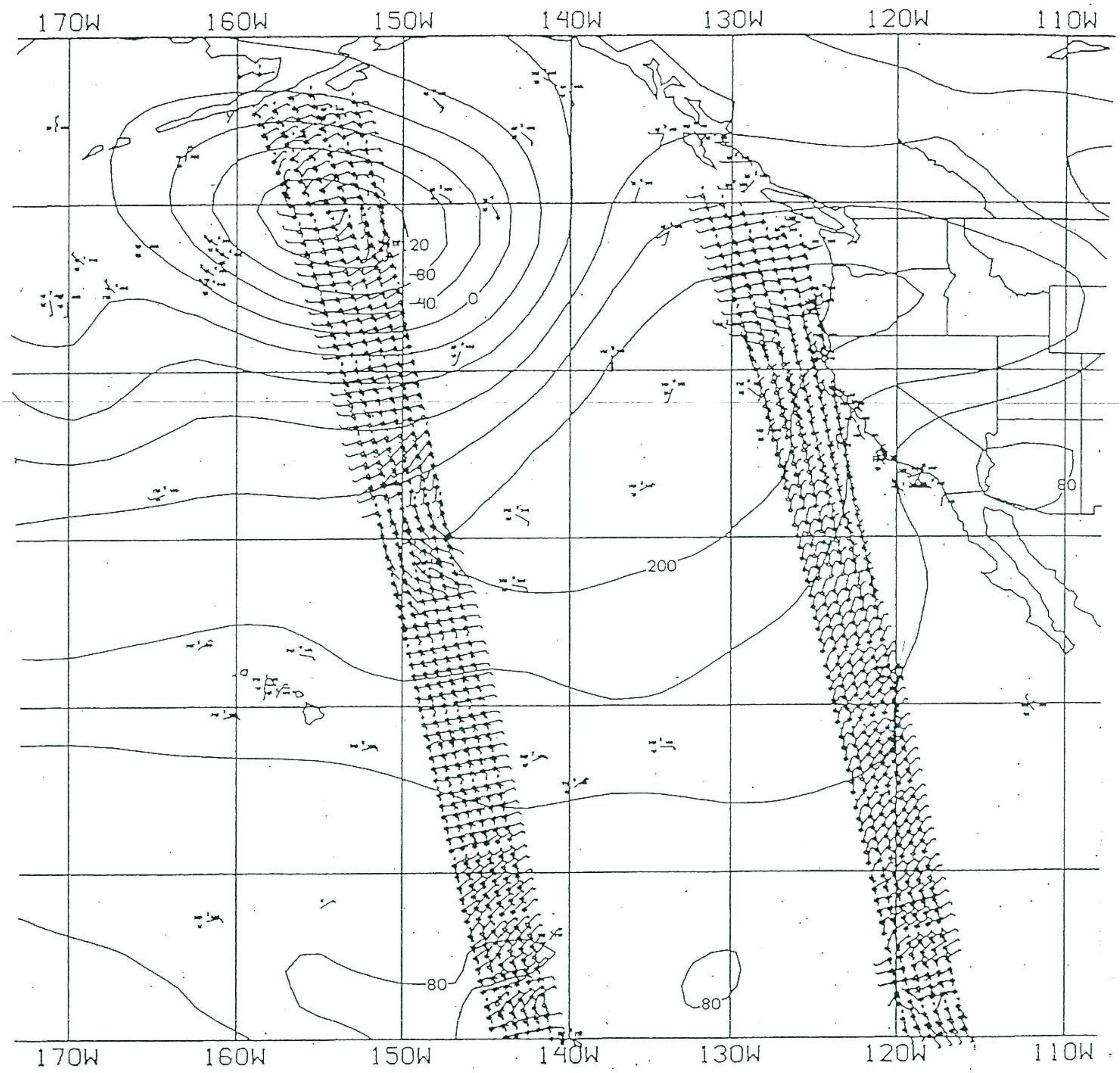

Figure 1. NECP 1000 mb height analyses with two swaths of ERS-1 winds Over the Gulf of Alaska region for 0006 UTC April 27, 1993

