Challenger Society for Marine Science
Special Interest Group on Wind Waves
Meeting

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Linking the long-term change in wave energy to various wave parameters

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Motivation

↓

Methodology

↓

Results

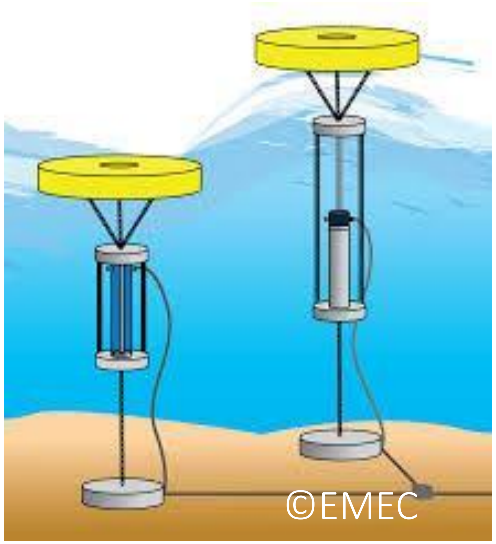
↓

Summary & Conclusion

Motivation

Advantages of Wave Energy:

- ✓ Predictable
- ✓ Endless
- ✓ High density
- ✓ Low visual and environmental impacts
- ✓ Broad geographic viability
- ✓ Adding to the diversity (+ co-location)



Usages:

- ✓ **Power generation**
- ✓ Desalination
- ✓ Hydrogen production
- ✓ Pumping and heating processes
- ✓ Coastal protection

Motivation

Wave farms contribute to mitigating climate change by two means:

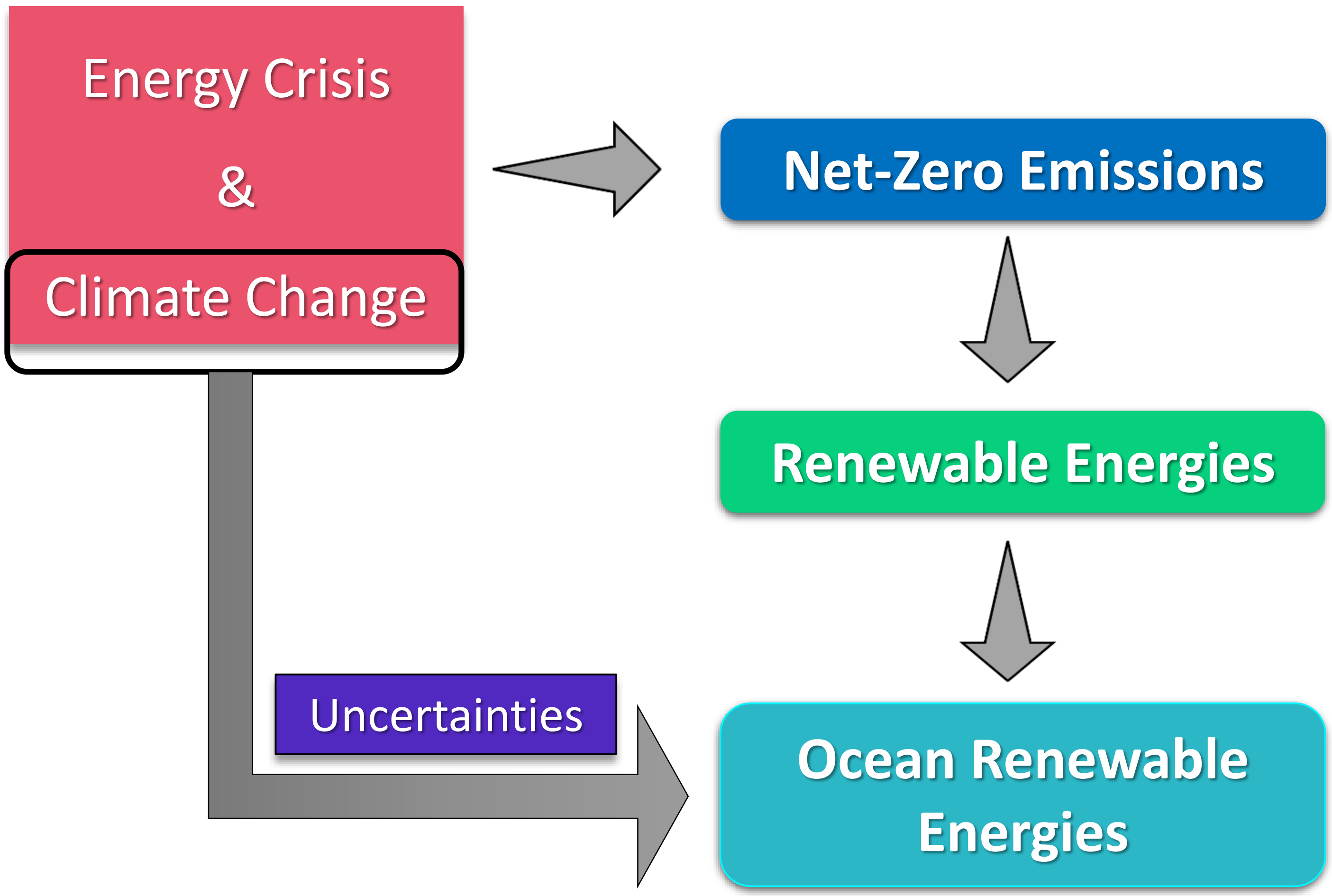
1) Cause: by bringing down carbon emission

2) Effect: By reducing coastal erosion (which has caused by sea level rise and increased storminess due to climate change)

Another major advantage: Adaptation!

Wave farms typically are floating structures → Adapt naturally to sea level rise

Motivation


Energy Crisis
&
Climate Change
Net-Zero Emissions
Renewable Energies
Uncertainties
Ocean Renewable Energies

Methodology

- **Goal:**
  - to investigate the link between the long-term change of wave power and different wave characteristics on a global scale.
  - To redefine the suitability of global coasts for wave energy extraction considering the long-term changes

- **Method:**
  - 60 years of modeled wave characteristics (1960-2019)
  - Model: Simulating WAves Nearshore (SWAN)
  - Wind input: re-analysis wind field (JRA-55: 60 km and 6 hours)
  - Bathymetry: GEBCO (30 arc-sec spatial resolution)

Methodology

Computational grid (global)

- Frequency domain: 0.03-1 Hz with 36 bins on a logarithmic scale
- Directional resolution of 10
- Spatial resolution:1 degree
- Computational time steps: 30 min

Outputs (global):

