Sea state assimilation

Peter Janssen

ECMWF

<peter.janssen@ecmwf.int>

thanks to: Saleh Abdalla, Jean Bidlot and Hans Hersbach

INTRODUCTION

Before we discuss the subject of assimilation of satellite observations in an ocean-wave forecasting system, first a brief introduction into the field of surface gravity waves and ocean wave forecasting is given.

The programme of my talk is therefore as follows.

- **WAVE FORECASTING**

  The basic evolution equation of the wave spectrum:

  the energy balance equation

  Discuss a number of applications, in deterministic and ensemble prediction.

- **ASSIMILATION OF ALTIMETER AND SAR**

  Discuss observation principle, method and impact on analysis

- **USE OF ALTIMETER WINDS AS VALIDATION TOOL**

  Although Altimeter wind speed data are not used in the analysis, they are extremely useful for validation purposes because they are really **independent**.

- **SCATTEROMETER WIND OBSERVATIONS**

  Obeys same observation principle as the SAR. Discuss the very recent introduction of ASCAT wind observations from Metop.

WAVE THEORY

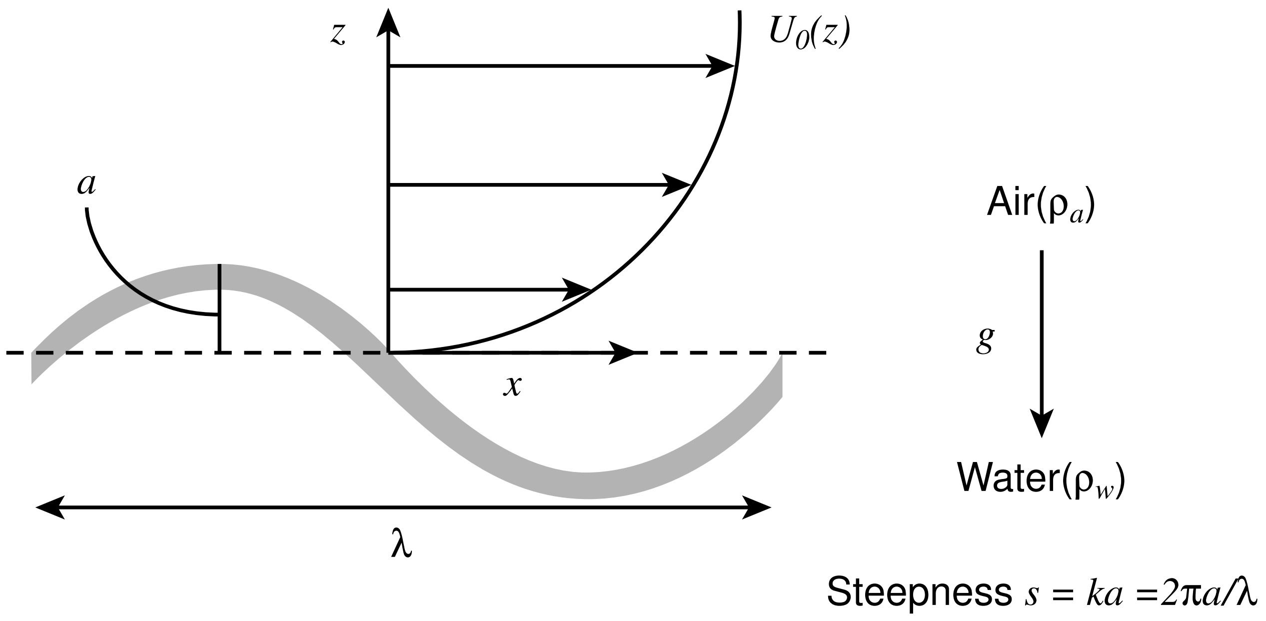


Figure 1: Schematic of the problem in two dimensions.

For various reasons forecasting of individual ocean waves is not possible, hence we consider the evolution of average seastate: a spectral description!

ENERGY BALANCE EQUATION

Therefore concentrate on the prediction of the ensemble average of the action density spectrum $N(\vec{k},t)$. Action plays the role of a number density and is defined in such a way that energy spectrum $F(\vec{k},t)$ is given as

$$F(\vec{k},t) = \omega(\vec{k}) \times N(\vec{k},t)$$

which is the usual rule in wave mechanics. From first principles one finds the following evolution equation

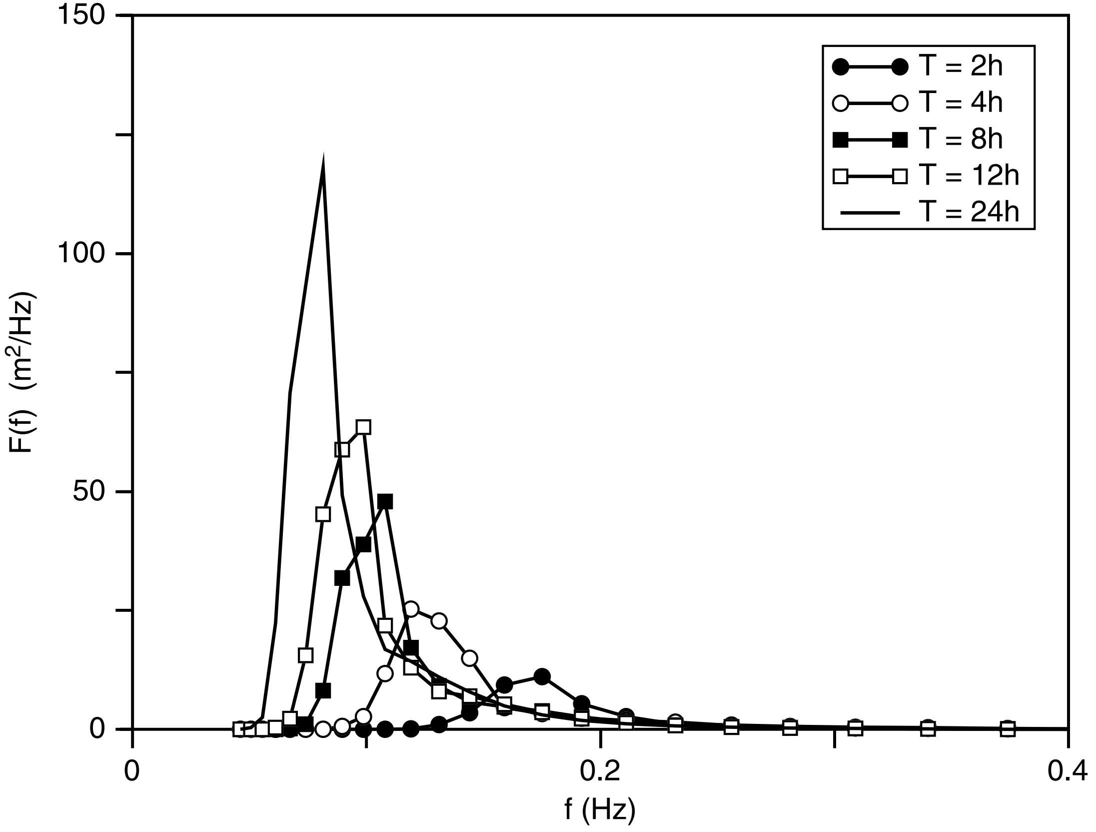
$$\boxed{\frac{\partial}{\partial t} N + \nabla_{\vec{x}} \cdot (\dot{\vec{x}} N) + \nabla_{\vec{k}} \cdot (\dot{\vec{k}} N) = S = S_{in} + S_{nl} + S_{ds},}$$

where $\dot{\vec{x}} = \partial\omega/\partial\vec{k}$, $\dot{\vec{k}} = -\partial\omega/\partial\vec{x}$, and the source functions S represent the physics of wind-wave generation, dissipation by wave breaking and nonlinear four-wave interactions.

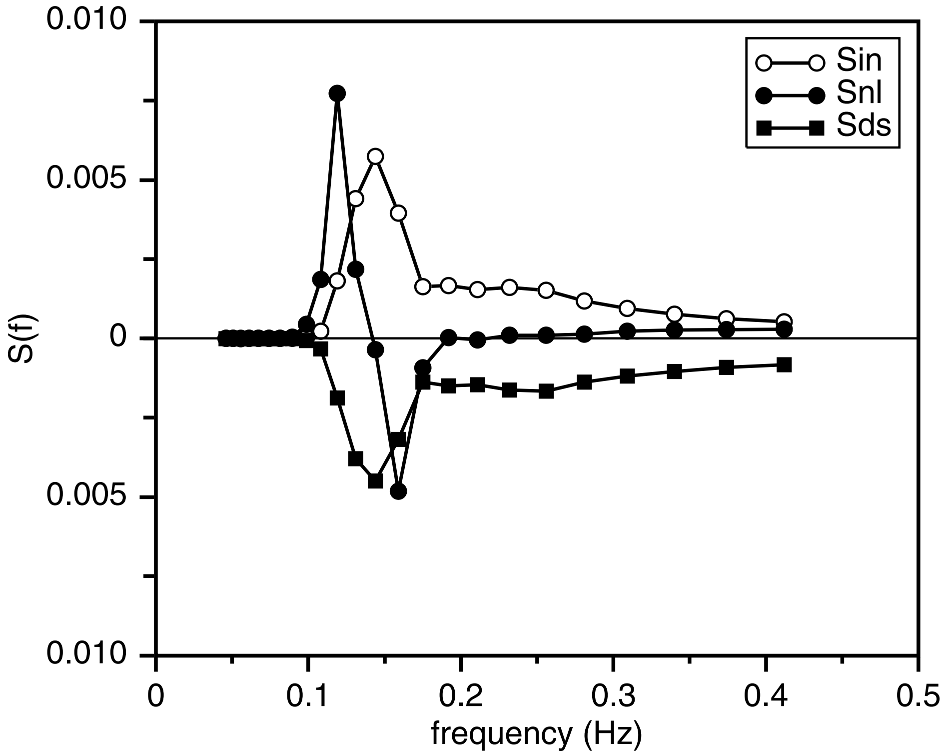
WAVE FORECASTING

The energy balance equation (including nonlinear transfer) is solved by modern wave prediction systems, where the forcing of the waves is provided by surface winds from weather prediction systems. For a large part (±80%) the quality of the wave forecast is determined by the accuracy of the surface wind field.

- An example of balance of source functions.
- Example of the forecast of wave height.
- Example of forecast wave spectra used as boundary condition for Irish limited area model.



Evolution in time of the one-dimensional frequency spectrum for a wind speed of 18 m/s.



The plot shows the energy balance of wind-generated ocean waves for a duration of 3 hrs, and a wind speed of 18 m/s.

Ocean wave forecasting at ECMWF is based on WAM cy4. Discuss global implementation only.

GLOBAL MODEL (81 deg S to 81 deg N)

coupled to atmospheric model [two-way interaction with feedback of ocean waves on ocean surface roughness (since June 29, 1998) thus giving a sea-state dependent momentum and heat flux]

- **Deterministic forecasts** :

  $F(f, \theta)$ has 30 frequencies and 24 directions

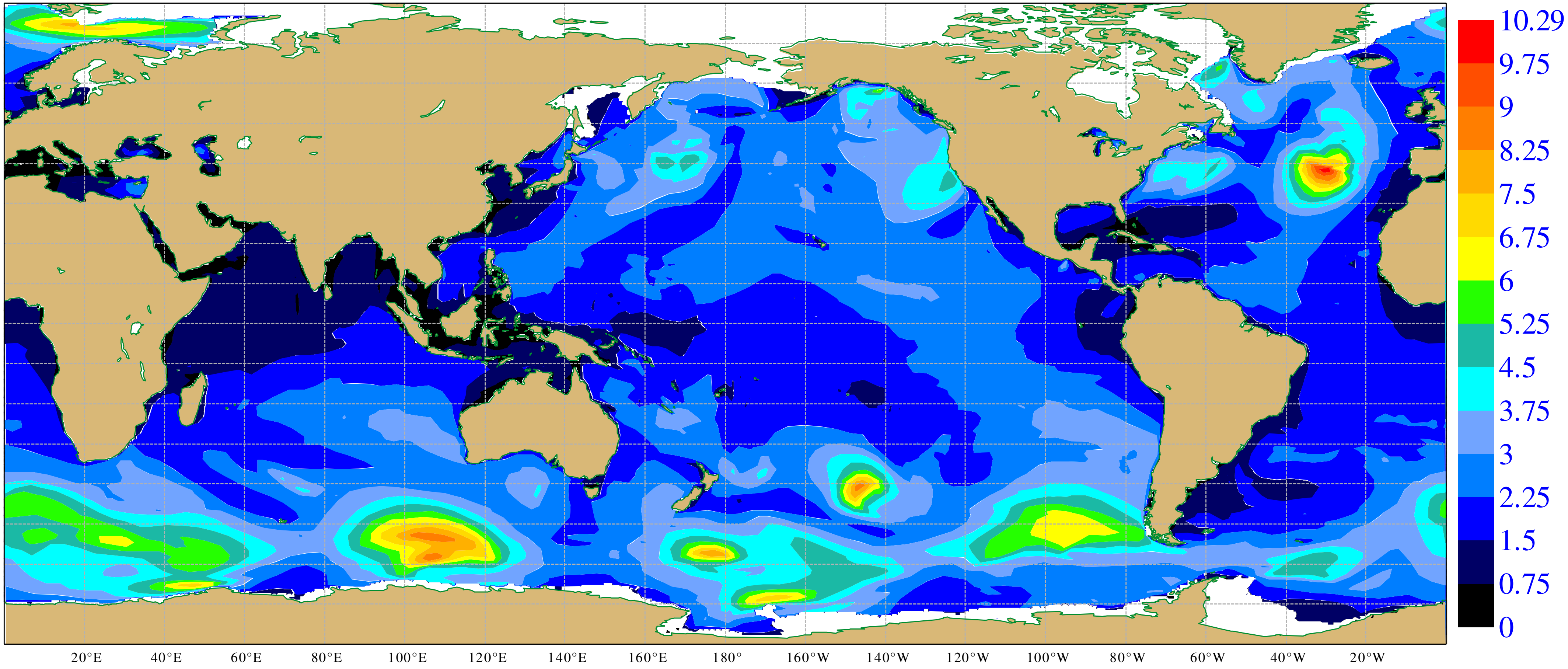
  runs on an irregular lat-lon grid, $\Delta x = 40$ km.

  assimilation of ENVISAT& Jason Altimeter H_S and ENVISAT ASAR spectra.

