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## FINAL REPORT

AD STOFFELEN, TILLY DRIESENAAR, JEROEN BEYSENS

THIS REPORT DESCRIBES A PROJECT CARRIED OUT IN THE FRAMEWORK OF THE NATIONAL USER SUPPORT PROGRAMME 2001-2005 (NUSP-2) UNDER RESPONSIBILITY OF THE NETHERLANDS AGENCY FOR AEROSPACE PROGRAMMES

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# EXECUTIVE SUMMARY

ERS scatterometer observations have proven important for the forecasting of dynamical weather, such as tropical cyclones. Recently, SeaWinds scatterometer measurements from QuikScat have become available. SeaWinds on QuikScat provides great coverage over the oceans. Routine operational near-real time processing of scatterometer winds is implemented at KNMI in the context of the Ocean and Sea Ice Satellite Application Facility (OSI SAF). The BCRS project contributed to the implementation of this processing as a preparation for the OSI SAF Initial Operations Phase (IOP).

The implementation follows development work at KNMI that also has been co-supported by the BCRS and the Numerical Weather Prediction (NWP) SAF:

- QuikScat product validation and inversion of the backscatter data to winds.
- A new procedure to quality control (QC) SeaWinds scatterometer observations, in particular to screen out rain-contaminated Wind Vector Cells (WVC), and
- A new procedure to assimilate QuikScat observations is developed at KNMI.
- Inversion at 100-km resolution, which appears much better than the 25-km winds.
- The ERS scatterometer two-dimensional variational ambiguity removal procedure, called 2D-VAR, was generalised to deal with ambiguous solution sets with more than two solutions of varying probability and quality.

The real-time use of SeaWinds data can only be reliable if appropriate quality monitoring and control routines are operated. The quality information is available and provided at the same time as the winds. As for ERS, for SeaWinds the WVC quality control rejection rate, the normalised inversion residual and the wind speed bias and wind direction standard deviation against a NWP model provide effective instrument and processing monitoring parameters. A scheme is implemented to provide guidance as to whether the real-time SeaWinds wind vector data are of nominal quality.

The SeaWinds processing at KNMI is the first step in the assimilation of scatterometer winds in meteorological analyses, such as in HiRLAM at KNMI or 4D-VAR at ECMWF, where the data are used routinely now. Moreover, the 2D-VAR product is useful for operational meteorologists in nowcasting or short-range forecasting and for use with OI data assimilation, which is currently run for KNMI HiRLAM.

KNMI meteorologists now find many cases where scatterometer data is of good use due to its extended coverage. Also meteorologists in other weather centres are using and providing feedback on the KNMI wind products. Examples are provided in the full report.

# PREFACE

The work in this report was funded by the BCRS in the context of the user support programme (GO). The objective of the work described in this report is the timely production of a good quality near-real time wind product from ERS or SeaWinds, that is guaranteed in the time frame between now and the METOP mission. The well-established scatterometer user community at large benefits from this activity, providing high-coverage scatterometer wind data in time. Here, we in particular focus on its benefit for NWP in Europe, and for the direct use by meteorologists at KNMI. KNMI has much experience on wind extraction from scatterometer data involving many projects. Within the Ocean and Sea Ice SAF the wind processing for ASCAT on METOP is prepared using ERS scatterometer data, serving the European user community at large. By using scatterometer winds with larger coverage such as SeaWinds, this preparation for ASCAT could be made more optimal. With the help of a EUMETSAT fellowship, KNMI participates in the work on the validation and interpretation of QuikScat data. In this work, KNMI collaborated with NASA and other European entities, such as the ECMWF, to demonstrate the methodology for the interpretation of QuikScat data, including aspects such as data validation, data quality control, and wind retrieval. In the NWP SAF KNMI collaborates with ECMWF and the Meteorological Office of the UK to develop a methodology for assimilation and monitoring of SeaWinds observations.

# CONTENTS

# 1 INTRODUCTION

Scatterometers provide accurate and spatially consistent near-surface wind information. Hardware permitting, there is a continuous series of scatterometers with at times ideal coverage of the ocean surface wind in the coming two decades. ERS scatterometer observations have proven important for the forecasting of dynamical weather, such as tropical cyclones. Moreover, the use of scatterometer winds in nowcasting, short range forecasting, and other applications are worth mentioned. The methodology developed for the successful application and assimilation of ERS winds was generalised to include the newer scatterometer concepts, such as SeaWinds. SeaWinds on QuikScat provides great coverage over the oceans. Quality monitoring, rain contamination, wind direction noise characteristics, and wind direction ambiguity selection were investigated (Stoffelen et al, 2000), now permitting routine and successful use in weather forecasting. The EUMETSAT Satellite Application Facilities (SAF) facilitate much of the development described in this report and the BCRS project reported on here supports the implementation of both routine ERS and SeaWinds scatterometer processing. Due to the fact that ERS operations hampered while the project was running, the focus was more directed towards SeaWinds implementation in order to be able to satisfy the users with a near-real time scatterometer wind product.

## 1.1 SATELLITE APPLICATION FACILITIES (SAF)

Both scatterometer research and development, and routine processing and monitoring are funded by EUMETSAT through the SAFs (EUMETSAT, 2002). More specifically, KNMI participates in the Numerical Weather Prediction (NWP) SAF, the Ocean and Sea Ice (OSI) SAF, and the Climate (CM) SAF for these purposes.

In the context of these SAFs KNMI provides

- Tailor-made SeaWinds QC in order to avoid unrepresentative wind data (e.g. rain contaminated);
- Generic scatterometer backscatter data inversion;
- Procedure to average backscatter measurements in a resolution cell of varying size, in order to provide spatially representative and accurate winds to NWP models;
- Generic scatterometer cost function to cope with all kinds of scatterometer data;
- Routine processing and monitoring of wind and in the future surface stress;
- Web-based product presentation, and distribution by FTP; and
- Web-based monitoring reports.SAF activity is currently mainly focused on SeaWinds, although much of the algorithms and software are generically applicable for ERS scatterometer and ASCAT on METOP (Stoffelen et al, 2000).

## 1.2 HERITAGE

ERS scatterometer winds have proven to be very useful for the forecasting of dynamic weather (*Isaksen and Stoffelen*, 2000). Increased coverage, such as from tandem ERS-1 and ERS-2 measurements, clearly improve the forecasts of extreme events (e.g., *Stoffelen and Beukering*, 1998; *Le Meur et al*, 1997). Improved coverage from the Ku-band SeaWinds scatterometers has thus great potential (*Atlas and Hoffman*, 2000). After the development of improved data characterisation and assimilation procedures, operational assimilation of SeaWinds at KNMI, ECMWF, and NCEP is a fact. Moreover, shift meteorologists for nowcasting are using the data.

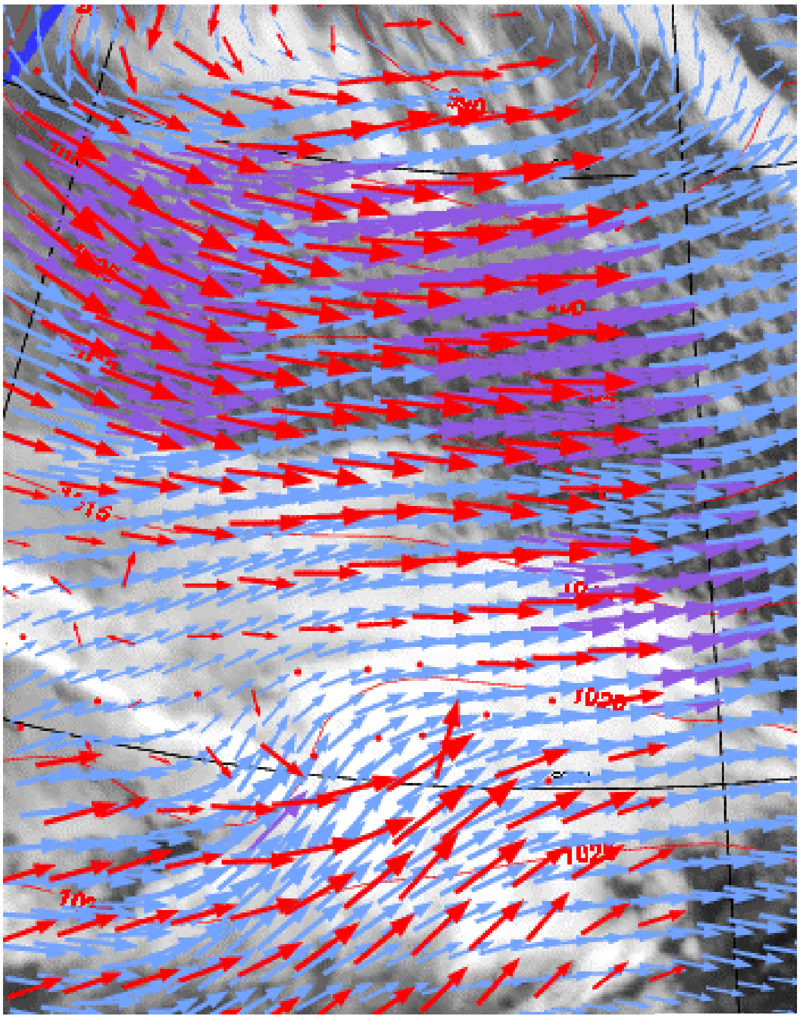

**Figure 1.1:** KNMI develops SeaWinds products and procedures for use in numerical and synoptic weather forecasting. Our emphasis lies on noise reduction, Quality Control, Quality Monitoring, and presentation. Link: [www.knmi.nl/scatterometer](www.knmi.nl/scatterometer)
The plot shows a developing storm to the southwest of Ireland not captured in location and phase by the HIRLAM forecast model, but well depicted by QuikScat.

