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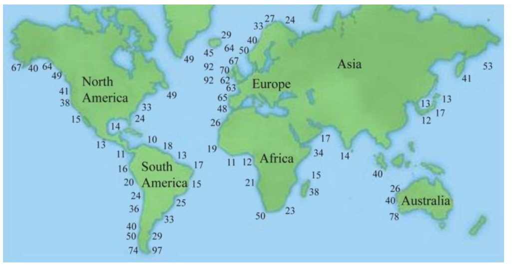
Coastlab

Wave Energy Resource



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4th CoastLab Teaching School, Wave and Tidal Energy, Porto, 17-20th January 2012

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Content

- Introduction
- What is wave energy?
- Methods to evaluate the resource
- Data bases
- Conclusions

This lecture *excludes* (see Barstow et al. 2008; Mackay 2012):

- Methods to evaluate extremes (survival)
- Detailed description of sea states

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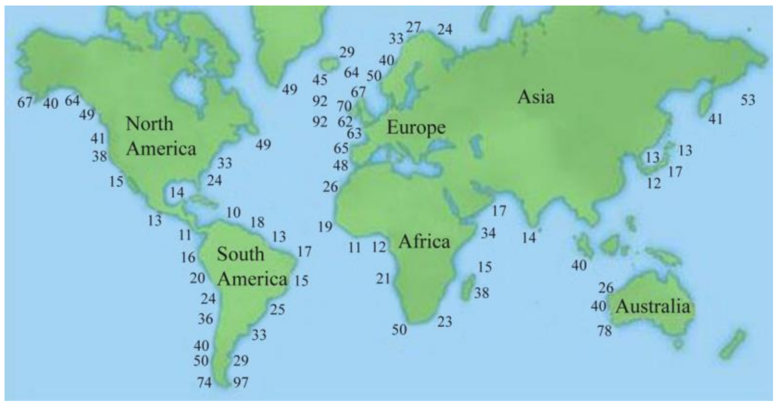
Introduction

Overview



Time averaged wave power world-wide in kW/m wave front based on numerical modelling

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Introduction

Some basics

- Wave energy is concentrated solar energy: the sun generates winds which generate waves
- The total wave energy resource is of the same order of magnitude as the world’s electricity (*not* energy) consumption namely ≈ 2 TWh, from which probably at most 10-25% could be exploited
- Generally speaking, the further away from the equator the larger is the wave power with maximum at about +50º/–50º; European west coast has about 50-70 kW/m
- The wave resource is variable on multiple scales: wave-to-wave, synoptic (weather system), seasonal, inter-annual and climatic; at least 10 years measurements are required to extrapolate the data
- Knowledge of the wave energy resource is a prerequisite for the evaluation of the economics of a WEC project
- Important parameters to characterise the wave energy resource are the wave height, period, directionality and extremes

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Introduction

Power matrix of an early version of Pelamis in irregular waves

Significant wave height H_{m0} (m) \ Energy period T_e (s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

Based on numerical modelling validated with scale model and full-scale measurements

H_{m0} = average of highest one-third of wave heights
T_e = for a given spectrum, this corresponds to the period of a regular wave which would have the same significant wave height and energy content as that spectrum

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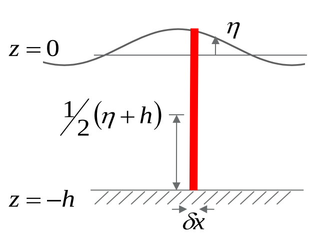
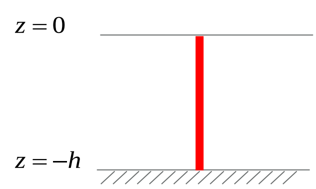
What is wave energy?

Total energy of wave = potential energy + kinetic energy

Potential Energy = "*mgh*" of wave motion – "*mgh*" of still water





$$"mgh" = [\delta x(\eta+h)\rho]g\left[\frac{\eta+h}{2}\right] = \frac{1}{2}\rho g(\eta+h)^2\delta x$$

$$"mgh" = [\delta x h\rho]g\frac{h}{2} = \frac{1}{2}\rho g h^2\delta x$$

ρ (kg/m^3) = fluid density h (m) = water depth g (m/s^2) = gravitational acceleration
δx (m) = increment m (kg) = mass η (m) = water surface elevation

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What is wave energy?

