Wave forecasting at ECMWF

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INTRODUCTION

I will briefly discuss progress in ocean wave forecasting at ECMWF during the past 10 years or so, by studying verification results of **forecast** wave height against verifying analysis, buoy data and Altimeter data. The quality of the **analysis** is judged by verification against independent buoy data for wave height and wave spectrum.

- considerable improvement in forecasting parameters such as H_S and T_p.
- large improvements in the wave model, but main reason is better quality of analyzed and forecast **wind**.

I will close the talk with a discussion of a new topic, namely the prediction of extreme events, such as for example freak waves.

The programme of the talk is as follows.

- **Laws of ocean wave forecasting**

  Ocean wave forecasting is about forecasting of the mean sea state in a grid box. The fundamental evolution equation for the wave spectrum is the **energy balance equation**. Recently, it is realized that also fluctuations around the mean can be predicted as they depend on the mean sea state.

- **Verification** Discuss validation of forecast against own analysis and buoy data. Quantify accuracy of analysis.

- **Wave Model Improvements** Wave model improvements are important, of course, but the major improvement of ocean wave forecasting skill comes from improved surface winds.

- **Forecasting Extreme Sea States**: On the open ocean extreme waves are generated by **nonlinear focussing**, a four-wave interaction process that also causes the Benjamin-Feir Instability. Theoretical developments in the past 10 years enable us to obtain, for given wave spectrum, the **probability distribution function (pdf)** of the wave height for surface gravity waves. In other words we can make statements about the probability of occurence of freak waves.

  An operational freak wave prediction scheme was introduced in October 2003, but extensive validation in the field is still required.

Forecasting of the mean sea state

Ocean waves obey a set of **deterministic** evolution equations. For operational forecasting, solving these equations is not practical because, apart from the initial amplitudes, knowledge of the phase of the waves is required. This information is not available. Furthermore, just as in the atmospheric problem, there is chaotic behaviour.

Therefore, consider the evolution of the **mean sea state** in a box with width $\Delta\vec{x}$ at location $\vec{x}$. The ensemble average is essentially an average over the phases of the waves.

The mean sea state is then given by the wavenumber spectrum $F(\vec{k};\vec{x},t)$, while the action density spectrum $N(\vec{k};\vec{x},t)$ is defined as

$$N = \frac{gF}{\sigma}$$

with $\sigma = \sqrt{gk\tanh(kD)}$. The action density is the number density of waves, hence the energy E of the waves is given by $E = \sigma N$, while the wave momentum $\vec{P}$ is given by $\vec{P} = \vec{k}N$.

Averaging the deterministic evolution equations then gives for waves on a slowly varying current $\vec{U}$ the energy balance equation

$$\frac{\partial N}{\partial t} + \nabla_{\vec{x}}.(\nabla_{\vec{k}}\Omega N) - \nabla_{\vec{k}}.(\nabla_{\vec{x}}\Omega\ N) = S.$$

Here, Ω represents the dispersion relation

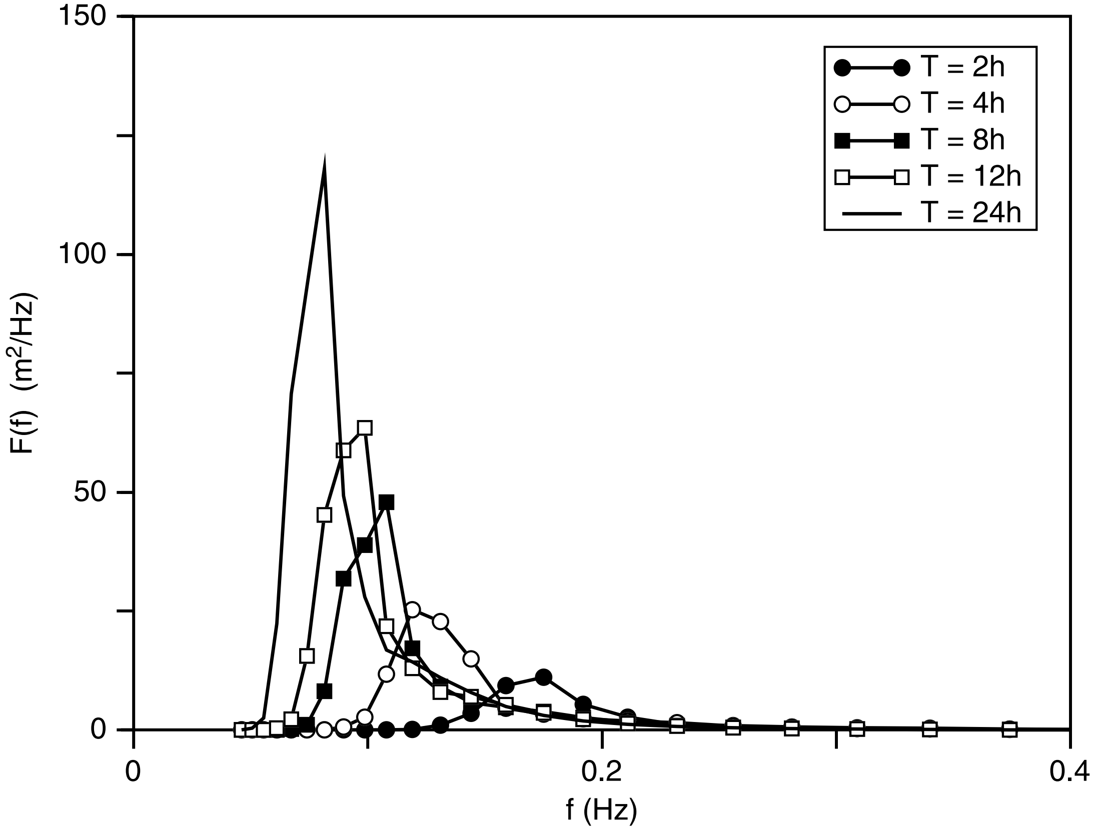
$$\Omega = \vec{k}.\vec{U} + \sigma,$$

The source function S on the right hand side represents the physics of wind-wave generation (S_{in}), dissipation by wave breaking and other causes (S_{dissip}) and four-wave interactions (S_{nonlin}). In other words,

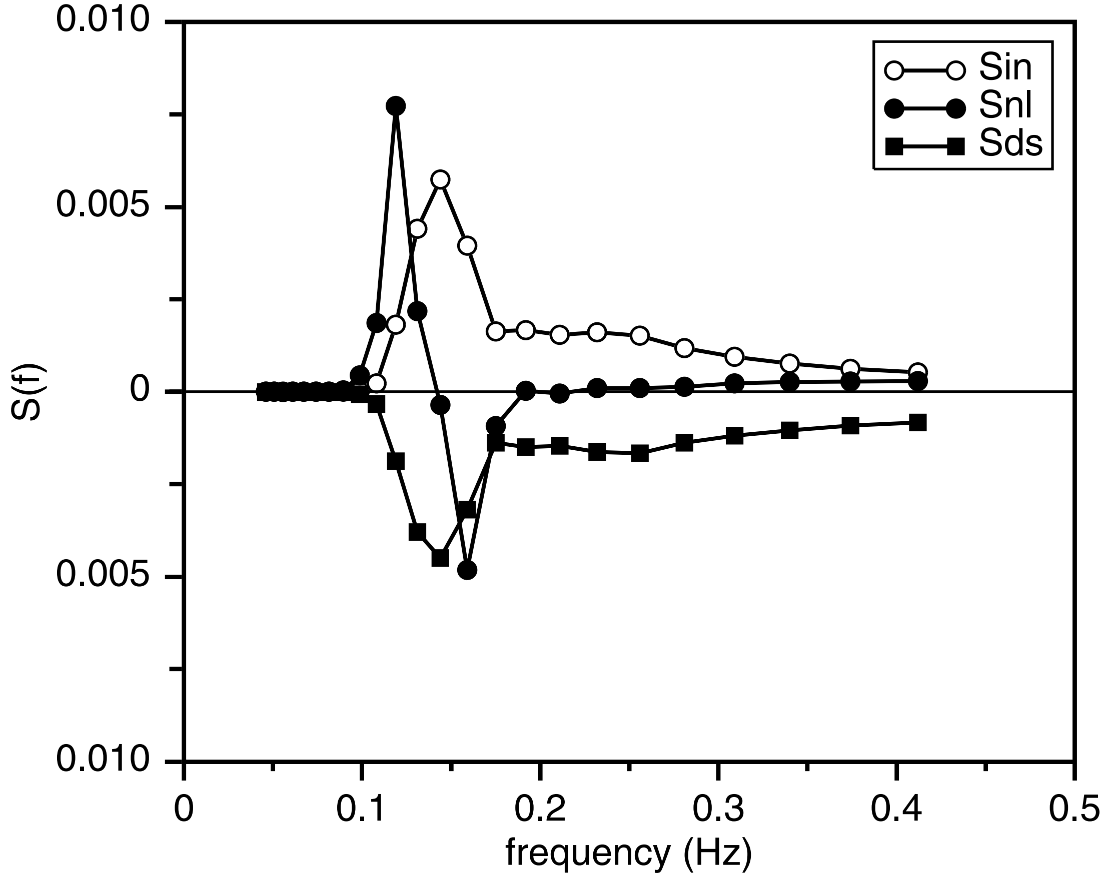
$$S = S_{in} + S_{nonlin} + S_{dissip}.$$

In the 1980's there was a dedicated effort to develop efficient parametrisations of all the source functions, which still is the basis of present day wave forecasting and the two-way interaction of ocean waves and atmosphere.

- Time evolution of the wave spectrum and source function balance.