Legend:

SeaWinds KNMI HIRLAM model wind

METEOSAT IR cloud image

10 m/s

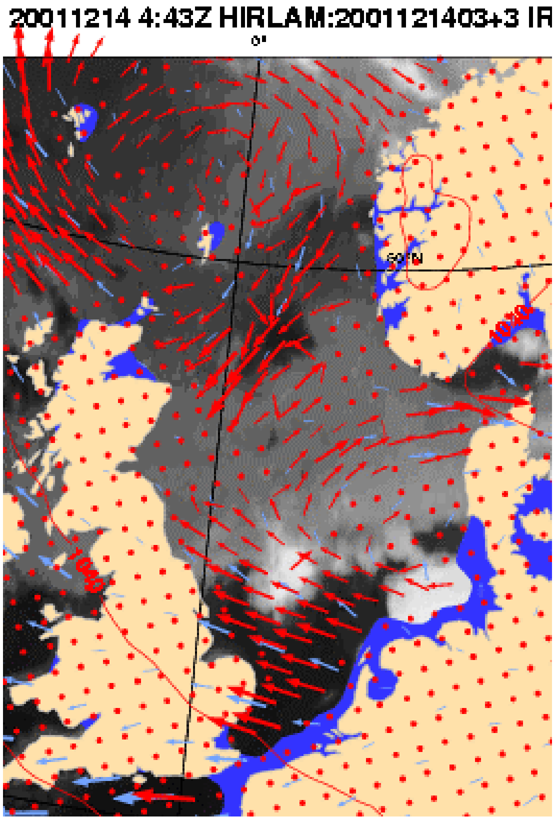


**Figure 1.2:** Legend as figure 1, but for a case with a small-scale development in the North Sea and at 25-km resolution. Numerical Weather Prediction models, such as HIRLAM, poorly forecast the jet pointing from the Norwegian coast towards Scotland. However, the jet resulted later in the day in a small-scale low in the middle of the North Sea causing unexpected rain and wind. Due to the generally cloudy conditions, the development was rather difficult to judge from geostationary satellite images. Oil platform and other conventional observations did also not provide much early evidence of the situation and development. SeaWinds provides a coverage that permits the routine and operational use by shift meteorologists.

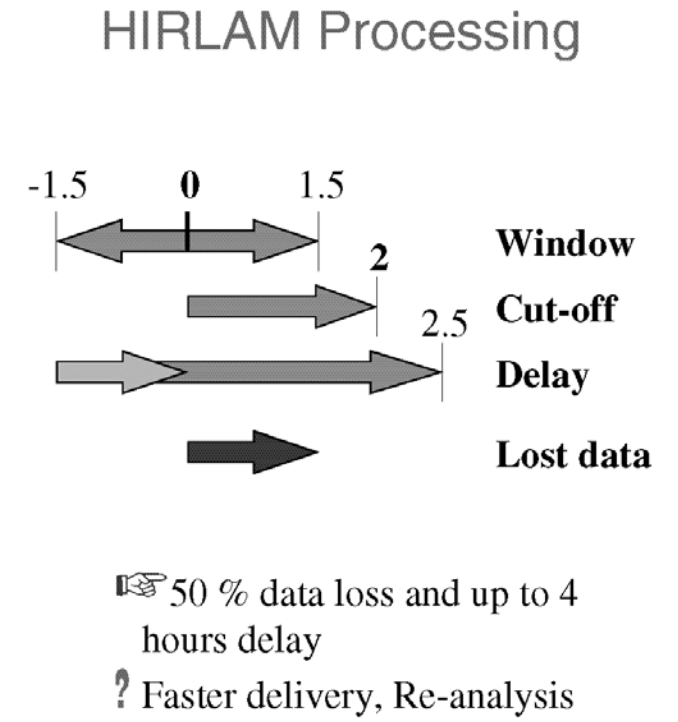


**Figure 1.3:** Timeliness of polar satellite observations. In the operational HIRLAM processing at KNMI a 3-hour assimilation window is used (top). The analysis is run after 30 minutes implying a 2-hour cut-off with respect to the processing window centre time (second row). For a delay of 2.5 hours of the orbit satellite data, HIRLAM would generally use 50% of the data (as for SeaWinds). Only in case of a large beneficial impact of the data, data assimilation centres would consider an update analysis in order to provide a better background for the next analysis cycle. Direct read-out facilities at satellite level would be most useful to facilitate the effective use of the high-resolution scatterometer information.

Severe storms that hit Europe often originate over the North Atlantic Ocean, where sparse meteorological observations are available. Consequently, the initial stage of severe storms is often poorly analysed and their development poorly predicted (*ESA*, 1999, *WMO*, 2000) as illustrated in figure 1. As a result, occasional devastating ocean or coastal wind and wave conditions remain a main challenge for NWP. The SeaWinds data coverage is such that developing storms are likely hit, thus depicting their position and amplitude. Moreover, the near-surface wind conditions drive the ocean circulation that in turn plays a major role in the climate system and in ocean life (e.g., fishery).

Figure 2 presents an example, showing the high spatial resolution in the QuikScat scatterometer winds, and the additional information content as compared to a NWP first guess.

## 1.3 TIMELINESS

Scatterometers are flown in polar orbits with ground link once per orbit or about 100 minutes. As such, scatterometer winds are delivered orbit-by-orbit within 3 hours.

However, for weather forecasting high spatial resolution observations are particularly relevant on the short time scales. Be it rapid cyclogenesis (see figure 1) or sub-synoptic scale developments (figure 2), observations need to be timely. Figure 3 presents an example from the HIRLAM data assimilation scheme at KNMI, where scatterometer data are available on average after 2.5 hours. The cut-off time is a trade-off between quality and timeliness. The longer the cut-off, the more observations are available, but the later the meteorologists can use the output NWP analyses and forecasts. Scatterometer observations are only one of the many data types available. The combination of cut-off time and scatterometer data availability for HIRLAM causes 50% of the data to be lost, which is a great pity since HIRLAM output is used for short range forecasting.

Ground link capability over the full 100-minute orbit is a costly affair. On the other hand, as explained above, most of the benefit of the high spatial resolution scatterometer winds is lost for weather forecasting, if this capability does not exist. Direct broadcast capability for scatterometer data should be developed for nowcasting applications.

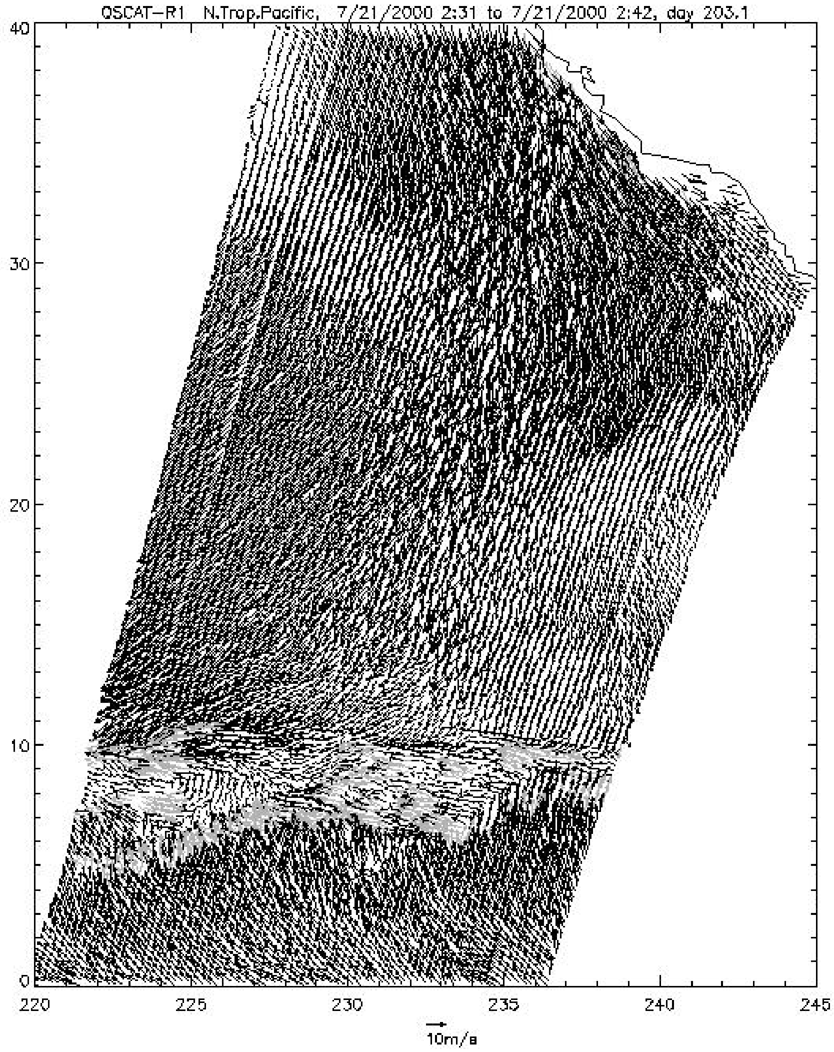


**Figure 1.4:** Sample archive SeaWinds product of JPL at 25-km resolution. A 1400-km wide central swath can be seen that is viewed by the inner and the outer beam of SeaWinds. Two outer swath strips of 200 km are visible that are viewed only by the outer beam. In the middle (nadir) region excessive noise is visible, which is due to the poorer azimuth sampling in this area. In a horizontal area at around 10N grey areas denote rain contamination as flagged by JPL (SeaWinds, 2002).

To overcome the problem depicted in figure 3, one could consider re-analysis. A reanalysis with a long cut-off time would incorporate more observations, 50% more in the case presented here, and thus provide a better analysis and background field for the next analysis. As such, the quality of the next analysis may be somewhat improved. The procedure would mean that all analyses are performed twice. The analysis is the most expensive part of the NWP forecast suite, so re-analyses are not desirable.

## 1.4 OPERATIONAL QUIKSCAT DATA

For the operational implementation we use QuikScat BUFR data. QuikScat BUFR data has a record structure. A BUFR record contains observed Earth-located radar backscatter measurements and retrieved wind vector information, available at the time of processing, collocated in 25 x 25-km wind vector cells (WVC's). Each BUFR record consists of a row of between 1 and 76 WVC's depending on the number of observations present. If there are no observations the row is not stored. A row of WVC's corresponds to a single cross-track cut of the SeaWinds instrument measurement swath and is uniquely identified by its row number and orbit number. In addition each WVC has a unique cell number. An orbit that covers the circumference of the Earth contains 1624 rows.

