ESA CONTRACT REPORT

European Space Agency Contract Report

EXECUTIVE SUMMARY

The ECMWF Contribution to the Characterisation, Interpretation, Calibration and Validation of ERS-1 Scatterometer Backscatter Measurements and Winds, and their use in Numerical Weather Prediction Models

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by

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1. INTRODUCTION

The ERS-1 satellite was launched on 17 July 1991, carrying a C-band scatterometer. The scatterometer instrument (Fig 1) was considered pre-operational and a fast-delivery product broadcast to several European real-time users. A calibration and validation exercise was planned to achieve performance according to specifications in a time span of several months. A project at the European Centre for Medium-Range Weather Forecasts (ECMWF) was established to give technical support for the global validation of ERS-1 AMI wind data. The real-time data assimilation system at ECMWF played an important role in the project.

After launch it quickly turned out that the ERS-1 scatterometer was not delivering winds within its pre-defined specifications. Subsequent calibration of the instrument by ESA in collaboration with ECMWF did not resolve the problem. It was necessary to investigate and improve all steps in the wind retrieval procedure in order to meet the design specifications. One and a half years after launch a wind product of high quality was achieved at ECMWF. The product has been further improved since then and its remaining errors characterised. Subsequent effort was directed to the assimilation of scatterometer data into the ECMWF numerical weather prediction model. The analysis and experimenters teams set up by ESA have provided useful guidance in the development of the scatterometer data interpretation.

Many of the steps necessary to interpret the scatterometer radar measurements had been tested prior to launch based on aircraft campaigns and experience from the 2-beam SEASAT-A scatterometer. In the following we will discuss the main new ideas and aspects leading to an improved interpretation, characterisation and assimilation of scatterometer data. A summary and recommendations will conclude this executive summary. A more detailed description and references are available in the main report.

2. RADAR CALIBRATION

The normalised radar backscatter cross section, called σ^o, can be calibrated in an absolute sense using transponders. ESA made an experimental set-up to use such transponders. In addition a relative calibration over the Amazon rain forest was performed which showed that the calibration of the fore, mid and aft beams of the scatterometer were different over the range of common incidence angle. By comparison of measured σ^0 to collocated σ^0, simulated from a filtered distribution of ECMWF wind speed and direction, we were able to recompute the σ^0 calibration to an accuracy of 0.2 dB (0.2 dB is the σ^0 measurement noise) and aid ESA in their calibration efforts by performing real time validation.

3. σ^0 SPACE

At each node on the Earth's surface the scatterometer provides three radar measurements from respectively the fore, mid and aft beams. These can be plotted in a 3D space and for each node the distribution of these triplets verified. For a particular node the incidence angles for the fore, mid and aft beam are given, and mainly wind speed and direction relative to the sub-satellite track determine the σ^0 triplet values, according to the transfer function dependencies. Therefore, the information contained in a σ^0 triplet should be reduced to two parameters after inversion. This implies that the σ^0 triplets should span a 2D surface in the 3D σ^0 space (see Fig 2).

We verified the existence of a cone-shaped surface in 3D σ^0 space. We found the σ^0 scatter perpendicular to the cone to be close to measurement noise specification (~ 5%), except at low wind speeds and at the inside swath (see Fig 3). Therefore, in general a two parameter transfer function is sufficient to describe the σ^0 triplets. In the cases where the scatter exceeds measurement noise, the deviation from the cone's surface may be correlated to geophysical parameters other than wind speed and direction, but such a correlation would not have a substantial effect on the general quality of the scatterometer wind product because of the generally low scatter normal to the cone.

We found that the pre-launch transfer function CMOD2 did not fit the distribution of σ^0 triplets in σ^0 space to adequate accuracy, and so the formulation of CMOD2 had to be revised. A new transfer function, called CMOD4, was validated to fit the σ^0 triplets generally within the specification of scatter normal to the cone. Subsequently, a quality control procedure has been set up to reject anomalous σ^0 triplets lying too far away from the cone (~2 % of cases). Further investigation is needed to explain the anomalous behaviour in these cases associated with extreme weather conditions.

After considering the coherence of the three σ^0 measurements, the next step is to assign to each point on the cone surface a geophysical interpretation. Physically, the extension of the cone in the 3D σ^0 space is related to the amplitude of capillary ocean waves, whereas the diameter of the cone is related to the anisotropy of backscattering of radar waves on these cm-wavelength ocean waves. In the empirically derived transfer function these two parameters are explicitly related to wind speed and direction.

4. INVERSION

When we assume that a σ^0 triplet measurement originates from a "true" σ^0 triplet on the cone surface, then the inversion problem is reduced to finding the most likely location of this triplet on the cone surface. Such a location corresponds uniquely to a wind speed and a direction. Unfortunately, the cone consists of two closely overlapping sheaths, so that in general two locations will be almost equally probable as a solution, resulting in a set of two ambiguous wind vectors approximately of equal strength and opposite direction. The curvature of the cone and the general distribution of measured σ^0 triplets around the cone determine the optimal projection of a measured σ^0 triplet onto the cone surface. We found an optimal and practical solution for the inversion problem by making use of the symmetric geometry of the ERS-1 scatterometer. A less symmetric geometry (such as the NSCAT design) would complicate the inversion problem. In earlier inversion algorithms, no account was taken of the prior knowledge of the shape of the cone surface and the distribution of measured σ^0 triplets around it, which has lead to systematic scatterometer wind direction errors. In the inversion procedure we propose, these systematic errors are not present.

The ECMWF inversion and ambiguity removal procedure is called PRESCAT.

5. AMBIGUITY REMOVAL

The inversion procedure results in an "upwind" and a "downwind" wind vector solution. Only after resolving this ambiguity at each node is a unique wind vector field obtained. Ambiguity removal schemes based solely on information in the σ^0 triplets (autonomous ambiguity removal) were attempted, but these are not very successful since both solutions are almost equally probable. Further, with an autonomous scheme two antiparallel fields have to be built up that are meteorologically consistent. In complicated synoptic situations this is not straightforward and the ESA operational ambiguity removal scheme fails to provide a wind solution in approximately 30% of cases. However, these cases are generally meteorologically the most interesting, since complicated wind structures are often associated with cyclogenesis. If an accurate short-range forecast is used to provide an initial ambiguity selection at each node, then high quality fields are usually obtained. For example, a 3 to 9 hour forecast was shown to successfully remove 95% of the ambiguities. However, the meteorological structure of the forecast wind field is carried over and any error in this structure will be transferred to the retrieved wind, which happens in 5% of cases. A scheme then has to be developed that corrects the wrongly selected solutions.