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 4 hrs, and a wind speed of 18 m/s.

Operational Configuration

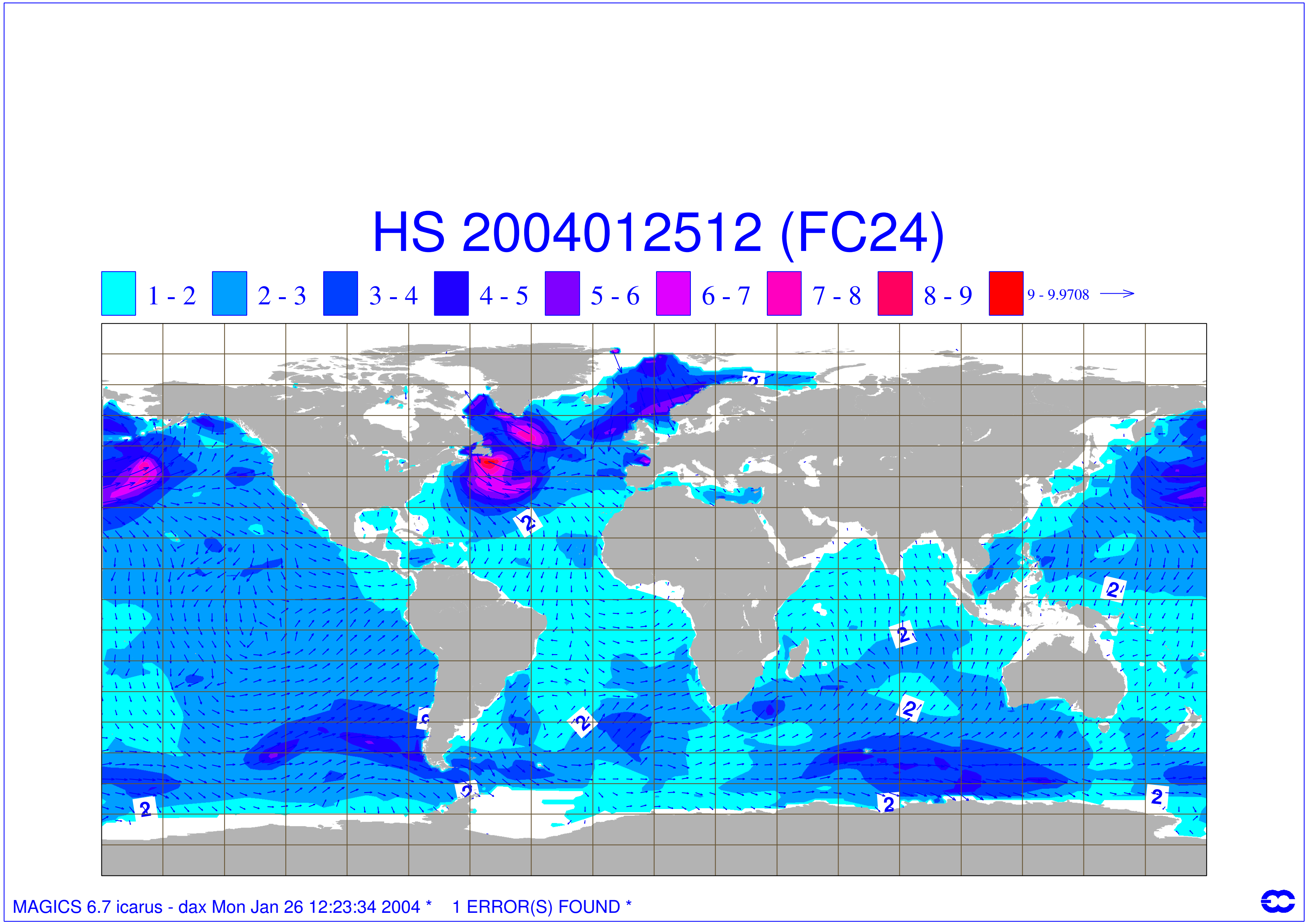
Ocean wave forecasting at ECMWF is based on WAM cy4. Discuss global implementation only.

GLOBAL MODEL (81 deg S to 81 deg N)

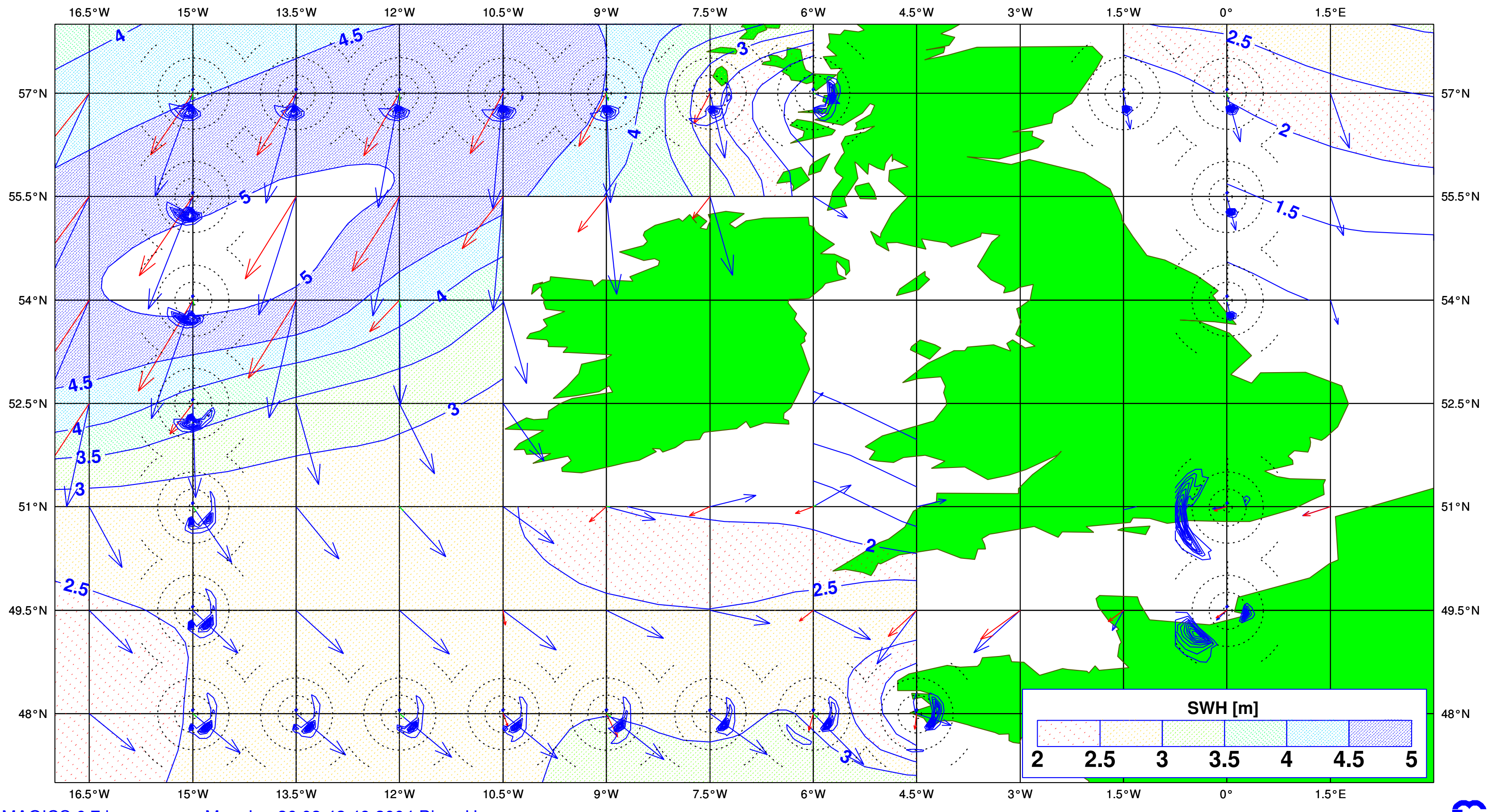
coupled to atmospheric model [two-way interaction with feedback of ocean waves on ocean surface roughness (since June 29, 1998) thus giving a sea-state dependent momentum and heat flux]

- **Deterministic forecasts**:

  $F(f, \theta)$ has 30 frequencies and 24 directions runs on an irregular lat-lon grid, $\Delta x = 55$ km. assimilation of ENVISAT Altimeter H_S and ERS-2 SAR spectra. 10 day forecasts from 00Z and 12 Z. coupled to 10 m winds from T_l511 ATM model every timestep $\Delta t = 15$ min.


