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TECHNICAL NOTE

HIGH-RESOLUTION OCEAN SURFACE WIND ANALYSES USING SATELLITE DERIVED OCEAN SURFACE WINDS: ANALYSIS VALIDATION USING SYNTHETIC SATELLITE 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.

No. 3. Auer, S. J., 1986: Determination of Errors in LFM Forecasts Surface Lows Over the Northwest Atlantic Ocean. Technical Note/NMC Office Note No. 313, 17pp.

No. 4. Rao, D. B., S. D. Steenrod, and B. V. Sanchez, 1987: A Method of Calculating the Total Flow from A Given Sea Surface Topography. NASA Technical Memorandum 87799., 19pp.

No. 5. Feit, D. M., 1986: Compendium of Marine Meteorological and Oceanographic Products of the Ocean Products Center. NOAA Technical Memorandum NWS NMC 68, 93pp.

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No. 8. Yu, T. W., 1987: A Technique of Deducing Wind Direction from Satellite Measurements of Wind Speed. Monthly Weather Review, 115, 1929-1939.

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1. INTRODUCTION

The need for accurate high-resolution regional and coastal ocean surface wind analyses is increasing with the arrival of high-resolution ocean modeling capabilities for: waves, circulation (currents), and storm surges (water levels). Fortunately, high-resolution (or meso-scale) ocean surface wind data, from several satellite systems, are now available in sufficient quantity to provide such support. However, the science of converting parameters measured from satellites into ocean surface winds is far from exact. It is necessary to be able to assess the impact of data from various satellites on wind analyses; and, to determine how to blend the data from these different satellite systems to produce accurate meso-scale ocean surface wind fields.

Currently, most ocean surface wind fields are available from global data assimilation systems. Even when satellite surface wind data are used in these analyses, the satellite data are made into "super-obs" at the scale of the model. A "super-ob" is simply the average of observations within the immediate neighborhood of a model grid point. But since the model resolution is less than that of the observation, the meso-scale wind information is lost through this process. Mullen (1994) compared objectively generated surface analyses (NCEP global model) over the North Pacific ocean with subjectively drawn analyses to show that the objective analyses not only misplace the locations of storm systems but also consistently underestimate their intensity. Therefore, an analysis technique is developed and tested to provide objective analyses of high-resolution ocean surface wind fields over selected U. S. coastal regions. This method is based on a reanalysis procedure in an attempt to regain some additional information from the observations which has been lost in the larger-scale global analysis system. This analysis is an extension of an earlier ocean surface wind analysis program (Gemmill, 1991). Those wind analyses were initially based on the reanalysis of real-time ocean surface wind data using ships, fixed buoys and coastal stations, on a high-resolution grid, with the initial wind analysis interpolated from the global data assimilation system (GDAS) at 2.5 X 2.5 latitude and longitude. This paper presents the methodology of the current technique which is based on a higher resolution initial grid of GDAS (at 1.0 X 1.0 latitude/longitude) and the incorporation of satellite data. An updated version of the analysis system was presented by Gemmill & Peters (1996).

Bumke and Hasse (1989) showed that it was possible to improve the resolution of a low-resolution global ocean surface wind analysis directly by reanalyzing surface observations of sea level pressure and surface wind. Sanders (1990) has pointed out that obtaining an accurate detailed sea level pressure analysis is no easy task, even when sufficient surface data (ERICA drifting buoys) are available. However, those studies were based on only direct surface measurements (buoys and ships), whereas today we have high-resolution (25km-50km) real-time wind data available over wide swaths from satellite borne sensors. The data now are available from four DMSP satellites using the SSM/I sensor to provide wind speed data across a 1500 km swath, and the ERS2 satellite using the scatterometer sensor to provide wind vectors across a 500 km swath.

2. THE DATA

In this report we will deal with the impact of synthetic satellite data on analyses to gain insights into the importance of the different satellite data sets. But, first we will review characteristics of the various data sets available for ocean surface weather analyses.

It is well known that in-situ ocean surface wind measurements are sparse. These data have been studied in some detail to determine their accuracy by Wilkerson and Earle (1990) and Pierson (1990). The basic conclusion of these studies is that ship data when compared to buoy data are not adequate for accurate analysis of the ocean wind field. In fact, whether the wind measurement was made by an anemometer or by visual procedures, the quality was about the same. Gilhousen (1987) reports that the buoy wind data, although not without some problems, are within the NDBC error specifications of 1 m/s or 10% for speed and 20 degrees for direction. Coastal stations can be used for analysis, but the exposure must be known. Some of these platforms sit over the water, while others may be on high cliffs at the water's edge. Unfortunately, there is no uniform height for wind measurements over the ocean. Buoy heights' range from 3.8 m to 14m, and ships somewhat higher at 20m, but that height depends on the size of the ship and its "load", and the problems with coastal stations have already been noted.

The DMSP satellite (SSM/I) provides wind speeds over periodic 102 minute polar orbits in swaths of 1500 km and at a horizontal resolution of 25 km and at a height of 20m above the sea. It is a passive microwave instrument (Table 1a). In mid-latitudes the satellite will pass over the same region twice a day on its ascending and descending passes. There are four SSM/I satellites (F10, F11, F13 & F14) which are in similar orbits. The "standard" SSMI wind algorithm, which converts brightness temperatures to wind speed through linear regression was calibrated to meet the error requirement for speed of 2 m/s or 10% (Goodberlet, Swift and Wilkerson, 1989). But, these SSMI wind speed data have two important limitations: winds cannot be measured 1) above 20 m/s and 2) for moderate moisture and rain events. Hence, an "all-weather" algorithm has been developed using the non-linear approach of neural networks (Krasnopolsky, Gemmill & Breaker, 1996). This algorithm gives improved wind speeds over the 5-25 m/s range for a wide range of moisture conditions.

The ERS2 satellite (with its scatterometer) provides wind vector data over periodic 102 minute polar orbits in swaths of 500 km, at a horizontal resolution of 50 km and at a height of 10m above the sea. This is an active microwave instrument (Table 1b). In mid-latitudes the satellite will pass over the same region twice a day on its ascending and descending passes. The "standard" scatterometer algorithm (which converts radar backscatter to wind speed through empirical functions) was calibrated to meet the error requirement for speed of 2 m/s or 10%, and for wind direction of 20 degrees. NCEP has been receiving the "fast-delivery" wind data from ESA in real-time for operational use. These wind speeds are of sufficient accuracy, but, the wind directions were found to lacking in accuracy when compared with buoys data. Since the raw radar backscatter data were also provided from ESA, NCEP processes these data to re-derive the wind speeds and directions (Peters et al, 1994) with substantial improvement in accuracy to the direction (Gemmill et al, 1994). In that study, we also compared various proposed transfer functions and showed that the transfer function (CMOD4) used by ESA was best for providing wind speeds.

Table 1. Satellite Specifications for SSM/I and Scatterometer Derived Ocean Surface Winds.

