Workshop working groups:

- **Modelling:**
  - **Coupling.**
  - **How to deal with multi scales.**
  - **Dangerous sea states.**
- **Physics**
  - **Dissipation.**
  - **Non linear source term.**
  - **Wave effect on the oceans.**
  - **Wave/current interaction.**
  - **Wave under extreme winds.**
  - **New source terms.**
- **Data**
  - **Analysis and re-analysis.**
  - **Future satellite missions.**
  - **Validations techniques.**
  - **Forecast products.**

PRESENT STATUS of WAVE FORECASTING AT E.C.M.W.F.

Jean-Raymond Bidlot

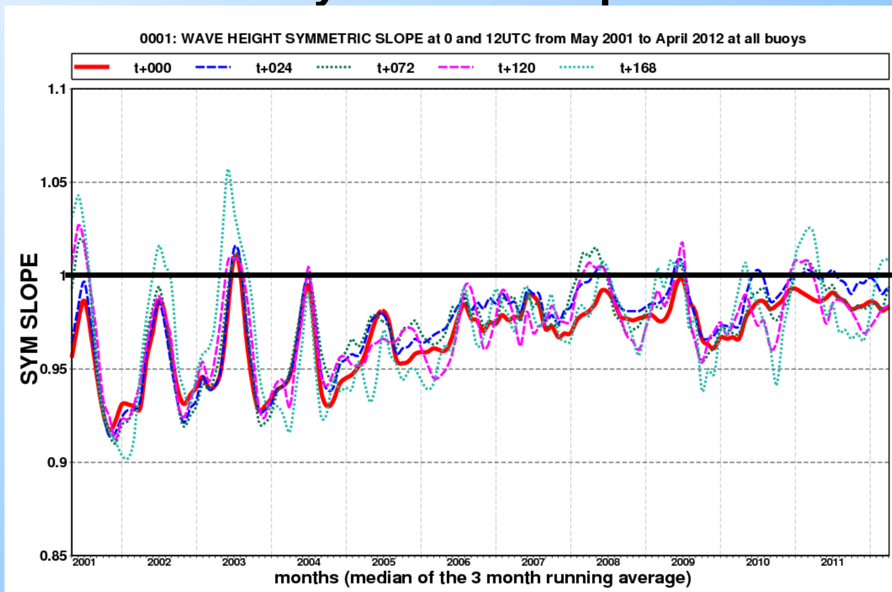
Marine Aspects Section

European Centre for Medium-range Weather Forecasts

Introduction: sustained improvement over the years

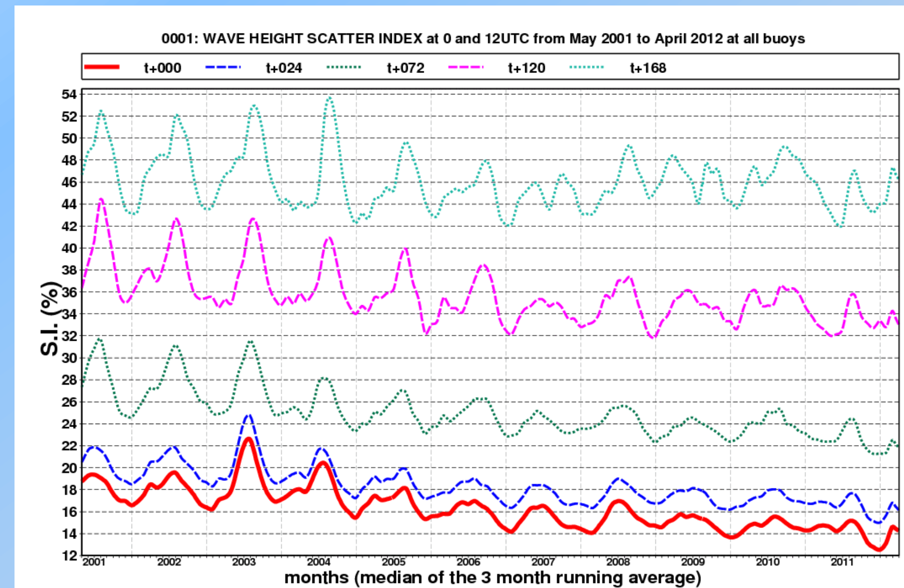
For example: global wave height forecast against buoy measurements:

Symmetric Slope

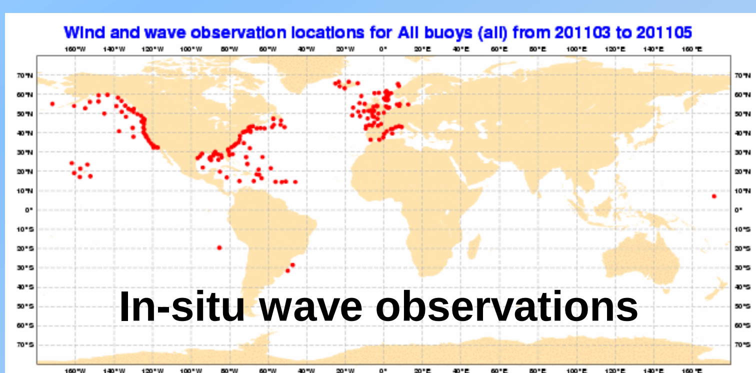


2001 **2011**

Scatter Index



2001 **2011**



7 day FC

5 day FC

3 day FC

1 day FC

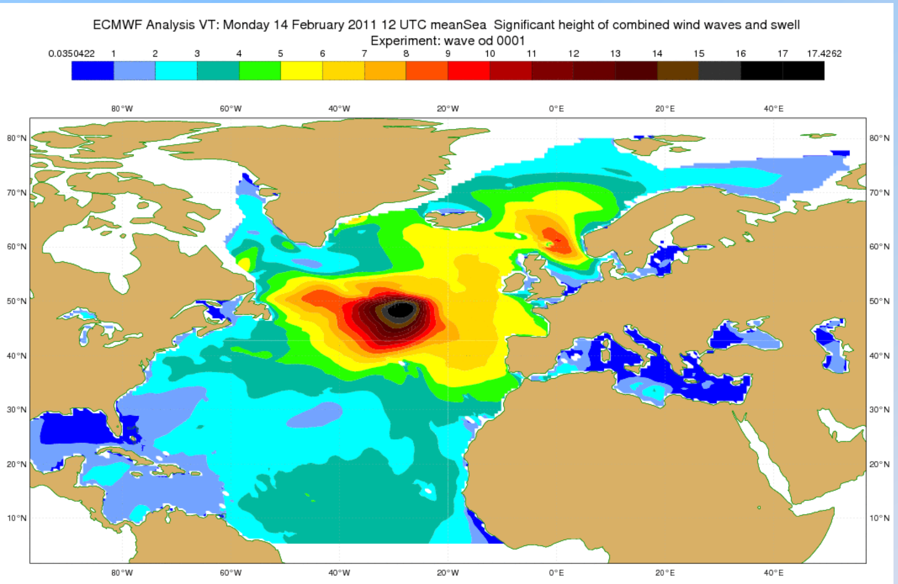
analysis

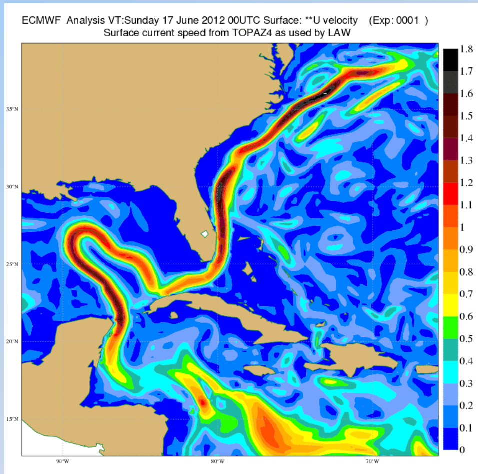
ECMWF

ECMWF Wave Model Configurations

1) Limited Area Wave model (LAW)

- **Limited extend.**
- **<u>11</u> km grid spacing.**
- **Stand alone.**
- **Forced by 10m neutral wind fields.**
- **Use surface currents from TOPAZ4.**
- **Data assimilation of altimeter data.**
- **2 daily forecasts extending to day 5.**
- **Output every hour, including spectra (*).**





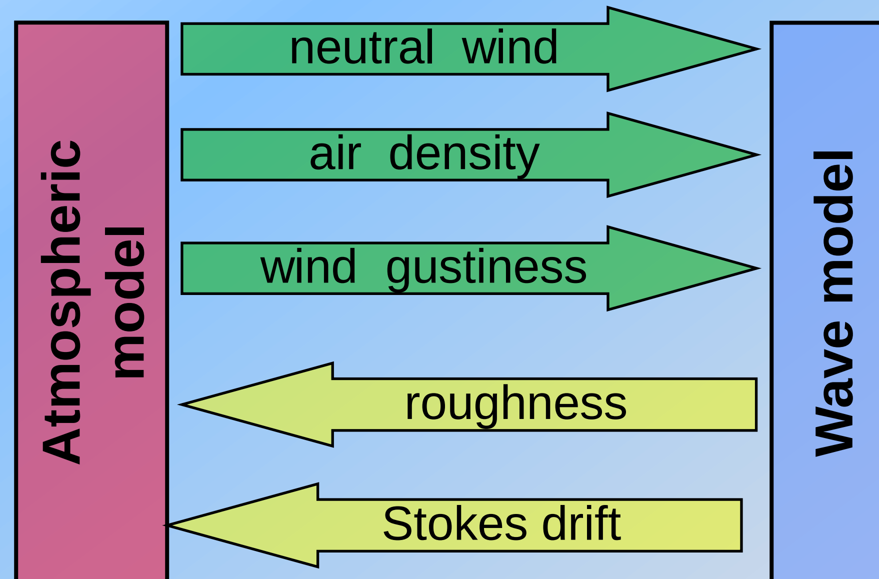
TOPAZ4 surface currents

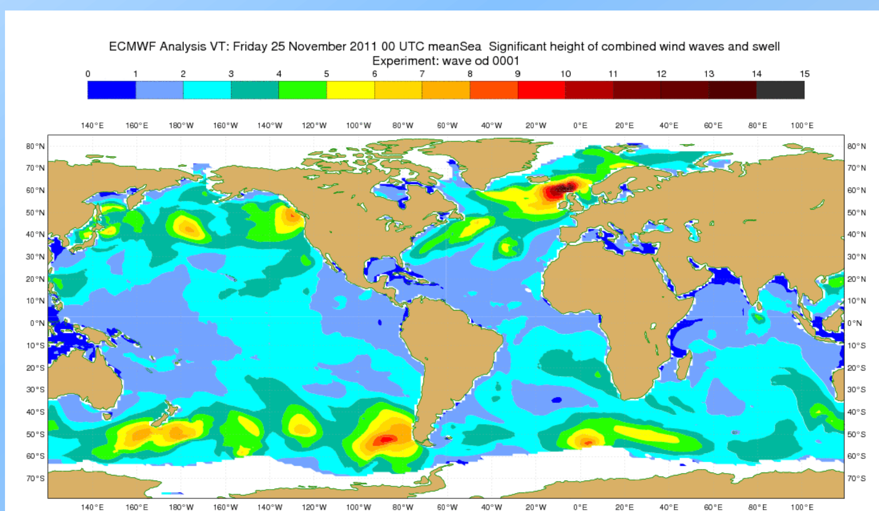
ECMWF

ECMWF Wave Model Configurations

2) Global models

- **Global.**
- **Coupled to the atmospheric model.**
- **Data assimilation of altimeter data.**
- **Part of all forecasting components (high resolution, ensemble, monthly, seasonal, re-analyses)**





Global from 81°S to <u>90</u>°N

Slide 5

ECMWF Wave Model Configurations

High resolution

- 28 km grid spacing.
- 36 frequencies.
- 36 directions.
- Coupled to the TL1279 model (16km).
- Analysis every 6 hrs and 10 day forecasts from 0 and 12Z.

Ensemble forecasts

- 55 km grid spacing.
- 30→ 25 frequencies *.
- 24 → 12 directions *.
- Coupled to TL639 (32 km) → TL319 model *.
- (50+1) (10+5) day forecasts from 0 and 12Z (monthly twice a week).

