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TECHNICAL NOTE

A PRELIMINARY EVALUATION OF SCATTEROMETER WIND TRANSFER FUNCTIONS FOR ERS-1 DATA

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No. 2. Richardson, W. S., D. J. Schwab, Y. Y. Chao, and D. M. Wright, 1986: Lake Erie Wave Height Forecasts Generated by Empirical and Dynamical Methods -- Comparison and Verification. Technical Note, 23pp.

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ABSTRACT

Transfer functions for ERS-1 scatterometer wind data have been evaluated at NMC along with the "fast-delivery" wind vectors from The European Space Agency (ESA) to provide improved wind vectors for use in numerical weather prediction models. The "fast-delivery" wind vector data from ESA were often found to be incorrectly de-aliased. Fortunately, the data received from ESA also contain the raw sigma-0 values which make it possible to process the vector retrievals directly using specified empirical transfer functions. This study was carried out using quality control (QC) procedures developed at the National Meteorological Center (NMC) to eliminate bad data points and duplicate reports. The directional selection algorithms were adapted from the U.K. Meteorological Office. Since several wind vector solutions may result from each transfer function, the direction is determined by a minimization method, using the NMC global surface wind analysis as background guidance during the procedure.

The selected wind vectors were then evaluated using one year's data from the NOAA fixed buoy network covering the northern hemisphere mid-latitudes and the TOGA buoy network covering the tropics. Of the five functions that were evaluated, two performed consistently better. The transfer function finally selected for operational processing was identical to the transfer function used by the "fast-delivery" product at ESA, however, the NMC winds are derived using different minimization and ambiguity removal procedures. The statistical comparisons show that there was a distinct improvement in the wind directions processed by NMC (RMS of 31 degrees). when compared to those processed by ESA (RMS of 57 degrees).

INTRODUCTION.

The European Space Agency (ESA) launched the ERS-1 spacecraft in July of 1991. The spacecraft data include measurements from a radar (scatterometer) that are used to estimate wind vectors at the sea surface. ESA made these data available daily to a few selected operational Meteorological Centers for their evaluation of the data for operational use.

The ERS-1 scatterometer is an active, five cm microwave instrument that measures the radar backscatter from gravity-capillary waves at the ocean surface. This backscatter is then related to wind stress (and wind) through the use of a radar backscatter-to-wind transfer function. Since more than two measurements of back-scattered power are necessary to resolve directional ambiguity in the wind data, this scatterometer was designed with three antennae to measure the backscatter from the ocean surface. The satellite follows a polar-orbit of 98 degrees of inclination and the time it takes to complete an orbit is about 102 minutes. This provides about three and one-half orbits per six hour period (about 14 orbits per day). The data coverage of backscatter measurements is across a swath of about 500km wide, with 19 cells across the swath at about 25 km apart. The spatial resolution is about 50 km for the measurement of each cell. The characteristics of the ERS-1 scatterometer wind data are presented in Table 1. The satellite coverage for a typical 6 hour period is shown in figure 1. The geometry of the satellite and its scatterometer wind cell distribution over the ocean surface is shown in figure 2.

NMC began receiving the fast delivery (FD) scatterometer wind data taken by the ERS-1 satellite from ESA during the spring of 1992. But, an evaluation of the ESA FD wind vectors showed that there were several deficiencies (mainly wrong directions) that made the wind data unacceptable for use in analysis and forecast models. Fortunately, the FD data include not only the wind vector (speed and direction) data as processed by ESA, but also the raw sigma-0 radar backscatter parameters, incident angles and pointing angle with related noise and quality parameters for each of the three antennae of the scatterometer. Since the raw data were available, it was decided that NMC should develop its own processing system in an attempt to improve the retrieved satellite ocean surface winds.

The ESA FD wind vector data were objectively evaluated using data from buoys and also subjectively compared with surface weather maps. These efforts clearly showed that, although the satellite derived wind speeds appear to meet specifications, the ESA selected directions do not. A sample of wind vectors obtained from ESA are shown in Figure 3. It is evident that the winds do not depict a consistent meteorological flow pattern. In addition, figure 4 shows that there are often duplicate vectors which may differ slightly in position and selected direction in the fast delivery product of ESA.

A major concern for operational weather centers, such as NMC, is that the data must arrive in a timely manner (near real-time) in order to be ingested into analysis and forecast models at the synoptic cycle times. The data must be received and be available no more than 3 hours after observation time, if it is to be used by the forecast model. An examination of the timeliness of the data received from ESA shows that most of the data meet the required time constraint. A sample recording of satellite observation times to receipt time at NMC computers are presented in figure 5. Occasionally, there are longer delays which prevents the use of the data for global forecast model, but as long as they are received at NMC with 8 hours they are still useful to the NMC Global Data Assimilation System (GDAS) which runs last in the operational cycle in order to ingest as much late data as possible into the final analysis. The analysis procedure (GDAS) is described in detail by Parrish & Derber(1992) and Derber, Parrish & Lord (1993) .

The NMC/JPL processing system consists of four steps: 1) quality control (QC) procedures, 2) a transfer function which converts the raw sigma-0 values to wind vectors (unfortunately with multiple solutions), 3) a least squares minimization algorithm to determine each of the multiple vector solutions and 4) the directional selection procedure to select the most likely wind vector. Some of the details on these steps were presented by Woiceshyn (1993).

A brief description of the evaluation of the transfer functions has been presented by Peters et al (1994a). At that time seven months of data had been collected. This paper will present some general statistics which were used to justify the selection of the transfer function which was implemented as part of NMC operations. The details concerning the processed ERS-1 winds vector data now available within NMC are described by Peters et al (1994b).

QUALITY CONTROL

Automated quality control procedures are required when processing large quantities of satellite data in real-time. It is necessary to remove erroneous data from entering into the analysis system, which may be due to any number of problems which are encountered in the flow of data between the satellite and the operational center. The data initially received from ESA are decoded from BUFR messages and collocated with the NMC Global Model wind, humidity, air temperature and sea surface temperature (SST) fields, either from the GDAS or from a six hour forecast. Since several ground stations may be processing data blocks along the satellite orbit, the data may not arrive at a particular meteorological center in a consistent time and position sequence. The result is data blocks that are out of order, missing or even duplicated. Duplicate blocks can occur when the data are received from more than one ground processing station and can even result not quite at identical positions. Thus, the data are sorted into an ordered time/location sequence along the orbit and duplicates are removed. Other QC checks include using the global SST analysis to identify and discard observations assumed to be over ice (i.e., where the SST is less than zero degrees centigrade) or discard those over land, ensuring that all three beams were functioning properly (resulting in three sigma naught measurements) and that the backscatter noise to signal ratio was less than 10%.

SCATTEROMETER WIND TRANSFER FUNCTION MODELS

An empirically based transfer function converts the radar backscatter parameters: sigma-0, look angle, and incident angle from three antennae into wind vectors: wind speed and direction at height of 10m over the ocean. It is necessary to use empirical transfer functions because the properties of backscatter radar signal from the ocean surface are yet too complex for direct theoretical conversion to wind vectors. In this study, five transfer functions were selected to compute wind vectors. These wind vectors as well as the wind vector data from ESA were then evaluated. The CMOD4 transfer function (developed at ECMWF) has gone through post-launch refinements and retuning, is generally accepted as the operational processing algorithm and it is now used by some meteorological centers. ESA uses the CMOD4 transfer function in its processing of the FD wind vector data. Offiler (1994) reviewed the developments of CMOD4 and shows that those scatterometer winds, when compared to special measurements and wind analyses over the North Sea, meet the ERS-1 user requirements for accuracy of 2 m/s RMS (or 10%, whichever is higher) and 20 degrees for direction. The transfer functions are identified in Table 2 and their functional forms are presented in the Appendix.

Identification	Originator
CMOD 4	ECMWF
CMOD 5I	IFREMER
CMOD 5L	ESA
CMOD 6	University of Hamburg
CMOD 7	NASA-JPL/Oregon State University
ESA CMOD4	ESA "fast delivery"

Table 2

Unfortunately, the transfer functions do not provide unique solutions for the wind vectors. There may be as many as six solutions, (but more likely four) depending on the wind direction relative to the direction of the satellite scatterometer antennae. A combination of two look-up tables generated "off-line" from the specific transfer function, a quadratic function, and derivatives of that function are used during the minimization process to determine the multiple wind vector solutions at each measurement cell node.

A statistical ranking procedure is employed to determine the probabilities of each vector solution as being "correct", using a cost function. Finally, the selection of the most likely wind vector is modified by the indirect use of an ocean surface wind analysis. For this study, the winds were obtained from the NMC global surface wind analysis provided by the GDAS. These "background" winds are used to modify the probabilities of the valid scatterometer wind vectors, taking into account the likely error of both the analysis and scatterometer wind vector solution.

An important difference to note on the selection of wind direction between ESA processing and NMC processing in this study is that the ESA wind product uses the ECMWF 18 to 36 hour wind forecast fields, whereas the NMC wind product uses the current analysis.

To check the local consistency of the wind vectors, a 5X5 node array "modal " filter is passed through the two-dimensional wind vector field in the scatterometer data swath. This filter is similar to a buddy check for vector to vector consistency, which is referred to as a Sequential Local Iterative Consistency Estimator (SLICE), and was developed at the UK Meteorological Office by Offiler (1992). He states, "SLICE should be considered as being an algorithm which 'tidies up' the scatterometer swath to be self-consistent. particularly in cases where the background wind is locally incorrect (e. g. location of low pressure centres)." Each scatterometer measurement location is sequentially processed in an across- and along-track spacecraft direction. If a local inconsistency is determined by SLICE, the probabilities are modified according to the fit of each wind solution to the local wind field. The wind vector solutions are then re-ranked. SLICE is iteratively repeated in alternative directions until fewer than a threshold number of locations had their ranking changed. No probability and re-ranking modifications are made if inconsistency is not detected by the SLICE algorithm. SLICE in this operation can be considered as a two-dimensional "filter" to provide a quality controlled field of consistent wind vectors along the satellite track.

The total processing package developed at NMC combines software to unpack from BUFR, match the individual scatterometer measurements with model values, and quality control the data, with minimization and wind vector selection algorithms adapted from the UK Met. Office (Offiler, 1992). The final result is a data set containing unique wind vectors at each scatterometer measurement node, which we will henceforth refer to as the "NMC/JPL Processed Product".

