

ON THE USE OF SCATTEROMETER WINDS IN NWP

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ABSTRACT

Over the last years the processing of ERS scatterometer winds has been refined. Subsequently, High Resolution Limited Area Model, HIRLAM, and ECMWF model data assimilation experiments have been carried out to assess the impact of one scatterometer, ERS-1 and of two scatterometers, ERS-1 and ERS-2, on the analyses and forecasts. We found that scatterometer winds have a clear and beneficial impact in the data assimilation cycle and on the forecasts. Furthermore, ECMWF has shown that ERS scatterometer data improve the prediction of tropical cyclones in 4Dvar, where unprecedented skillful medium-range forecasts result of potential large social-economic value. Nevertheless, scatterometer winds contain much sub-synoptic scale information where the smallest scales resolved are difficult to assimilate into a Numerical Weather Prediction, NWP, model. This is mainly due to the otherwise general sparsity of the observing system over the ocean. In line with this it is found that scatterometer data coverage is very important for obtaining a large impact. In that respect future scatterometer systems such as SeaWinds on QuikSCAT and ADEOS-II, and ASCAT on EPS are promising.

1. INTRODUCTION

After the launch of ERS-1 much improvement has been made in the interpretation of scatterometer backscatter measurements and a good quality wind product has emerged (Stoffelen and Anderson, 1997a, 1997b and 1997c). The consistency of the scatterometer winds over the swath makes them particularly useful for nowcasting purposes and several examples of the usefulness of the direct visual presentation of scatterometer winds to a meteorologist can be given. However, we will focus in this work on the data assimilation impact in numerical weather prediction (NWP) as gathered with the ERS-1 and ERS-2 scatterometer winds. As such, the scatterometer data preprocessing system (PRESCAT) has been further developed at KNMI and ECMWF and implemented in the High Resolution Limited Area weather forecasting Model (HIRLAM) and the ECMWF model. Impact experiments are carried out to test the usefulness of the data for the analyses and for short-range forecasts up to two days in HIRLAM. A meteorologically active period where both ERS-1 and ERS-2 scatterometer data are available has been selected to test the impact of an increased data coverage. In Stoffelen and Beukering (1997) these developments are described in detail, and here a brief summary is provided. At ECMWF, ERS-1 and ERS-2 scatterometer winds were used to carry out similar experiments, but at the global scale and for medium-range forecasting. The scatterometer proves beneficial in dynamic weather conditions, though the static 3D assimilation systems are probably not optimal for surface wind assimilation in such conditions. ECMWF carried out 4Dvar scatterometer impact experiments, where the model tendencies are taken into account in the data assimilation cycle, and a dynamically more consistent analysis results. It is shown that scatterometer winds in 4Dvar lead to unprecedented accurate medium-range forecasts of tropical cyclones.

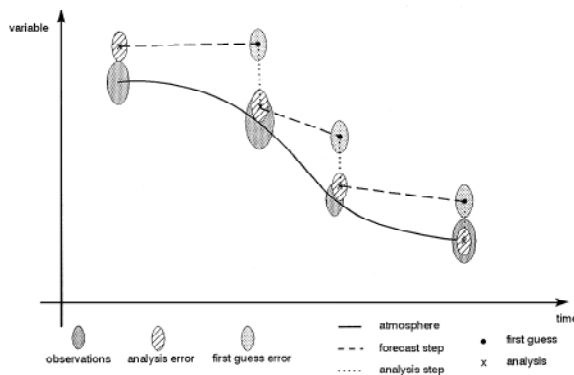


Figure 1 OI or 3Dvar analysis of the atmospheric state (vertical) over time (horizontal). © ESA, 1996.

Accurate weather and wave forecasts are essential to monitor safety at sea for ship routing and tourism, and to issue warnings for coastal land protection in extreme wind and wave conditions, such as tropical cyclones. The prediction of extreme weather events has obviously potentially large social and economic value. The accuracy of short-range weather and wave forecasts over Europe depends to a large extent on the real-time availability of accurate observations over the Atlantic ocean, where conventional measurements are sparse. For the medium range, the coverage over the Pacific and in the tropical hurricane area also becomes critical. ERS-1 scatterometer data have been used to increase the data coverage over the oceans in different Numerical Weather Prediction (NWP) models and showed in general improvement in the short range weather forecasts (e.g., Stoffelen and Anderson, 1997c). In the medium range, beneficial impacts were seen particularly in the Southern Hemisphere (e.g., Bell, 1994). Furthermore, the use of NWP data, with scatterometer winds included, results in improved WAM wave forecasts (Janssen and Hansen, 1996).