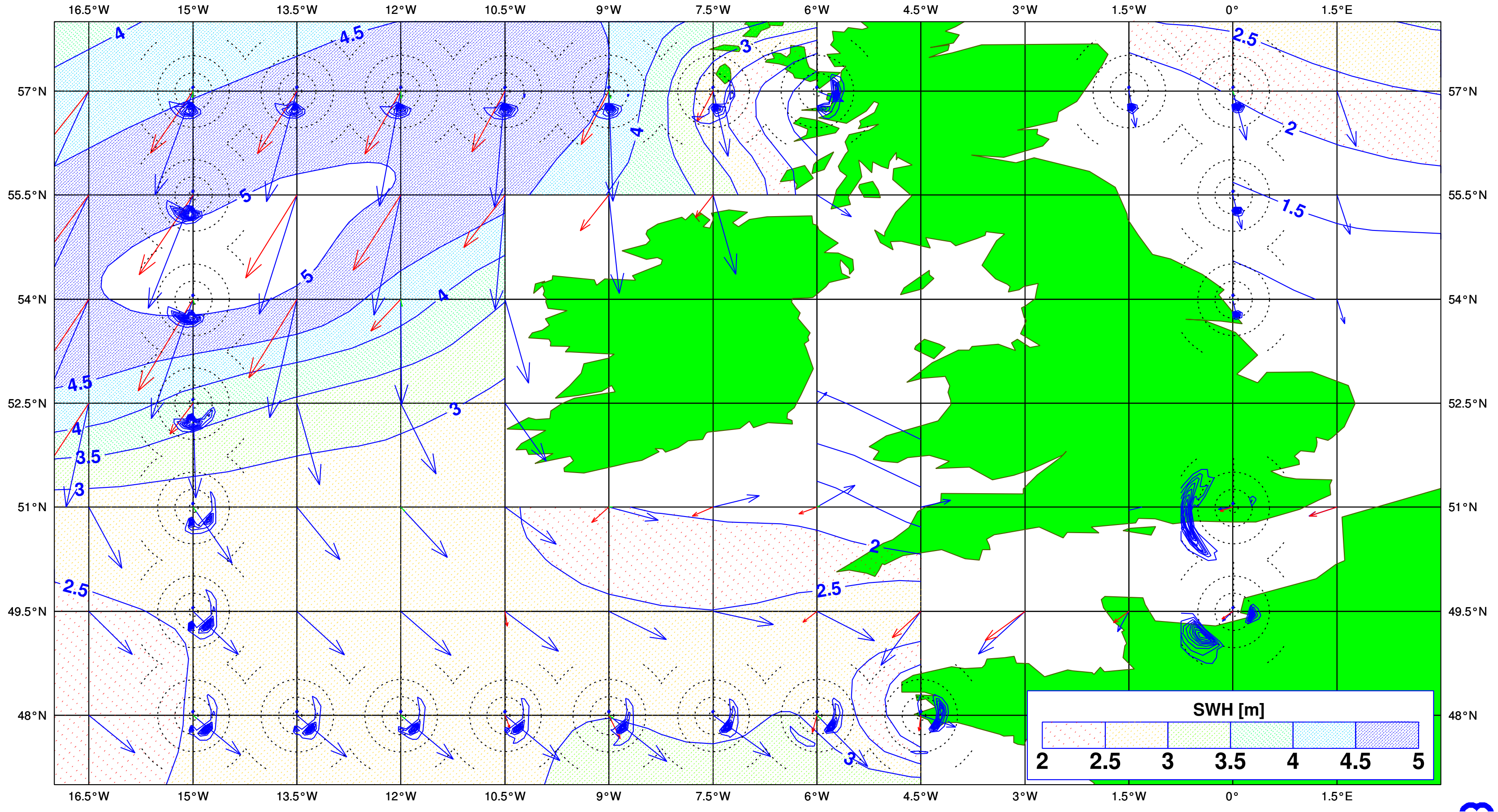
  10 day forecasts from 00Z and 12 Z.

  coupled to 10 m winds from T_l799 ATM model every timestep $\Delta t = 12$ min.

Tuesday 14 March 2006 00UTC ECMWF Forecast t+36 VT: Wednesday 15 March 2006 12UTC Surface: significant wave height



Sunday 25 January 2004 12UTC ECMWF Forecast t+24 VT: Monday 26 January 2004 12UTC
Surface: 2-d wave spectrum EXP: 0001

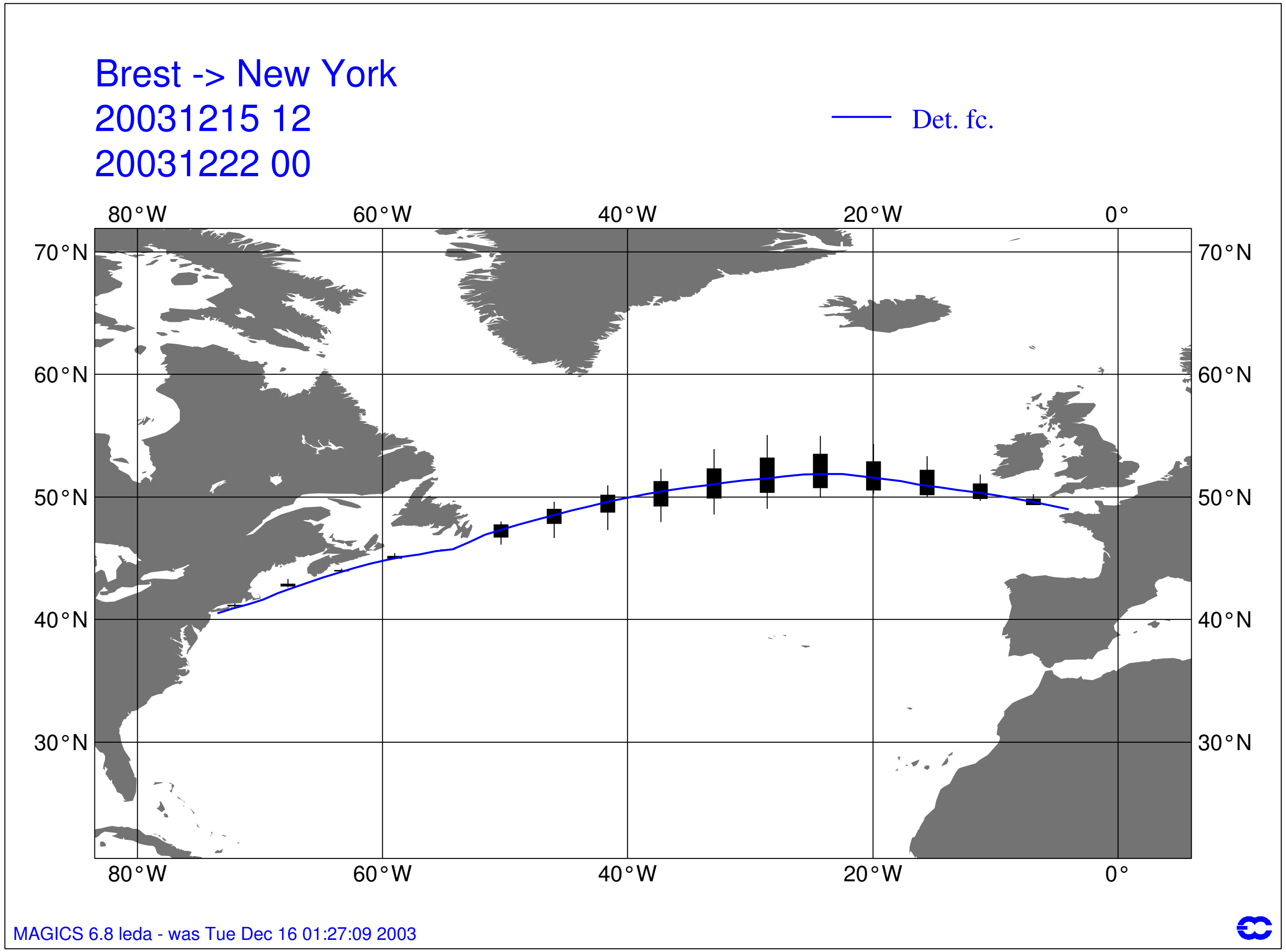


MAGICS 6.7 icarus - waa Mon Jan 26 03:42:49 2004 Bjorn Hansen

- **Probabilistic Forecasts** :

  (50+1) 1 deg ×1 deg 10-day wave ensemble forecasts coupled to the 10 m winds from the $T_l 399$ ATM model.

  Potential use: Probability of high sea state and Ship Routing. For example, error in forecast ship route may be obtained from the 50 shiproutes generated by the winds and waves of the 50 member ensemble.


Brest -> New York
20031215 12
20031222 00
Det. fc.
80°W
60°W
40°W
20°W
0°
70°N
60°N
50°N
40°N
30°N
MAGICS 6.8 leda - was Tue Dec 16 01:27:09 2003

MAXIMUM WAVE HEIGHT

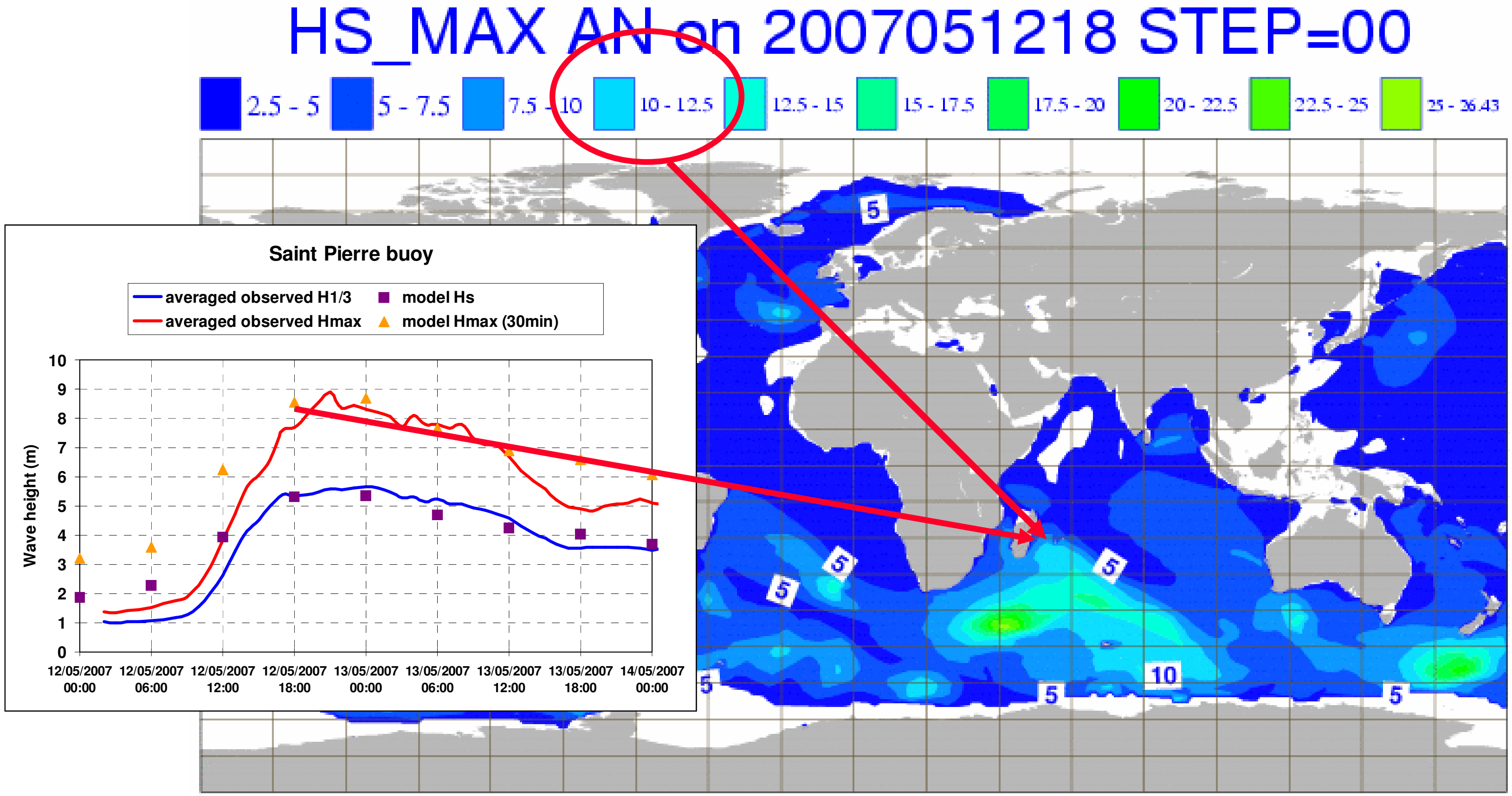
Although wave forecasting is about the mean sea state in a grid box one can also make statements about deviations from the mean: e.g. maximum wave height.

Example is the recent extreme event at La Réunion.

Large swell reaching la Réunion: the model

A new parameter is being developed. Namely the maximum wave height that can be expected within a certain time window (here 3 hours).
It will be introduced in operations soon.

New parameter: Maximum wave height on May 12, 18UTC



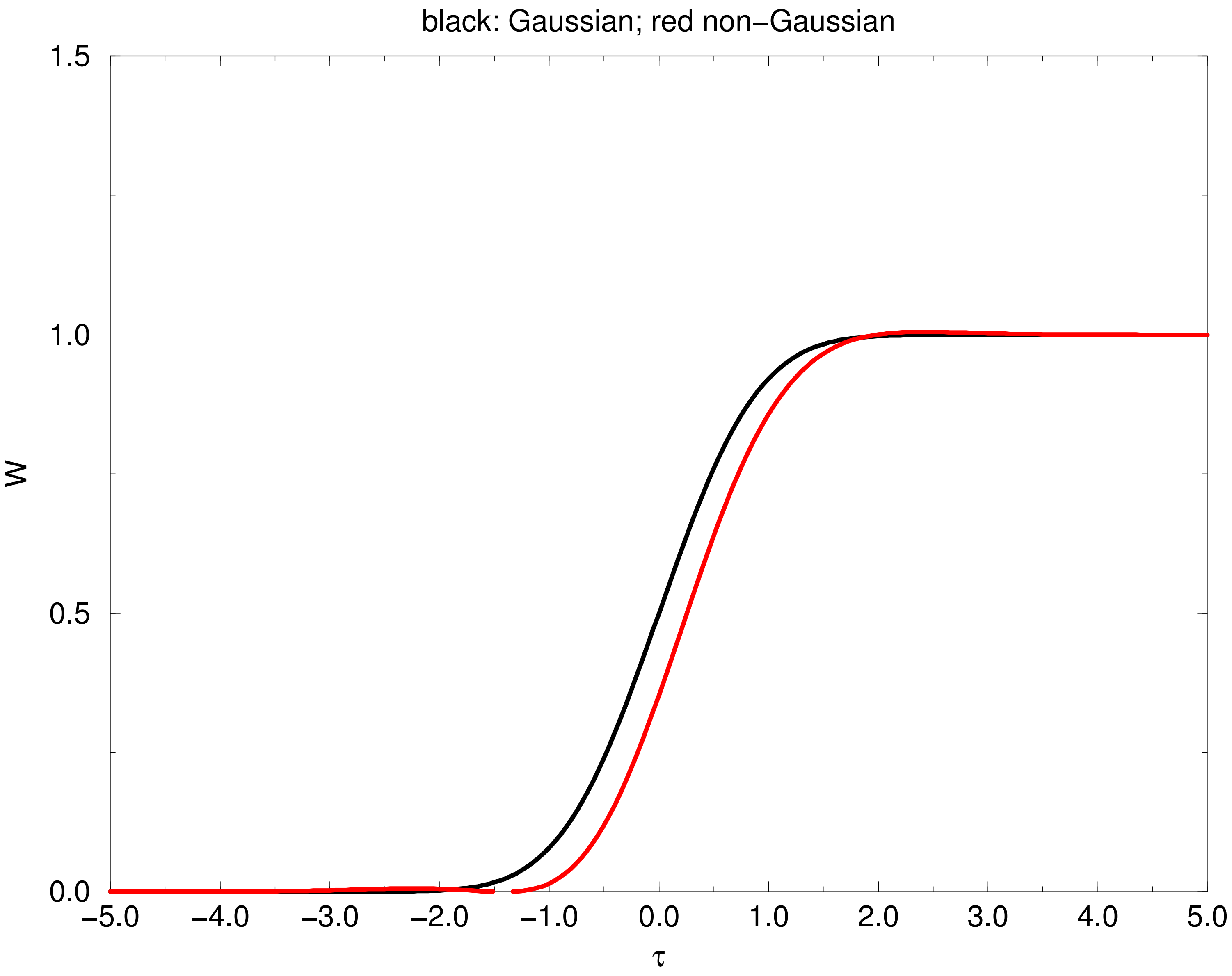
ALTIMETER DATA

MEASUREMENT PRINCIPLE

The altimeter is a radar (usually operating at Ku-band) that transmits a pulse towards the sea surface at nadir. **Significant wave height** is then determined from the slope of the return pulse (the wave form), while **wind speed** follows from the total backscatter.

