G. Courbet.

Wave energy:

making best use of a variable resource

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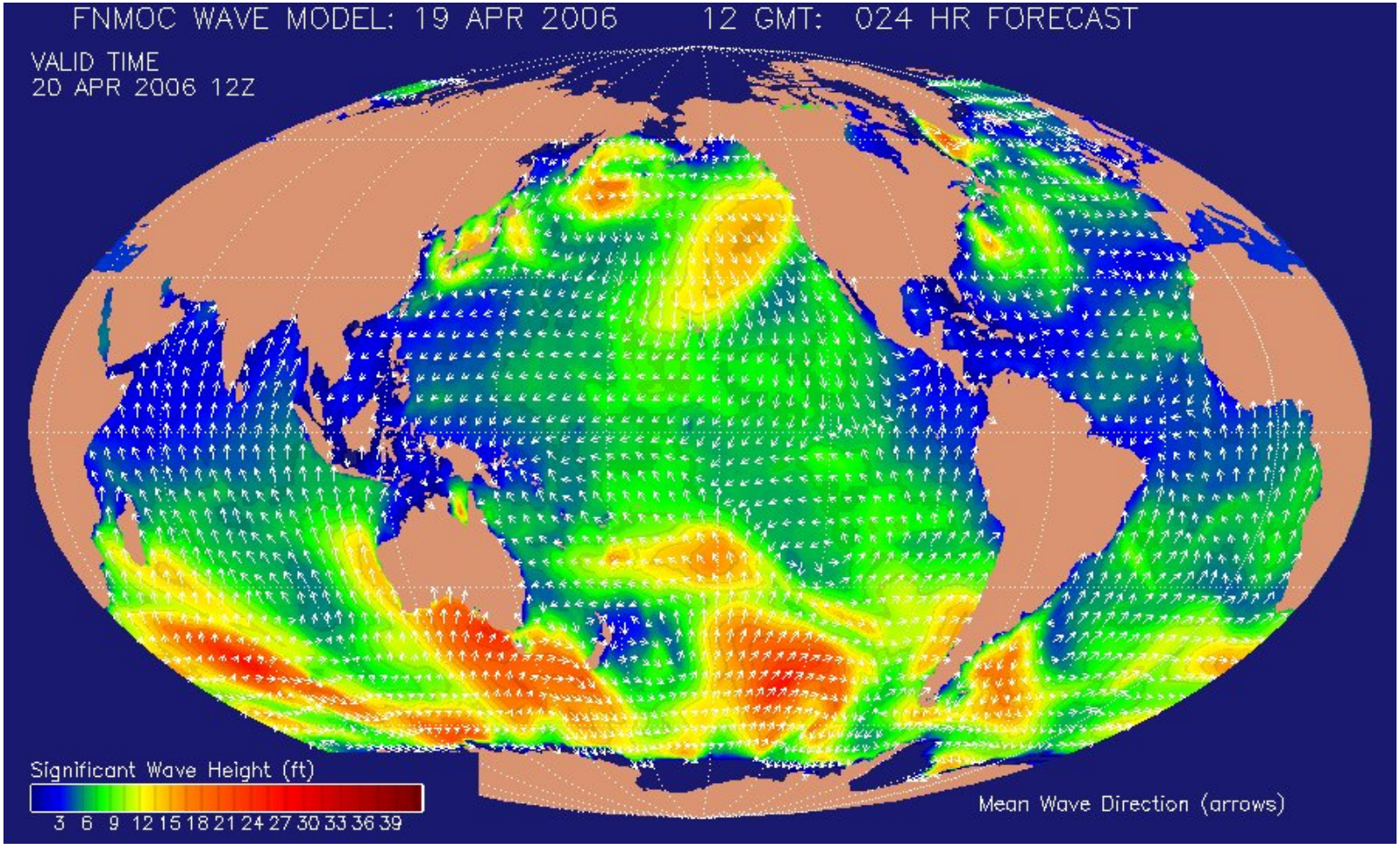
2. Deep water surface waves
3. Directional spectra
4. Devices
5. Estimating the resource
6. Deploying and integrating renewables

1 The wave energy resource



sun

$\longrightarrow$

wind

$\longrightarrow$

wave

sun – *heat*

$\longrightarrow$

wind

$\longrightarrow$

wave

sun – *heat*

$\longrightarrow$

wind – *mechanical* - medium moves

$\longrightarrow$

wave

sun – *heat*

$\longrightarrow$

wind – *mechanical* - medium moves

$\longrightarrow$

wave – *mechanical* - medium oscillates

sun – 1.3 $\mathrm{kW/m^2}$

$\longrightarrow$

wind

$\longrightarrow$

wave

sun – 1.3 $\mathrm{kW/m^2}$

$\longrightarrow$

wind – up to 0.2 $\mathrm{kW/m^2}$

$\longrightarrow$

wave

sun – 1.3 $\mathrm{kW/m^2}$

$\longrightarrow$

wind – up to 0.2 $\mathrm{kW/m^2}$

$\longrightarrow$

wave – up to 50 kW/m $\quad (\approx 5\ \mathrm{kW/m^2})$

World resource $\sim$ 2 TW

UK resource $\sim$ 1 TWh/day

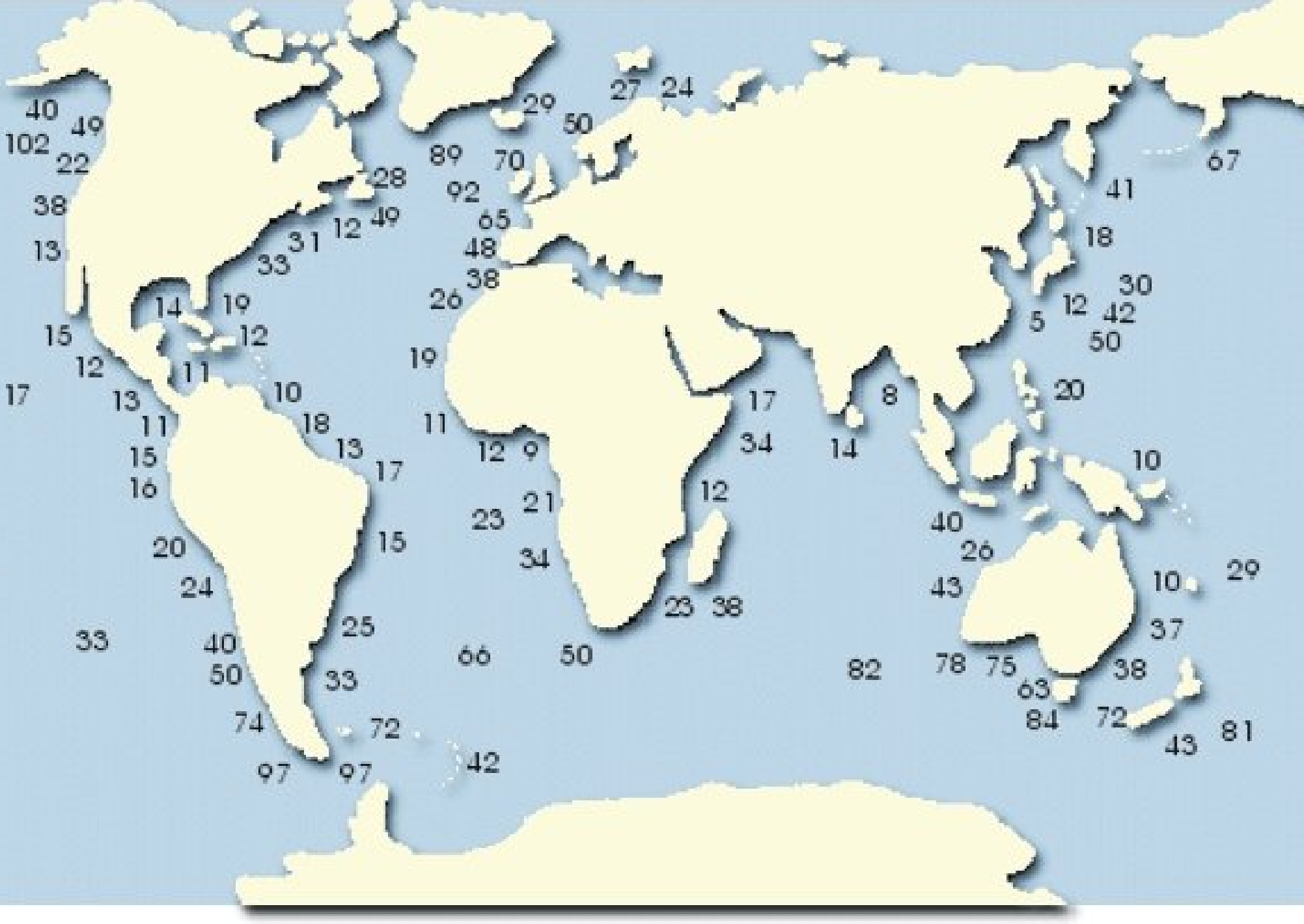
World resource $\sim$ 2 TW

$\sim$ World elec. usage

UK resource $\sim$ 1 TWh/day

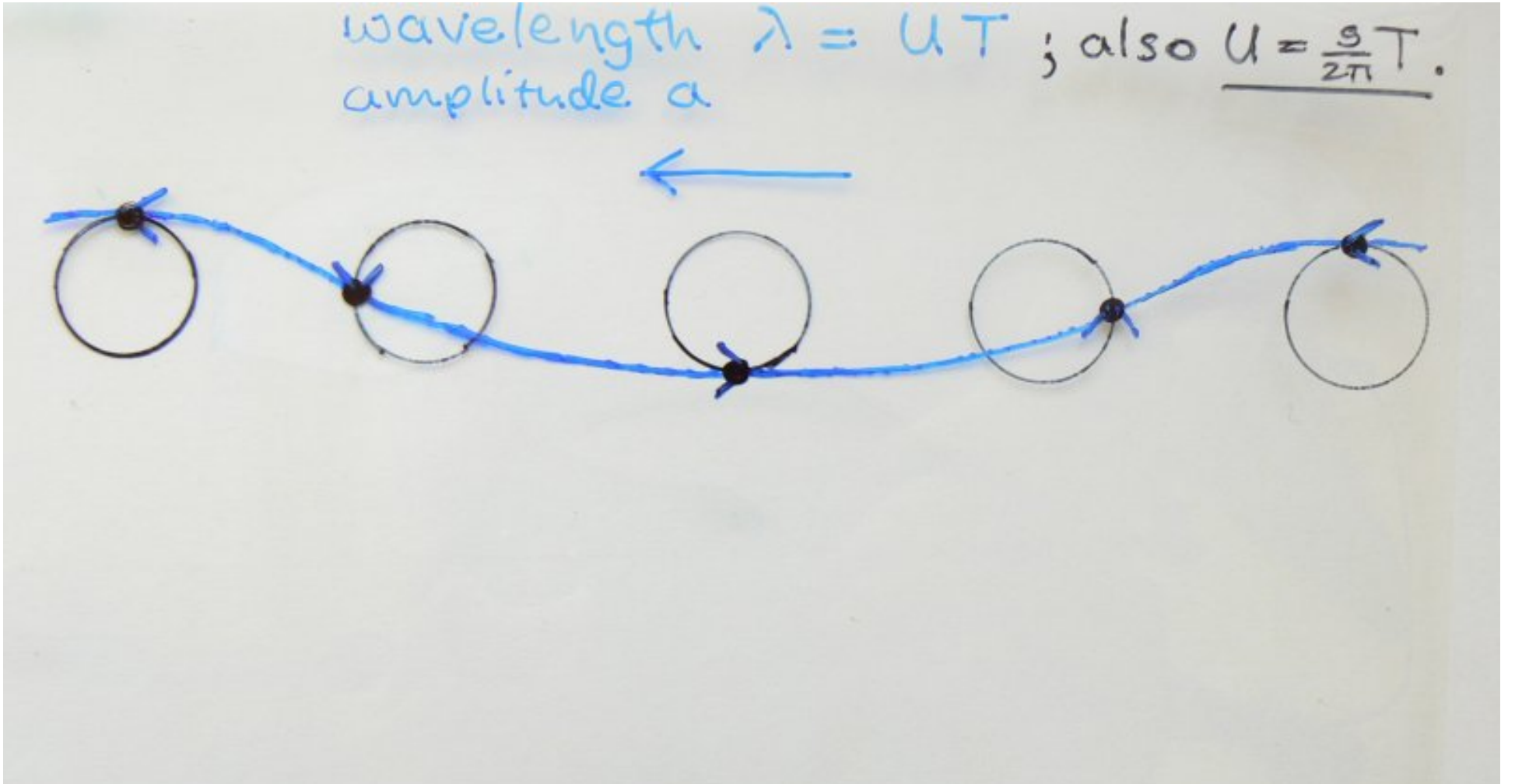
$\sim$ UK elec. usage

1 TWh $\sim$ Indian ocean tsunami


40
49
102
22
38
13
15
12
17
13
11
15
16
20
24
33
40
50
74
97
97
72
33
25
15
17
13
18
10
11
14
19
12
11
28
49
12
31
33
29
50
27
24
89
70
92
65
48
38
26
19
11
12
9
21
23
34
66
50
42
17
34
12
23
38
82
8
14
67
41
18
30
12
42
5
50
20
10
40
26
43
10
29
37
78
75
38
63
84
72
43
81

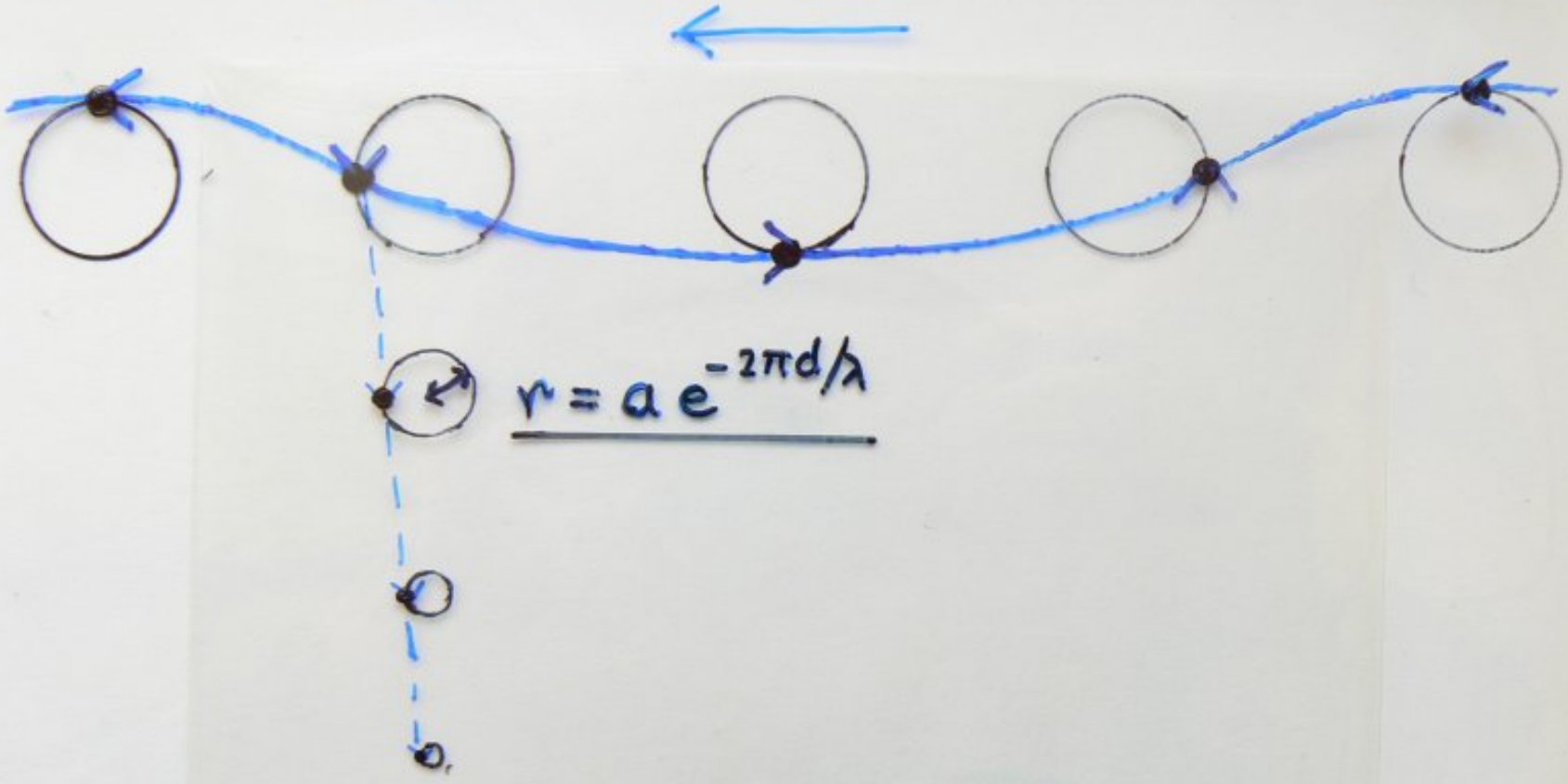
2 Deep water surface waves

Single frequency wave



wavelength $\lambda = uT$; also $u = \frac{\omega}{2\pi} T$.

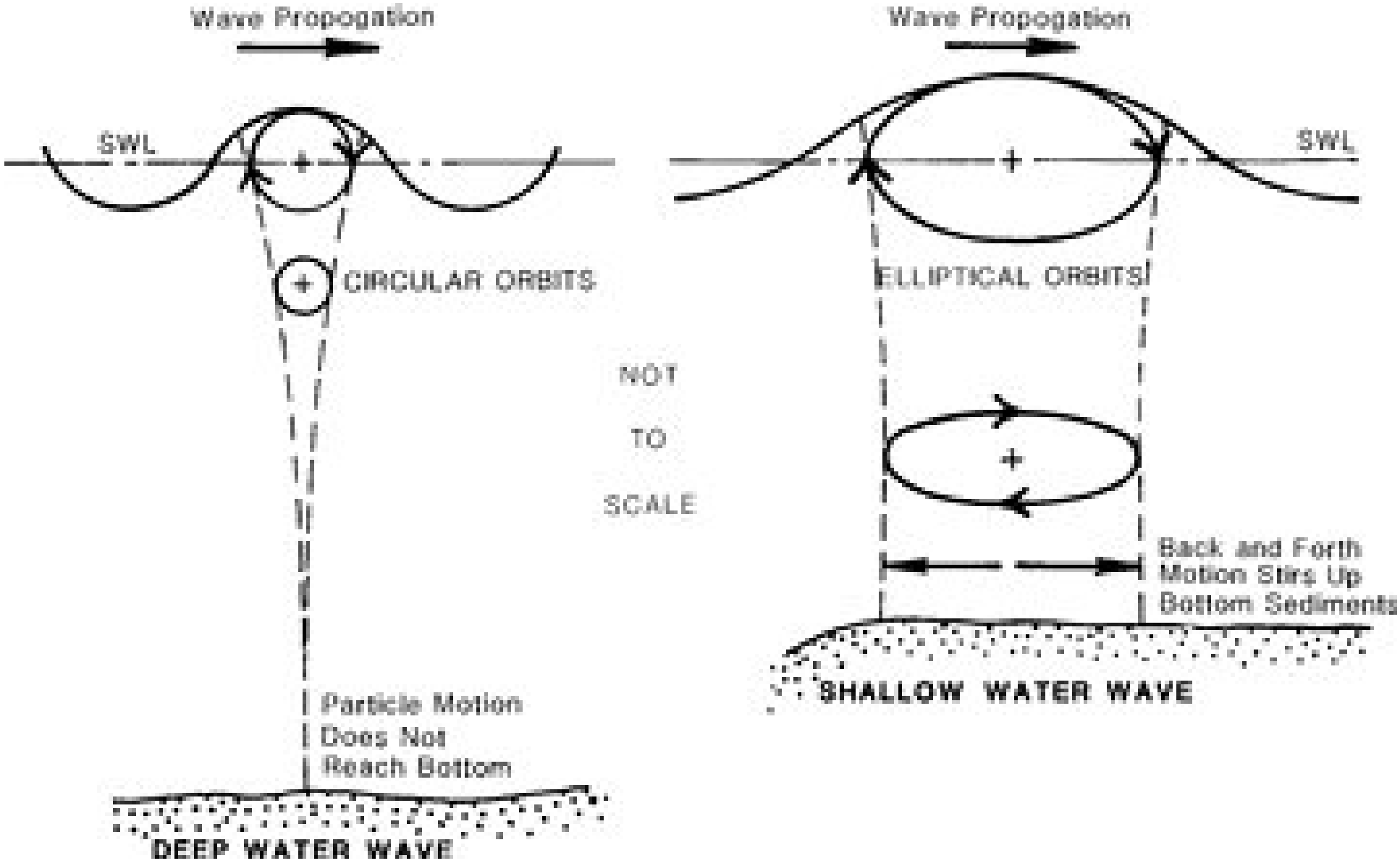
amplitude a



Energy $\propto \frac{1}{2} a^2 = H_{rms}^2$

Power = $E \times u = k H^2 T$

$(k \doteq 7.9)$


Wave Propogation
SWL
CIRCULAR ORBITS
Particle Motion
Does Not
Reach Bottom
DEEP WATER WAVE
NOT
TO
SCALE
Wave Propogation
SWL
ELLIPTICAL ORBITS
Back and Forth
Motion Stirs Up
Bottom Sediments
SHALLOW WATER WAVE

