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407

Impact of ERS Scatterometer Winds in ECMWF's Assimilation System

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Abstract

The impact of ERS scatterometer winds on the European Centre for Medium-Range Weather Forecasts (ECMWF) three-dimensional variational (3D-Var) and four-dimensional variational (4D-Var) assimilation systems is investigated. ERS scatterometer winds are found to be of consistent high quality in comparison to other surface wind observations. Both 3D-Var and 4D-Var systems assimilate the data well and a small but significant positive impact is found on medium-range weather and wave forecasts. ERS scatterometer winds are not affected by rain or clouds, so they give valuable wind information near intense cyclones, tropical cyclones and in baroclinic regions. It is shown how the 4D-Var method allows for dynamically consistent propagation of the surface wind information in the vertical. Four case studies that highlight important aspects of ERS scatterometer wind assimilation are presented. The main drawback for the ERS scatterometer instrument is the rather narrow swath compared to most other satellite instruments.

1 Introduction

Surface wind observations over the oceans are needed for a wide range of meteorological and oceanographic applications. High quality surface winds are required to drive ocean circulation models and surface wave models. Knowledge of surface winds is also essential to calculate momentum, heat and moisture fluxes. Furthermore, surface wind data have the potential to provide unique and valuable information on the initial condition for numerical weather prediction.

Conventional surface wind observations from buoys (DRIBU) and ships (SHIP) are important components of the global observing system, but are limited in coverage. Buoys wind observations have high accuracy but sparse coverage as they are mostly located near coasts in the Northern Hemisphere. Ships only cover limited regions, tend to avoid the worst weather and their observations have at times poor accuracy.

Moore and Pierson (1967) were the first to propose the use of a space based scatterometer to measure wind speed and direction over the oceans. Their proposal opened up the possibility to obtain surface wind fields on a global scale and with high spatial resolution. A demonstration on Skylab in 1973 was followed by the launch of the first (14.6 GHz Ku-band) satellite scatterometer on SeaSat in 1978 (Grantham *et al*. 1997) . Seasat unfortunately failed after three months in operation. The next (5.3 GHz C-band) scatterometer was launched in 1991 on ERS-1 (Attema 1991), which was followed by ERS-2 in 1995, (14.0 GHz Ku-band) NSCAT in 1996 (Naderi *et al*. 1991) , (13.4 GHz Ku-band) SeaWinds instrument on QuikSCAT in 1999 (Lungu 2001) and a similar SeaWinds on Advanced Earth Observing Satellite-II (ADEOS-II) in 2002.

First attempts to use scatterometer data in weather analysis showed hardly any improvements in forecast skill. For example, Seasat scatterometer data impact studies (Baker *et al*. 1984 ; Duffy *et al*. 1984 ; Yu and McPherson 1984; Anderson *et al*. 1991) demonstrated potential for SeaSat winds to significantly change the surface analysis, but failed to show a measurable improvement in numerical weather prediction forecasts.

The first ERS scatterometer experiments, assimilating backscatter measurements, were performed by Hoffman (1993), followed by Stoffelen and Anderson (1997b) who assimilated ERS scatterometer wind data for eleven days (18–28 March 1993) in the then operational ECMWF assimilation system. These impact studies showed no improved forecast skill in the medium range. The analysis method was based on a multivariate, Optimum Interpolation (OI) scheme (Lorenc 1981). In contrast, the UKMO experience was more encouraging, Andrews and Bell (1998) found a 4% reduction in the five day southern hemisphere 500 mb geopotential height rms error for assimilation experiments covering the same period in 1993. Without scatterometer data the ECMWF forecasts were better than the UKMO's corresponding forecasts using scatterometer wind data (Stoffelen and Anderson 1997b). However, ECMWF's forecasts at that time were far from perfect so one would expect to see some positive impact from a high quality source like the scatterometer data. The forecast improvements by Andrews and Bell (1998) was most likely due to the introduction of an additional balance step that derived balanced surface pressure and potential temperature increments from wind increments.

On 30th of January 1996 ECMWF replaced the operational OI assimilation scheme with a 3D-Var scheme (Courtier *et al*. 1998) . The 3D-Var scheme had the potential to assimilate surface wind data better and to propagate surface wind data information better to pressure and temperature variables. Trials with the 3D-Var scheme showed that the scatterometer winds had favourable impact on atmospheric analysis and forecast and even on ocean wave analysis and forecast (Andersson *et al*. 1998) , therefore ERS-1 scatterometer data was included in the operational system.

ECMWF's 3D-Var assimilation system was upgraded to a 4D-Var assimilation system (Rabier *et al*. 2000 ; Mahfouf and Rabier 2000; Klinker *et al*. 2000) on 25th of November 1997, the fourth dimension being time. This system allows for a better treatment of asynoptic data such as scatterometer data and a more dynamically consistent propagation of surface data in the vertical, as first shown by Thépaut *et al*. (1993) . Impact studies on the benefit of variational assimilation of ERS scatterometer and NSCAT data have also been performed by Isaksen (1997), Tomassini *et al*. (1998) , Isaksen and Stoffelen (2000), Buehner (2002) and Leidner *et al*. (2003) . Atlas *et al*. (2001) gives a detailed review of assimilation impact of scatterometer wind data.

The objective of this paper is to document the impact of ERS scatterometer data on analysis and forecast in ECMWF's 3D-Var and 4D-Var assimilation systems. In particular, we study its impact in the operational 4D-Var system, and for the period 1993-2000 in the ECMWF 40 year Re-Analysis project (ERA-40) 3D-Var assimilation (Simmons and Gibson 2000). This is the first time ERS-1 scatterometer wind observations have been assimilated over an extended period and the first time ERA-40 surface wind assimilation results are published. A short description of the ERS-1/ERS-2 satellites, the scatterometer instrument and how the winds are derived is given in section 2. Section 2 also provides an assessment of the general quality of ERS scatterometer winds by a comparison against ECMWF short-range forecasts. The importance of performing a global quality control ensuring consistency of the backscatter scatterometer measurements during the data screening phase is emphasized. In section 3 it is described how scatterometer data are assimilated at ECMWF. Section 4 discusses how the large scale general analyses and forecasts are improved by assimilating ERS scatterometer wind data. The impact of scatterometer winds on the analysis is compared to the impact of surface winds from other observing systems. The scatterometer impact on forecasting weather and ocean waves is illustrated by a 29 day 3D-Var assimilation experiment during January 1999. In section 5 three case studies of scatterometer wind data impact on tropical cyclone assimilation are presented. For the first time it is illustrated how the 4D-Var assimilation system handles problems associated with ambiguous wind directions and how higher resolution models benefits assimilation of ERS winds. Section 5 finally presents the impact of scatterometer winds on a polar low analysis. Concluding remarks and a discussion of issues related to assimilation of ERS scatterometer wind data in ECMWF's variational assimilation system are given in section 6.

2 The ERS satellites and derived scatterometer winds

ERS-1 was launched by ESA in July 1991 and provided observations on sea state (Altimeter, SAR) and winds (scatterometer and Altimeter) in operational mode until June 1996. Since then it has continued in hibernating mode until it stopped functioning in December 1999. ERS-2 took over the operational data delivery from ERS-1 in June 1996 and is still functioning. ERS-1 and ERS-2 are very similar multi-instrument platforms, but in this paper only the impact of AMI scatterometer wind data (Attema 1991) will be investigated. Due to onboard gyroscope problems ERS-2 scatterometer winds of acceptable quality have not been available since January 2001, but good quality wind are expected to be distributed operationally again from the middle of 2003.

The AMI scatterometer instrument is a C-band (5.7 cm wavelength) active backscatter radar instrument. Due to the choice of wavelength rain and clouds do not contaminate the observations. Therefore, ERS is able to deliver wind measurements even near tropical cyclones and extra-tropical lows whereas temperature and humidity information from satellite sounding instruments is unreliable due to cloud and precipitation effects and SeaWinds data are not available due to potential rain contamination.

The scatterometer is an instrument that emits a microwave pulse under an incidence angle θ (for ERS between 18° and 57°). This radiation will be scattered and reflected and a small part of the emitted pulse will be returned to the detector of the instrument. Data is available for a 500 *km* data swath where values are accumulated for 50x50 km^2 ocean surface areas. Bragg scattering is thought to be the main mechanism for scattering. For Bragg scattering, the backscattered return is proportional to the spectral energy density of the ripple spectrum at the Bragg scattering wave length. The energy of the ripple spectrum at those wavelengths is found empirically to depend on the wind speed, U_{10}, and the propagation direction, ϕ, of the short waves relative to the wind direction. Hence, the corresponding normalised radar cross section, σ_0, is empirically given by

$$\sigma_0 = \sigma(\theta, U_{10}, \phi), \tag{1}$$

and an important task is to determine this empirical relationship in a reliable manner. This was achieved by Stoffelen and Anderson (1997a) by collocating backscatter observations with ECMWF analysed surface winds. The geophysical model function was called CMOD4. When CMOD4 was used in ECMWF's analysis system, Gaffard and Roquet (1995) found a considerable underestimation of wind speed in the high wind speed range, resulting in less deep lows (by as much as 8 hPa). As a consequence, the quality of the atmospheric forecast suffered. This problem with CMOD4 was alleviated by applying a wind speed dependent bias correction which was obtained by a comparison with buoy wind speed observations. Therefore a wind speed and incidence angle dependent bias correction of CMOD4 will be used throughout this paper.

