Processing of Wave Directional Spectra into a climatology of swell events

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« Time-series analysis in Marine science and applications for industry »
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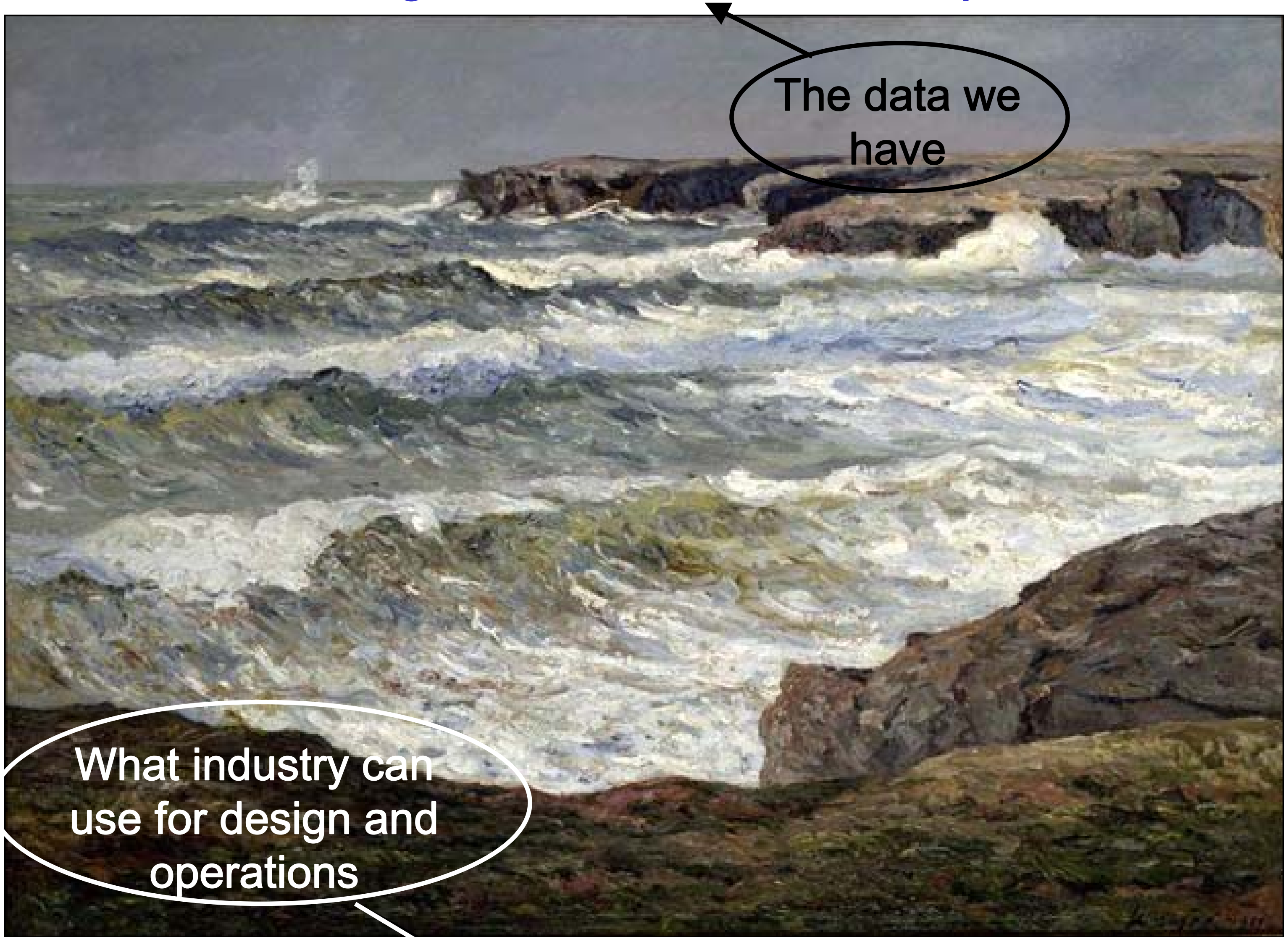
Processing of Wave Directional Spectra



… into a climatology of swell events

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Some applications require detailed knowledge of the long-term spectral wave climate at a given location.

Structural fatigue

Coastal erosion

Wave energy extraction

Etc...

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Problem: predict likely wave action over a long future duration, typically a few decades, when responses are sensitive to height, period and direction.

If sea states can be represented by a single triplet H,T,θ, and occurrence probability, and if their sequencing has neglectible influence:

Binning of the database parameters, selection of a few representative cases

Order of magnitude: 10^2 to 10^3

Computation of action for those cases

For Fatigue: Simulations, RAOs, QTFs, FE models

Estimation of the short term effects

Summation over the sea states, weighted by the occurrence probabilities

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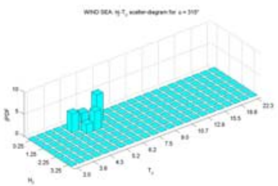
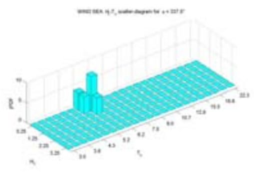
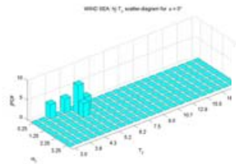
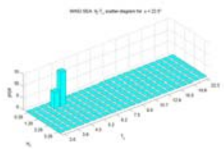
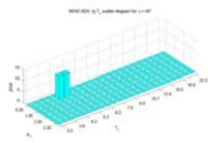
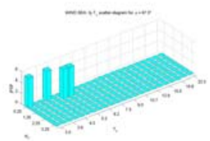
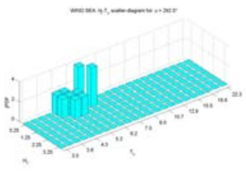
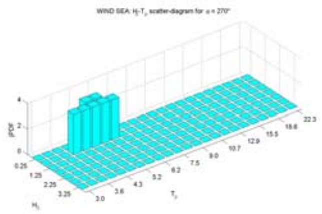
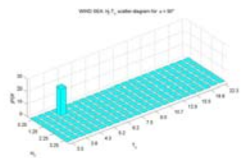
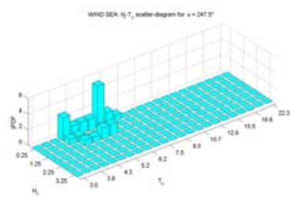
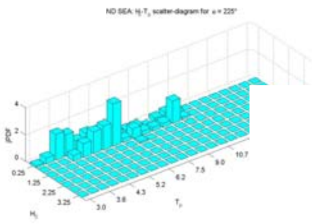
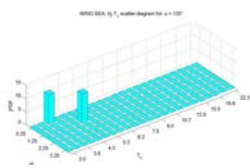
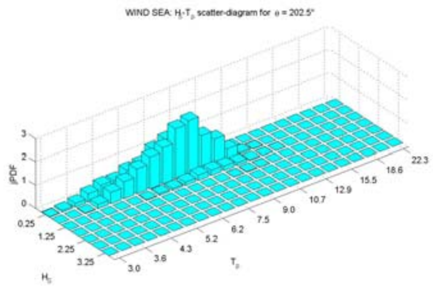
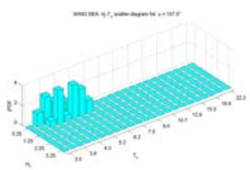
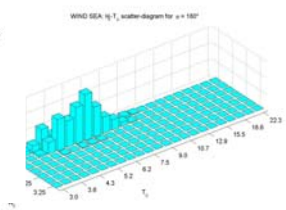
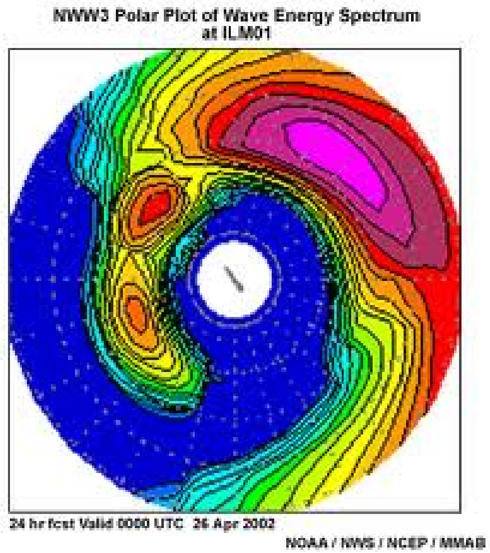









The database describing the wave climate is commonly summarized by a set of occurrence diagrams:

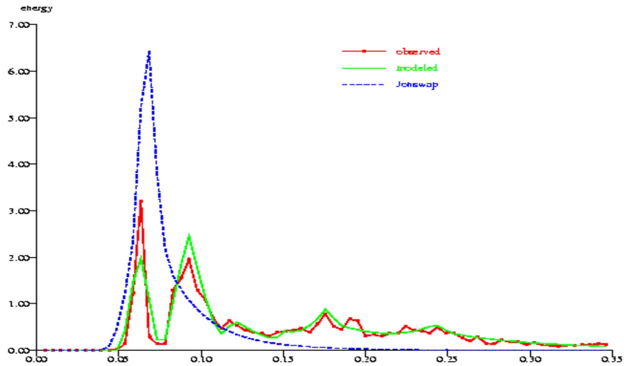
Hs-Tp per direction

On the other hand, directional measurements are costly to set up, and they often cover only short durations before they come to an end,



...and at some locations, individual directional spectra can already not be characterized without a large number of parameters, let not say what it is for time-series of them !



