Leonid Lopatoukhin,
Alexander Boukhanovsky

EXTREME AND FREAK WAVES

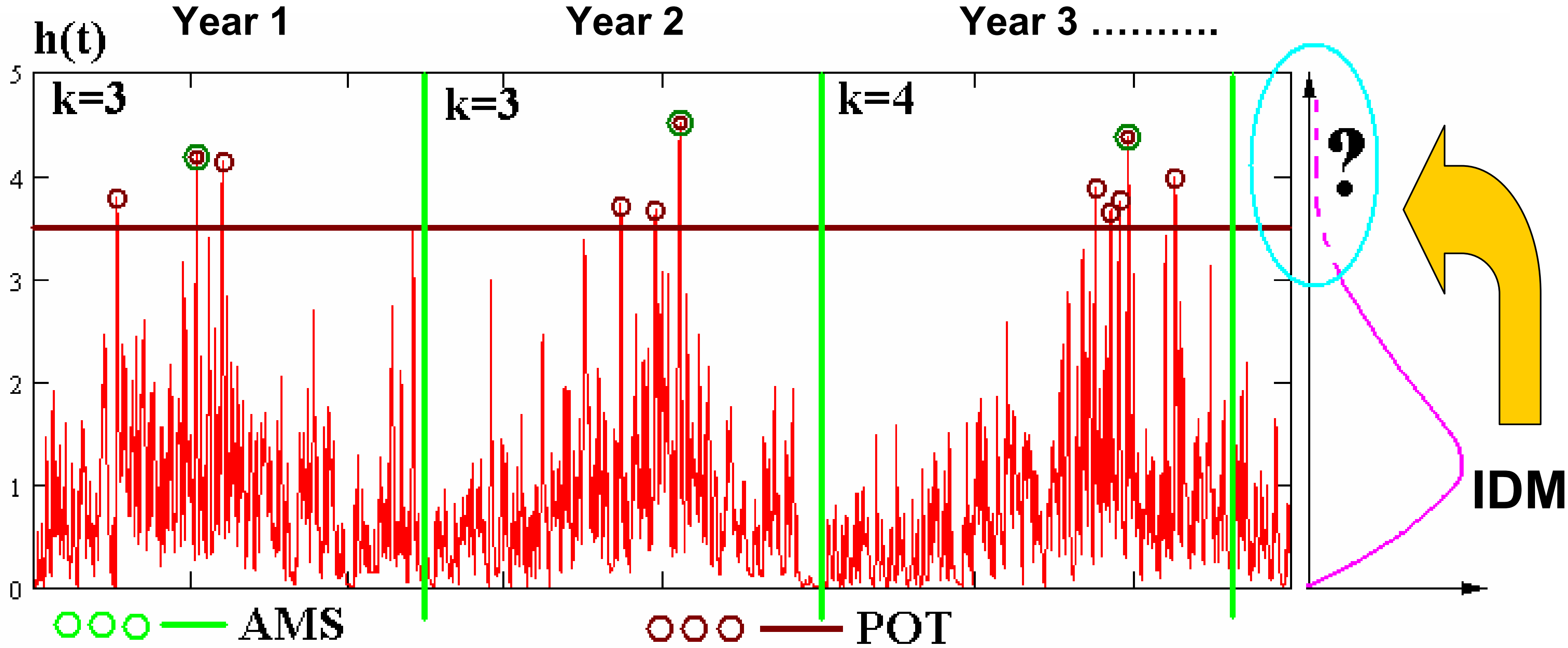
(The Difference and Similarity)

State University (dep. Oceanology), leonid-lop@yandex.ru,
State University of Information Technologies., avb-mail@mail.ru

EXTREME WAVES

- Extremes at a point
- Extremes at a field
- Multivariate extremes

MAIN APPROACHES to METOCEAN EXTREME ANALYSES



IDM: the type of initial distribution in a tail is unknown.

AMS: the type of the tail is known, but the sample is small.

POT: the type of the distributions of both intensity and number of maxima are known only for limit case (high level ~ small sample)

MENU: the type of initial distribution is unknown

How to compute the extremes at a point?

Some methods for extreme estimation

IDM Approach

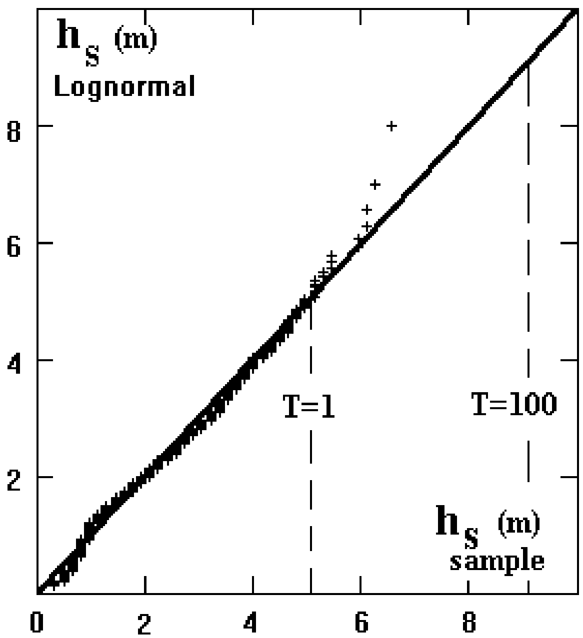
$$h_T = F^{-1}(p(T))$$

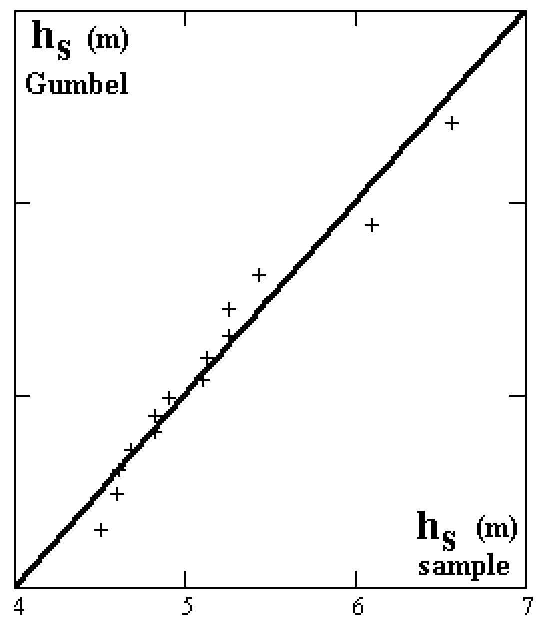
AMS Approach

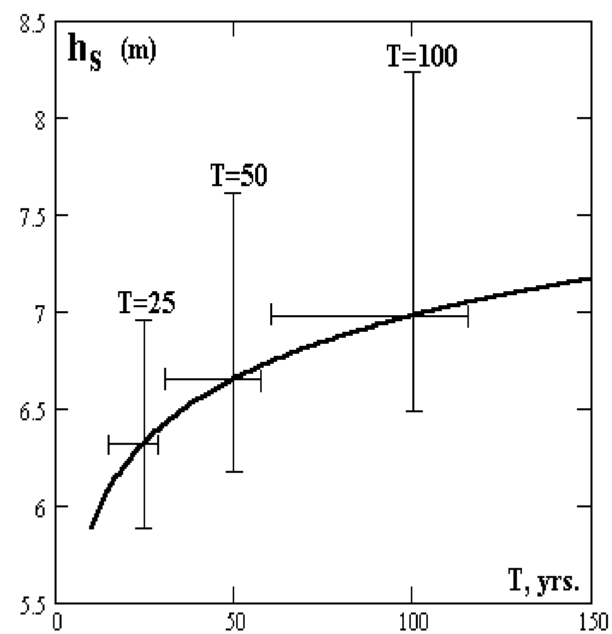
$$F_{\max}(x) = \exp\{-\exp\{-a_N[x - b_N]\}\}$$

POT Approach

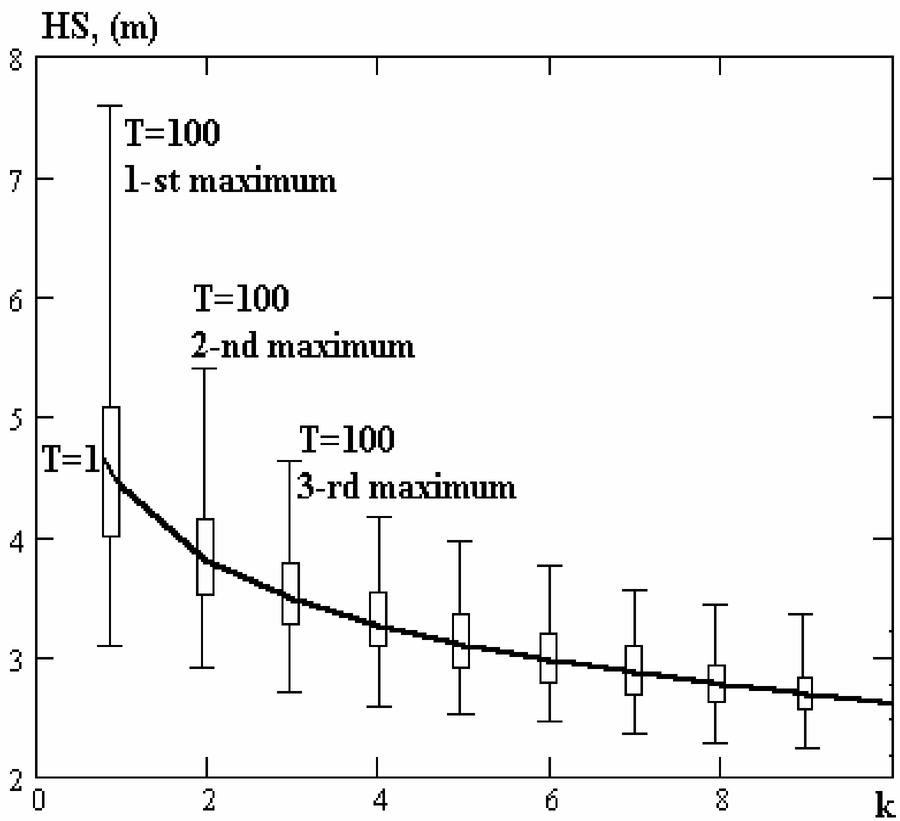
$$F(h) = \sum_k p_k G^k(h)$$







Extremes at the point: BOLIVAR approach



Multivariate quantile function of consequent annual maxima HS. Barents Sea

Ranking procedure of extremes

$$(h^+_{11} \ge h^+_{12} \ge \ldots \ge h^+_{1k})$$
$$(h^+_{21} \ge h^+_{22} \ge \ldots \ge h^+_{2k})$$
$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$
$$(h^+_{n1} \ge h^+_{n2} \ge \ldots \ge h^+_{nk})$$

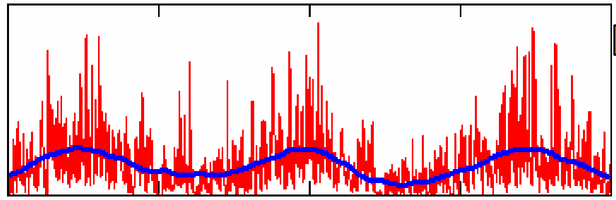
where n is the number of n–th consequent maxima in a year,
k is the number of the year.

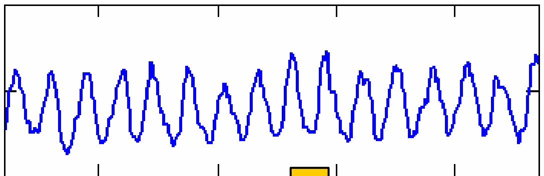
Approximation of multivariate quantile function

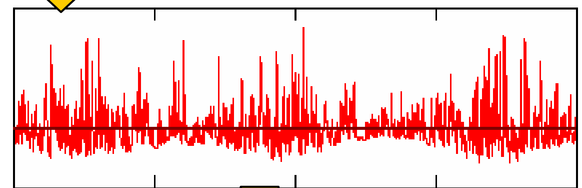
$$F(x_1,\ldots x_k) = \sum_{k=1}^{\infty} p_k G(x_1,\ldots,x_k)$$

Estimation of quantile function – by means of multiscale stochastic modeling

THE STEPS OF MODELING & SIMULATION







IDENTIFICATION OF THE MODEL

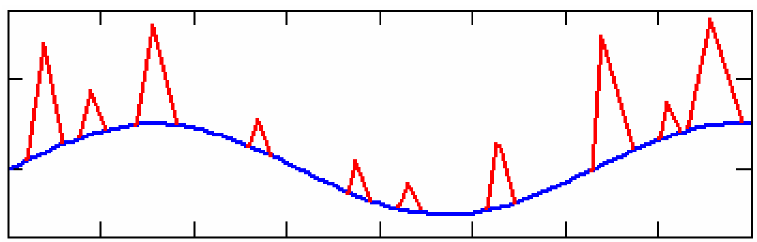
Estimation of parameters of PCSP model (annual & year-to-year variability)

Estimation of parameters of distributions $F(h,T), F(\Theta)$ for all the months

SIMULATION

Simulation the time series of level Z(t)

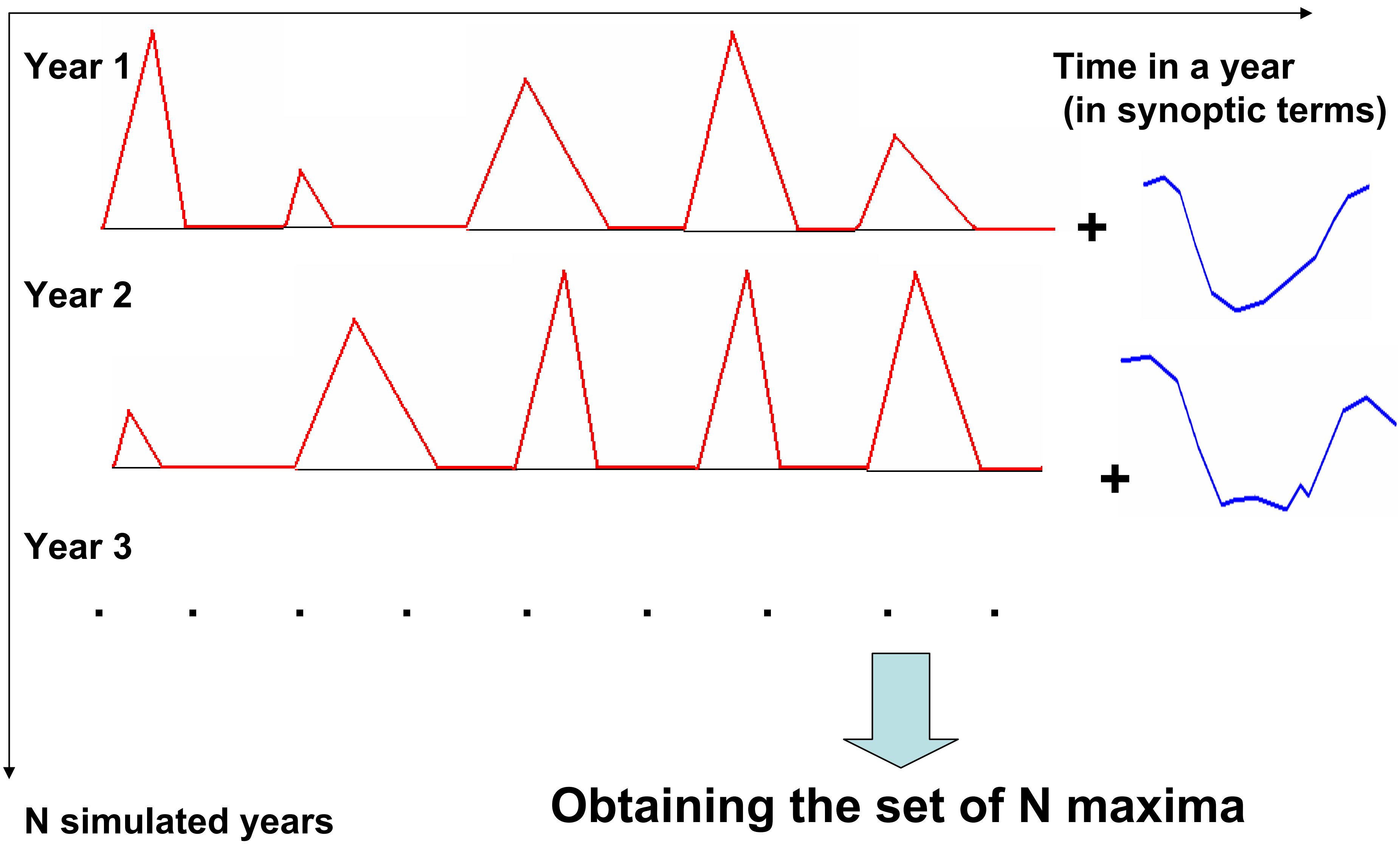
Simulation the triangle impulses above the level Z(t)



M times for N years (for interval estimation of N-years extremes)

Essence of BOLIVAR procedure

From storms and calms – to events once T years



Obtaining the set of N maxima (for each year)

ADVANTAGES

1. The annual and year-to-year variability is taking into account.
2. Sample size for model identification is not small (40-70T, where T is the length of initial data series).
3. The limit (analytical) "control points" for (h,T,Θ) distributions are available.
4. The definition of "event once T years" is natural (from the annual maxima).
5. The secondary maxima are in consideration.