SATELLITE OCEAN SURFACE WIND SPECIFICATIONS

- POLAR ORBITER (102 MINUTES)

- TWICE DAILY AREAL COVERAGE
  (ONE ASCENDING & ONE DESCENDING PASS)

	ERS1/2	DMSP
SENSOR	SCATTEROMETER	SPECIAL SENSOR MICROWAVE / IMAGER
MODE	ACTIVE MICROWAVE 3 ANTENNA, 1-SIDED	PASSIVE MICROWAVE BT's at 7 CHANNELS
DATA	WIND SPEED & DIRECTION	WIND SPEED
SWATH No. OF POINTS	500 km 19 CELLS	1492 km 64 CELLS
FOOTPRINT	50 km	40 km
WIND HEIGHT	10 m	20 m
SPEED RANGE	4 -24 m/s	3 - 25 m/s
SPEED ACCURACY	+/- 2 m/s, for > 20 m/s (10%)	+/- 2 m/s, for > 20 m/s (10%)
DIRECTION ACCURACY	+/- 20 deg	N / A

3. THE ANALYSIS PROCEDURE

The first guess for the wind field is provided the NCEP Global Data Assimilation System (Derber, Parrish and Lord, 1991) on a 1.0 X 1.0 degree latitude/longitude grid. These winds are obtained from the midpoint of the lowest sigma layer of the model (about 45 m above the ocean surface), are interpolated to the fine mesh grid which was chosen to be ½ degrees in longitude and 1/3 degrees in latitude and are reduced to 20m using the neutral log-profile for a constant flux layer and the winds. The test region for this analysis was selected to be the Northwestern Atlantic Ocean adjacent to the U. S. east coast. The technique used to reanalyze the winds is based on a conditional relaxation method, which is applied as follows. At each step the wind field is separated into "u" and "v" components, and each component is analyzed independently. The Laplacian of the first guess field component is calculated to be used as the forcing function. Wind data, by components, are used to correct the wind field at the nearest grid point, which then are set as fixed internal grid points.

Winds at non-corrected internal ocean grid points are determined by numerical relaxation against the forcing function. A conditional relaxation method is applied in two steps; first, after the ERS2 scatterometer wind vector data have been incorporated into the analysis, and then after the SSMI wind speed data have been incorporated for the final analysis. The SSMI wind speed is decomposed into "u" and "v" components using the directions from the nearest four neighbors after the ERS2 winds have been taken into account. The conditional relaxation method corrects the analysis to the data where data exist and spreads the influence of the data to the rest of the field by preserving the second derivative (Laplacian) of the first guess field. The use of the Laplacian as the forcing function essentially preserves the original first guess shape of the field at grid points where no data were available. See appendix A for a description of the conditional relaxation procedure.

The conventional surface data of buoys, ships and c-man stations are withheld from the analysis. Buoys are to be used for validation only.

During the reanalysis process, the satellite data has corrected the first guess surface wind field to reflect the new data. But now one would suspect that the first guess surface pressure analysis will not necessarily be consistent (in balance) with the reanalyzed wind field. Therefore, a "new" sea level pressure analysis is generated through the use of the diagnostic "balance equation" with the inclusion of friction terms, using the reanalyzed winds. Table 2 summarizes the flow of the analysis procedures.

Table 2. Overview For the Sequence of Steps to Perform Satellite Wind Analyses

Field or Data Source	Operation Step
The First Guess Surface Wind	Interpolate Global Wind Analysis to High-Resolution Grid
Satellite Data	Scatterometer Wind Vector Data is Retrieved
Intermediate High-Resolution Surface Wind Analysis	Execute Wind Analysis Program
Satellite Data	SSM/I Wind Speed Data is Retrieved
New High-Resolution Surface Wind Analysis	Execute Wind Analysis Program
Balanced Sea Level Pressure Analysis	Apply The Balance Equation
Buoy Data	Perform Validation of Surface Wind and Sea Level Pressure Analysis

4. ANALYSIS METHOD VALIDATION

a) Synthetic Data Tests

"Synthetic" data fields of pressures and winds are constructed which are assumed to represent the "true" state of the atmosphere. These fields provide the basis for evaluating the analysis procedure described in the previous section. A sea level pressure field is generated first by designing a mathematical formulation, which contains large scale and small scale information. This is designated as the "true" pressure field as shown in figure 1. For this case study, the "true" pressure analysis is specified to have a deep storm system with a central pressure of 992.6 mb located near 38N & 67W. To determine the "true" surface wind field, the gradient wind field is computed, then rotated and reduced to simulate the frictional effects of the boundary layer. For this study the wind directions are rotated 15 degrees to the left (toward low pressure) from the gradient (and geostrophic) wind direction, and gradient speeds reduced by 30% (see figure 2).

Now, the "first guess" sea level pressure and surface wind fields are estimated. The "first guess" sea level pressure field is created by removing the small scale information from the mathematical formulation of the "true" sea level pressure analysis, and shifting the location of major pressure systems to simulate the loss of detail created by smoothing and typical errors of first guess fields as shown in figure 3. For the first guess, the intensity of the storm is reduced to a central pressure of 1001.4 mb, (an increase of almost 9 mb higher than the "true" central pressure), and displaced to near 41N & 65W (a distance of almost 350 km to the northeast of the the "true" location). To determine the "first guess" surface wind field, the same operations are performed as above to determine the "true" wind field; the gradient wind field is computed, then rotated and reduced to simulate the frictional effects of the boundary layer (see figure 4).

Consider now the problem of introducing satellite wind measurements. It is assumed that the satellite wind data are free of any errors and are simply extracted from the "true" wind field (figure 2) to simulate the passes of one scatterometer (SCAT 1) and two SSMI (SSMI 1 & SSMI 2) sensors over the region at the time of the "true" analysis of the satellites. The swath of wind vector data (SCAT 1, figure 5) passes directly over the center of the storm, whereas the one swath of wind speed data (SSMI 1, figure 6) also passed over the center of the storm the but other swath of wind speed data (SSMI 2) passes far to the northeast (figure 7). In reality the time window used in analyses for satellite or conventional data is typically +/- 3 hours centered at the analysis time. For the sake of this analysis it is assumed that there are no errors in the data due to time differences between the analyses and data. An ideal set of synthetic buoy data (figure 8) are also extracted from the true wind field, with locations near the coastal areas to simulate available ground truth used for evaluation of the analyses.

We now have constructed a first guess wind and pressure field, representing the "real world". We also have perfect satellite wind data, which allow can be used to determine directly the impact of on the analysis. The analysis procedure (described in section 3) is then executed using the perfect synthetic satellite wind data to correct the first guess wind field, and a new surface wind analysis is created. But since the wind field has been altered with the satellite data, the original sea level pressure first guess field will no longer be in balance with the new wind field. The new surface winds

APPENDIX A: CONDITIONAL RELAXATION

Each of the components (u and v) is treated separately. Initially, the forcing function (the Laplacian) is computed from the appropriate component of the first guess which was obtained from the global analysis interpolated to the high-resolution grid;

$$F = \nabla^2 U_{fg} \qquad (1a)$$

where ∇^2 Is the Laplacian operator, U(fg) is the appropriate first guess component.

The wind observations are separated by components, then checked for gross errors against the first guess, and suspect data is discarded. The "good" observations are used to correct the nearest grid point. Data are averaged if there more than one observation. All non-data grid points are relaxed to determine new values of the appropriate component. Grid points that are external boundaries, land, or have been corrected by data will held fixed through the relaxation. This process is continued until the difference between the Laplacian of corrected wind field component and its forcing function is nearly zero. This is done by solving iteratively (a2) at all non-data grid points to reduce the residual (R):

$$R = \nabla^2 U_n - F \qquad (a2)$$

A new value for U is obtained by using the residual, R, and a relaxation coefficient (a) as follows,

$$U_{n+1} = U_n + R/a \qquad (a3)$$

so that after n iterations:

$$R < \epsilon, \text{ for small } \epsilon \qquad (a4)$$

at all grid points.

APPENDIX B. THE BALANCE EQUATION

The balance equation can be written as:

$$\varrho \nabla^2 p = f \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} - u \frac{\partial f}{\partial y} - 2 \frac{\partial u}{\partial y} \frac{\partial v}{\partial x} - \frac{\partial u}{\partial x} \frac{\partial v}{\partial y}$$

Where; ϱ = specific density and f = coriolis parameter

One can solve for p by solving the balance equation, given u & v components of a wind field, by Simultaneous Over-Relaxation (SOR) using the subroutine published by Press et al (1989).

$$\nabla^2 p = F(x, y)$$

where F (the forcing function) contains only terms ϱ, f, u & v

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TABLE 3. SYNTHETIC DATA TEST CASE STUDIES:

- Evaluation Statistics of Analysis Errors Based On Gridded True Fields.