* Change in resolutions after 10 days

NB: also in seasonal forecast at lower resolutions

Ocean Wave Modelling: ECWAM

- **The ocean wave modelling at ECMWF is based on the wave mode WAM cycle 4 (Komen et al. 1994), albeit with frequent improvements.**
- **Wave model page on the Centre's web site:**

  http://www.ecmwf.int/products/forecasts/wavecharts/index.html#forecasts

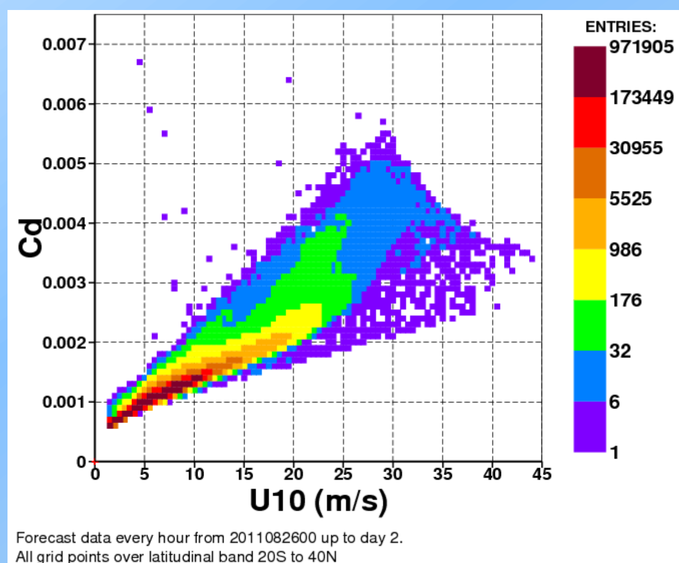
- **General documentation**:

  http://www.ecmwf.int/research/ifsdocs/CY36r1/index.html

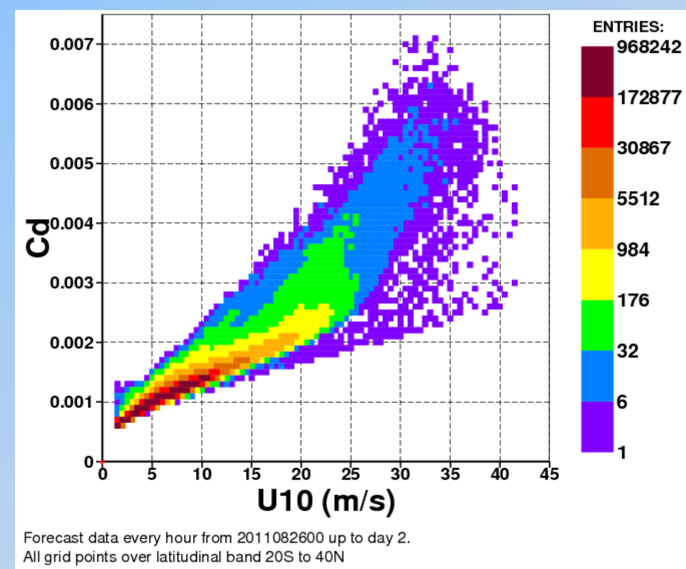
Latest upgrade to operational system (CY38R1) (19 June 2012):

- **Wave model main changes:**
  - Sinput + Sdiss + Sbottom
  - Bug fix to wave stress table.

Drag Coefficient versus wind speed (coupled runs):



with bug

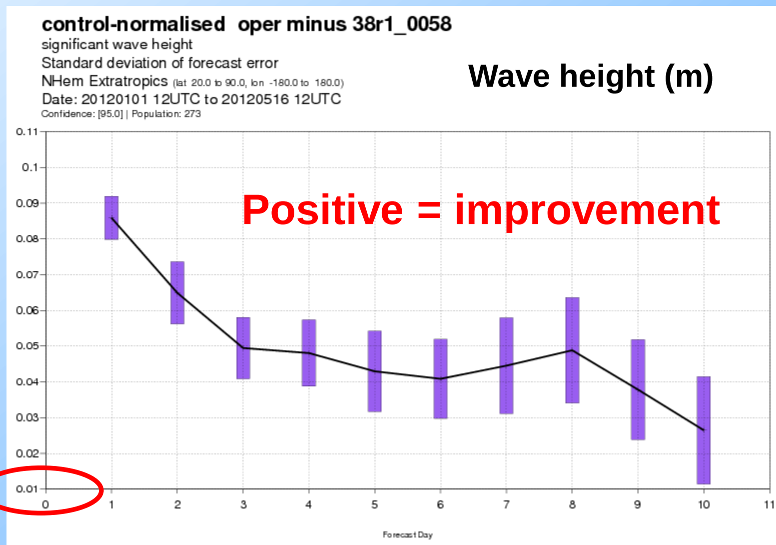


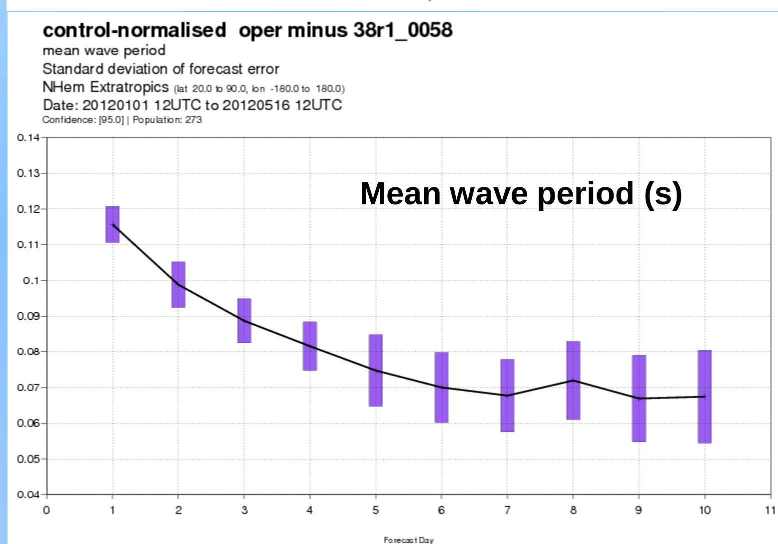
corrected

CY38R1: wave scores

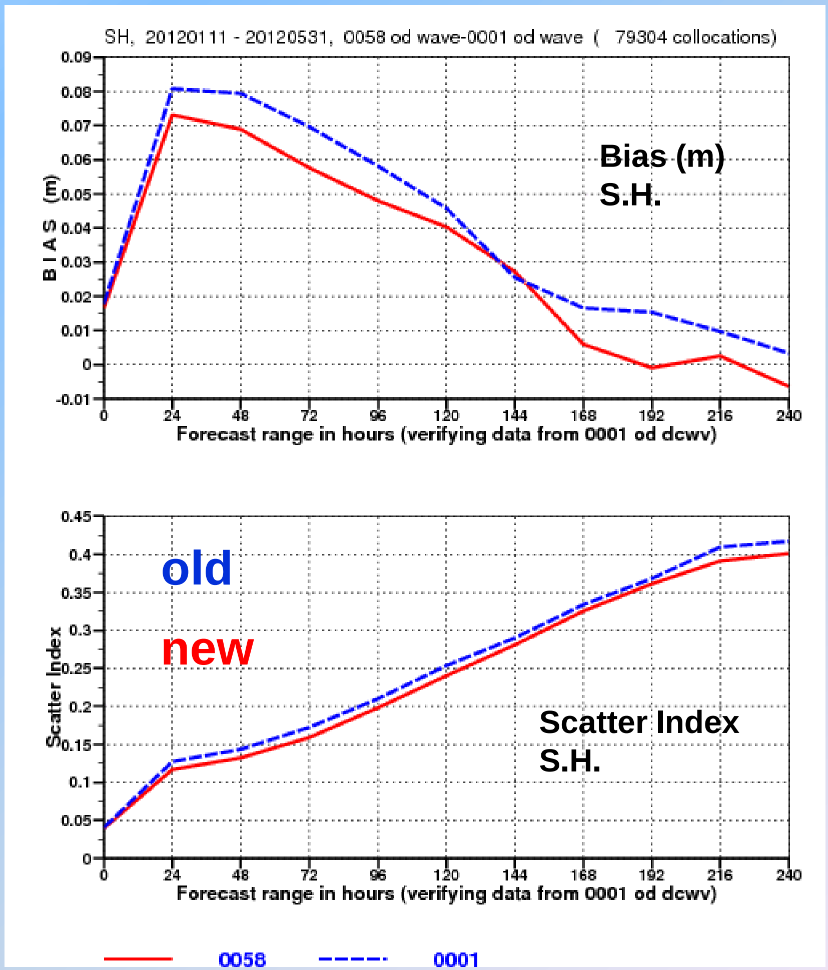
Compared to model analysis:

Stdev
error
N.H.





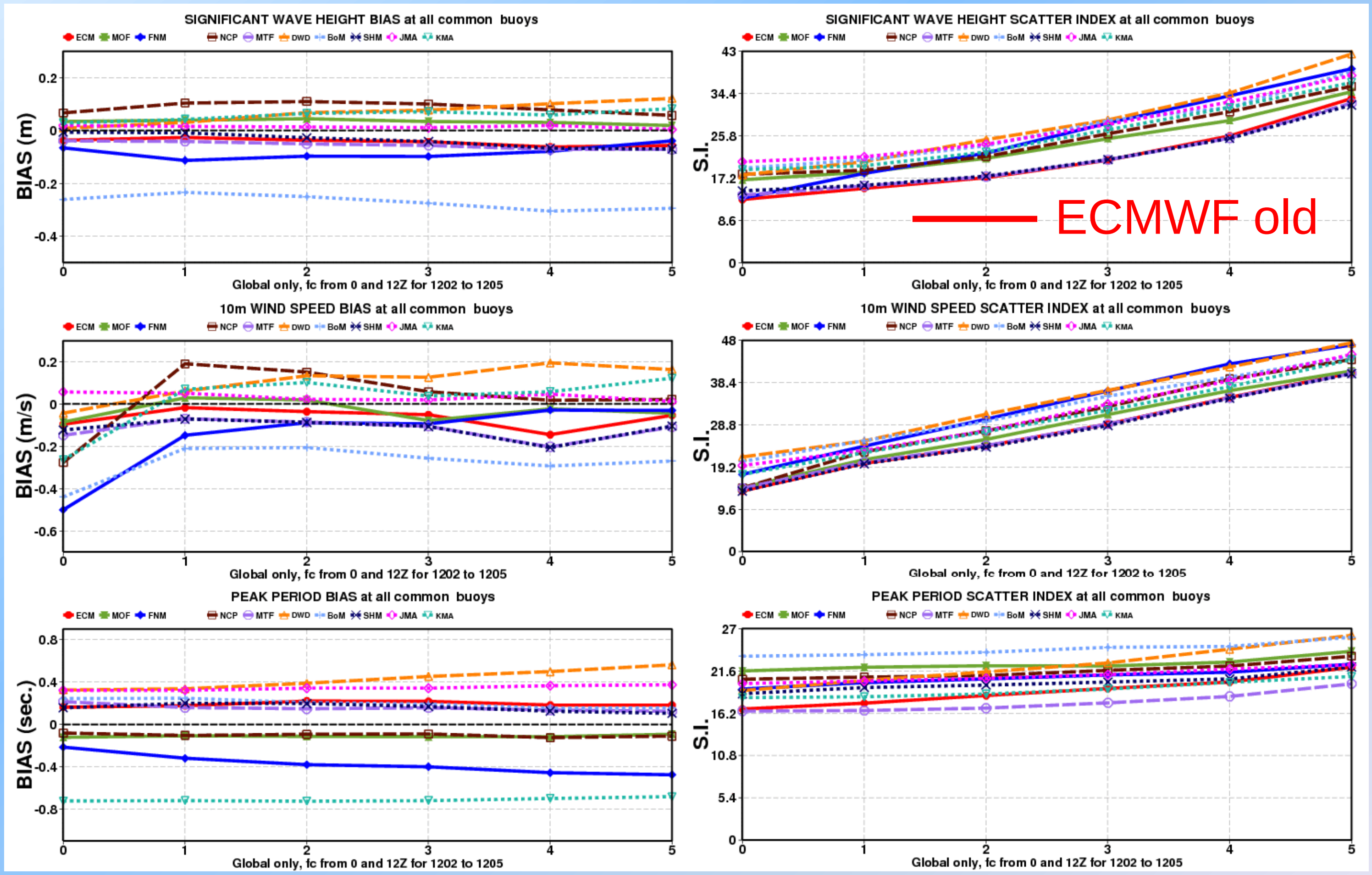
Compared to altimeter data:



Comparison with 17 operational centres at a set of buoys as part of the activities of JCOMM Expert Team on Waves and Storm surges (ETWS):

Global systems at all buoys, February-May 2012:

Bias (model-obs) Scatter Index



Wave height

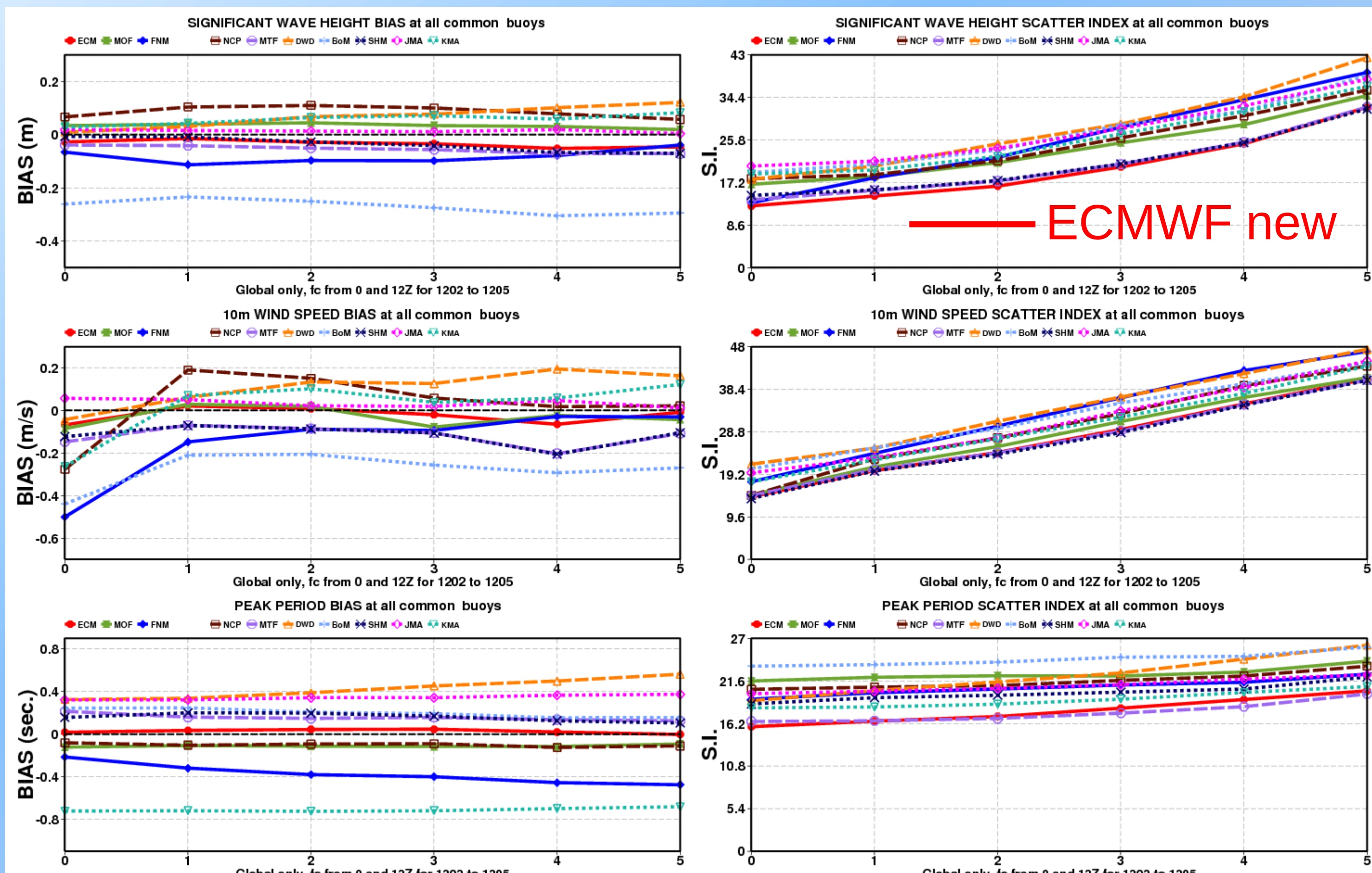
Wind speed

Peak period

Comparison with 17 operational centres at a set of buoys as part of the activities of JCOMM Expert Team on Waves and Storm surges (ETWS):

Global systems at all buoys, February-May 2012:

Bias (model-obs) | Scatter Index



Wave height

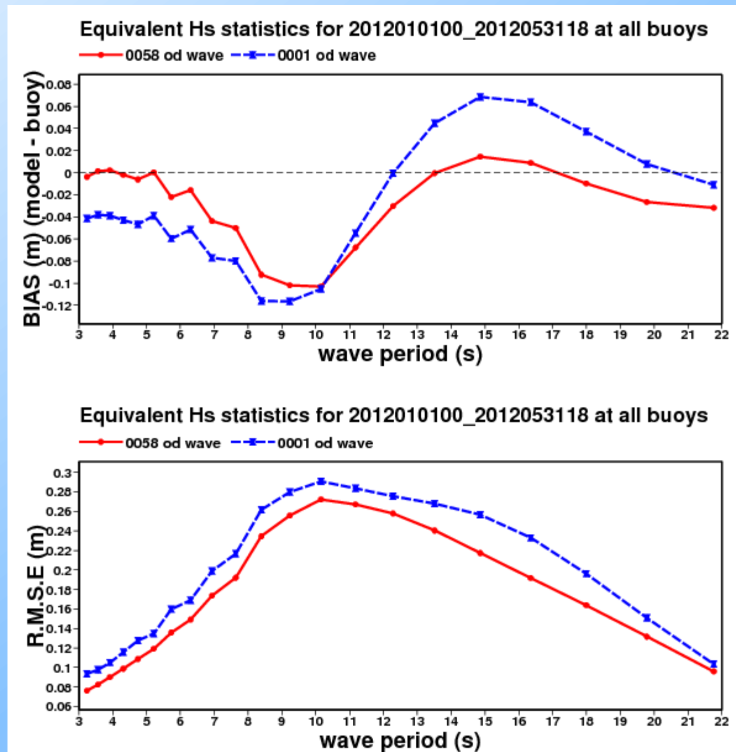
Wind speed

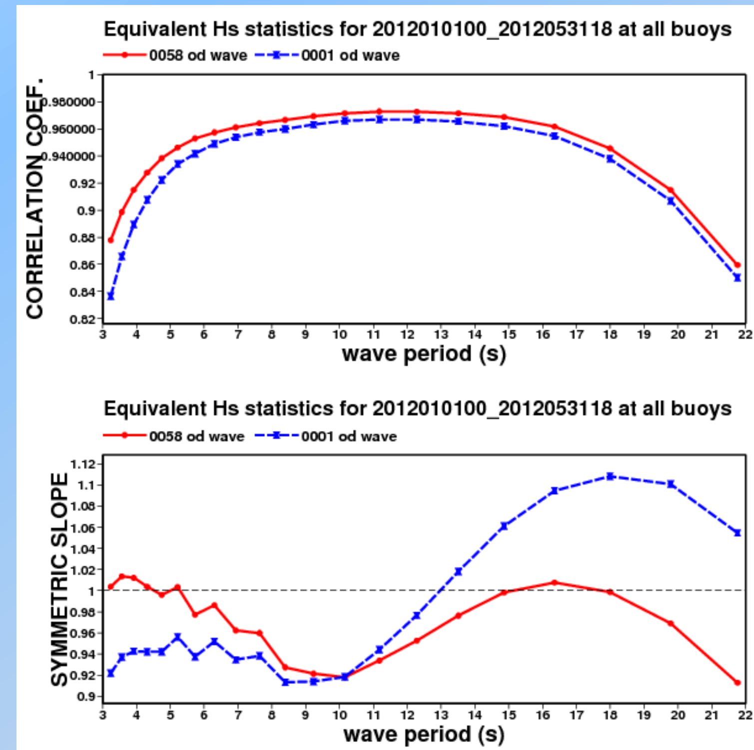
Peak period

CY38R1: comparison with buoy spectra

CY38R1

CY37R3





Data from NDBC (US), ISDM (Canada), CDIP (US)

Present status of ECWAM:

- The 2-D spectrum $F(f,\theta)$ follows from the energy balance equation (in its simplest form: deep water case):

$$\frac{\partial F}{\partial t} + \mathbf{V}_g \cdot \nabla F = S_{in} + S_{nl} + S_{diss}$$

where the group velocity V_g is derived from the dispersion relationship which relates frequency and wave number.

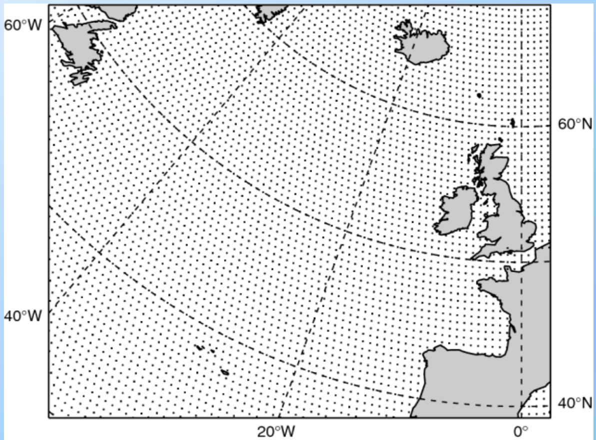
S_{in}: wind input source term (generation).

S_{nl}: non-linear 4-wave interaction (redistribution).

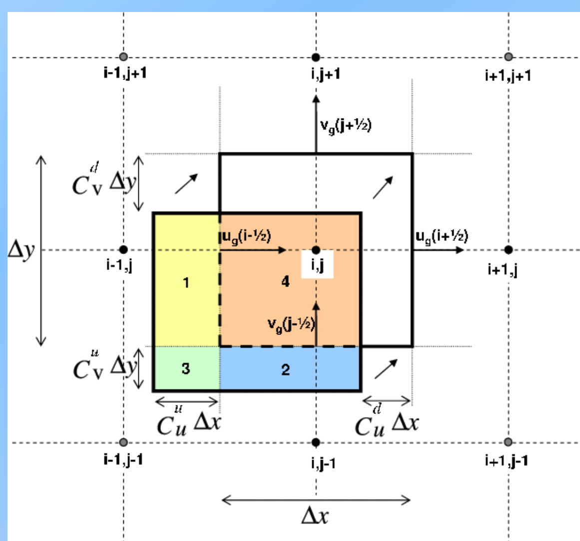
S_{diss}: dissipation term due to whitecapping (dissipation).

Grid and Advection:

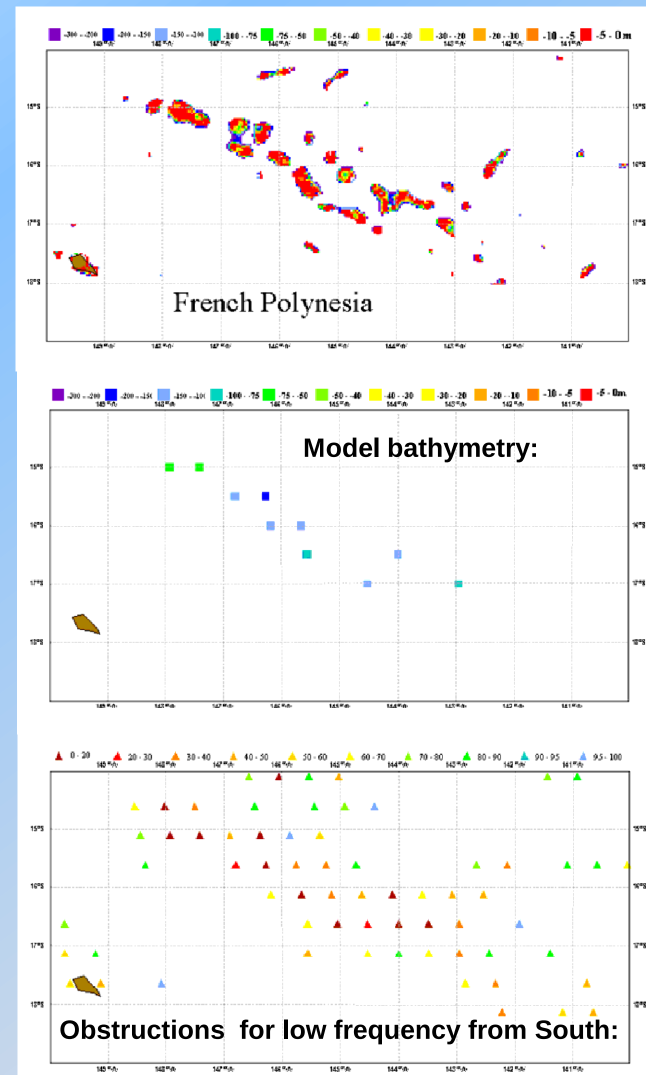
Irregular lat-lon grid to keep the distance between grid points roughly constant



Corner Transport Upstream scheme:



Unresolved bathymetry obstructions:



Wind input S_{in}: based on Janssen (1991):

neutral 10m wind U_{10}

air density

$$U_{10} = \frac{u_*}{\kappa} \ln\left(\frac{10}{z_o}\right)$$

κ von Karman constant

u_* friction velocity

z_o surface roughness

ρ_a air density

ρ_w water density

ϕ wind direction, $F(f,\theta)$

c phase speed, g

$$S_{in} = \frac{\rho_a}{\rho_w} \frac{\beta_{max}}{\kappa^2} e^Z Z^4 \left(\frac{u_*}{c} \max\left(\cos(\theta-\phi), 0\right)\right)^2 \omega F$$

β_{max} = 1.2 (as before)

where Z is the effective wave age:

$$Z = \ln\left(\frac{g z_o}{c^2}\right) + \frac{\kappa}{\cos(\theta-\phi)(\frac{u_*}{c} + z_\alpha)}$$

z_α : wave age tuning parameter:

New: $z_\alpha = 0.008$ (0.011 before CY38R1)

roughness

z_o sea state dependent

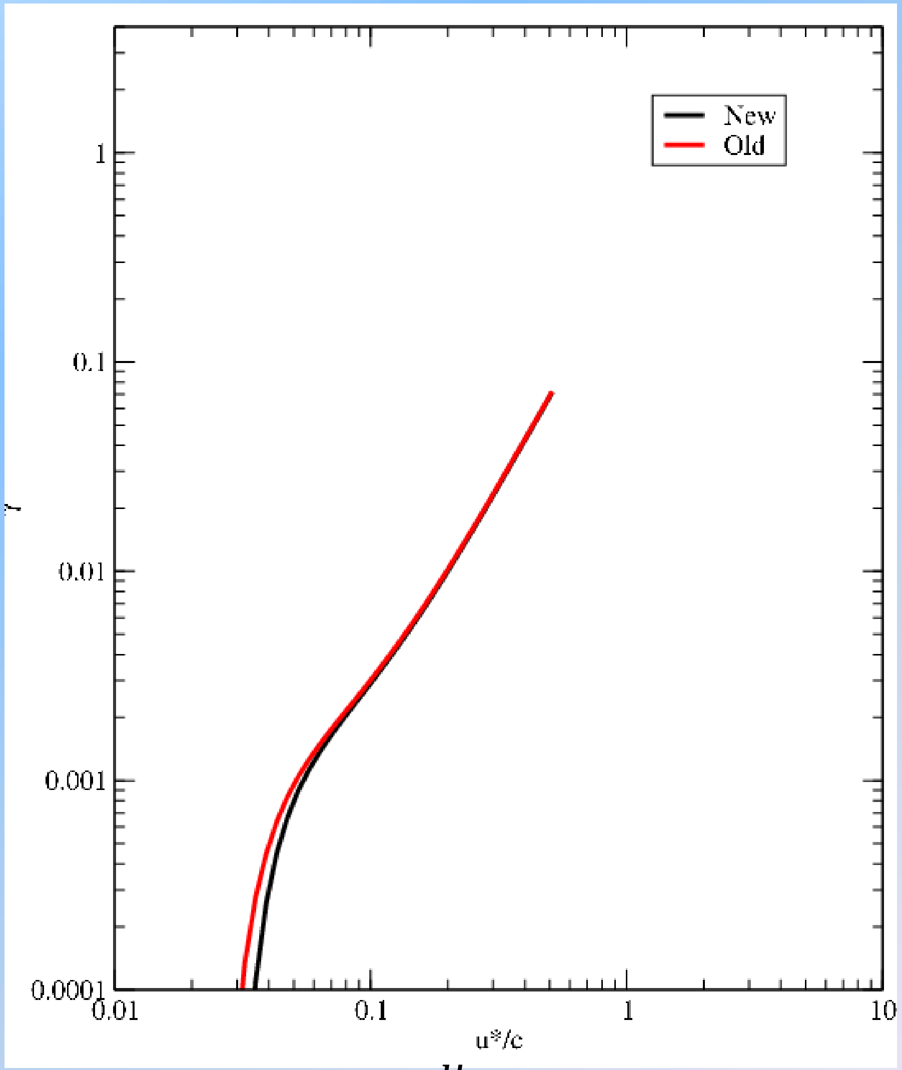
Wind input S_{in}:

$$S_{in} = \gamma F$$

$$\frac{\gamma}{\omega} = \frac{\rho_a}{\rho_w} \beta \left(\frac{u_*}{c} \max\left(\cos(\theta - \phi), 0\right) \right)^2$$

$$\beta = \frac{\beta_{\max}}{\kappa^2} e^Z Z^4$$

$$\frac{\gamma}{\sigma}$$



$$\frac{u_*}{c}$$

Wind input S_{in}: gustiness parameterisation

$$S_{in} = \gamma \, F$$

wind gustiness

$$\bar{\gamma}(u_*) = \frac{1}{\sigma_* \sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left\{ - \frac{(u_* - \bar{u}_*)^2}{2\sigma_*^2} \right\} \gamma(u_*) du_*$$

σ_* : standard deviation of u*

$$\bar{\gamma}(u_*) \approx 0.5 \left[\gamma(u_* + \sigma_*) + \gamma(u_* - \sigma_*) \right]$$

$$\sigma_* = \frac{u_*}{U_{10}} \left(1 + \frac{0.5 U_{10} \, 0.08 \, 10^{-3}}{C_d} \right) \left\{ b + 0.5 \left(\frac{z_i}{-L} \right) \right\}^{1/3}$$

$$u_* = \sqrt{C_d} \; U_{10} \qquad C_d = (0.8 + 0.08) 10^{-3} \, U_{10}$$

from the atmospheric model :

z_i Inversion height

L Monin Obukhov length

$b = 0$

ECMWF

Wind input S_{in}: linear swell damping

$$S_{in} = \gamma F$$

Following Janssen (2004), the small effect of turbulent eddies on the waves can be modelled as

$$\frac{\gamma}{\omega} = \frac{\rho_a}{\rho_w}\left\{\beta\left(\frac{u_*}{c}\max\left(\cos(\theta-\phi),0\right)\right)^2 + 2\kappa\left(\frac{u_*}{c}\right)^2\left(\cos(\theta-\phi)-\frac{c}{V}\right)\right\}$$

V : wind speed at height z = $1/k$

Sdiss

S_{diss} following Bidlot, Janssen and Abdalla (BJA) 2007, back to Komen et al. 1994 form:

$$S_{diss} = -C_{ds}\,\omega_{mean}\left(k_{mean}^2 m_0\right)^2\left[(1-\delta)\frac{k}{k_{mean}} + \delta\left(\frac{k}{k_{mean}}\right)^2\right]$$

$$C_{ds} = 1.33 \qquad \delta = 0.5$$

$$\omega_{mean} = \frac{\int \omega\, F\, df d\theta}{m_0} \qquad \sqrt{k_{mean}} = \frac{\int \sqrt{k}\, F\, df d\theta}{m_0} \qquad m_0 = \int F\, df d\theta$$

Snl:

- The calculation of the non linear source term is still based on the Discrete Interaction approximation (DIA).
- For shallow water, the transfer coefficients are re-scaled:

$$Transf_{nl}(\text{shallow}) = f(k,h)\, Transf_{nl}(\text{deep})$$

- Following Janssen and Onorato (2005), using the narrow band approximation, it was shown that the scaling factor could be written as

$$f(k,h) = \frac{R^2}{T^8 \frac{\partial v_g}{\partial k}}$$

where

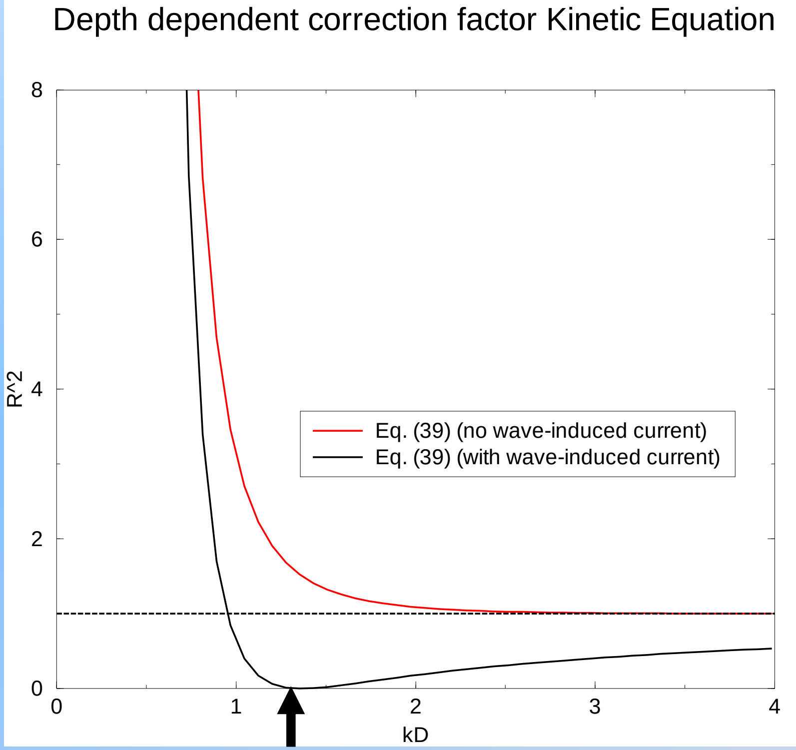
$$\frac{\partial v_g}{\partial k} = [T - kh(1-T^2)]^2 + 4(kh)^2 T^2 (1-T^2)$$

$$T = \tanh(kh), \quad v_g = 0.5c(1 + \frac{2kh}{\sinh(2kh)}), \quad c = \frac{\omega}{k}, \quad c_s = \sqrt{gh}, \quad \omega^2 = gkT$$

Shallow water Snl

$$f(k,h) = \frac{R^2}{T^8 \frac{\partial v_g}{\partial k}} \qquad R = \frac{9T^4 - 10T^2 + 9}{8T^3} - \frac{1}{kh}\left\{ \frac{(2v_g - c/2)^2}{c_s^2 - v_g^2} + 1 \right\}$$

R^2



kh=1.363

$$T = \tanh(kh),$$

$$v_g = 0.5c\left(1 + \frac{2kh}{\sinh(2kh)}\right),$$

$$c = \frac{\omega}{k}, \quad c_s = \sqrt{gh},$$

$$\omega^2 = gkT$$

ECMWF

Sbottom:

S_{bottom} (see Komen et al. 1994):

$$S_{bottom} = -2\,C_{bot}\,\frac{k}{\sinh(2\,k\,h)}$$

$$C_{bot} = \frac{0.038}{g}$$

Bottom induced wave breaking:

Dissipation due to bottom induced wave breaking was added to the source terms. Following Battjes, Janssen and Beji:

$$S_{dis} = -C_{BJ}\alpha Q_b \langle f \rangle F(f,\theta)$$

$$H_{max} = \gamma h \qquad \alpha = 2\frac{H_{max}^2}{H_s^2}$$

Q_b : fraction of breaking waves $\qquad Q_b = \exp\{-\alpha(1-Q_b)\}$

$$breaker\ parameter\ \gamma = 0.6$$

$C_{BJ} = 1 \qquad \langle f \rangle = mean\ frequency$

Coupling to the waves: Warm skin layer model

- **Following Takaya et al. (JGR 2010), a skin layer model is used to represent the Daily SST Amplitude.**

Stokes drift

- **In this scheme, the temperature profile is controlled by the turbulent diffusivity $K_w(z)$:**

$$K_w(z) = \frac{-\kappa z u_w^* f(L_a)}{\phi_h(z/L)}$$

Langmuir number $$L_a = \sqrt{\frac{u_w^*}{U_{Stokes}}}$$

- **Following Grant and Belcher (JPO 2009),**

for stable condition only and for $f(L_a) > 1$:

$$f(L_a) = \frac{1}{L_a^{2/3}}$$

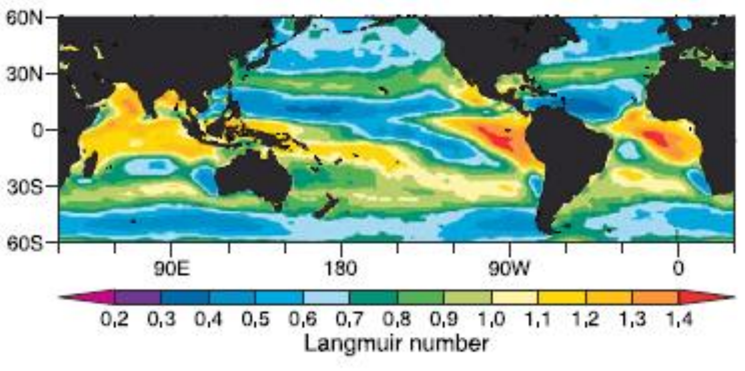


Figure 4. The average of the Langmuir number computed with forecasts starting from 1 January 1990–2007.

u_w^* : friction velocity in water $\phi_h(z/L)$: similarity function, L: Obukhov length

Data assimilation:

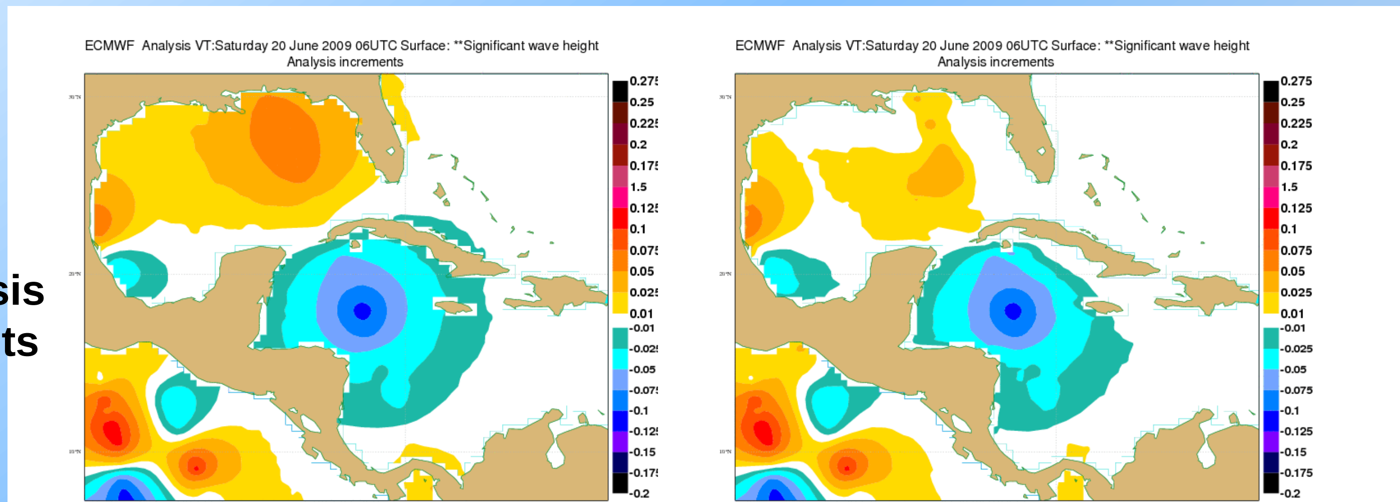
- Currently only using Jason-2 wave heights.
- Resuming use of Jason-1 under evaluation.
- Still using the Optimum Interpolation scheme from Lionello et al. (1992).
- Some minor adaptations:

Land recognition:

The model background error should recognize the presence of land

default | **Land detected**

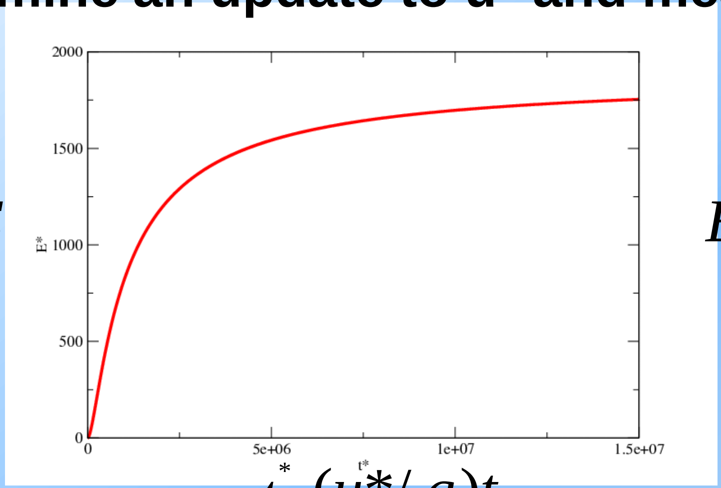
Hs analysis increments



Shallow water spectral update:

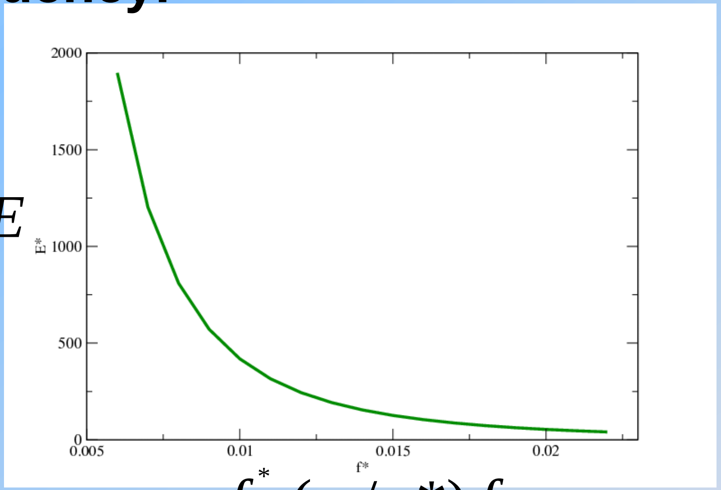
Windsea update relies on deep water model growth curves in order to determine an update to u* and mean frequency:

$$E^* = \left(\frac{u^{*4}}{g^2}\right) E$$



$$t^* = (u^*/g)\,t$$

$$E^* = \left(\frac{u^{*4}}{g^2}\right) E$$

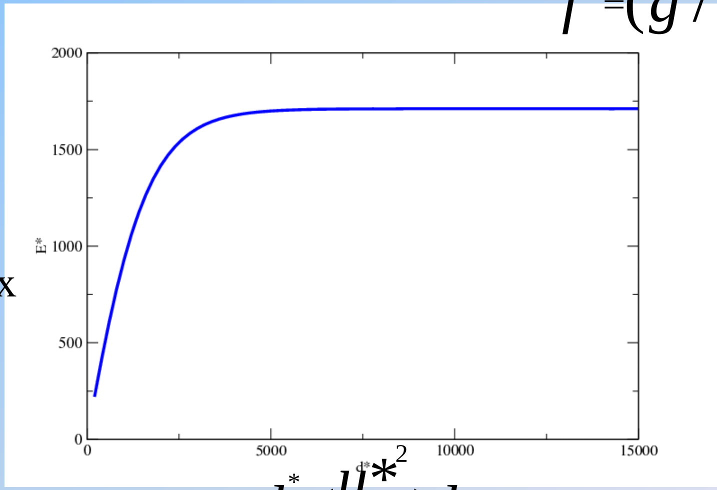


$$f^* = (g/u^*)\,f$$

But in shallow water E* is limited by depth,

Hence use deep water relation <u>but</u> only to E^*_{max}

E^*_{max}



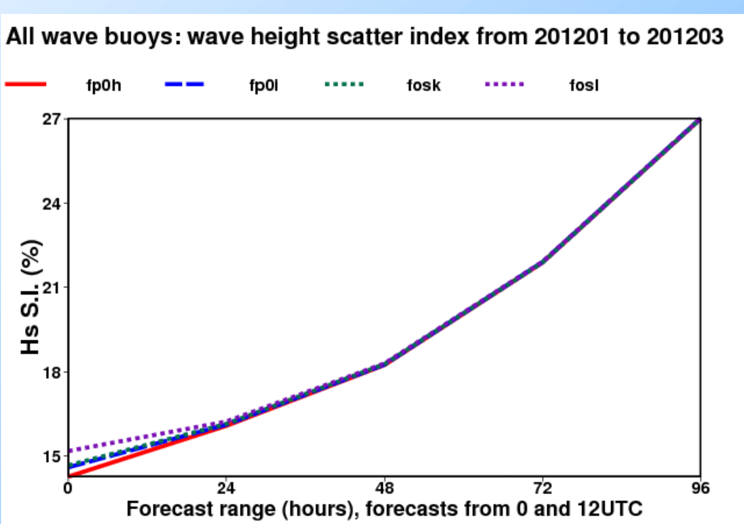
$$d^* = \left(\frac{u^{*2}}{g}\right) d$$

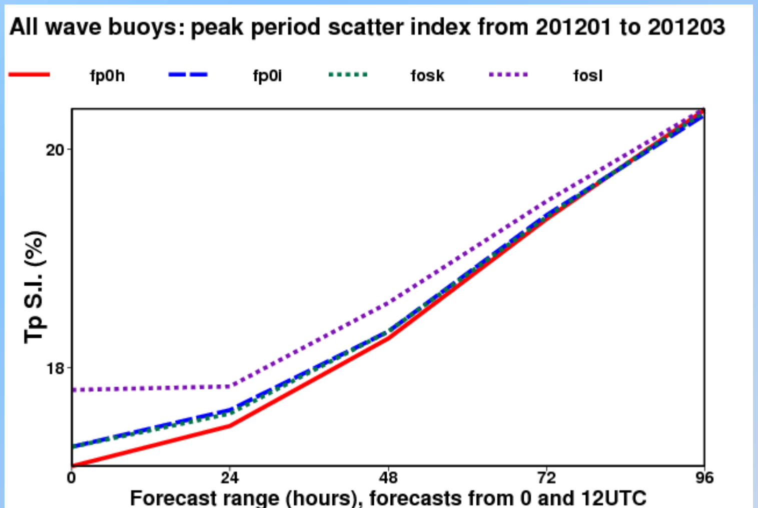
ECMWF

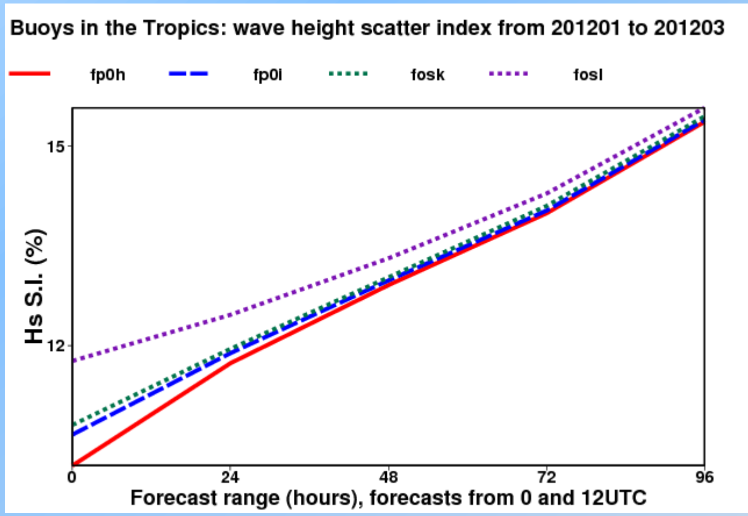
Data assimilation

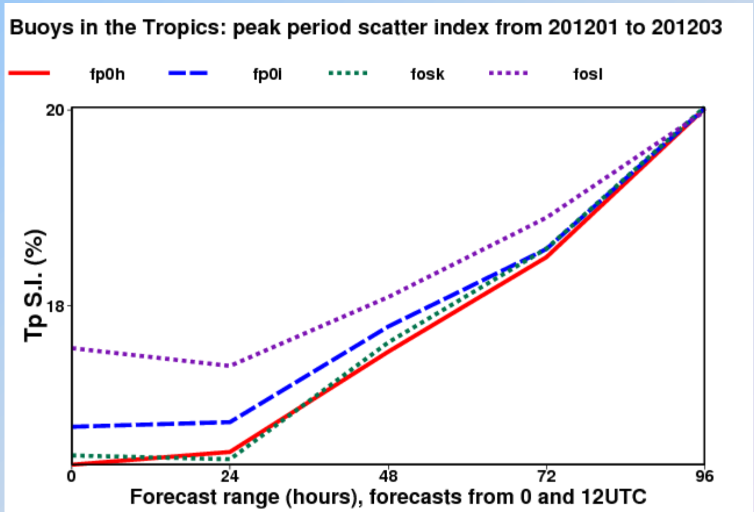
- Impact still limited:

Jason-2 + ENVISAT
Jason-2
ENVISAT
No data







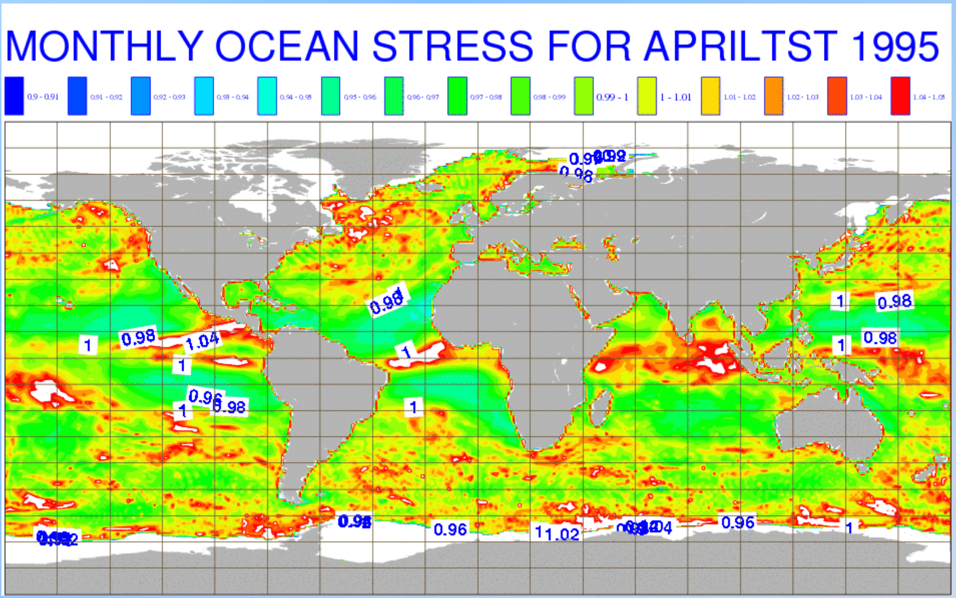


Products:

- All “standard” wave parameters in the operational catalogue.
- Including wave spectra.
- A few ‘freak wave parameter’, including Hmax.
- New set of parameters to include wave effects on the ocean fluxes:

New parameters:

- A small portion of the stress is retained by the wave field to be released later.
- Hence, one can compute the stress that is actually acting on the oceans.



