# A comparison of ASCAT wind measurements and the HIRLAM model over the Baltic Sea*

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**Abstract**

This paper presents a comparison of the wind data measured by the ASCAT polar-orbiting satellite scatterometer and winds forecast by the numerical weather prediction model HIRLAM in the Baltic Sea region during the stormy season in 2009. Two different resolution models were used in the comparison. Mutual quality and uncertainty characteristics of the measurements and predictions are determined. The results of the study show that the ASCAT wind data are well

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The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

correlated with the HIRLAM predicted winds, which raises the credibility of both data sources in operational and hindcasting applications over the Baltic Sea. A case of phase error in a HIRLAM forecast of cyclonic activity over the Baltic Sea is discussed.

## 1. Introduction

The Advanced Scatterometer (ASCAT) on the Meteorological Operational (MetOp) satellite of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) is a C band radar, whose primary objective is to determine the wind field at the ocean surface (Figa-Saldaña et al. 2002). Wind scatterometers are instruments that are used to infer data on wind speed and direction from radar measurements of the sea surface. They rely for their operation on the fact that winds blowing over the sea influence the radar backscattering properties of the surface in a manner that is related to wind speed and wind direction (Stoffelen 1998, Gelsthorpe et al. 2000, Portabella 2002, Chelton & Freilich 2005). The EUMETSAT ASCAT wind products provide the wind speed and direction measurements at 10 m above the sea surface. Data is provided either with a grid spacing of 12.5 km and a spatial resolution of 25 km or with a grid spacing of 25 km at a 50 km resolution across and along two 550-km wide swaths on either sides of the nadir track. The radar measurements are provided in three azimuth directions – fore, mid and aft – respectively pointing 45°, 90° and 135° away from the satellite propagation vector, to resolve the wind direction and speed (Figure 1).

The ASCAT data are processed and distributed jointly by the EUMETSAT Ocean and Sea Ice (OSI) Satellite Application Facility (SAF) and Advanced Retransmission Service (EARS) ground system, both implemented at the Koninklijk Nederlands Meteorologisch Instituut (KNMI). The ASCAT wind products are freely available worldwide (see www.knmi.nl/scatterometer/), either through EUMETCAST, FTP or GTS. The ASCAT 12.5 km wind data visualization in the Baltic Sea region has been operational at the Estonian Meteorological and Hydrological Institute (EMHI) since the spring of 2010.

The ASCAT mission has been primarily designed to provide global ocean wind vectors operationally. The main applications are in the use of the high-resolution ASCAT winds in operational nowcasting (Von Ahn et al. 2006) and assimilation of those winds into numerical weather prediction (NWP) models (Figa-Saldaña et al. 2002). The use of scatterometer observations in data assimilation systems can extend their usefulness substantially and lead to improved sea level pressure analyses, improved upper air analyses of both

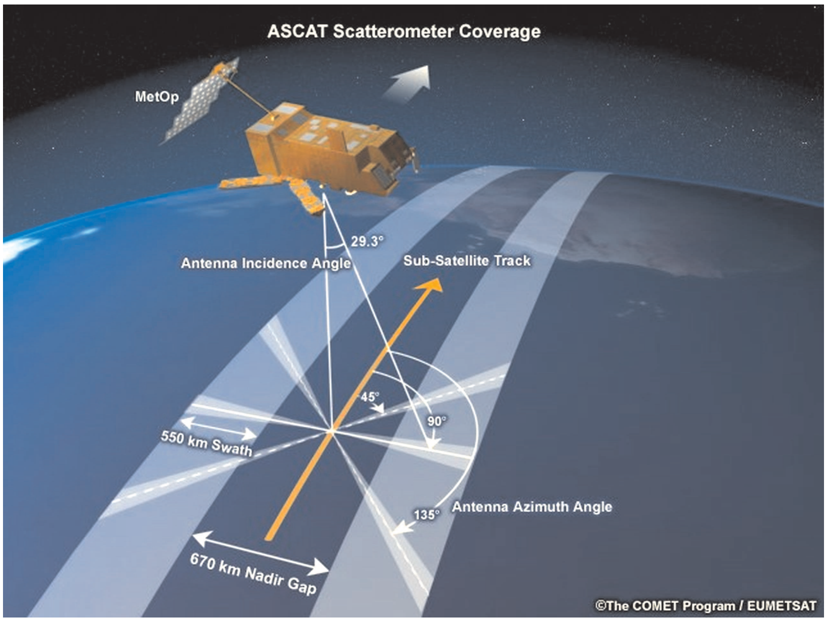


**Figure 1.** The ASCAT Scatterometer Coverage. Source: COMET® http://www.moisturemap.monash.edu.au/aaces/aaces-1/ascat.php; accessed on 28th Apr. 2010

wind and geopotential, and improved short and extended-range numerical weather forecasts (Atlas et al. 2001).