- Spatial resolution:1 degree
- Temporal resolution: 6 hours

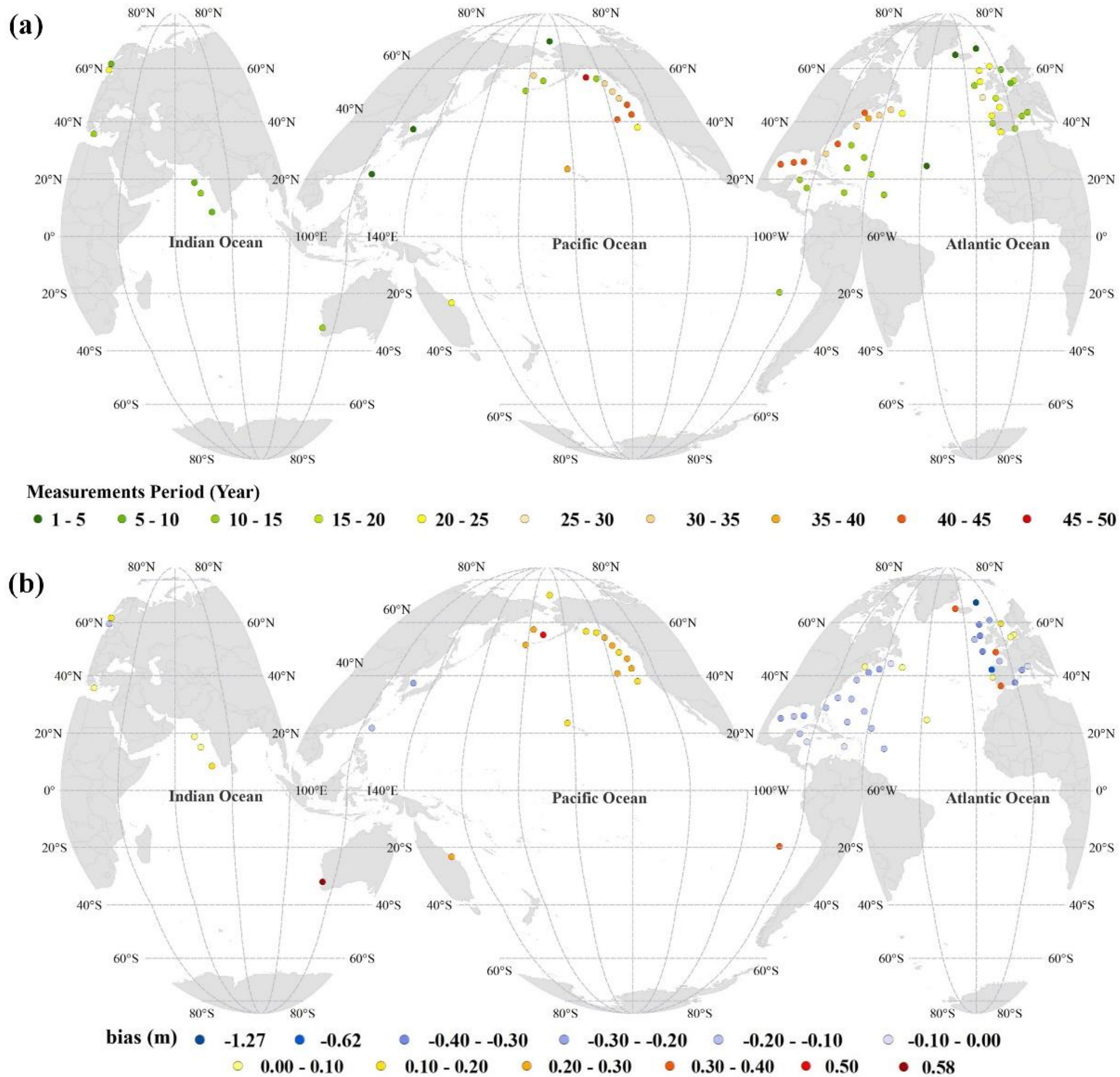
Wave power was calculated based on the deep water approximation formula:

($P \approx 0.49 \times H_s^2 \times T_e$)

Methodology

Validation:

Comparison with 64 buoys distributed around the world with various recording periods (1978-2019), obtained from Copernicus Marine Environment Monitoring Service (CMEMS)



Map of (a) wave measurement period at each buoy location and (b) the bias in for H_s.

Methodology

Validation:

$$RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i-M_i)^2} \qquad SI=\frac{RMSE}{\frac{1}{N}\sum_{i=1}^{N}M_i} \qquad bias=\sum_{i=1}^{N}\frac{1}{N}(P_i-M_i) \qquad Nbias=\frac{1}{\frac{1}{N}\sum_{i=1}^{N}(M_i)}\sum_{i=1}^{N}\frac{1}{N}(P_i-M_i)$$

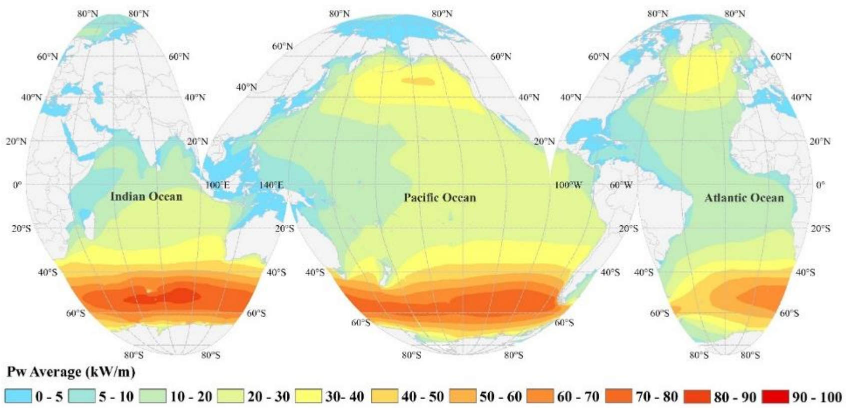
M_i is the measured value. P_i is the predicted value. N is the number of data.

