

GC
1
.073
no.96

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL METEOROLOGICAL CENTER
OCEAN PRODUCTS CENTER

TECHNICAL NOTE

OPERATIONAL PROCESSING OF
ERS-1 SCATTEROMETER WINDS:
A DOCUMENTATION

CHRISTOPHER A. PETERS *
VERA M. GERALD
PETER M. WOICESHYN **
WILLIAM H. GEMMILL

SEPTEMBER 1994

OPC Contribution No. 96

THIS IS AN INTERNALLY REVIEWED MANUSCRIPT, PRIMARILY
INTENDED FOR INFORMAL EXCHANGE OF INFORMATION
AMONG NMC STAFF MEMBERS

* General Sciences Corporation, Laurel, Maryland

** NASA/JPL, Pasadena, California

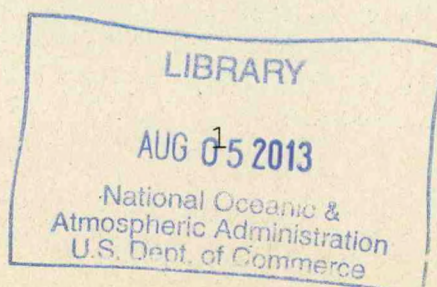
OPC CONTRIBUTIONS

- No. 1. Burroughs, L. D., 1987: Development of Forecast Guidance for Santa Ana Conditions. National Weather Digest, Vol. 12 No. 1, 7pp.
- 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.
- No. 6. Auer, S. J., 1986: A Comparison of the LFM, Spectral, and ECMWF Numerical Model Forecasts of Deepening Oceanic Cyclones During One Cool Season. Technical Note/NMC Office Note No. 312, 20pp.
- No. 7. Burroughs, L. D., 1987: Development of Open Fog Forecasting Regions. Technical Note/NMC Office Note. No. 323, 36pp.
- No. 8. Yu, T. W., 1987: A Technique of Deducing Wind Direction from Satellite Measurements of Wind Speed. Monthly Weather Review, 115, 1929-1939.
- No. 9. Auer, S. J., 1987: Five-Year Climatological Survey of the Gulf Stream System and Its Associated Rings. Journal of Geophysical Research, 92, 11,709-11,726.
- No. 10. Chao, Y. Y., 1987: Forecasting Wave Conditions Affected by Currents and Bottom Topography. Technical Note, 11pp.
- No. 11. Esteva, D. C., 1987: The Editing and Averaging of Altimeter Wave and Wind Data. Technical Note, 4pp.
- No. 12. Feit, D. M., 1987: Forecasting Superstructure Icing for Alaskan Waters. National Weather Digest, 12, 5-10.
- No. 13. Sanchez, B. V., D. B. Rao, S. D. Steenrod, 1987: Tidal Estimation in the Atlantic and Indian Oceans. Marine Geodesy, 10, 309-350.
- No. 14. Gemmill, W.H., T.W. Yu, and D.M. Feit 1988: Performance of Techniques Used to Derive Ocean Surface Winds. Technical Note/NMC Office Note No. 330, 34pp.
- No. 15. Gemmill, W.H., T.W. Yu, and D.M. Feit 1987: Performance Statistics of Techniques Used to Determine Ocean Surface Winds. Conference Preprint, Workshop Proceedings AES/CMOS 2nd Workshop of Operational Meteorology, Halifax, Nova Scotia, 234-243.
- No. 16. Yu, T.W., 1988: A Method for Determining Equivalent Depths of the Atmospheric Boundary Layer Over the Oceans. Journal of Geophysical Research, 93, 3655-3661.
- No. 17. Yu, T.W., 1987: Analysis of the Atmospheric Mixed Layer Heights Over the Oceans. Conference Preprint, Workshop Proceedings AES/CMOS 2nd Workshop of Operational Meteorology, Halifax, Nova Scotia, 2, 425-432.
- No. 18. Feit, D. M., 1987: An Operational Forecast System for Superstructure Icing. Proceedings Fourth Conference Meteorology and Oceanography of the Coastal Zone, 4pp.
- No. 19. Esteva, D.C., 1988: Evaluation of Preliminary Experiments Assimilating Seasat Significant Wave Height into a Spectral Wave Model. Journal of Geophysical Research, 93, 14,099-14,105.
- No. 20. Chao, Y.Y., 1988: Evaluation of Wave Forecast for the Gulf of Mexico. Proceedings Fourth Conference Meteorology and Oceanography of the Coastal Zone, 42-49.

1. Introduction

This office note describes a new dataset internally available at the National Meteorological Center (NMC): surface wind vectors from the ERS-1 scatterometer. The data are processed in real time using a NMC/NASA-JPL developed system. The system combines quality control and data management procedures designed at NMC with vector ambiguity removal and directional selection algorithms adapted from the United Kingdom Meteorological Office (UK Met. Office). The scatterometer is a spaceborne radar that measures the intensity of its backscattered radiation returned from wind-driven ocean surface waves. Since the magnitude of the ocean roughness is correlated with the wind at the ocean surface, the radar backscatter measurements from the scatterometer (also called sigma naughts) can be processed to obtain surface winds. An empirical transfer function relates the sigma naughts to the surface wind speed. The scatterometer has three separate antennae with which to probe the ocean surface, thus enabling it to produce a direction for the wind as well as a speed. This ability to measure both wind speed and direction makes the scatterometer a potentially valuable source of satellite ocean wind data, particularly in data sparse regions of the equatorial and southern oceans. At present, other satellite based passive instruments (such as the SSM/I or altimeter) cannot determine a wind direction independently.