For a random sea the return pulse also depends on the probability distribution of the ocean waves. In good approximation this is a Gaussian, but nonlinear effects, giving sharper crests and wider throughs, result in a skewed distribution. As a consequence, the waveform is retarded, as illustrated in the next figure, and therefore an Altimeter measures a slightly longer **Range** (of the order of $5\% H_S$) than the actual distance between satellite and mean ocean surface. The difference between the two is called the **sea-state bias** and is directly related to properties of ocean waves such as the mean square slope and wave age (Melville et al, 2004; Kumar et al, 2003).

Waveform versus normalised time



ANALYSIS METHOD

Two problems in wave height analysis:

- The wave spectrum has 30 × 24 degrees of freedom while we only provide observed information on an integral of the wave spectrum ⇒ **too many degrees of freedom** !
- Windsea is **strongly coupled** to the generating winds, hence a change in wave height implies, to be consistent, a change in local wind.

The many degrees of freedom problem is solved by using our knowledge on the evolution of ocean waves. Analysed spectrum is obtained by scaling the first-guess spectrum, where the scaling constants A and B depend on first-guess and observed parameters

$$F_{an}(f,\theta) = AF_{fg}(Bf, \theta + \Delta\theta),$$

where F_{fg} is rotated by an amount $\Delta\theta$ if this information is available (e.g. from a SAR). The scaling constants A and B follow from the dynamics of waves.

Consider the example of **windsea**.

JONSWAP(1973) has shown that the windsea spectrum has a universal shape depending on a single parameter, the wave age χ,

$$\chi = \frac{c_p}{u_*}, \; c_p = \frac{g}{\omega_p},$$

where ω_p is the peak frequency of the windsea. Hence the dimensionless energy $\epsilon_* = g^2 E/u_*^4$ follows from the scaling law

$$\epsilon_* = const \; \chi^3.$$

A simple analysis scheme can then be build by making the basic assumption that the first-guess wave age χ_{fg} is correct!

Then, from analysed H_S (using Optimum Interpolation) and first-guess H_S the analysed friction velocity $u_{*,an}$ becomes

$$u_{*,an} = u_{*,fg} \sqrt{\frac{H_{S,an}}{H_{S,fg}}},$$

while the peak frequency $f_{p,an}$ follows from $\chi_{an} = \chi_{fg}$.

Finally, the two scaling parameters of the spectrum follow from the requirement that analysed spectrum gives the analysed wave height, hence,

$$A = \left(\frac{H_{S,an}}{H_{S,fg}}\right)^2 B, \; B = \frac{f_{p,an}}{f_{p,fg}}$$

In a comprehensive wind and wave assimilation system, corrected winds would go into the atmospheric assimilation scheme to provide an improved wind field in the forecast. This approach has not been pursued yet.

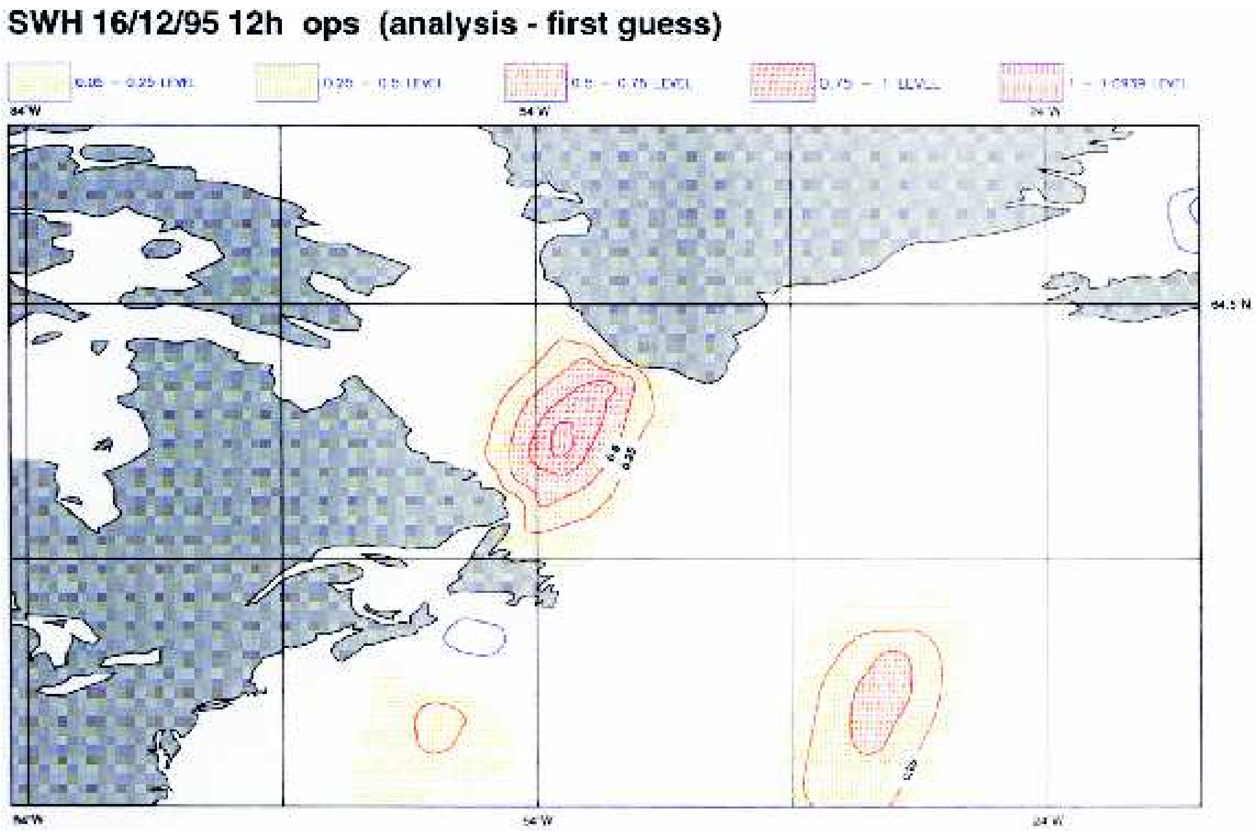
RESULTS

Optimum Interpolation schemes of the type just described have been operational since mid 1993 at UKMO (until beginning 2000) and ECMWF (while at NCEP from 1998 until February 2000). More recently also at Meteo France and BoM.

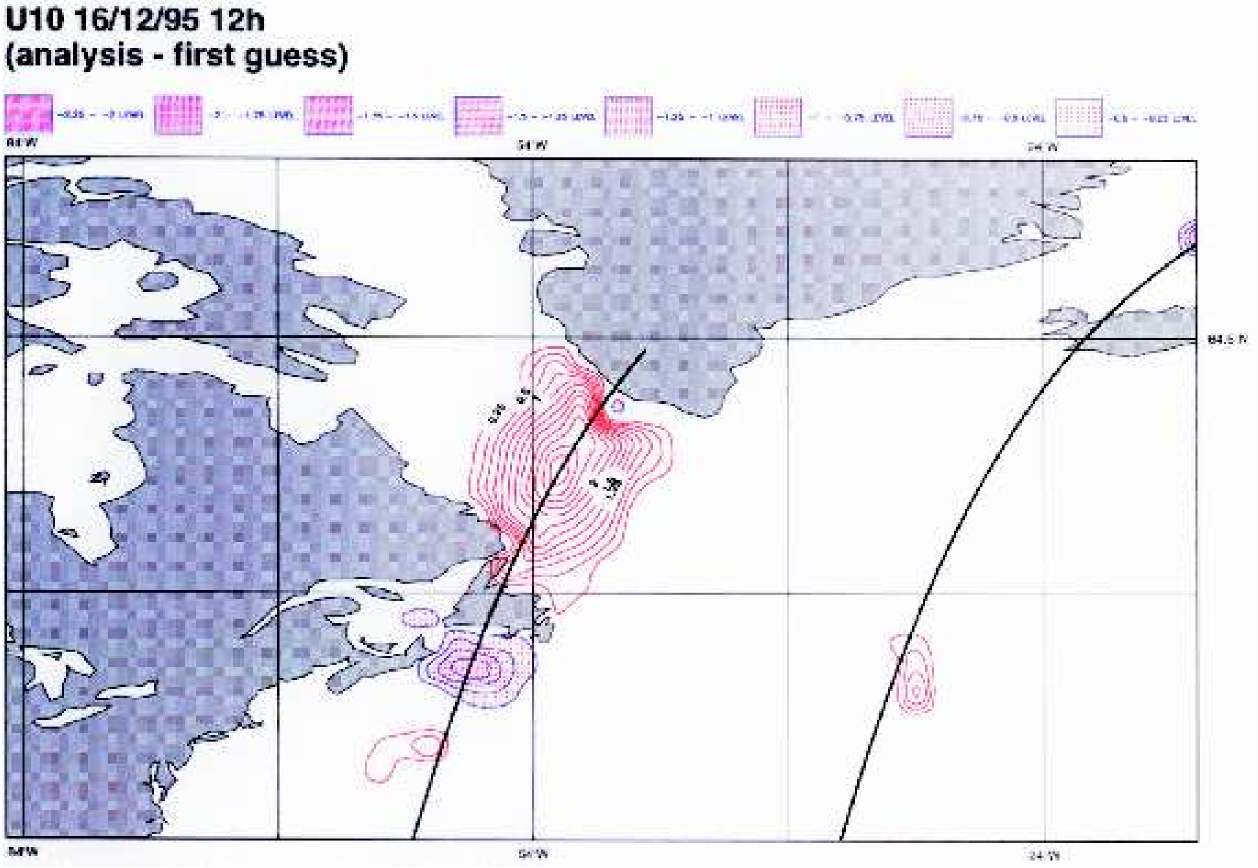
Results at ECMWF show that the impact of Altimeter data on wave analysis and forecast is **positive**. However, all this relies on the **quality** of the observations from the ESA Altimeters. For example, the ERS-2 Altimeter produced, when compared to buoy data, much better estimates of significant wave height than its predecessor ERS-1. This was immediately evident when the ERS-2 Altimeter was introduced on April 30 1996 (and the ERS-1 assimilation was switched off) as the analyzed wave height bias (compared to Buoy data) reduced considerably. Impact on **Reanalysis**.

In the next view graphs we show by way of an example that the **wind-wave analysis** scheme works well, producing when compared to the Altimeter winds, reasonable estimates of wind speed.

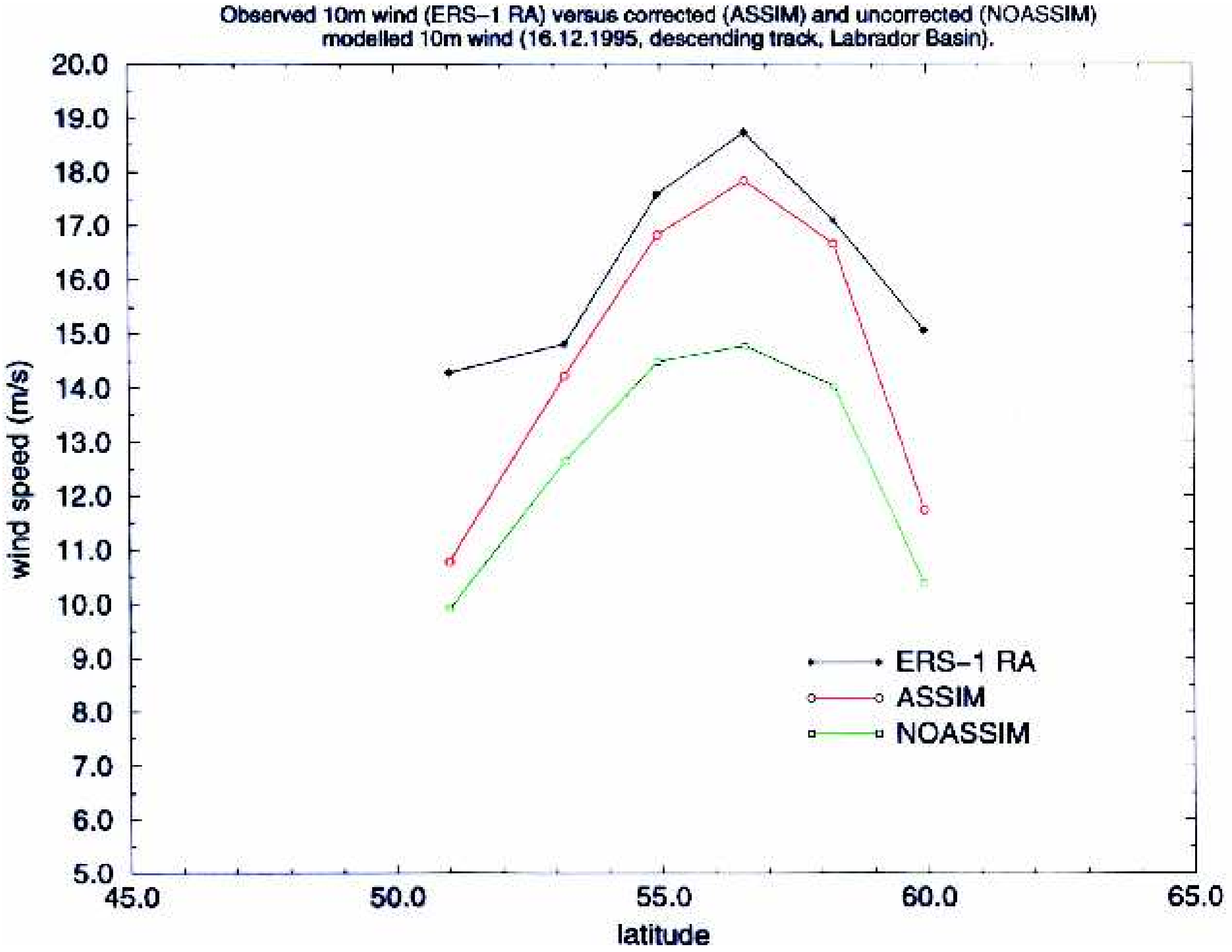
The importance of the **quality** of Altimeter wave height data is illustrated as well.