In many applications, such as storm surge and wave prediction, marine warnings and ocean forcing, NWP analysis winds are used as input, but lacking in mesoscale detail. For both operational real-time marine applications and oceanographic research it is important to characterize the differences between the scatterometer and NWP products (Stoffelen et al. 2006). Global NWP models do not generally describe the small scales observed by scatterometers (Stoffelen et al. 2010), and it is of interest to investigate the assimilation of small scales by a high-resolution NWP model.

HIRLAM (Undén et al. 2002) is a High Resolution Limited Area Model, which serves as the main NWP platform for short-range, up to three days', operational weather forecasting and NWP applications in its member countries. HIRLAM gained operational status at EMHI in 2007. Besides its usual application as the weather prediction model, HIRLAM acts as the driving model for the local HIROMB marine modelling system (Funkquist et al. 2000), which is currently used for storm surge warnings.

Because of the scarcity of marine wind observations in the Baltic Sea region, EMHI is interested in the quality of satellite-based ASCAT winds as a complementary data source of weather over the sea. The main interest of EMHI in the ASCAT winds as a possible solution for the operational monitoring of marine winds lies in the verification of storm warnings, as the network of coastal weather stations is insufficient for assessing weather conditions over the sea. The potential of ASCAT wind measurements as a means of improving the data assimilation process in HIRLAM is an area of interest as well. The current study compares ASCAT 10-m wind measurements with the respective numerical predictions of the operational HIRLAM models. The quality of the ASCAT winds has been assessed before, mostly over the large areas of oceans using comparisons with buoy measurements (Verhoef & Stoffelen 2009). The present study attempts to assess whether the same quality and uncertainty characteristics apply to the narrow, almost enclosed Baltic Sea basin as well. The comparison further aims to assess the quality and uncertainty range of HIRLAM NWP model predictions, as its output is often used for driving marine models in operational forecasting and hindcasting regimes. Two different resolutions of the NWP model are compared to see whether the resolution increase can play a significant role in forecasting over the enclosed Baltic Sea.

## 2. Material and methods

In the present study the EARS ASCAT 12.5-km gridded wind speed and wind direction were studied during the two-month period from 01.10 to 03.12.2009. The period was chosen to represent the stormy season over the Baltic Sea. HIRLAM forecasts from the archive of operational runs at the EMHI for the same period were used for comparison. Unfortunately, buoy measurements from the Baltic Sea were not available for inclusion in the study.

The NWP environment at EMHI is based on HIRLAM version 7.1.2 and consists of two modelling areas, ETA_II and ETB_II, with different grids. _II refers to EMHI's in-house second generation of modelling areas and will be omitted further on in the current manuscript for ease of reading.

Figure 2 illustrates the HIRLAM modelling areas and their geographical location. The ETA modelling domain has a horizontal grid distance of 11.1 km and the smaller ETB model domain has a 3.3 km grid. It should be noted that the HIRLAM has a rotated-pole latitude-longitude grid (here, the south pole is located at 30°S and 0°E). The boundary fields for the HIRLAM ETA model are provided by the European Centre for Medium-Range Weather Forecasting (ECMWF) model, and the boundary fields for the ETB model are provided by the ETA forecasts. The 54-hour forecasts of the ETA model are calculated four times a day with forecast starting-points at 00, 06, 12 and 18 UTC. For the ETB domain the 36-hour forecasts are