The backscatter measurements in the BUFR data are WVC-composites that are appropriately averaged finer grained $\sigma^0$ data. The finer grained $\sigma^0$ data can be either whole radar pulses or "eggs" or egg slices, which are range resolution elements of an egg. Per WVC four "flavours" of backscatter measurements (views) can be present. Based on the antenna geometry we distinguish between a fore inner, fore outer, aft inner and aft-outer view. For each WVC the antenna geometry is different so additional parameters/flags are present describing the measurement conditions. Described are beam geometry, $\sigma^0$-location, antenna polarisation, noise characteristics, the Earth's surface condition, and $\sigma^0$-quality.

For the implementation we used SeaWinds BUFR data that are disseminated by NOAA/NESDIS in near real time. The data were first obtained from ECMWF, but at the expense of a one-hour delay. From September 2001 onwards, a link was arranged through the UK Met.Office. NOAA provides the SeaWinds data to the UK Met.Office through a dedicated link; the products are subsequently put to KNMI. Transmission time losses are minimal.

## 1.5 SEAWINDS 100-KM PROCESSING

Figure 4 displays part of the SeaWinds swath as processed by JPL at 25 km. The figure clearly denotes different parts of the swath, and developments are ongoing to apply all these parts of the swath. The so-called sweet swath excludes the outer swath and the nadir region, and is the most uniquely determined and accurate part of the swath. The nadir (middle) region has the same amount of nadir views, but the views are closer together and as such provide less independent information on wind direction, leading to less unique and accurate winds, as may be noted from the figure. In the outer swath region only two azimuth views are available in a single radar polarization, which means that no residual information is available for the quality control (QC) of the resulting winds. This is problematic, since the measurements are affected seriously by rain. KNMI processes data from WVC's 13-64, corresponding to the "sweet part" and nadir of the swath. These WVC cells are re-grouped and accumulated by view type in squares of 4x4, corresponding to 100 km sampling. Portabella and Stoffelen (2002) show that 100-km data are more unique and more accurate.

## 1.6 USEFULNESS OF THE WIND PRODUCTS

The KNMI 100-km SeaWinds product has been used at the UK Met.Office, at KNMI, and at DNMI for evaluation. It is apparent that a 100-km scatterometer wind product has added value for synoptic meteorological analysis. The main reasons are:

- More and better information on the detailed structure of the wind field
- Accurate estimation of the position and movement of low pressure systems
- Positioning of fronts, troughs and ridges
- The great advantage of a large coverage;
- Confirming/refuting model forecasts/analysis

The KNMI 100-km SeaWinds product is routinely used at KNMI in the HIRLAM model. Plans to use the 100-km data exist at the India Met.Office, UK Met.Office, and in the HIRLAM community.

# 2 DATA FLOW

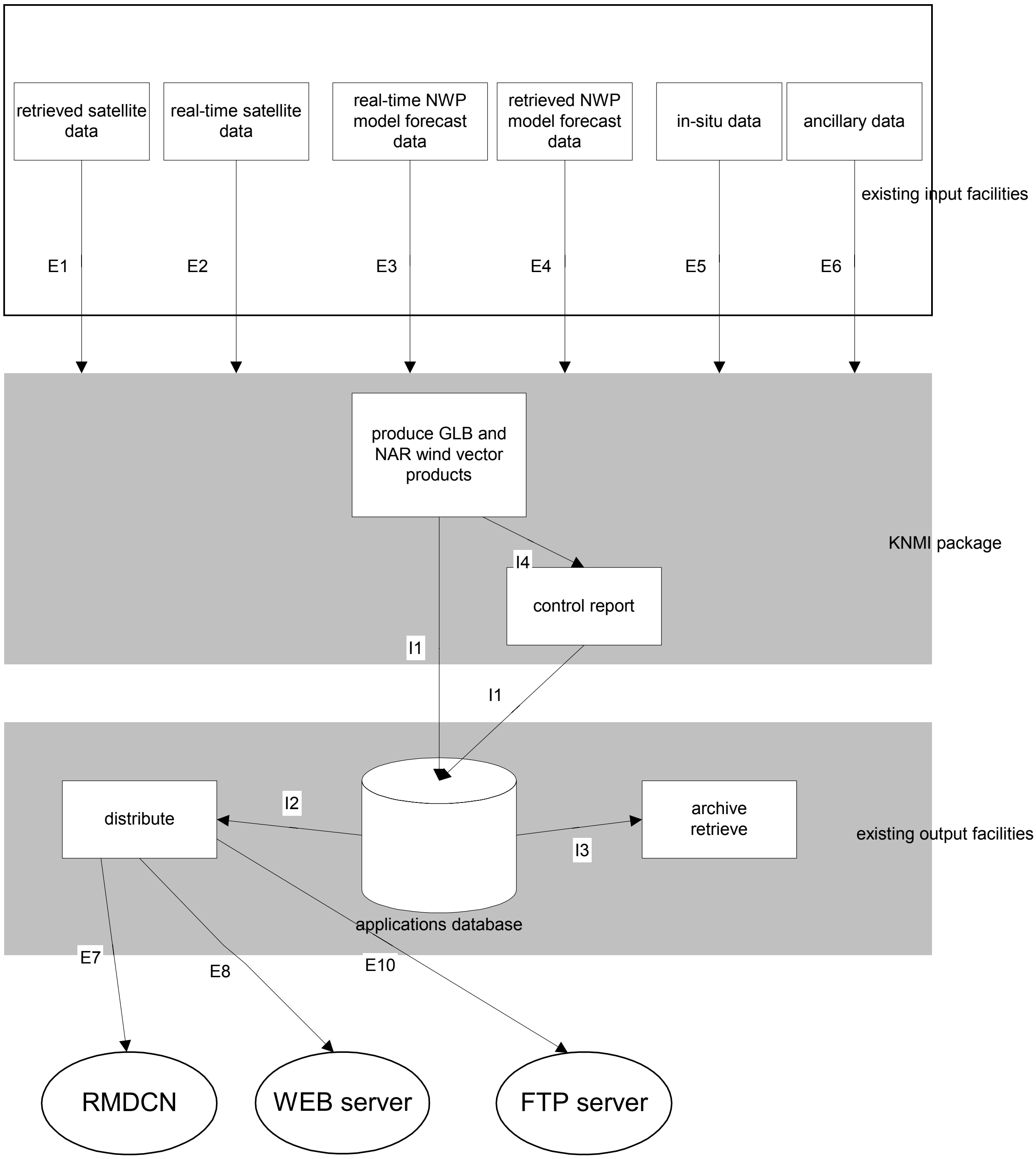


**Figure 2.1:** External interfaces of the KNMI wind production

## 2.1 INTERFACE OVERVIEW

Figure **2.1** (from OSI SAF ICD) shows all interfaces of the O&SI SAF wind production package at KNMI. The grey boxes contain the functions considered by KNMI in the frame of this project. Throughout this document, the interfaces identified with a name beginning with E are the external interfaces, whereas interfaces beginning with I are internal interfaces.

Each interface is described in the OSI SAF ICD stating which data are crossing the interface. Each of these data is described by its content, format, volume, frequency and exchange protocol.

## 2.2 EXTERNAL INTERFACES

### 2.2.1 REAL-TIME SATELLITE DATA (E2)

#### *2.2.1.1 Interfaced components*

This interface describes the way the O&SI SAF wind production and control package is provided with the most important input, the real-time scatterometer data. Scatterometer data dealt with are data from ERS SCAT, from QuikScat SeaWinds, and in future ASCAT data from METOP. The different satellites are interfaced to the O&SI SAF package differently.

**2.2.1.1.1 SCAT data**

These data are ERS-2 AMI data, where its backscatter values are referred to as Normalized Radar Cross Section or sigma naught ($\sigma^0$). They were acquired in near real-time at KNMI while the instrument was operating nominally until February 2001.

The pre-processed level 1b SCAT data were received by KNMI via GTS in BUFR format. At KNMI the GTS/RMDCN stream of data (figure 2) is currently handled by the Message Switching System (MSS), which temporarily stores the SCAT data into the BUFR section of the Real-Time Binary database (RTBIN). MSS is operationally running at KNMI with 24 hours monitoring by operational attendant, as is RTBIN.

**2.2.1.1.2 SeaWinds data**

KNMI tried to arrange distribution of regional data through GTS, but no feasible solution could be catered for with the resources available. As such, NOAA distributes orbit files by FTP. SeaWinds data from QuikScat are distributed by FTP by NOAA/NESDIS to the UK Met.Office in BUFR as described in OSI SAF OPFD. KNMI receives the data from the Met Office (UK) by FTP since September 2001. The data are put on the KNMI FTP server, where the O&SI SAF package can access them via the KNMI network using FTP. Before September 2001 data were received through ECMWF with on average a further one-hour delay.

KNMI processes orbit files, which are named qs_dYYDDD_cSHSM_eEHEM_bOOOOOOO, where the following codes are used *(Leidner et al*, 2000)

| | |
|---|---|
| YY | Year of century; |
| DDD | Day of year; |
| SH | Hour at file start; |
| SM | Minutes at file start; |
| EH | Hour at file end; |
| EM | Minutes at file end; |

OOOOOOO Orbit code.

The number of characters of the code corresponds with the number of digits provided. All data are chronological, but subsequent files are overlapping and a procedure exists at KNMI to filter overlapping parts.

**2.2.1.1.3 ASCAT data**

These data are scatterometer data as expected from METOP. They would be acquired in near real-time at KNMI through a NRT (Near Real-Time Terminal) situated at KNMI.

##### *2.2.1.2 Data flow*

The volume of the SCAT data is about 10 MB a day (about 700 kB per orbit of 100 min.) for the GBL processing.

The SCAT data is organized in messages. Each message consists of a 25-km grid of 19 x 19 cells or nodes each providing a wind measurement. MSS puts each message in a separate file of about 9100 Byte with a unique name.

