5-DAY AVERAGE WIND OVER NORTH-WEST ATLANTIC FROM ERS1 USING A VARIATIONAL ANALYSIS

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A variational method is developed to produce 5-day gridded wind fields from the first European Remote Sensing (ERS1) scatterometer wind data only. The study focuses on the northwest Atlantic during a 3-month period from August to October of 1992. ERS1 wind data, processed by the Jet Propulsion Laboratory, are binned first on a 1 degree grid for 5-day periods, each period shifted by one day. The analysis method is based upon minimizing a cost function. This function is a set of constraints expressing proximity of resulting wind vector components and wind speed to ERS1 values, a smoothing term and a kinematic constraint on the curl of the resulting wind field. Relative weights for each of the constraints are adjusted by means of statistical comparisons of analysed winds with independent buoy data, and tests of sensitivity. Salient characteristics of the resultant ERS1 5-day wind and wind-curl fields are analyzed and compared with those in surface wind products from ECMWF and buoy winds. They show a general good agreement and highlight the new information provided by ERS1 data on the space and time variability of the wind over the ocean.

Keywords: ERS1 scatterometer; ocean winds; variational analysis; North Atlantic

INTRODUCTION

Like all processes involving air-sea interaction, modeling the general ocean circulation requires the best possible estimates of surface winds. In this context, space-borne scatterometers are attractive tools, as they should provide wind observations over the world ocean for the next ten years.

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Although scatterometer data are found to have a global positive impact on numerical weather prediction (Hoffman, 1993; Atlas, 1997), Global Circulation Model products of surface winds are not accurate enough for many climate and ocean applications, and are characterized by particularly poor spatial resolution. Preliminary studies on simulated scatterometer data suggest for their part that satellite scatterometer data could be useful for ocean modeling with no prior assimilation in meteorological models (Barnier et al., 1991 and 1994). Millif et al. (1996) have demonstrated with synthetic data that the realism of the circulation produced by a quasi-geostrophic model is quite sensitive to the high wave-number spectral content that should be found in scatterometer winds. As was pointed out in these studies, scatterometer data from the European Remote Sensing (ERS1) satellite would benefit from analysis/processing prior to being used in ocean modeling applications. The ERS satellite coverage is shown for a 5-day period in Figure 1 and illustrates the sequential aspect of the swaths and the gaps in-between.

Attempts to provide regular wind fields from scatterometer winds began with Seasat. Legler and O'Brien (1985), for example, used spatial and temporal averaging to interpolate scatterometer data in the gaps, which produced smooth wind fields that retained only the very large-scale features. Difficulties in processing the data associated with the satellite sampling

FIGURE 1 JPL-ERS1 scatterometer winds from the 16th to the 20th of September. One vector out of 12 is plotted for convenience. The satellite data coverage shows significant gaps.
(irregular spatial and temporal coverage) have been discussed using simulated data (Kelly and Caruso, 1990; Zeng and Levy, 1995). With the launch of the ERS1 in July 1991, the sampling issue could be studied with real cases. Bentamy et al. (1996) applied a geostatistical analysis in the tropical Atlantic. Le Meur et al. (1994) implemented an objective analysis over the North Atlantic ocean at Météo-France. Tang and Liu (1994) use a successive correction technique to provide global wind fields.

Variational analyses are good candidates to solve the sampling problem since they allow for the inclusion of physical constraints, with few limitations on their number, or their formulation. Moreover, they can be quite simple, cost little in computer time and do not explicitly use any statistical formulation. As a consequence, steps of calibration are needed. Nonetheless, they are among the only practical methods to estimate relevant short-term global wind fields. If the analysis is able to retain the variability contained in the scatterometer winds at a 1-degree scale, this will represent an important improvement compared to climatologies and analyses from Numerical Weather Prediction centres.

The aim of the study is to define a variational analysis process able to provide fully developed gridded wind fields from ERS1 data only, which retain the space and time scales that are relevant to basin scale oceanography. To develop and test the method, we focus on a northwest region of the Atlantic Ocean (20–45°N; 55–80°W) during a 3-month period, August through October 1992. These choices are believed to allow conclusions that will be useful for basin-size ocean modeling; the geographical domain is an area in the world ocean where the winds are best known, and the season (summer to fall) sees a large variety of wind patterns, from calm summer winds to strong storms in the fall.

