Wave Resource

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Contents

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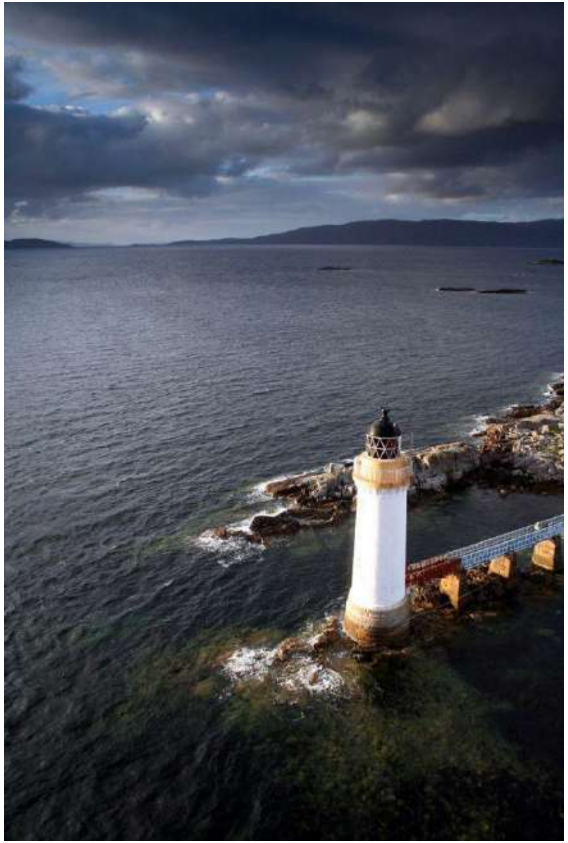
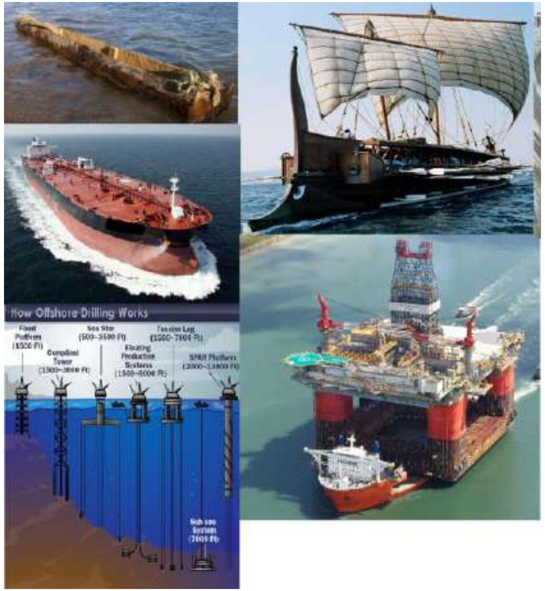
1. Introduction

The Sea



The Sea

Mankind has managed to use the Sea **almost** as well as inlands.



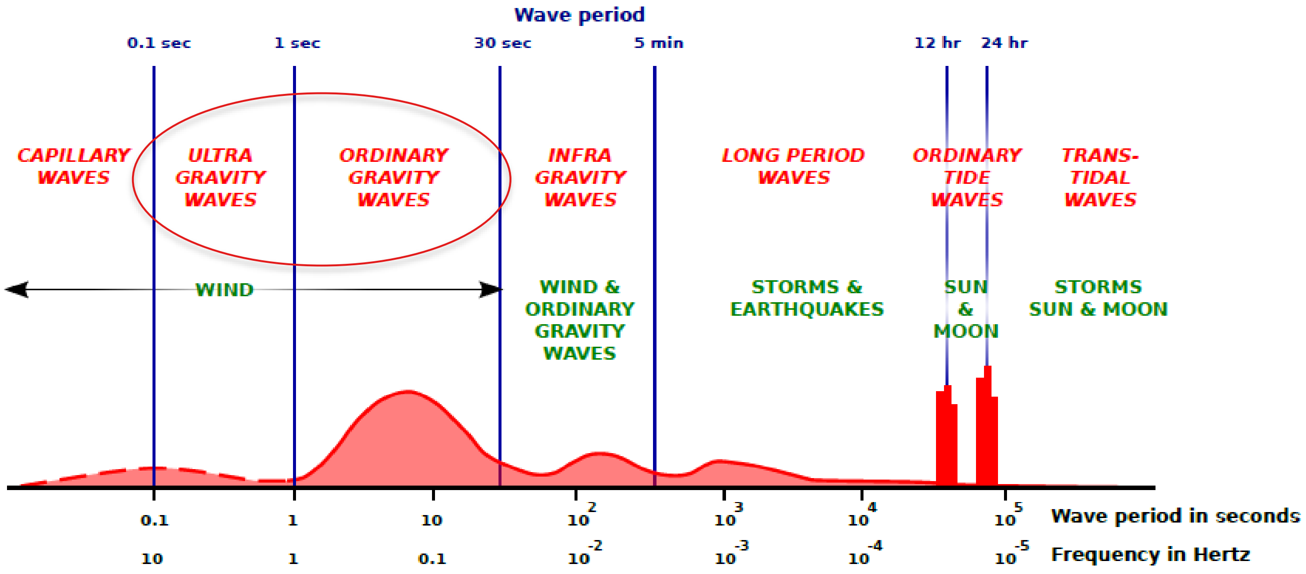
After you leave….

- What are the basic wave principles
- How environments add complexity
- How are waves characterised
- How to monitor waves & usefulness of waves
- How to estimate wave energy resource
- Replicating the Ocean in tanks

Definition

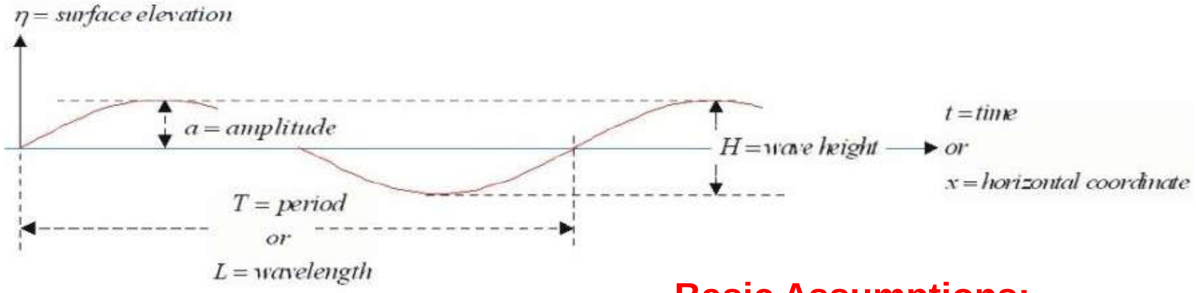
In general an ocean/sea wave is:
"the mean of vertical motion of the ocean surface"

*Vertical motion can be either due to **wind**, **gravity**, tectonic plates, etc.. There are numerous "wave" version(s), however we focus at **wind generated waves**.*



Linear Waves

Airy's theory (1845) summarizes small-amplitude or linear wave theory



$$\eta(\chi, t) = \alpha \sin(\omega t - \kappa \chi)$$

With $\boldsymbol{\omega}$ based on dispersion:

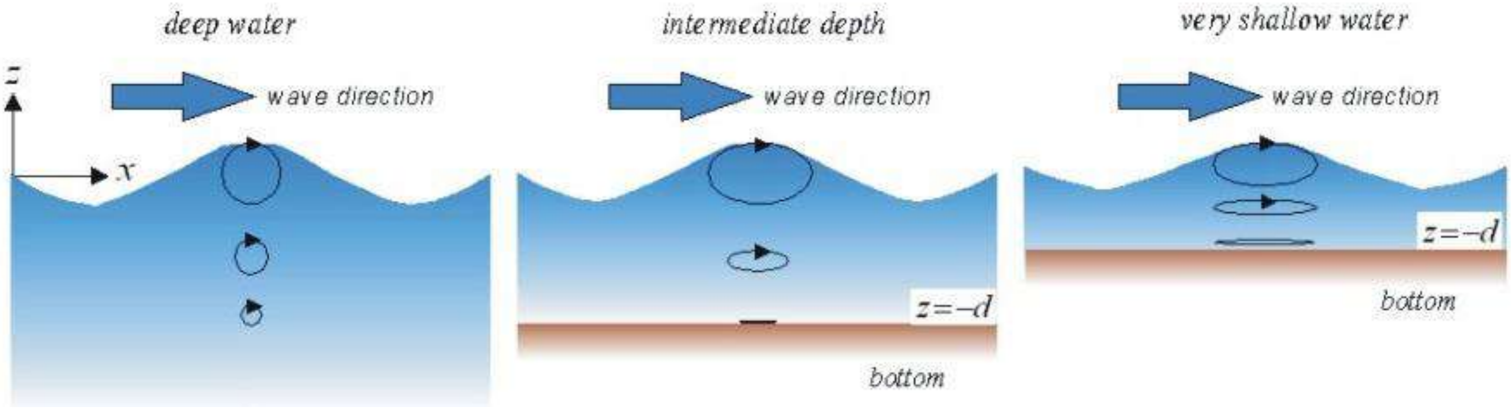
$$\omega^2 = g\kappa \tanh(\kappa d)$$

Basic Assumptions:

- *Fluid is homogeneous, incompressible & Ideal (inviscid)*
- *Surface tension-Coriolis neglected*
- *Pressure is constant and uniform*
- *Boundaries are zero*
- ***α** is **very very small** in space-time domain*

*Waves with different lengths propagate at different speeds, i.e. they are dispersive. The dispersion relationship is implicit in **κ** so an iterative scheme must be used to solve for **κ** if **ω** is known.*