The daily volume of QuikScat SeaWinds BUFR is about 210 MB for GBL processing. The data is organized in 2 x 14 BUFR files (about 7700 kB each) containing a little more than half an orbit each, including some overlap between files, again with a unique naming convention.

#### 2.2.2 RETRIEVED SATELLITE DATA (E1)

For reprocessing purposes the scatterometer data described in 2.2.1 can be retrieved from archiving systems. SCAT and SeaWinds data (in BUFR format) can be retrieved from the local archiving system at KNMI (MOS), using MOS retrieval tools.

#### 2.2.3 REAL-TIME NWP DATA (E3)

##### *2.2.3.1 Interfaced components*

This interface provides the O&SI SAF wind production with the Numerical Weather Prediction (NWP) model outputs: i.e. land/sea mask for quality monitoring and 10 m wind u and v component necessary for ambiguity removal. Awaiting more advanced processing, the Sea Surface Temperature (SST) field of the NWP model output is used for ice screening.

For GLB wind products output parameter fields can be used of the 3, 6, 9, 12, 15, … hour forecast of the 12-hour run at one-degree lat/lon resolution of the ECMWF model. All times are in UTC. The availability of some of the fields from the 0-hour run is not secured in the future. In case of unavailability the 12-hour run data are used.

The ECMWF output fields are sent to KNMI by FTP over the RMDCN link on request. At KNMI the data is further processed into GRIB formatted files in the APL environment. The GRIB files are temporarily stored in the applications database. The APL runs operationally at KNMI with 24-hours monitoring by operational attendant, and constitutes the environment for all KNMI operational processes.

If it is decided to use HIRLAM forecast for NAR wind products, the fields from the 3-hour forecast of the 0, 3, 6, … hour run are used. HIRLAM is run at KNMI in APL and the output files are made available in the applications database in ASIMOF/GRIB format (see ICD). The

ASIMOF/GRIB format is equal to GRIB with some extra information at the beginning of the file allowing direct access to each field stored in the file.

For SeaWinds processing the NCEP model information included in the input BUFR is used in the 100-km wind processing.

#### *2.2.3.2 Data flow*

The ECMWF fields are available to the O&SI SAF wind production in WMO GRIB format; HIRLAM fields are in ASIMOF/GRIB format (see ICD). Both are accessible in the applications database.

The data volume crossing the interface from the applications database to the O&SI SAF wind production depends on the way the fields are organized in the applications database. If the requested fields have to be retrieved from files containing also other fields the volume is larger than if the organization is dedicated to the O&SI SAF wind production processing.

For the global ECMWF model, the minimum data volume is about 8 MB (containing 3 forecasts with 1 degree x 1 degree resolution).

### 2.2.4 RETRIEVED NWP DATA (E4)

For reprocessing purposes the data described in 2.2.3 can be retrieved from the local archiving system at KNMI (for HIRLAM data) or from MARS (Meteorological Archiving and Retrieval System) at ECMWF (for ECMWF NWP model data).

### 2.2.5 IN SITU DATA (E5)

In situ 10-m wind speed and direction measurements available from ships and buoys can be used for product validations. The format is text (ASCII), and a measurement should contain date, time, latitude, longitude, wind speed (m/s), and wind direction (degrees).

### 2.2.6 ANCILLARY DATA (E6)

For the ice screening module (IFREMER) maximum ice extent climatology has to be installed as permanent data in a binary file.

### 2.2.7 DISTRIBUTION TO USERS

The distribution of the wind products to users is done by distribution through RMDCN and by putting the products on the FTP server at KNMI. The UMARF archiving facility is also seen as user and is able to receive the products through the same means.

The control reports are distributed via the Web server, via the FTP server and via UMARF.

# 3 IMPLEMENTATION

This chapter gives a short summary of the geophysical algorithms and key functions that are implemented in the QuikScat Data Processor system for the processing of SeaWinds scatterometer data. The ERS processing is similar and is discussed in the one but last section of this chapter. Further OSI SAF documentation is listed in the last section.

## 3.1 OVERVIEW

Figure 3.1 gives an overview of the entire processing system.

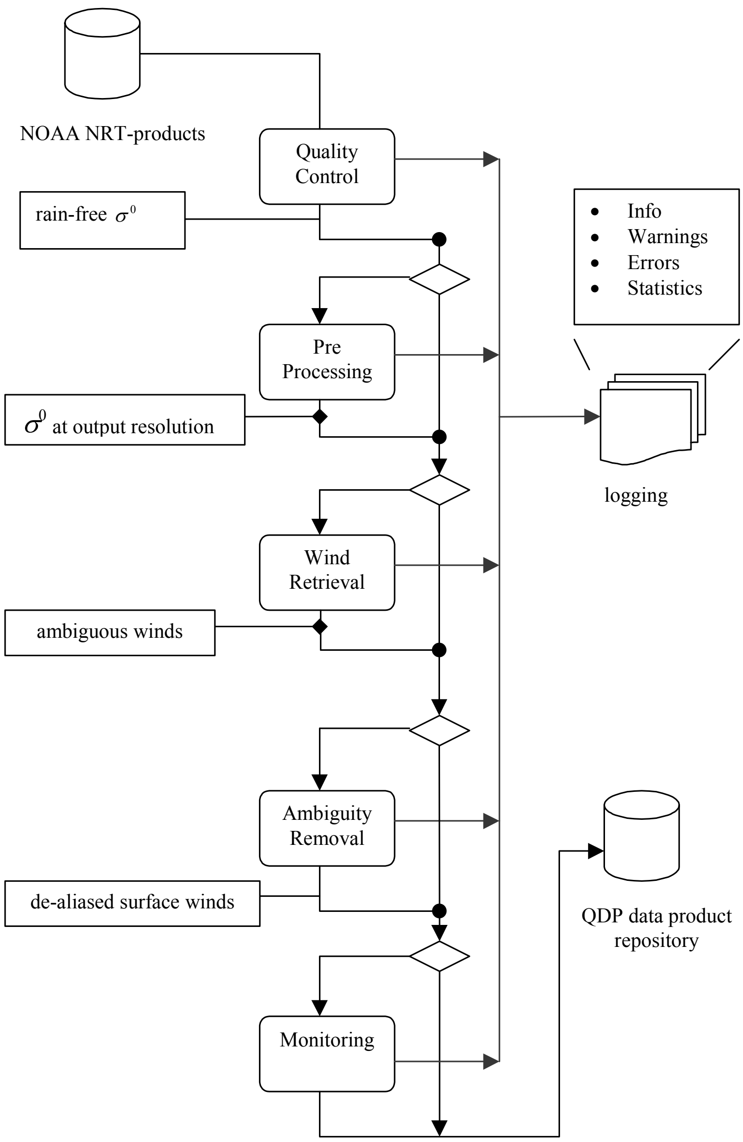


**Figure 3.1**: The QuikScat Data Processor (from NWP SAF user manual).

The QuikScat Data Processor is a system to process QuikScat observations in BUFR format to create products suitable for use in numerical weather prediction (NWP) models. The baseline QDP consists of five main functions that transform NOAA QuikScat BUFR products into new products of specified resolution. The output products are also stored in BUFR format. These products are quality controlled and contain rain-free backscatter measurements, retrieved ambiguous wind vector solutions and an ambiguity-removal flag that defines the selected surface wind vector in each WVC. The flow chart shows that the QDP is designed to conditionally execute the functional modules of pre-processing, wind retrieval, ambiguity removal, and monitoring. The user can specify what is executed.

During processing the functional modules briefly report on their status to a central log. The user can specify the level of logging.

The main processing chain has a monitoring function that generates processing statistics and a flag that enable the user to monitor the data processing itself as well as the health of the SeaWinds instrument on board QuikScat.

## 3.2 THE DATA INPUT

The expected input for the QDP is a Level 2B data product in BUFR format. This product contains grouped backscatter measurements, noise, quality and geographic information as well as retrieved and de-aliases winds represented on a rectangular grid that covers the measurement swath. In operational practice the Level 2B product is either the 25km near real-time BUFR product to the meteorological user community by NOAA, or a product that has already been processed previously by the QDP. In current operations, a product is processed within 10 minutes after receival.

## 3.3 QUALITY CONTROL

To obtain high-quality surface winds from QuikScat, suitable for use in NWP, it requires a good assessment of the information content of the measurements. An acute problem with Ku-band scatterometers like SeaWinds on QuikScat is the sensitivity to rain. However, QC procedures developed for ERS have been extended to NSCAT and SeaWinds (*Stoffelen*, 1998, *Figa and Stoffelen*, 1999, *Portabella and Stoffelen*, 2000).

Rain obscures the view of the Ku-band scatterometer on the ocean surface and scatters the incident microwave radiation resulting in a strong backscatter signal measured by the instrument. This in turn will result in the retrieval of wind vectors with high wind speeds. In the wind retrieval process a set of rain-contaminated backscatter measurements will be inconsistent with the Geophysical Model Function (GMF), which is derived for fair wind conditions. This leads to a large value for the "distance-to-cone" (see section 2.5) or Maximum Likelihood Estimator (MLE). A thresholding procedure based on the MLE normalized by its expected value is used to distinguish between windy measurements and rainy measurements. The magnitude of the expected MLE is a function of wind speed and the WVC position in the swath. If the normalized MLE exceeds the threshold value in a particular WVC, then the measurements in that WVC are rejected (*Portabella and Stoffelen*, 2000, 2001).

This QC procedure is implemented in the QDP and is applied on the WVC in the 25-km input product, whether it is the NOAA near real-time product or the QDP product at 25-km resolution. No additional QC exists at other resolutions. The rain flags in the product itself are ignored.

## 3.4 DATA PREPROCESSING

This function prepares the data ingested by the QDP for further processing.

### 3.4.1 SORTING

The SeaWinds data is defined as rows of wind vector cells. A batch of WVC rows that has been read from file is sorted based on orbit number, row number and time order using index sort. Sorting is necessary to assure spatial consistency, which is required in the ambiguity removal function (see section 2.6). It also allows for the processing of multi-orbit input data.