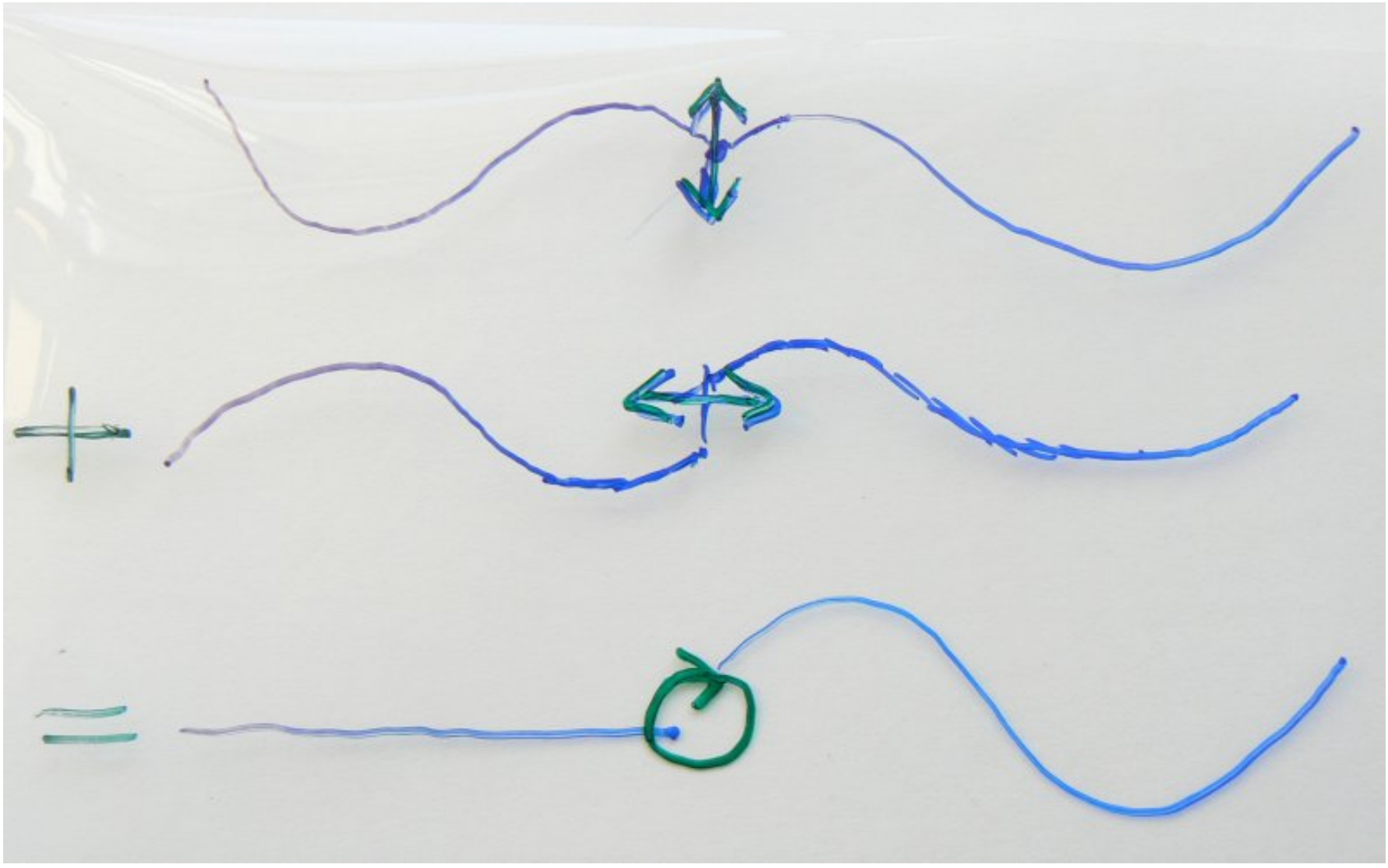
Group velocity is $U/2$ in deep water

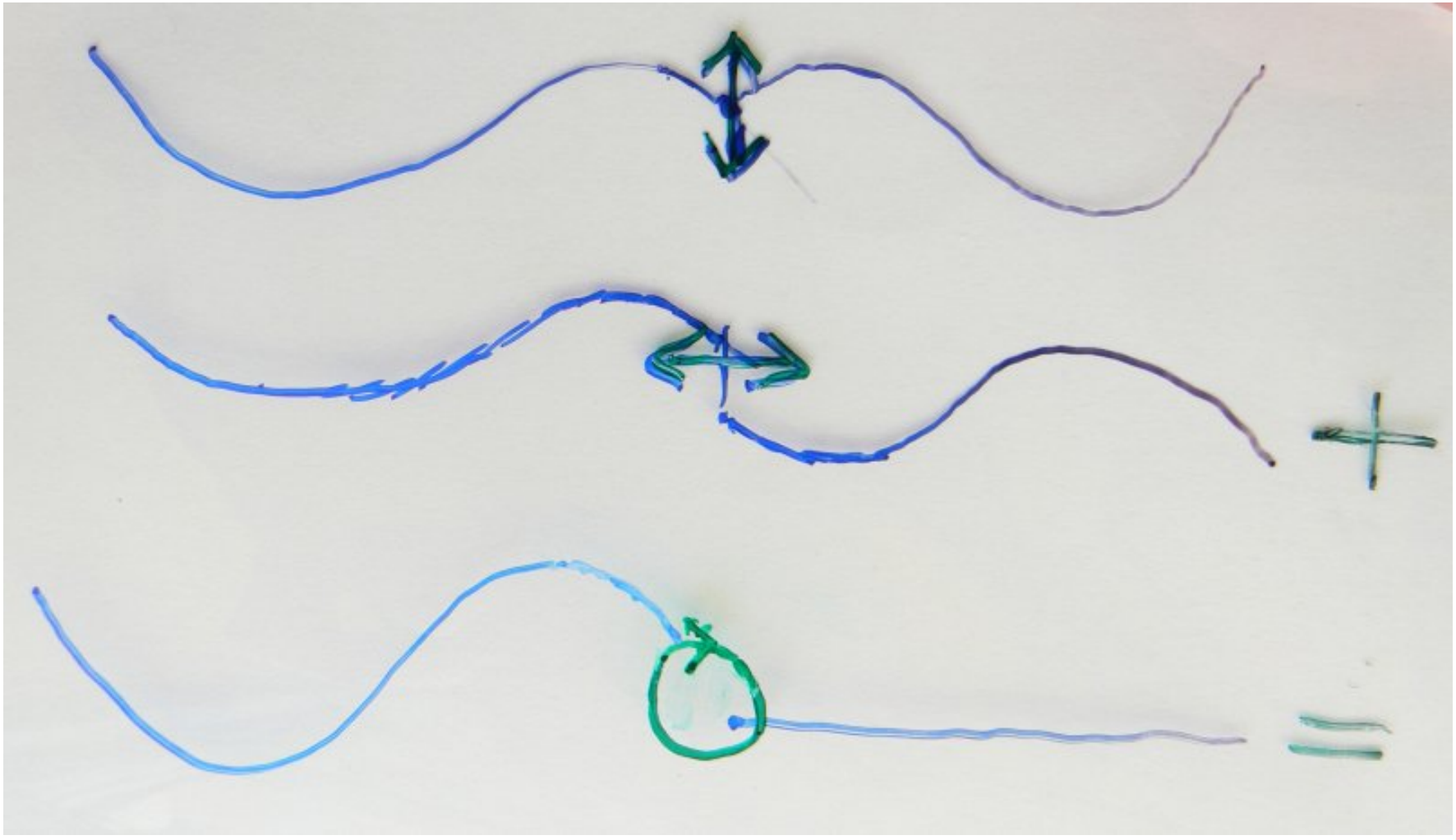
– dispersive waves

but $\approx U$ in shallow water

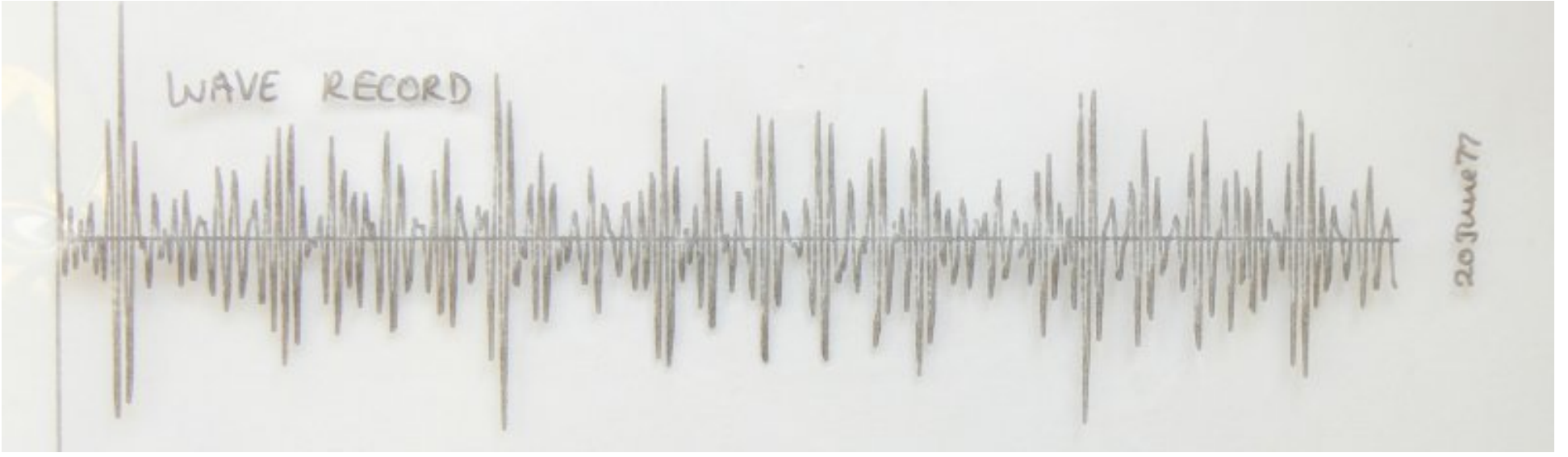
– soliton (tsunami)

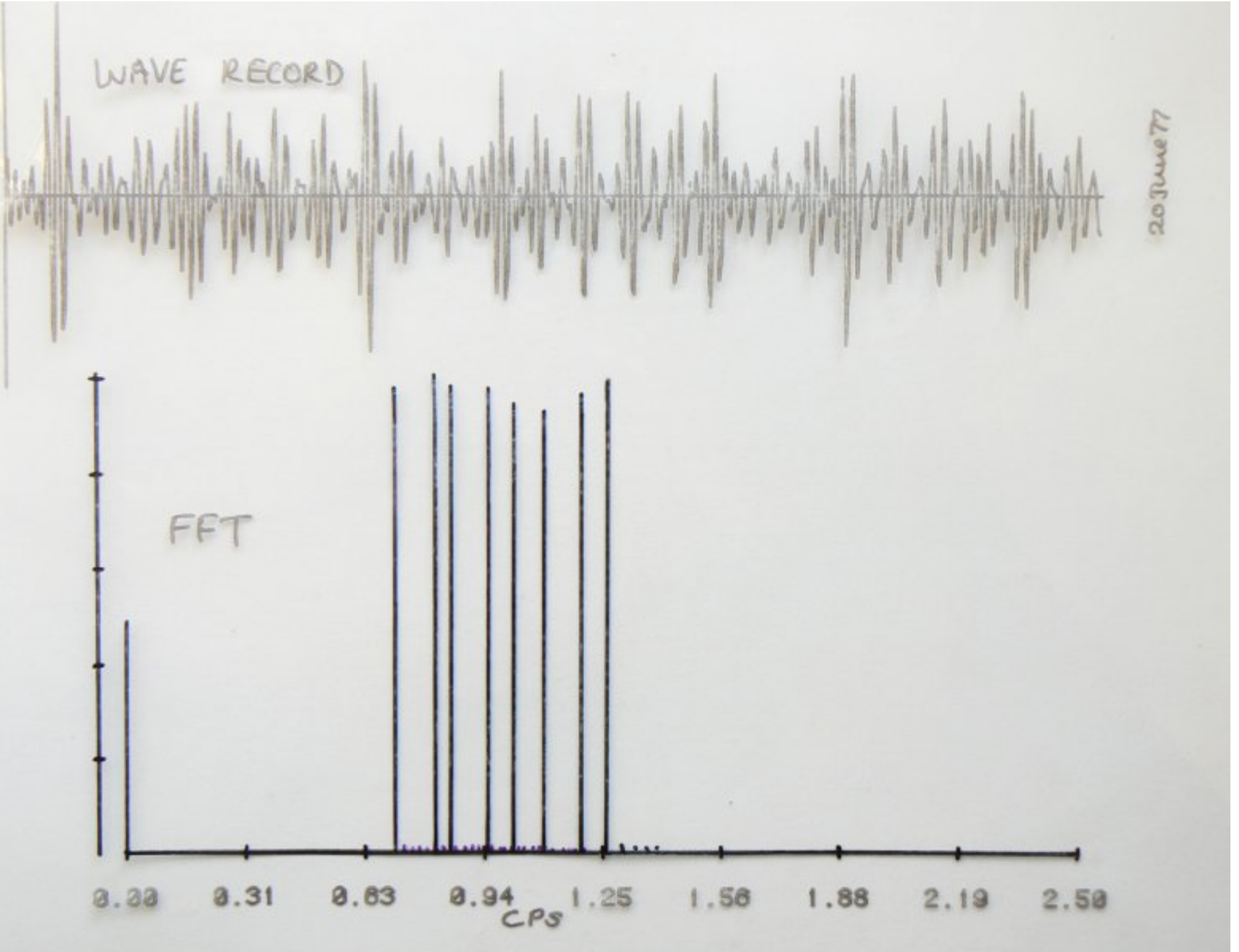
Waves are additive

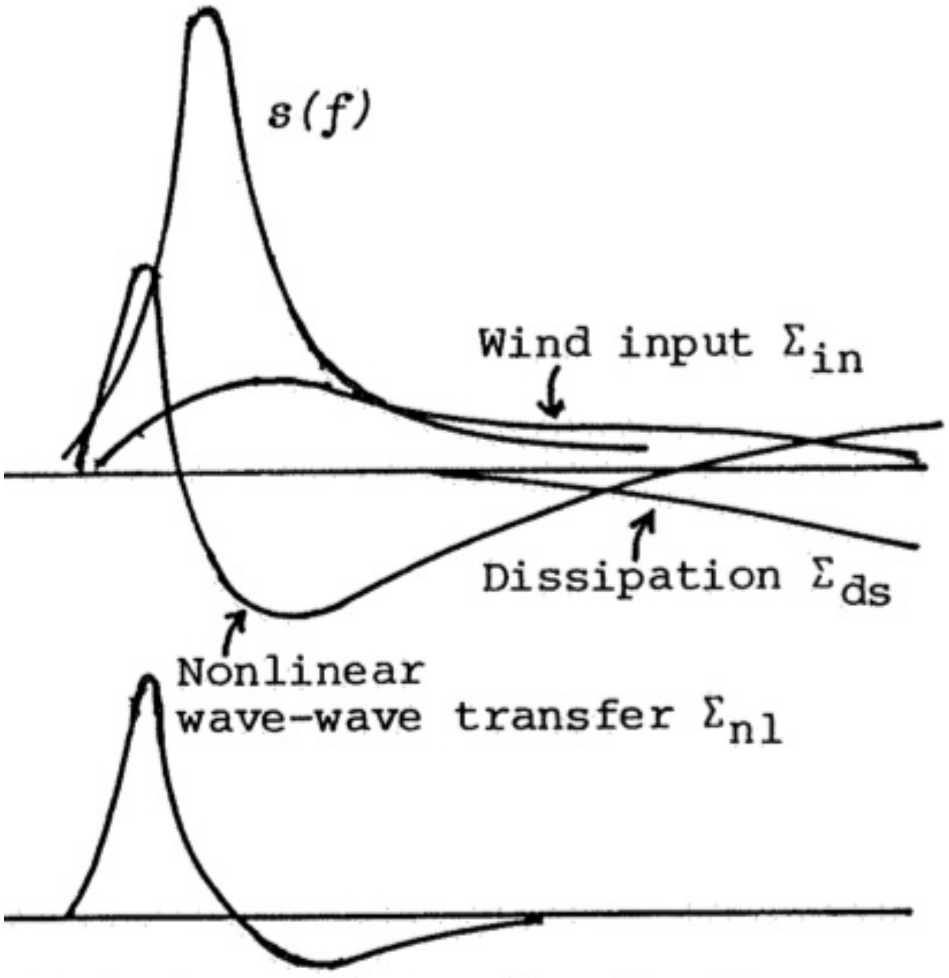


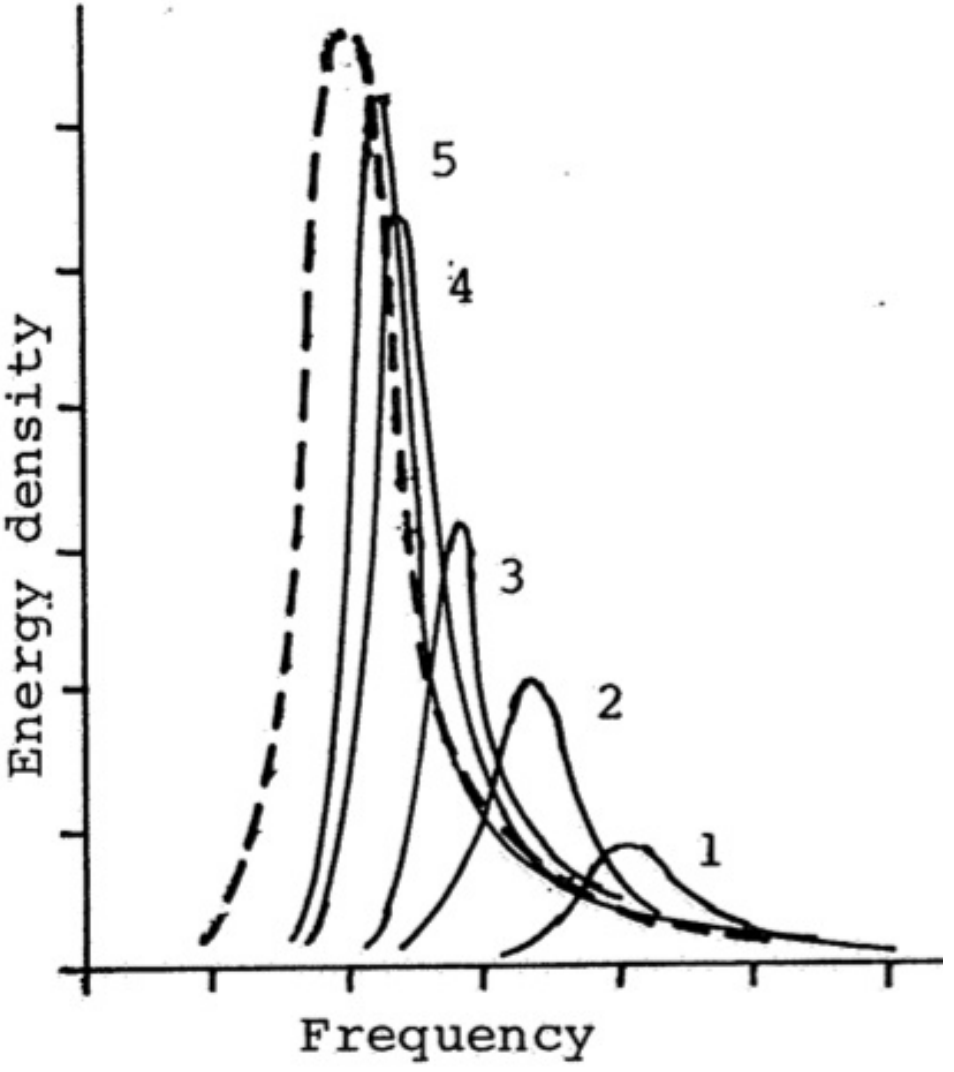


Sum of many frequencies

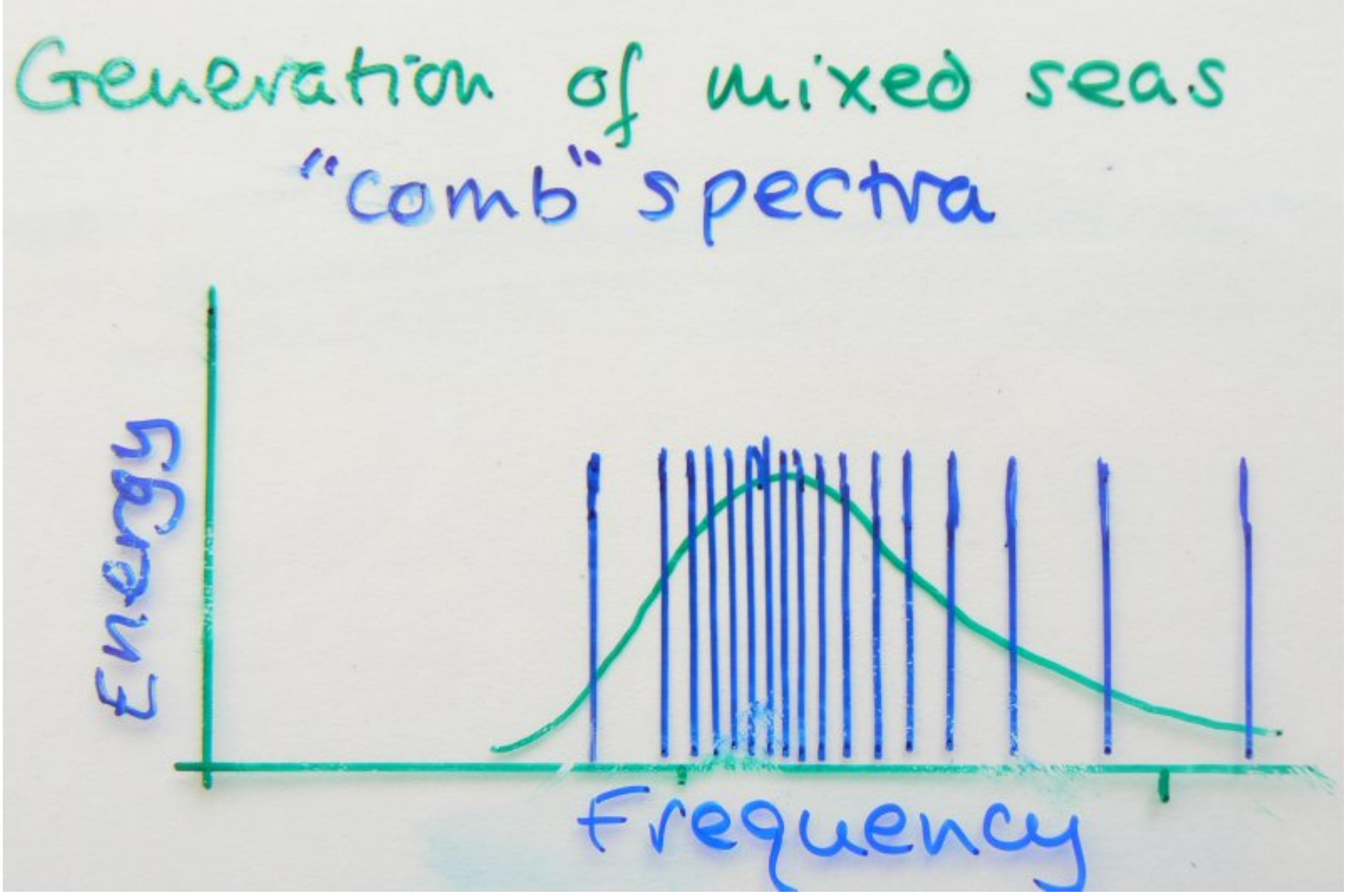



WAVE RECORD
20 June 77
FFT
0.00
0.31
0.63
0.94
1.25
1.56
1.88
2.19
2.50
CPS


s(f)
Wind input Σ_{in}
Dissipation Σ_{ds}
Nonlinear
wave-wave transfer Σ_{nl}
Net transfer = $\Sigma_{in}+\Sigma_{nl}+\Sigma_{ds}$