We developed such a filter based on a scheme used by the UK Meteorological Office, called SLICE. Our filter uses a measure of confidence: areas where the forecast wind vector is close to one of the two scatterometer wind vector solutions, and where the retrieved scatterometer wind directions are estimated to be accurate, are initially given high confidence. Subsequently, the filter propagates information from these high confidence areas to areas where the confidence in the initially selected solution is less. When, at a certain node, a selected solution is not consistent with its neighbours, the second solution is selected if it has a better consistency with its neighbours. Our experience was that the constraint of wind vector consistency provides a better basis for ambiguity removal than a constraint based solely on wind direction consistency (see e.g. Fig 4).

The filter developed at ECMWF was compared with the ESA operational scheme and SLICE for several cases and was found to be generally beneficial. A large-scale check for meteorological consistency, which is part of the ECMWF statistical interpolation analysis scheme (called OI), is used to reject remaining serious ambiguity removal errors such as present in Fig 5 (~ 0.1% of wind vectors).

6. A NEW TRANSFER FUNCTION

To aid geophysical interpretation we collocated scatterometer winds with ECMWF wind speed and direction. We found that CMOD2 did not provide an adequate interpretation of the scatterometer triplet measurements. We reformulated the transfer function so that it was able to fit the characteristics of the σ^0-to-wind relationship observed from the ERS-1 scatterometer. The 18 coefficients of the function were estimated with a Maximum Likelihood Estimation (MLE) method. In such a method, it is important that the error characteristics of the winds and the σ^0s used in the estimation are correctly simulated, so considerable effort was expended in characterising the errors of both the σ^0 and the ECMWF winds. Further, the non-linear σ^0-to-wind relationship had to be taken into account when posing the estimation procedure. In this regard, we found that it was crucial to use the components of the wind, rather than wind speed and direction, and to use the logarithm of σ^0 rather than σ^0, in the estimation. We filtered the input σ^0 and wind data to obtain smooth distributions and to avoid low quality or correlated input data. The retrieved model function is denoted CMOD4.

7. TRANSFER FUNCTION VALIDATION

The first requirement for a transfer function is to fit the distribution of σ^0 triplets in the 3D σ^0 space. We derived an objective measure to compute the average fit of the transfer function surface to the distribution of σ^0 triplets. CMOD4 provides a good general fit to the σ^0 triplets whereas CMOD2 does not (see e.g. Fig 3).

Scatterometer winds, computed using the newly derived transfer function, were compared systematically to the ECMWF analyses and short-range forecasts. Scatterometer winds computed from CMOD4 compare better to the ECMWF model winds than real-time available conventional surface wind data (ship, buoy, or island reports). This surprising result can be explained by the so-called representativeness error. The ECMWF model represents spatial scales larger than approximately 250 km and temporal scales larger than 30 minutes, which compares reasonably well with the equivalent of 50 km and 5 minutes for the scatterometer, whereas conventional wind data represent all relevant spatial scales and temporal scales larger than 10 minutes. The representativeness error accounts for the spatial and temporal scales measured by an observing system, but not resolved by the forecast model. This error is largest for the conventional wind data.

The ESA analysis team compared the ECMWF transfer function CMOD4, amongst other transfer function proposals, with the Haltenbanken campaign wind data set (see Table 1). On its recommendation ESA implemented CMOD4 in daily operations.

	CMOD2	ESTEC	IFREMER	CMOD4	OREGON
Number of observations	14529	21278	21298	21298	21218
Speed bias (ms^{-1})	0.45	-0.38	0.53	0.06	0.72
Speed SD (ms^{-1})	2.20	1.93	1.71	1.65	2.21
Direction bias (deg)	0.94	0.88	-0.15	0.76	0.31
Direction SD (deg)	18.96	17.37	17.56	16.69	19.98
Vector RMS (ms^{-1})	4.28	3.25	3.36	3.18	3.60
Figure of merit	0.868	1.081	1.088	1.146	0.949

Table 1 Comparison between various transfer functions and RENE-91 campaign data. The transfer function labelled ESTEC is tuned on RENE-91 data, IFREMER is tuned on NOAA buoy data, OREGON is based on NMC and ECMWF analyses. The figure of merit is an attempt to measure the average performance of a transfer function. Higher values indicate a better performance.

At ECMWF we further investigated the spatial structure of the errors in the scatterometer winds. We found that for scales larger than 50 km no significant spatial error correlation is present. A dependency of the transfer function on spatially smooth geophysical parameters, other than wind, can therefore generally be neglected. In line with this, scatterometer winds were found to contain relevant synoptic detail on scales down to 50 km.

8. ASSIMILATION

Given the quality of the PRESCAT scatterometer winds it is worthwhile to assimilate them into the ECMWF model. In a data assimilation scheme, a compromise is sought between a short-range forecast and recent observations. To do this, the error characteristics of the observational and forecast data have to be specified. We have explored both the assimilation into the well-established "optimal" interpolation (OI) scheme, and into the 3D- and 4D-variational schemes (3D-Var and 4D-Var).

8.1 **OI**

The OI analysis is a linear combination of the observations and a meteorological short-range forecast, called the background or first guess field. All information is weighted according to its estimated accuracy, and is distributed according to estimated covariances of error between different meteorological parameters at different locations. In order to use scatterometer data in this scheme, the winds were made unambiguous with PRESCAT. We used the scatterometer data at a resolution of 100 km.

The OI performs a check, called "buddy" check, where it compares an observation with an analysis comprising all observations except the one being checked. The buddy check is used effectively in rejecting areas of erroneous vectors (~ 0.1% of cases). Thus, the current ambiguity removal/OI scheme works satisfactorily.

Analysis and forecast experiments carried out using the PRESCAT wind product show positive analysis and short-term forecast impacts. More specifically, we found that a 12 hour forecast run from an analysis using scatterometer data fits scatterometer data significantly (~ 5%) better than a forecast run from an analysis without scatterometer data. Also, for upper air data the 6 hour forecast is improved throughout the vertical (~ 1.5%), when scatterometer winds are used in the analysis as verified against SATOB. We further identified cases where the ambiguity removal is improved when scatterometer data have been used in previous analyses as shown in Fig 6. Five-day forecast skill scores (height anomaly correlations) show a neutral impact with respect to the inclusion of the winds. However, a significant positive impact is found when NOAA SAtellite TEMperature soundings (SATEM) are not used in the analysis as illustrated in Fig 7, suggesting that for medium-range forecasting (i.e. on larger synoptic scales) scatterometer winds and NOAA SATEM are not complementary.