### 3.4.2 SPATIAL AVERAGING

If output products are specified with a resolution lower than that of the input product, than the backscatter measurements and viewing geometry (azimuth and incidence angle) of groups of WVC's are averaged. In addition the background wind is averaged as well.

## 3.5 WIND RETRIEVAL

The SeaWinds wind retrieval function operates on each WVC separately. It requires per WVC the input of 4 (averaged) backscatter measurements with different observation geometry (azimuth and incidence angle) as in SeaWinds BUFR manual (*Leidner, Hoffman, Augenbaum*, 2000). The implementation of the retrieval algorithm uses maximum likelihood estimation to determine between 1 and 4 wind vector solutions and what is known as the "distance-to-cone", i.e., the residual of the cost function used in the retrieval, called MLE. The algorithm was developed at KNMI. It uses a Geophysical Model Function that is specified in an ancillary Look-Up-Table (LUT) file (*Stoffelen, Voorrips, de Vries*, 2001), (*Stoffelen*, 1998a).

## 3.6 AMBIGUITY REMOVAL

The ambiguity removal (AR) function selects the most probable surface wind vector at each observation location from a set of ambiguous wind vector solutions that result from the prior wind retrieval step. In addition to the ambiguous wind vector solutions the procedure implemented in this function requires the input of a short-range forecast for the 10m wind (background) interpolated to the location of the observations. The implemented procedure is based on a variational method called 2DVAR, which is similar to the variational methods used in meteorological analysis. 2DVAR formulates AR as a minimization problem based on a maximum probability formulation. In doing so, it attempts to minimize the cost function (*Stoffelen, Voorrips, De Vries*, 2001)

$$J(\delta \underline{x}) = J_b + J_o^{scat}$$

This function penalizes deviation of the control variable $x$ from the background and the observations. 2DVAR adopts a field-based approach and uses a regular grid on which the control variable is defined to overlay batches of WVC rows. After minimization the control variable contains the most probable state of the surface wind. This state is used to select in each WVC the ambiguous wind vector solution that is closest in terms of vector RMS difference. The selected wind vector is considered to be the observed wind vector. The output of the AR function is the rank of the selected wind for each WVC.

## 3.7 MONITORING

The monitoring function keeps track of trends in processing parameters on a sub-orbital level to enable detection of causes that may compromise the quality of the generated products as well as to alarm for possible deterioration of the health of the SeaWinds instrument. Key parameters utilized for monitoring are the fraction of WVC's affected by QC, the "distance-to-cone" produced during the wind retrieval, and the wind speed and wind direction bias and SD of difference with respect to the background wind (*Stoffelen, Voorrips, de Vries*, 2001). The output is incorporated as a flag in the output products, and registered in the central log, where it is made suitable for automatic presentation.

## 3.8 FTP, WWW, GTS

The output directory contains all output results from the processing chain described above. The output BUFR files are put on a user account on the KNMI ftp site, where users can copy them. Current users are DNMI, DMI, UK Met.Office, India Met. Office, the EU MAMA project, and KNMI. There is currently no GTS transmission due to the limited bandwidth of this secured network. Since also input is through FTP, there is no large additional risk involved in this procedure. The products are further displayed on the KNMI WWW at http://www.knmi.nl/scatterometer .

## 3.9 ERS IMPLEMENTATION

Before summer 2001 it was decided by the OSI SAF Steering Group that KNMI should complete the implementation of the ERS processing as set out in the OSI SAF project proposal, but was released from the commitment to restart operational processing if good quality ERS-2 scatterometer data would become available again. Pre-operational processing of SeaWinds data was commenced in the context of this BCRS project. At the time of writing this report, the possibility exists that reasonable quality ERS scatterometer data will become available in autumn 2002. KNMI has no approved plans yet to process these data. However, the software developed and implemented by KNMI will be used by KNMI for a reprocessing effort in the context of the EUMETSAT climate (CM) SAF for ERS scatterometer data, and be the baseline for the ASCAT processor development inn the OSI SAF IOP. Particular ERS developments are described here.

### 3.9.1 GROUND STATION OVERLAP

The ERS scatterometer looks forward, aside and aft, and at one particular time these beams are thus viewing different parts of the ocean. In order to provide collocated fore, mid and aft measurements, information observed at different timers is needed. However, measurements received at one ground station are not transmitted to the next ground station that is used for read out, thus resulting is orbit parts where fore beam or aft beam information is missing, and less often also mid beam measurements. Two or one backscatter measurements are not sufficient to provide wind and QC information and are rejected altogether. This is a pitiful loss since the ground station overlap problem appears in the Atlantic Gulf Stream area, where weather disturbances hitting Europe are typically formed. To reduce these data losses, KNMI developed a procedure to collocate ERS scatterometer BUFR products from different ground stations in order to obtain valid backscatter triplets.

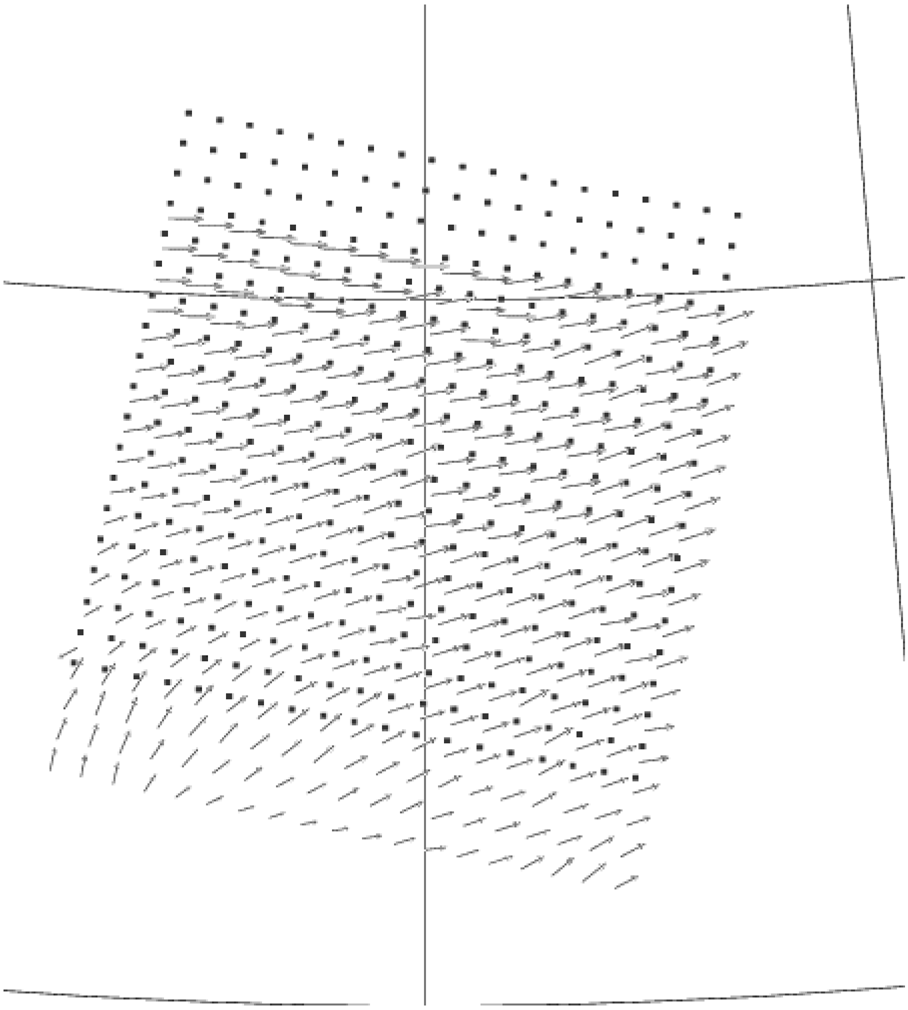

**Figure 3.2:** Two overlapping ERS-2 scatterometer products from two different ground stations.

Figure 3.2 shows two overlapping ERS-2 scatterometer products from two different ground stations. One message is always received about 100 minutes earlier than the other; in this respect we refer here to respectively the older and the newer message. Note the timing difference of the two ground stations, shown here as an along-track (vertical) displacement of the scatterometer nodes. The across-track displacement is always negligible. The 25-km nodes contain information on 50 km resolution, due to the application of a spatial filter. As such, we expect that a maximal displacement of 12.5 km between the fore, mid, or aft backscatter measurements would not be very harmful for the wind retrieval, and the closest match is taken, rather than interpolated backscatter data. Our collocation procedure thus matches along-track nodes, and finds for each across-track node position the matching closest nodes in time. Time matching is the simplest, since distance matching would require coordinate transformations. Of any two matched nodes of two overlapping products, we check the ESA quality flag and the presence of the backscatter and geometry information in the usual way for fore, mid, and aft beam, and determine whether one of these is of acceptable quality. We verified that only occasionally both nodes are acceptable for the same beam. In this case we