Energy density
5
4
3
2
1
Frequency

Generation of mixed seas "comb" spectra



SCALING:

$$\text{wind power} = (mU^2/2) \times U \quad \sim U^3$$

$$\text{wave power} = (cH^2) \times U$$

$$= (c'U^4) \times U \quad \sim U^5$$

$$\propto \text{wind power} \times \text{fetch}$$

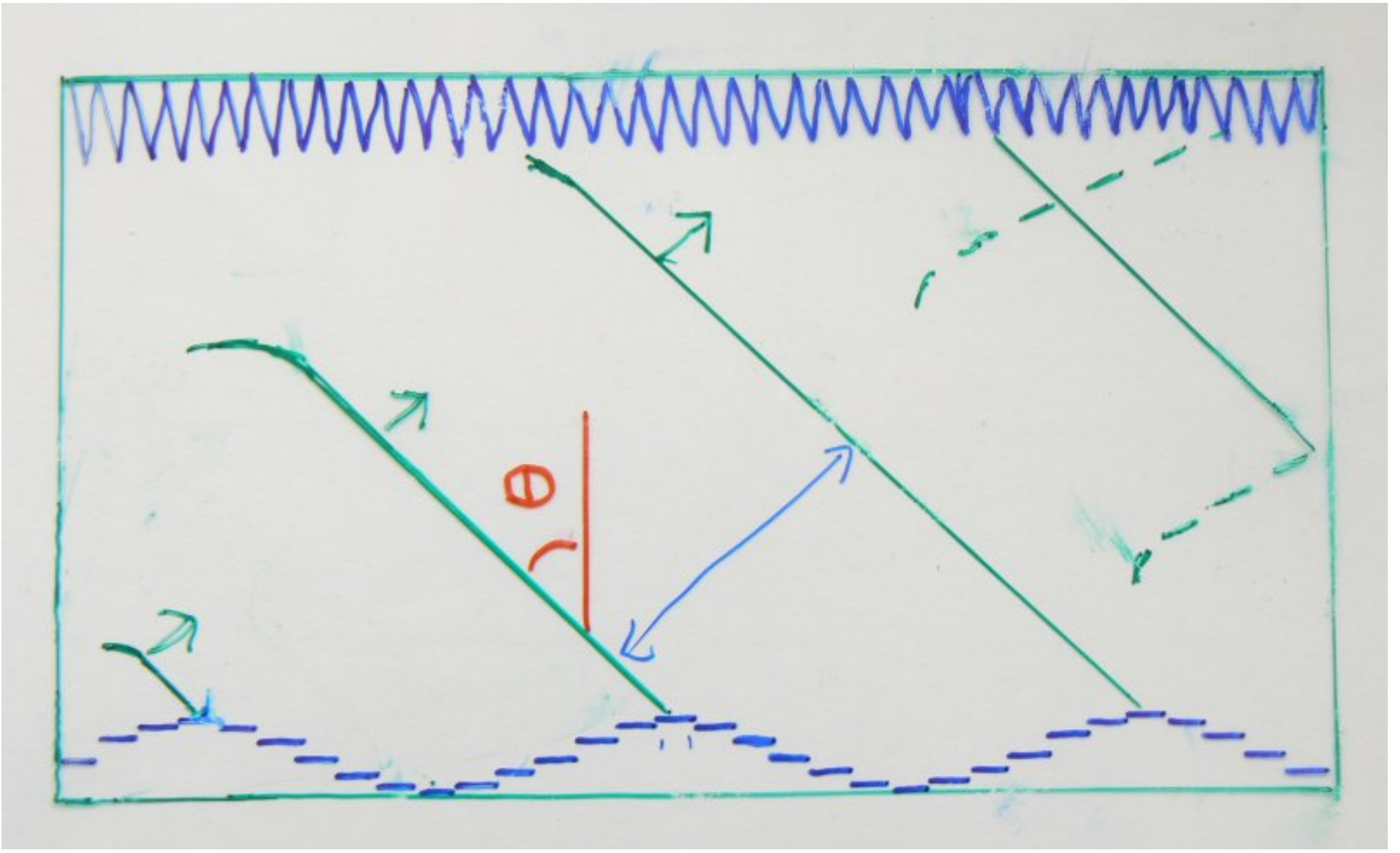
(fetch like H scales as wavelength, $\propto U^2$)

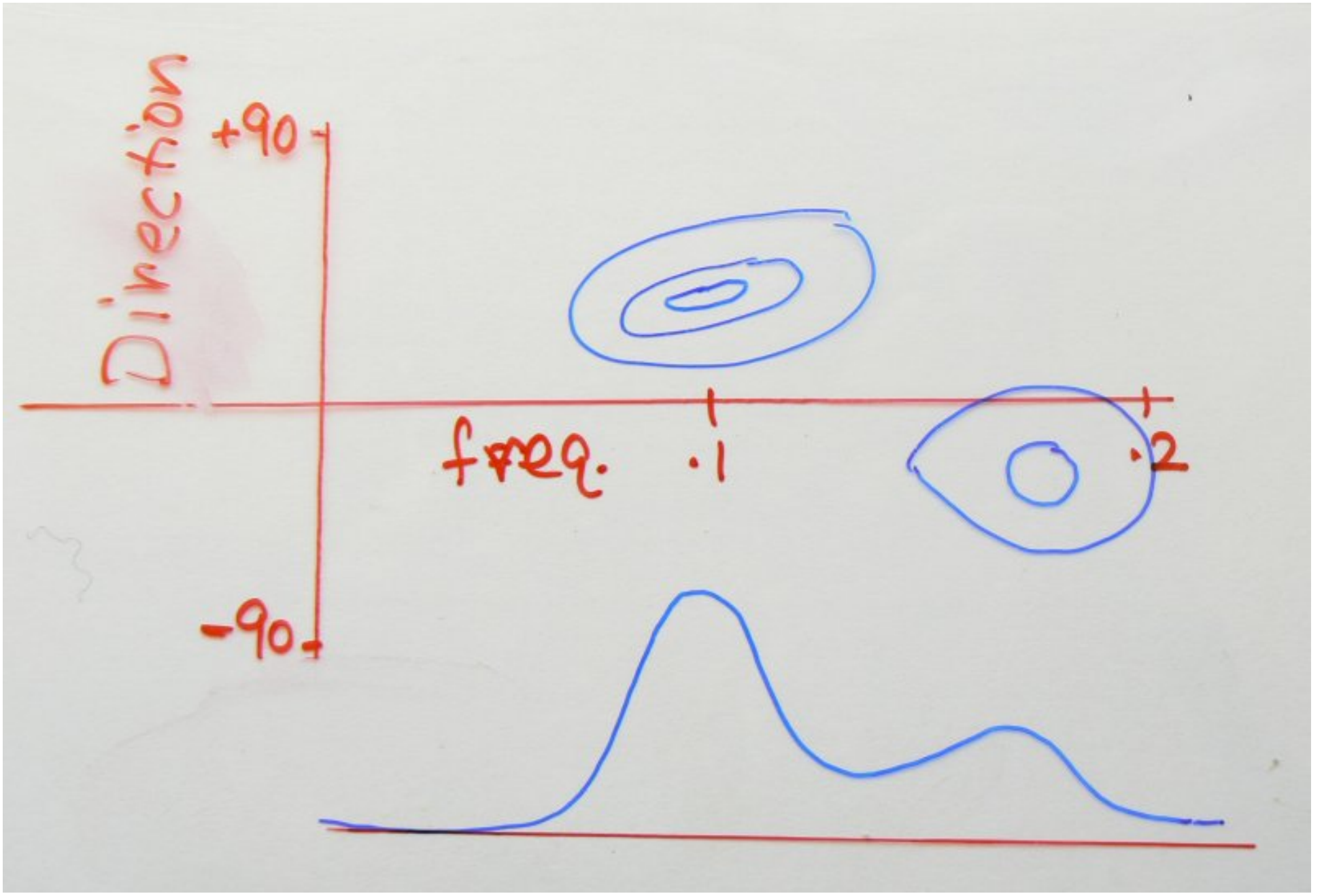
Variability over time:

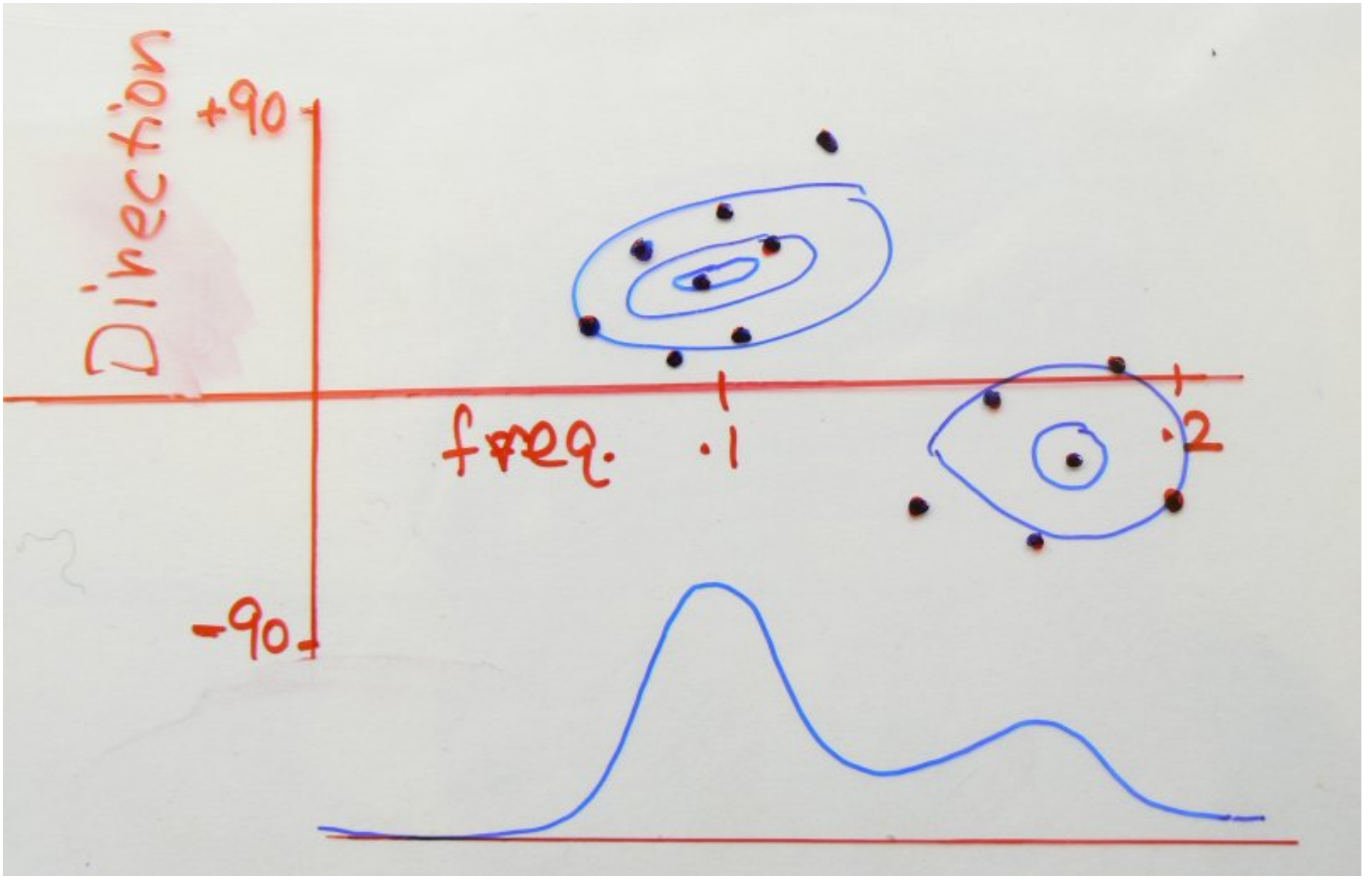
On a scale of seconds or metres, wave power at a point is much more variable than wind

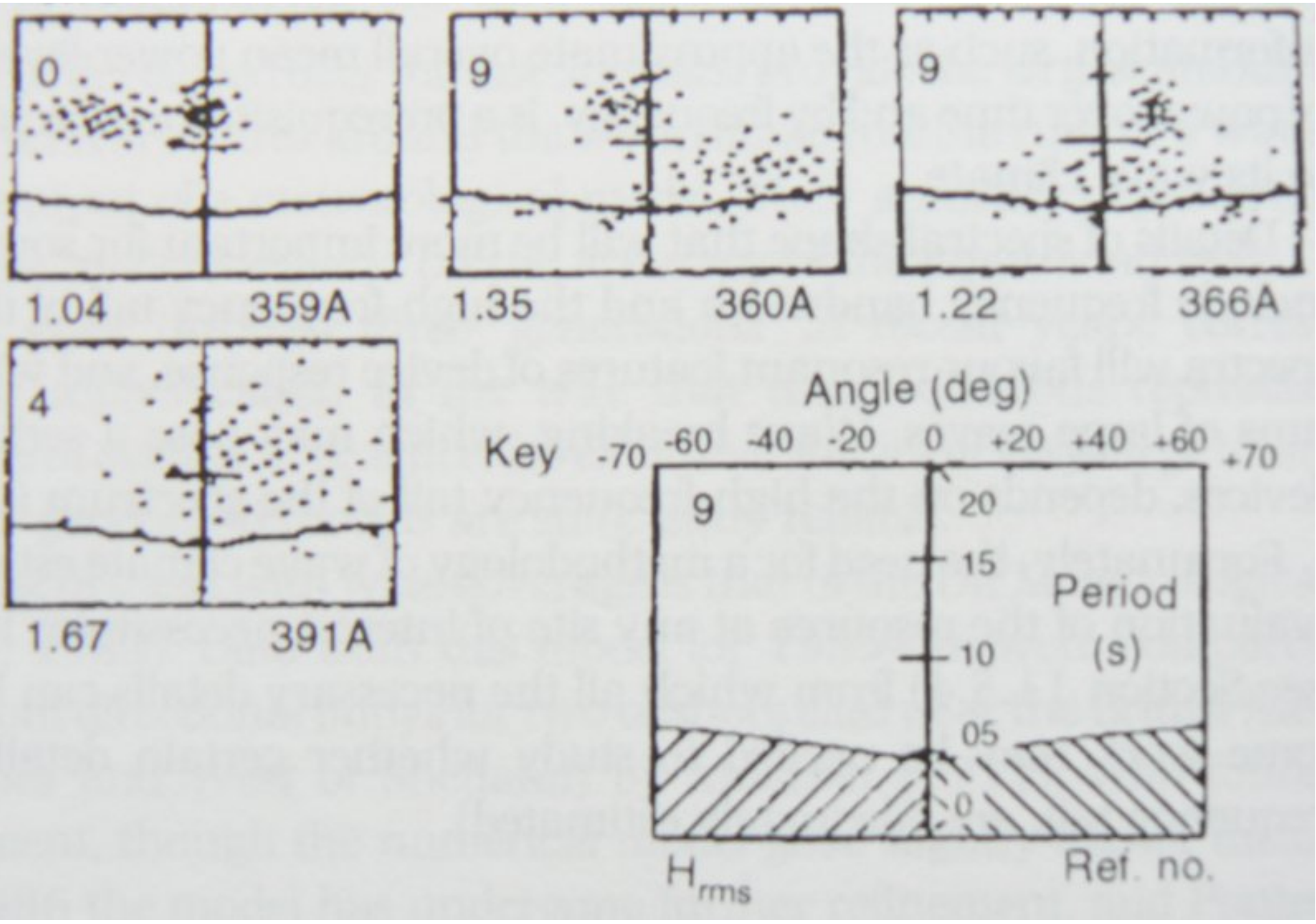
On a scale of hours or kilometres, the *sea state* is significantly less variable than the wind, with mean power $P = kH_{rms}^2 T_e$

