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EGU Outstanding Student Poster & PICO Contest

Investigation of the stochastic structure of wind waves for energy production

European Geosciences Union General Assembly 2019, 7-12 April, 2019 Vienna, Austria

HS5.3.1/ERE2.8 : Advances in modeling and control of environmental systems: from drainage and irrigation to hybrid energy generation (co-organized)

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We gratefully acknowledge ATTIKO METRO S.A. for sponsoring the printing of the poster.

1. Introduction

Nowadays, we are all becoming aware of that our society depends entirely on energy. As the fossil fuels tend to run out and there are concerns about global warming, air pollution and acid precipitation, we must turn to renewable energy sources with minimal environmental impacts. One of the most promising renewable energy resources is ocean with an enormous energy potential.

At this research we examine three possible areas that could generate wave energy. We analyze several wind-wave timeseries mostly close to shore, which are located (1) in the Northern Adriatic Sea with almost 40 years of 3-hour resolution of recorded wave heights and frequencies, (2) in Bowen, Queensland, Northern Australia with 23 years of 3 hours resolution (wave heights/periods) and (3) in Western Gulf of Alaska with 27 years of 1-hour resolution (wave heights/periods). We estimate marginal seasonal properties, as well as second-order dependence structures in terms of the climacogram (i.e. variance of the averaged process vs. scale) that is shown to be advantageous as compared to more traditional stochastic tools such as the autocovariance.

Finally, we propose a stochastic model that can adequately simulate the observed variability of time-series in state and scale and we also recommend technologies for each area.

2. Aim of the study

For hundreds of years we have relied on burning fossil fuels to generate energy. The use of fossil fuels such as oil and natural gas can congest air and water pollution, damage to public health and global warming emissions. Furthermore, fossil fuels will deplete one day and we must turn to renewable energy sources which are friendlier to the environment and to the human being. One of the most important potential sources of energy is ocean. Oceans cover more than 70% of earth surfaces, thus, they are infinite energy sources.

Ocean energy has many advantages, one of which is that it uses only the wave energy and does not produce greenhouses gases or other pollutants. Thus, it could be the key to limit the greenhouse gas emissions. Additionally, the highest wave energy is observed in winter and it is synergistically affected with solar energy which is maximum at summer, one of the reasons why it can be a very good alternative solution for remote islands, where is very expensive to operate power plants.

Why?

3. Data Acquisition

Gulf of Venice (AAOT)

Abbot Point, Bowen, Queensland

Gulf of Alaska (NOAA)

➢ **Specifications**

1. *Gulf of Venice:* "Acqua Alta" Oceanographic Research Tower (AAOT) Northern Adriatic Sea. Data from 1/1/1979 to 31/12/2017.
2. *Abbot Point:* Bowen, Queensland, Northeastern Australia. Data from 7/5/1977 to 28/6/2000.
3. *Gulf of Alaska:* Western Gulf of Alaska 175NM SE of Kodiak, AK (Station ID 46001, NOAA). Data from 12/10/1979 to 12/10/2006.

4. Statistical tools and modeling

Periodicities

$f(i) = a*\cos(\theta + \frac{i}{12}) + c$, for every harmonic fit.

$f(i) = a*\cos(\theta + \frac{i}{12} - \frac{\pi}{2}) + c$, only for fitting mean wave frequency per month for the data of the station at the Gulf of Venice.

Error functions

$\{1\}$ Error $= \Sigma|1-\frac{observed}{model}| * \Sigma\,|observed - model| * \Sigma|1-\frac{model}{observed}|$

$\{2\}$ Error $= \Sigma\,(observed\text{-}model)^2$

Climacogram

$$\gamma(k) = \frac{\lambda}{\left(1+\frac{k}{q}\right)^{2-2H}} \quad [a] \text{ , where}$$