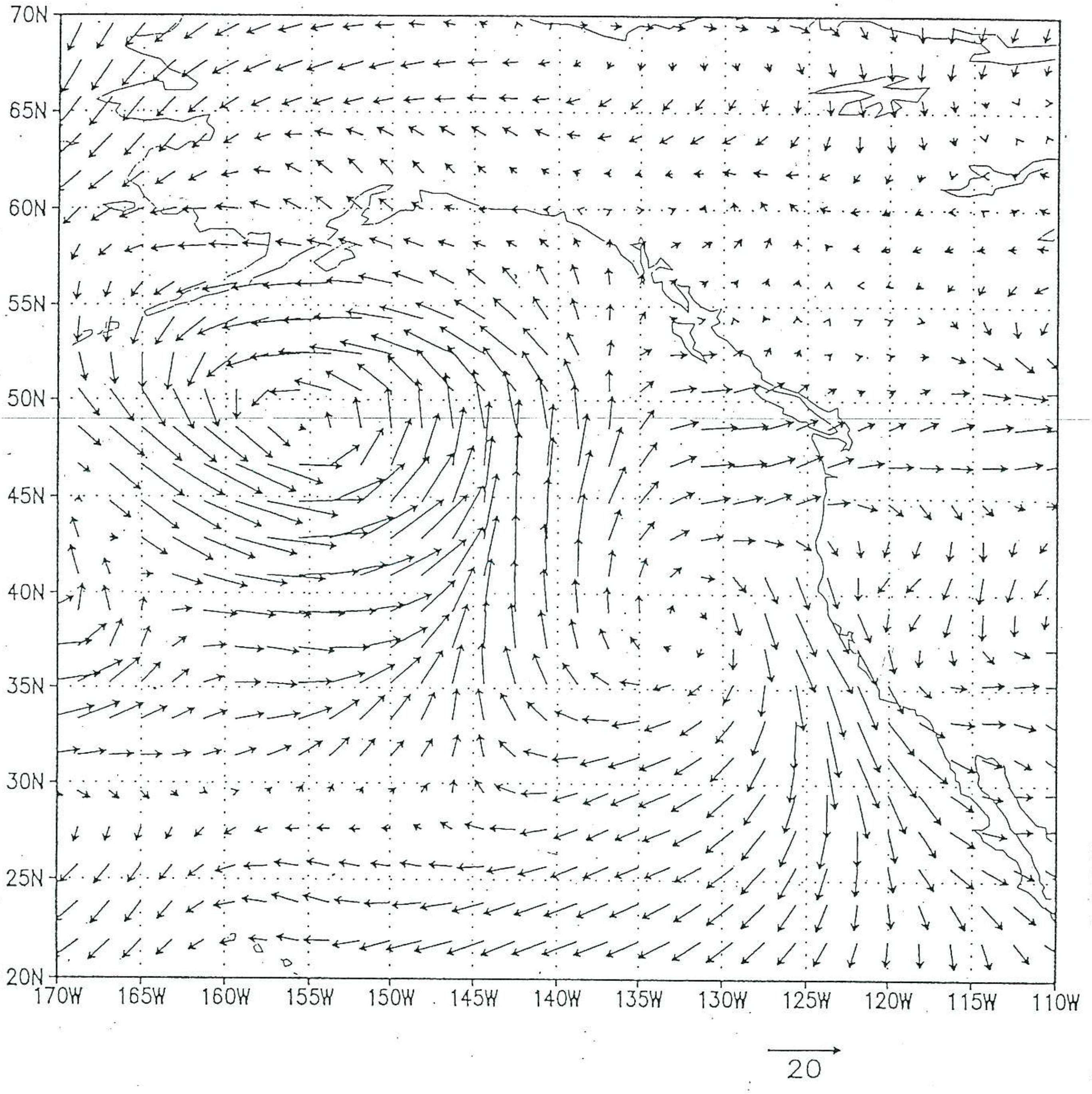

Figure 2a. First sigma level (40 meters above the oceans) wind analyses for Exp. A (the Control Run, without the use of ERS-1 σ° data in the analyses) valid at 0006 UTC April 27, 1993