WORLD METEOROLOGICAL ORGANIZATION

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (OF UNESCO)

ESTIMATION OF EXTREME WIND WAVE HEIGHTS

by

L.J. Lopatoukhin, V.A. Rozhkov, V.E. Ryabinin, V.R. Swail, A.V. Boukhanovsky and A. B. Degtyarev

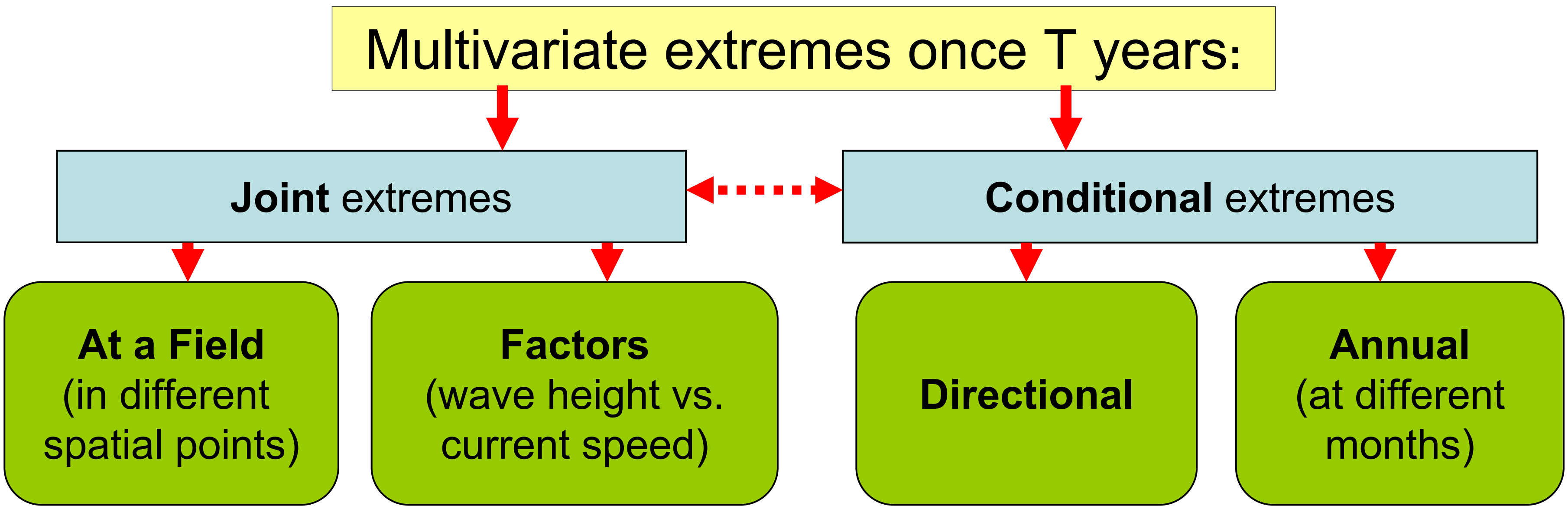
WMO/TD-No. 1041

2000

JCOMM Technical Report No. 9

Multivariate metocean extremes: problem of definition

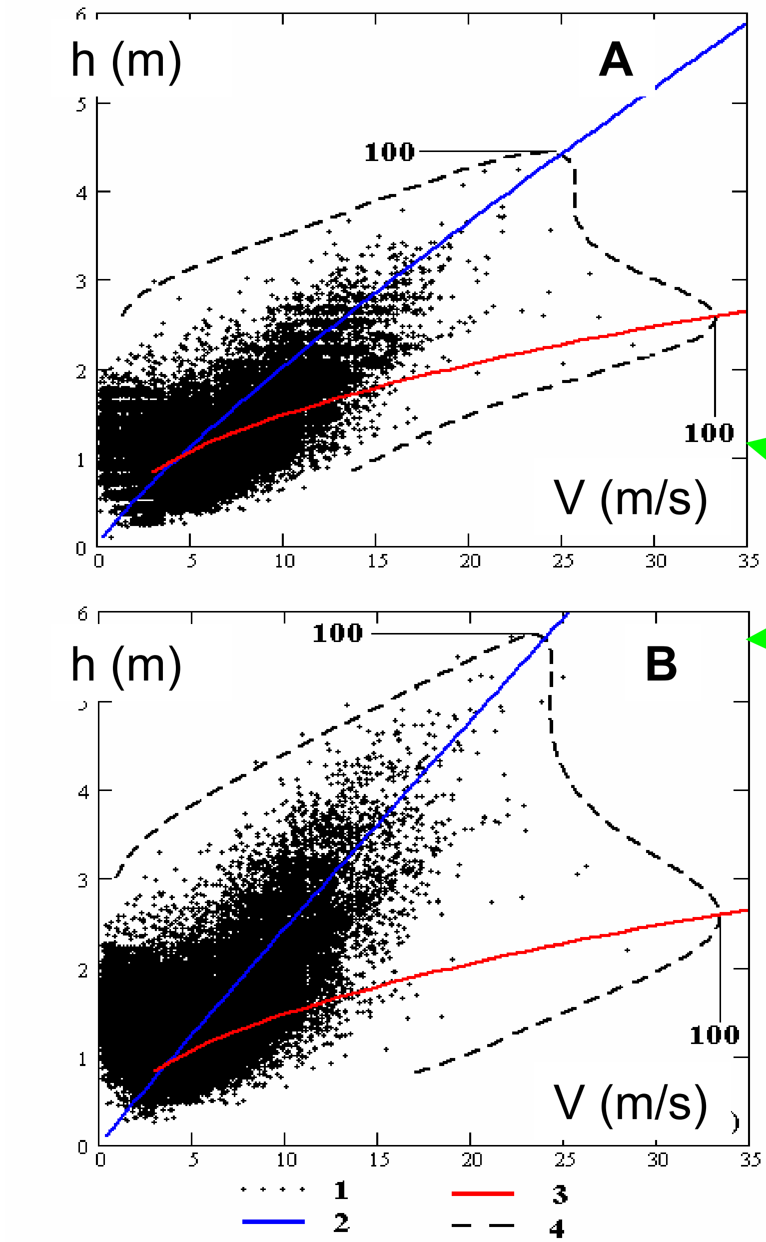
Univariate extremes of process X(t) - **once T years**: ~ with probability **p**(T)



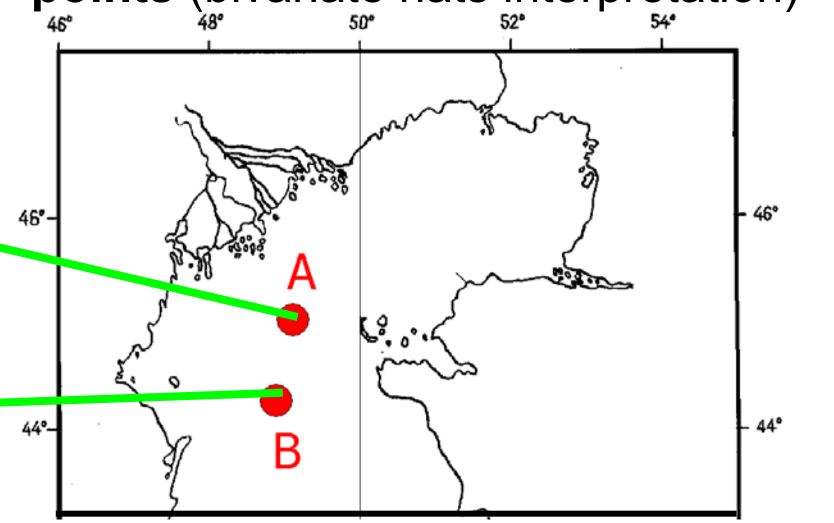
Uncertainty in interpretation of joint extremes of (X,Y)

- Expected value of **Y**, associated with extreme of **X** , possible once T years
- Expected value of **X**, associated with extreme of **Y** , possible once T years
- Joint occurrence of combinations **(X,Y),** possible once T years

Joint (bivariate) extremes of metocean processes



North Caspian Sea:
Significant wave height h (m) vs. mean wind speed V (m/s) in different spatial points (bivariate hats interpretation)



$$\boxed{F(h,V) = p}$$

Bivariate hat $\equiv$ implicit solution of quantile equation

1 – sample data;
2 & 3 – regressions (associated values);
4 – 100-years “hat”

How to estimate the joint extremes of metocean processes

Processing of bivariate (multivariate data sample)

Choice of bivariate distribution model

Identification of the parameters of distribution

Definition of the probability corresponding to extreme events

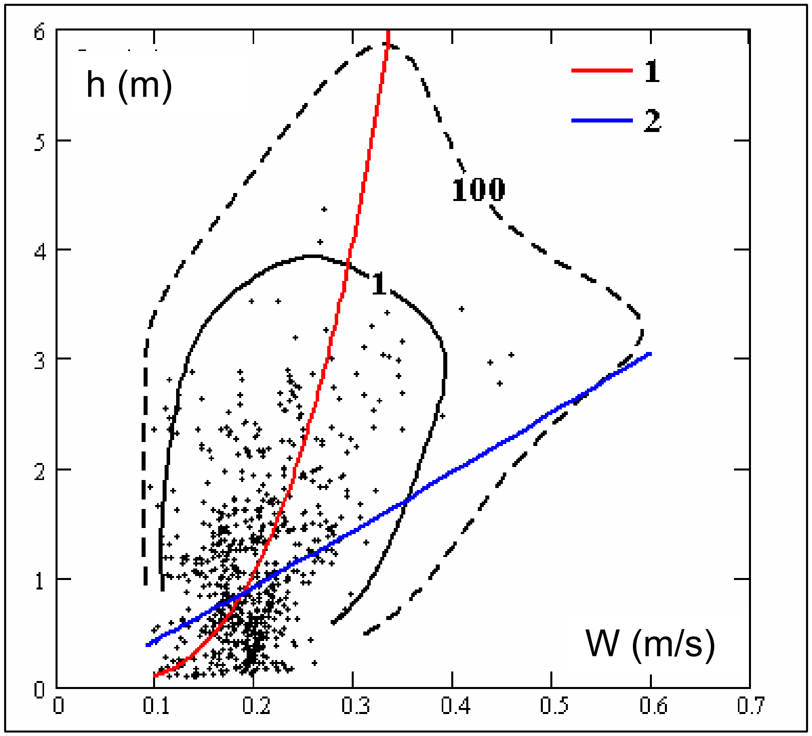
Calculation of equiprobable contours

Selection of the "critical" points

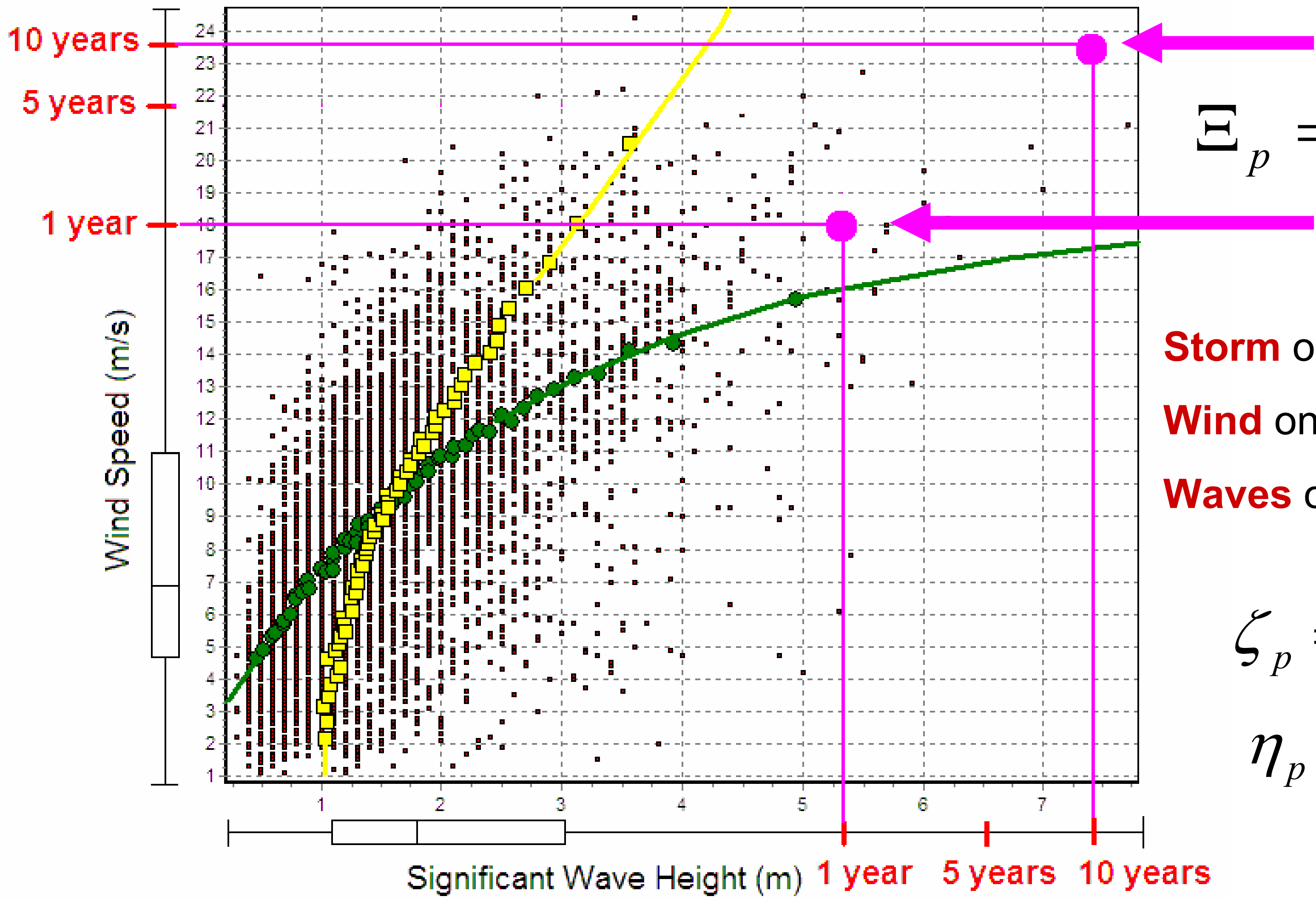
Choice the extreme analysis model

Initial DataSet

Southern Barents sea: wave height h (m) vs. surface current speed (m/s)



Definitions of two-dimensional extremes:
1) Composition of one-dimensional (marginal) extremes



$$\Xi_p = (\zeta_p, \eta_p)$$

Storm once T-years =

Wind once T years +

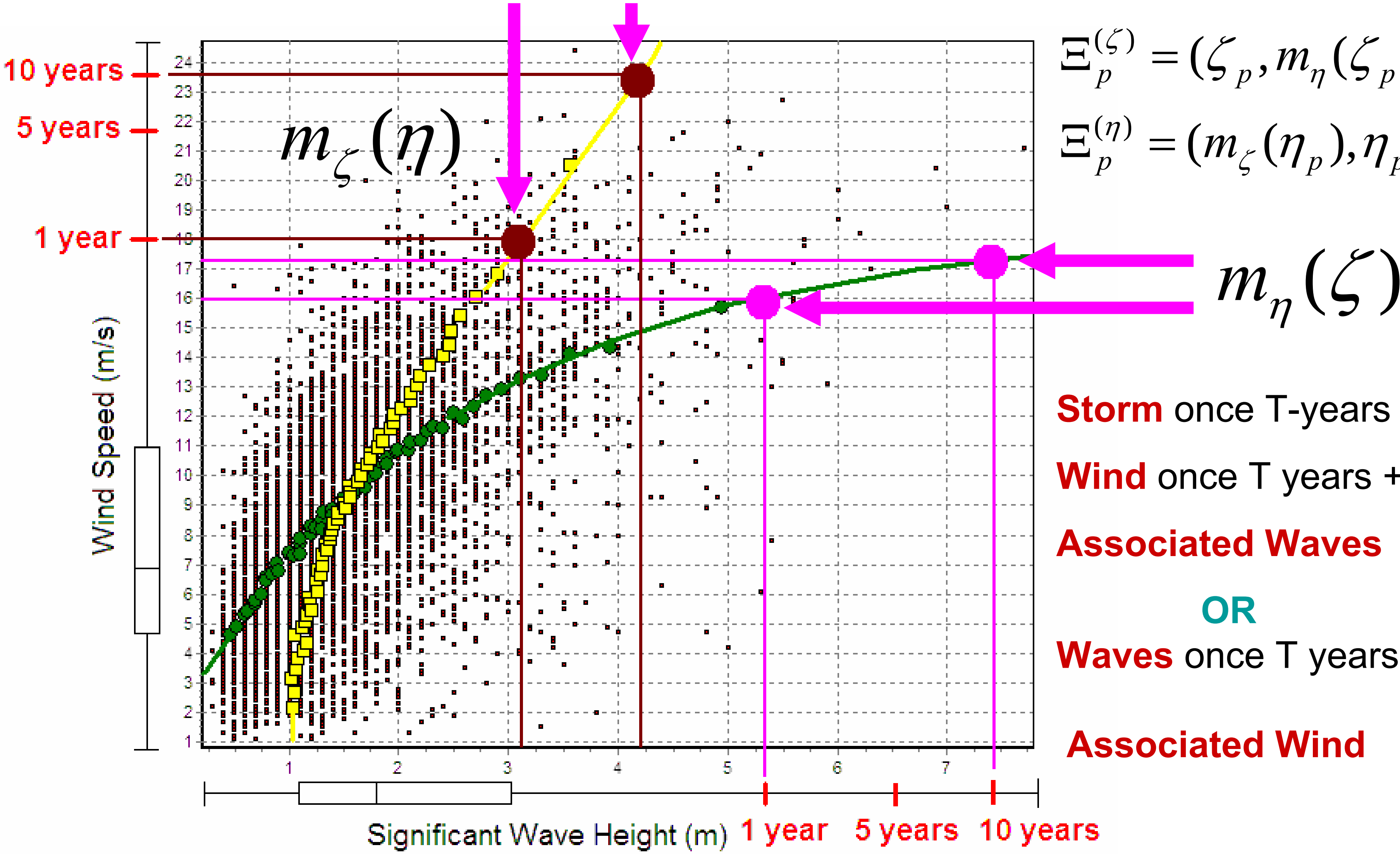
Waves once T years

$$\zeta_p = F_\zeta^{-1}(p),$$

$$\eta_p = F_\eta^{-1}(p)$$

Definitions of two-dimensional extremes:

2) Values, associated to marginal extremes



$$\Xi_p^{(\zeta)} = (\zeta_p, m_\eta(\zeta_p));$$

$$\Xi_p^{(\eta)} = (m_\zeta(\eta_p), \eta_p)$$

Storm once T-years =

Wind once T years +

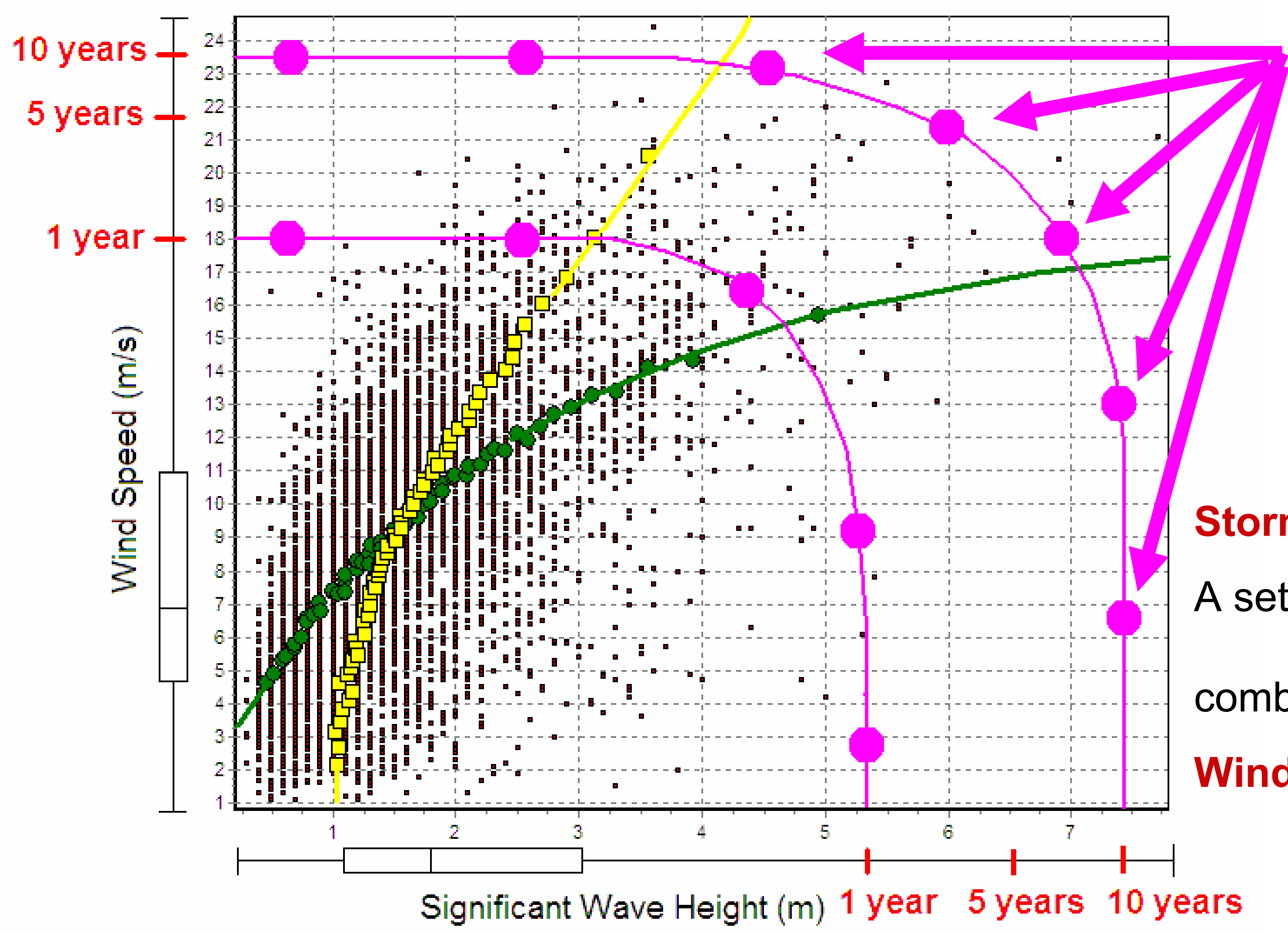
Associated Waves

OR

Waves once T years +

Associated Wind

Definitions of two-dimensional extremes:
3) Contours of equal probability



$$F_{\zeta\eta}(x, y) = p$$

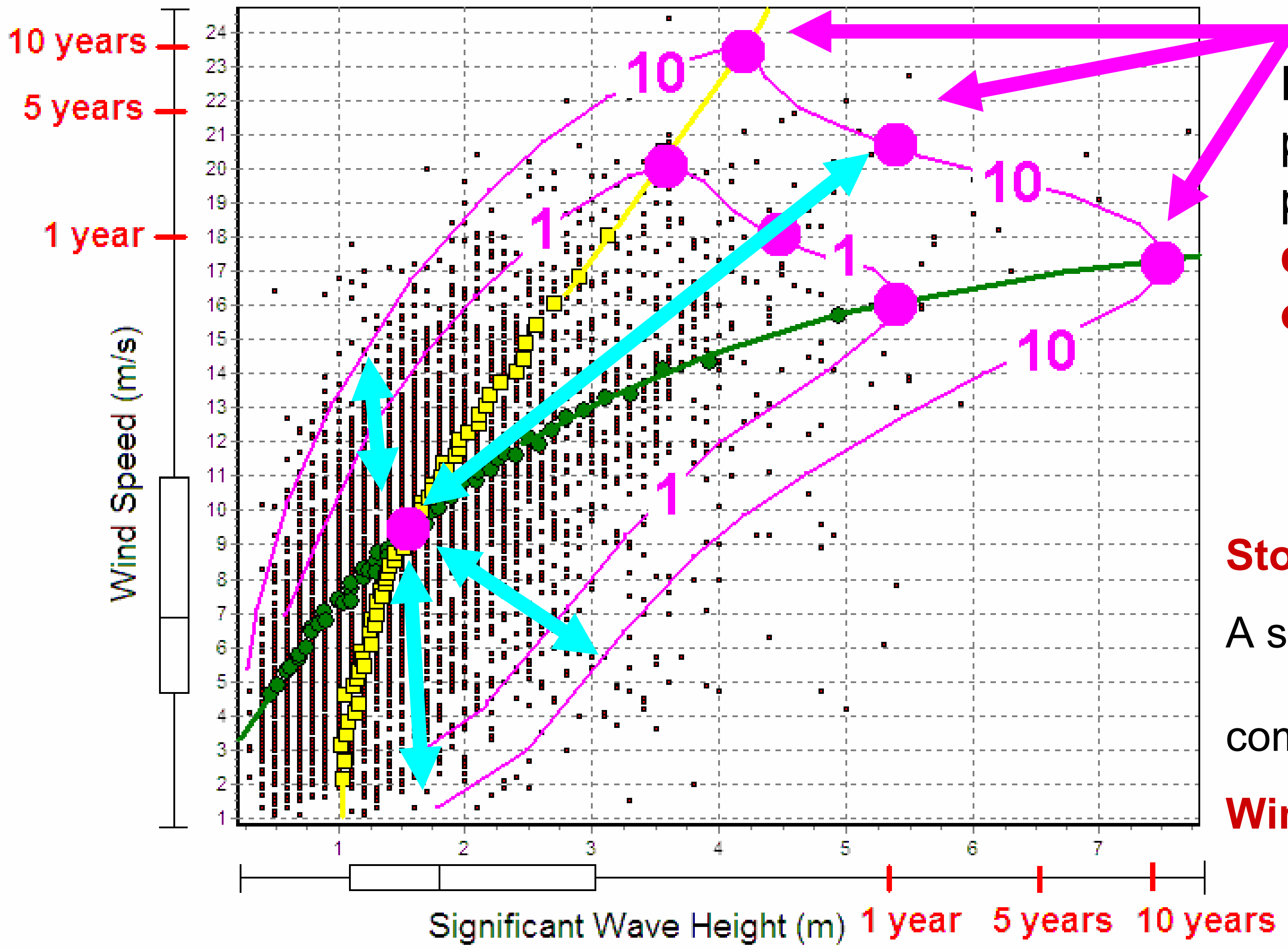
Storm once T-years =

A set of equiprobable

combinations of

Wind and **Waves**

Definitions of two-dimensional extremes:
4) Contours of equal rarity



For all these points: the probability **to differ from origin** is equal

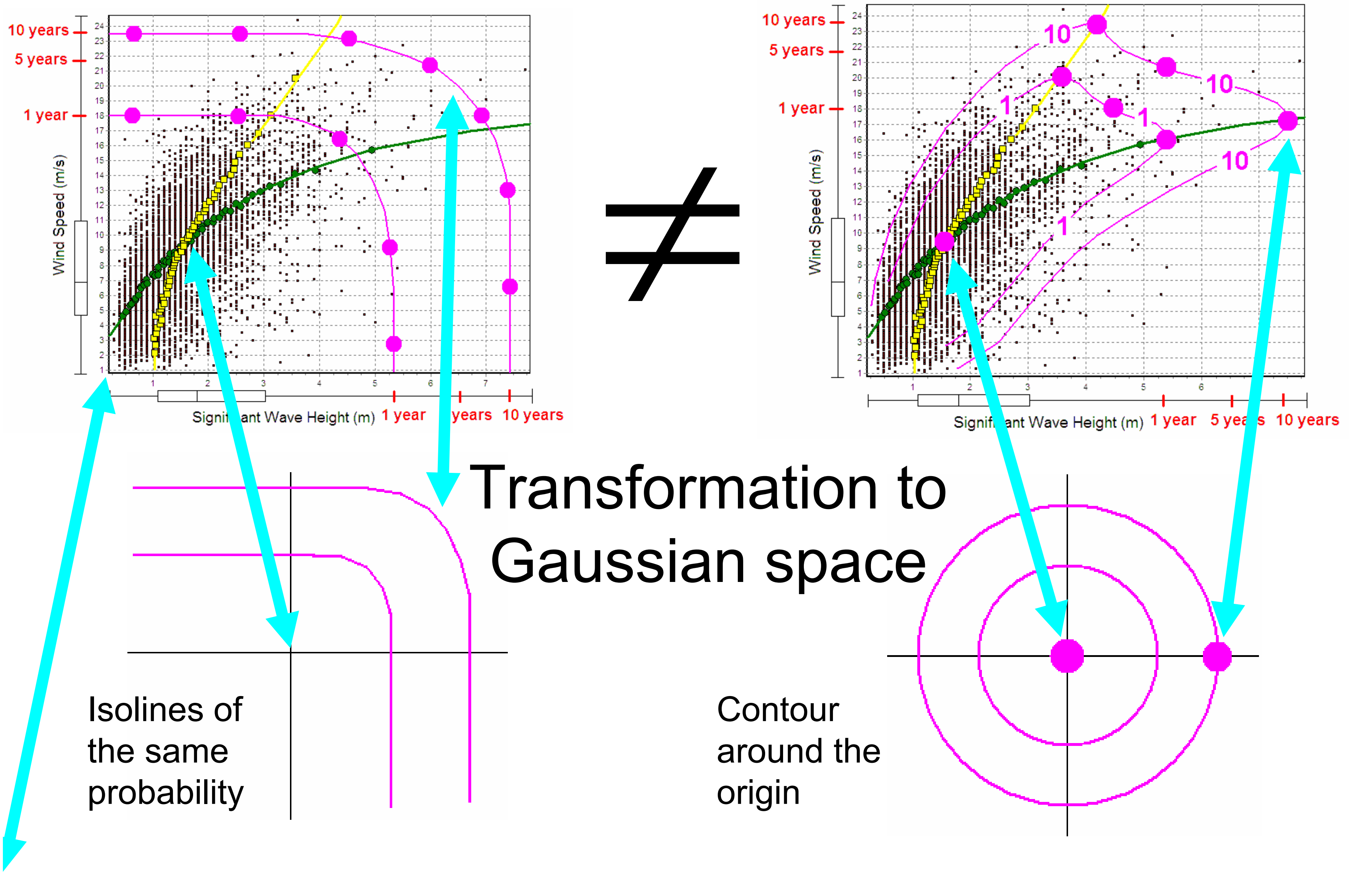
Storm once T-years =

A set of equiprobable

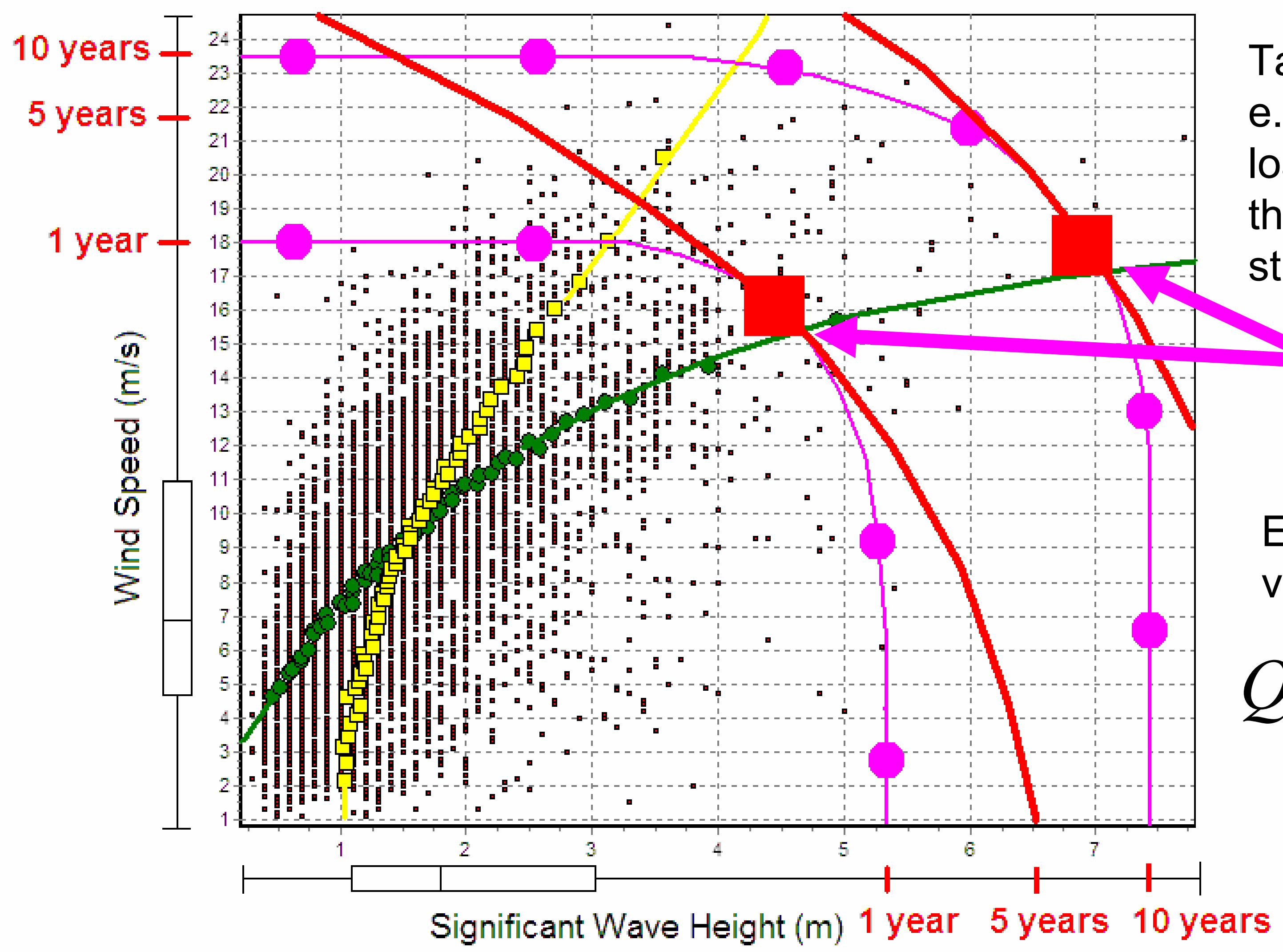
combinations of

Wind and **Waves**

Difference between equal probability and the equal rarity (FORM, SORM)



Choice of the point in a diagram
(equal probability, equal rarity)



