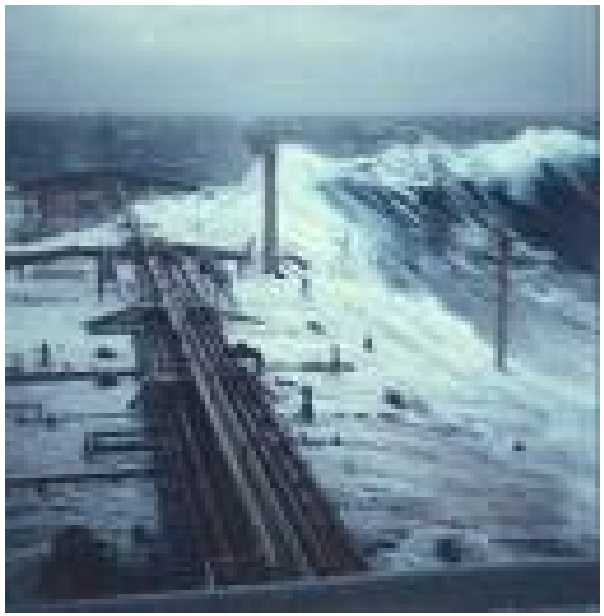
Rogue (Freak) Waves: Measurements, Statistics, and Prediction

Peter C. Chu
Naval Ocean Analysis and Prediction Laboratory
Naval Postgraduate School
http://faculty.nps.edu/pcchu
pcchu@nps.edu
831-656-3688 (O)
831-656-3686 (F)

Rogue (Monster) Waves

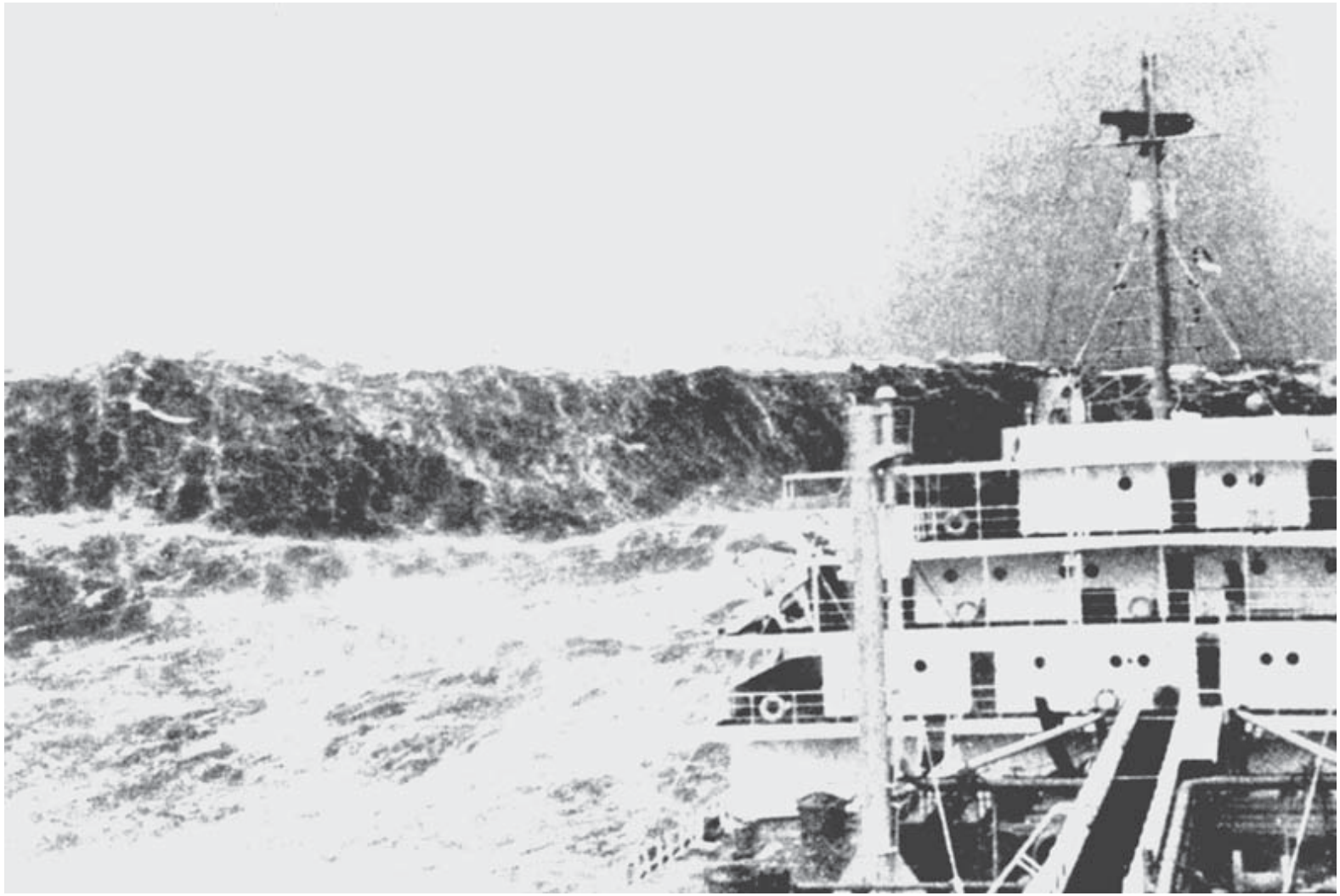








An extreme wave, a so-called “white wall”, approaching a merchant vessel in the Bay of Biscay (NOAA Picture Gallery)



The Wilstar after being hit by a Rogue wave in the Agulhas current

- To develop standards for the design of ship hulls, one must predict not only the likelihood of rogue waves but also the forces that they exert on the hull.



Outlines

- (1) What is a rogue (freak) wave?
- (2) Some statistics
- (3) Wave measurements
- (4) Mechanism and prediction
- (5) Effects of rogue (freak) waves on ships (DDG 1000) and offshore structures

(1) What is a rogue (freak) wave?

$$H_{max}/H_s > 2$$

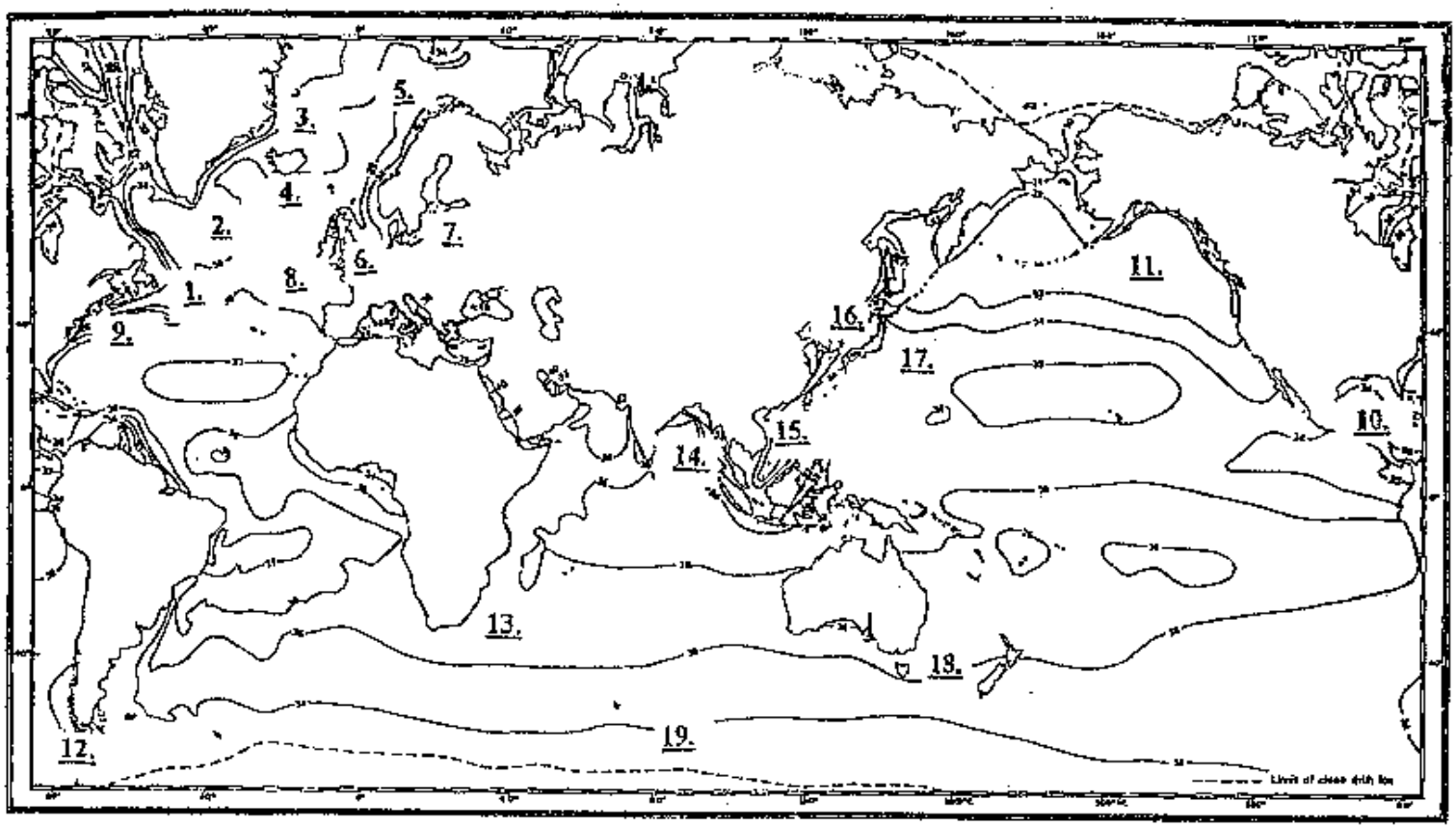
How high can this ratio be?

Areas with Rogue Waves

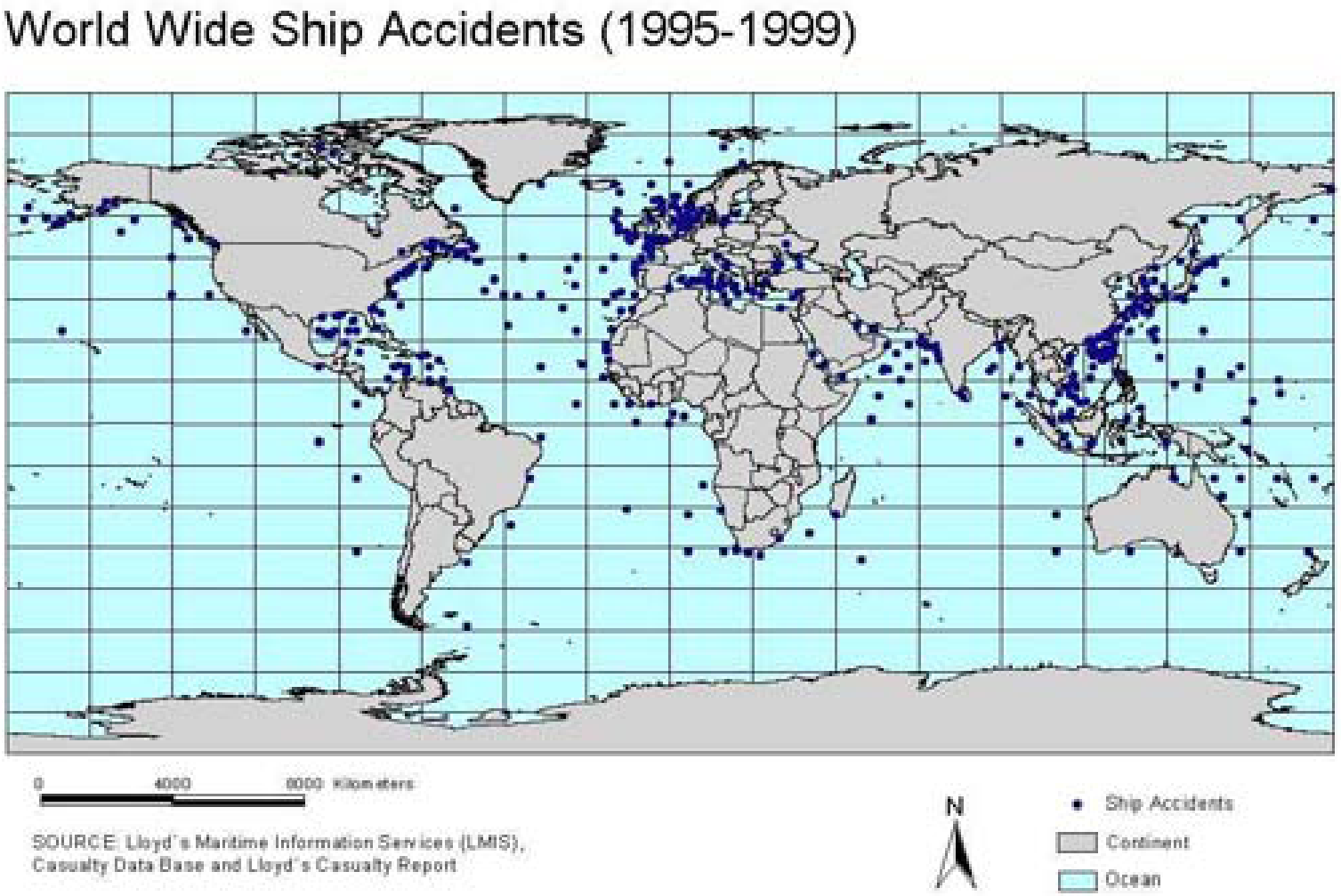
1	New Foundland Banks
2	The Sea south of Greenland
3	Coastal areas near Iceland
4	Coastal areas near Færø Islands
5	Coastal areason the Norwegian coast
6	The North sea
7	The Baltic Sea

8	The Biscay Bay
9	Gulf Stream on the east coast of USA.
10	The Mexican Gulf
11	The Sea west of British Columbia.
12	The Sea near Cap Horn
13	Aghulhas current east of South Africa
14	The Bengal Sea

15	The South China Sea
16	The Japan Sea
17	The Pacific Sea east of Japan
18	Coastal areas near Australia
19	Areas south of 40 degr. South
20	Mediterranean Sea
21	Great Lakes

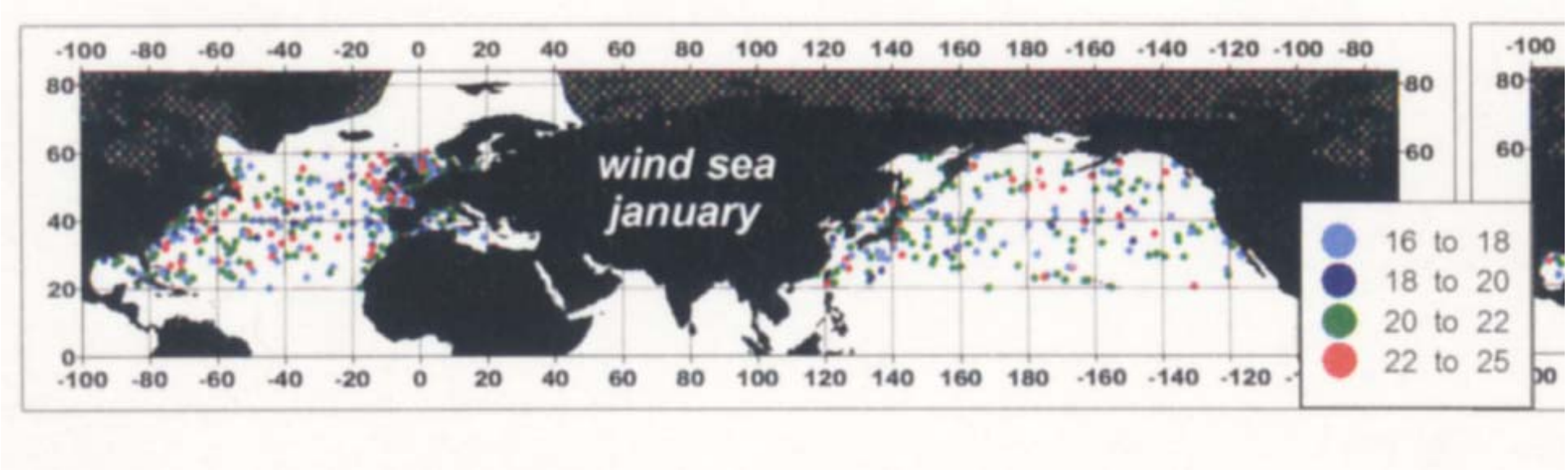


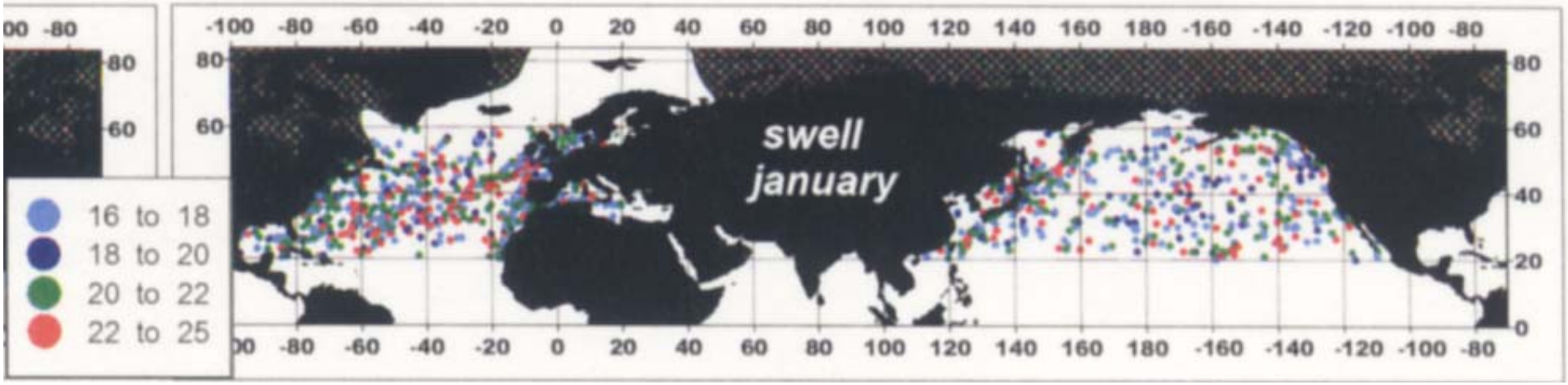
Ship accidents (1995-1999) from Hapag Loyds database

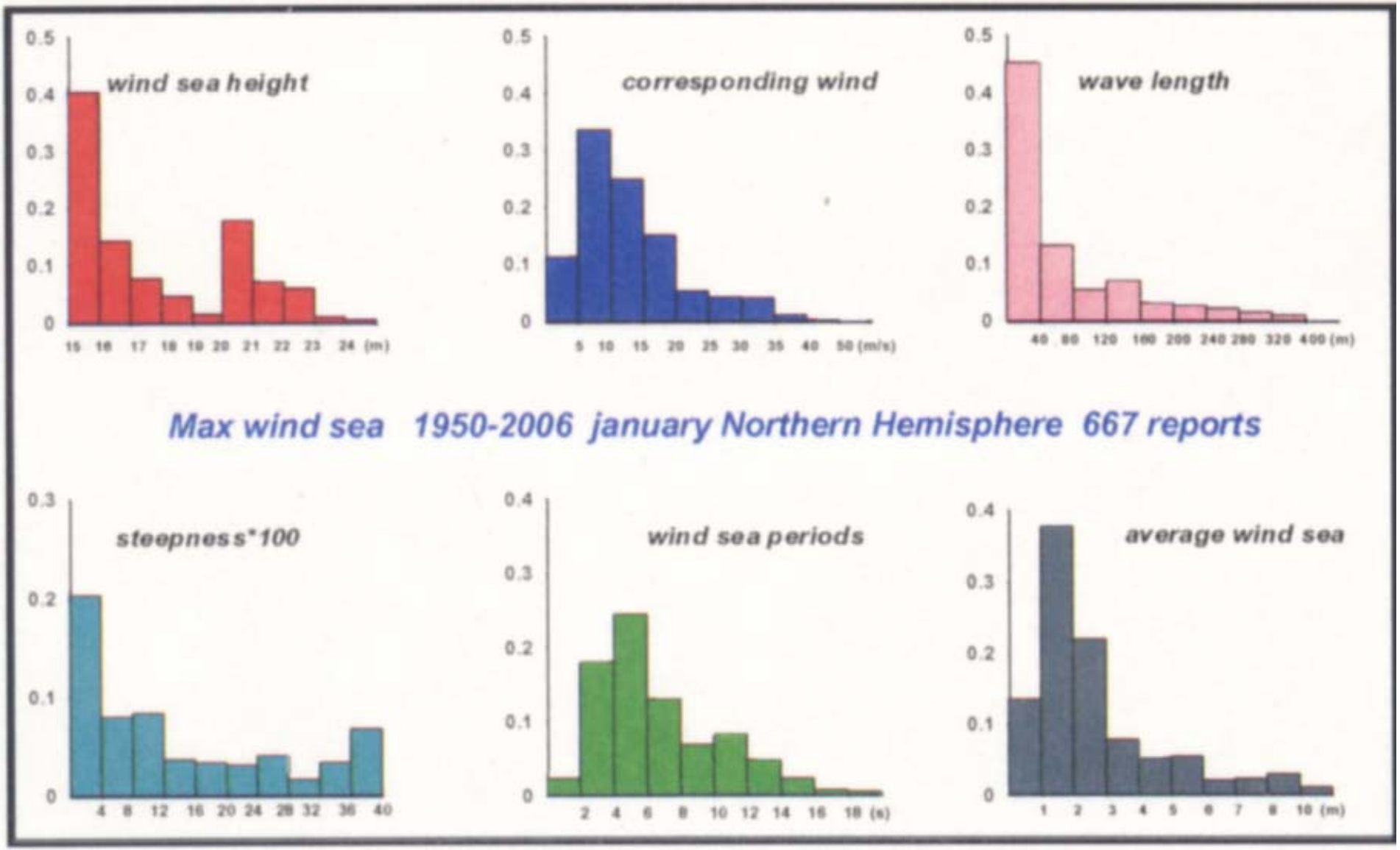


(2) Some Statistics

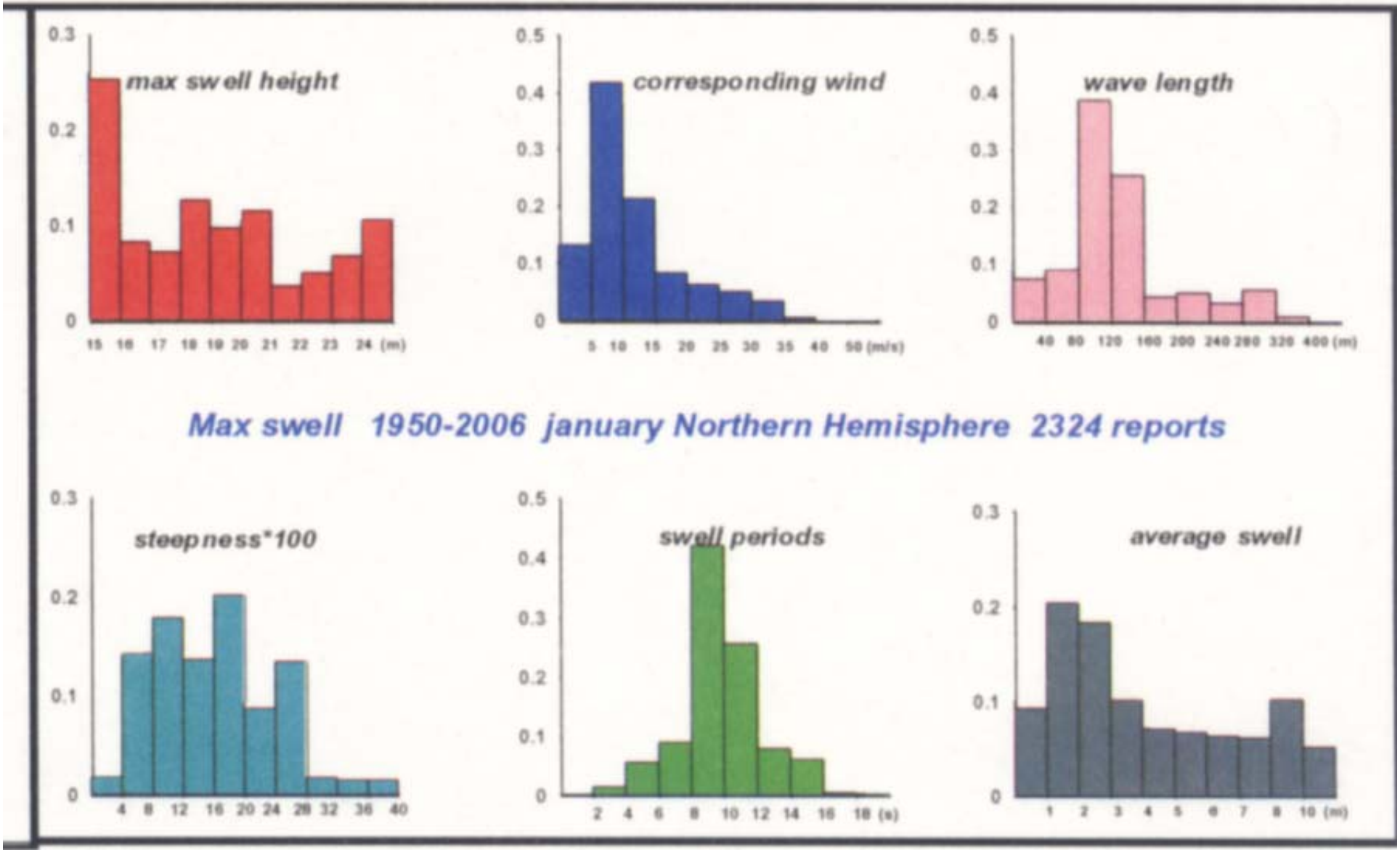
Extreme wind sea and swell height (m) January 1950-2006 (Grigorieva & Gulev 2008)