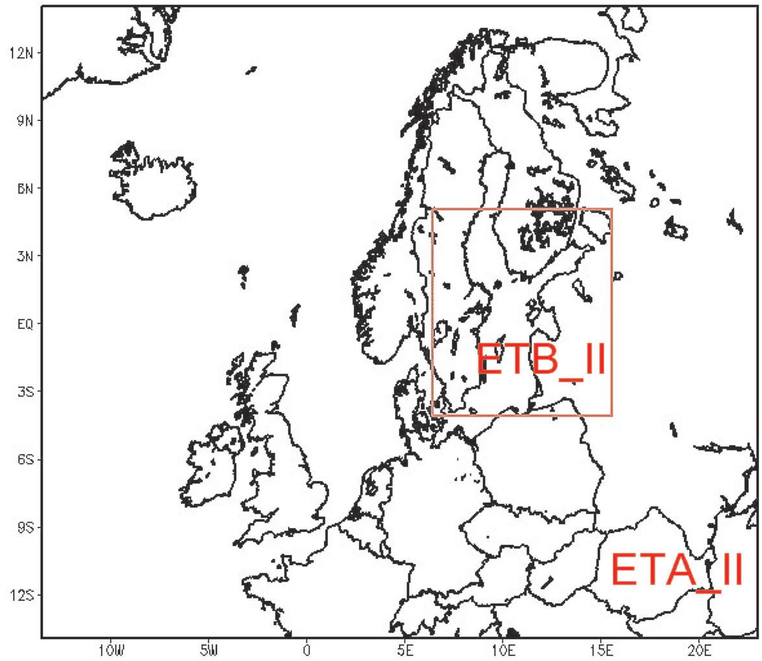


**Figure 2.** HIRLAM ETA and ETB modelling areas. The geographical coordinates are the latitudes and longitudes in the Earth's system with rotated poles as defined in HIRLAM

calculated twice a day with starting-points at 00 and 12 UTC. To maintain the analysis cycle, 6-hour forecasts at 06 and 18 UTC are calculated for ETB as well. Forecast fields are available with a 3-hour time resolution. Further properties of models and the parameterization schemes applied in the NWP environment at EMHI can be found in the paper by Keevallik et al. (2010).

The physical definition of the ASCAT winds is that of equivalent neutral winds. In the most common definition, equivalent neutral wind speed is the mean wind speed that would be observed if there was neutral atmospheric stratification (Geernaert & Katsaros 1986). The only difference between neutral and real ASCAT winds is a bias of +0.2 m $s^{-1}$ for the neutral winds as compared to the real winds (Verhoef & Stoffelen 2009). Of course, the differences between the HIRLAM real and 10-m neutral winds will be variable, but with an expected statistical mean of 0.2 m $s^{-1}$ (Hersbach 2010). In the assessment of ASCAT winds, the HIRLAM model forecast wind components at 10-metre height were used. The stability conditions in the forecasts were not checked, however.

The area of interest in the Baltic region was 55°–62.3°N and 14.5°–27.8°E. As ASCAT is an instrument on a polar orbiting satellite, the measurements in this area are made from one to three times per day and in the time interval around 17–20 UTC. For comparison of the ASCAT and HIRLAM winds, the time of the ASCAT data measurements had to be coordinated with the time of the HIRLAM wind forecasts. During this study 06-hour, 18-hour and 30-hour forecasts of both the ETA and the ETB model were used. While the ASCAT measurements were made about at 18 UTC, the HIRLAM 06-hour and 30-hour forecasts were chosen at the 12 UTC starting-point and the 18-hour forecast at the 00 UTC starting-point. If the ASCAT measurements were made more than once per day, the ASCAT data were chosen with a minimal time difference between the NWP model and ASCAT winds (less than one hour). The 10-m wind from the HIRLAM analyses were not used in the comparison as they are reported to be of lower quality than the short-range predictions by Keevallik et al. (2010).

The HIRLAM wind components at 10-m height were interpolated into the ASCAT points of measurements using the bilinear interpolation method. The bias, root mean square (RMS) error and correlation coefficient were calculated between the ASCAT and HIRLAM models for two wind speed intervals – 0–22 m $s^{-1}$ and 4–22 m $s^{-1}$. The upper level of the wind speed was the maximum wind speed during the observed period. Comparison of wind data was performed through the wind speed and direction, and the wind velocity components, where $u$ is the zonal and $v$ is the meridional wind component. All statistical characteristics were computed on a homogenized dataset, which means that if one of the model forecasts was missing, the datum for comparison with the ASCAT winds was eliminated from the analysis. The quality characteristics used here are associated with sampling length distributions.