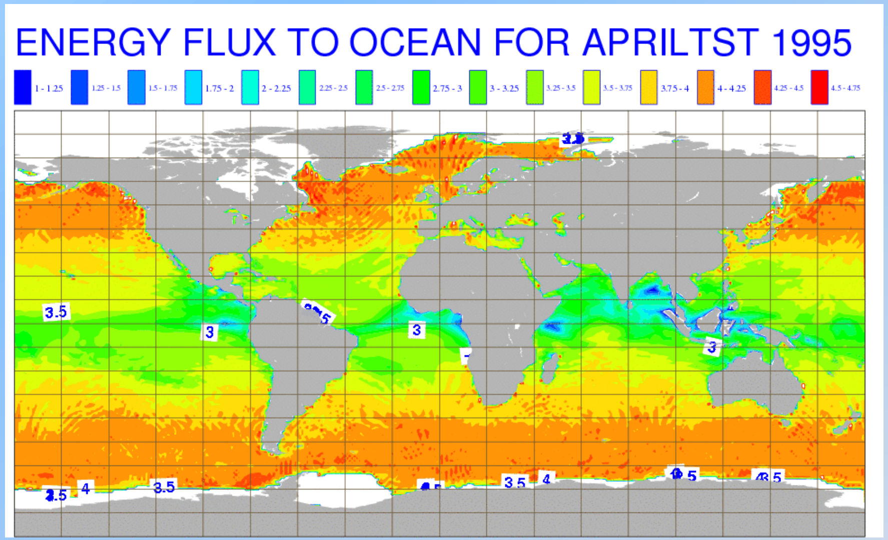
Monthly mean of the <u>normalised</u> stress into the ocean as derived from ERA-Interim data

Slide 30

It is normalised by $\rho_a u_*^2$

New parameters

- Similar consideration can be made for the energy fluxes passing first into the waves.
- It is then dissipated by the waves and transferred into the upper oceans where it will contribute to the mixing of the top of the oceans.
- Both quantities are connected to the wave model source terms.

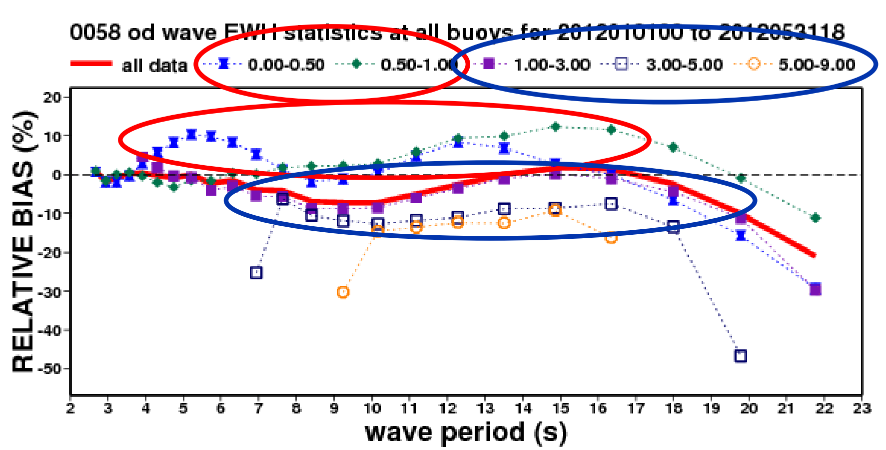


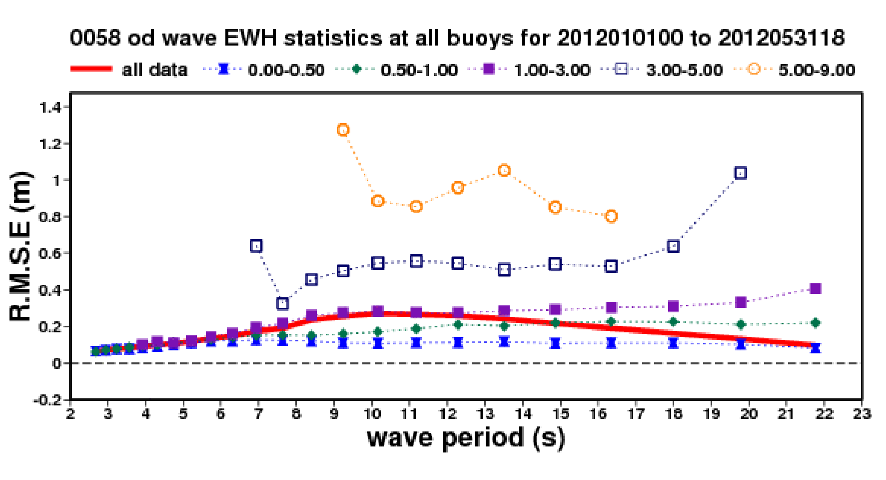
Monthly mean of the <u>normalised</u> energy flux into the ocean as derived from ERA-Interim data.

It is normalised by $\rho_a u_*^3$

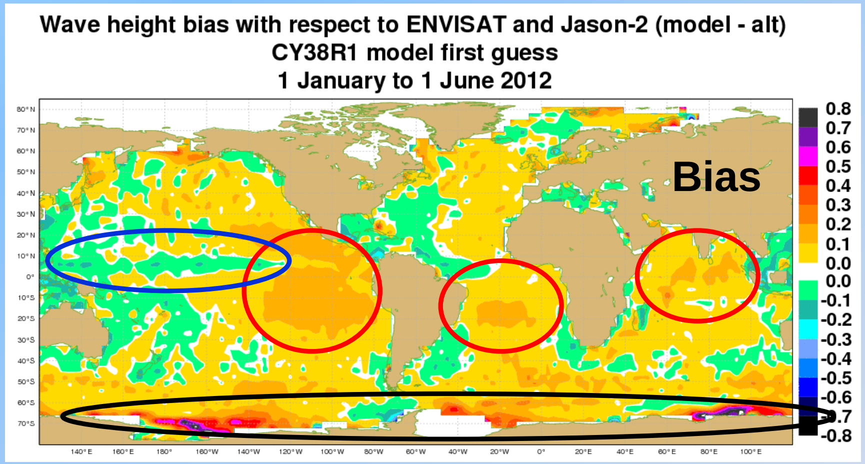
Can we still improve ?

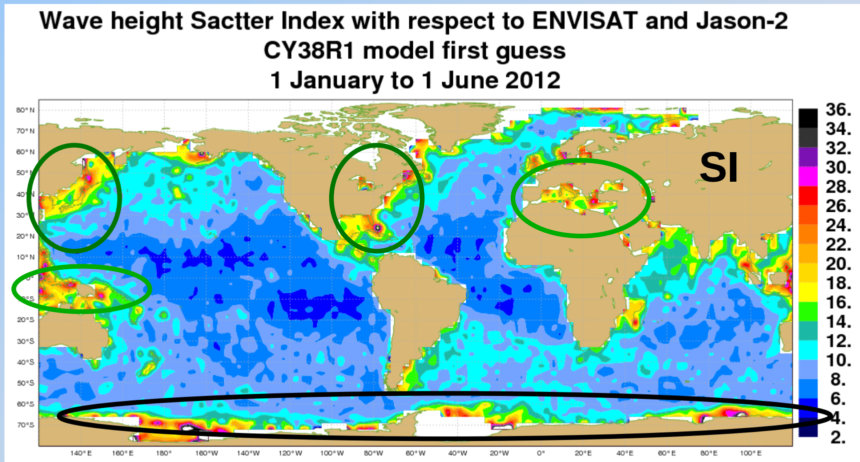
Comparison to buoy spectra, stratified by energy level:





Comparison to altimeter wave heights :

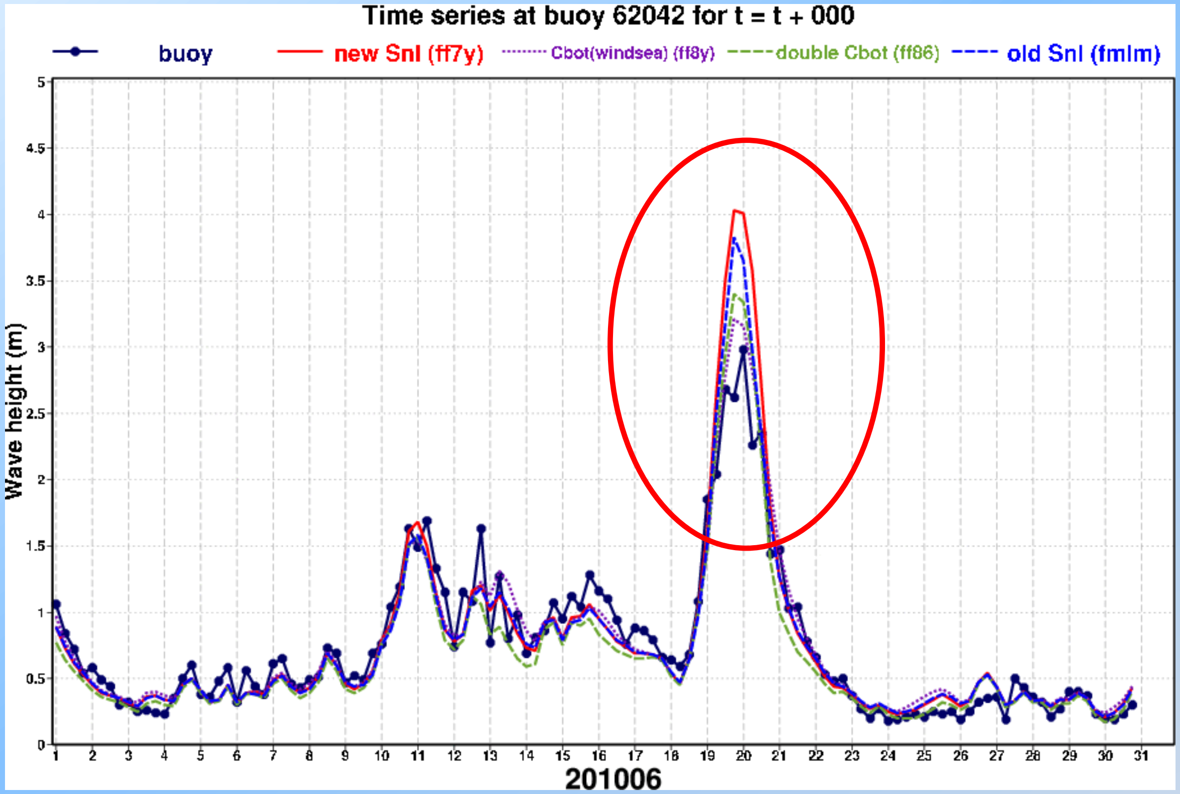




Latest CY38R1 compared to observations, January to May 2012

Can we still improve ?

Shallow water issues:

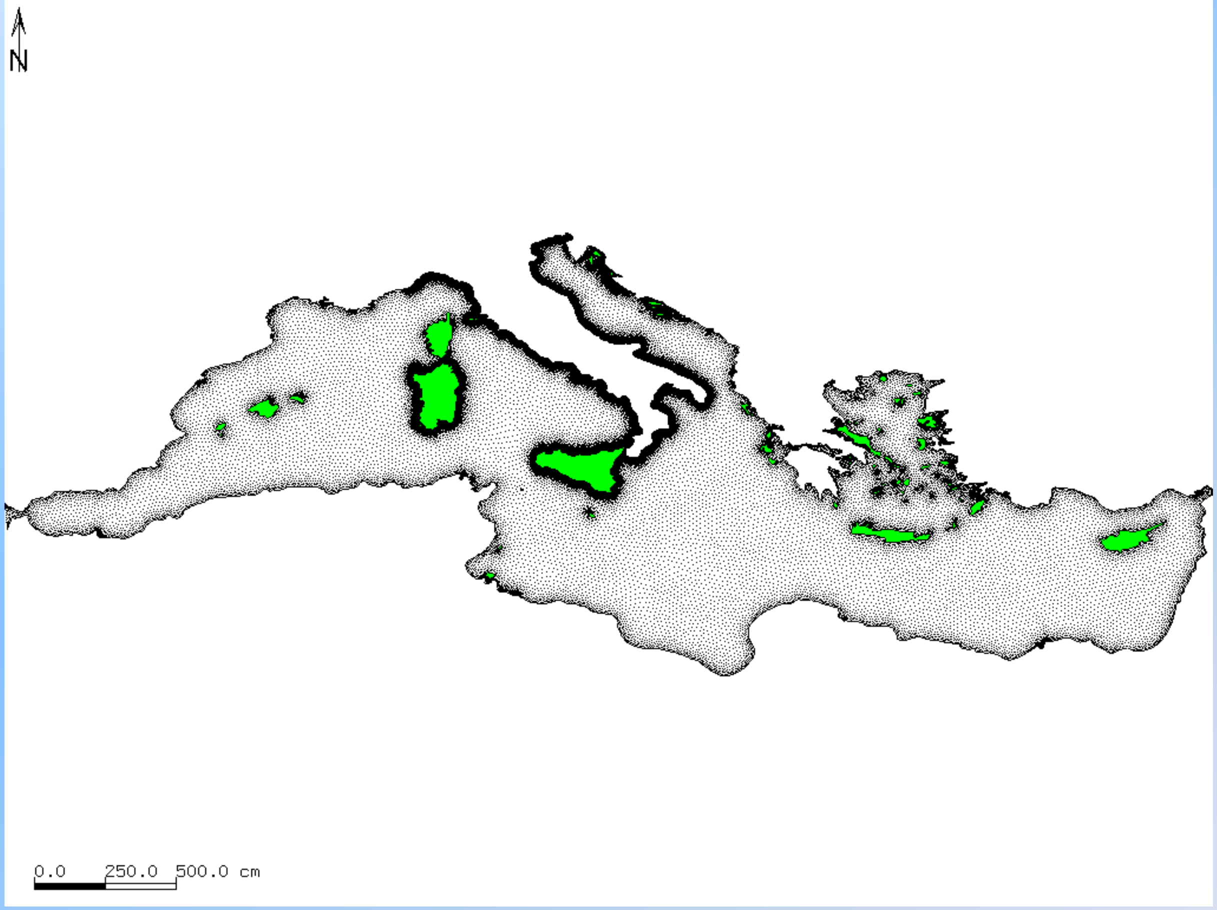


62042: UK CEFAS buoy, located on the north shore of East Anglia in 18m of water

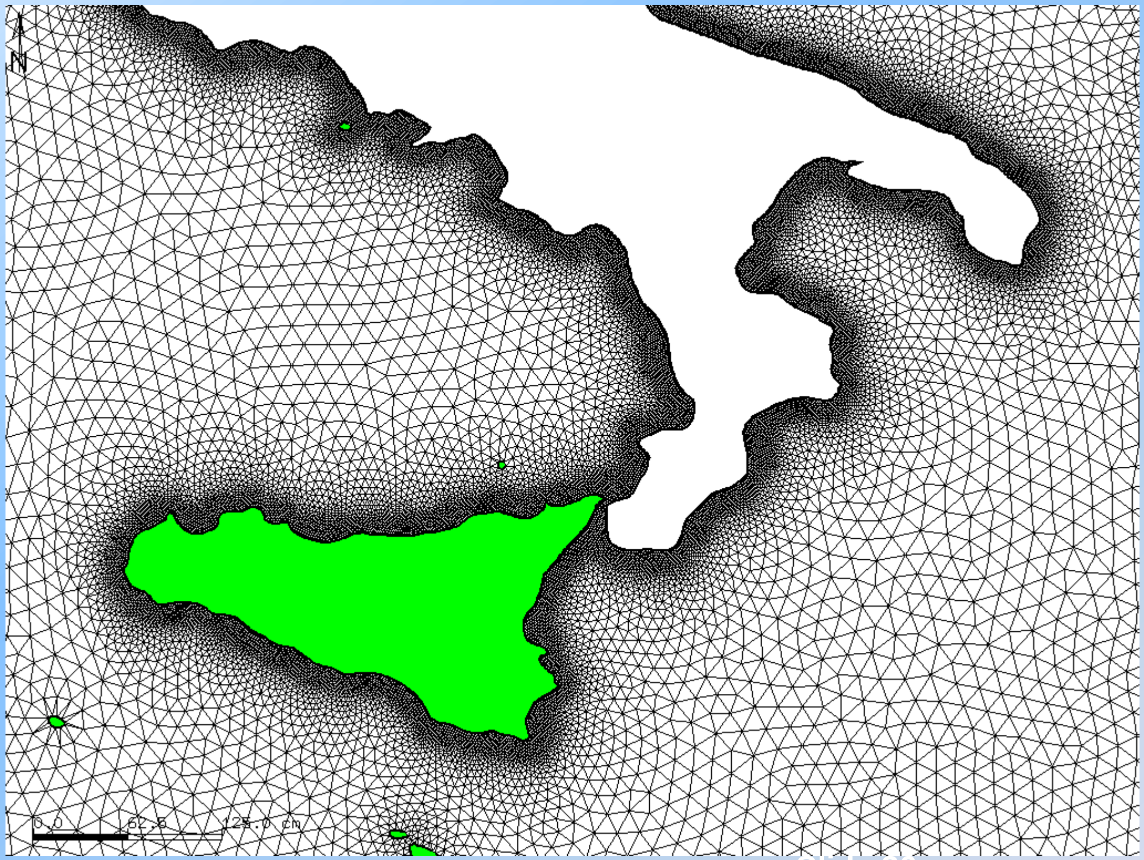
Ongoing developments:

- Integration of the atmosphere-wave-ocean models.
- Unstructured grid option.
- Sea ice damping.
- Sbottom.
- …
- Many more following this workshop…

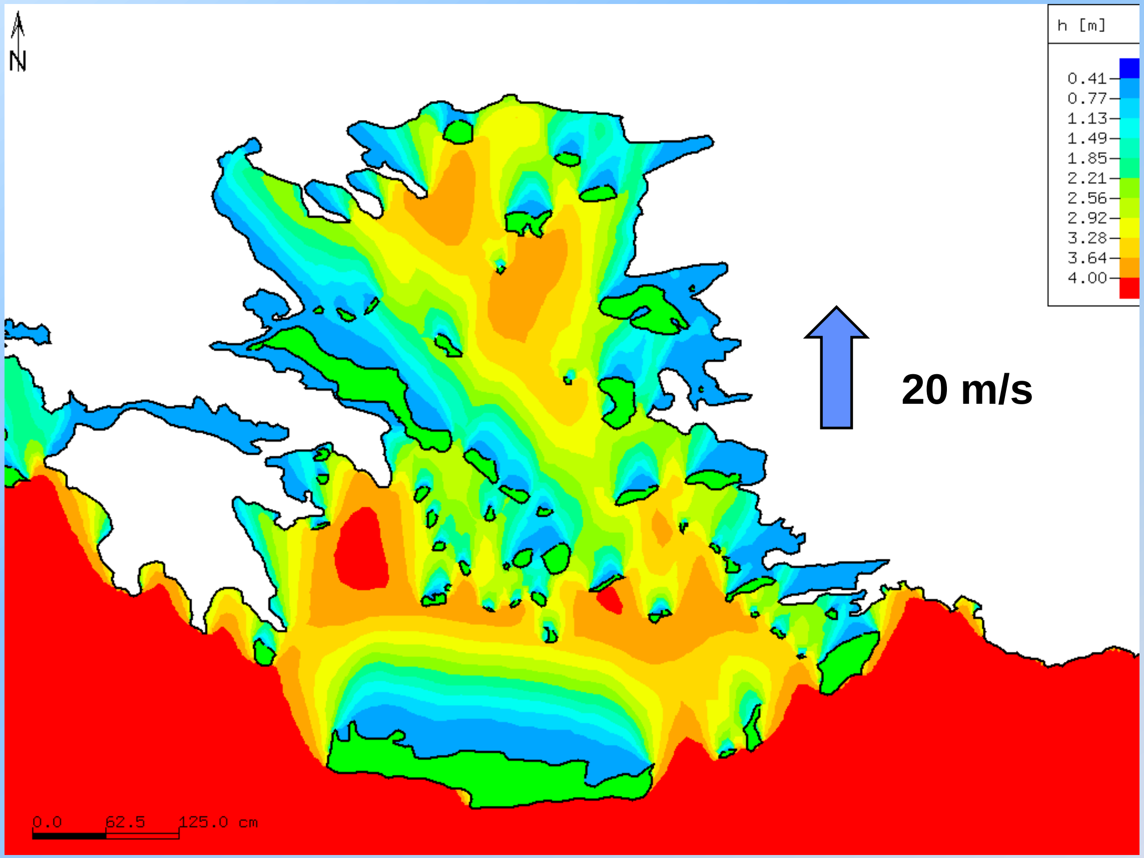
Future developments: unstructured grid



Future developments: unstructured grid



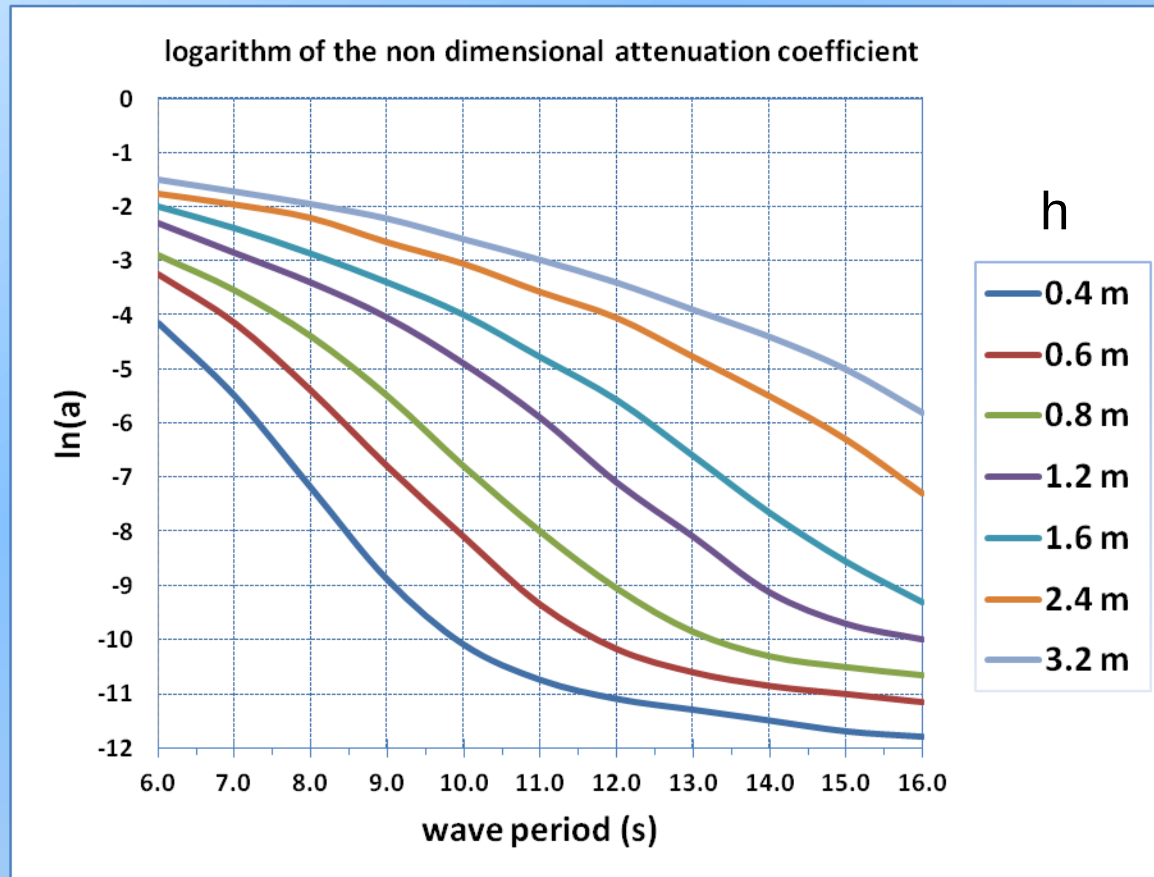
Future developments: unstructured grid



Future developments: sea ice damping:

$$\alpha = ci\,\frac{a}{2\overline{D}}$$

The non-dimensional attenuation coefficient “a” was found to depend only on wave period and sea ice thickness “h”