HS 2004012512 (FC24)
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 - 9.9708
2
MAGICS 6.7 icarus - dax Mon Jan 26 12:23:34 2004 * 1 ERROR(S) FOUND *

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

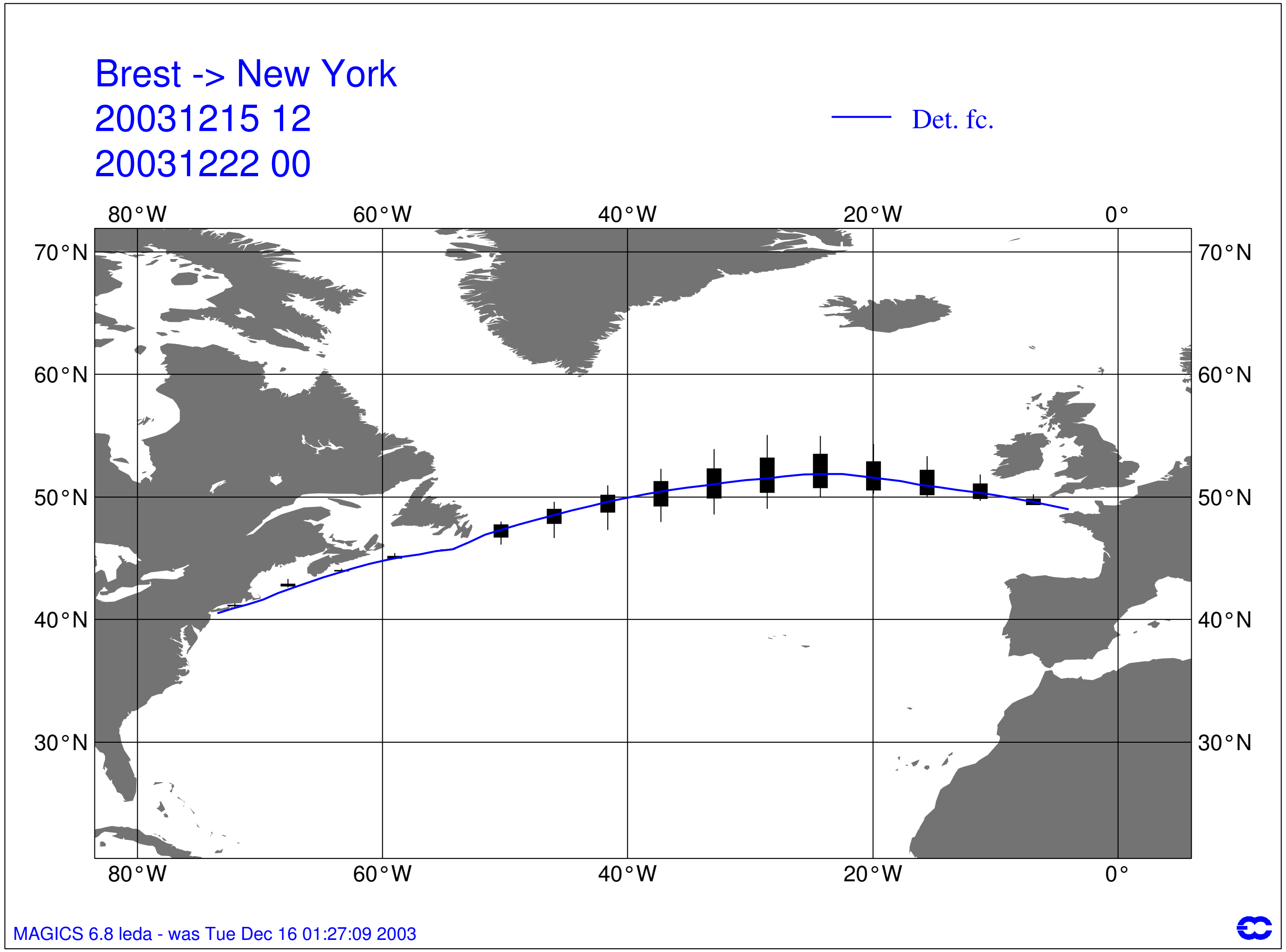


MAGICS 6.7 icarus - waa Mon Jan 26 03:42:49 2004 Bjorn Hansen

- **Probabilistic Forecasts** :

  (50+1) 1 deg $\times$1 deg 10-day wave ensemble forecasts coupled to the 10 m winds from the T_l255 ATM model.

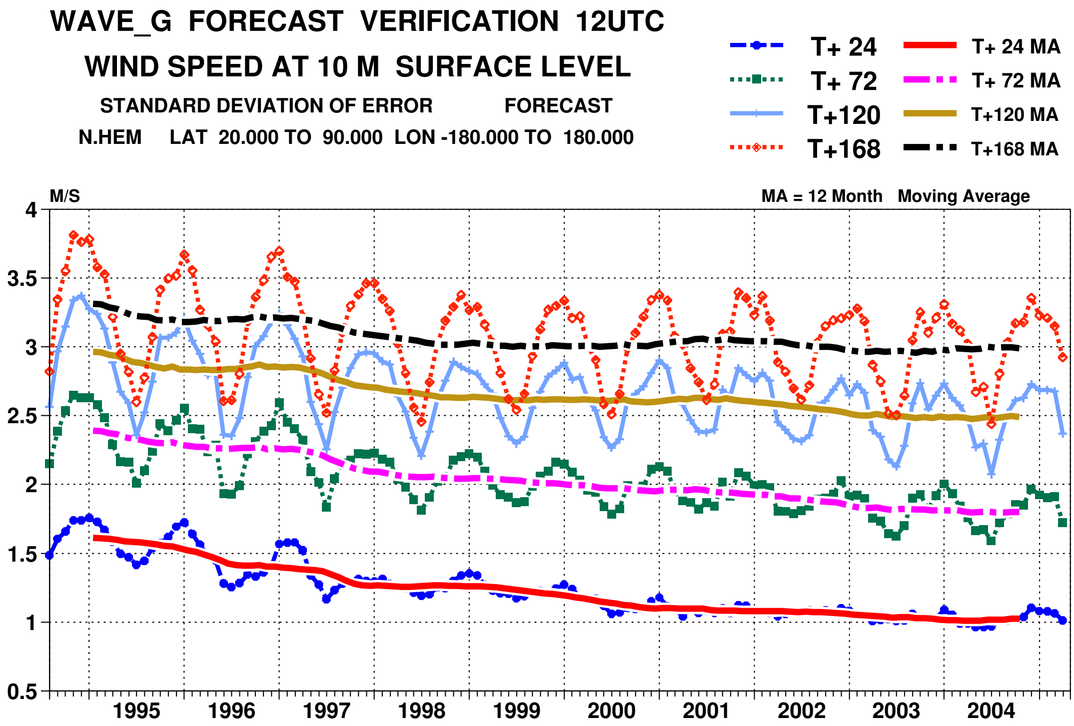
  Potential use: Probability of high sea state and Ship Routing. For example, error in forecast ship route may be obtained from the 50 shiproutes generated by the winds and waves of the 50 member ensemble.

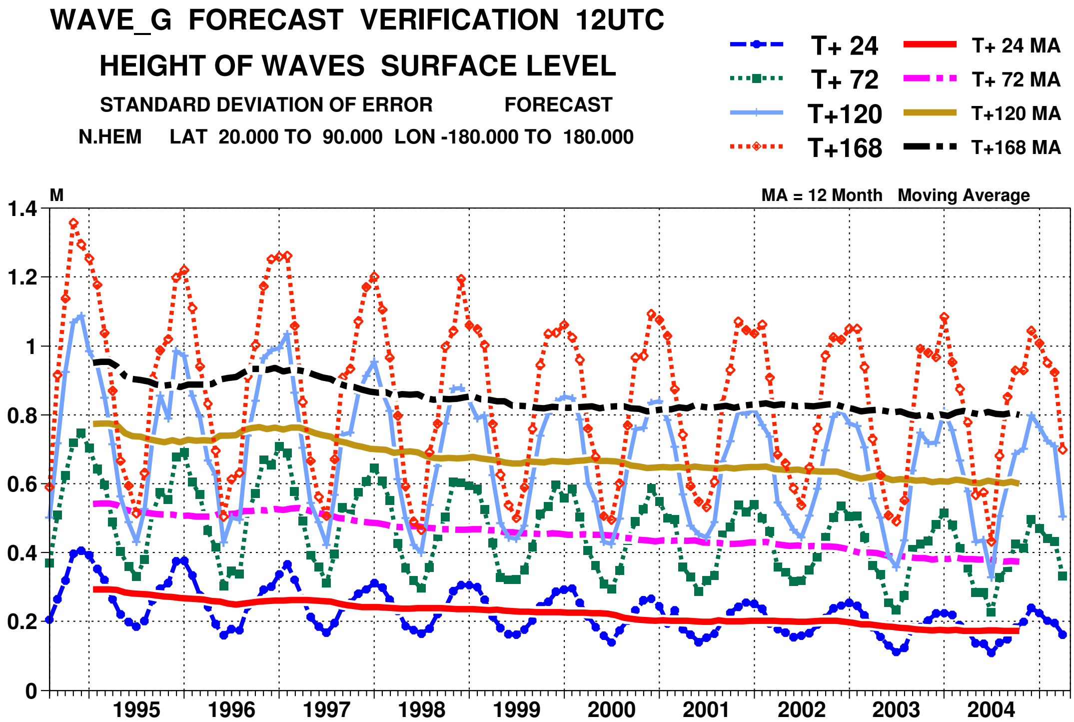

Brest -> New York
20031215 12
20031222 00
Det. fc.
80°W
60°W
40°W
20°W
0°
70°N
60°N
50°N
40°N
30°N
MAGICS 6.8 leda - was Tue Dec 16 01:27:09 2003