3 Directional spectra

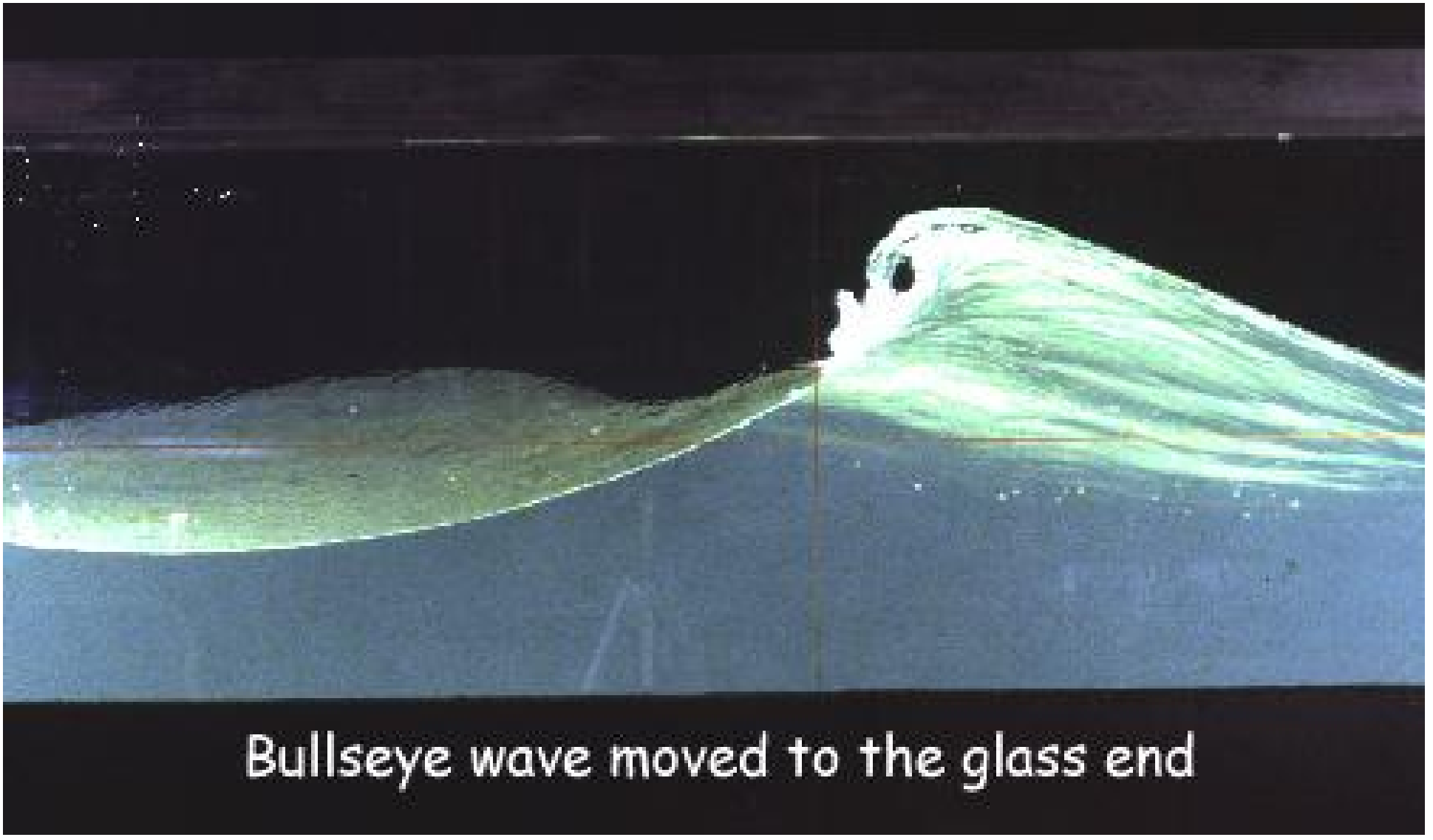

θ


Direction
+90
-90
freq.
.1
.2

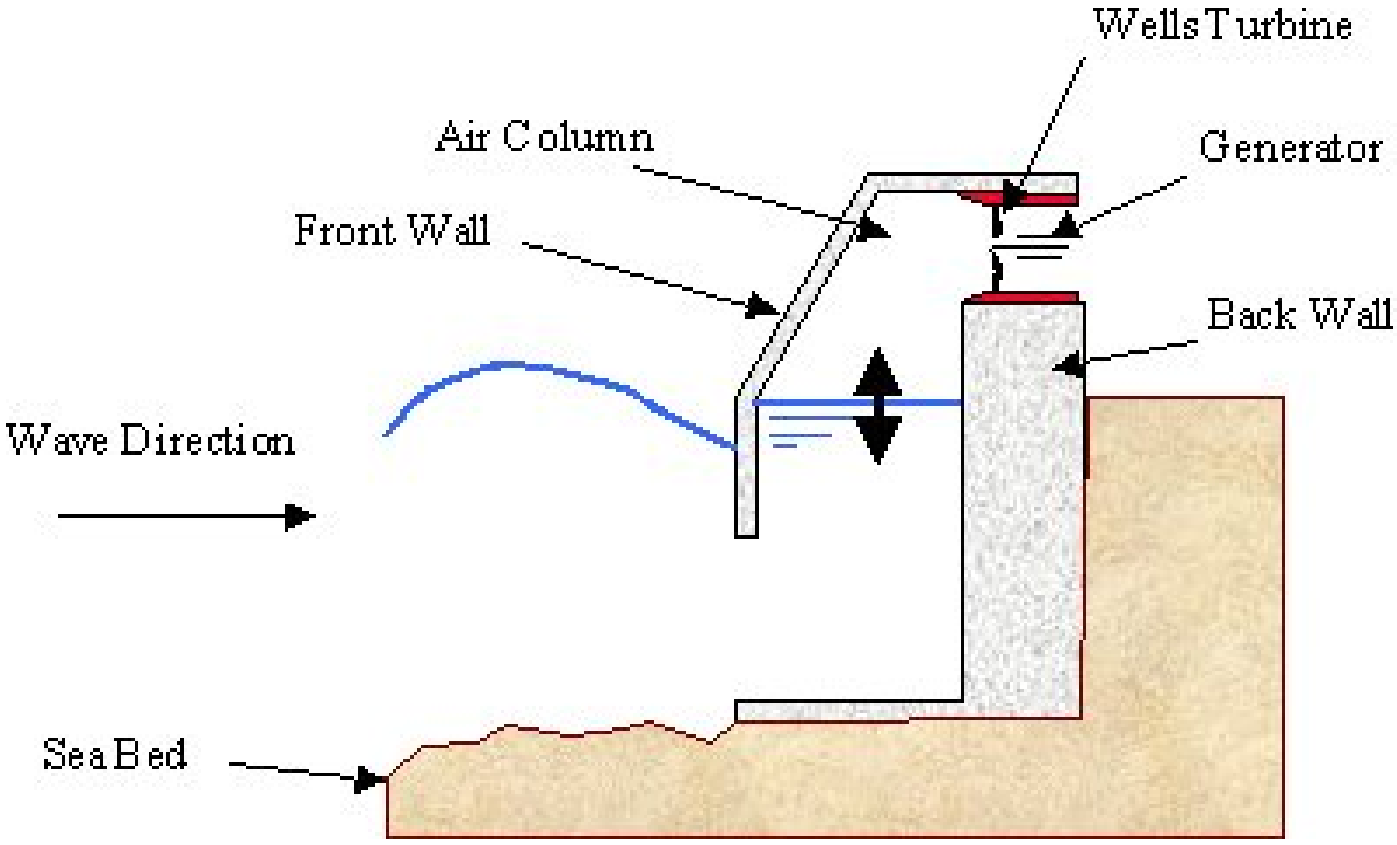

Direction
+90
-90
freq.
.1
.2


0
1.04
359A
9
1.35
360A
9
1.22
366A
4
1.67
391A
Angle (deg)
Key
-70
-60
-40
-20
0
+20
+40
+60
+70
9
20
15
10
05
0
Period
(s)
H_{rms}
Ref. no.

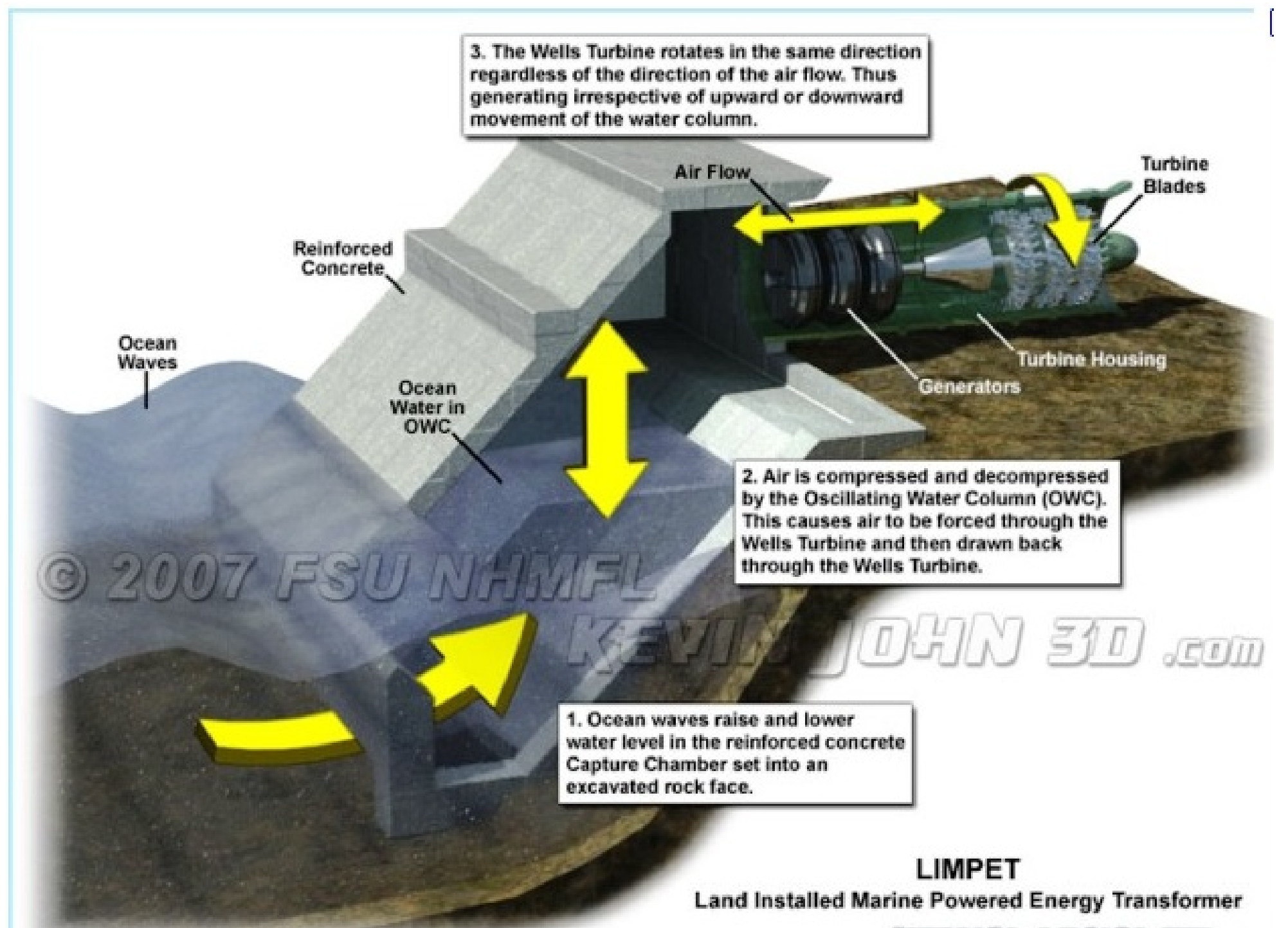
Phase control $\rightarrow$ *designer waves*

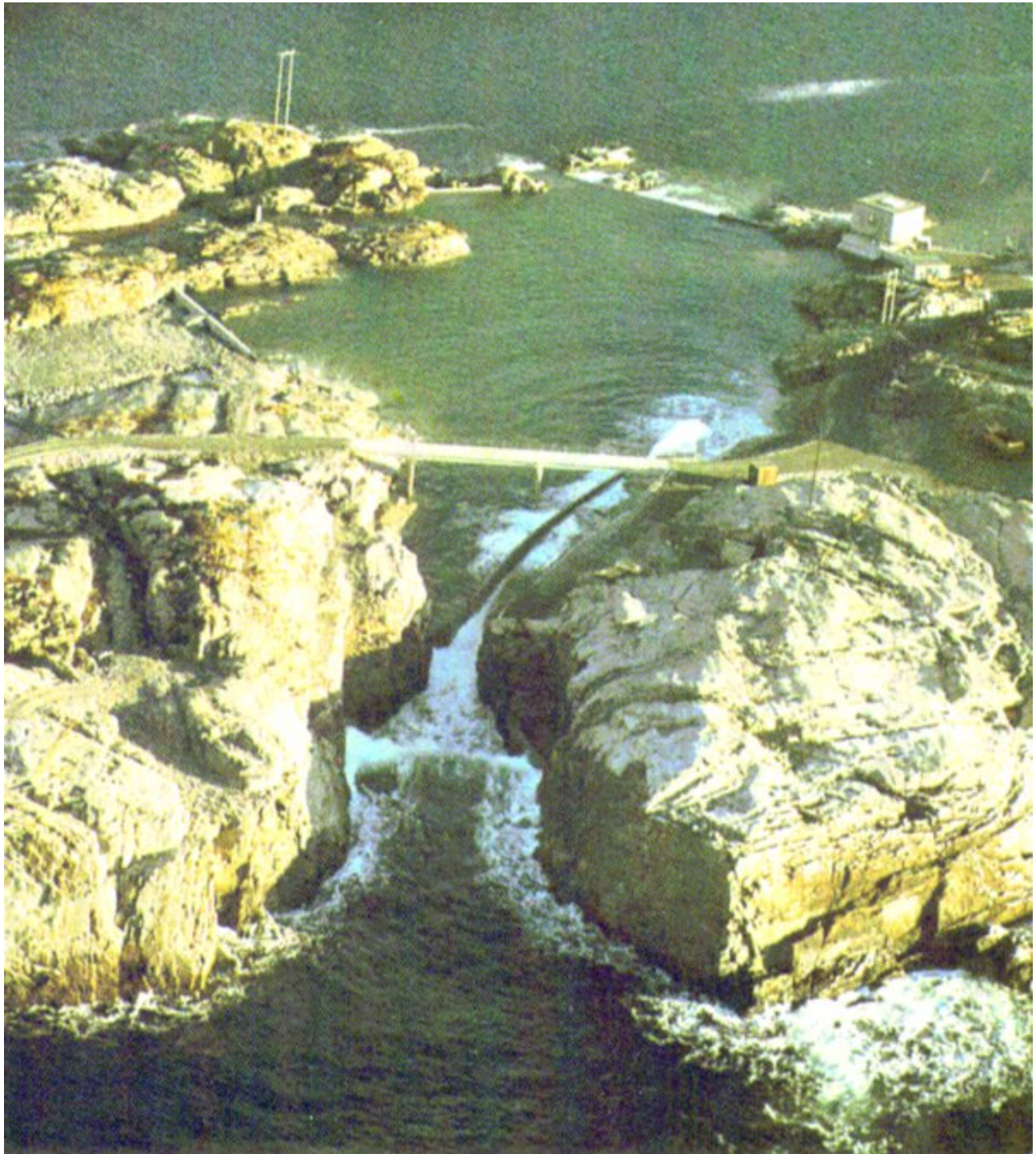


4 Devices



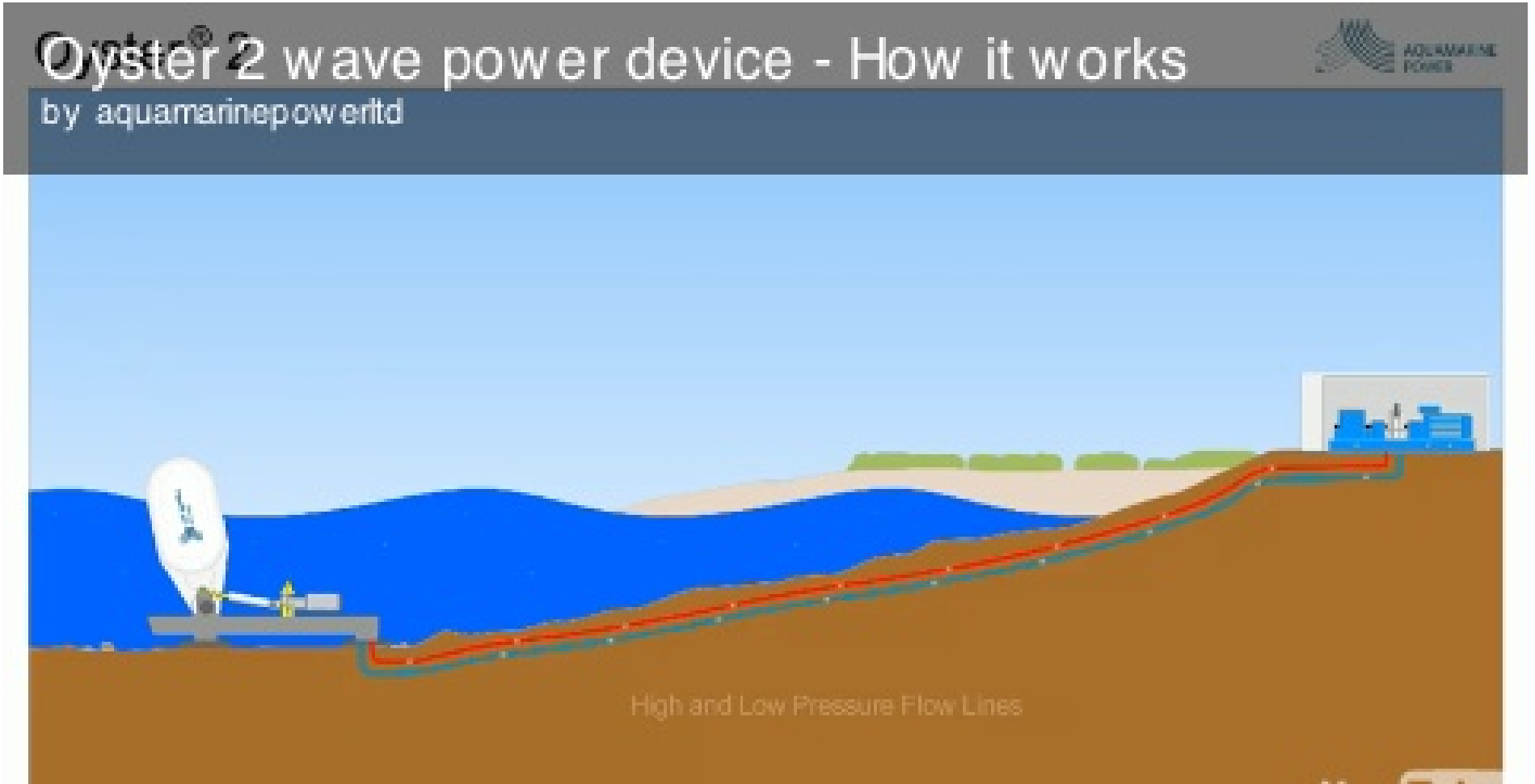
Oscillating water column


3. The Wells Turbine rotates in the same direction regardless of the direction of the air flow. Thus generating irrespective of upward or downward movement of the water column.
Air Flow
Turbine Blades
Reinforced Concrete
Ocean Waves
Ocean Water in OWC
Turbine Housing
Generators
2. Air is compressed and decompressed by the Oscillating Water Column (OWC). This causes air to be forced through the Wells Turbine and then drawn back through the Wells Turbine.
© 2007 FSU NHMFL
1. Ocean waves raise and lower water level in the reinforced concrete Capture Chamber set into an excavated rock face.
LIMPET
Land Installed Marine Powered Energy Transformer



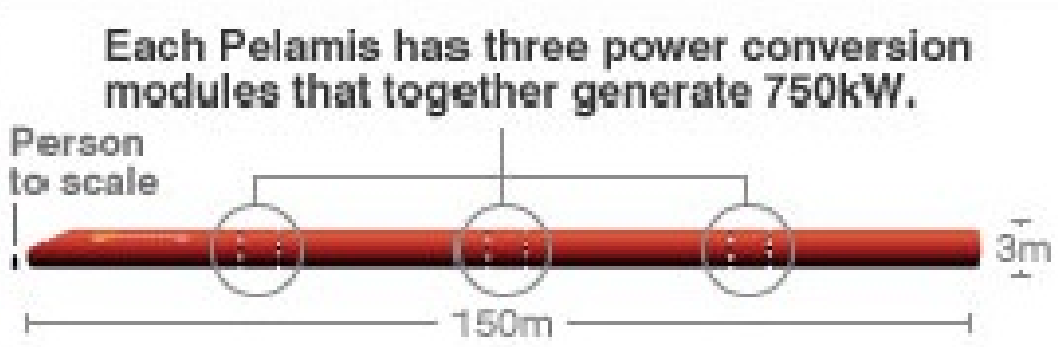
In essence, the Oyster wave power device is simply a large pump which provides the power source for a conventional onshore hydro-electric power plant.

Once commercialised, multiple Oyster wave power devices will be deployed in farms typically of 100MW or more.



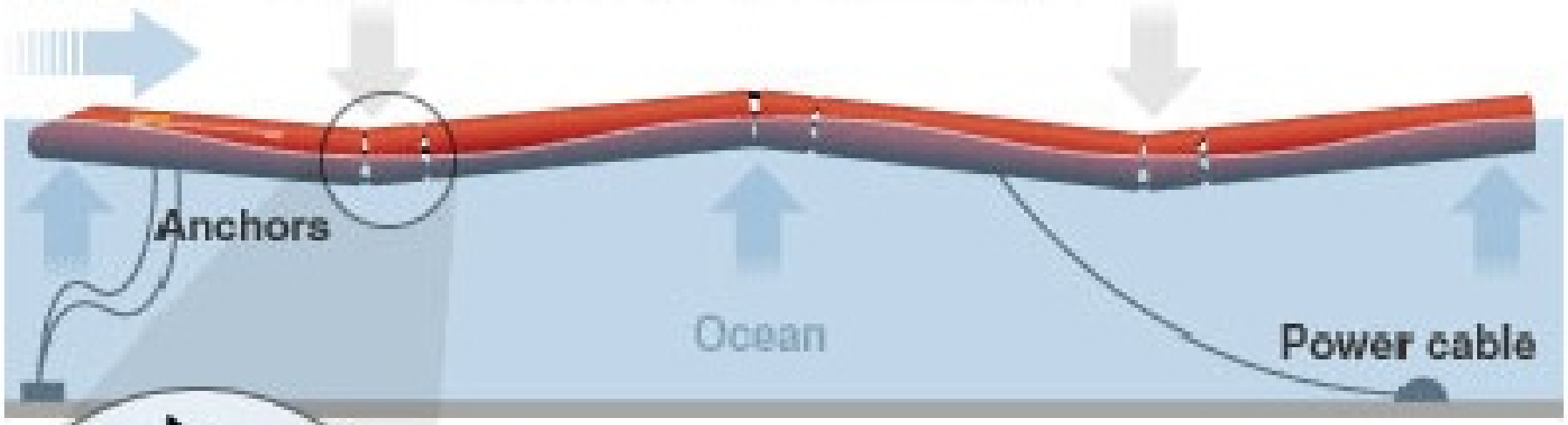
Pelamis

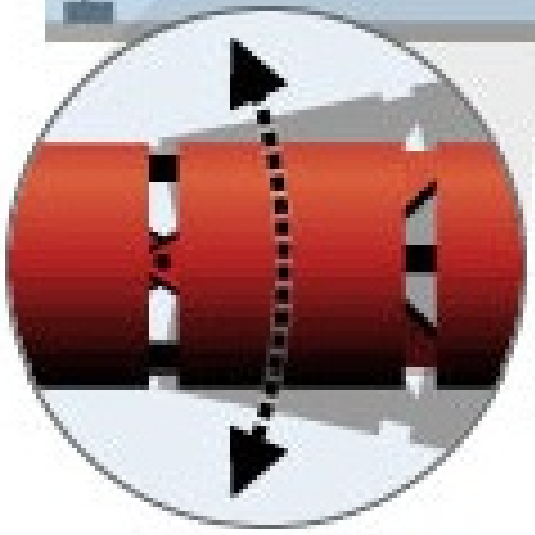
(*see* http://www.oceanpd.com/)



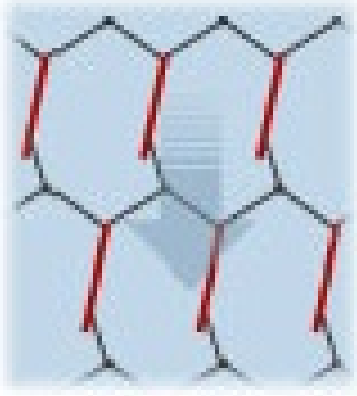
Wave direction

Waves move across the sea and cause the Pelamis to rise and fall in a snake-like motion.