CASE 1: Wind Vector data swath across center of true storm (figures 5, 9 & 10).
CASE 2: Wind Speed data swath across center of true storm (figures 6, 11 & 12).
CASE 3: Wind Speed data swath northeast of true storm center (figures 7, 13 & 14).
CASE 4: All wind data sets

PERFECT FLD	CASE 1	CASE 2	CASE 3	CASE 4
SPEED - BIAS	(m/s)			
FG - TRUE	-0.89	-0.89	-0.89	-0.89
NEW - TRUE	0.01	0.30	-0.80	0.18
SPEED - RMS	(m/s)			
FG - TRUE	2.33	2.33	2.33	2.33
NEW - TRUE	1.20	0.76	2.16	0.67
SLP - BIAS	(mb)			
FG - TRUE	0.60	0.60	0.60	0.60
NEW - TRUE	-0.34	-0.43	0.48	-0.50
SLP - RMS		(mb)		
FG - TRUE	1.99	1.99	1.99	1.99
NEW - TRUE	0.87	1.36	1.76	0.86
LOWEST SLP	(MB)			
FG	1001.4	1001.4	1001.4	1001.4
NEW	992.9	989.5	1000.6	990.3
TRUE	992.6	992.6	992.6	992.6

TABLE 4. SYNTHETIC DATA TEST CASE STUDIES:
- Evaluation Statistics of Analysis Errors Using Synthetic Buoy Data (figure 8).

CASE 1: Wind Vector data swath across center of true storm (figure 5, 9 & 10).
CASE 2: Wind Speed data swath across center of true storm (figure 6, 11 & 12).
CASE 3: Wind Speed data swath northeast of true storm center (figure 7, 13 & 14).
CASE 4. All wind data

BUOY DATA	CASE 1	CASE 2	CASE 3	CASE 4
SPEED - BIAS	(m/s)			
FG - DATA	-3.16	-3.16	-3.16	-3.16
NEW - DATA	-0.40	0.64	-3.27	0.48
SPEED - RMS	(m/s)			
FG - DATA	4.56	4.56	4.56	4.56
NEW - DATA	2.17	1.31	4.89	1.34
DIRECTION - BIAS	(Deg)			
FG - DATA	-2	-2	-2	-2
NEW - DATA	-3	3	1	-3
DIRECTION - RMS	(Deg)			
FG - DATA	20	20	20	20
NEW - DATA	5	22	19	7
SLP - BIAS	(mb)			
FG - DATA	1.61	1.61	1.61	1.61
NEW - DATA	-0.91	-2.12	0.88	-1.27
SLP - RMS	(mb)			
FG - DATA	2.49	2.49	2.49	2.49
NEW - DATA	1.42	2.57	1.80	1.87

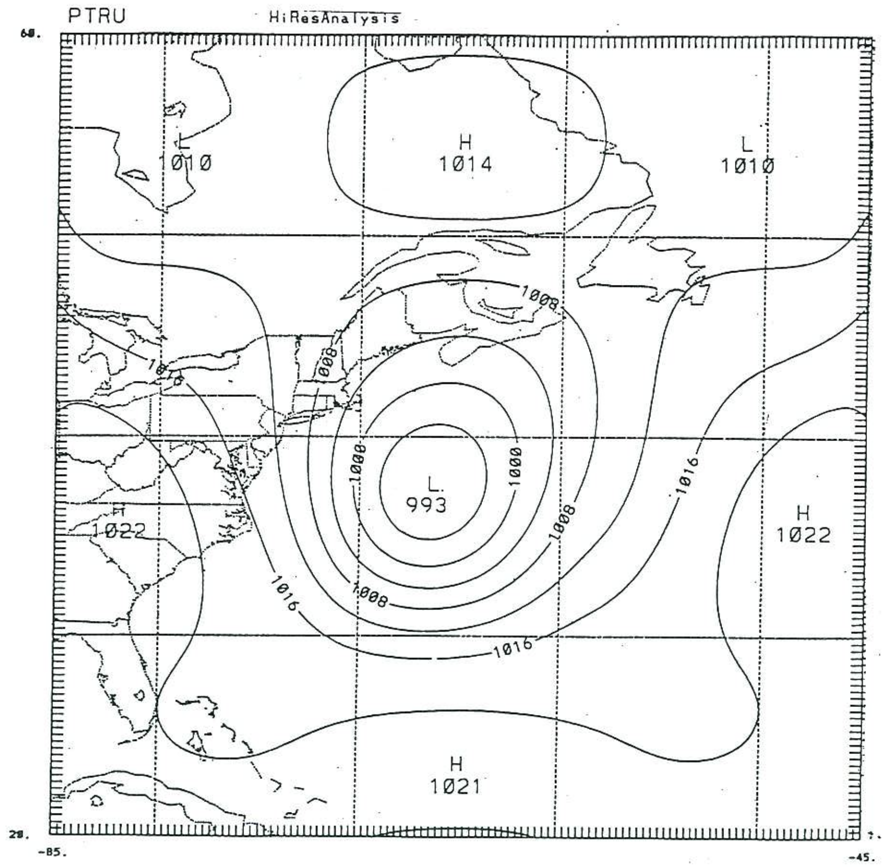

Figure 1. The "true" sea level pressure analysis (mb).

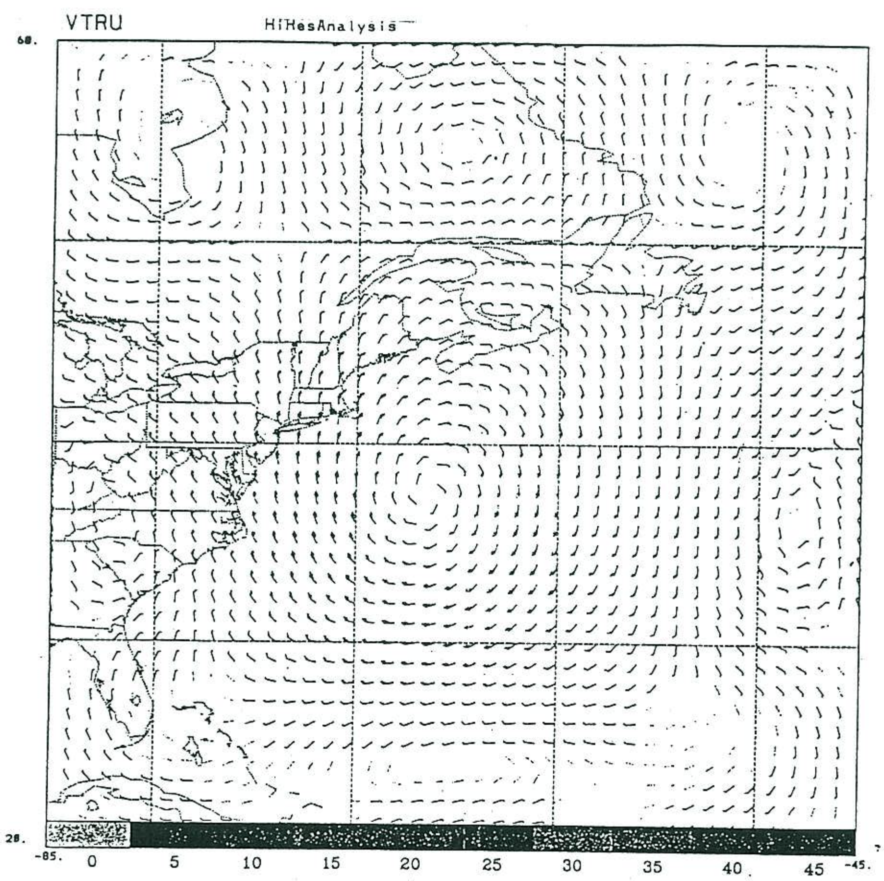

Figure 2. The "true" surface wind analysis (knots).