Summary of error statistics in the estimated H_s and mean periods determined for 64 buoy locations

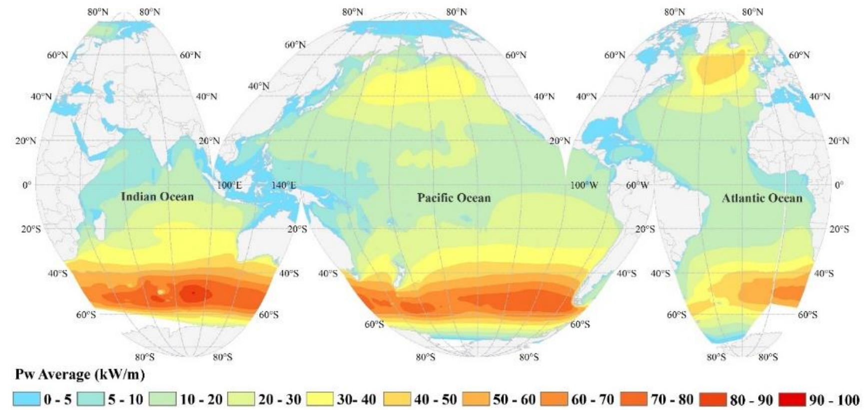
	H_s					T_{m02}					Distance from the closest grid point (°)
	R	SI	bias (m)	N.Bias	RMSE (m)	R	SI	bias (s)	N.Bias	RMSE (s)	
Lowest	0.81	0.17	0.02	-0.51	0.27	0.51	0.13	0.01	-0.41	0.69	0.00
Mean	0.89	0.29	0.22	-0.03	0.58	0.72	0.21	0.67	-0.08	1.24	0.40
Largest	0.95	0.46	-1.27	0.24	1.73	0.83	0.40	-2.59	0.11	3.12	0.69

Methodology

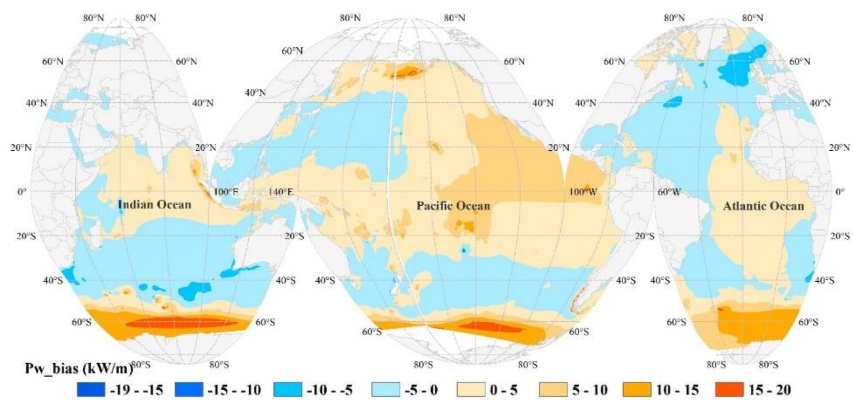
Validation:



Mean annual P (kW/m) , SWAN output



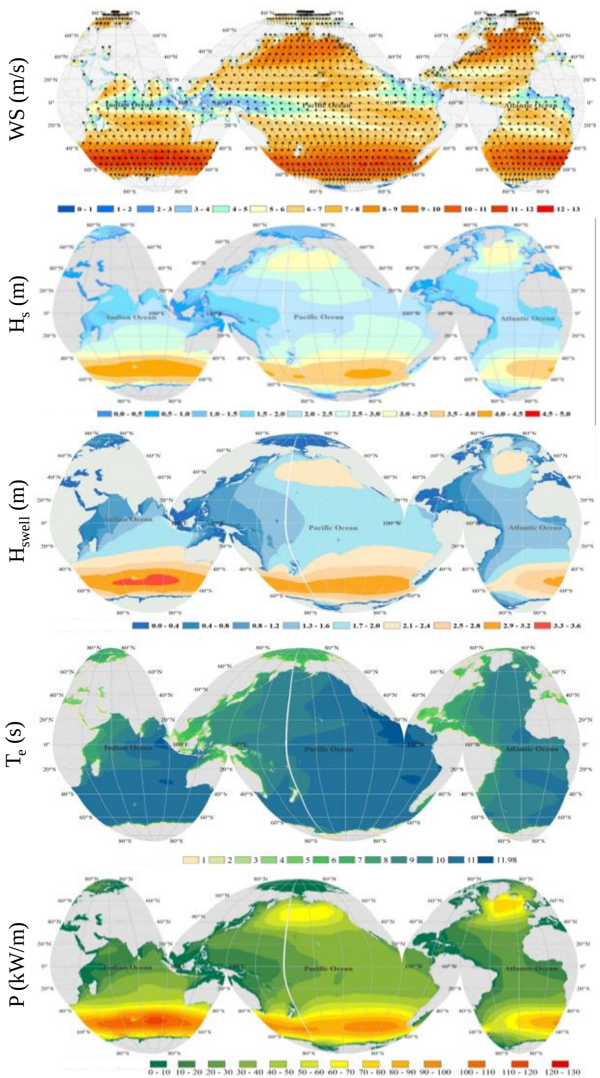
Mean annual P (kW/m), ERA-5



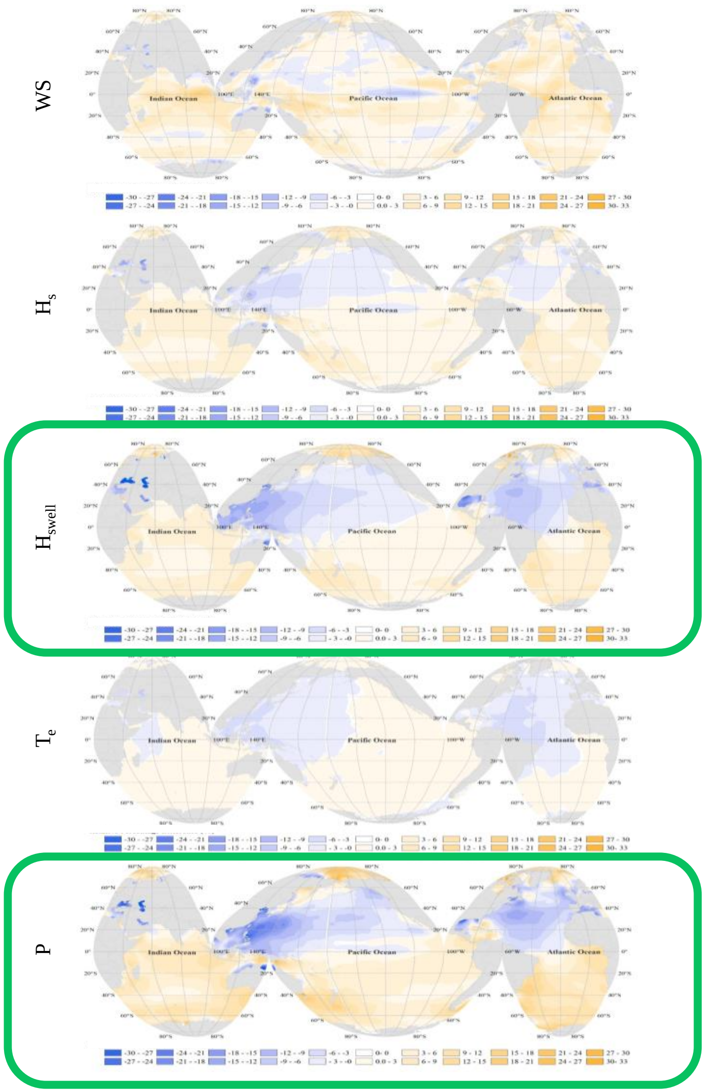
Bias (kW/m)

Results

Change in 30-yearly mean annual wind and wave (Per_1: 1960-1989, and Per_2: 1990-2019)



Annual mean values of different parameters in Per_1



Relative change of annual mean values of different parameters in Per_2 compared to Per_1 (%)

Results

Change in 30-yearly mean annual wind and wave (Per_1: 1960-1989, and Per_2: 1990-2019)

- It is essential to choose a suitable interval for wave energy resource assessment.
- Contrary to IEC's recommendation for a minimum of 10 years for wave energy assessment, we showed that even with longer-term (e.g., 30 years) wave energy assessment, the change of assessment period can lead to an over/under-estimation of around 25% in wave power.
- The change in wave power correlates follows the change in swell wave height rather than the significant wave height.