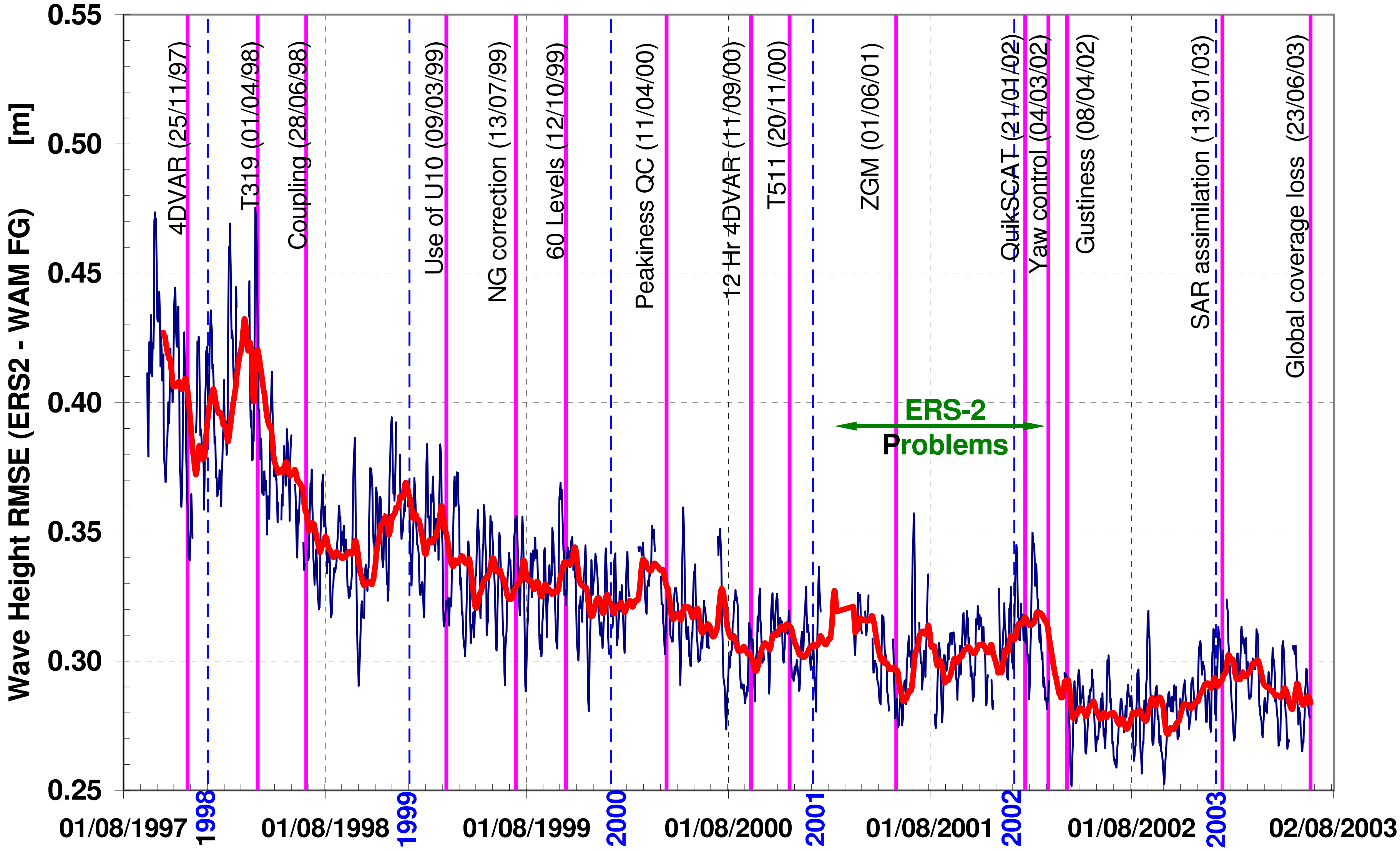
Verification

Over the years we have done extensive verifications of the skill of the wave forecasting system. Here we concentrate on one application only, namely the global deterministic model:

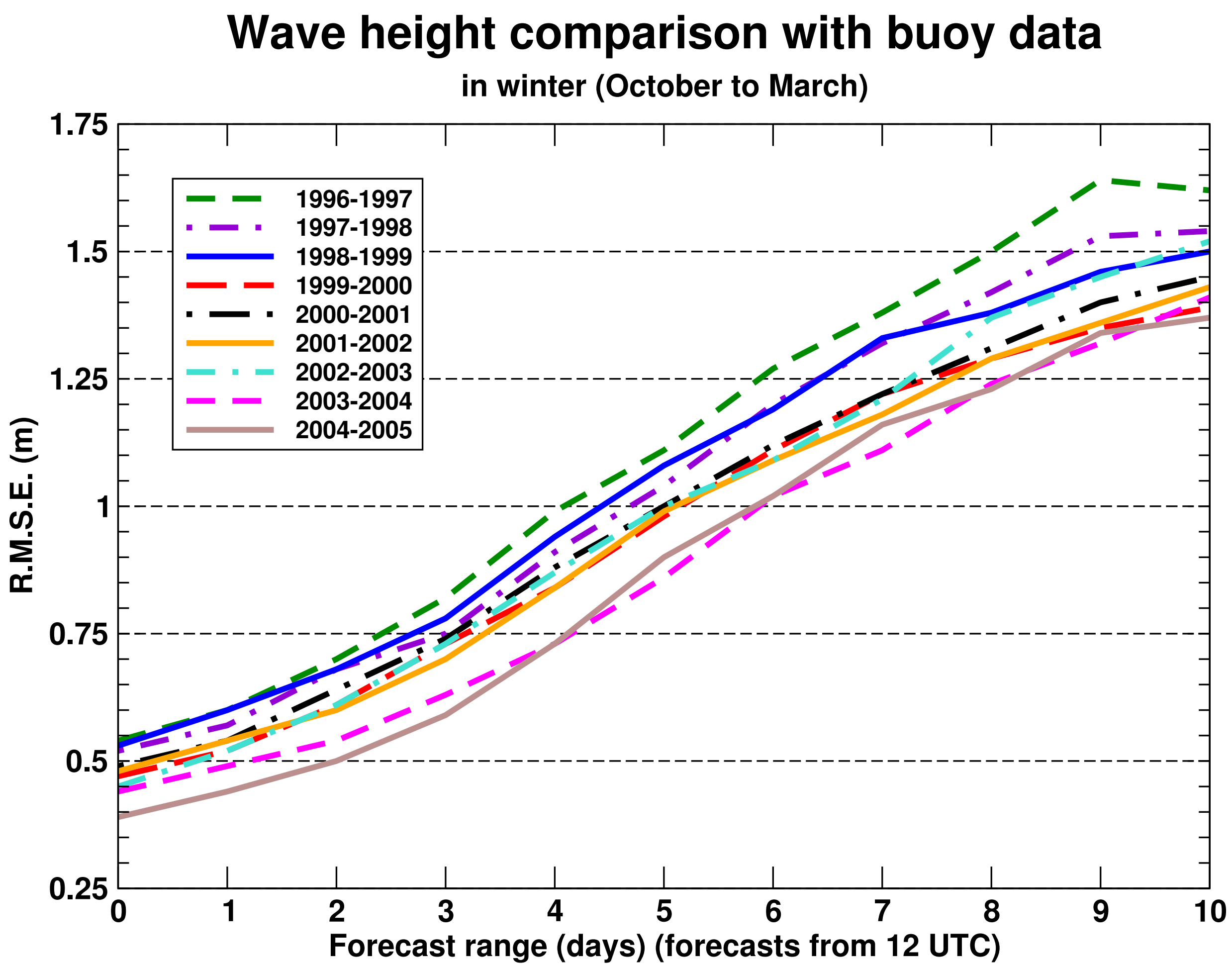
- Verification against **analysis**. Shown are timeseries of standard deviation of error of forecast wind and ocean wave height for Northern Hemisphere, Tropics and Southern Hemisphere. A substantial improvement is seen.
- Verification of first-guess wave height against **altimeter** data from ERS-2, which confirms the improvement
- Verification of wave model data against **independent buoy** observations. Both analysed and forecast wave height, and also analysed spectra.


WAVE_G FORECAST VERIFICATION 12UTC
WIND SPEED AT 10 M SURFACE LEVEL
STANDARD DEVIATION OF ERROR FORECAST
N.HEM LAT 20.000 TO 90.000 LON -180.000 TO 180.000
T+ 24
T+ 72
T+120
T+168
T+ 24 MA
T+ 72 MA
T+120 MA
T+168 MA
M/S
MA = 12 Month Moving Average
4
3.5
3
2.5
2
1.5
1
0.5
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004