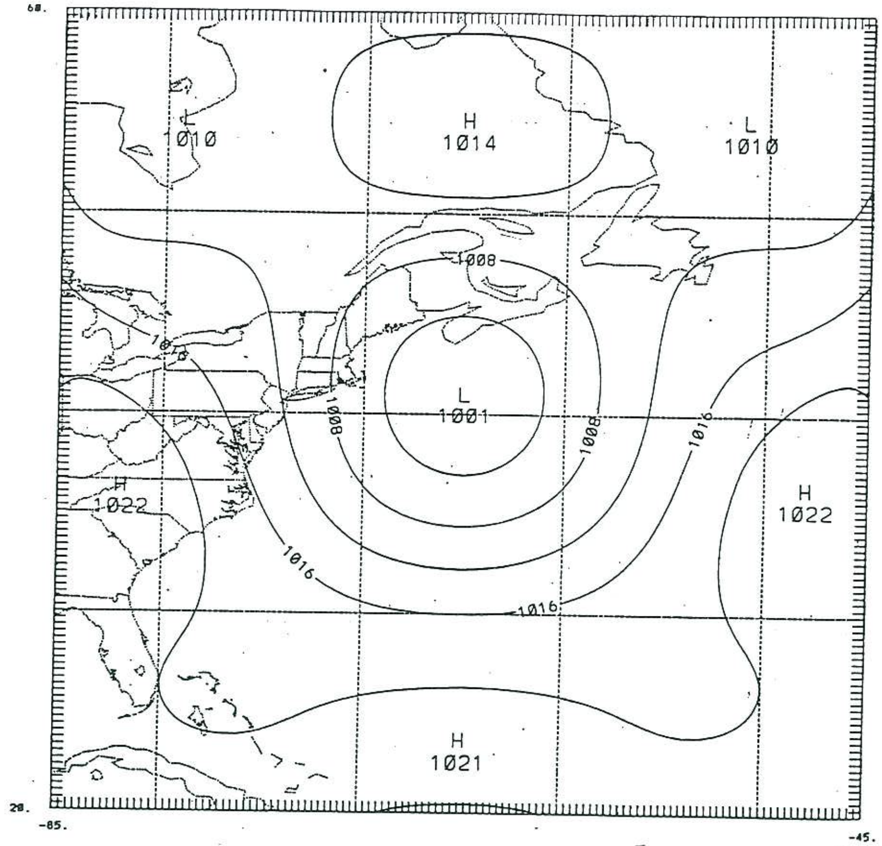

Figure 3. The first-guess sea level pressure analysis (mb).

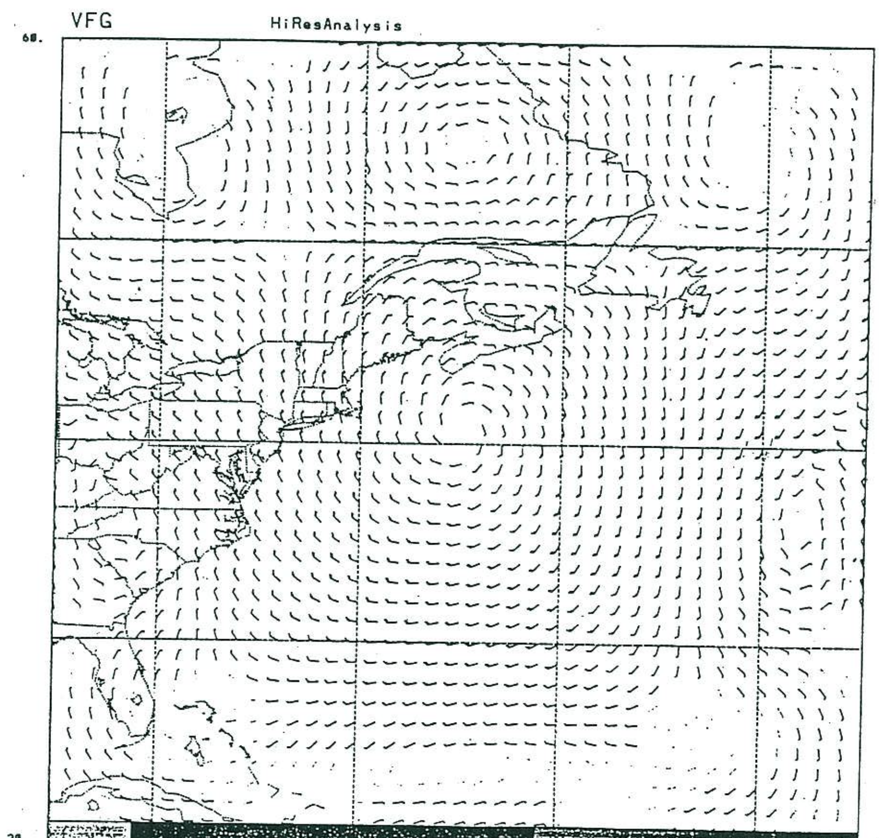

Figure 4. The first-guess surface wind analysis (knots).

