

DUPLICATE

# Numerical Weather Prediction

The letters 'NWP' are rendered in a large, bold, sans-serif font. The letters are white with a blue outline. They are set against a background of a blue sky with white clouds. The clouds are visible through the letters, creating a layered effect.

Forecasting Research Technical Report No. 349

The Assimilation of Ambiguous Scatterometer Winds Using a Variational  
Technique: Method and Forecast Impact

August 2001

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# **The Assimilation of Ambiguous Scatterometer Winds Using a Variational Technique: Method & Forecast Impact**

**NWP Technical Report 349**

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## **ABSTRACT**

The European Remote Sensing (ERS) satellite series carry a scatterometer instrument that emits radar beams at the earth's surface in three different azimuthal directions. Ocean surface wind vectors can be derived from the backscatter measurements and this technique has the advantage that cloud and rain only weakly affect the backscatter at the wavelengths used. However due to uncertainties in both the geophysical model (which relates the observed backscatter to wind vectors) and the measurements themselves normally two wind vectors can be retrieved from each observation. We have now developed a route in which each wind pair is presented to the variational assimilation system via a dual-wind cost function. This takes advantage of the variational approach by using a cost function which contains the properties of the observations.

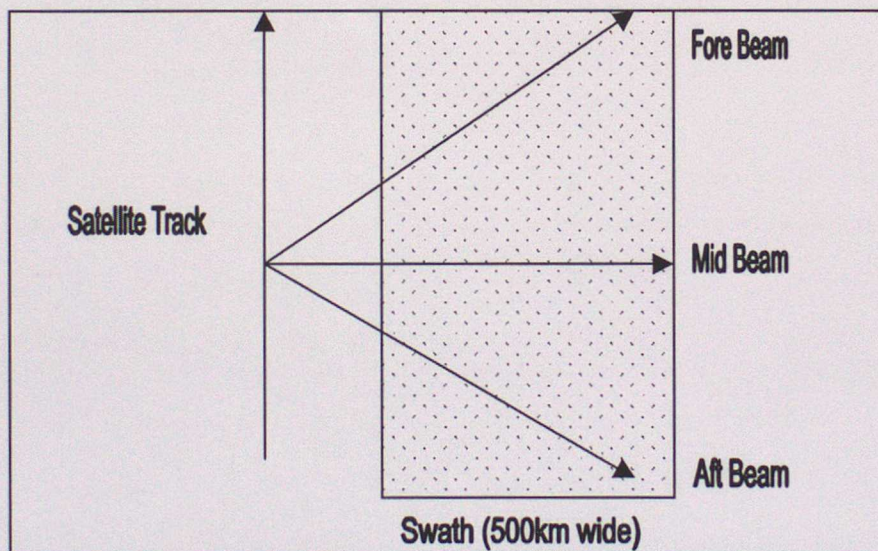
Impact trials using the new scatterometer scheme show a positive improvement in the short-range forecasts in both the Tropics and the Southern Hemisphere. The forecast improvement has been measured by both using conventional validation sources and also by using independent global observations of ocean windspeed from the ERS Radar Altimeter.



## 1. Introduction

Surface wind observations over the ocean are routinely made from commercial ships and meteorological buoys. These measurements are an important component in the production of Numerical Weather Prediction (NWP) analyses since in addition to the low level atmospheric flow they also help to define the fluxes of heat and moisture from the ocean into the atmosphere. Ideally these observations should be uniformly spread across the oceans, but in practice this is far from the case. Ships tend to be confined to commercial shipping lanes, which are mainly in the Northern Hemisphere and buoys tend to be positioned close to coasts. This leaves large areas of ocean without any low-level atmospheric observations, which can lead to large uncertainties in NWP analyses and their resulting forecasts. Estimates of wind vectors from satellite-based scatterometer instruments can give information in these data sparse areas and so complement the *in situ* observations.

Scatterometers are radars that emit pulses of microwave radiation towards the Earth's surface and then measure the resulting backscatter power<sup>1</sup>. Instruments are designed to emit several beams in different directions so that each patch of surface is sampled by a number of beams with differing azimuthal angles to the wind direction. In the case of the Earth Remote Sensing (ERS) scatterometer three beams (fore, mid and aft) are emitted with an angular separation of 45° (Figure 1) and at a radar frequency of 5.3 GHz (C-band).



**Figure 1.** The orientation of the radar beams with respect to the ground track for the ERS scatterometer. The backscatter data are averaged into 19 cells of size 50km x 50km. Mid beam incidence angle ranges from 17°-46° (measured from the local vertical) whilst the range for the fore and aft beams are 25°-57°.

Over the ocean wind vector solutions from the three beams can be derived via a model (either physically or empirically based) which relates the amount of backscatter to the windspeed and relative direction to the wind. In practice a single wind vector cannot

<sup>1</sup> Backscatter Power is calibrated as the return per unit area relative to a theoretical target, and is denoted by  $\sigma^0$ , in either linear measure or decibels (dB).



be determined from each observation triplet and usually two winds are retrieved with similar windspeeds but differing in direction by about 180°. This upwind/downwind ambiguity is not confined to the ERS design as the latest scatterometer design, Seawinds, which has two rotating beams, can have between two and four likely wind vector solutions depending on the number of beams used in the retrieval and the azimuthal separation between them.

Experiments at The Met Office (Bell, 1994; Candy *et al*, 1999) have demonstrated that the assimilation of ERS winds into an NWP model results in an improvement in the forecast skill, particularly in the Southern Hemisphere. In both these sets of experiments an ambiguity removal step was performed prior to assimilation to select the most likely wind, which is then assimilated in a similar manner to a ship or buoy observation. This method was used operationally at the Met Office from 1994 to 1999 and for further details on the ambiguity removal process see Offiler (1995).

A different approach has been adopted at other NWP centres. ECMWF have used ERS scatterometer data operationally since a variational data assimilation scheme was implemented for their global model. In this approach a cost function is minimised which contains a term specifying the departure from the latest atmospheric model state for each observation. Based on ideas from Stoffelen & Anderson (1997a) the scatterometer cost function contains both ambiguous winds and so no dealiasing prior to assimilation is required. Such an approach, in which essentially the dealiasing is performed within the analysis and so uses other independent observations to choose the correct wind solutions, has also been shown to provide a positive NWP forecast impact (Gaffard & Roquet, 1995), in particular for forecasting the movement of tropical cyclones (Isaksen & Stoffelen, 2000).

Since early 1999 a variational analysis scheme has been operational at the Met. Office (Lorenc *et al*, 2000) which allows a similar approach to ECMWF for assimilating scatterometer winds. Whilst a significant improvement over the old scatterometer assimilation method is not anticipated, moving to a variational approach offers the following benefits. Firstly it removes the need to maintain the ambiguity removal software and secondly (and perhaps more importantly) by modification of the cost function we can assimilate data from other scatterometer instruments including those with up to four ambiguous winds such as the Seawinds instrument.

The first part of this report describes the method of assimilating ambiguous scatterometer winds in the Met Office's Global NWP model. Section 2 outlines the wind retrieval method, which in many respects is similar to that used at other NWP centres. In section 3 aspects of the assimilation scheme are discussed. The latter part of this report describes impact trials and case studies which test the impact of the new method, including the validation of the analyses and forecasts against an independent set of windspeed measurements from the ERS-2 radar altimeter.

## **2. Wind Retrieval**

For wind retrieval the assumption is made that the principle scattering surface is due to the small, centimetre-scale, wind-generated waves on the ocean. A relationship is then expected between the near-surface wind and the measured backscatter. For the



ERS instruments backscatter models have been determined empirically, either from collocations with buoy data or using NWP wind vector estimates, as a function of windspeed ( $U$ ) incidence angle ( $\theta$ ) and azimuthal angle relative to the wind direction( $\varphi$ ):

$$\sigma_{mo}^0 = f(U, \theta, \varphi) \quad (1)$$

The model currently used is CMOD4 (Stoffelen & Anderson, 1997b) which describes the surface of an interleaved cone in  $\sigma^0$  space. The first step in retrieving a wind vector involves using the inverse of the model to estimate the windspeed from the observed triplet assuming varying trial wind directions. Using the trial windspeed and directions model backscatter triplets can be calculated via the forward model. The observed wind direction can then be found by minimising a cost function ( $\hat{J}$ ) which describes the deviation between the observed backscatter triplet and the CMOD4 cone surface:

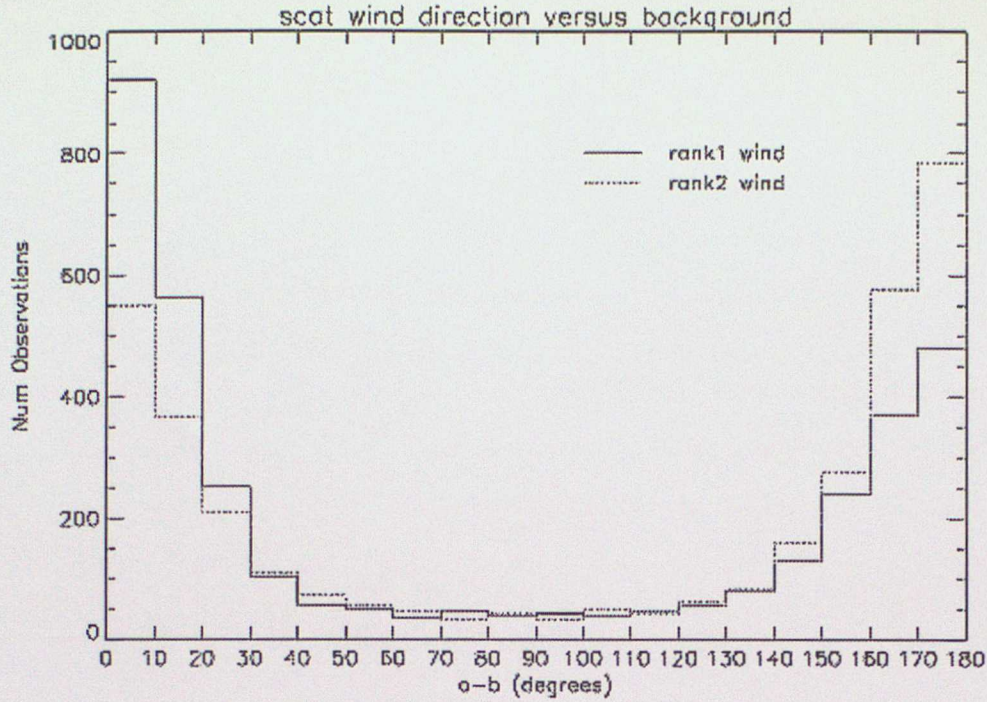
$$\hat{J} = \frac{1}{SD^2} \sum_{i=1}^3 (z_{moi} - z_{obsi})^2 \quad (2)$$

where the  $z$  transformation ( $z = (\sigma^0)^{0.625}$ ) results in a more circular cross section for the CMOD4 cone which aids the minimisation process.  $SD$  is an estimation of the scatter normal to the cone surface due to both instrument noise and uncertainty in the backscatter model. Stoffelen and Anderson (1997c) empirically derived this to be a function of the observed backscatter triplet, incidence angle and windspeed.

In most cases two minima are found approximately  $180^\circ$  apart resulting in two wind vector solutions and an upwind-downwind ambiguity. There is little skill in the minimisation process for removing this ambiguity as Figure 2 shows. The Rank1 solution has the smallest value of  $\hat{J}$  with Rank2 the next smallest; in general  $\hat{J}_1$  and  $\hat{J}_2$  are very similar values. In some cases a third and fourth solution exist, but at much larger values of  $\hat{J}$  and so are ignored.

The value of  $\hat{J}_1$ , can be used to quality control observations. If it is large for an observation then this implies that the observed backscatter triplet does not fit the model closely, which can be due to a number of reasons such as ice, rain, land contamination, or a highly variable wind vector within the observation footprint. Even changes to the orbit of the satellite platform can raise the value of  $\hat{J}_1$  by causing biases in the observed backscatter. In these situations it is likely that the retrieved wind pair will not represent the actual surface wind and so the observation should be rejected. In order to compare the likelihood of poor retrievals between observations the estimated scatter normal to the model needs to be well characterised as a function of node (incidence angle) and windspeed.  $\hat{J}_1$  is also found to vary across the node values and so the quality indicator used (referred to as 'distance to cone') is normalised by node:





**Figure 2** The difference in the retrieved scatterometer wind direction against the background (T+6) NWP wind field for the wind pairs.

$$D_{cone} = \sqrt{\frac{\hat{J}_1}{\langle \hat{J}_{node} \rangle}} \quad (3)$$

where  $\langle \hat{J}_{node} \rangle$  is the mean observed value of  $\hat{J}_1$  for each node across the swath. The expected value for  $D_{cone}$  is unity; for ERS-2 data are rejected if they exceed a value of 2.5.

In addition to using distance to cone values the following quality tests are performed on the data:

- Rejecting observations contaminated by land (via flags in the satellite data)
- Rejecting windspeeds outside the range (2-25 ms<sup>-1</sup>)
- Rejecting observations on or close to the sea-ice edge (using latest NWP sea-ice and sea surface temperature analyses)

Since the analysis grid is at a lower resolution than the scatterometer the observations are thinned prior to their use in the assimilation scheme to 1 per 100 km (or roughly 1 in 16 observations), which also removes the use of neighbouring observations in the swath whose errors can be highly correlated.



### 3. Assimilation of Wind Pairs

The Met Office's global data assimilation scheme uses a variational method (Lorenc *et al.*, 2000). This involves finding, by successive iterations, the atmospheric state which minimises a global cost function consisting of an observation term and a background forecast term:

$$J = J_o + J_b \quad (4)$$

where the observation cost,  $J_o$ , is a sum of the contributions from each observation to be used in the analysis. Normally for an observation such as a wind vector recorded from a ship the cost is a quadratic function of the deviation from the latest atmospheric state inversely weighted by the estimated observation error. For scatterometer winds there is an upwind/downwind ambiguity which needs to be resolved before the observation can be successfully assimilated. Prior to the variational approach the ambiguity removal was performed upstream of the assimilation, but if a two wind cost function is constructed then either wind can influence the analysis, depending on the latest atmospheric state. The approach is similar to that used at DNMI (Schyberg & Breivik, 1998) except here we account for the possibility of erroneous observations where neither wind is correct (following Lorenc & Hammon, 1988).

If each wind in an observation pair is considered to have a gaussian distribution due to random errors, whilst a flat distribution represents gross errors, then the total probability distribution function,  $P(u,v)$ , is the following:

$$P(u, v) = \sum_{i=1}^2 P_i \frac{1}{2\pi s^2} e^{-j_i} + P_g k \quad (5)$$

where

$$j_i = \frac{1}{2} \frac{(u - u_i^{ob})^2 + (v - v_i^{ob})^2}{s^2} \quad (6)$$

and:

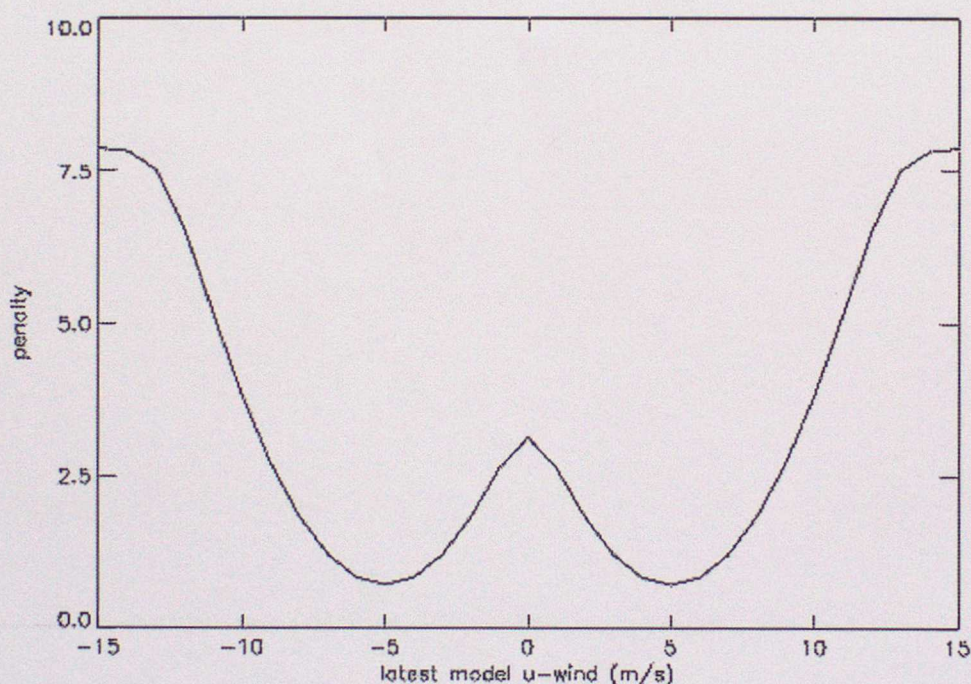
- $P_i$  = the *a priori* probability that wind  $i$  of the pair is the correct one
- $P_g$  = the *a priori* probability that the observation is erroneous ( $\sum P_i + P_g = 1$ )
- $k$  = constant representing a gross error distribution over a large but finite range,  $\frac{1}{\sqrt{k}}$  in  $u$  and  $v$  since  $\iint k du dv = 1$
- $u$  = latest atmospheric state estimate of the  $u$  component of the 10m wind
- $u_i^{ob}$  =  $u$  component of each ambiguous wind
- $v$  = latest atmospheric state estimate of the  $v$  component of the 10m wind
- $v_i^{ob}$  =  $v$  component of each ambiguous wind