Total energy of wave = potential energy + kinetic energy

The **average potential energy** is obtained as the integral over one wavelength

$$E_P = \frac{1}{\lambda}\int_{x_0}^{x_0+\lambda}\left[\frac{1}{2}\rho g(\eta+h)^2 - \frac{1}{2}\rho g h^2\right]dx$$

Adopting linear wave theory

$$\eta = a\sin(\omega t - kx) \qquad \int_{x_0}^{x_0+\lambda}\sin(\omega t - kx) = 0 \qquad \int_{x_0}^{x_0+\lambda}\sin^2(\omega t - kx) = \frac{\lambda}{2}$$

Using these results yields the potential energy as

$$\boxed{E_P = \frac{1}{4}\rho g a^2}$$

Note that the energy is **proportional** to the **square** of the wave **amplitude**

a (m) = wave amplitude *k* (1/m) = wave number λ (m) = wave length ω (1/s) = angular frequency

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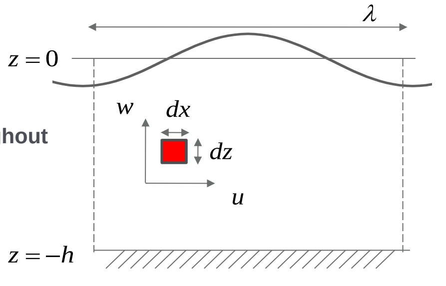
What is wave energy?

Total energy of wave = potential energy + kinetic energy

The **total kinetic energy** is given as the sum of " 1/2*mv*²" over all fluid particles.

$$(velocity)^2 = u^2 + w^2$$

$$\frac{1}{2}mv^2 = \frac{1}{2}\rho(u^2 + w^2)dxdz$$



This expression must be integrated **throughout** the fluid flow

$$E_K = \frac{1}{\lambda}\int_{x_0}^{x_0+\lambda}\int_{-h}^{0}\frac{\rho}{2}(u^2 + w^2)dxdz$$

The velocity components (*u*, *w*) are

$$u = a\omega\frac{\cosh k(z+h)}{\sinh(kh)}\sin(\omega t - kx) \qquad w = a\omega\frac{\sinh k(z+h)}{\sinh(kh)}\cos(\omega t - kx)$$

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What is wave energy?

Total energy of wave = potential energy + kinetic energy

Substituting the expressions for (u, w) yields the **kinetic energy** as

$$\boxed{E_K = \frac{1}{4}\rho g a^2}$$

and the total wave energy is

$$\boxed{E = E_P + E_K = \frac{1}{2}\rho g a^2}$$

Often it is useful to express the energy as **energy per unit wavelength**

$$E_\lambda = E\lambda = \frac{1}{2}\rho g a^2 \lambda$$

Assuming **deep water condition** with $\omega^2 = gk$ gives

$$E_\lambda = \frac{1}{4\pi}\rho g^2 a^2 T^2$$

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What is wave energy?

Total energy of wave = potential energy + kinetic energy

The energy calculated so far is associated with the **total fluid motion** and this relates to water that (averaged over time) **remains** at the **same location**

What is the transport of energy across vertical sections of water?

An expression relevant for the **energy** that is **carried forward** (transfer of energy) is the group velocity

$$c_g = \frac{c}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right]$$

where c is the **phase velocity**

$$c = \frac{\omega}{k}$$

The **transmitted power** is the product of the **energy** and the **group velocity**

$$\boxed{P = Ec_g = \frac{1}{2}\rho g a^2 c_g}$$

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What is wave energy?

Total power P

For *regular* waves in deep-water written with wave height H instead of a:

$P = \rho g^2 H^2 T/(32\pi)$ with $H = 2a$ and $c_g = gT/(4\pi)$

For *irregular* waves in deep-water:

$P = \rho g^2 H_s^2 T_z/(64\pi)$

H_s = significant wave height (average of highest one-third of wave heights)
T_z = average wave period

Check of units: $[kg/m^3][m^2/s^4][m^2][s] = (kgm/s^2)/s = N/s = (Nm/s)/m = W/m$

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Methods to evaluate the resource

Overview

Three main categories are available:

In-situ measurements
- *Buoy*
- Pressure transducers
- Wave staff
- Ship-borne wave recorders

Remote sensing
- *Satellite Radar Altimetry RA*
- Satellite Synthetic Aperture Radar SAR
- Marine wave radar