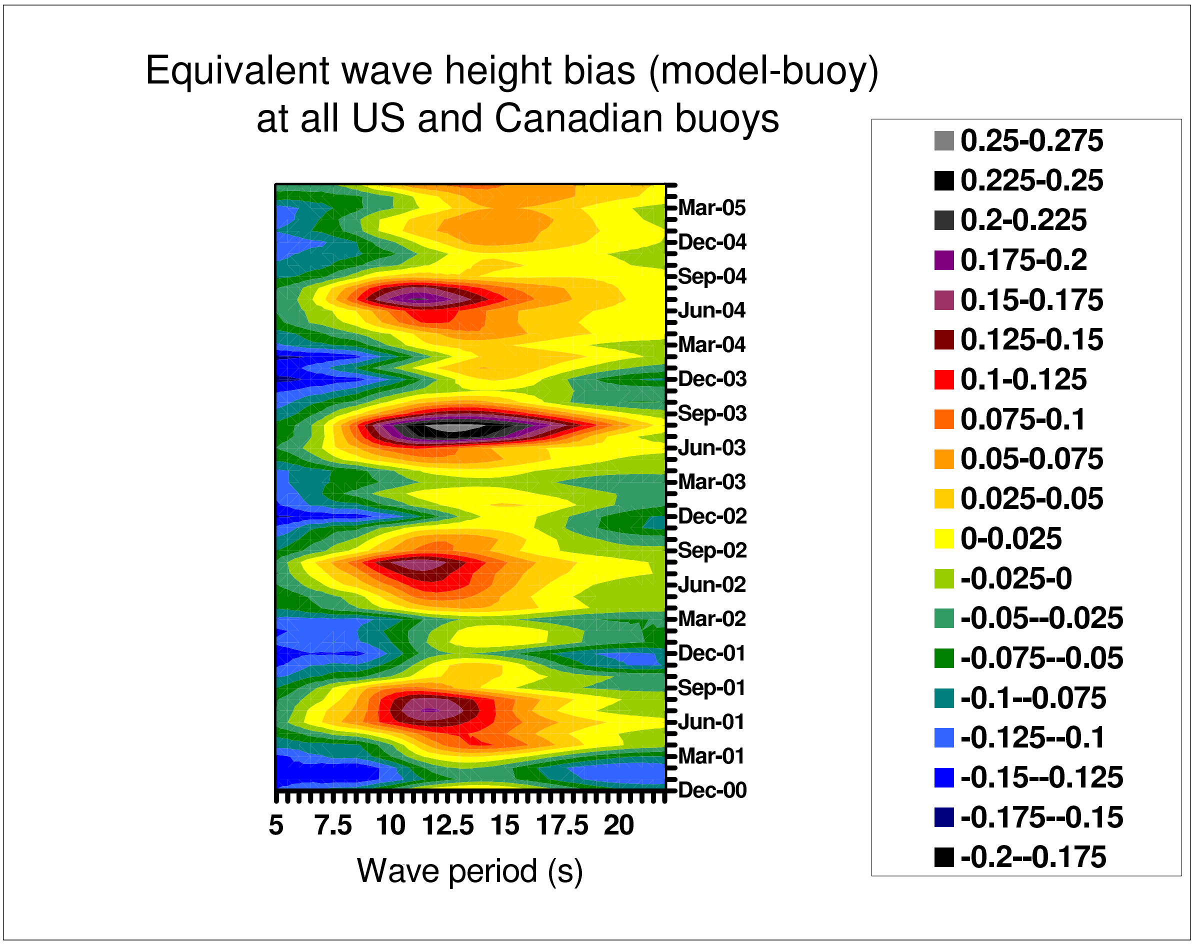

WAVE_G FORECAST VERIFICATION 12UTC
HEIGHT OF WAVES SURFACE LEVEL
STANDARD DEVIATION OF ERROR FORECAST
N.HEM LAT 20.000 TO 90.000 LON -180.000 TO 180.000
T+ 24
T+ 72
T+120
T+168
T+ 24 MA
T+ 72 MA
T+120 MA
T+168 MA
M
MA = 12 Month Moving Average
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004



RMS error of first-guess wave height against ERS-2 Altimeter data for the whole globe over the period of August 1997 until August 2003.



RMS error of analysed and forecast wave height against Buoy wave height data for all winters from 1996 onwards.



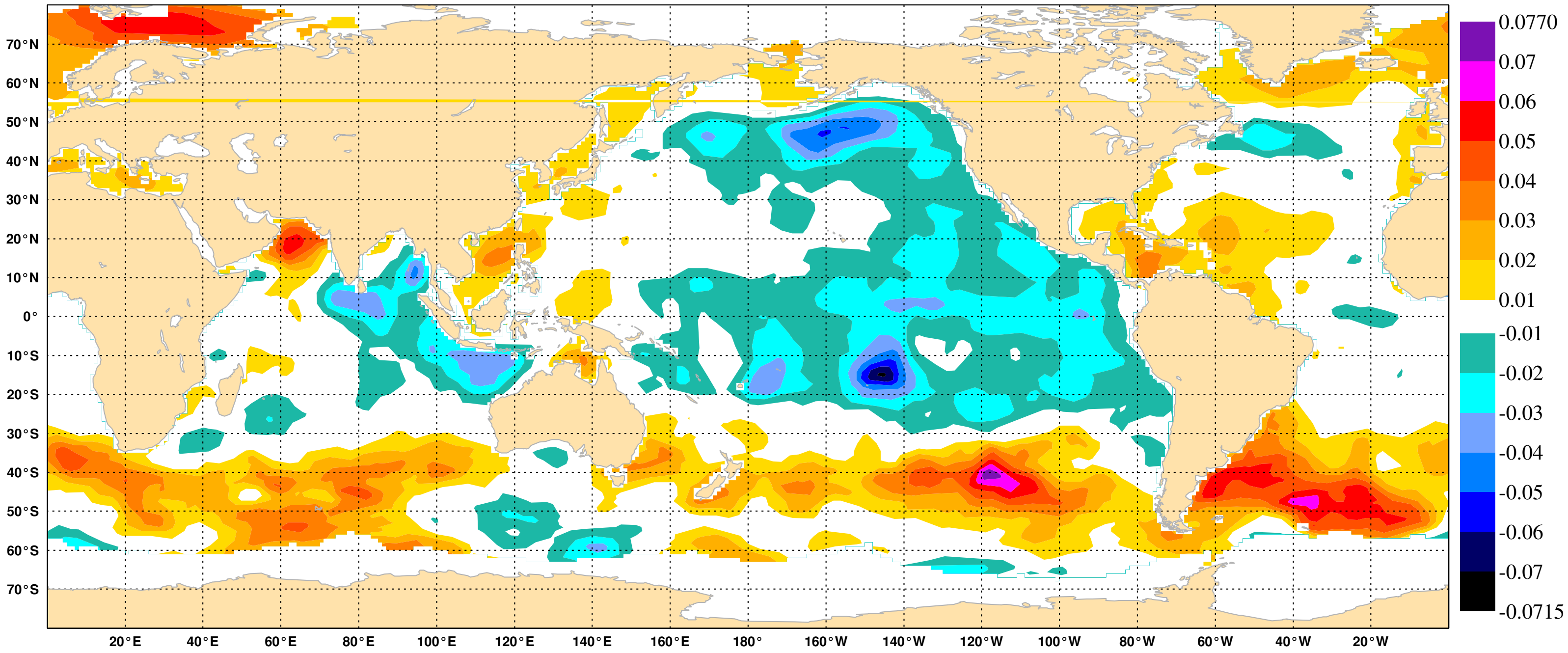
Equivalent wave height bias as function of wave period at all US and Canadian buoy locations for the period December 2000 to May 2005.

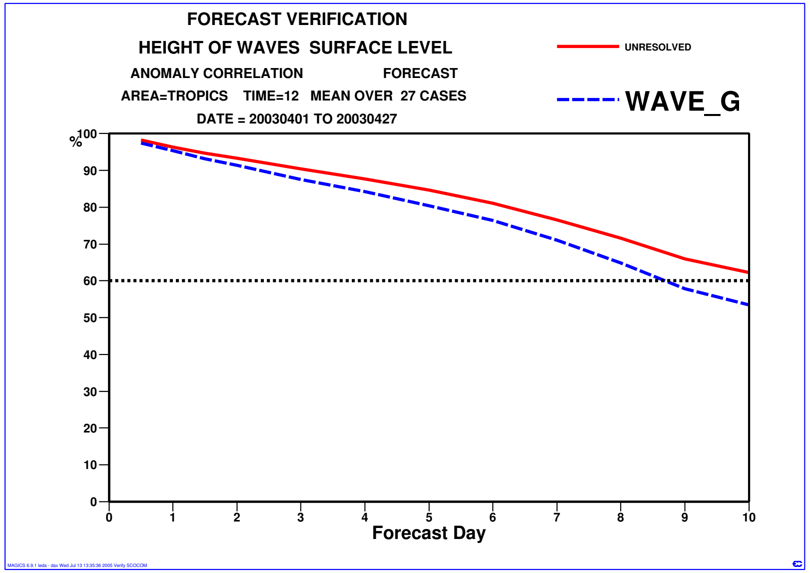
Wave model Improvements

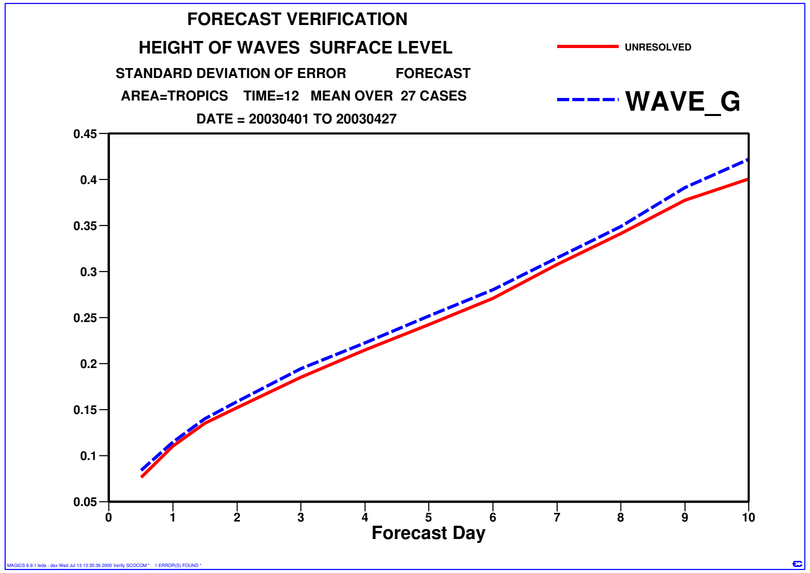
In the past few years we have introduced a number of improvements to our wave forecasting system. The main ones are:

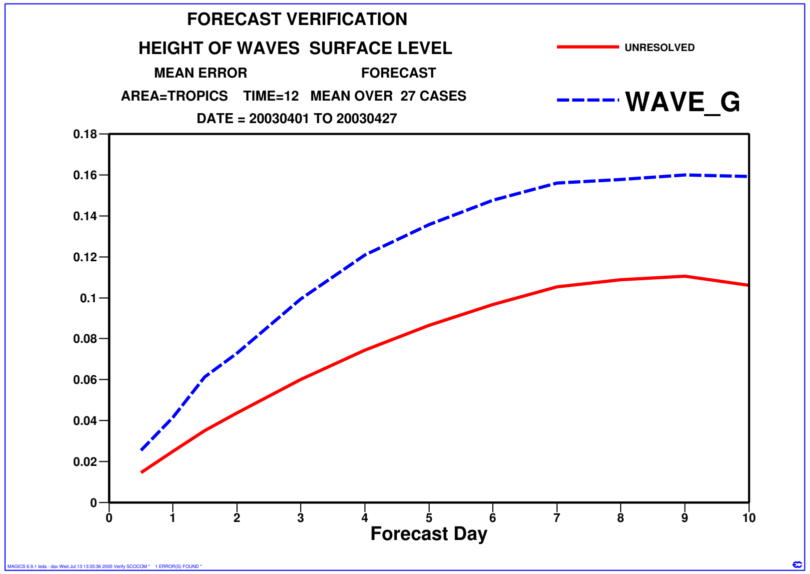
- **Effects of unresolved bathymetry** Analysis increments in the summertime show large scale systematic errors in the whole North Pacific. Caused by small islands and atols which are not resolved by coarse resolution models. Introduce a blocking factor which is proportional to the fraction of land inside a grid box in the wave propagation direction. Major impact on tropical scores.
- **Changes to wave dissipation** New definition of steepness parameter in wave dissipation. Large impact on spectral shape, hence on parameters such as the mean frequency, mean wave direction, directional spread.