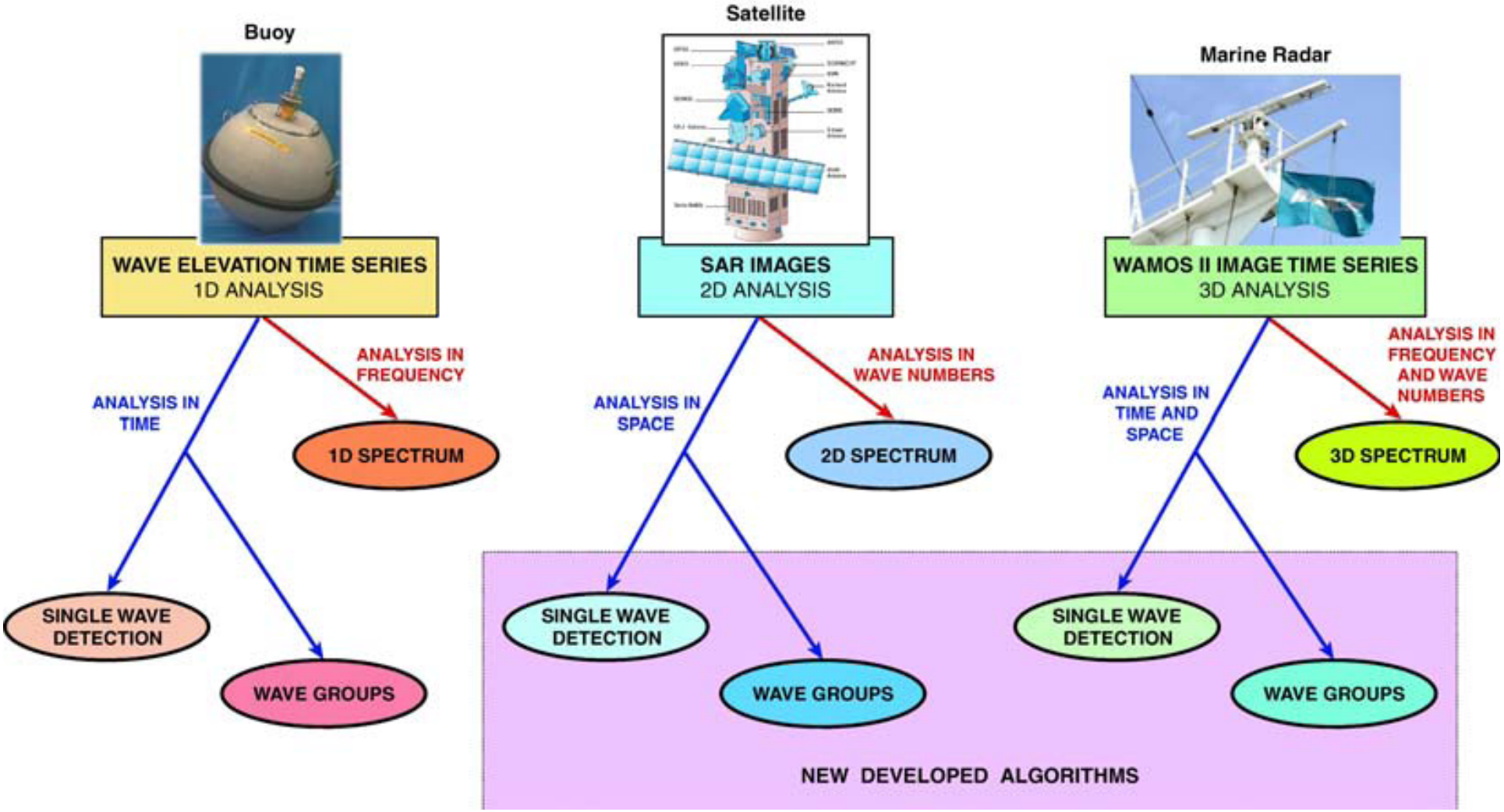
Grigorieva & Gulev (2008)



Grigorieva & Gulev (2008)

Gr

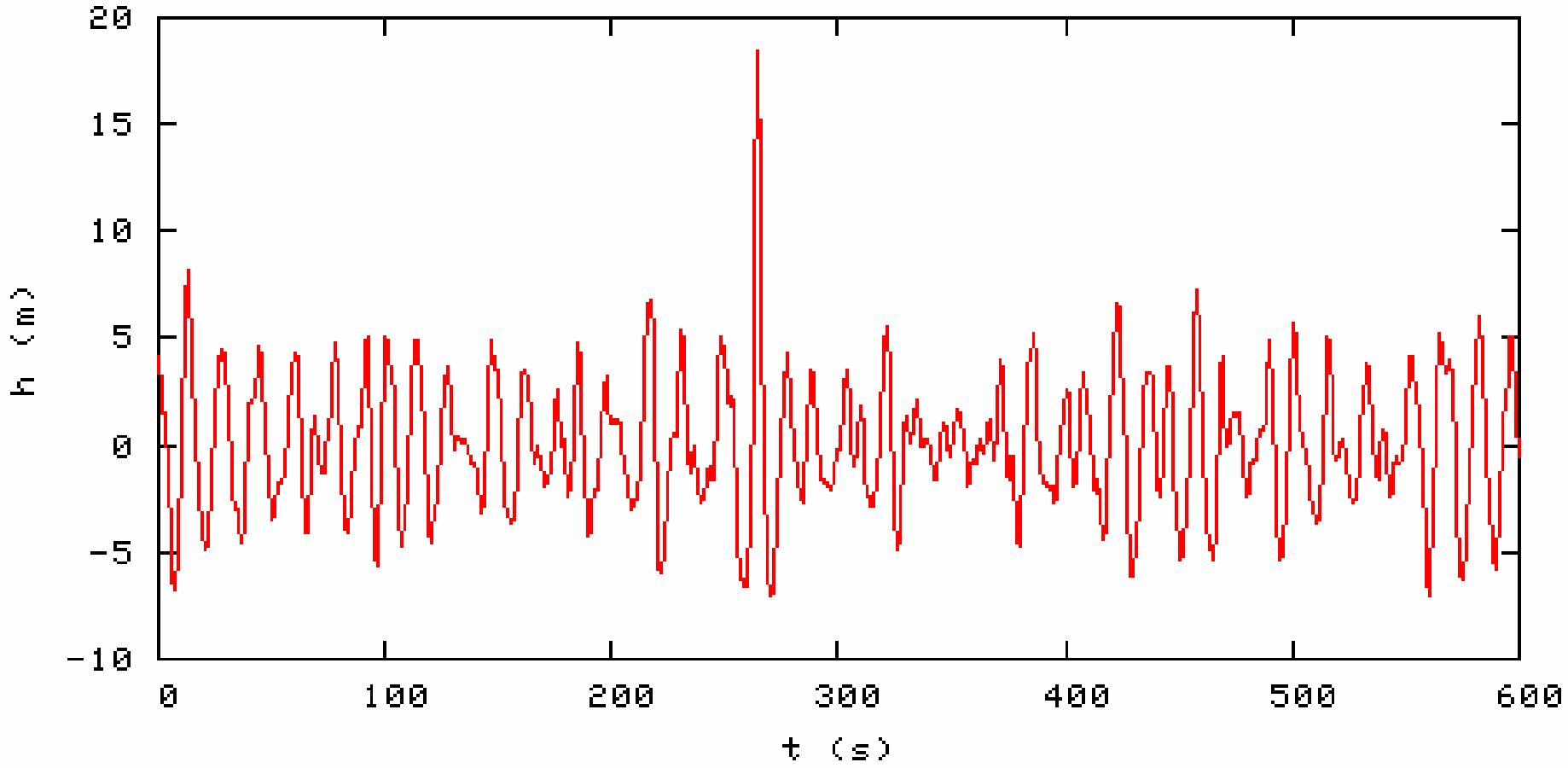
(3) Wave Measurements



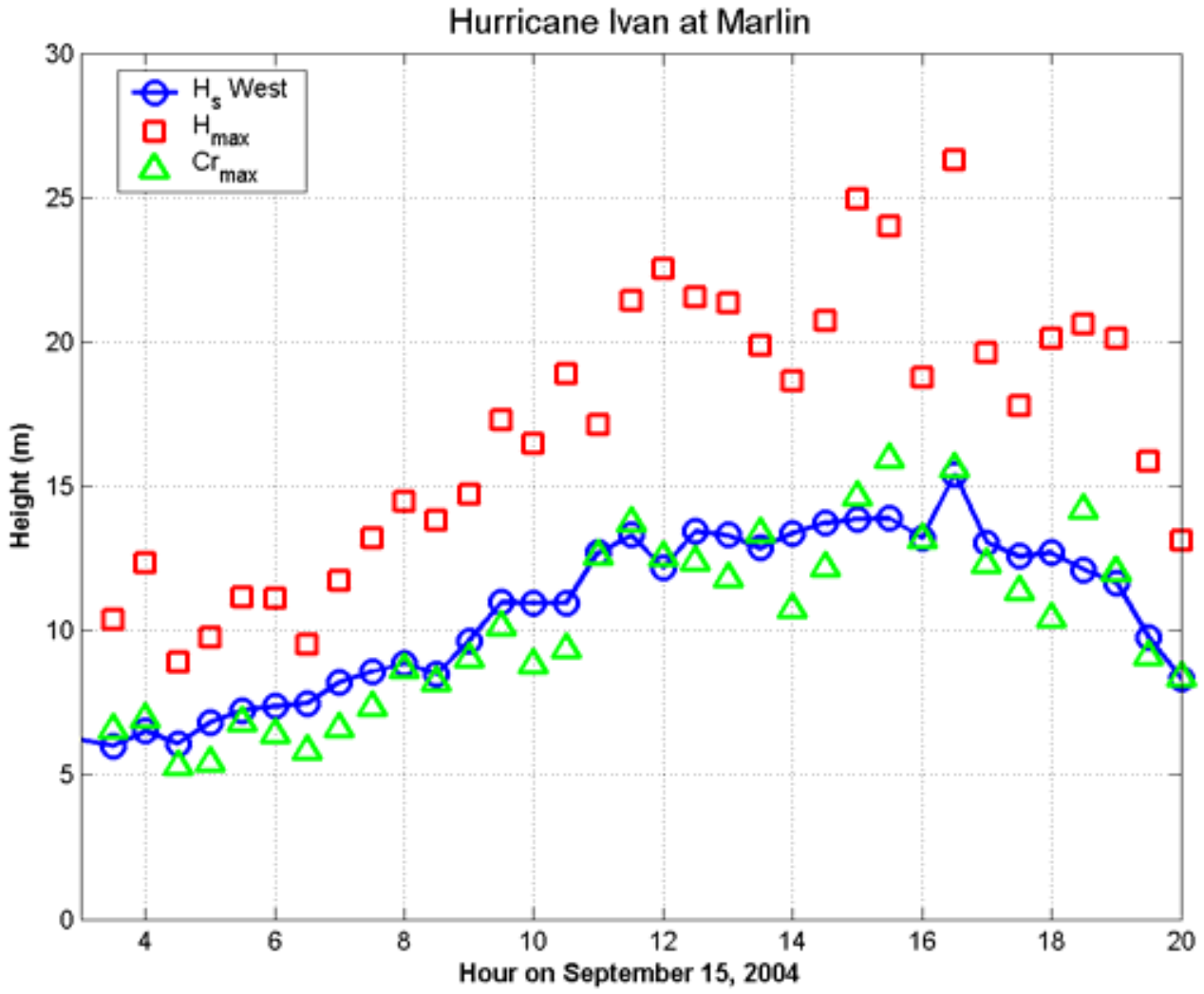
Limitation

- Most wave observation is near the coast, such as at the offshore structure, very few near the ship!

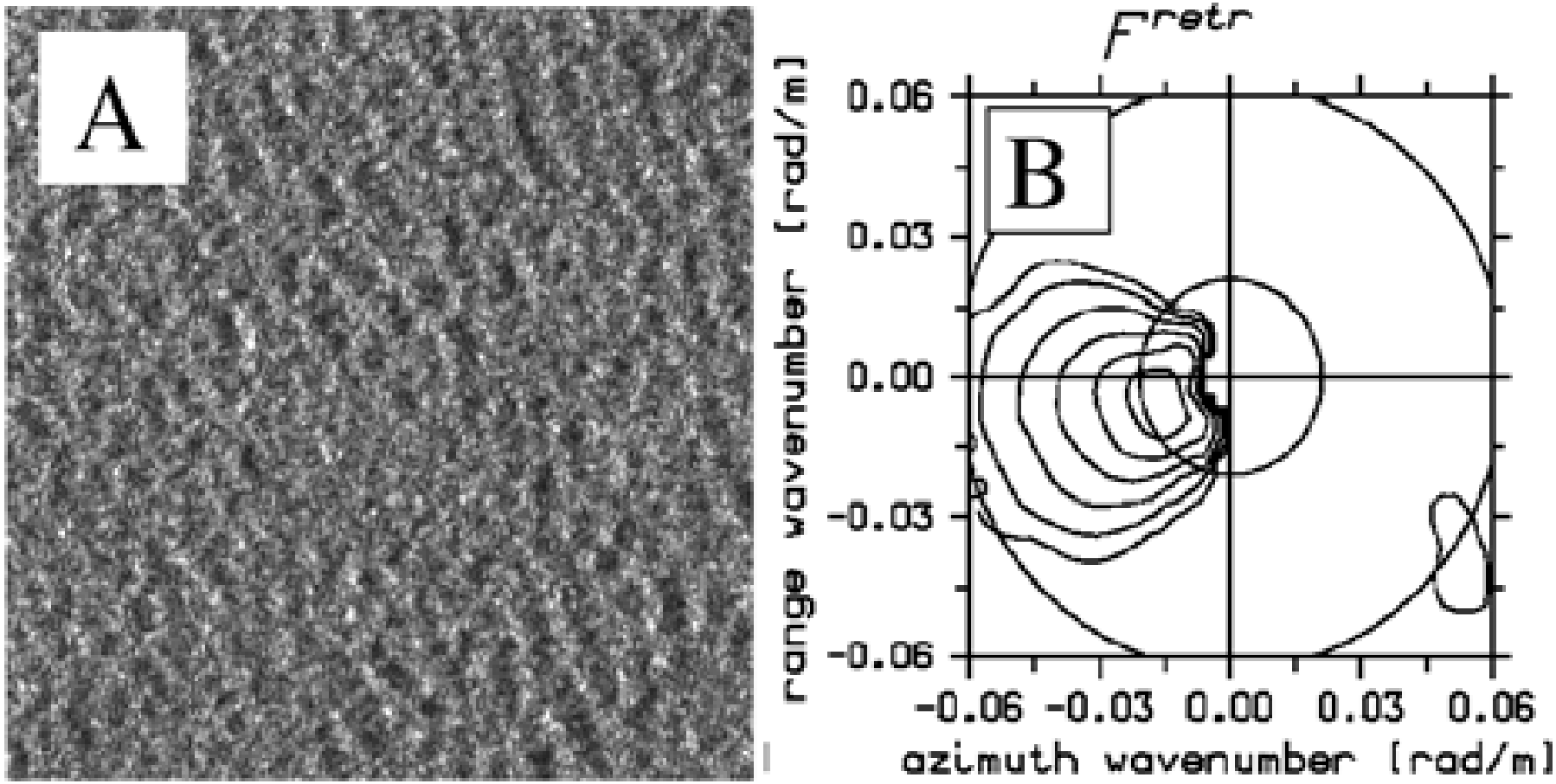
Wave elevation at the Draupner platform (58.1°N, 2.28°E) → Draupner wave, January 1, 1995



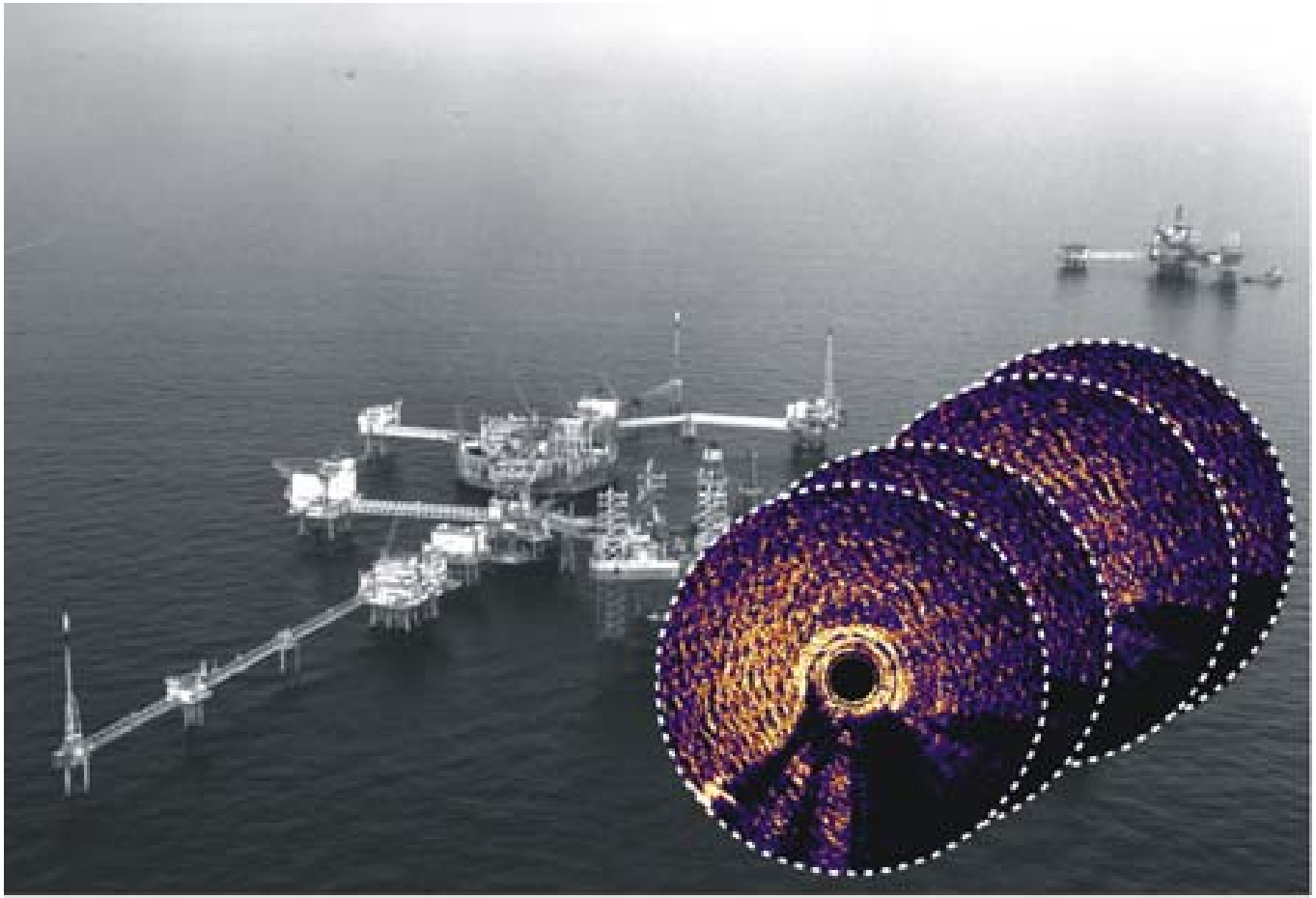
Wave and crest heights measured during Hurricane Ivan at the Marlin platform in the Gulf of Mexico (Forristall 2005)



SAR → 2D Spectrum (Wavenumber)



Marine radar measurements
3D ←→ 2D + time
Spectrum of Wavenumber & Frequency



Wave Measurement from a Marex Wave Recorder

(Liu and **MacHutchon, 2005)**

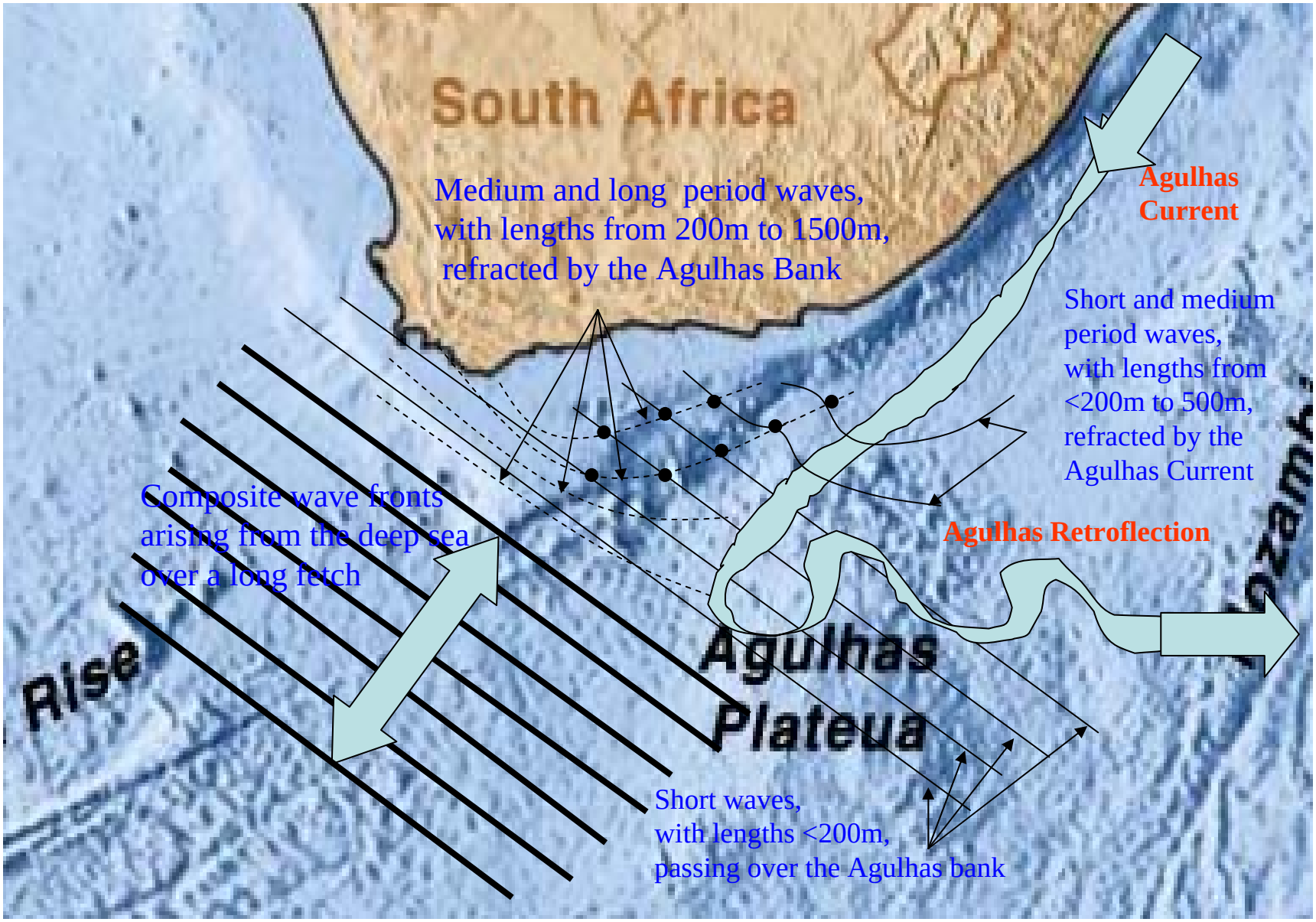
Significant wave height (H_s)

Maximum wave height (H_{max})

Average zero crossing wave period (T_z)

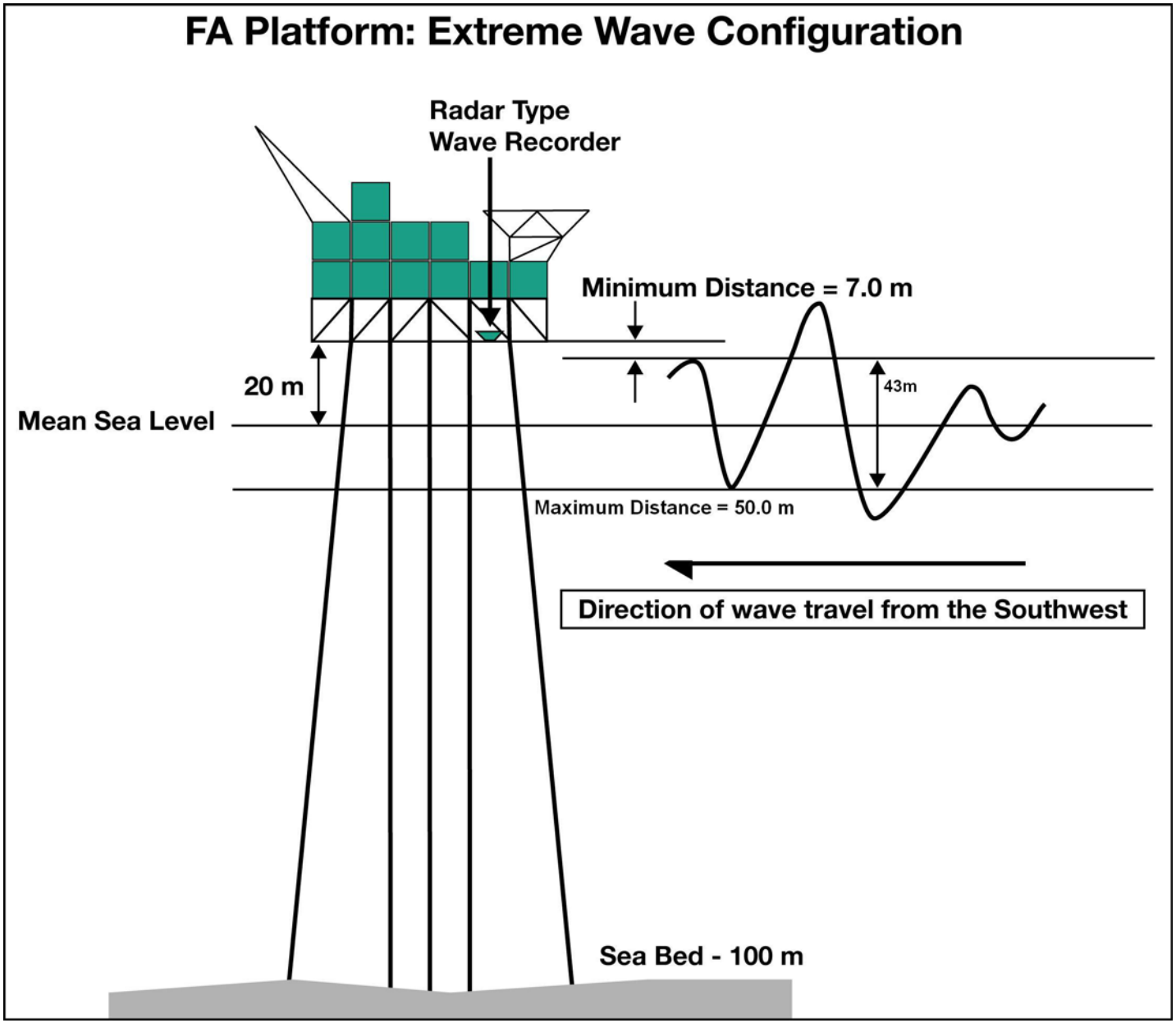
Western Cape Coast Line of South Africa showing FA Platform location

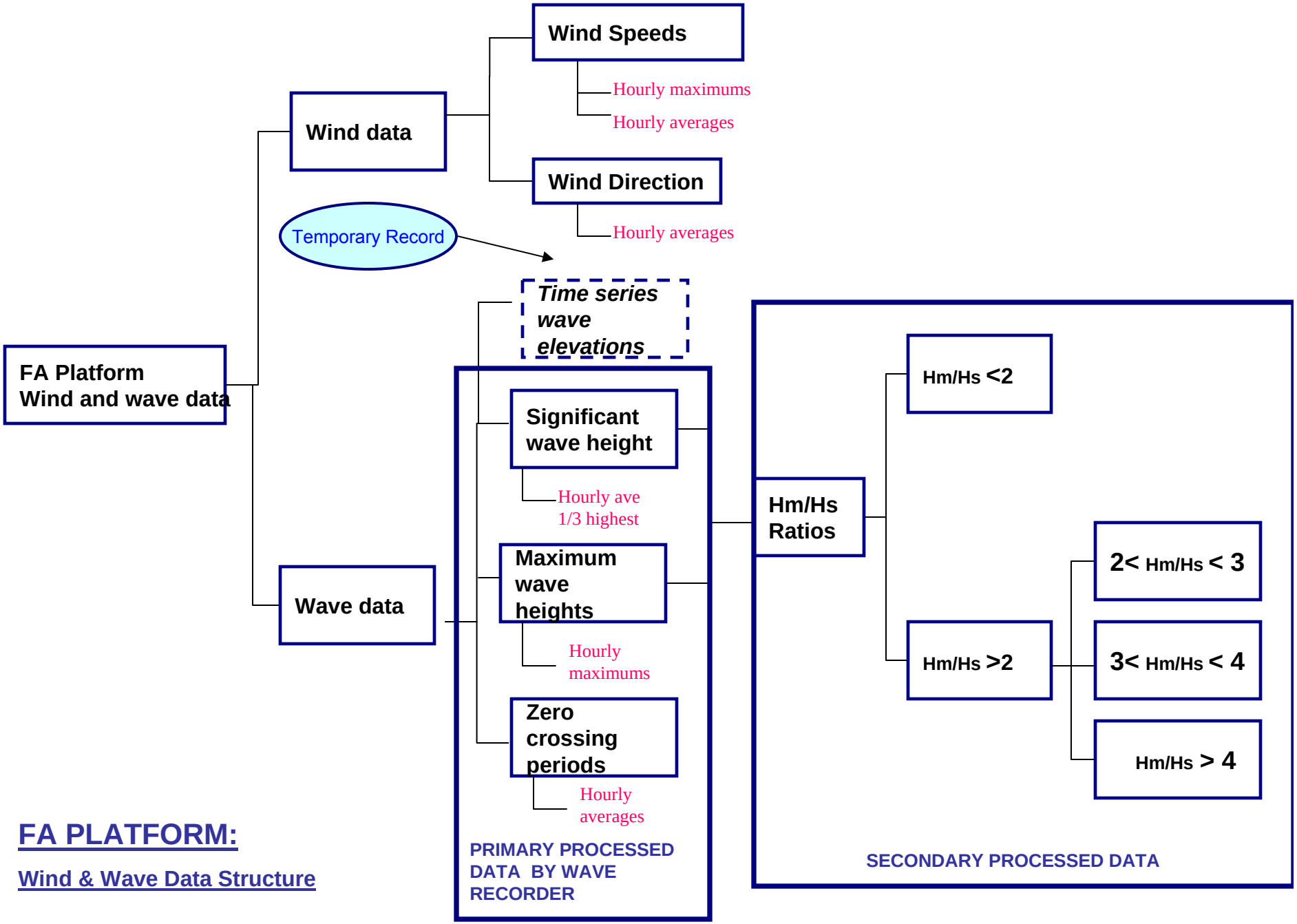




Schematic Diagram showing a possible mechanism for the combination of wave spectra, leading to the presence of Freak Waves, on the Agulhas Bank