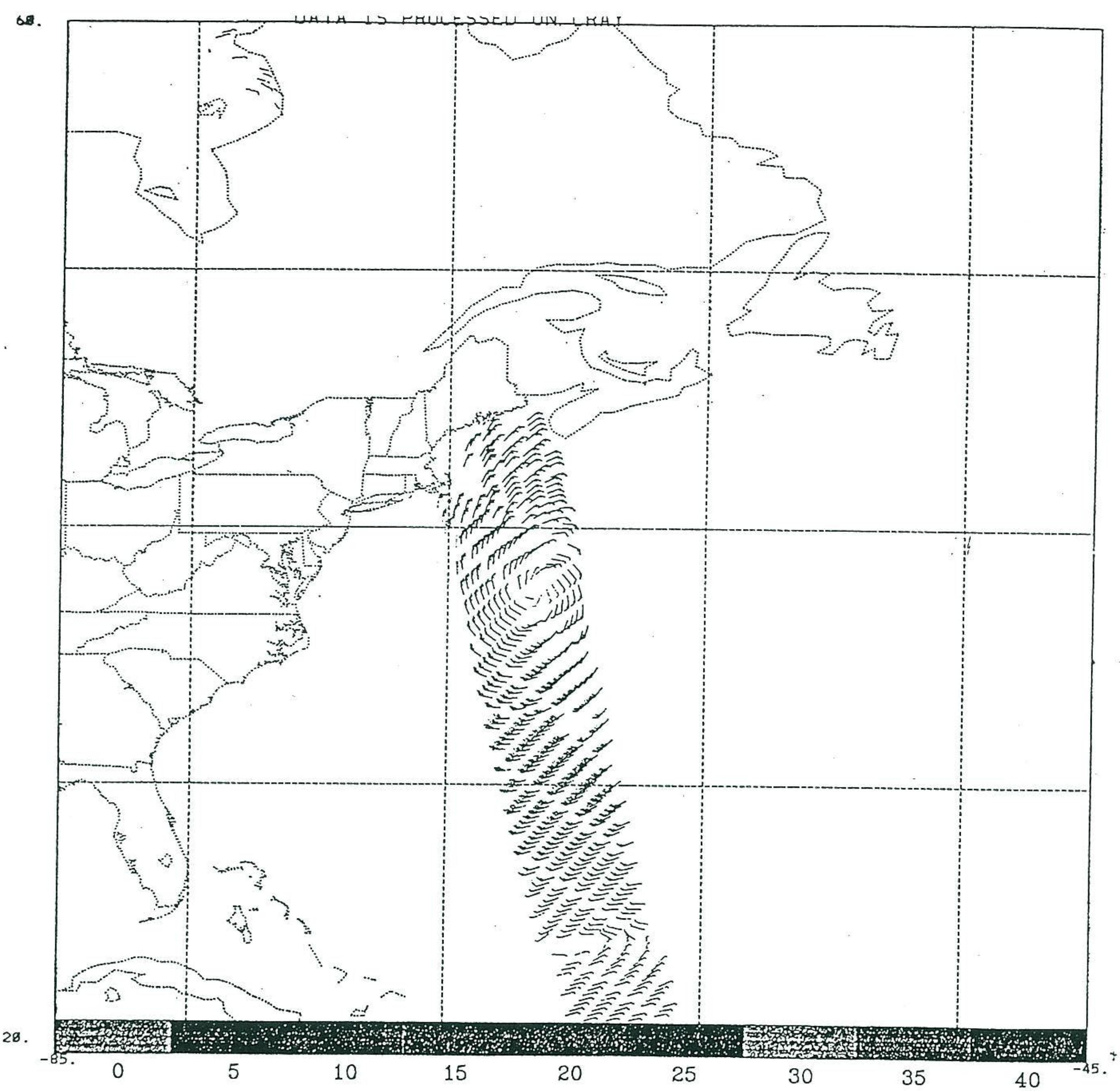

Figure 5. Swath of synthetic scatterometer wind vector data (knots) passing over storm

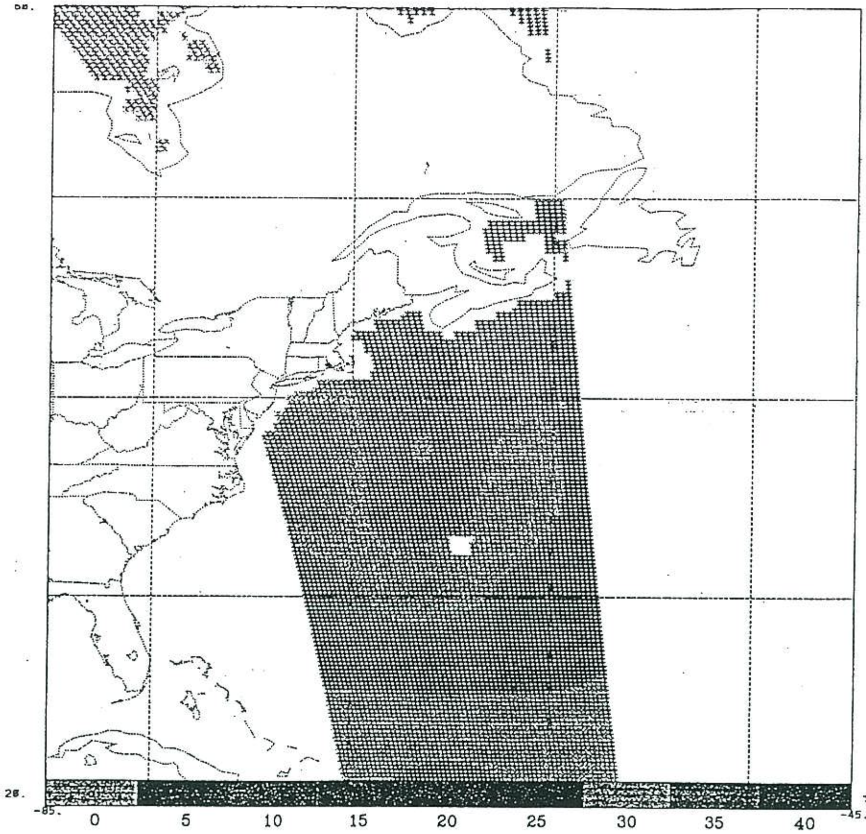

Figure 6. Swath of synthetic SSM/I wind speed data (knots) passing over storm.

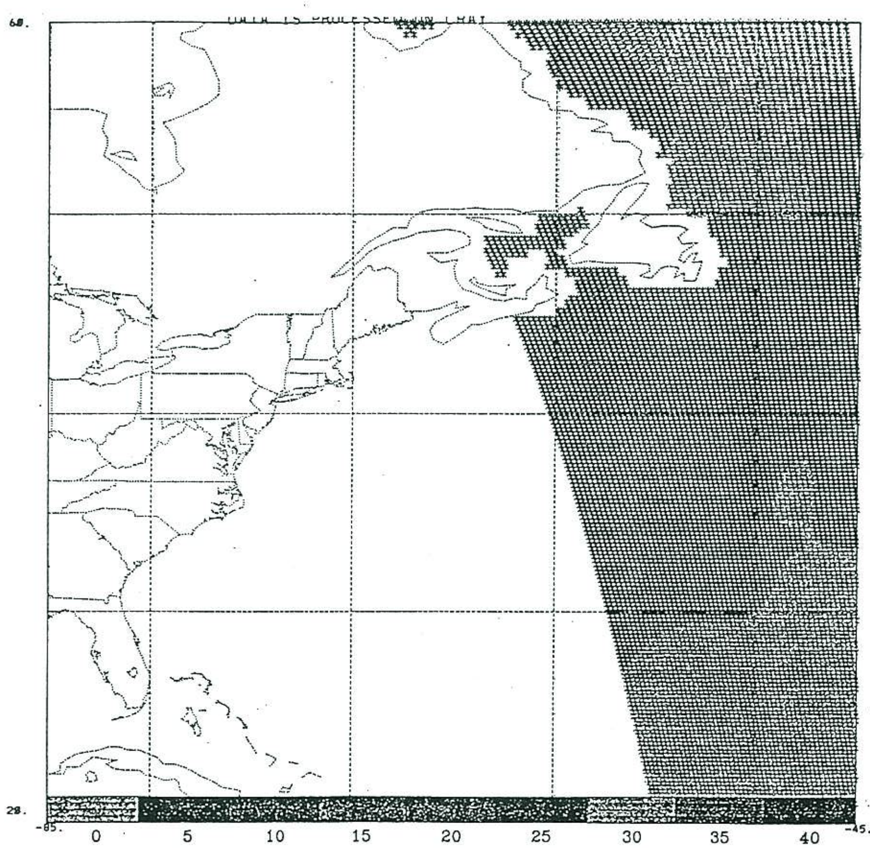

Figure 7. Swath of synthetic SSM/I wind speed data (knots) passing to the northeast of storm.