ERS1 scatterometer wind data are presented in the second section. Methodologies, including a pre-processing, definitions of a cost function and the first guess, are described in section 3. Section 4 describes the adjustment of the analysis and sensitivity to external parameters and fields. The analysed ERS1 wind fields are compared and validated against buoy data and ECMWF analyses in section 5, and results are discussed in section 6.

2. ERS1 WIND DATA

The ERS1 satellite was launched by the European Space Agency (ESA) in July 1991 with a 5.3-Ghz (C-band) Active Microwave Instrument comprising the Wind Scatterometer onboard.
ERS1 winds used in this study are those processed by the Jet Propulsion Laboratory (JPL) with a retrieving model function defined by statistical comparisons with co-located satellite data and analyses from the National Meteorological Center (now National Center for Environmental Predictions), (Dunbar, 1992; Freilich, 1992). Halpern et al. (1993) indicate that there are too many low winds in the JPL data set. However, monthly means compare well with climatological monthly mean wind fields. On the other hand, very high winds are nearly absent in satellite scatterometer data, as well as in buoy or GCM data (Brown, 1997).

Several poorly resolved ambiguities are identified in rows 1 and 2 of the swath corresponding to measurements at high angle of incidence. The first row is thus systematically discarded while the second row is retained if only one vector solution is proposed. This slightly reduces the coverage (by less than 4%) but sensibly increases the quality of the processed winds.

Some unresolved ambiguities also inevitably remain in the JPL data set, but recent model functions now available from ESA or Institut Français de Recherche pour l' Exploitation de la MER (IFREMER) show significant improvement in wind retrieval. The quality of the scatterometer winds is obviously of crucial importance for the quality of the analysed field, and the JPL data set shows an overall quality adequate for the implementation and development of the method.

3. METHODOLOGY

3.1. Pre-processing

The pre-processing hereafter described consists in a gridding of the satellite data. Then, to increase the statistical significance of input data provided for the analysis, ERS1 data are averaged in time over periods of 5 days lagged by one day, and in space over areas of 1° x 1°, e.g., Figures 2a to 4a. The gridding of the North East Atlantic domain on a 1-degree grid results in 594 ocean grid points, and 88 five-day mean wind fields are obtained over the 3-month period.

A 1-degree space scale is considered as being a good compromise between the ERS1 scatterometer resolution, the number of ERS1 raw data points in each preprocessed wind vector, and needs in terms of basin scale ocean modeling.

For similar reasons, the 5-day-averaging period is chosen as being a good compromise on the time scale. Large et al. (1991) showed that the global and basin scale circulations produced by present wind driven ocean models are
not sensitive to variability in the wind forcing at periods shorter than 3 days. With ERS1 data sampling, 3-day and 5-day periods show a comparable coverage. However, 5-day periods are processed because more data would be available.

In the following, we refer to the pre-processed ERS1 data as ERS1 data, and the original JPL data will be referred to as raw data.

3.2. The Cost Function

The variational method consists in designing and minimizing a cost function expressing misfits to prescribed constraints. The cost function $F(\vec{V})$ is chosen to remain simple for further interpretation of the effect of each constraint. It includes (eq. I) proximity constraints on the components (first term) and the magnitude of the wind (second term), a smoothing (or penalty) term (third term) and a kinematic proximity constraint on the curl of the wind (fourth term). It is dimensionalised in $s^{-2}$;

$$F(\vec{V}) = \lambda_1 \frac{1}{L^2} \sum_i \alpha_i [(u_i - u_{0,i})^2 + (v_i - v_{0,i})^2]$$

$$+ \lambda_2 \frac{1}{L^2} \sum_i \alpha_i [u_i - u_{0,i}]^2$$

$$+ \lambda_3 L^2 \sum_i [(\nabla^2 u_i - u_{\text{ref},i}) + \nabla^2 (v_i - v_{\text{ref},i})]^2$$

$$+ \lambda_4 \sum_i \alpha_i [\text{rot}(\vec{V} - \vec{V}_{0,i})]^2$$

where the index $i$ stands for the grid point, $\vec{V}$, $u$, $v$ and $V$ are respectively the vector, zonal and meridional components, and magnitude of the analyzed wind vector; $\vec{V}_0$, $u_0$, $v_0$ and $V_0$ are the same variables defining the first guess; $u_{\text{ref}}$ and $v_{\text{ref}}$ are the components of the reference field used in the smoothing term. The coefficients $\lambda_1$ to $\lambda_4$ are the “weights” defining the balance between the constraints; $\alpha$ is a “swath flag” which is 1 within the satellite swath, 0 outside; and $L$ is the characteristic length of our problem, i.e., 1 degree (the variation of the length of the degree with latitude is taken into account).