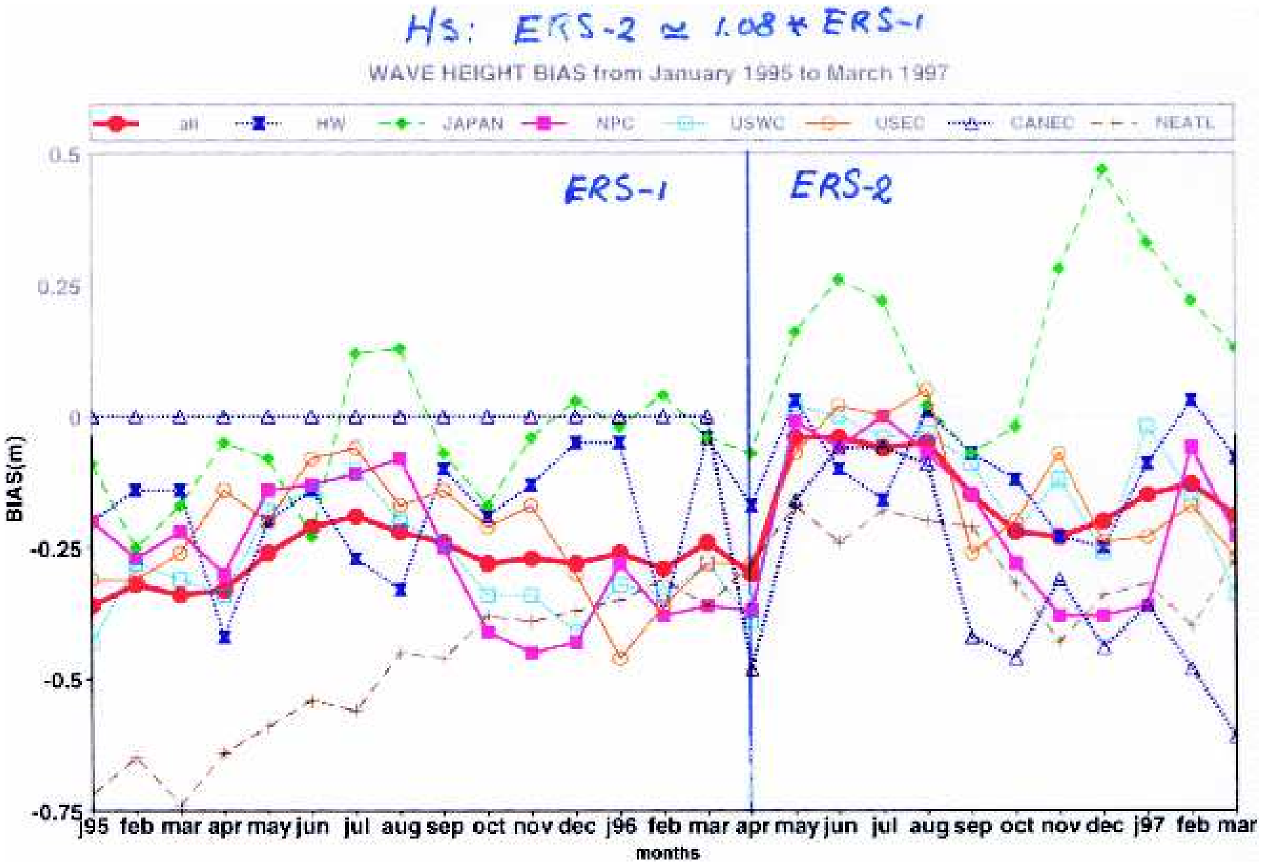
Wave height increments



Wind speed increments consistent with wave height increments



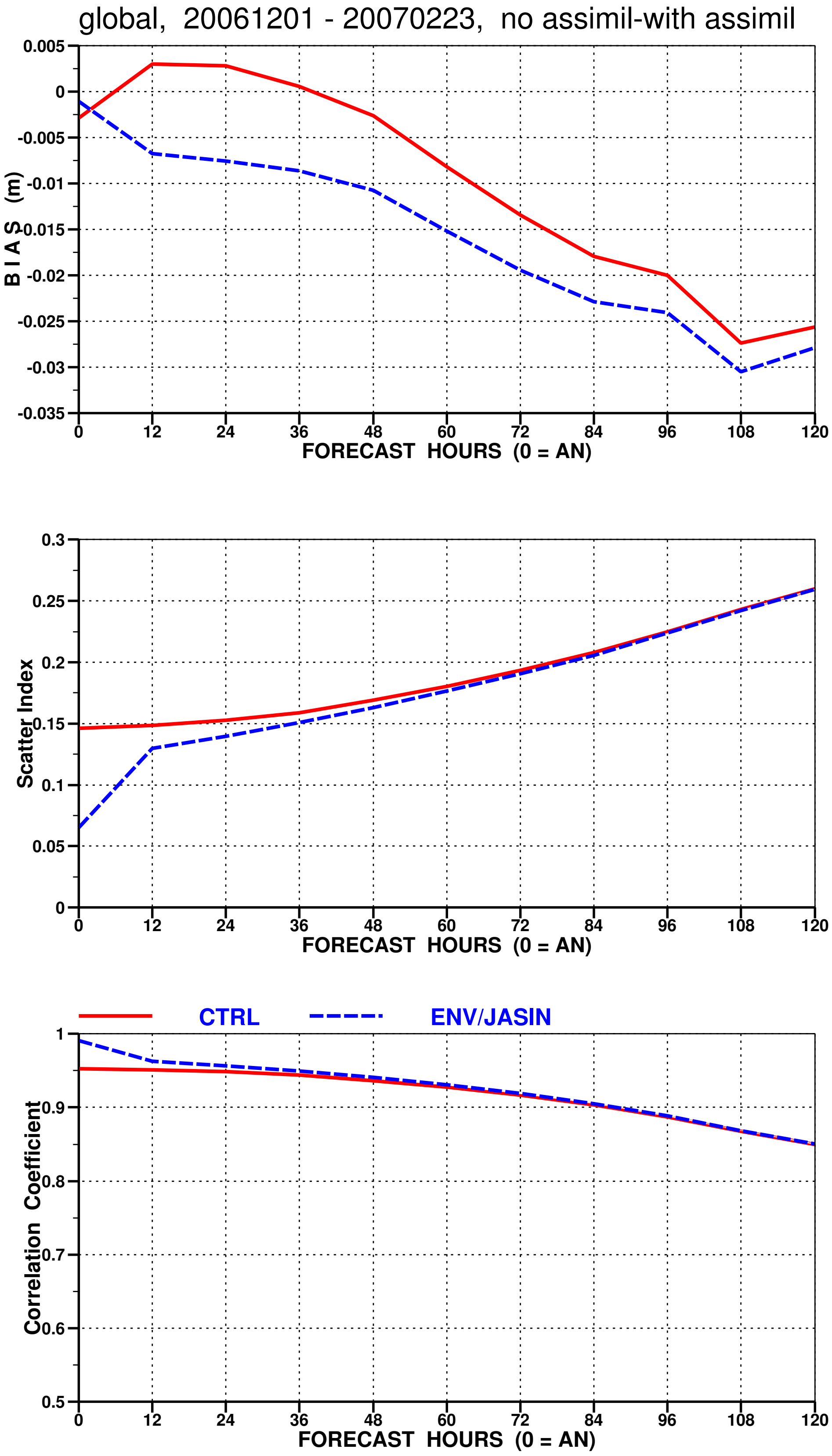
Validation of analyzed wind against Altimeter winds

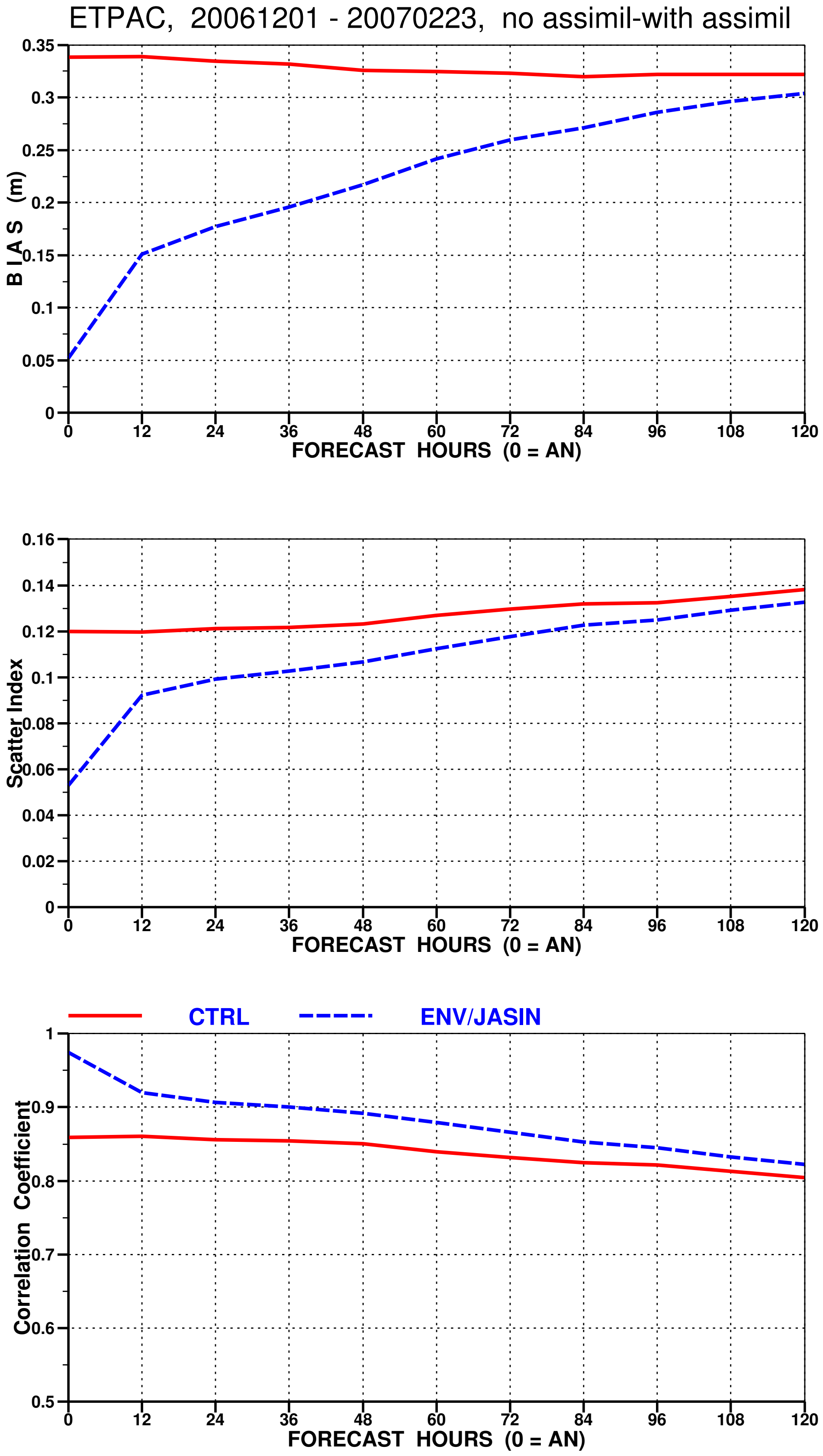


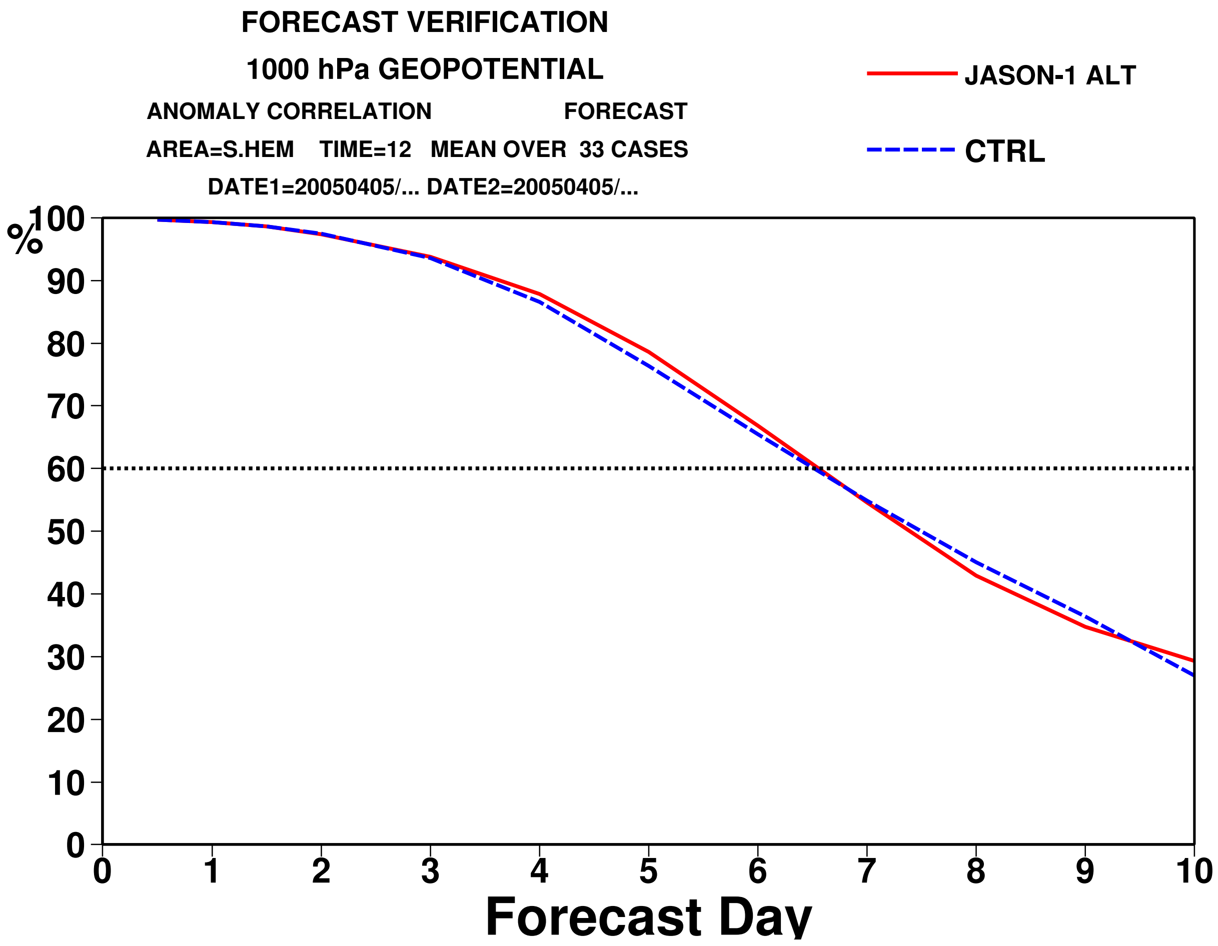
Importance of data quality as follows from validation of model against buoy data