Figure 1 shows the statistics for collocated ERS scatterometer winds and ECMWF ERA-40 background winds for a six months period in 1993. Because the quality of ERS data is very consistent it has been possible to apply

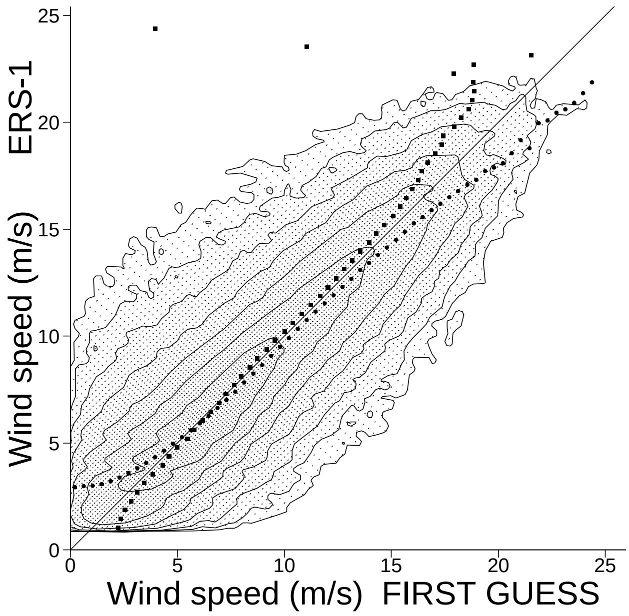


Figure 1: ECMWF six hour background 10 metre winds versus ERS scatterometer winds as used in ERA-40. All used ERS-1 data in ERA-40 during the period May-October 1993 is included (2080259 wind vectors). The obs-background bias is -0.02 ms^{-1} and standard deviation 1.62 ms^{-1}. The ERS wind vector ambiguity closest to the ECMWF background wind field is used for the statistics. The contouring represent the collocation data volume in dB.

a constant speed bias correction to CMOD4 for the whole ERS-1 mission period and a similar constant speed bias correction for the whole ERS-2 mission period. The simple bias correction method seems to works well. As seen in Fig. 1 the bias is only -0.02 ms^{-1} and standard deviation is only 1.62 ms^{-1}.

Scatterometer wind measurements from all launched instruments (SeaSat, ERS-1, ERS-2, NSCAT, SeaWinds on QuikSCAT and SeaWinds on ADEOS-II) suffer from the inability to determine one unique wind solution. This is caused by the fact that the scatterometer observes the state of short ocean surface gravity waves, which implies that they observe aspects of the frozen short wave spectrum. Hence, there is an ambiguity in wind direction. If only two beams are used, as in Seasat, the wind direction is determined only to within two to four possible solutions. In the 1980s this ambiguity was regarded a serious problem which was thought to prevent an optimal use of the surface wind information. For this reason the ERS active microwave instrument (AMI) was designed with three beams and, in principle, the solution is unique, but in the presence of unavoidable noise, there normally remains a residual 180° ambiguity (Stoffelen and Anderson 1997b). The added complications of this aspect for the assimilation system will be discussed in section 5.

3 How ERS scatterometer data is assimilated at ECMWF

ECMWF's 3D-Var and 4D-Var assimilation system use the incremental method (Courtier *et al*. 1994) to determine a modified model state $\mathbf{x}$ from the background state $\mathbf{x_b}$ at a start of the 6 or 12 hours assimilation window which minimizes the objective cost function J

$$J(\delta\mathbf{x}) = \delta\mathbf{x}^T\mathbf{B}^{-1}\delta\mathbf{x} + \sum_{i=1}^{TS}(\mathbf{H}_i\mathbf{M}_i\delta\mathbf{x} - \mathbf{d}_i)^T\mathbf{R}^{-1}(\mathbf{H}_i\mathbf{M}_i\delta\mathbf{x} - \mathbf{d}_i) + J_c \tag{2}$$

where $\delta\mathbf{x} = \mathbf{x} - \mathbf{x_b}$, $\mathbf{B}$ is the covariance matrix of background errors, $\mathbf{H}_i$ a tangent linear approximation of the observation operator H_i in the vicinity of $\mathbf{x}$ at time i at TS discrete 30 or 60 minute time-slots throughout the assimilation window. $\mathbf{M}_i$ is the tangent linear approximation of the forecast model M_i and $\mathbf{R}$ is the covariance matrix of observation errors. J_c represent a gravity wave constraint.

The innovations, $\mathbf{d}_i$, are calculated at high resolution at time-slots i:

$$\mathbf{d}_i = \mathbf{y}_i - H_iM_i\mathbf{x}_b \tag{3}$$

where $\mathbf{y}_i$ represents the observations at timeslot i.

The minimization is done iteratively, using a tangent linear/adjoint method. The incremental method allows efficient use of computational resources because the tangent linear and adjoint iterations can be performed at lower resolution (e.g. T_l159) than the innovation calculations (e.g. T_l511). The notation (T_l511/T_l159) will be used in this paper.

The cost function terms for conventional surface wind observations is represented by the quadratic expression

$$J_{conv}(d_u, d_v) = (\frac{d_u}{\sigma_u})^2 + (\frac{d_v}{\sigma_v})^2 \tag{4}$$

where d_u, d_v are wind component innovations and σ_u, σ_v are the associated standard deviations of background errors.

For ERS scatterometer the most likely solution and its approximate 180° ambiguity is supplied to the minimization problem, using the cost function devised by Stoffelen and Anderson (1997b)

$$J_{scat}(d_{u1}, d_{v1}, d_{u2}, d_{v2}) = (J_{conv}(d_{u1}, d_{v1})^{-4} + J_{conv}(d_{u2}, d_{v2})^{-4})^4 \tag{5}$$

where $d_{u1}, d_{v1}, d_{u2}, d_{v2}$ represent the two ambiguous scatterometer winds and the definition (4) is used.

This formulation allows for a dynamic selection of the correct wind vector from each ambiguous pair. The functional form is designed to have a stronger constraint for ambiguity removal than would have been the case using a pure maximum likelihood estimate based method like Lorenc (1988).

Based on the knowledge that σ_0 triplets represent wind measurements approximately belonging to a cone in the three-dimensional backscatter space (Cavanié and Lecomte 1987) Stoffelen and Anderson (1997a) devised a method whereby a normalised distance-to-the-cone measure gave a good estimate of the quality of the observation. This information is available for individual measurements and is used to discard measurements far away from the cone. During ERS orbital manoeuvres where the satellite platform wobbles, typically for a few hours, the observation error for the individual measurements is significantly increased, but often not enough to trigger individual data rejection. At ECMWF a powerful global quality control method has been developed whereby the average normalised distance-to-the-cone for each node across swath is calculated over one or six hourly periods making it possible clearly to detect orbital manoeuvres. Figs. 2(a) and (b) show six hourly average normalised distance-to-the-cone values for nodes 3-4 and 11-14, respectively, for a 25 day period. The values are close to one, except for 0600 UTC 25 August for nodes 11-14 where the average value is almost two. Because all observations are poor during orbital manoeuvres, the averaging makes the results statistically significant. The signal is clearest for higher node number which corresponds to higher incidence angles. The retrieved winds (Fig. 2c-d) are typically biased low by 2 ms^{-1} during such events for all nodes, because CMOD4 is supplied with an incidence angle that does not reflect the true measurement. It is often difficult for the assimilation system to identify through regular means that such measurements are corrupted because all scatterometer winds are internally consistent. Fig. 2(e) shows the erroneous ERS scatterometer winds east of Hawaii during the orbital manoeuvre and Fig. 2(f) shows ECMWF background winds. They have similar wind direction but ERS wind speeds are biased low by up to 5 ms^{-1} in the affected region. In ECMWF's assimilation system all ERS scatterometer observations are rejected if the average normalised distance-to-the-cone value for any node exceeds a statistically determined (two times standard deviation) threshold value.

4 General impact of ERS scatterometer winds in ECMWF's assimilation system

The assimilation of ERS scatterometer winds in Optimum Interpolation (OI) was first performed by Hoffman (1993). In Stoffelen and Anderson (1997b) the procedure applied in the OI-system is well described. The scatterometer data are quality controlled (QC) by checking for inconsistencies in the messages, checking the magnitude of the distance-to-the-cone, eliminating any possible land or ice contamination, rejecting wind speeds above 20 ms^{-1} and by performing a tight monitoring of all scatterometer data in batches of six hours (see Stoffelen and Anderson 1997b). Except for the ambiguity removal filter and a rejection wind speed limit of 25 ms^{-1} similar QC is also performed in the 3D-Var and 4D-Var assimilation system used here.

Forecast and comparison of observed values with model background values are performed at higher resolution, but the resolution of the minimization step is typically 120-250 km, therefore scatterometer winds are thinned to a resolution of 100 km before assimilation. We show later that the data, despite the thinning, still are valuable in the analyses of tropical cyclones. Stoffelen and van Beukering (1997), have shown that slight improvements of extra-tropical analyses can be obtained by averaging the scatterometer winds at 100 km resolution, but only the thinning method has been applied at ECMWF.

The main benefits of ERS scatterometer wind data are improved analyses and forecasts of severe weather systems, improved ocean surface wave forecasts, improved surface wind stress fields and improved surface