After minimizing the function, we obtain a smooth gridded wind field, $\vec{V}$, retaining scatterometer information in terms of the different operators defined.

The proximity constraint on the magnitude (second term in 1) is included because of the ambiguity problem in the wind retrieving process, which
essentially affects the direction. This term makes the function non-linear but provides more consistent fields, with smaller rms differences of magnitude and direction with buoy data.

The curl represents the direct ocean wind forcing at large scales (the Ekman divergence). The kinematic constraint on the curl (fourth term in 1) is the one term retaining spatial variability at short scales. The constraint is applied here on the curl of the pre-processed wind field. Experiments have also been run using an instantaneous curl estimated within the swath. Although they were then binned over the one degree grid and averaged over the time-step, the resulting curl fields remain noisy and have a negative impact on the analysis.

The smoothing term (third term in 1) is a well-proven Laplacian term (Hoffman, 1981 and 1984; Legler et al., 1989) applied to the difference between the analysed wind and a reference field. The latter is the average over a specified 5-day period of ECMWF winds between 1986 and 1991. Note that the smoothing term acts on the whole domain (no swath coefficient \( \alpha \) is applied on it).

The numerical schemes of the kinematic and smoothing constraints are centered finite difference schemes. Tests were also run using alternative finite difference schemes for the curl with no significant improvement.

All the constraints are weak according to the definition given by Sasaki (1970) i.e., no wind data are dictated. The minimization of the cost function is performed by the conjugate gradient algorithm CONJG (Shanno, 1978; Shanno and Phua, 1980) which has already been used by Legler et al. (1985 and 1989) to analyse simulated scatterometer data, and monthly averaged pseudo-stress.

3.3. First Guess

The first guess is constructed with the pre-processed ERS1 wind field beneath the satellite swath and complementary data outside. Zero values outside the swath could be used since there is no constraint applied to these non-satellite data, except via the smoothing term. The prime advantage of defining a non-zero first guess wind is a gain in computation time, as the analysis converges faster. Also, at boundaries with no satellite data and during periods of poor satellite data coverage, the analysis conserves partly the first guess, and zero or weak vectors may not be adequate.

The choice of the complementary field is subjective and it was decided to use the wind field analysed at the previous time-step. An assumption of persistence is consequently introduced. Since the analysis is performed on
5-day time-steps lagged by one day, the fields used to build the first guess are comparable and the persistence assumption concerns a period of one day only.

3.4. Independent Data

As the variational analysis does not provide error estimates, independent data are consequently needed to adjust the analysis and validate the results.

Available independent buoy winds (from Global Telecommunication System surface marine observations), adjusted to a 10-meter height, and processed with the binning and time-averaging previously described, are used for these purposes. Data from buoys near the coast are discarded because of the different boundary problems that might affect the analysis. On average, data from 11 buoys are retained at each time-step, the buoys being mostly located 200 miles off the coast (example Figs. 2c to 4c).

Performance of the analysis is then diagnosed by comparison statistics between colocated analysed satellite winds and buoy winds.

4. ADJUSTING THE ANALYSIS

4.1. Relative Weights of the Constraints

Relative weights of the constraints are discussed here; the usefulness of each constraint is tested and optimal values of their weights are sought, to obtain an optimal balance between the different analysis constraints.

The investigation is conducted over three periods with different characteristics. August 4 to 13 is a period of steady and calm winds. September 13 to 22 is characterized by low data coverage. October 8 to 17 is a period of good satellite data coverage with strong and highly variable winds.

Usefulness of the Constraints

The usefulness of each proximity constraint is investigated by means of validation experiments switching on and off each unit-weighted proximity constraint. It is assessed by statistical differences with the independent buoy data, Table I, which are commented hereafter in relation to the prescribed accuracy of the ERS1 mission. Accuracies are denoted \( \text{acc}_u = 2 \text{ m/s} \) for the wind speed and \( \text{acc}_\theta = 20^\circ \) for the wind direction.
TABLE I Tests on the usefulness of the constraints. Rms differences in direction ($\theta$) and magnitude ($U$) between analysed ERS1 winds and independent buoy winds are indicated beneath and outside the swath, for several sets of weights $\lambda_i$ applied to the constraints (components, magnitude, smoothing, curl). Each experiment is run with one of the 3 proximity constraints eliminated by setting the respective $\lambda_i$ to zero, while the smoothing term, $\lambda_3$, is always maintained.