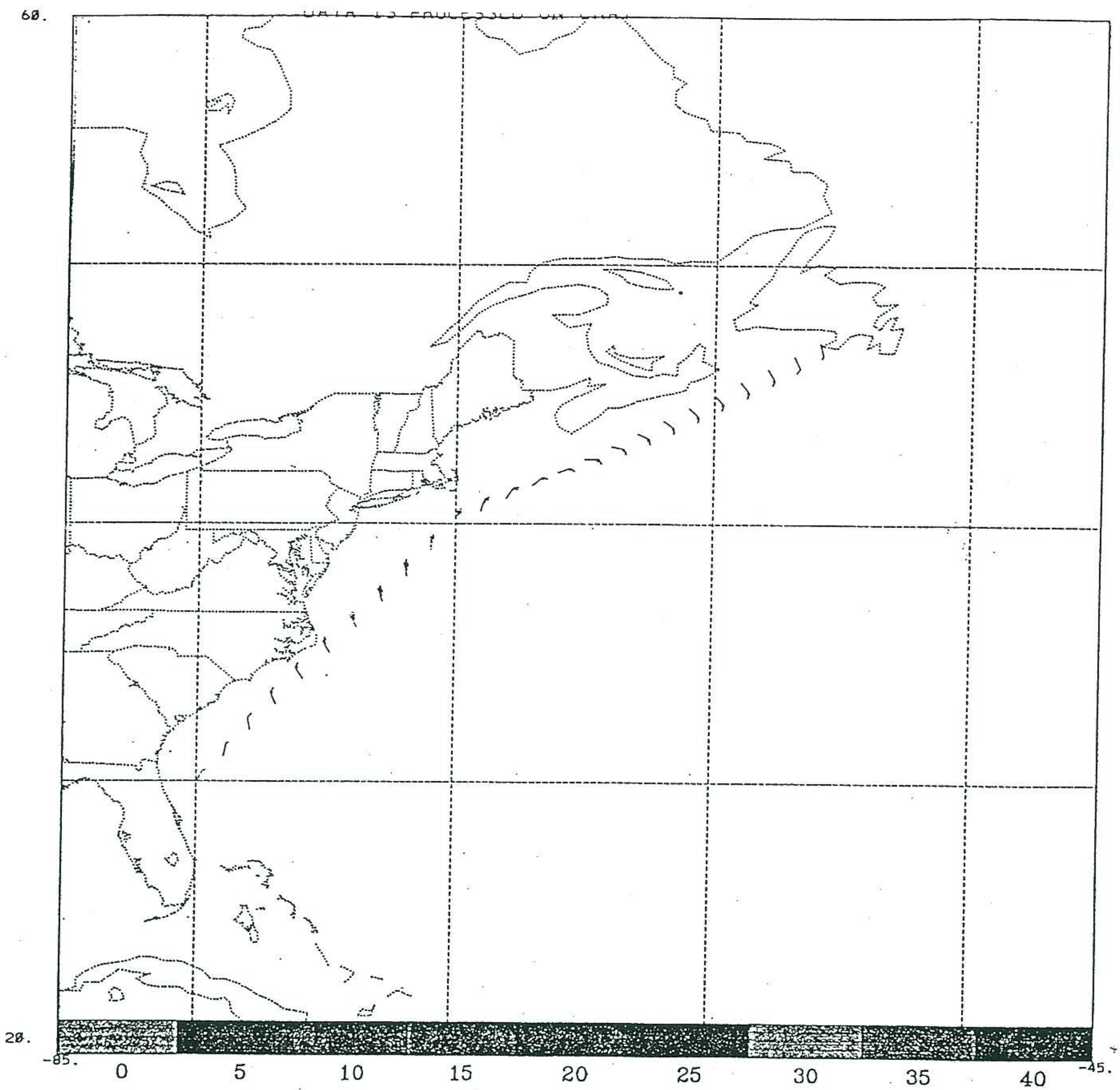

Figure 8. Locations of synthetic buoy wind data (knots).

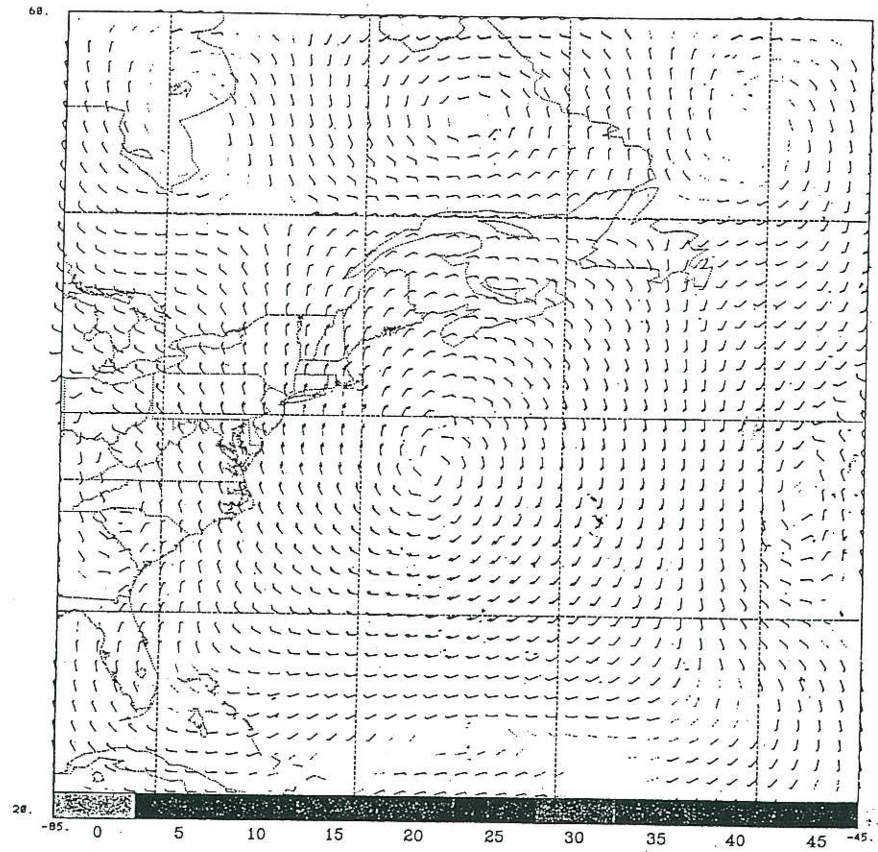

Figure 9. Re-analyzed surface wind analysis (knots) using synthetic scatterometer wind vector data passing over the storm.

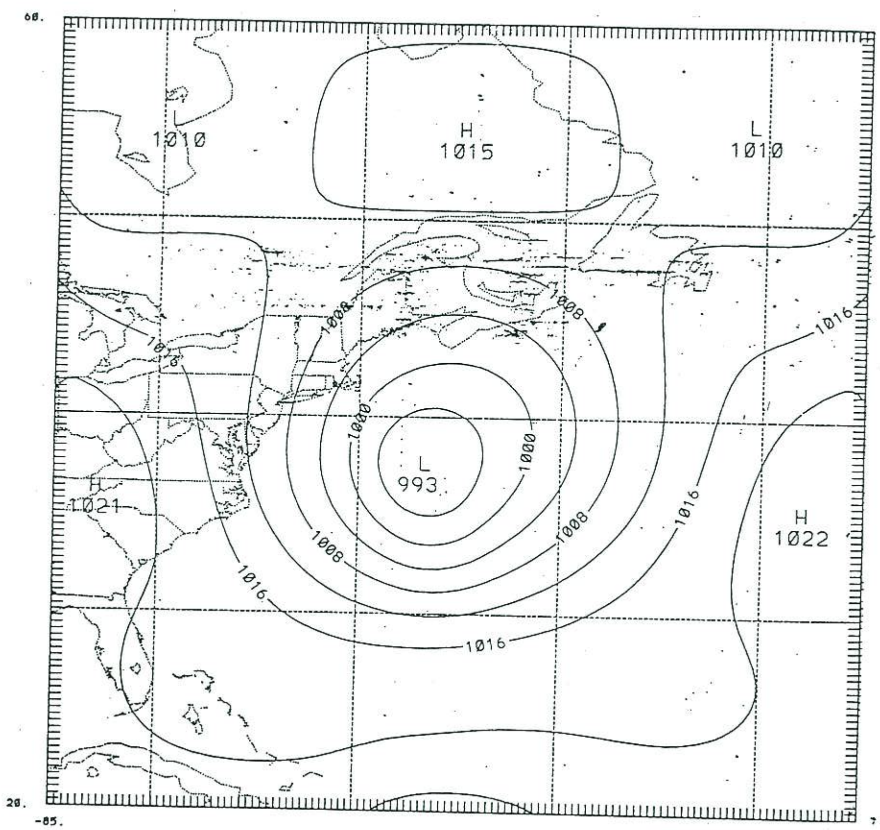

Figure 10. Sea level pressure analysis (mb) based on the balanced equation using the re-analyzed surface wind analysis generated from the synthetic scatterometer wind vector data passing over the storm.