Linear Waves

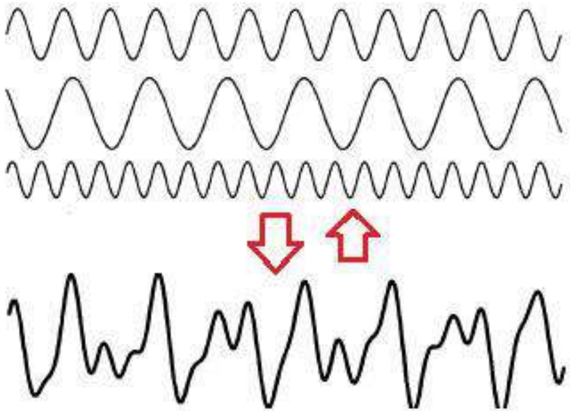


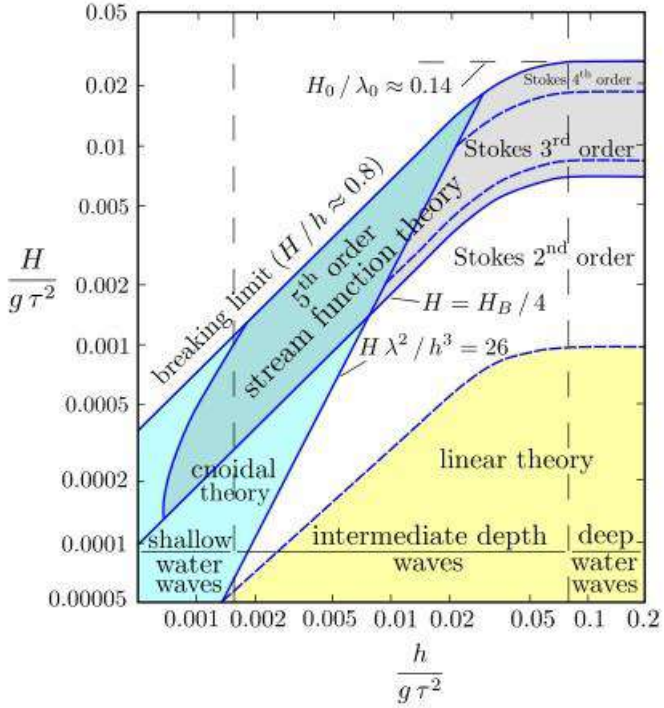
Local characteristics affect waves

Non-Linear Waves

Affected by depth (wave steepness)

Waves are not ideal



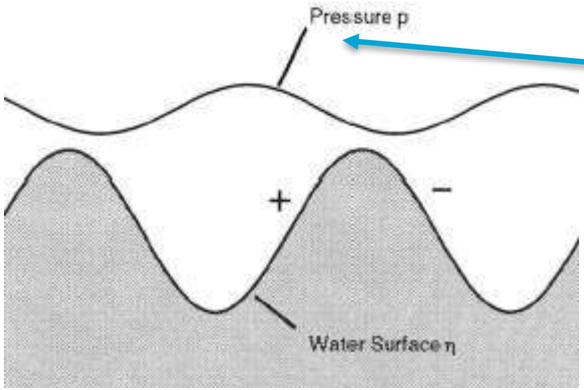


Waves have to “broken”
into smaller pieces (decomposed).

2. Ocean Waves

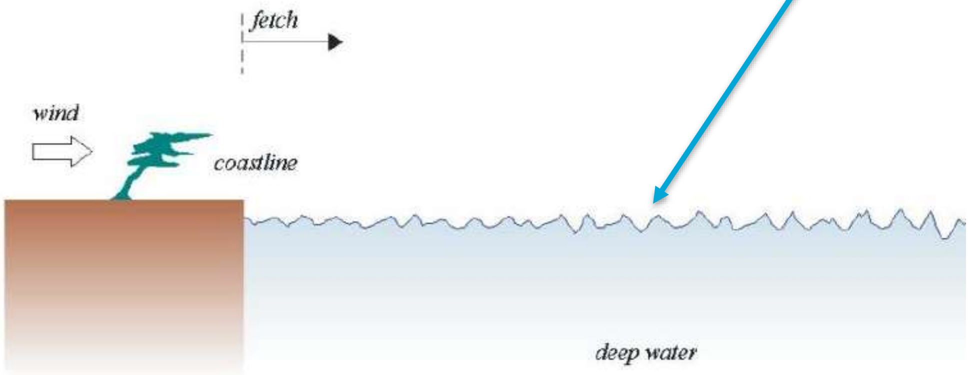
Wind generated waves

Real ocean waves are more complex and most are irregular waves



Wind pressure is applied to sea surface

Wind generated waves often occur at small regions and are usually of lower height.

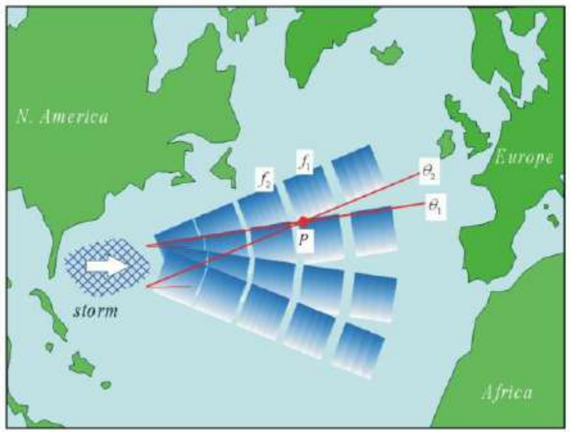


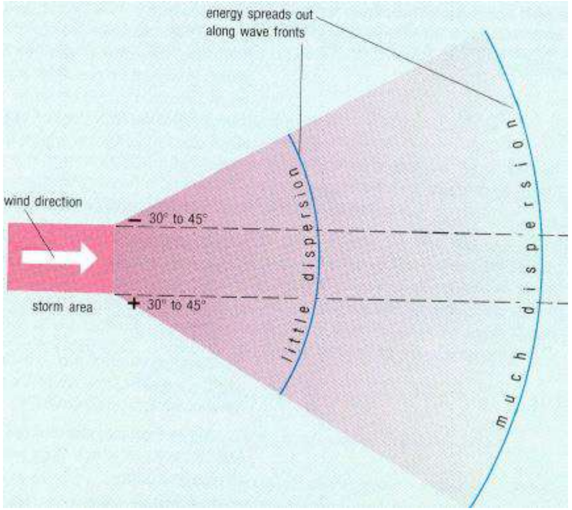
However.....

Swells

Wind generated waves travelling long distances, "transform“ into swells

They tend to maintain a constant direction with some directional spreading

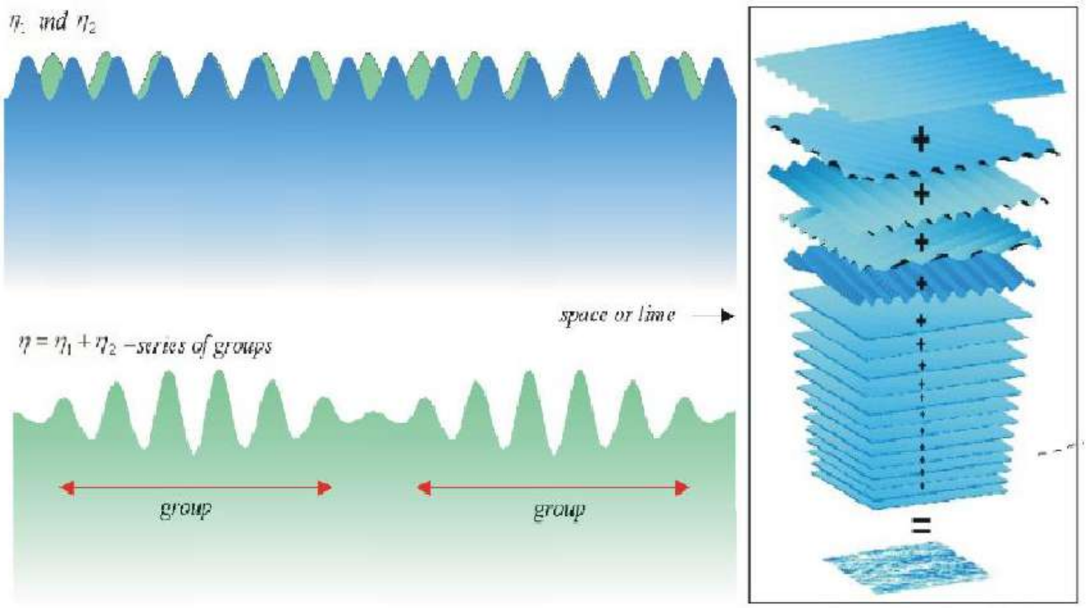




- High frequency (low periods) "merge" to form lower frequency
- Lower frequency waves, travel faster

Real waves

Real Seas encompass waves that have multiple characteristics (regular, irregular, swells, wind-waves etc.).



They constitute a variety of periods/frequencies and elevations.

Wave Spectra

Basic concept : Wave spectrum is surface elevation as a function of time, always considering numerous harmonic waves

- ✓One directional spectrum (1D)
- ✓Two directional spectrum (2D)

$$\underline{\eta}(t) = \sum_{i=1}^{N} \underline{\alpha_i} \cdot cos(2\pi \cdot f_i \cdot t + \underline{\phi_i})$$

This is the random-phase amplitude model !!