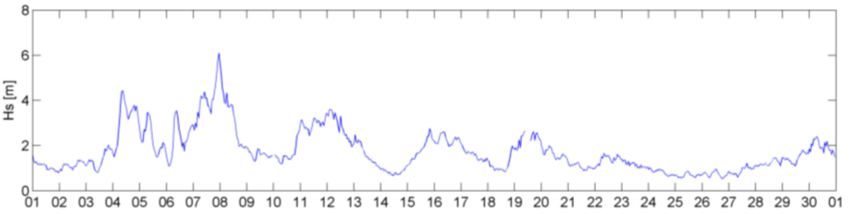
Numerical wave models
- Deep-water models: WAM (WAve Model from ECMWF), WaveWatch III
- Shallow-water models (include bottom friction, breaking): SWAN, TOMAWAC, MIKE21

Methods to evaluate the resource: In-situ measurements

Waverider buoy

- Applied to measure waves since the early 1960s
- Work with motion sensors such as accelerometers
- About 3000 buoys are currently under operation
- Buoys can be moored or free floating

Example: significant wave height H_s measured for 31 days with a buoy at EMEC, Scotland



Mackay (2012)

Methods to evaluate the resource: In-situ measurements

Waverider buoy

Advantages:

- Measure wave height, period, mean direction, position, water temperature, wind speed, atmospheric pressure as temporal averages
- Direct and accurate measurement at 4 Hz
- Work up to 3 years without service
- Often used to calibrate/validate other systems

Disadvantages:

- Point measurement
- Long-term buoy wave measurement networks are relatively few and far between
- Relatively expensive to measure large areas

Ideal for:

- Local measurement next to a WEC
- Calibration and validation of other systems

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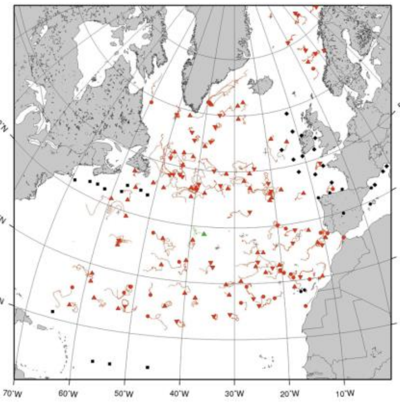
Methods to evaluate the resource: In-situ measurements

Buoys

Buoys are mainly operated by meteorological organisations (not all of them measure wave data) and data are available from e.g.:

- Data Buoy Cooperation Panel DBCP (joint body of the World Meteorological Organisation and Intergovernmental Oceanographic Commission of UNESCO)
- E-SURFMAR (Surface Marine observation programme of the Network of European Meteorological Services)
- ECMWF (European Centre for Medium-range Weather Forecast)



E-SURFMAR buoy network in March 2010

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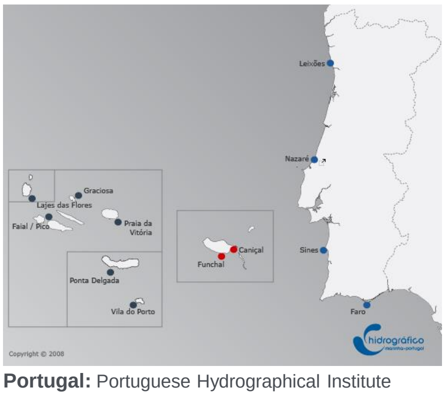
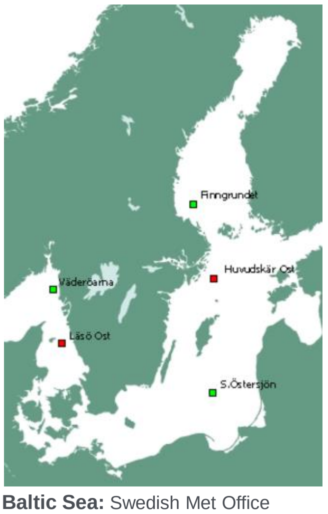
Methods to evaluate the resource: In-situ measurements

Buoys in Europe (Meyers et al. 2011)



Portugal: Portuguese Hydrographical Institute



Baltic Sea: Swedish Met Office

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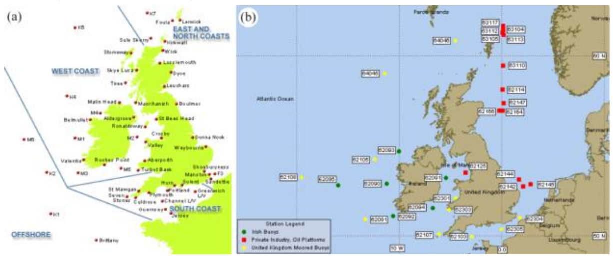
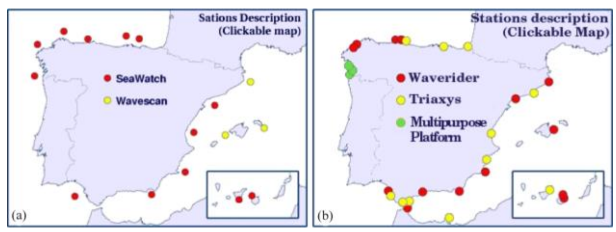
Methods to evaluate the resource: In-situ measurements