Sections move against each other on hinges resisted by hydraulic rams, driving generators to produce electricity.

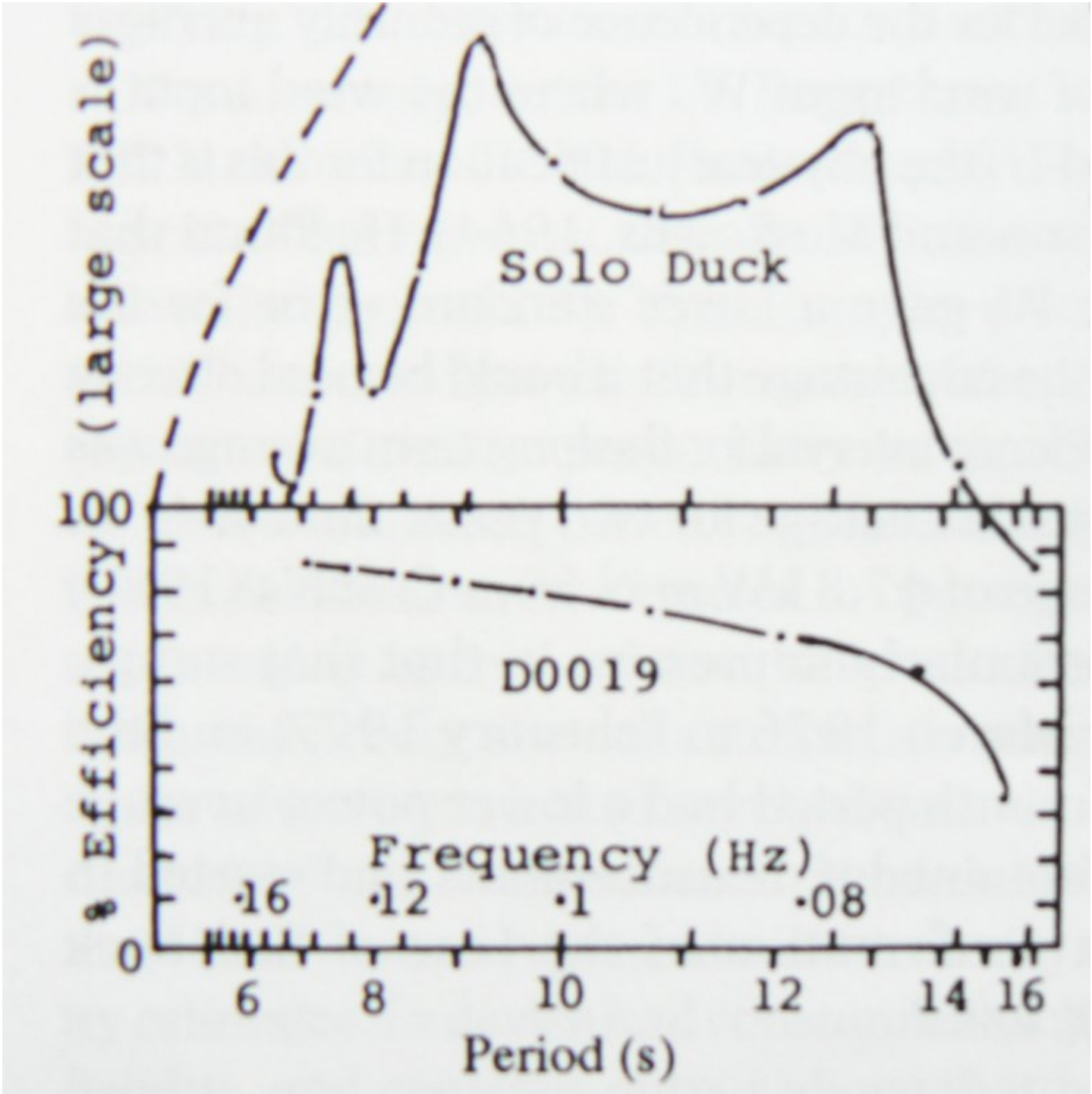


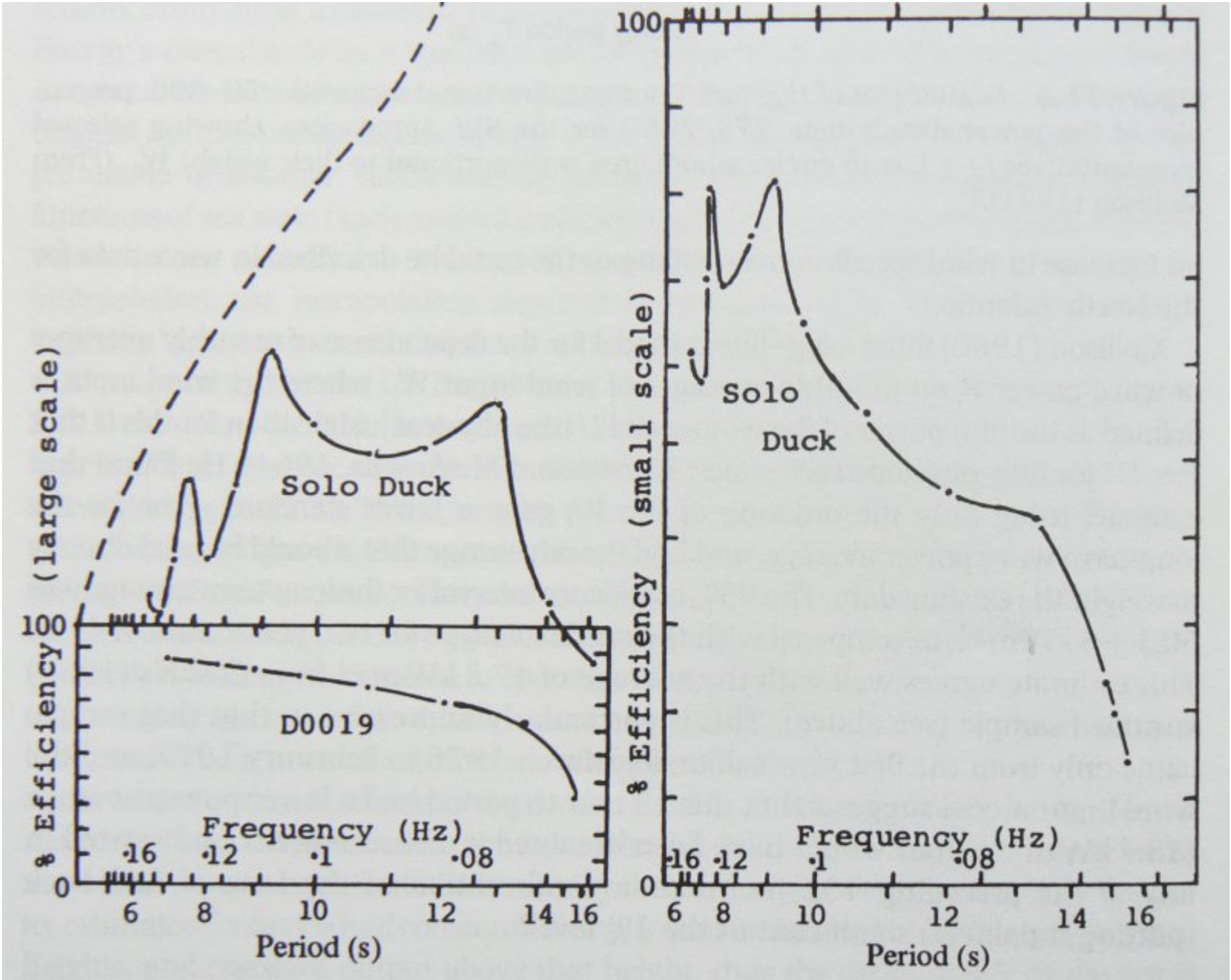
A 'wavefarm' would have 40 machines over a square km, generating power for 20,000 homes.

Small devices benefit from the point-absorber effect:

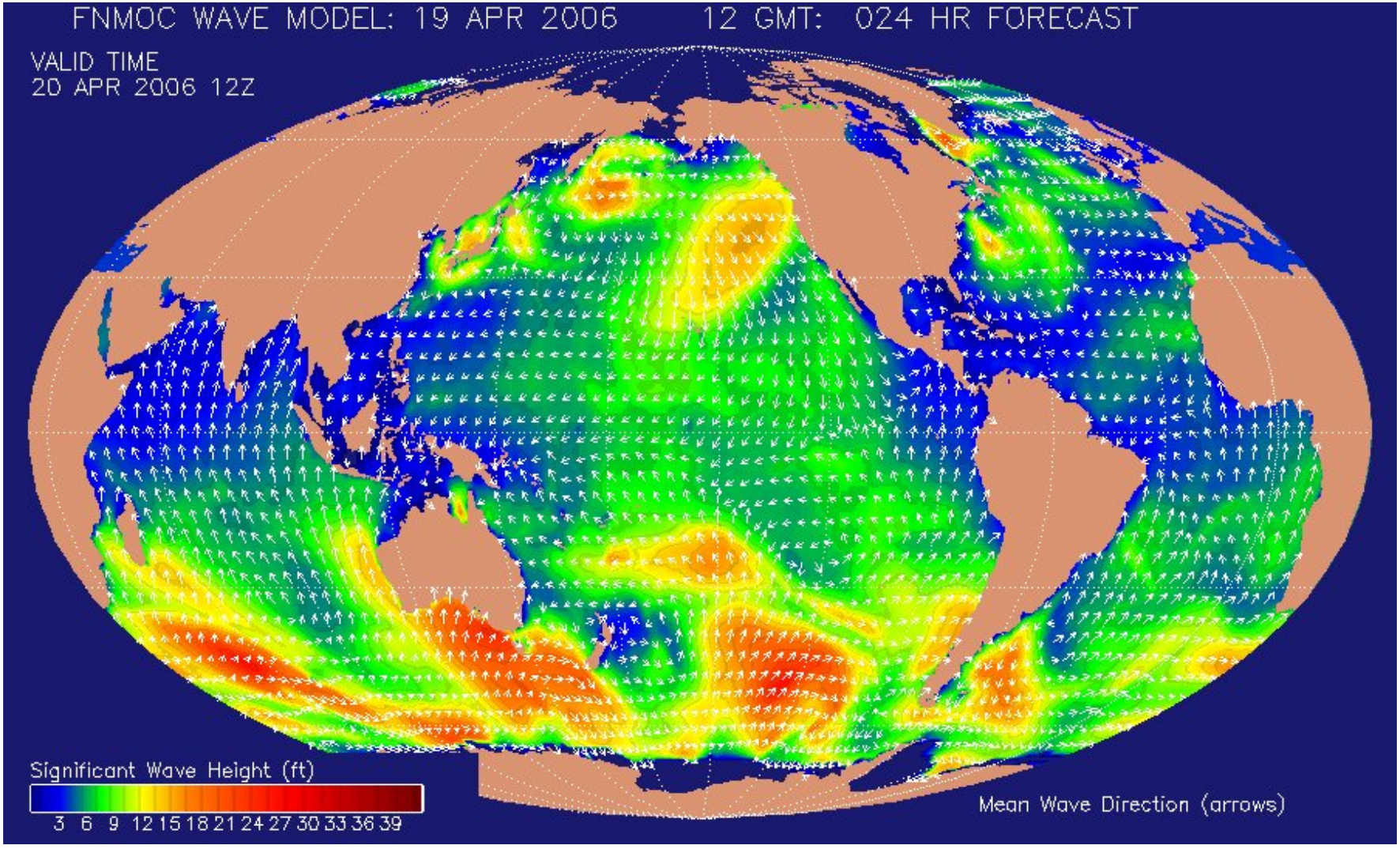
"capture width" $= \lambda/\pi$

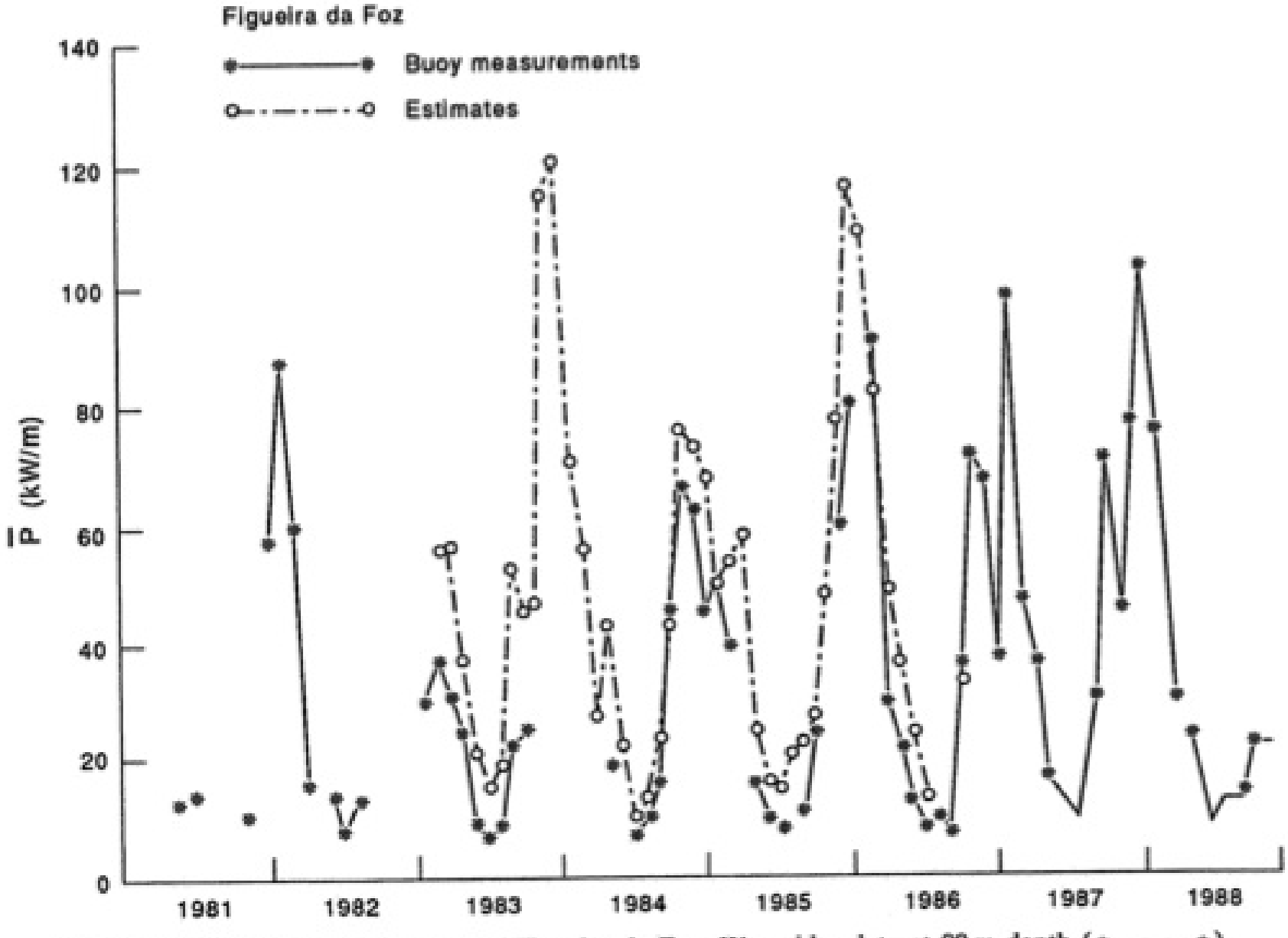
(Evans, ca. 1980)

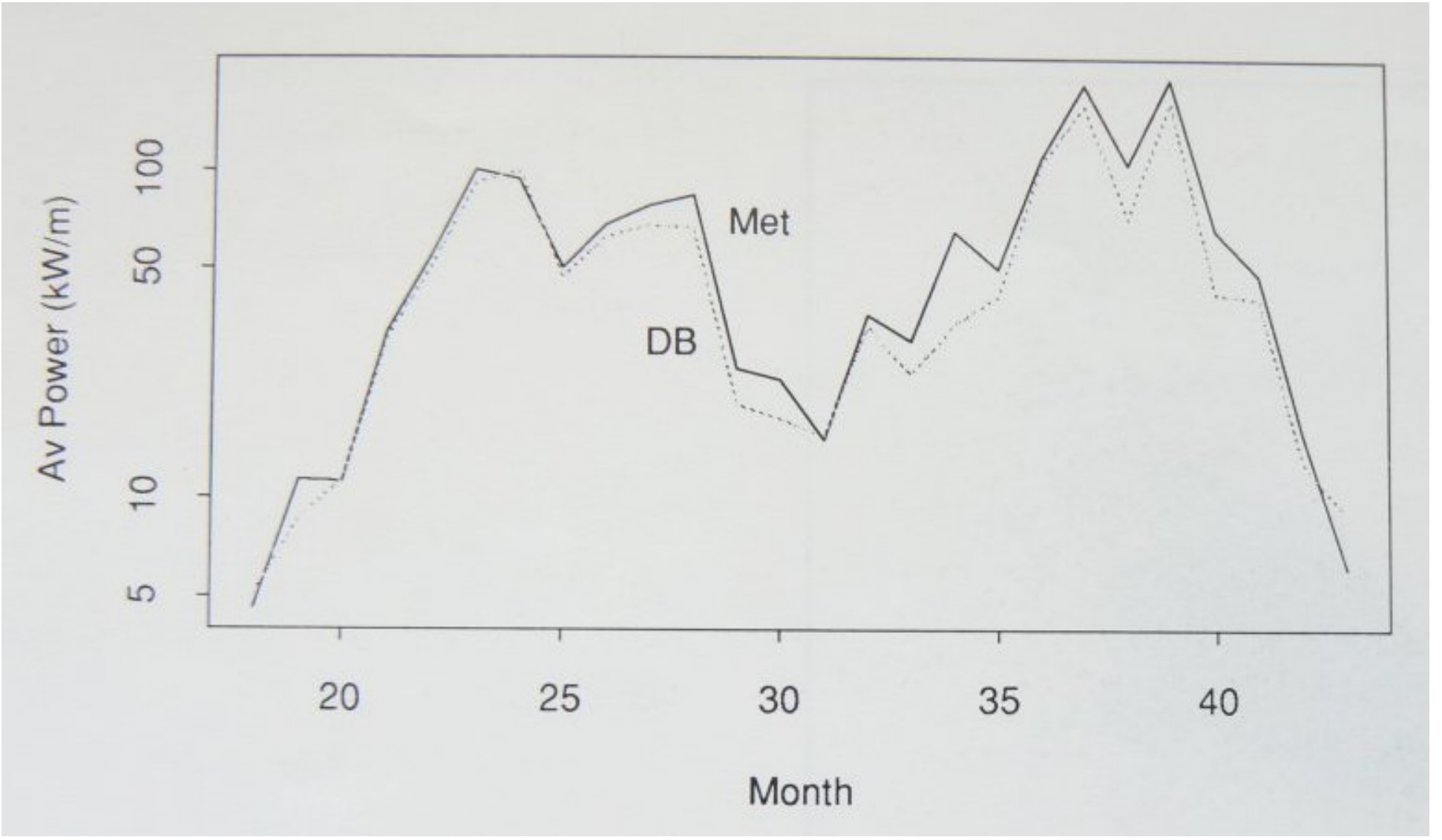

% Efficiency (large scale)
Solo Duck
100
D0019
0
Frequency (Hz)
·16
·12
·1
·08
6
8
10
12
14
16
Period (s)

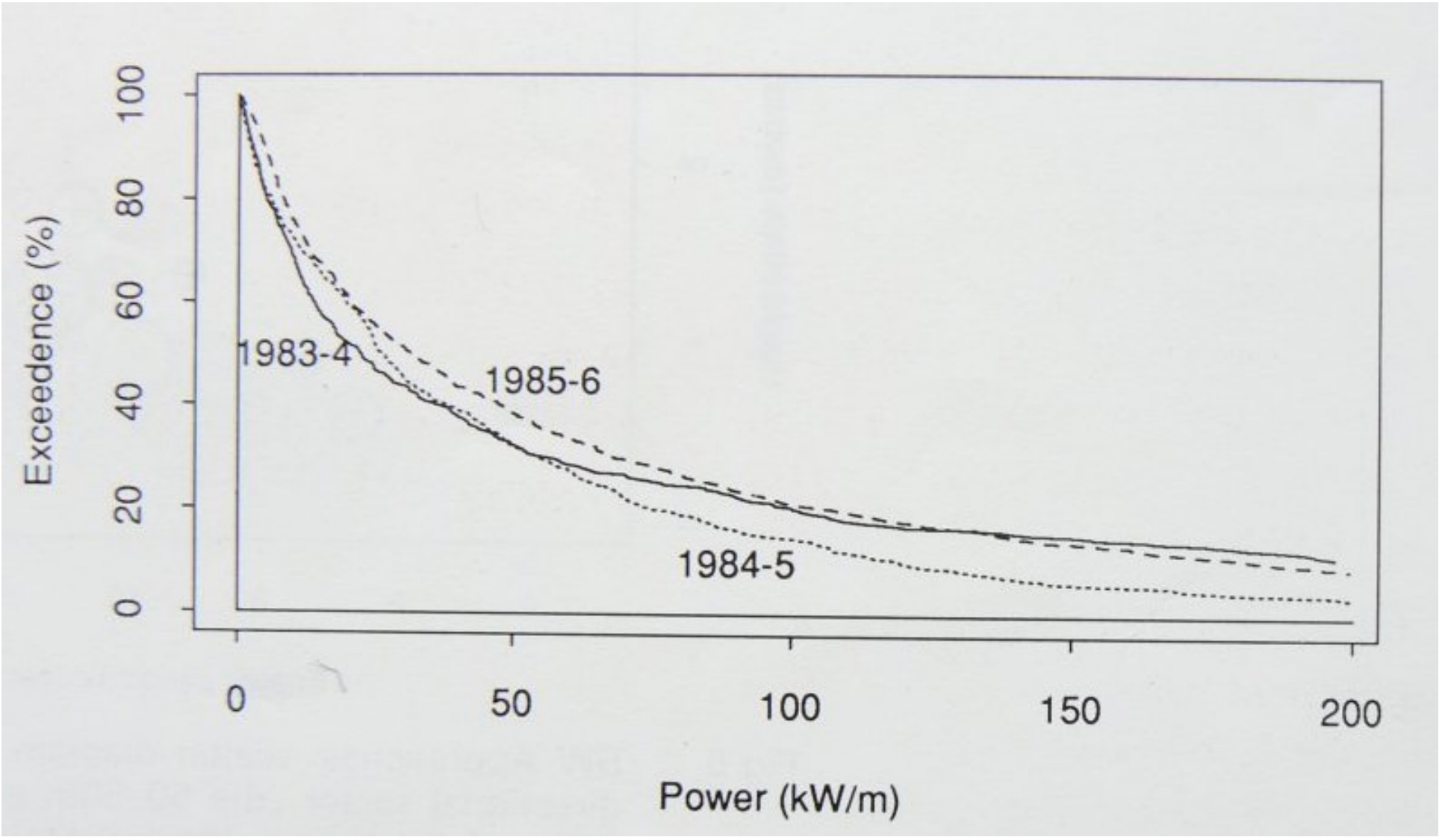

% Efficiency (large scale)
100
0
Solo Duck
D0019
Frequency (Hz)
·16
·12
·1
·08
6
8
10
12
14
16
Period (s)
% Efficiency (small scale)
100
0
Solo
Duck
Frequency (Hz)
·16
·12
·1
·08
6
8
10
12
14
16
Period (s)