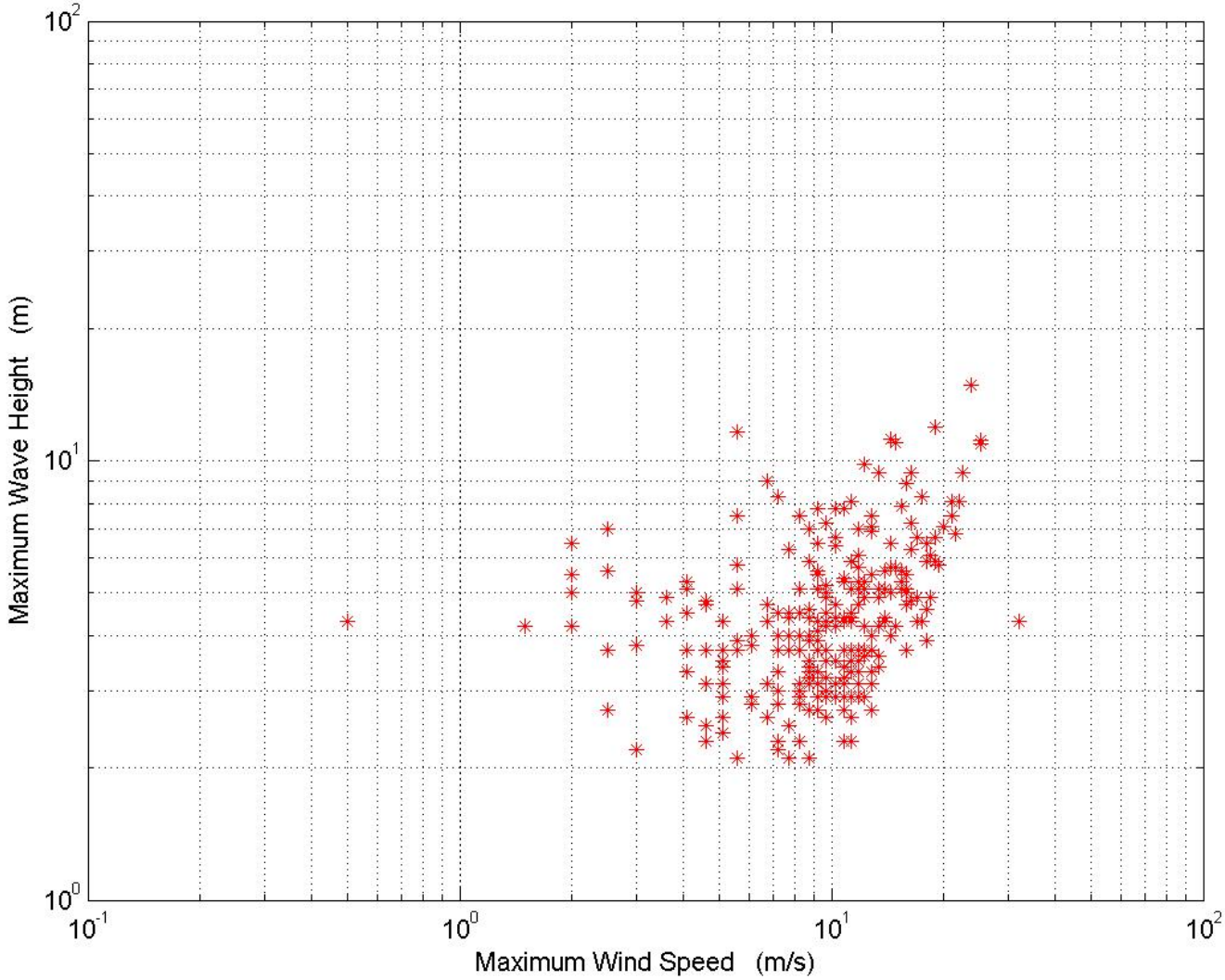


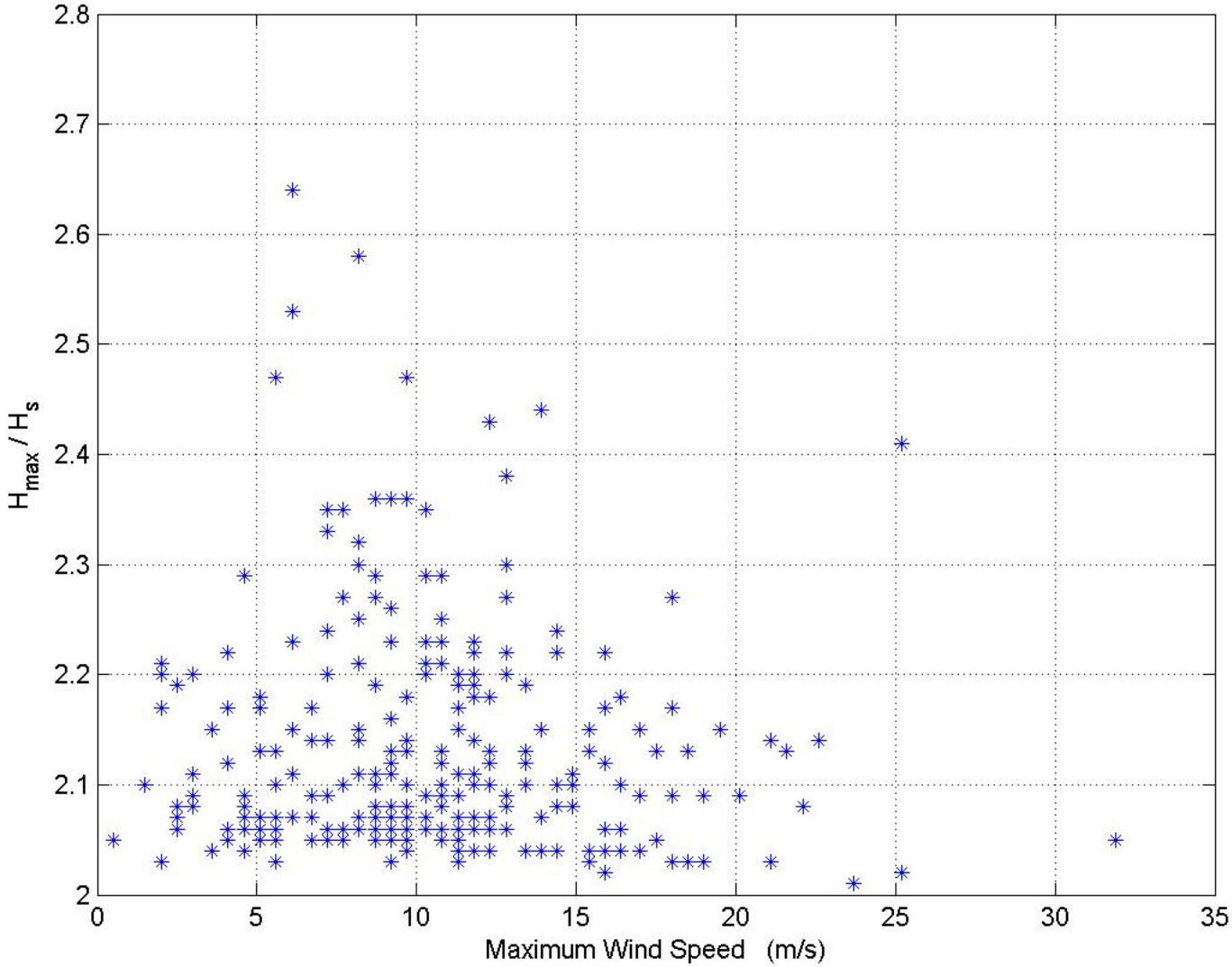

FA Platform: Extreme Wave Configuration
Radar Type
Wave Recorder
Minimum Distance = 7.0 m
20 m
Mean Sea Level
43m
Maximum Distance = 50.0 m
Direction of wave travel from the Southwest
Sea Bed - 100 m

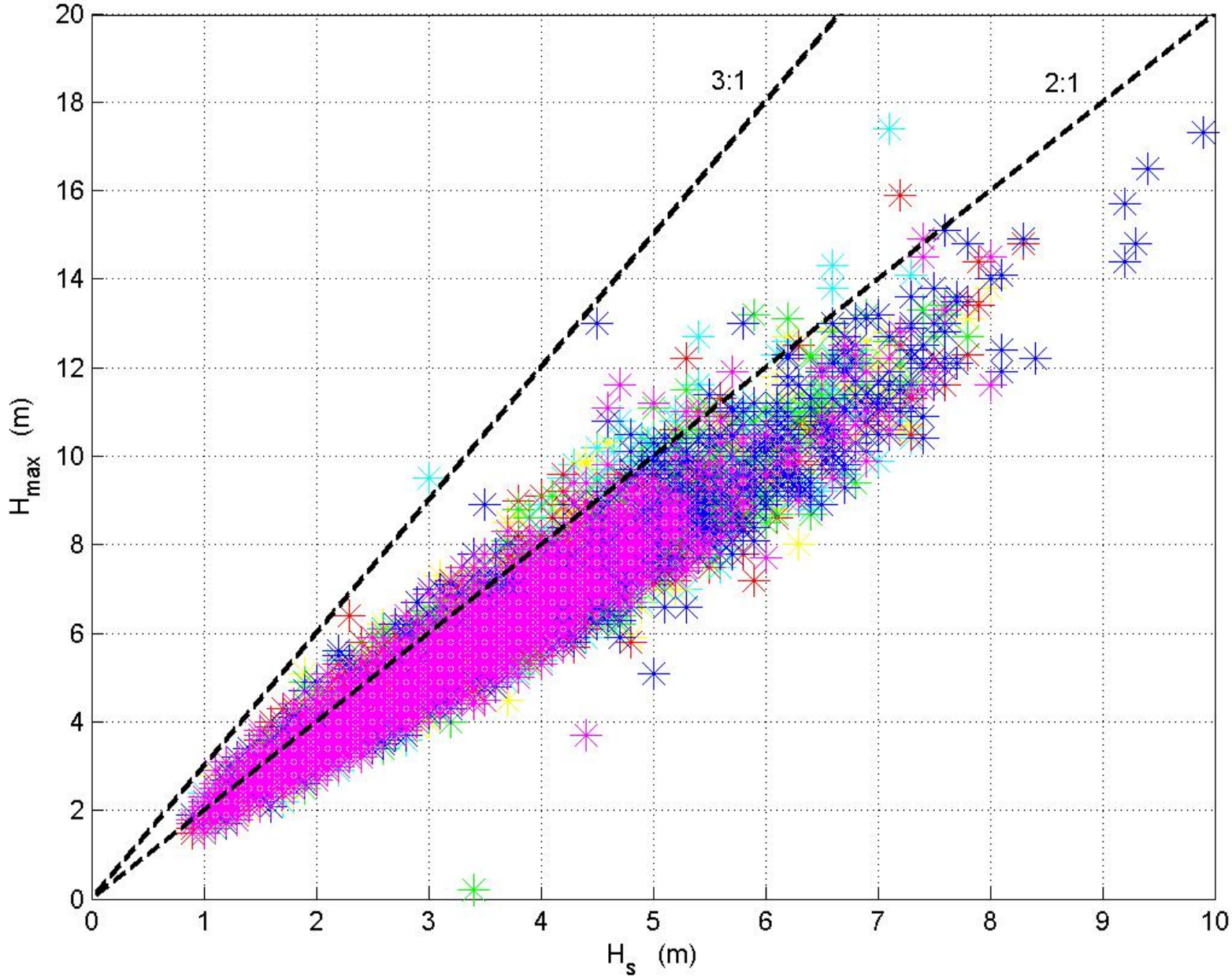


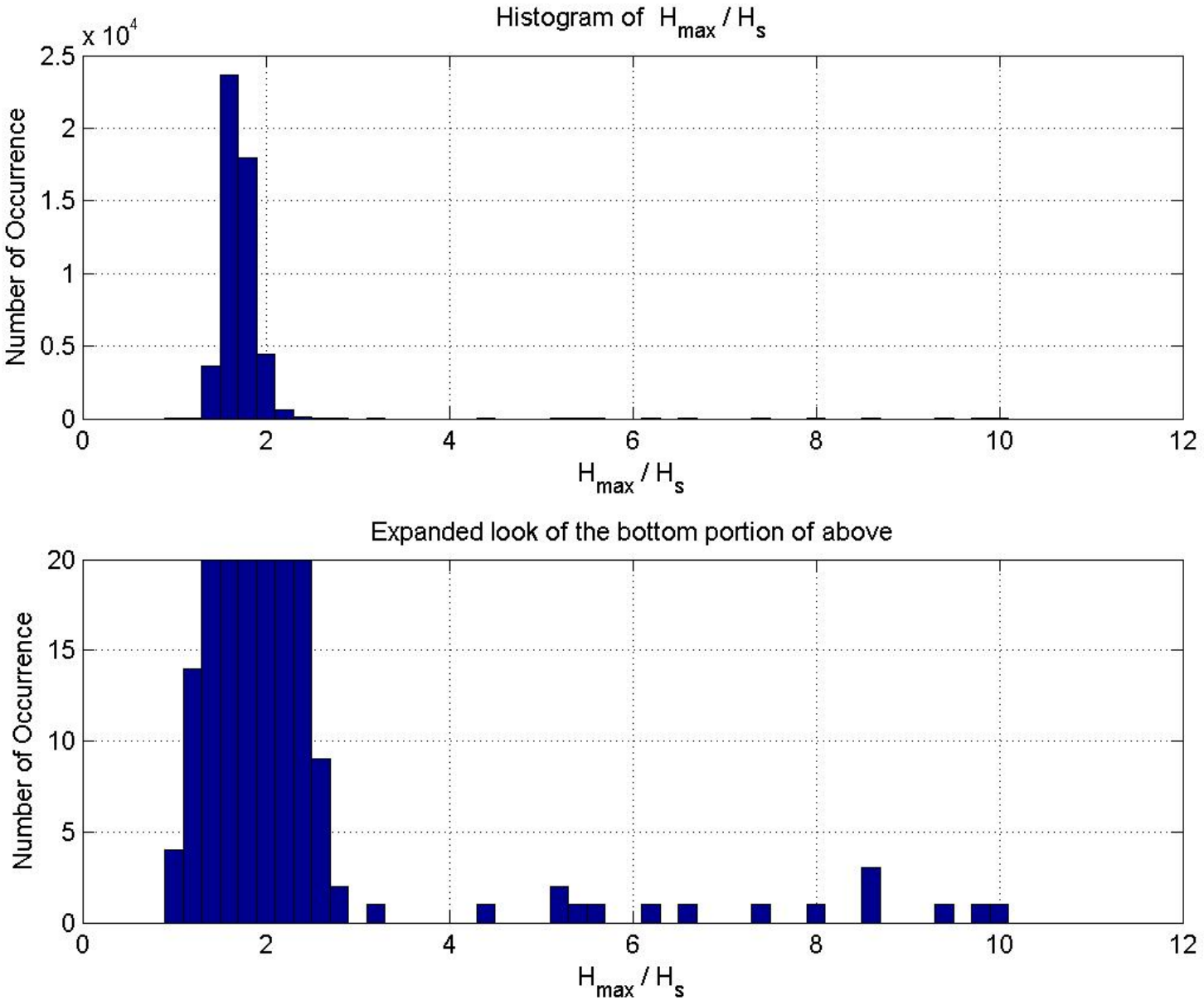
FA PLATFORM:

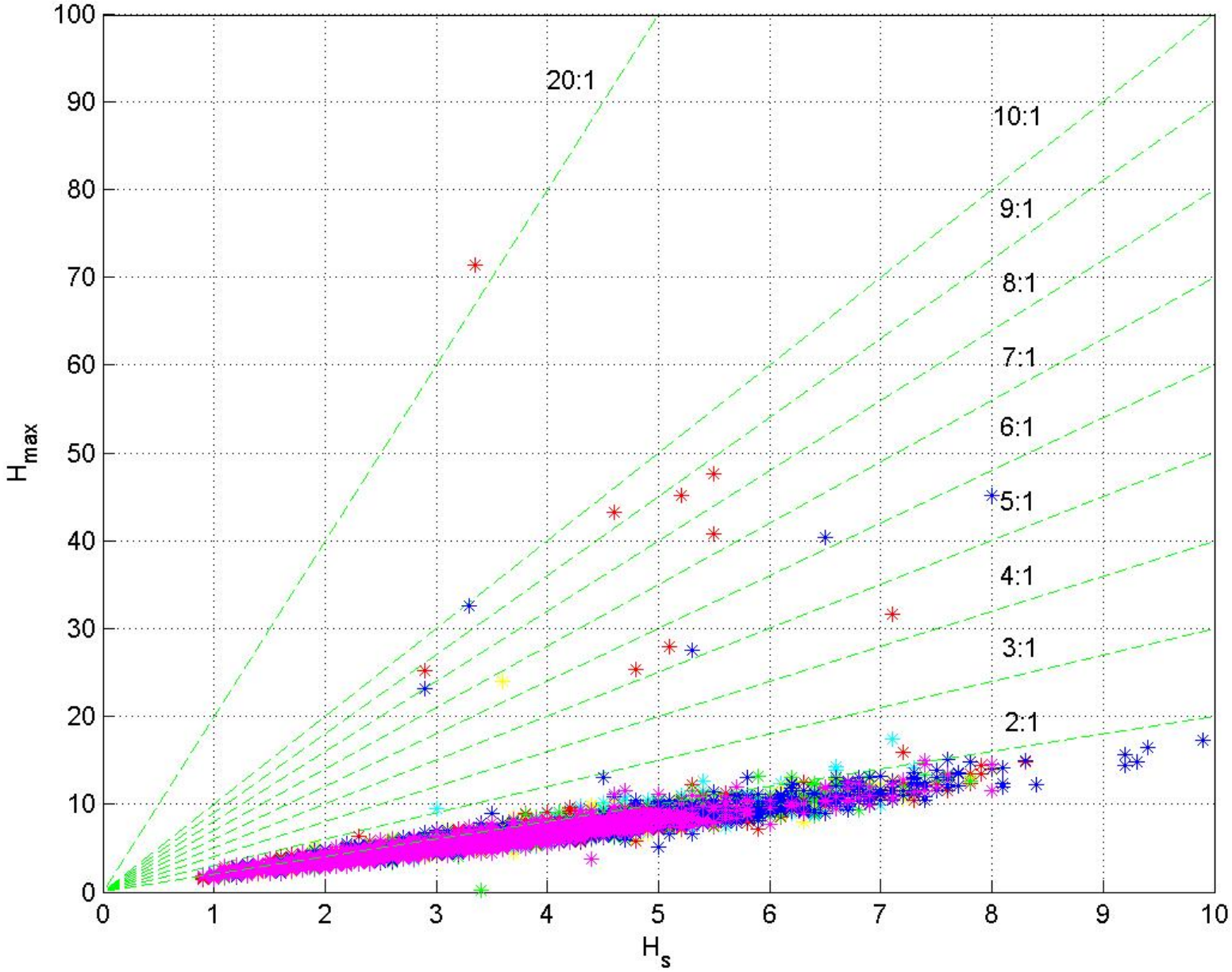
Wind & Wave Data Structure


Maximum Wave Height (m)
Maximum Wind Speed (m/s)
10^2
10^1
10^0
10^-1
10^0
10^1
10^2

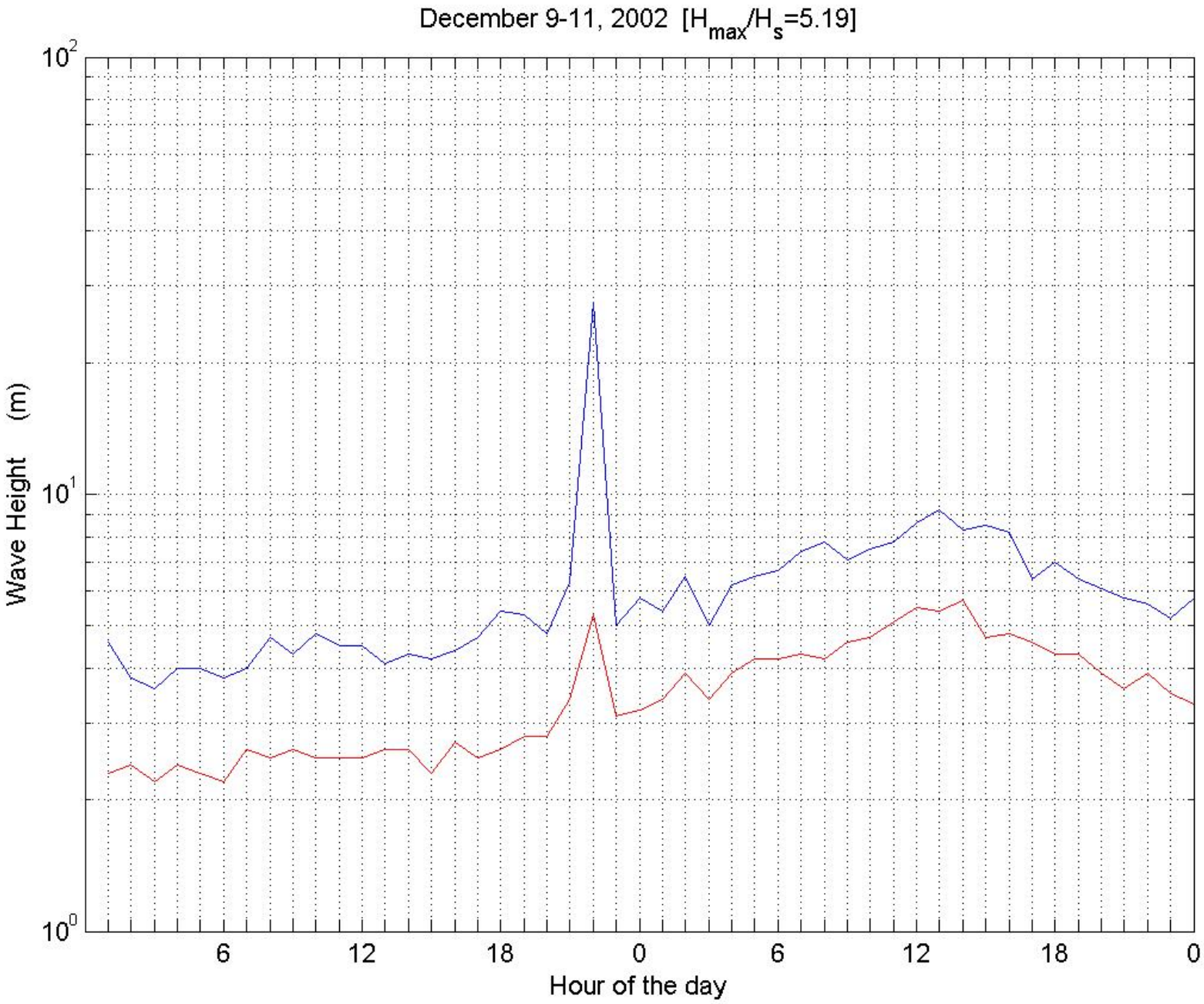

2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
H_{max} / H_s
0
5
10
15
20
25
30
35
Maximum Wind Speed (m/s)