$$\lambda = \left(1+\frac{1}{q}\right)^{2-2H}$$

Generalized Pareto Distribution

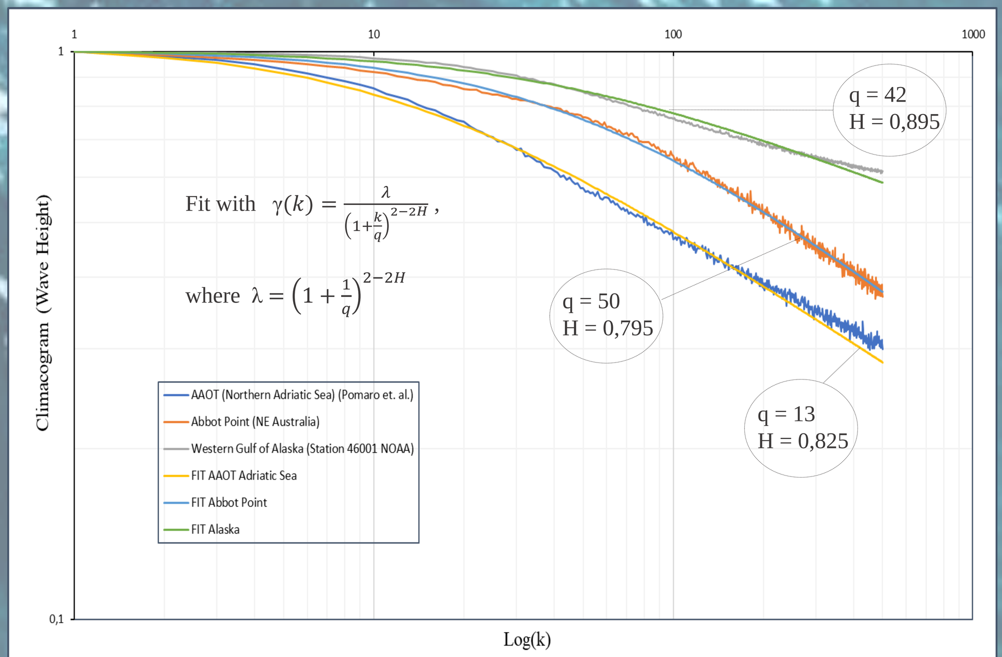
$$F(x) = 1 - \frac{1}{\left(1+\frac{x}{a}\right)^{b}}$$

➢ **Description**

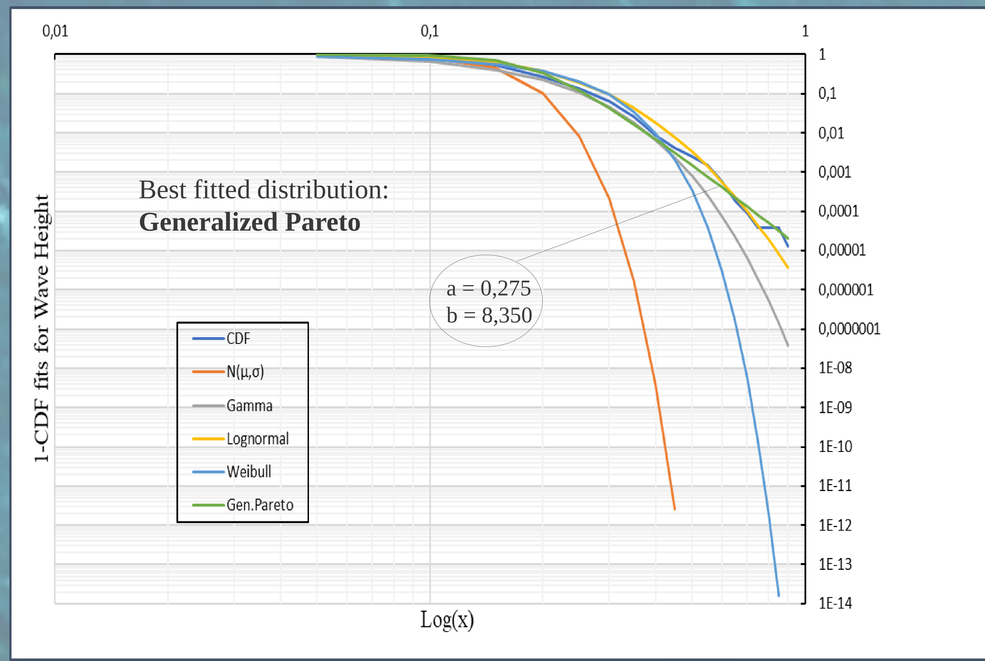
- We estimate the empirical climacogram for each timeserie for all years, fitting a combined Markov-HK model; see equation [a]. The climacogram has the smallest mean squared error and the smallest uncertainty, whilst it requires less operations and smaller storage space in a programming environment.
- Moreover, for the marginal distribution functions of wave height and frequency (or period), we check the Normal, Gamma, Lognormal, Weibull and Generalized Pareto distributions.
- We also apply a simple model of single periodicity for mean and standard deviation moments, where the process is assumed to be cyclostationary in seasonal scale. We use three dimensionless coefficients in the function f(i); a, θ, c, where all of them are constant for every month, while i describes the month number.
- Finally, it is vital to check the fitting distributions via error functions as mentioned above; equations {1} and {2}.