## 3. Results

### 3.1. Statistical comparison of HIRLAM and ASCAT

Over the evaluation period the observed winds in general showed remarkably good coincidence with those predicted by the model. As an example of good coincidence, Figure 3 presents the observed and predicted winds over the Baltic Sea on 03.11.2009. Unfortunately, the area of interest is not shown in full here (54.6°N–60.3°N, 16°E–24.5°E), owing to the high density of the wind barbs.

In wind verification, a speed of over 4 m $s^{-1}$ is often used (Gelsthorpe et al. 2000, Verspeek et al. 2008, Verhoef & Stoffelen 2009) to estimate quality characteristics; this approach is followed here. In particular, this is

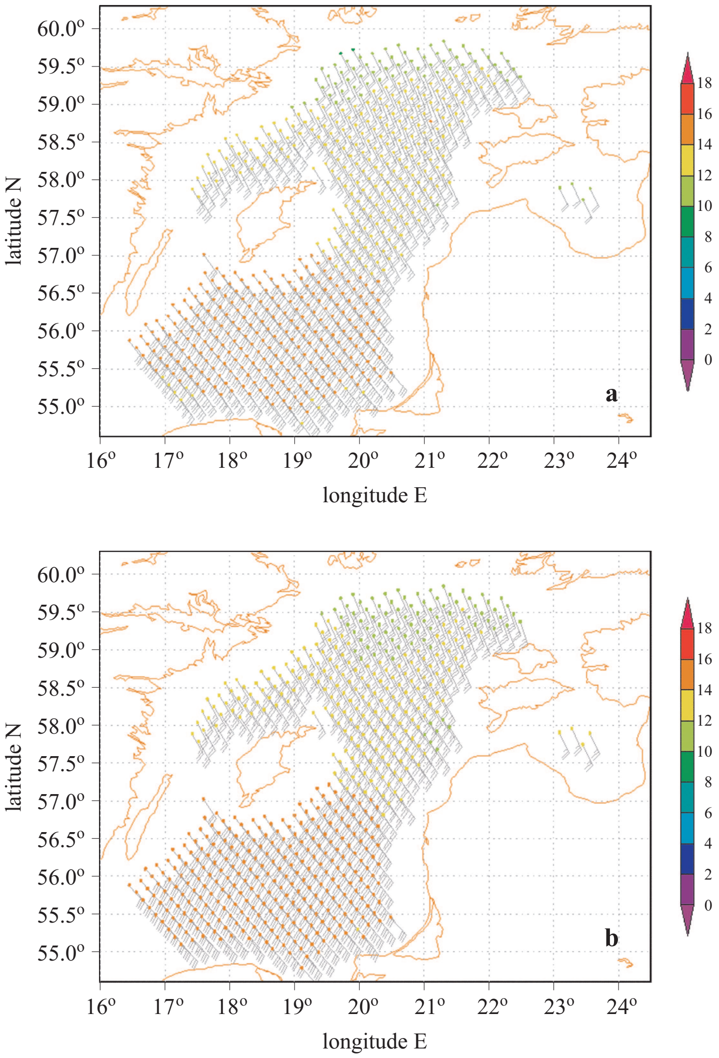


**Figure 3.** The winds of the ASCAT (top) 03.11.2009 at 18:09 UTC and the HIRLAM ETA model 03.11.2009 at 12 UTC 06-hour forecast (bottom)

done when computing wind direction statistics, which would otherwise be determined to a large extent by low winds (Stoffelen 1998).

The ETA 06-hour forecast and ASCAT measurement scatterplots of wind speed and direction are shown in Figure 4 (0–22 m $s^{-1}$) and Figure 5 (4–22 m $s^{-1}$). As seen in Figure 4, the coincidence of the ETA 06-hour forecast and ASCAT wind speed is reasonably good. The wind direction scatterplots also show good correlation, whereas the scattering is much smaller when low speed winds are filtered out (see Figure 5).