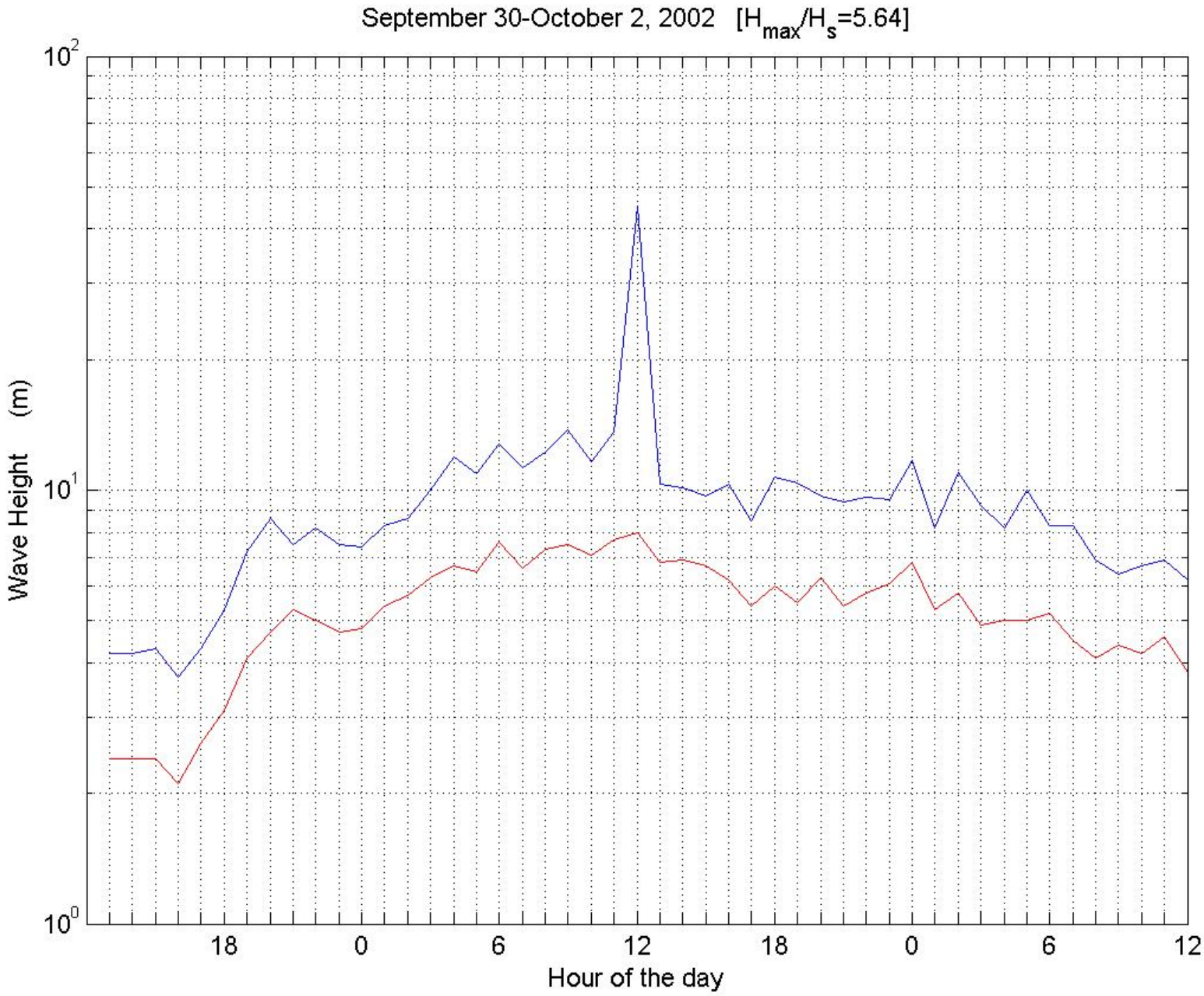

3:1
2:1
H_{max} (m)
H_s (m)
0
2
4
6
8
10
12
14
16
18
20
0
1
2
3
4
5
6
7
8
9
10

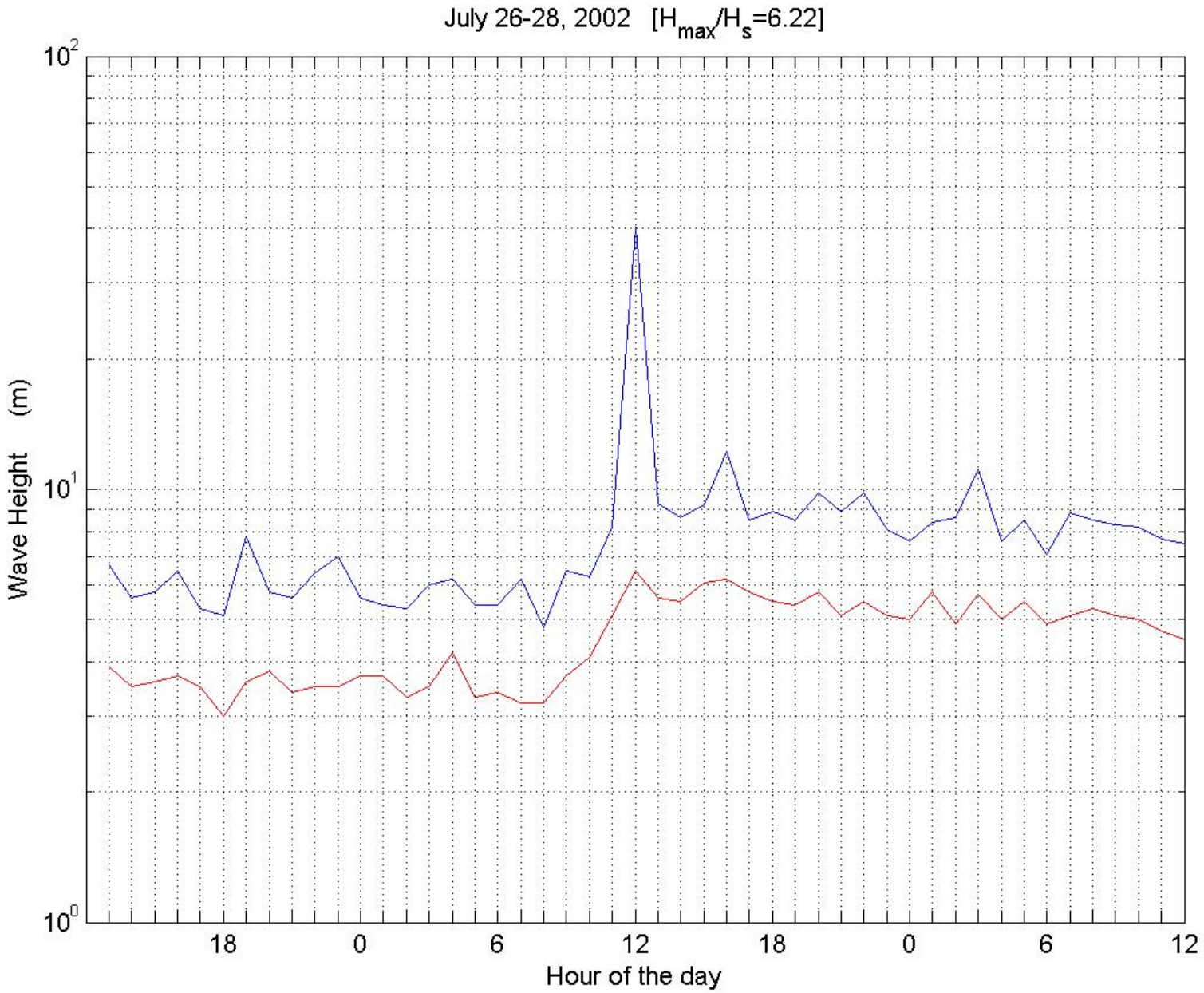

Histogram of H_{max} / H_s
x 10^4
2.5
2
1.5
1
0.5
0
Number of Occurrence
0
2
4
6
8
10
12
H_{max} / H_s
Expanded look of the bottom portion of above
20
15
10
5
0
Number of Occurrence
0
2
4
6
8
10
12
H_{max} / H_s

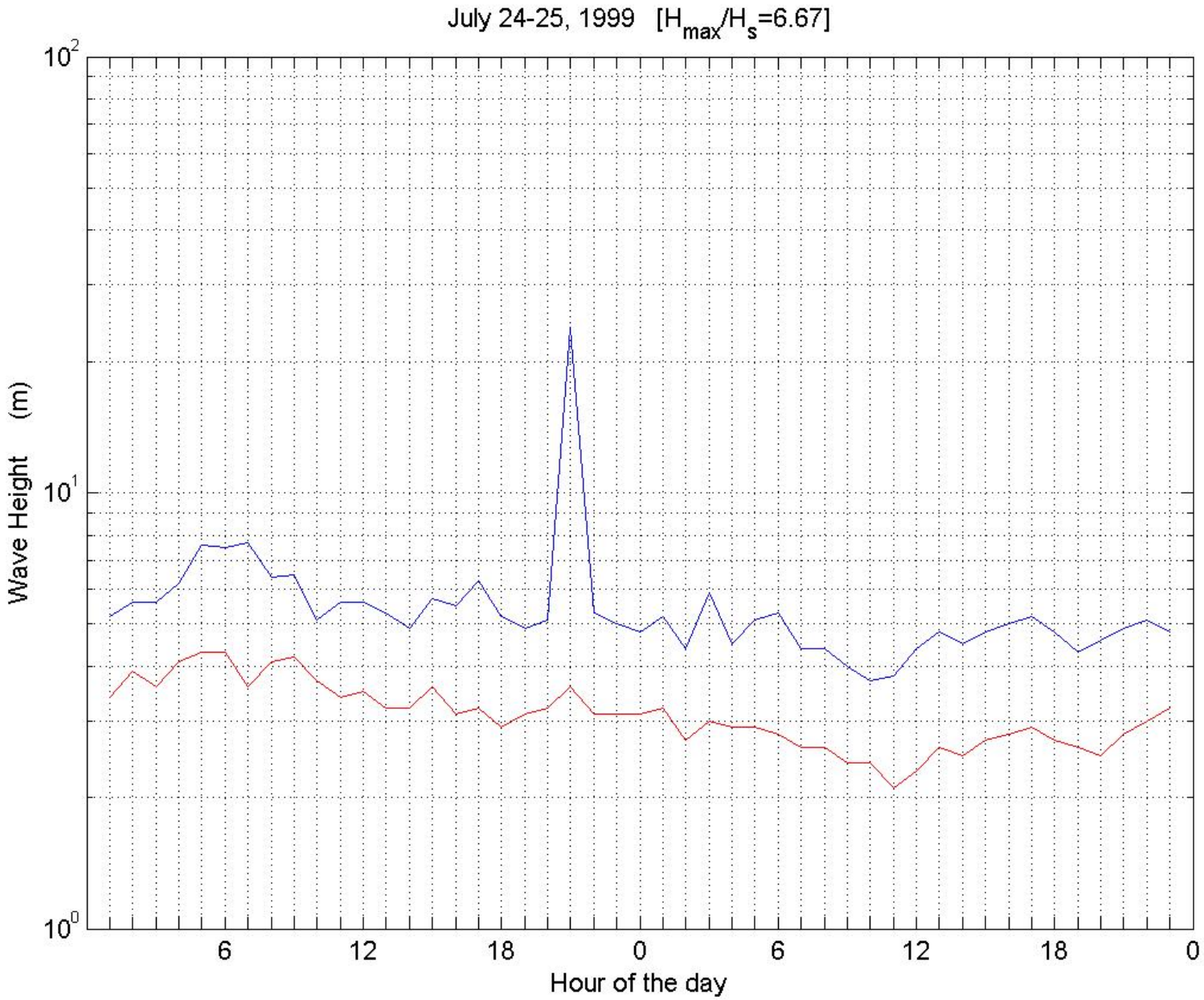

20:1
10:1
9:1
8:1
7:1
6:1
5:1
4:1
3:1
2:1
H_{max}
H_s
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
6
7
8
9
10

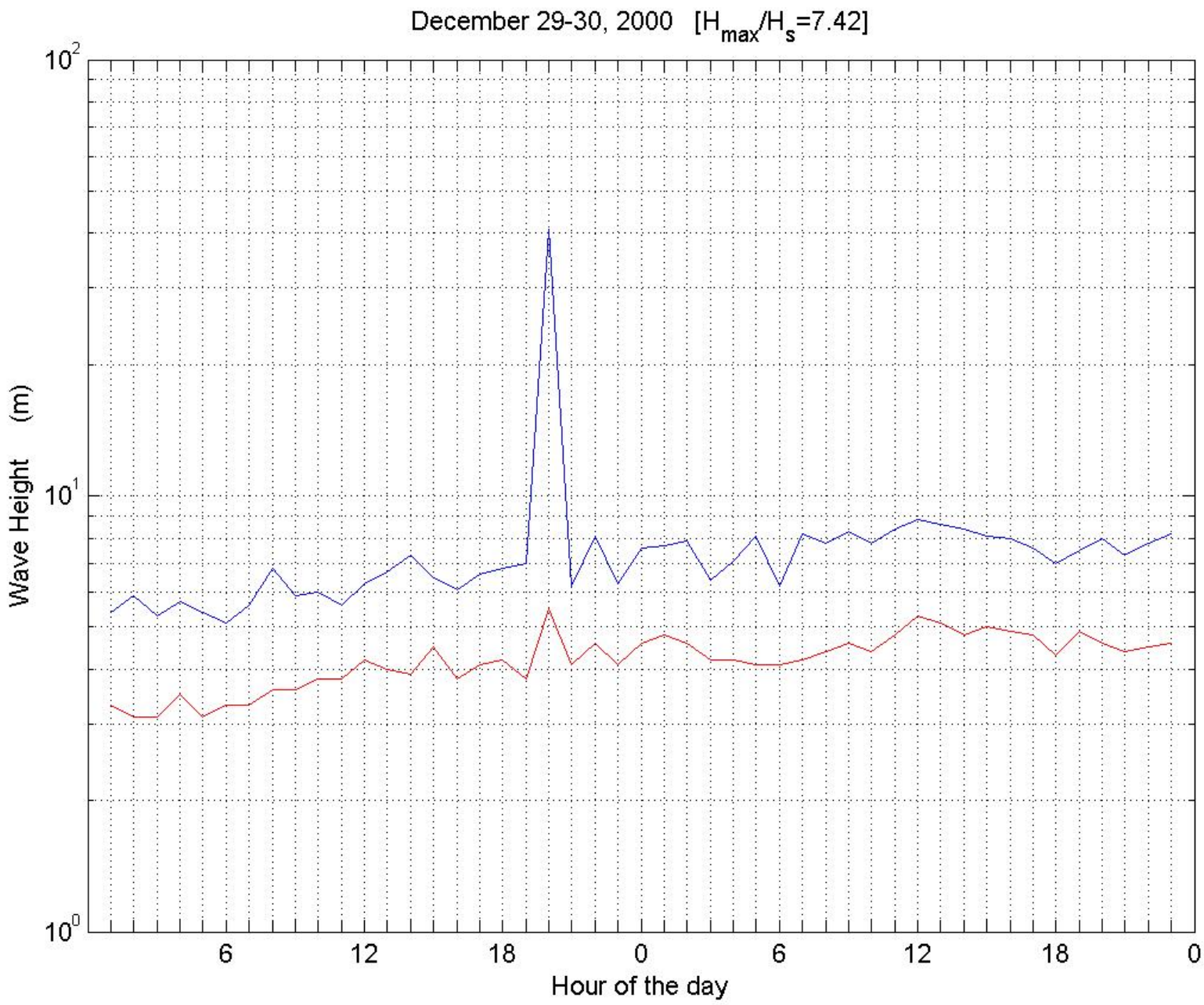
What happen when H_{max}/H_s is much larger than 2?

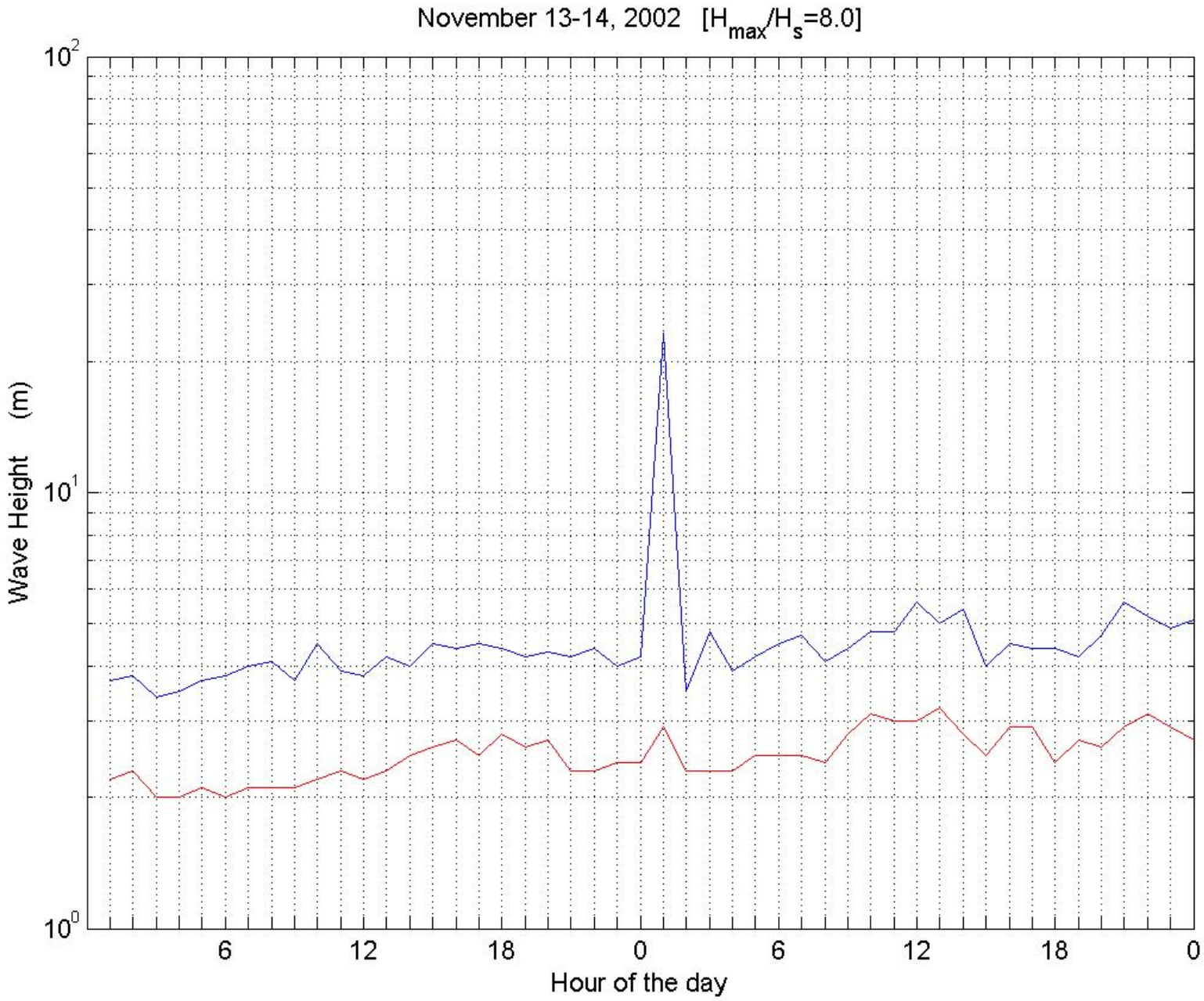

December 9-11, 2002 [H_{max}/H_s=5.19]
10^2
10^1
10^0
Wave Height (m)
6
12
18
0
6
12
18
0
Hour of the day

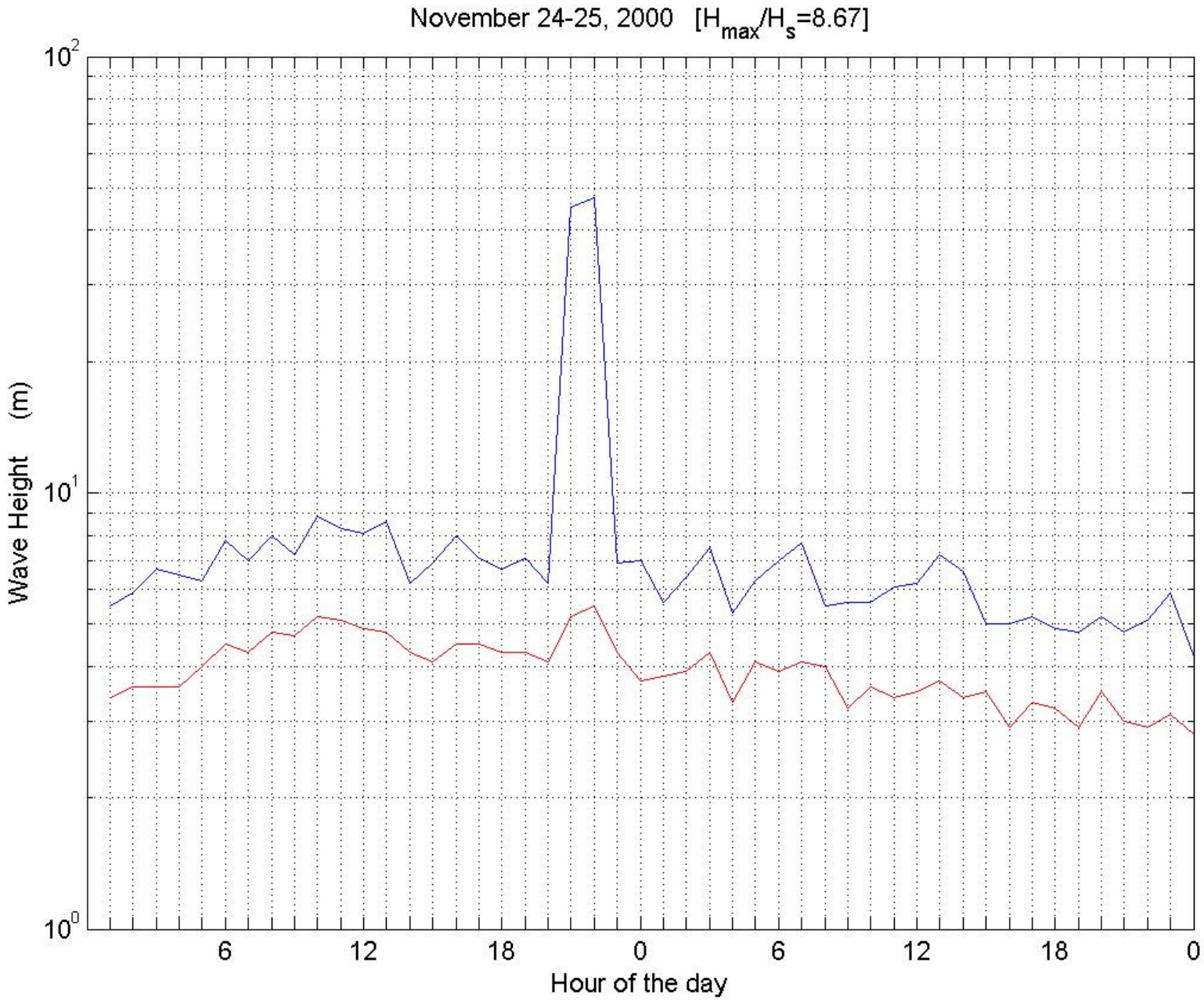

September 30-October 2, 2002 [H_{max}/H_s=5.64]
10^2
10^1
10^0
Wave Height (m)
18
0
6
12
18
0
6
12
Hour of the day

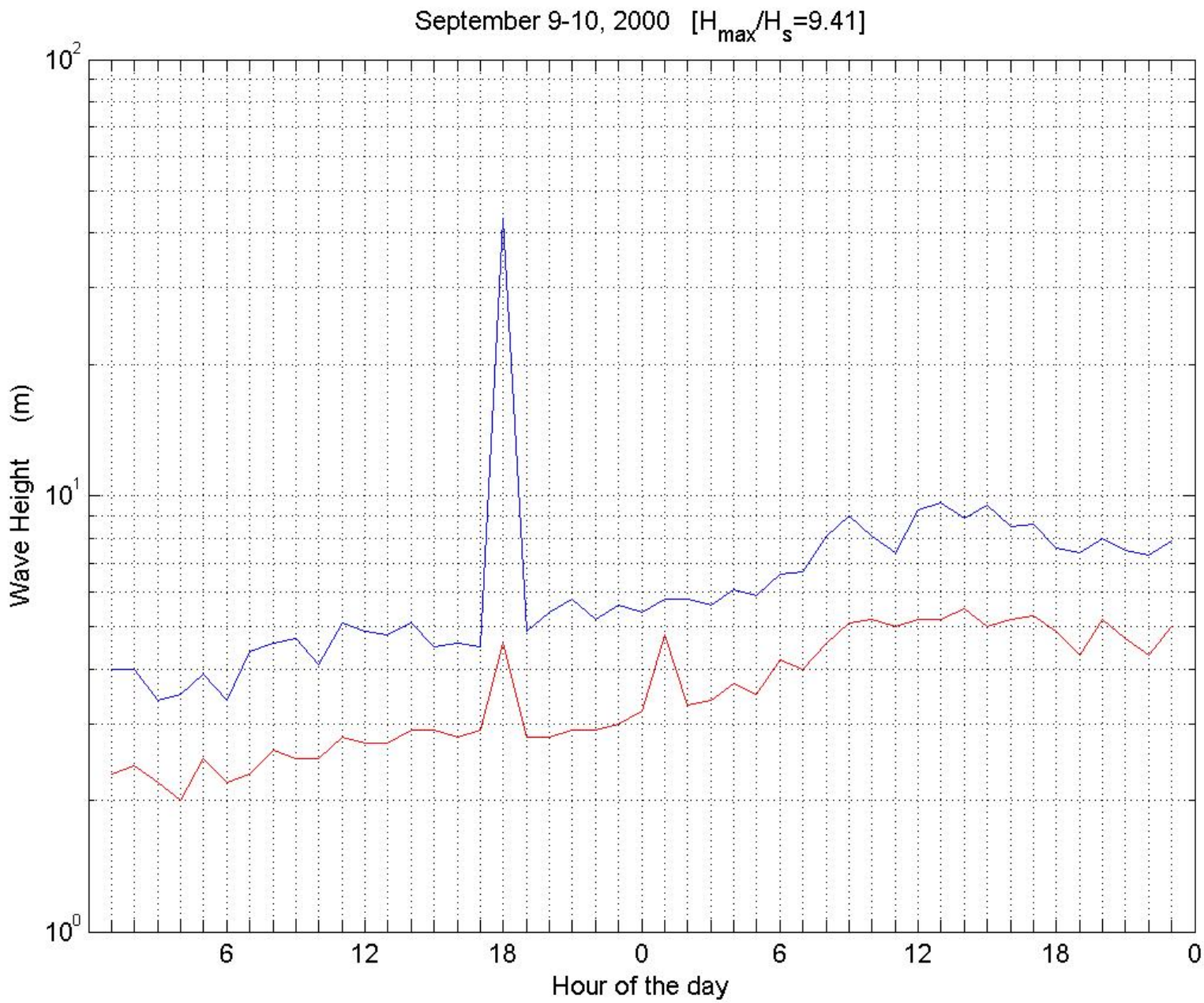

July 26-28, 2002 [H_{max}/H_s=6.22]
10^2
10^1
10^0
Wave Height (m)
18
0
6
12
18
0
6
12
Hour of the day

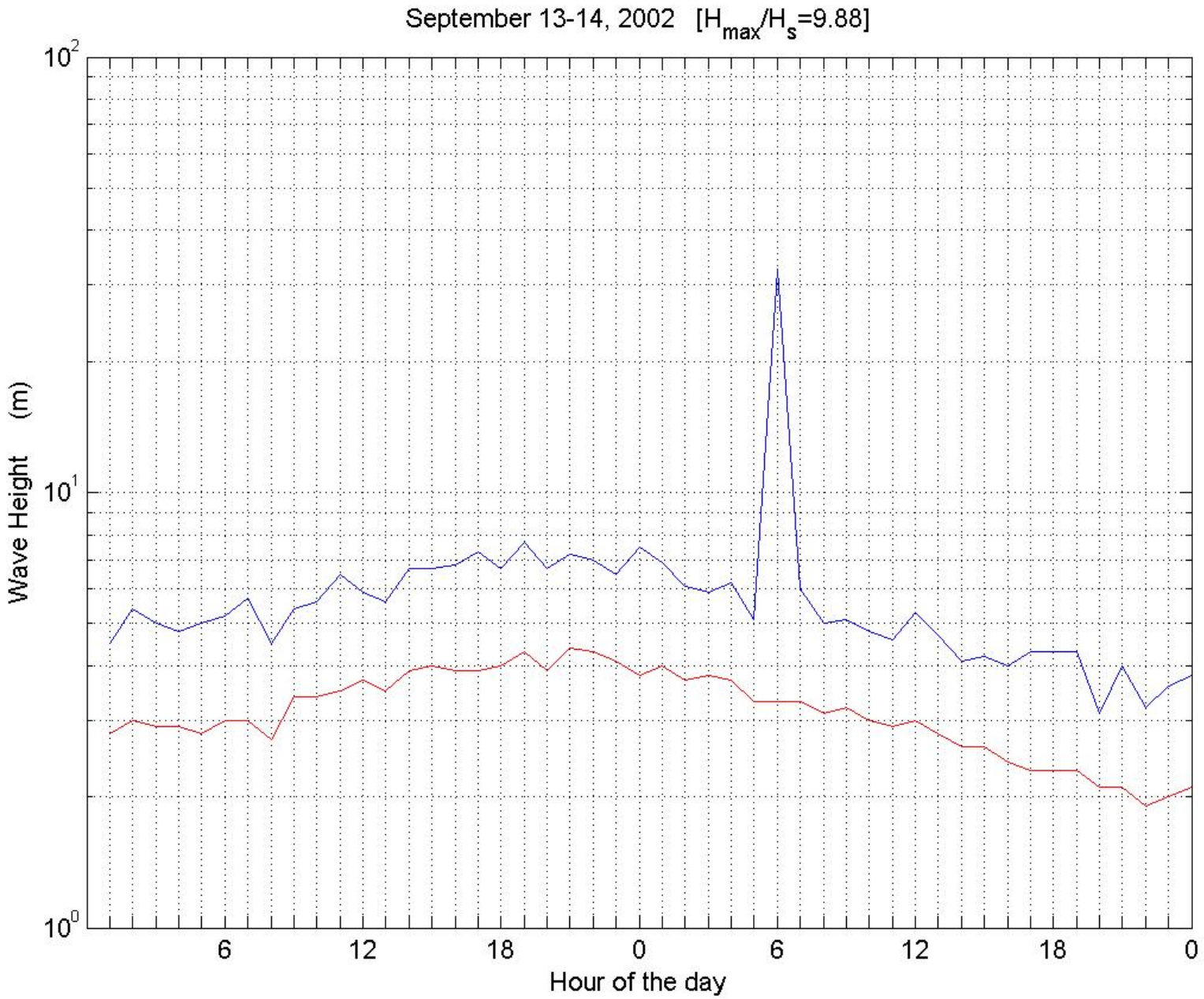

July 24-25, 1999 [H_{max}/H_s=6.67]
10^2
10^1
10^0
Wave Height (m)
6
12
18
0
6
12
18
0
Hour of the day