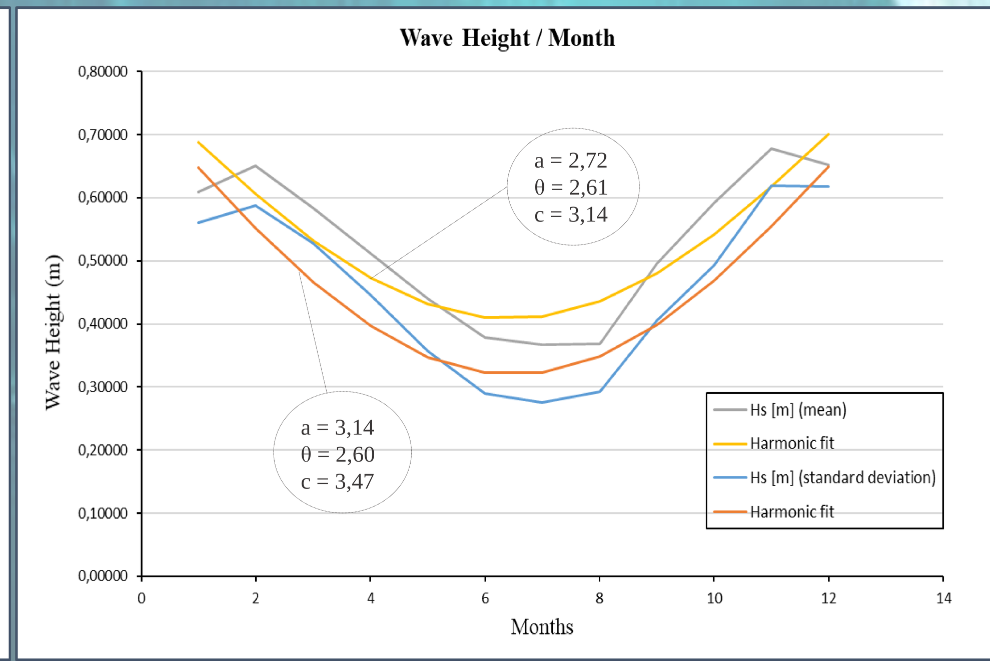
5. Results

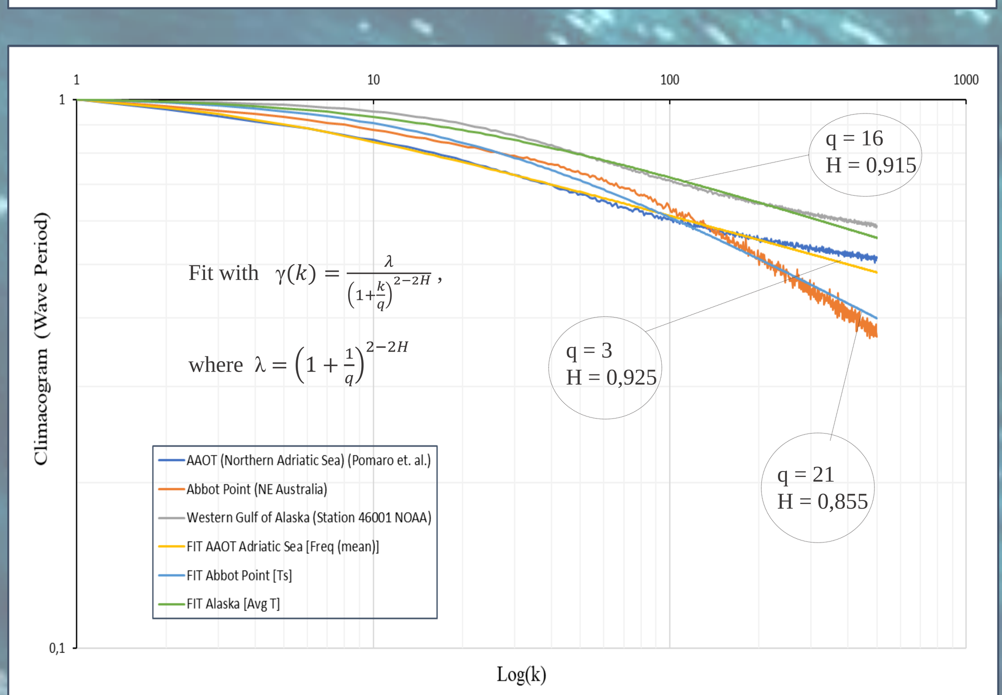
Climacograms (full time-series, three stations).