5 Estimating the resource



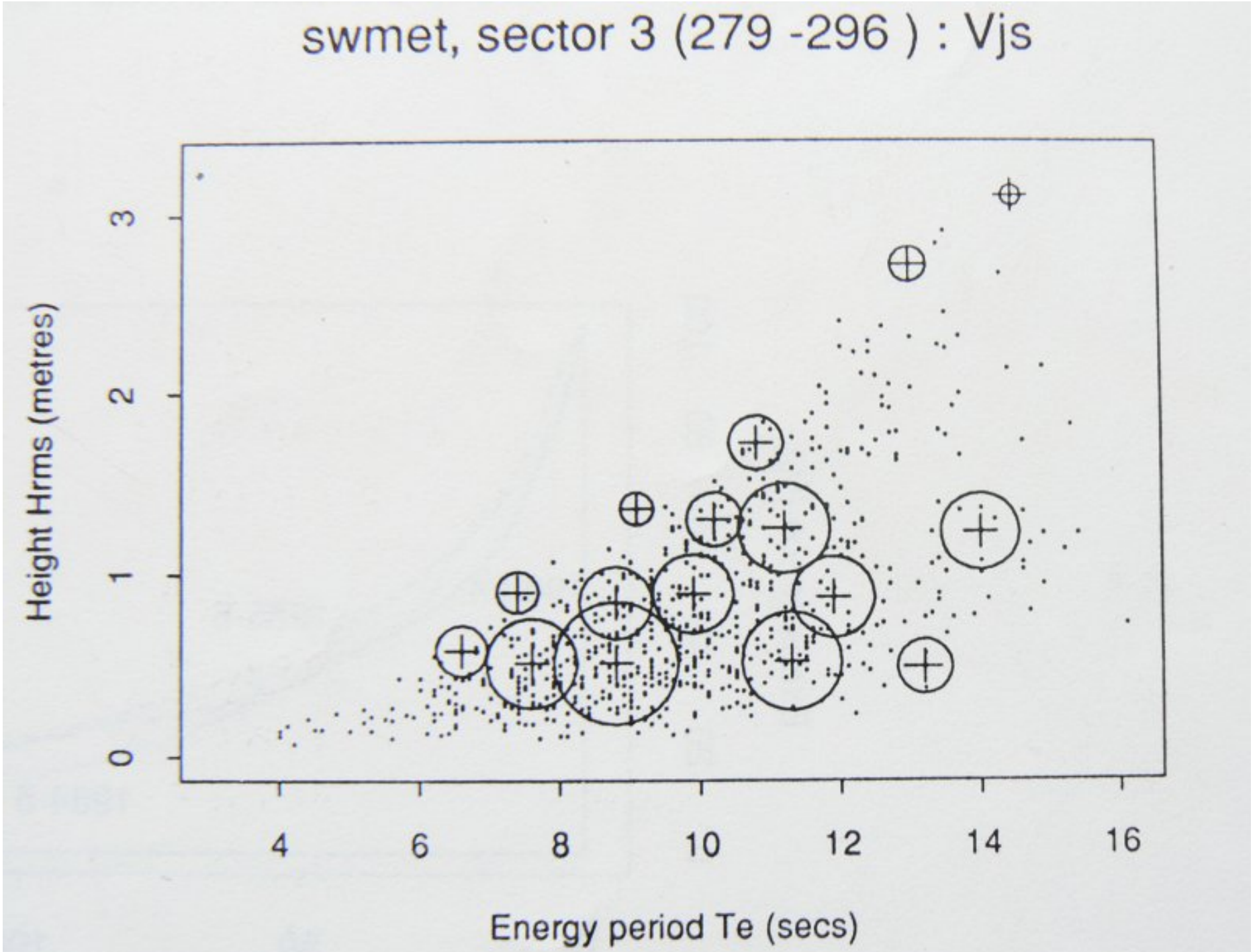

Figueira da Foz
Buoy measurements
Estimates
P (kW/m)
140
120
100
80
60
40
20
0
1981
1982
1983
1984
1985
1986
1987
1988


Av Power (kW/m)
5
10
50
100
Met
DB
20
25
30
35
40
Month

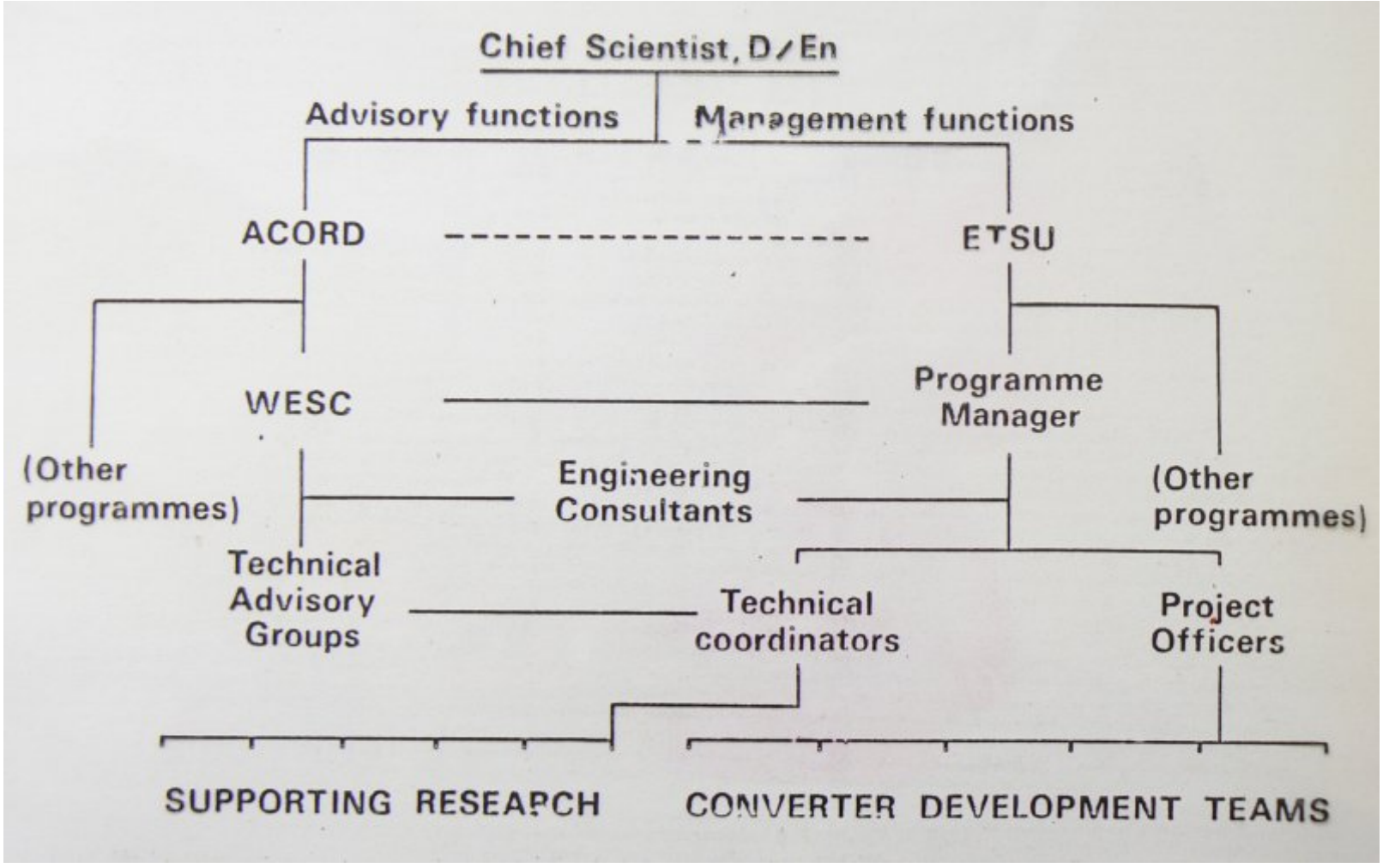

Exceedence (%)
0
20
40
60
80
100
1983-4
1985-6
1984-5
0
50
100
150
200
Power (kW/m)

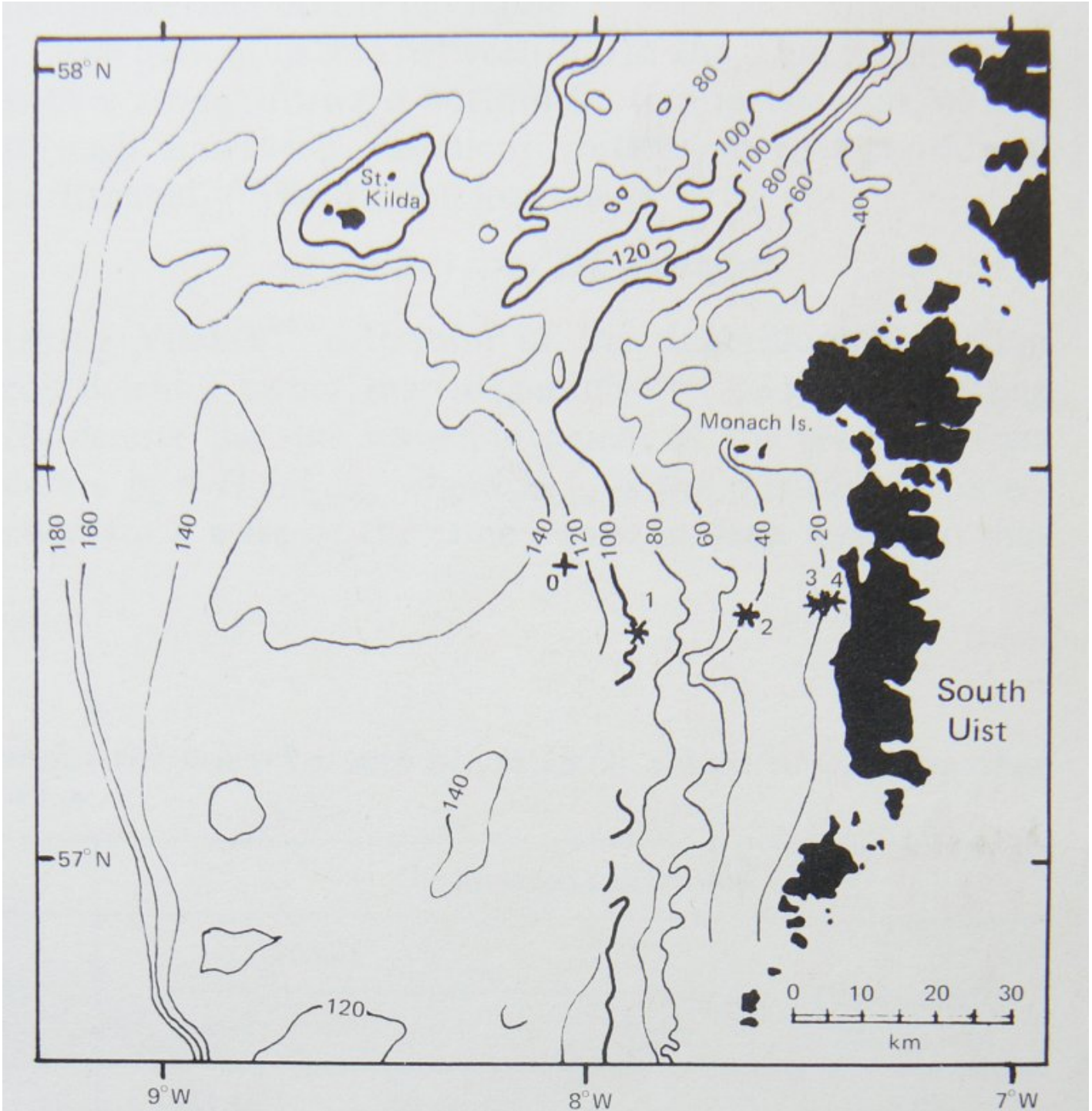
37
64
67
43
27
46
Bergen
45
67
49
70
62
42
47
63
DB1

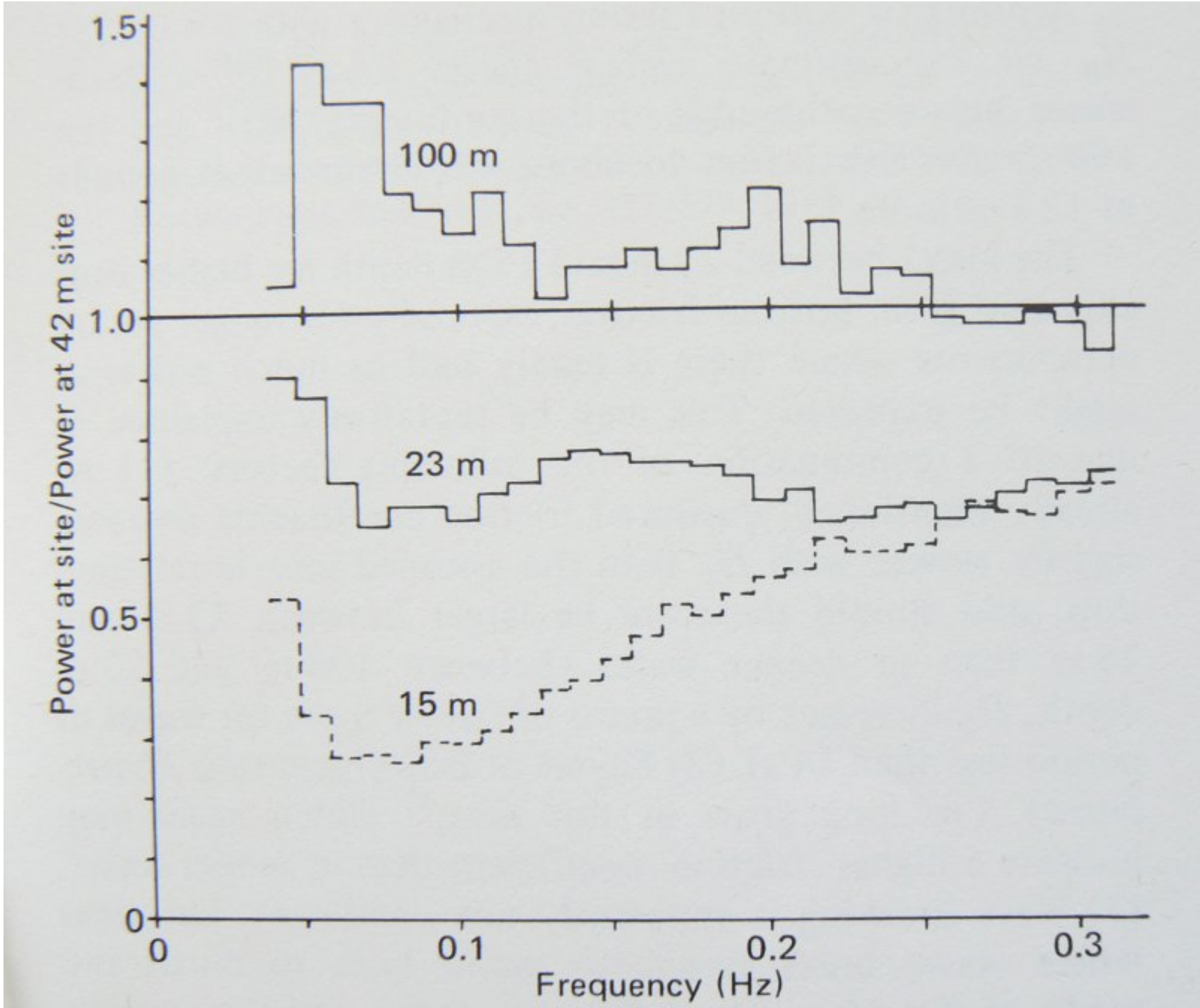
47
63
DB1
65
43
48
35
38
29
26
19

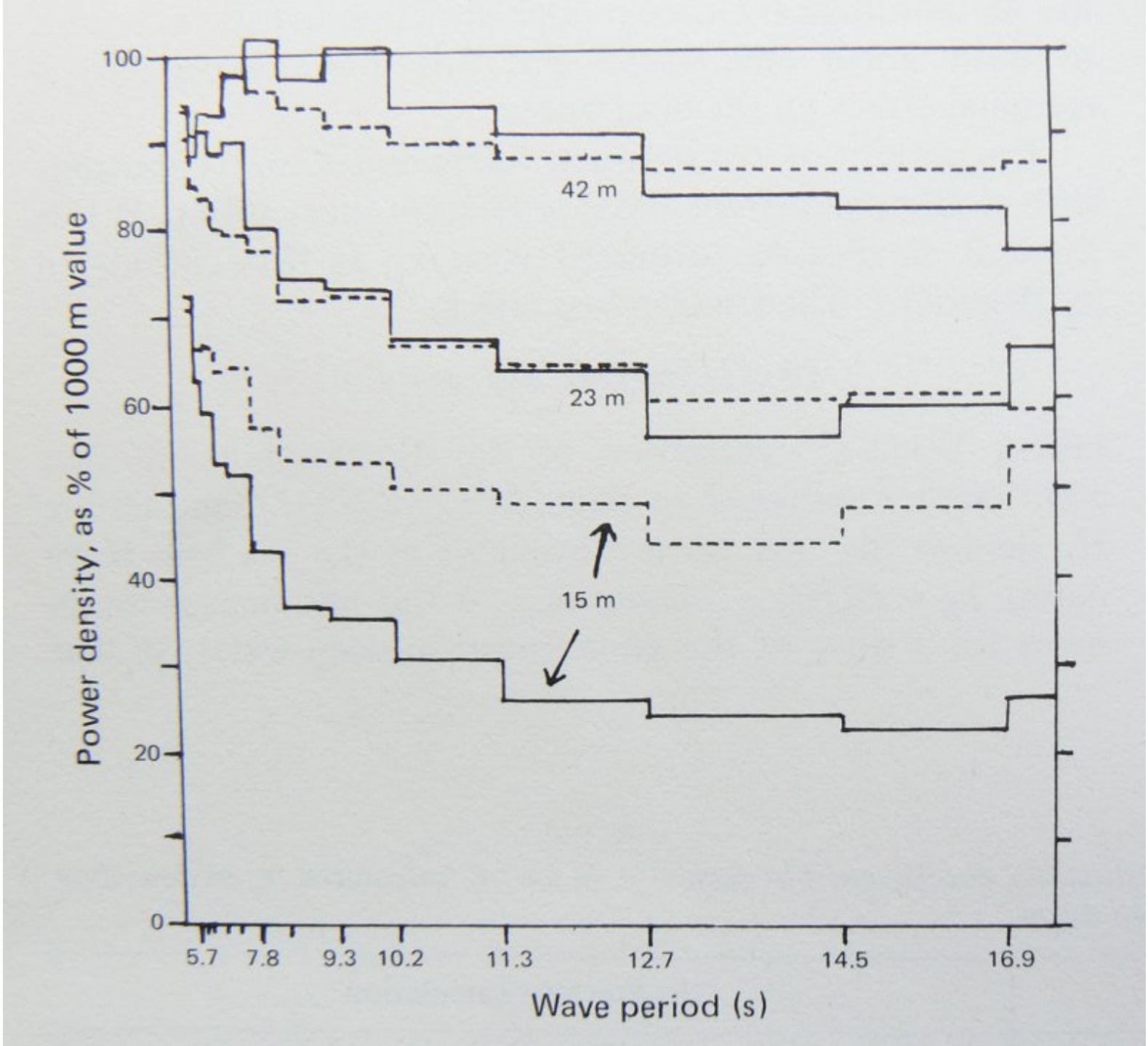

swmet, sector 3 (279 -296) : Vjs
Height Hrms (metres)
0
1
2
3
4
6
8
10
12
14
16
Energy period Te (secs)