DATA MATCH-UPS

The data collected for this study covers a one year period, from September 9, 1993 through September 9, 1994. A program was executed four times a day to collocate the NMC Processed ERS-1 scatterometer satellite data (time, position, ESA wind speed and direction, and the radar backscatter information for the three antennae), with NMC wind analyses and with wind data from the NOAA's National Data Buoy Center (NDBC) fixed buoy network and the Tropical Ocean Global Atmosphere (TOGA) moored buoys. The NDBC buoys provided data that meet the speed and direction accuracy specification of +/- 1.0 m/s and 10 degrees, respectively, based on

8.5 minute averages (Gilhousen, 1987). The NDBC buoys take wind measurements at heights ranging from 5m to 15m. The wind data received from the TOGA buoys have been averaged for one hour taken at a height of 3.8m (Hayes et al, 1991).

Buoy data were matched up with satellite data four times per day at 00, 06, 12, 18 UTC for data within a +/- 3 hour window and within 1.5 degrees radius of the buoy location. The wind analysis was taken from the surface wind analysis of GDAS, by interpolating to the location of the satellite cell node. Unfortunately, the height of the wind measurements is not the same: the GDAS winds are provided at a height of about 45m, the buoy wind observations are measured at heights ranging from 3.8m for the TOGA buoys and from 5m to 15m for the NDBC buoys whereas the scatterometer winds are specified at 10m (all heights are above sea level). It was necessary to adjust all wind speed data to the height of the satellite estimate (10m), which was done using the simple neutral log wind profile relation. The location of buoy data used in this study are identified in figures 6a,b,c.

The raw sigma-0 measurements are QC'ed by the methods described above. Using an empirical transfer function, solutions for up to six directions (ambiguities) may be obtained. The minimization, ranking, wind field background fit and SLICE techniques are applied to obtain a set of consistent satellite wind vectors. This process is repeated five times, once for each transfer function. The ESA data are QC'ed only by virtue of collocation to the QC'ed NMC processed data. The remaining ESA wind vectors are accepted as they are delivered. The data are then ready to be evaluated.

STATISTICAL EVALUATION

Ocean surface winds obtained 1) from utilizing through the five transfer functions and scatterometer measurements from the ERS1 satellite, 2) from NMC analyses and 3) from buoys can now be compared by calculating various statistical measures. For this study, only the high-seas buoys will be used to avoid land contamination on the satellite data and/or to land induced local circulations. The satellite derived wind vectors were collocated within a 0.5 degree latitude, longitude box with the buoy at the center (a subset of the original data), and within +/- 3 hour of the observation. This time and space specification of collocation was chosen to be similar to the scales used by GDAS (for the AVN & MRF models) to make super-obs of high density data. This specification for the co-location of match-ups is coarser than what is required for algorithm development and validation which is usually specified to be +/- 30 minutes and 25 km. The statistics from these data match-ups will then be poorer than those presented from validation reports, because of the difference in time and space, but also, because only superficial QC has been applied to the buoy data. To determine the impact of time and space scales on averaging in the comparisons, the satellite data can be assigned to other time and space windows, It is also important to observe that although these winds are all at a common reference height (10m), there are differences in time and space scales of the wind measurement made by buoys, satellites and analyses. The buoy makes a "spot" measurement averaged for 8.5

minutes (NDBC) or 1 hour (TOGA), the satellite measurement is spatially averaged (50km) and takes 2 to 7 minutes for collocation of the three antennae, and the model is a spatially averaged and smoothed estimate at a given time. The NDBC and TOGA buoys will be used as the "sea-truth" for this study.

Table 3 shows some composite statistics for the evaluation based on all the data. The sample size is the total number of satellite data points that were matched to buoys; calm winds were included in the speed but not the direction statistics. The left side of the table presents the mean speed and standard deviation for each data source (satellite, model, buoy), whereas, the right side presents comparison statistics between the data sources: for the bias, RMS, speed correlation, an average Figure of Merit (FoM) and a vector correlation which is defined by Crosby et al (1993). The Figure of Merit is a composite type of statistic which measures how close the satellite derived wind speeds and directions meet specifications. It includes the bias, standard deviation, RMS and the vector RMS for comparisons with buoys and analyses. A FoM greater than one indicates the derived wind data are meeting the specified requirements . The average Figure of Merit is defined as:

$$FoM = (F1 + F2 + F3)/3$$

where $F1 = 40/(SPD(bias) + 10SPD(sd) + DIR(bias) + DIR(sd))$

$F2 = (2/SPD(rms) + 20/DIR(rms))/2$

$F3 = 4/Vector(rms)$

In order to determine more easily which wind transfer function performed best when compared to the buoys, each of the transfer functions was ranked in order of performance (1 is best and 6 is worst) by each of the statistical categories.

TABLE 3a

BUOY VS TRANSFER FUNCTION WIND STATISTICS

NDBC and TOGA buoys, High Seas, All Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Dates 93 09 09 - 94 09 09

--- CMOD 4 Number: 9371

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.3	6.7	6.9	SPD BIAS	-0.3	-0.5	-0.2
SD SPD	2.8	2.8	2.7	SPD RMS	1.7	1.8	1.9
				SPD CORR	0.82	0.80	0.77
				DIR RMS	23	31	29
				VECT CORR	0.92	0.87	0.89
				FOM	1.15	0.93	0.97
SPD MAX	20.7	21.7	20.1				
NUM CALM	0	0	107				

--- CMOD 5I Number: 9310

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	7.2	6.7	6.9	SPD BIAS	0.5	0.3	-0.2
SD SPD	3.1	2.8	2.7	SPD RMS	1.8	1.8	1.9
				SPD CORR	0.83	0.82	0.77
				DIR RMS	23	32	29
				VECT CORR	0.92	0.88	0.89
				FOM	1.10	0.92	0.97
SPD MAX	20.7	21.7	20.1				
NUM CALM	0	0	104				

--- CMOD 5L Number: 9224

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	5.5	6.7	6.9	SPD BIAS	-1.2	-1.4	-0.2
SD SPD	3.3	2.8	2.7	SPD RMS	2.2	2.4	1.9
				SPD CORR	0.83	0.81	0.76
				DIR RMS	24	32	28
				VECT CORR	0.90	0.85	0.89
				FOM	1.04	0.85	0.97
SPD MAX	21.8	21.7	20.1				
NUM CALM	0	0	88				

--- CMOD 6 Number: 9322

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	5.6	6.7	6.8	SPD BIAS	-1.1	-1.3	-0.2
SD SPD	2.9	2.8	2.7	SPD RMS	2.1	2.2	1.9
				SPD CORR	0.79	0.77	0.77
				DIR RMS	28	35	29
				VECT CORR	0.90	0.85	0.89
				FOM	0.99	0.84	0.97
SPD MAX	21.1	21.7	20.1				
NUM CALM	0	0	103				

--- CMOD 7 Number: 9025

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.1	6.8	7.0	SPD BIAS	-0.7	-0.9	-0.2
SD SPD	3.5	2.7	2.6	SPD RMS	2.2	2.3	1.9
				SPD CORR	0.80	0.80	0.76
				DIR RMS	28	37	27
				VECT CORR	0.90	0.85	0.90
				FOM	0.96	0.81	1,00
SPD MAX	26.3	21.7	20.1				
NUM CALM	0	0	70				

--- ESA Number: 8755

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.5	6.8	7.0	SPD BIAS	-0.3	-0.5	-0.2
SD SPD	2.7	2.8	2.6	SPD RMS	1.6	1.7	1.9
				SPD CORR	0.82	0.80	0.76
				DIR RMS	56	57	28
				VECT CORR	0.75	0.71	0.90
				FOM	0.75	0.71	0.99
SPD MAX	20.0	21.7	20.1				
NUM CALM	0	0	72				

Table 3b
TRANSFER FUNCTION RANKINGS

NDBC and TOGA buoys, High Seas, All Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Dates 93 09 09 - 94 09 09

	CMOD4	CMOD5I	CMOD5L	CMOD6	CMOD7	ESA
SPD BIAS	2	1	6	5	4	2
SPD RMS	2	2	6	4	5	1
SPD COR	3	1	2	6	3	3
DIR RMS	1	2	3	4	5	6
VECT CORR	2	1	3	3	3	6
FOM	1	2	3	4	5	6

These data are further stratified by season, winter and summer and geographical location, mid-latitude and tropical to compute the error statistics . These are presented in the following tables.

Table 4 presents the statistics for the mid-latitude NDBC buoys for the winter months, November 1, 1993 through April 31, 1994.
Table 5 presents the NDBC buoys for the summer months September 9, through October 31, 1993 and May 1, through September 9, 1994.
Table 6 presents the statistics for the tropical TOGA buoys for the winter months, November 1993 through April, 1994.
Table 7 presents the TOGA buoys for summer months September 9, through October, 1993 and May through September 9, 1994.