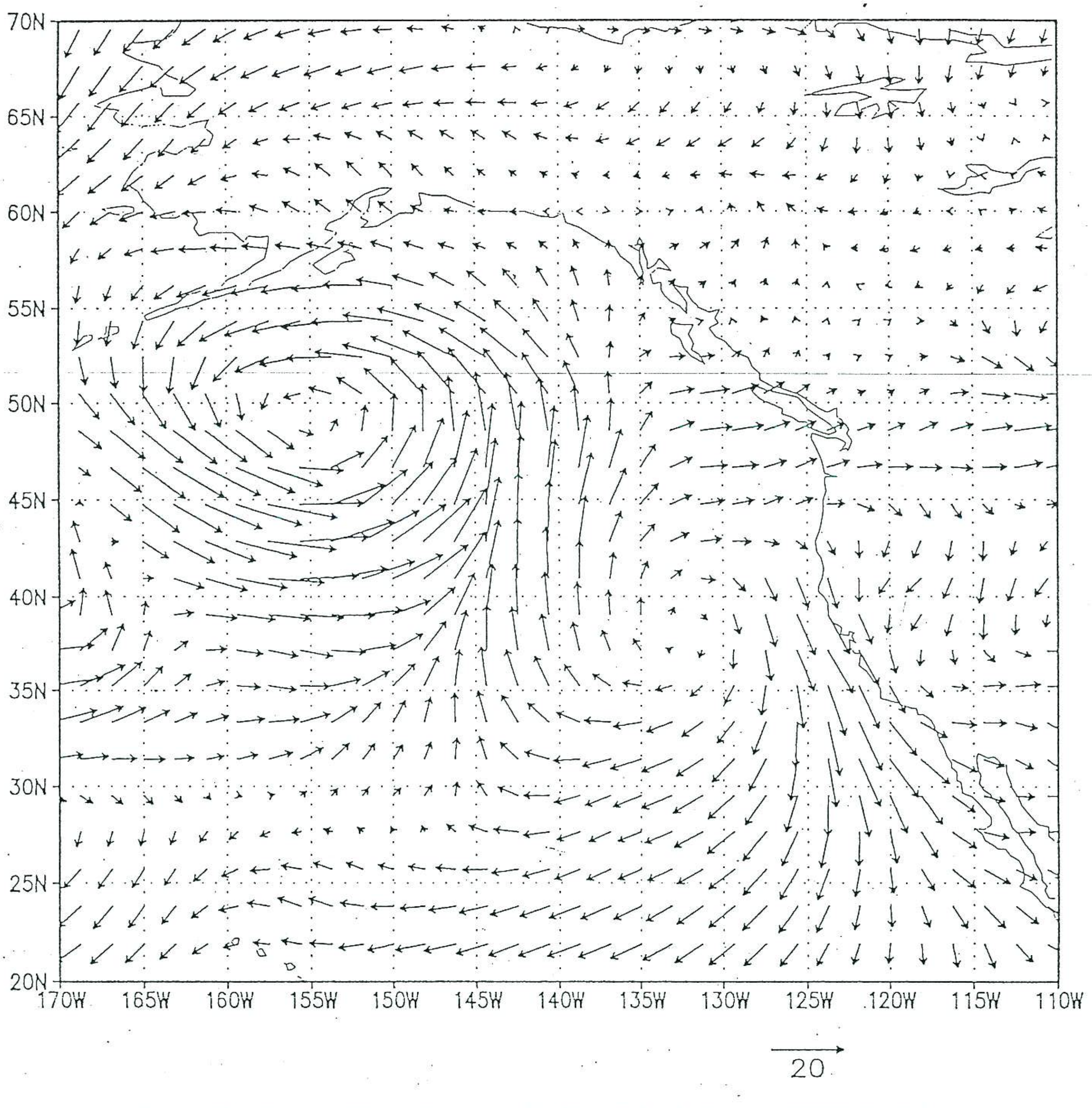

Figure 2b. Same as Figure 2a except for Exp. B (with the use of ERS-1 σ° data in the analyses)