Target Function Q = e.g. the integral loading on the vessel or marine structure

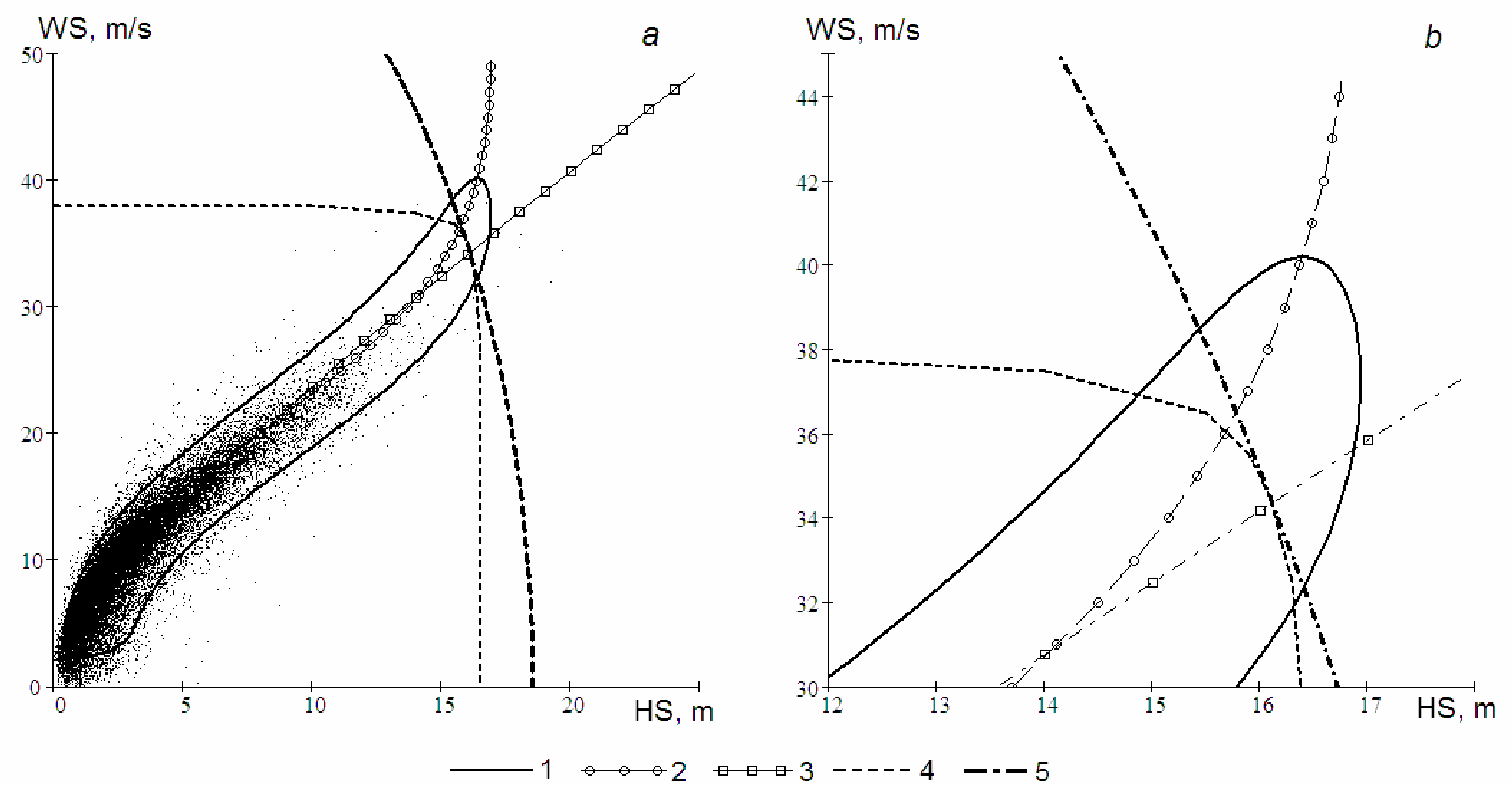
$$Q(\zeta,\eta) \rightarrow \max$$

E.g. for moored vehicles

$$Q = a\zeta^2 + b\eta^2$$

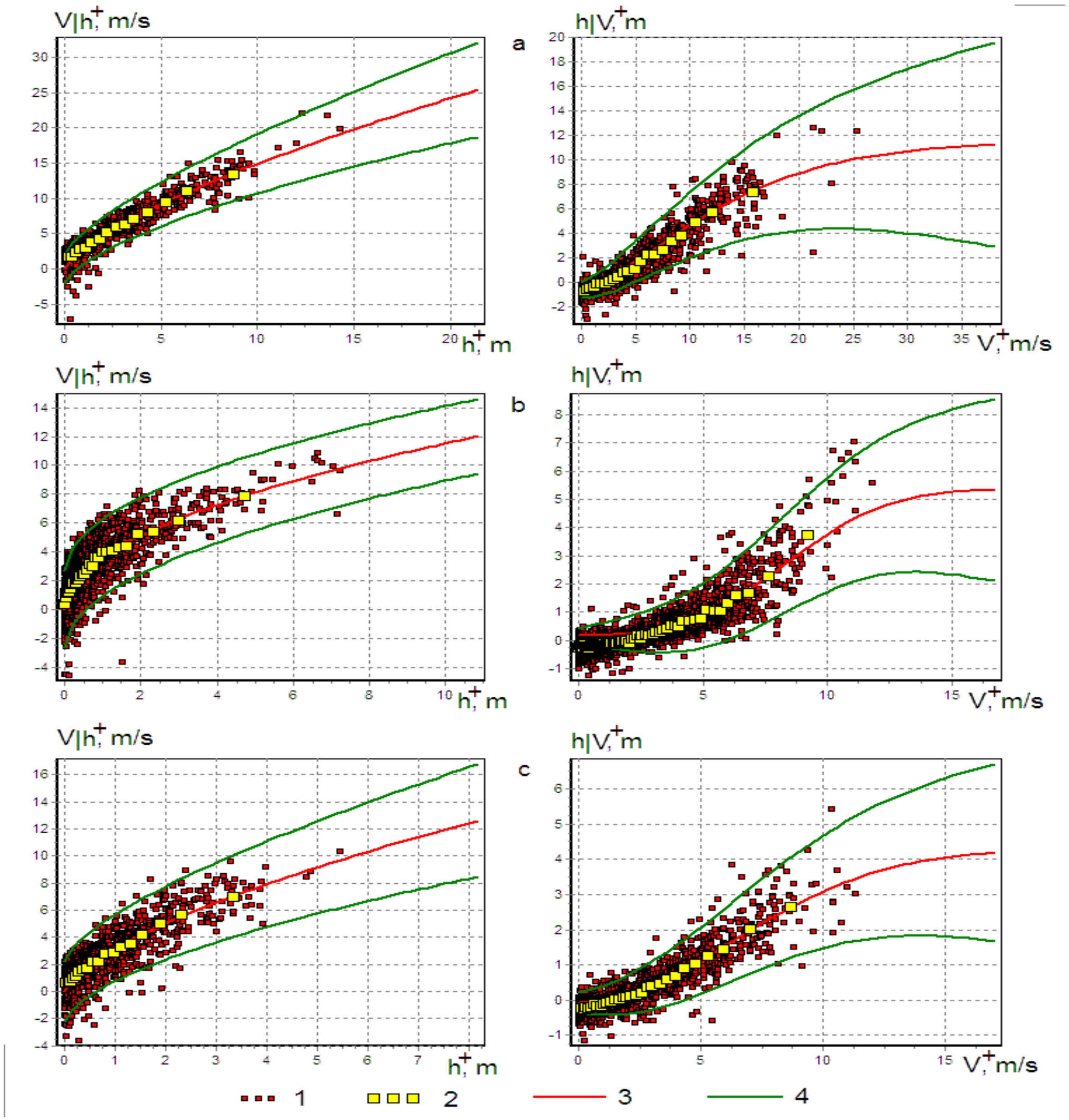
Joint Extremes of Metocean Events: differences in definitions

Definitions of joint 10-years extremes of WS and HS in the North Sea



1 – “hat”, 2,3 – regressions, 4 – probability contour, 5 – quadratic target function (for mooring objects)

Parameterization of dependencies between storm impulses and associated values



Conditional Weibull-Lognormal distribution techniques

(a) – North Sea

(b) – Mediterranean Sea

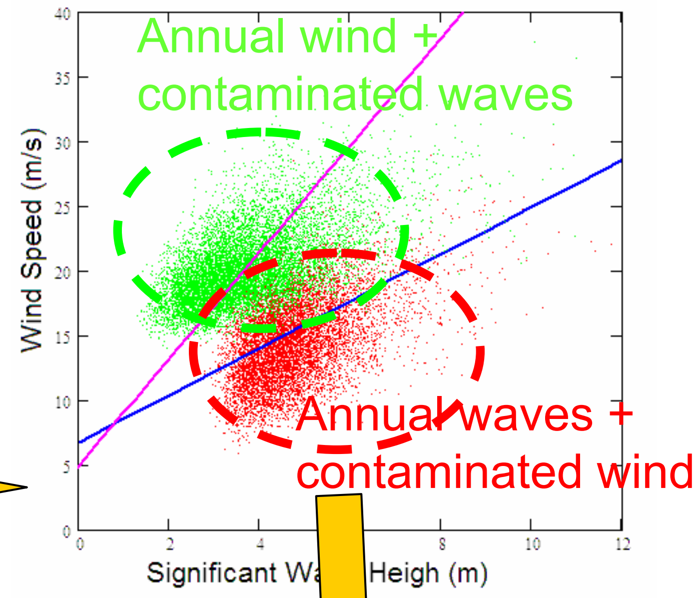
(c) – Baltic Sea

Left – WIND, associated with the WAVE impulses

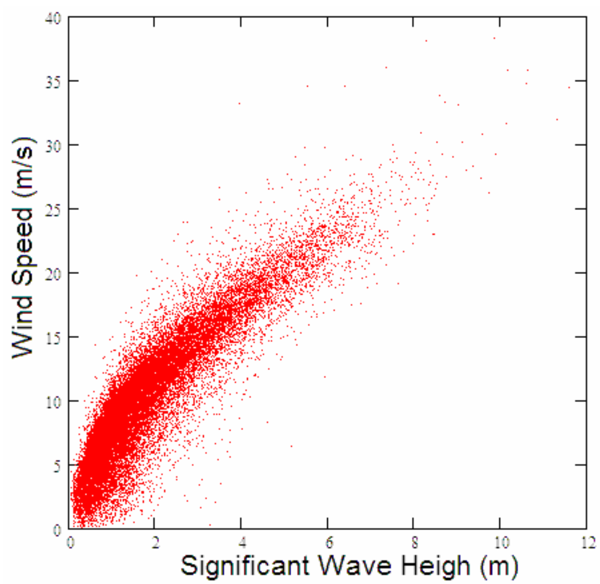
Right – WAVES, associated with wind impulses.

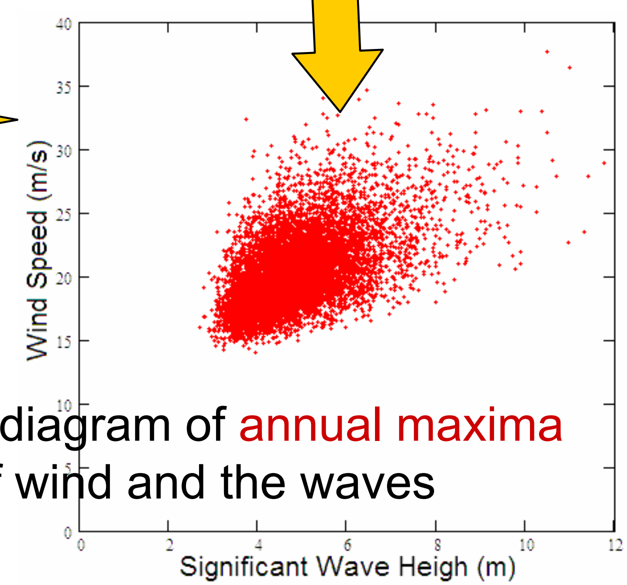
From individual events – to annual maxima:
how to define two-dimensional **annual** extremes

Scatter diagram of contaminated wind and waves annual values



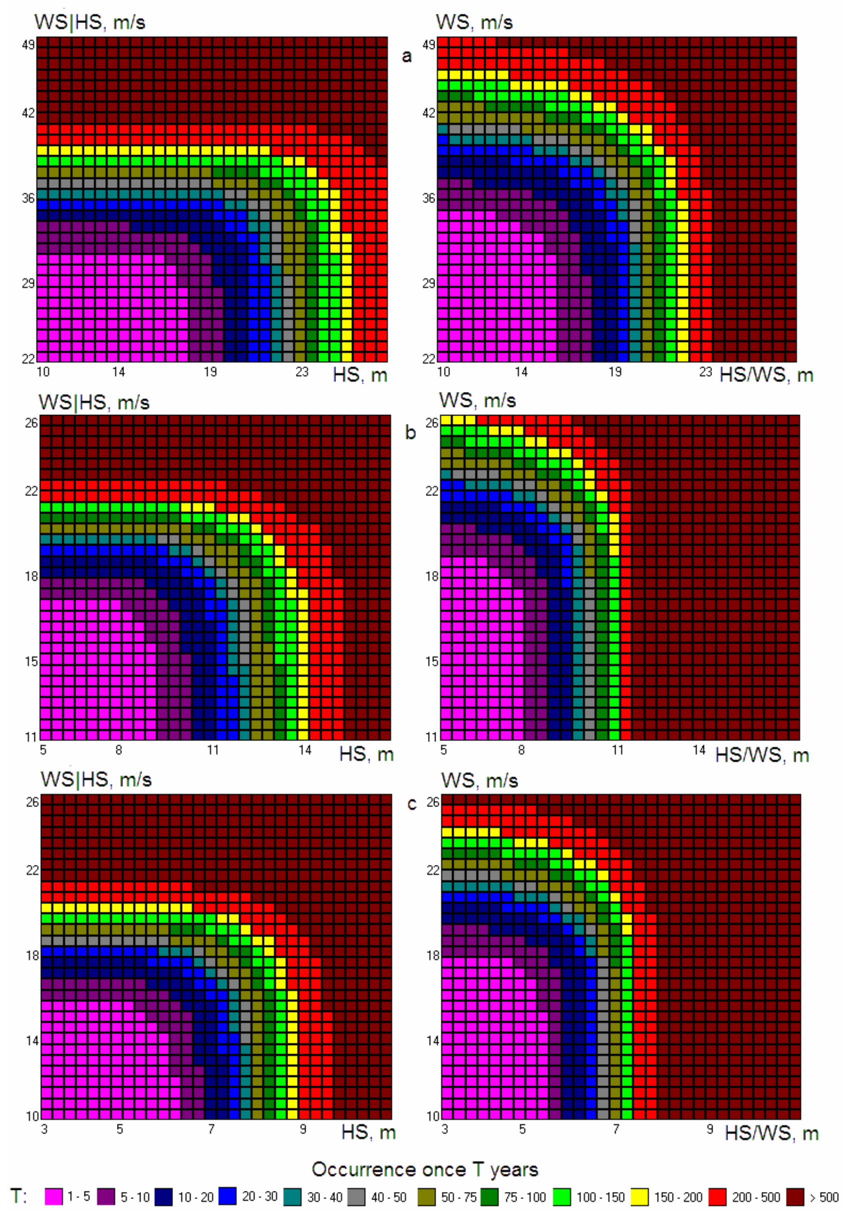
Scatter diagram of wind and waves in the same time (synoptic terms)





Scatter diagram of annual maxima of wind and the waves

Estimation of the conditional extreme occurrence
(from storms and calms – to events once T-years)