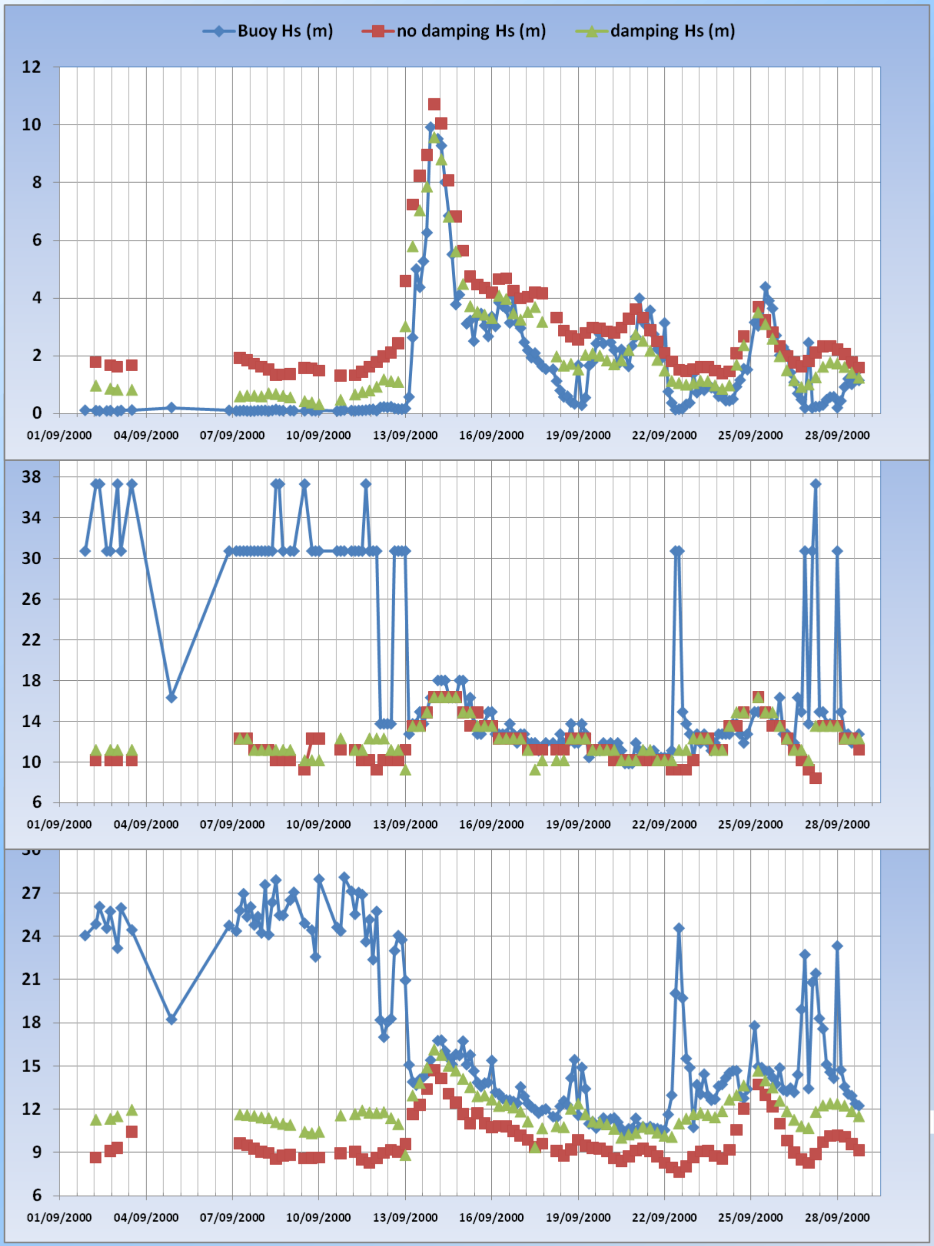


From Kohout and Meylan (JGR 2008), Figure 6.

Hs (m)

Tp (s)

Tm (s)



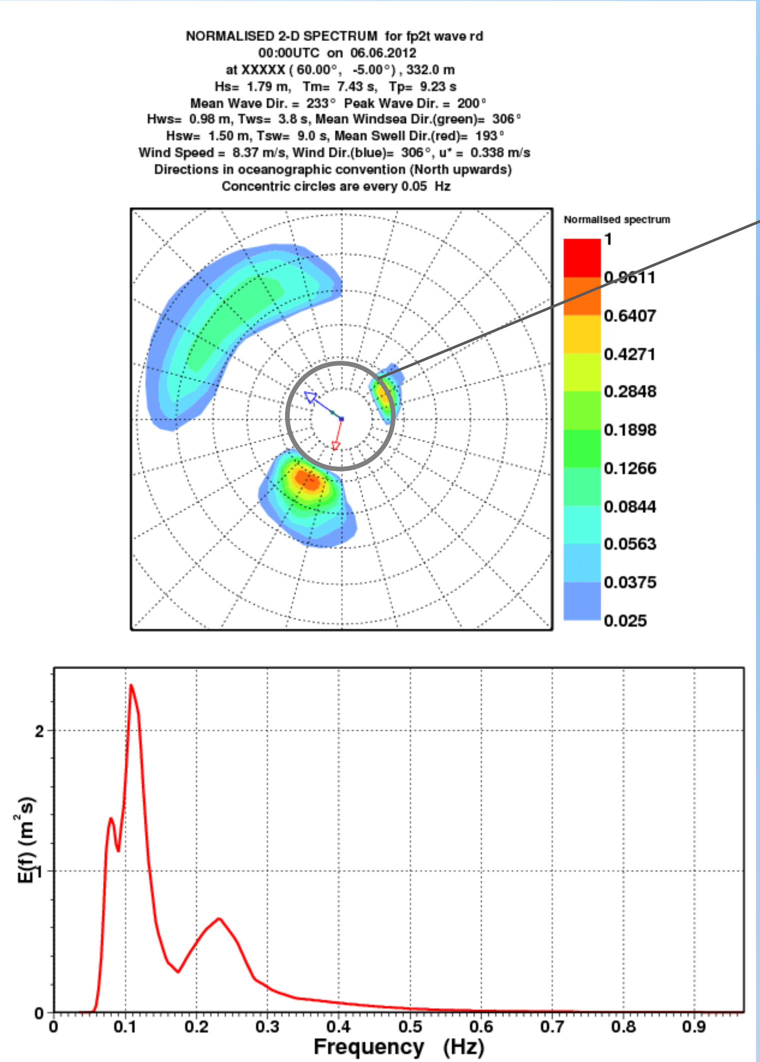
Raw buoy data (further QC still needed!)

Model, with wave propagation only When sea ice cover > 30%

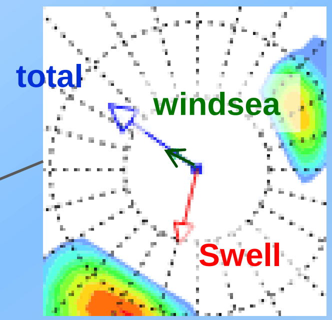
Model, with sea ice damping up to sea ice cover of 90% (ci_{block}=0.9)

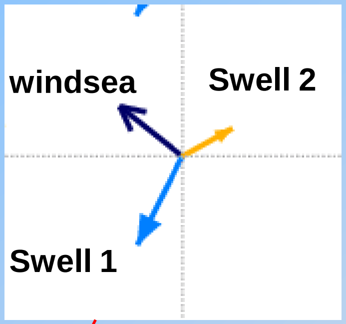
Questions/comments?

Future developments: spectral partitioning

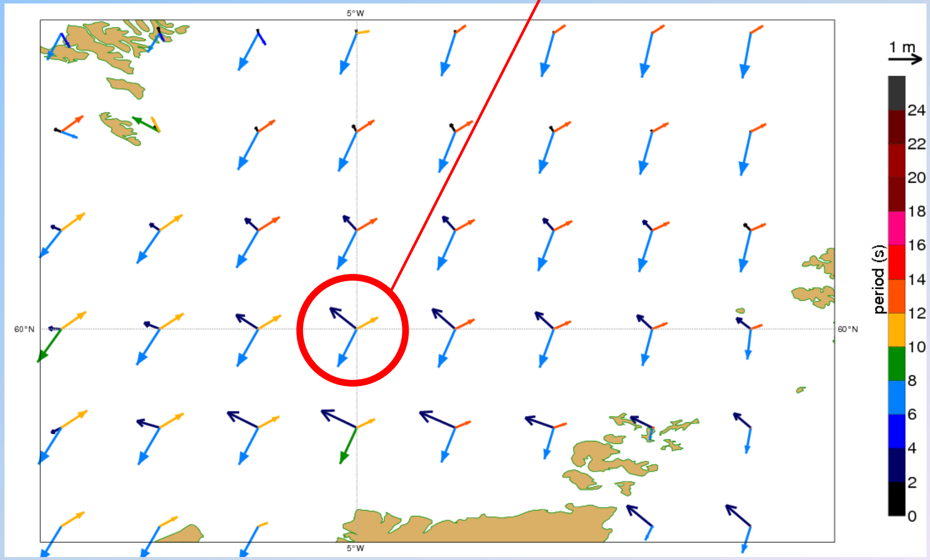


Operational:





New decomposition:



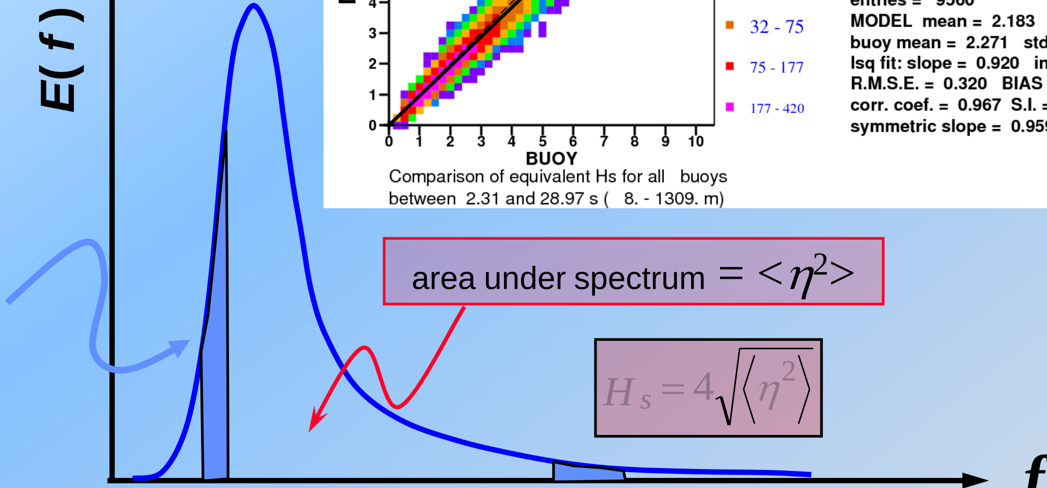
ECMWF

Verification against buoy frequency spectra

EWH,
Equivalent Wave Height
for a given frequency bin:

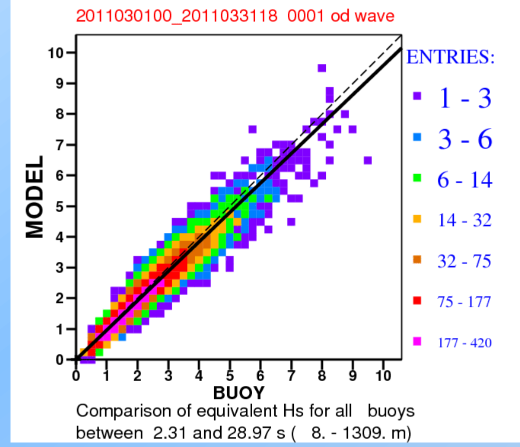
$$EHW = 4\sqrt{A}$$

where A is the area under curve for a given frequency bin



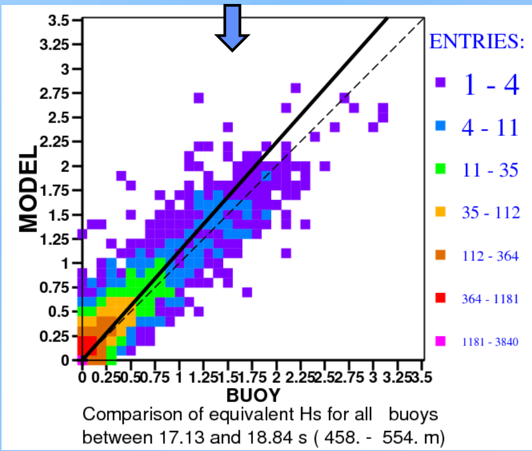
area under spectrum $= \langle \eta^2 \rangle$

$$H_s = 4\sqrt{\langle \eta^2 \rangle}$$



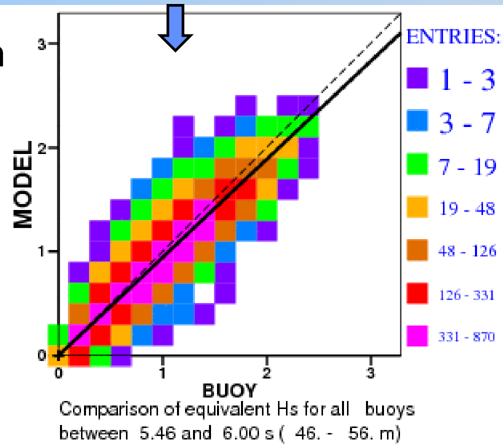
Hs,
significant wave height.

entries = 9560
MODEL mean = 2.183 stdev = 1.140
buoy mean = 2.271 stdev = 1.198
lsq fit: slope = 0.920 intr = 0.094
R.M.S.E. = 0.320 BIAS = -0.088
corr. coef. = 0.967 S.I. = 0.135
symmetric slope = 0.959



EWH for waves with periods between 17s and 19s.

entries = 9560
MODEL mean = 0.216 stdev = 0.334
buoy mean = 0.165 stdev = 0.314
lsq fit: slope = 0.969 intr = 0.056
R.M.S.E. = 0.147 BIAS = 0.051
corr. coef. = 0.911 S.I. = 0.836
symmetric slope = 1.120



EWH for waves with periods between 5.5 s and 6.0 s.

entries = 9560
MODEL mean = 0.894 stdev = 0.442
buoy mean = 0.953 stdev = 0.456
lsq fit: slope = 0.905 intr = 0.031
R.M.S.E. = 0.176 BIAS = -0.060
corr. coef. = 0.933 S.I. = 0.173
symmetric slope = 0.944