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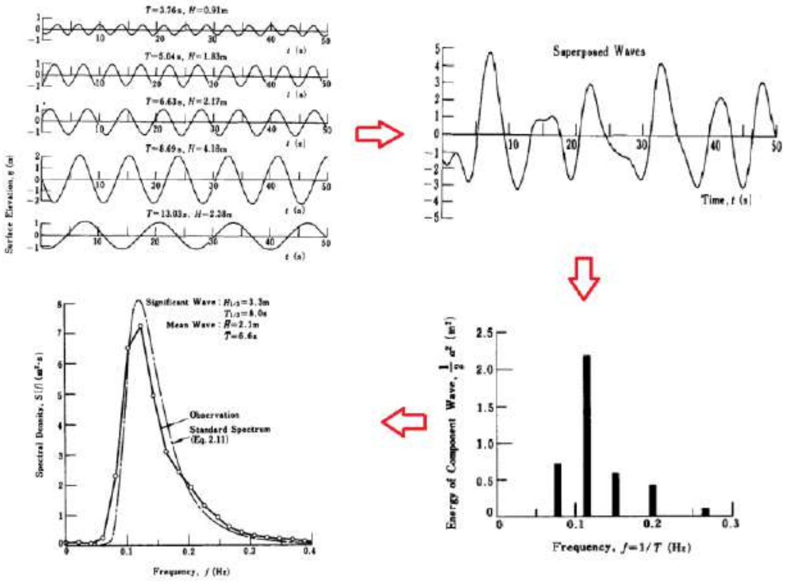
1D Spectrum

Seas **do not** have pre-defined **OR** discrete range of frequencies, **nor** are they stationary in time.



$$E(f) = \lim_{\Delta f \to 0} \cdot \frac{1}{\Delta f} \cdot E \cdot \{\frac{1}{2} \cdot \underline{\alpha}^2\}$$

$$E_{energy}(f) = \rho \cdot g \cdot E(f)$$

Units in:

$E(f)=[m^2\ s]$ or $[m^2/Hz]$

The 1D spectrum describes large number of waves in the time/frequency domain

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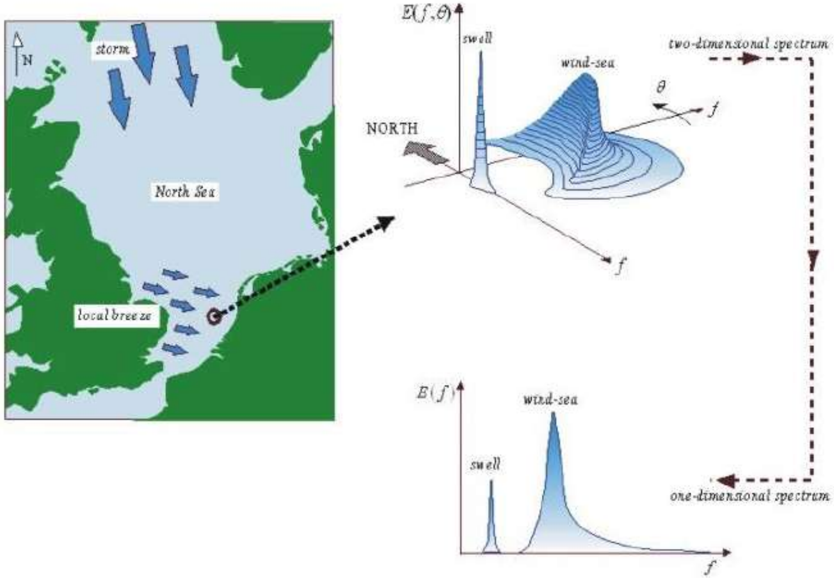
2D spectrum



$$E(f,\theta) = \lim_{\Delta f \to 0} \lim_{\Delta\theta \to 0} \frac{1}{\Delta f \Delta\theta} E\{\frac{1}{2}\underline{\alpha}^2\}$$

$E(f)=[m^2/Hz/rad]$ or $[m^2/Hz/deg]$

Description of spectral for real waves

Wave Energy Spectra

- Wind generated waves are random
- Superposition of larger number of waves
- Waves is described according to amplitudes and energy variance
- Some variations of spectra exist

Spectra (Empirical)

- Pierson-Moskowitz (PM)
- Joint North Sea Wave Project (JONSWAP)
- Other empirical formulations

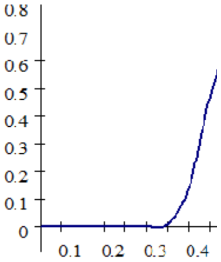
Ocean spectra of real waves provide realistic descriptions.

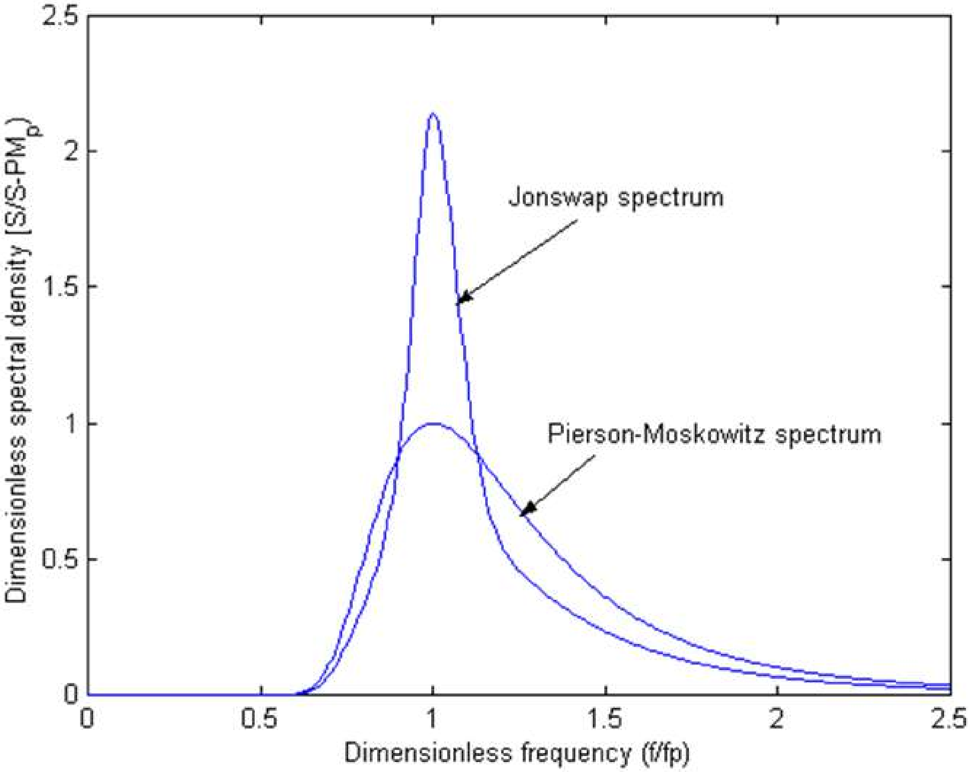
Major consideration is that wind acts as the generating and propagating force

Spectra

Pierson-Moskowitz (PM

JONSWAP





$$E(f,\theta) = \alpha_{PM} \cdot g$$

$$f_m = \frac{\nu_{19.5}^{PM} g}{U_{19.5}}$$

$$\sigma_{peak,param} = \{ \sigma_\beta \quad f > f_m$$

Complexities

Waves do not just propagate and increase their energy, environmental interactions that reduce energy content and shift to higher frequencies.

Reasons:

- Quadruplets
- Triad interactions
- Whitecapping
- Dissipation Terms
- Shallow water mechanics
- Current & Tidal Components

and more intricate based on local environment (but with less importance)

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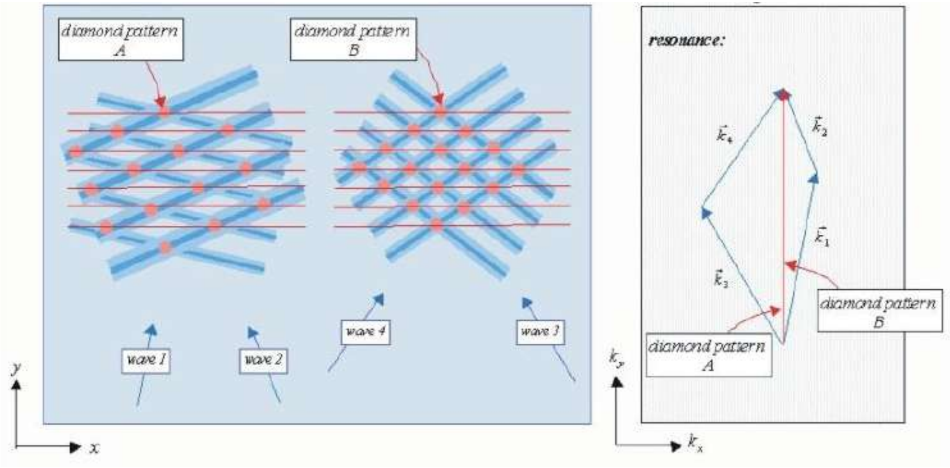
Non-Linear for Deep water (Quadruplet)

i. Effective frequency (re-) distribution
ii. Interactions between four wave numbers
iii. Effective **ONLY** when resonance condition are met →
iv. Always Energy is balanced at the end

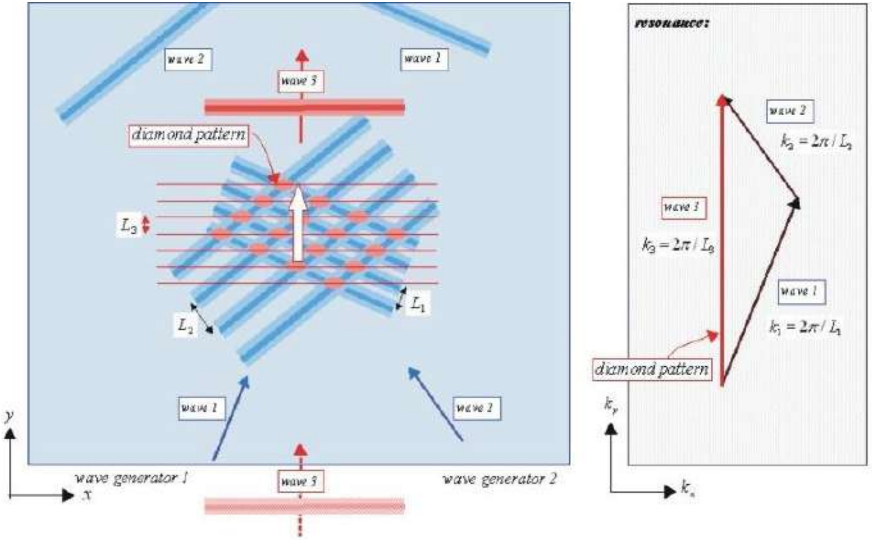
$$\kappa_1 + \kappa_2 = \kappa_3 + \kappa_4$$
$$\omega_1 + \omega_2 = \omega_3 + \omega_4$$



Non-Linear for Shallow (Triads)

i. Effective frequency (re-)distribution
ii. Interactions between three waves
iii. Nearshore & mid-depth waters
iv. Final Energy is balanced, again !