The cost function is then formed by taking the negative natural logarithm (Lorenc, 1986) :



$$J_{scat} = -\ln(P(u, v)) = -\ln\left(\sum_{i=1}^2 P_i e^{-j_i} + P_g 2\pi s^2 k\right) \quad (7)$$

The function is shown in Figure 3 for a wind pair with a windspeed of  $5\text{ms}^{-1}$ . The *a priori* probabilities regarding the ambiguity ( $P_1$  &  $P_2$ ) control the dept of the two minima of the function and in practice we set  $P_1 = P_2$  as the wind retrieval contains little skill in discriminating between the upwind and downwind solution (e.g. as in Figure 2). Figure 3 shows that if, for example, the latest state is a westerly flow, then the observation at  $u=+5\text{ ms}^{-1}$  is effectively 'chosen' and will influence, through the minimisation of the total cost, the resulting analysis. However the decision on which wind influences the analysis is not fixed at the start of the minimisation; it can change as the latest atmospheric state evolves. By using this approach a combination of neighbouring independent observations (e.g. ship winds) and the background short range NWP forecast (which itself contains information from previous observations) is used to choose the correct wind.



**Figure 3** The scatterometer observation cost function for ambiguous winds (taken along the  $v=0$  line). The ambiguous wind pair are at  $u=5, v=0$  &  $u=-5, v=0$ . The *a priori* probability of gross error is non-zero.

The scatterometer cost function also includes quality control. If  $P_g$ , the *a priori* probability that the complete observation is erroneous, is set to zero then even if the latest state is far from the observation one of the winds will influence the analysis, since its contribution to the gradient of the total cost function is always non-zero. In the old scheme scatterometer observations had quality control applied prior to the analysis step. This consisted of comparing each observation to a background short-range forecast and those with large deviations from the forecast wind field were



rejected. The problem with such a scheme is that if the background forecast is very wrong in, say, describing the position of a storm, then such a test will remove the very observations that could be used to improve the subsequent analysis! The variational quality control method that has been applied to the cost function is based on that described by Andersson & Järvinen (1999). Initially in the analysis process  $P_g$  is set to 0 and so all scatterometer observations can influence the atmospheric state. Then after about half the iterations in the analysis process  $P_g$  is set to 0.01 which activates the quality control. As is shown in Figure 3 if any observation is still far from the latest atmospheric state it is rejected and plays no further part in forming the analysis as in these cases the contribution to the gradient of the cost function is now zero. Further details on the application of quality control via the cost function can be found in Appendix 1.

Whilst the prior rejection technique is performed separately on each observation, the variational technique allows information from across the satellite swath to influence the analysis (e.g. in repositioning a low pressure centre) prior to switching on the quality control term. If any observations are still far from the latest atmospheric state they are rejected in the second half of the analysis process. In this way it is possible for the evolving analysis to discriminate between good and bad scatterometer observations, providing of course that the incidence of erroneous observations is low.

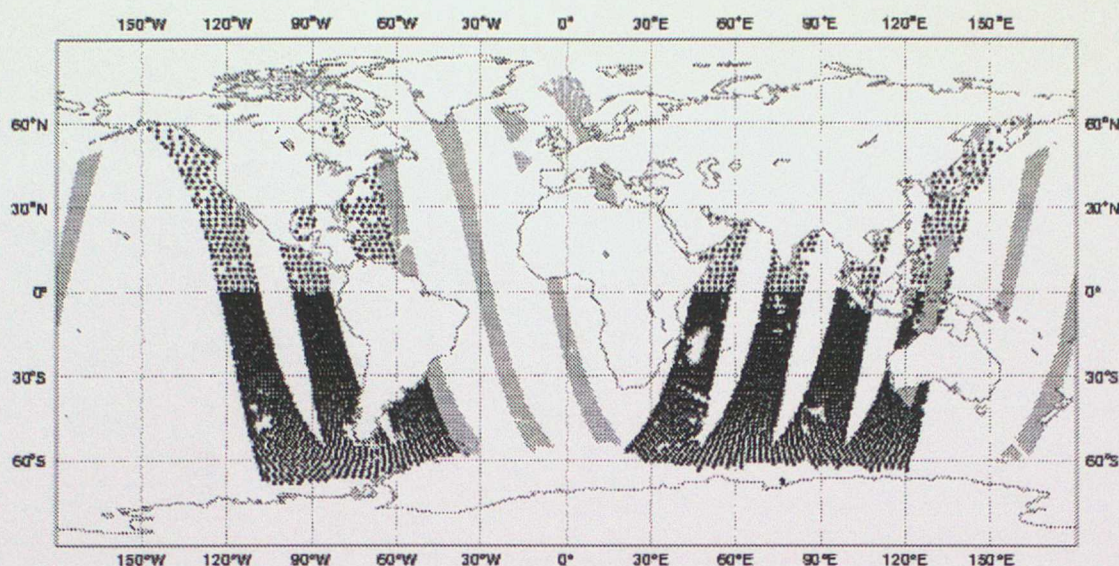
## **4. Forecast Impact Trials**

### **4.1 Introduction**

To test this new use of scatterometer winds two trials were run of the Met Office's global atmospheric model over the periods covering December 1999 and July 2000. For each period a control run was performed based on the current operational configuration of the model and excluding the use of scatterometer winds. A test run was then performed in which scatterometer winds were also assimilated.

Operationally the model currently uses another source of satellite near-surface ocean winds (speed only) from the passive Special Sensor Microwave/Imager (SSM/I) instrument. Previous studies by Ridley & Ballard (2000) suggest that assimilating scatterometer data (retrieved by the old operational scheme) and SSM/I wind data can deliver a small, but measurable, impact on forecast skill when compared with analyses containing only SSM/I wind data. This can in part be attributed to the orbits of the SSM/I and the scatterometer platforms. Figure 4 shows for a six hour assimilation period the scatterometer swath fills in regions 'missed' by the SSM/I instrument.





**Figure 4.** Data from the ERS-2 scatterometer (grey swath) and SSM/I (black swath) which can be assimilated in a typical six hour period. The SSM/I platform is DMSP 14. SSM/I data are thinned to 1 observation every 100km in the Northern Hemisphere.

So in the following trials of the scatterometer scheme a small positive impact is also expected. At the Met Office global model forecast skill is expressed as a weighted sum for various parameters (pmsl, aviation level winds, etc) and forecasts can be verified against preceding analyses or observations.

In addition to this we also use wind observations from the ERS-2 altimeter as an independent validation source to measure the improvement in the wind forecasts. Comparisons with *in situ* data (e.g. Cotton et al., 1997) show that the accuracy of the altimeter windspeed retrievals are  $\sim 1.4 \text{ ms}^{-1}$  and so are comparable to those from the scatterometer.