The assumptions on meteorological balance of the forecast error imply, for example, that if the forecast wind at a certain location is found to be wrong, then it is assumed that the forecast wind, pressure and temperature are also wrong in an area above, below (if appropriate) and around this location. For example, when we have only SATEM data, then we will improve on the temperature fields of the forecast, and have an accurate temperature analysis. However, because of our assumptions on forecast error structure, we will also adapt the forecast wind field. By verification of the operational surface wind analyses and forecasts with scatterometer winds, it was found that the forecast surface wind field is adversely affected during the analysis by the observations, when scatterometer data are not used. It is thought that the use of flow-independent structure functions, and the absence of information on the special meteorological conditions in the PBL in the structure functions, contribute to this effect. To make observational systems more complementary and useful for Numerical Weather Prediction, the effects of the structure functions have to be investigated more precisely. In a 4D-Var the implication of the assumptions on forecast error structure will be less.

8.2 **3D- and 4D-Var**

In a variational data assimilation scheme a penalty function is minimised with two main terms, one is a weighted distance of the observations from the selected state, and the other is a weighted distance of the background field from the selected state. The selected state (at the minimum penalty) represents the most likely "true" meteorological state of the atmosphere, and is a compromise between the background (6 hour forecast in case of 3D-Var) and the observations. In order to compute this compromise properly we need to know what the probability of an observed wind vector is, given the "true" wind vector, in the case of a wind measurement. In the case of conventional wind data this probability simply depends on experience of how well the observational system fits the 6 hour forecast wind in general. Similarly, for scatterometer data it has also been found that the observation error can easily be described using the components of the wind. In terms of back-scattered power, however, the observation error structure is very complicated. This is due to the non-linear wind-to-radar relationship, embodied in the transfer function, and the relatively small detection error of the measured radar power. Therefore, in 3D- and 4D-Var, scatterometer data are most easily treated like other surface wind data, i.e. the σ^0 data are not directly assimilated, (in contradiction to satellite radiance data which are assimilated directly).

By defining an observation cost function with two minima the ambiguity of scatterometer winds can be taken into account. Meteorological balance constraints (i.e. geostrophy) on the resulting analysis will then be taken into account for the selection of the proper wind direction solution. This should result in a better ambiguity removal than the constraint of wind vector consistency currently used in PRESCAT. In this respect the first results from 3D-Var look promising. An example of a 3D-Var analysis with scatterometer data is shown in Fig 8.

It is expected that the best use of surface wind data can be made within 4D-Var. Scatterometer information will then effect the atmosphere in a dynamically consistent manner that depends on meteorological conditions.

9. SUMMARY AND RECOMMENDATIONS

At a NWP centre a wealth of information is available and used to obtain the best possible meteorological analysis. This information from conventional observations and the meteorological model was collocated with ERS-1 scatterometer measurements, to provide a successful basis for the characterisation, interpretation, calibration and validation of the scatterometer. Here, the real-time data assimilation system at ECMWF and the real-time access to the ERS-1 data played an important role. The measurements from the Haltenbanken field campaign provided only a limited set of conditions, and were inadequate to provide a validation in the full wind domain. The wind measurements from the campaign, however, proved useful in confirming the results obtained at ECMWF. Given the large footprint of the ERS scatterometers, care has to be taken when comparing scatterometer winds to local measurements such as from ships or buoys.

Large differences between measured σ^0s and σ^0s simulated from ECMWF analysis winds were found immediately after launch. The non-linear relationship between σ^0 and wind made it difficult to interpret these differences. Therefore, alternative means of validation were sought.

The σ^0 triplets can be plotted in a 3D space. We validated that the distribution of triplets spans a well-defined cone-shaped surface in this 3D space. The surface consists of two closely overlapping sheaths, which gives rise to the dual ambiguity of scatterometer winds. The characteristics of the cone surface were inadequately described by CMOD2 but a new transfer function, CMOD4, was devised which fits the data well. Anomalous triplets, not close to the cone surface, were usually found to be correlated with temporally varying winds, and a procedure was developed to reject these (~ 2%). Deviations from the cone surface may be related to geophysical parameters other than wind, but such a relationship would generally not effect the global quality of the wind product.

The inversion can be posed so as to find the optimal triplet on the cone surface, given a measured triplet. A probabilistic formalism (Bayes theorem) was needed to solve this non-linear problem, and for our approximation the symmetric geometry of the ERS-1 scatterometer proved to be essential. For an asymmetric geometry (e.g. as NSCAT) the inversion problem will be more difficult. Further, in general, a different geometry will make a different retrieval necessary. Other inversion schemes generally do not take into account the a priori known distribution of measured σ^0 triplets in the 3D σ^0 space. This is not correct and therefore we recommend our inversion scheme and associated σ^0 triplet quality control.

To resolve the dual ambiguity of the scatterometer winds, prior information of the highest accuracy is needed. The scheme developed at ECMWF takes the closest of the two wind vector solutions to a short-range forecast. When the agreement between the selected scatterometer wind and the forecast wind is high, a high confidence is given to the selection. Also when the scatterometer wind direction is accurate, the initial confidence is increased. A spatial filter then propagates information of high confidence to areas where confidence is low by constraining wind vector consistency.

To improve the quality of the operational ESA product we recommend providing both wind vector solutions to the operational user. Most operational centres will be in possession of accurate information on the surface wind to enable correction of the solution in the FDP if necessary. Some real-time users may benefit from an immediate delivery of σ^0s only and a subsequent local inversion and ambiguity removal. ESA should then provide the necessary software, for which we recommend the above procedure, called PRESCAT. Processing and archiving facilities may use the ECMWF short-range forecasts and PRESCAT in a delayed mode.

The ambiguity removal currently uses wind vector consistency as a constraint. Information on the spatial structure of error of a short-range forecast is likely to be more useful in the ambiguity removal. First tests with the 3D-Var data assimilation scheme do suggest this. We recommend further investigation and the development of a 2D scheme, using similar constraints.

The current operational transfer function CMOD4 was demonstrated to fit the distribution of σ^0 triplets in the 3D σ^0 space rather well, and a better fit would not contribute substantially to the FDP quality. The second validation of a transfer function concerns wind errors. We found that PRESCAT scatterometer winds fit the ECMWF model better than conventionally available wind data (i.e. from ships, buoys or islands). Further, on scales larger than 50 km no significant spatial error correlation was detected and substantial information on the small synoptic scales is present. Furthermore, the PRESCAT product meets the design specifications of 2 m/s or 10 % in speed and 20 degrees in wind direction, at least over the speed range 4-18 m/s. The wind speed accuracy of 2 m/s is also met for speeds below 4 m/s.