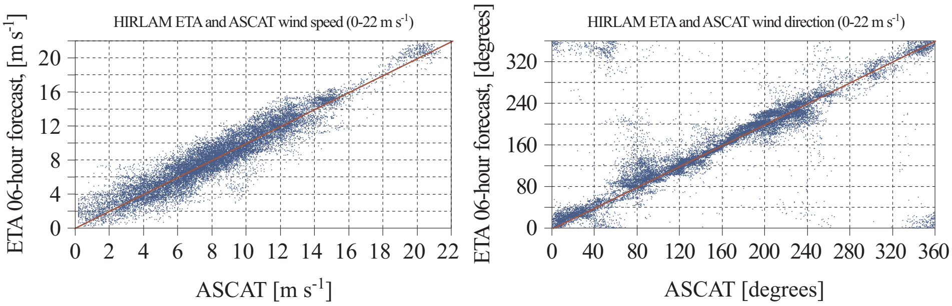


**Figure 4.** HIRLAM ETA 06-hour forecast and ASCAT wind direction and speed scatterplots (0–22 m $s^{-1}$)

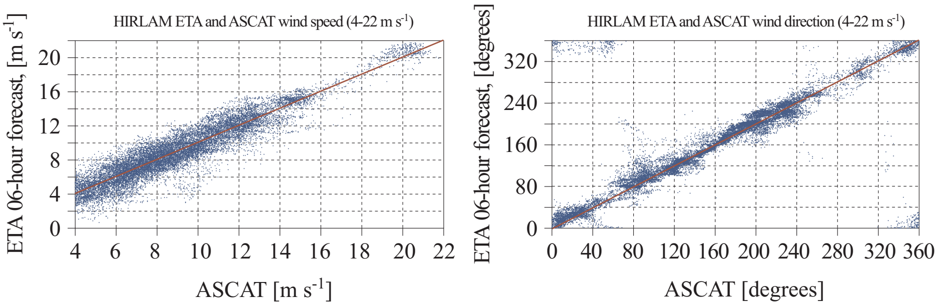


**Figure 5.** HIRLAM ETA 06-hour forecast and ASCAT wind direction and speed scatterplots (4–22 m $s^{-1}$)

Analysis of similar scatterplots of the HIRLAM ETB model and both models with forecast lengths of 18 and 30 hours shows that the characteristics of distribution do not change qualitatively in time. Thus, for the sake of brevity, the scatterplots are not shown here. The scatterplots of the wind components of the ASCAT and HIRLAM winds were also compared (see Figure 6). The scatterplots of the wind components show good coincidence between the observed and predicted wind components. However, scattering increases on both the type and model scatterplots with growing forecast length, which is a natural and expected effect. Some quality characteristics are computed for all forecast periods for both the ETA and the ETB models and are summarized in Tables 1 and 2. In computations of wind direction statistics the errors due to 360-degree aliasing were eliminated by manual inspection.

The quality characteristics are worse when all wind speeds are taken into account (compared only to the 4–22 m $s^{-1}$ range), which can be explained by the fact that, according to Stoffelen (1998), in the presence of weak winds, wind speed error distributions are skewed at low winds with slightly

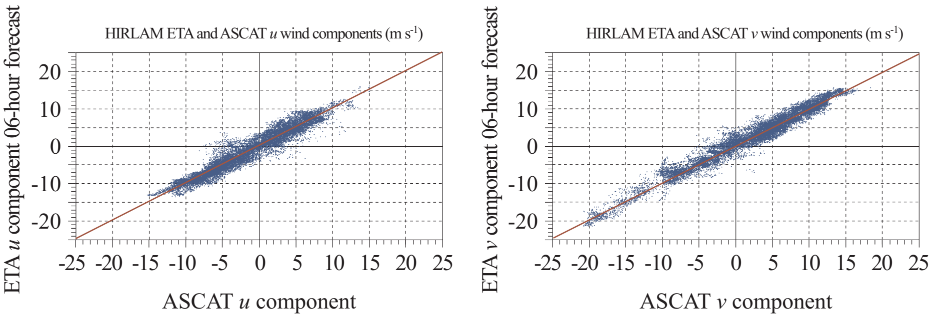


**Figure 6.** HIRLAM ETA 06-hour forecast and ASCAT $u$ and $v$ wind component scatterplots (4–22 m s$^{-1}$)

increased variance differences. The wind speed correlations decrease in the case of the 4–22 m s$^{-1}$ range, since the correlation depends on the ratio of domain over scatter; hence, reducing the wind speed domain decreases the correlation. The differences are related mostly to effects of atmospheric wind variability and differences in spatial representation, which are well expressed as constant errors in the wind components. As far as the wind speed is concerned, the bias of both the ETA and ETB models in the 4–22 m s$^{-1}$ range is almost non-existent, whereas a weak, negative bias growth may be noted with increasing forecast length. In the case of wind direction the bias is appreciable, and a weak anticlockwise turning with growing forecast length may be observed. The RMS error of the wind speed was mostly less than 2 m s$^{-1}$ in all forecasts and wind speed intervals. The results in Table 2 show that the bias of the wind component is quite small and in some cases even decreases to 0 m s$^{-1}$. However, the RMS value gradually increases with the forecast length.