A brief overview of the ERS-1 scatterometer, along with a more detailed description of the processing scheme and final product follows. The programs to decode the data and perform the processing were implemented as part of the operational job stream on September 7, 1994. It is anticipated that numerical weather prediction (NWP) models, particularly the NMC Global Model (AVN and MRF), will soon begin experiments aimed at assimilating this new dataset.



GC
1
073
no. 96

2. The ERS-1 Scatterometer

The scatterometer is an active, five cm C-band radar on board the ERS-1 satellite, which was launched by the European Space Agency (ESA) in July 1991. The instrument has three antennae which emit radar signals, striking the ocean surface at varying angles. The radar power backscattered from the wind-driven wavelets on the ocean surface is then received by the satellite and correlated with surface wind speed. The higher the amount of back-scattered radar power received by the satellite, the rougher the sea surface, and the higher the wind speed. Since the magnitude of the received power for each antenna relates to wind direction differently, having three separate measurements of backscattered power from three different view angles makes the deduction of wind direction possible but somewhat complex. Problems in determining the correct wind field arise due to an incomplete understanding of the physical processes which govern the relationships between winds, ocean waves, and the scattering of the radar signal (Offiler, 1994). An empirically based "transfer function" is required to convert the backscattered power received to a wind speed and direction at a height of 10 meters above the sea surface. Several empirical transfer functions have been derived using data from field experiments conducted during pre-launch and post-launch periods of the ERS-1 satellite (see Attema, 1992; Stoffelen, 1992), each of which produces multiple wind vector solutions. Further processing is necessary to statistically rank the solutions, assigning each a probability of being "correct" in representing the wind field. Finally, a single solution must be chosen as the "correct" one. Outside information, such as a background surface wind field from a numerical model, often assists in the process of deciding which vector represents the most likely solution.

With regard to instrument resolution, the measurements of backscattered power actually

consist of a 50 km wide area average of many pulses for each wind cell measurement. The measurement locations (cells) are separated by 25 km, giving an effective resolution of about 50 km. The width of the swath is about 500 km, with nineteen cells across a satellite track. The polar orbital period is roughly 101 minutes, yielding about fourteen orbits per day. The ERS-1 has a sun synchronous circular orbit at a mean altitude of about 785 km and an inclination of 98.5 degrees (a near-polar orbit).

3. NMC Processing

NMC has been receiving the ERS-1 scatterometer data since January, 1992 in the form of a "Fast Delivery" (FD) product from ESA. The ESA FD product includes three measurements of backscattered power (sigma naughts) at each measurement location (node), along with wind speeds and directions calculated by ESA, using their own de-aliasing and ranking procedures. The ESA processed vectors provided by the FD product have been monitored at NMC for over two years, and have been found to be lacking in quality. For example, in some regions winds blowing at 180 degrees opposite to each other at adjacent points are commonly observed, indicating that the ESA processing scheme doesn't adequately resolve the correct direction from the available set of solutions (up to six). Problems also arise in regions of light wind speeds, with confused, randomly appearing flow patterns present in the FD vectors. Gemmill et al (1994) present a more detailed evaluation of the ESA FD data, noting several deficiencies. Thus, it was decided that NMC should develop its' own processing scheme for ERS-1 scatterometer data, with two purposes in mind: First, to obtain an improved set of vectors for use by operational forecasters, and second, to upgrade the quality of the ERS-1 vectors for

assimilation into numerical models.

3.1 Data Receipt and Co-location

The ERS-1 data arrives at NMC via the WMO GTS from ESA-ESRIN (Frascati, Italy) in BUFR format generally two to four hours after measurements are taken by the scatterometer. The data are decoded from BUFR (see WMO Manual on Codes, Volume 1, FM 94, 1988) and co-located with NMC model data four times per day. Each processing cycle contains a window of plus or minus three hours of scatterometer measurements, i.e. the 12Z cycle decodes data measured from 09Z to 15Z. A delay of at least two hours usually occurs between the actual time of measurement and the time the ERS-1 data arrive at NMC. Occasionally, this delay may be greater, as much as six hours or more. Thus, the NMC/NASA-JPL processing scheme must consider these delays in data arrival. Also, for the data to be of use to NWP models, they must be made available in a timely fashion, say within three hours of real time. These realities led to the decision to initialize the data unpacking and co-location programs several hours "after the fact" (i.e. the 12Z cycle begins execution around 14Z), early enough to be of use to NWP models, but late enough to capture a reasonable amount of data. As a result, some "cut-off" of data is inevitable before assimilating it into the NMC forecast models. One possible remedy we have undertaken is to process twice for some cycles - an early run to get the data ready for assimilation, and a late run to capture all the data in its' entirety (more on this below).

After decoding, measurements at each node are co-located with fields from the NMC global model. Either a six-hour forecast from the AVN run (first guess) or the actual analysis from the Global Data Assimilation System (GDAS) is used to provide surface winds, air

temperature, humidity and sea surface temperature. The "early" 00Z, 06Z, and 18Z runs use a six-hour AVN first guess, while the "late" 00Z, and both "early" and "late" 12Z runs take advantage of the availability of the GDAS analysis in their model ingest (see Table 1). The processing scheme makes use of these model fields for quality control and re-ranking procedures, which shall be described below.