High quality high wind speed information is sparse. After 3 years of operation of ERS-1 there is a case for a more detailed evaluation of the σ^0-to-wind relationship for high wind speeds.

Operational monitoring of the ERS-1 scatterometer FDP winds and σ^0s should continue. To monitor the distribution of σ^0 triplets in 3D σ^0 space, we recommend monitoring the average normalised residual (inversion product).

The good quality PRESCAT scatterometer winds had a positive impact on the analyses and short term wind forecasts. A significant positive impact on the medium range was found when TOVS temperature soundings from NESDIS were not used. In the O/I assimilation system, a redundancy between these TOVS data and scatterometer winds was found for the medium-range forecast. Further evidence was found that the structure of forecast error assumed in data assimilation is inadequate. In a 4D-Var data assimilation system this limitation will be less of a problem and surface wind data are expected to be assimilated in a better manner. However, the development of improved surface data assimilation in 3D schemes will remain essential for the future.

Because of the non-linear σ^0-to-wind relationship and the small contribution of errors in σ^0 to the total observation (wind) error, it is more straightforward to assimilate ambiguous winds in a variational data assimilation scheme rather than to assimilate σ^0s directly.

The synoptic detail in scatterometer winds makes them particularly suitable for impact studies with high resolution NWP models. For most European countries the North Atlantic will be of particular interest from an operational point of view. The lack of scatterometer data in this particular area represents a serious weakness in the ERS-1 system.

Wave model predictions are sensitive to a changed wind input. They should therefore benefit from an improved wind analysis. This could be verified with (SAR or altimeter) wave observations and wave analyses. Also in the area of ocean circulation modelling and climate, improved surface wind analyses are most important.

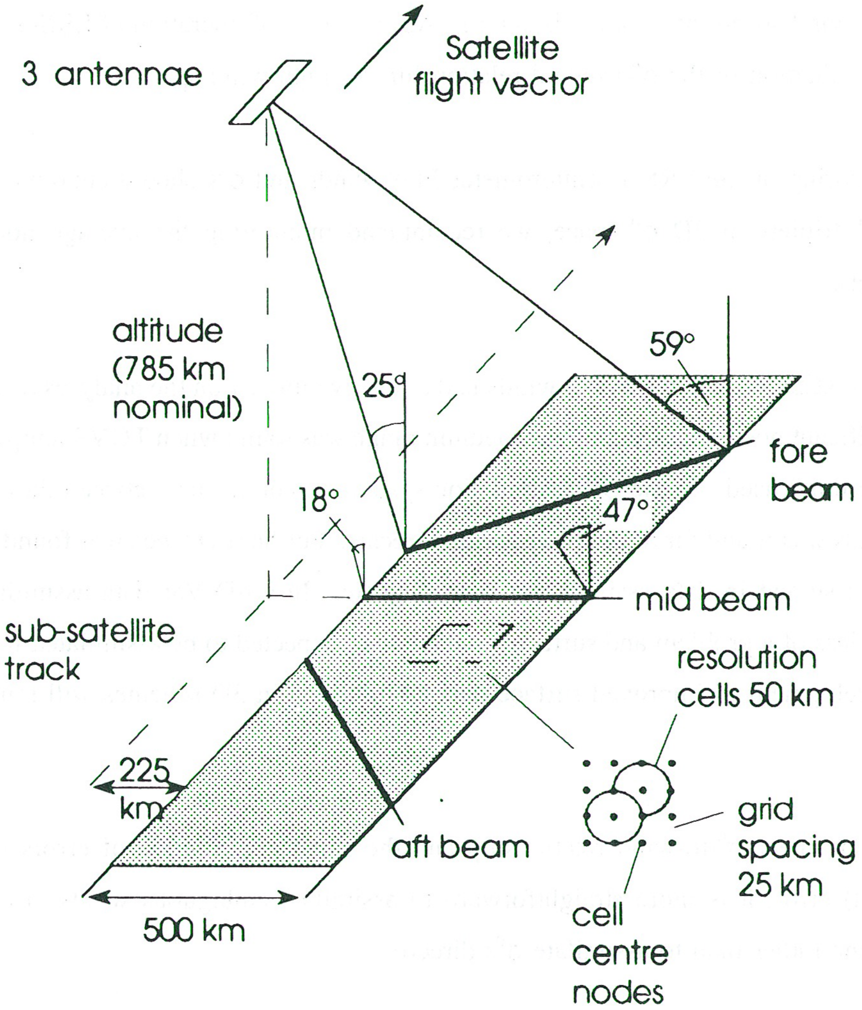


Fig 1 Schematic representation of the ERS-1 scatterometer.