Comparison of the results in Tables 1 and 2 shows a higher correlation between the ASCAT and HIRLAM winds present in the wind components ($> 0.90$ for all the forecasts), whereas the correlation coefficients in Table 1 are much lower, especially in the wind direction. According to Stoffelen (1998), the wind component errors are better described than wind speed or wind direction. The wind component errors have a symmetrical distribution for the scatterometer and model forecast, and as mentioned before, the random errors of wind direction clearly depend on wind speed.

ETA seems to perform slightly better than the high resolution ETB model, whereas the expectation was that the high-resolution model would perform better. An explanation for this could be that when more small scales are represented in ETB than in ETA, these scales do not appear to tally with the scatterometer winds. The reason for this might be that the

**Table 1.** ASCAT and HIRLAM models: statistical characteristics (bias, RMS error, correlation) of wind speed and direction

| HIRLAM ETA | | 06-hour forecast | | | 18-hour forecast | | | 30-hour forecast | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | bias | RMS | corr. | bias | RMS | corr. | bias | RMS | corr. |
| 0–22 m s$^{-1}$ | wind speed | 0.12 | 1.30 | 0.94 | 0.14 | 1.46 | 0.92 | −0.10 | 2.05 | 0.85 |
| | wind direction | 5.34 | 24.89 | 0.75 | 4.53 | 27.13 | 0.76 | 2.14 | 33.23 | 0.72 |
| 4–22 m s$^{-1}$ | wind speed | 0.03 | 1.28 | 0.93 | 0.01 | 1.39 | 0.91 | −0.31 | 1.97 | 0.84 |
| | wind direction | 3.46 | 16.19 | 0.82 | 2.45 | 18.60 | 0.82 | 1.40 | 27.52 | 0.75 |
| HIRLAM ETB | | 06-hour forecast | | | 18-hour forecast | | | 30-hour forecast | | |
| | | bias | RMS | corr. | bias | RMS | corr. | bias | RMS | corr. |
| 0–22 m s$^{-1}$ | wind speed | 0.12 | 1.38 | 0.94 | 0.12 | 1.51 | 0.92 | −0.07 | 2.08 | 0.85 |
| | wind direction | 5.13 | 25.36 | 0.73 | 4.90 | 28.43 | 0.72 | 2.80 | 32.76 | 0.71 |
| 4–22 m s$^{-1}$ | wind speed | 0.03 | 1.35 | 0.93 | −0.01 | 1.46 | 0.91 | −0.28 | 2.03 | 0.83 |
| | wind direction | 3.26 | 16.31 | 0.80 | 3.10 | 19.72 | 0.78 | 1.79 | 26.68 | 0.75 |

**Table 2.** ASCAT and HIRLAM models: statistical characteristics (bias, RMS error, correlation) of wind components

| HIRLAM ETA | | 06-hour forecast | | | 18-hour forecast | | | 30-hour forecast | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | bias | RMS | corr. | bias | RMS | corr. | bias | RMS | corr. |
| 0–22 m $s^{-1}$ | $u$ comp. | 0.16 | 1.61 | 0.96 | 0.04 | 1.80 | 0.94 | −0.01 | 2.22 | 0.92 |
| | $v$ comp. | 0.34 | 1.58 | 0.98 | 0.15 | 1.77 | 0.97 | −0.09 | 2.72 | 0.92 |
| 4–22 m $s^{-1}$ | $u$ comp. | 0.17 | 1.59 | 0.96 | 0.00 | 1.77 | 0.95 | 0.01 | 2.16 | 0.93 |
| | $v$ comp. | 0.29 | 1.52 | 0.98 | 0.13 | 1.72 | 0.97 | −0.15 | 2.78 | 0.93 |
| **HIRLAM ETB** | | **06-hour forecast** | | | **18-hour forecast** | | | **30-hour forecast** | | |
| | | bias | RMS | corr. | bias | RMS | corr. | bias | RMS | corr. |
| 0–22 m $s^{-1}$ | $u$ comp. | 0.20 | 1.69 | 0.95 | 0.03 | 1.89 | 0.94 | −0.01 | 2.24 | 0.92 |
| | $v$ comp. | 0.28 | 1.66 | 0.97 | 0.15 | 1.84 | 0.96 | −0.08 | 2.77 | 0.92 |
| 4–22 m $s^{-1}$ | $u$ comp. | 0.20 | 1.68 | 0.96 | 0.00 | 1.90 | 0.94 | −0.01 | 2.20 | 0.93 |
| | $v$ comp. | 0.23 | 1.61 | 0.98 | 0.12 | 1.82 | 0.97 | −0.12 | 2.84 | 0.93 |