3.2 Quality Control Procedures

In order to maximize accuracy of the scatterometer wind vectors and minimize unnecessary processing of bad data, some quality control (QC) procedures have been developed. The scatterometer is one of three operating Active Microwave Instrument modes (AMI) operating from the ERS-1 satellite, which also functions in a Synthetic Aperture Radar (SAR) Image mode, or in a SAR Wave mode. Whenever the AMI switches to the Image or Wave mode, data gaps result in the scatterometer measurements. The scatterometer data over land is flagged, but ice is not. To identify data over ice covered regions, the NMC processing utilizes co-located NMC model analysis values of SST equal to zero degrees C or less as a cut off to discard the data. The ESA land flags are used to exclude data over land during processing. Since the data come into NMC from different satellite "view stations" around the globe, they must be time sorted, and any duplicate reports originating from multiple reporting stations removed. During the minimization phase, NMC only processes triplets of sigma naughts (to ensure a directional solution). Another condition for processing is that the "noise to signal" ratio of each sigma naught must be less than 10 %. Each sigma naught represents a series of radar pulses over an interval of time and distance, with the number of "missing" pulses included in the ESA FD data. When

the total number of missing pulses from a triplet of sigma naughts exceeds fifteen, we exclude that particular node from further processing. At this point, the data have been quality controlled, and are ready for further processing.

3.3 Minimization and Directional Selection Procedures

The minimization and directional selection algorithms developed at the United Kingdom Meteorological Office (UK Met Office) have been adopted as the basis for NMC's processing software (Offiler, 1992, Woiceshyn, 1993). Most of the major changes in the overall processing scheme developed at NMC concern data management, the co-location of NMC field data, and the initialization and quality control procedures described above. Changes to the wind direction selection algorithms received from the UK Met Office were minimal, and will be briefly described below. After compiling datasets containing co-located scatterometer winds and buoy reports for one year, both statistics and case studies indicated that vectors derived from the CMOD4 transfer function were more accurate when compared with several other candidate transfer functions (see Gemmill et al, NMC Technical Note; Peters et al, 1994). The CMOD4 transfer function, derived at the European Center for Medium Range Forecasting (ECMWF), was thus chosen as NMC's "operational" empirical algorithm for processing of scatterometer data. It was developed using ECMWF analysis wind fields as the "sea truth" data. Details of the formulation of CMOD4 can be found in Offiler et al, 1994. A combination of two look up tables (LUT's) generated "off-line" from the CMOD4 transfer function, a quadratic function, and derivatives of that function invert the sigma naughts to wind vector solutions at each measurement node. Also established during the minimization are probabilities for each vector solution at each node, reflecting

instrument skill in selecting the "most likely" solution. After ranking all vectors based on their relative probabilities, the NMC global model surface wind field is employed as guidance. Probabilities of each vector solution as being "correct" are modified based on estimates of likely errors (standard deviation) in both the background meteorological wind field and the scatterometer wind solutions (Offiler, 1992). The surface six hour "first guess" forecast winds from the GDAS (see Kalnay et al., 1990; Parrish and Derber, 1992), co-located with sigma naughts in step one of the processing system, are used to modify the probabilities. Finally, a local consistency or "buddy" check is performed on the wind field. The buddy check consists of a five by five node array modal filter which the entire wind vector field must pass through. This algorithm, named Sequential Local Iterative Consistency Estimator (SLICE), was developed at the UK Met Office by Offiler (1992), and works by iteratively checking for local inconsistencies and repairing them. The SLICE algorithm repeats until fewer than a threshold number of nodes have had their probabilities re-ranked.

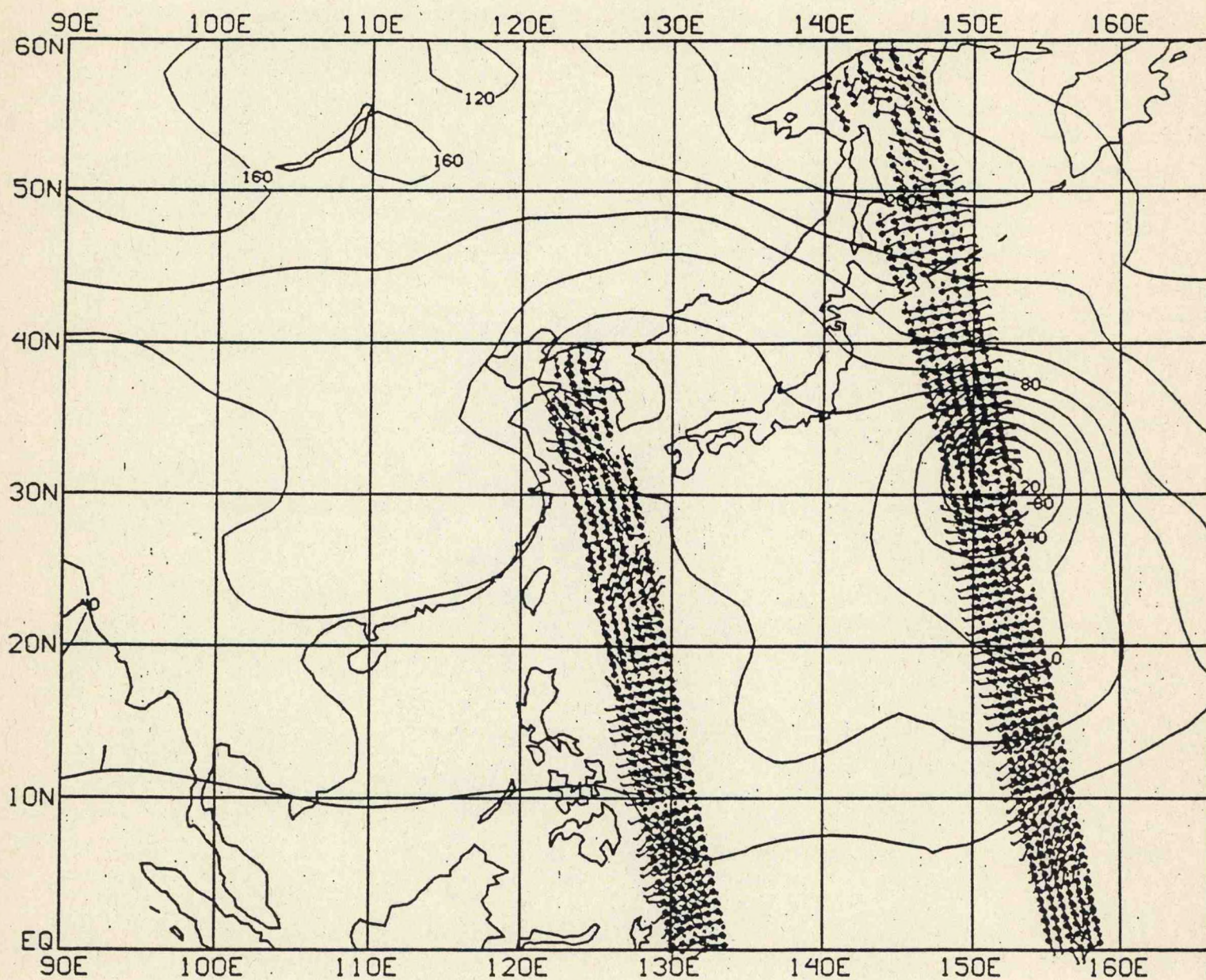
With regard to algorithmic/numerical differences between NMC's processing and the processing done at ESA, the ESA processing uses tables that are discretized in 0.5 m/s increments in speed and five degree increments in direction for finding wind vector solutions during the minimization, while NMC uses a combination of tables, functions, and derivatives to compute the wind vectors. The ESA processing uses an 18 to 36 hour forecast from the ECMWF for the background wind field during directional selection, whereas NMC uses either an analysis or first guess from the AVN model. In addition, ESA and NMC use different direction selection algorithms. The wind direction selection (often called ambiguity removal) algorithms used by NMC produce more meteorologically consistent wind fields than those obtained from ESA.