Resource in shallow water



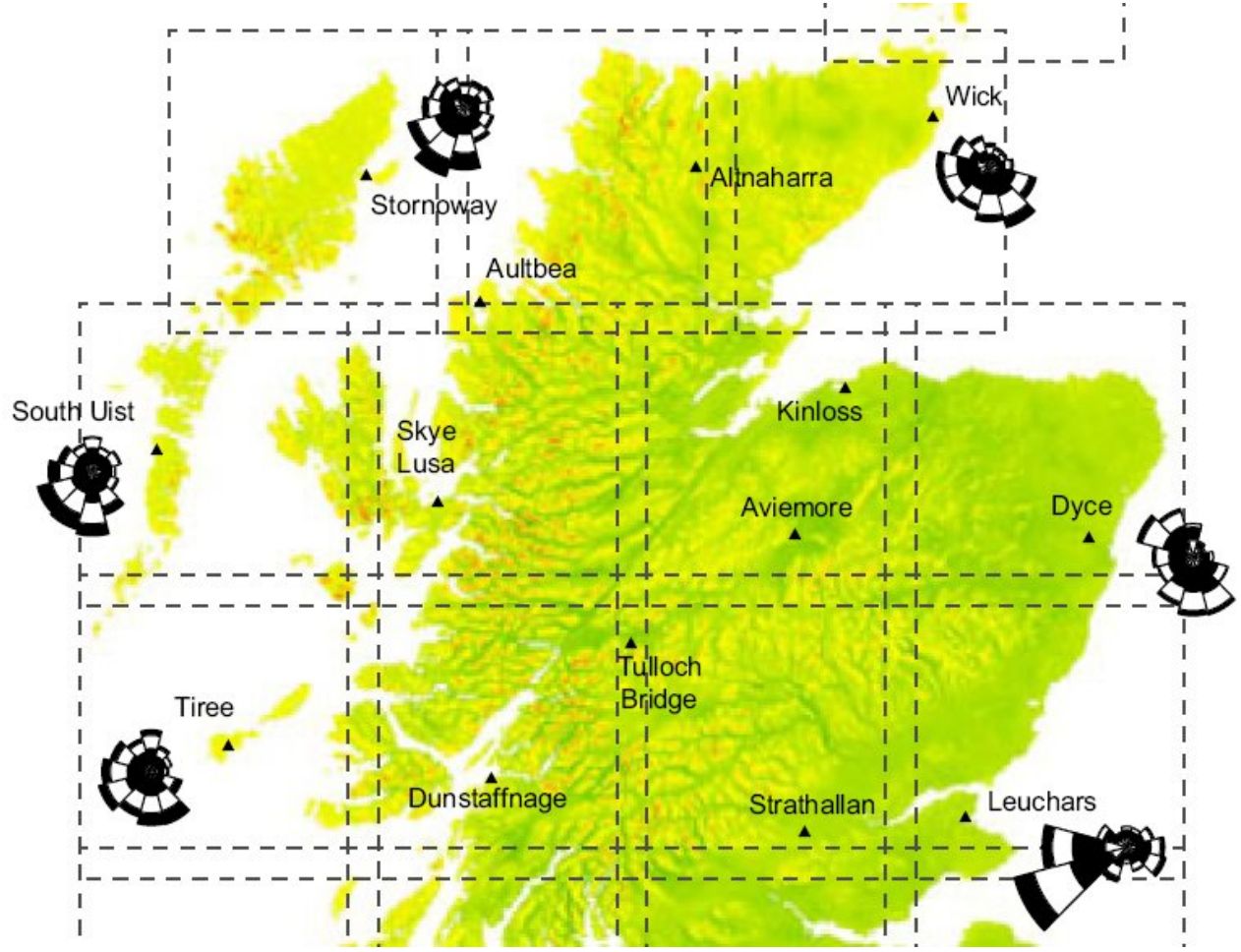

58° N
57° N
9° W
8° W
7° W
St. Kilda
Monach Is.
South Uist
180
160
140
120
100
80
60
40
20
1
2
3
4
0
10
20
30
km


1.5
1.0
0.5
0
Power at site/Power at 42 m site
100 m
23 m
15 m
0
0.1
0.2
0.3
Frequency (Hz)

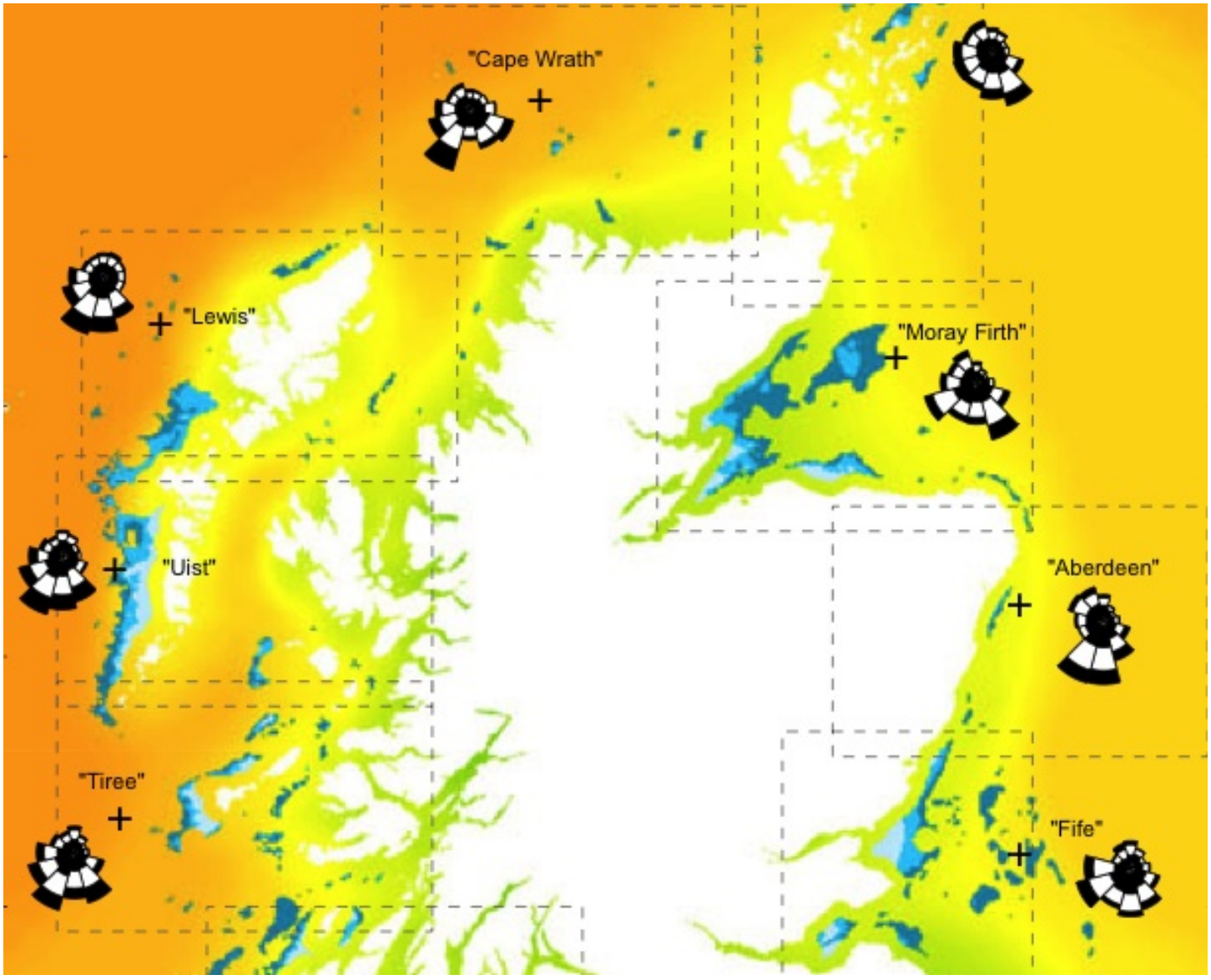

100
80
60
40
20
0
Power density, as % of 1000 m value
42 m
23 m
15 m
5.7
7.8
9.3
10.2
11.3
12.7
14.5
16.9
Wave period (s)