Buoys in Europe (Meyers et al. 2011)



UK and Ireland: UK's Met Office and U.S. National Data Buoy Center



Spain: Spanish National Ports & Harbours Authority

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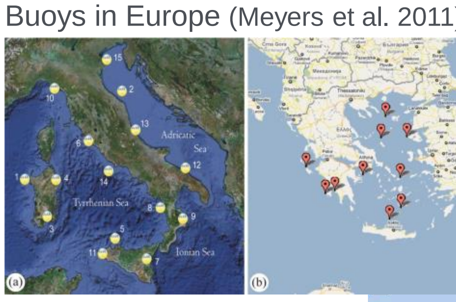
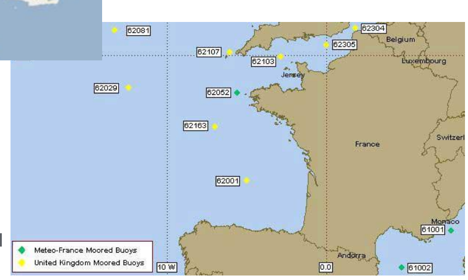
Methods to evaluate the resource: In-situ measurements

Buoys in Europe (Meyers et al. 2011)



Italy and Greece: Vicinanza et al. (2009) and POSEIDON programme



France and of South UK: U.S. National Data Buoy Center

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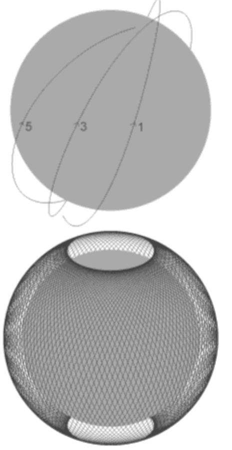
Methods to evaluate the resource: Satellite Altimetry

Satellite radar

- Satellite with coastal applications: NASA (SEASAT, 1978), US Navy (GEOSAT), NASA with French Space Agency (TOPEX/Poseidon, Jason-1/2) and European Space Agency (Envisat, ERS-1/2)
- Satellites orbit the Earth on a constant path with a repeat period of 10 to 35 days
- Two types: *satellite Radar Altimetry RA* (e.g. ERS-2, SEASAT) and *Synthetic Aperture Radar SAR* (e.g. ERS-2, TOPEX/Poseidon)
- SAR records a square area of 100×100 km^2
- RA takes a measurement each 7 km (1 Hz) with footprint diameter of 2-10 km; it sends a radar pulse and records return pulse; its shape provides significant wave height and travel time distance



TOPEX: first 5 passes of a cycle (top) and (bottom) full cycles, Mackay (2012)

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Methods to evaluate the resource: Satellite Altimetry

Satellite Radar Altimetry RA

Advantages:

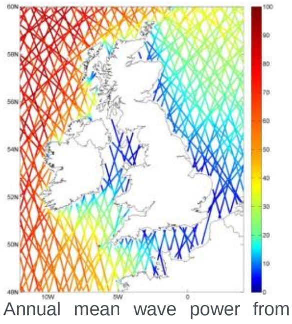
- Measure instantaneous averages of significant wave height H_s, wave period, water temperature, wind speed and current over an area
- Cover nearly the whole globe with continuous recordings since 1991
- Accuracy of H_s similarly as for buoy measurements (5%)

Disadvantages:

- Spatial and temporal resolutions low
- No data last 10 km as satellite passes from sea to land and about 20-30 km of no or low-quality data as satellite passes from land to sea
- Require calibration, e.g. with in-situ measurements
- Data during rainfall need normally to be excluded

Ideal for:

- Wave energy resource assessment on large scale
- Initial estimation of the wave resource
- Tracking of swells over very long distances



Annual mean wave power from several altimeters, Mackay (2012)