The processing with SLICE is the final stage of de-aliasing, resulting in a unique wind vector existing at each node of quality controlled scatterometer measurement. Figure 1 demonstrates an example of the de-aliased wind vectors. Figure 2 shows a schematic chart outlining the total NMC/NASA-JPL processing package.

4. Final Datasets : Encoding and Further Details

The NMC processed scatterometer vectors, along with the latitude, longitude, and time of each measurement node have been encoded in BUFR, and reside on the NAS-9000. For documentation on BUFR, see "A Guide to the WMO Code Form FM 94 BUFR", by W. Thorpe, or the WMO Manual on Codes, WMO # 306, FM 94 BUFR. The NMC processing scheme uses NMC W3 library routine W3FI85 to encode the vectors in BUFR. Several W3 library routines to decode from BUFR exist: W3FI78, and W3FI88 represent the latest. The data are processed six times per day, once for the 06Z and 18Z cycles, and twice for the 00Z and 12Z cycles. The 00Z and 12Z cycles are processed twice in order to make an "early" run for model assimilation and a "late" run for fuller data capture. For each cycle, data are generally available by about three hours "after the fact"; the 12Z scatterometer vectors, for example, should be available by no later than 15Z. To capture all the available data, waiting until five hours after the cycle time may be necessary. The names of the production datasets containing NMC/NASA-JPL processed scatterometer winds, and the times at which the programs to create these datasets execute are given in Table 1. The NMC scatterometer wind vector datasets contain a series of BUFR messages concatenated into a single file. In order to decode the BUFR messages, it is necessary to know which descriptors were used in the encoding. Descriptors are listed in Table 2.

Figure 1. Example of NMC/JPL processed wind vectors. Background field is AVN 1000 mb height. Valid 12Z 17 Sep 1994.