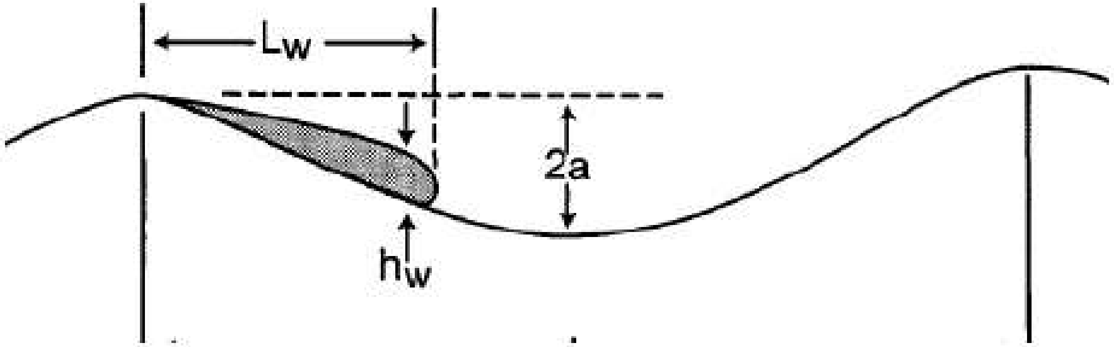
$$\kappa_{tr,1} + \kappa_{tr,2} = \kappa_{tr,3}$$
$$f_{tr,1} + f_{tr,2} = f_{tr,3}$$
$$\beta_{tr1,2} = \phi_{tr,1} + \phi_{tr,2} - \phi_{tr,1+tr,2}$$



Whitecapping

Least understood of dissipation mechanisms.

It is only negative (loss) of energy.



Depth Effects

Bottom friction

- Effects of seabed on water column
- Negative effects
- Depends on seabed particles roughness
- Site specific
- Material specific

Depth breaking

- At shallow depth breaking is more often
- Cannot be predicted always
- Preferred to obtain by a ration of wave height-to-depth

$$\frac{H_{max}}{d} \approx 0.75$$

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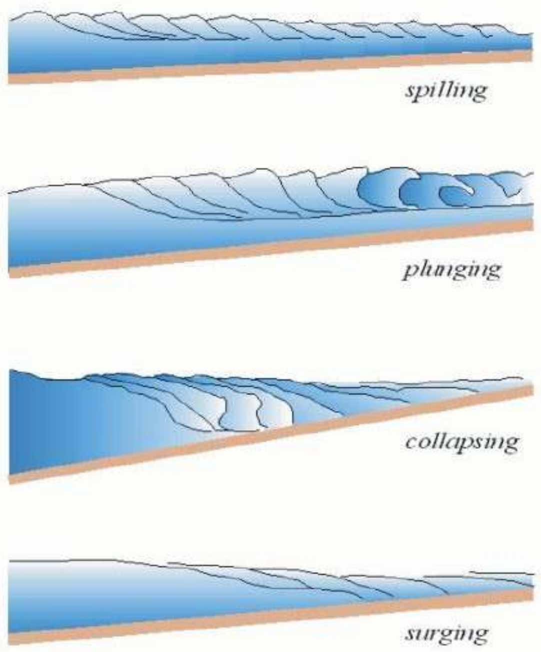
Depth Induced breaking (Depth Effects)

Depth induced breaking due to the reduction of bathymetry (shallow water)

$$\xi = \frac{\tan \cdot \alpha}{\sqrt{\frac{H_\infty}{L_\infty}}}$$



Breaking Waves

Spilling

$if\ \xi_\infty < 0.5\ or\ \xi_{br} < 0.4$

Plunging

$if\ 0.5 < \xi_\infty < 3.3\ or\ 0.4 < \xi_{br} < 2.0$

Collapsing/Surging

$if\ \xi_\infty > 3.3\ or\ \xi_{br} > 2.0$

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Near & Shallow waters

Shoaling & Reflection

- Phase speed = Group velocity
- Waves disperse less
- Waves will reflect on coastlines
- Pending on morphology (i.e. sloped, vertical etc.)
- Returning waves cause higher non-linear losses

Refraction & Diffraction

- Waves slowly change direction as they move ashore
- As in the case of other wave types (i.e. Snel's Law similarities)
- Long-crested waves prefer to propagate to lower energy region
- Waves **will** propagate to sheltered lower resource region

Dominant physical processes in nearshore environments and can affect the spectrum and directional components

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Tides & currents

- Local environmental characteristics also include, local wave current and tidal resources.
- Pending on region and resolution at which is observed, tidal & current effects can alter direction and reduce wave energy propagated.
- These consideration will depend on the level of study, and application
- Different approach to higher non-linear physical solution is needed

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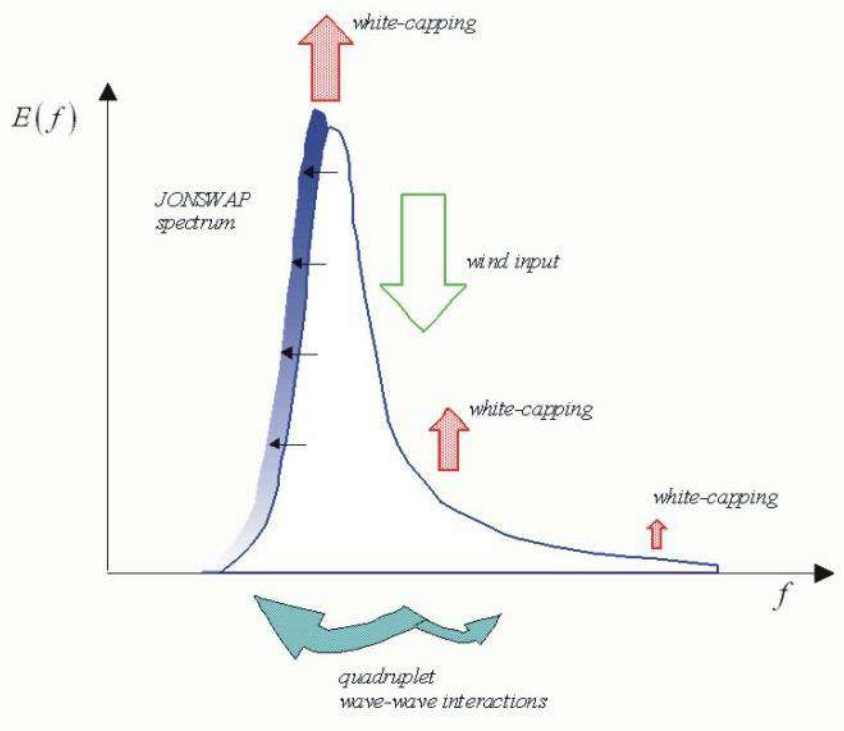
Final outcomes from generation & dissipation



Why data acquisition & monitoring ….

Applications

- Maritime
- Marine structures
- Offshore platforms
- M&O
- Offshore energies

More.....

Objectives

- Hindcasts
- Forecast studies (short/long & term)
- Climate Change

More ......

Methods

1. Buoys/ADCP
2. Ship observations
3. Satellites
4. Numerical Wave Models (NWM)

Buoys/ADCP

Limitations

- Area coverage
- Time recording duration
- Monitored quantities
- Dependence on moorings
- Breakdown events (non-recording)
- Filtering processes required




Ship Observation

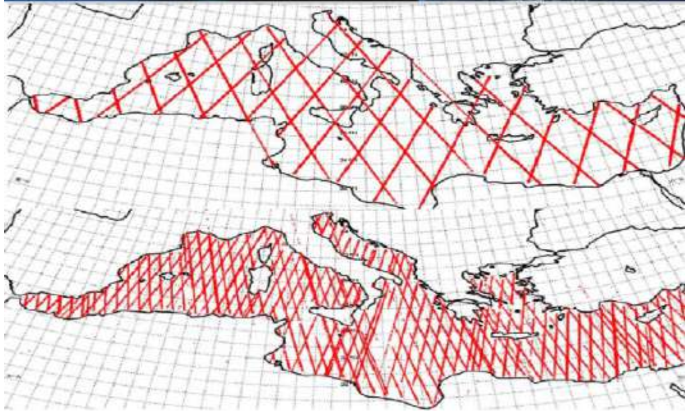
Limitations

- Requires experienced personnel
- Short duration-expedition
- Limited applicability