If sea states can be represented by a <u>single triplet</u> H,T,θ, and <u>occurrence probability</u>, and if their sequencing has neglectible influence:

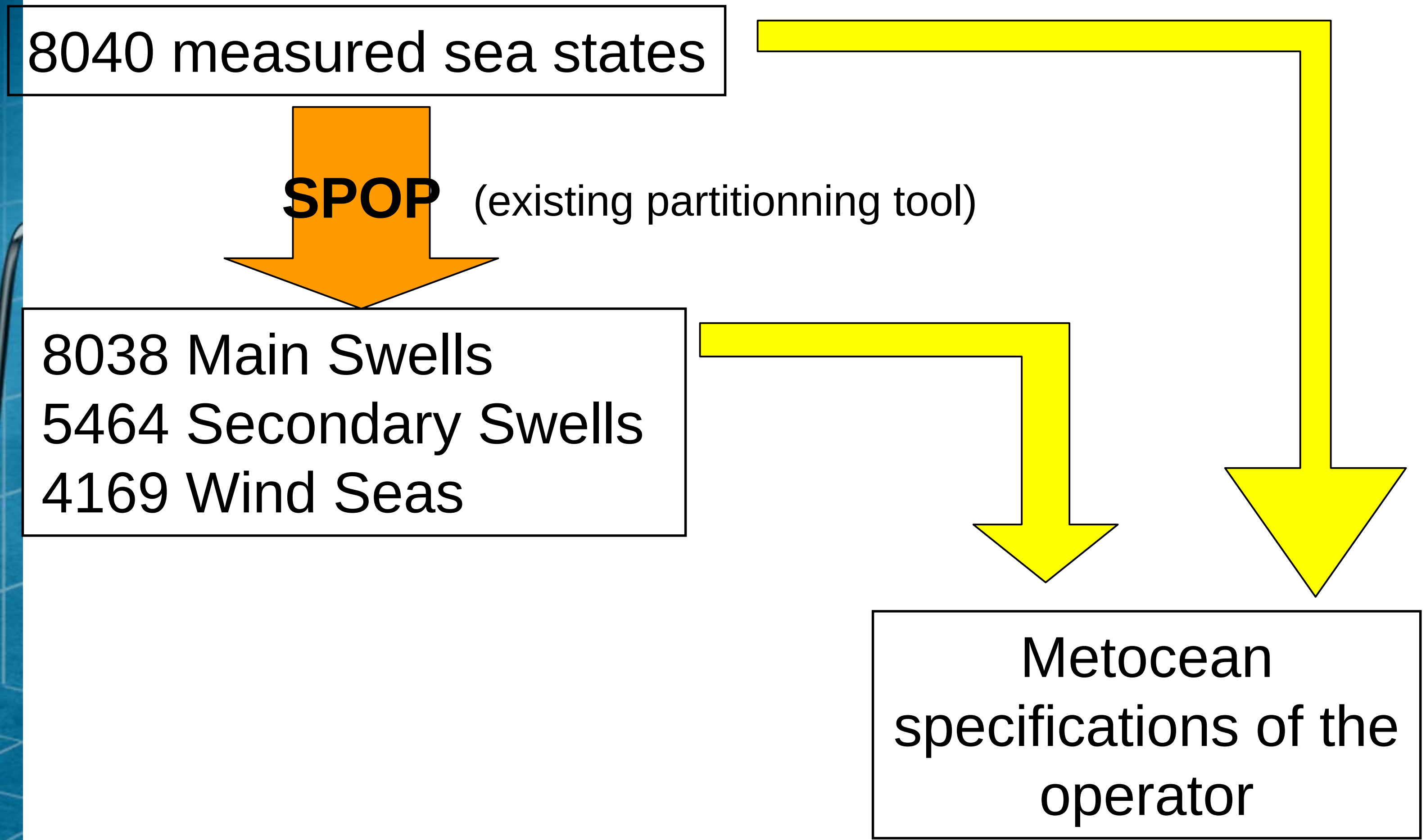
Not enough data to estimate properly

Predictive value of study falls dramatically !

Commonly 3 triplets, sometimes even more

Order of magnitude of the number of cases to consider raises to 10^9 !

To illustrate Joint Probabilities estimation difficulty



Naive reconstruction

	after partition		after assemblage	
	Number	Frequency [%]	Number	Frequency [%]
main swell	8038	99.97	8037	99.96
secondary swell	5464	67.96	5289	65.78
wind sea	4169	51.85	4088	50.85

Table 3: Proportions of the components.

	after partition		after assemblage	
	Number	Frequency [%]	Number	Frequency [%]
MS only	1158	14.40	1212	15.07
MS + SS	2713	33.74	2740	34.08
MS + WS	1416	17.61	1536	19.10
MS + SS+ WS	2751	34.22	2549	31.70
no MS (i.e. WS only)	2	0.03	3	0.05
Total	8040	100	8040	100

Table 4: Proportions of the combinations.

…does not provide the right sea states !

based on empirical statistics of the metocean database

	MS only	MS+SS	MS+WS	MS+SS+WS
$\overline{H_S}$ [m]	1.59	1.40	1.25	1.22
σ_{H_S} [m]	0.48	0.40	0.32	0.32
χ_{H_S} [m^3]	0.95	1.01	1.16	1.19
κ_{H_S} [m^4]	3.65	4.35	5.81	5.15
$H_{S,1/3}$ [m]	2.14	1.85	1.60	1.58
$H_{S,1/10}$ [m]	2.63	2.23	1.90	1.91
$\overline{T_p}$ [s]	12.23	11.21	9.06	9.36
σ_{T_p} [s]	2.00	1.51	1.63	1.82
χ_{T_p} [s^3]	0.15	0.45	0.23	0.14
κ_{T_p} [s^4]	2.39	3.03	2.71	2.61
$T_{p,1/3}$ [s]	14.48	12.90	10.90	11.38
$T_{p,1/10}$ [s]	15.73	14.15	12.06	12.62
$\overline{\theta}$	208.26	202.08	210.50	206.09
σ_θ	8.84	7.05	10.47	8.91
χ_θ	0.38	0.24	1.16	0.55
κ_θ	2.79	4.05	8.89	3.32
$\theta_{1/3}$	218.10	209.66	222.00	216.20
$\theta_{1/10}$	225.23	215.39	229.71	223.30

based on the new statistics from metocean specifications

	MS only	MS+SS	MS+WS	MS+SS+WS
$\overline{H_S}$ [m]	0.99	1.27	1.20	1.43
σ_{H_S} [m]	0.49	0.50	0.46	0.47
χ_{H_S} [m^3]	0.97	0.71	0.96	0.74
κ_{H_S} [m^4]	4.65	3.96	4.88	4.13
$H_{S,1/3}$ [m]	1.25	1.46	1.27	1.64
$H_{S,1/10}$ [m]	1.75	1.90	1.77	2.05
$\overline{T_p}$ [s]	11.08	11.72	8.69	9.45
σ_{T_p} [s]	2.49	1.94	2.21	2.06
χ_{T_p} [s^3]	0.68	0.33	0.52	0.26
κ_{T_p} [s^4]	3.40	3.03	3.06	2.80
$T_{p,1/3}$ [s]	11.78	12.49	9.49	10.28
$T_{p,1/10}$ [s]	14.13	14.30	11.70	12.21
$\overline{\theta}$	205.80	205.96	205.76	205.92
σ_θ	9.14	9.10	9.07	9.03
χ_θ	1.62	1.64	1.62	1.63
κ_θ	7.93	7.97	7.90	7.95
$\theta_{1/3}$	202.5	202.82	202.5	202.82
$\theta_{1/10}$	225	225	224.73	224.82

Table 7: Statistical properties of combinations parameter.

Especially, single swells lead to highest Hs in measurements, to lowest in naive reconstruction.

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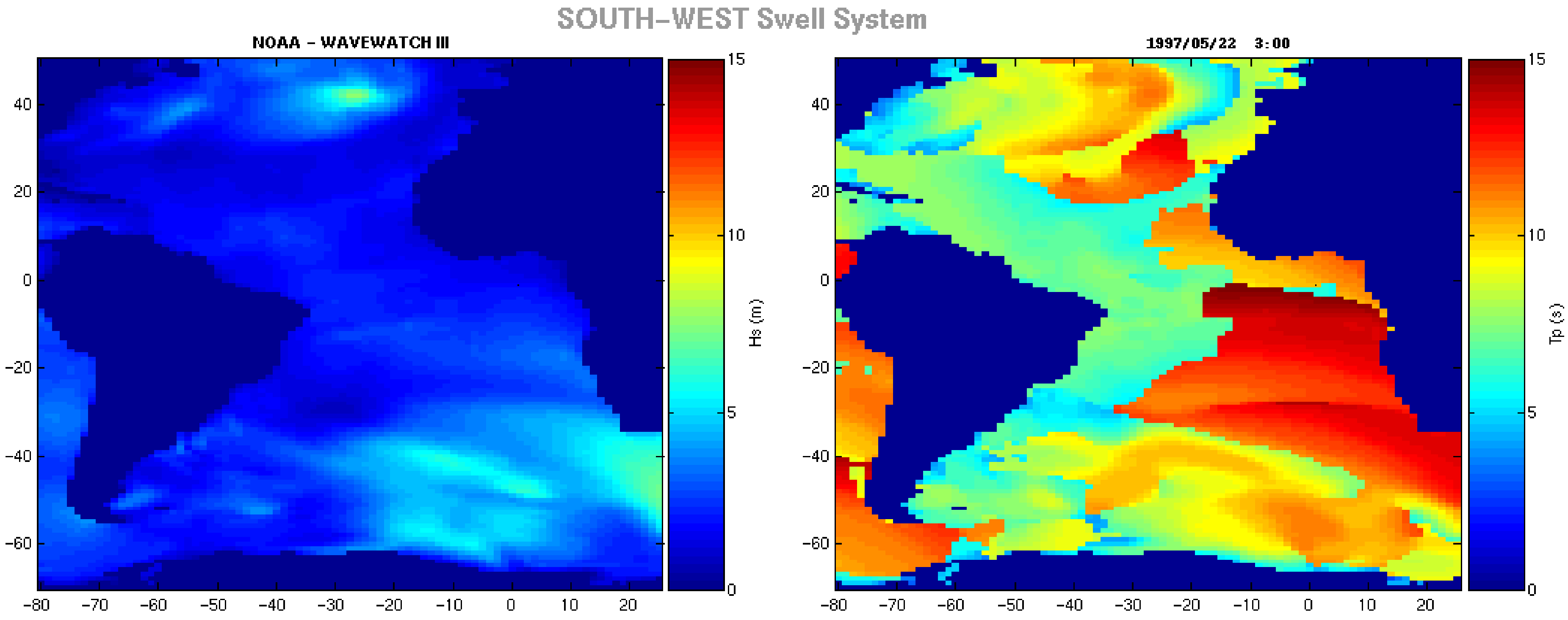
What makes the observed spectra’s swell part ?



Let’s consider swell arriving on West Africa oil fields (or endangered shorelines).

Left displays significant wave height, thus storms passing by in the roaring forties, and right dominant wave periods, thus the front of the overtaking of the existing swells by a new primary one sent by the storm.