In regional weather forecasting the emphasis lies on the short range and on the sub-synoptic spatial scales. Wind observations with a high spatial coverage are essential to resolve these. The scatterometer provides such data, albeit only at the surface. The use of ERS-1 and ERS-2 tandem scatterometer data in HIRLAM may therefore be expected to be more beneficial than the use of only one ERS scatterometer. Also, the ASCAT scatterometer on board the future EUMETSAT METOP satellite and the NASA scatterometer SeaWinds for QuikSCAT or on board of the Japanese ADEOS-II, have such an increased coverage. The HIRLAM data assimilation system at KNMI is started with a cut-off time for observations of 2 hours. Usually only 50% of the ERS scatterometer data are received within two hours. Our experiments confirm the importance for Europe of scatterometer data and suggest that a delivery of data within 2 hours would be very useful.

2. RESULTS

2.1 Quality Control and Monitoring

The ERS-2 geophysical validation strategy includes an “ocean” sigma naught calibration procedure as described by Stoffelen (1998a). Moreover, instrument monitoring, see Le Meur (1996a), and backscatter QC (Stoffelen and Anderson, 1997a) results in a product with well characterized quality. It can not be stressed too often that a few low quality observations may destroy the beneficial impact of many good quality observations, and that Quality Control and Monitoring is essential.

2.2 Wind Tuning

In order to avoid systematic slowing down or speeding up of the HIRLAM model by scatterometer data assimilation we adopted a careful wind validation. Gaffard and Roquet(1998) show the detrimental effect of systematic wind bias on NWP impact. The results of a wind calibration method taking into account the error characteristics of *in situ*, satellite and model winds by Stoffelen (1998b) or Le Meur et al (1997) has been used to estimate the wind biases of the HIRLAM model and ECMWF model with respect to the scatterometer. Although scatterometer winds delivered by PRESCAT are known to be approximately 5% low, the HIRLAM first guess has a negligible bias with respect to the ERS scatterometers, and thus is also biased low with respect to the true wind. The ECMWF model is biased high though. We estimate the random ERS scatterometer wind component error to be 1.8 m s^{-1} . The NWP model random error is estimated to be smaller than this, i.e., $1.0 - 1.2 \text{ m s}^{-1}$.

ERS scatterometer backscatter measurements are delivered on a grid of 25 km, but have a spatial resolution of 50 km. The HIRLAM and ECMWF model grid distances are nominally 50 km and 60 km respectively. In order to present the scatterometer data to the HIRLAM model in a spatial representation consistent with the model, we averaged the scatterometer data to a grid of 100 km, whereas ECMWF thins the winds to this same grid. As is argued below, this spatial representation was still too fine to be assimilated by the HIRLAM or ECMWF models in some cases. Anyway, after the ocean calibration and wind tuning, PRESCAT delivers accurate ERS-1 and ERS-2 winds with much sub-synoptic scale information.

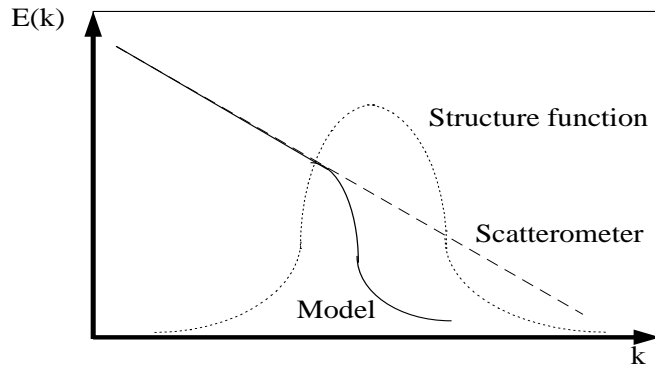


Figure 2 The ERS scatterometer resolves sub-synoptic scale information with large wave number k (dashed) that the NWP model does not resolve (solid). The analysis structure functions (dotted) are designed to incorporate the observed smaller scale structures into the NWP model energy spectrum, $E(k)$.