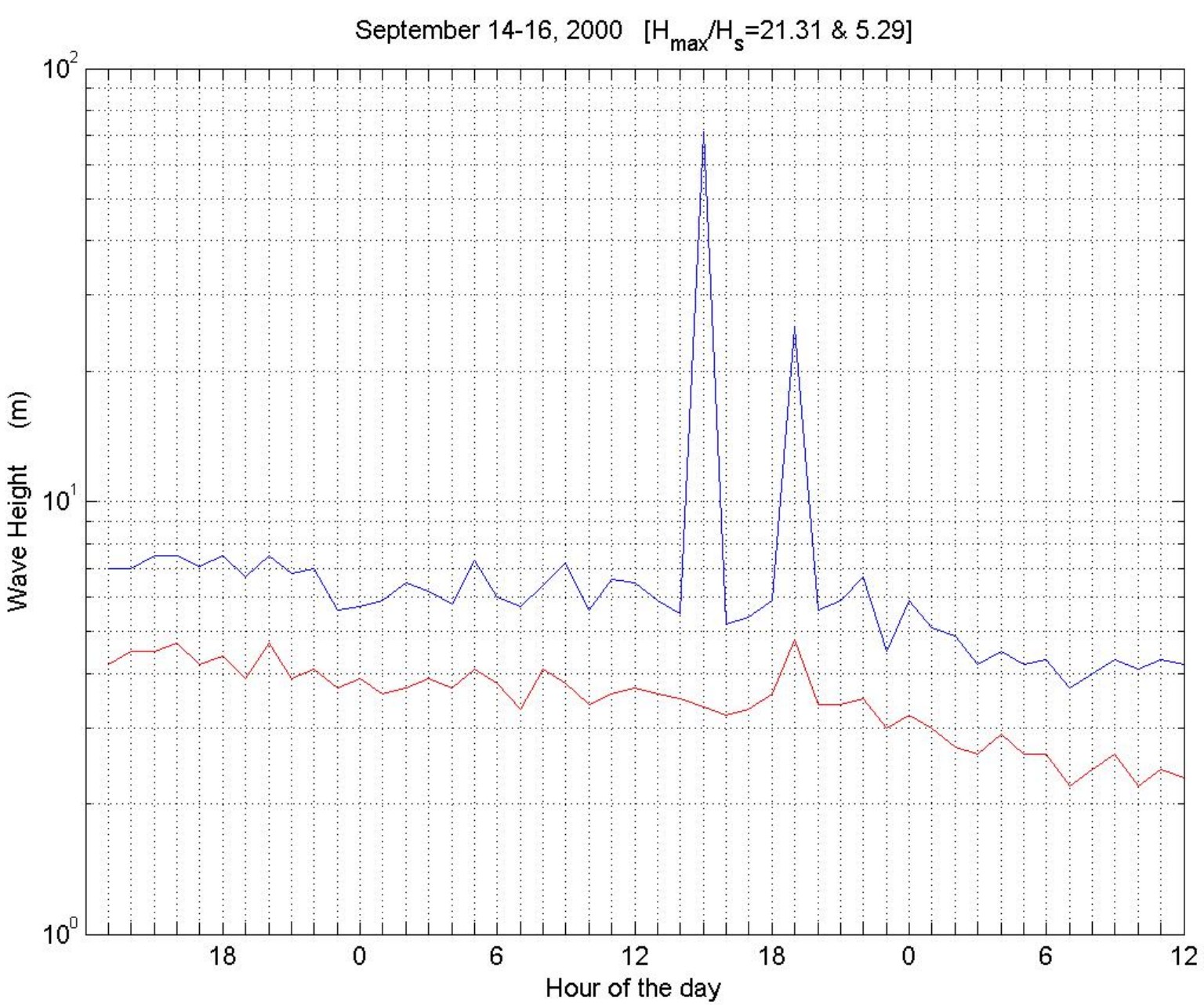

December 29-30, 2000 [H_{max}/H_s=7.42]
10^2
10^1
10^0
Wave Height (m)
6
12
18
0
6
12
18
0
Hour of the day


November 13-14, 2002 [H_{max}/H_s=8.0]
10^2
10^1
10^0
Wave Height (m)
6
12
18
0
6
12
18
0
Hour of the day

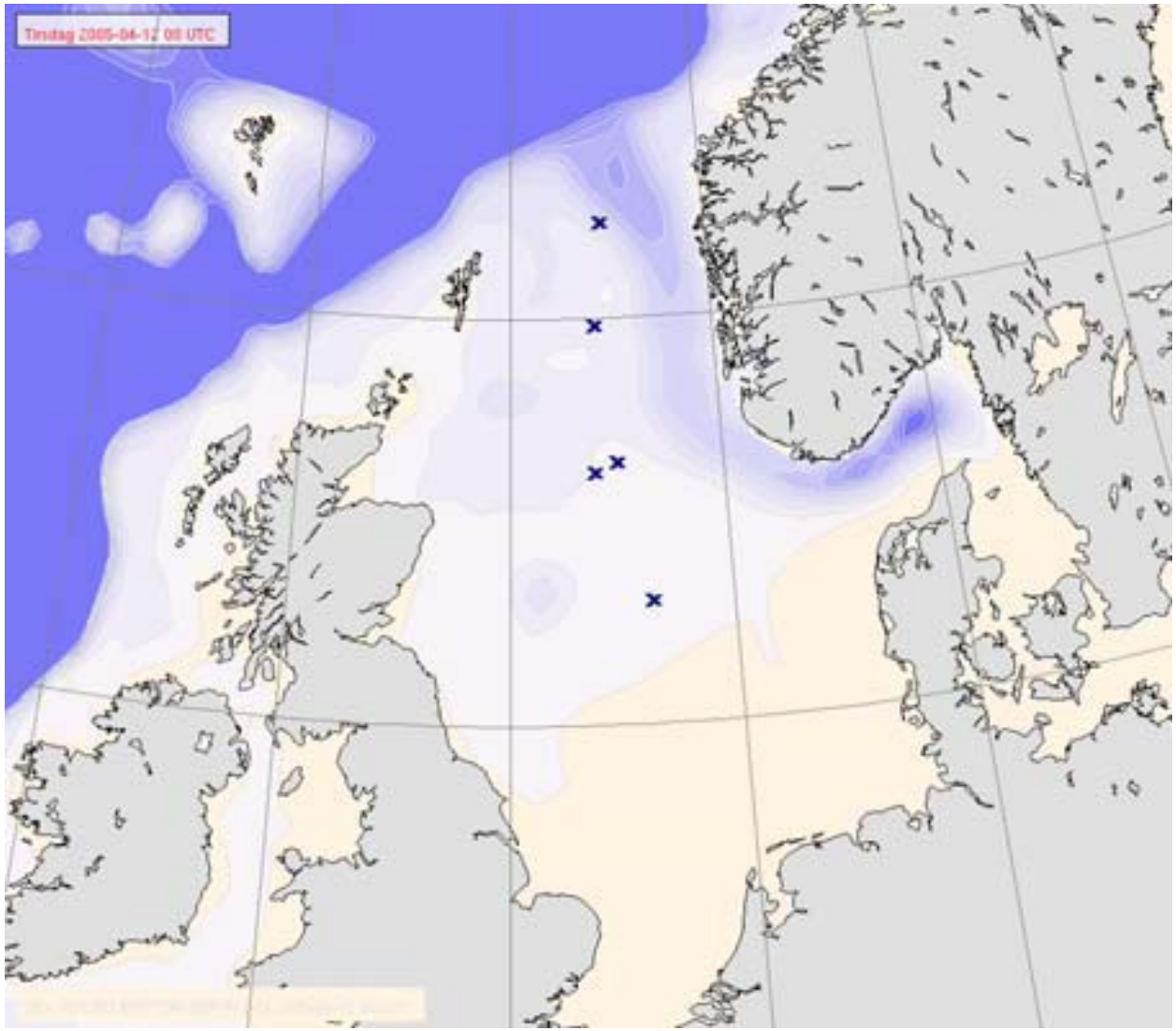

November 24-25, 2000 [H_{max}/H_s=8.67]
10^2
10^1
10^0
Wave Height (m)
6
12
18
0
6
12
18
0
Hour of the day


September 9-10, 2000 [H_{max}/H_s=9.41]
10^2
10^1
10^0
Wave Height (m)
6
12
18
0
6
12
18
0
Hour of the day

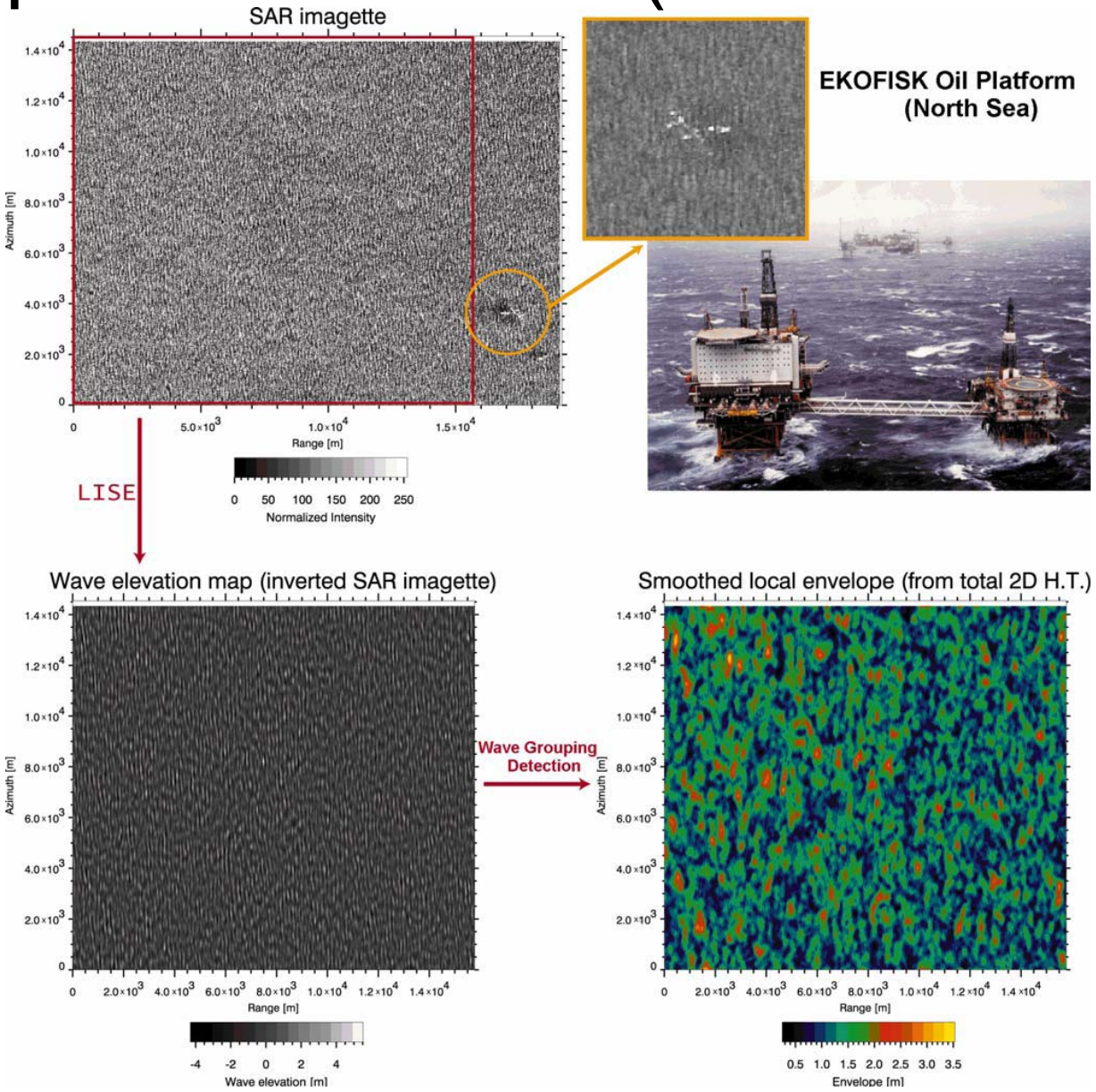

September 13-14, 2002 [H_{max}/H_s=9.88]
10^2
10^1
10^0
Wave Height (m)
6
12
18
0
6
12
18
0
Hour of the day


September 14-16, 2000 [H_{max}/H_s=21.31 & 5.29]
10^2
10^1
10^0
Wave Height (m)
18
0
6
12
18
0
6
12
Hour of the day

Ekofisk in central North Sea (N56.5,E3.2), southernmost point in Figure



Wave groups measured at the oil platform Ekofisk (Lehner 2005)

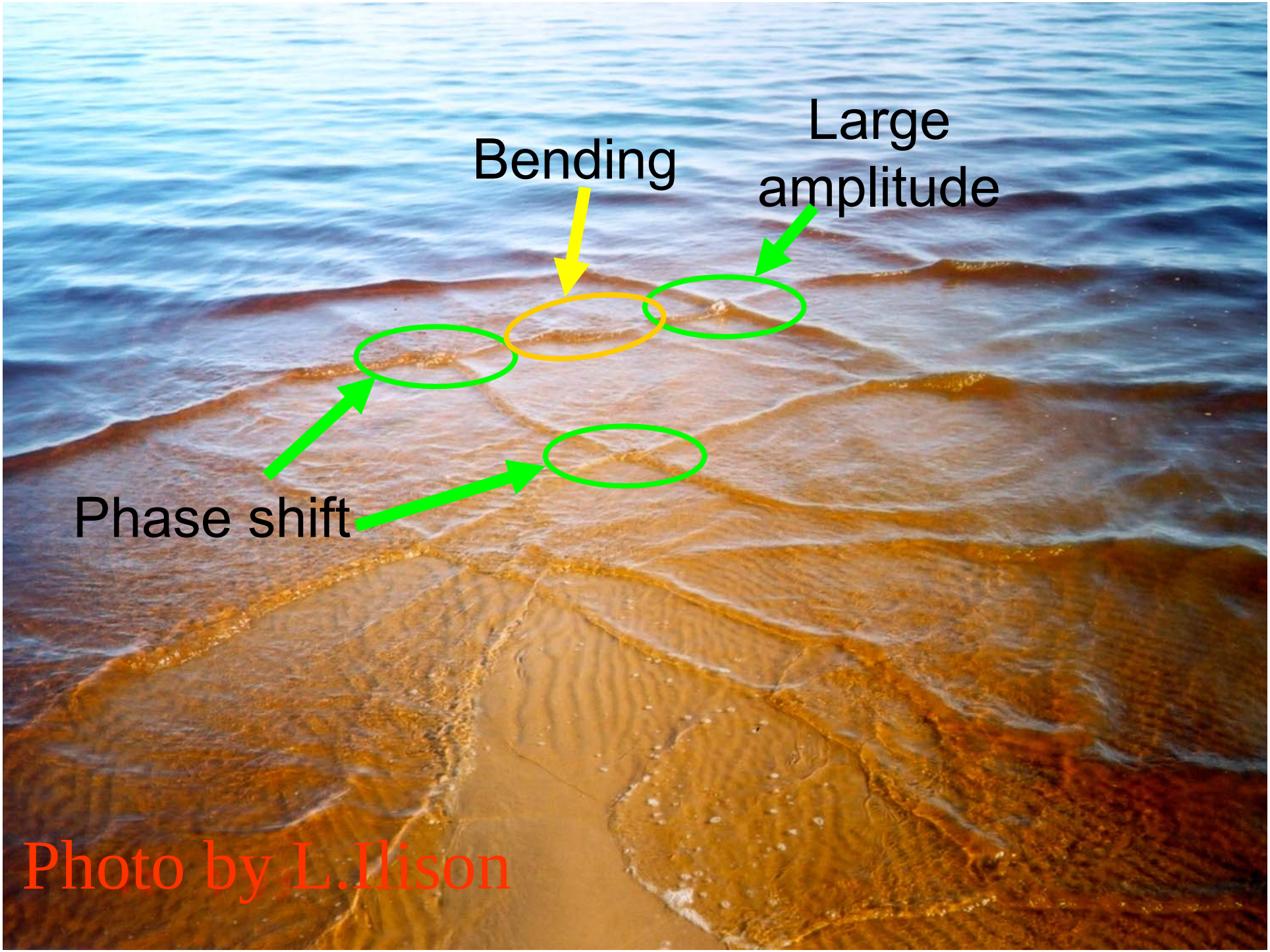


(4) Mechanisms and Prediction

- Solitary waves
- Nonlinear four wave interaction

Long surface waves in shallow areas




Bending
Large amplitude
Phase shift
Photo by L.Ilison



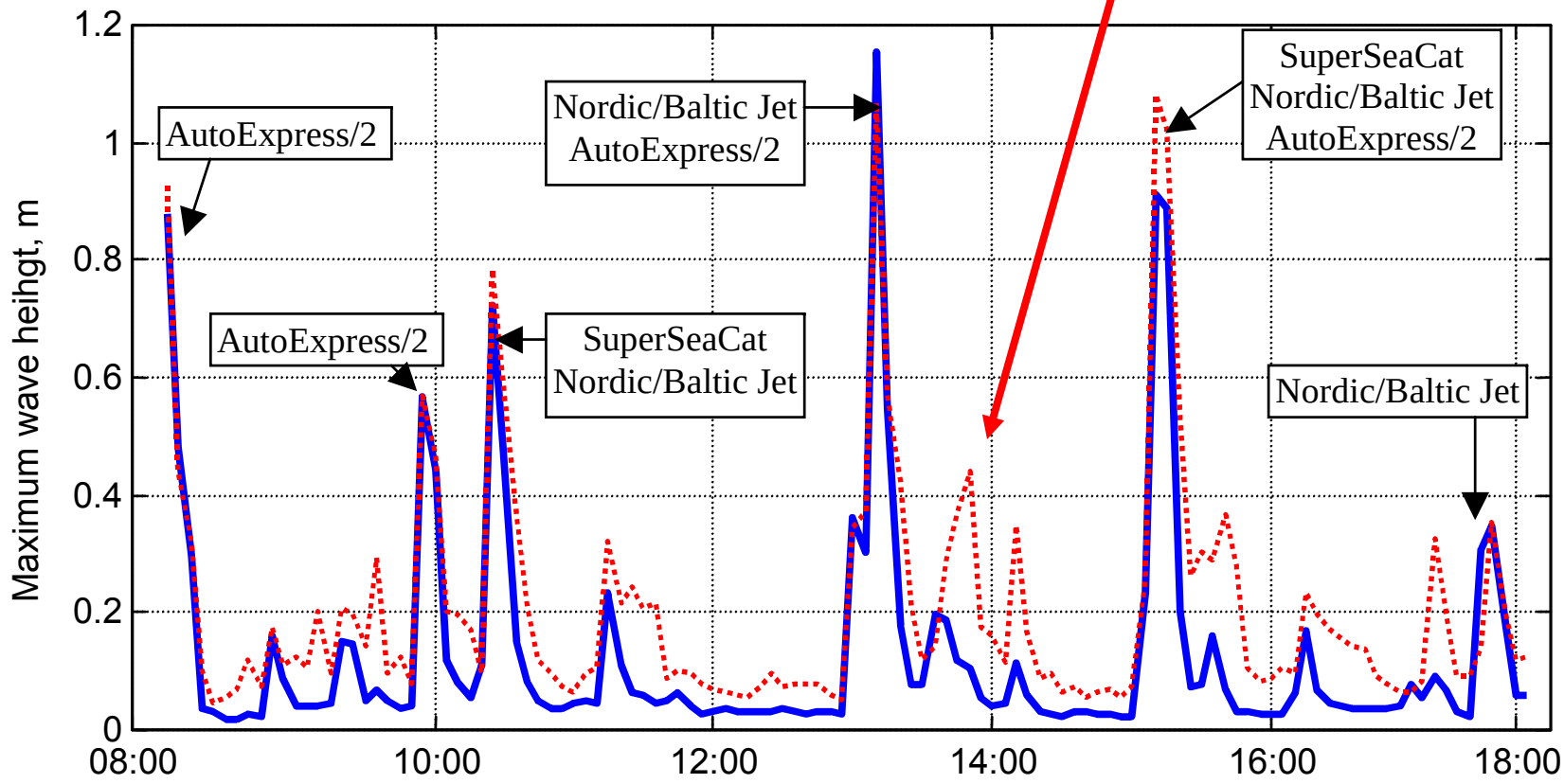
Fast ferries: source of long-crested soliton-like waves