IMPACT ON FORECAST

- Altimeter wave height data have a limited impact on **global** forecast skill, but in areas where **swell** is important impact on forecast is more substantial. This is shown over a three month period in the winter of 2006-2007 by verifying forecasts against ENVISAT altimeter wave height data.
- However, occasionally there is a systematic impact also in windsea cases on atmospheric scores. Note that ECMWF runs a coupled weather, ocean wave model where the roughness over the oceans is sea state dependent.


global, 20061201 - 20070223, no assimil-with assimil
B I A S (m)
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
-0.035
0
12
24
36
48
60
72
84
96
108
120
FORECAST HOURS (0 = AN)
Scatter Index
0.3
0.25
0.2
0.15
0.1
0.05
0
FORECAST HOURS (0 = AN)
CTRL
ENV/JASIN
Correlation Coefficient
1
0.9
0.8
0.7
0.6
0.5
FORECAST HOURS (0 = AN)


ETPAC, 20061201 - 20070223, no assimil-with assimil
B I A S (m)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
12
24
36
48
60
72
84
96
108
120
FORECAST HOURS (0 = AN)
Scatter Index
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
FORECAST HOURS (0 = AN)
CTRL
ENV/JASIN
Correlation Coefficient
1
0.9
0.8
0.7
0.6
0.5
FORECAST HOURS (0 = AN)


FORECAST VERIFICATION
1000 hPa GEOPOTENTIAL
ANOMALY CORRELATION
FORECAST
AREA=S.HEM
TIME=12
MEAN OVER 33 CASES
DATE1=20050405/... DATE2=20050405/...
JASON-1 ALT
CTRL
%
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
Forecast Day

SYNTHETIC APERTURE RADAR DATA

MEASUREMENT PRINCIPLE

The Synthetic Aperture Radar (SAR) measures the modulation of short waves (observed by Bragg scattering) by long gravity waves, slicks, internal waves, currents, etc.

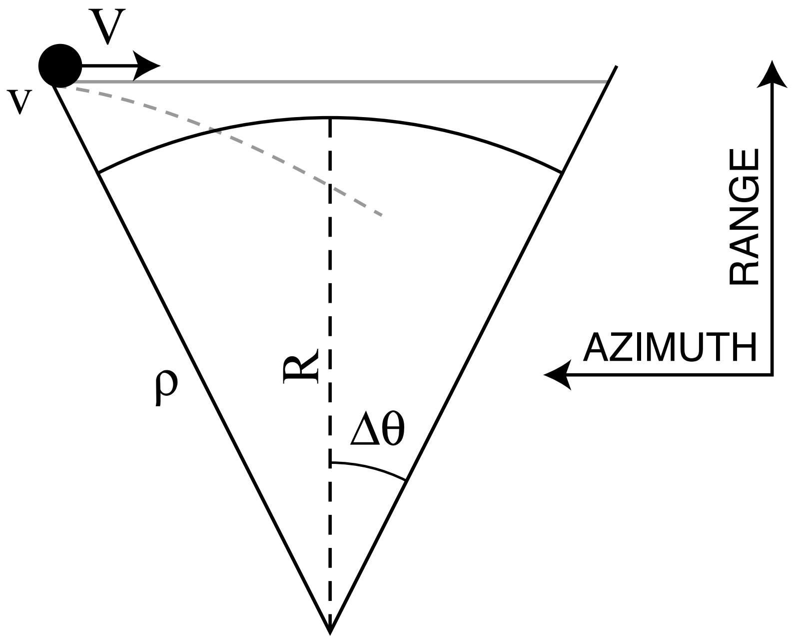
The SAR inversion scheme of Hasselmann and Hasselmann considers three types of **modulation**

- tilt modulation.
- hydrodynamic modulation (refraction caused by orbital motion of long waves.
- velocity bunching: phase information distorted by long wave orbital motion.

As a consequence, the **SAR image spectrum** is a nonlinear function of the wave spectrum. Inversion requires a reliable, accurate first-guess spectrum. The MPI inversion algorithm, operational at ECMWF uses as first-guess the appropriate model wave spectrum.

Velocity bunching.

A SAR scans the modulated backscatter field $I_R(\vec{x}, t)$ in the range (across-track) direction and achieves spatial resolution of the order of 10 m, but in the azimuth (along-track) direction resolution is poor. In order to improve on this the SAR uses phase information to locate the azimuthal position of the backscattering element: the facet is located at **zero Doppler shift**.



Definition sketch of the velocity bunching problem with a SAR.

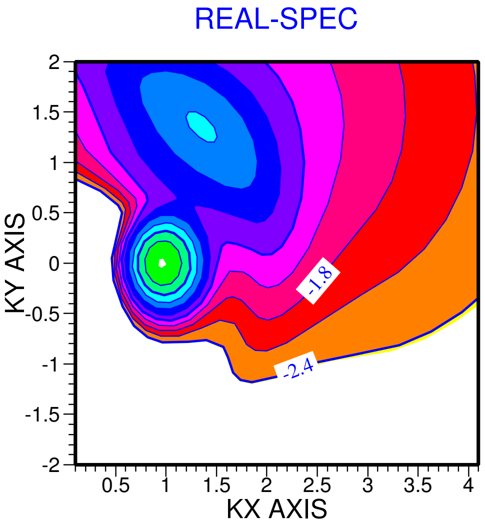
This localization in azimuth works very well for stationary objects, but when an facet resides on a moving surface with range component of the orbital velocity v, then there is an additional Doppler shift, and hence the SAR positions the object in the wrong location. The corresponding azimuthal displacement $\xi(\vec{x})$ at a location $\vec{x}$ is then given by

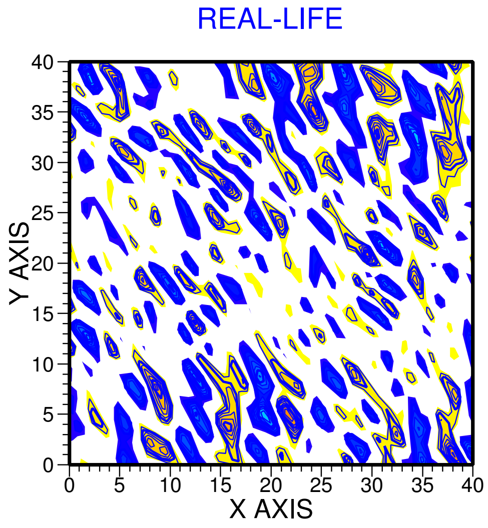
$$\xi(\vec{x}) = \beta v, \ \beta = R/V = \mathcal{O}(100)$$

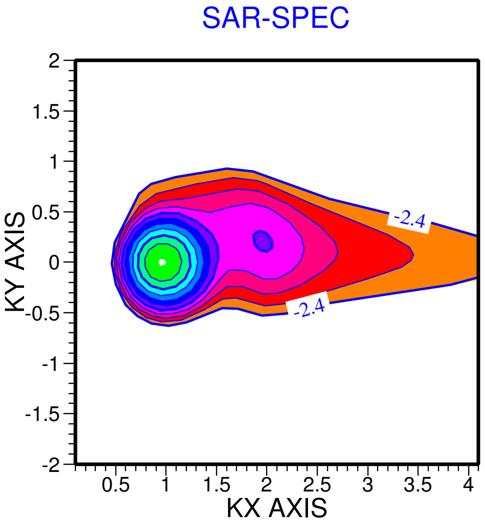
Because β is large this results in displacements of the order of 200 m.

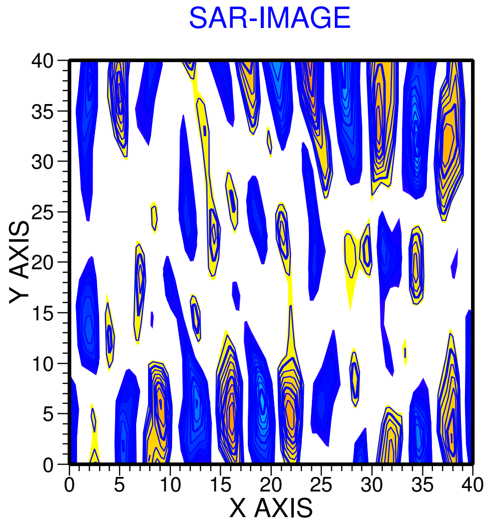
The velocity bunching effect leads to considerable distortions of the actual surface wave spectrum $F(\vec{k})$ as observed by a SAR. In the so-called quasi-linear approximation one finds for the SAR spectrum $F_{SAR}(\vec{k}) =$

$$F_{SAR}(\vec{k}) = \exp(-\beta^2 \langle v^2 \rangle k_y^2) \times F(\vec{k})$$


REAL-SPEC


REAL-LIFE


SAR-SPEC


SAR-IMAGE

ANALYSIS METHOD

Assume that we have given a SAR spectrum which is obtained from the SAR image spectrum using the first-guess WAM model spectrum.

The method to assimilate SAR data proceeds as follows:

- Identify a number of **dominant wave systems** in the SAR spectrum and in first-guess and label these by means of energy, mean direction and peak frequency.
- Apply the **scaling laws**

  $$F_{an}(f,\theta) = AF_{fg}(Bf, \theta + \Delta\theta),$$

  with $B = f_{p,an}/f_{p,fg}$ and $A = BE_{an}/E_{fg}$ but now to each wave system.
- For the **windsea system** infer analysed wind speed by means of scaling law between energy and wave age.

RESULTS

According to the literature (Breivik et al, 1997; Dunlop et al, 1998) impact of SAR data on analysis is relatively small. After a lot of work Jean Bidlot found a somewhat larger impact.

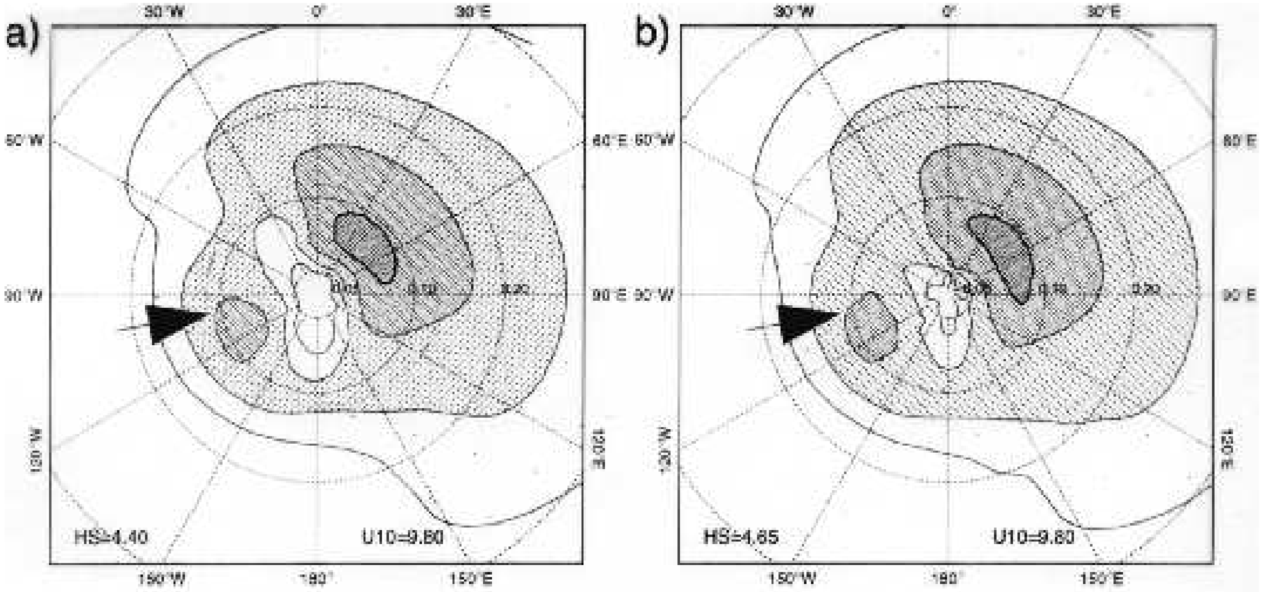
One reason for the small impact on wave height is probably the relative **abundance** of Altimeter wave height data. Also, results depend on how in the inversion scheme the SAR data are **calibrated**. Comparison of SAR and buoy spectra (Voorrips et al, 2001) suggests that this calibration has not always been optimal in the past.

To illustrate the impact of SAR data we quote statistics from an experiment for February 1998, where all results are compared with buoy data. Note that more recent experiments have shown a less favourable impact for SAR data.

EXP	rms (m)	Bias (m)	SI(%)
REF	0.583	-0.285	0.167
SAR	0.531	-0.224	0.158
ALT	0.537	-0.191	0.165
ALT+SAR	0.510	-0.177	0.157

Table 1: Scores for H_S ($N = 5560$) for February 1998. REF is the reference run (a hincast), SAR means only SAR assimilation, ALT means only Altimeter assimilation and ALT+SAR means assimilating both data.

Viewgraphs show example of an inversion, and a comparison of analysis increments from SAR and Altimeter assimilation



Results after 1st iteration:
a) First guess spectrum used in the inversion system.
b) Inverted SAR spectrum.