forcing of these scales in the HIRLAM model is weak and the phases of these small-scales are not well determined. In such a case, the added small-scale variance will not reduce the variance of the differences, but will tend to cause the difference variances to increase. This is usually referred to as the 'double penalty' in verification. To determine small scales, they need to be either observed or generated by downscale cascading and parameterizations. Other possible explanations may be that the HIRLAM parameterization schemes are fine-tuned to 15 km resolution and therefore do not work so well at high resolution, or that the proximity of the boundary conditions introduces distortions in small domains.

### 3.2. A case with phase error in cyclonic activity

ASCAT winds may be useful when NWP model phase shift errors need to be corrected over the open sea, as for example on 02.12.2009. Figures 7a and 7b illustrate the difference between the ASCAT and HIRLAM ETA 06-hour wind forecasts. In this figure the difference between the ASCAT and HIRLAM forecasts is not so significant. There are a few differences in

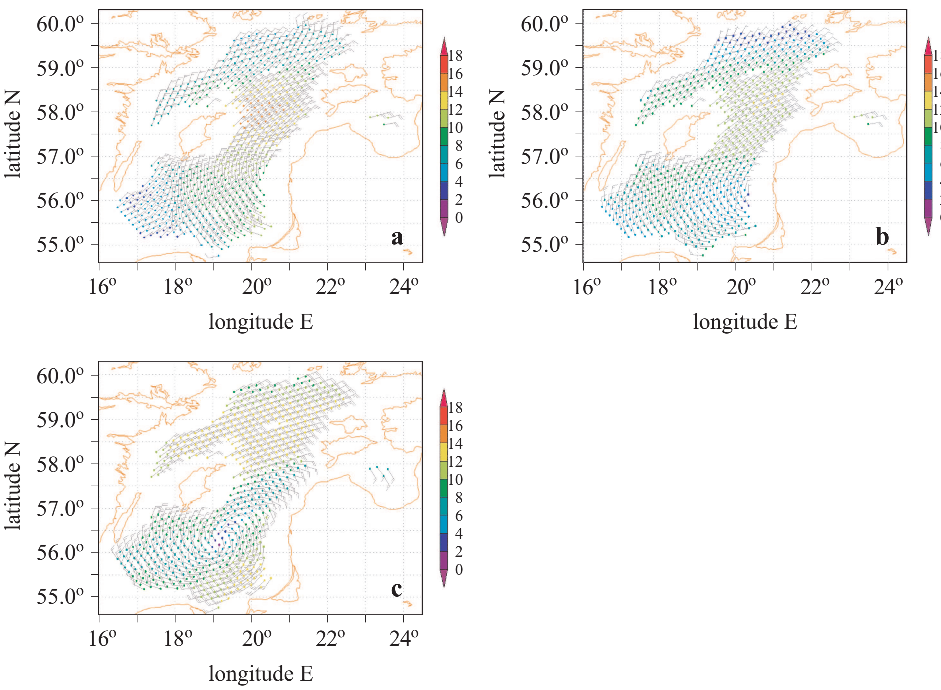


**Figure 7.** The winds of the ASCAT – 02.12.2009 at 18:09 UTC (a), HIRLAM ETA model – 02.12.2009 at 12 UTC 06-hour forecast (b), HIRLAM ETA model – 01.12.2009 at 12 UTC 30-hour forecast (c)

the wind direction between the ASCAT winds and the HIRLAM forecast for 02.12.2009 in the southern Baltic Sea at 18°E.