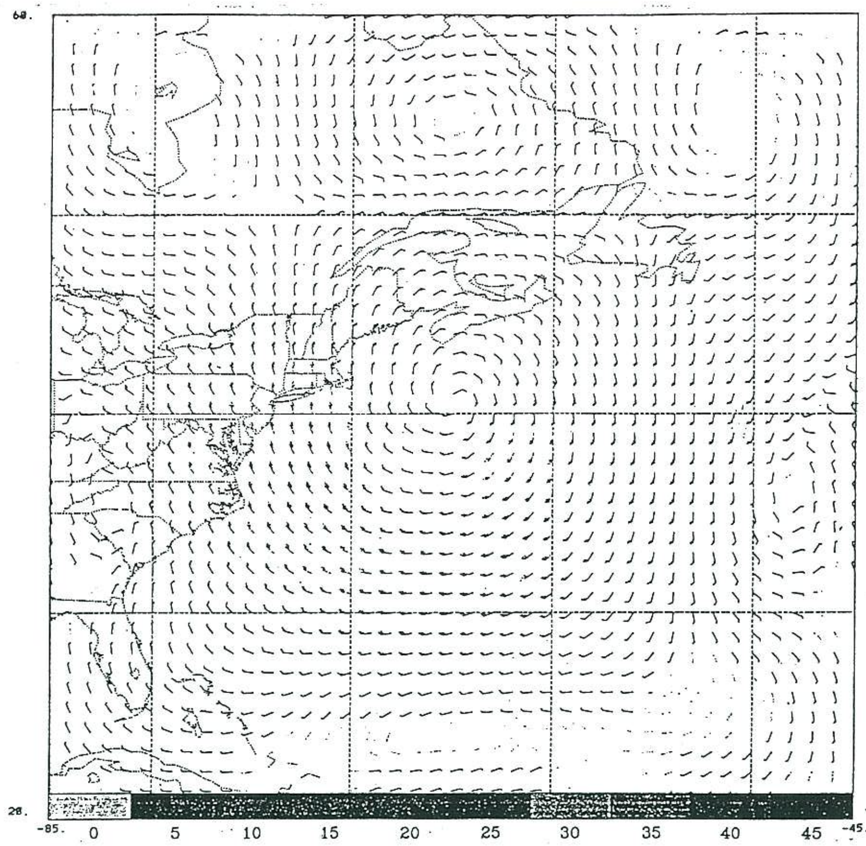

Figure 11. Re-analyzed surface wind analysis (knots) using synthetic SSMI wind speed data passing over the storm.

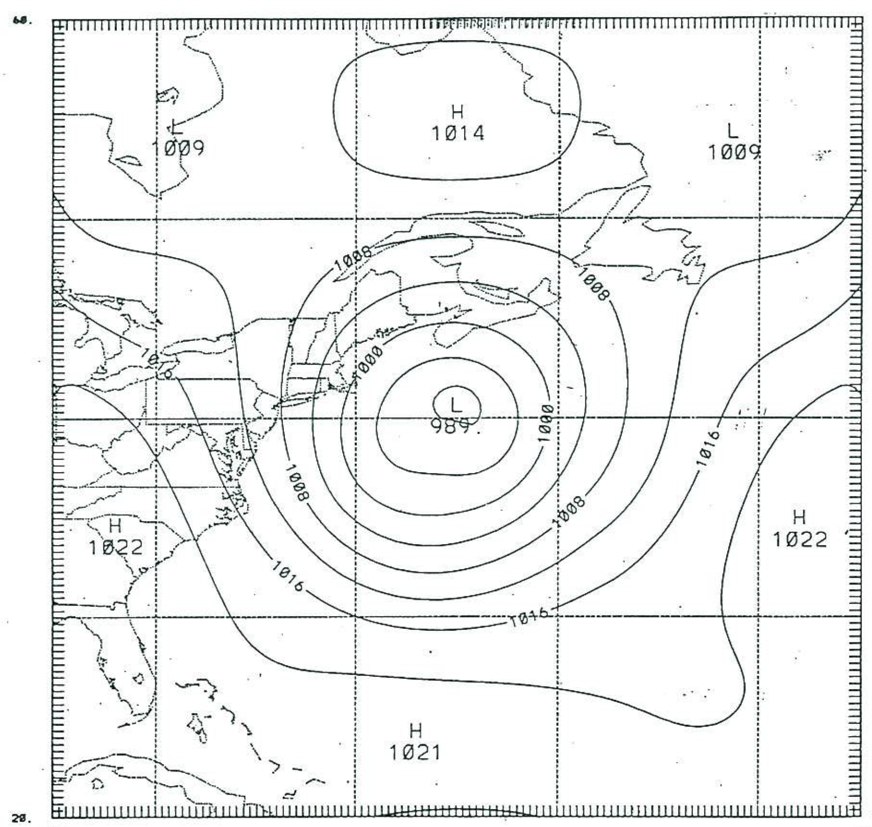

Figure 12. Sea level pressure analysis based (mb) on the balanced equation using the re-analyzed surface wind analysis generated from the synthetic SSMI wind speed data passing over the storm.

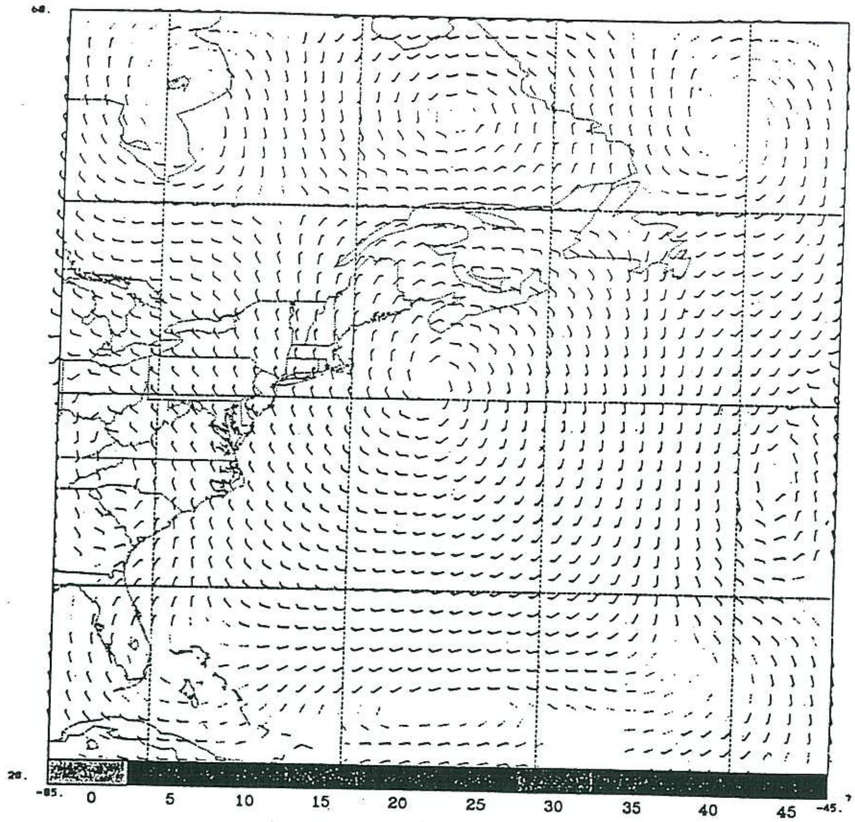

Figure 13. Re-analyzed surface wind analysis (knots) using synthetic SSMI wind speed data passing to the northeast of the storm.