Fig shows example of inversion

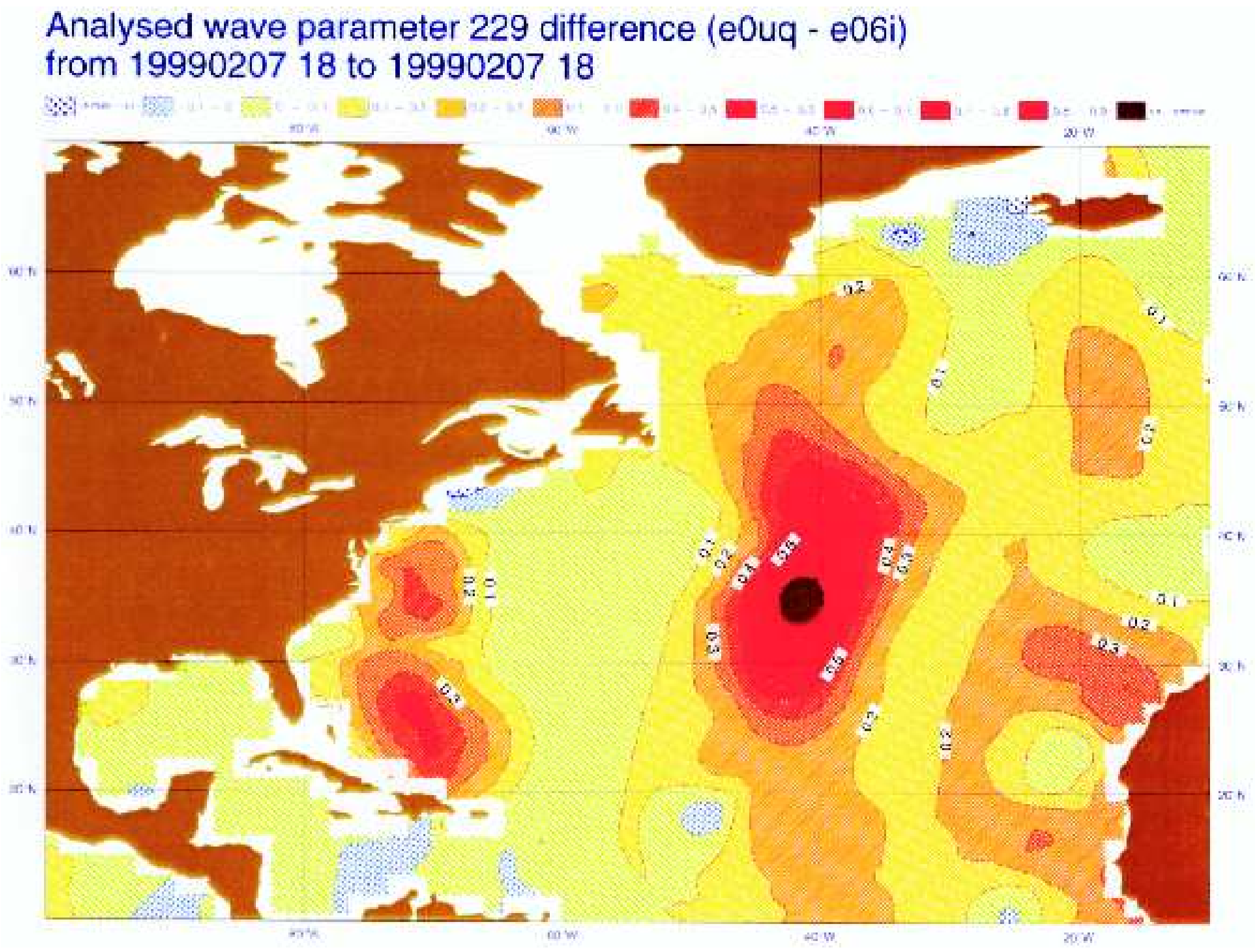
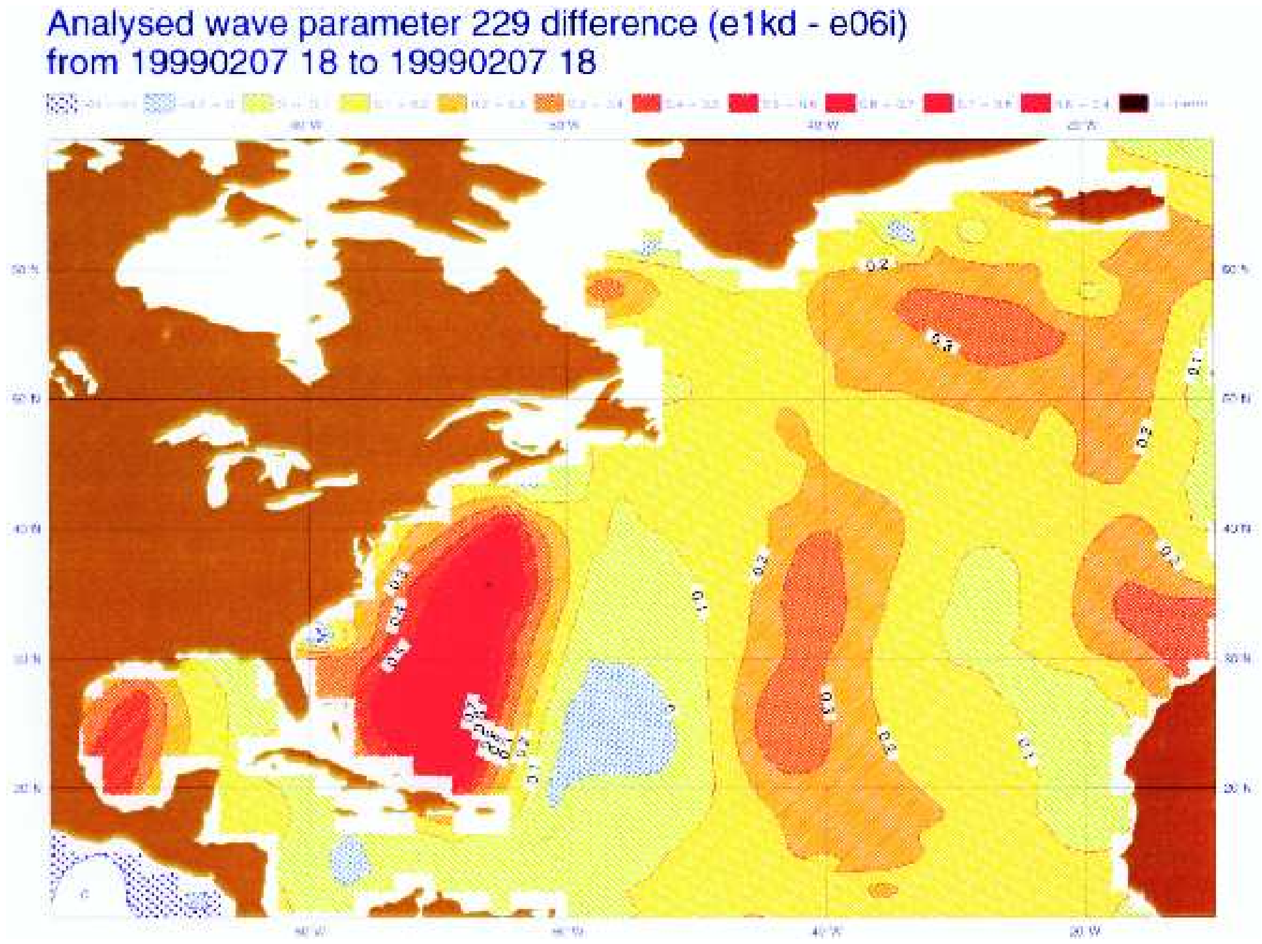


Fig shows analysis increments due to SAR data



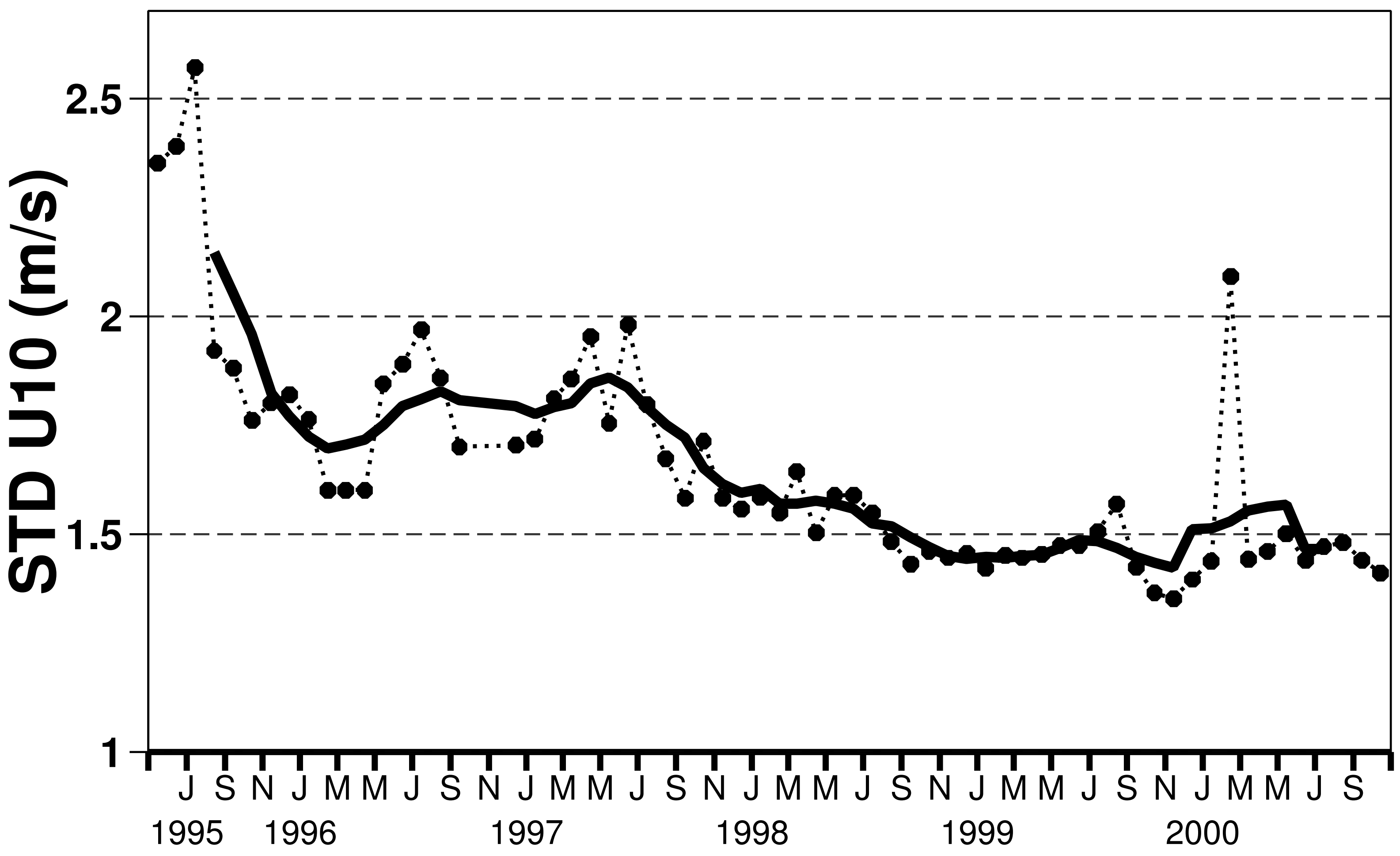
Analysed wave parameter 229 difference (e1kd - e06i)
from 19990207 18 to 19990207 18

Fig shows analysis increments due to Altimeter data

ALTIMETER WIND SPEED DATA

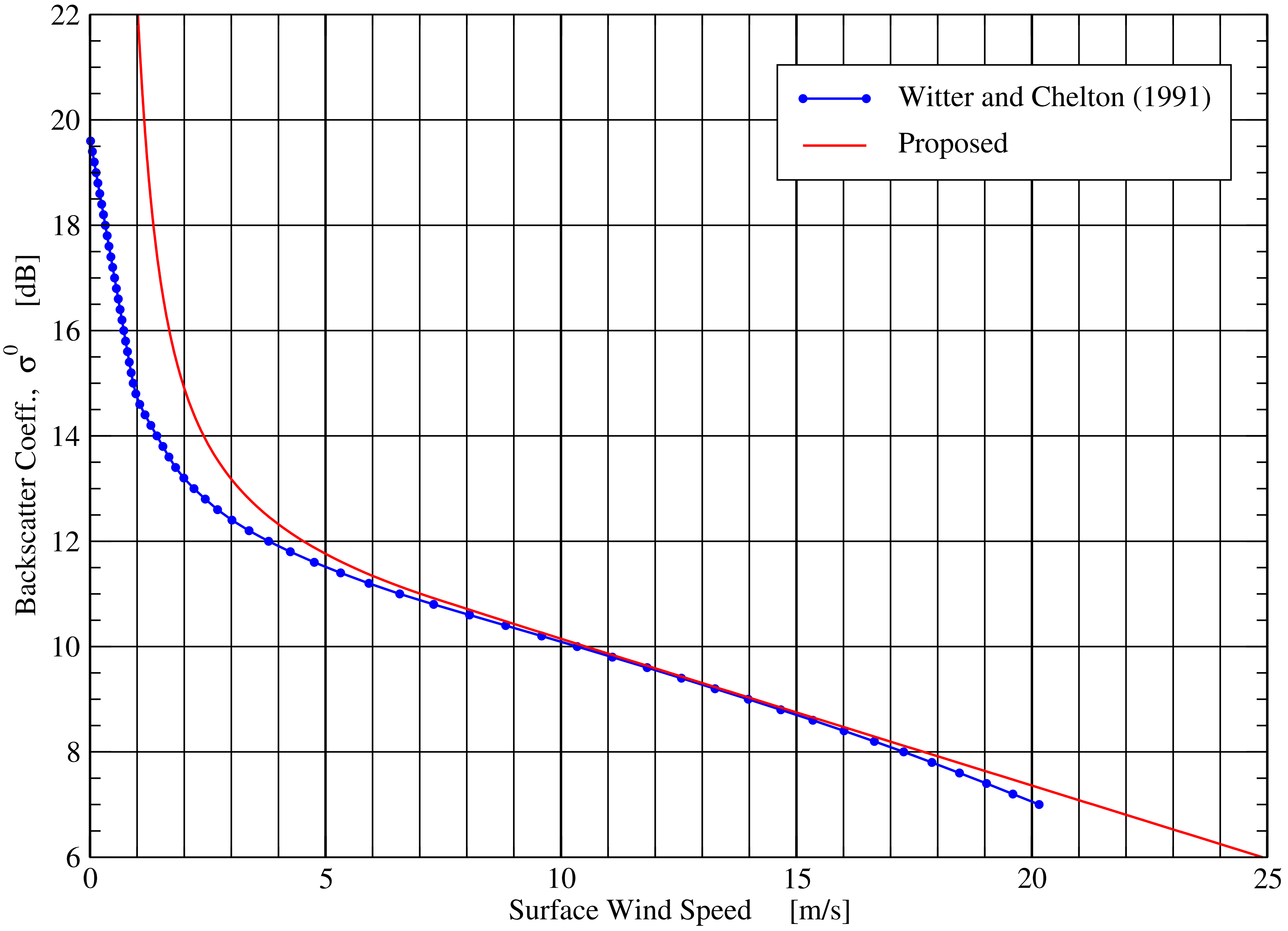
We do not assimilate altimeter wind speed data in our atmospheric model, but we rather use these (independent) data to **monitor** the quality of the modelled surface wind speeds.