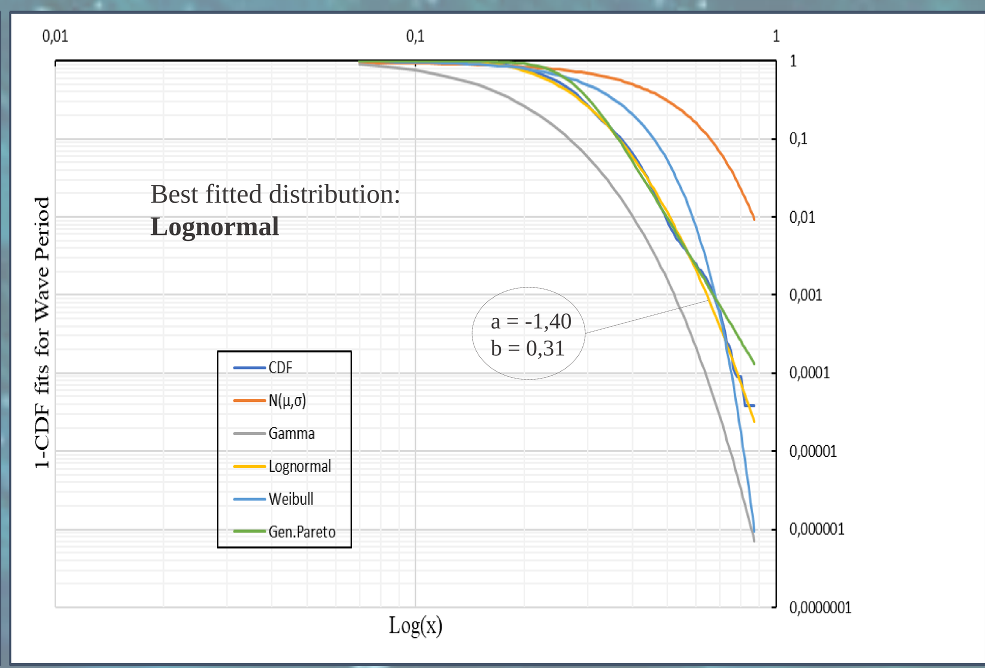


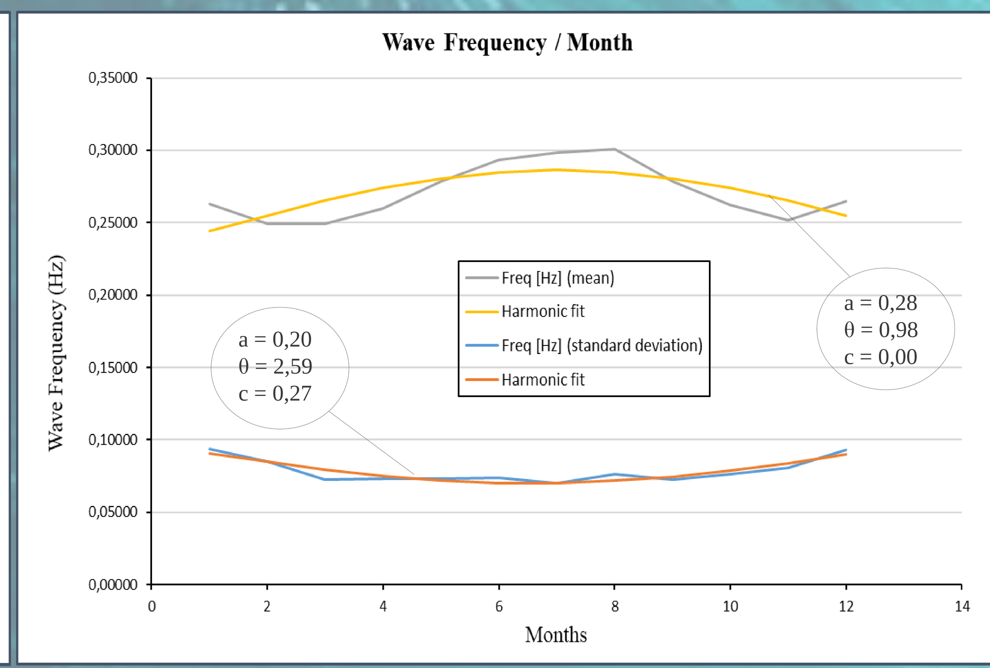
CDF tails and Periodicities (Station at the Gulf of Venice).











❖ **Comments**

The diagrams on the right show the climacograms of the wave height and period per station for the whole time-series, the tail of the cumulative distributions of the data from the station at the Gulf of Venice, as well as the seasonal first and second moments of the data from the same station to determine the periodicities. Additionally, fitted distributions are added with their parameters. Same analysis was conducted for the other two stations; the results are shown below.