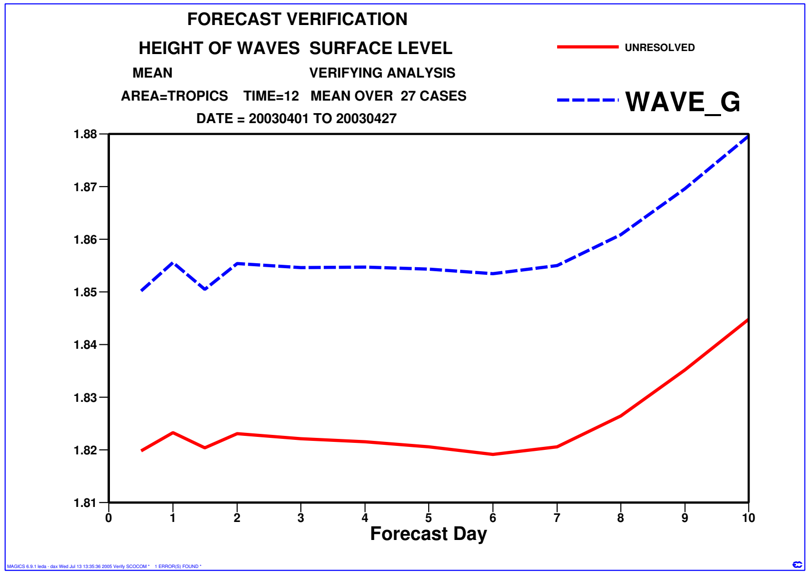
Mean wave height increments for July 2001



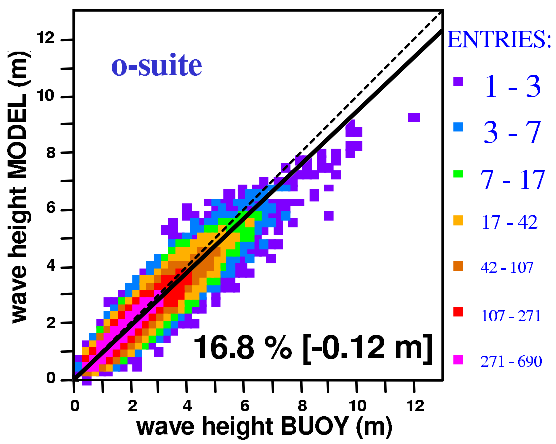

FORECAST VERIFICATION
HEIGHT OF WAVES SURFACE LEVEL
ANOMALY CORRELATION FORECAST
AREA=TROPICS TIME=12 MEAN OVER 27 CASES
DATE = 20030401 TO 20030427
UNRESOLVED
WAVE_G
%
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10
Forecast Day

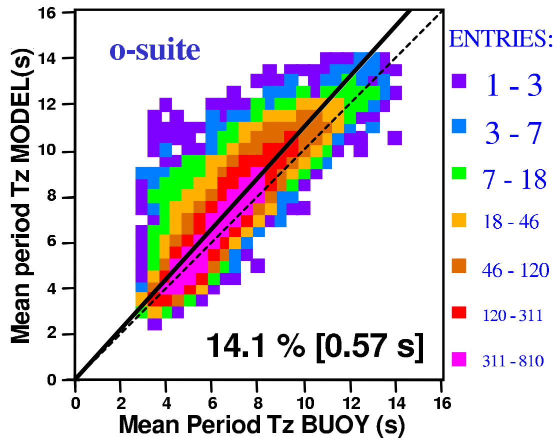

FORECAST VERIFICATION
HEIGHT OF WAVES SURFACE LEVEL
STANDARD DEVIATION OF ERROR FORECAST
AREA=TROPICS TIME=12 MEAN OVER 27 CASES
DATE = 20030401 TO 20030427
UNRESOLVED
WAVE_G
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0 1 2 3 4 5 6 7 8 9 10
Forecast Day

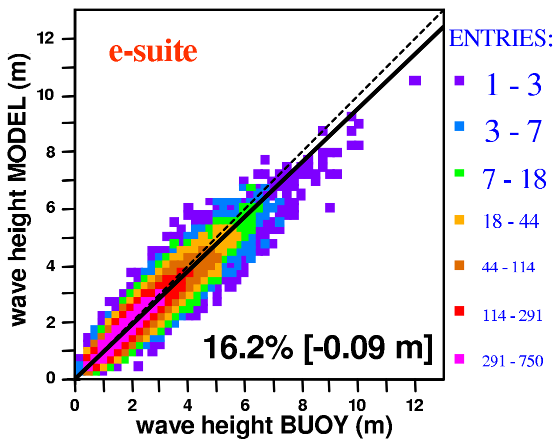

FORECAST VERIFICATION
HEIGHT OF WAVES SURFACE LEVEL
MEAN ERROR FORECAST
AREA=TROPICS TIME=12 MEAN OVER 27 CASES
DATE = 20030401 TO 20030427
UNRESOLVED
WAVE_G
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 1 2 3 4 5 6 7 8 9 10
Forecast Day

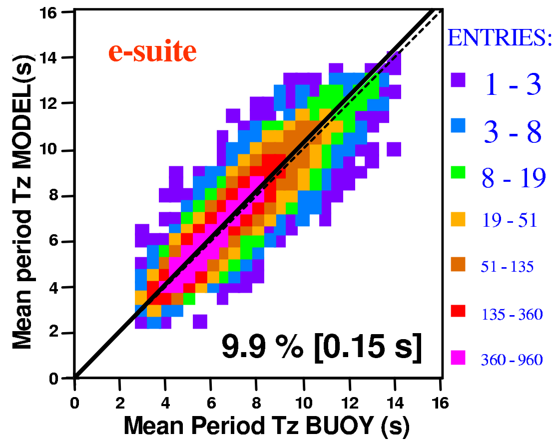

FORECAST VERIFICATION
HEIGHT OF WAVES SURFACE LEVEL
MEAN VERIFYING ANALYSIS
AREA=TROPICS TIME=12 MEAN OVER 27 CASES
DATE = 20030401 TO 20030427
UNRESOLVED
WAVE_G
1.88
1.87
1.86
1.85
1.84
1.83
1.82
1.81
0 1 2 3 4 5 6 7 8 9 10
Forecast Day