#### 4.2 December 1999 Trial

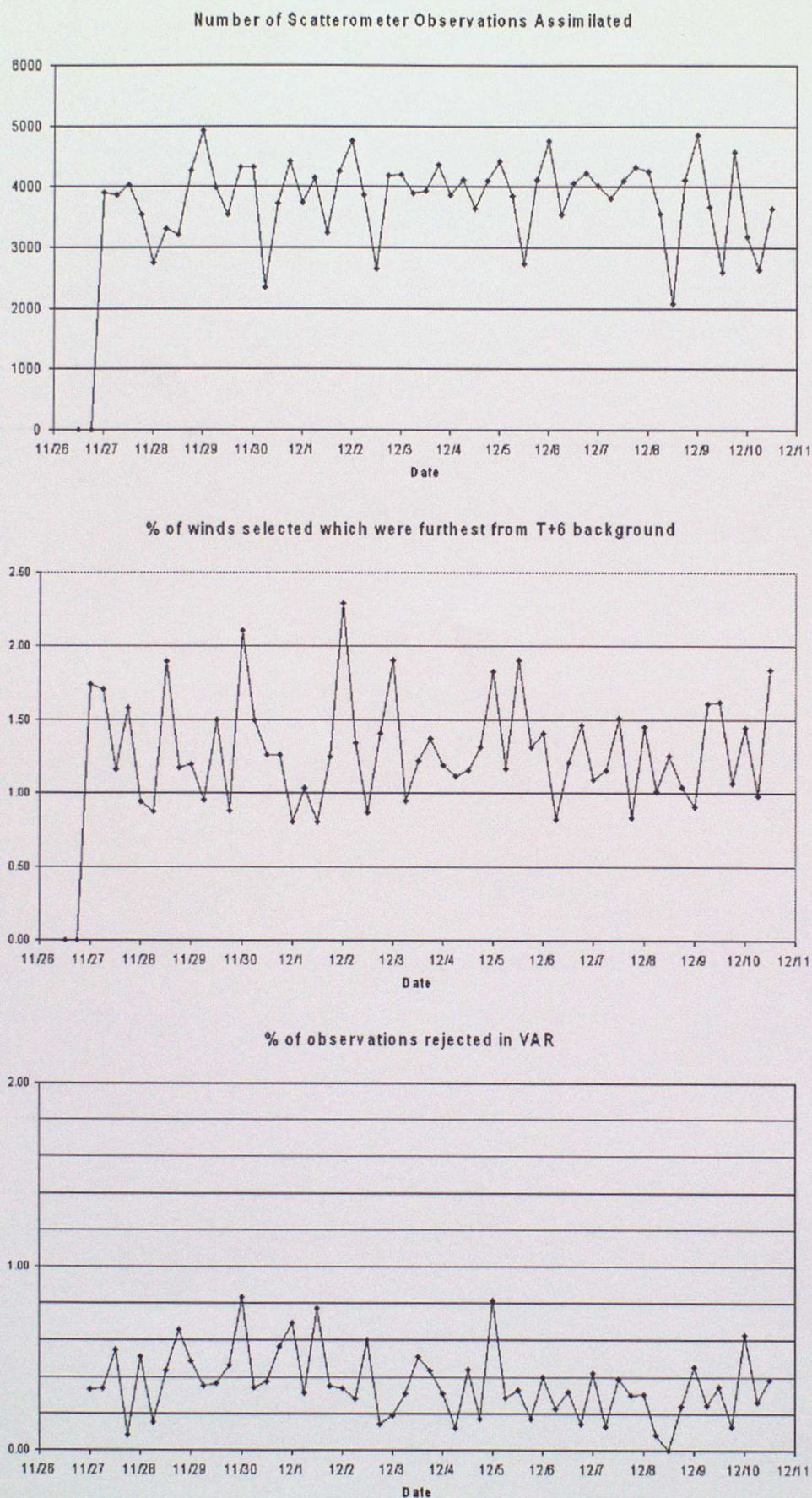
Figure 5 summarises the scatterometer data used during the trial, which ran from the 26<sup>th</sup> November through to the 18<sup>th</sup> December. In any six hour analysis period about 4000 scatterometer observations are passed to the assimilation scheme (cf. other ocean wind data: 600 ship observations; 5000 SSM/I observations). The lower two panels of Figure 5 highlight the performance of the assimilation scheme. During the analysis about 1% of the winds 'flip over' in the sense that the wind chosen as closest to the six hour background forecast is discarded and the other wind solution is used to influence the analysis. This tends to occur in tropical regions where the windspeed is low and the direction is probably poorly defined in the background forecast.

The lower panel shows the number of observations that are rejected by the assimilation scheme after quality control has been switched on, typically this is a low number. During the generation of the analysis observations with an updated probability of gross error exceeding 0.75 are considered rejected.



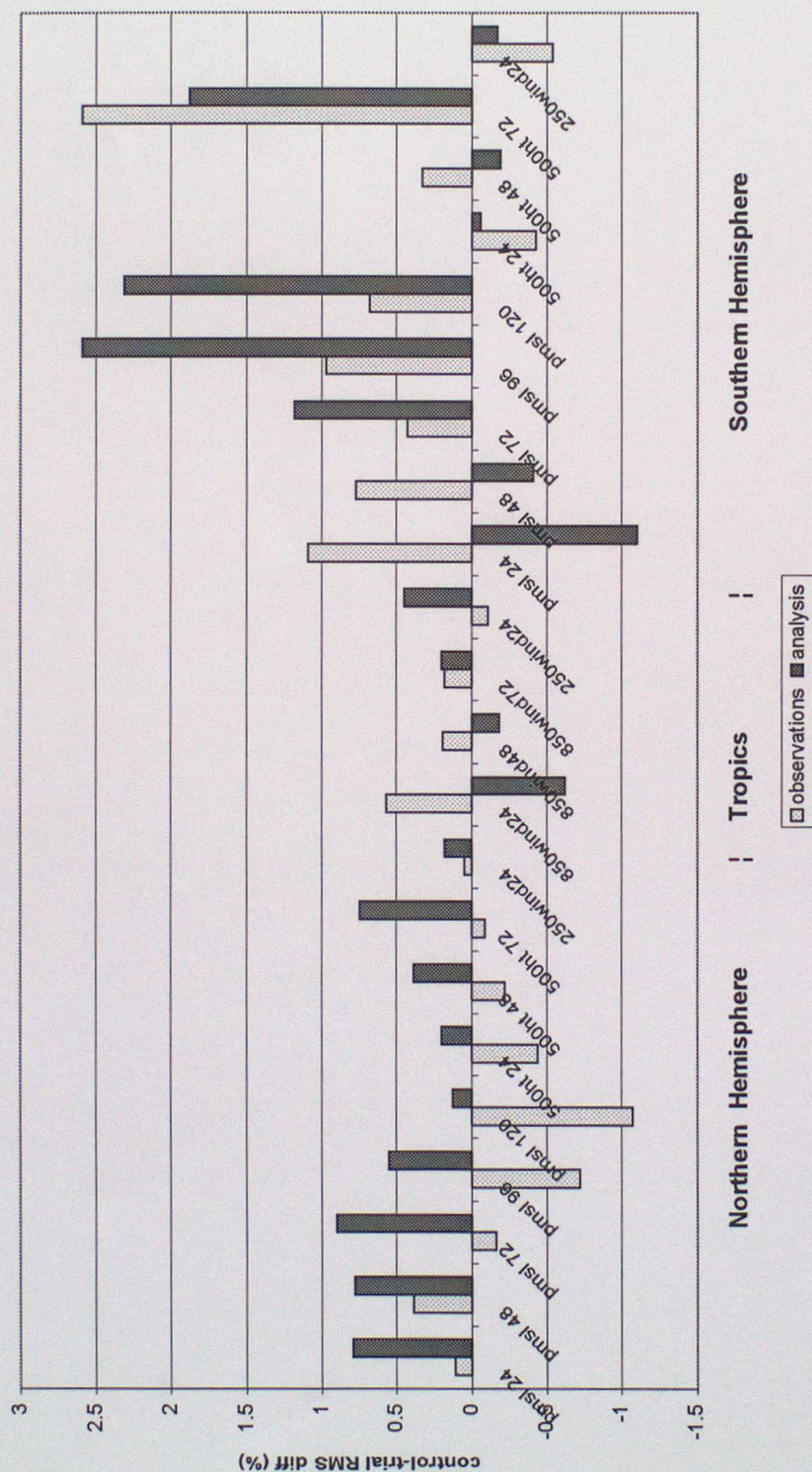
For the 21 days of the trial the mean improvement in the rms forecast errors using both analyses and observations to verify the forecasts are shown in Figure 6. The largest improvements are in the Southern Hemisphere, in particular the medium-range forecasts of pmsl and 500 hPa height where they are  $\sim 2\%$ . In the case of verification against analyses there is also improvement in the Northern Hemisphere pmsl forecasts, though much reduced. For verification using observations there is evidence of a detriment in forecast accuracy for the Northern Hemisphere pmsl forecasts. This could be associated with the treatment of scatterometer data close to the Arctic ice edge and is discussed in the next section. Overall, the impact on the NWP index was a small positive improvement;  $+0.2\%$  with respect to analyses and  $+0.1\%$  with respect to observations.