ESA FAST DELIVERY DATA

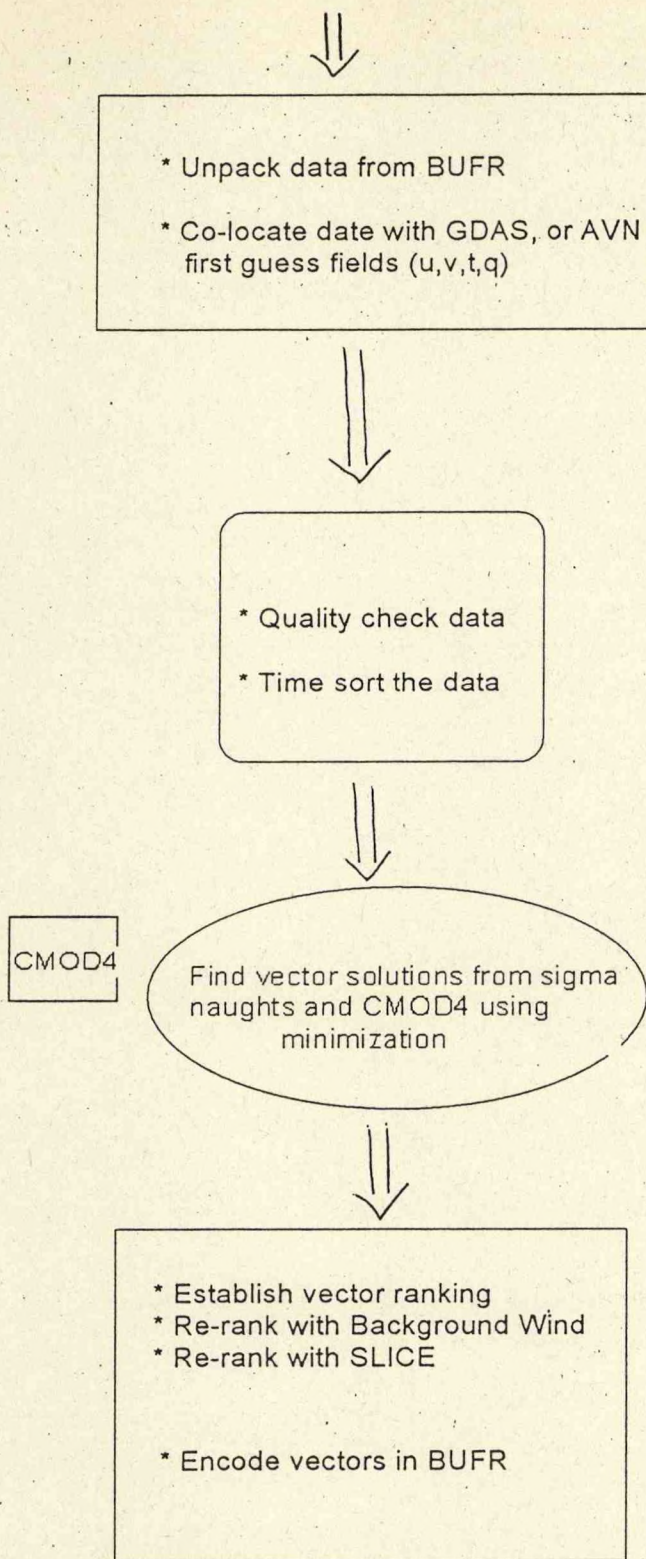


Figure 2. Flow chart showing elements of NMC/JPL processing scheme

Table 1. ERS-1 Processed Wind Datasets

Cycle	Dataset Name *	Execution Begins	Model
00Z Early	NMC.PROD.ERS1WNDS.BUFRT00Z	02Z	AVN FG
00Z Late	NMC.PROD.ERS1WNDS.BUFRT00Z	05Z	GDAS
06Z	NMC.PROD.ERS1WNDS.BUFRT06Z	11Z	AVN FG
12Z Early	NMC.PROD.ERS1WNDS.BUFRT12Z	14Z	GDAS
12Z Late	NMC.PROD.ERS1WNDS.BUFRT12Z	17Z	GDAS
18Z	NMC.PROD.ERS1WNDS.BUFRT18Z	22Z	AVN FG

* Note that all datasets reside on the NAS 9000

Table 2. List of Descriptors Used and their Units

Descriptor #	Type	Units
1. Year	Integer	---
2. Month	Integer	---
3. Day	Integer	---
4. Hour	Integer	---
5. Minute	Integer	---
6. Second	Integer	---
7. Latitude	Real	Degrees
8. Longitude	Real	Degrees (-180 to 180, Positive Eastward)
9. Wind Speed	Real	meters/sec
10. Wind Direction	Real	Degrees

5. Acknowledgments

We thank David Offiler of the UK Meteorological Office, Bracknell, Berkshire, UK, for allowing the use of several of his subroutines and functions in the NMC processing of ERS-1 scatterometer data. We are grateful for the efforts of Rachel Teboulle in support of this work, particularly in developing the time sorting algorithm used in the NMC processing. We thank D.B. Rao for his helpful advice and comments. This work was supported by the Coastal Hazards program of the National Oceanic and Atmospheric Administration, and performed in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautic and Space Administration.

References

- Attema, E. editor, 1992: ERS-1 Geophysical Validation: Workshop Proceedings - "ERS-1 Geophysical Validation", ESA document ESA-WPP-36, available from ESA, 8-10 rue Mario Nikis, F-75738, Paris, France, pp 205.
- Gemmill, W. H., Woiceshyn, P., Peters, C. A., and Gerald, V. M., "A Preliminary Evaluation of Scatterometer Wind Transfer Functions for ERS-1 Data," NMC/OPC Technical Note, September 1994. Ocean Products Center, NMC, Camp Springs, MD 20746.
- Kalnay, E., M. Kanamitsu, and W. Baker, "Global numerical weather prediction at the National Meteorological Center," *Bull. Amer. Met. Soc.*, **71**, 1410-1428, 1990.
- Offiler, D., 1992: ERS-1 Wind Retrieval Algorithm and Ambiguity Removal, EDIPVS Project Note 9, U.K. Met Office, Bracknell, Berks, UK (Dec 17, 1992).
- Offiler, D., "The Calibration of ERS-1 Satellite Scatterometer Winds," *Journal of Atmospheric and Oceanic Technology*, **11**, 1002-1017, 1994.
- Parrish, D. F., and J. C. Derber, "The National Meteorological Center's spectral statistical interpolation analysis system," *Mon. Wea. Rev.* **120**, 1747-1763, 1992.
- Peters, C. A., Gemmill, W. H., Woiceshyn, P., and Gerald, V. M., "Evaluation of Empirical Transfer Function for ERS-1 Scatterometer Data at NMC." Preprint, Seventh Conference on Satellite Meteorology and Oceanography, June 6-10, 1994, Monterey, CA, American Meteorological Society, pp. 550-552.
- Stoffelen, A., D. L. T. Anderson, and Peter M. Woiceshyn, "ERS-1 scatterometer calibration and validation activities at ECMWF: B. From backscatter characteristics to wind vector solutions. ESA WPP-36 Workshop Proceedings, pp. 89-93, 1992.
- Stoffelen, A. "Surface Wind Observations from the ERS Scatterometers", ECMWF Newsletter, Number 66, Summer 1994, pp. 3-16. ECMWF, Shinfield Park, Reading, Berkshire U.K.
- Thorpe, W. A Guide to the WMO Code Form FM 94 BUFR. Fleet Numerical Meteorology and Oceanography Center, Monterey, CA, 1994.
- Woiceshyn, P., Yu, T.-Y., and Gemmill, W. H., : Use of ERS-1 Scatterometer Data to Derive Ocean Surface Winds at NMC. Preprints, 13th Conference on Weather Analysis and Forecasting Including Symposium on Flash Floods, August 2-6, 1993, Vienna, VA, American Meteorological Society, pp. 239-240.