Comparison with US and Canadian buoy data for January to March 2005





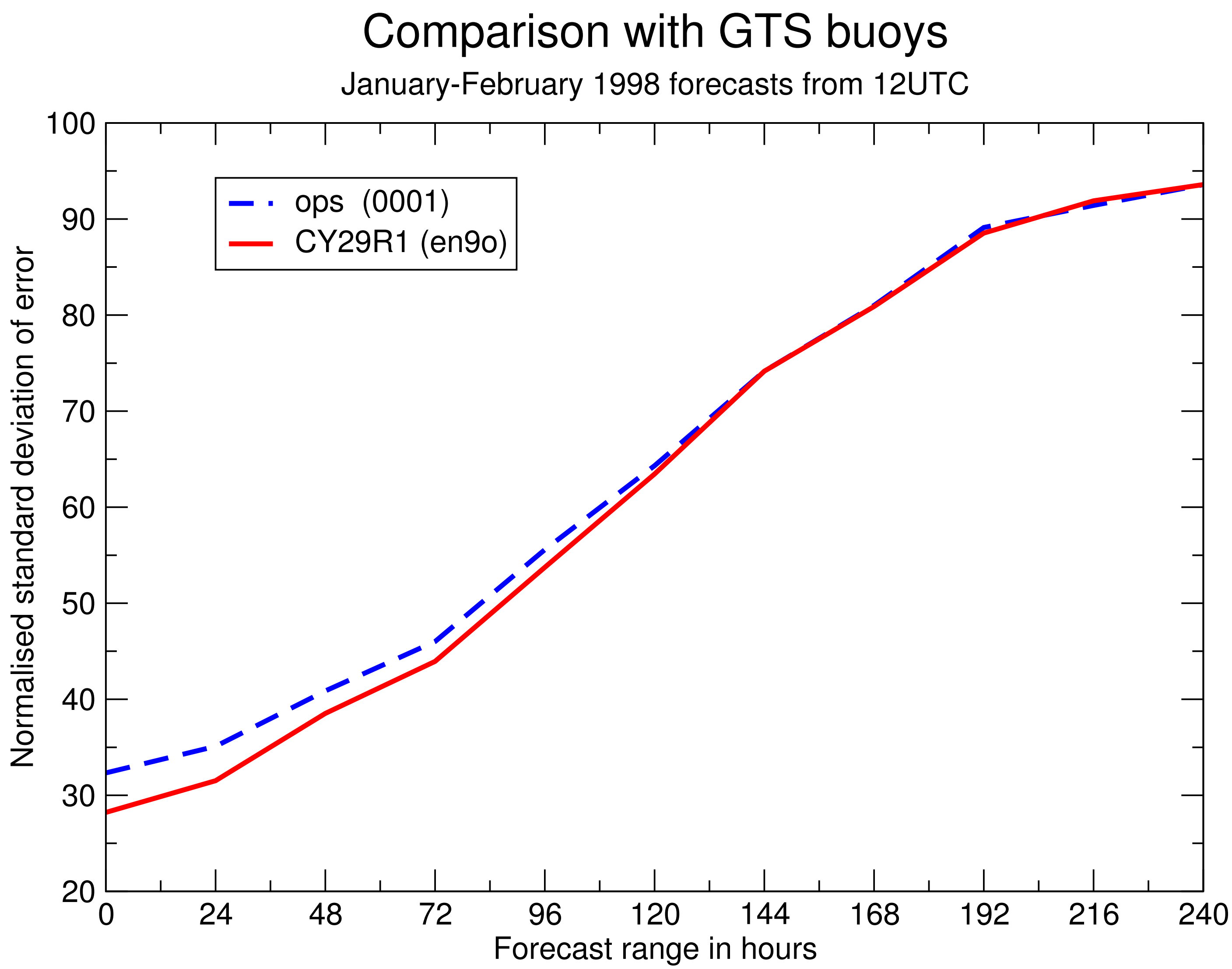




Importance of forecast skill in wind

These wave model improvements have, however, only a limited impact on forecast skill of wave height in the Extra-Tropics during winter time. Quality of the surface wind is important.

We have shown this by running the latest wave model on the period Jan-Feb 1998 using operational winds, and compared with operational wave height results. Using these old winds we only see improvements with the new wave model up to day 4. From day 5 onwards the skill is completely determined by the quality of the wind.



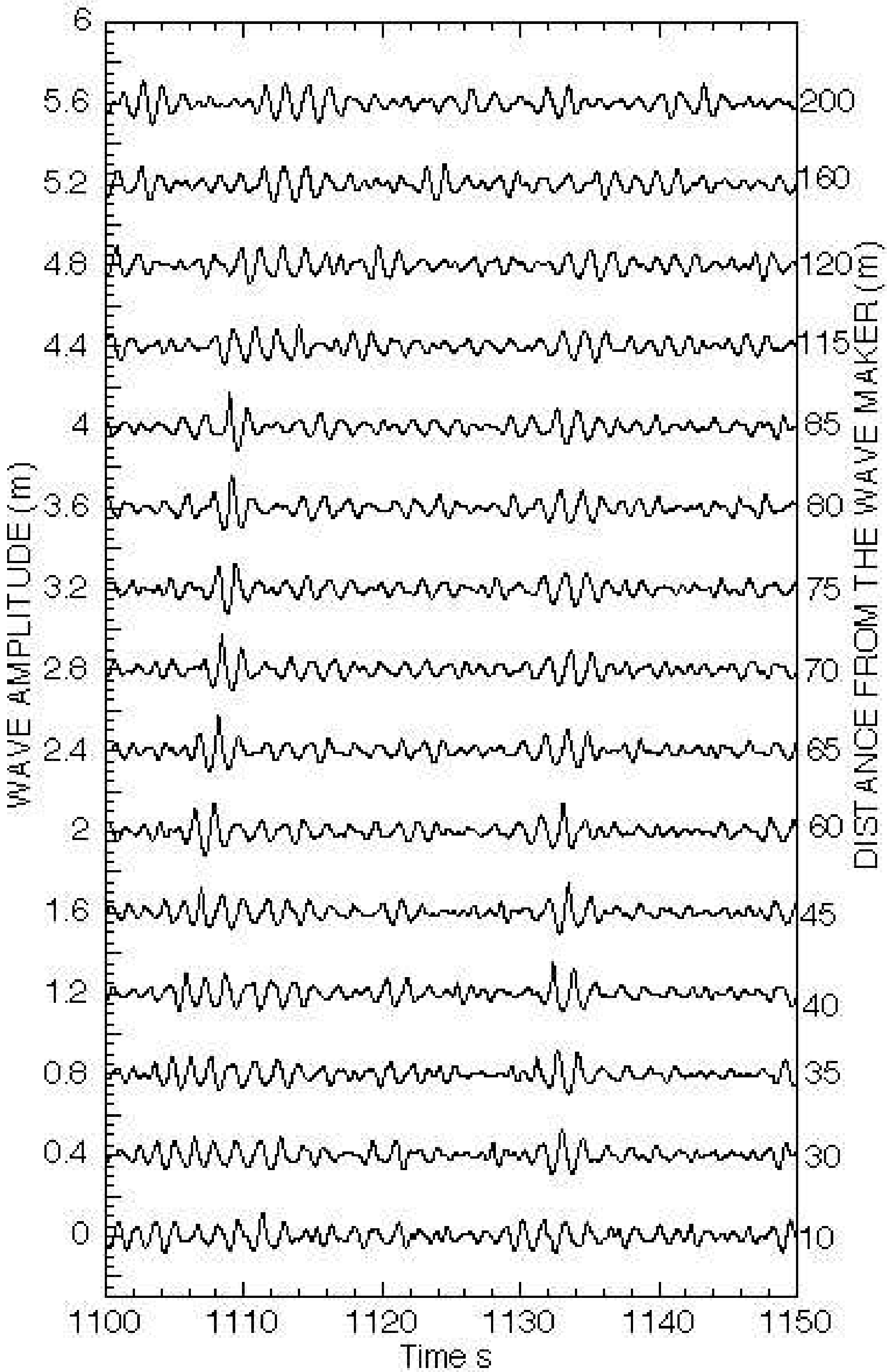
Comparison with GTS buoys
January-February 1998 forecasts from 12UTC
ops (0001)
CY29R1 (en9o)
Normalised standard deviation of error
Forecast range in hours
100
90
80
70
60
50
40
30
20
0
24
48
72
96
120
144
168
192
216
240

New development: Freak Waves

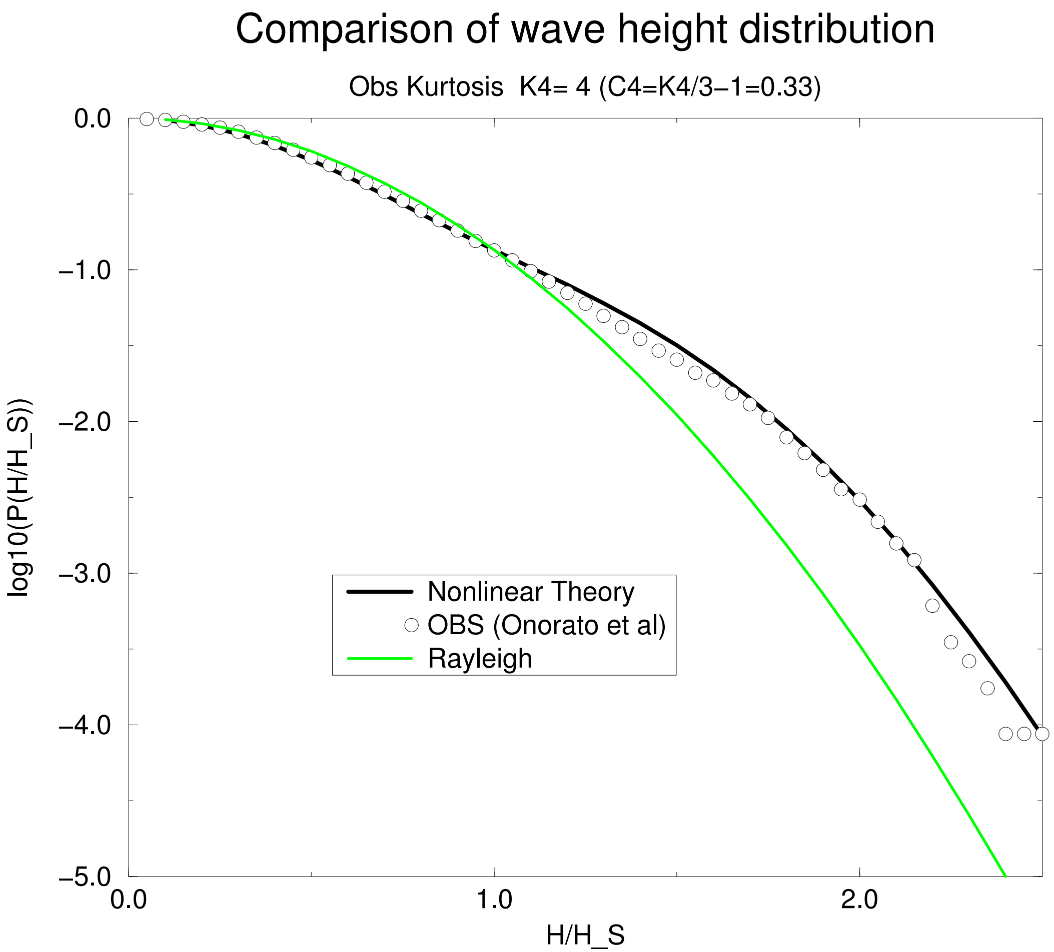
- **Linear theory** No wave-wave interaction. Focussing of wave energy only occurs when the phases of the waves are favourable (**constructive interference**). Gives at best a doubling of wave height $\rightarrow$ Gaussian pdf for elevation η.