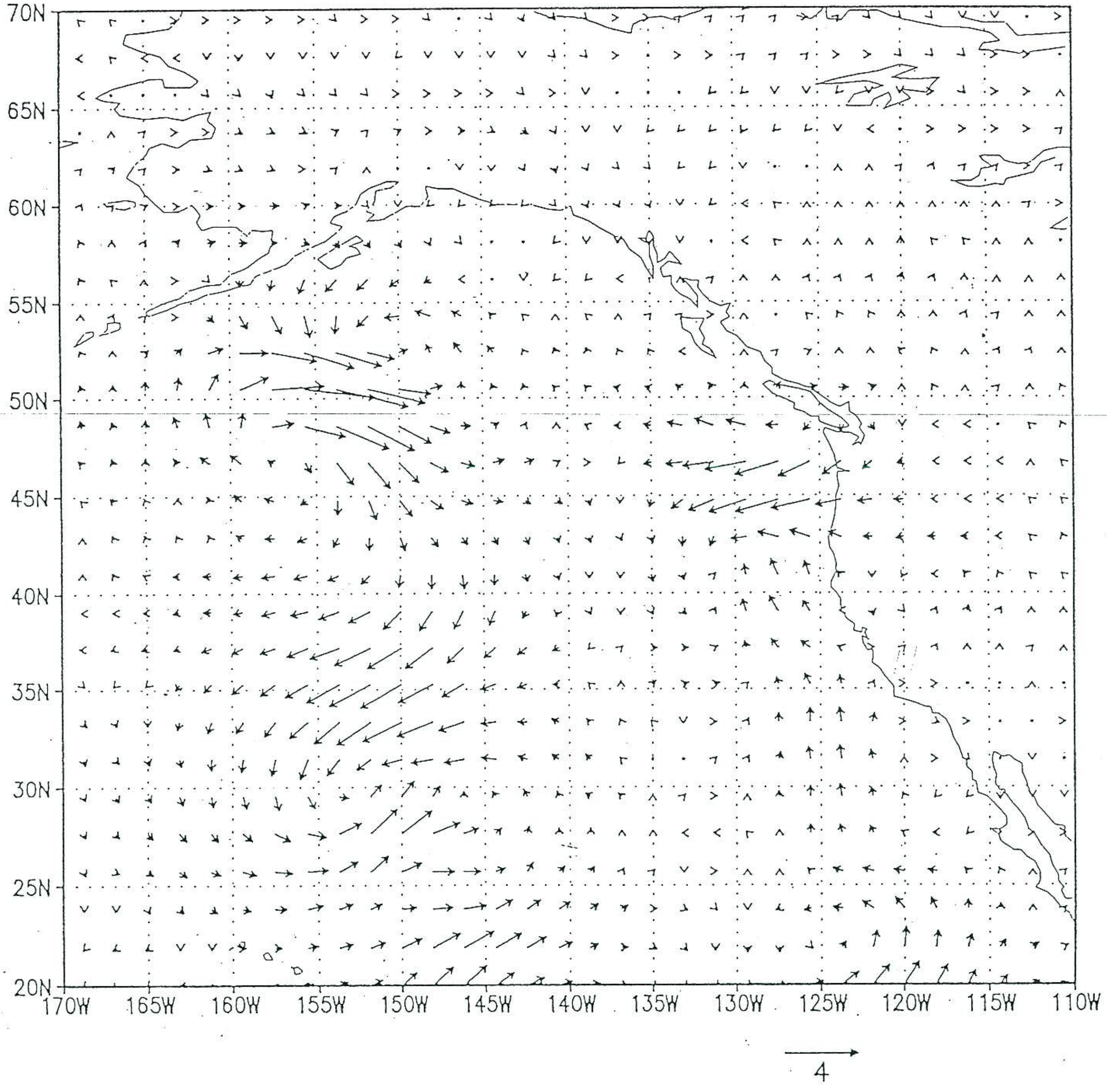

Figure 3. Vector wind difference (m/sec) between Exp. A and Exp. B at the first sigma level for 0006 UTC April 27, 1993.