6 Deploying and integrating renewables

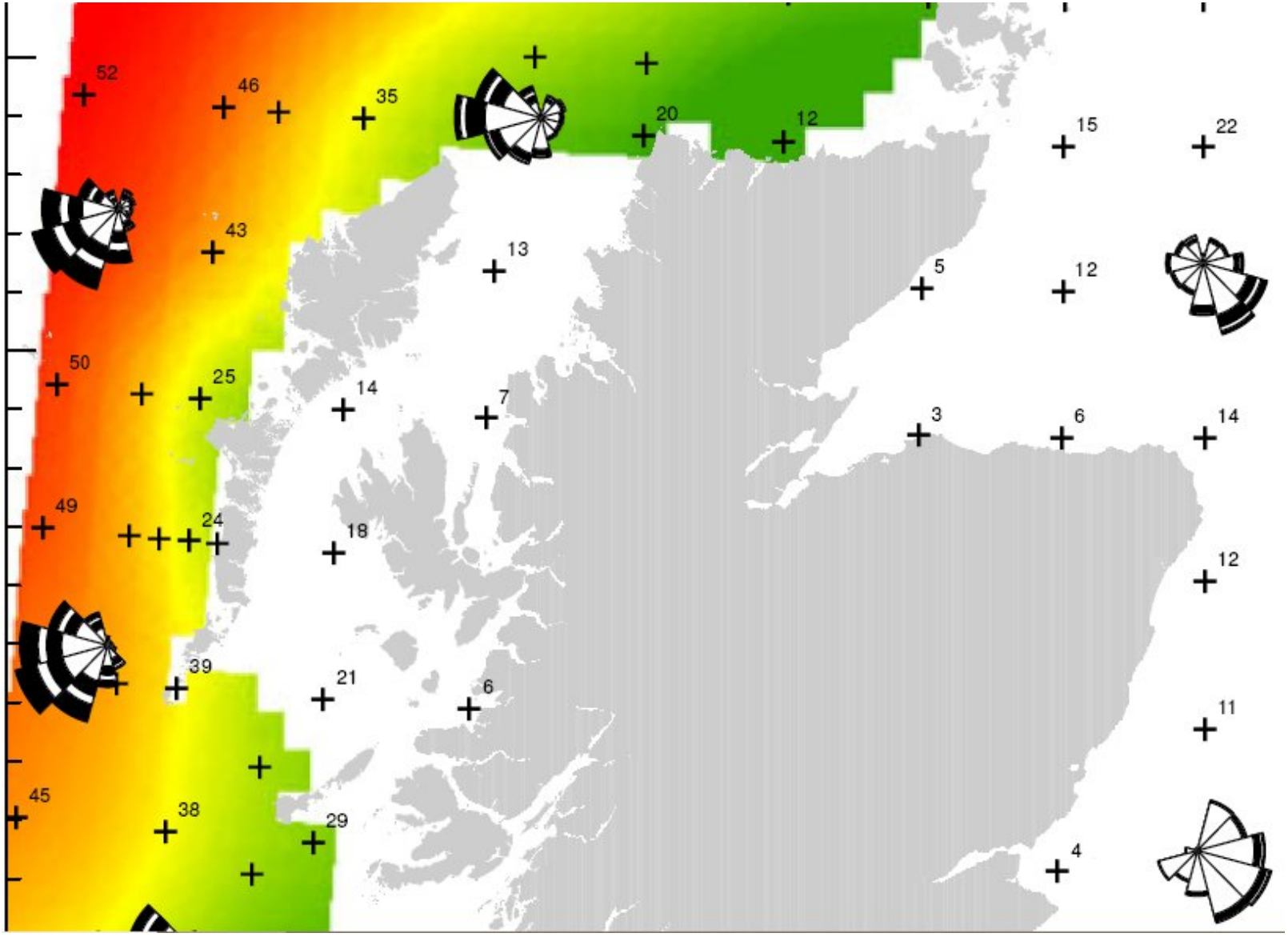
Onshore wind resource



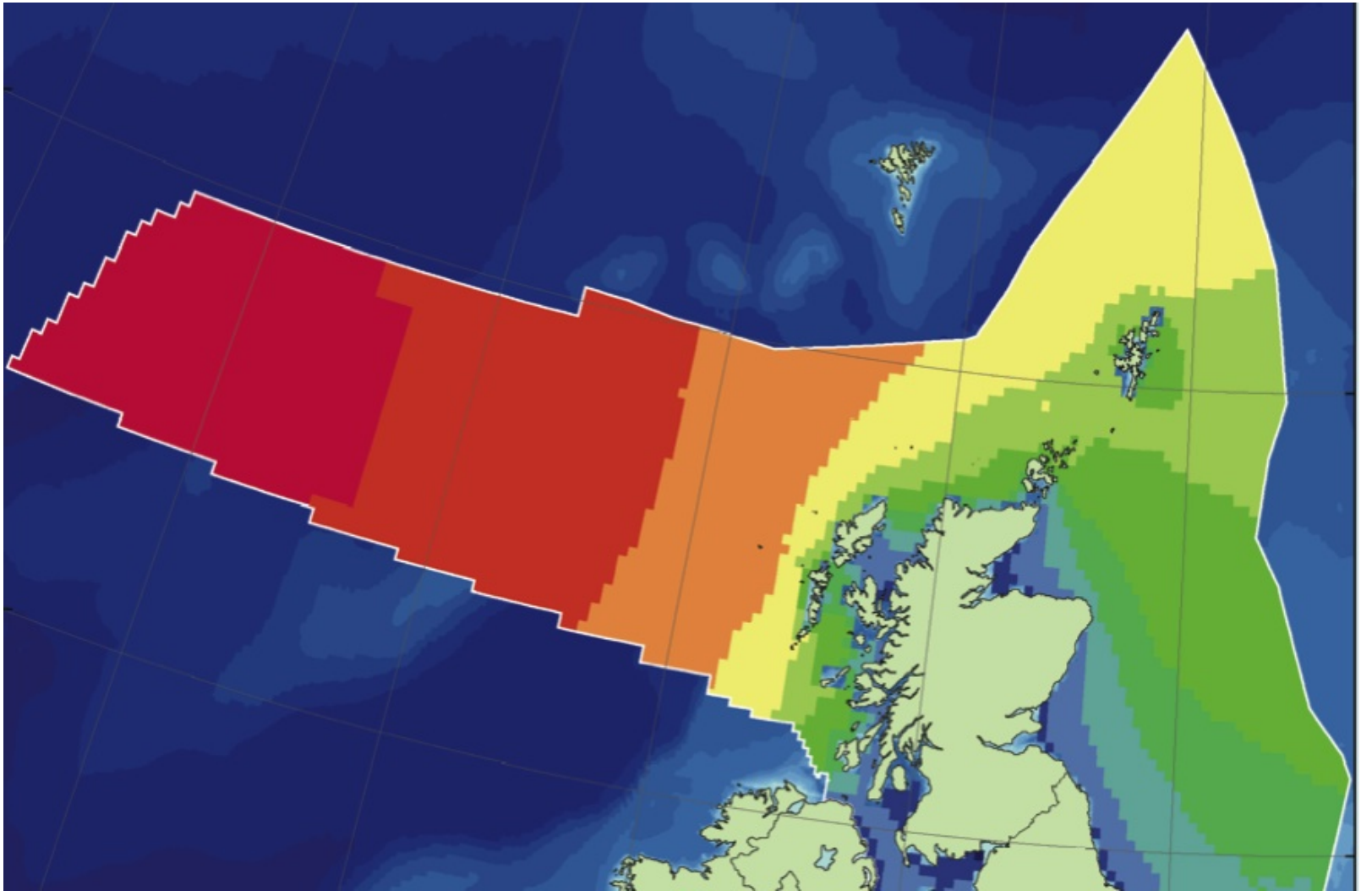
Offshore wind resource



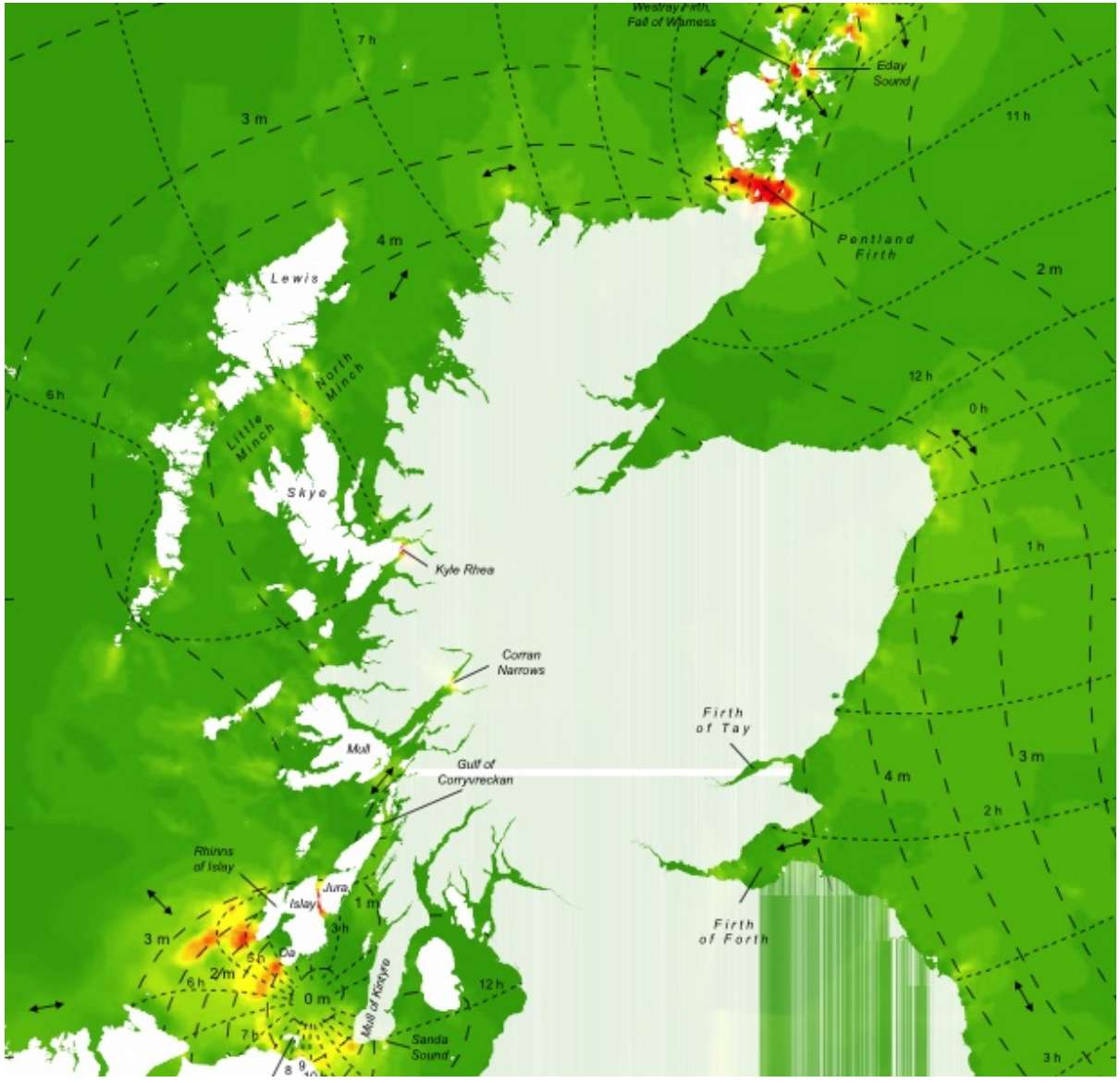
Wave resource

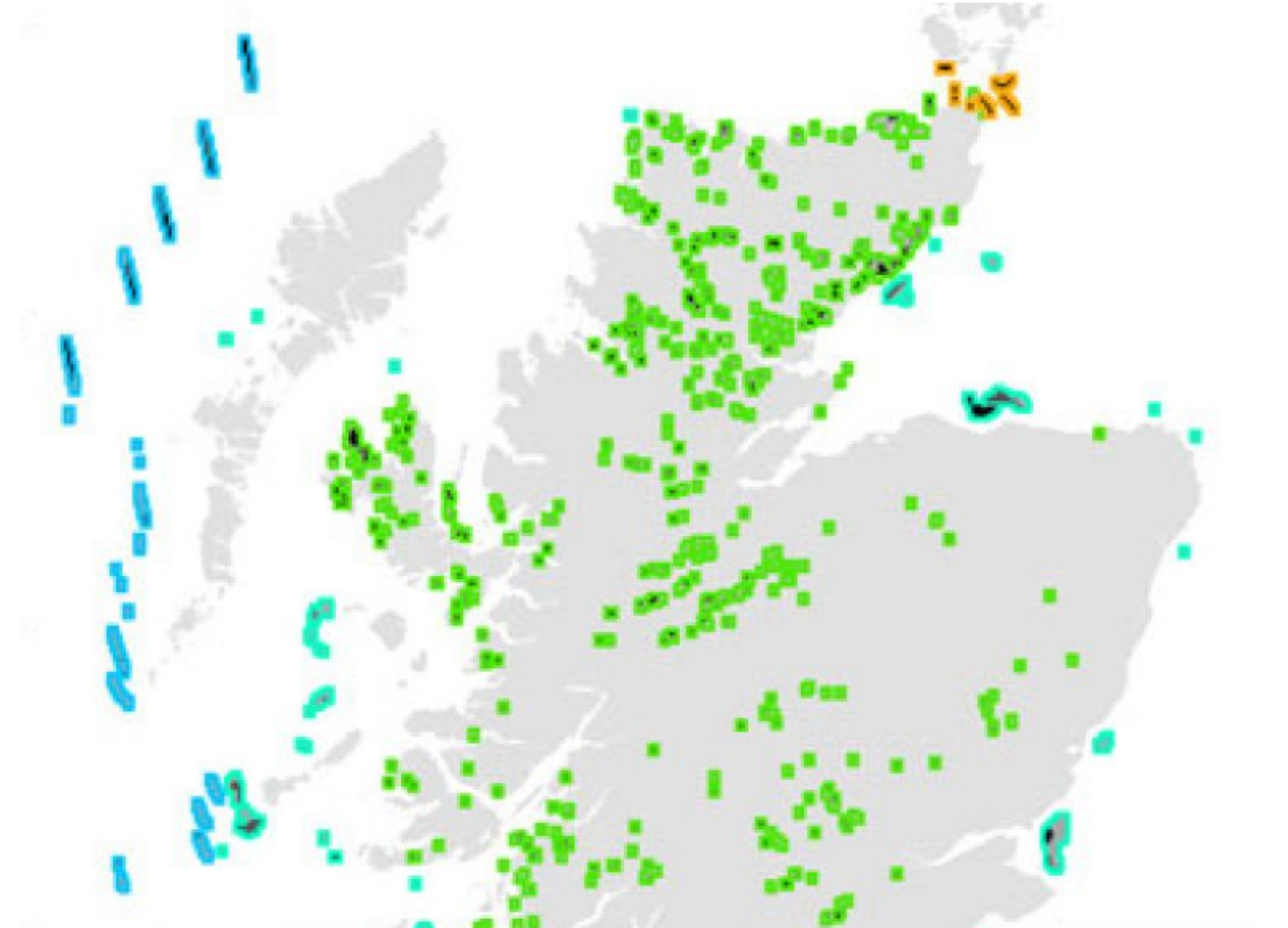


Differences between wave and wind



Tidal resource





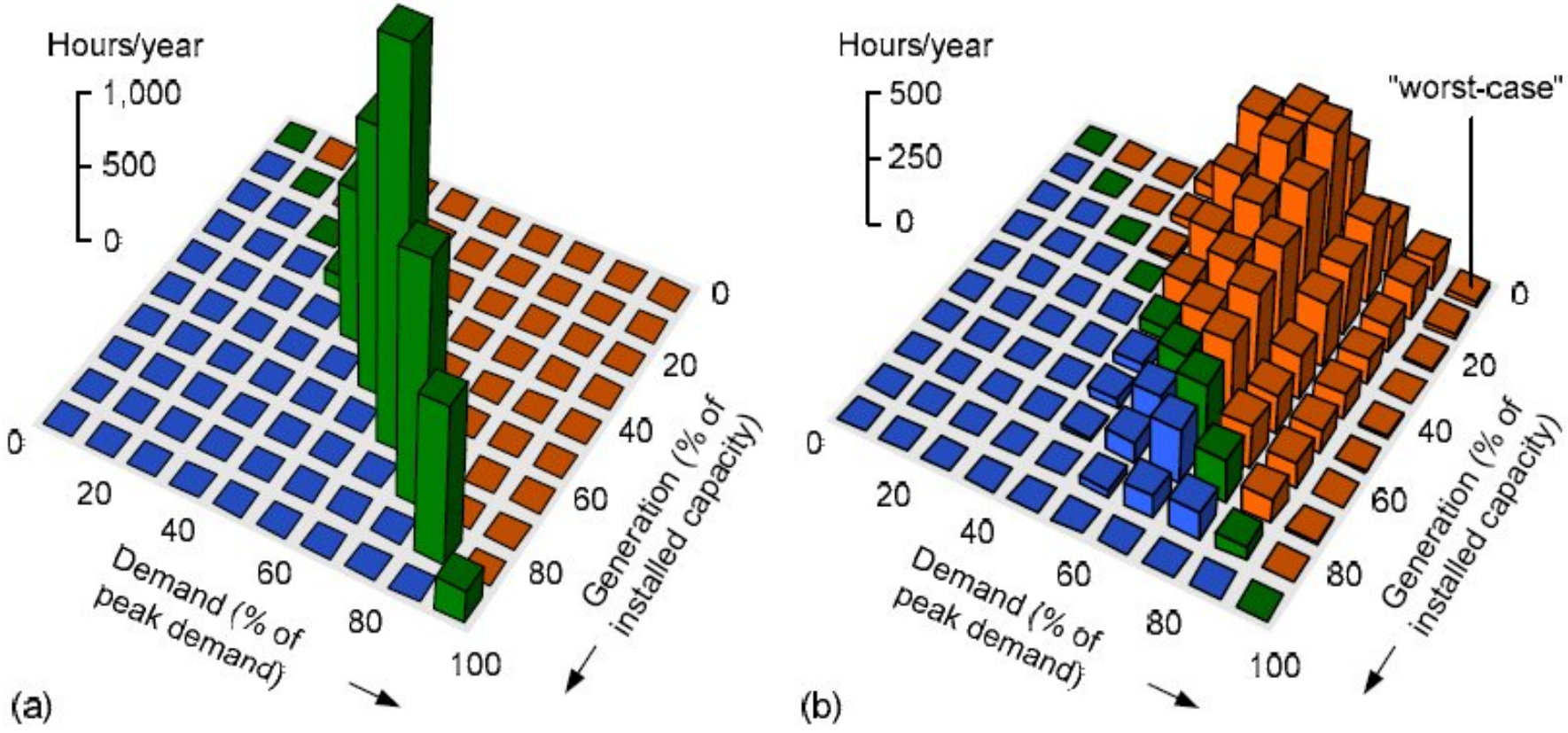
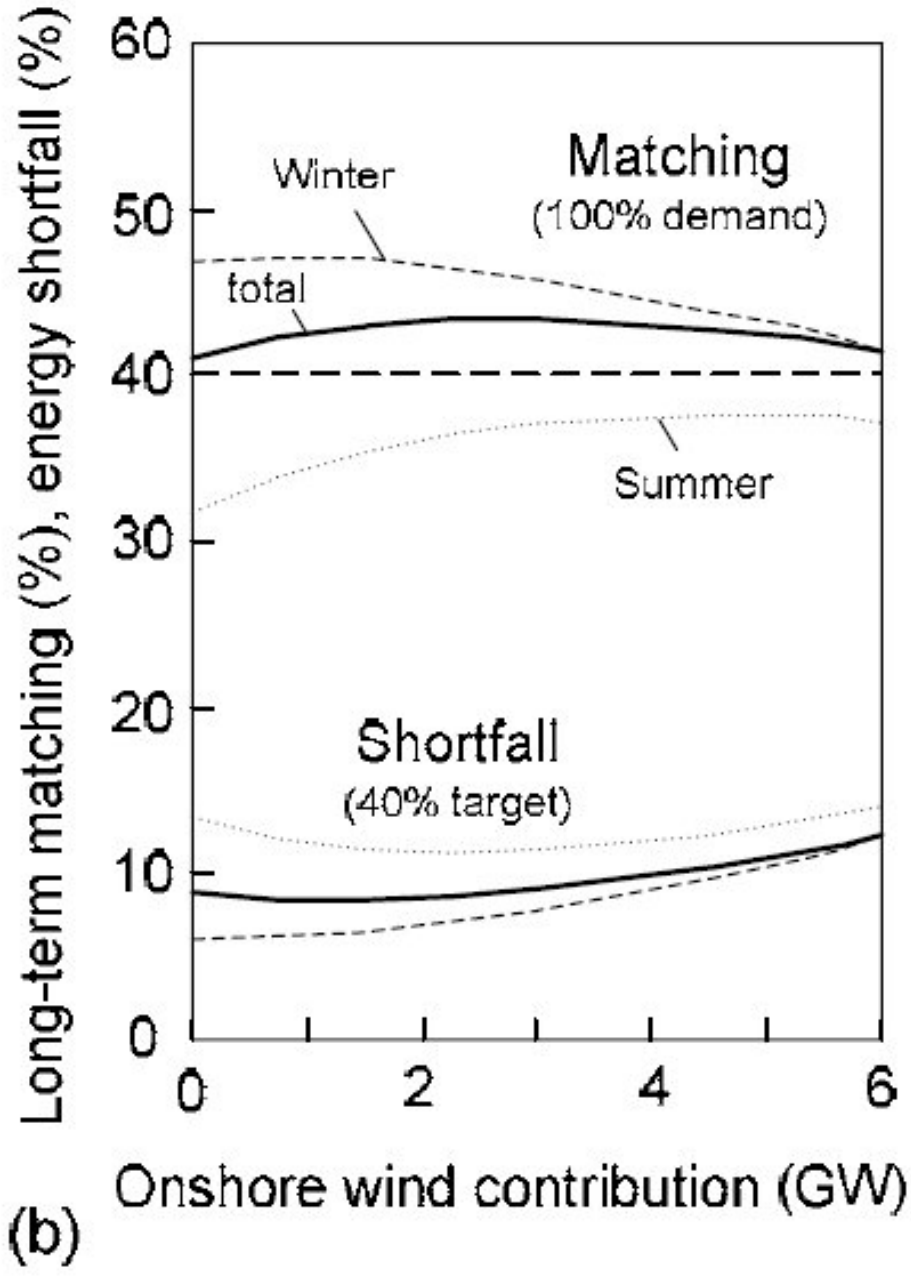
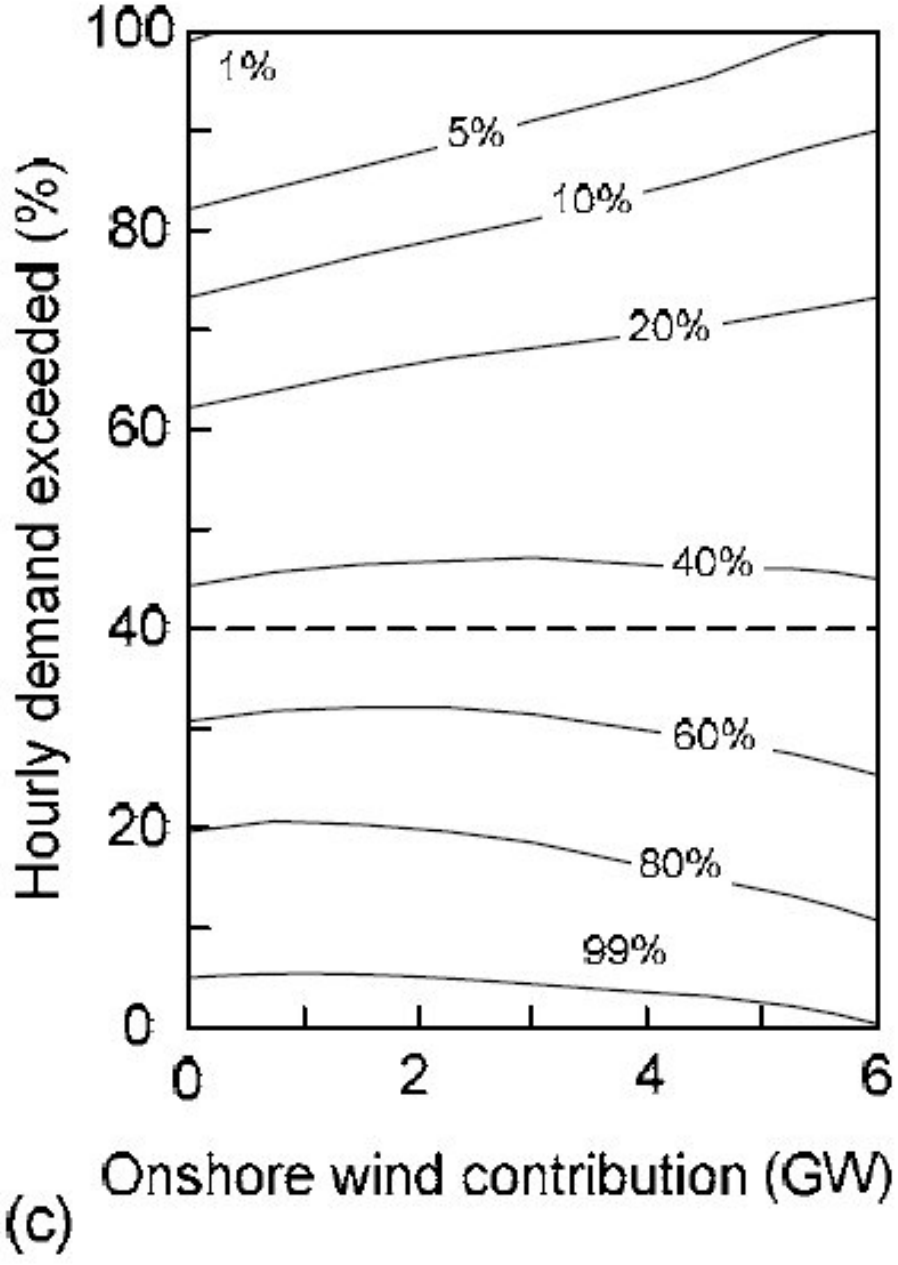


Figure 5.4 Coincident-hours histograms.
(a) Imaginary situation where generation and demand are always matched;
(b) Scenario with 6 GW broad-mix of technologies.


Long-term matching (%), energy shortfall (%)
60
50
40
30
20
10
0
0
2
4
6
Winter
Matching
(100% demand)
total
Summer
Shortfall
(40% target)
Onshore wind contribution (GW)

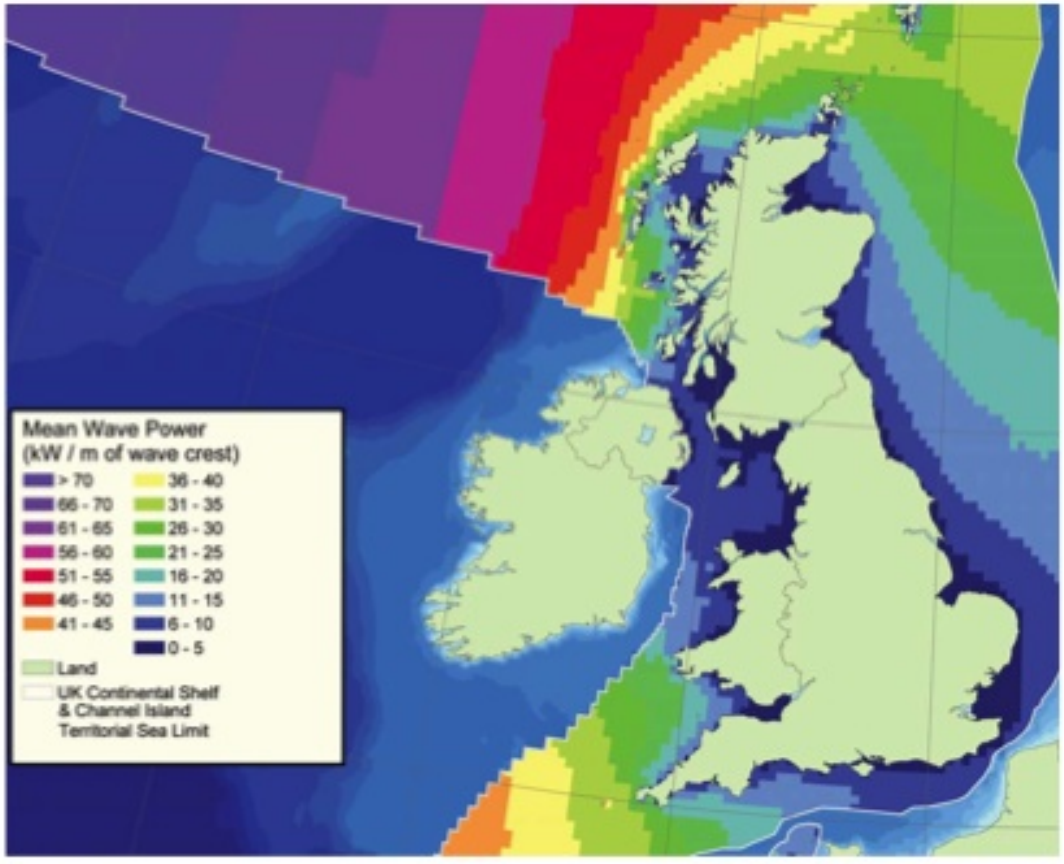
(b)


Hourly demand exceeded (%)
100
80
60
40
20
0
0
2
4
6
1%
5%
10%
20%
40%
60%
80%
99%
Onshore wind contribution (GW)

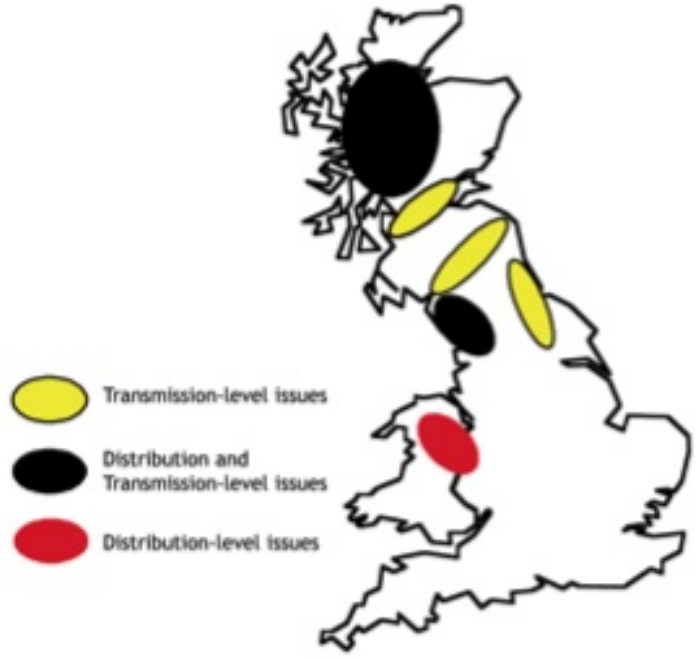
(c)

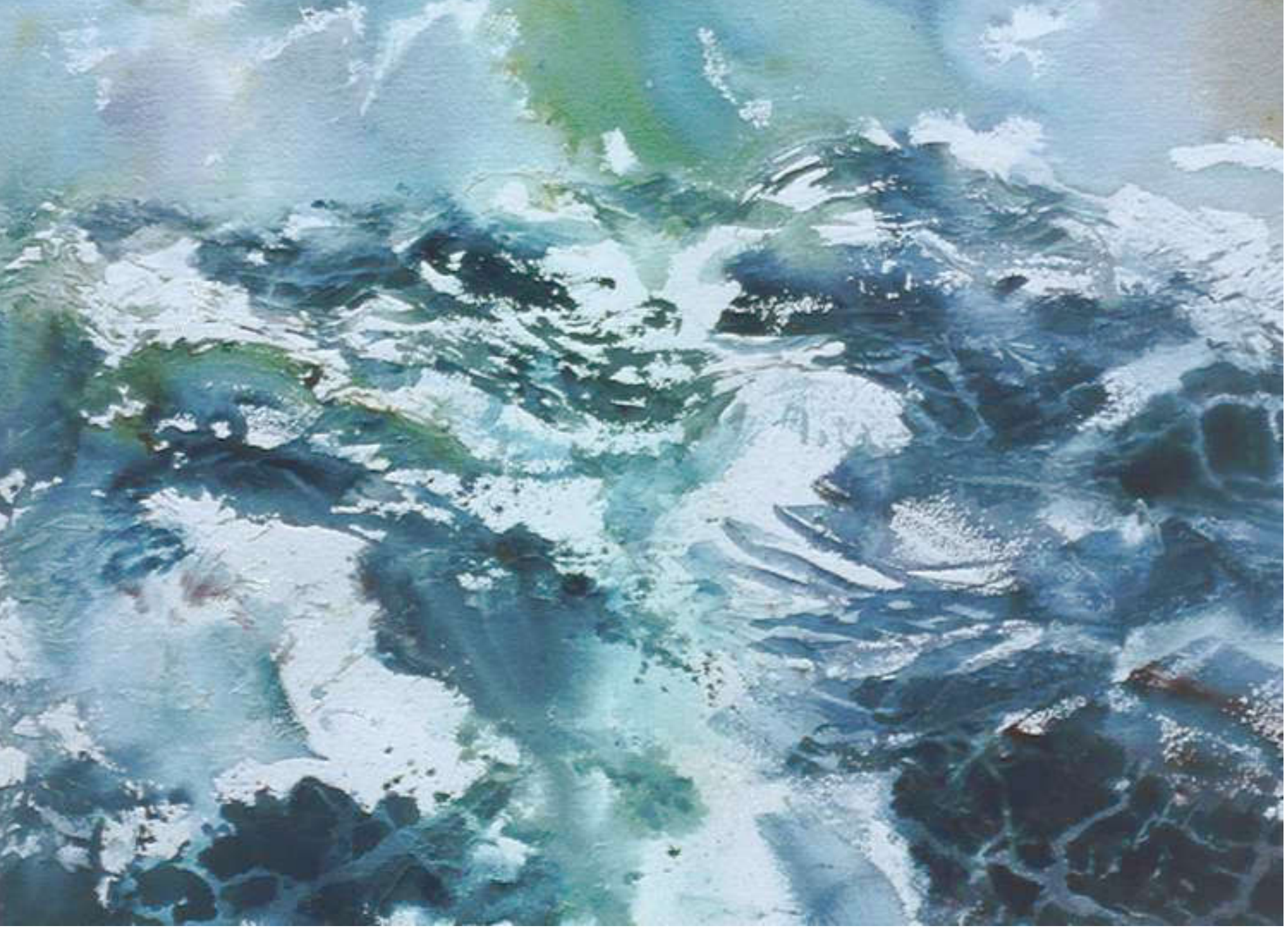
Transmission constraints?

Figure 14 *UK areas of high wave energy and grid capacity constraints*



a) Areas of high wave energy



b) Key system capacity constraints

Sources: Carbon Trust & DTI (2004), Renewables Network Impacts Study; DTI (2004), Atlas of UK Marine Renewable Energy Resources