<table>
<thead>
<tr>
<th>$(\lambda_1, \lambda_2, \lambda_3, \lambda_4)$</th>
<th>(1, 1, 1, 1)</th>
<th>(0, 1, 1, 1)</th>
<th>(1, 0, 1, 1)</th>
<th>(1, 1, 1, 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$ (degree)</td>
<td>46.3, 50.0</td>
<td>47.0, 51.8</td>
<td>47.8, 51.8</td>
<td>47.8, 51.8</td>
</tr>
<tr>
<td>$U$ (m/s)</td>
<td>2.92, 2.23</td>
<td>2.85, 2.23</td>
<td>2.85, 2.23</td>
<td>2.85, 2.23</td>
</tr>
<tr>
<td>$\theta$ (degree)</td>
<td>60.6, 98.3</td>
<td>60.9, 103.8</td>
<td>60.9, 103.8</td>
<td>60.9, 103.8</td>
</tr>
<tr>
<td>$U$ (m/s)</td>
<td>2.05, 2.79</td>
<td>1.93, 2.69</td>
<td>1.93, 2.69</td>
<td>1.93, 2.69</td>
</tr>
<tr>
<td>$\theta$ (degree)</td>
<td>58.3, 48.0</td>
<td>58.8, 55.3</td>
<td>58.8, 55.3</td>
<td>58.8, 55.3</td>
</tr>
<tr>
<td>$U$ (m/s)</td>
<td>2.61, 3.04</td>
<td>2.56, 2.94</td>
<td>2.56, 2.94</td>
<td>2.56, 2.94</td>
</tr>
</tbody>
</table>

Note that the constraint on the wind components has a generally negative impact on the wind speed (between 2.5% and 6% of the accuracy) compensated by a positive impact on the wind direction (between 1.5% and up to 36.5%).

In contrast, the constraint on the magnitude has a positive impact on the wind speed quantified at 8% (and 11%) of acc$_U$, but no impact on the wind direction beneath the swath (and 8% of acc$_\theta$ outside the swath). This emphasizes the contribution of the magnitude constraint in the conservation and propagation of the satellite data information.

Results are more blurred with regard to the constraint on the curl. The overall impact of this constraint remains globally positive, except in the second period, which is one of low satellite coverage.

However, the best compromise (i.e., low rms) for both wind speed and wind direction, is obtained with all four constraints.

**Evaluation of the Relative Weights**

A large number of tests has been performed in order to empirically determine optimal value for each weight. Evaluation of an order of magnitude is done for each weight with unit-weighted complementary constraints. A set of weights is then evaluated by successive trials and comparisons of the resulting analyses with the independent buoy data. Then, a sensitivity analysis (Meyers et al., 1994) is performed to quantify the effect of the weight on the analysis, and to focus on the most sensitive constraints.

The final set of weights used over the 3 months is (1, 1.5, 2, 1.5), respectively, for the constraint on the components, the magnitude, the smoothing and the curl. These values minimise statistical differences
between analysed winds and buoy data, Table II. To place these statistics in their context, it should be added that, from the first guess to the analysed field, rms are decreased by 13% (direction) and 0% (speed) outside the swath and by 6% (direction) and 4% (speed) beneath the swath.

Several comments are worth being made. One concerns the difficulty of achieving optimal statistical differences both in magnitude and in direction; significant smoothing is generally an efficient way of decreasing by a few degrees rms differences in terms of direction with buoy winds, but at some point it degrades rms differences in terms of magnitude.

The fact that analysed wind speeds do not converge significantly better towards buoy winds may be a consequence of too many low ERSI winds retrieved by JPL, leading to an underestimation of the pre-processed ERSI wind speeds. It confirms, however, the usefulness of the magnitude term of the cost function in retaining the initial wind speed by opposition with the smoothing term.

Between successive 5-day periods, optimal weights may change. However, no simple dependency of the optimal set of weights on defined characteristics of the wind field (coverage, variability of the wind, curl ratio, etc) has been found. The chosen set has thus been evaluated and optimised over the total 3-month period.

Sensitivity of the Analysis to the Set of Weights

For the sensitivity analysis, the diagnostics are the overall rms differences in terms of direction ($R_d$) and speed ($R_u$), with an independent and complete field represented by colocated ECMWF analysed winds.