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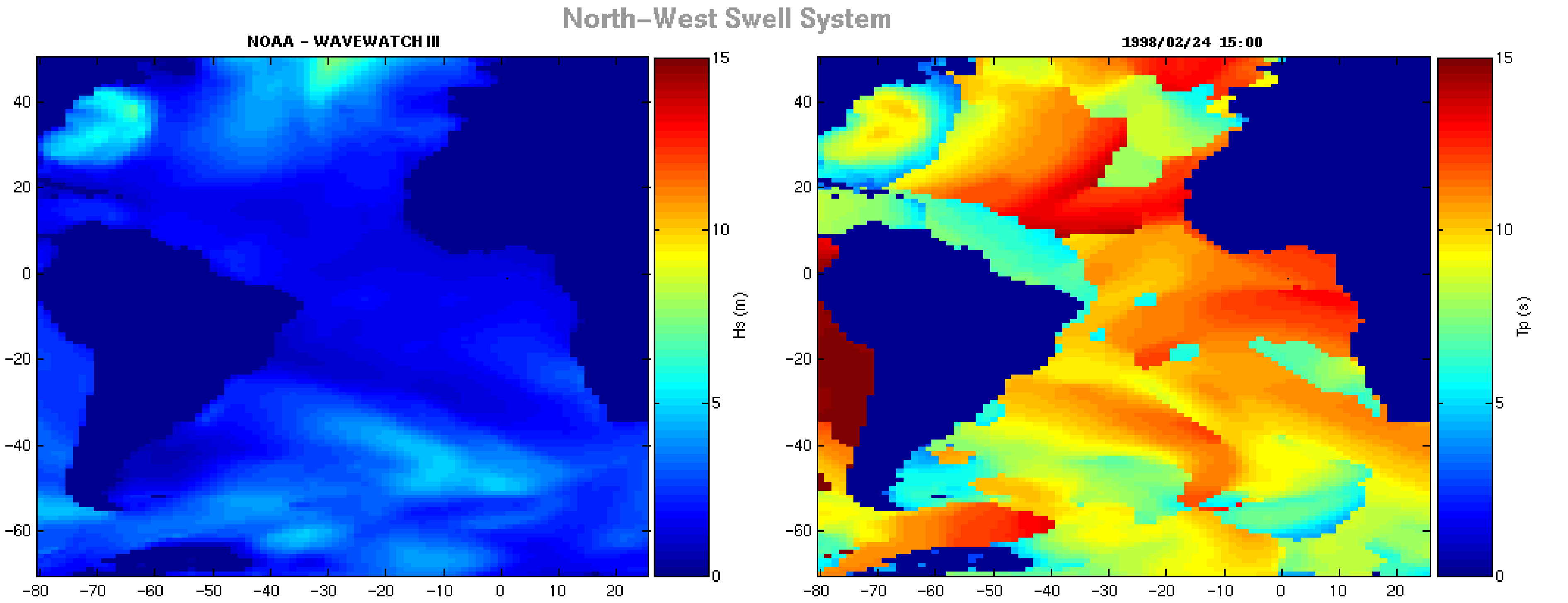

In some conditions, swells from the North Atlantic may hit beamside structures heading to the southwesterly dominant waves: there is no way to construct some equivalent spectrum with single Hs, Tp, direction for several swells present in a sea state.

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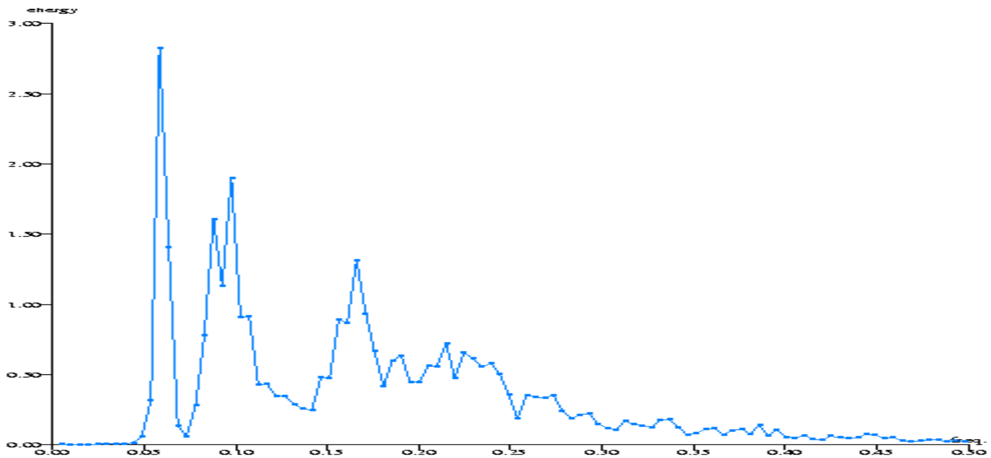
Characteristics of W.A. spectra

- Multiple swell peaks
- Deep troughs in between
- Still some wind sea



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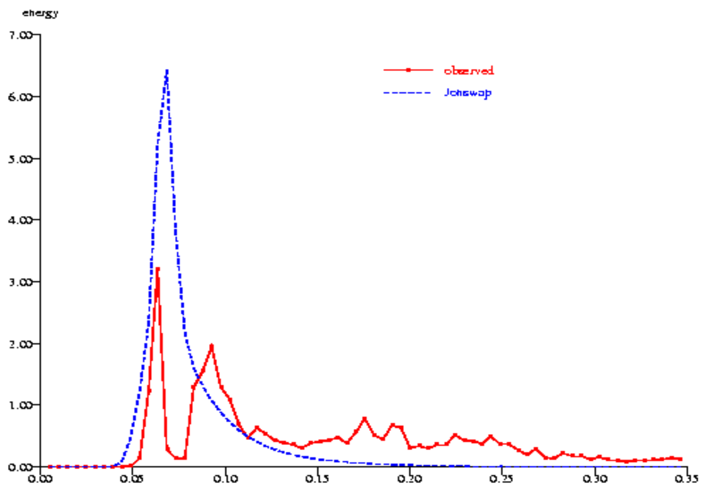
Limitations of standard models

- **2 peaks at most.**
- **Spectral shapes for individual systems are fully or not fully developed WIND seas.**
- **Gaps between peaks poorly represented.**
- **High γ values, no physical meaning, numerical and sampling problems.**



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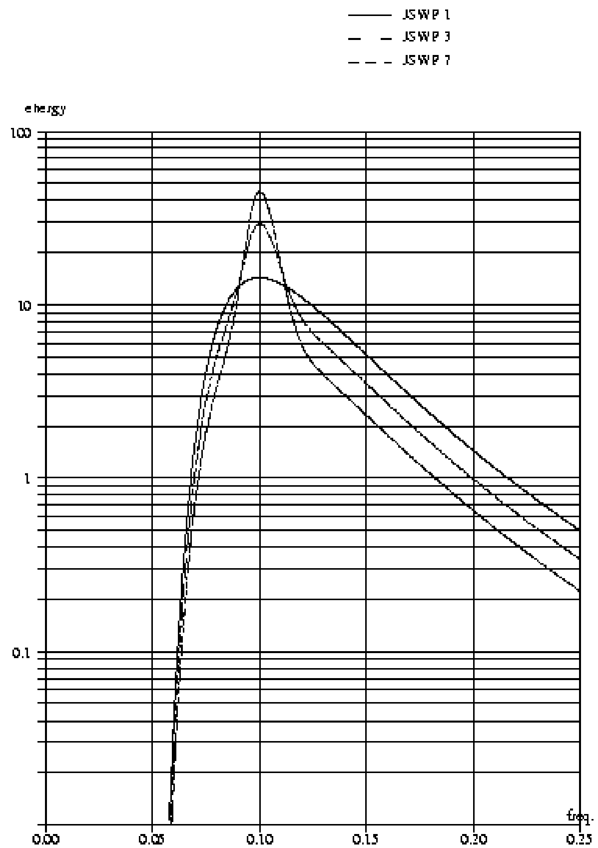
Is JONSWAP suited to swell ?

- **JONSWAP model means that wind has not blown enough to fill-in the missing part with respect to a P-M.**
- **It is an enhancement of the model for wind to waves spectral energy transfer to account for what happens <u>before</u> equilibrium is reached.**



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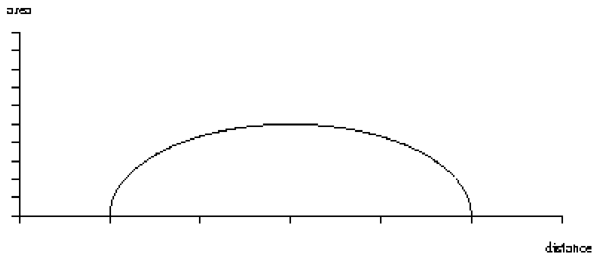
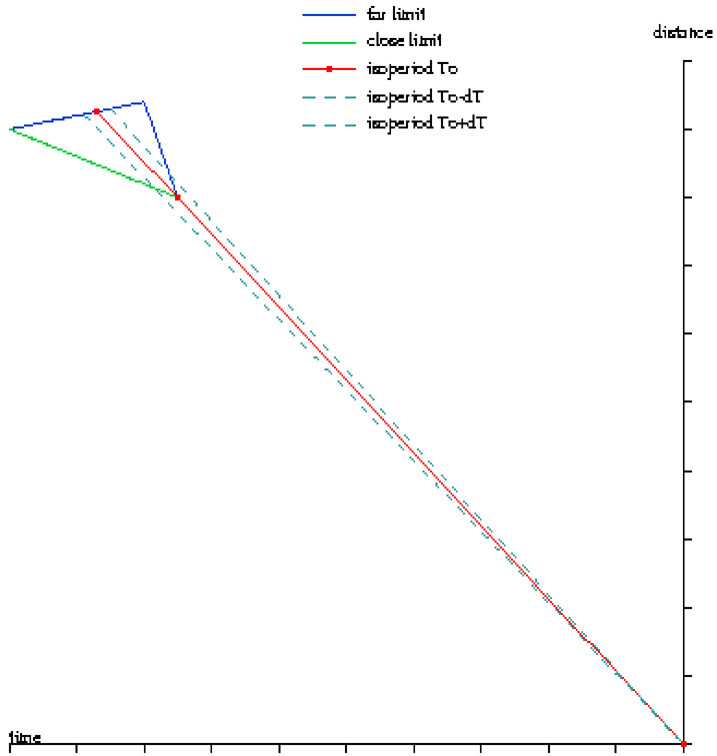
Swell is governed by propagation





For swell, we have a generating area at some time in the past, and propagation.