FM 94 BUFR: W. M. O. Manual on Codes, Volume 1: International Codes. WMO # 306,
1988 edition. Available from World Meteorological Organization.

OPC CONTRIBUTIONS (Cont.)

- No. 21. Breaker, L.C., 1989: El Nino and Related Variability in Sea-Surface Temperature Along the Central California Coast. PACCLIM Monograph of Climate Variability of the Eastern North Pacific and Western North America, Geophysical Monograph 55, AGU, 133-140.
- No. 22. Yu, T.W., D.C. Esteva, and R.L. Teboulle, 1991: A Feasibility Study on Operational Use of Geosat Wind and Wave Data at the National Meteorological Center. Technical Note/NMC Office Note No. 380, 28pp.
- No. 23. Burroughs, L. D., 1989: Open Ocean Fog and Visibility Forecasting Guidance System. Technical Note/NMC Office Note No. 348, 18pp.
- No. 24. Gerald, V. M., 1987: Synoptic Surface Marine Data Monitoring. Technical Note/NMC Office Note No. 335, 10pp.
- No. 25. Breaker, L. C., 1989: Estimating and Removing Sensor Induced Correlation from AVHRR Data. Journal of Geophysical Research, 95, 9701-9711.
- No. 26. Chen, H. S., 1990: Infinite Elements for Water Wave Radiation and Scattering. International Journal for Numerical Methods in Fluids, 11, 555-569.
- No. 27. Gemmill, W.H., T.W. Yu, and D.M. Feit, 1988: A Statistical Comparison of Methods for Determining Ocean Surface Winds. Journal of Weather and Forecasting, 3, 153-160.
- No. 28. Rao, D. B., 1989: A Review of the Program of the Ocean Products Center. Weather and Forecasting, 4, 427-443.
- No. 29. Chen, H. S., 1989: Infinite Elements for Combined Diffraction and Refraction . Conference Preprint, Seventh International Conference on Finite Element Methods Flow Problems, Huntsville, Alabama, 6pp.
- No. 30. Chao, Y. Y., 1989: An Operational Spectral Wave Forecasting Model for the Gulf of Mexico. Proceedings of 2nd International Workshop on Wave Forecasting and Hindcasting, 240-247.
- No. 31. Esteva, D.C., 1989: Improving Global Wave Forecasting Incorporating Altimeter Data. Proceedings of 2nd International Workshop on Wave Hindcasting and Forecasting, Vancouver, B.C., April 25-28, 1989, 378-384.
- No. 32. Richardson, W. S., J. M. Nault, D. M. Feit, 1989: Computer-Worded Marine Forecasts. Preprint, 6th Symp. on Coastal Ocean Management Coastal Zone 89, 4075-4084.
- No. 33. Chao, Y. Y., T. L. Bertucci, 1989: A Columbia River Entrance Wave Forecasting Program Developed at the Ocean Products Center. Technical Note/NMC Office Note 361.
- No. 34. Burroughs, L. D., 1989: Forecasting Open Ocean Fog and Visibility. Preprint, 11th Conference on Probability and Statistics, Monterey, Ca., 5pp.
- No. 35. Rao, D. B., 1990: Local and Regional Scale Wave Models. Proceeding (CMM/WMO) Technical Conference on Waves, WMO, Marine Meteorological of Related Oceanographic Activities Report No. 12, 125-138.
- No. 36. Burroughs, L.D., 1991: Forecast Guidance for Santa Ana conditions. Technical Procedures Bulletin No. 391, 11pp.
- No. 37. Burroughs, L. D., 1989: Ocean Products Center Products Review Summary. Technical Note/NMC Office Note No. 359, 29pp.
- No. 38. Feit, D. M., 1989: Compendium of Marine Meteorological and Oceanographic Products of the Ocean Products Center (revision 1). NOAA Technical Memo NWS/NMC 68.
- No. 39. Esteva, D. C., Y. Y. Chao, 1991: The NOAA Ocean Wave Model Hindcast for LEWEX. Directional Ocean Wave Spectra, Johns Hopkins University Press, 163-166.
- No. 40. Sanchez, B. V., D. B. Rao, S. D. Steenrod, 1987: Tidal Estimation in the Atlantic and Indian Oceans, 3° x 3° Solution. NASA Technical Memorandum 87812, 18pp.

OPC CONTRIBUTIONS (Cont.)