- **Nonlinear Waves** Now there are **four-wave interactions** . Thus, a wave may borrow energy from its neighbours. Because of this extra focussing wave height may become at most 3 times as large in 1D, while it 2 D it becomes 4.5-5 times as large as the average wave height$\rightarrow$ Large deviations from Gaussian.

  The fun is that these deviations can be obtained by means of the usual **statistical mechanics** approach for wave-wave interactions.



Evolution of surface elevation in space and time from the big wave tank in Trondheim (from Onorato et al, 2004). The formation of Freak Waves is clearly seen.



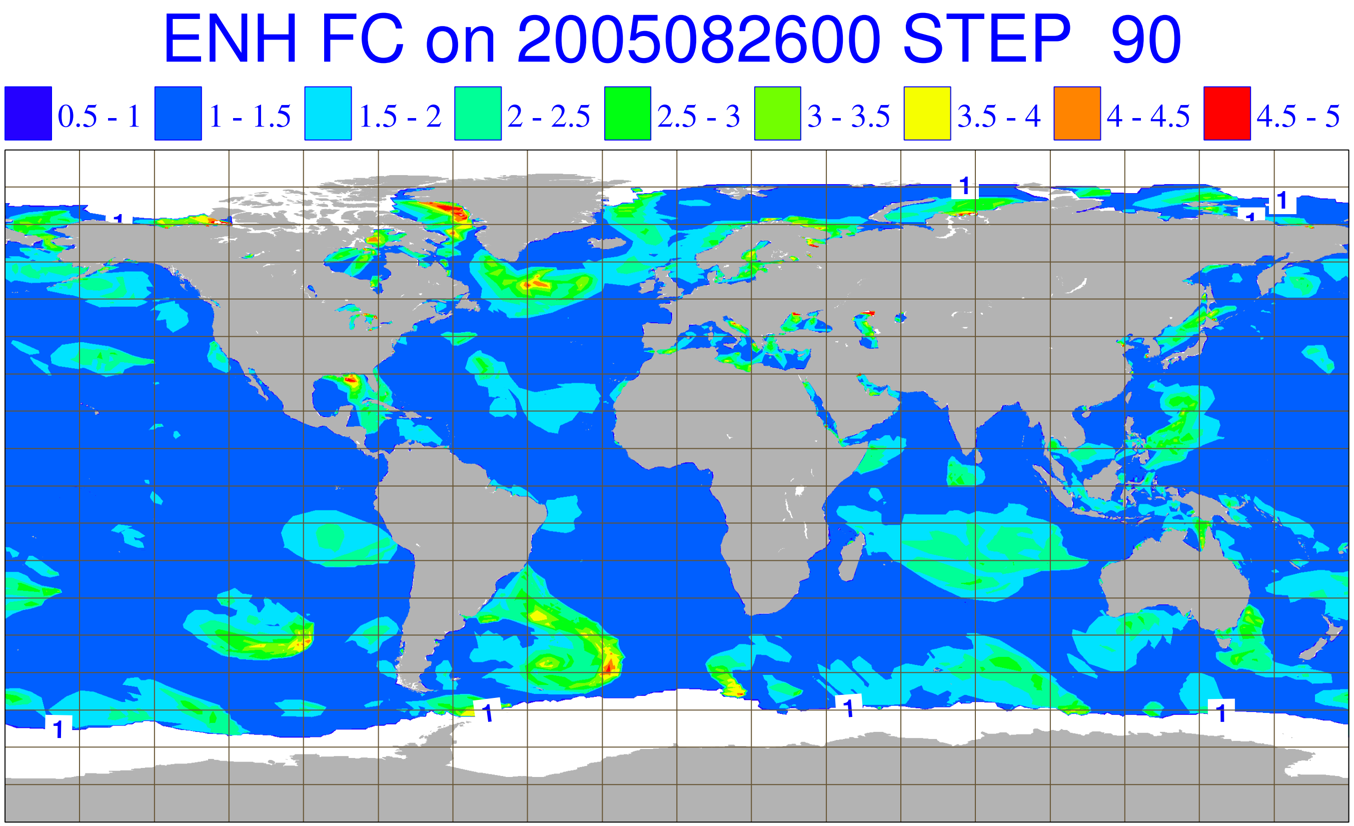
Comparison of theoretical and observed (Onorato et al, 2004) wave height distribution. For reference, the linear Rayleigh result is shown as well.

OPERATIONAL IMPLEMENTATION

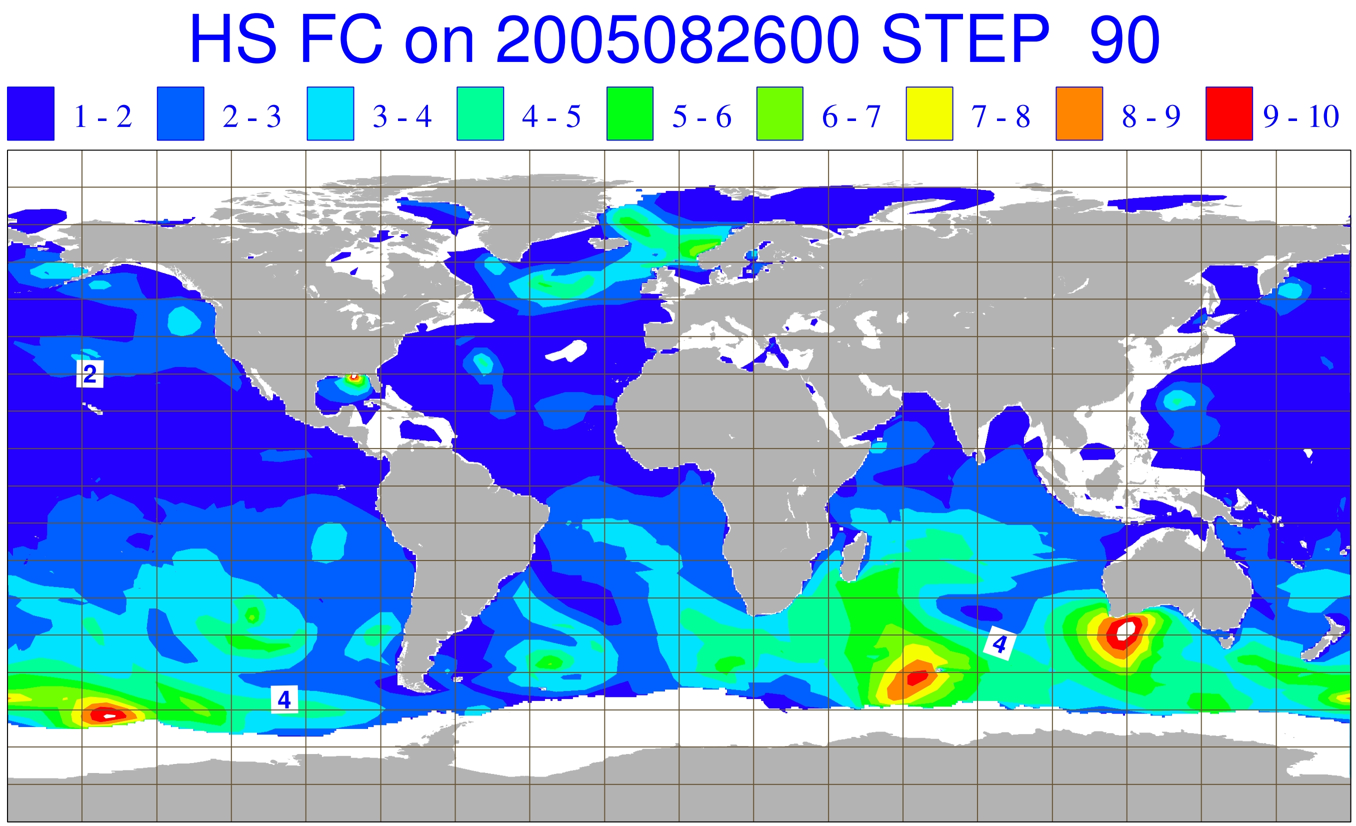
Thus, there is nowadays an improved understanding why extreme sea states do occur and deviations from the Normal Distribution can be expressed in terms of a spectral shape parameter, called the Benjamin-Feir Index: this is basically the ratio of the steepness of the waves and the width of the spectrum.

Hence, we have implemented the following scheme:

- From the predicted wave spectrum we infer the B.F. Index.
- From the B.F Index we obtain the deviations from the Normal distribution, e.g. as measured by the Kurtosis.
- Given the kurtosis and the significant wave height, we are able to answer question such as what is the enhanced probability on extreme events.



Enhancement of extreme events caused by nonlinear focussing for the 90 hr forecast of the landfall of hurricane Katrina.



Significant wave height for the 90 hr forecast of the landfall of hurricane Katrina.

CONCLUSIONS

- In the past few years we have seen considerable improvements in the modelling of the shape of the wave spectrum. Delicate parameters such as the Benjamin-Feir Index can now be determined accurately.

  Now is the time ripe to concentrate on the coastal zone problem and to study issues such as the interaction of ocean waves and tidal motion, effects of bottom-induced wave breaking and nonlinear interactions.

- Recent observations of freak waves have confirmed the theoretical picture of freak waves generation that already existed in 1965!

  Using well-established methods one can, for given average sea state, obtain estimates of the enhanced probability of extreme events. The theoretical results are confirmed by laboratory results. Hence, in this sense, freak wave prediction is feasible.

  However, validation of all this in the field is of course desirable.