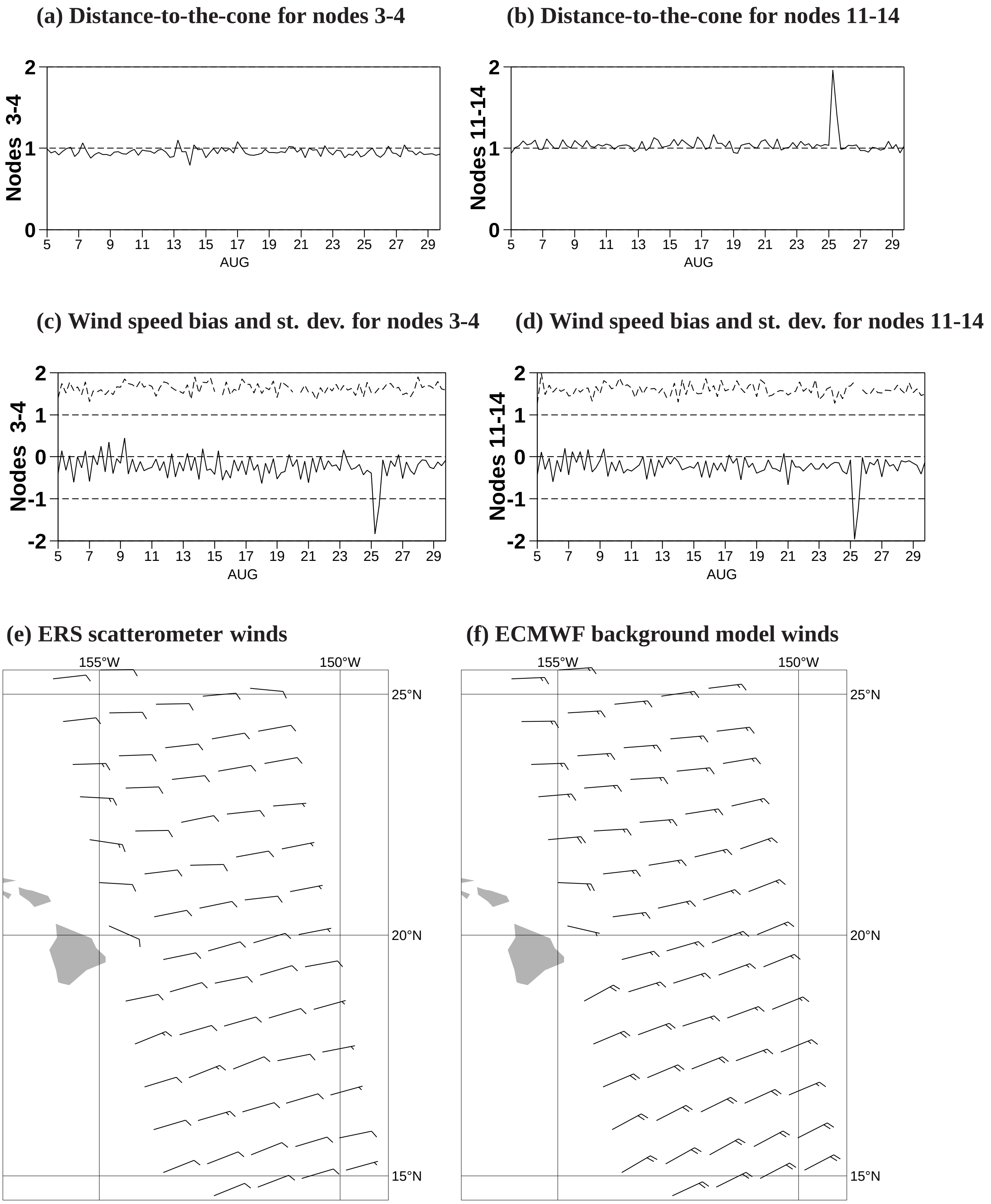


Figure 2: Normalised "distance to the cone" for nodes 3-4 (a) and nodes 11-14 (b) during a 25 day period in August 1998. The standard deviations and biases for obs-background wind speed data for nodes 3-4 (c) and nodes 11-14 (d). Note an ERS inclination correction manoeuvre took place on 25 August 1998. Observed erroneous ERS scatterometer winds (e) and ECMWF background winds (f) during the inclination correction manoeuvre.

fluxes over the oceans (Hsu *et al*. 1997) . These improvements are typically small but consistent. Figure3(a) shows global average ERA-40 statistics for the monthly obs-background and obs-analysis departures for ERS winds during the period 1993-2000. It is seen that ERS winds have high and consistent quality and are very well assimilated in ERA-40. The standard deviation compared to analysis versus compared to background fields show a very large reduction (a global average standard deviation reduction from 1.62 ms^{-1} to 0.97 ms^{-1}). One notes that the evolution of obs-background and obs-analysis standard deviation statistics are very consistent and uniform during the whole 1993-2000 period. There is a slight improvement in the latter years, most likely, due to general improvement of the background wind fields due to an increased volume of sounding and cloud motion wind satellite data. The HIRS assimilation was also improved 1 January 1997. The dotted lines show bias statistics. The ERS-1 winds (until June 1996) are in good agreement with the background wind fields, whereas the ERS-2 (available from October 1995) has a consistent small positive bias of 0.20 ms^{-1}. ERA-40 used (T_l159/T_l159, 60 levels) six hour 3D-Var for the assimilations.

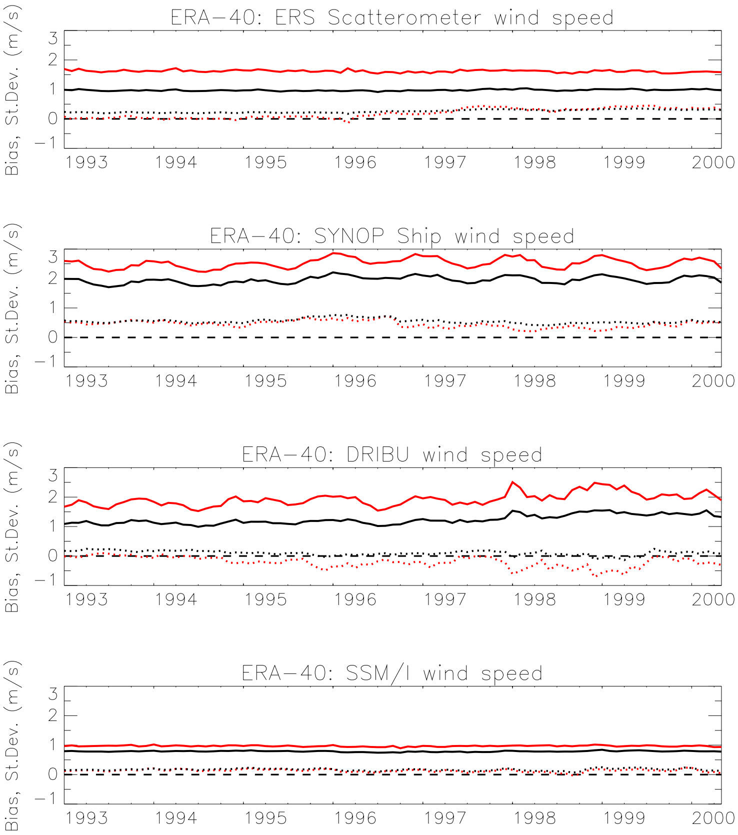


Figure 3: 10 metre wind speed observations compared against the ECMWF six hour background 10 metre winds. Standard deviation (solid lines) and biases (dashed lines) is calculated from all data used in ECMWF's 40 year Reanalysis project during the years 1993-2000. Red lines represent obs-background departures and black lines represent obs-analysis departures. (a) ERS scatterometer wind data, (b) SHIP wind observations, (c) Drifting Buoy wind observations, (d) SSM/I wind speed data.

Three other observing systems are also included in Fig. 3. Panels b and c show the statistics for SHIP and DRIBU, respectively. It is seen that the quality for SHIP and DRIBU is generally worse than for ERS with larger biases and standard deviations compared against background fields (standard deviation 2.52 ms^{-1} and 1.87 ms^{-1}, respectively). The higher obs-analysis departures for DRIBU and SHIP data (standard deviation

1.94 ms^{-1} 1.19 ms^{-1}, respectively) reflects the lower analysis weight assigned to these observations than to the ERS data. The SSM/I derived wind speed data (panel d) does not seem to benefit ERA-40 very much. Due to the high background dependence of these wind speed retrievals, they are assigned low weight and contribute relatively little to the wind analysis (background departures standard deviation of 0.97 ms^{-1} reduced to an dep. of 0.79 ms^{-1}) in ECMWF's assimilation system.

To assess the general impact of ERS scatterometer data in ECMWF's assimilation system a 29 days assimilation experiment during January 1999 with and without use of ERS scatterometer data was performed. A 3D-Var assimilation system (T_l159/T_l95, 60 levels), almost the same as ERA-40, was used. Figs. 4(a) and (b) show the Southern Hemisphere extratropical 500 hPa geopotential height forecast scores for this experiment. A small but significant positive impact is found for this region for all tropospheric levels (t–test significance levels of 99.0%-99.9% for 72 hour forecasts and 90.0%-99.5% for 120 hour forecasts). For other regions of the globe the impact of the experiment is neutral (not shown). These results are in agreement with earlier variational assimilation data denial impact studies by Isaksen (1997) and Buehner (2002).

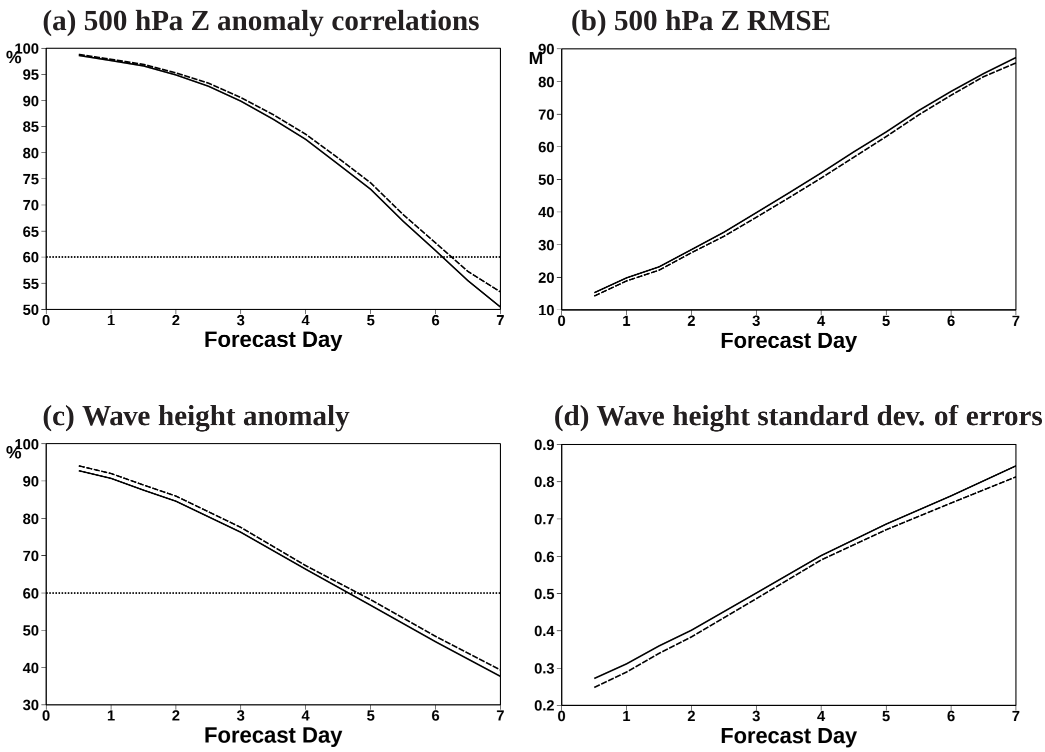


Figure 4: Southern hemisphere extra-tropical forecast verification scores for two 3D-Var 29 days assimilation experiments in January 1999 without use of ERS scatterometer wind data (solid ref curve) and with use of ERS scatterometer wind data (dashed blue curve), respectively. Panel (a) 500 hPa geopotential height anomaly correlation scores, (b) 500 hPa geopotential height root-mean-square-errors, (c) wave height anomaly correlation scores, (d) wave height standard deviation of errors. All forecasts are verified against ECMWF's operational analyses, which used ERS-2.