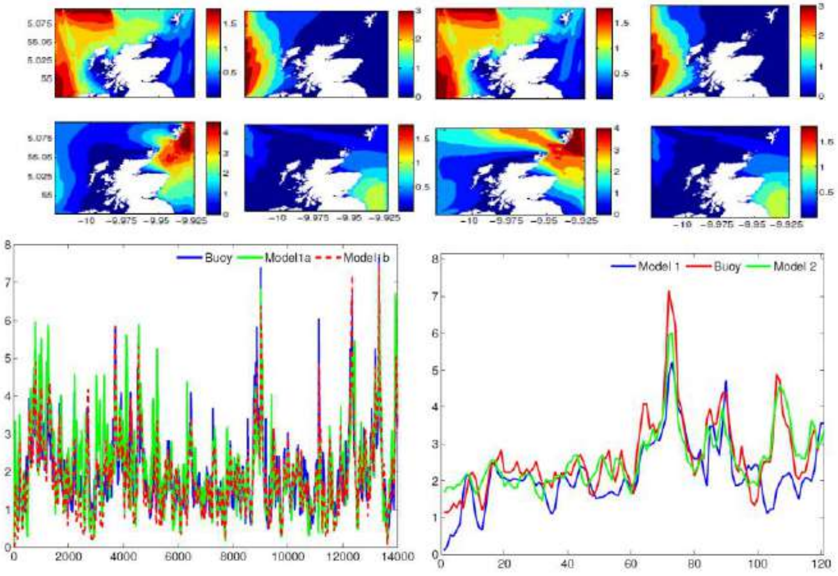
Satellites

Limitations

- Temporal recordings
- Coverage
- Applicability nearshore & coastal waters
- Filtering processes are necessary
- Not immediately available



Numerical Models



Limitations

- Inputs quality
- Physical calibration
- Need benchmarking
- Computational resources
- Experienced User
- High level of tuning

3. Wave Resources

Why is the wave resource important?

Short answer: It helps us with day-to-day operations

Long answer: It provides necessary information that can be expanded to many different sectors

- ✓ Naval, maritime (Commercial & Military)
- ✓ Weather forecasting
- ✓ Structures/platforms
- ✓ Ships
- ✓ Fisheries
- ✓ Climate Analysis
- ✓ Climate Change
- ✓ Energies
- ✓ ….

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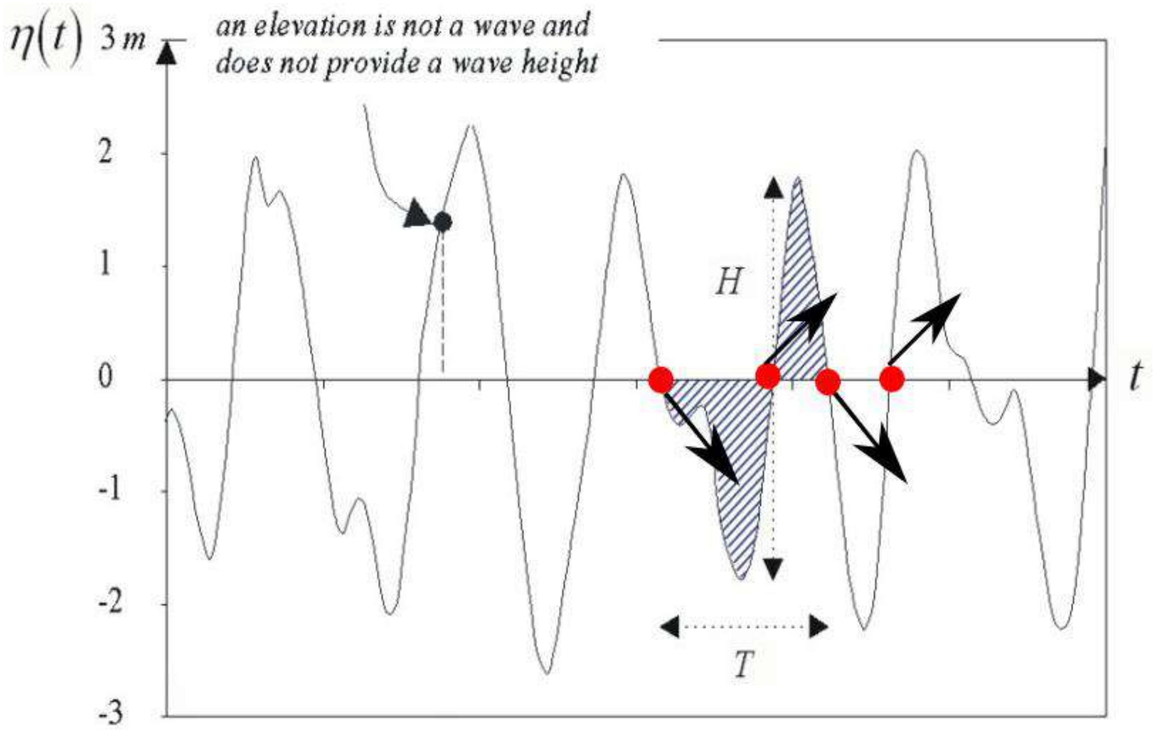
Metocean characteristics

A wave **is not** every surface elevation



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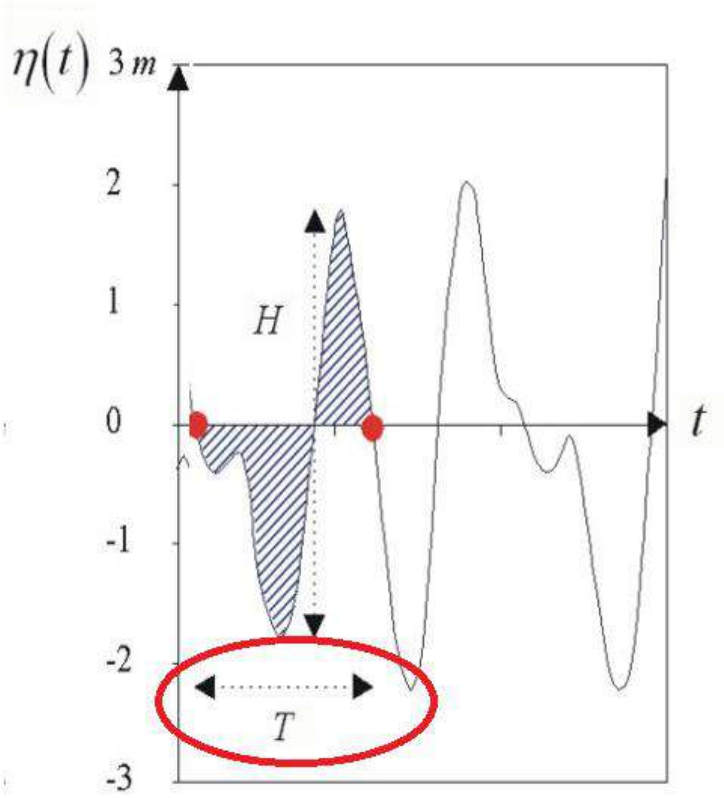
Height & Period(s)



Distribution(s)

Pending on the description desired, waves can be distinguished in two ways:

I. Weather

II. Climate

These two will ultimately use different approaches & outcomes: **Short-term & Long-term** Statistical analysis.

- For shorter periods changes are easily observed i.e. foreshores and shallow water waves.
- Local Characteristics have serious effects

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Short-Term Statistics

- ✓ 15-30 min or for a storm 6-12 hr
- ✓ Easily "accessible"
- ✓ Suitable short time intervals & storm
- ✓ Assume Gaussian and stationary
- ✓ Used analyse structures, fatigues and instantaneous characteristics
- ✓ Determine physical wave characteristics

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Long-Term Statistics

- ✓ Non-stationary
- ✓ Design condition for offshore & coastal structures
- ✓ For energy applications
- ✓ Climate analysis
- ✓ Difficult to obtain data
- ✓ No theoretical distribution model
- ✓ Requires preparation of dataset

Extreme Value Analysis (EVA) is useful in many sectors and very important for estimating survivability, applicable to the energy sector

Extreme Value Analysis (EVA)

Usually 20, 50, 100 years of return periods are investigated.

- ✓ Suitable method/empirical distributions need proper selection
- ✓ Access/Development and preparation of datasets
- ✓ "Goodness-of-Fit" assessment
- ✓ Estimation and determination of probabilities of exceedance that **may** occur in the future
- ✓ Awareness of extreme events and expected return values is vital to the design in offshore industries

Recommended duration > 10 years, ideally not less that 20% of the desired return period

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EVA requirements

- ✓ Extract long timeseries
- ✓ Ensure Identically Independent Distributed (i.i.d)
- ✓ Set threshold value appropriate selection (*u*)
- ✓ Filter i.i.d sample with threshold values
- ✓ EVA of new timeseries
- ✓ Selection of method
- ✓ Evaluation "goodness-of-fit"
- ✓ Return Period

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Applied EVA Theories

Depending on the nature of our analysis 2 extreme theories can be used.