TABLE 4a

BUOYS VS TRANSFER FUNCTION WIND STATISTICS

NDBC Mid-latitude, High-Seas, Winter Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Date 93 11 01 - 94 04 31

--- CMOD 4 Number: 3114

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	7.3	7.8	7.6	SPD BIAS	-0.4	-0.3	0.1
SD SPD	3.2	3.4	3.1	SPD RMS	1.9	2.1	2.3
				SPD CORR	0.85	0.80	0.76
				DIR RMS	24	37	33
				VECT CORR	0.93	0.86	0.89
				FOM	1.07	0.78	0.80
SPD MAX	20.4	21.7	19.1				
NUM CALM	0	0	33				

--- CMOD 5I Number: 3082

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	8.2	7.8	7.7	SPD BIAS	0.4	0.5	0.1
SD SPD	3.4	3.4	3.1	SPD RMS	1.9	2.1	2.3
				SPD CORR	0.86	0.81	0.76
				DIR RMS	23	36	27
				VECT CORR	0.73	0.87	0.89
				FOM	1.06	0.77	0.80
SPD MAX	20.0	21.7	19.1				
NUM CALM	0	0	33				

--- CMOD 5L Number: 3090

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.7	7.8	7.7	SPD BIAS	-1.1	-1.0	-0.1
SD SPD	3.8	3.4	3.1	SPD RMS	2.3	2.5	2.3
				SPD CORR	0.85	0.80	0.76
				DIR RMS	23	36	33
				VECT CORR	0.92	0.86	0.89
				FOM	1.00	0.74	0.80
SPD MAX	21.8	21.7	19.1				
NUM CALM	0	0	29				

--- CMOD 6 Number: 3100

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.6	7.8	7.6	SPD BIAS	-1.1	-1.0	0.1
SD SPD	3.1	3.4	4.2	SPD RMS	2.3	2.4	2.3
				SPD CORR	0.82	0.76	0.76
				DIR RMS	29	40	33
				VECT CORR	0.92	0.85	0.88
				FOM	0.93	0.74	0.80
SPD MAX	21.1	21.7	19.1				
NUM CALM	0	0	33				

--- CMOD 7 Number: 3011

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	7.2	7.8	7.7	SPD BIAS	-0.6	-0.5	0.1
SD SPD	4.0	3.3	3.1	SPD RMS	2.3	2.5	2.2
				SPD CORR	0.84	0.79	0.76
				DIR RMS	27	41	31
				VECT CORR	0.92	0.86	0.89
				FOM	0.94	0.71	0.83
SPD MAX	26.3	21.7	19.1				
NUM CALM	0	0	26				

--- ESA Number: 3026

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	7.4	7.8	7.7	SPD BIAS	-0.4	-0.3	0.1
SD SPD	3.1	3.3	3.1	SPD RMS	1.8	2.1	2.2
				SPD CORR	0.85	0.79	0.76
				DIR RMS	60	62	32
				VECT CORR	0.77	0.75	0.89
				FOM	0.66	0.62	0.82
SPD MAX	17.6	21.7	19.1				
NUM CALM	0	0	27				

Table 4b
TRANSFER FUNCTION RANKINGS

NDBC Mid-latitude, High-Seas, Winter Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Date 93 11 01 - 94 04 31

	CMOD4	CMOD5I	CMOD5L	CMOD6	CMOD7	ESA
SPD BIAS	1	3	5	5	5	1
SPD RMS	1	1	5	4	5	1
SPD CORR	2	1	2	6	4	4
DIR RMS	3	1	1	4	5	6
VECT CORR	2	1	2	5	2	6
FOM	1	2	3	3	5	6

TABLE 5a

BUOYS VS TRANSFER FUNCTION WIND STATISTICS

NDBC Mid-latitude, High-Seas, Summer Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Date 93 09 09 - 93 10 31 and 94 05 01 - 94 09 09

--- CMOD 4 Number: 2871

	SAT	MOD	BUOY
MEAN SPD	5.6	5.9	6.4
SD SPD	2.5	2.6	2.6
SPD MAX	16.2	18.8	20.1
NUM CALM	0	0	49

	SAT - MOD	SAT - BUOY	MOD - BUOY
SPD BIAS	-0.3	-0.8	-0.4
SPD RMS	1.5	1.7	1.7
SPD CORR	0.85	0.83	0.81
DIR RMS	23	30	27
VECT CORR	0.93	0.90	0.91
FOM	1.27	1.03	1.09

--- CMOD 5I Number: 2860

	SAT	MOD	BUOY
MEAN SPD	6.3	6.0	6.4
SD SPD	2.9	2.6	2.7
SPD MAX	16.3	18.8	20.1
NUM CALM	0	0	46

	SAT - MOD	SAT - BUOY	MOD - BUOY
SPD BIAS	0.3	-0.1	-0.4
SPD RMS	1.6	1.6	1.7
SPD CORR	0.85	0.84	0.81
DIR RMS	24	31	27
VECT CORR	0.93	0.90	0.91
FOM	1.20	1.03	1.09

--- CMOD 5L Number: 2776

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	4.7	6.1	6.5	SPD BIAS	-1.4	-1.9	-0.4
SD SPD	3.0	2.6	2.5	SPD RMS	2.2	2.5	1.7
				SPD CORR	0.84	0.82	0.80
				DIR RMS	25	30	26
				VECT CORR	0.90	0.87	0.91
				FOM	1.10	0.91	1.10
SPD MAX	18.6	18.8	20.1				
NUM CALM	0	0	34				

--- CMOD 6 Number: 2868

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	4.9	5.9	6.4	SPD BIAS	-1.0	-1.5	-0.4
SD SPD	2.4	2.6	2.6	SPD RMS	1.8	2.2	1.7
				SPD CORR	0.82	0.79	0.81
				DIR RMS	30	35	27
				VECT CORR	0.91	0.88	0.91
				FOM	1.07	0.91	1.09
SPD MAX	16.0	18.8	20.1				
NUM CALM	0	0	45				

--- CMOD 7 Number: 2707

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	5.1	6.2	6.6	SPD BIAS	-1.1	-1.5	-0.5
SD SPD	3.2	2.5	2.5	SPD RMS	2.1	2.4	1.7
				SPD CORR	0.82	0.82	0.79
				DIR RMS	32	39	25
				VECT CORR	0.90	0.87	0.92
				FOM	0.99	0.84	1.10
SPD MAX	18.5	18.8	20.1				
NUM CALM	0	0	29				

--- ESA Number: 2556

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	5.8	6.1	6.6	SPD BIAS	-0.3	-0.8	-0.5
SD SPD	2.4	2.5	2.5	SPD RMS	1.4	1.7	1.7
				SPD CORR	0.84	0.82	0.79
				DIR RMS	62	63	27
				VECT CORR	0.78	0.76	0.91
				FOM	0.78	0.72	1.10
SPD MAX	16.6	18.8	20.1				
NUM CALM	0	0	20				

Table 5b
TRANSFER FUNCTION RANKINGS

NDBC Mid-latitude, High-Seas, Summer Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Date 93 09 09 - 93 10 31 and 94 05 01 - 94 09 09

	CMOD4	CMOD5I	CMOD5L	CMOD6	CMOD7	ESA
SPD BIAS	2	1	5	4	4	2
SPD RMS	1	1	5	4	6	1
SPD CORR	2	1	2	6	3	3
DIR RMS	1	3	1	4	5	6
VECT CORR	1	1	4	3	4	6
FOM	1	1	3	3	5	6

TABLE 6a
BUOYS VS TRANSFER FUNCTION WIND STATISTICS

TOGA Tropical, High-Seas, Winter Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Date 93 11 01 - 94 04 31

--- CMOD 4 Number: 1965

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.0	6.3	6.6	SPD BIAS	-0.3	-0.6	-0.2
SD SPD	2.4	2.2	2.4	SPD RMS	1.6	1.7	1.5
				SPD CORR	0.76	0.79	0.80
				DIR RMS	23	27	26
				VECT CORR	0.81	0.81	0.83
				FOM	1.17	1.10	1.22
SPD MAX	14.3	14.0	13.3				
NUM CALM	0	0	25				

--- CMOD 5I Number: 1942

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	7.0	6.3	6.6	SPD BIAS	0.7	0.4	-0.2
SD SPD	2.7	2.1	2.3	SPD RMS	1.8	1.6	1.5
				SPD CORR	0.79	0.81	0.80
				DIR RMS	25	29	26
				VECT CORR	0.82	0.82	0.83
				FOM	1.06	1.05	1.22
SPD MAX	14.8	14.0	13.3				
NUM CALM	0	0	25				

--- CMOD 5L Number: 1938

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	5.2	6.3	6.6	SPD BIAS	-1.1	-1.4	-0.3
SD SPD	2.8	2.1	2.3	SPD RMS	2.1	2.2	1.5
				SPD CORR	0.77	0.79	0.80
				DIR RMS	25	30	26
				VECT CORR	0.79	0.79	0.83
				FOM	1.02	0.95	1.22
SPD MAX	14.5	14.0	13.3				
NUM CALM	0	0	25				

--- CMOD 6 Number: 1940

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	5.1	6.3	6.6	SPD BIAS	-1.2	-1.5	-0.2
SD SPD	2.5	2.2	2.4	SPD RMS	2.1	2.3	1.5
				SPD CORR	0.71	0.73	0.80
				DIR RMS	28	31	26
				VECT CORR	0.78	0.77	0.83
				FOM	0.99	0.92	1.22
SPD MAX	13.9	14.0	13.3				
NUM CALM	0	0	25				

--- CMOD 7 Number: 1897

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	5.8	6.3	6.7	SPD BIAS	-0.5	-0.8	-0.3
SD SPD	3.1	2.1	2.3	SPD RMS	2.1	2.1	1.5
				SPD CORR	0.77	0.80	0.79
				DIR RMS	29	33	25
				VECT CORR	0.80	0.80	0.83
				FOM	0.97	0.93	1.22
SPD MAX	15.7	14.0	13.3				
NUM CALM	0	0	25				

--- ESA Number: 1900

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.1	6.3	6.6	SPD BIAS	-0.2	-0.5	-0.3
SD SPD	2.2	2.1	2.3	SPD RMS	1.5	1.5	1.5
				SPD CORR	0.78	0.79	0.79
				DIR RMS	48	48	26
				VECT CORR	0.67	0.68	0.82
				FOM	0.86	0.86	1.22
SPD MAX	14.6	14.0	13.3				
NUM CALM	0	0	25				

Table 6b
TRANSFER FUNCTION RANKINGS

TOGA Tropical, High-Seas, Winter Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Date 93 11 01 - 94 04 31

	CMOD4	CMOD5I	CMOD5L	CMOD6	CMOD7	ESA
SPD BIAS	3	1	5	6	4	2
SPD RMS	3	2	5	6	4	1
SPD CORR	3	1	3	6	2	3
DIR RMS	1	2	3	4	5	6
VECT CORR	2	1	4	5	3	6
FOM	1	2	3	5	4	6

TABLE 7a

BUOYS VS TRANSFER FUNCTION WIND STATISTICS

TOGA Tropical, High-Seas, Summer Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Date 93 09 09 - 93 10 31 and 94 05 01 - 94 09 09 4

--- CMOD 4 Number: 1446

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.1	6.3	6.5	SPD BIAS	-0.1	-0.3	-0.2
SD SPD	2.0	1.7	1.8	SPD RMS	1.9	1.4	1.8
				SPD CORR	0.50	0.78	0.51
				DIR RMS	21	28	27
				VECT CORR	0.76	0.69	0.74
				FOM	1.16	1.07	1.07
SPD MAX	19.4	11.2	17.7				
NUM CALM	0	0	0				