Figs. 4(c) and (d) show a significant positive impact on the wave height scores. Both control and ERS assimilation experiments used the two-way coupled wavemodel (WAM) (Janssen *et al*. 2002) . The quality of the wave model results are very dependent on the quality of the near surface winds delivered by the forecast model, likewise the near surface winds are influenced by the wave model dependent roughness length values. Table 1 compares background model six hour forecasts with ERS altimeter wind data from a six week assimilation experiment in August-October 1995 using the 1996 operational ($T213/T63$, 31 levels) setup of 3D-Var, with

Table 1: Impact of assimilating ERS-2 winds in ECMWF's 3D-Var system

Type of data	Altimeter Wind	Altimeter Wind	Wave height	Wave height
Type of assimilation	ERS winds used	ERS winds passive	ERS winds used	ERS winds passive
Data entries	20316	20316	20316	20316
Mean ECMWF value	9.10 ms^{-1}	9.17 ms^{-1}	3.39 m	3.38 m
Bias (ERS-ECMWF)	-0.11 ms^{-1}	-0.17 ms^{-1}	-0.18 m	-0.17 m
Standard Deviation	1.77 ms^{-1}	1.99 ms^{-1}	0.45 m	0.50 m
Scatter index	0.194	0.217	0.132	0.147
Correlation	0.906	0.882	0.947	0.936

and without active use of ERS data. It is clearly seen that the biases, standard deviation and scatter index are improved considerably when ERS scatterometer data is assimilated. Note that Altimeter wind speeds give an independent validation method because they are not assimilated. As a consequence of the improved winds, the standard deviation and scatter index for the wave height validated against ERS altimeter wave heights are also clearly reduced.

5 Tropical cyclone and polar low case studies

Previous studies on impact of ERS scatterometer data (Tomassini *et al*. 1998 ; Isaksen and Stoffelen 2000) on tropical cyclones in ECMWF's assimilation system showed that the 3D-Var and 4D-Var assimilation system are capable of utilizing surface wind data more efficiently than the previously used OI assimilation system. The inclusion of ERS scatterometer data further improves the analyses and forecasts of tropical cyclones. This was verified by a range of longer period tropical cyclone related assimilation studies. The positive impact of NSCAT wind data on tropical cyclone assimilation has been shown by Leidner *et al*. (2003) . In this paper, we will present two tropical cyclone examples where ERS scatterometer data is responsible for large improvements of analyses and forecasts. The cases highlight the ability of the 4D-Var assimilation method to propagate surface wind information in a dynamically consistent way throughout the troposphere, and demonstrate the effectiveness of the dynamic ambiguity selection method that uses the cost function (5).

5.1 Ambiguity selection and vertical propagation of ERS wind information

The first case is tropical cyclone Gemma. It is a tropical cyclone near Reunion Island and Madagascar in the Indian Ocean on 7 April 1998. The assimilation system used was the operational six hour 4D-Var with $T_l319/T63$ resolution. It used conventional data, radiance soundings, cloud motion wind data from geostationary satellites and ERS-2 scatterometer winds. For this analysis cycle there were ERS-scatterometer winds and a few cloud motion winds in the region of interest. Fortunately, the ERS-2 track captured the central parts of Gemma well. The ERS data used is shown in Fig. 5(b) (only best ERS wind is plotted) on top of the streamline plot of the 10 metre analysis winds. Panel (a) shows the six hour background 10 metre winds as a streamline plot. It is clear that the ERS-2 data played a large part in moving the whole tropical cyclone by almost 500 km to exactly the right location.

Figs. 5(c) and (d) show cross-sections along an axis through the tropical cyclone centre of the background and of the analysis (from top-left to bottom-right in the panel (a) plot). It is clear that, by just using surface data, 4D-Var is able to move the whole vertical structure of Gemma to the right location. The tropical cyclone is also intensified and given a sharper structure.

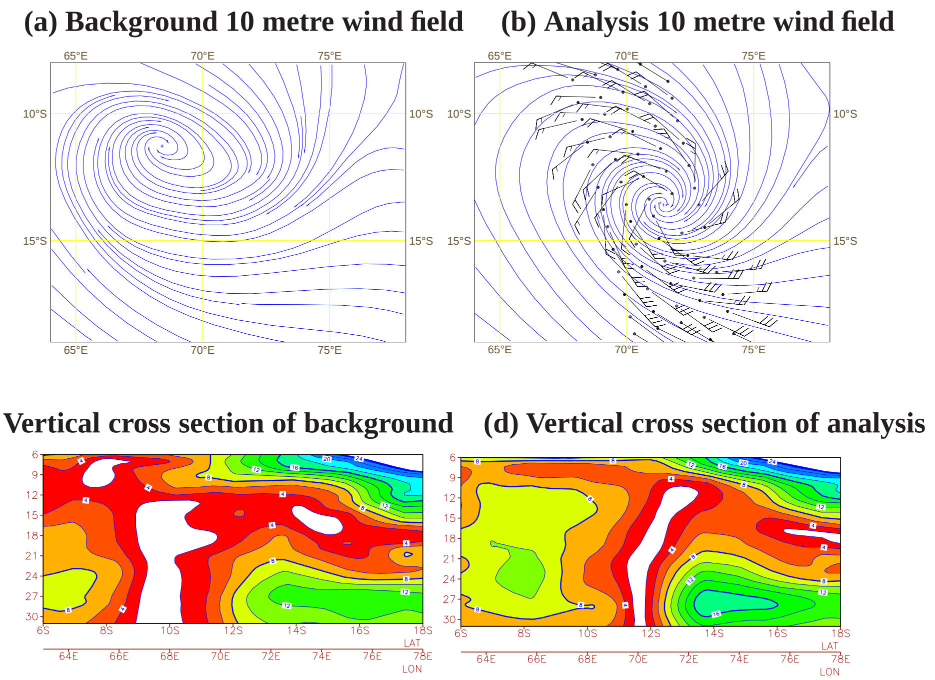


Figure 5: (a) Six hour background 10 metre wind field (stream function) for tropical cyclone Gemma (7 April 1998). (b) Analysis 10 metre wind field (stream function) with used ERS scatterometer winds (closest to the analysis field) overlayed. (c) Vertical cross section of six hour background wind speed (ms^{-1}) along a line from top left to bottom right in panel (a). (d) Like panel (c), but for analysis wind field.

It should be kept in mind that due to the nature of scatterometer measurements the 4D-Var assimilation has got two approximately 180° separated ambiguous wind vectors for each data location, so it is not a trivial job for 4D-Var to use the correct of the two ambiguous ERS winds because the background field is so far off from the right centre location. Figure 6(a) shows the active ERS scatterometer data in the vicinity of Gemma. The black wind flags are the correct ambiguities based on the observed location. In this case the observed location coincides with the analysis location (marked with a blue diamond). The grey wind flags show the other ERS wind that differ by approximately 180°. Note that near the centre ERS-scatterometer measurements may be affected by confused sea-state effects typically resulting in a ambiguity angle difference considerably less than 180°. One ERS data point just east of the centre of Gemma shows this feature, it has been rejected by 4D-Var's variational quality control (Andersson and Järvinen 1999) and is marked red. Due to the symmetric antennae geometry for ERS there are almost always only two viable ambiguities of which one has the correct wind direction. In this case the solution with smallest distance-to-the-cone is wrong by 90° for one data point south-east of Gemma's centre, so the wrong pair of ambiguities are presented to the analysis. Both unrealistic winds are rejected (marked red) by 4D-Var's variational quality control. As shown in Fig. 5(a) the six hour background wind field has in this case an extraordinarily large location error for tropical cyclone Gemma. The centre location in the background field is marked with a green triangle on Fig. 6. Due to the misplacement a large fraction of the scatterometer winds (coloured green) has the wrong ambiguity in closest agreement with the poor background wind field. So the observation penalty function J_o must initially move away from the local minima of the double-welled non-quadratic cost function. In this case 4D-Var is very successful and swaps all ERS wind selections from the wrong to the correct one. This is partially because the winds are relatively low in this early phase of Gemma's evolution. But it is also because the 4D-Var incremental approach (Courtier *et al*. 1994) is used at ECMWF with two outer loop trajectory updates. The first minimization is using the data further away from Gemma's centre (where the ambiguity selection based on background wind field is