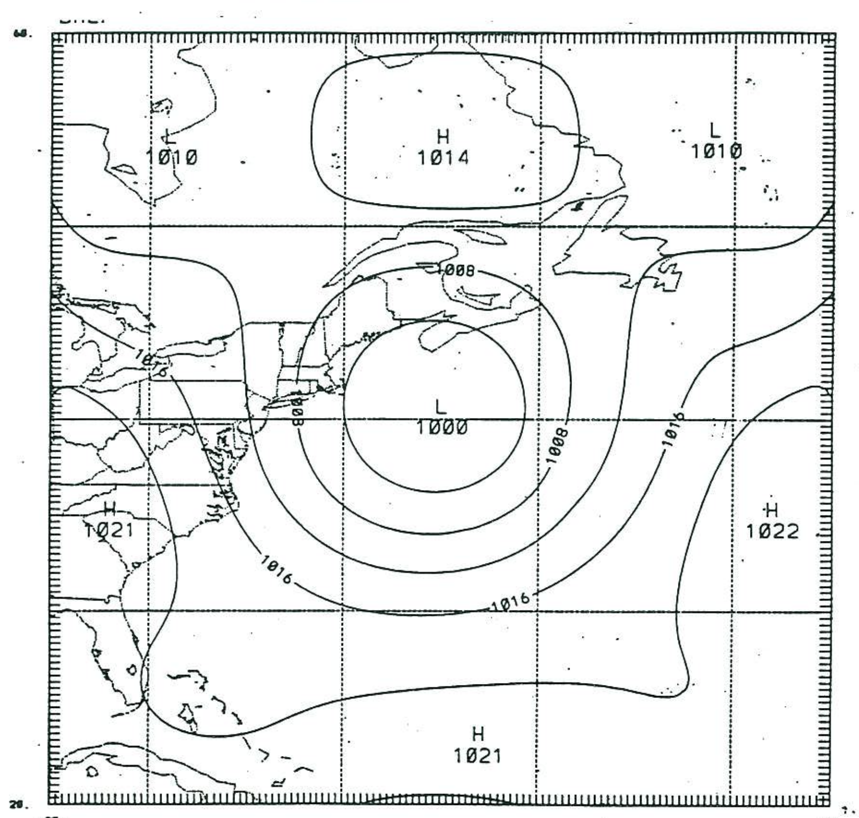

Figure 14. Sea level pressure analysis (mb) based on the balanced equation using the re-analyzed surface wind analysis generated from the synthetic SSMI wind speed data passing to the northeast of the storm.

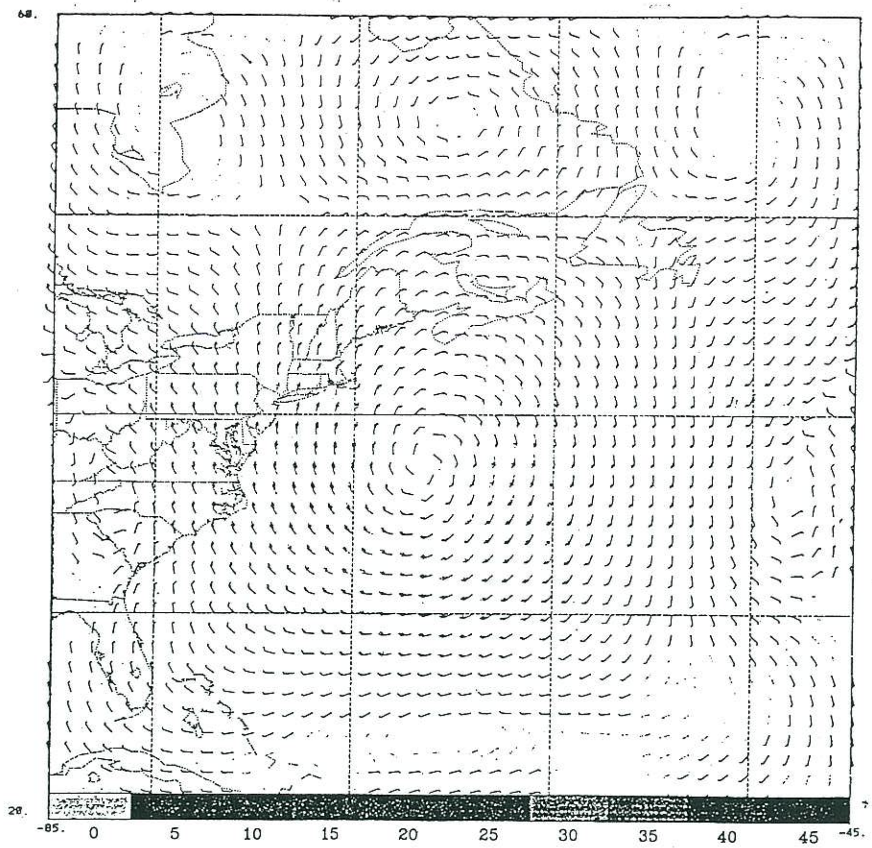

Figure 15. Re-analyzed surface wind analysis (knots) using all synthetic wind data sets.

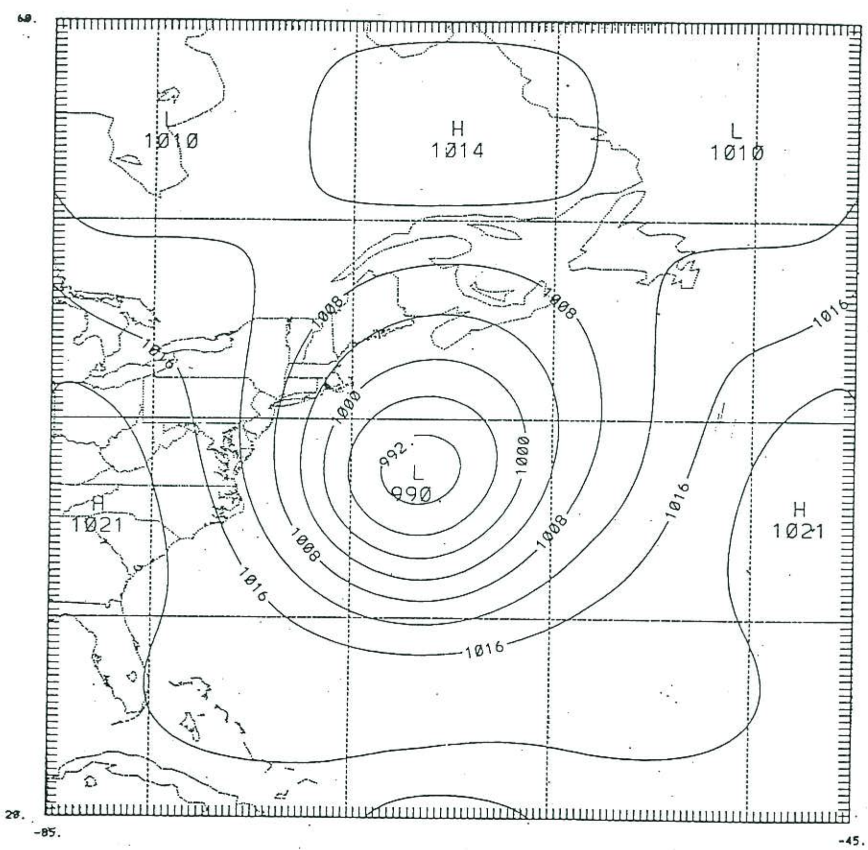

Figure 16. Sea level pressure analysis (mb) based on the balanced equation using the re-analyzed surface wind analysis generated from all synthetic wind data sets.

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