Comparison of the HIRLAM ETA 30-hour forecast with the ASCAT winds shows that there is a significant difference between wind directions in Figures 7a and 7c. On the southern part of the image the HIRLAM ETA model generates cyclonic winds, which do not fit the ASCAT winds. The results of the same forecasts from ETB model data show practically the same difference with the ASCAT winds. This is a clear signal that HIRLAM predicted a cyclonic development with a phase shift in the forecast with start time 12 UTC 01.01.2009 and corrected it later. The situation can be used to study the reasons for such phase shifts over the open sea and to correct them.

## 4. Discussion

HIRLAM ETA and HIRLAM ETB 10 m wind predictions show good correspondence with the measurements. The speed predictions practically lack a systematic error, although a very weak negative bias in wind speed may be observed with growing forecast length. This shows that the friction parameterization over the sea is roughly correct in HIRLAM. However, a small wind direction bias does exist.

The results of the higher resolution ETB model tend to be slightly worse than those of the operational suite; we may speculate that they are the result of the poor determination of 50-km scales over the Baltic, due to the relatively weak forcing and the lack of observations, or perhaps they are due to the proximity of the boundary zone, which introduces dynamic distortions in too small a domain, or they may be the effect of physical parameterizations not being tuned to such a high resolution.

The uncertainty ranges fit well with the expected quality characteristics reported in the literature. According to Gelsthorpe et al. (2000), determination of speeds in the range 4–24 m $s^{-1}$ with an accuracy of 2 m $s^{-1}$ (or 10%) and directions with an accuracy of ±20 deg is required. These criteria are met in both comparisons up to the 18-hour forecast lengths. In the case of the 30-hour forecasts these criteria are exceeded only slightly for the wind speed, but not for the wind direction. According to Figa-Saldaña et al. (2002), the accuracy target for ASCAT winds generated by the OSI SAF is 2 m $s^{-1}$ root mean square wind component error and 0.5 m $s^{-1}$ bias for all speeds below 25 m $s^{-1}$. The wind components of the HIRLAM and ASCAT presented in Table 2 show that the wind component statistics fit the required accuracy thresholds well. The RMS of wind components higher than 2 m $s^{-1}$ is present only in the 30-hour forecasts. The bias of the components is lower than that required in all HIRLAM forecasts.

In a comparison of the ASCAT and ECMWF analysis in northern cceanic areas (30°N–60°N), Bentamy et al. (2008) determined standard deviations of 1.77 m $s^{-1}$ for wind speed and 20 degrees for wind direction. According to Verhoef & Stoffelen (2010), the global ASCAT-ECMWF standard deviation of difference for wind speed is 1.26 m $s^{-1}$ and for wind direction is 15 degrees for the 25-km gridded product. The $u$ wind component standard deviation of the ASCAT-ECMWF winds is 1.45 m $s^{-1}$; the corresponding $v$ component is 1.63 m $s^{-1}$. More recently and in line with these results, Hersbach & Janssen reported at the 2010 International Ocean Vector Winds Meeting (18–20 May 2010) a vector RMS difference of $\sim$2.2 m $s^{-1}$ in the Baltic (http://coaps.fsu.edu/scatterometry/meeting/docs/2010_may/gridded/hersbach.pdf). HIRLAM wind speeds and directions show similar or slightly worse results over these ranges. Again, the HIRLAM model may contain smaller scales than ECMWF that are not well resolved by the physical parameterizations and the observing systems. Generally, 100-km scales evolve fast and need to be sampled densely in both time and space. To reduce the uncertainty in HIRLAM wind predictions, more observations over the Baltic may be necessary. The fact that the comparison of ASCAT and HIRLAM winds is generally in line with results from other similar studies confirms that the ASCAT 10-m winds are a reliable data source over the Baltic Sea, which is of great importance for marine and NWP communities operating in the region. Unfortunately, sea buoy or ship measurements in the Baltic Sea region were not available for the study, but it would be really advantageous to extend the study in this respect.

A case of phase error in the HIRLAM predictions of cyclonic development over Baltic Sea was spotted on 2.12.2009. This situation needs further analysis to identify the causes of the phase error. Nonetheless, it illustrates the potential of ASCAT measurements for identifying such a phase shift error over open sea areas and may help in the development of better deterministic models in the future.

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