- No. 41. Crosby, D.S., L.C. Breaker, and W.H. Gemmill, 1990: A Defintion for Vector Correlation and its Application to Marine Surface Winds. Technical Note/NMC Office Note No. 365, 52pp.
- No. 42. Feit, D.M., and W.S. Richardson, 1990: Expert System for Quality Control and Marine Forecasting Guidance. Preprint, 3rd Workshop Operational and Metoerological. CMOS, 6pp.
- No. 43. Gerald, V.M., 1990: OPC Unified Marine Database Verification System. Technical Note/NMC Office Note No. 368, 14pp.
- No. 44. Wohl, G.M., 1990: Sea Ice Edge Forecast Verification System. National Weather Association Digest, (submitted)
- No. 45. Feit, D.M., and J.A. Alpert, 1990: An Operational Marine Fog Prediction Model. NMC Office Note No. 371, 18pp.
- No. 46. Yu, T. W. , and R. L. Teboulle, 1991: Recent Assimilation and Forecast Experiments at the National Meteorological Center Using SEASAT-A Scatterometer Winds. Technical Note/NMC Office Note No. 383, 45pp.
- No. 47. Chao, Y.Y., 1990: On the Specification of Wind Speed Near the Sea Surface. Marine Forecaster Training Manual.
- No. 48. Breaker, L.C., L.D. Burroughs, T.B. Stanley, and W.B. Campbell, 1992: Estimating Surface Currents in the Slope Water Region Between 37 and 41°N Using Satellite Feature Tracking. Technical Note, 47pp.
- No. 49. Chao, Y.Y., 1990: The Gulf of Mexico Spectral Wave Forecast Model and Products. Technical Procedures Bulletin No. 381, 3pp.
- No. 50. Chen, H.S., 1990: Wave Calculation Using WAM Model and NMC Wind. Preprint, 8th ASCE Engineering Mechanical Conference, 1, 368-372.
- No. 51. Chao, Y.Y., 1990: On the Transformation of Wave Spectra by Current and Bathymetry. Preprint, 8th ASCE Engineering Mechanical Conference, 1, 333-337.
- No. 52. NOT PUBLISHED
- No. 53. Rao, D.B., 1991: Dynamical and Statistical Prediction of Marine Guidance Products. Proceedings, IEEE Conference Oceans 91, 3, 1177-1180.
- No. 54. Gemmill, W.H., 1991: High-Resolution Regional Ocean Surface Wind Fields. Proceedings, AMS 9th Conference on Numerical Weather Prediction, Denver, CO, Oct. 14-18, 1991, 190-191.
- No. 55. Yu, T.W., and D. Deaven, 1991: Use of SSM/I Wind Speed Data in NMC's GDAS. Proceedings, AMS 9th Conference on Numerical Weather Prediction, Denver, CO, Oct. 14-18, 1991, 416-417.
- No. 56. Burroughs, L.D., and J.A. Alpert, 1993: Numerical Fog and Visiability Guidance in Coastal Regions. Technical Procedures Bulletin. No. 398, 6pp.
- No. 57. Chen, H.S., 1992: Taylor-Gelerkin Method for Wind Wave Propagation. ASCE 9th Conf. Eng. Mech. (in press)
- No. 58. Breaker, L.C., and W.H. Gemmill, and D.S. Crosby, 1992: A Technique for Vector Correlation and its Application to Marine Surface Winds. AMS 12th Conference on Probability and Statistics in the Atmospheric Sciences, Toronto, Ontario, Canada, June 22-26, 1992.
- No. 59. Yan, X.-H. and Breaker, L.C., 1993: Surface Circulation Estimation Using Image Processing and Computer Vision Methods Applied to Sequential Satellite Imagery. Photogrammetric Engineering and Remote Sensing, 59, 407-413.
- No. 60. Wohl, G., 1992: Operational Demonstration of ERS-1 SAR Imagery at the Joint Ice Center. Proceeding of the MTS 92 - Global Ocean Partnership, Washington, DC, Oct. 19-21, 1992.

OPC CONTRIBUTIONS (Cont.)

- No. 61. Waters, M.P., Caruso, W.H. Gemmill, W.S. Richardson, and W.G. Pichel, 1992: An Interactive Information and Processing System for the Real-Time Quality Control of Marine Meteorological Oceanographic Data. Pre-print 9th International Conference on Interactive Information and Processing System for Meteorology, Oceanography and Hydrology, Anaheim, CA, Jan. 17-22, 1993.
- No. 62. Breaker, L.C., and V. Krasnopolsky, 1994: The Problem of AVHRR Image Navigation Revisited. Int. Journal of Remote Sensing, 15, 979-1008.
- No. 63. Crosby, D.S., L.C. Breaker, and W.H. Gemmill, 1993: A Proposed Definition for Vector Correlation in Geophysics: Theory and Application and Oceanic Technology. 10, 355-367.
- No. 64. Grumbine, R., 1993: The Thermodynamic Predictability of Sea Ice. Journal of Glaciology, 40, 277-282, 1994.
- No. 65. Chen, H.S., 1993: Global Wave Prediction Using the WAM Model and NMC Winds. 1993 International Conference on Hydro Science and Engineering, Washington, DC, June 7 - 11, 1993. (submitted)
- No. 66. Krasnopolsky, V., and L.C. Breaker, 1993: Multi-Lag Predictions for Time Series Generated by a Complex Physical System using a Neural Network Approach. Journal of Physics A: Mathematical and General, (submitted).
- No. 67. Breaker, L.C., and Alan Bratkovich, 1993: Coastal-Ocean Processes and their Influence on the Oil Spilled off San Francisco by the M/V Puerto Rican. Marine Environmental Research, 36, 153-184.
- No. 68. Breaker, L.C., L.D. Burroughs, J.F. Culp, N.L. Gunasso, R. Teboulle, and C.R. Wong, 1993: Surface and Near-Surface Marine Observations During Hurricane Andrew. Technical Notes/NMC Office Note #398, 41pp.
- No. 69. Burroughs, L.D., and R. Nichols, 1993: The National Marine Verification Program - Concepts and Data Management, Technical Note/NMC Office Note #393, 21pp.
- No. 70. Gemmill, W.H., and R. Teboulle, 1993: The Operational Use of SSM/I Wind Speed Data over Oceans. Pre-print 13th Conference on Weather Analyses and Forecasting, AMS Vienna, VA., August 2-6, 1993, 237-238.
- No. 71. Yu, T.-W., J.C. Derber, and R.N. Hoffman, 1993: Use of ERS-1 Scatterometer Backscattered Measurements in Atmospheric Analyses. Pre-print 13th Conference on Weather Analyses and Forecasting, AMS, Vienna, VA., August 2-6, 1993, 294-297.
- No. 72. Chalikov, D. and Y. Liberman, 1993: Director Modeling of Nonlinear Waves Dynamics. J. Physical, (submitted).
- No. 73. Woiceshyn, P., T.W. Yu, W.H. Gemmill, 1993: Use of ERS-1 Scatterometer Data to Derive Ocean Surface Winds at NMC. Pre-print 13th Conference on Weather Analyses and Forecasting, AMS, Vienna, VA, August 2-6, 1993, 239-240.
- No. 74. Grumbine, R.W., 1993: Sea Ice Prediction Physics. Technical Note/NMC Office Note #396, 44pp.
- No. 75. Chalikov, D., 1993: The Parameterization of the Wave Boundary Layer. Journal of Physical Oceanography, (to be submitted).
- No. 76. Tolman, H.L., 1993: Modeling Bottom Friction in Wind-Wave Models. Ocean Wave Measurement and Analysis, O.T. Magoon and J.M. Hemsley Eds., ASCE, 769-783.
- No. 77. Breaker, L., W. Broenkow, 1994: The Circulation of Monterey Bay and Related Processes. Oceanography and Marine Biology: An Annual Review, 32, 1-64.
- No. 78. Chalikov, D., D. Esteva, M. Iredell and P. Long, 1993: Dynamic Coupling between the NMC Global Atmosphere and Spectral Wave Models. Technical Note/NMC Office Note #395, 62pp.
- No. 79. Burroughs, L.D., 1993: National Marine Verification Program - Verification Statistics - Verification Statistics, Technical Note/NMC Office Note #400, 49 pp.