--- CMOD 5I Number: 1447

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	7.1	6.3	6.5	SPD BIAS	0.9	0.6	-0.2
SD SPD	2.3	1.7	1.8	SPD RMS	2.1	1.5	1.8
				SPD CORR	0.57	0.78	0.51
				DIR RMS	20	29	27
				VECT CORR	0.77	0.70	0.74
				FOM	1.13	0.99	1.07
SPD MAX	19.4	11.2	17.7				
NUM CALM	0	0	0				

--- CMOD 5L Number: 1441

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	5.3	6.3	6.5	SPD BIAS	-1.0	-1.2	-0.2
SD SPD	2.4	1.7	2.8	SPD RMS	2.3	2.0	1.8
				SPD CORR	0.55	0.77	0.50
				DIR RMS	21	29	26
				VECT CORR	0.75	0.67	0.74
				FOM	1.09	0.95	1.07
SPD MAX	19.0	11.2	17.7				
NUM CALM	0	0	0				

--- CMOD 6 Number: 1435

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	5.3	6.3	6.5	SPD BIAS	-1.0	-1.2	-0.2
SD SPD	2.0	1.7	1.8	SPD RMS	2.2	1.9	1.8
				SPD CORR	0.45	0.73	0.51
				DIR RMS	24	31	27
				VECT CORR	0.73	0.68	0.74
				FOM	1.03	0.95	1.06
SPD MAX	17.0	11.2	17.7				
NUM CALM	0	0	0				

--- CMOD 7 Number: 1431

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.0	6.3	6.5	SPD BIAS	-0.3	-0.5	-0.2
SD SPD	2.6	1.7	1.8	SPD RMS	2.3	1.8	1.8
				SPD CORR	0.52	0.77	0.50
				DIR RMS	26	33	26
				VECT CORR	0.73	0.68	0.74
				FOM	0.97	0.91	1.07
SPD MAX	20.8	11.2	17.7				
NUM CALM	0	0	0				

--- ESA   Number: 1294

	SAT	MOD	BUOY		SAT - MOD	SAT - BUOY	MOD - BUOY
MEAN SPD	6.2	6.3	6.5	SPD BIAS	-0.1	-0.3	-0.2
SD SPD	2.0	1.7	1.8	SPD RMS	1.8	1.3	1.8
				SPD CORR	0.53	0.80	0.50
				DIR RMS	44	44	26
				VECT CORR	0.69	0.64	0.75
				FOM	0.88	0.92	1.08
SPD MAX	20.0	11.2	17.7				
NUM CALM	0	0	0				

Table 7b

TRANSFER FUNCTION RANKINGS

TOGA Tropical, High-Seas, Summer Data
Space Box: 0.5 degree, Time Window: +/- 3 hours
Date 93 09 09 - 93 10 31 and 94 05 01 - 94 09 09 4

	CMOD4	CMOD5I	CMOD5L	CMOD6	CMOD7	ESA
SPD BIAS	1	4	5	5	3	1
SPD RMS	2	3	6	5	4	1
SPD CORR	2	2	4	6	4	1
DIR RMS	1	2	2	4	5	6
VECT CORR	2	1	5	3	3	6
FOM	1	2	3	3	6	5

RESULTS AND CONCLUSIONS.

The statistics used to determine the performance of the scatterometer backscatter-to-wind transfer functions evaluated in this study are presented in Table 3a and the rankings are presented in table 3b, for the high-seas data. These tables show that two of the transfer functions CMOD4 (ECMWF) and CMOD5I (IFREMER) performed better than the other three. The fixed buoy data are used as the reference "sea truth", and the final decision of choosing an algorithm for operational implementation is based on the comparisons made from examining the satellite versus buoy data (the middle column for the second sets of statistics). The data were further subdivided to determine seasonal and regional differences, which are presented in Tables 4, 5, 6 and 7.

However, it should be observed that the satellite NMC versus model analysis comparisons are almost the same as the buoy versus satellite. This is probably because the satellite scatterometer may be measuring space scale closer to the analysis than the buoy. There is a small negative speed bias for CMOD4 whereas, CMOD5I is high by about the same amount. Both CMOD4 and CMOD5I have a speed RMS of 1.8 m/s which is well within the defined specification of 2 m/s (or 10%, whichever is higher). The other transfer functions have RMS's above 2 m/s. Both these models are slightly better than the NMC model wind speed versus buoy wind speed comparisons, whereas CMOD5L, CMOD6 and CMOD7 are worse. The direction statistics of CMOD4 and CMOD5I are slightly better with RMS's in the low 30 degrees range which is poorer than the ERS-1 specification of 20 degrees. However, this is in part due to using all wind speed data, except calm speeds, and larger time and space windows. In a wind study of this type, it is important to know the performance at high winds, but it was found that the maximum buoy wind speed used in the matchups, for the entire year that data was collected, was only 21.7 m/s (42 kts). Thus, little can be stated about how well the wind algorithms perform at high wind from this study..

The ESA FD wind speed statistics are similar to the NMC processing with CMOD4, which is not unexpected since its transfer function is the same. But, the high RMS of direction comparisons of 57 degrees and and the low vector correlation (0.71) from the ESA processed winds clearly shows that there are directional problems in the data.

Table 3b presents the ranking of all the high-seas data, with CMOD5I being slightly better than CMOD4 when comparing different parameter categories. The statistics chosen varied in their ability as discriminators because of their range, but the poorest was definitely the speed correlation coefficient which had a narrow range of only 0.77 to 0.80. However, when the Figure of Merit between CMOD4 and CMOD5I are compared, CMOD4 ranks slightly ahead of CMOD5I. As noted earlier, the Figure of Merit is defined as a composite type of statistic which measures how close the satellite derived wind speeds and directions meet instrument specifications overall.

Now, when the data are separated by regions and seasons CMOD4 is as good as CMOD5I. The NDBC mid-latitude buoy and satellite comparisons show that the winter statistics (Table 4a) are not as good as summer statistics (Table 5a), i. e., the RMS for both speed and direction are lower in summer, but, this is mainly due to lower wind speeds during the summer. The low biases are larger for the summer months, suggesting that the transfer functions provide winds with a low bias at low wind speeds. Also of interest, the statistics of satellite versus NMC model data are in all categories just slightly better than the statistics of satellite versus buoys data, for both summer and winter suggesting that in general one can not expect much impact with the scatterometer wind data over the northern hemisphere. However, their greater impact will come in specific case studies, which is the subject of a separate paper. The rankings show that for the mid-latitude buoys the performance of the CMOD4 and CMOD5I transfer functions are the better functions and there is little indication on seasonal dependence.

The TOGA buoy and satellite comparisons show that there are small differences in the statistics between winter (Table 6a) and summer (Table 7a). The mean speed remains about the same, but the range of wind speeds is higher for the winter than for summer, and, surprisingly there were no calm reports from the buoys during summer. The satellite versus model statistics are almost the same as the satellite versus buoy statistics for winter, but for summer they are poorer, indicating that the scatterometer wind data will improve the tropical analyses. Again the rankings (tables 6b and 7b) show CMOD4 and CMOD5I perform better, suggesting that the transfer functions are not regionally dependent.

Figure 7a shows a plot of the data as they are received from ESA and figure 7b shows a plot of the processed wind data after the NMC procedures are applied to the raw satellite data. Clear improvements in scatterometer wind direction accuracy have resulted from NMC processing and quality control.

THEREFORE, based upon the results of this study and the use by other operational meteorological centers, NMC started using the CMOD4 transfer function within its scatterometer satellite data processing system to generate "real-time" ocean surface wind vectors in September 1994 (Peters et al, 1994b). The internal use of these data in the operational analyses and forecasts systems will begin soon.

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Appendix A

Scatterometer σ°-to-Wind Transfer Function Models

The following five σ° to wind transfer functions were examined by means of comparisions of derived winds compared to buoy winds at a reference level of 10 meters above the sea surface, where:

U = wind speed at 10 m height above the sea surface and corrected for moisture and heat fluxes

φ = $\chi - \varphi_w$ where χ is the antenna look angle of the scatterometer antenna with respect to North and φ_w is the wind direction

θ is the incidence angle, the angle difference between ERS1 nadir and scaterometer measurement cell location at the sea surface

1) CMOD4 (ECMWF);

$$\sigma^o_{linear} = b_o b_r (1 + b_1 \cos\varphi + b_3 \tanh(b_2) \cos 2\varphi)^{1.6}$$

$$where \quad b_o = 10^{\alpha + \gamma \times F1\ (U + \beta)}$$

and,

$$F1\ (y) = \begin{cases} 0 & if \quad y \leq 0 \\ 10 \log(y) & if \quad 0 < y \leq 5 \\ (\sqrt{y})/3.2 & if \quad y > 5 \end{cases}$$

α, β and γ are expanded as Legendre polynomials of only θ

b_1, b_2 and b_3, however, are expanded as Legendre polynomials of both U and θ

b_r is a residual factor as a function of θ from 16 to 60 degrees given in table format

The Legendre polynomials are expanded to a total of 18 coefficients.

2) CMOD5I (IFREMER) and

3) CMOD5L (ESA) are both defined as:

$$\sigma^o_{linear} = b_0 (1 + b_1 \cos\varphi + b+_2 \cos 2\varphi)$$

where $b_0 = 10^{\alpha+\beta\sqrt{u}-\delta}$

α, β and δ are expanded as Legendre polynomials of only θ

b_1 and b_2, however, are expanded as Legendre polynomials of both U and θ

The Legendre polynomials are expanded to a total of 22 coefficients. The two models used a different set of coefficients.