The sensitivity is defined here as the increment of an overall diagnostic, denoted $\Delta R$, over the increment of the weight, $\Delta \lambda$. The relative sensitivities,

<table>
<thead>
<tr>
<th>Magnitude (m/s)</th>
<th>Beneath the swath</th>
<th>Outside the swath</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1, 1, 1, 1.5, 2, 1.5</td>
<td>1, 1, 1, 1.5, 2, 1.5</td>
</tr>
<tr>
<td>$Rms$</td>
<td>2.56, 2.54</td>
<td>58.4, 56.5</td>
</tr>
<tr>
<td>$Mean$</td>
<td>-1.47, -1.43</td>
<td>5.1, 5.3</td>
</tr>
<tr>
<td>$Rms$</td>
<td>2.81, 2.78</td>
<td>72.0</td>
</tr>
<tr>
<td>$Mean$</td>
<td>-94, -120</td>
<td>1.2</td>
</tr>
</tbody>
</table>
and $S_U$, are then defined by reference to the accuracy expected from scatterometer winds $\text{acc}_\theta$ and $\text{acc}_U$:

$$S_\theta = \frac{\Delta R_\theta}{\Delta \lambda} \times \frac{\lambda}{\text{acc}_\theta}, \quad S_U = \frac{\Delta R_U}{\Delta \lambda} \times \frac{\lambda}{\text{acc}_U}$$

A positive sensitivity thus defines a positive increase of the diagnostic for a positive increment of the parameter.

The corresponding sensitivities are presented for the period August 4 to 13, Table III. Greatest sensitivities are found for the smoothing term ($\lambda_3$), and then for the magnitude ($\lambda_2$) term on both response functions. The 3-month period indicates equivalent sensitivities.

Meyers et al. (1994) define the analysis error due to the uncertainty in defining the weights as a rms of the different sensitivities:

$$S = \sqrt{\frac{1}{4} \sum_{l=1}^{4} S(\lambda_l)^2}$$

This definition leads to error percentages due to the weight inaccuracies of 3% (9%) in relation to the speed within the swath (outside the swath) and 2% (13%) in relation to the direction of the wind.

4.2. Sensitivity of the Analysis to External Fields
The First Guess

The complementary data used to fill in gaps in the pre-processed ERS1 field to form the first guess may influence the analysis through the smoothing term. In specific boundary regions with no initial satellite data, especially along the coasts, complementary data may be retained just as provided.

| Sensitivity of the analysis to the weights of the constraints (%) |
|-------------------------|-------------------------|-------------------------|-------------------------|
| weights                  | $\lambda_1 = 1$         | $\lambda_2 = 1.5$      | $\lambda_3 = 2$        | $\lambda_4 = 1.5$      |
| direction                |                         |                         |                         |                         |
Tests have been carried out with different complementary field; a zero wind field (already commented in section 3), the ECMWF analysed winds, and the ERS1 analysed field computed at the previous time-step. The impact on the analysis, estimated by statistical comparisons with independent buoy data, establish that the most suitable complementary data is the analysed ERS1 winds at the previous time-step. For the initialisation of the analysis (first five days, August 1 to 5), ERS1 winds averaged over the first fifteen days of August are used.

Tests were also carried out to investigate the impact of using ECMWF winds over land. This would permit to use centered finite difference schemes along coasts involving ECMWF analysis instead of the truncated schemes used in the present study. The effect is very important as, over the three months of analysis, rms differences with buoy winds are decreased by 9° and 0.35 m/s (27° and 0.75 m/s) beneath (and outside) the swath. This highlights the considerable effect of the boundary conditions on the analysis. As this study concerns analysis of ERS1 winds only, this solution is not retained and no information from any external analysis is used. In future productions of surface wind fields, operational winds may be used over land surfaces.

The Reference Field

The sensitivity of the analysis to the reference field used in the smoothing term is slight. Nevertheless, a reasonable climatology field is required.

Tests carried out to use alternative fields converged to the solution described in section 3.2. A zero wind field has been tried. It successfully smoothes the analysed field, but the smoothing is found very uniform and axisymmetric, which has no physical sense. The 1992 ECMWF analysis was also tried because it is concomitant to the ERS1 mission.

5. EVALUATION OF THE ANALYSED ERS1 WINDS

5.1. Instantaneous Wind Fields

Analysed wind fields are shown in Figures 2 to 4 in comparison to ECMWF analysed wind fields and buoy winds.