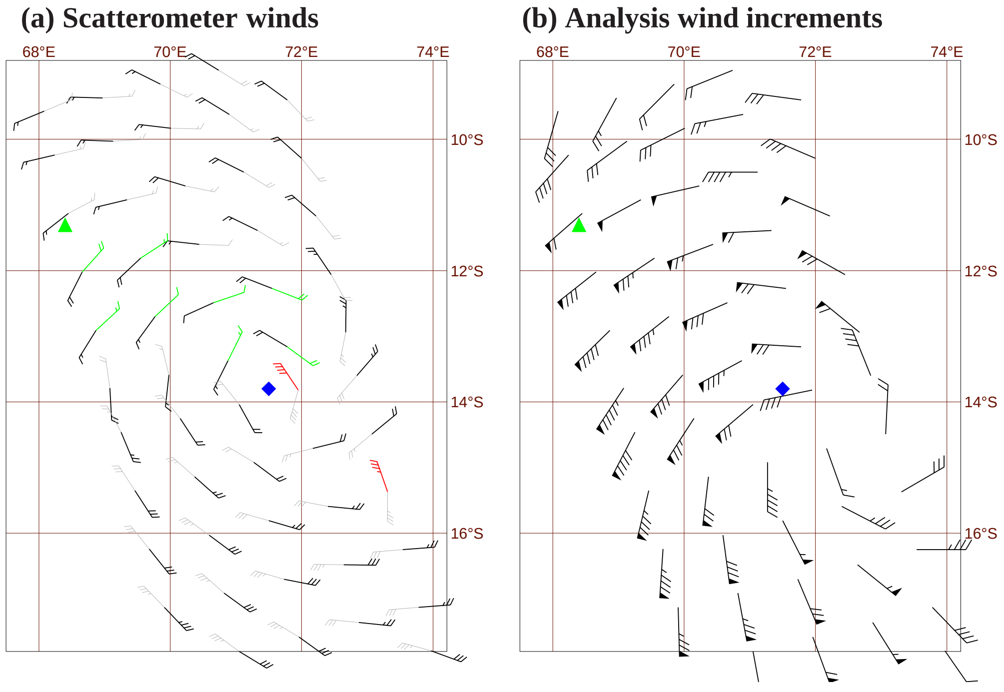


Figure 6: (a) Scatterometer winds near the centre of tropical cyclone Gemma (marked with a diamond). Black wind flags show the ERS winds closest to the analysis winds, grey wind flags show the other ERS ambiguity. The triangle marks the centre of tropical cyclone Gemma according to the background fields. The green wind flags highlights the observations where the background wind field is best in agreement with the ERS wind that is wrong by approximately 180°. *Finally the two red flags show observations rejected by 4D-Var's variational quality control. A full barb represents a wind speed of 5 ms*$^{-1}$*, a half barb represents a wind speed of 2.5 ms*$^{-1}$*. (b) Analysis increments for 10 metre winds at ERS scatterometer locations. Flag values are scaled up by a factor of five, so a full barb represents a wind speed increment of 1 ms* $^{-1}$ *and a pennant represents a wind speed increment of 5 ms*$^{-1}$.

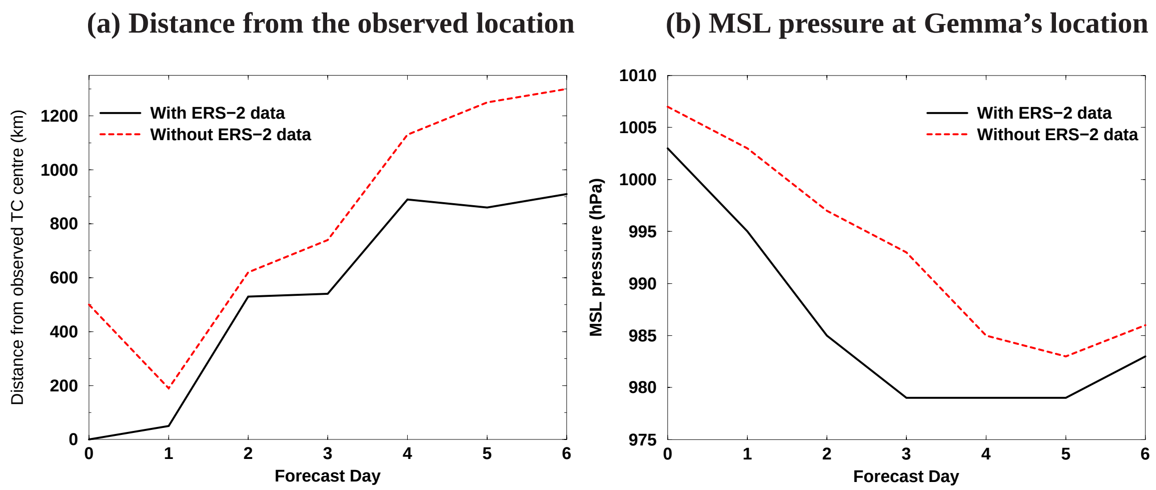


Figure 7: (a) Distance of tropical cyclone Gemma from the observed location (in km) in a forecast based on the 4D-Var assimilation using ERS wind data (solid line) and without use of ERS data (dashed line), during the first six forecast days. (b) Like (a) but showing the MSL pressure development (in hPa) at the tropical cyclone location.

correct) to a higher extent than the winds that look inconsistent near the centre. The second trajectory forecast therefore moves the tropical cyclone towards the right location, bringing the updated background field in closer agreement with the correct scatterometer wind. The second minimization therefore has a much better starting point and is able to utilize most of the information supplied by the ERS scatterometer data. Figure 5(b) shows the analysis increments for 10 metre winds at ERS scatterometer locations (note the flag values are scaled up by a factor of 5). The substantial movement of Gemma to the correct location is clearly seen by the consistent large cyclonic increments. To investigate if the above arguments were correct an additional assimilation experiment was performed where only one ambiguity (closest to the background field or updated trajectory) was used in the assimilation. The analysis improved primarily because of a more correct trajectory produced from the first analysis update. This meant that the second minimization could use more scatterometer data consistently and therefore move Gemma quite a lot towards the correct location (not shown), though not to the perfect location as seen above.

An analysis without use of ERS-2 data for the analysis cycle was performed. It confirmed that the improved analysis of Gemma was solely due to ERS-2 data: the analysis without use of ERS-2 was virtually identical to the background field in this region (see the large initial location error on Fig.7(a), dashed curves starting point). A forecast was run from the analysis without use of ERS-2 data and it was compared with a forecast starting from the analysis that used ERS-2 data (Fig. 5(b)). Figure 7 shows how the improved analysis of intensity and position of Gemma is retained in the forecast for at least six days. For example at 1200 UTC on 10 April 2000 the observed central pressure is 985 hPa, compared to the 994 hPa in the noscat assimilation forecast and 981 hPa in the ERS-2 assimilation forecast.

5.2 Tropical cyclone Luis – the benefit of 4D-Var with ERS scatterometer data

The second tropical cyclone case is the Atlantic hurricane Luis. which hit St. Maarten (The Netherlands) on the 6th of September 1995. The reported wind speed was 115 *knots* and the surface pressure was 942 hPa. Several people died and the estimated damage for St. Maarten, alone, was 1.8 billion dollars. This exemplifies the importance of accurate forecasts of tropical cyclones.

Figure 8 shows how valuable ERS-1 data was assimilated on the 1st of September 1995 at 00 UTC. Panel (a) shows the analysed Mean Sea Level (MSL) pressure field with the used ERS-1 data superimposed (note that only unambiguous winds are shown for clarity, whereas the analysis uses both ambiguities). Panel (b) shows how much the background MSL pressure was changed by the analysis. This impact is fully related to the ERS-1 data because no other observational data was available in the vicinity of the tropical cyclone. Luis almost doubled in intensity from background to analysis in this case.

Although ERS winds clearly impact the data assimilation cycle, it is usually more difficult to demonstrate medium-range forecast impact. Generally it has been seen that 4D-Var analysis increments from ERS survive and help to improve forecasts to a larger extend than in OI and 3D-Var (Isaksen and Stoffelen 2000) Figure9(c) shows the 5-day forecasts starting at 1200 UTC 1 September 1995 12 hourly after the analysis shown in Fig.8. Hurricane Luis is easy to identify and the forecast is in good agreement with the verifying analysis (Fig.9(d)). Note also the excellent forecast of the next tropical depression south of Cap Verde. Five day forecasts from the operational OI system (Fig. 9(a)) and 4D-Var assimilation system without use of ERS scatterometer data (Fig. 9(b)) makes it evident that the intense hurricane Luis in the SCAT assimilation forecast is triggered by the scatterometer winds. Fig. 9(a) shows the inability of the OI system to capture Luis. Improvements in the forecasts are found even in cases where ERS-scatterometer data only is available on the fringe of the hurricane, i.e., several hundred kilometers away from the centre. It supports the general view that the development and track of a hurricane is to a large extent determined by a proper description of the convergent inflow from the surroundings (Gray 1998).

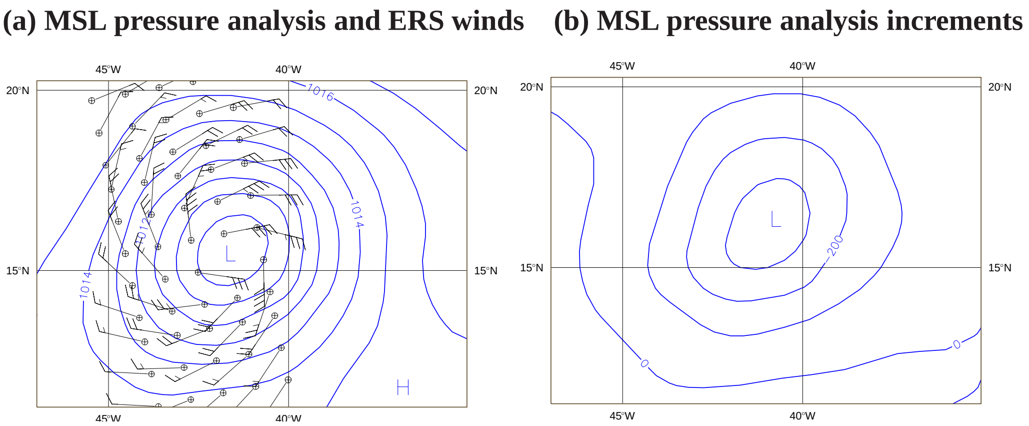


Figure 8: (a) MSL pressure analysis of tropical cyclone Luis 0000 UTC 1 September 1995. ERS-1 scatterometer winds used by assimilation (ambiguity closest to background wind field) are shown. (b) MSL pressure analysis increments for the (a) analysis. Isolines are 1 hPa in both panels.