Aegna, 14.04.2002

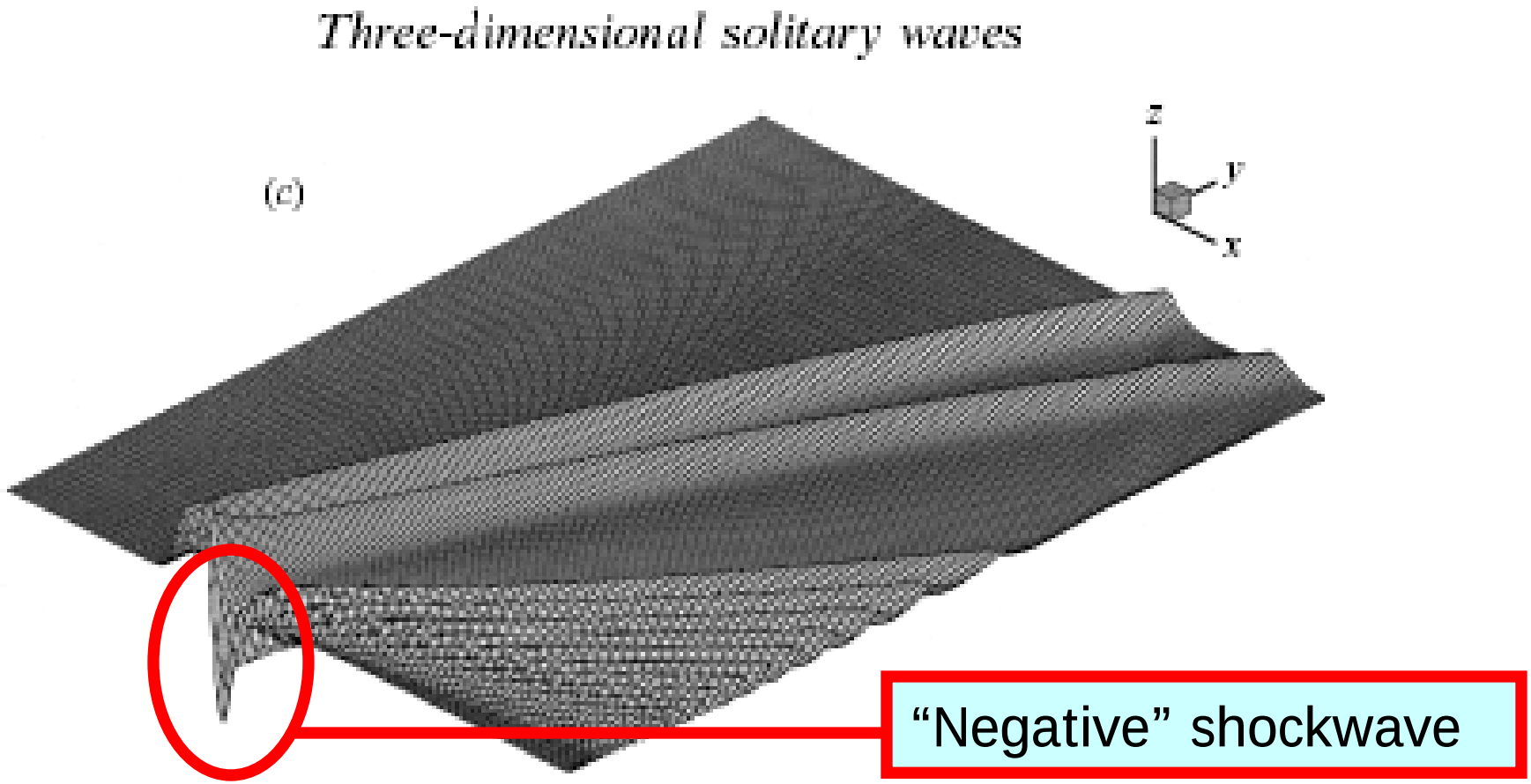
Ship wave heights are moderate

Blue: long components T>8s

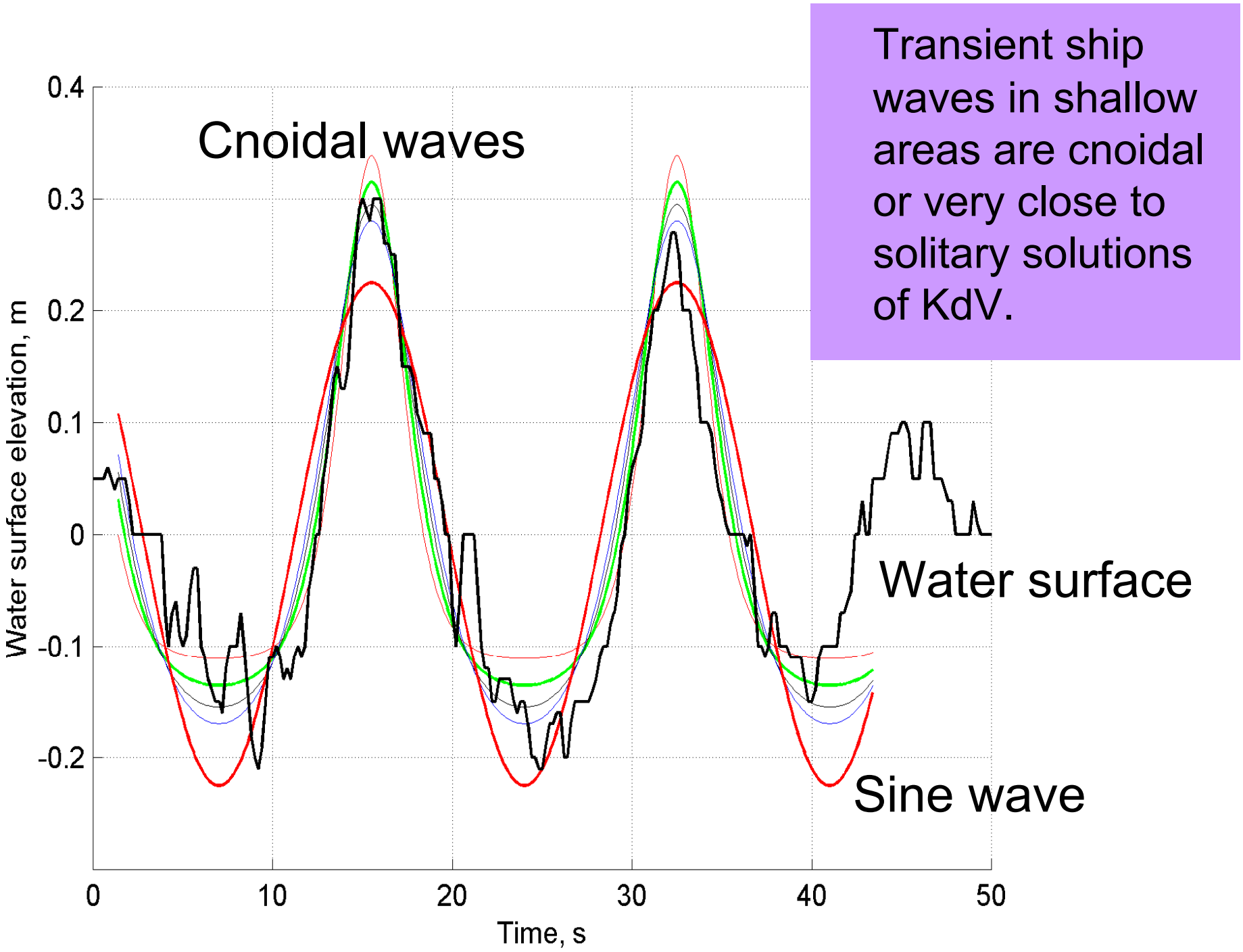
Red: all components



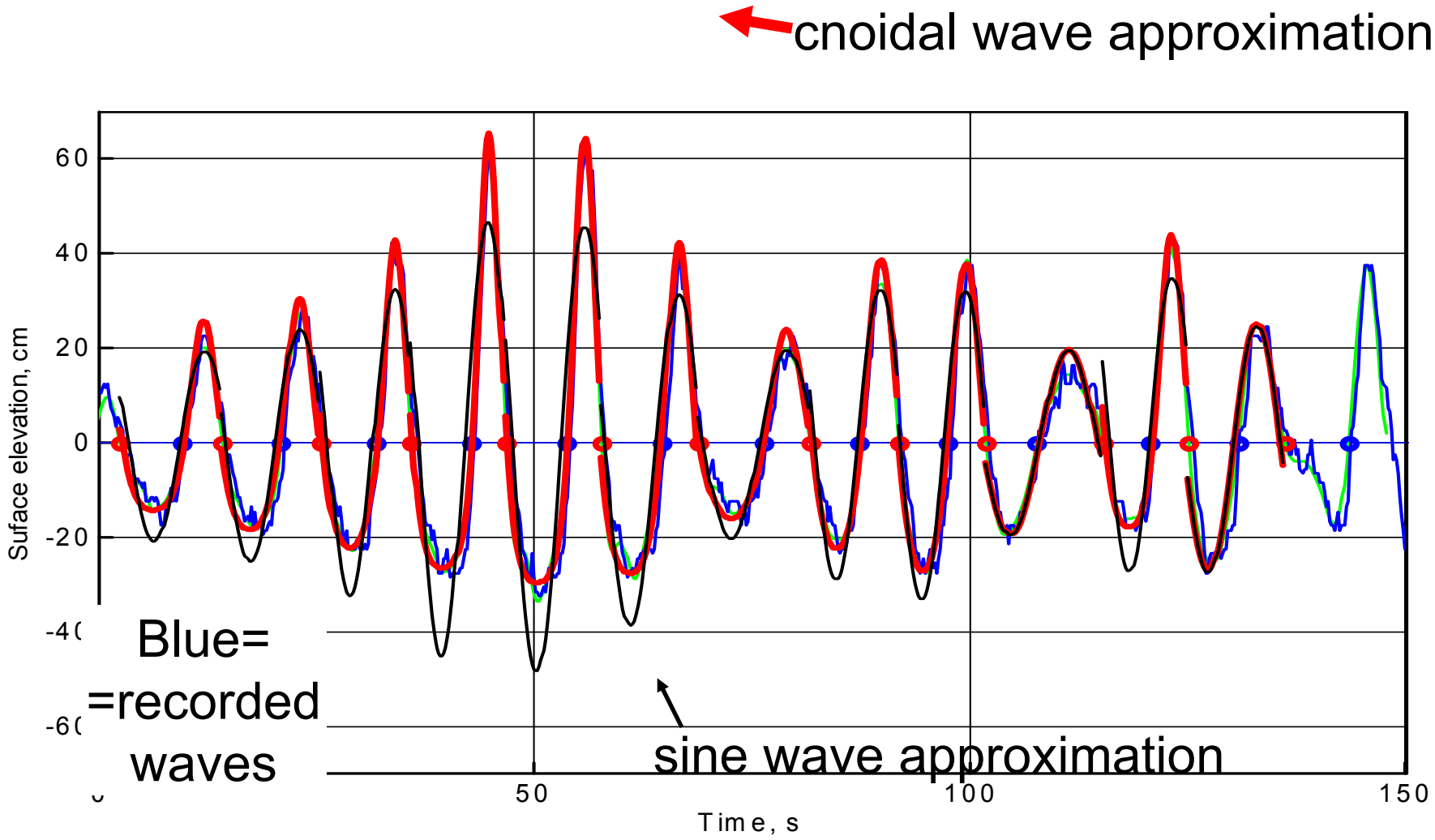
Ships may produce solitons



Three-dimensional nonlinear solitary waves in shallow water generated by an advancing disturbance, YILE LI AND PAUL D. SCLAVOUNOS, J.Fluid Mech. (2002), vol. 470, pp. 383-410. 2002


Cnoidal waves
Transient ship waves in shallow areas are cnoidal or very close to solitary solutions of KdV.
Water surface
Sine wave
Water surface elevation, m
Time, s
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
10
20
30
40
50

Long ship waves are highly nonlinear



Long waves approaching shallow area are:

- highly nonlinear
- and have shapes close to soliton solutions of the KdV equation

Linear and nonlinear equations for surface waves

Classical surface waves:

$$\phi_{xx}+\phi_{yy}+\phi_{zz}=0$$

solutions to the Laplace equation

Nonlinear surface wave equations:

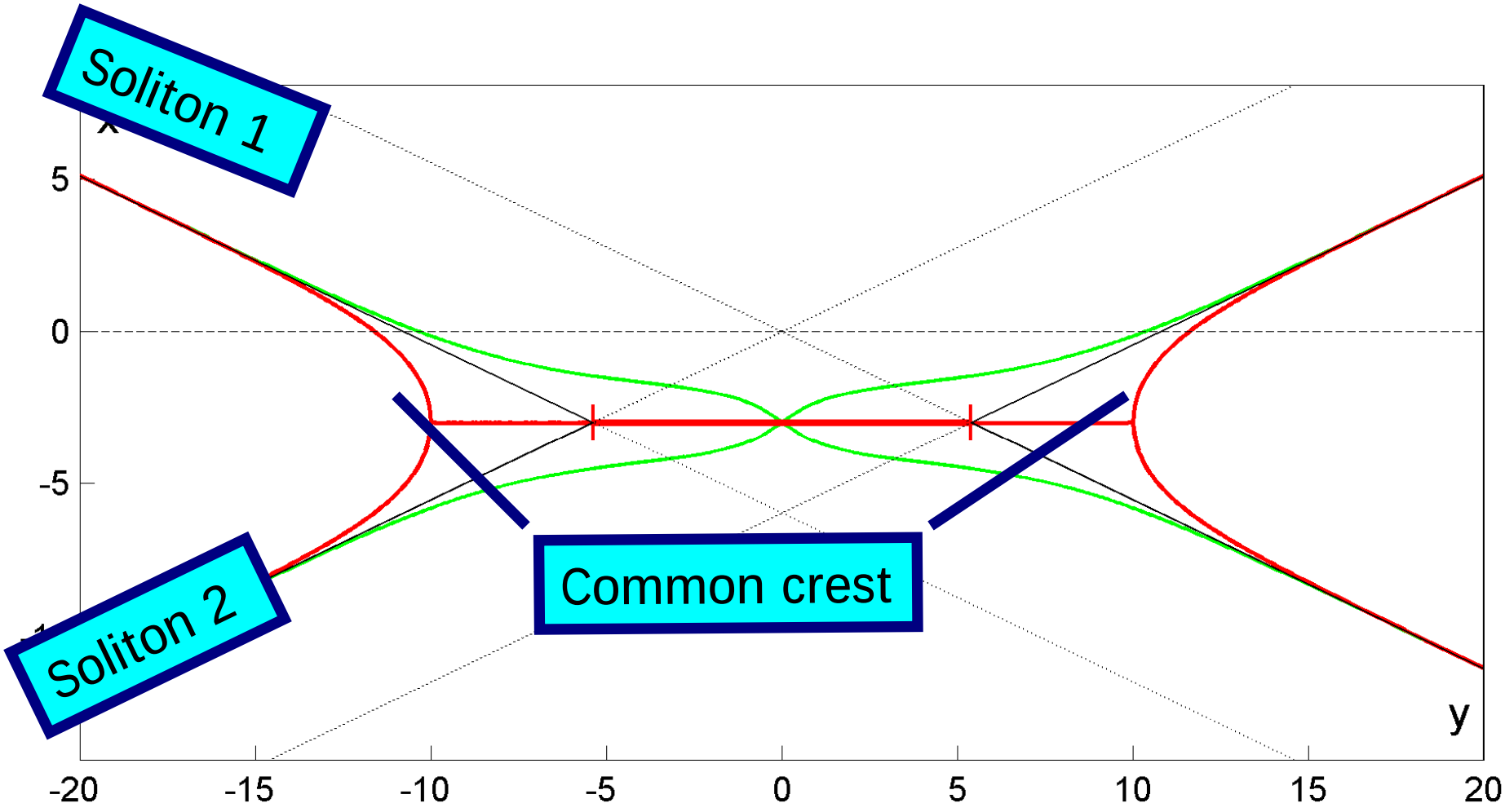
Korteweg-de Vries (KdV) equation (1+1D)

$$\eta_t+6\eta\eta_x+\eta_{xxx}=0$$

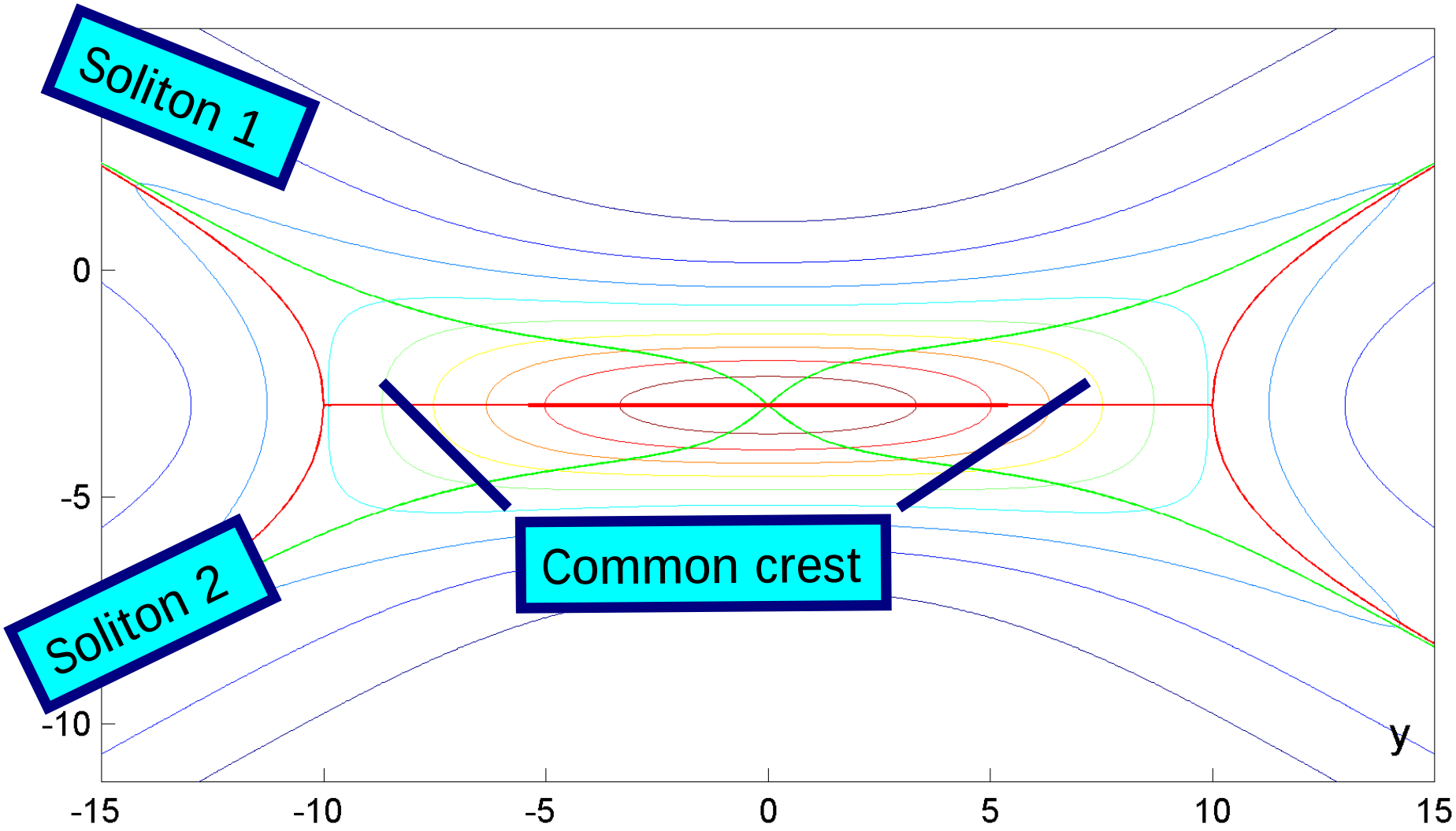
Kadomtsev-Petviashvili equation (weak 2+1D)

$$\left(\eta_t+6\eta\eta_x+\eta_{xxx}\right)_x+3\eta_{yy}=0$$

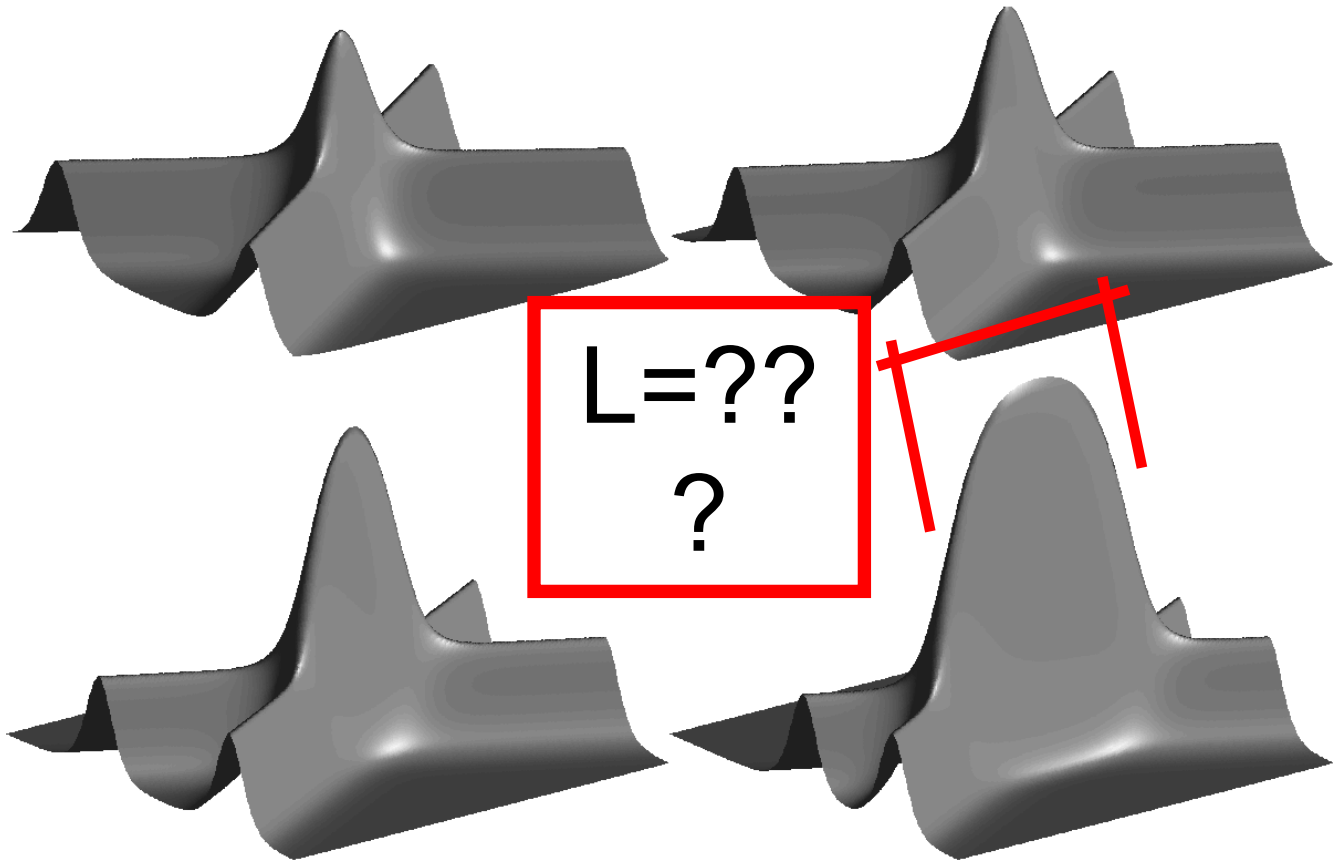
A part of solitons merge



The central part may be particularly high

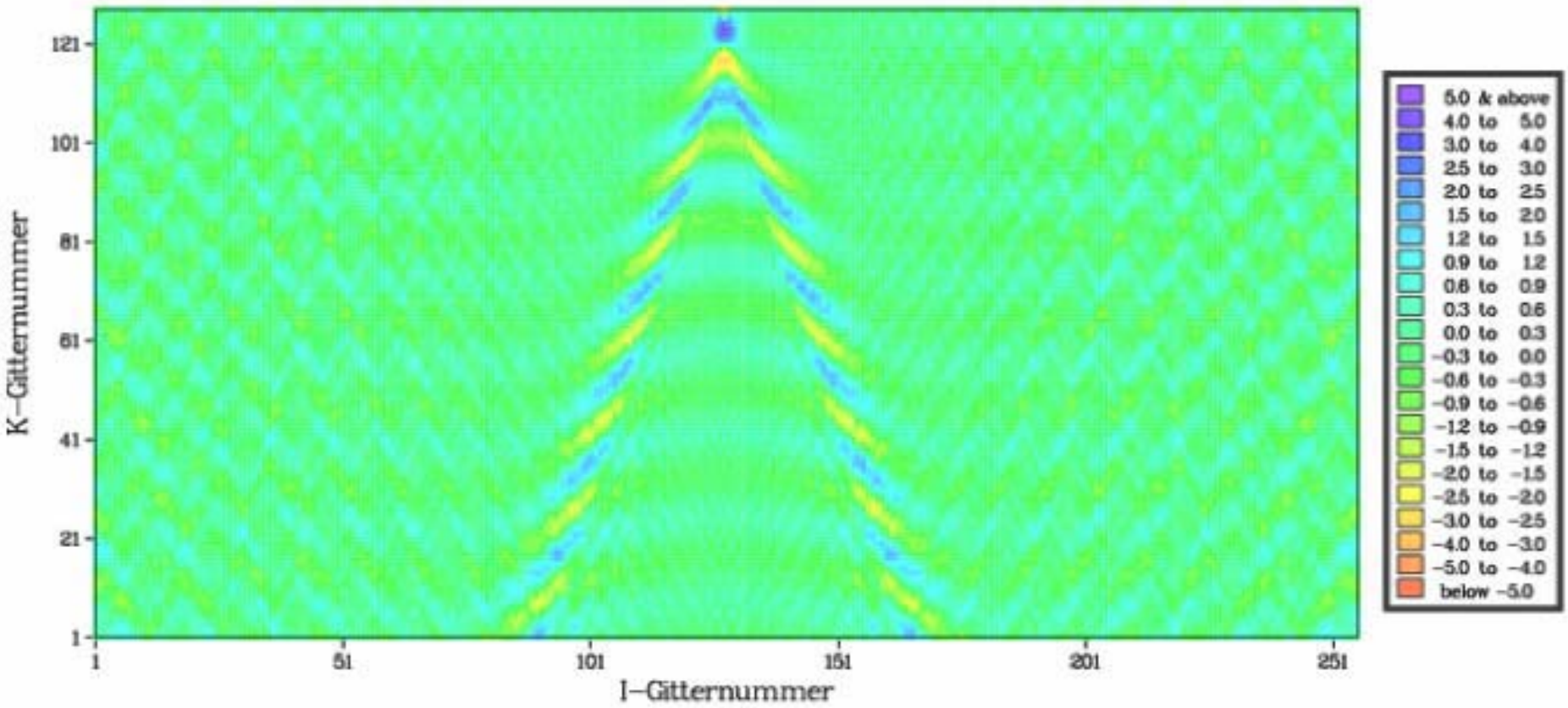


Wave height increases drastically: up to four times



Nonlinear four wave interaction

Stable extreme wave group of a ship wake like pattern generated from a standard JONSWAP spectrum (Rosenthal 2005)



JONSWAP spectrum

$$E(\omega) = \frac{\alpha g^2}{\omega_p^5} \left(\frac{\omega_p}{\omega}\right)^4 \exp\left(-\frac{\omega_p^4}{\omega^4}\right) \gamma^{\exp\left(\frac{(\omega-\omega_p)^2}{2\sigma_p^2\omega_p^2}\right)}$$

ω/ω_p «internal» parameter to describe spectral form

U_h/C_p «external» - wave age - effect of external forcing

$$\alpha = \alpha_0 \left(U_h \omega_p / g\right)^{\kappa_\beta}$$

No explicit dependence on duration (t) or fetch (x)

$$E_{tot} \sim t^p\,(x^p); \quad \omega_{mean} \sim t^{-q}\,(x^{-q})$$

γ = Smax/Sp(fm) → Peak enhancement factor

Wave Spectral Characteristics

Multi-Directional Waves

Two-Dimensional Spectrum $S(f,\theta)$

Total Variation of
Sea Surface Elevation →

$$\sigma_\eta^2 = \int_0^\infty \int_{-\pi}^{\pi} S(f,\theta)\,df\,d\theta$$

Directional Spectral Density
Function →

$$S(f,\theta) = S(f)\cdot D(f,\theta)$$

Angular Spreading
Function → $D(f,\theta)$ →

$$\int_{-\pi}^{\pi} D(f,\theta)\,d\theta = 1$$

S(f) → One Dimensional
Energy Spectral Density
Function

$$D(f,\theta) = G(S)\cos^{2s}[(\theta - \theta_m)/2]$$

Wave Spreading Parameter *s*

$$G(S) = \frac{2^{2s}}{2\pi} \frac{\Gamma^2(s+1)}{\Gamma(2s+1)}$$

Fourier coefficients (a_0, a_1, b_1, a_2, b_2)

→ s

(Cartwright 1963)

$$s_1 = \frac{r_1}{1 - r_1} \qquad s_2 = \frac{1 + 3r_2 + (1 + 14r_2 + r_2^2)^{1/2}}{2(1 - r_2)}$$

$$r_1 = \frac{\sqrt{a_1^2 + b_1^2}}{a_0} \text{ and } r_2 = \frac{\sqrt{a_2^2 + b_2^2}}{a_0}$$

Other Forms for s

Mitsuyasu et al. (1975 JPO) → $$s_U = 11.5(c_m/U)^{2.5}.$$

Wang (1992) → $$s_L = 0.2(H_S/L_p)^{-1.28}.$$

Kumar et al. (2000) →

$$s_3 = 5.28 F_C^{0.59}(f/f_p)^b \quad \text{with } b = 5 \text{ for } f \leq f_p$$
$$\text{and} \quad b = -2.5 \text{ for } f > f_p$$

Nonlinearity parameter → $$F_C = \sqrt{\frac{H_S}{d}}\left(T_{02}\sqrt{\frac{g}{d}}\right)^{\frac{5}{2}}$$

Wave Spreading

Directional Width →

$$\sigma = \sqrt{2(1 - r_1)}$$

Mean Spreading Angle →

$$\theta_k = \arctan\left[\frac{\sqrt{0.5\ b_1^2\ (1+a_2) - a_1\ b_1\ b_2 + 0.5\ a_1^2\ (1-a_2)}}{a_1^2 + b_1^2}\right]$$

Long Crestedness Parameter →

$$\tau = \left[\frac{1 - \sqrt{a_2^2 + b_2^2}}{1 + \sqrt{a_2^2 + b_2^2}}\right]^{1/2} .$$

The Hasselmann equation

$$dn_k/dt = S_{nl} + S_{input} + S_{diss}$$

S_{input} , S_{diss} - empirical parameterizations

Four-wave interaction →

$$S_{nl} = 2\pi \int |T_{0123}|^2 (n_0 n_2 n_3 + n_1 n_2 n_3 - n_0 n_1 n_2 - n_0 n_1 n_3)$$
$$\times \delta(\omega_0 + \omega_1 - \omega_2 - \omega_3)\delta(\mathbf{k}_0 + \mathbf{k}_1 - \mathbf{k}_2 - \mathbf{k}_3) d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3$$

Key Point

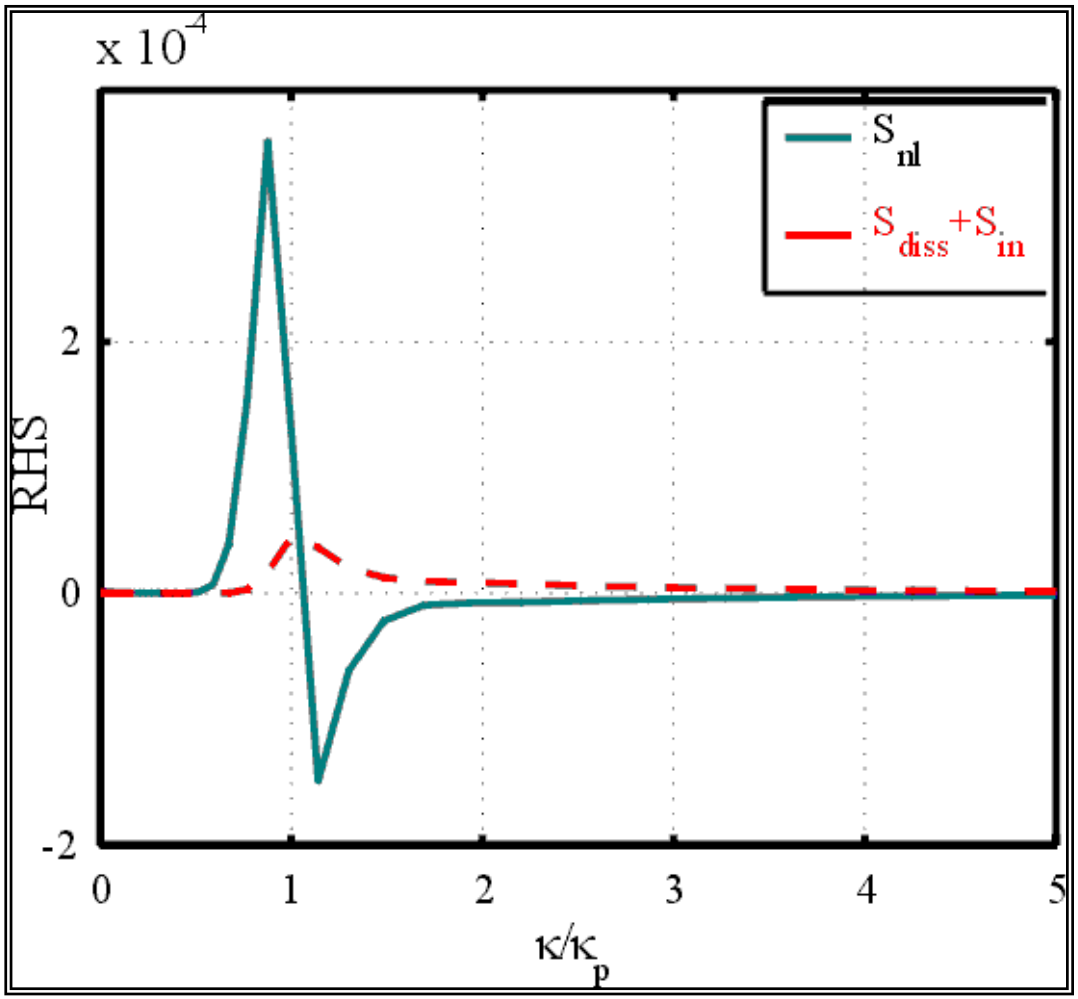
Nonlinearity dominates !