4) CMOD6 (Univ. of Hamburg)

$$\sigma^o_{linear} = b_0 + b_1 \cos\varphi + b_2 \cos\varphi$$

where $b_i = \alpha_i U^{\gamma i}$, $i = 0, 1, 2$

α and γ are expanded as ordinary polynomials of θ to a total of 18 coefficients

5) CMOD7 (Univ. of Oregon State):

$$\sigma^o_{linear} = b_0 + b_1 \cos\varphi + b_2 \cos 2\varphi$$

where

the coefficients b_0, b_1, and b_2 are all entries within a (LUT) as a function of U and θ in increments of:

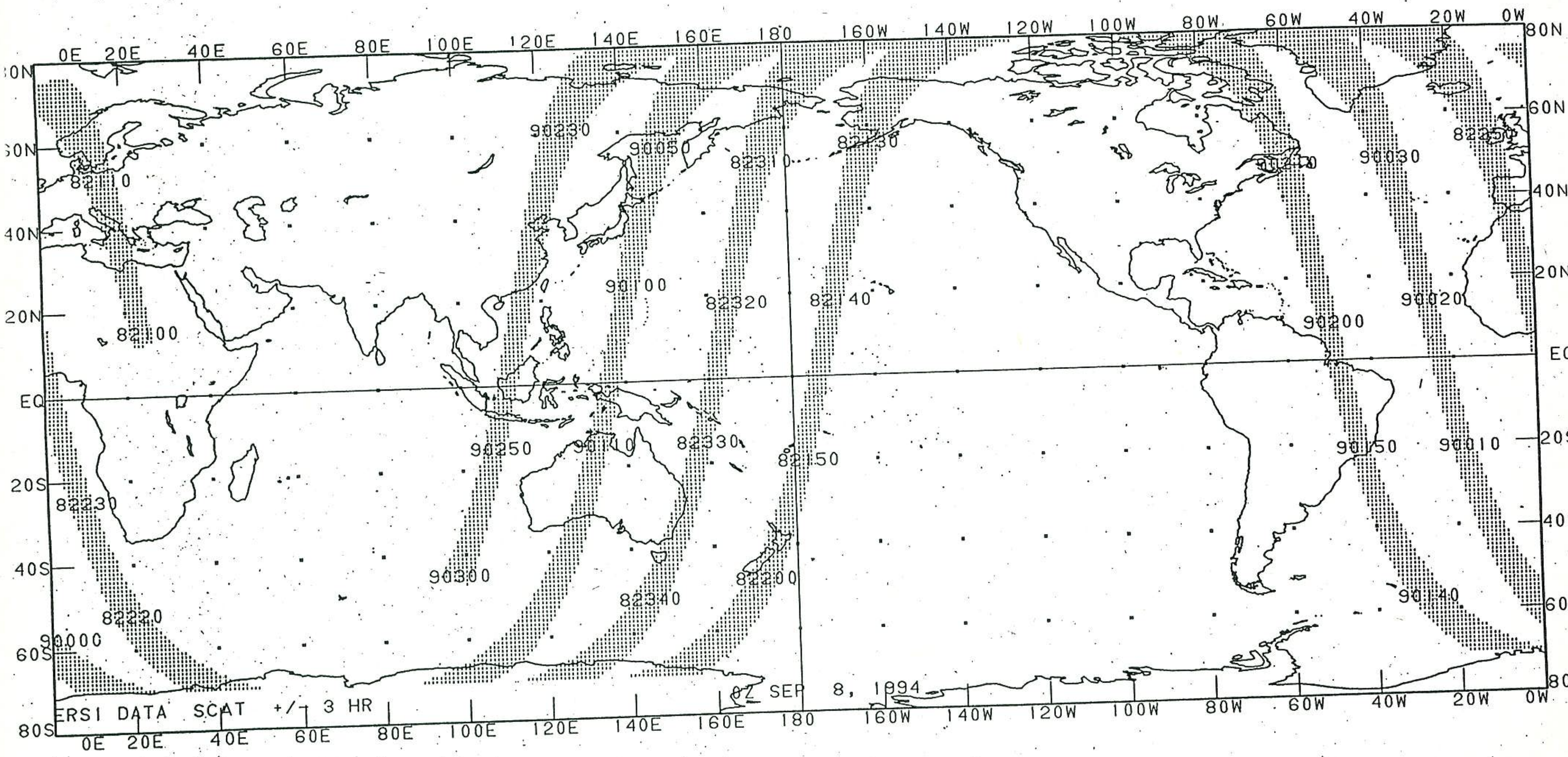
$1\ ms^{-1}$ for U from 1 to 25 ms^{-1}
2^0 for θ from 16 deg. to 58 deg.

The formulations, assumptions, or bases that provide the 1650 entries of b_0, b_1, and b_2 in the look-up table (LUT) are unknown.

* ESA SATELLITE (ERS1)

- Scatterometer
    - wind speed and direction data
    - Active microwave - 3 antennae
    - 102 Minute Orbit
    - 500 km Swath
    - 50 km "footprint"
    - 10 m height
    - speed range 4 to 24 m/s
    - speed accuracy ±2 m/s (or 10% above 20 m/s)
    - direction accuracy ±20°

Table 1. ERS-1 Scatterometer Instrument Specification



ERSI DATA SCAT +/- 3 HR

0Z SEP 8, 1994

FIGURE 1. Orbital coverage for the ERS-1 satellite, for a 6 hour period.

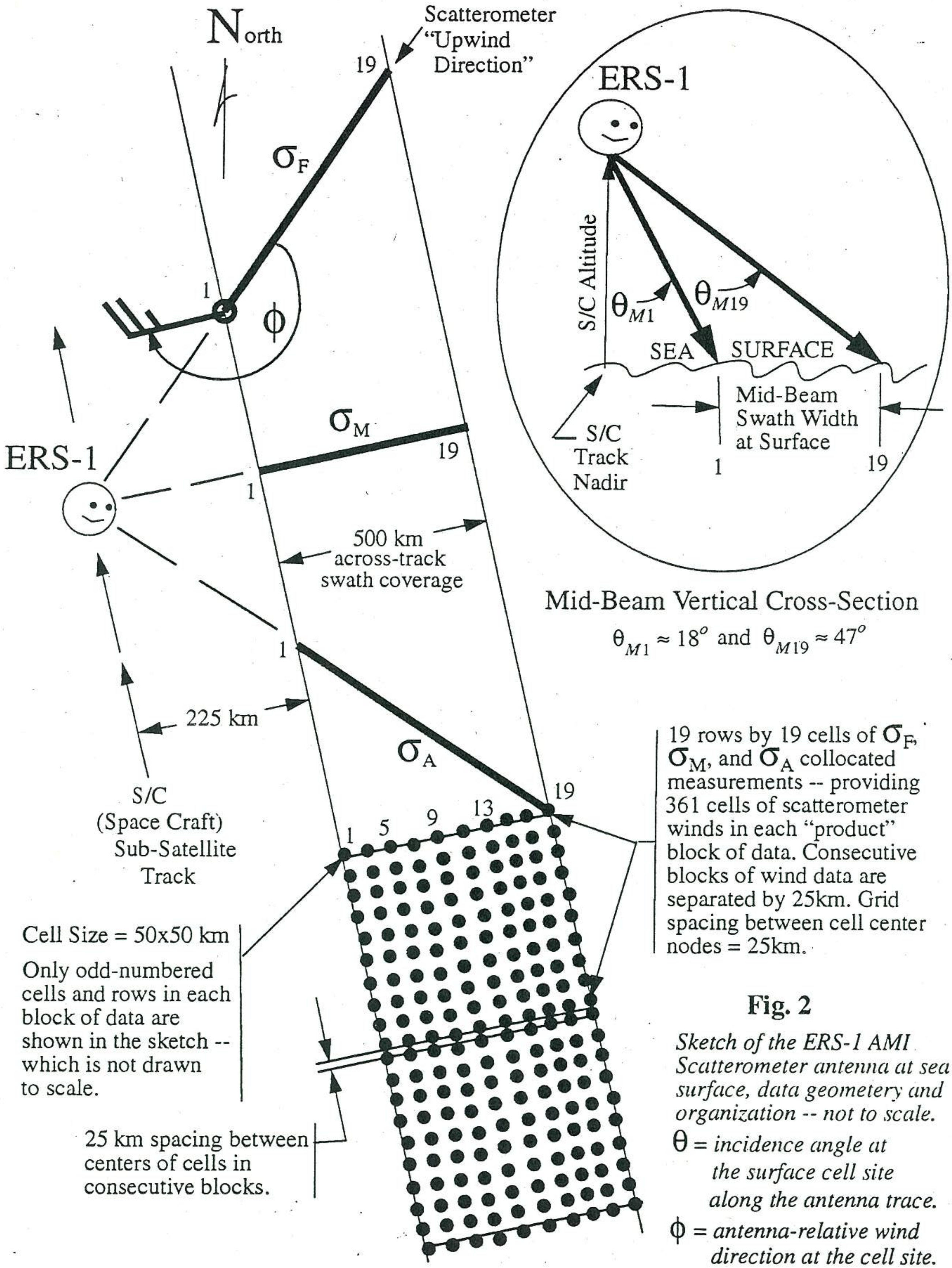


Fig. 2

Sketch of the ERS-1 AMI Scatterometer antenna at sea surface, data geometery and organization -- not to scale.