Abbot Point, Bowen, Queensland, SE Australia

CDF tails: Best fitted distribution for both wave height and period seems to be the Generalized Pareto with the adequate parameters (a=0.6, b=6 for Hs and a=3.2, b=15 for Ts).

Periodicities: Harmonic fits for both wave height and period with the coefficients as follows: a=0.91, θ=2.48, c=1.44 for mean Hs, a=0.69, θ=2.56, c=0.93 for standard deviation of Hs, a=0.71, θ=2.33, c=3.86 for mean Ts, a=0.65, θ=2.53, c=1.07 for standard deviation of Ts.

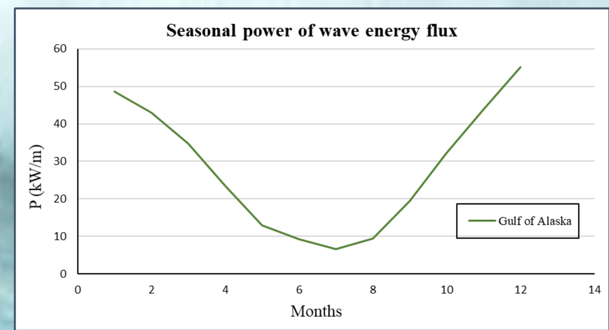
Station at the Western Gulf of Alaska

CDF tails: Best fitted distribution for both wave height and period seems to be the Lognormal with the adequate parameters (a=1.03, b=0.385 for Hs and a=1.9, b=0.175 for Ts).

Periodicities: Same as previously with: a=20.25, θ=2.60, c=22.18 for mean Hs, a=7.05, θ=2.60, c=7.92 for standard deviation of Hs, a=16.33, θ=2.58, c=22.37 for mean Ts, a=2.57, θ=2.56, c=3.52 for standard deviation of Ts.

We also calculate the seasonal power of the wave energy flux per meter of wave crest via the formula: $\mathbf{E}=\frac{\rho * g^2}{64*\pi} * H_s^2 * T_s$, where Hs and Ts are the mean values of wave height and period.

The results as shown below, depict higher power in winter and lower in summer, with the values from the Gulf of Alaska being much greater, due to the fact that the data were gathered from an offshore buoy in deep waters. Produced power from the Gulf of Venice and Abbot Point show similar values, yet a weaker variance of the latter.



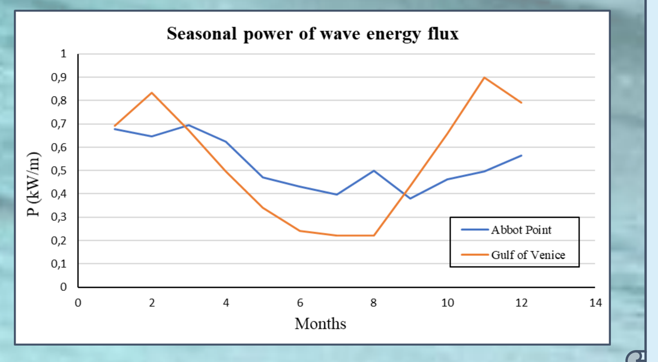
Despite the fact that the data nearshore show a low harvesting potential, we propose technologies for each location near the three stations, keeping also in mind the bathymetry.

Gulf of Venice and Abbot Point

The Archimedes Wave Swing (submerged pressure differential): The device is located nearshore and is fixed to the seabed. It has two main parts: a sea bed fixed air-filled cylindrical chamber with a moveable upper cylinder. The device works when the waves passing through it, while the level above the device rises and falls.

Gulf of Alaska

The Pelamis: A semi-submerged device composed of cylindrical sections linked by hinged joints. The device depends on the curvature of the waves and not on the wave height, thus, it produces electricity from the motion of them.



6. Conclusions

- ✓ The climacograms for every station are fitted with a combined Markov-HK model of well-defined parameters.
- ✓ The main distributions of fitting the CDFs are the Generalized Pareto and the Lognormal with adequate parameters as well.
- ✓ The analyzed data in seasonal scale follow a simple model of single periodicity with three well-defined coefficients in the harmonic functions, while the process is assumed to be cyclostationary.
- ✓ The energy potential is higher in winter than in summer; the wind is more intense during the winter period. Additionally, the energy production at Abbot Point is almost constant during the year, while the one at the Gulf of Alaska is much greater, due to the offshore location (higher wave heights and periods).

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Links: https://www.noaa.gov/ , https://data.qld.gov.au/ , https://www.itia.ntua.gr/en/