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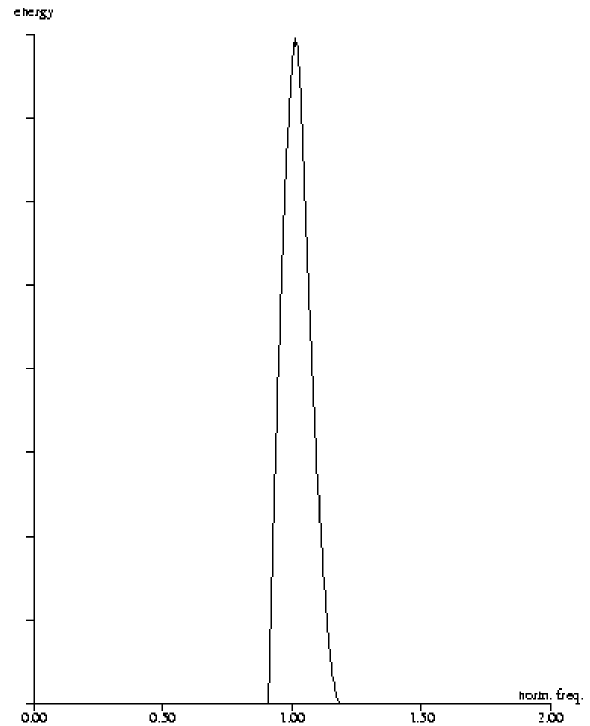
Each storm's influence is to be considered separately

Propagation carves out a shape from the one in the generation area.

Suggestion:
use a simple spectral triangle for each system.



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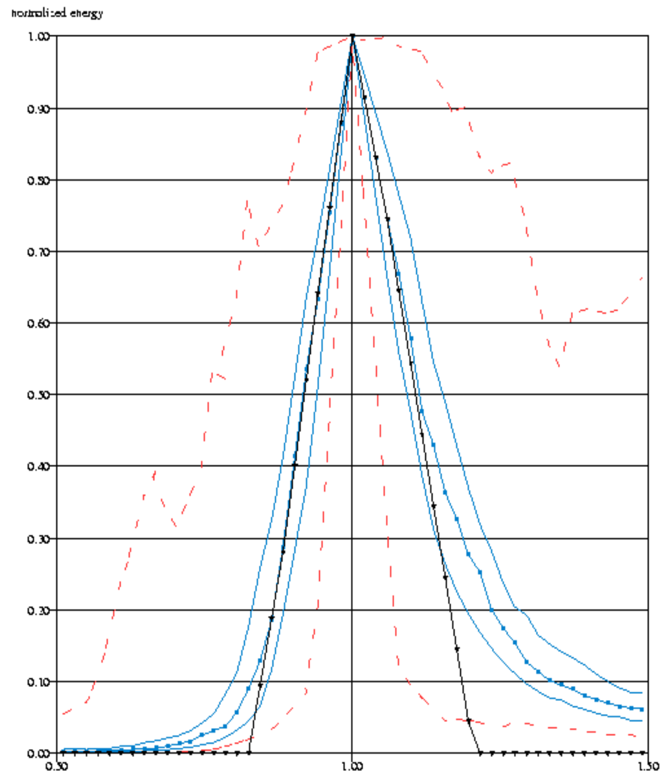
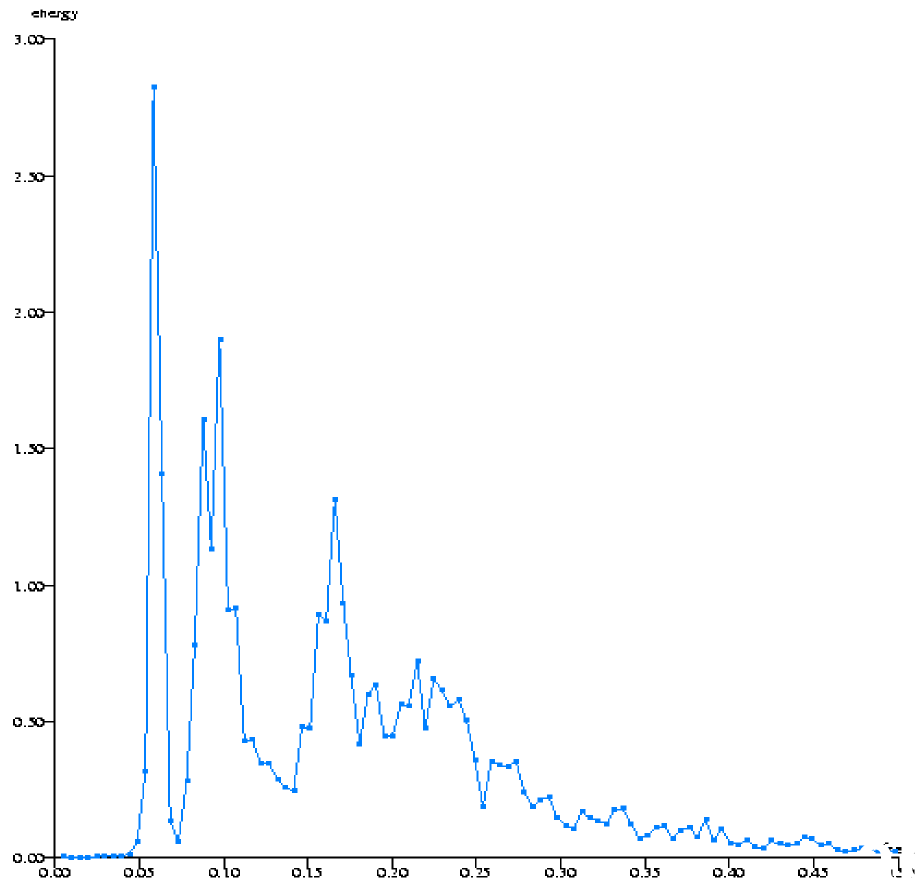
Triangular shape

- Fitting method from Olagnon (2001).
- Extend from (m-1)/m fp to m/(m-1) fp.
- m in the vicinity of 6
- m may need to be increased at some locations.
- Note that m is related to the peakedness factor (Goda parameter) by $\varepsilon_{Qp} = (4m-2)/3$



Swell

Extraction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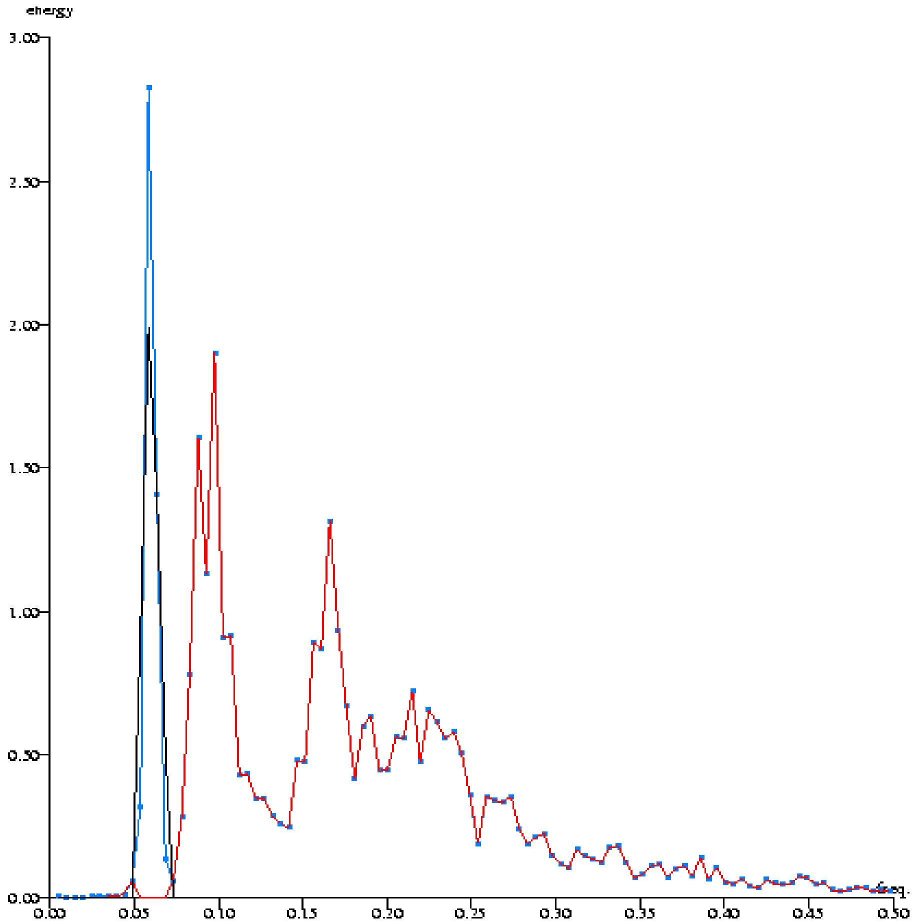