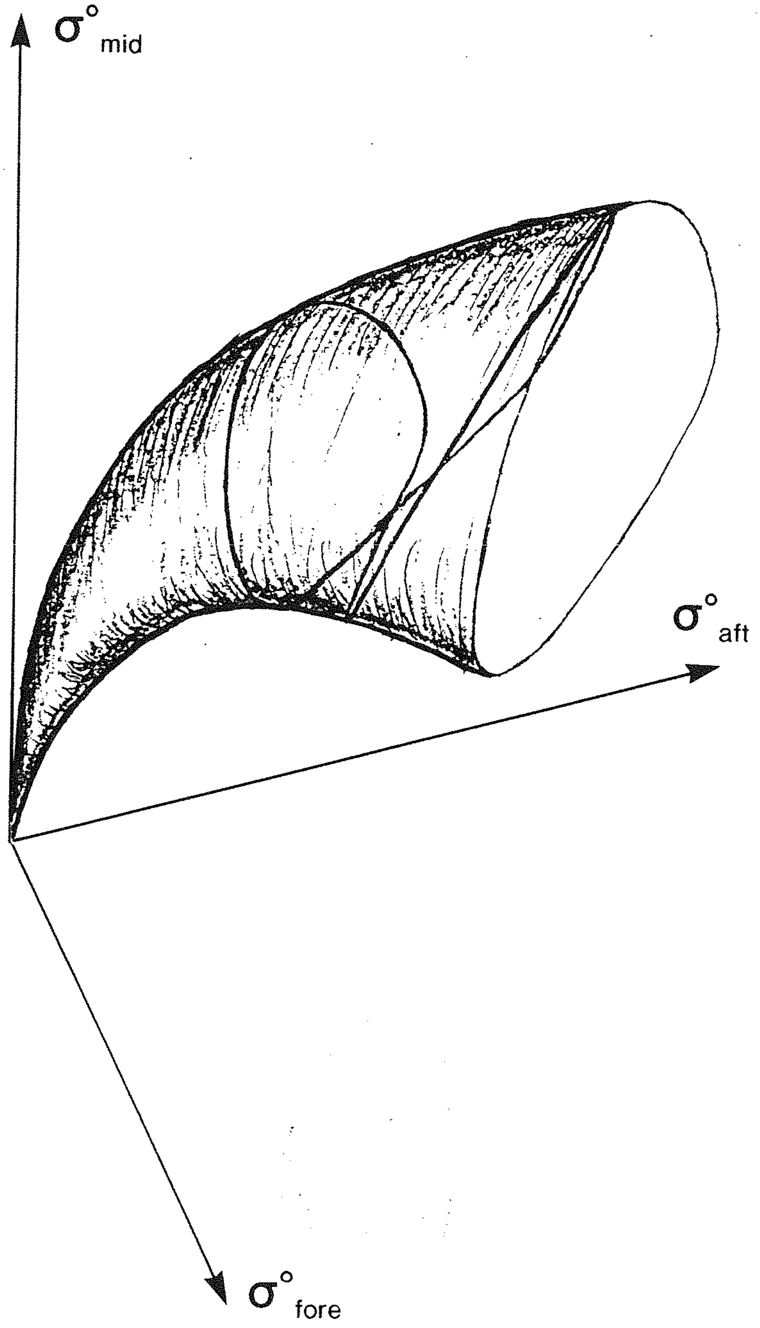


Fig. 2 Schematic representation of the surface on which σ^0 triplets should lie for a given node. The surface actually consists of two skins which can intersect, but this is not shown in the schematic. The shape and proximity to each other of the two skins is a function of node number across the swath. A schematic curve of constant speed is drawn on the surface of the cone. Based on *Cavanie and Lecomte* (1987).

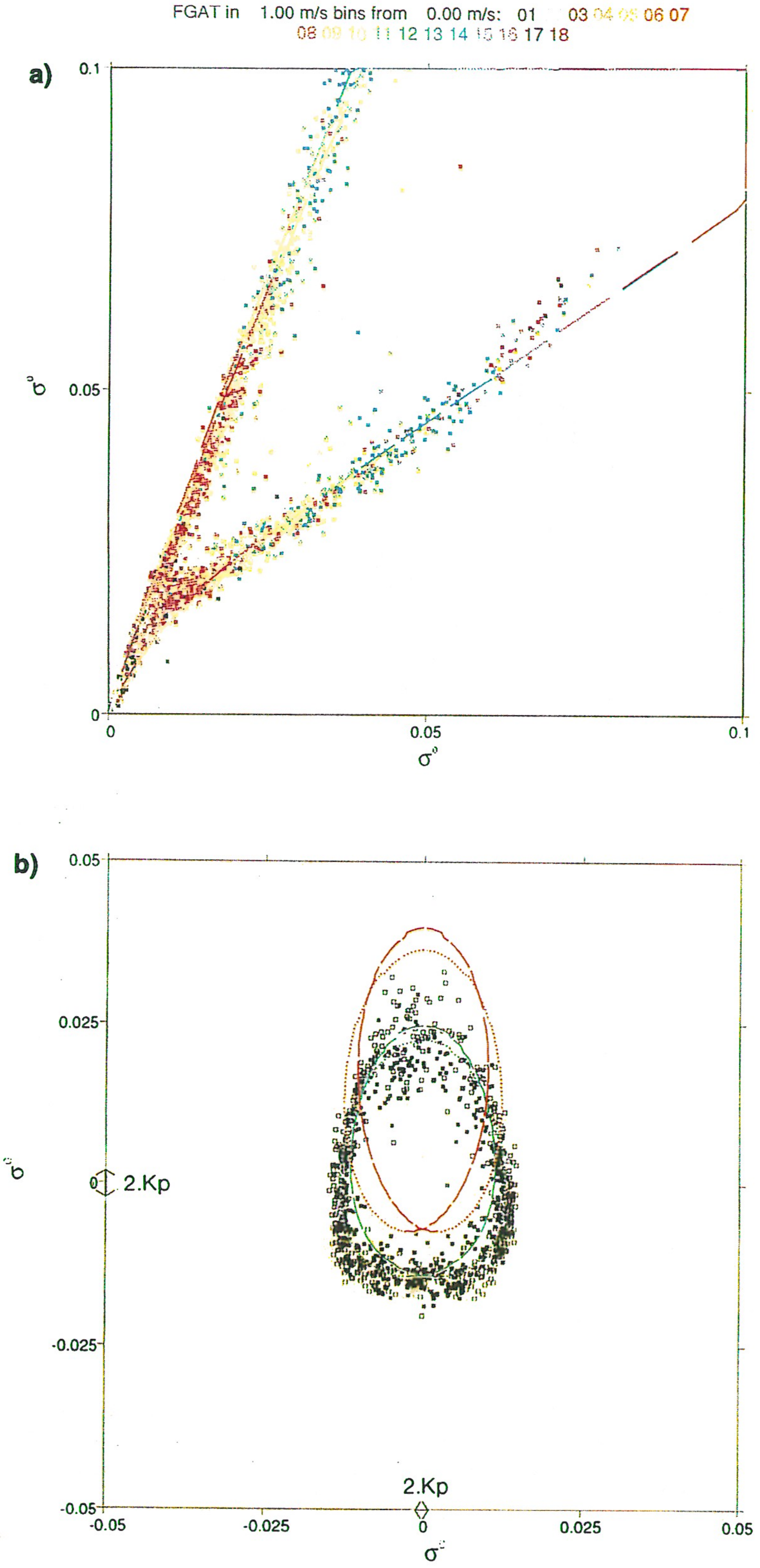
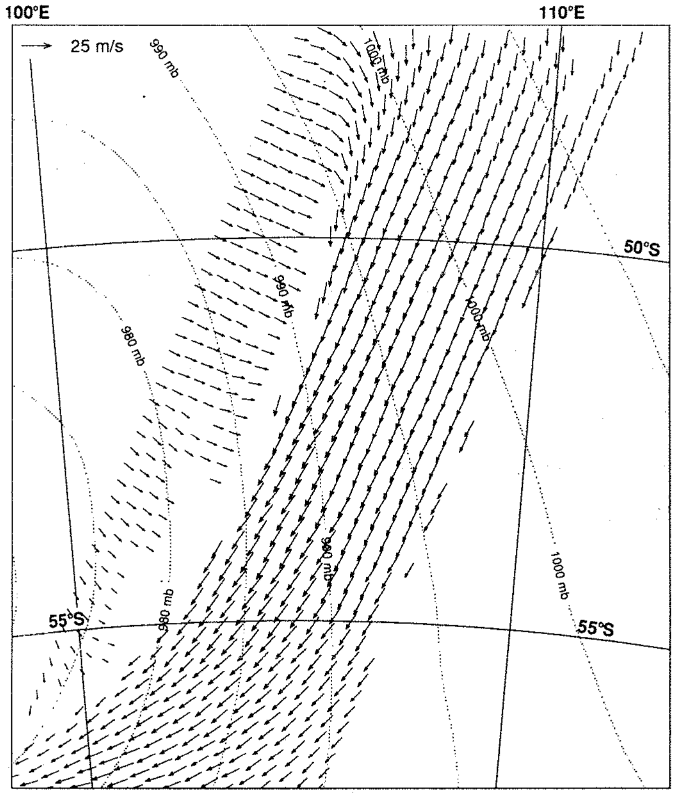