Results

Decadal variation of mean annual wind and wave characteristics

(a) Mean annual values in Dec_1,

relative change in mean annual values in

(b) Dec_2 compared to Dec_1,

(c) Dec_3 compared to Dec_2,

(d) Dec_4 compared to Dec_3,

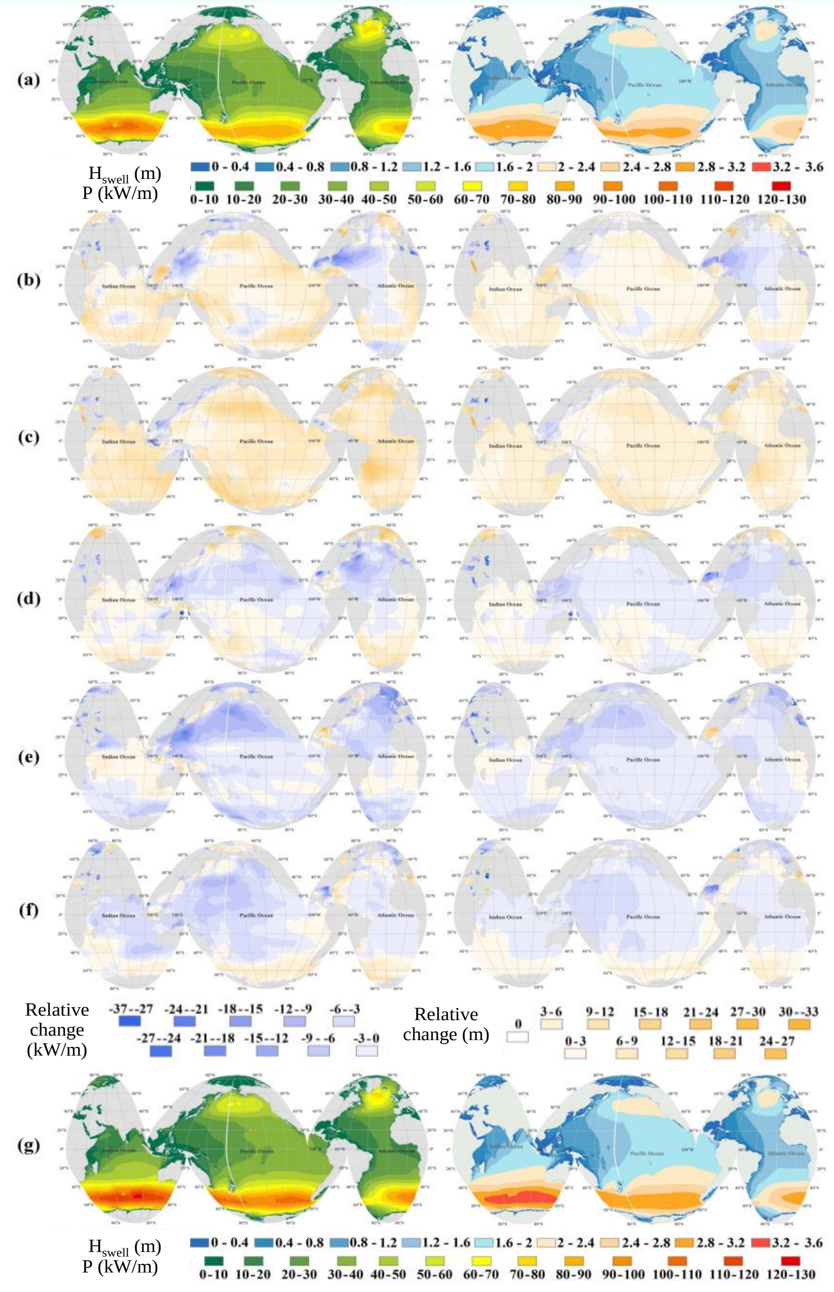
(e) Dec_5 compared to Dec_4,

(f) Dec_6 compared to Dec_5,

(g) Mean annual values in Dec_6.