**Figure 5** A summary of the December 1999 trial. Each data point represents a 6-hour assimilation cycle.

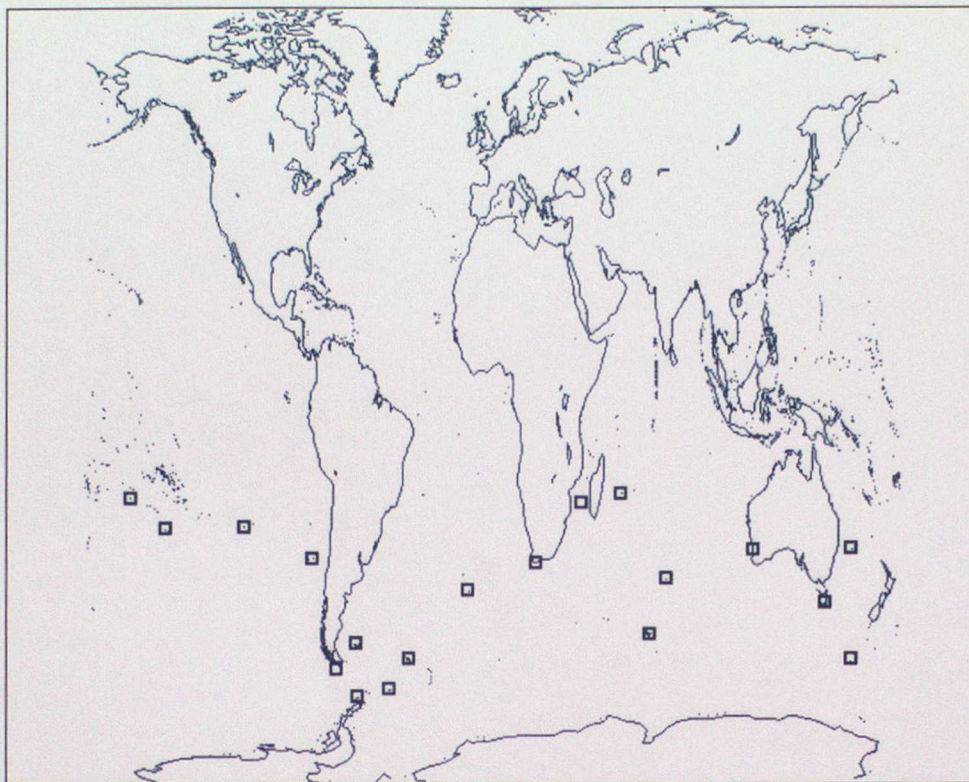




**Figure 6** The improvement in the RMS forecast errors for various parameters during the December 1999 scatterometer trial. Parameters 1 to 8 are for the Northern Hemisphere, parameters 9 to 13 are for the Tropics and parameters 14 to 22 are for the Southern Hemisphere.



Since the scatterometer changes the lowest analysis levels and is only used over the ocean, to obtain a better estimate on the improvement of the forecasts twenty synoptic stations were selected in the Southern Hemisphere (Figure 7). Coastal stations were selected whose height above sea level did not exceed 50m.

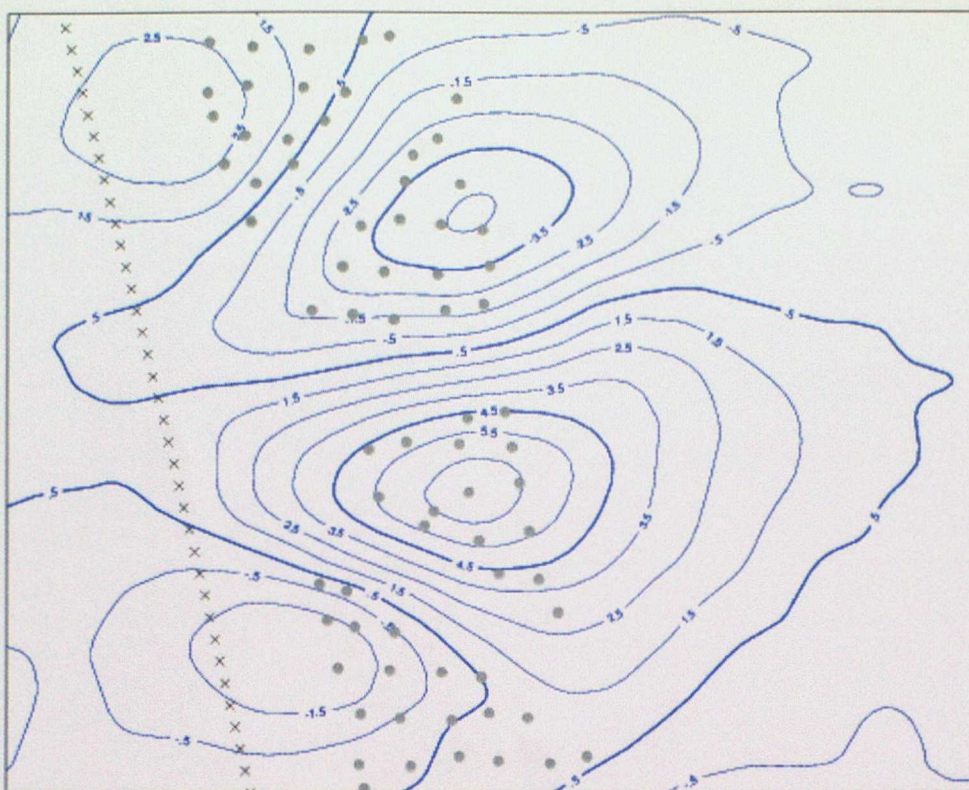


**Figure 7** Coastal Stations used to validate short-range wind forecasts.

Using these stations as verification sites the mean improvement for the wind strength forecast when scatterometer observations are assimilated was found to be 1.7% for the 6 hour forecast and 1.9% for the 24 hour forecast. Similarly the rms difference between global SSM/I retrievals of windspeed and the six hour forecast improved by 2% when scatterometer data are assimilated.

Both the SSM/I and coastal data are assimilated into the NWP model. A better test of the changes in forecast skill is to compare against independent data that does not influence the model forecasts. An example is ERS-2 altimeter data which has the advantage that it is almost co-located with the scatterometer. Figure 8 shows that whilst the nadir-looking altimeter footprint is offset from the scatterometer swath by 250km, the analysis increments due to the scatterometer spread out across the altimeter swath. The altimeter then is ideal for measuring the changes in the analysis due to inclusion of scatterometer data.





**Figure 8** The analysis – 6 hour forecast difference in  $u$  at 10m over a tropical cyclone for an assimilation using scatterometer data. The scatterometer winds which were used are overlaid as circles, whilst the altimeter track is overlaid as crosses.

These analysis changes along with the short range forecast improvements are shown in Table 1. The comparisons were made for a two week period within the trial for short-range forecasts at valid at 12z. The analyses and forecasts with scatterometer data fit closer to the altimeter winds, with the largest improvements in the Southern Hemisphere and Tropics.

Forecast	Improvement in the rms fit to altimeter winds (%)		
	Southern Hemisphere (pole to 30°S)	Tropics (between 30°S & 30°N)	Northern Hemisphere (pole to 30°N)
Analysis	12.0	9.5	1.9
6 hour forecast	2.2	1.6	0.0
24 hour forecast	1.1	1.1	-0.8

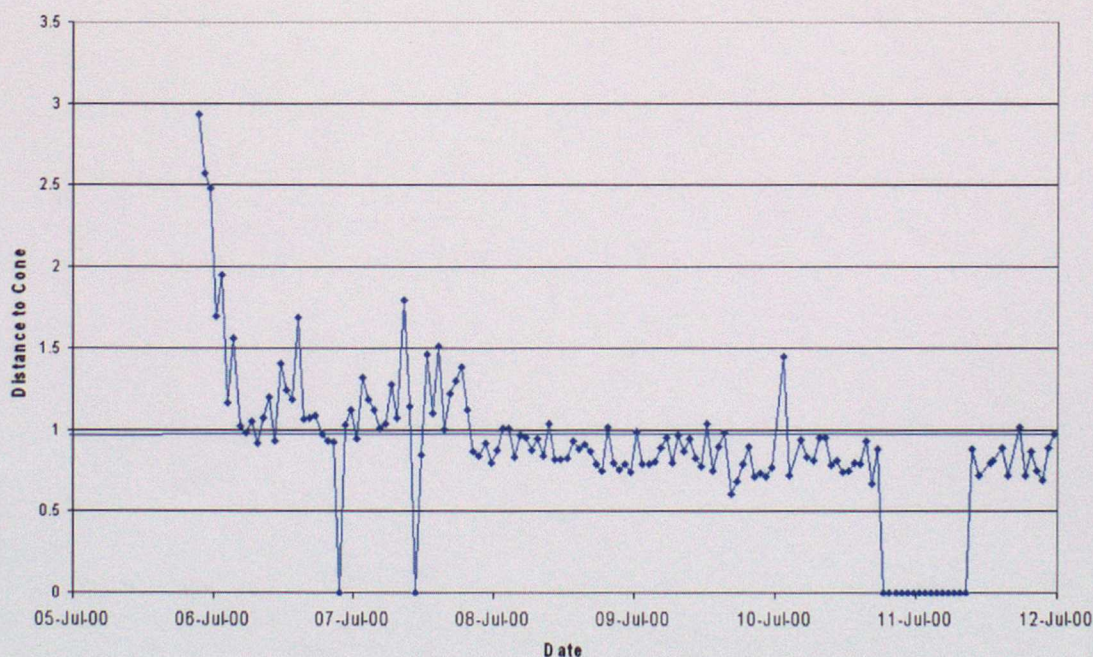
**Table 1** The improvement in the rms difference between altimeter observations and short-range NWP model forecasts during December 1999 when scatterometer data are assimilated.