θ = *incidence angle at the surface cell site along the antenna trace.*

ϕ = *antenna-relative wind direction at the cell site.*

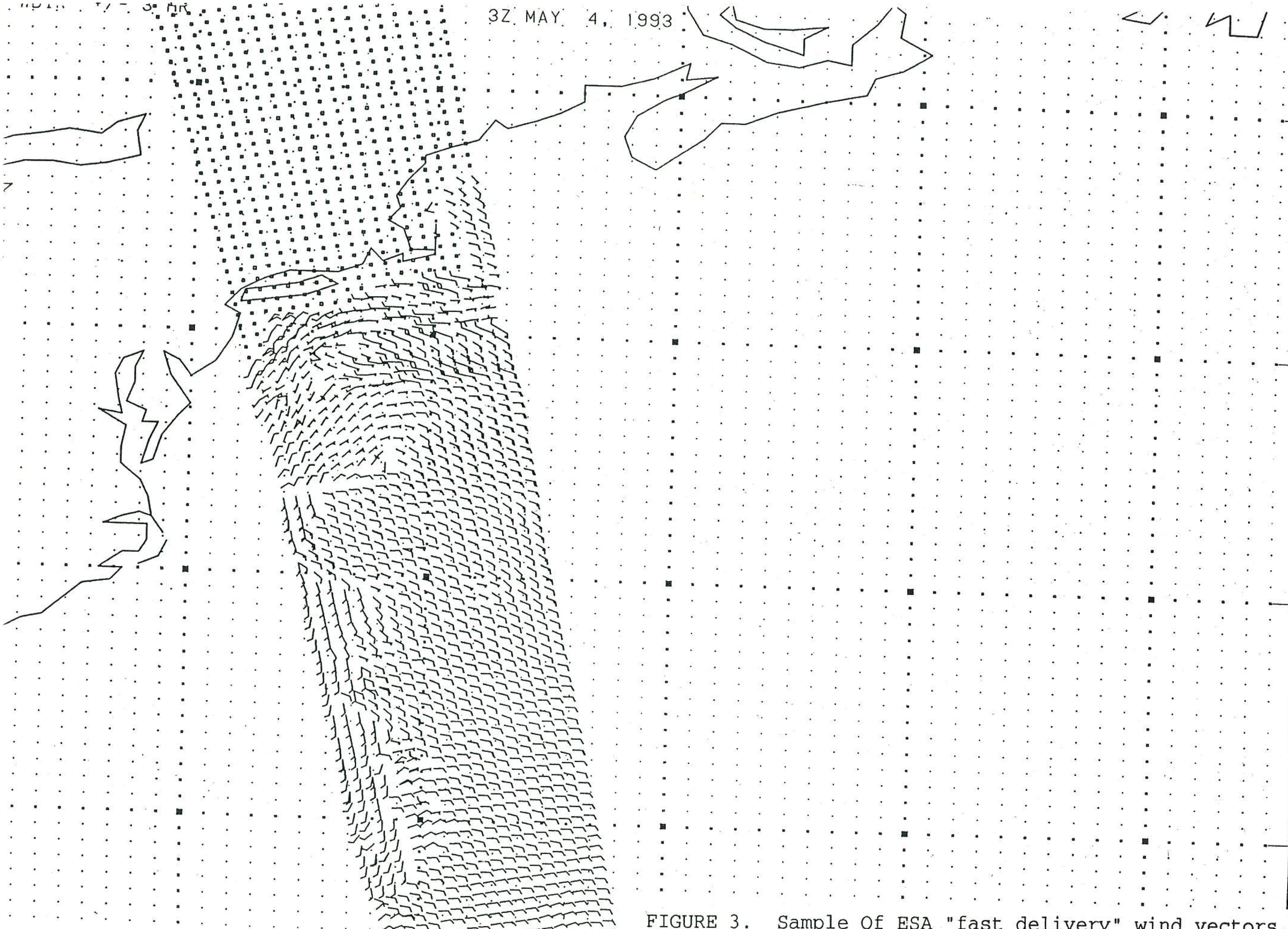


FIGURE 3. Sample Of ESA "fast delivery" wind vectors, with no quality control.

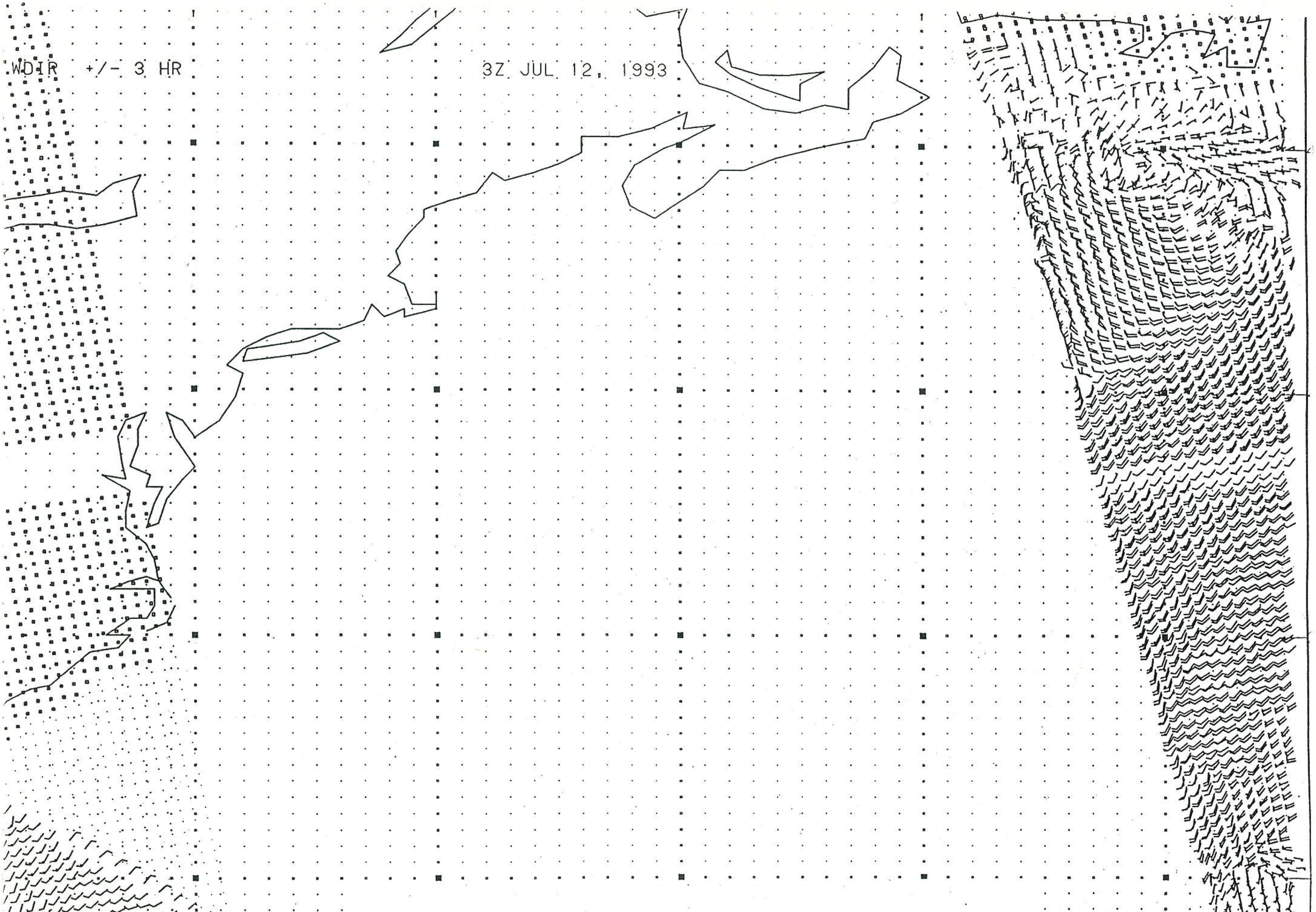


FIGURE 4. Sample of ESA "fast delivery" wind vectors, duplicate reports, before quality control.

****** ERS-1 DATA INGESTED REPORT ON 94249 0301 ******

NO	INGESTED TIME	DSN	PROD CNT	TIME GAP
1	09/05/94 03.04.56	NSS.UWIX.E1.D940905.S0027.E0040	13	2:37
2	09/05/94 03.15.31	NSS.UWIX.E1.D940905.S0041.E0042	2	2:34
3	09/05/94 03.27.07	NSS.UWIX.E1.D940905.S0043.E0043	1	2:44
4	09/05/94 03.47.44	NSS.UWIX.E1.D940905.S0046.E0046	1	3: 1
5	09/05/94 04.29.58	NSS.UWIX.E1.D940905.S0047.E0047	1	3:42
6	09/05/94 04.44.31	NSS.UWIX.E1.D940905.S0048.E0048	1	3:56
7	09/05/94 05.18.50	NSS.UWIX.E1.D940905.S0049.E0116	23	4:29
8	09/05/94 05.29.01	NSS.UWIX.E1.D940905.S0104.E0143	35	4:25
9	09/05/94 05.41.21	NSS.UWIX.E1.D940905.S0144.E0218	30	3:57
10	09/05/94 05.50.34	NSS.UWIX.E1.D940905.S0219.E0248	38	3:31
11	09/05/94 05.59.01	NSS.UWIX.E1.D940905.S0249.E0315	24	3:10
12	09/05/94 06.09.01	NSS.UWIX.E1.D940905.S0316.E0340	21	2:53
13	09/05/94 06.21.33	NSS.UWIX.E1.D940905.S0341.E0352	10	2:40
14	09/05/94 06.32.18	NSS.UWIX.E1.D940905.S0352.E0410	16	2:40
15	09/05/94 06.42.55	NSS.UWIX.E1.D940905.S0411.E0431	18	2:31
16	09/05/94 06.52.05	NSS.UWIX.E1.D940905.S0433.E0434	2	2:19
17	09/05/94 12.46.06	NSS.UWIX.E1.D940905.S0639.E0643	4	6: 7
18	09/05/94 12.53.26	NSS.UWIX.E1.D940905.S0644.E0702	16	6: 9
19	09/05/94 13.34.05	NSS.UWIX.E1.D940905.S0703.E0711	8	6:31
20	09/05/94 12.31.52	NSS.UWIX.E1.D940905.S0712.E0736	21	5:19
21	09/05/94 12.41.37	NSS.UWIX.E1.D940905.S0737.E0754	15	5: 4
22	09/05/94 12.35.36	NSS.UWIX.E1.D940905.S0755.E0805	9	4:40
23	09/05/94 16.17.09	NSS.UWIX.E1.D940905.S0843.E0853	10	7:34
24	09/05/94 16.28.23	NSS.UWIX.E1.D940905.S0855.E0946	44	7:33
25	09/05/94 16.40.29	NSS.UWIX.E1.D940905.S0947.E1159	26	6:53
26	09/05/94 13.43.58	NSS.UWIX.E1.D940905.S1000.E1000	1	3:43
27	09/05/94 13.55.05	NSS.UWIX.E1.D940905.S1001.E1005	4	3:54
28	09/05/94 14.06.38	NSS.UWIX.E1.D940905.S1006.E1012	6	4: 0
29	09/05/94 14.09.21	NSS.UWIX.E1.D940905.S1013.E1019	6	3:56
30	09/05/94 14.23.09	NSS.UWIX.E1.D940905.S1020.E1024	4	4: 3
31	09/05/94 14.32.58	NSS.UWIX.E1.D940905.S1025.E1026	2	4: 7
32	09/05/94 14.44.45	NSS.UWIX.E1.D940905.S1027.E1030	3	4:17
33	09/05/94 14.57.02	NSS.UWIX.E1.D940905.S1031.E1036	5	4:26
34	09/05/94 15.07.47	NSS.UWIX.E1.D940905.S1037.E1045	8	4:30
35	09/05/94 15.18.33	NSS.UWIX.E1.D940905.S1047.E1101	13	4:31
36	09/05/94 15.30.03	NSS.UWIX.E1.D940905.S1102.E1116	13	4:28
37	09/05/94 15.41.29	NSS.UWIX.E1.D940905.S1117.E1122	5	4:24
38	09/05/94 15.53.15	NSS.UWIX.E1.D940905.S1123.E1128	5	4:30
39	09/05/94 16.03.48	NSS.UWIX.E1.D940905.S1129.E1134	5	4:34
40	09/05/94 16.49.23	NSS.UWIX.E1.D940905.S1200.E1246	39	4:49
41	09/05/94 16.56.43	NSS.UWIX.E1.D940905.S1247.E1318	27	4: 9
42	09/05/94 17.05.40	NSS.UWIX.E1.D940905.S1319.E1319	1	3:46
43	09/05/94 17.15.28	NSS.UWIX.E1.D940905.S1320.E1332	11	3:55
44	09/05/94 17.26.29	NSS.UWIX.E1.D940905.S1333.E1344	10	3:53
45	09/05/94 17.36.32	NSS.UWIX.E1.D940905.S1345.E1358	12	3:51
46	09/05/94 17.46.42	NSS.UWIX.E1.D940905.S1400.E1414	13	3:46
47	09/05/94 17.57.04	NSS.UWIX.E1.D940905.S1415.E1431	14	3:42
48	09/05/94 18.08.23	NSS.UWIX.E1.D940905.S1432.E1450	16	3:36
49	09/05/94 18.19.02	NSS.UWIX.E1.D940905.S1452.E1458	6	3:27
50	09/05/94 18.28.37	NSS.UWIX.E1.D940905.S1459.E1504	5	3:29
51	09/05/94 18.39.05	NSS.UWIX.E1.D940905.S1505.E1518	12	3:34
52	09/05/94 18.49.50	NSS.UWIX.E1.D940905.S1519.E1522	3	3:30
53	09/05/94 19.00.24	NSS.UWIX.E1.D940905.S1523.E1531	8	3:37
54	09/05/94 19.10.52	NSS.UWIX.E1.D940905.S1532.E1539	7	3:38
55	09/05/94 19.21.19	NSS.UWIX.E1.D940905.S1541.E1549	8	3:40
56	09/05/94 19.31.12	NSS.UWIX.E1.D940905.S1550.E1556	6	3:41
57	09/05/94 19.43.19	NSS.UWIX.E1.D940905.S1557.E1607	9	3:46