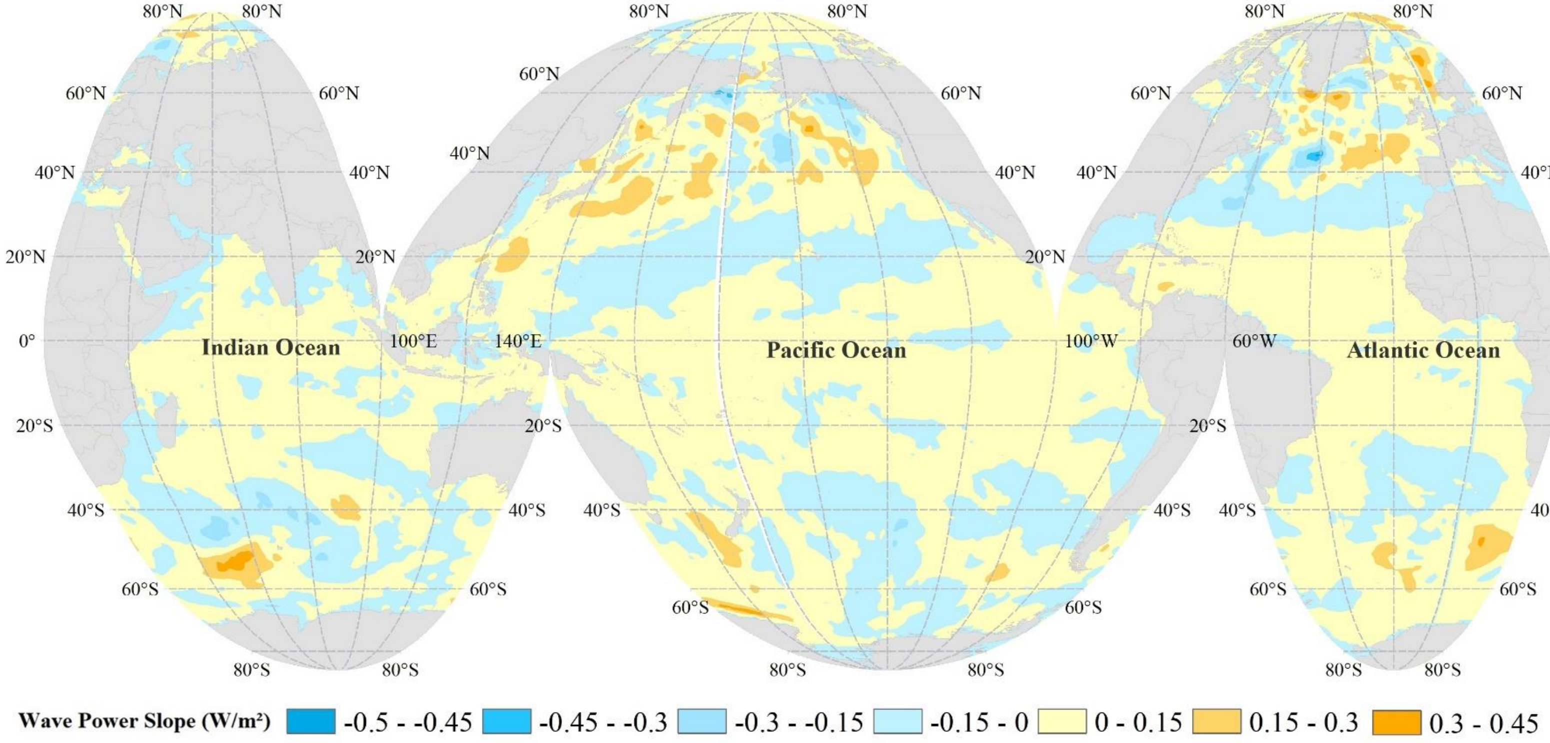
Left panel: P (mean values (a and g) in kW/m, relative changes in %).

Right panel: H_{swell} (mean values (a and g) in m, relative changes in %).