### 4.3 Summer 2000 Trial

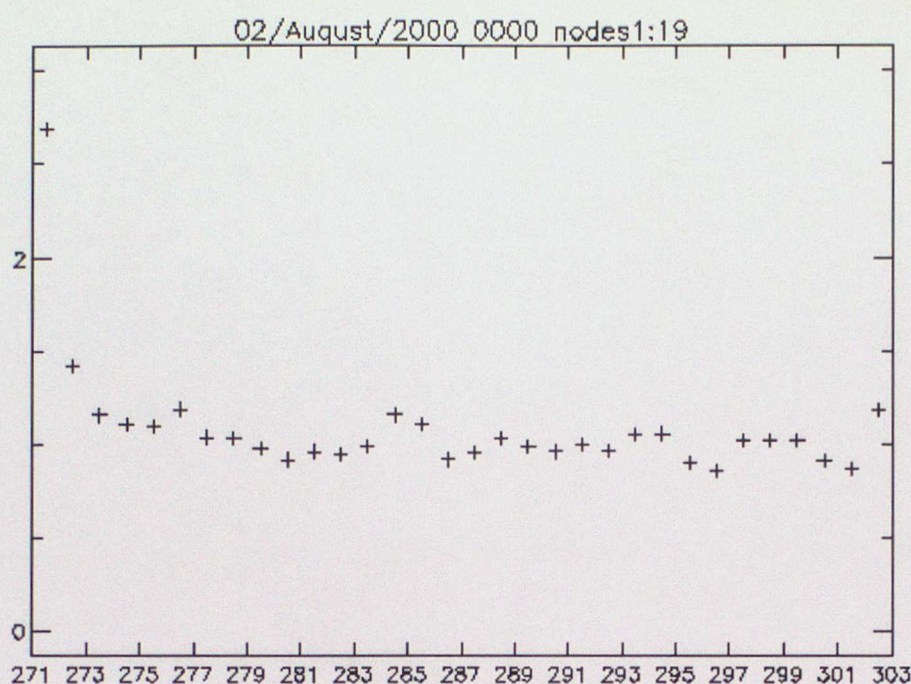
It was intended to run this trial with data from the month of July, however the ERS-2 platform suffered an outage between the 1<sup>st</sup> and the 5<sup>th</sup> July, following an anomaly in the operation of the radar altimeter. Operation of the scatterometer recommenced on the 5<sup>th</sup>, but monitoring of the wind retrieval via the distance to cone parameter (Figure 9) revealed that the data did not agree with the backscatter model. This was due to the attitude of the spacecraft as it was placed in Fine Pointing Mode (FPM). Normally the platform operates under Yaw Steering Mode (YSM) in which the direction of the pitch axis oscillates slightly during each orbit. However in FPM the onboard filters only partially compensate for the doppler shift in the return signal, resulting in errors in the measured backscatter which can subsequently degrade wind retrieval. Figure 9 shows that the retrievals improve once the platform is operating in YSM, although there was a second short outage between the 10<sup>th</sup> & 11<sup>th</sup> July. Consequently the trial started on the 12<sup>th</sup> July 1999 and ran for 30 days.

Initial results of the improvements to the short range forecasts in the Southern Hemisphere were disappointing so results from the scatterometer quality control scheme were analysed, in particular the distance to cone values along the orbit. When these are averaged in intervals of the analysed sea surface temperature a clear trend can be seen of poor retrievals as the ice edge is approached, even when observations have been ice cleared using the latest NWP ice analysis (Figure 10). A possible reason for this is that the analysis underestimates the extent of the marginal ice zone. Based on Figure 10 an SST cutoff of 273.15K was applied as an extra quality test to the observations, which effectively makes the ice edge more conservative. The summer trial was then rerun with this extra quality test.



**Figure 9** Distance to cone values ( $D_{cone}$ ) averaged over hourly intervals. A value of zero denotes missing observations.





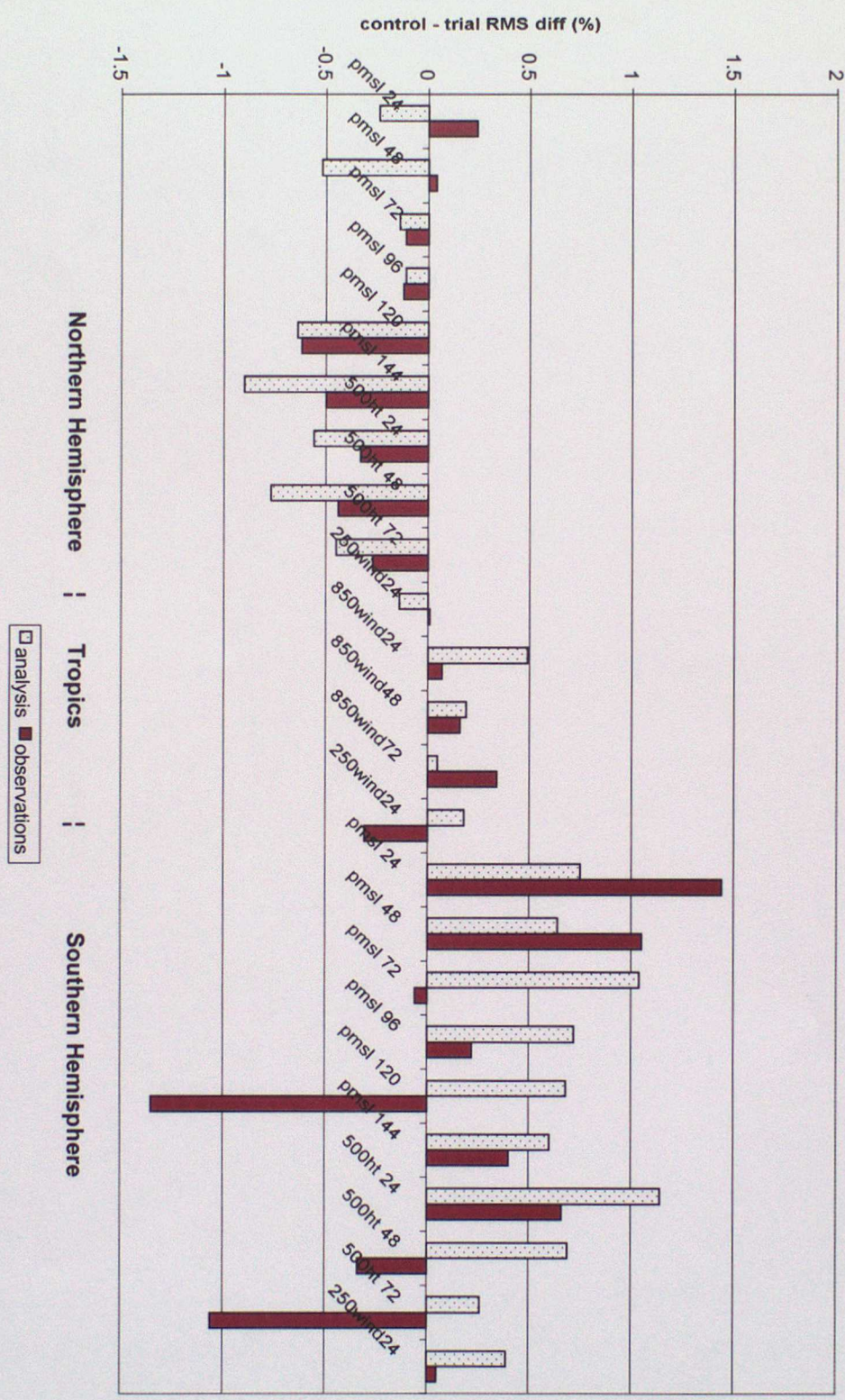
**Figure 10** Distance to cone values ( $D_{cone}$ ) averaged over degree intervals of Sea Surface Temperature(units: K) from the global analysis. The observations have been screened for ice using the model sea-ice analysis valid for the day of interest.

The mean improvement in the forecast errors for the 30 days of the trial are shown in Figure 11, as before the forecasts are verified using analyses and observations. With the exception of the longer-range forecasts, the addition of scatterometer data has improved the forecast errors in the Southern Hemisphere. In contrast, the Northern Hemisphere forecast errors have been degraded by inclusion of the data. Overall the NWP index (verified against observations) fell by 0.1%. In spite of this, verification using the altimeter again shows encouraging improvements in the analysis and in short range forecasts (Table 2).