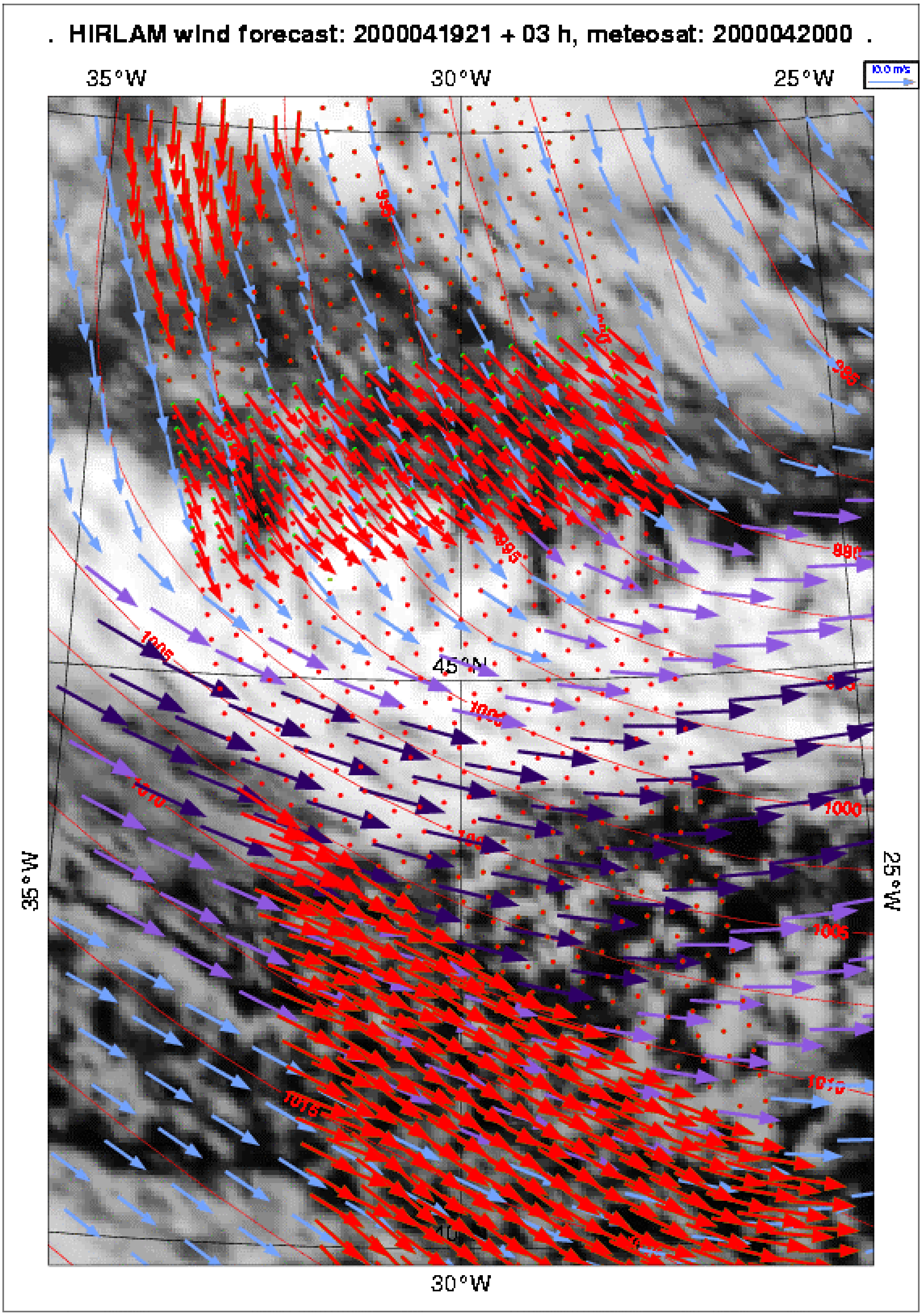


**Figure 3.3:** Wind retrieval of ERS products at KNMI, from two overlapping swath from two different ground stations. Legend as in figure 1.1.

accept the newer as valid and reject the older. In fact, we copy the information from the older message into the newer message only if the backscatter information in the older message is of better quality than the information in the newer message.

This way, the number of valid triplets indeed increases as can be seen in figure 3.3. However, note that still two areas exist with no wind data. The nodes in between these two areas just above 45N have been fixed by the KNMI scheme and show consistent wind solutions. The areas with red dots are areas where there data is lost, due to data read-out time constraints. In the lower area aft beam measurement data is missing, while in the upper area fore beam data is missing. Only by allowing more overlap in the data read-out at the different ground stations, this problem could be solved. As before, the problem regretfully occurs in the Gulf Stream area in the Atlantic where often relevant weather systems develop.

#### 3.9.2 ERS AMBIGUITY REMOVAL STEP

The ERS processing has been separated into a separate inversion step and an ambiguity removal step. The inversion step runs PreScat until inversion on a product-by-product basis, as they would be received at KNMI. The ambiguity removal step subsequently takes batches of data in order to provide spatial continuity. However, no ERS stream has been available to further test these modules in NRT. Off-line tests have been conducted in collaboration with DNMI and IFREMER.

## 3.10 OSI SAF DOCUMENTATION CHAIN

The OSI SAF, NWP SAF, and CM SAF each include a documentation chain to document user requirements, software requirements, hardware and software configurations, interfaces and formats, algorithms, i.e., documenting all aspects of the software or product deliverables. Here we list the documents of the OSI SAF relevant for the implementation of PreScat.

ADD Architectural Design Document for the wind product of the Ocean and Sea Ice SAF;

ICD Interface Control Document for the Wind Product of the Ocean and Sea Ice SAF;

TR Test Report for the Wind Product of the Ocean and Sea Ice SAF – DRAFT;

CMP Configuration Management Plan for the Wind Product of Ocean and Sea Ice SAF;

OPFD Ocean & Sea Ice SAF Output Products Format Document;

SVVP Software Verification and Validation Plan for the Wind Product of the Ocean and Sea Ice SAF.

These are living documents subject to regular external review by a review committee established by EUMETSAT and the OSI SAF SG. These documents can be obtained from the author.

# 4 MONITORING

The last but not least important bit of the SeaWinds processing chain is the product monitoring. Product monitoring is implemented to guarantee that the products distributed do not suffer a common problem in the instrument functionality or data processing. In fact, a common problem could lead to serious problems in NWP data assimilation, since the analysis draws to incorrect winds, and as a consequence model forecasts may well be seriously corrupted. The monitoring of ERS data has led to the detection of a handful of cases with unexpected (by the user) instrument behaviour. The monitoring strategy for ERS is to

1. Check that the number of rejected WVC is nominal;
2. Verify that the normalised "distance to the cone" of the accepted WVC is close to unity;
3. Compute the mean and standard deviation of wind speed difference between scatterometer and NWP model; and
4. The mean and standard deviation of wind direction difference between scatterometer and NWP model.

The testing of the ERS procedure is part of the OSI SAF development phase, and described in the OSI SAF TR (see section 3.10). We further checked the validity of this strategy for SeaWinds (Stoffelen et al, 2001) and are now implementing a monitoring scheme and presentation in the OSI SAF IOP.

Besides QC on a node-by-node basis, the idea has emerged to provide health-monitoring information in the processed scatterometer products at KNMI. A monitoring flag is computed based on a short history of data, which is incorporated into the product. Besides this flag, the monitoring information will be presented on the WWW pages in near-real time. The extraction of the required information from the products has been completed in the frame of the BCRS project. Validation and presentation are now being completed in the OSI SAF IOP.

# 5 QUIKSCAT DATA PRODUCTS AND PRESENTATION

This chapter gives an overview of the data products created by the QuikScat Data Processor and the presentation of output products.

## 5.1 CONTENT, FORMAT, AND DISTRIBUTION

In each node or wind vector cell (WVC) of the NOAA BUFR product a total of 118 data descriptors are defined. These descriptors are listed in the SeaWinds BUFR manual (*Leidner, Hoffman, Augenbaum*, 2000). Output products from the QDP contain for each WVC the same descriptors as the input product. Apart from that the following information is added to the processed BUFR message:

- The value of byte 18 in section 1, defined in table <TBD>, identifies the generating application.
- The Wind Vector Cell Quality Flag (table 021109) is augmented with the following definitions:
    - Monitoring flag;
    - Monitoring value;
    - Rain flag KNMI;
    - Variational quality control flag;

    If the latter is set when the selected solution is rejected due to spatial inconsistency. The mapping of these definitions onto the bits of the Wind Vector Cell Quality Flag is given in the QDP User Manual (NWP SAF deliverable), which can be obtained through the KNMI scatterometer WWW site.

Distribution of the global SeaWinds BUFR files by FTP is controlled by a SCAT user account. GTS distribution to users is usually problematic due to the small bandwidth. KNMI HIRLAM uses the unique scatterometer winds as a pseudo-buoy report. This prevented additional interface development effort. For the next generation HIRLAM data assimilation systems, an interface to the KNMI SeaWinds products has been built and impact experiments are being carried out at DMI and DNMI.

## 5.2 WWW PRESENTATION

http://www.knmi.nl/scatterometer presents the KNMI scatterometer home page, providing access to all KNMI SAF deliverables. The data products of QuikScat thus may be accessed. These are presented in a global overview or, by choice, a European overview over a period of data of 22 hours and separated for ascending and descending orbits in order to provide a sense of time continuity in the plots and be able to present a reasonable amount of data. Moreover, wind speeds are colour coded on these maps, thus enabling the user to focus on the areas of dynamical interest (see figure 5.1).