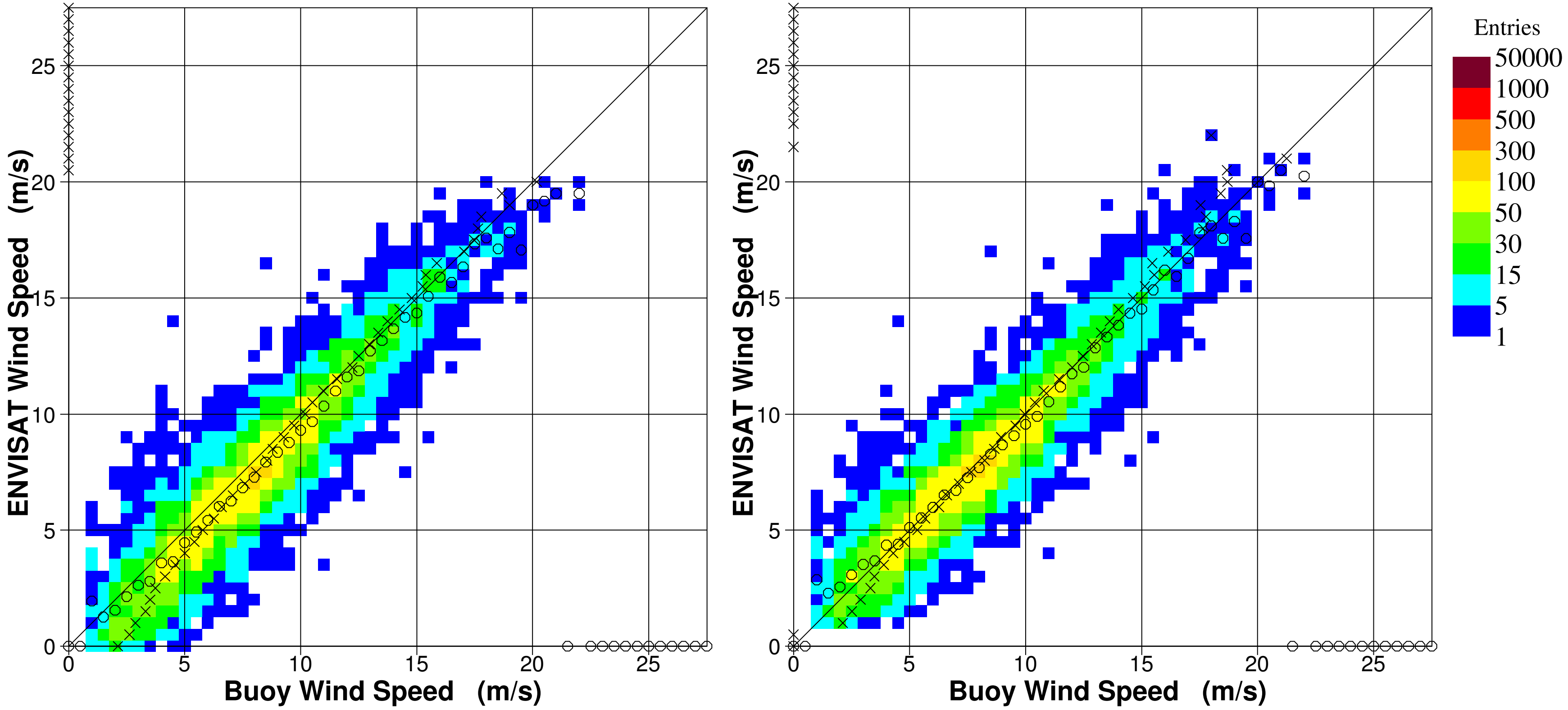
- Improvements in modelled winds and waves


STD U10 (m/s)
2.5
2
1.5
1
J
S
N
J
M
M
J
S
N
J
M
M
J
S
N
J
M
M
J
S
N
J
M
M
J
S
N
J
M
M
J
S
1995
1996
1997
1998
1999
2000

Nevertheless, there are problems for the low wind speed range.

Abdalla (2007) found based on the assumption that σ_0 only depends on the surface wind speed U_{10} (hence **no sea state effects**) a very satisfactory solution. A fit was made using collocated model wind speed data and buoy winds.


Backscatter Coeff., σ^0 [dB]
22
20
18
16
14
12
10
8
6
0
5
10
15
20
25
Surface Wind Speed [m/s]
Witter and Chelton (1991)
Proposed

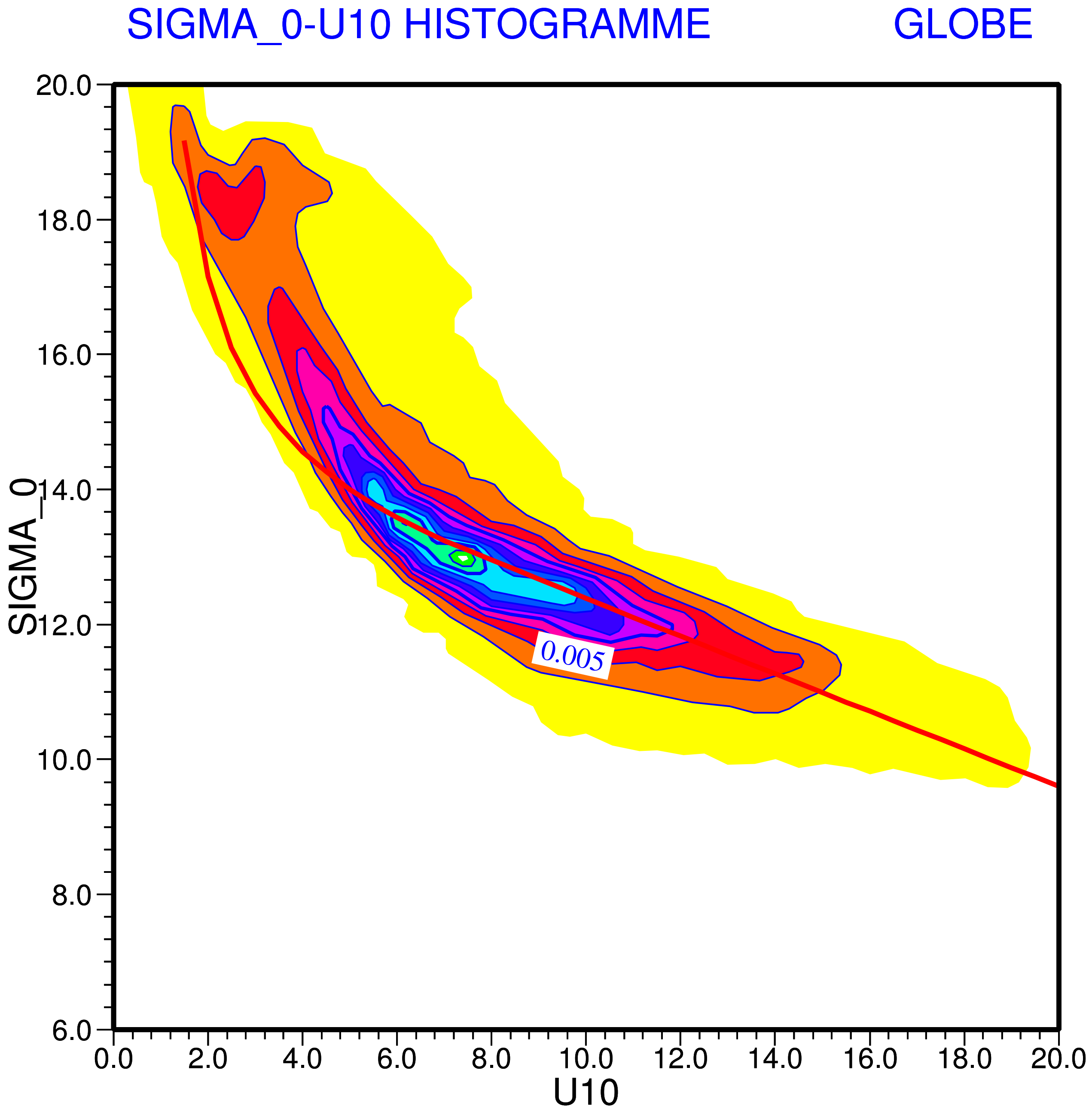

ENVISAT Wind Speed (m/s)
Buoy Wind Speed (m/s)
0
5
10
15
20
25
ENVISAT Wind Speed (m/s)
Buoy Wind Speed (m/s)
0
5
10
15
20
25
Entries
50000
1000
500
300
100
50
30
15
5
1

According to **theory**:

$$\sigma_0 = \frac{|R(0)|^2}{s^2}$$

We have made our own 'physical' wind speed algorithm that uses the mean square slope s^2 from the wave model. The high-wavenumber part of the spectrum is obtained from the **VIERS** model (includes wind input, nonlinear 3-wave interactions and dissipation).

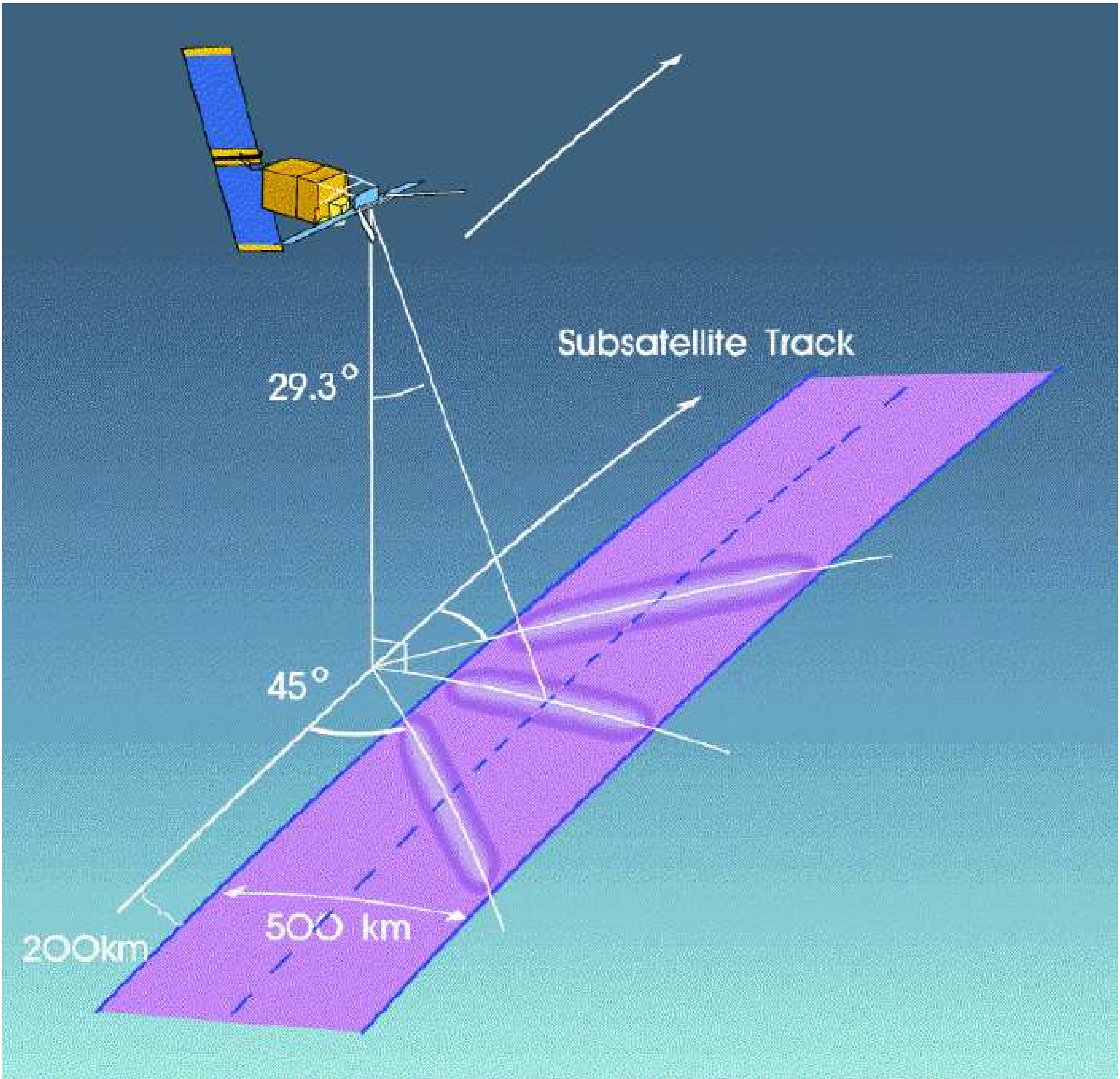
The 'physical' wind speed algorithm shows good agreement with the Abdalla fit (corrected by 2.24 dB to refer to absolute backscatter), therefore σ_0 depends on the sea state. However, since the mean square slope is largely determined by the high-wavenumber part of the spectrum, σ_0 highly correlates with the surface wind speed.


SIGMA_0-U10 HISTOGRAMME
GLOBE
SIGMA_0
U10
0.005
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0