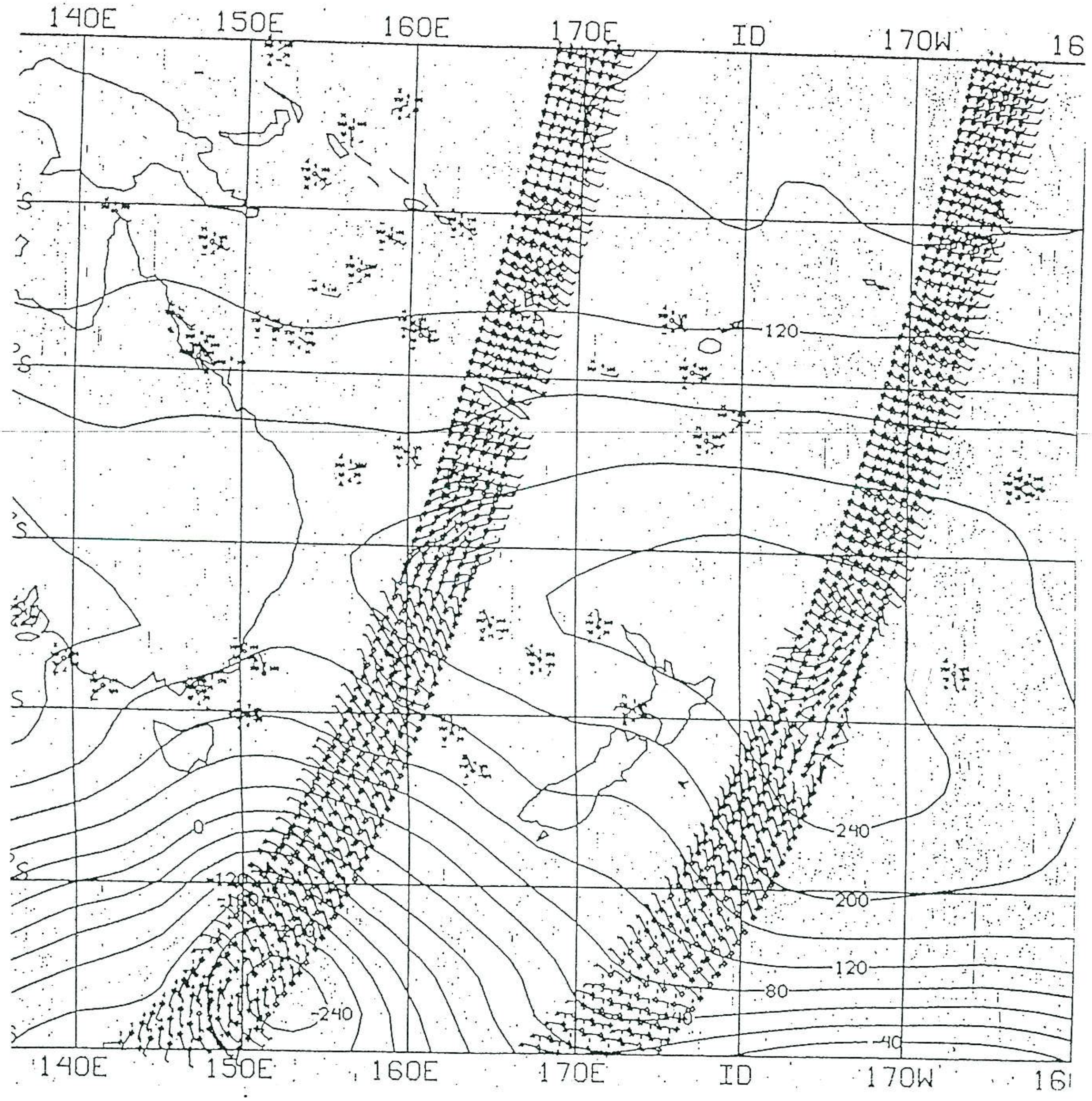

Figure 4. NCEP 1000 mb height analyses with two swaths of ERS-1 winds over the Southern Hemispheric oceans for 0000 UTC, May 2, 1994.