2.3 Assimilation

2.3.1 HIRLAM

The tandem scatterometer data assimilation experiment ran from 6-18 February 1996, a period with a disturbed westerly flow over western Europe. Since the North Atlantic is an area with a sparse meteorological observation coverage, scatterometer data are expected to fill in this gap and thus may provide an impact on the weather forecasts over western Europe. The grid used is by approximation equidistant and 5000 by 4000 km with Dublin in the center.

The analysis is a combination of the information provided by a HIRLAM 3-hour forecast, called background, and the observations available in the 3-hour time window centered around the verification time of the forecast (Figure 1). The impact of observations in the analysis depends on the ratio of the estimated background over observation error. The scatterometer observation errors are assumed to be spatially uncorrelated (Stoffelen, 1996), and the spatial projection of scatterometer information in the analysis depends solely on the estimated background error structure (Figure 2). The typical horizontal projection scale is 250 km. The error structures are multivariate and balanced, indicating that the scatterometer wind observations influence the pressure and temperature fields. Also, the information is projected in the vertical, e.g., a modification of the wind at the surface due to a scatterometer observation results in a fraction 0.25 of that modification at 500 mb. From most scatterometer experiments carried out so far, it can be concluded that forecast impact can only be obtained when the upper air is improved in a consistent way with the modifications at the surface.

For the selected period in February '96 three data assimilation experiments were run

- * noERS, control without scatterometer winds,
- * ERS1, with only ERS-1 winds assimilated, and
- * ERS12, with both ERS-1 and ERS-2 included.

2.3.1.2 Impact over Sea

The background wind fields of all these three experiments were verified against the scatterometer winds. It was found that both the ERS1 and the ERS12 background had a roughly 20% smaller error than the noERS background. We found that the ambiguity removal in experiment ERS12 worked clearly the best, followed by that of experiment ERS1, and the worst performance in experiment noERS. This suggests that phase errors of meteorological systems are smallest for experiment ERS12.

2.3.1.2 Impact over Land

To verify the impact over land we compared the RMS mean sea level pressure (MSLP) modifications, increments, in the analysis. Since over land the same observations are used in the three experiments, a smaller RMS increment indicates a better background MSLP. The RMS analysis increments over land in the ERS1 and ERS12 experiments were 10-20 % lower than in the noERS experiment, indicating that the background is also improved over land by the assimilation of scatterometer winds.

2.3.1.3 High resolution?

Although we anticipated that the HIRLAM data assimilation system would not be capable of resolving all the sub-synoptic detail in the scatterometer winds, and we had averaged the winds to a 100 km resolution, we still found that the observation consistency check in the analysis rejects scatterometer winds close to sharp troughs and fronts, and substantially smoothes the winds on scales smaller than a few hundred kilometers. In other words, the small-scale information in the scatterometer winds is smoothed out by the analysis. This is due to the estimate of the spatial error correlation scale of the background error. It is determined by what spatial scales the HIRLAM model can

realistically describe (Figure 2). Over the ocean this is not so much determined by the grid distance used by the model, but by the density of the network of meteorological observations, i.e., a decrease of the grid distance and associated with this an increase of the variability on the smaller scales would only result in a larger error, since no data is available to determine the flow on these small scales.

Scatterometer and other single level wind data will help improve this situation, but probably upper air wind profile observations will be needed for a substantial improvement over the oceans (Ingmann et al, this issue).