Fig 3 Cross-sections through 3D σ^0 space (a) along the cone and (b) across the cone. ERS-1 data are for June 1993. In (a) wind speed is coloured in 1 m/s intervals and increases from the lower left to the upper right. The colour of the triplets (squares) is determined by the collocated analysis wind speed. In (b) open squares are used for triplets to denote a collocated analysis wind vector component along the mid beam ("downwind") and solid squares for triplets with an analysis vector component against the mid beam ("upwind"). The average analysis wind speed for the triplets plotted in (b) is 8 m/s. The curve in (a) and the lower curve in (b) represent CMOD4. The upper curve in (b) denotes CMOD2.

a) PRESCAT CMOD4 for 2:17
3 hour forecast for 93032700



b) ESA SOLUTIONS

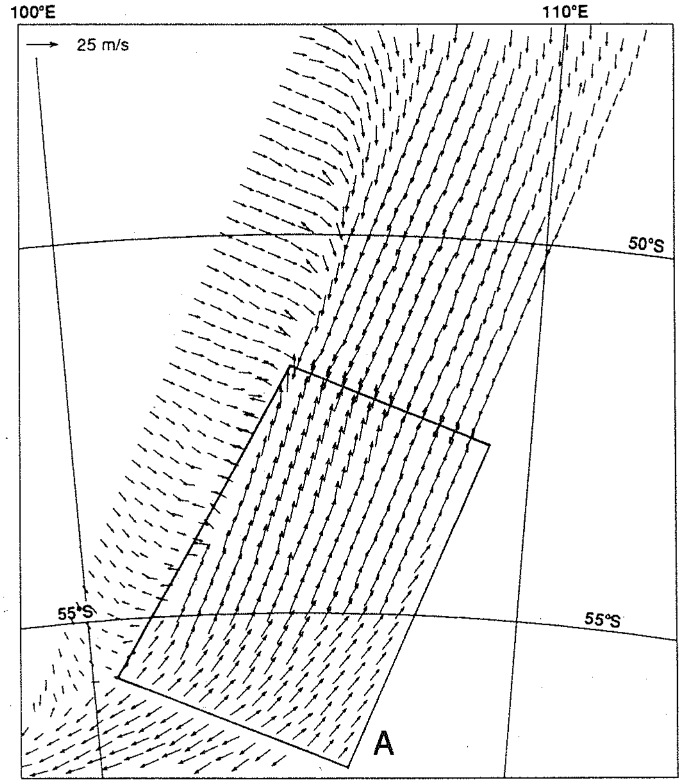


Fig 4 (a) ERS-1 scatterometer winds processed at ECMWF showing a sharp front with large gradients in wind speed and direction. (b) The solution provided by the ESA fast delivery product containing a block of wrongly selected ambiguities.