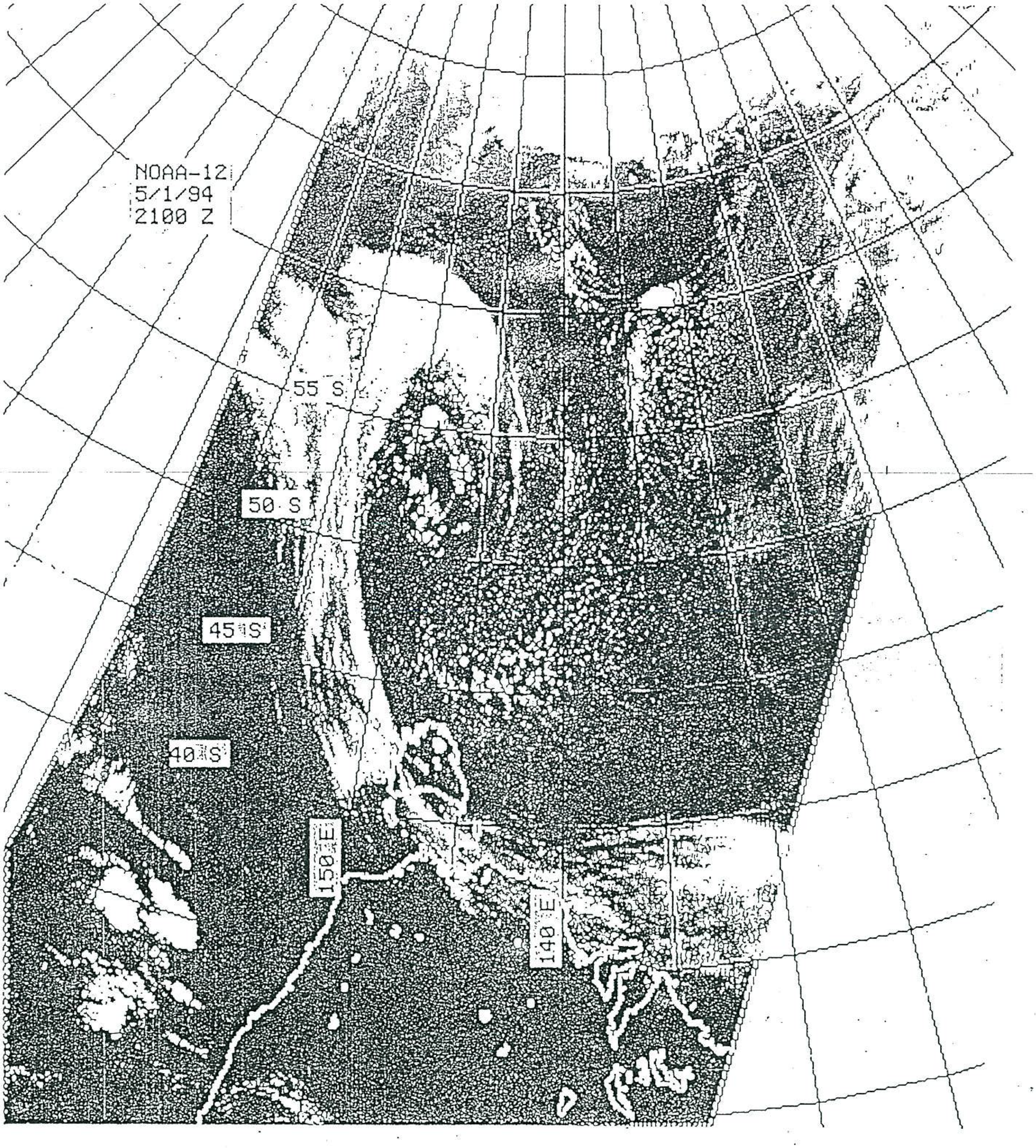

Figure 5. NCAA-12 satellite imagery over the Southern Hemispheric oceans for 2100 UTC, May 1, 1994