2.3.2 ECMWF 4Dvar

Effects in the global assimilation of scatterometer winds at ECMWF are similar to those observed at KNMI in case of 3Dvar and Optimum Interpolation, OI, methods (Le Meur et al, 1996b). However, ECMWF put a 4Dvar data assimilation scheme into operations in November 1997. In 4Dvar the dynamics of the forecast model over the assimilation window, 6 hours currently, are adapted according to the observations available. As such, the model state can be changed in a dynamically consistent way. This is expected to make a difference in particularly the most dynamical situations. In line with this it is found that tropical cyclones are much better represented and retained in the 4Dvar assimilation cycle than in the 3Dvar assimilation cycle. Scatterometer data are found to often increase the intensity of tropical cyclones, and correct their position. However, if a tropical cyclone is partially captured in the scatterometer swath and not well represented in the ECMWF model, then the analysis of the cyclone may not result in the correct structure (Isaksen et al, 1998). This is due to the influence of the spatial structure functions representing the average error in the ECMWF background, but that do not provide the most ideal analysis increments in all situations. Experiments with situation-dependent structure functions or high resolution analysis are recommended to investigate possible improvements.

2.4 Forecast Impact

2.4.1 HIRLAM

From the 00 UTC and 12 UTC analyses of all the experiments we ran two-day forecasts. The forecasts for forecast leads of 12, 24, 36 and 48 hours were systematically verified with the corresponding analyses for surface wind, pressure and temperature, and 500 mb wind and temperature. Up to a forecast lead of 24 hours, the verifications clearly depend on whether we use the noERS, ERS1, or ERS12 analyses for verification. For the 48 hour forecasts this is not the case, and our conclusions can be firm. It is clear that the ERS12 forecasts are better than the ERS1 and noERS forecasts. On the other hand, the two-day ERS1 forecasts are on average not demonstrably better than the noERS forecasts. This confirms the conclusion of Le Meur (1996) with the ECMWF NWP model that a tandem scatterometer has more than twice the impact of a single scatterometer. Scatterometer data coverage is thus important.

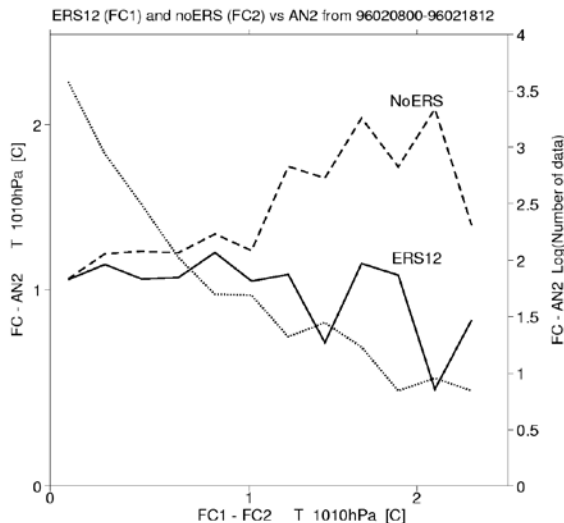


Figure 3 Verification of the ERS12 (solid) and NoERS (dashed) forecasts (left) versus 48-hour forecast impact of ERS1 and ERS2. The right axis represents the number of cases (dotted). The more the ERS12 and NoERS forecasts are different, the better the ERS12 forecast and the worse the NoERS forecast. When scatterometer data has impact, it is thus generally beneficial.

The average forecast impact was different for different parameters and different forecast ranges, but again we find that the forecast impact is generally similar at the surface and in the upper air, indicating that in case of positive impact the scatterometer information at the surface is well propagated in the vertical.

2.4.1 Tropical Cyclones and 4Dvar

The forecasts from 4Dvar analyses in case of tropical cyclones are spectacular. For tropical cyclone George in September 1998, the ECMWF 10-day forecasts over a 13-day period made unprecedented medium-range forecasts of its track. This forecast skill is due to the better representation of tropical cyclones in the 4Dvar assimilation, with respect to their representation in 3Dvar or OI. Parallel experiments with and without the use of scatterometer winds were conducted in order to determine the role of scatterometer data in the forecasts. Isaksen et al (1998) shows detailed results, indicating that scatterometer winds play an essential role in 4Dvar to the improved forecasts of tropical cyclones.

3. RESUME AND OUTLOOK

The ERS-1 and ERS-2 scatterometers provide detailed sub-synoptic-scale information that is relevant for nowcasting and longer range forecasting. QC and monitoring routines (in PRESCAT) make the routine use of the winds in NWP models feasible.