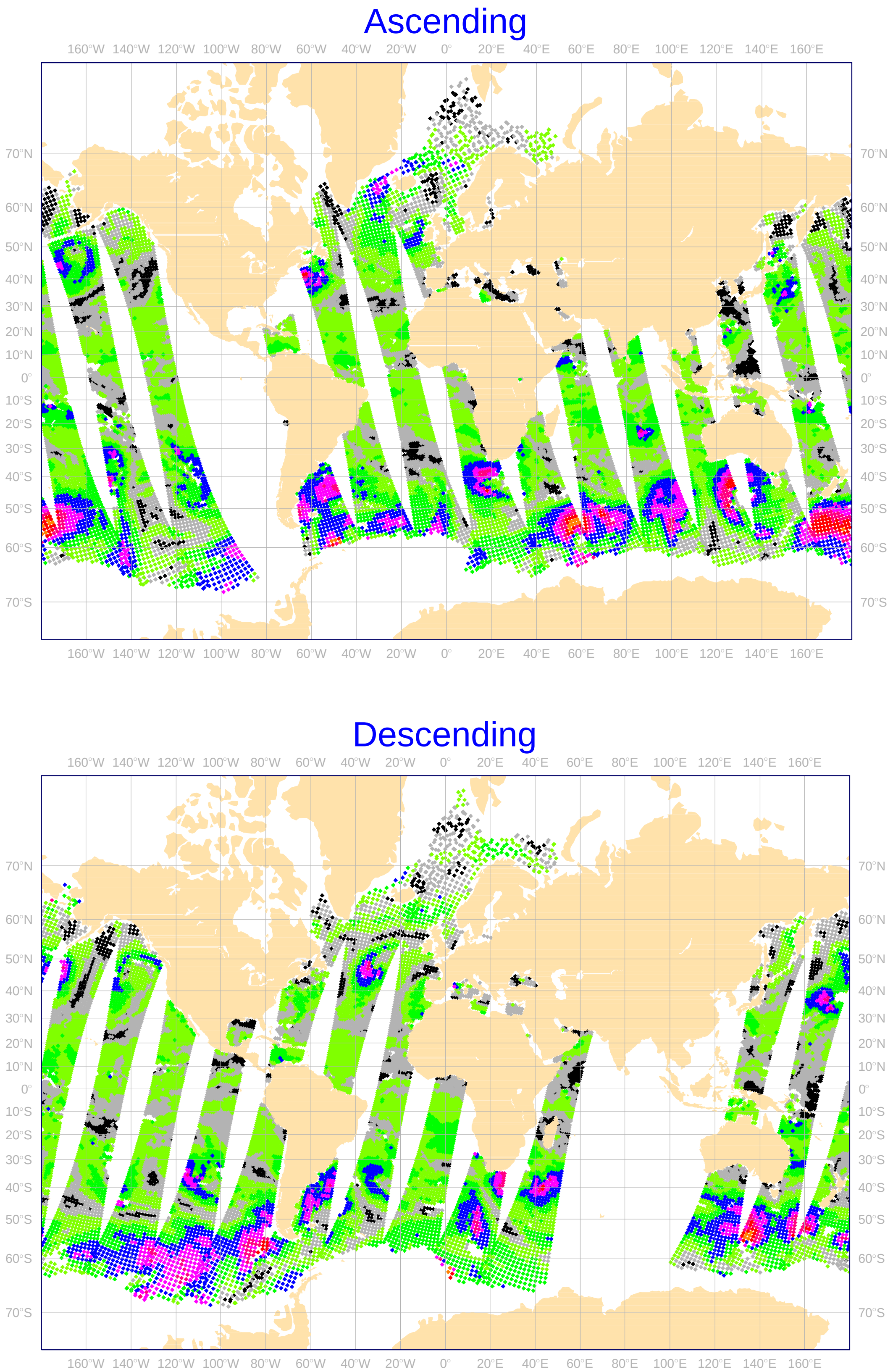


**Figure 5.1:** Global WWW presentation of QuikScat products at KNMI.

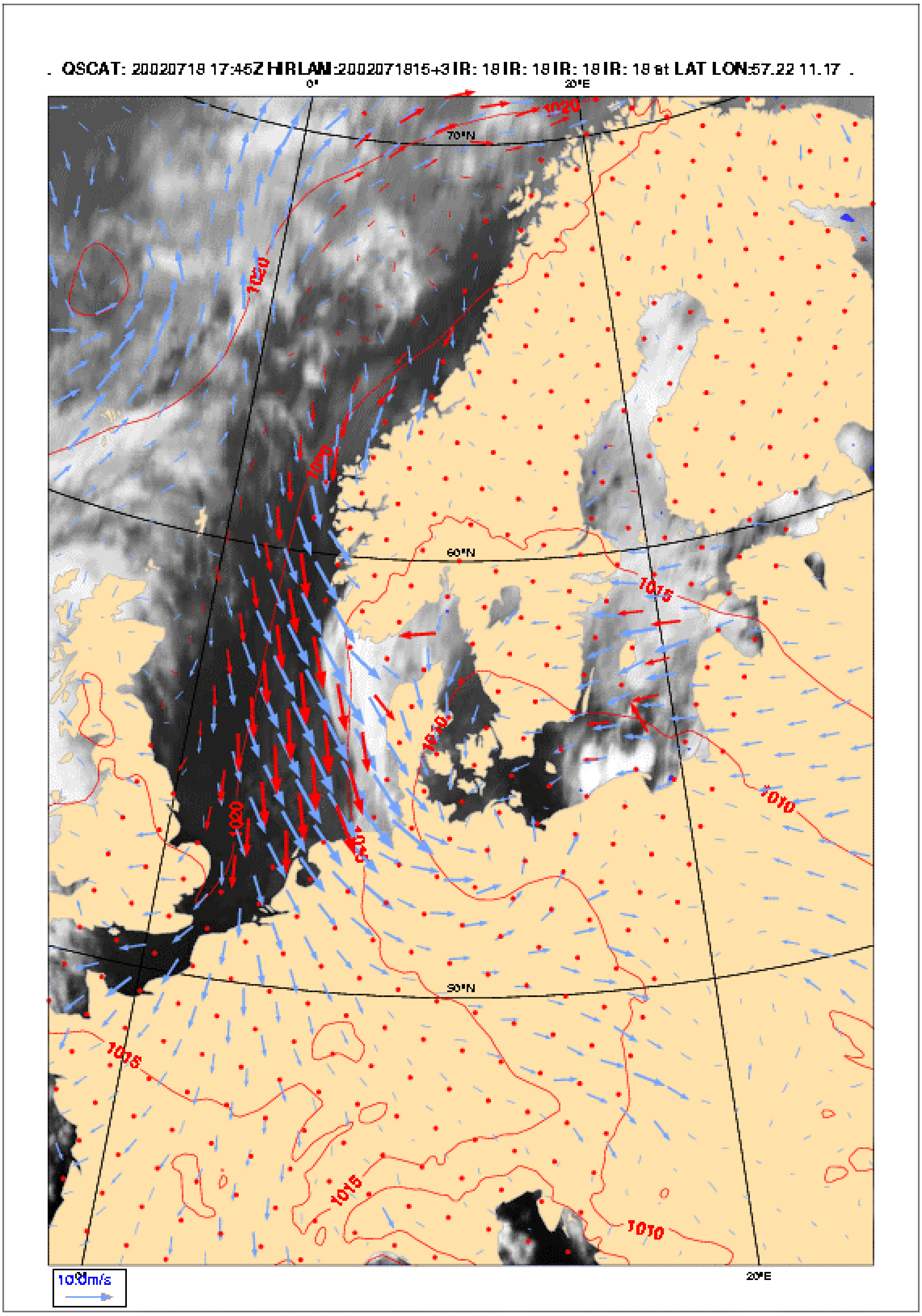


**Figure 5.2:** Regional WWW presentation of QuikScat products at KNMI, obtained by clicking on the Netherlands in the descending map of figure 5.1. Legend as in figure 1.1.

Following the description provided on this products page, one can click on the ascending or descending map and obtain a detailed regional presentation of the KNMI SeaWinds product, as in figure 5.2. The web page that is obtained in this way further provides links to nearby products, referenced by latitude, longitude, and observation time. SeaWinds wind vectors at 100-km resolution are displayed every 2000 km along orbit. During the wind processing the latitude and longitude positions of the centre of the images is computed and output.

Since the 100-km SeaWinds BUFR product is currently the main output of the OSI SAF global wind processor, ancillary data used for WWW presentation of the products are not under configuration control. These data are

- Regional HIRLAM NWP 10-m wind (10U), mean-sea-level pressure (PMSL), and sea-surface temperature (SST);
- Geostationary satellite IR imagery.

HIRLAM output is available every three hours over an area spanning almost the complete North Atlantic Ocean down to about 30N, and the Mediterranean. At its boundaries it will resemble the ECMWF 24-hour forecast, but as you get closer to the Netherlands, the impact of recent meteorological observations of many kinds will become more pronounced. SST is used to denote the (remote) possibility of sea ice for SST<0. PMSL and 10U are used for guidance to the KNMI meteorologists.

3-hourly METEOSAT (5 and 6), and GOES (E and W) geostationary IR imagery is used as a background and guide to the meteorologists looking at the visual presentation of the scatterometer products on the KNMI web site (see e.g. figures 1.1, 1.2, and 5.2).

3-hourly windows for HIRLAM and imagery are selected by computing the mean time of the SeaWinds file. Since SeaWinds files contain about half an orbit or 50 minutes, the mean time could deviate up to 25 minutes from the actual time of observation in a particular region. Image and HIRLAM times could further deviate up to 90 minutes from the SeaWinds file mean time. A time discrepancy of 45-60 minutes is thus typical, but 140 minutes thus could exist as a maximum between SeaWinds wind vectors and the ancillary data presented.

The imagery is selected based on the difference in longitude position of the geostationary satellite and the product to be displayed. The closest distance found will correspond with the image selection of that particular geostationary satellite.

# 6 VERIFICATION AND VALIDATION

Verification and validation of the ERS processing chain was carried out in the context of the OSI SAF DP and this project. In particular the test report (TR) of all the reports mentioned in section 3.10 describes this. Comparisons to the ESA products and other tests were carried out in order to validate and verify the improvements. The tests verify whether the products are conform the OSI SAF SRD (Software Requirements Document), which in turn is in line with the EPS User Requirements Document (EURD) of EUMETSAT.

In the absence of an ERS data stream, SeaWinds data have been processed at 100 km resolution at KNMI and presented on the WWW since August 2001. In the OSI SAF IOP the SeaWinds data stream is being carried over from pre-operational to operational status. Although the processing has been run in a pre-operational environment, user access has been possible, and several cases have been documented where the QuikScat data of KNMI provided important guidance to the meteorologist. We provide a documented recent example here from KNMI.

## 6.1 STORM 20020309

On Saturday 9 March the Netherlands was hit by a storm. A vigorous storm field accompanied a low-pressure system over the North Sea around 18 UTC with strong gusts over the Netherlands. The shift meteorologists were surprised by the vigour of the storm, since the NWP analyses and short-range forecasts did not indicate such high winds. Looking at SeaWinds scatterometer data, we now believe that the storm did not develop in the vicinity of the European coast, but actually developed already way out in the ocean. On Thursday morning 6 UTC SeaWinds detected 20 m/s winds in an area where satellite imagery indicated a disturbance. This is 2.5 days before the storm occurred and in principle sufficient to issue timely and reliable warnings. The disturbance has been carried forward by the mean flow, keeping its strength. Only, when the storm arrives in the vicinity of in situ observations close to Ireland, it is incorporated into the NWP analyses, but still at too little strength. This is why short-range model forecasts were unreliable.