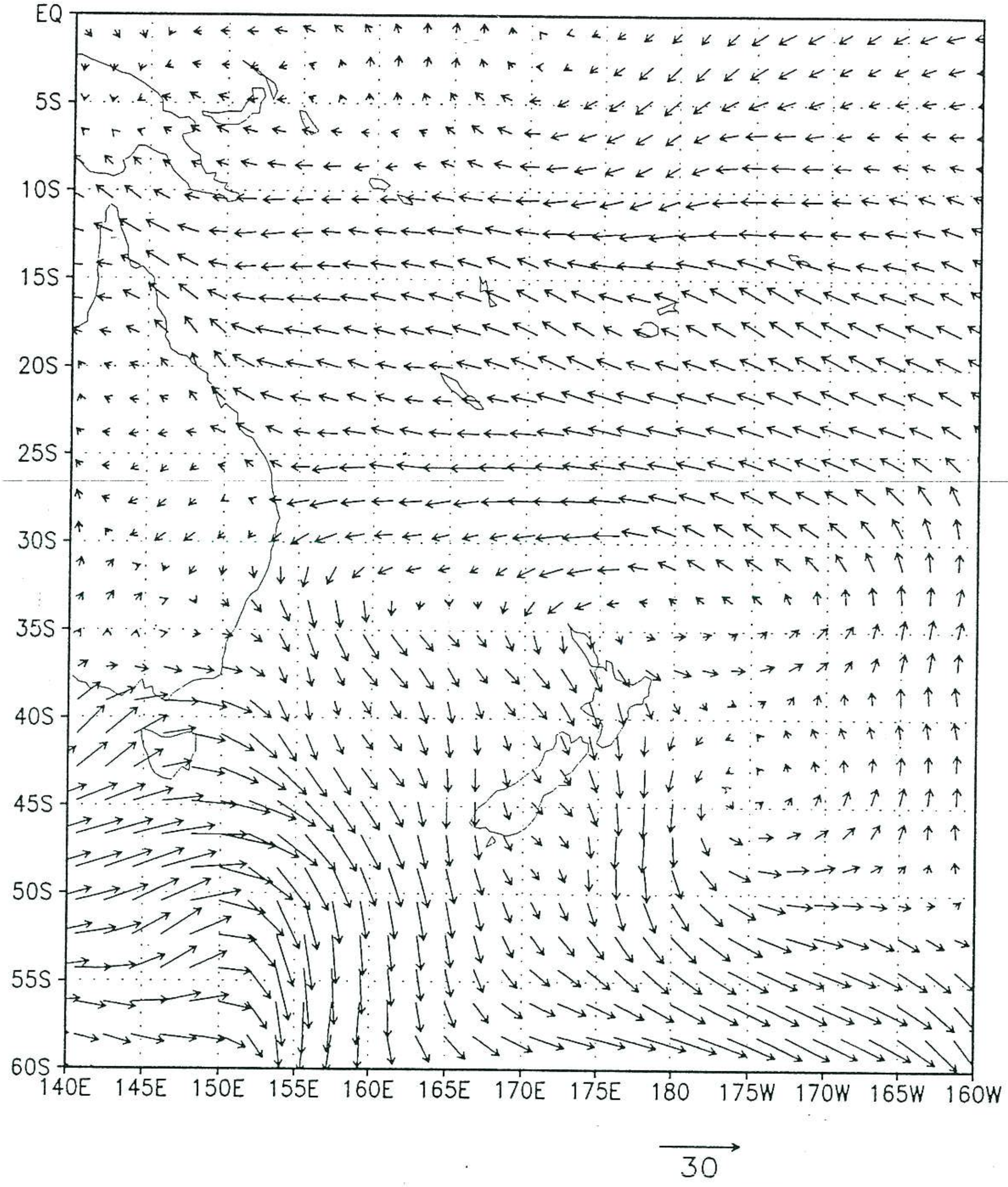

Figure 6a. First sigma level (40 meters above the ocean surface) wind analyses for Exp. A (the Control Run, without the ERS-1 σ° data in the analyses) Valid at 0000 UTC May 2, 1994

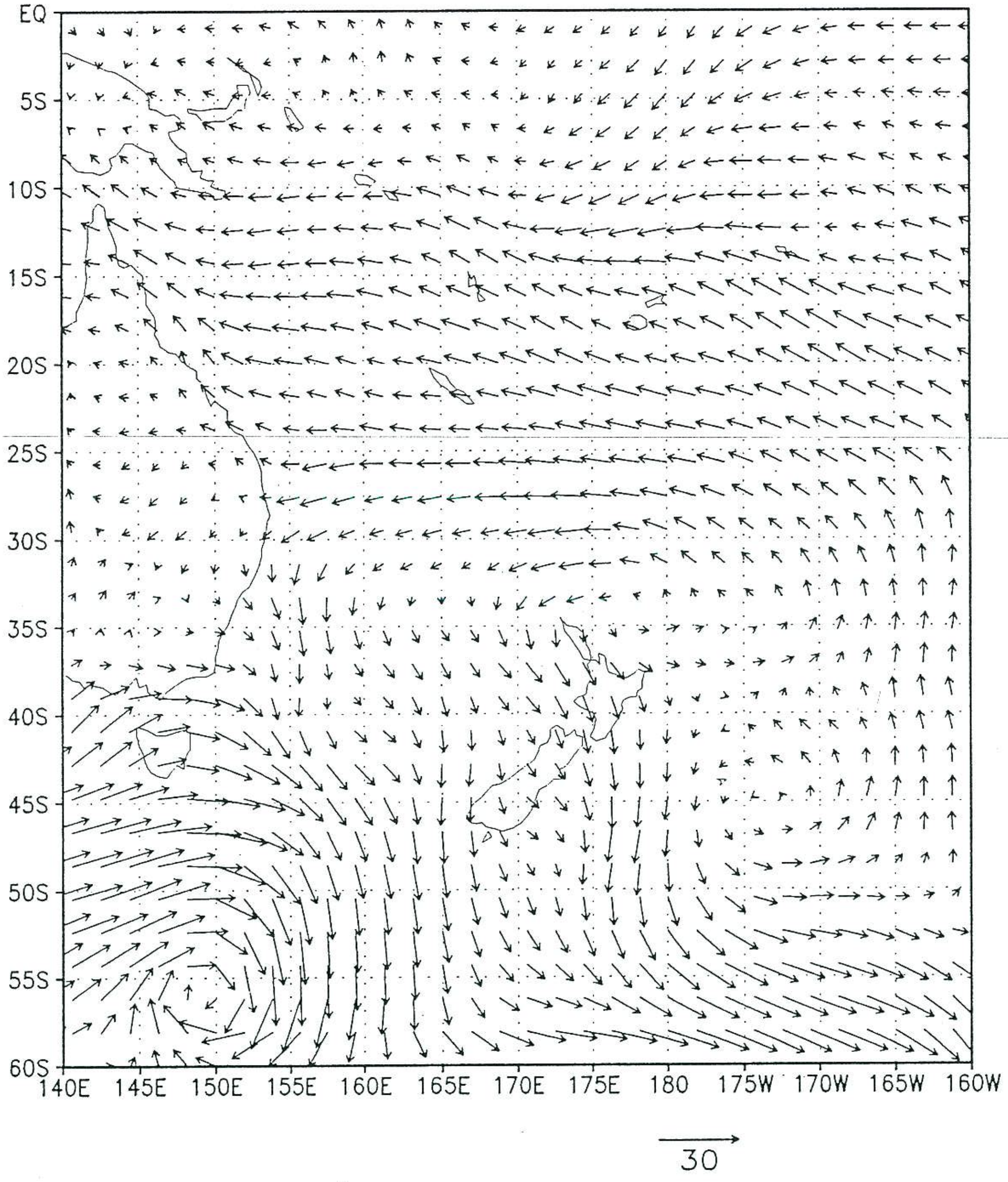

Figure 6b. Same as Figure 6a except for Exp.B (with the use of ERS-1 σ° data in the analyses)