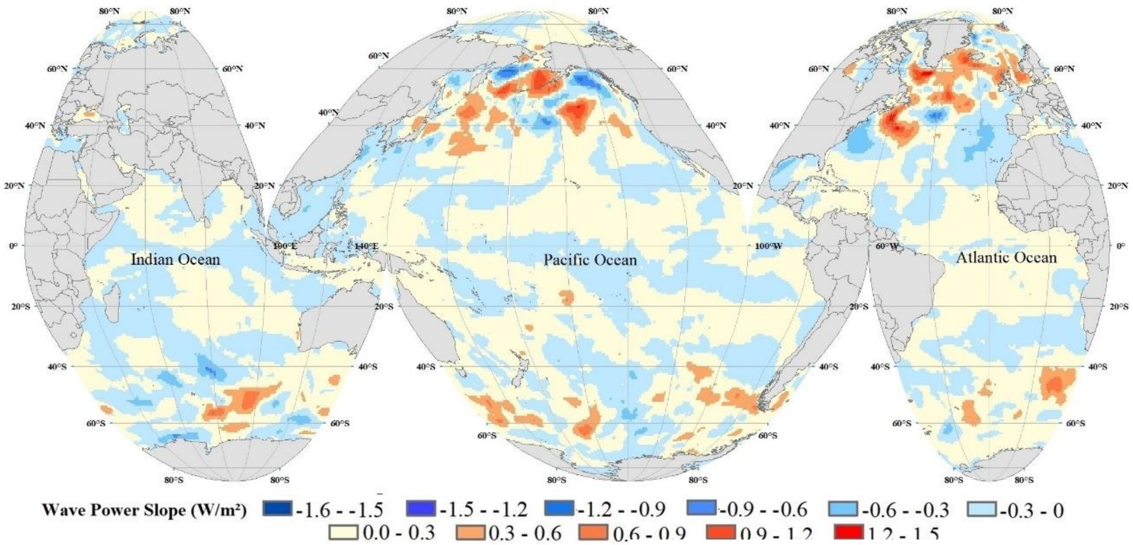
Results

Rate of Change (RoC), wave power (P): 60 yearly period

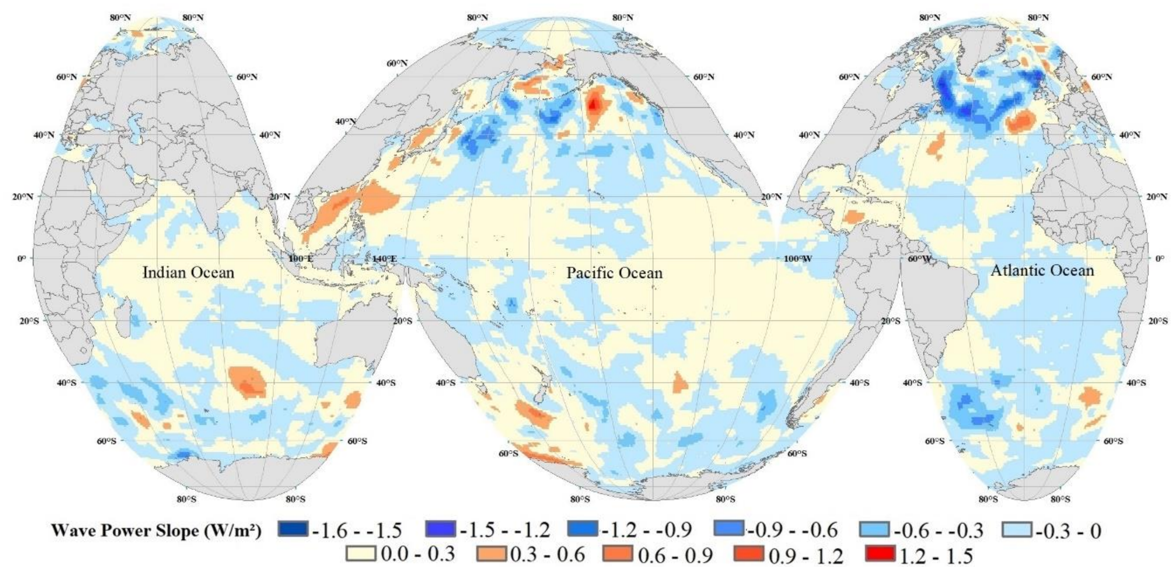


Results

Rate of Change (RoC), wave power (P): 30 yearly periods



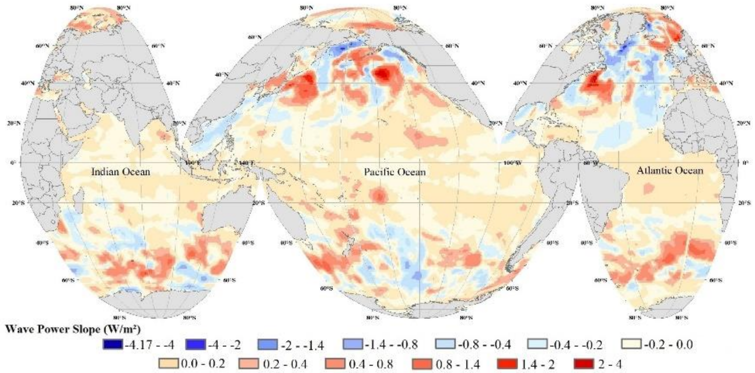
1960 - 1989



1990_2019

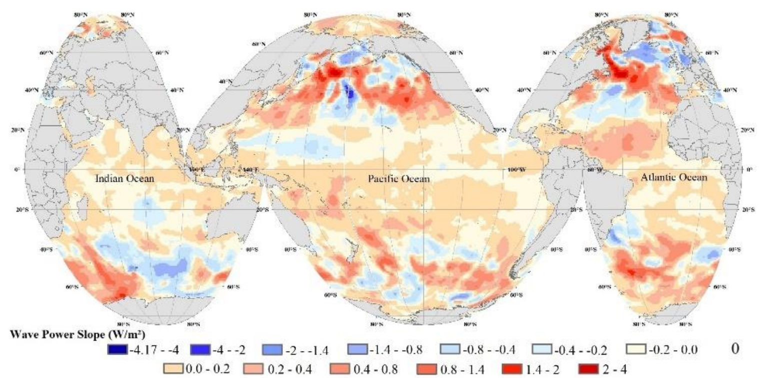
Results

Rate of Change (RoC), wave power (P): 20-yearly periods

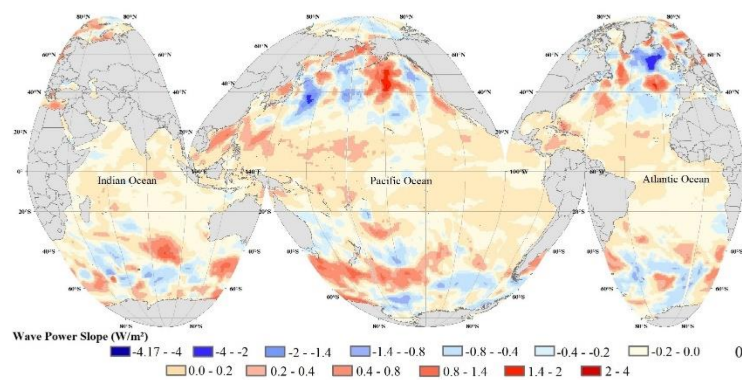


1960_1979

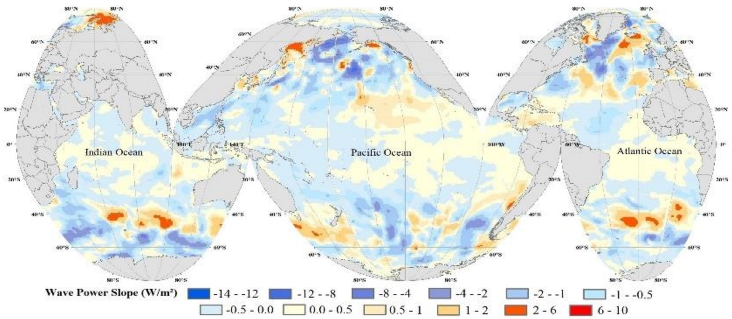
1980_1999



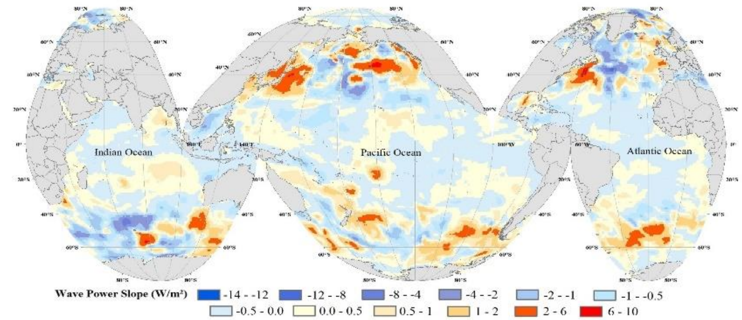
2000_2019



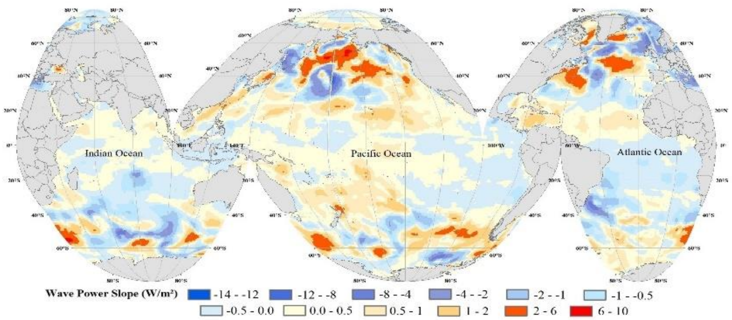
Rate of Change (RoC), wave power (P): 10-yearly periods