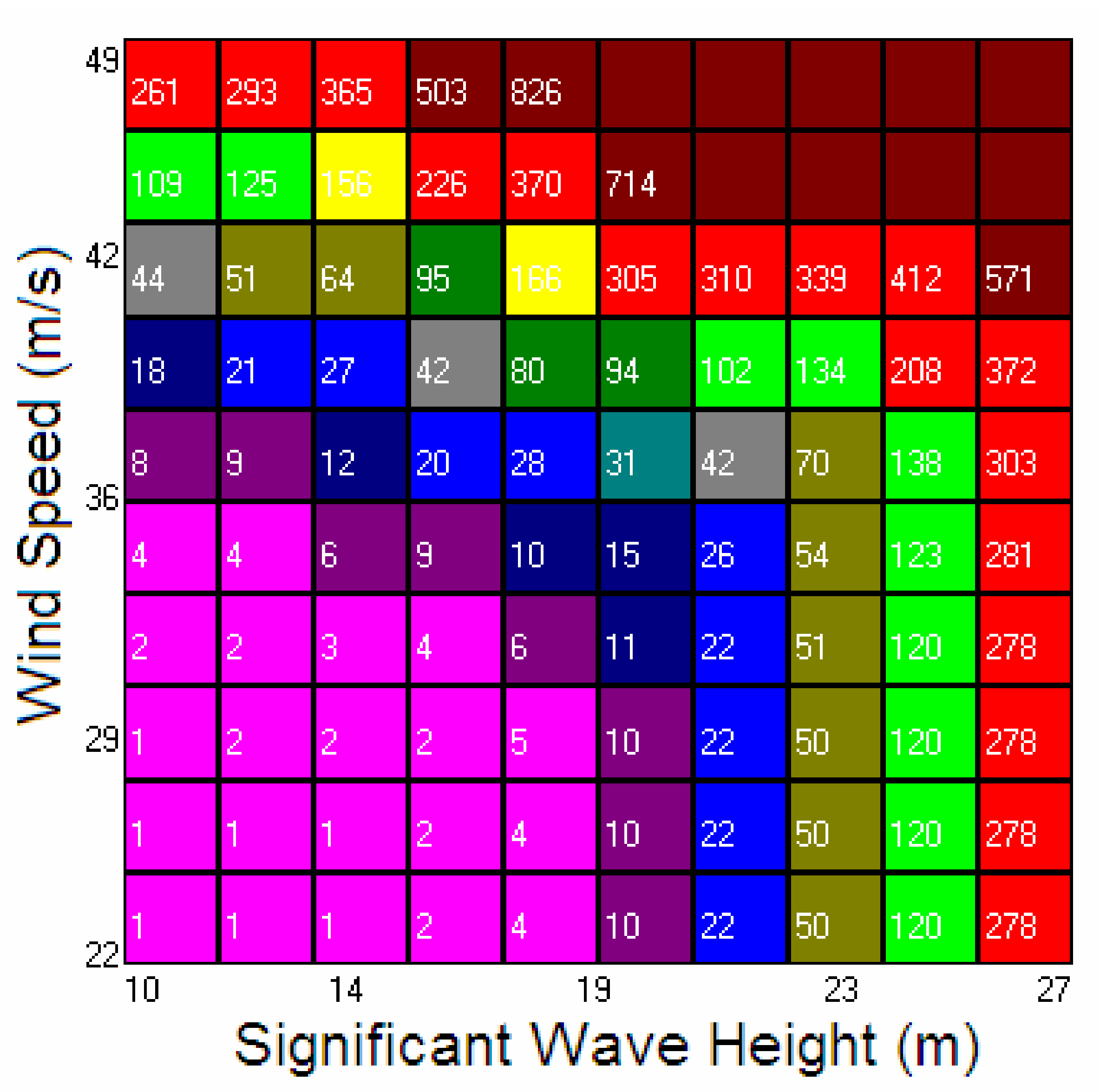


North Sea

Mediterranean Sea

Baltic Sea

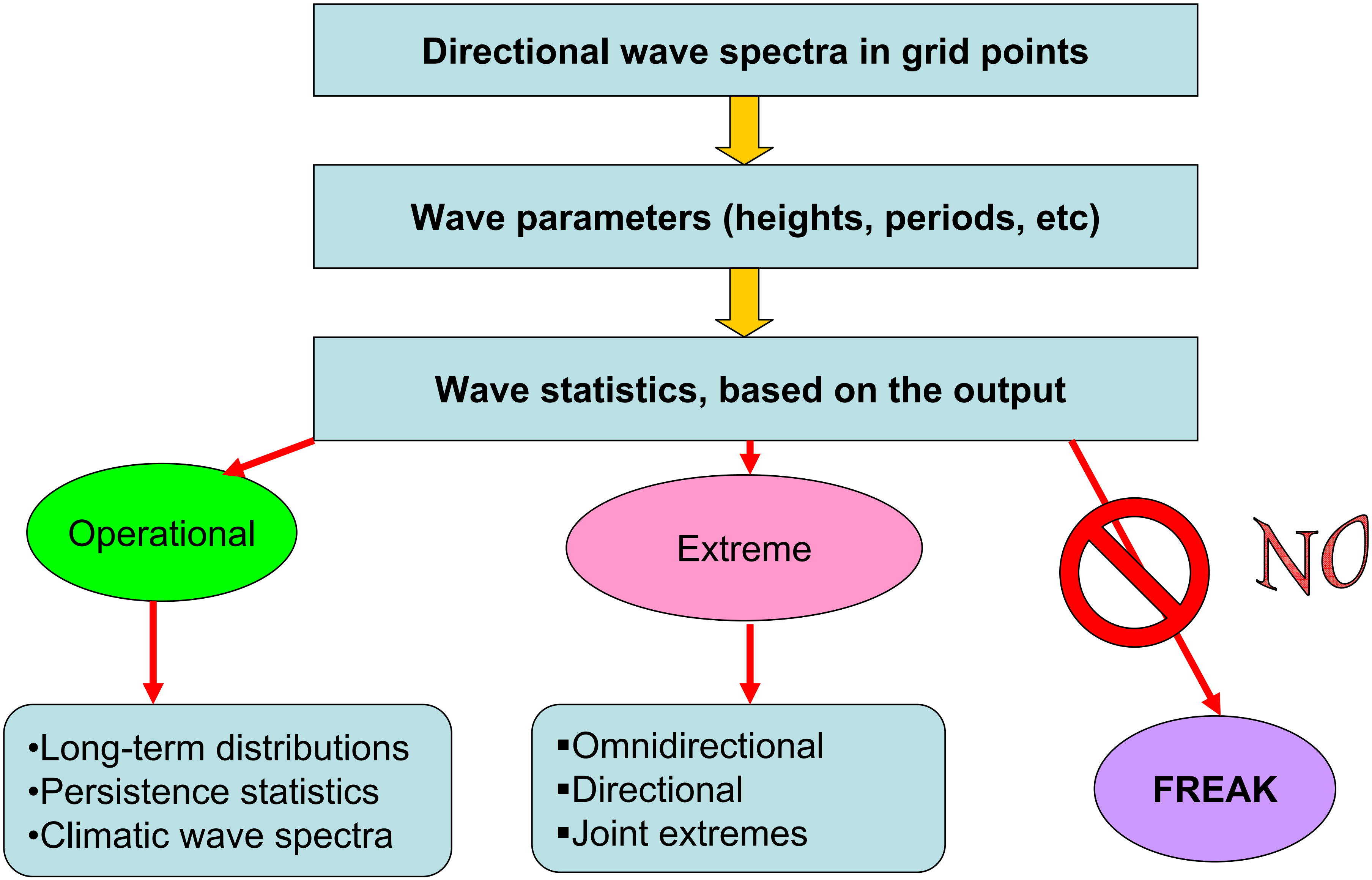
Joint occurrence of wind and waves once T years in the Central part of North Sea



Это – расчетный пример с цифрами (белыми) – означающими число целых лет, один раз в которые…

Здесь белый цвет – самый лучший (все остальные цвета еще хуже видно)

Hindcast and forecast of sea waves



FREAK WAVES

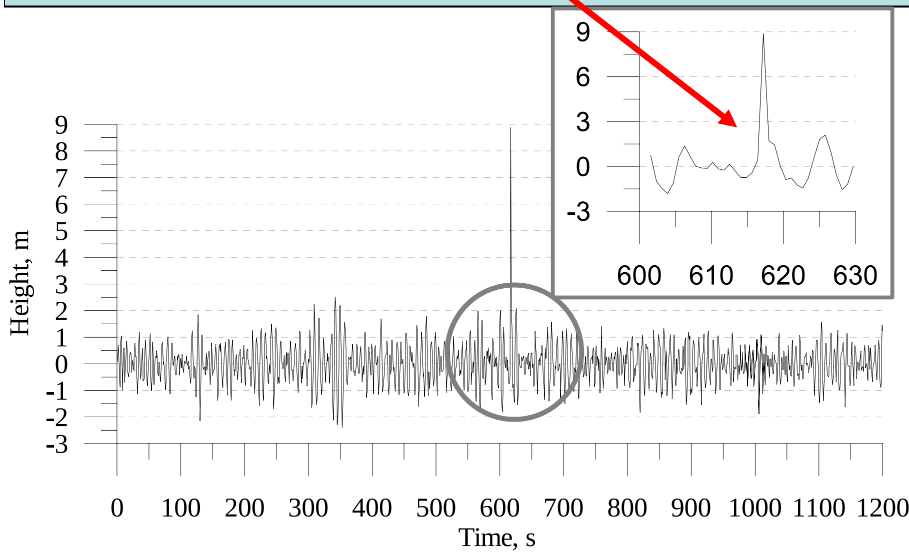
The **DIRECTIONAL WAVERIDER**
is a buoy which measures wave heights
and wave directions.

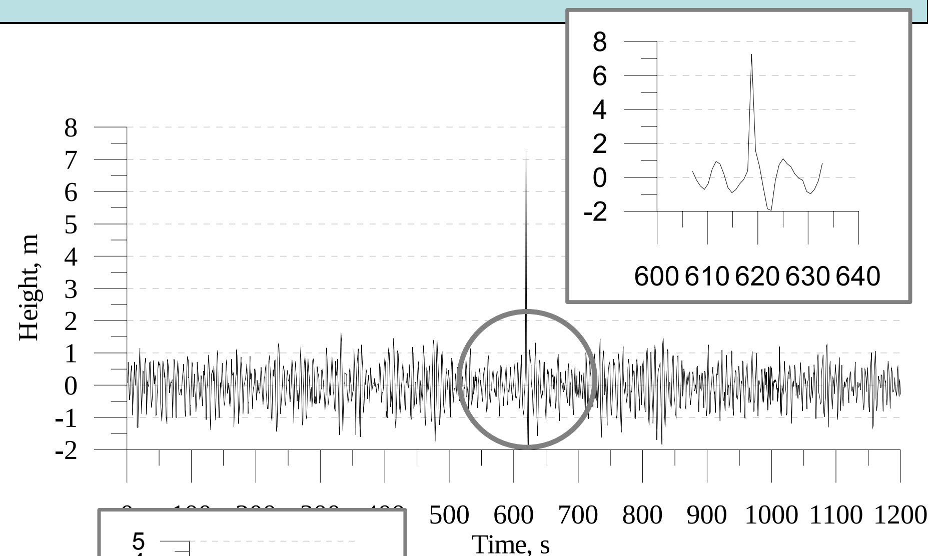
Specification:

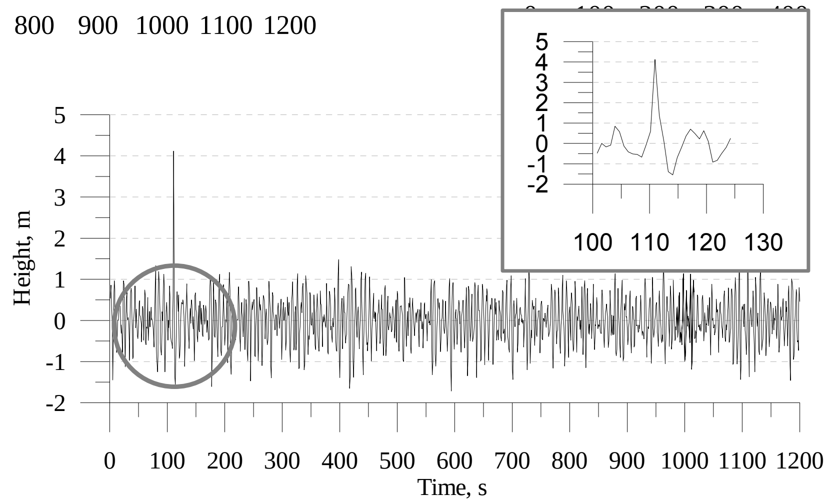
Time of operating	1996 -2004
Point of installation	44°30.4 N, 37°58.8 E
Depth	85 m
Volume of the received information	> 13 thousand records

Freak waves measurements in the Black Sea

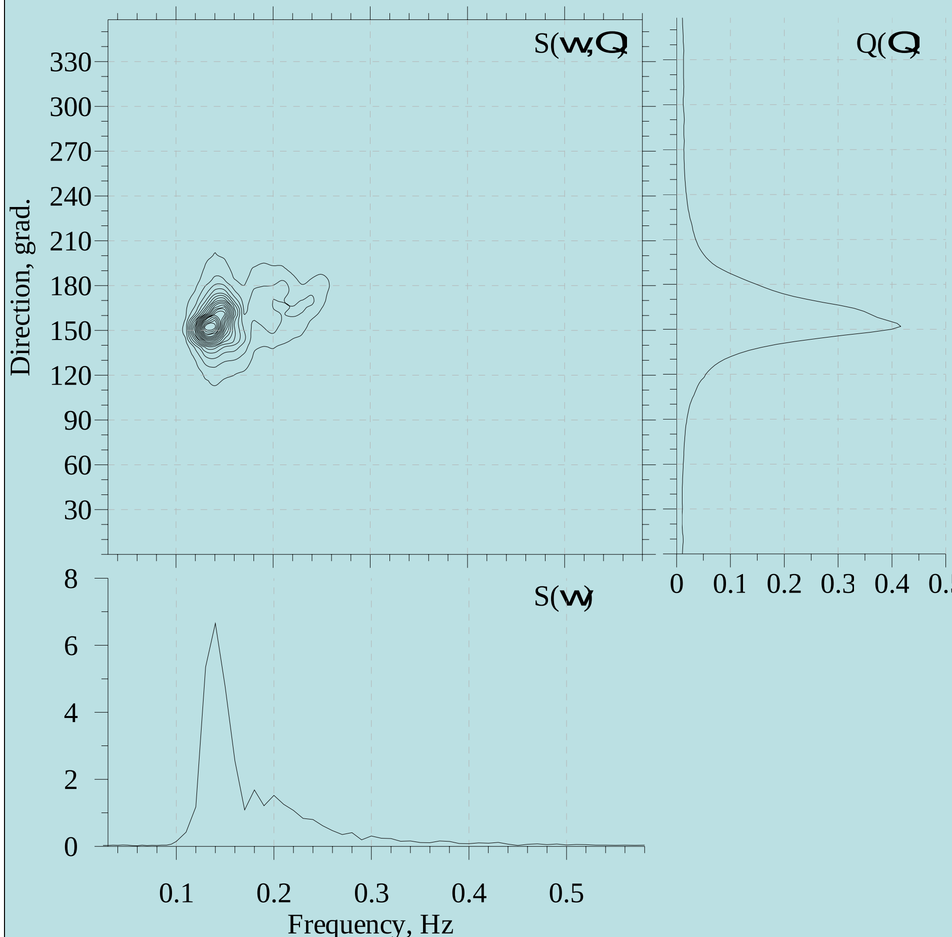
Series	Date	h_{max}	h_{max}/h_s	h_{max}/h^-	h_{max}/h^+	c/h_{max}	t_+/t_-
1	16.12.2000	9.21	4.17	5.10	4.44	0.79	1.00
2	22.11.2001	10.32	3.91	4.86	2.84	0.86	0.92
3	24.11.2001	5.67	2.71	2.74	3.50	0.73	1.00