Case 13 (August 13–17, 1992), Figure 2, describes a typical stable situation, with a center of depression and cyclonic circulation, together with a reversal of the wind around 41°N. The center of depression is located at 33.5°N, 59°W in the ERS1 field, and at 35°N, 56°W in the ECMWF field.
Hurricane Bonnie is well described on case 47 (September 16–20, 1992), Figure 3. It is centered at $35^\circ$N, $57.5^\circ$W in the ERS1 field and at $38^\circ$N, $56^\circ$W in the ECMWF field. Winds at the buoy ($42^\circ$N, $52^\circ$W) support the ERS1 field position more so than the position offered by ECMWF. The tracking of the hurricane (U.S. National Hurricane Center) also supports the position in the resultant fields.

In case 78 (October 12–17, 1992), Figure 4, describes a highly variable situation. The structures of both analyses generally agree, but ERS1 winds show more structures.
Over the entire period studied, typical regions of disagreement are Washington Bay, and very generally the North American coast. The agreement is generally not bad elsewhere, although misfits in the location of structures like hurricanes or fronts may be noticed. The large-scale structures agree well. Stable winds, like trade winds, are very comparable in both analyses, but more spatial variability is apparent in the ERS1 winds. Buoy winds are generally quite well represented in the ECMWF analysed wind fields, while more discrepancies are found in comparisons to ERS1 wind fields.
FIGURE 4 An example of gridded (a) and analysed (d) ERS1 wind field in comparison with the ECMWF (b) and buoy winds (c) for case 78, i.e., from 17th to 21st of October.

The curl of the wind field for case 47, Figure 5, indicates that the sign and magnitude of the curl of the winds agree, but the ERS1 analysed curl shows more spatial variability and larger gradients. One may wonder whether the patterns do not exhibit a satellite sampling signature, but this is not confirmed in the curl spectra (Fig. 10).

5.2. Comparisons with Independent Buoy Data

Time series of analysed ERS1 and buoy wind components are shown at location (24°N, 77°W), Figure 6, and at location (42°N, 62°W), Figure 7.
AVERAGE WIND OVER NW ATLANTIC FROM ERSI

FIGURE 5  An example of the curl of an analysed ERSI wind field in comparison with the curl of ECMWF winds for case 47, i.e., from 16th to 20th of September.

These locations correspond to processed buoy data that are well inside the domain and to analysed winds that are not affected by boundary effects. Each buoy data accounts for around 40 observations. There are as many ERSI observations at the northern buoy since several satellite pathways cover the location, but never more than 13 satellite observations at the southern buoy because of the proximity of the land and its effect on the scatterometer.

Corresponding ECMWF time series are very informative because buoy data are assimilated in the analysis of the Meteorological Center. The ECMWF signal appears to be very close but slightly smoother compared to that of the buoy. The ERSI signal shows more discrepancies with buoy
winds. However, ERS1 and buoy winds show equivalent temporal variability.

Correlation coefficients between the series are good, especially at southern buoy, Table IV. However, the ERS1 zonal wind component is underestimated at the southern buoy during August and September by around 2 m/s compared to the buoy wind, and by even more at the northern buoy during August. Agreement on the magnitude is better with the meridional component. Largest discrepancies are likely due to the satellite sampling and the pre-processing. For example, some events seen in buoy data but misrepresented in ERS1 analysed winds can be related to time-steps of poor
WIND COMPONENTS TIME SERIES AT LOCATION (42°N, 62°W)

FIGURE 7 Time series of zonal (top) and meridional (middle) wind components at location (42°N, 62°W). Solid lines represent the buoy wind, dashed lines the ERS1 wind and dotted lines the ECMWF wind. Also shown (at bottom) is the total number of ERS1 observations available at this 1-degree grid location.

TABLE IV Correlation coefficients of the ERS1, ECMWF and buoy time series of the zonal and meridional wind components (u1, v1) at location (24°N, 77°W) and (u2, v2) at (42°N, 62°W)

<table>
<thead>
<tr>
<th>Components</th>
<th>Correlation coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>u1</td>
</tr>
<tr>
<td>buoy-ERS1</td>
<td>0.70</td>
</tr>
<tr>
<td>buoy-ECMWF</td>
<td>0.74</td>
</tr>
</tbody>
</table>
satellite data coverage, as indicated for time-steps 4 to 8, 32 to 40 and 64 to 68 by the bottom plot of Figure 7. Events missed by the ECMWF analysis are also noted, for example at time-steps 70 to 75 on the meridional wind component at southern buoy, or time-steps 10 to 14 on the zonal wind component at northern buoy.