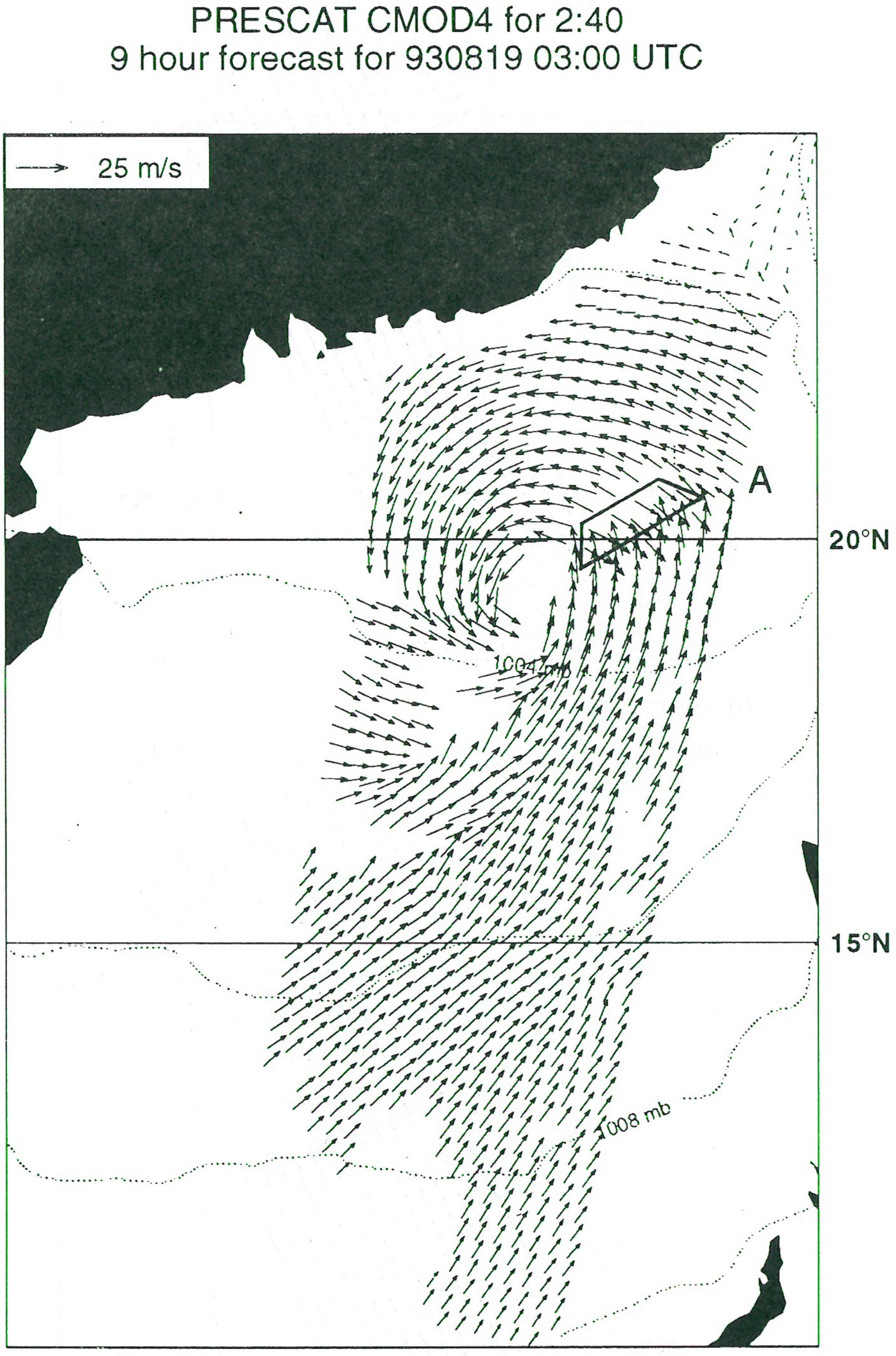
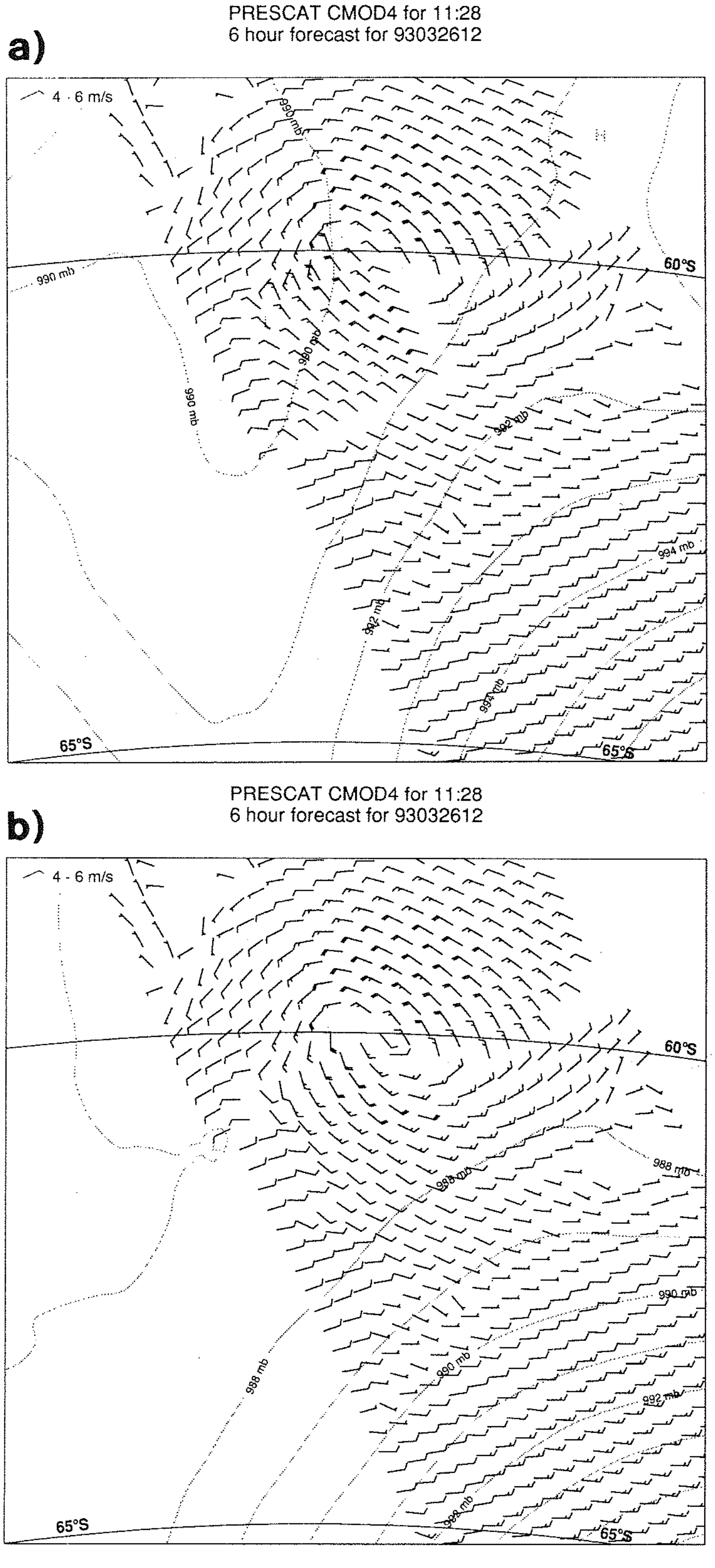

PRESCAT CMOD4 for 2:40
9 hour forecast for 930819 03:00 UTC

Fig 5 ERS-1 scatterometer winds processed at ECMWF for a view on tropical storm "Ed". The ECMWF short-range forecast has mispositioned this storm leading to some erroneous vectors marked at A. The ECMWF analysis scheme contains a quality control to reject these. The ESA Fast Delivery Product did not contain a solution.



a)

PRESCAT CMOD4 for 11:28
6 hour forecast for 93032612

b)

PRESCAT CMOD4 for 11:28
6 hour forecast for 93032612

Fig 6 PRESCAT scatterometer winds for a view on a polar low. The ECMWF short-range forecast has missed this system when no scatterometer data were assimilated (a) and as a consequence the ambiguity removal failed. In a parallel series of experiments where scatterometer winds were assimilated the ECMWF short-range forecast improved and the PRESCAT ambiguity removal was correct (b). For comparison the ECMWF mean sea level pressure is shown.