Generalized Extreme Value (GEV) | Generalized Pareto Distribution (GPD)

$$P_r \cdot \{M_n\} = P_r \cdot \{X_1 \leq z, X_2 \leq z, \ldots\ldots, X_n \leq z\}$$
$$P_r \cdot \{M_n\} = P_r \{\{X_1 \leq z\} \cdot \{X_2 \leq z\} \cdot \ldots\ldots \cdot \{X_n \leq z\}\}$$
$$P_r \cdot \{M_n\} = \{F(z)\}^n$$

for example:

For H_{50} return of 10 years sample size are expressed as return value:

$$P_{H_{m0_N} \leq x_N} = 1 - \frac{1}{N}$$

An Introduction to Statistical modelling of extreme values (2001)" by Stuart Coles, Springer Series in Statistics

GEV

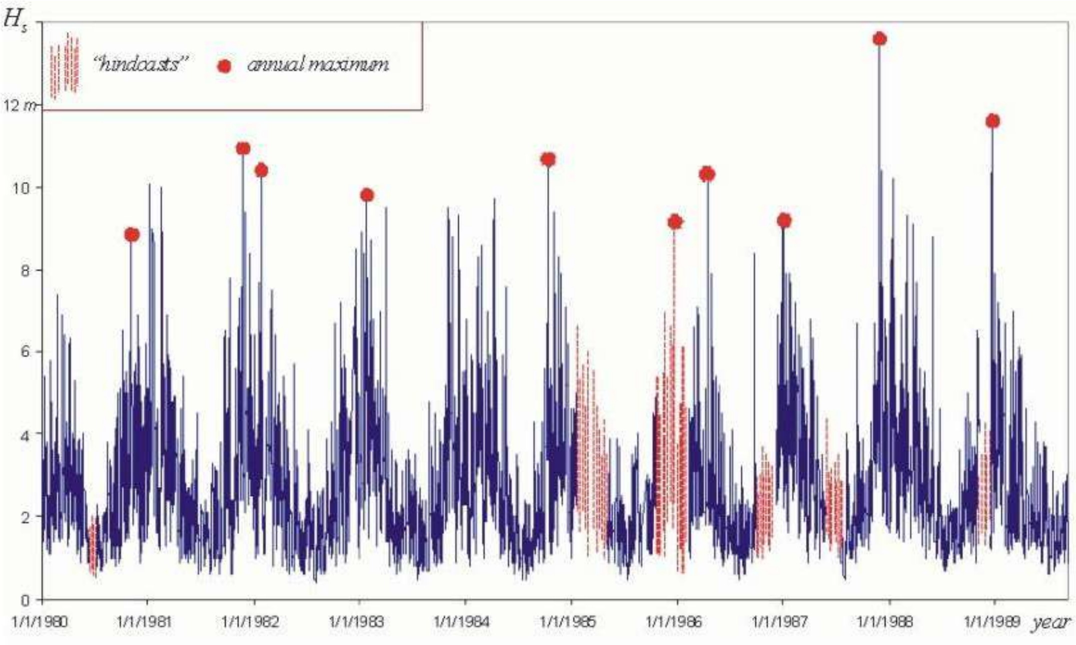
$$G\{z\} = \begin{cases} exp\left\{-\left[1+\xi\cdot\left(\frac{z-\mu}{\sigma}\right)\right]^{\frac{1}{\xi}}\right\} & \xi \neq 0 \\ exp\left\{-exp\cdot\left[-\left(\frac{z-\mu}{\sigma}\right)\right]\right\} & \xi = 0 \end{cases}$$

Pending of parameters **ξ, μ, σ** distributions are determined by:

$$\begin{cases} TypeI & \xi = 0 \\ TypeII & \xi > 0 \\ TypeIII & \xi < 0 \\ -\infty < \mu < \infty & \\ -\infty < \xi < \infty & \\ \sigma > 0 & \end{cases}$$

GEV & AMM

Usual method to filter/decluster dataset when using GEV is Annual Maxima Method (AMM).



Threshold is usually only **one** value, the annual maxima

GPD

Alternative developed to alleviate pitfalls from GEV.

$$F\{z\} = \begin{cases} 1-\left(1+\xi\cdot\frac{z}{\hat{\sigma}}\right)^{-\frac{1}{\xi}} & \xi \neq 0 \\ 1-exp\cdot\left(-\frac{z}{\hat{\sigma}}\right) & \xi = 0 \end{cases}$$

Pending on **ξ** from fitted data & thresholds

$$\begin{cases} TypeI & \xi = 0 \\ TypeII & \xi > 0 \\ TypeIII & \xi < 0 \\ z > 0, \hat{\sigma} > 0, \sigma > 0 & \\ \left(1+\xi\cdot\left(\frac{z}{\hat{\sigma}}\right)\right) > 0 & \end{cases}$$

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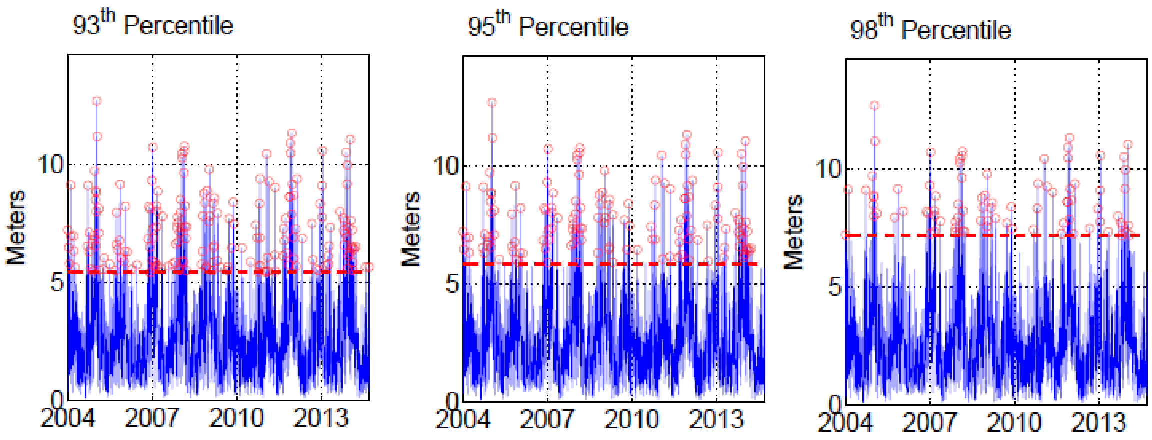
GPD & POT

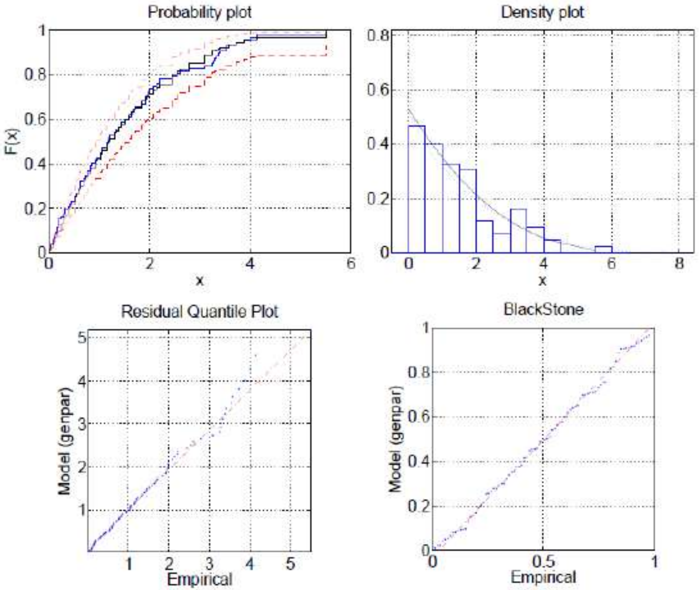


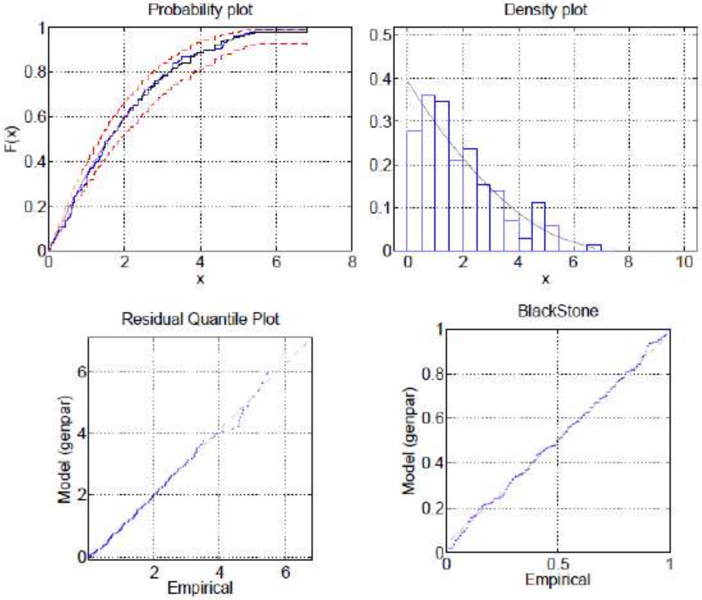
$$\lambda_u = \frac{k}{n_{years}}$$

Return period based on GPD

$$z_p = u + \frac{\hat{\sigma}}{\xi} \cdot \left[(N \cdot \lambda_u)^{\xi} - 1 \right]$$

Assessing the fits





Resource assessment

A resource assessment that is applicable over wide spatio-temporal conditions can be done (predominately in two ways):

- Satellite Data
- Numerical Wave Modelling

Preparation is Key!!

Depending on data produced or sampled filtering, clearing, modelling and set-up is vital. Usually to ensure proper assessment a numerical multi-model is the most suitable method.

- ✓ Wind Components
- ✓ Bathymetry information
- ✓ Constructing the model code
- ✓ Boundary conditions
- ✓ Initial conditions
- ✓ Determine time duration
- ✓ Determine parameters
- ✓ Nesting & Multi-model combination
- ✓ and many more intrinsic and project specific details.