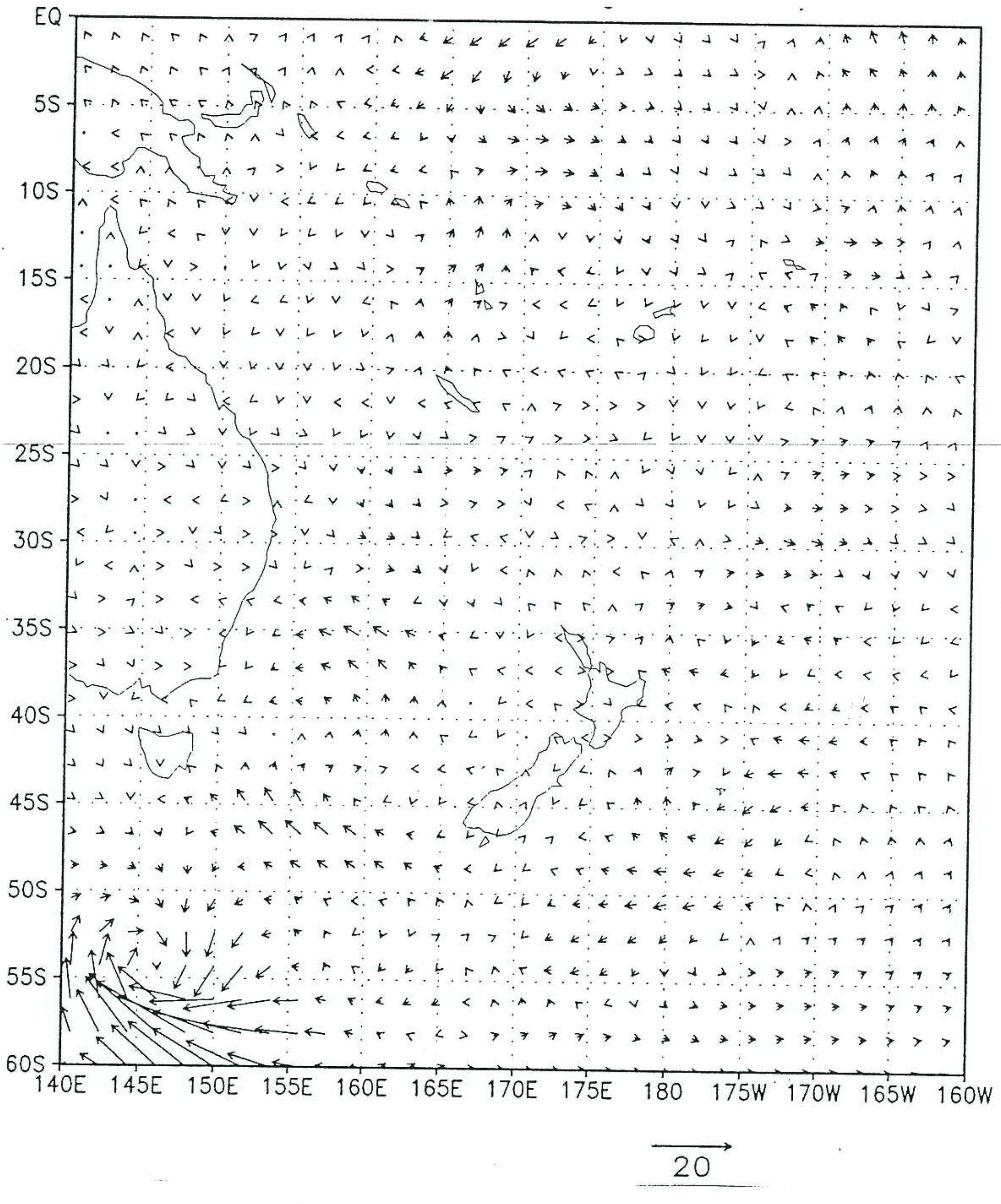

Figure 7. Vector wind differences (m/sec) between Exp. A and Exp. B at the first sigma level for 0000 UTC May 2, 1994.

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