$$S_{nl} >> S_{input}\ ,\ S_{diss}$$

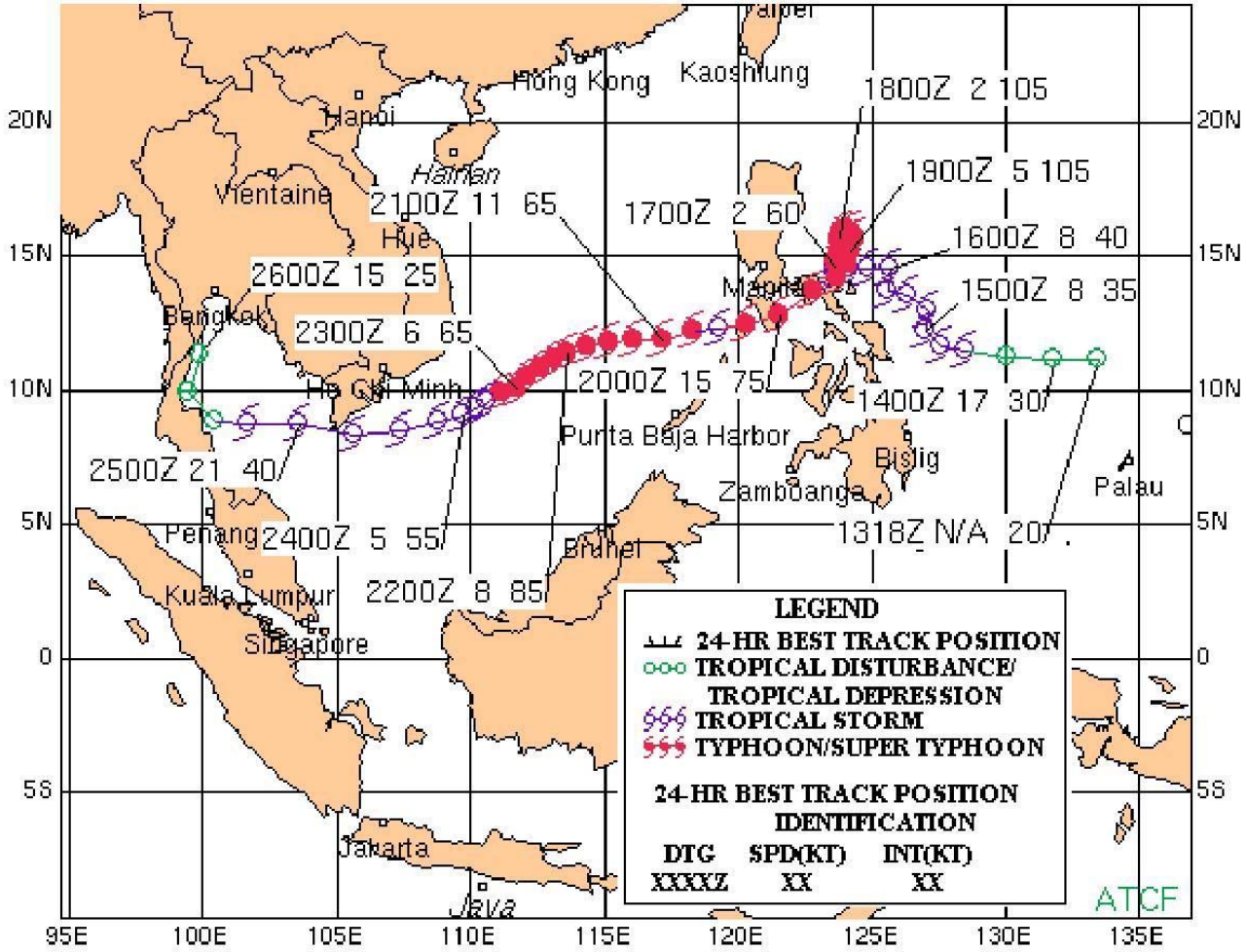
There is no characteristic scale (deep water waves),
i.e. homogeneity of the collision integral gives

$$S_{nl} \sim \boldsymbol{n^3 k^{19/4}}$$

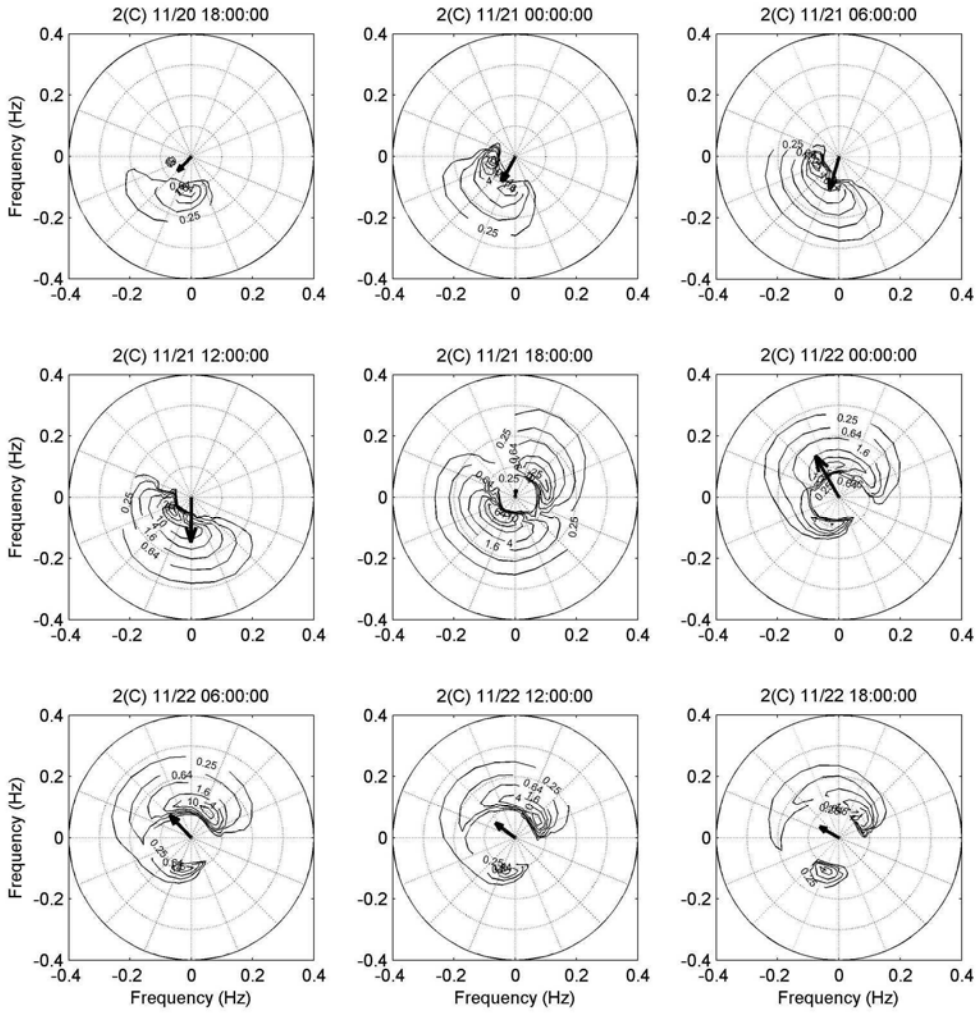
S_{nl} *vs* $S_{diss}+S_{in}$



The Best Track Passage of TY Muifa (2004).

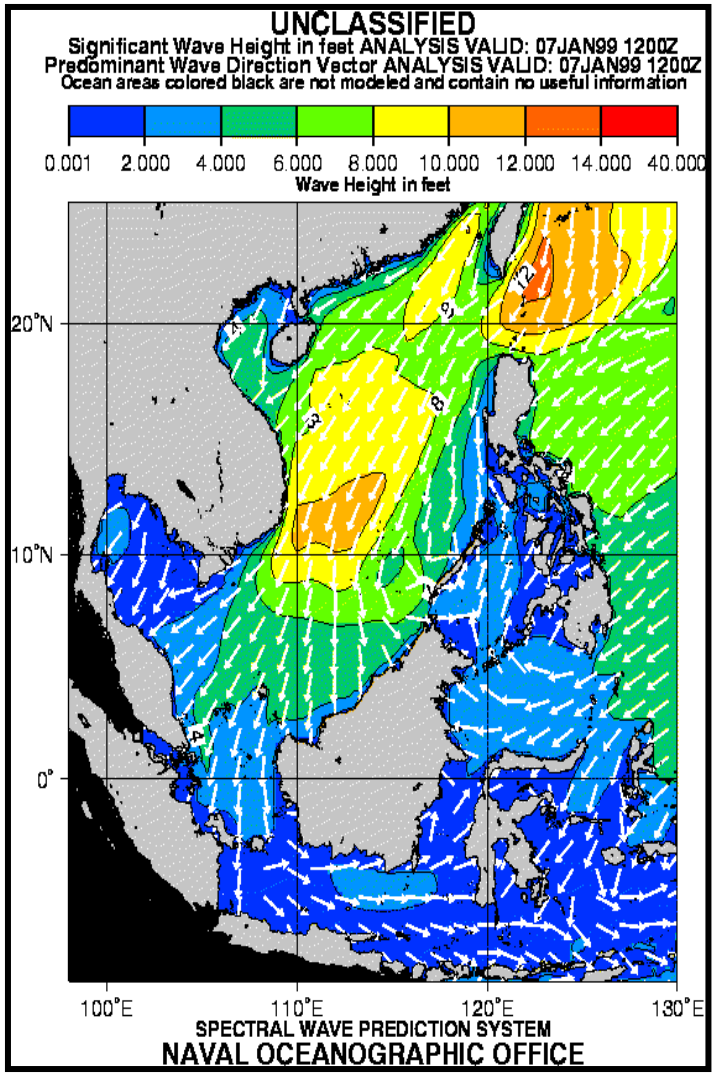


Evolution of Directional Wave Spectra during TY Muifa (2004) in the South China Sea. The Arrow presents Wind Vector. (Chu and Chen 2006 JO)



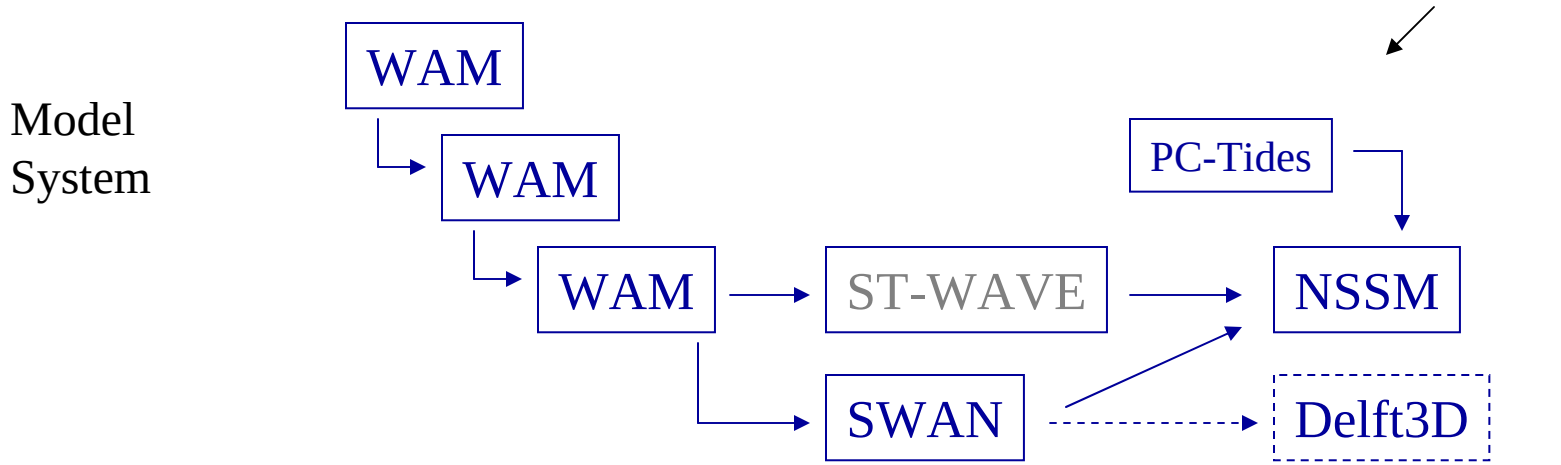
WAVE MODEL (WAM)

- **Relocateable, variable resolution** (1/4º-1/12º)
- **Deep water model (> 20 meters)**
- **Analysis + Forecast to 48 hours** (twice daily)
- **Surface wind forcing using FNMOC's NOGAPS and COAMPS models**
- **Gridded set of wave parameters**
  - predominant wave direction
  - significant wave height
  - swell direction, period and height
  - wind wave height
  - average wave period
- **Area coverage:**
  - GLOBALLY RELOCATEABLE
  - Currently running many domains



Automated product on website

DIOPS is an integration of “small” versions of shallow water Wave, Tide, and Surf models



Benjamin-Feir Index (BFI) and Kurtosis

$$C_4 =< \eta^4 > /3 < \eta^2 >^2 -1, \qquad C_4 = \frac{\pi}{3\sqrt{3}} \times BFI^2,$$

$$C_4 = \frac{4}{g^2 m_0^2} \int d\vec{k}_{1,2,3,4} T_{1,2,3,4} \delta_{1+2-3-4} (\omega_1 \omega_2 \omega_3 \omega_4)^{\frac{1}{2}} \times R_r(\Delta\omega, t) N_1 N_2 N_3, \tag{6}$$

$$BFI = \epsilon \sqrt{2} / \sigma'_\omega,$$

relative width of the frequency spectrum →

$$\sigma'_\omega = \sigma_\omega / \omega_0$$

wave steepness →

$$\epsilon = (k_0^2 < \eta^2 >)^{\frac{1}{2}}$$

BFI and Peakedness

Goda Peakednes Factor → $$Q_p = \frac{2}{m_0^2} \int \mathrm{d}\omega \; \omega E^2(\omega)$$

$$BFI = k_0 m_0^{1/2} Q_p \sqrt{2\pi}$$

Probability that wave height exceeds $h \times H_S$

$$P_H(h) = e^{-2h^2} \left[1 + C_A B_H(h)\right]$$

$$B_H(h) = 2h^2 \left(h^2 - 1\right) .$$

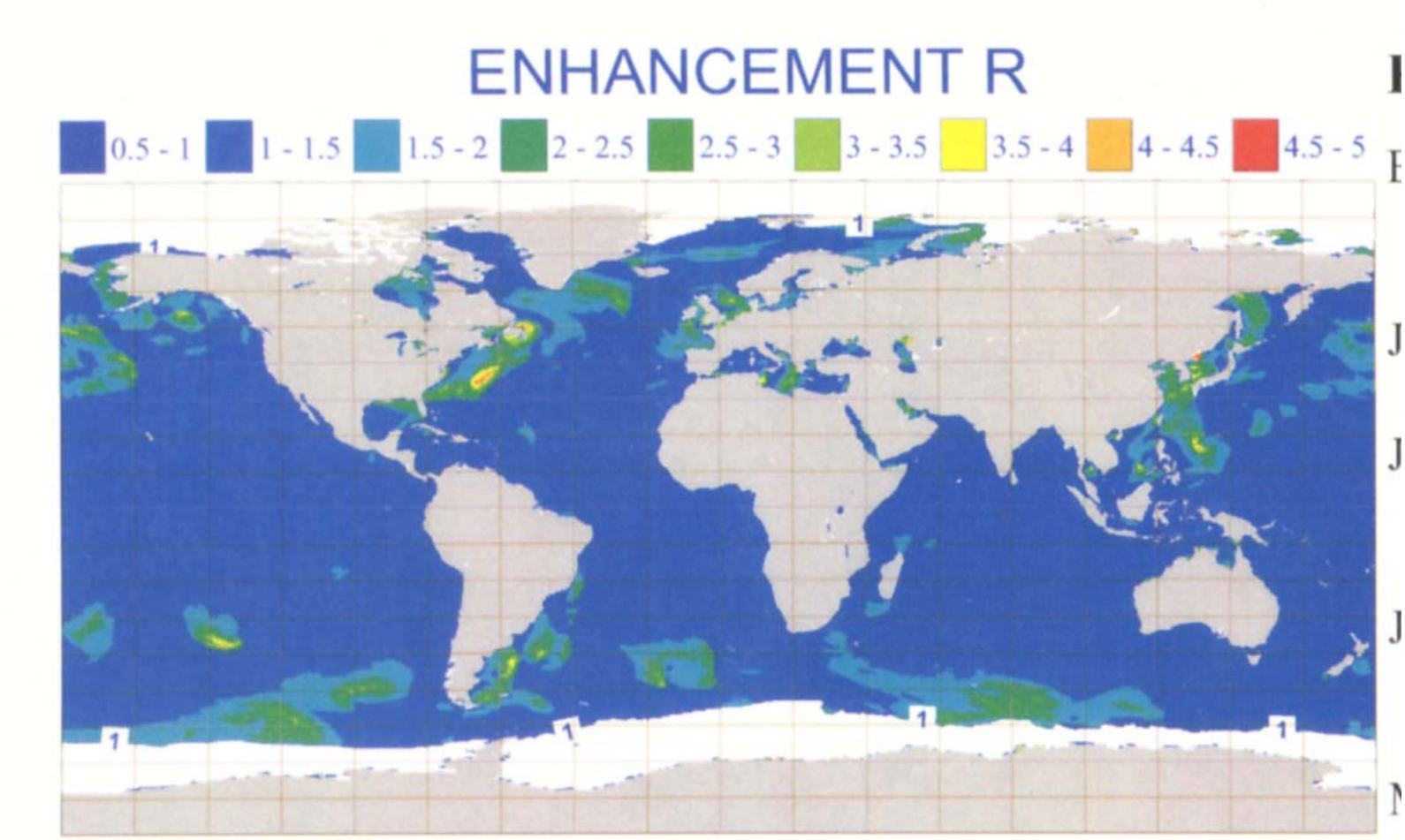
Wave Spectral Model → Prediction of Rogue Waves

- Spectral evolution
- PDF of surface elevation
- BFI obtained from Kurtosis using the Kurtosis/BFI relationship
- Goda peakedness factor from BFI

Operational Implementation

- From the predicted wave spectrum we infer the BFI.
- From the BFI 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, such as the Rogue (Freak) waves

Enhancement of extreme events caused by nonlinear focusing for the one-day forecast from 21 October 2003.



Cross-Sea Index (Toffoli et al. 2003)

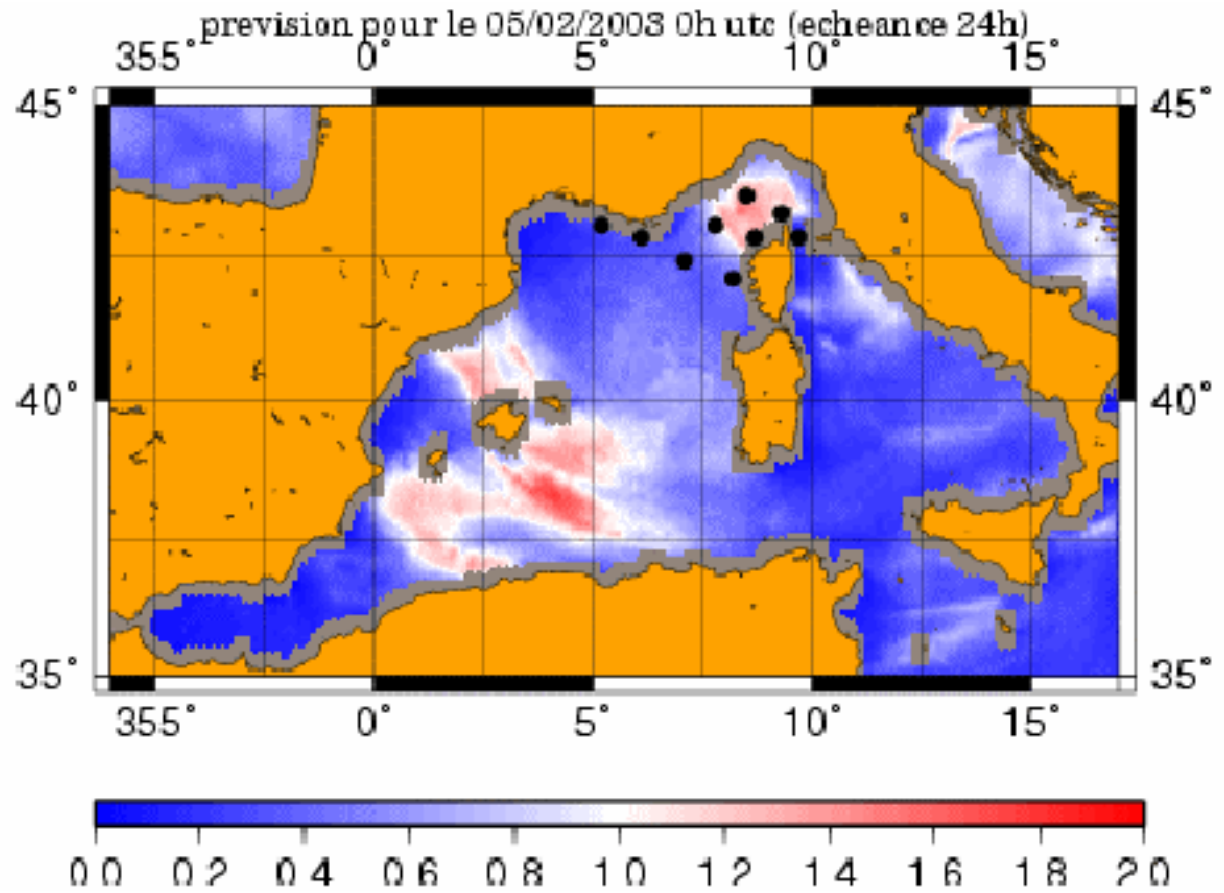
Swell and wind sea “almost” aligned →

→ Extreme waves → accidents

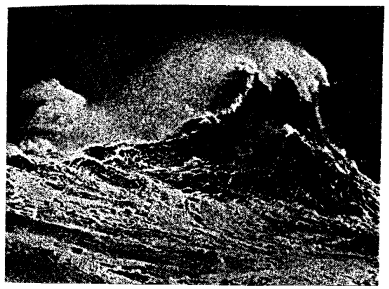
$$CSI \equiv Hs/2 * \exp\cdot(-10\cdot(spread-1)^2)$$

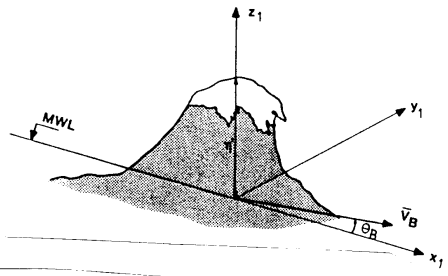
Cross-Sea Index for May 2, 2003 by French Meteorological Office (Toffoli et al. 2003)

$$CSI \equiv Hs/2 * \exp\cdot(-10\cdot(spread-1)^2)$$



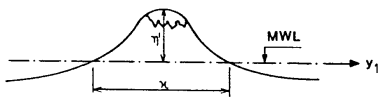
(5) Effects of Rogue (Freak) Waves on Ships and Offshore Structures





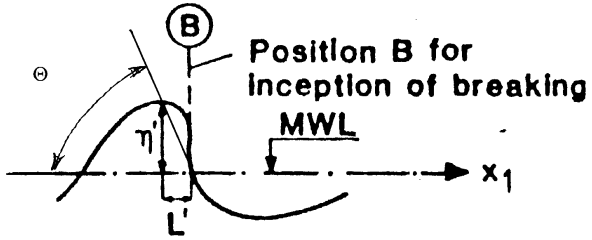
DEFINITION OF CREST LENGTH $\varkappa$ AND 3-D CREST SHAPE FACTOR β IN SYNOPTIC DOMAIN :

$\beta \equiv \frac{\eta'}{\varkappa}$



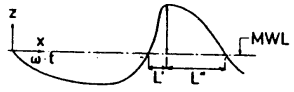
DEFINITION OF CREST FRONT STEEPNESS ϵ_X IN SYNOPTIC DOMAIN :

$\epsilon_{X,B} \equiv \frac{\eta'}{L'}$



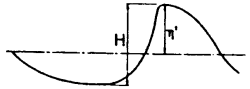
VERTICAL ASYMMETRY FACTOR

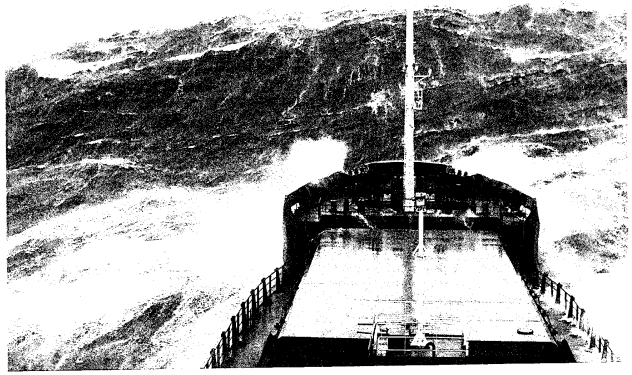
$\lambda = \frac{\epsilon}{\delta} = \frac{L''}{L'}$