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Numerical Modelling

Strengths	Weaknesses
Global and/or Local coverage	Experience of User
Computing Speed	Data for calibration, validation
Accuracy	Storage requirement
Historical data	Computing requirements
Forecast data	Tuning of physical properties
Results for multiple industries	Improvements for physical terms
Multiple nesting	Quality of inputs
Physical solutions of complex terms	
Timescale of results	
Tuning of physical properties	
Data Assimilation	
HPC multi-threading (computing)	
Opportunities	**Threats**
Data assimilation	User Experience
Multi-model communication	Instability of propagation schemes
HPC multi-threading (computing)	Allocation of computing resources
Quality of Inputs	Processes based on empirical formulations

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Distinction

	Oceanic waters	Coastal water		
Process		Shelf Seas	Nearshore	Shallow
Wind generation	■ ■ ■	■■	■■	□
Quadruplets	■ ■ ■	■ ■ ■	■	□
Whitecapping	■ ■ ■	■ ■ ■	■	□
Bottom Friction	□	■■	■ ■ ■	■
Depth breaking	□	■	■ ■ ■	■■
Currents	□	■	■■	■ ■ ■
Triads	□	■	■■	■
Reflection	□	□	■ ■ ■	■ ■ ■
Refraction	□	□	■ ■ ■	■ ■ ■

■ ■ ■=Dominant,■■=Significant,■=Minor,□ = Negligible

Action Balance Equation

The Action Balance Equation is applicable both on Cartesian & Spherical, with a full spectral non-stationary solution.

$$\frac{\partial N\cdot(\sigma;\lambda;\theta;t)}{\partial t}+\frac{\partial C_{g,\lambda}\cdot N\cdot(\sigma;\lambda;\theta;t)}{\partial\lambda}+\cos\phi^{-1}\cdot$$
$$\frac{\partial C_{f,\phi}N(\sigma;\lambda;\theta;t)}{\partial\phi}+\frac{\partial C_{f,\theta}\cdot N\cdot(\sigma;\lambda;\theta;t)}{\partial\theta}+$$
$$\frac{\partial C_{f,\sigma}\cdot N\cdot(\sigma;\lambda;\theta;t)}{\partial\sigma}=\frac{S\cdot(\sigma;\theta;\lambda;\varphi;t)}{\sigma}$$

radian frequency=(σ), time $=t$ solution, latitude$=\lambda$, longitude $=\varphi$, frequency$=\sigma$, direction$=\theta$, and group velocities $=C_g$ (for latitude & longitude)

Sink terms

Wave theory and its translation into a working numerical model is presented in terms of the action density balance equation, with an overview of the physics and their importance in the resource analysis (per regional applicability)

$$S_{tot} = S_{in} + S_{nl4} + S_{ds,w} + S_{nl3} + S_{ds,b} + S_{ds,br} + S_{xx}$$

Deep water
S_{in}=Wind Input
S_{nl4}=Quadruplet Interactions
$S_{ds,w}$=Whitecapping

Nearshore/Shallow
S_{nl3}=Triad Interactions
$S_{ds,b}$=Bottom Friction
$S_{ds,br}$=Depth Breaking
S_{xx}=user defined

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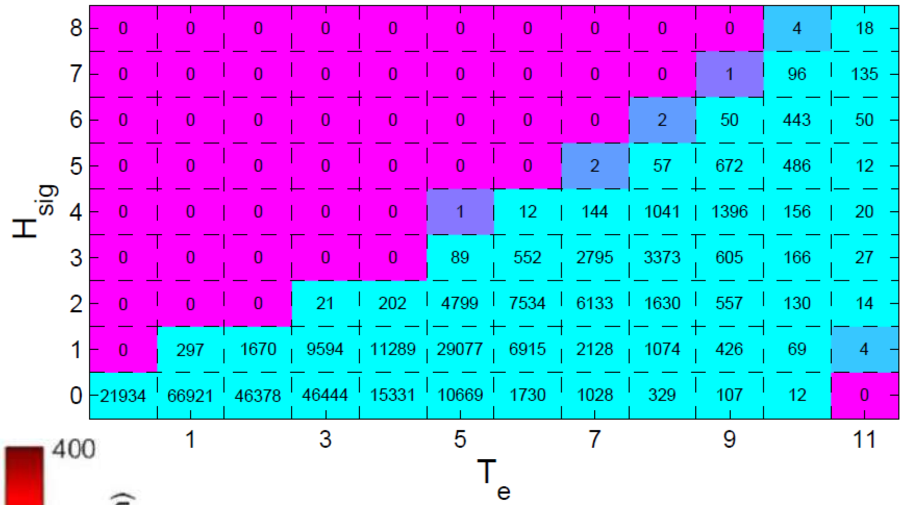
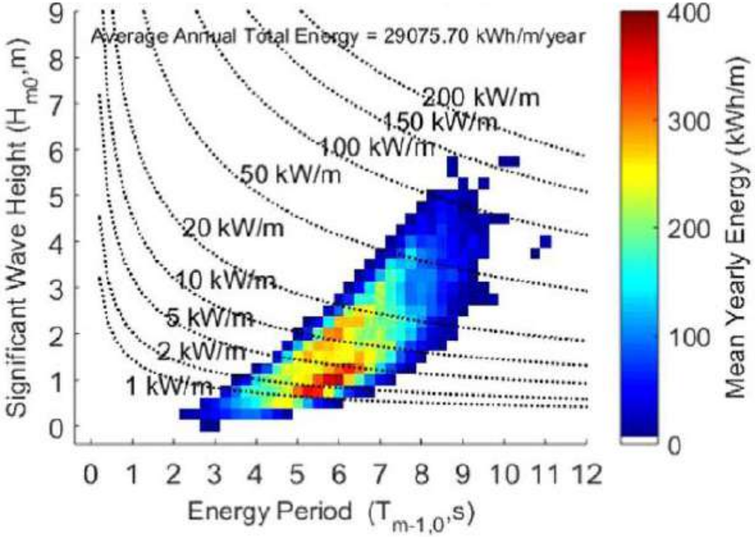
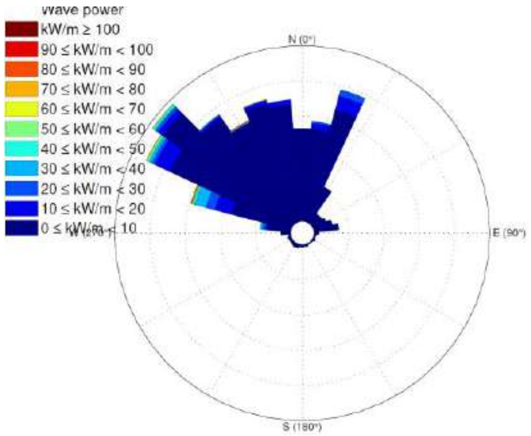
Presenting the Data

1 . Location

- Bivariate distributions
- Wind & Wave roses
- Polar Diagrams
- Spectral conditions