The HIRLAM analyses are clearly improved by PRESCAT winds, both over land and over sea, and both in case of one and in case of two scatterometers. However, the information provided by the scatterometer on a scale of 100 km is rejected by the HIRLAM model. An increased density of meteorological observations over the oceans, also in the upper air, is believed to be necessary in order to improve the situation. Experimentation with higher resolution data assimilation and forecast systems is recommended as well however.

In line with the above from our experiments it is found that scatterometer data coverage is very important to obtain forecast impact. For the HIRLAM experiments, we were not able to demonstrate the forecast impact of one scatterometer, but found a clear beneficial impact in case we assimilated the ERS-1 and ERS-2 scatterometer wind data in tandem. The synergy of two scatterometers is present also in the ECMWF system.

In fact it has been realized before that coverage is a weak point of the ERS-1 or ERS-2 scatterometer, and its successor ASCAT on METOP will obtain a threefold coverage. In preparation for METOP KNMI is developing calibration and validation tools and the wind processing chain within the EUMETSAT Ocean and Sea Ice Satellite Application Facility. By the end of 1998 KNMI plans to have a prototype processing chain running in near real-time with ERS data. This prototype is based on PRESCAT. Developments on a. o. ice screening and ambiguity removal are performed in collaboration with IFREMER.

In order to bridge the gap between the ERS scatterometer series and ASCAT on METOP, the meteorological community will have to rely on a new scatterometer concept being developed by NASA, SeaWinds. QuikSCAT will be a dedicated SeaWinds scatterometer mission, scheduled for launch in late 1998. NOAA plans to have a near real-time distribution of the data in place by mid 1999. In 2000, ADEOS-II is planned for launch with a copy of the NASA SeaWinds scatterometer on board.

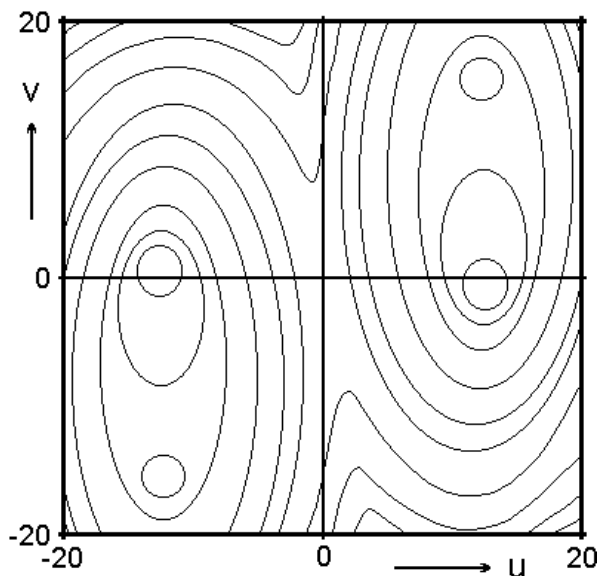


Figure 4 Illustration of the wind probability contours as a function of the wind components u and v for a SeaWinds wind vector cell with four measurements at different azimuths and for the two polarizations. Multiple minima may exist.

Fortunately, QuikSCAT will have a large data coverage with its swath of 1800 km wide. That part of the swath that contains a similar amount of information on the full near-surface wind vector as that provided at the nodes of the ERS or NSCAT scatterometers, is of similar width than the total swath width of NSCAT or ASCAT. However, the remaining outer and middle parts of the swath will contain less information than for instance the ERS or NSCAT measurement cells. The "sweet spots" in the swath will have slightly greater ambiguity in the wind domain than the ERS scatterometers (Stoffelen and Anderson, 1997c), and its effect need to be tested to arrive at a practical solution. In collaboration with NASA and with EUMETSAT support, KNMI and ECMWF plan to contribute towards an effective interpretation and quality control of the SeaWinds data to the benefit of NWP. The sensitivity of the NASA scatterometers to rain is of particular concern. Figa and Stoffelen (1998) propose a QC algorithm rejecting many rain points, that will be tested for use with SeaWinds as well.

Given the importance of data coverage and the resolution of the scatterometer wind product, it may be clear that a timely data delivery has a high priority.

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