OPC CONTRIBUTIONS (Cont.)

- No. 80. Shashy, A.R., H.G. McRandal, J. Kinnard, and W.S. Richardson, 1993: Marine Forecast Guidance from an Interactive Processing System. 74th AMS Annual Meeting, January 23 - 28, 1994.
- No. 81. Chao, Y.Y., 1993: The Time Dependent Ray Method for Calculation of Wave Transformation on Water of Varying Depth and Current. Wave 93 ASCE.
- No. 82. Tolman, H.L., 1994: Wind-Waves and Moveable-Bed Bottom Friction. Journal of Physical Oceanography, 24, 994-1009.
- No. 83. Grumbine, R.W., 1993: Notes and Correspondence A Sea Ice Albedo Experiment with the NMC Medium Range Forecast Model. Weather and Forecasting, (submitted).
- No. 84. Chao, Y.Y., 1993: The Gulf of Alaska Regional Wave Model. Technical Procedure Bulletin.
- No. 85. Chao, Y.Y., 1993: Implementation and Evaluation of the Gulf of Alaska Regional Wave Model. OPC Office Note, 35 pp.
- No. 86. WAS NOT PUBLISHED.
- No. 87. Burroughs, L., 1994: Portfolio of Marine Meteorological and Oceanographic Products of the Ocean Products Center (OPC). NOAA Tech Memo. In preparation.
- No. 88. Tolman, H.L., D. Chalikov, 1994: Development of a third-generation ocean wave model at NOAA-NMC. Proc. Waves Physical and Numerical Modelling, M. Isaacson and M.C. Quick Eds., Vancouver, 724-733.
- No. 89. Peters, C., W. Gemmill, V. Gerald, and P. Woiceshyn, 1994: Evaluation of Empirical Transfer Functions for ERS-1 Scatterometer Data at NMC. 7th Conference on Satellite Meteorology and Oceanography, June 6-10, 1994, Monterey, CA., pg. 550-552.
- No. 90. Breaker, L.C., and C.R.N. Rao, 1994: The Effects of Aerosols from the Mt. Pinatubo and Mt. Hudson Volcanic Eruption on Satellite-Derived Sea Surface Temperatures. Journal of Geophysical Research. (To be submitted).
- No. 91. Yu, W., P. Woiceshyn, W. Gemmill, and C. Peters, 1994: Analysis & Forecast Experiments at NMC Using ERS-1 Scatterometer Wind Measurements. 7th Conference on Satellite Meteorology and Oceanography, June 6-10, 1994, Monterey, CA., pg. 600-601.
- No. 92. Chen, H.S., 1994: Ocean Surface Waves. Technical Procedures Bulletin.
- No. 93. Breaker, L.C., V. Krasnopolsky, D.B. Rao, X.-H. Yan, 1994: The Feasibility of Estimating Ocean Surface Currents on an Operational Basis using Satellite Feature Tracking Methods. Bulletin of the American Meteorological Society. (In press).
- No. 94. Krasnopolsky, L. Breaker, and W. Gemmill, 1994: Development of Single "All-Weather" Neural Network Algorithms for Estimating Ocean Surface Winds from the Special Sensor Microwave Imager. NMC, OPC Contribution Note.
- No. 95. Breaker, L.C., D.S. Crosby and W.H. Gemmill, 1994: The application of a New Definition for Vector Correlation to Problems in Oceanography and Meteorology. Journal of Applied Meteorology. (in press).
- No. 96. Breaker, L.C., L.D. Burroughs, Y.Y. Chao, J.F. Culp, N.L. Gunasso, R. Teboulle, and C.R. Wong, 1994: Surface and Near-Surface Marine Observations During Hurricane Andrew. Weather and Forecasting, 9, (in press).
- No. 97. Gemmill, G., P. Woiceshyn, C. Peters, and V. Gerald, 1994: A Preliminary Evaluation Scatterometer Wind Transfer Functions for ERS-1 Data. OPC Technical Note.
- No. 98. Chen, H.S., 1994: Evaluation of a Global Ocean Wave Model at NMC. International Conference on Hydro-Science and Engineering. Beijing, China, March 22 - 26, 1995.

OPC CONTRIBUTIONS (Cont.)

- No. 99. Aikman, F. and D.B. Rao, 1994: NOAA Perspective on a Coastal Forecast System.
- No. 100. Rao, D.B. and C. Peters, 1994: Two-Dimensional Co-Oscillations in a Rectangular Bay: Possible Application to Water Problems. OPC Office Note.

NOAA CENTRAL LIBRARY
3 8398 1013 4310 5