Forecast	Improvement in the rms fit to altimeter winds (%)		
	Southern Hemisphere (pole to 30°S)	Tropics (between 30°S & 30°N)	Northern Hemisphere (pole to 30°N)
Analysis	6.9	9.5	9.1
6 hour forecast	1.4	0.4	2.4
24 hour forecast	-0.6	1.1	1.3

**Table 2** The improvement in the rms difference between altimeter observations and short-range NWP model forecasts during July 2000 when scatterometer data are assimilated.





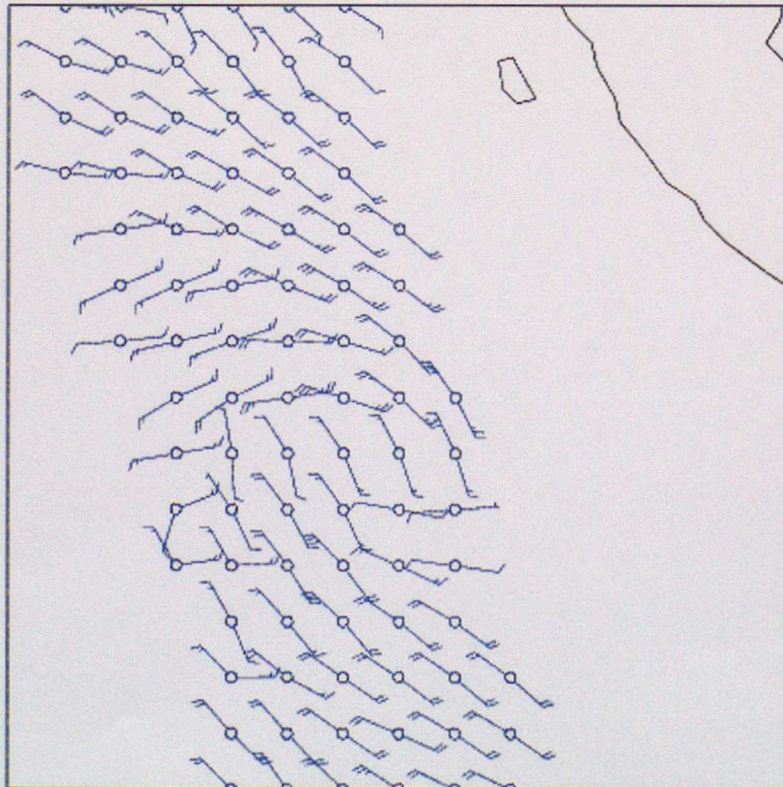
**Figure 11** The improvement in the RMS forecast errors for various parameters during the July 2000 scatterometer trial. Parameters 1 to 8 are for the Northern Hemisphere, parameters 9 to 13 are for the Tropics and parameters 14 to 22 are for the Southern Hemisphere.



## 5. Case Study: Forecast of a Tropical Cyclone

The previous section has shown that a general improvement is found to the short and medium range forecasts when scatterometer data are assimilated. However the scatterometer can make a large impact on forecasts of particular weather systems, e.g. tropical and mid-latitude cyclones. The largest improvement in the tropical pmsl & 500mb height forecasts, as measured by the anomaly correlation coefficient, was between the 11<sup>th</sup> and 14<sup>th</sup> December 1999. During these this period four tropical cyclones were active, including Tropical Storm Ilsa which was first viewed by the scatterometer on the 9<sup>th</sup> December. The overpass reveals a developing low centre (Figure 12).

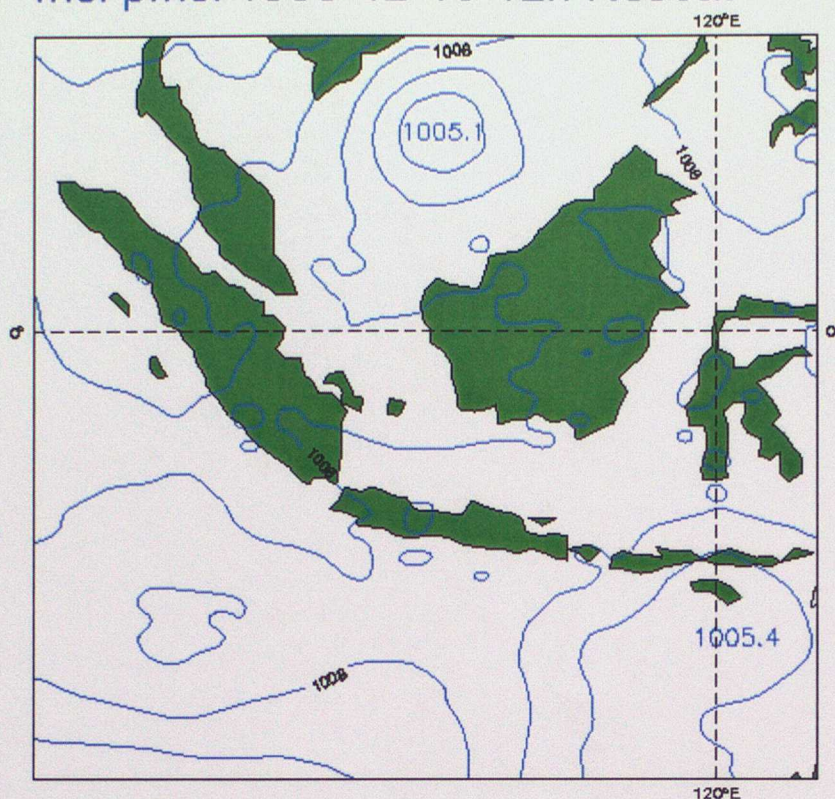
The scatterometer made a second (partial) overpass of the storm on the 10<sup>th</sup> Dec (at 6z) and these two sets of observations helped to define Ilsa in the analysis. Figure 13 shows that the trial analysis has a deeper low pressure centre than the control for a cyclonic system located south of the Indonesian island of Sumatra. Resulting forecasts from these analyses (Figures 14 & 15) are markedly different, the deeper cyclone in the scatterometer trial has strengthened in the forecast, whilst in the control forecast it is missing. Overlaid on the forecasts are the reported locations of the two observed tropical cyclones in the area and the trial forecast of Ilsa is very close to its reported position. Such cyclone reports, made via satellite imagery, are used to form 'Bogus Observations' which initialise cyclones in the analysis (see Heming et al, 1995 for further details). Bogus observations for Ilsa were available from 18z onwards on the 10<sup>th</sup> December, yet prior to this successive assimilations of scatterometer data have resulted in a good short-range forecast of the system.



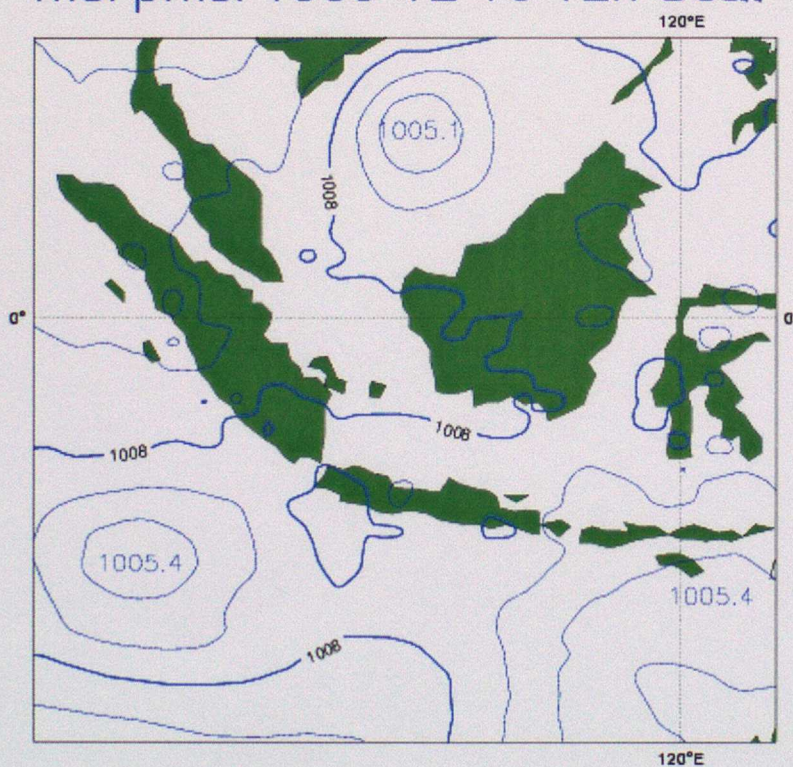
**Figure 12** Scatterometer observations of Tropical Storm Ilsa made on 9<sup>th</sup> December 1999 (18z). Each observation consists of an ambiguous wind pair.