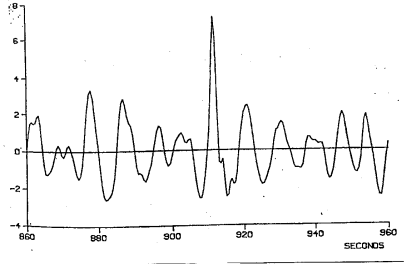


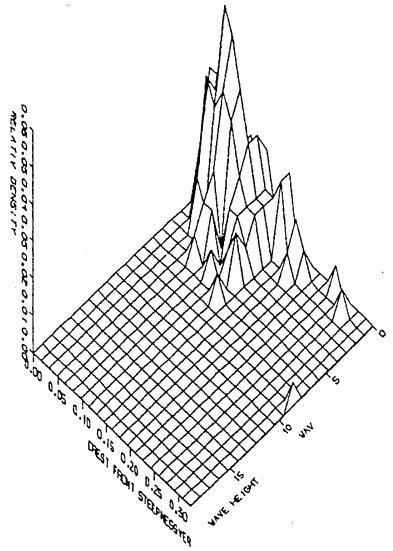
HORIZONTAL ASYMMETRY FACTOR

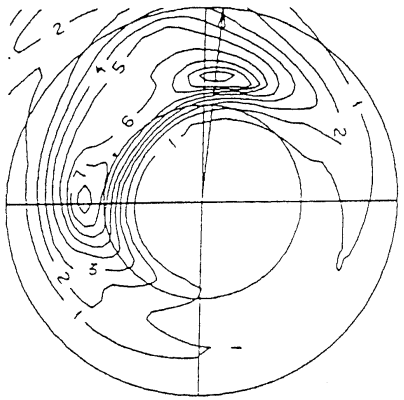
$\mu = \frac{\eta'}{H}$

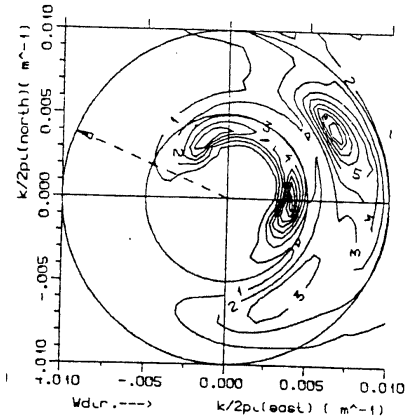








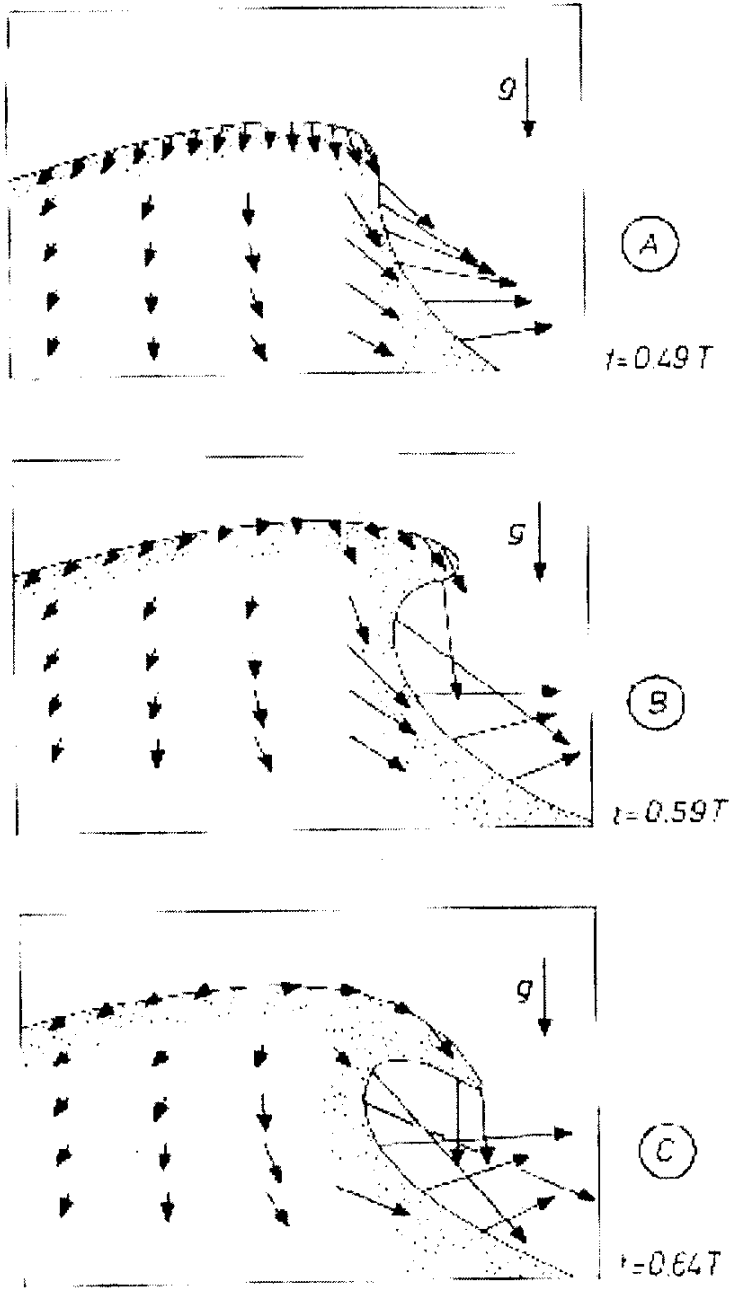



k/2pi(north)(m^-1)
0.010
0.005
0.000
-.005
-.010
-.010
-.005
0.000
0.005
0.010
Wdir.--->
k/2pi(east) (m^-1)



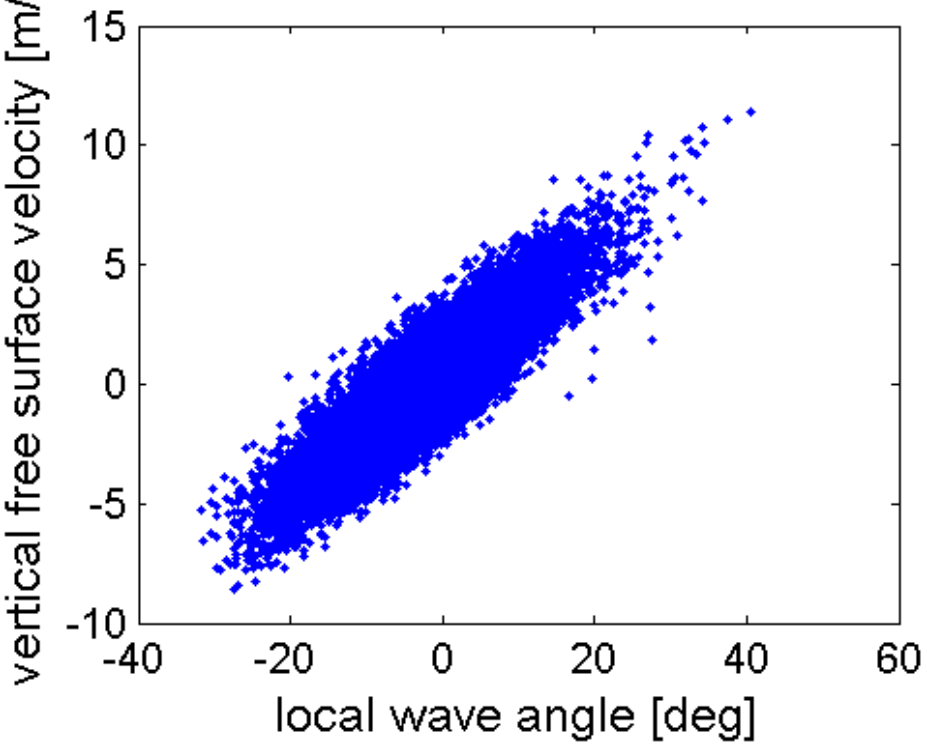
Simulation of local particle accelerations in deep water (Kjeldsen 2008).

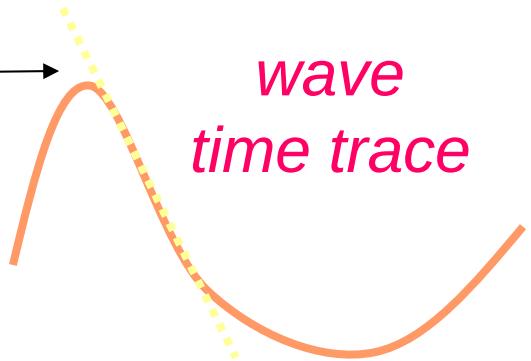
The vertical arrow indicates the gravity acceleration $g = 9.81\ m/s^2$.
Local particle accelerations attain values up to 3 g.



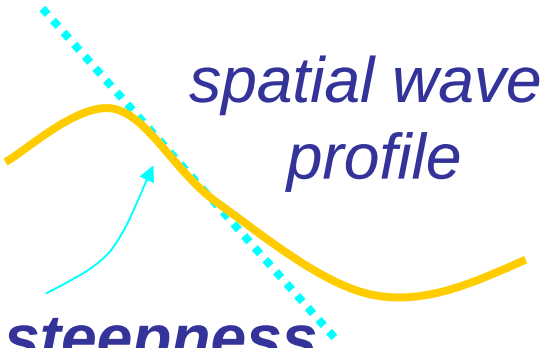
Vertical Free Surface Velocity

$\frac{d\eta}{dt}$ ***velocity***





wave time trace

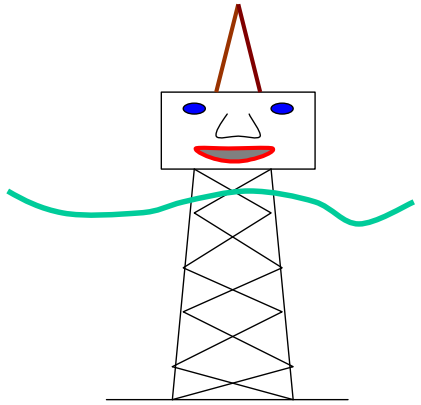


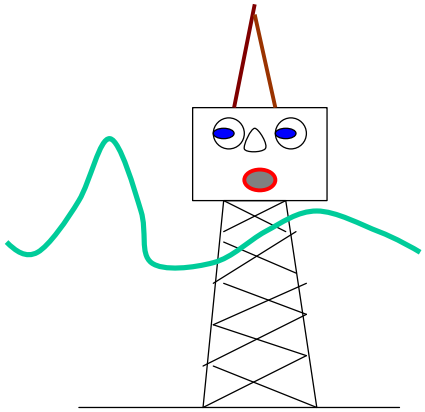
spatial wave profile

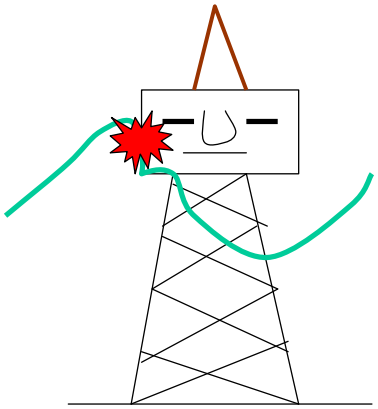
$\frac{d\eta}{dx}$ ***steepness***

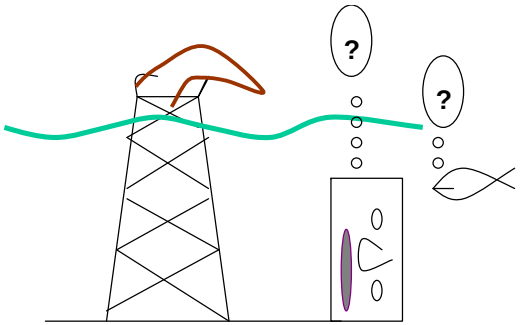
Effect of Rogue Waves

For ship or platforms, freak waves will mainly represent a problem if their crest hits a structural element which is not designed for wave loads.





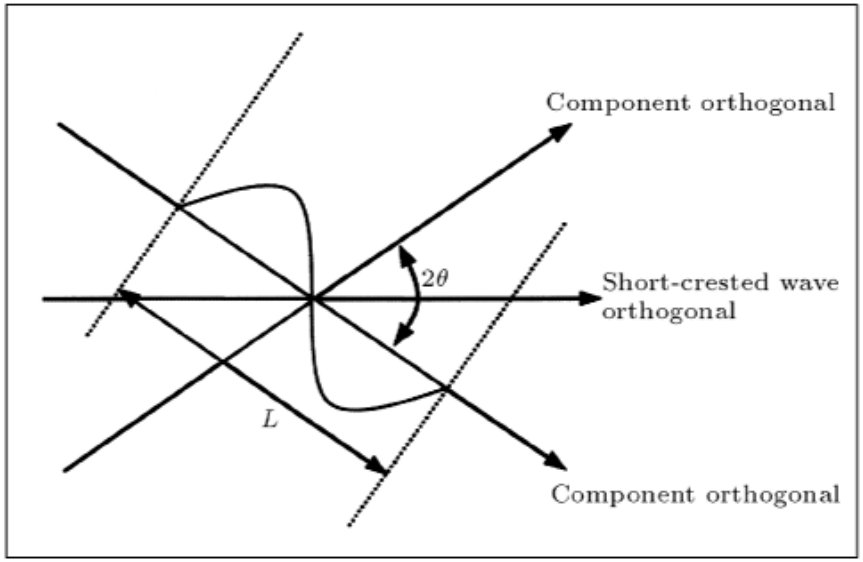




A short-crested wave system, as is produced by two progressive waves propagating at an oblique angle to each other.

$$\phi(x,y,z,t) = \frac{-igH}{2\omega}\frac{\cosh(\kappa(z+h))}{\cosh(\kappa h)}\exp\{i(\kappa_{nn}x+\kappa_{nt}y)\}$$

$$\cos(-\kappa_{tn}x + \kappa_{tt}y + \theta)e^{-i\omega t}, \qquad (4)$$



θ → Transverse Phase Lag

6 DOF for Ship and Moored Semisubmersible Structure

$$(\mathbf{M} + \mathbf{M}_a^t)\ddot{\mathbf{X}} + \mathbf{B}_e^t|\dot{\mathbf{X}}_0|\dot{\mathbf{X}} + (\mathbf{K}_h + \mathbf{K}_m(\mathbf{X}))\mathbf{X} = \mathbf{F}(t),$$

M → physical mass matrix of the structure (6 X 6)

X → displacement of the center of gravity and orientation of the structure (6X1)

$\mathbf{K}_h$ → hydrostatic stiffness matrix (6X6)

$\mathbf{K}_m(\mathbf{X})$ → nonlinear stiffness matrix (6X6)

Forcing Vector **F**(*t*)

$$\mathbf{F}(t) = \sum_j \mathbf{M}_a^j \ddot{\xi} + \sum_j \mathbf{F}_{FK}^j + \sum_j \mathbf{B}_e^j |\dot{\xi}_0| \dot{\xi},$$

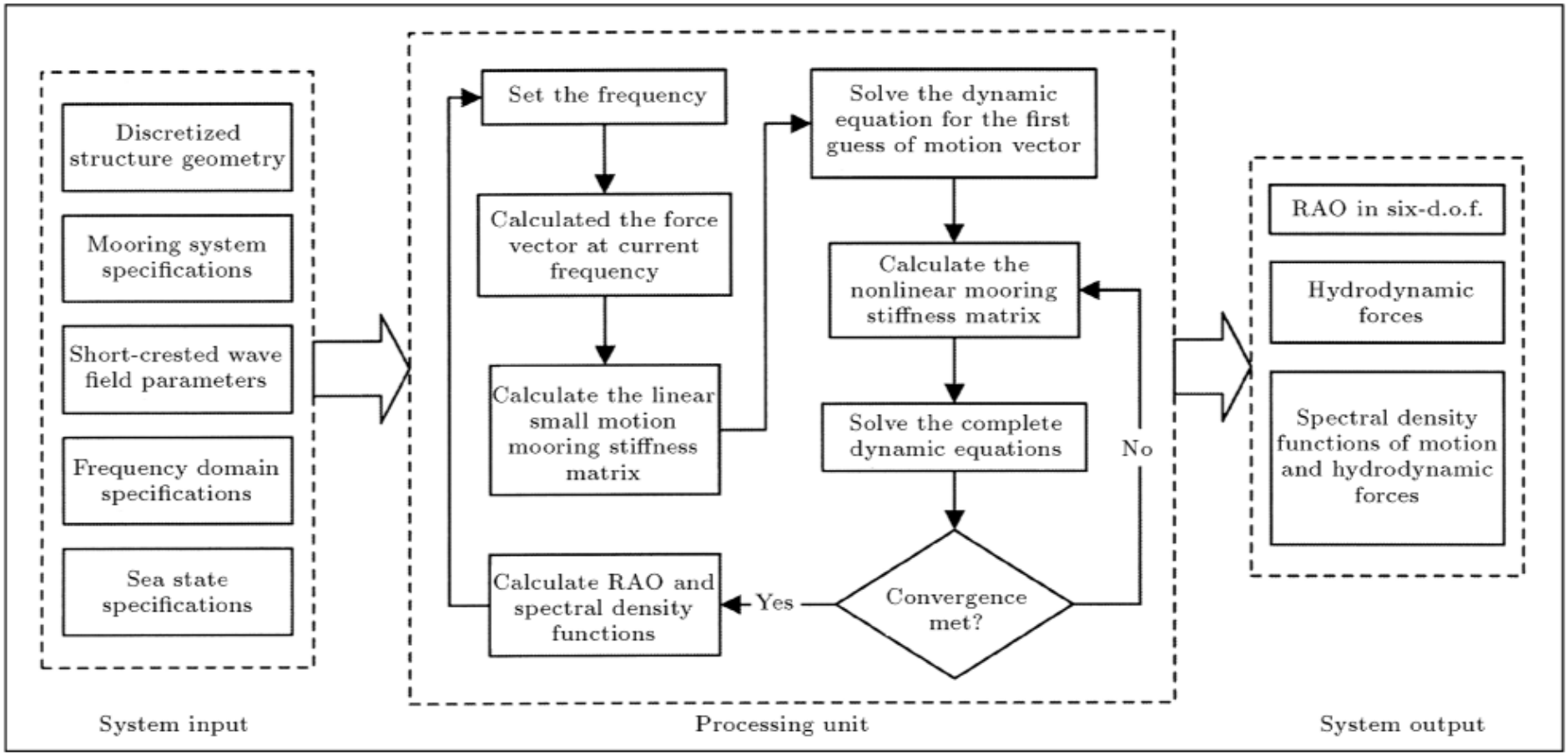
$\mathbf{F}_{FK}^j$ - → Froude-Krylov force vector on the jth element (6X1)

$\mathbf{B}_e^t$ → Linearized Damping Matrix

$\dot{\xi}$ → Water Particle Velocity Vector (6X1)

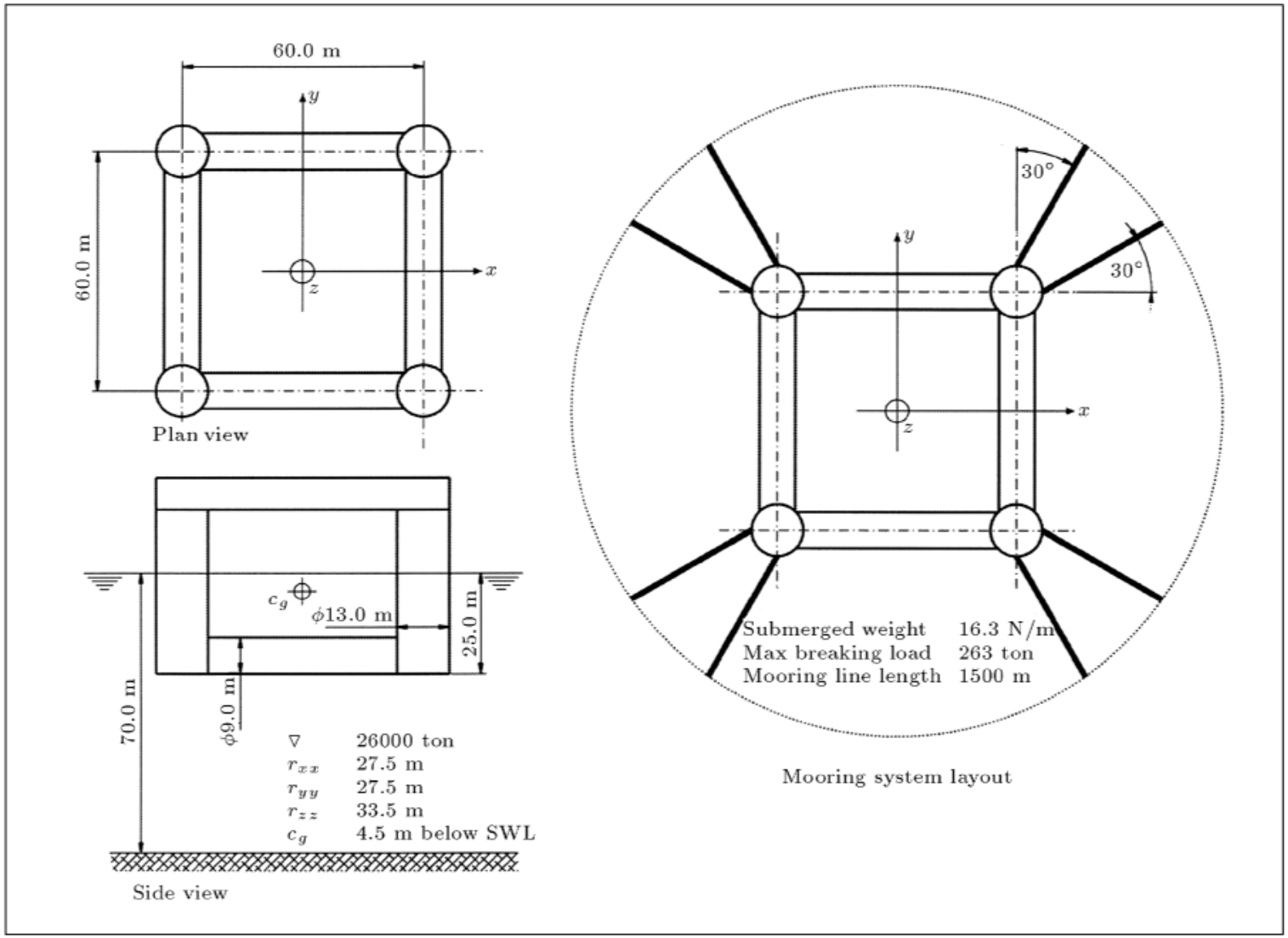
$\dot{\xi}_0$ → Amplitude of $\dot{\xi}$

Flow Chart of Computational System (Heideri et al. 2004)

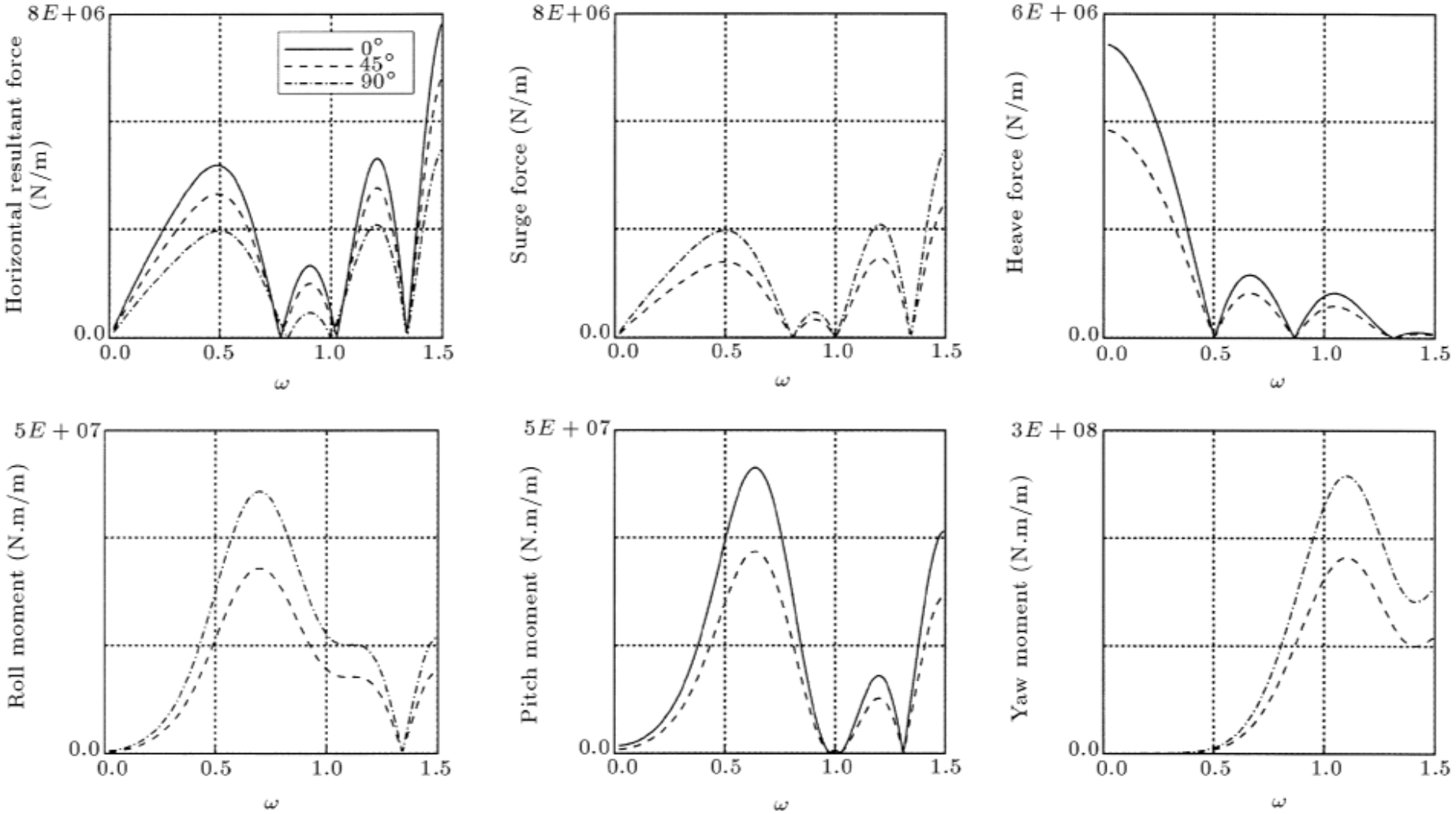


RAO → Response Amplitude Operator

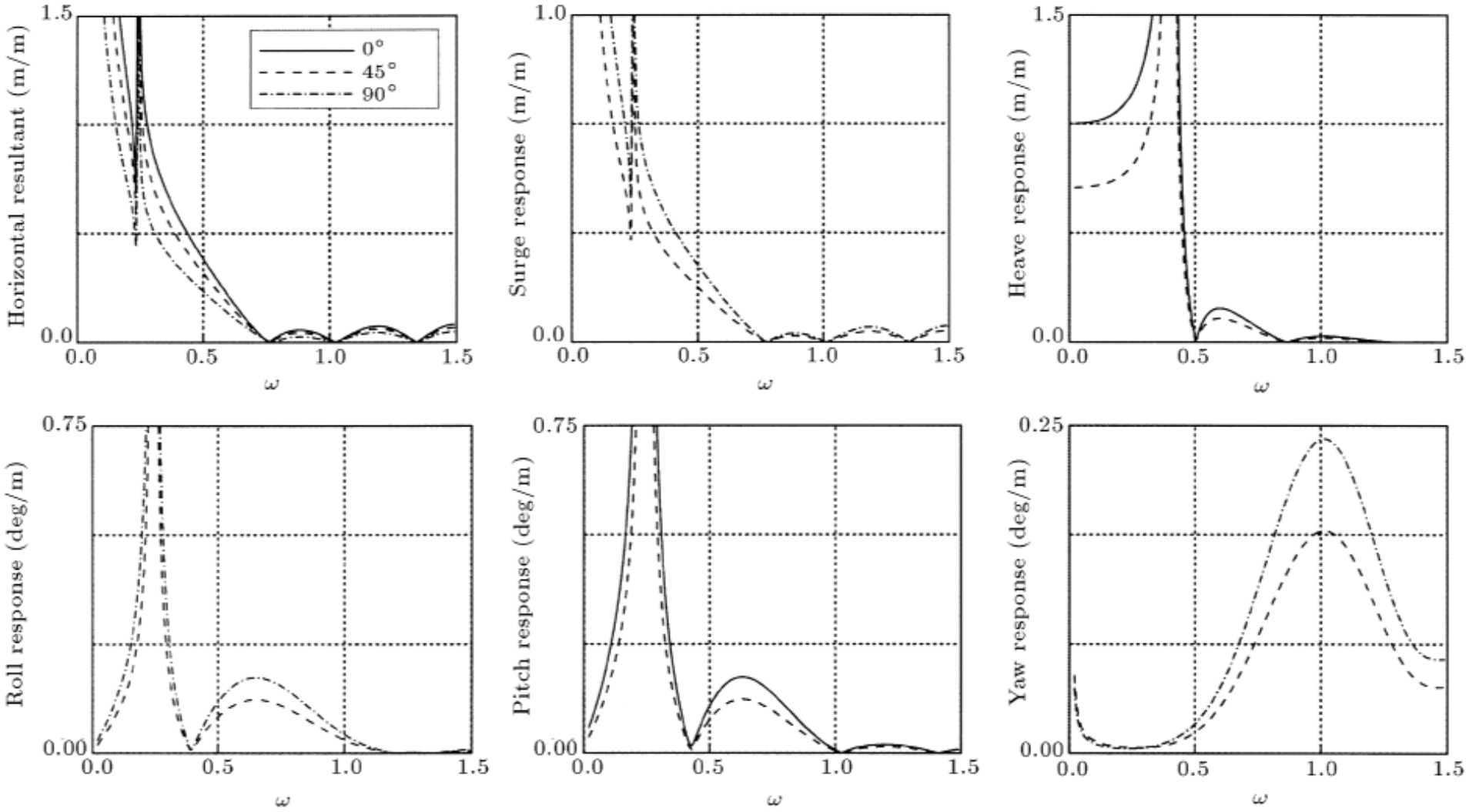
Geometrical specications and mooring system layout of the semisubmersible (Heidari et al. 2004)



Hydrodynamic forces and moments for different values of transverse phase lag



Response amplitude operators for different values of transverse phase lag



Summary

- (1) More extensive routine measurements with useful precision
- (2) High-resolution wave models
- (3) Thorough on effects of rogue waves on ships (such as DDG 1000)