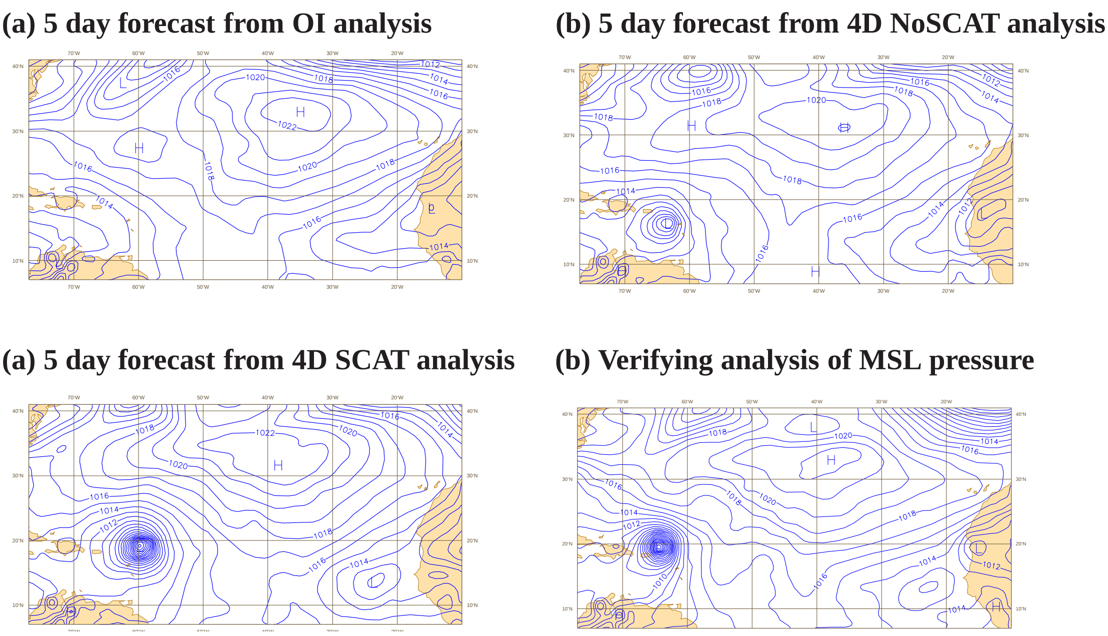


Figure 9: Five day MSL pressure forecast of tropical cyclone Luis 1200 UTC 5 September 1995. (a) ECMWF's operational forecast based on optimum interpolation and the forecast model available in 1995. (b) 4D-Var assimilation without use of ERS data. (c) 4D-Var assimilation with use of ERS scatterometer data. (d) Verifying analysis from the 4D-Var assimilation experiment with use of ERS scatterometer data. An up-to-date forecast model was used for the 4D-Var assimilations (panels (b), (c) and (d)).

The fact that ERS measurements are unaffected by cloud and rain and are of consistently high quality from day to day is of great advantage. The main disadvantage is the narrow swath (500 km) with the consequence that tropical cyclones and extra-tropical events are not always captured by the satellite. Generally ERS data improves the analyses and forecasts of tropical cyclones, but can occasionally cause degradation. Unwanted side effects may occur due to discrepancies between the relatively course resolution assimilation system and the higher resolution scatterometer data. The statistically determined background error structure functions (Derber and Bouttier 1999) are not well representative near tropical cyclones and problems may also occur when tropical cyclones are only partially captured by ERS scatterometer data. These positive and negative aspects are discussed further by Isaksen and Stoffelen (2000). The benefit of increasing the resolution of the analysis for assimilation of NSCAT scatterometer data is presented in Leidner *et al.* (2003) .

5.3 Tropical cyclone Bonnie - the benefit of higher model resolution

In August 1998 the category 3 hurricane Bonnie caused substantial damage and created great havoc when it made landfall in North Carolina. Fig. 10(a) show the MSL pressure analysis 48 hours before landfall (0000 UTC 25 August 1998) from a ($T_l 319/T106$, 31 levels) assimilation experiment, Fig. 10(b) shows the same analysis from a ($T_l 639/T106$, 31 levels) assimilation. The two assimilations, started 3 days earlier are virtually identical in the vicinity of hurricane Bonnie. Both at 0600 UTC and 1800 UTC 25 August 1998 ERS tracks covered hurricane Bonnie as shown in Fig. 10(c)-(f). The ERS scatterometer data usage is very similar for the two assimilation experiments because the minimization is performed at $T106$ resolution in both experiments. Note the very realistic ERS scatterometer wind vectors, even near the centre of Bonnie. Some data is rejected near the centre, by default, because the data or first guess wind is above 25 ms^{-1}. Equation (1) and (2) show that the forecast model is a vital part of the assimilation system. In this case study it is clear that the $T_l 639$ higher resolution forecast model allows the assimilation system (Fig. 10(d) and (f)) to make better use of the ERS scatterometer data than the $T_l 319$ assimilation system (Fig. 10(c) and (e)). Just 18 hours after virtually identical analyses the higher resolution system is producing a central MSL pressure of 978 *hPa* compared to 987 *hPa* for the lower resolution system. The observed MSL pressure was 963 *hPa* at 1800 UTC 25 1998 according to National Hurricane Center, NOAA, USA. As expected, even $T_l 639$ resolution is too coarse to represent the core of intense tropical cyclones exactly.

5.4 A polar low case study - improvement of an extra-tropical analysis

Polar lows are small arctic cyclonic disturbances (Rasmussen 1979) that develop when very cold air is advected southwards over a relatively warm ocean. On 18 January 1998 a polar low with a scale of 500 km was present between Iceland and Norway (see Fig. 11(a)). An ERS-2 satellite orbit captured the polar low at 2200 UTC 17 January 1998. The scatterometer winds in the vicinity of the polar low are shown in Fig. 11(b). The ECMWF MSL pressure analysis is shown together with the ERS winds closest to the analysis. The polar low is clearly a very intense small scale cyclonic system with observed ERS-2 winds up to 25 ms^{-1} northwest of the low. Also note the strong cross isobaric flow present in the ERS-2 data. The ECMWF analysis is able to represent this polar low with correct location and relatively intense pressure field, despite the fairly coarse model resolution ($T_l 319/T63$) six hour 4D-Var used for this assimilation. In this region there are typically few conventional observations, in this six hour assimilation window there is a radiosonde ship, the Jan Mayen radiosonde, a Faroe Island synop and a drifting buoy (shown on Fig. 12(a)). The ERS scatterometer data used by the assimilation is shown in Fig. 12(b). Assimilation experiments were performed with and without use of ERS scatterometer data. Comparison of 10 metre wind speed isotachs for the experiment without ERS scatterometer data (Fig. 12(a)) and with ERS scatterometer data (Fig. 12(b)) shows that the ERS data helped the analysis to correctly increase surface wind speeds south and west of the polar low. The analysis has drawn

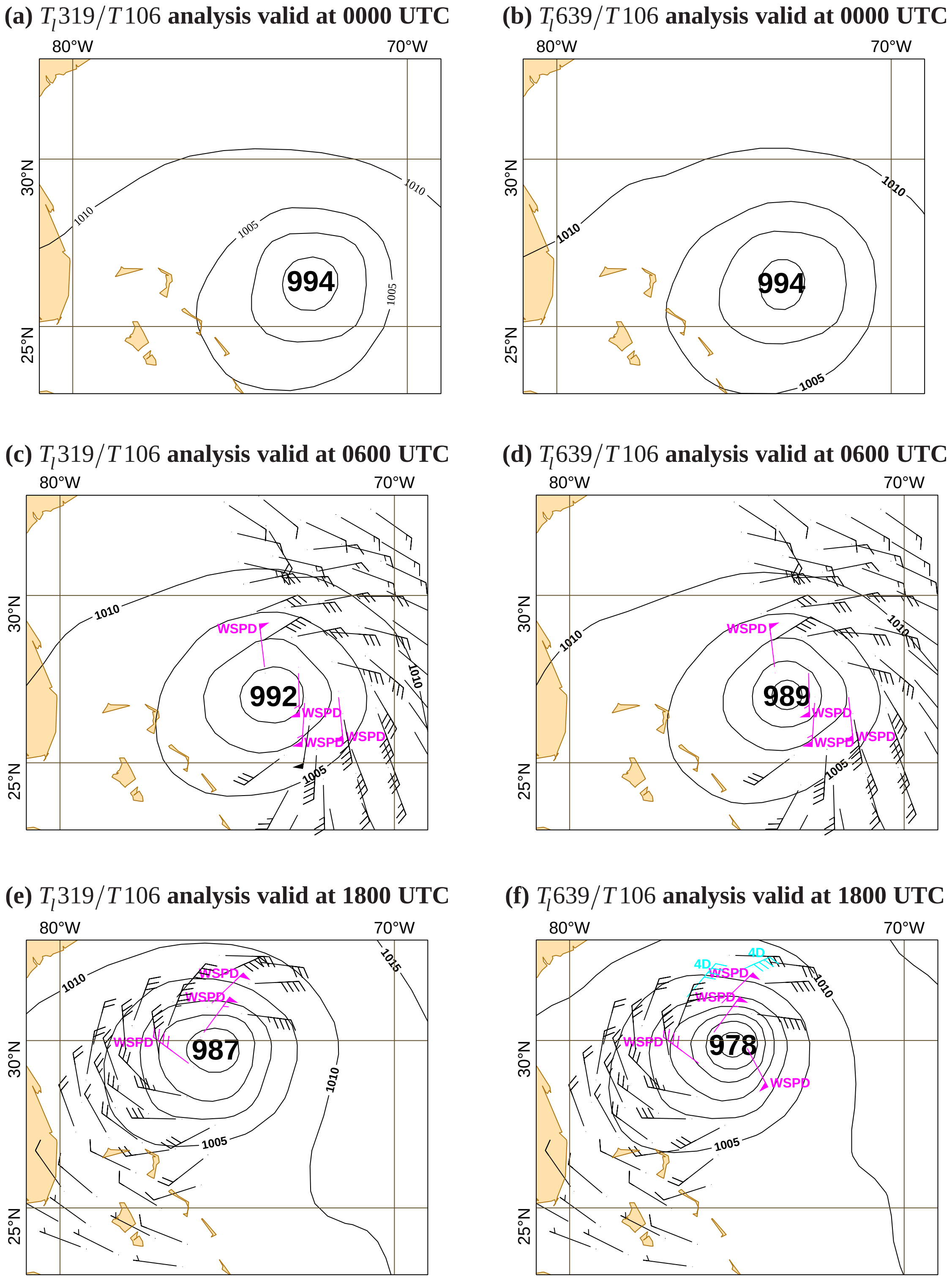
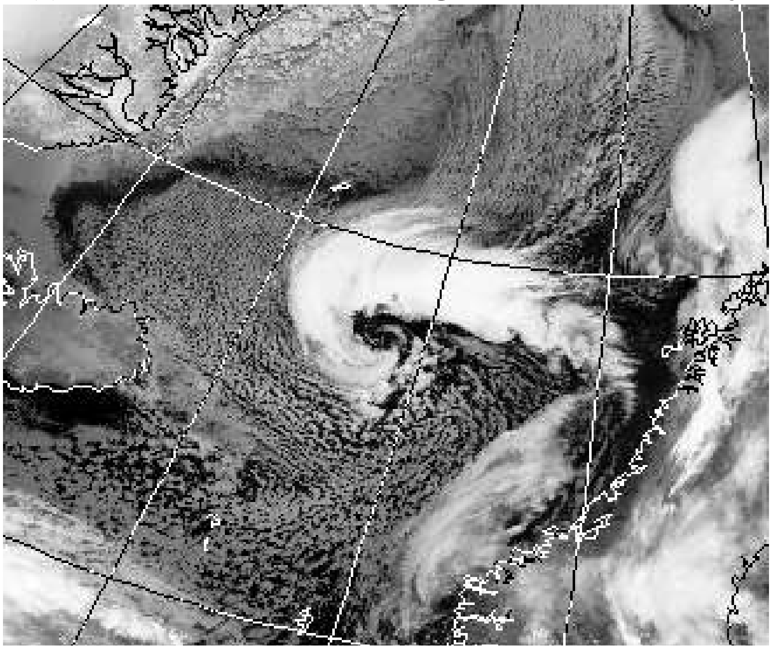