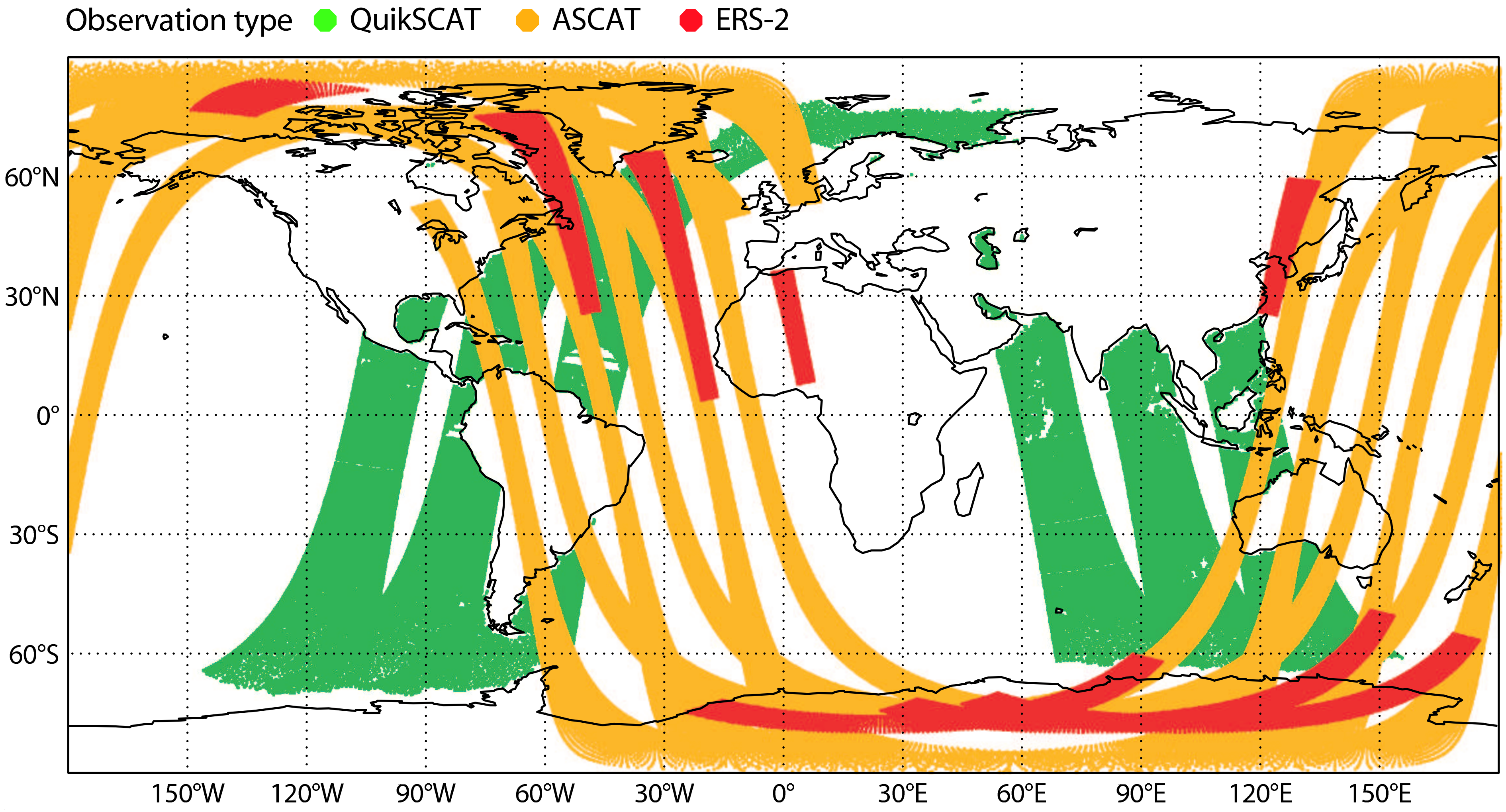
SCATTEROMETER WINDS

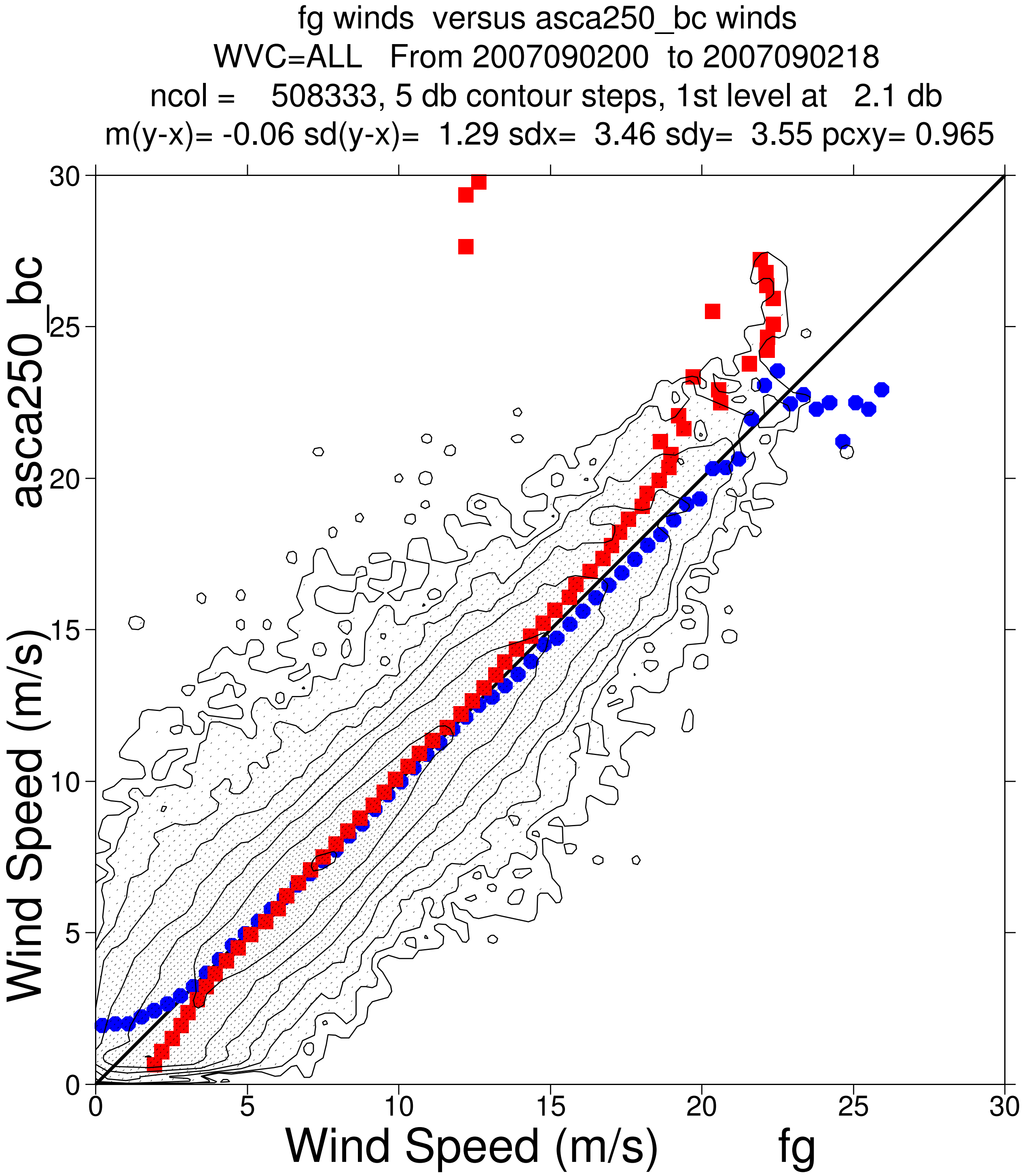
Scatterometer winds follow from the same physical principle as the SAR images, i.e. Bragg Scattering, but rather than looking at the modulations in the backscatter, one records the average backscatter over an area of say 25×25 km..

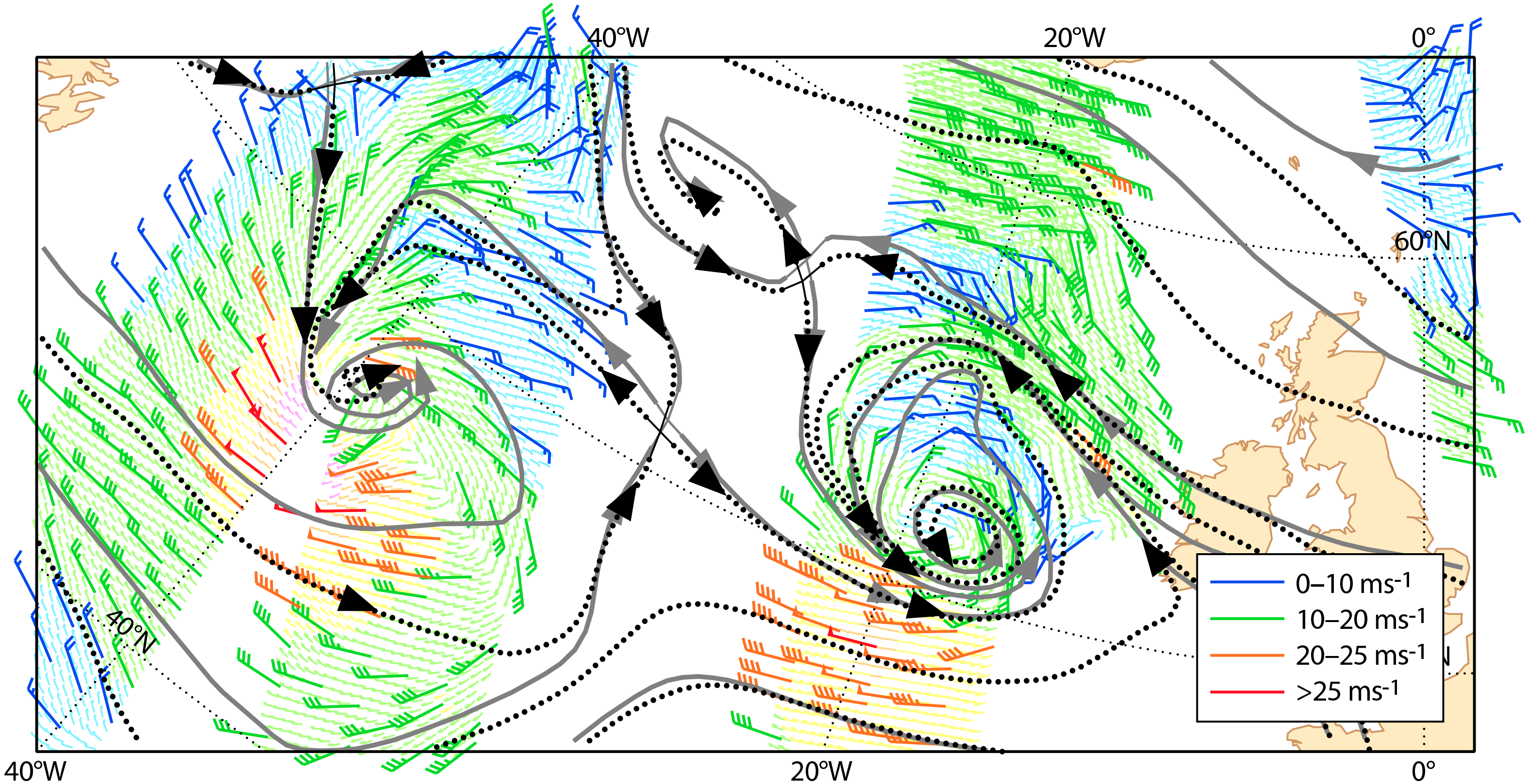
Recently, ASCAT data were introduced in the operational analysis, after assessing the quality of the observed winds against the model's first-guess and after an impact study. In operations, improvements were immediately evident after a comparison with Altimeter winds (**Synergy**).

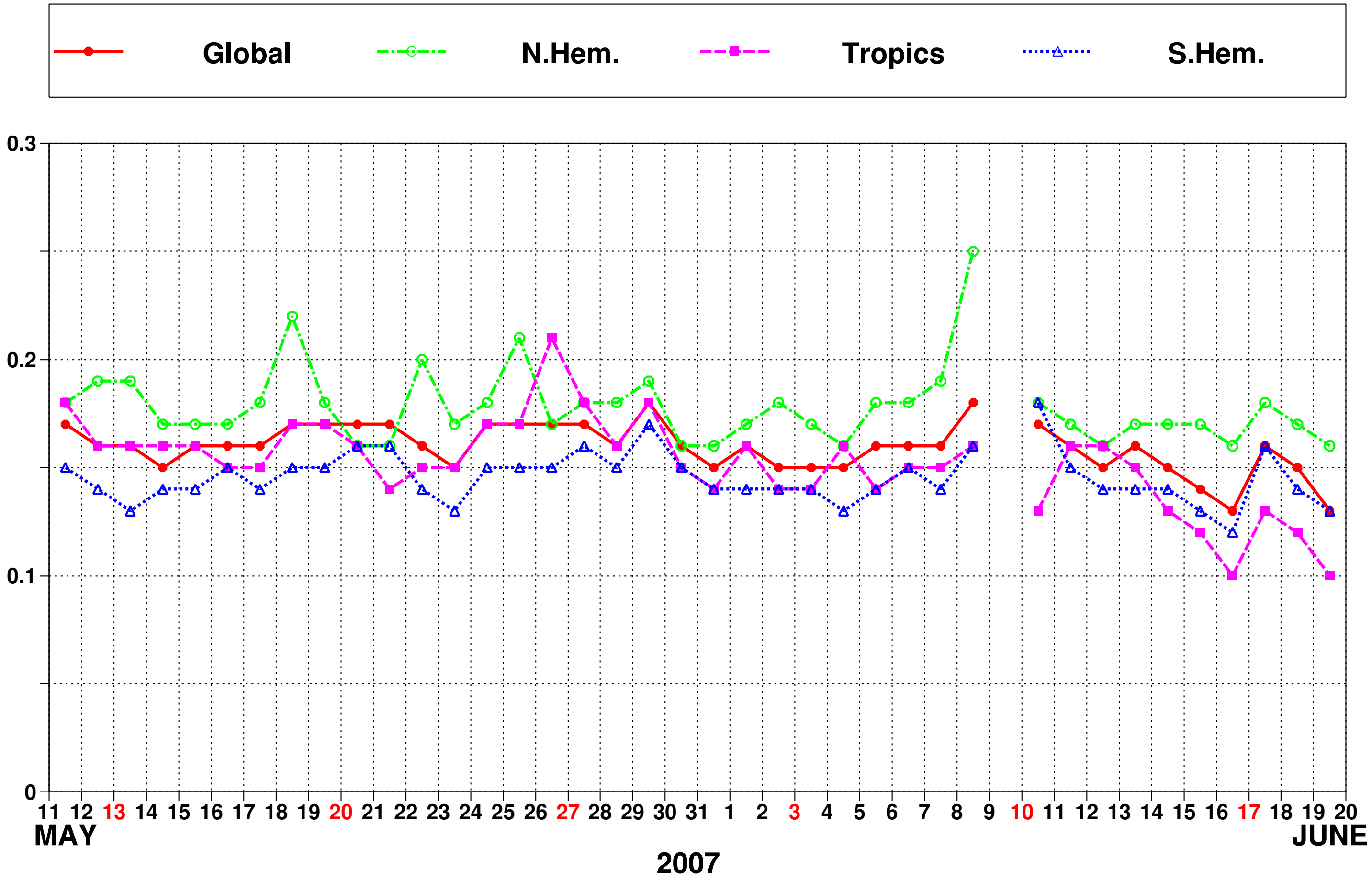


Radar geometry for the Wind Scatterometer.


Observation type
● QuikSCAT
● ASCAT
● ERS-2
60°N
30°N
0°
30°S
60°S
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E


fg winds versus asca250_bc winds
WVC=ALL From 2007090200 to 2007090218
ncol = 508333, 5 db contour steps, 1st level at 2.1 db
m(y-x)= -0.06 sd(y-x)= 1.29 sdx= 3.46 sdy= 3.55 pcxy= 0.965
Wind Speed (m/s) asca250_bc
Wind Speed (m/s) fg
0
5
10
15
20
25
30


40°W
20°W
0°
60°N
40°N
40°W
20°W
0°
0–10 ms^{-1}
10–20 ms^{-1}
20–25 ms^{-1}
>25 ms^{-1}



ENVISAT Radar Altimeter wind Wind Speeds: Timeseries of scatter Index (SI) (analysis)

CONCLUSIONS

- Altimeter wave height data and SAR spectral data are of high quality, producing an **accurate** surface wave analysis, while Scatterometer data, in particular ASCAT data, have considerable value for the surface wind analysis (and even in the upper layers of the atmosphere).
- Altimeter wave height and wind speed data have tremendous value for **diagnosing** wave model problems and problems with the model surface winds
- Recently it was shown that using only wave model information a realistic representation of specular reflection from the ocean surface may be given. This implies that wave model information will be of value in specifying the **ocean surface albedo** and it will be of value in the interpretation of other satellite sensors such as scatterometer, ATOVS, SSM/I.