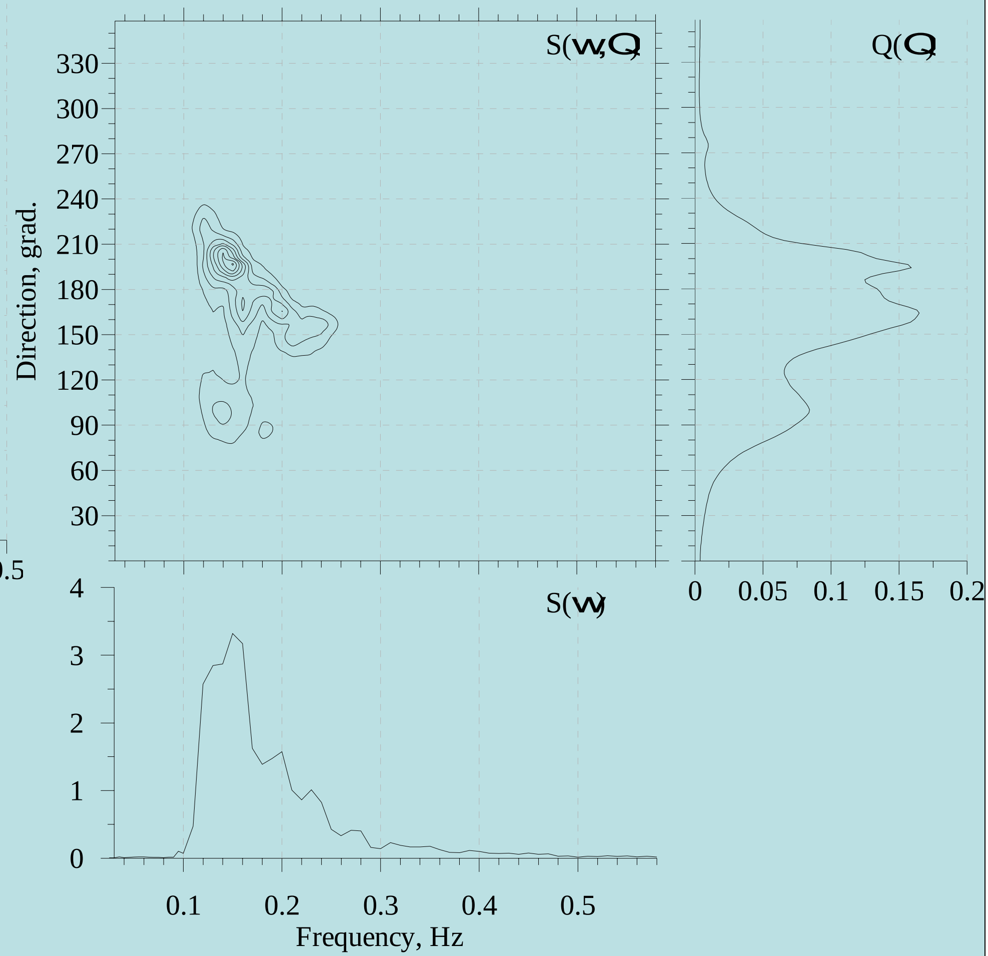






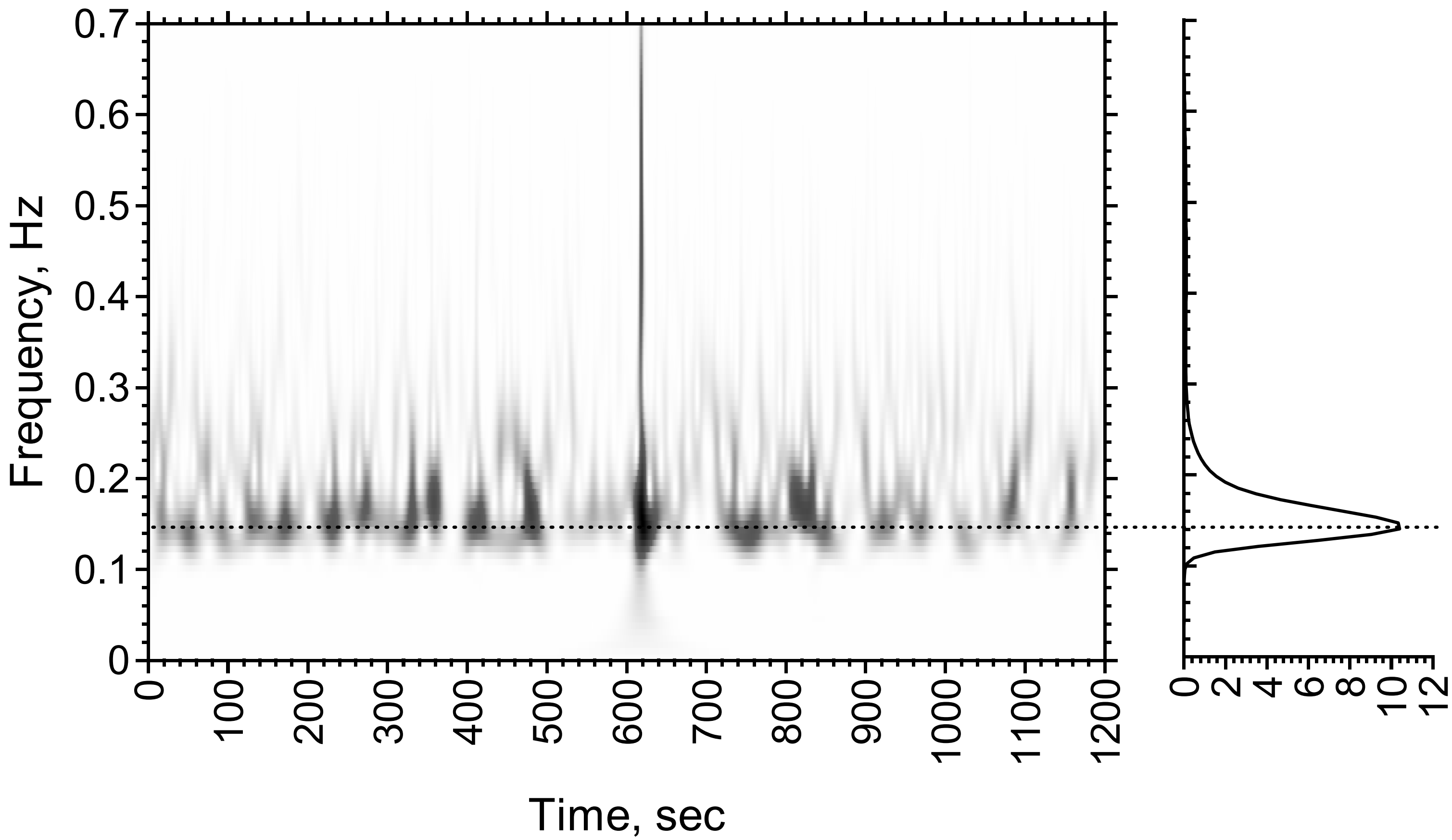
Directional waves spectra for the cases of freak waves measurements in the Black Sea



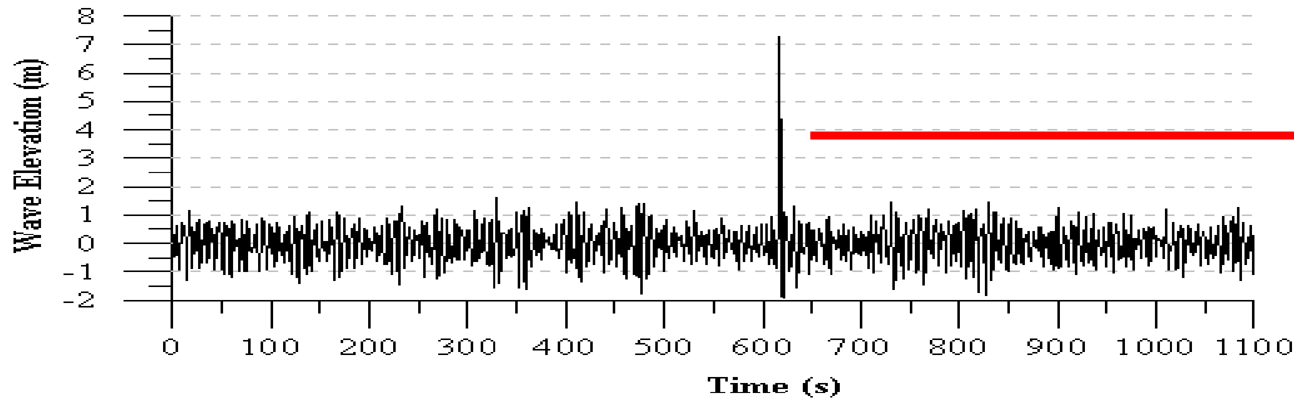


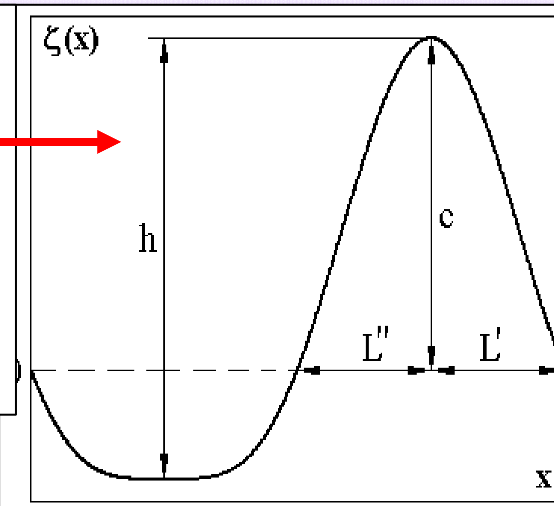
Wavelet

(Black Sea, DEC.16.2000)



Freak Waves as Multivariate Extreme





REASONS

External	Internal
•Wave and opposing current interaction; •Focused wave groups and their interaction; •Refraction around shoals or from inclined sea beds; •Wave caustics from diffraction at coastlines and around islands; •Young waves are steep; especially in intensifying winds. •Crossing wave systems and (or) opposing wave trans.	•Frequency modulation in random sea. •Variable met. conditions generated the frequency modulated wind wave packets. Frequency modulation leads to larger amplification of the freak waves than the amplitude modulation. •Cooperative effect of four- and five-wave interactions. •The high-order nonlinearties more than third order •Temporal-spatial focusing. Nonlinear focusing (BF instability). •The phasing and direction of freely propagating wave components is such, that large number of waves crest arise at one point. Directionality of a wave field play a crucial role. Large ocean waves occur as isolated events.
An inherent energy fluctuation with a period much lager than 20 minutes.	

CRITERIA:

$h/HS \geq 2.4$

$\delta=(gT2\ /2\pi hs) > 0.5$

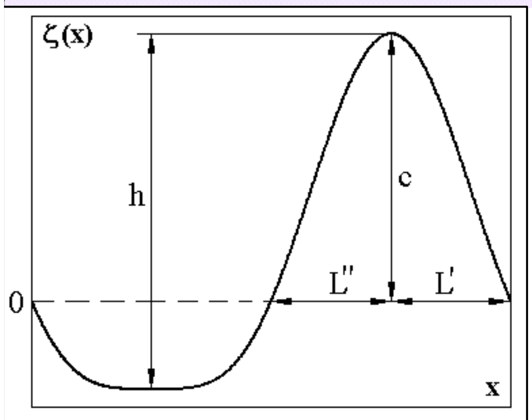
$h>2h-\ , h>2h+\ ,\ c>0.65h$

$\mu=(c/h)\approx 0.7$

$\Lambda=(L''\ /L')>2.0$

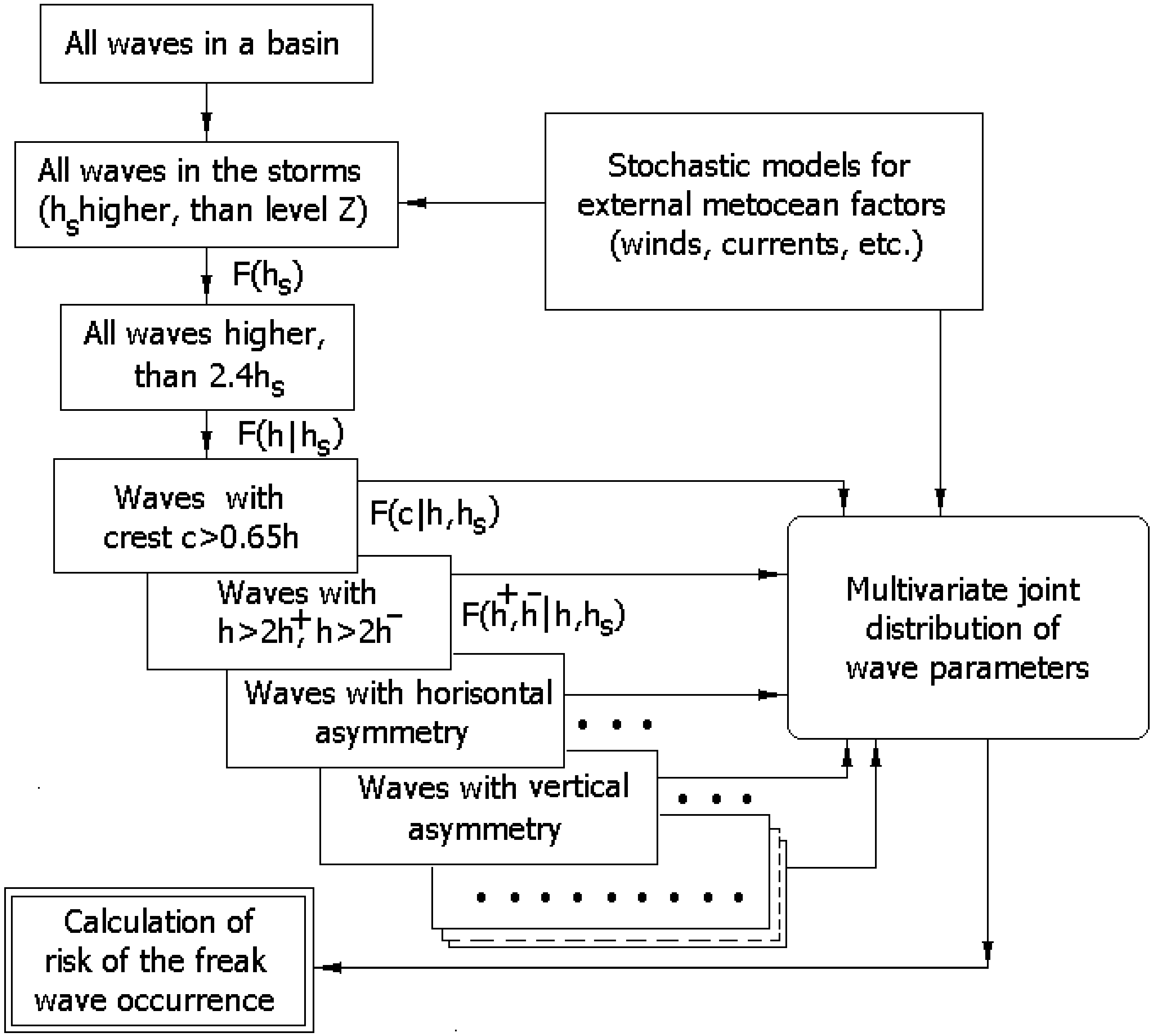
$\varepsilon=c/L'$

Sequence of freak wave detection among other waves



$$F_{\Xi}(X) = F_h(x_1)F_{c|h}(x_2|x_1)F_{\delta|h}(x_3|x_1)\ldots$$

Parametrical analysis of multivariate distributions of wave parameters is required



Statistical description of freak wave

$$\Phi_{\varsigma}(X) = (1-\varepsilon)F_{\Xi}(X) + \varepsilon\hat{F}_{\Xi}(X)$$

X vector of wave parameters
-(e.g., height, crest, steepness),

ε - probability of freak wave arising in specific place at a moment t, due to external factor

$F_{\Xi}(X)$

$\hat{F}_{\Xi}(X)$

Joint distribution of wave parameters due internal reasons

Joint distribution of wave parameters due external reasons

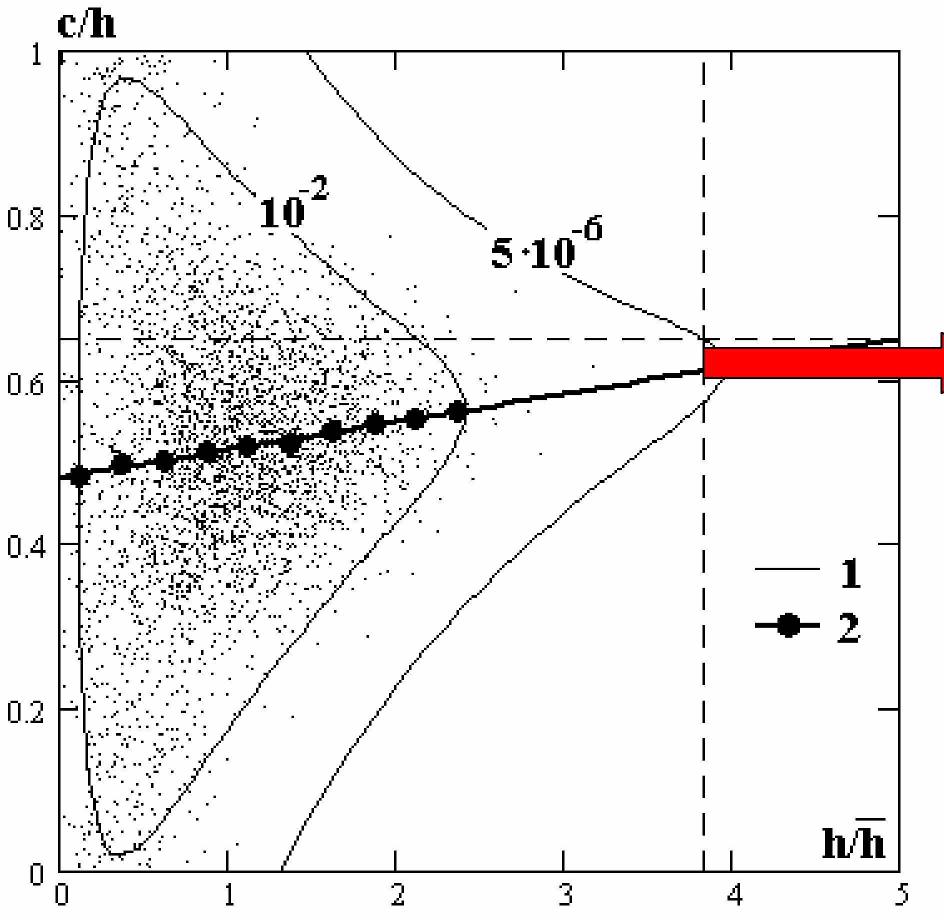
Freaks are arise always

There are some situations increasing the freak occurrence

Asymptotic analysis of the rare combinations of ordinary wave parameters

Analysis of the wave-making conditions in synoptic scale

Probability of freak wave



Joint distribution of individual wave **height** and associated normalized wave **crest**

Here $\bar{h}$ - mean wave height

(Wave heights, crest heights)

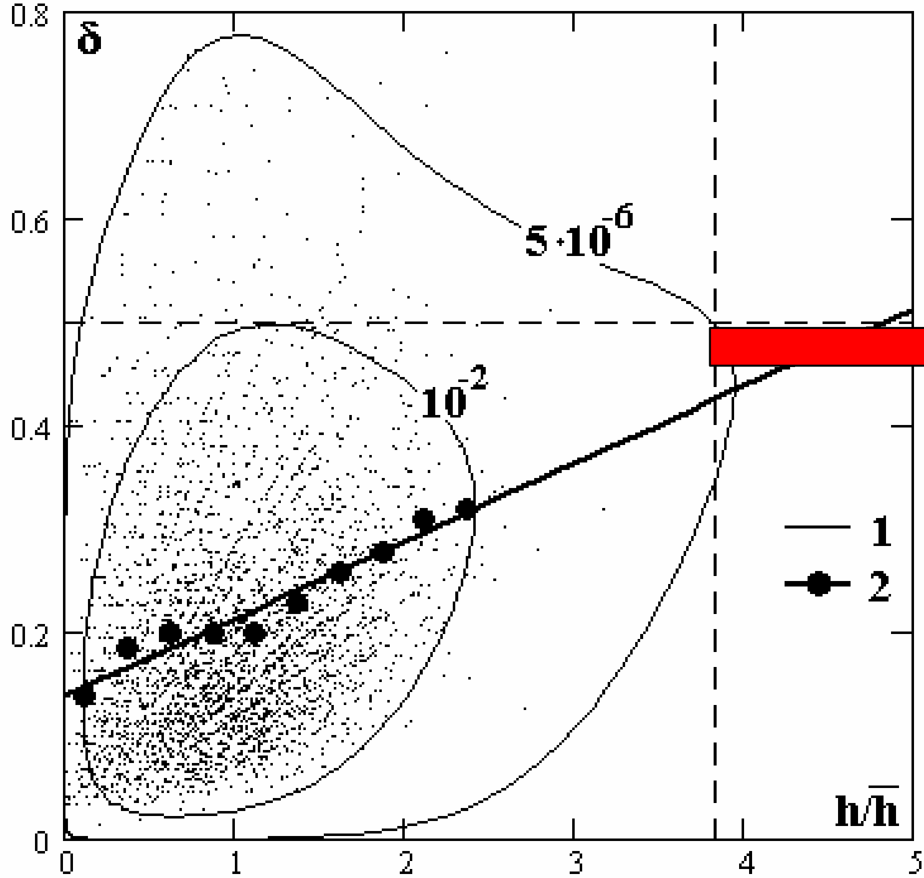
For any steepness δ

$$\delta = \frac{4\pi^2 h}{g\tau^2} = 2\pi \, h/\lambda$$

Prob$\{(h/\bar{h})\geq 3.8,\ (c/h)\geq 0.65\} =$

$$5\cdot 10^{-6}$$

Probability of freak wave



Joint distribution of individual wave **height** and associated **steepness**

Here $\bar{h}$ - mean wave height

(Wave heights, steepness)