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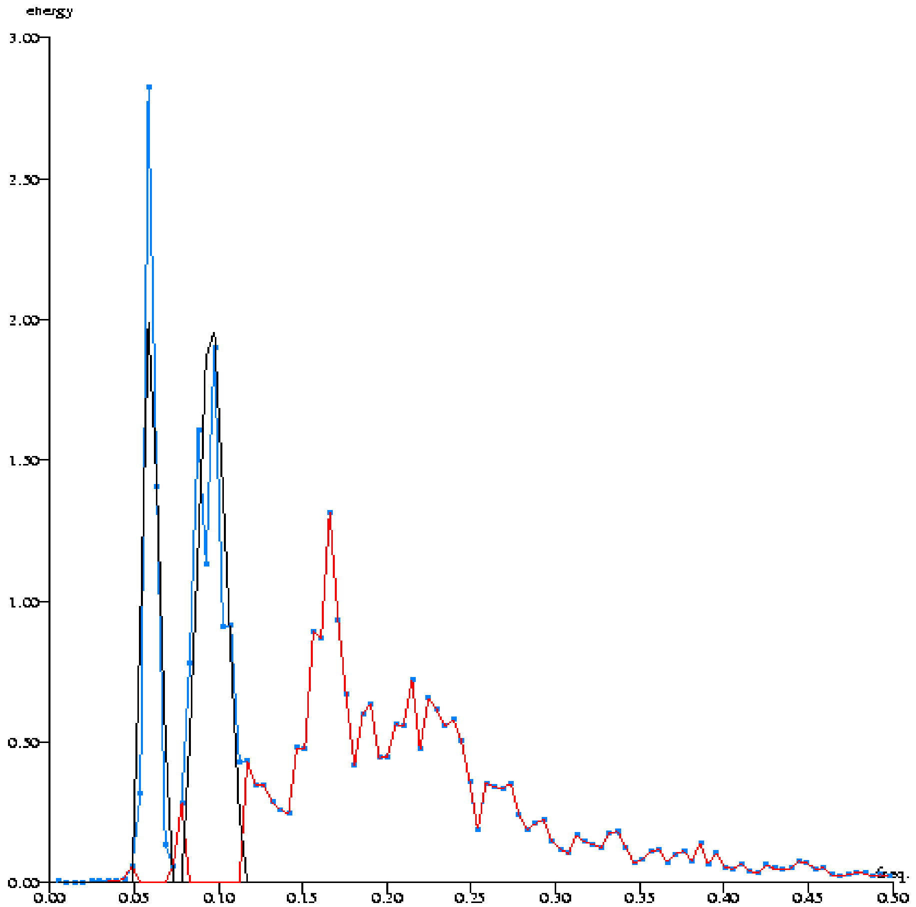

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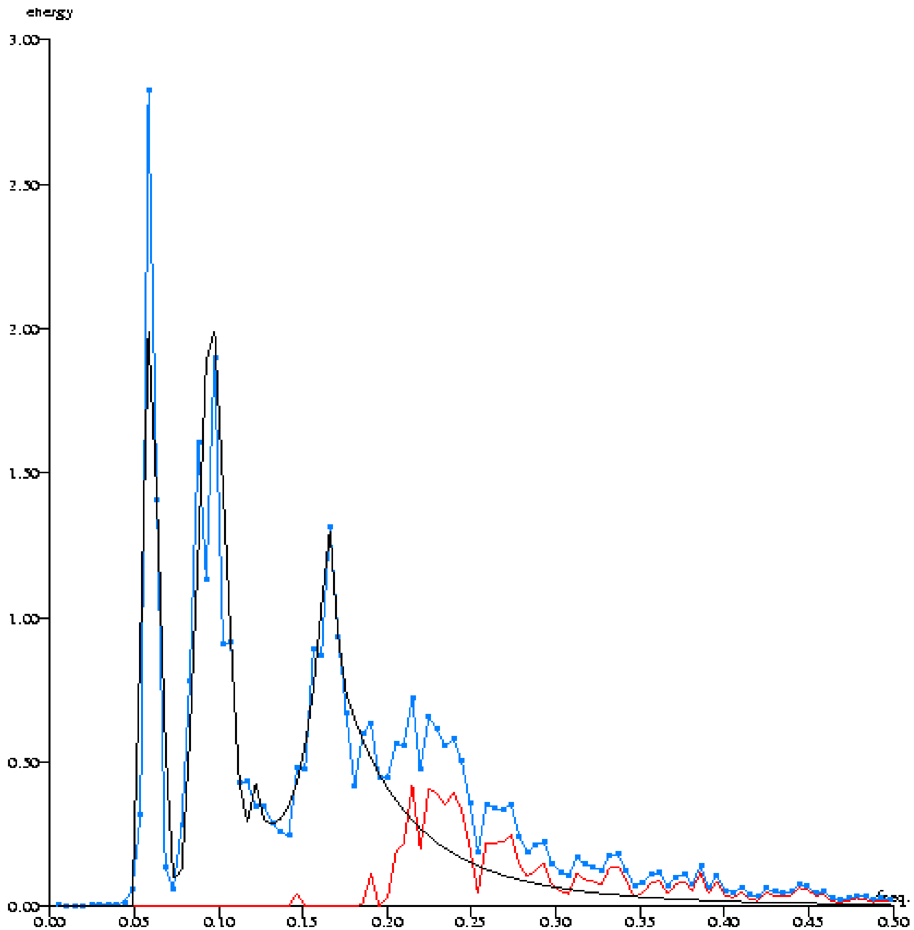

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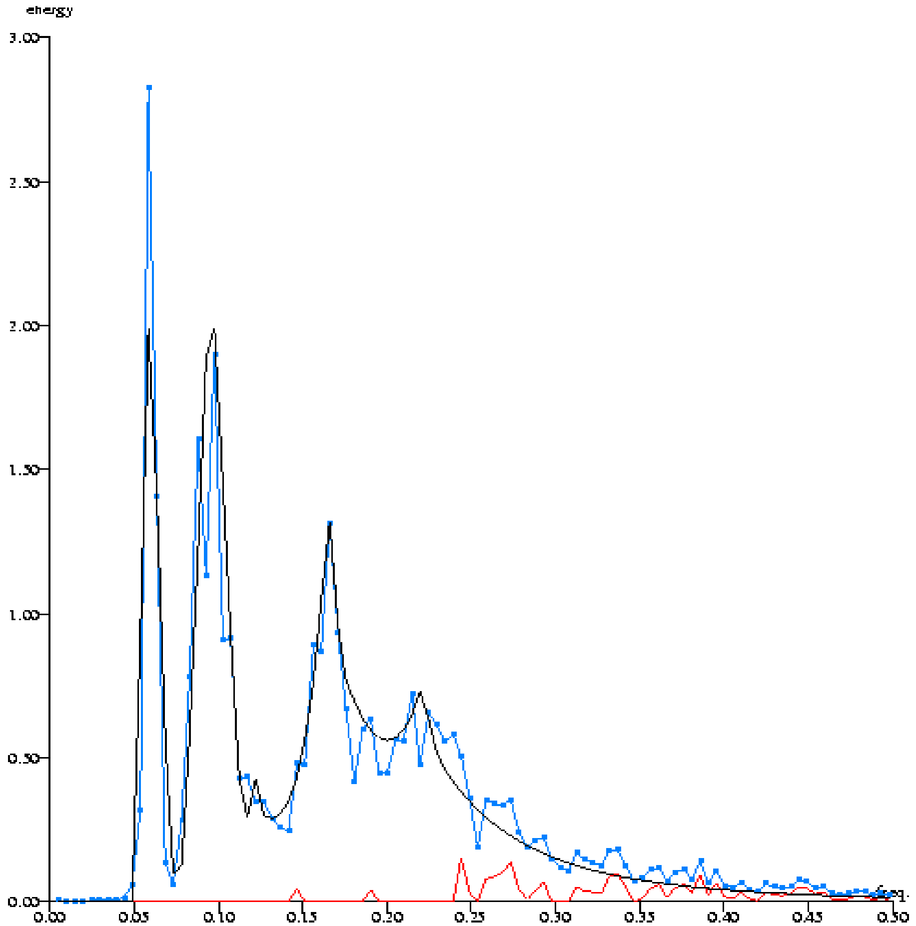

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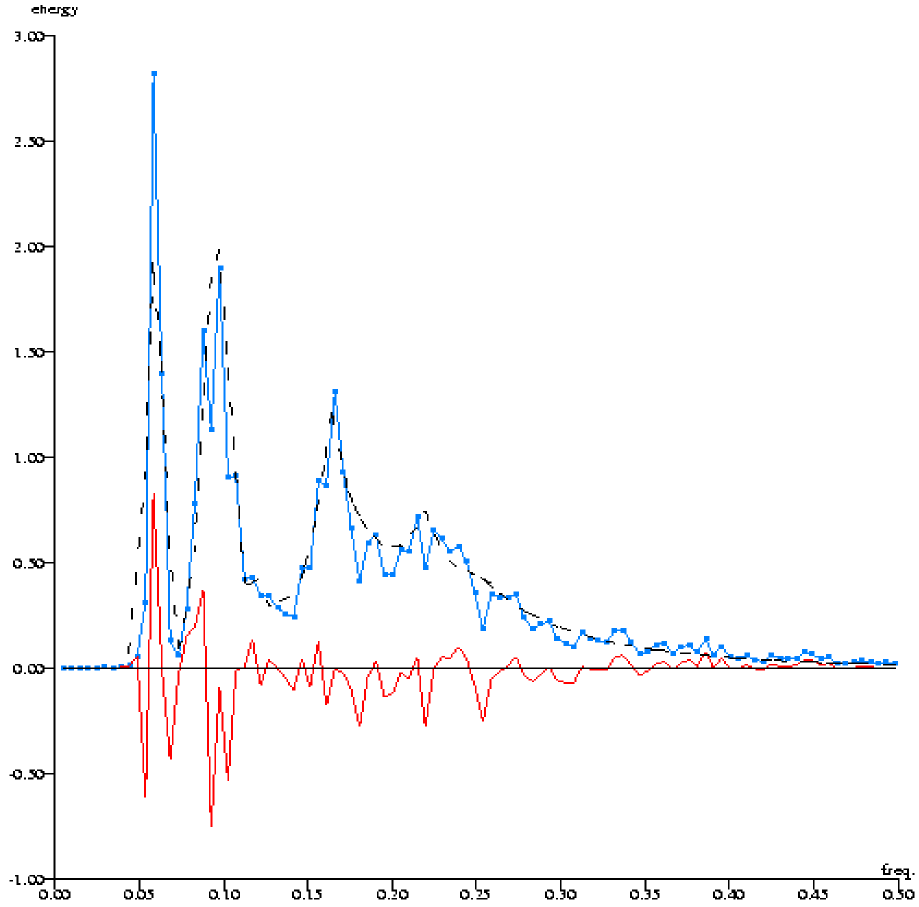