At each time-step, the differences in speed and direction between ERS1, buoy and ECMWF winds are calculated at every grid point beneath the swath. Then mean and rms over all grid points are calculated, Figures 8 and 9.

Mean and rms speed differences between buoy and analysed ERS1 data are in the range $[-2.4, 3.8]$ m/s and $[1, 3.9]$ m/s respectively, while the mean and rms differences between buoy and ECMWF winds are respectively in the range $[-2.4, 1.6]$ m/s and $[0.7, 3]$ m/s. Buoy winds are generally stronger than ECMWF winds, which themselves are stronger than analysed ERS1 winds.

The differences in direction, Figure 9, are significantly more variable. Those between buoy and ERS1 analysed winds are in the ranges $[-65.0, 60.0]°$ for the mean and $[10.0, 115]$° for the rms, while those between buoy and ECMWF winds are in the ranges $[-30.0, 70.0]°$ and $[4.0, 85]$°.

Differences between the buoy and ERS1 analysis appear less chaotic when the coverage is good and stable (end of October).

The overall statistical differences, averaged over all grid points and time steps, Table V, indicate that ECMWF and ERS1 wind speed estimates are weaker than buoy estimates by 0.65 m/s and 1.43 m/s respectively on average. It is recalled that JPL-ERS raw wind data were found to contain too many low winds. However, ECMWF analysed wind speeds are themselves lower than buoy wind speeds though they are not independent of these data. It is also noticeable that differences between ERS1 and ECMWF estimates are weaker than those between ERS1 and buoy estimates.

Similar comments apply to wind direction, but the mean differences do not appear to be significant and the rms differences are quite large, and even significantly greater outside rather than beneath the swath.

5.3. Wave Number Energy Spectra of the Curl

Meridional and zonal sections of the ECMWF and ERS1 analysed wind curls are defined every 5 degrees in the domain. Independent spectral densities are computed every 10 days and then averaged over the 3 months, Figure 10.
The most significant feature is the difference in levels of energy, especially at the shortest scales. The slopes are comparable at large scales, but ECMWF indicates a breakdown in the spectra between 500 and 1000 km, which is not seen in the ERS1 spectra.

Moreover, the analysed ERS1 winds are smoothed and do not show incongruous peaks at any swath scale.
FIGURE 9 Time series of mean (top) and rms (middle) wind direction differences between buoy, analysed ERSI and ECMWF winds. Solid lines represent the buoy minus ECMWF differences, dashed lines the buoy minus ERSI. At the bottom is the number of buoy data locations involved in the comparison (dashed line) and the satellite data coverage in one-per-ten (solid line).

TABLE V Statistical comparisons between ERSI analysed winds, independent buoy data and ECMWF analyses from August to October 1992. Rms (and mean) differences computed on the magnitude (U) and the direction (θ) of the wind.

<table>
<thead>
<tr>
<th>Rms (Mean) differences</th>
<th>beneath the swath</th>
<th>outside the swath</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U (m/s)</td>
<td>θ(°)</td>
</tr>
<tr>
<td>ERSI-buoy</td>
<td>2.53 (-1.43)</td>
<td>56.5 (5.3)</td>
</tr>
<tr>
<td>ECMWF-buoy</td>
<td>1.44 (-0.65)</td>
<td>40.7 (-2.2)</td>
</tr>
<tr>
<td>ERSI-ECMWF(buoy locations)</td>
<td>2.35 (-0.78)</td>
<td>54.3 (2.0)</td>
</tr>
<tr>
<td>number of comparisons</td>
<td>132</td>
<td>102</td>
</tr>
<tr>
<td>ERSI-ECMWF(overall)</td>
<td>2.24 (-0.46)</td>
<td>47.5 (3.3)</td>
</tr>
<tr>
<td>number of comparisons</td>
<td>7478</td>
<td>5892</td>
</tr>
</tbody>
</table>
5.4. Monthly Means

Monthly means for August, September and October are shown Figures 11 to 13 for four different data sets: the JPL-ERSI raw gridded winds, the ERSI analysed winds, the ECMWF analyses and the buoy wind.
The raw ERS1 gridded winds show a complete coverage for each month, but do not behave consistently and the signature of the asynoptic sampling of the swath width can be recognised. ERS1 analysed winds are very consistent and very comparable to the ECMWF analysed winds. Large-scale structures agree generally well. Disagreements are always located over the same regions; along the North American coast and South of Newfoundland, and more generally at the boundaries of the domain of the analysis. The agreement is good over the trade wind region, except for the month of October during which ERS1 winds show more spatial variability than...
FIGURE 12 Monthly averaged wind fields; ERS1 gridded and analysed winds, ECMWF winds and buoy winds.