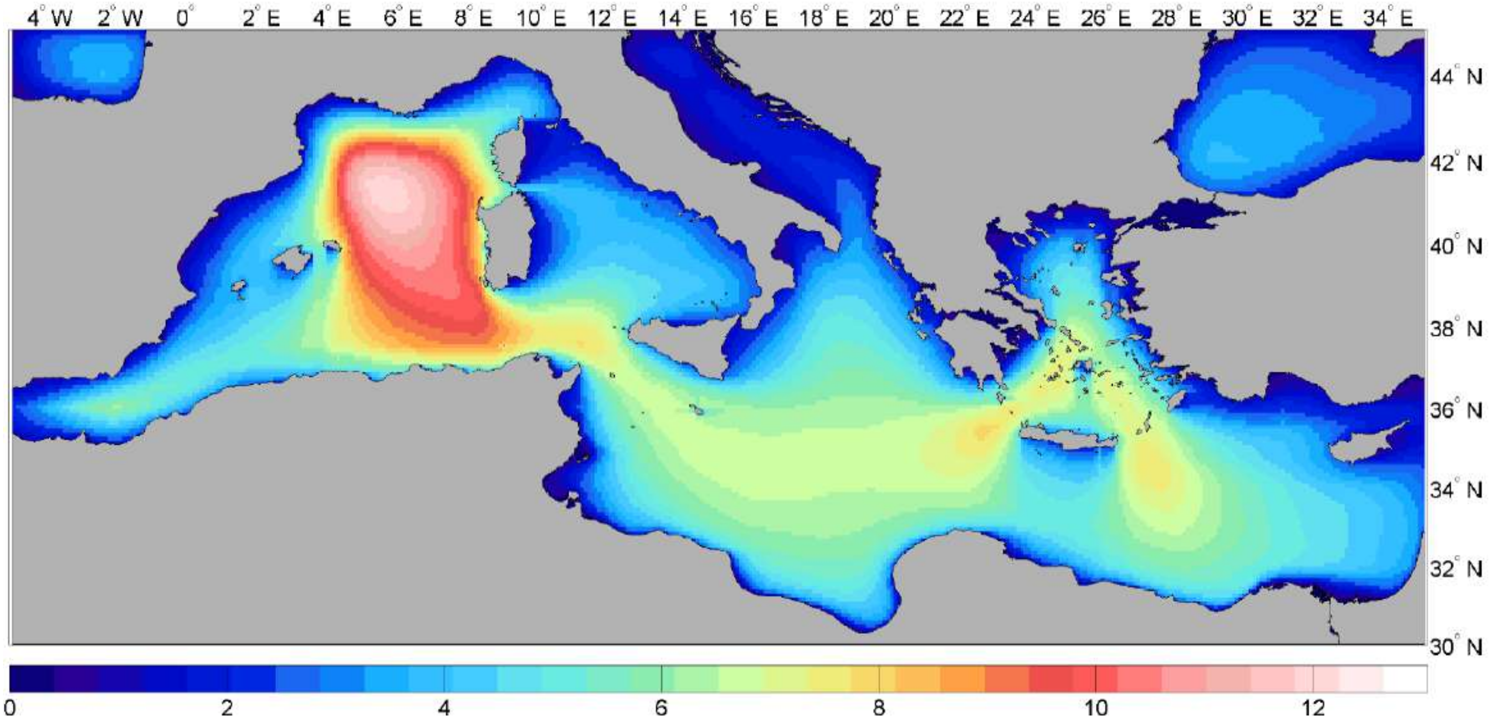






Presenting the Data

2. Spatial (Maps)



Presenting the Data

<table>
<tr><th>Annual</th><th>Seasonal</th><th>Monthly</th><th>Daily</th></tr>
<tr><td colspan="3">Resource Assessment (Intra–Annual, Decadal, Seasonal)</td><td>Hourly Variability</td></tr>
<tr><td colspan="3">Variability Analysis (Intra–Annual, Decadal, Seasonal)</td><td>Neural Networks</td></tr>
<tr><td colspan="3">Mean Values</td><td>Instant variations (i.e. over seconds)</td></tr>
<tr><td colspan="3">Maximum Values</td><td>Power Quality</td></tr>
<tr><td colspan="3">High percentiles ($99^{th}, 95^{th}$) Values</td><td></td></tr>
<tr><td colspan="3">Dominant MetOcean Conditions</td><td></td></tr>
<tr><td colspan="3">Coefficient of Variation (CoV)</td><td></td></tr>
<tr><td colspan="3">Wave Energy Development Index (WEDI)</td><td></td></tr>
<tr><td colspan="3">Availability</td><td></td></tr>
<tr><td colspan="3">Accessibility</td><td></td></tr>
<tr><td colspan="3">Climate Persistence</td><td></td></tr>
<tr><td colspan="3">EVA</td><td></td></tr>
<tr><td colspan="3">Skewness, Distribution Statistics</td><td></td></tr>
<tr><td colspan="4">Resource Cross-Correlation</td></tr>
<tr><td colspan="4">Overlap of Production (multiple windows)</td></tr>
</table>

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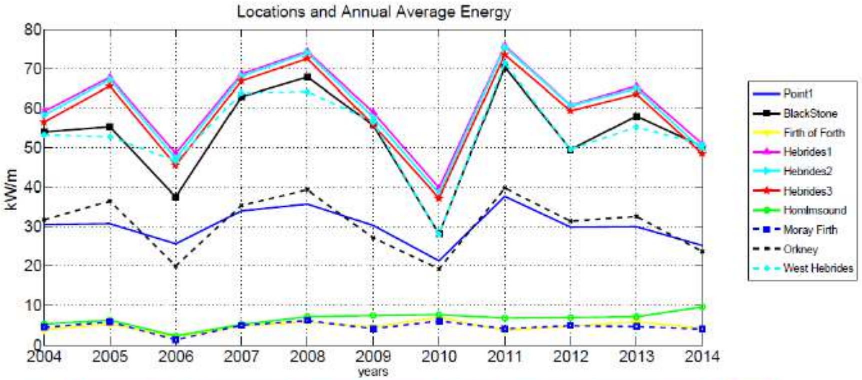
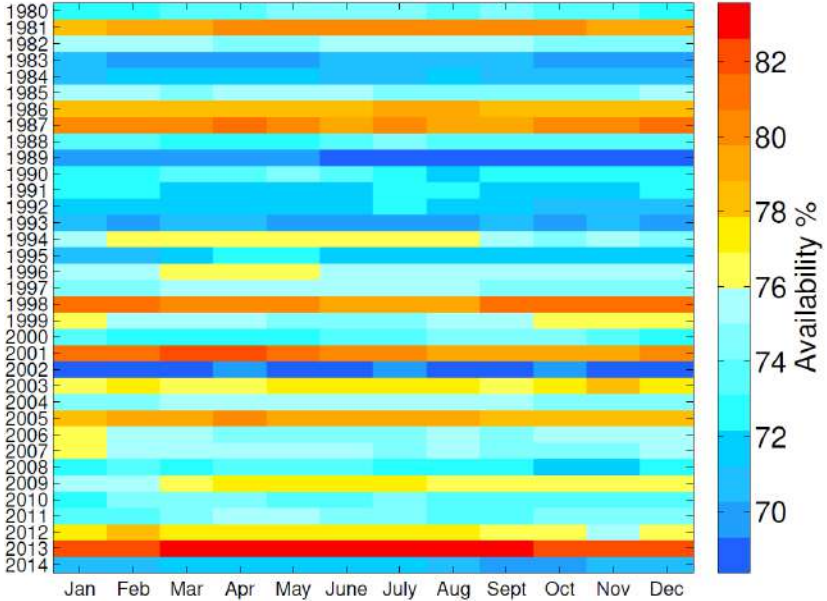
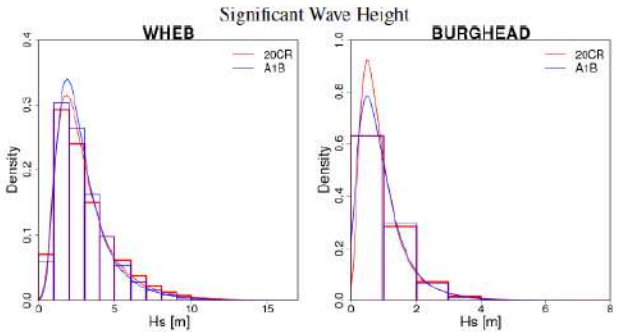
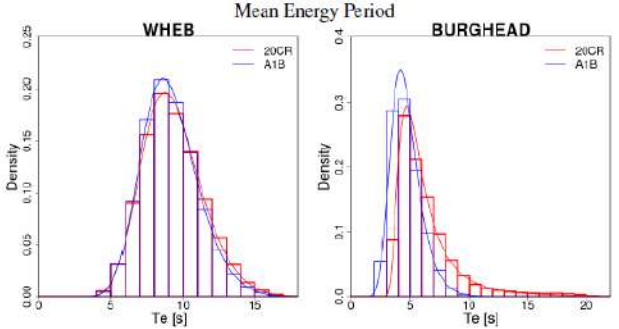
Location Analysis









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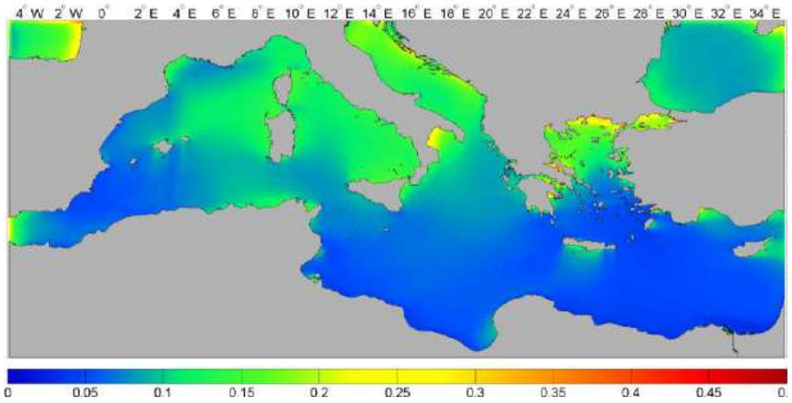
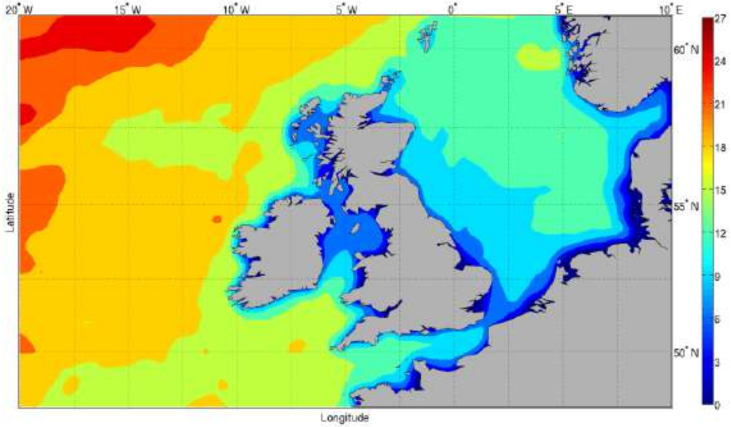
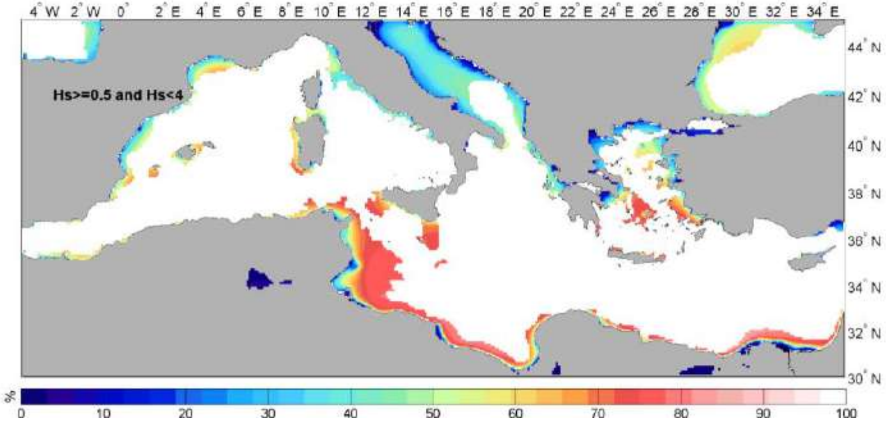
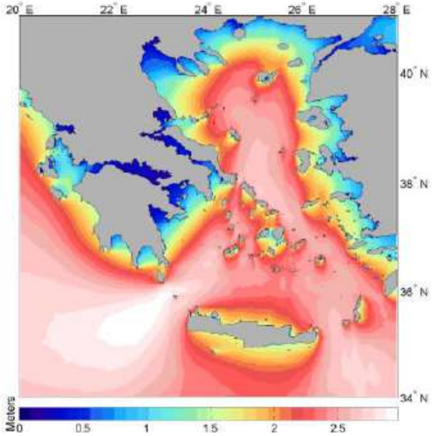
Spatial Analysis









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Thank you very much for your attention !

If interested and would like more information:

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