Figure 10: MSL pressure analyses of tropical cyclone Bonnie on 25 August 1998 from two different resolution six hour 4D-Var assimilation systems, both using ERS scatterometer winds. (a) $T_l319/T106$ analysis valid at 0000 UTC. (b) $T_l639/T106$ analysis valid at 0000 UTC. (c) $T_l319/T106$ analysis valid at 0600 UTC. (d) $T_l639/T106$ analysis valid at 0600 UTC. (e) $T_l319/T106$ analysis valid at 1800 UTC. (f) $T_l639/T106$ analysis valid at 1800 UTC. ERS-1 scatterometer winds used by assimilation (ambiguity closest to analysis wind field) are shown for the two assimilations. WSPD marked winds are rejected due to large wind speed, 4D marked winds are flagged by variational QC. MSL pressure isolines are 5 hPa in all panels.

(a) Infra-red NOAA satellite image 2200 UTC 17 January 1998



(b) MSL pressure analysis, increments and ERS scatterometer winds

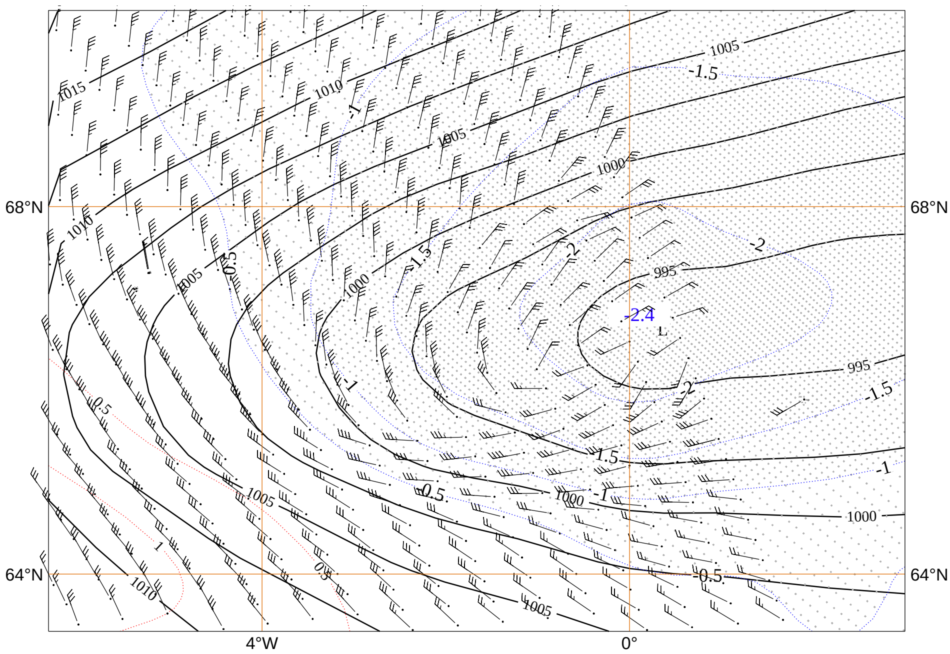
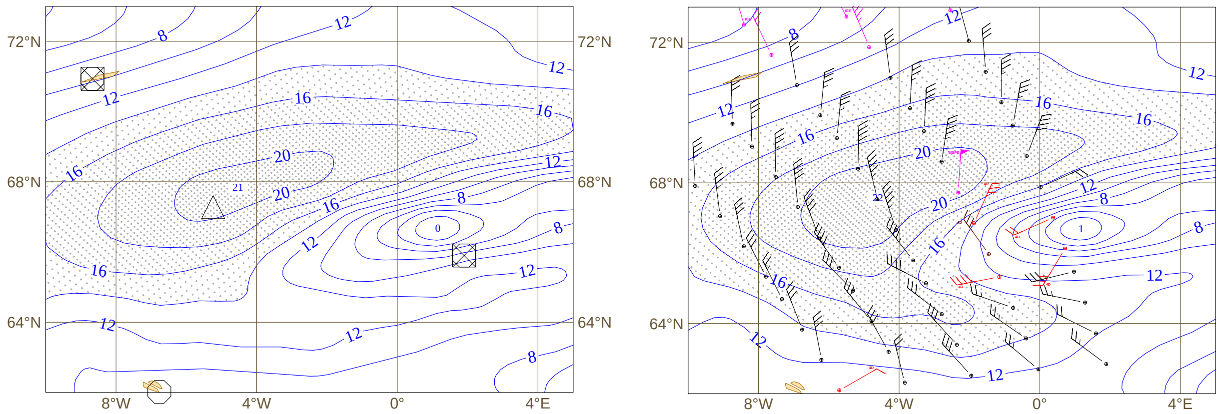


Figure 11: (a) North Atlantic infra-red NOAA satellite image of a polar low 2200 UTC 17 January 1998 (Dundee Satellite Receiving Station). (b) ERS scatterometer winds (flags) and MSL pressure analysis (hPa, solid lines) valid 0000 UTC 18 January 1998. The dashed lines and associated hatching represent MSL pressure analysis increments (in hPa).

closer to the scatterometer data. Fig. 12(c) shows how the final analysis J_o cost function values for almost all the scatterometer data in the region are reduced compared to the background J_b values. In this case the scatterometer wind data accounted for approximately 80% of the J_b cost function reduction in the region shown in Fig. 12(a) and (b), partly because the background field was in good agreement with the radiosonde ship that measured near the centre of polar low. The analysis improved in the surrounding regions with higher wind.

(a) Analysis without scatterometer wind data **(b) Analysis using scatterometer wind data**



(c) Cost function values at ERS scatterometer locations

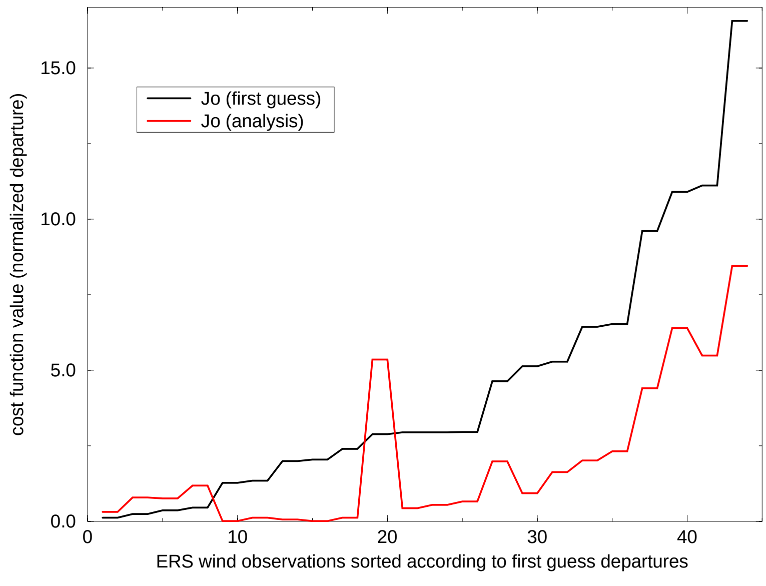


Figure 12: (a) Isotachs (in ms^{-1}) near the polar low in Figure 11 for a 4D-Var assimilation without use of ERS scatterometer wind data. All observations in the area used by the assimilation is shown (SYNOPs as circle, DRIBUs as a triangle, TEMPs as a crossed-square, no satellite data was available in the region). (b) Like (a) but for the analysis using ERS scatterometer wind data in addition to other observations. Black flags show used ERS data. Red show rejected data due to variational quality control or data rejected due to wind speeds above 25 ms^{-1}. (c) J_o cost function values for obs-background and obs-analysis for the ERS scatterometer winds in polar low area. Calculated using the definition in (5).

6 Conclusion and discussion

In the context of 3D-VAR and 4D-VAR it has been shown that ERS scatterometer data in general have a positive impact on the analysis and forecasting of weather and ocean waves. This was followed by a detailed study of three tropical cyclone developments and a polar low case study. In particular, in the 4D-VAR analysis of tropical cyclones large impacts are found in the near surface analysis and even deep in the troposphere. These large analysis increments lead to a considerable improvement in cyclone forecasts. It is shown that ERS scatterometer data improves the analyses more when a high resolution forecast model is used in the assimilation system.

This paper also shows that ERA-40 benefits from the use of ERS scatterometer data. It has been shown that the ERS scatterometer data is of high consistent quality without cloud/rain contamination problems. ERA-40 assimilates the ERS scatterometer data well, according to certain measures even better than SSM/I, DRIBU and SHIP data. It is expected that ERS benefits ERA-40's handling of tropical cyclones and intense extra-tropical cyclones, but this still needs to be investigated.