FIGURE 5. Sample listing of data delivery time and delay at the NMC computer system. Time gap is shown in last column

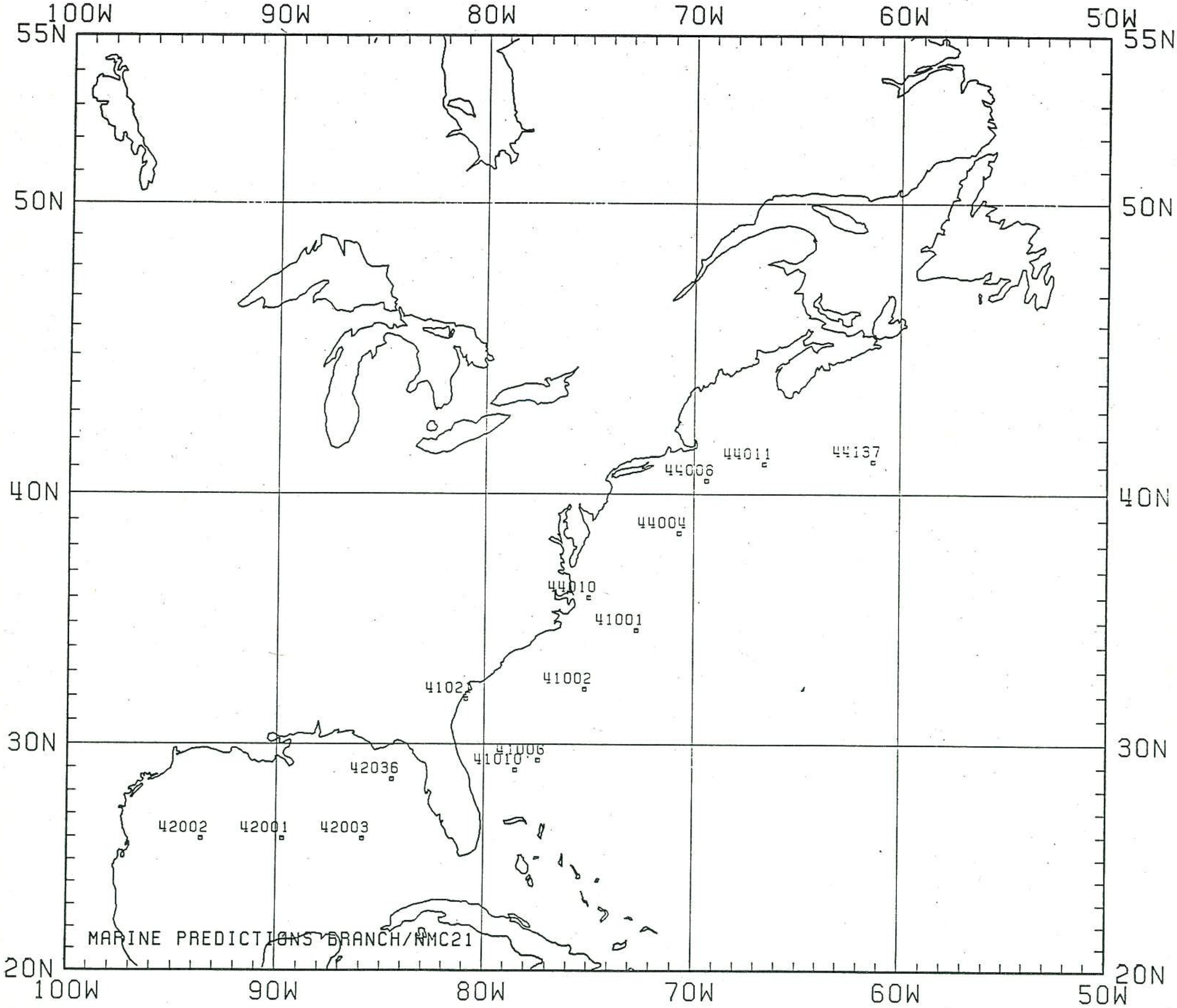


Figure 6a Location of NDBC fixed buoys over the Northwest Atlantic Ocean and Gulf of Mexico used for verification.

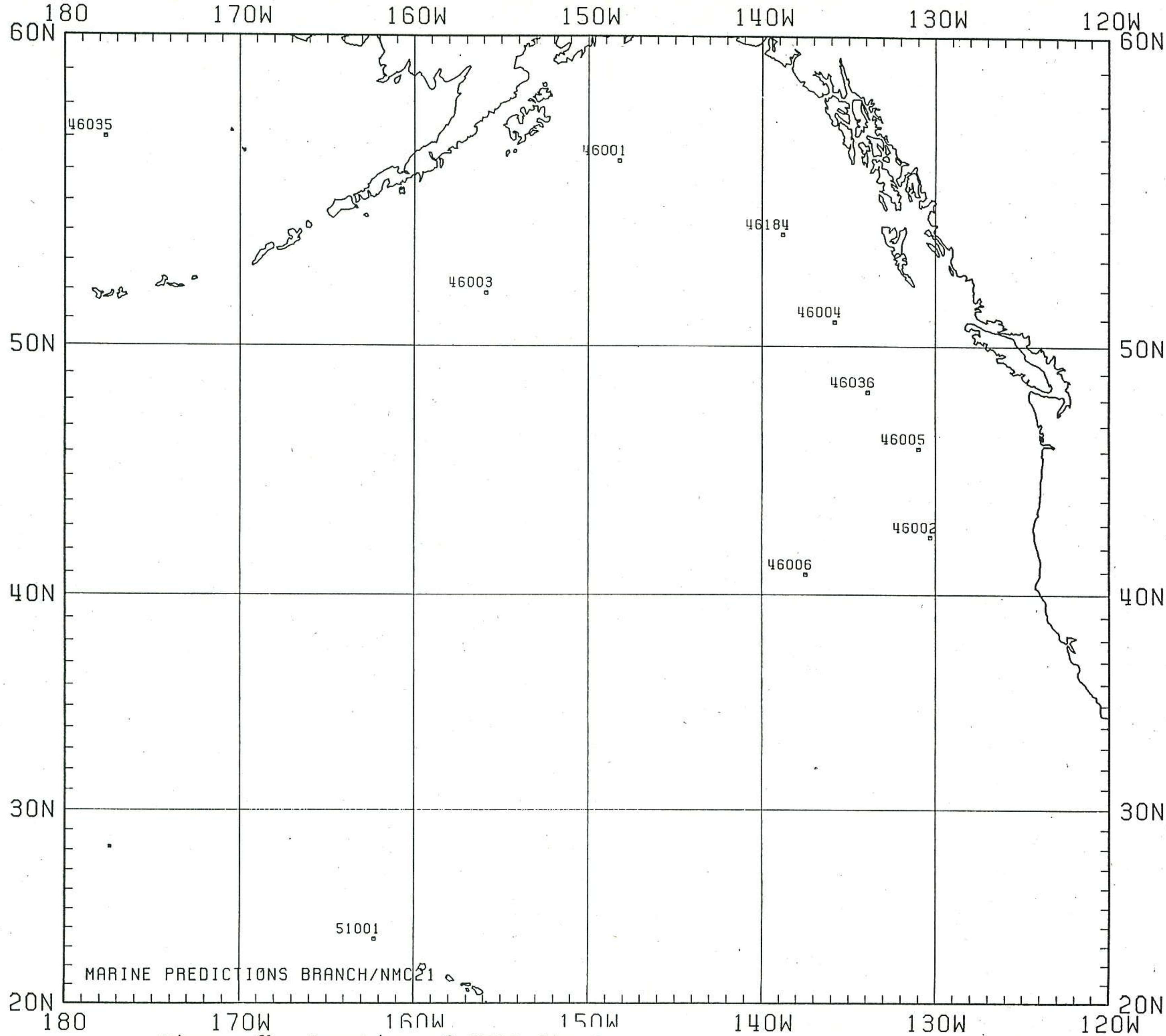


Figure 6b Location of NDBC fixed buoys over the Northeast Pacific Ocean used for verification.