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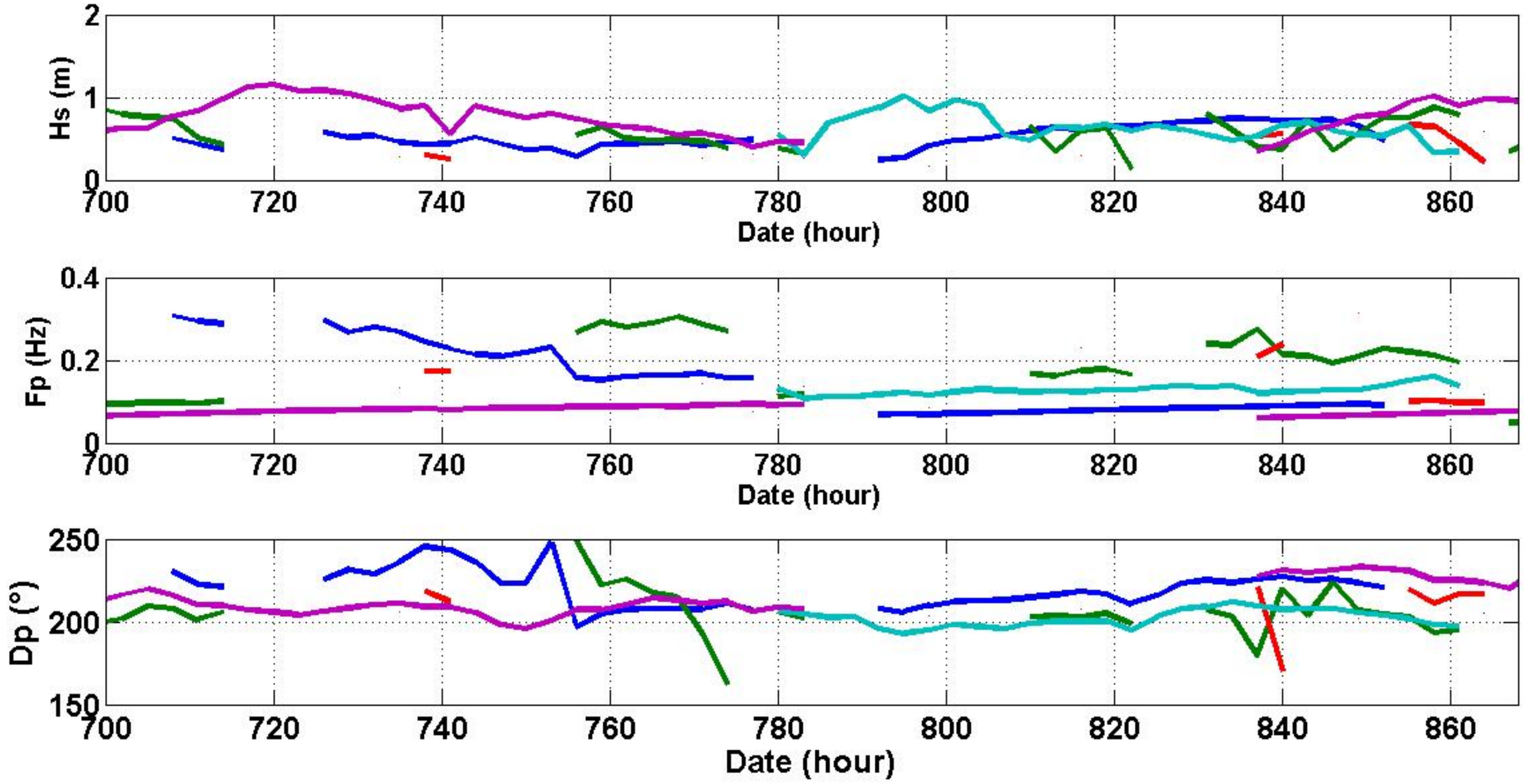
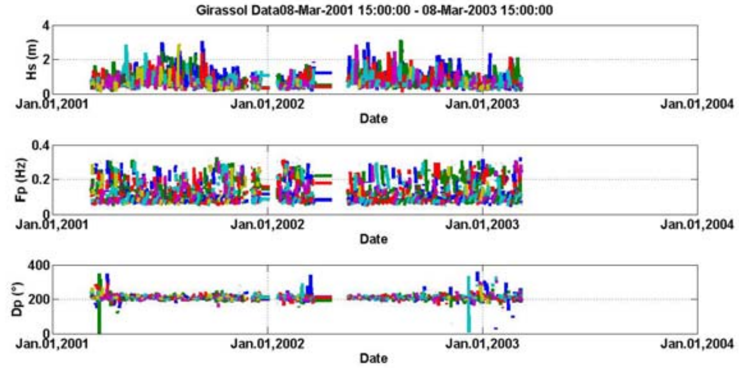
Systems



We have successfully replaced a time-history of spectra with a time-history of a variable number of parameters.



Now, we can rely on the same “construction” idea and method that we used to model spectra from single peaks so as to model the process from single wave systems.

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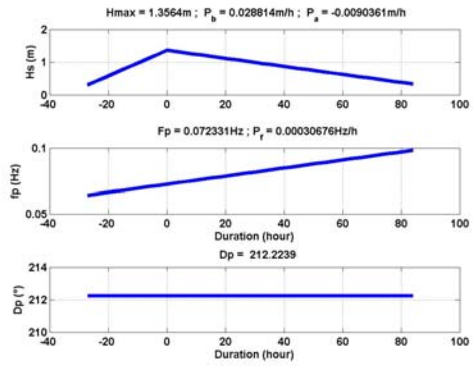
Let us define an event:



A climate event is a phenomenon:

- ✓ **that can be found in all successive observations within a finite, yet significant, duration;**
- ✓ **that can be modeled consistently throughout for each of those observations;**
- **for which the model parameters variations are slow and can be themselves modeled;**
- **and last but not least, that can be traced back to a unique meteorological origin.**

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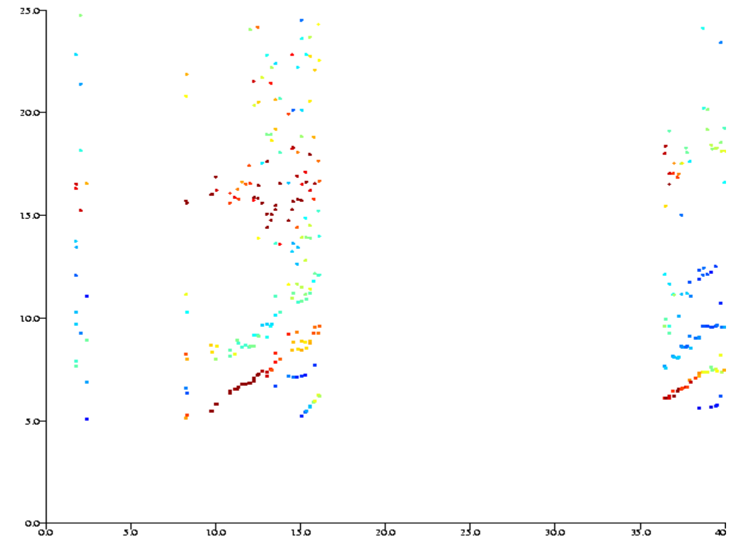
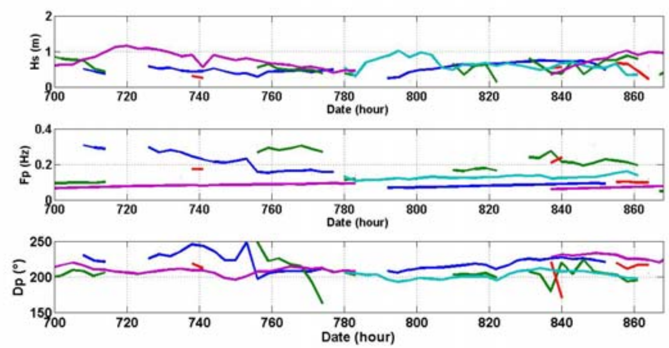
Systems are already “coloured”, i.e. one can follow them over many time-steps, yet some of them may not be pure (at some point, the waves from a new storm are mistaken for the continuation of the swell from an older one), may be short parts of longer events truncated by some measurement or partition problem, etc.





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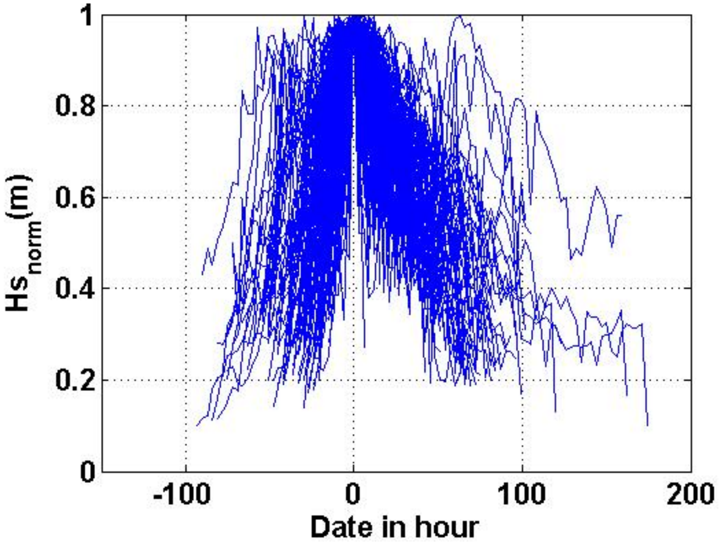
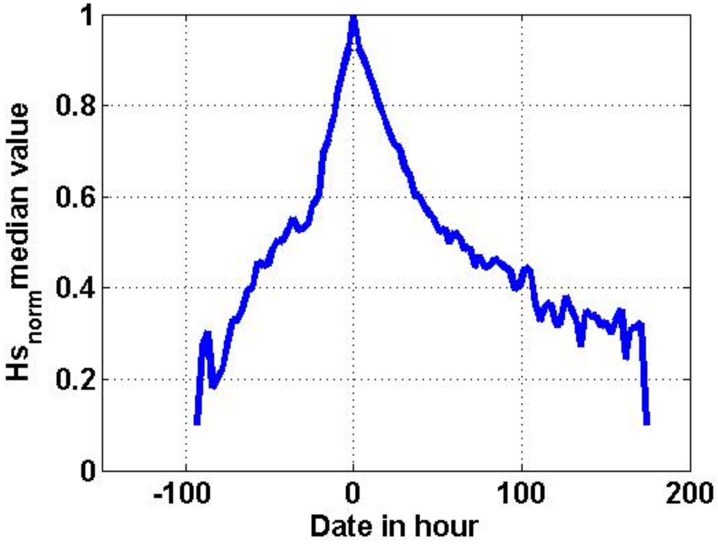
A set of the best events is selected, and a model is sought for their normalized parameters time histories with the same method (Olagnon 2001) as for spectral peaks.