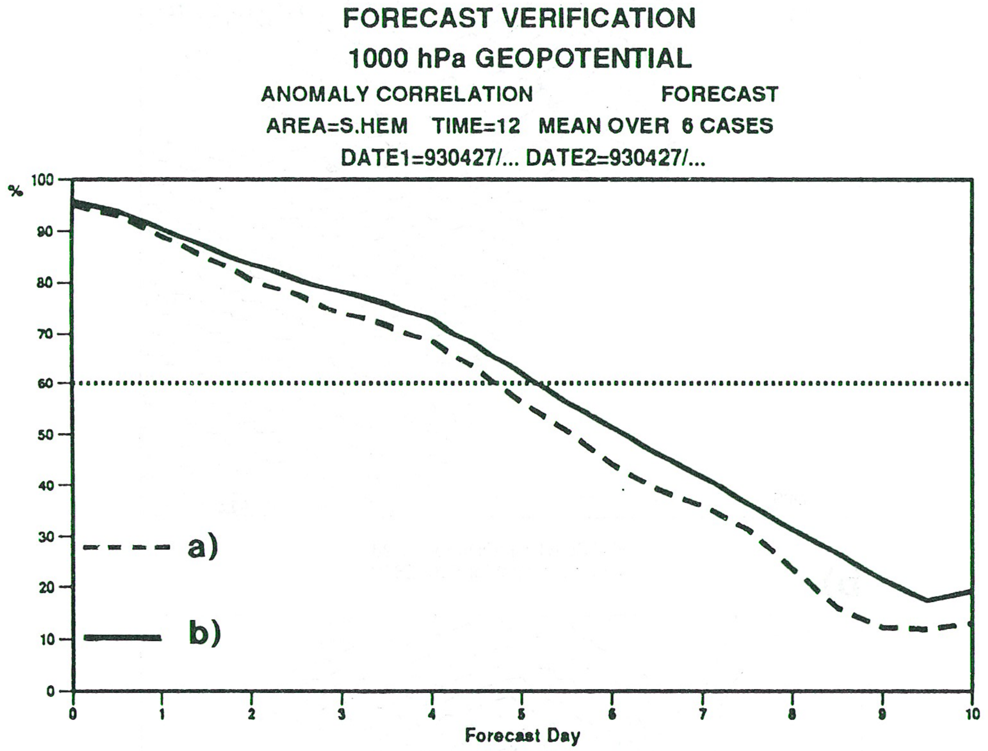


Fig 7 Southern hemisphere skill scores of 10-day forecasts from different analysis. A skill score of higher than 60% is considered useful. The scores are for assimilation experiments where (a) no scatterometer winds were used and (b) PRESCAT winds were assimilated. In both experiments no upper air satellite data were used.

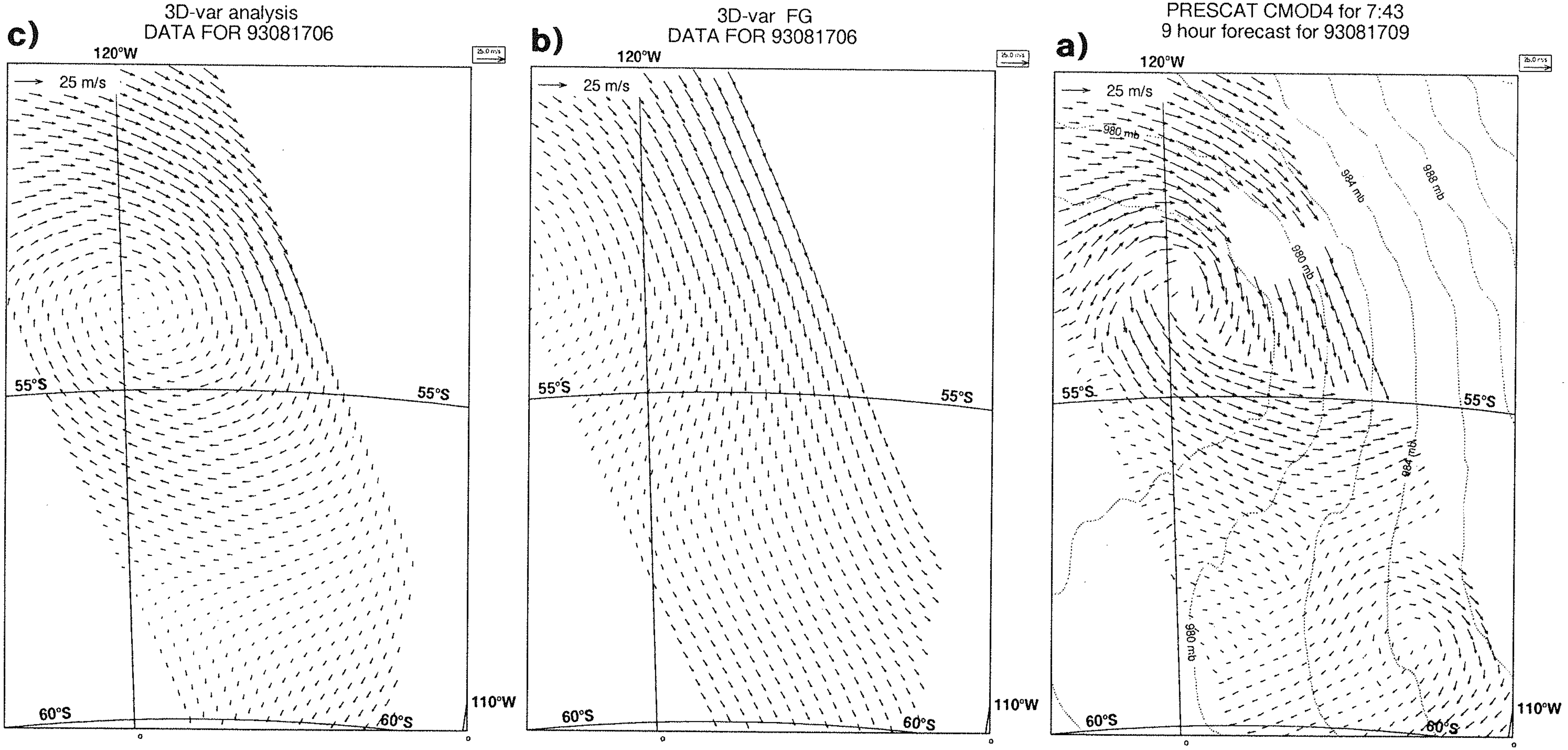


Fig 8 (a) PRESCAT winds for 930817 8 UTC. A large portion of the winds in the lower half of the plot is clearly incorrect. ESA FDP winds had a similar pattern (not shown). This is one of the worst cases for PRESCAT we encountered. A 9 hour ECMWF forecast of Mean Sea Level pressure valid at 9 UTC is shown for comparison.(b) Forecast winds used in the 3D-var analysis. (c) 3D-var analysis using ambiguous wind information and the winds in (b). Although little information is present in the forecast (b), nor in other observations (not shown) 3D-var is able to reconstruct the low indicated by the scatterometer data. The assimilation system (at T106 spectral truncation) used here does not analyse the sub-synoptic scales. This results in a less vigorous feature, than shown in (a).