Figure 6.1 provides an illustration of this case, when the storm hits Ireland. The NOAA and KNMI winds report 25 m/s, while the ECMWF (and other) analysis do provide less than 20 m/s. In fact, a complication was that in this case a buoy report in the Irish Sea was wrong over an extensive time period, but was being used for the analysis, thereby systematically reducing the winds.

## 6.2 USERS

Meanwhile several users exist for the SeaWinds data of KNMI. These include HIRLAM countries, such as DMI and DNMI, the UK and India Met. Services, the EU MAMA project, and the Defence Italian Met. Service. ECMWF uses code developed together with KNMI. We do not keep a track record of who visits our WWW site, but started to count the hit rate, which is increasing. We expect this to continue as we go into the operational phase in the year to come.

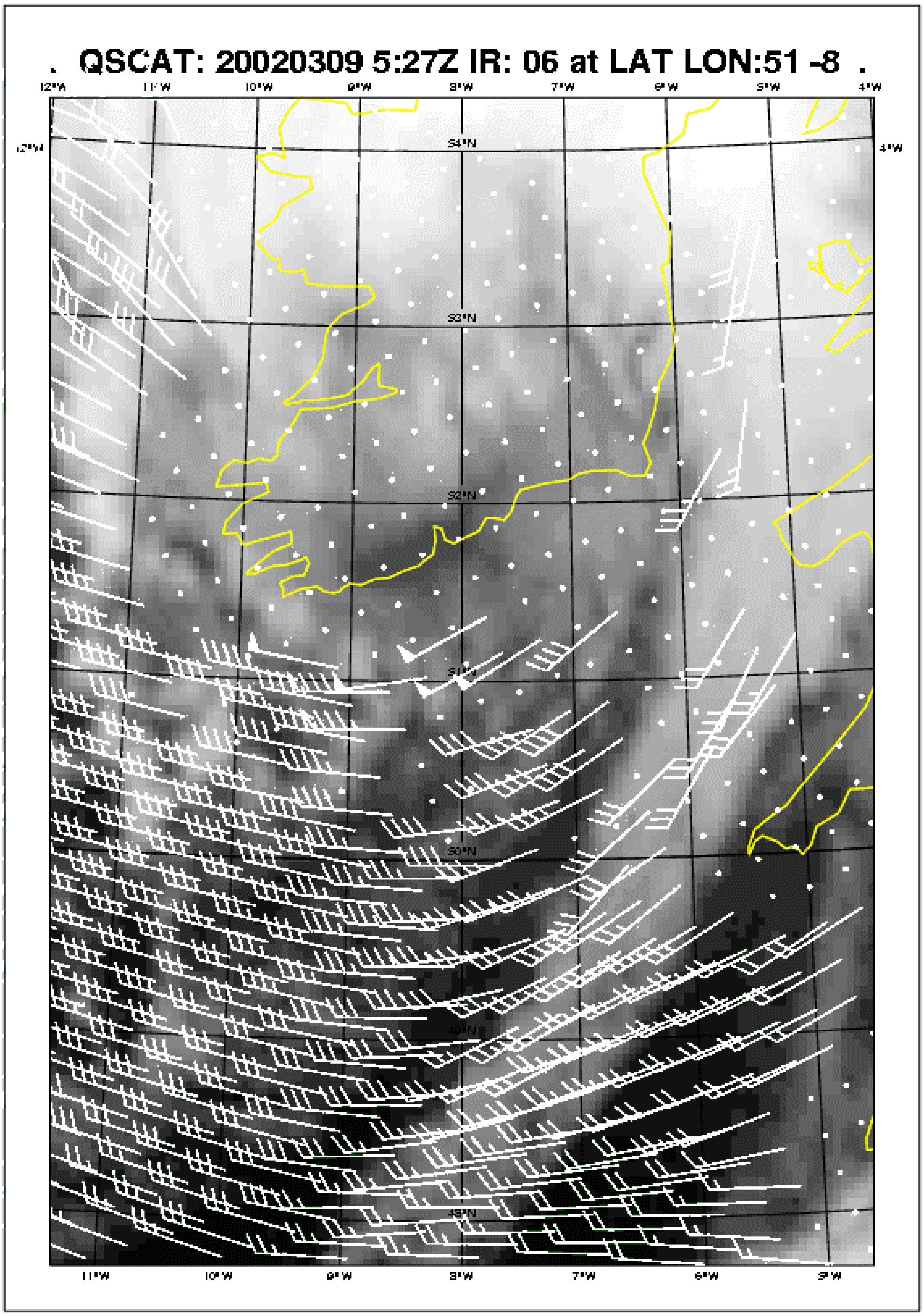


**Figure 6.1:** QuikScat winds for a case that leads to a storm at the Dutch coast. The storm was not predicted well.

# 7 CONCLUSIONS AND RECOMMENDATIONS

Within the EUMETSAT-funded NWP Satellite Application Facility, SAF, a SeaWinds processing package is being developed that checks, spatially averages, and inverts backscatter data. After these steps a 2D-VAR-ambiguity routine is run. A preliminary version of this software was implemented at KNMI through this project. We apply a backscatter data averaging to 100 km before inversion, resulting in more accurate wind fields. We experience from our users that the carefully screened, smoothed, and assimilated SeaWinds scatterometer data from QuikScat and ADEOS-II have great potential in weather prediction.

Challenges remain in the interpretation of the SeaWinds data at higher resolutions, and in those parts of the swath and geophysical conditions where the wind vector and its quality are poorly determined by the backscatter measurements available. AMSR on ADEOS-II will provide rain rate data and is potentially very powerful in avoiding problems with rain contamination. However, it has been made clear to KNMI through NOAA, NASA, and NASDA, that the near-real time availability of AMSR is, regretfully, not possible.

We implemented at KNMI a SeaWinds scatterometer processing system, with visualisation, inversion, quality control, 2D-VAR ambiguity removal, and validation tools. These tools formed a good basis for further development and implementation as reported here.

As such, data assimilation experiments are carried out to test the product in more full meteorological systems, such as 3D-Var or 4D-Var. SeaWinds data are now used at KNMI, DNMI, and at ECMWF. Moreover, the system will be adapted to work at a resolution of 50 km, where it will probably still provide reliable high-quality synoptic-scale meteorological information of great potential in nowcasting and short-range forecasting by direct presentation to the on-duty meteorologists.

In conclusion our SeaWinds product provides

- The great advantage of a large coverage;
- Information of acceptable quality on the detailed structure of the wind field;
- Accurate estimation of the position and movement of low pressure systems;
- Positioning of fronts, troughs and ridges; and
- Confirmation or corrections of NWP model forecasts and analysis.

For the real-time operational application of our products we conclude and recommend

- NWP impact of SeaWinds should be further tested at several Ness as planned;
- Further checks on product quality, in particular ambiguity removal may be further improved;
- The easy accessibility through the use of a clickable map is important to control the abundance of wind products of SeaWinds;
- Untimely availability of the wind products renders them useless in many cases for the meteorologists; and
- A 50-km resolution product may be a better compromise between wind structure and accuracy for use in nowcasting and short range forecasting.

Familiarity with the products will be increased through user support, which is being facilitated by the SAFs.

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# ACRONYMS

| | |
|---|---|
| 2D-VAR | 2-dimensional AR |
| 3D-Var | 3-dimensional variational meteorological analysis |
| 4D-Var | Variational meteorological analysis in space and time |
| ADD | Architectural Design Document |
| ADEOS-I | Advanced Earth Observation System (1996-7) |
| ADEOS-II | Advanced Earth Observation System (2002) |
| AMSR | Advanced Microwave Instrument on ADEOS-II |
| AR | Ambiguity Removal |
| ASCAT | Advanced scatterometer on METOP |
| BCRS | Beleidscommissie Remote Sensing (Dutch) |
| BUFR | Binary Universal Format Representation |
| CM | Climate |
| CMP | Configuratie Management Plan |
| ECMWF | European Centre for Medium-range Weather Forecasts |
| ERS | European Remote Sensing Satellite |
| ESA | European Space Agency |
| EUMETSAT | European Organisation for the Exploitation of Meteorological Satellites |
| DP | Development Phase |
| GMF | Geophysical Model Function |
| GMT | Greenwich time |
| HH | Horizontal polarisation emitted-Horizontal received |
| HIRLAM | HIgh-Resolution Limited-Area Model |
| ICD | Interface Control Document |
| JPL | Jet Propulsion Laboratory |
| KNMI | Royal Netherlands Meteorological Institute |
| METOP | Meteorological Operational satellite (2003) |
| MLE | Maximum Likelihood Estimator |
| NASA | National Aeronautics and Space Administration (USA) |
| NCEP | National Centre for Atmospheric Prediction (USA) |
| NOAA | National Oceanographic and Atmospheric Administration (USA) |
| NRMS | Normalised RMS |
| NRSP | National Remote-Sensing Programme (Dutch) |
| NSCAT | NASA Scatterometer |
| NWP | Numerical Weather Prediction |
| OI | Optimal (statistical) Interpolation |
| OPFD | Output Products Format Document |
| OSI | Ocean and Sea Ice |
| PreScat | Processor of ERS scatterometer data at KNMI |
| QC | Quality Control |
| QuikScat | NASA scatterometer mission with SeaWinds |
| RMS | Root-Mean-Squared |
| SAF | EUMETSAT Satellite Application Facility |
| SAG | Science Advisory Group |
| SD | Standard Deviation |
| SDE | Standard Deviation of Error |

| | |
|---|---|
| SeaWinds | NASA rotating pencil-beam scatterometer |
| SNR | Signal-to-Noise Ratio |
| SSM/I | Special Sensor Microwave Instrument |
| SWVC | Super WVC |
| SVVP | Software Verification and Validation Plan |
| TR | Test Report |
| VV | Vertical polarisation emitted-Vertical received |
| WMO | World Meteorological Organisation |
| WVC | Wind Vector Cell |

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