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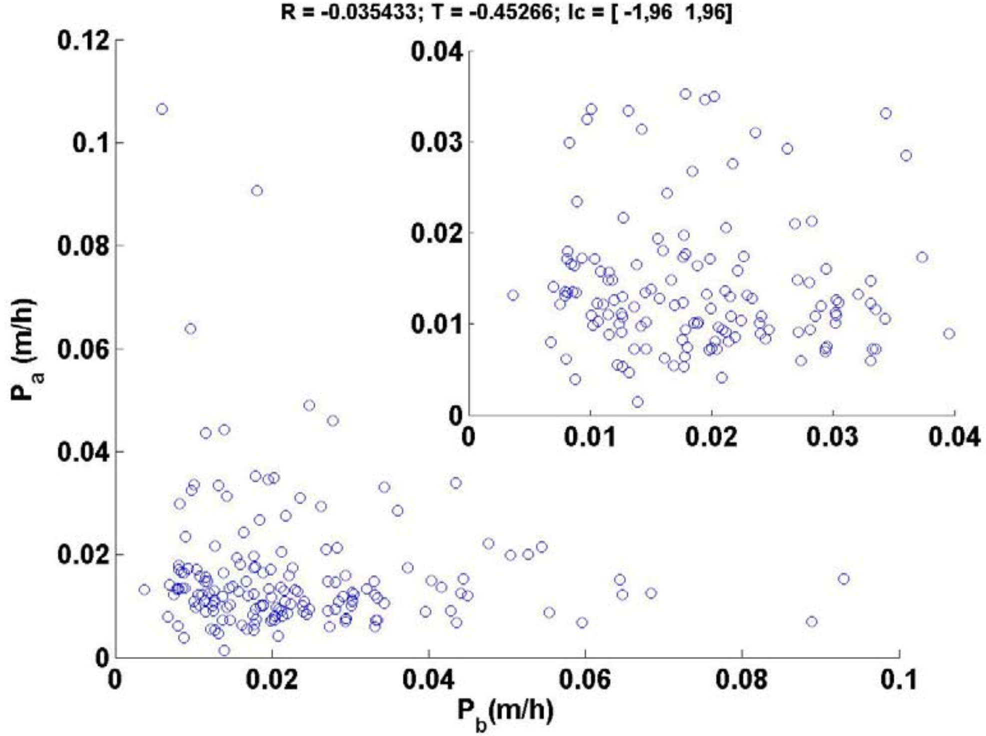
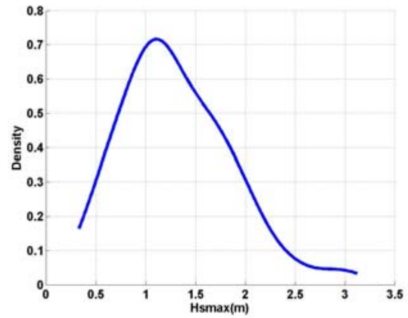
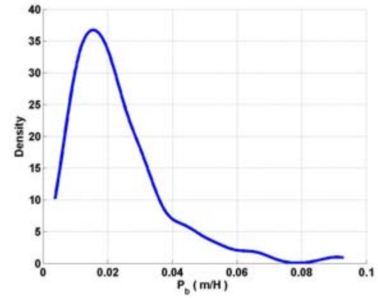
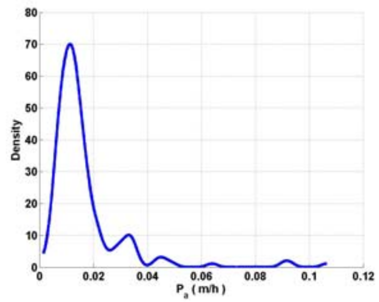
Hs is thus modeled by Hs_max of the event, a left slope for swell growth, a right slope for swell decay. No significant correlations.









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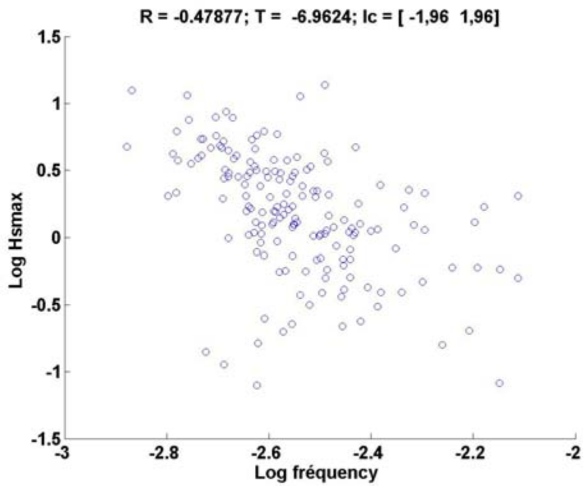
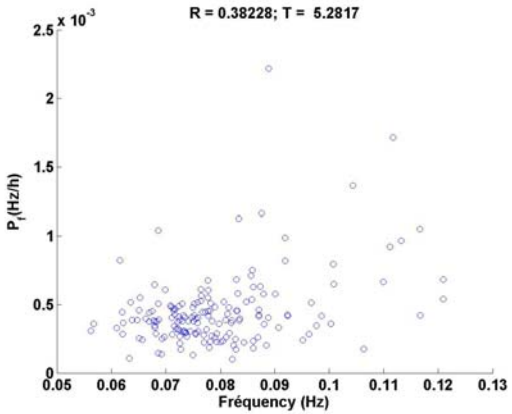
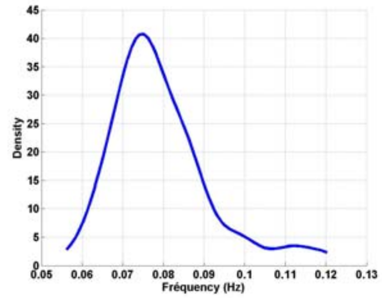
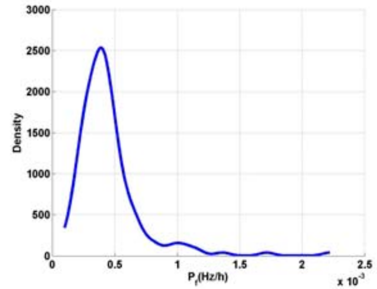
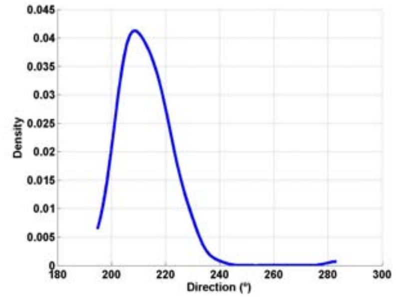
Frequency is steadily increasing and direction nearly constant, frequency is correlated to Hs and frequency slope to frequency.











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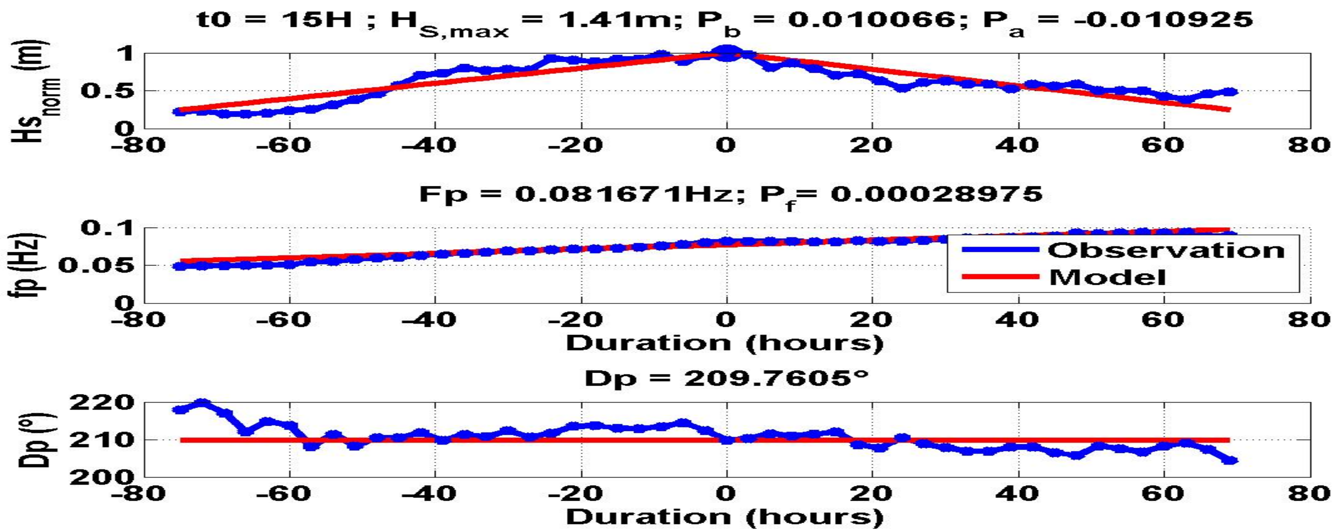
Thus the following model for an individual swell event:

- Hs: Triangle with growth slope independent of decay slope.
- Fp: Linear increase, with value at Hs_max dependent on Hs_max.
- Dp: Constant.