For any wave crest

Prob$\{(h/\bar{h}) \geq 3.8, (\delta) \geq 0.5\} =$

$$5\cdot10^{-6}$$

For Stokes waves **δ=2π·(1/7)=0.88**

$$\delta = \frac{4\pi^2 h}{g\tau^2} = 2\pi \, {h}/{\lambda}$$

PROBABILITY of a FREAK WAVE

Three-dimensional distribution

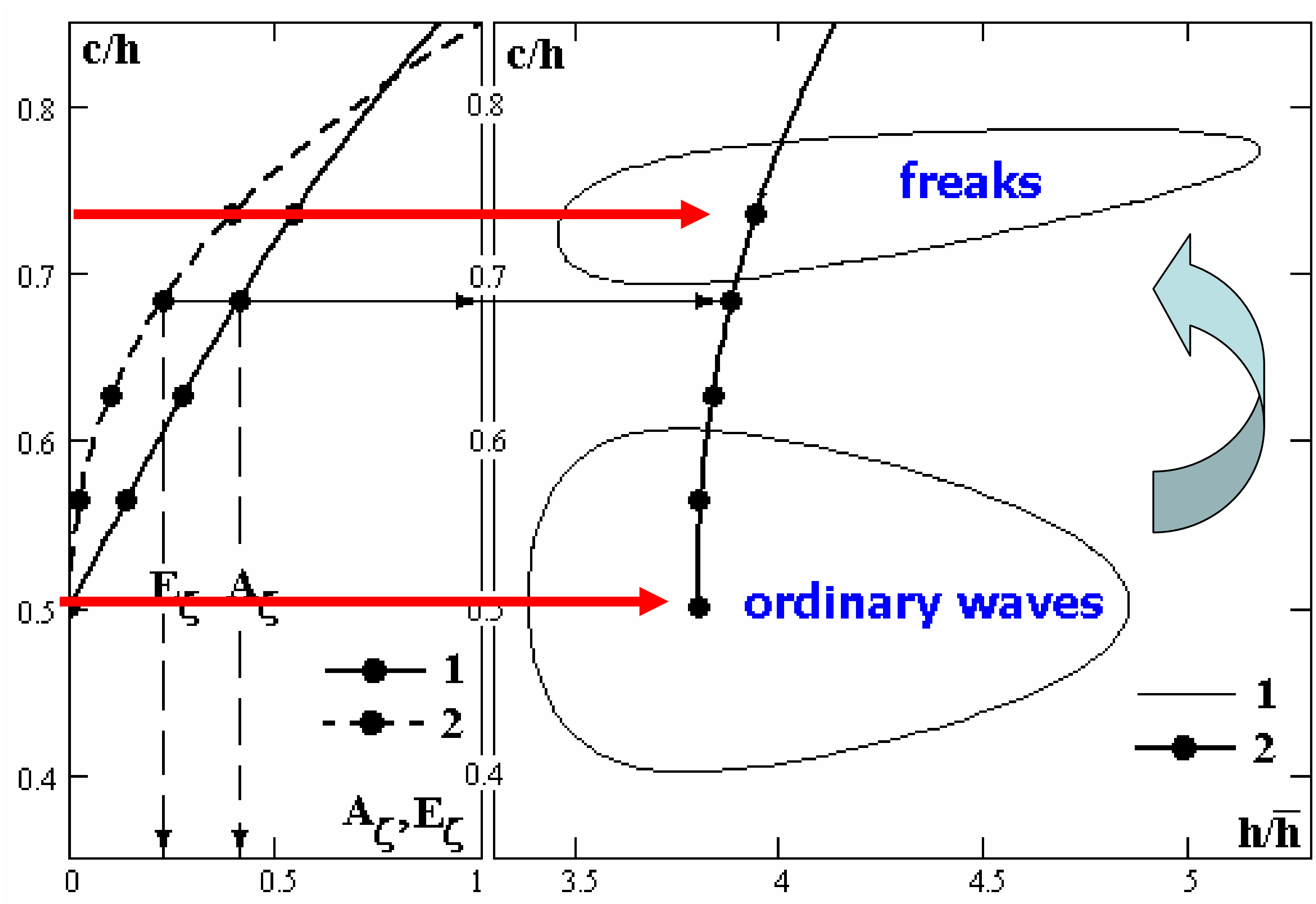
Prob $\{(h/\bar{h}) \geq 3.8,\ (c/h) \geq 0.65,\ \delta \geq 0.5\} =$

$$6 \cdot 10^{-7}$$

i.e. one wave from 1700000 waves will be freak (by these parameters).

This is lower border of freak wave probability.

Asymmetry A, kurtosis E and freak waves



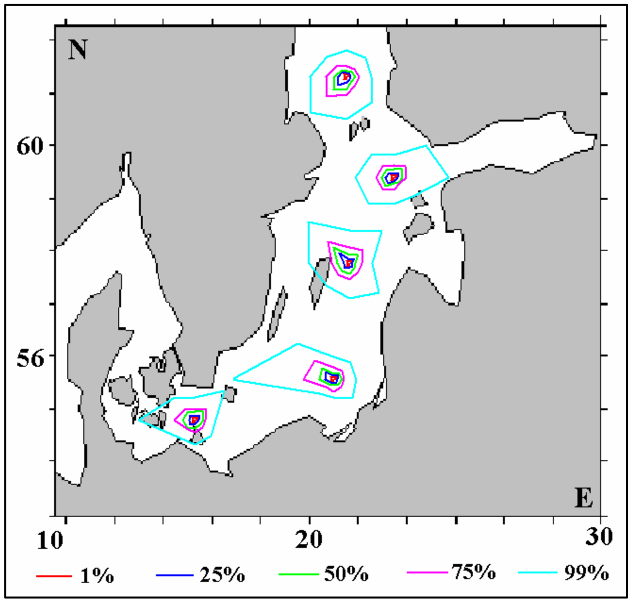
External factors, increasing the probability of freak wave

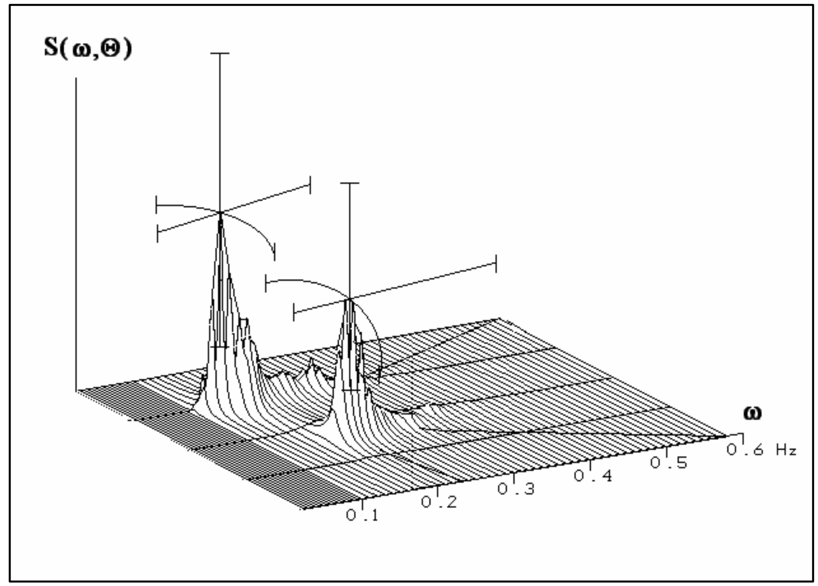
Freak waves may arise

due to

Wave field spatiotemporal inhomogeneity

Wave field structural inhomogeneity





Large gradients of wind fields, currents, bathymetry et al.

$$\boxed{\Psi_{\Xi}(\mathbf{X}) = \int \mathbf{F}_{\Xi}(\mathbf{X},\xi)\, d\Phi_{\xi}(\xi)}$$

Complex shape of sea wave spectrum

Combined distribution multiscale model

System of warning

What factors are increase the probability of freaks?

Direct external factors *OR* **Indirect factors**

Direct external factors:

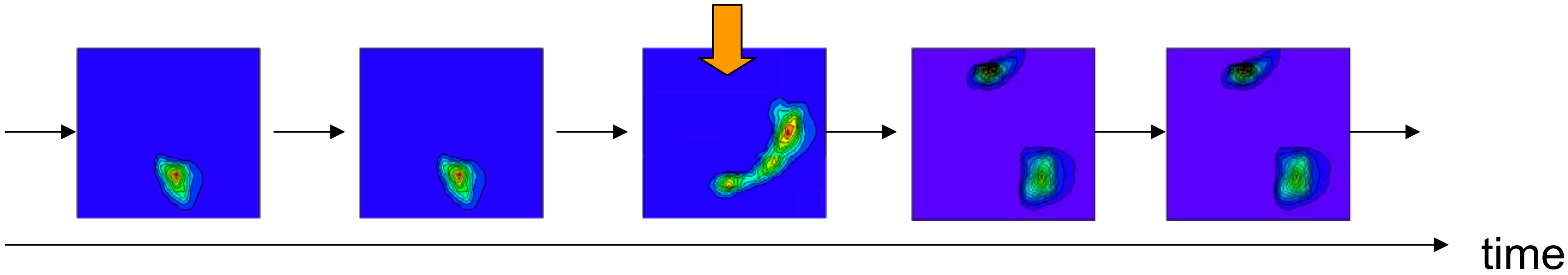
- Wave and opposing current interaction;
- Focused wave groups and their interaction;
- Refraction around shoals or from inclined sea beds;
- Wave caustics from diffraction at coastlines and around islands;
- Young waves are steep; especially in intensifying winds.
- Crossing wave systems and (or) opposing wave trans.

Indirect factors:

CLIMATIC WAVE SPECTRA

Relation to Freaks: Variable States of Sea Wave Spectra

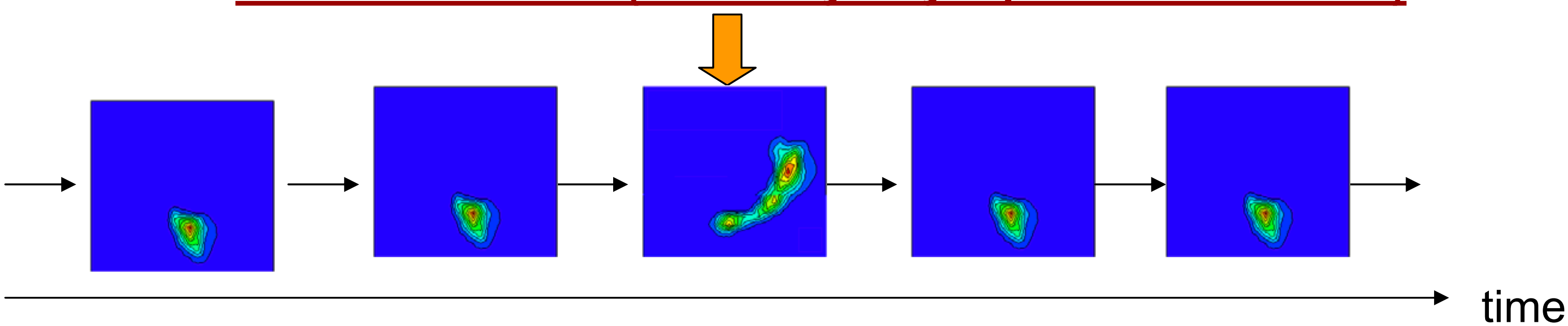
“Jump” states (exist only 1 synoptic term – 3hours)



Total occurrence: **7.7%**

Including: Class I (wind waves) – 1%
Class II (swell) - 0.5%
Class III (wind waves & fresh swell) – **3.4%**
Class IV (wind waves & old swell) – 1%
Class V (complicated sea) – 1.8%

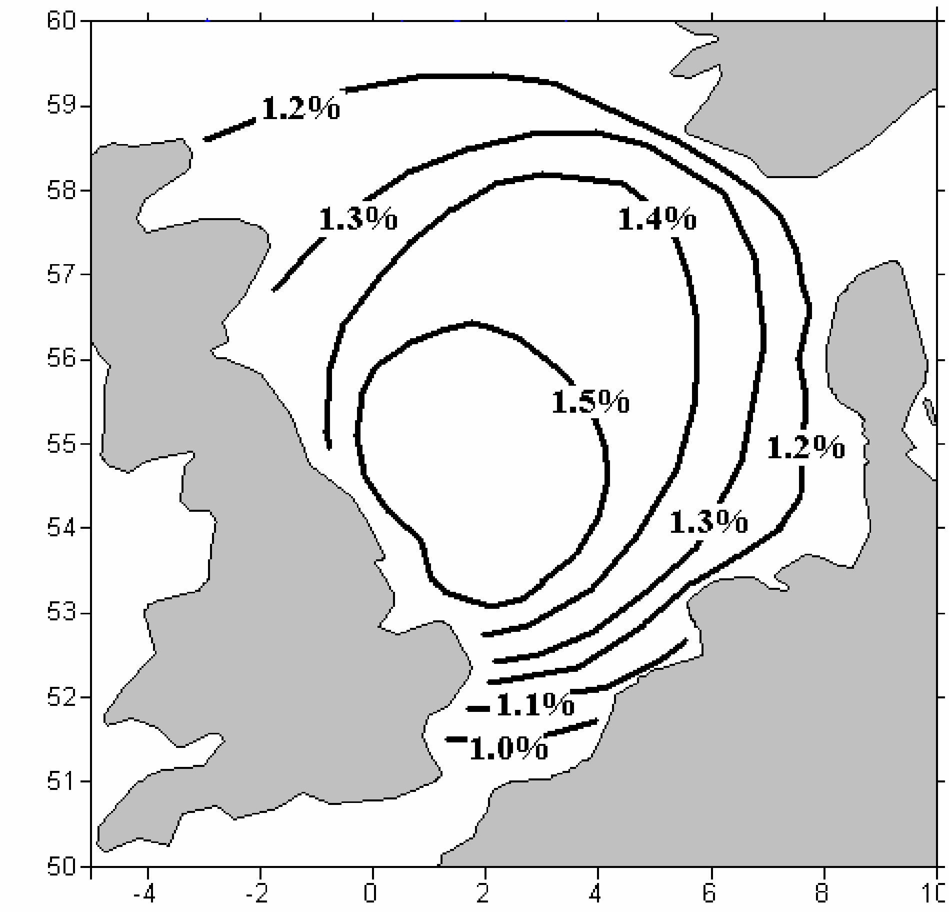
“Unstable” states (exist only 1 synoptic term – 3hours)



Including: Class I (wind waves) – 0.4%, Class II (swell) - 0.1%
Class III (wind waves & fresh swell) – **1.6%**
Class IV (wind waves & old swell) – 0.4%
Class V (complicated sea) – 0.9%

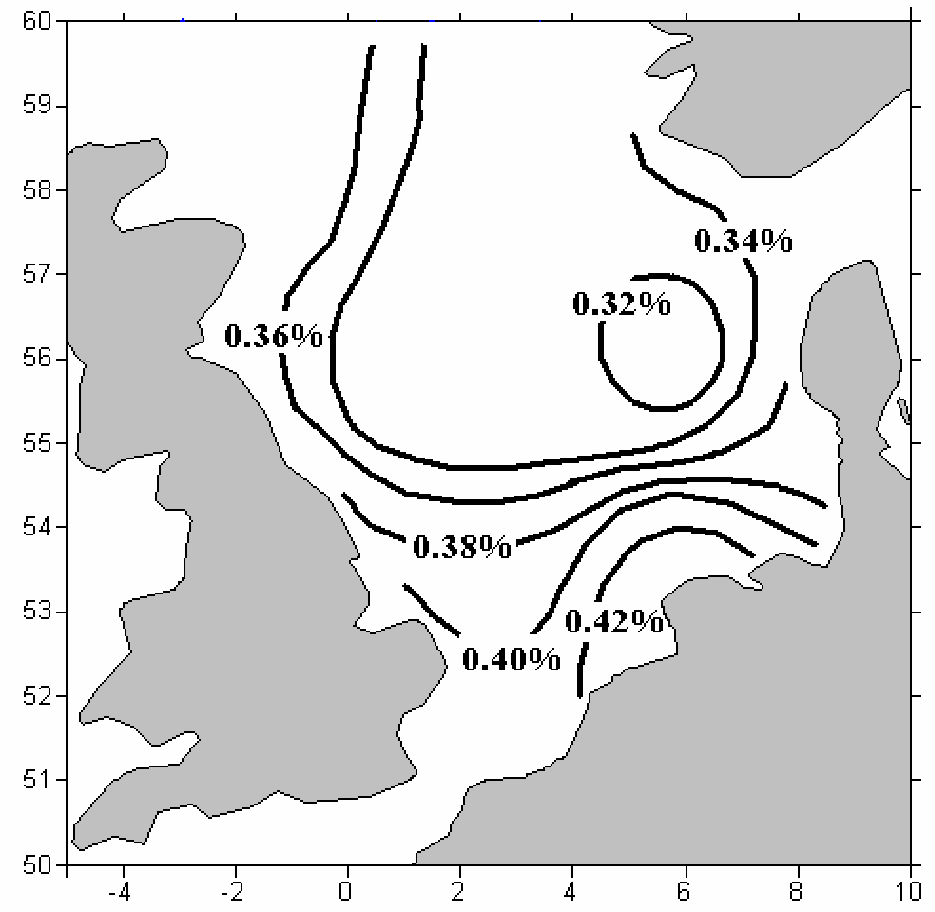
Total occurrence: **3.4%**

Probability of the spectral jumps



I-III-I

(from wind waves – to wind sea with fresh swell, and back)