All in all it may be concluded that the introduction of ERS scatterometer data benefit weather and wave forecasting at ECMWF, and has presented us with challenges to better understand the assimilation of near surface winds. Furthermore, a strong point of the ERS C-band scatterometers is the absence of rain contamination. However, due to the narrow swath and therefore a fairly low data coverage, the large scale impact on analyses and forecasts is modest. We experience larger forecast impact with SeaWinds because of the three times wider swath. Unfortunately, because of the shorter wavelength Seawinds is less effective in tropical cyclone detection, because of rain contamination problems. It is expected that the next ESA scatterometer, the Advanced SCATterometer (ASCAT) (to be launched in 2006), will combine the benefits of ERS and Seawinds, namely a wider swath and no rain contamination.

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8 References

Anderson, D., Hollingsworth, A., Uppala, S. and Woiceshyn, P. **1991:** A study of the use of scatterometer data in the European Centre for Medium-range Weather Forecasts operational analysis-forecast model. 2. Data impact. *J. Geophys. Res.*, **96,** 2635–2647

Andersson, E., Haseler, J., Undén, P., Courtier, P., Kelly, G., Vasiljević, D., Brankovic, C., Cardinali, C., Gaffard, C., Hollingsworth, A., Jakob, C., Janssen, P., Klinker, E., Lanzinger, A., Miller, M., Rabier, F., Simmons, A., Strauss, B., Thépaut, J.-N. and Viterbo, P. **1998:** The ECMWF implementation of three-dimensional variational assimilation (3D-Var). III: Experimental results. *Q. J. R. Meteorol. Soc.*, **124,** 1831–1860

Andersson, E. and Järvinen, H. **1999:** Variational quality control. *Q. J. R. Meteorol. Soc.*, **125,** 697–722

Andrews, P. L. and Bell, R. S. **1998:** Optimizing the United Kingdom Meteorological Office data assimilation for ERS-1 scatterometer winds. *Mon. Weather Rev.*, **126,** 736–746

Atlas, R., Hoffman, R. N., Leidner, S. M., Sienkiewicz, J., Yu, T. W., Bloom, S. C., Brin, E., Ardizzone, J., Terry, J., Bungato, D. and Jusem, J. C. **2001:** The Effects of Marine Winsd from Scatterometer Data on Weather Analysis and Forecasting. *Bull. Amer. Meteorol. Soc.*, **82,** 1965–1990

Attema, E. P. W. **1991:** The active microwave instrument on-board the ERS-1 satellite. *Proc. IEEE* **79,** 791–799

Baker, W.E., Atlas, R., Kalnay, E., Halem, M., Woiceshyn, P. M., Peteherych, S. and Edelmann, D. **1984:** Large-scale analysis and forecast experiments with wind data from the SeaSat-A scatterometer. *J. Geophys. Res.* **89**, 4927–4936

Buehner, M. **2002:** Assimilation of ERS-2 Scatterometer Winds Using the Canadian 3D-var *Atmosphere-Ocean*, **40,** 361–376

Cavanié, A. and Lecomte, P. **1987:** Vol 1-Study of a method to dealias winds from ERS-1 data. Vol 2-Wind retrieval and dealiasing subroutines. *ESA contract 6874/87/CP-I(sc) report*, ESA publications division, Noordwijk, The Netherlands

Courtier, P., Thépaut, J.-N., and Hollingsworth, A. **1994:** A strategy for operational implementation of 4D-Var, using an incremental approach. *Q. J. R. Meteorol. Soc.*, **120,** 1367–1388

Courtier, P., Andersson, E., Heckley, W., Pailleux, J., Vasiljević, D., Hamrud, M., Hollingsworth, A., Rabier, F. and Fisher, M. **1998:** The ECMWF implementation of three dimensional variational assimilation (3D-Var). Part I: Formulation. *Q. J. R. Meteorol. Soc.*, **124,** 1783–1808

Derber, J. and Bouttier, F. **1999:** A reformulation of the background error covariance in the ECMWF global data assimilation system. *Tellus* **51A,** 195–221

Duffy, D., Atlas, R., Rosmond, T., Barker, E. and Rosenberg, R. **1984:** The impact of SeaSat scatterometer winds on the Navy's operational model. *J. Geophys. Res.* **89,** 7238-7244

Gaffard, C. and Roquet, H. **1995:** Impact of the ERS-1 scatterometer data on the ECMWF 3D-Var assimilation system. ECMWF Tech. Memo. No. 217. Available from ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX ,UK.

Grantham, W. L., Bracalente, E. M., Jones, W. L. and Johnson, J. W. **1977:** The Seasat-A satellite scatterometer. *IEEE J. Oc. Eng.*, **OE-2,** 200–206

Gray, W. M. **1998:** The Formation of Tropical Cyclones. *Meteorol. Atmos. Phys.* **67,** 37–69

Hoffman, R. N. **1993:** A preliminary study of the impact of the ERS 1 *C*-band scatterometer wind data on the ECMWF global data assimilation system. *J. Geophys. Res.*, **98,** 10233–10244

Hsu, C. S., Liu, W. T. and Wurtele, M. G. **1997:** Impact of Scatterometer Winds on Hydrological Forcing and Convective Heating through Surface Divergence. *Mon. Weather Rev.*, **125,** 1556–1576

Isaksen, L. **1997:** Impact of ERS scatterometer data in the ECMWF 4D-Var assimilation system. Preliminary studies. *Proc. 3rd Symp. on Space at the Service of our Environment*, Florence, Italy [SP-414]. 1829–1851. Available from ESA Publications Division, ESTEC Noordwijk, NL

Isaksen, L. and Stoffelen, A. **2000:** ERS scatterometer wind data impact on ECMWF's tropical cyclone forecasts. *IEEE Trans. Geosci. Remote Sens.*, **38,** 1885–1892

Janssen, P. A. E. M., Doyle, J. D., Bidlot, J., Hansen, B., Isaksen, L. and Viterbo, P. **2002:** Impact and feedback of ocean waves on the atmosphere. in *Advances in Fluid Mechanics*, **33,** Atmosphere-Ocean Interactions ,Vol. I, Ed. W.Perrie, 155–198

Klinker, E., Rabier, F., Kelly, G. and Mahfouf, J.-F. **2000:** The ECMWF operational implementation of four-dimensional variational assimilation. III: Experimental results and diagnostics with operational configuration. *Q. J. R. Meteorol. Soc.*, **126,** 1191–1215

Leidner, S. M., Isaksen, L. and Hoffman, R. N. **2003:** Impact of NSCAT Winds on Tropical Cyclones in the ECMWF 4DVAR Assimilation System. *Mon. Weather Rev.*, **131,** 3–26

Lorenc, A. C. **1988:** Optimal nonlinear Objective Analysis. *Q. J. R. Meteorol. Soc.*, **114,** 205–240

Lorenc, A. C. **1981:** A gobal three-dimensional multivariate statistical interpolation scheme. *Mon. Weather Rev.*, **109,** 515–543

Lungu, T. (editor) **2001:** QuikSCAT Science Data Product. User's Manual. Overview and Geophysical Data Products. Version 2.2 December 2001. JPL D-18053, 95 pages. Available from Jet Propulsion Laboratory, Pasadena, California 91109, USA.

Mahfouf, J.-F. and Rabier, F. **2000:** The ECMWF operational implementation of four-dimensional variational assimilation. II: Experimental results with improved physics. *Q. J. R. Meteorol. Soc.*, **126,** 1171–1190

Moore, R. J. and Pierson, W. J. **1967:** Measuring sea state and estimating surface winds from a polar orbiting satellite, in *Proc. of the Symposium on Electromagnetic Sensing of the Earth from Satellites*, R. Zirkland (Ed.), Polytechnic Press, New York, R1–R28

Naderi, F. M., Freilich, M. H. and Long, D. G. **1991:** Spaceborne radar measurement of wind velocity over the ocean—an overview of the NSCAT scatterometer system. *Proc. IEEE*, **79,** 850–866

Rabier, F., Järvinen, H., Klinker, E., Mahfouf, J.-F. and Simmons, A.**2000:** The ECMWF operational implementation of four-dimensional variational assimilation. I: Experimental results with simplified physics. *Q. J. R. Meteorol. Soc.*, **126,** 1143–1170

Rasmussen, E. **1979:** The polar low as an extratropical CISK-disturbance. *Q. J. R. Meteorol. Soc.*, **105,** 531–549

Simmons, A. J. and Gibson, J. K. **2000:** The ERA-40 project plan. *Era-40 Project Report Series No. 1*. Available from ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX ,UK.

Stoffelen, A. and Anderson, D. **1997a:** Scatterometer Data Interpretation: Measurement Space and inversion. *J. Atm. and Ocean Tech.*, **14,** 1298–1313

Stoffelen, A. and Anderson, D. **1997b:** Ambiguity removal and assimilation of scatterometer data. *Q. J. R. Meteorol. Soc.*, **123,** 491–518

Stoffelen, A. and Anderson, D. **1997c:** Scatterometer data interpretation: estimation and validation of the transfer function CMOD4. *J. Geophys. Res.* **102**, 5767–5780

Stoffelen, A. and van Beukering, P. **1997:** Implementation of improved ERS scatterometer data processing and its impact on HIRLAM short range weather forecasts. HIRLAM Technical Report 31, 77 pages, Irish Meteorological Service, Dublin, Ireland

Thépaut, J.-N., Hoffman, R. N. and Courtier, P. **1993:** Interactions of dynamics and observations in a four-dimensional variational assimilation. *Mon. Weather Rev.*, **121,** 3393–3414

Tomassini, M., LeMeur, D. and Saunders, R. W. **1998:** Near-surface satellite wind observations of hurricanes and their impact on ECMWF model analyses and forecasts. *Mon. Weather Rev.*, **126** 1274–1286

Yu, T. W. and McPherson, R. D. **1984:** Global data assimilation experiments with scatterometer winds from SEASAT-A. *Mon. Weather Rev.*, **112,** 368–376