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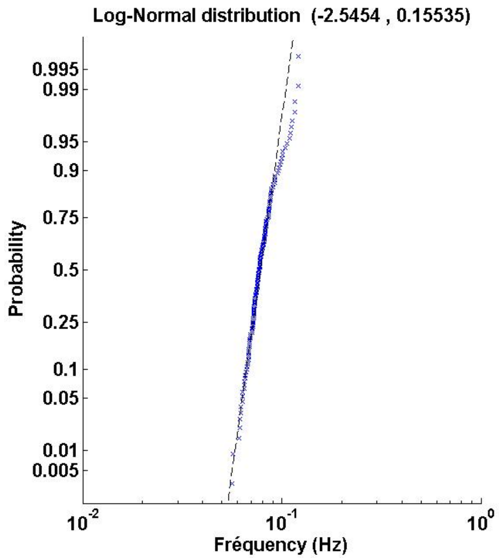
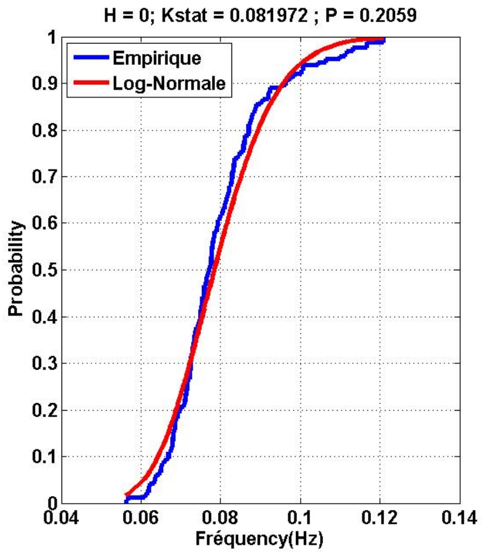
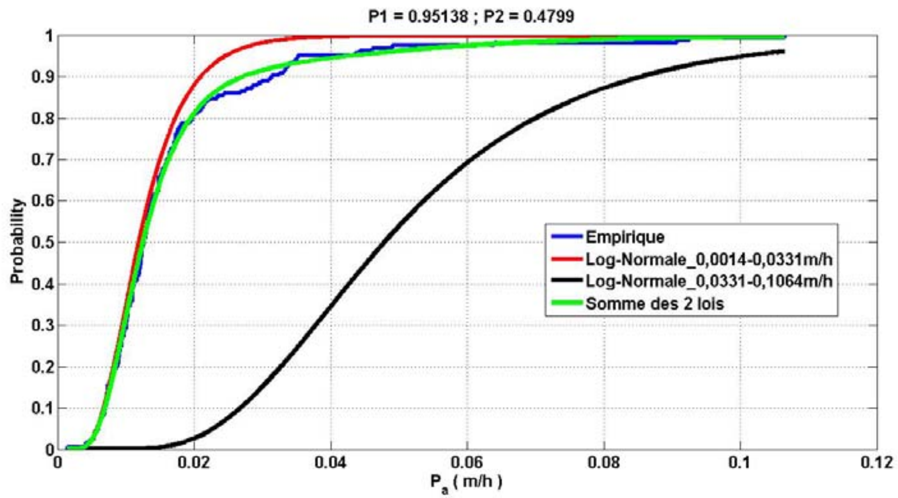
Then we can fit distributions and further investigate correlations for the parameters: Hs, fp, Dp, Hs slope left, Hs slope right, fp slope







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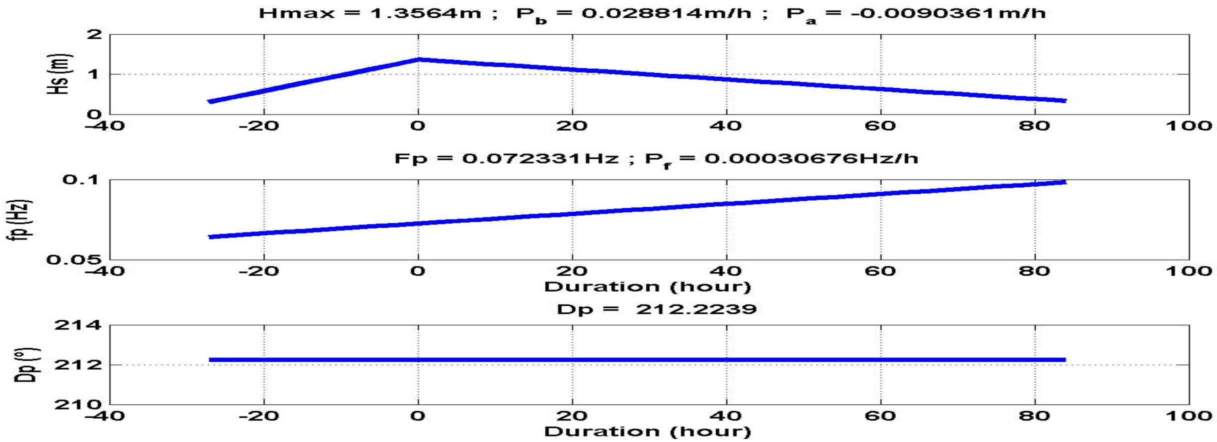
... and the distributions for the parameters are:

- Hs_max: log-normal distribution.
- Ascending Hs slope: log-normal distribution.
- Descending Hs slope: sum of 2 log-normal distributions.
- Fp: log-normal distribution, dependent on Hs.
- Fp slope: log-normal distribution, dependent on Fp.
- Dp: 99% truncated normal distribution, with discrete addition. *Most swell systems come from the Southwest sector (South Atlantic), yet on rare but verified instances (about 1%), Northern Hemisphere swells make it to the location where they arrive from the Northwest.*



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Now we can simulate all the events that would occur within a given duration. We only need to fulfill some condition as to the number of events: since we have only selected “beautiful events”, we don’t know the true occurrence density of events. We impose the condition that the yearly averaged Hs should be the same as the observed one. It has reasonnable interannual variability (c.o.v. 8%), so should be correctly estimated over our 2 years of data.

We need a model for the process of the occurrence of events. This is a topic for future research, still we can make a quick and dirty simulation as follows:

- Assume a given distribution shape for the the time-durations between the times of Hs_max of successive events (for instance, log-normal or sum of 2 log-normals);
- Adjust the parameter(s) of that distribution so as to meet some constraint(s) (for instance, average number of events present at any time = the observed average);
- Draw random independent intervals between events accordingly.

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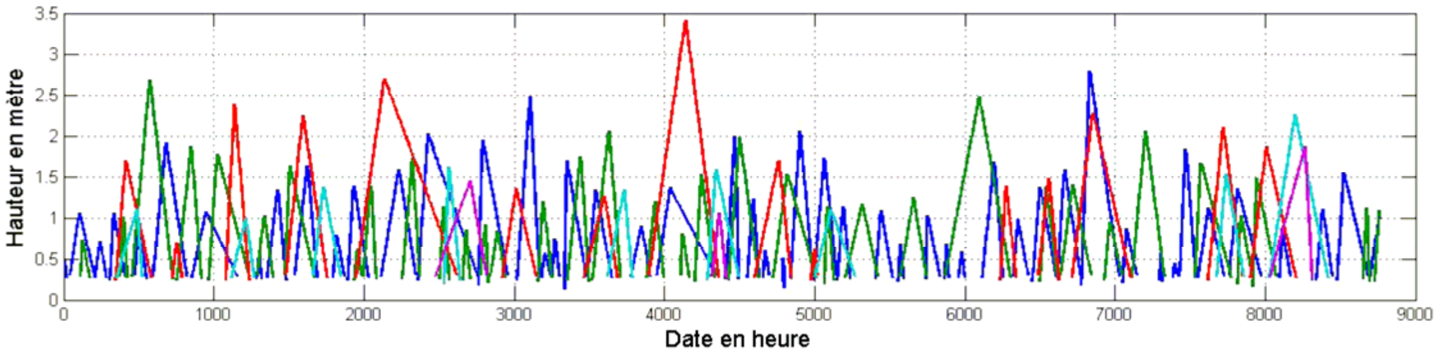
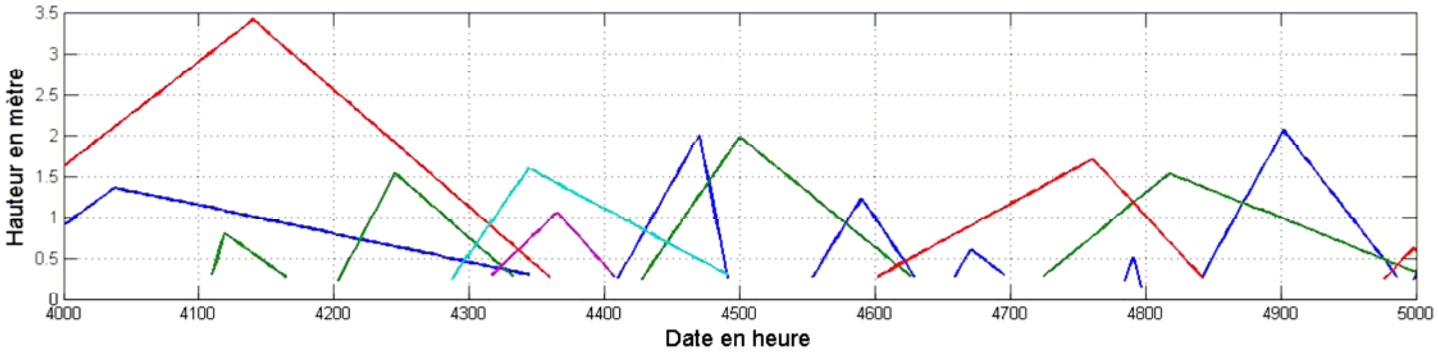
Reconstructed history





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Example of properties

- **Yearly rms Hs**: assuming times of no swell are measurement failures, database => 1.28m, hindcast on nearby location => interannual c.o.v. 8%

- Reconstruction with target 1.28 conditionned on those sea-states with at least one swell present, inter-event duration weighted sum of 2 log-normals 2.5 and 3.5 days => 1.21m c.o.v. 9%, value 1.28 at fractile 65% of marginal distribution.

- **FPSO Vertical bending moment fatigue damage**: extrapolated to 100 years from the 1.64 validated year of the database => 0.566

- With the above reconstruction of 100 years, damage => 0.529, interannual c.o.v. 55% down to 41% for 1.64 years, value 0.566 at fractile 65% of distribution.

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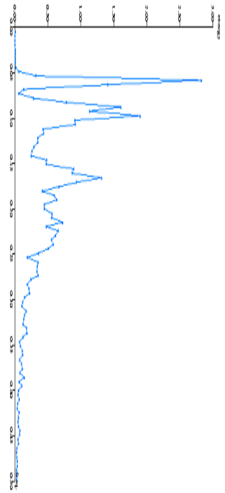
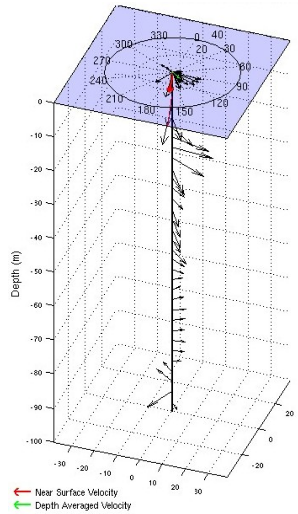
Conclusion

- If we use a sensible model for the process of swell events rather than the quick and dirty method, we can expect very satisfactory results for almost any application.

- We have developed a method that consists in identifying a model for time-consistent events, and then looking for such events in the data.

- Why not use the same method for the analogs of systems (f.i. eof's) in current profiles ?





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