ECMWF winds. Over the rest of the domain, the patterns agree well, but can be shifted by one and even two degrees.

Comparison with the monthly averaged buoy winds is interesting; though the buoys are involved in the ECMWF analyses, they do not compare much better with ECMWF than with ERS1 analysed winds. For example, in October, the buoy located at 74°W and 34°N agrees better with the ERS1 analysed wind than with the ECMWF wind. As the observation had been made on “instantaneous” wind fields, the agreement at buoy locations is
often better between the ERS1 and ECMWF analysed winds than with buoy winds.

Monthly means of the curl are also computed and the September mean is shown in Figure 14. ERS1 and ECMWF curl fields only roughly agree; patterns can be recognised from one figure to the other, and the sizes of typical patterns as well as their magnitudes are comparable, but the agreement stops here. The differences in the curl fields illustrate differences or shift in the location of wind events between the two analyses. As a result
of more variability, the ERSI monthly averaged curl appears to be smoother than the ECMWF monthly averaged curl, especially in the trade winds.

6. DISCUSSION

Firstly, let us summarize the entire processing applied to the ERSI scatterometer wind data. 5-day periods, lagged by one day are studied, over which data are binned on a one-degree resolution grid. Voids in the resulting pre-processed wind field are filled with the previously analysed winds to
form the first guess. A variational analysis is then performed consecutively on the 88 5-day periods of the 3-month period.

The results indicate that the method provides wind fields which are consistent with independent buoy data. ECMWF and ERS1 analysed wind fields compare quite well; there is a general agreement in the features and their occurrence. The analysed winds appear to have correct large-scale and long-term characteristics. It is more difficult to assess small-scale and short-term behaviour as few suitable comparison data are available. Significant differences appear in coastal boundary regions and in the location of events. The complete wind fields provided by the analysis are consistent and do not exhibit incongruous peaks or breakdowns in the energy spectra at any swath scale. Moreover, ERS1 data show more spatial and temporal variability, and as such, provide new information about ocean winds.

Though several diagnostics (time series and comparisons outside the swath) suggest that the satellite sampling and coverage is not always sufficient for producing such short-term wind fields, meaningful from a meteorological point of view, it may be expected, from the results of simulated wind-driven ocean models, that ERS1 analysed winds will be an interesting tool for ocean modeling, and in particular will retain the space and time scales that are relevant to basin scale oceanography.

The rms of wind differences with buoy measurements (around 2.5 m/s, 50°) may appear to be large compared to the ESA specifications which were to retrieve winds with an accuracy of 2 m/s and 20°. However, it should be pointed out that the error of the analysed fields is composed of the instrumental error, errors in the retrieval, in the 5-day averaging as well as in the variational analysis processes, and thus in the propagation of the information throughout the swath gaps. Nevertheless, although the buoy winds are input data in the analysis process of ECMWF, buoy winds do not agree much better with ECMWF than with ERS1 analysed winds.

This study enabled a variational analysis to be implemented and checked. The method is quite simple and its computational cost is low. The great potential of scatterometer tools in providing wind retrieved at short time and space scales is again demonstrated, as well as the great potential a variational analysis can bring in basin size wind field estimation.

Weaknesses and strengths of both the analysis and the scatterometer data have been pointed out. Several improvements may be anticipated; for example the use of more recent and more accurately controlled retrieved ERS1 winds, such as the off-line CERSAT data set (Bentamy et al., 1994); also, a more thorough validation of the pre-processing, which conditions the results; as well as new terms in the cost function. The use of supplementary
satellite wind data (in particular from SSM/I) would partly overcome the sampling weakness of ERS1. Finally, analysis of a larger domain would diminish deleterious boundary effects. Moreover, the method has been tested in a well observed region, which displays high variability. Larger gains are therefore expected at the scale of the world ocean, and in particular in the tropical and Southern oceans where direct observations are rare, a challenge for a further study.

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