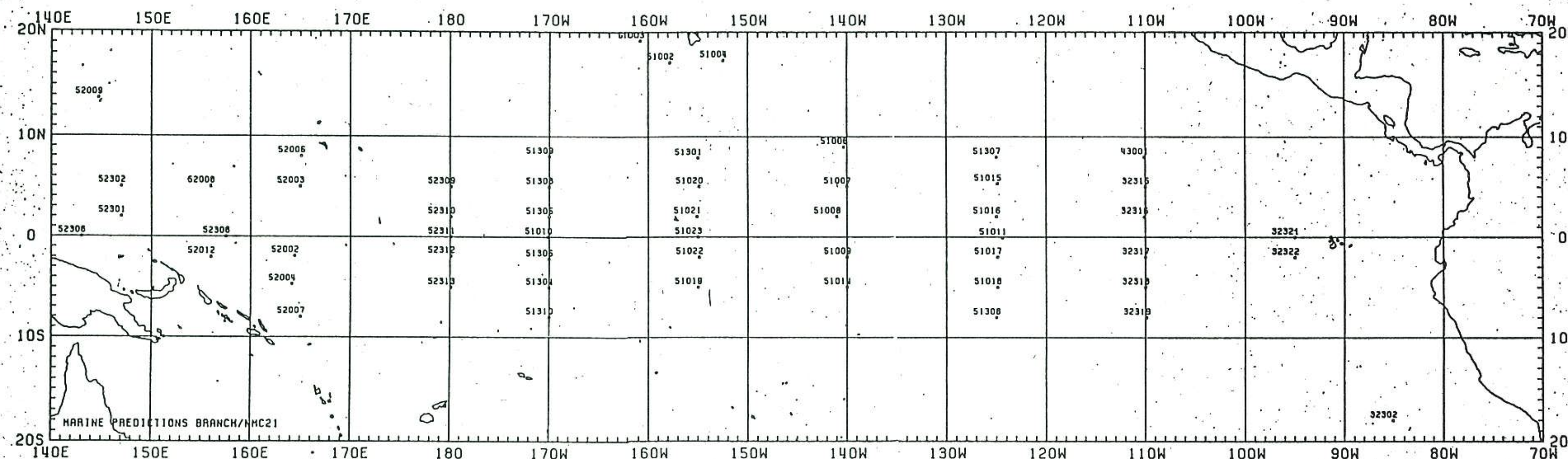


Figure 6c Location of TOGA fixed buoys over the Tropical Pacific Ocean used for verification.

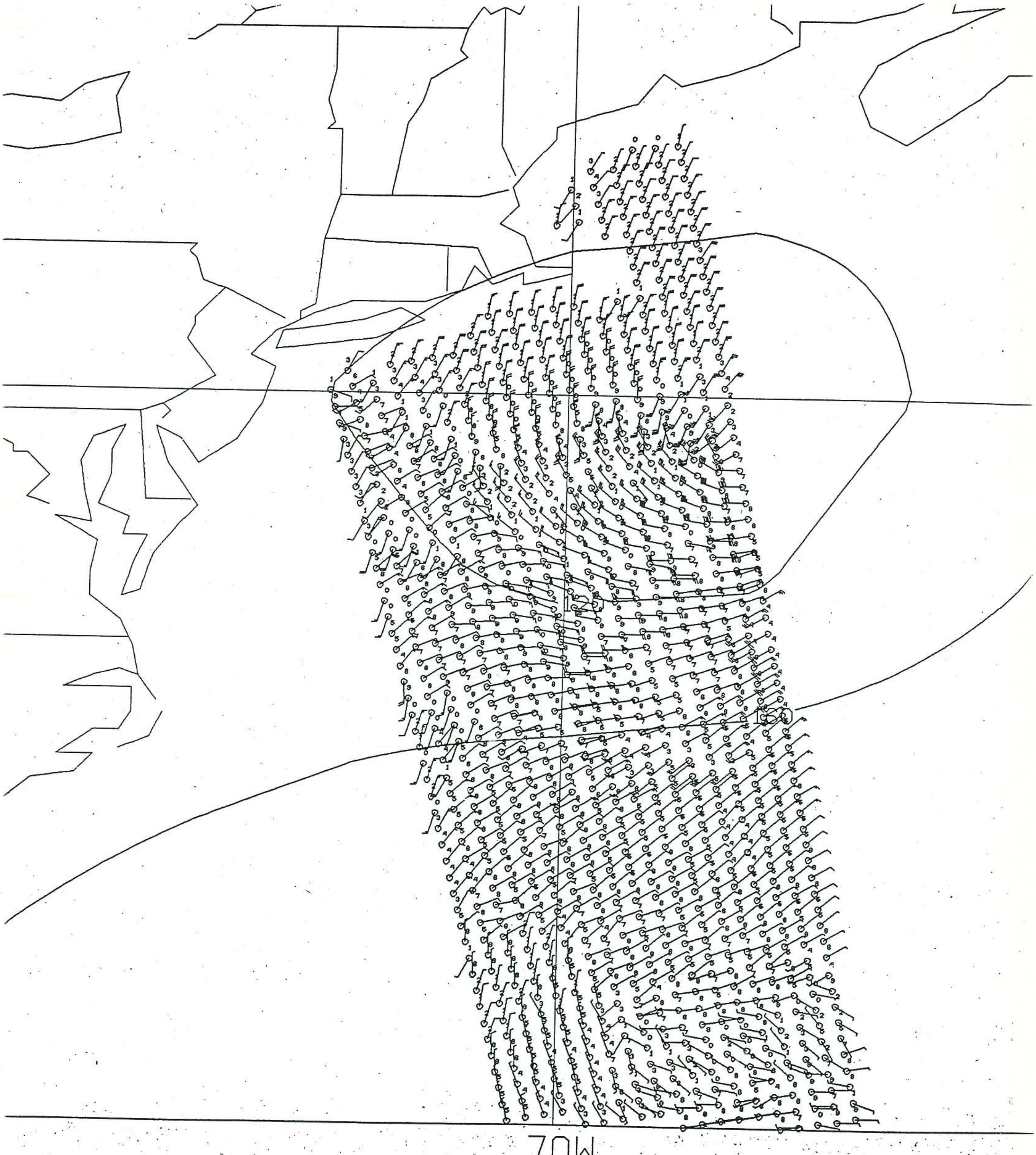


Figure 7a. ESA Fast Delivery Scatterometer Wind Data for 06 UTC, September 2, 1993.

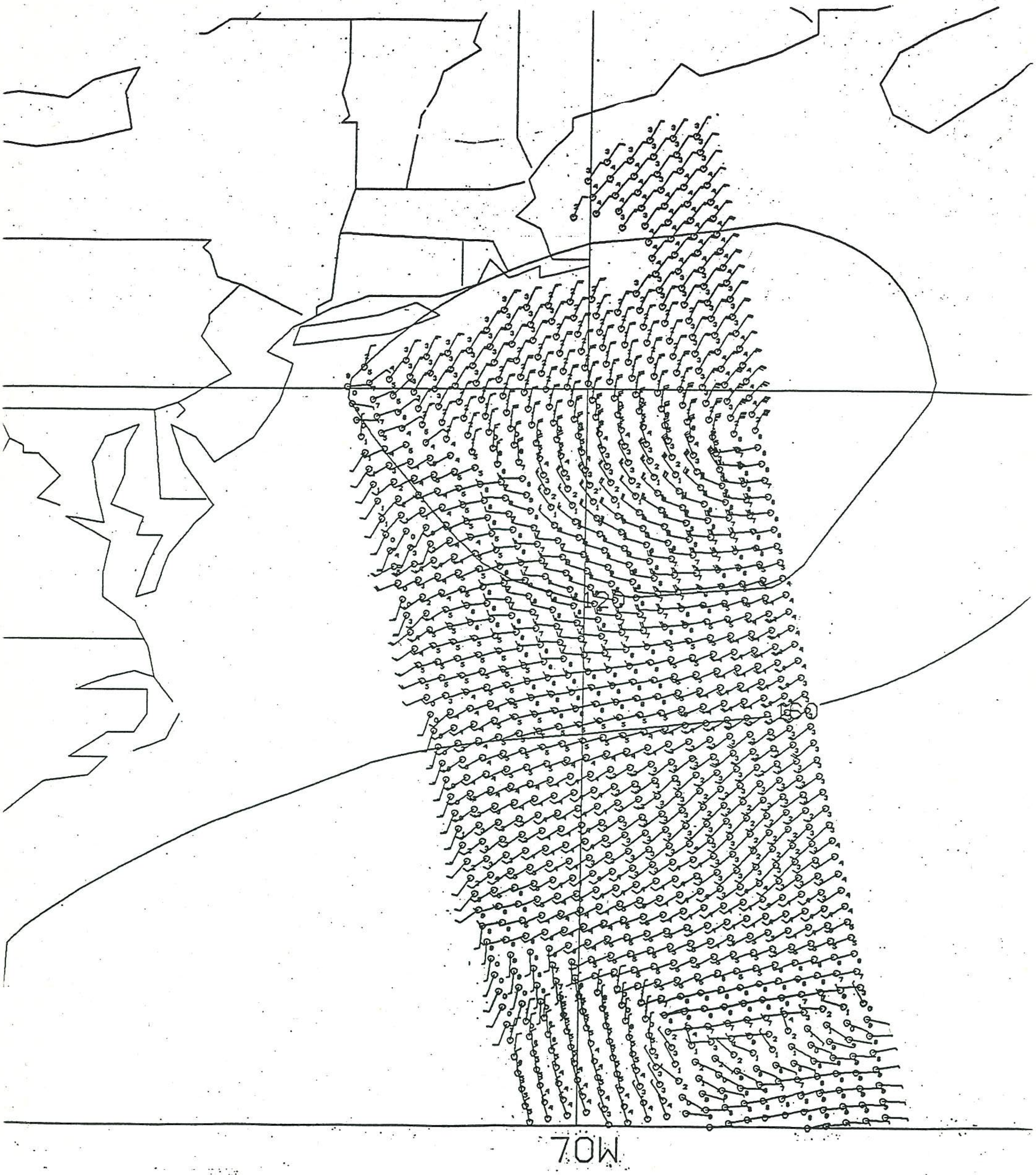


Figure 7b. NMC Processed Scatterometer Wind Data for 06 UTC, September 2, 1993.

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