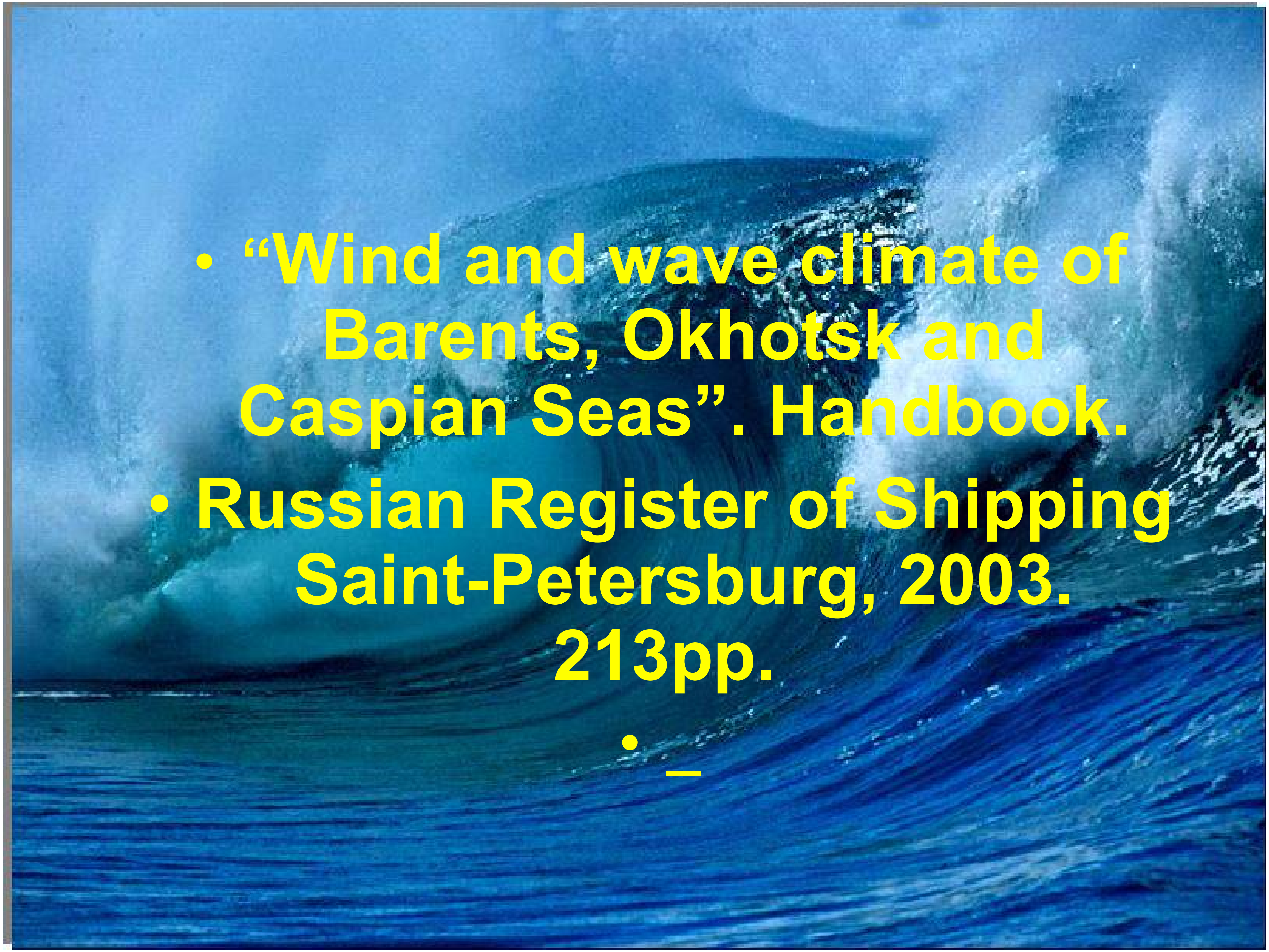
I-V-I

(from wind waves – to complicated sea, and back)

Relations to freaks: “jumps” of the spectra and observations of freak waves

Dates and types of spectral jumps from the one class to another (in comparison with the wave measurements in the North Sea).

Position	Date	Sequence of classes (each 3 hours)
North Alwyn	16.11.1993	1 ***1 3*** 3 ***3 1*** 1 1
“	18.11.1993	1 1 1 ***1 3*** 3 ***3 1***
N. Cormorant	04.01.1993	***1 5 5 3 1*** 1 1 1
“	12.01.1993	3 3 3 ***3 1*** 1 1 1
“	18.01.1993	***1 3*** 3 3 3 ***3 1*** 1
“	12.03.1996	1 1 1 1 1 1 1 1
Draupner	01.01.1995	1 1 ***1 3 3 1*** 1 1


• "Wind and wave climate of Barents, Okhotsk and Caspian Seas". Handbook.
• Russian Register of Shipping Saint-Petersburg, 2003. 213pp.
• _

PART 1 (2003)

Background, including main approaches

- Numerical models (short description)
- Short-term statistics:

(wave heights, periods, lengths, crests distributions), frequency and directional spectra;

- Long-term statistics:

Operational statistics: distributions, persistence, climatic spectra

Extreme statistics:

(based on WMO publication (www.wmo.ch → JCOMM → Publications)

Approach to wave heights with return period of 1000 and 10000 years.

PART 2 (2003)

Reference data (monthly, detailed by regions)

<u>Extreme statistics</u>

- *Extreme winds with return periods 1, 5, 10, 25, 50 and 100 years. (Omnidirectional and for 8 directions)*
- *Wave heights, periods, lengths (mean, significant, 3%, 1%, 0.1%) and wave crests with return periods1, 5, 10, 25, 50 and 100 years*

<u>Operational statistics</u>

- *One-dimensional distributions (winds, waves)*
- *Persistence statistics (mean, rms, max) for wind and waves .*
- *. Wave heights: Monthly storm and weather windows durations.*
- *Monthly probabilities of wave heights and direction.*
- *Joint probability of wave heights and periods*

СПРАВОЧНЫЕ ДАННЫЕ
ПО РЕЖИМУ ВЕТРА И ВОЛНЕНИЯ БАЛТИЙСКОГО, СЕВЕРНОГО, ЧЕРНОГО, АЗОВСКОГО И СРЕДИЗЕМНОГО МОРЕЙ

РОССИЙСКИЙ МОРСКОЙ РЕГИСТР СУДОХОДСТВА

1913

СПРАВОЧНИК 2006

“Wind and wave climate of Baltic, North, Black, Azov and Mediterranean Seas”. Handbook.

Russian Register of Shipping Saint-Petersburg,

2006. 450pp.

- ***www.rs-head.spb.ru***

PART 1 (2006)

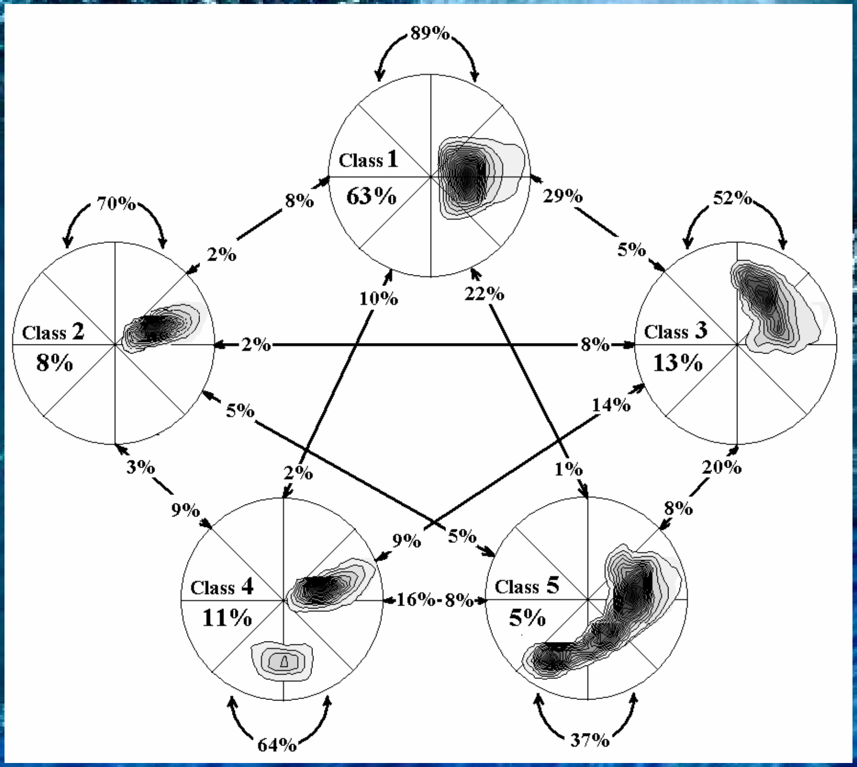
As in 2003 edition, but with more details for:

- assimilation data in reananlysis;
- persistence statistics;
- Climatic wave spectra;
- Freak waves (with example of the loss of ship “Aurelia” in February 2005)

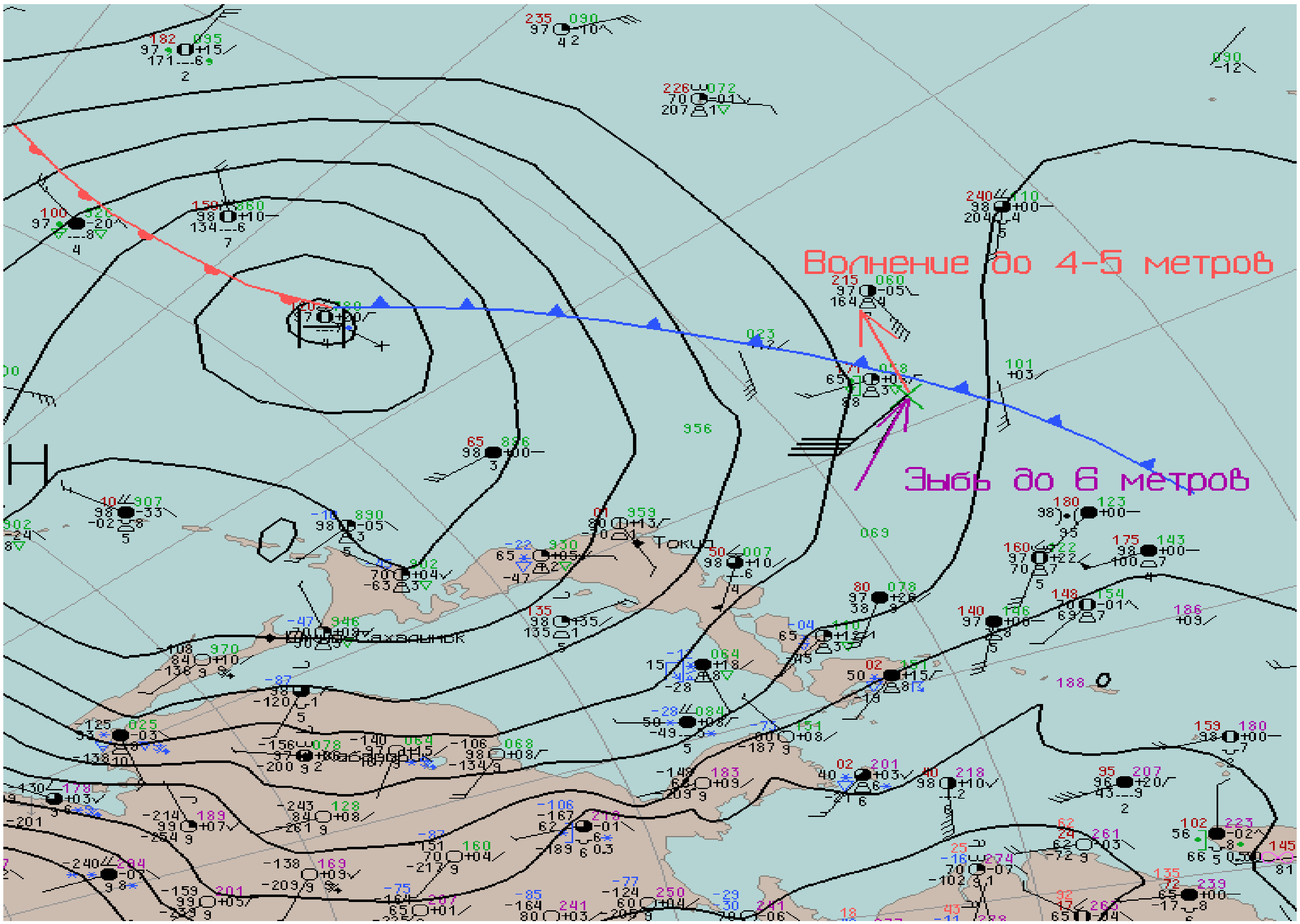
PART 2 (2006)

The same as in 2003 edition, but for the first time in the World practice:

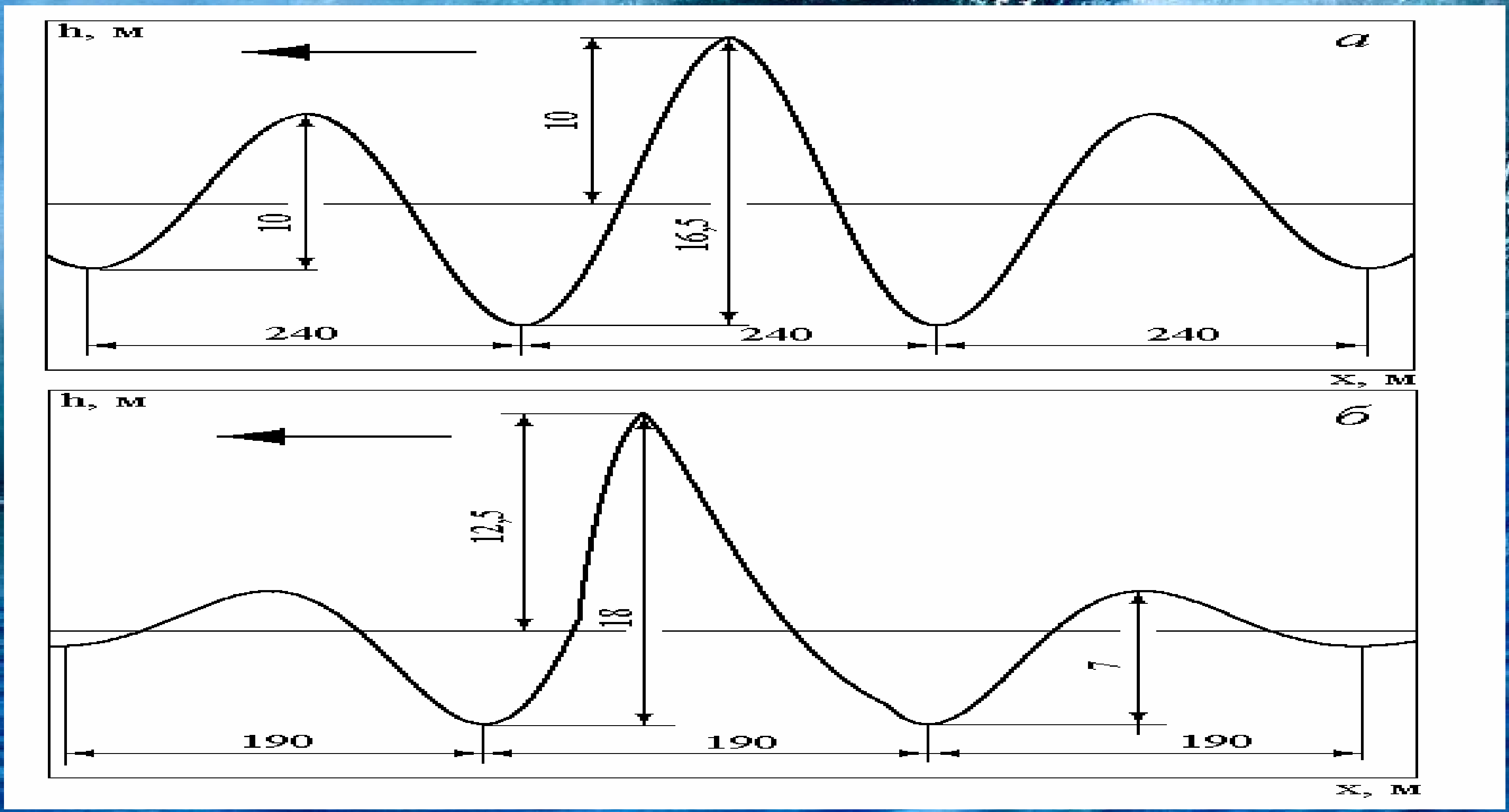
Climatic wave spectra for every area



Loss of the ship “Aurelia”
(02 Febr. 2005)



Possible usual (a) and unusual (freak б) waves at the moment of loss of "Aurelia"



SUMMARY (about freaks)

1. In order become freak, wave have to obtain some features.
2. Freak wave is multidimensional extreme.
3. Arising of a freak connected both with nonlinear property of wave field and some external factors.
4. Statistical description of nonlinear wave properties is mixture of distribution.
5. All nonlinear processes and events have their own freaks.

St. Petersburg