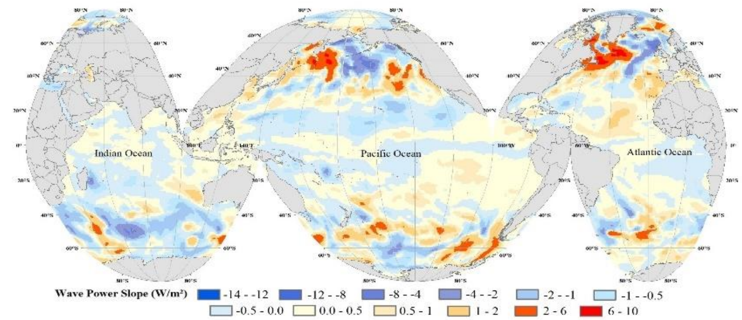
1960-1969



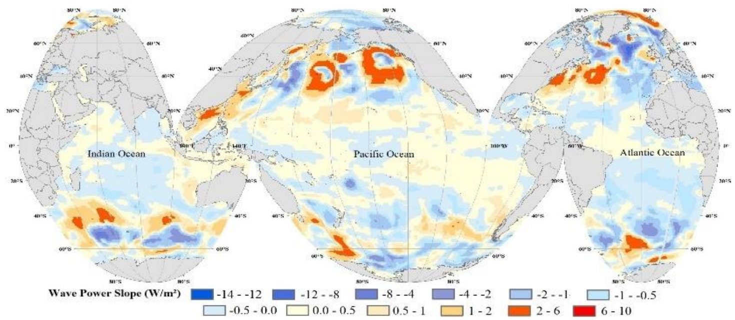
1970_1979



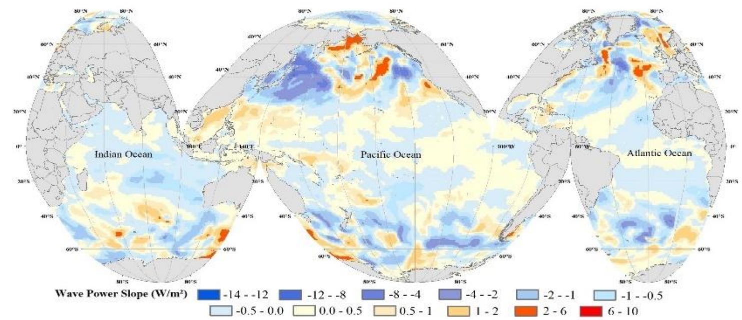
1980_1989



1990_1999



2000_2009



2010_2019

Results

Decadal variation of

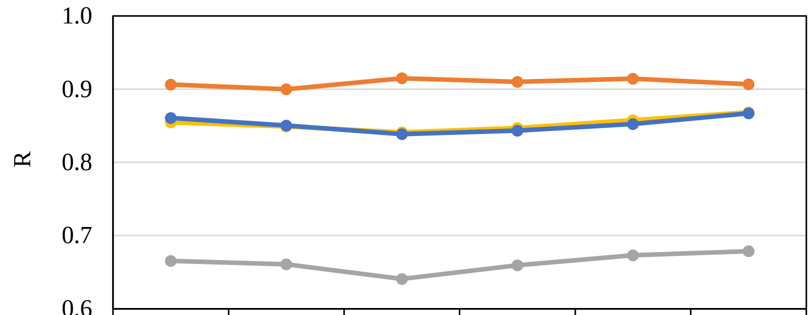
(a) correlation coefficient (R) of RoCs

(b) ratio of RoCs, for P and wind or wave parameters

(c) the average values

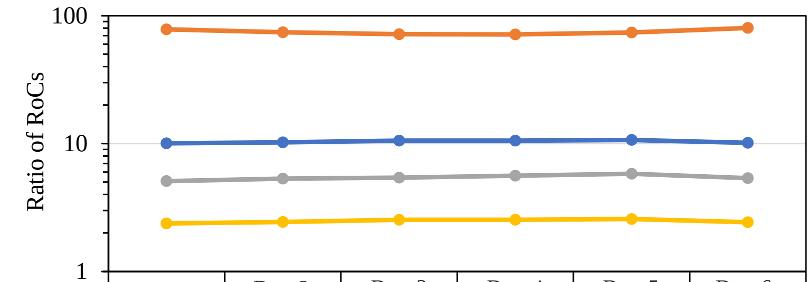
$$\text{Weighted arithmetic mean} = \frac{\sum_{i=1}^{i=6}(\text{Ratio of RoCs}_i \times R_i^2)}{\sum_{i=1}^{i=6}(R_i^2)}$$

(a)



	Dec_1	Dec_2	Dec_3	Dec_4	Dec_5	Dec_6
P - WS	0.85	0.85	0.84	0.85	0.86	0.87
P - H_s	0.86	0.85	0.84	0.84	0.85	0.87
P - H_{swell}	0.91	0.90	0.91	0.91	0.91	0.91
P - T_e	0.67	0.66	0.64	0.66	0.67	0.68

(b)



	Dec_1	Dec_2	Dec_3	Dec_4	Dec_5	Dec_6
P - WS	2.38	2.44	2.53	2.54	2.58	2.43
P - H_s	10.06	10.23	10.56	10.57	10.68	10.15
P - H_{swell}	78.32	74.20	71.81	71.43	73.94	80.31
P - T_e	5.09	5.33	5.41	5.61	5.81	5.38

(c)

	Average R	Average weighted ratio of RoCs
P - WS	0.85	2.48
P - H_s	0.85	10.37
P - H_{swell}	0.91	74.99
P - T_e	0.66	5.44

Results

- The change in wave power correlates highly with the change in swell wave height rather than the significant wave height, and hence, it is possible to predict the change in wave power solely based on the predicted change in the swell climate.

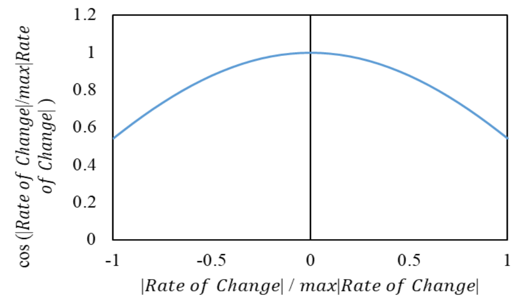
- Considering the above-mentioned points, it is necessary to consider both short-term variation and long-term changes in selecting priority areas for energy extraction from the ocean waves.

Results

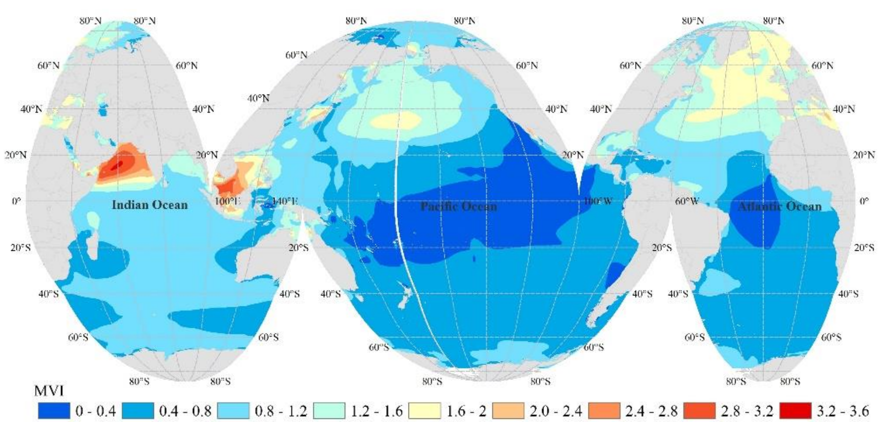
Priority coasts considering the variation and change in resources

Ideal condition:

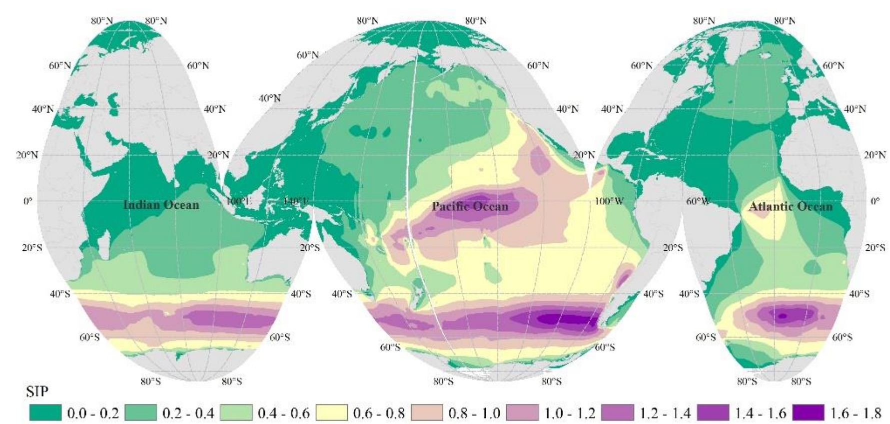
- Highest P
- Lowest MVI
- Lowest rate of change (negative or positive)



$$SI_P = \frac{\frac{P_{annual\ mean}}{\max(P_{annual\ mean})} \times \cos\frac{Rate\ of\ change}{max|Rate\ of\ change|}}{MVI}$$

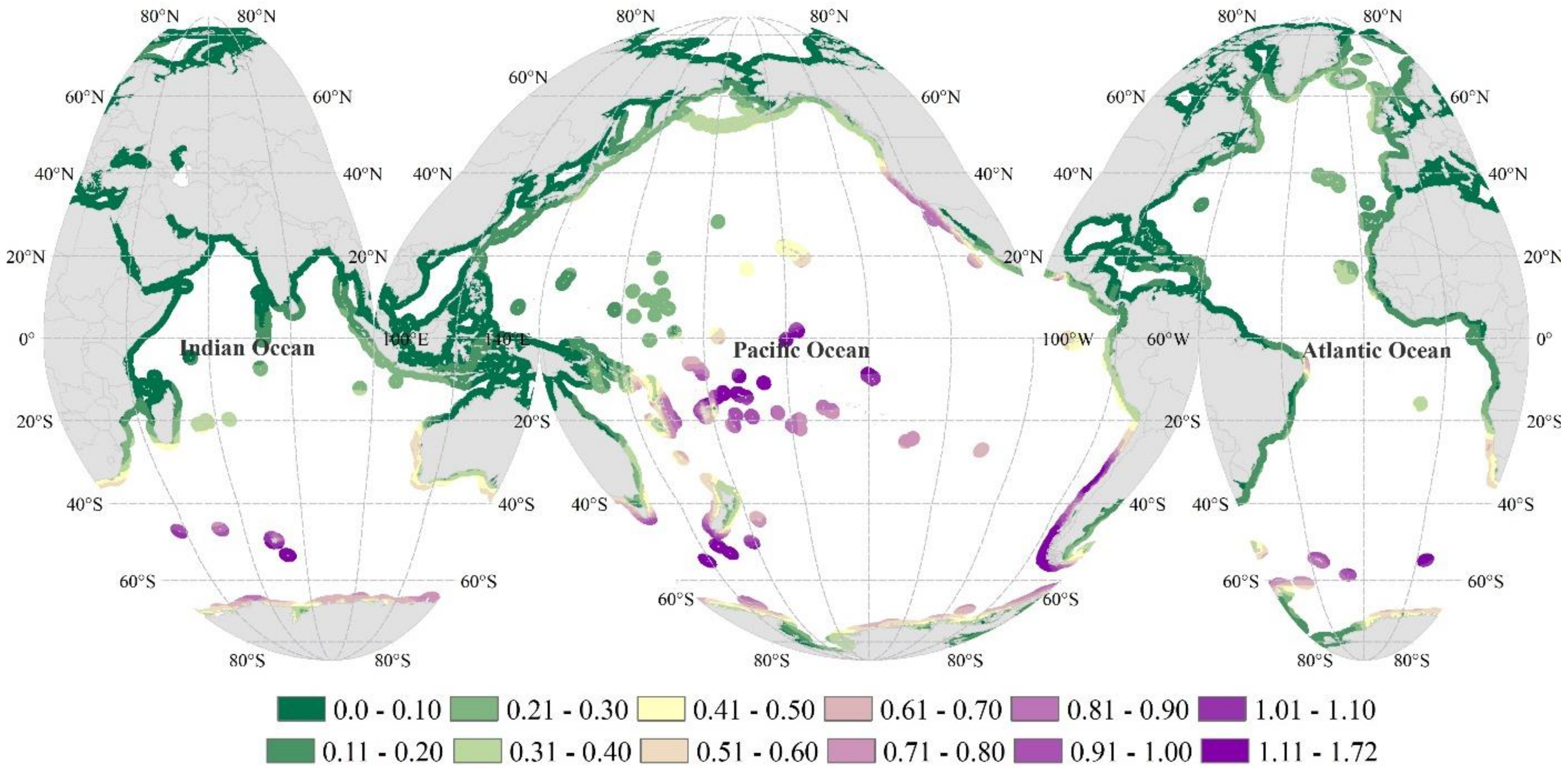


Monthly Variability Index (MVI)



Sustainability Index (SI_p)

Results



Indian Ocean
Pacific Ocean
Atlantic Ocean
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
100°E
140°E
100°W
60°W
0.0 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.60
0.61 - 0.70
0.71 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.10
1.11 - 1.72

Summary & Conclusion

- The selection of the time slice affects the estimation of available wave energy due to the change in climate.

- Selection of different assessment periods can cause up to ±25% difference in wave power resource assessment in deep waters.

- The long-term change in wave power appears to be a function of change in swell wave height rather than the combination of swells and seas.

- The decadal variability analysis revealed that the change in wave power again follows that of change in swell wave height. However, the change in wave climate has been different in different decades.

- The RoC of wave power was found to be ~75 and 2.5 times the RoC of Hswell and WS with 91% and 85% accuracies, respectively.

Summary & Conclusion

- Sustainability Index (SI_p) was utilized to detect the areas with the highest available wave power, lowest intra-annual fluctuations, and lowest long-term change in wave power.

- The classification based on SI_p revealed the priority areas mainly in the southern hemisphere, including south and northwest of New Zealand, southeast and southwest of Australia, eastern coasts of Papua New Guinea, and south and southwest coasts of South Africa and Namibia.

- The Pacific islands and islands in the southern Indian Ocean are among the most suitable locations for wave energy extraction.

- The priority areas in the northern hemisphere are the west coasts of North America, western and eastern coasts of Canada, east of Japan and Russia, west of Europe, Iceland, and south of Greenland.

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- SWAN team at Delft University of Technology

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Linking the long-term variability in global wave energy to swell climate and redefining suitable coasts for energy exploitation

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Hokkaido, Japan
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