msl pmsl 1999-12-10 12h Noscot



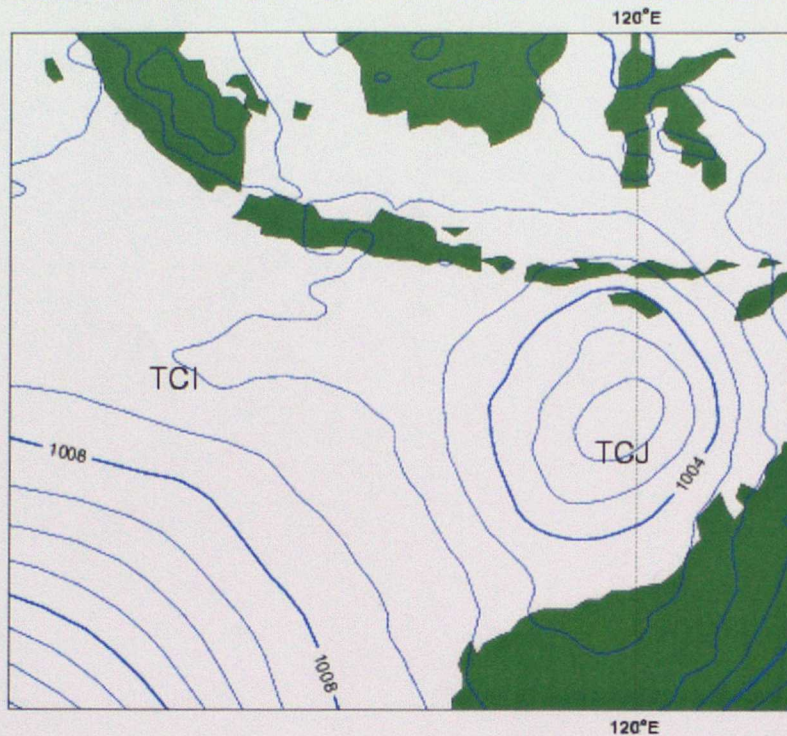
msl pmsl 1999-12-10 12h Scat



**Figure 13** Control (NoScat) & Trial (Scat) pmsl analyses for 10<sup>th</sup> December 1999.

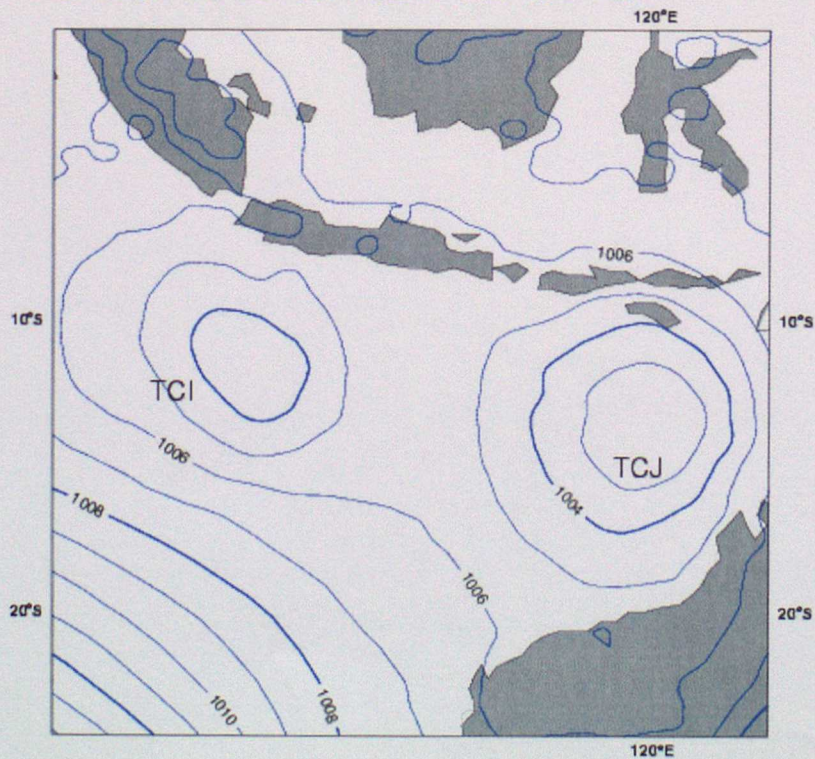


## NOSCAT t+48 vt:1999-12-12 12h



**Figure 14** 48-hour pmsl forecasts from the noscat analysis (previous figure) The reported locations of tropical cyclones Ilsa (TCI) and John (TCJ) at the validity time of the forecast are also overlaid.

## SCAT t+48 vt:1999-12-12 12h



**Figure 15** As Figure 14 but for the experiment containing scatterometer data.



## 6. Conclusions

This report has outlined a method to use ambiguous scatterometer winds in a 3D variational analysis scheme. The winds are ambiguous in the sense that there is a choice in the direction of the retrieved wind for each observation and we deal with this problem by creating a dual wind observation cost function. This approach removes the need for a step prior to assimilation in which the most likely wind is chosen from each vector pair. In the new scheme this choice is made as the global cost function is minimised, and so will be influenced by both the background and other independent observations.

Two forecast trials have been completed which allowed the comparison of assimilating scatterometer winds via the new method against control assimilations with no scatterometer data. For both winter and summer seasons the largest improvements were in the Southern Hemisphere forecasts of pmsl, in the short range (up to T+48 hours) for the NH summer case and in the medium range (T+72) for the NH winter case. Evidence has also been found that scatterometer data can improve the forecasts of developing tropical cyclones.

This work has concentrated on observations from the ERS-2 instrument. Throughout the two trial periods the quality of these observations was good, apart from early in July 2000 when the platform underwent changes in its attitude. Such changes degrade the retrieved winds, but can be identified by monitoring the distance to cone parameter. An extension to the work described here is the inclusion of automatic monitoring of this parameter, on an orbit by orbit basis, and subsequent rejection of all data in a six hour window if it exceeds a given limit.

At the time of writing ERS-2's successor will be ASCAT on Metop-1, which is due for launch in 2005. It seems likely that there will be a gap in observations from fan beam instruments and so a future development of the scheme will be to apply the variational technique described here to the Seawinds series of rotating beam scatterometer instruments.

## 7. PostScript: Transition to Operations

Based on the results presented here the scatterometer assimilation package was accepted for inclusion into the Met Office's operational suite. However prior to the change day (13<sup>th</sup> February 2001) another gyro on the ERS-2 platform failed, leaving one useable gyro onboard. Since this failure the platform has been placed out of YSM and so currently the measured  $\sigma^0$ s are not of sufficient quality to be used operationally. A  $\sigma^0$  bias correction scheme is planned by ESA and hopefully this will be implemented within the coming months, allowing the re-introduction of ERS-2 observations into the operational analyses.



## 8. Acknowledgements

The wind retrieval code was based on an original version written by Dave Offiler. Andrew Lorenc proposed both the variational quality control term and the quadratic approximation to the scatterometer penalty function. Aaron Berney, Adam Maycock and Adam Clayton also gave much advice to the author in the design and testing of various UM software components.

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## **Appendix 1 Quality Control via the Scatterometer Cost Function**

The gradient of Equation 7 can be determined as partial derivatives in  $u$  and  $v$ , i.e.

$$\frac{\partial}{\partial \underline{v}} = \begin{pmatrix} \frac{\partial}{\partial u} \\ \frac{\partial}{\partial v} \end{pmatrix} \quad (A1)$$

which produces:

$$\frac{\partial J_{scat}}{\partial \underline{v}} = \sum_{i=1,2} P_i^n \left( \frac{\partial j_i}{\partial \underline{v}} \right) \quad (A2)$$

where  $P_i^n$  scales the gradient contribution from each wind. It is of the form:

$$P_i^n = \frac{P_i e^{-j_i}}{\sum_{m=1,2} P_m e^{-j_m} + P_g 2\pi s^2 k} \quad (A3)$$

Hence when both winds are far from the latest state,  $j_i$  (Equation 6) is large, resulting in small latest state probabilities for both winds which in turn means that the gradient of the cost function is small and so the observation is given little weight in forming the analysis.

This can be expressed in an alternative fashion since the term  $(1 - \sum P_i^n)$  can be shown to be equal to the updated probability of gross error,  $P_g^{new}$  (Andersson & Jarvinen, 1999; Ingleby & Lorenc, 1993), assuming that the latest atmospheric state is correct. Hence when  $P_g^{new}$  is large the observation has little weight in the analysis.