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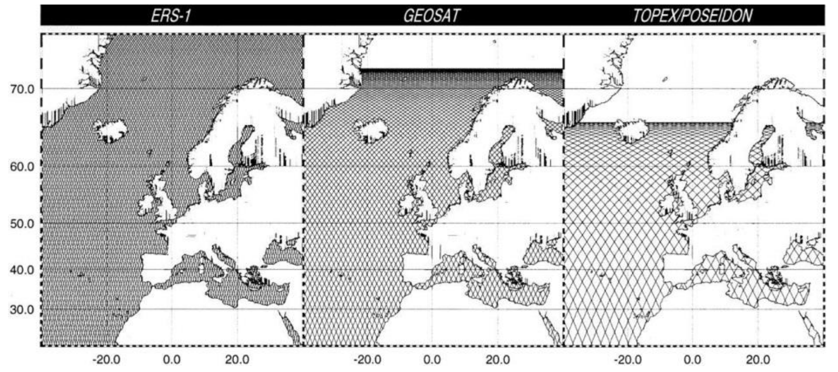
Methods to evaluate the resource: Satellite Altimetry

Examples satellites

ERS-1
1991 - 1996
Operated by European Space Agency, with RA system

GEOSAT
1986 - 1989
Operated by US Navy (mainly classified data)

TOPEX/POSEIDON
1992 - 2005
Operated by NASA and CNES RA system



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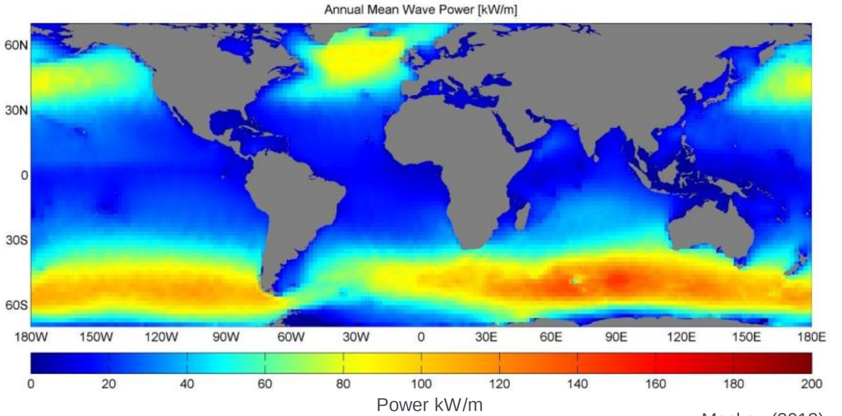
Methods to evaluate the resource: Satellite Altimetry

Annual mean wave power between 1996-2007 from several satellite altimeters binned in 2° (latitude) × 2° (longitude)



Mackay (2012)

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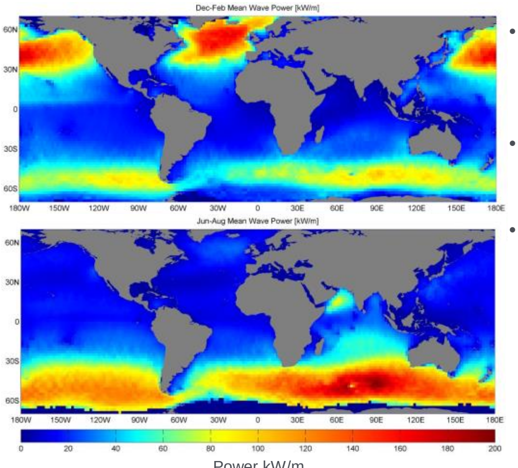
Methods to evaluate the resource: Satellite Altimetry

Comparison mean wave power from Winter and Summer



Mackay (2012)

- Central North Pacific and Central North Atlantic over 150 kW/m in winter, but only 25 kW/m in summer
- High level in Arabic sea in summer due to Monsoon winds
- European west coast has high, but quite variable wave energy resource

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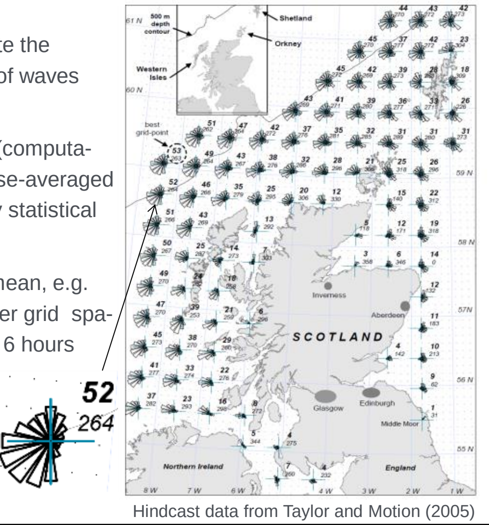
Methods to evaluate the resource: Numerical modelling

Numerical modelling

- Wave models attempt to replicate the growth, propagation and decay of waves based on winds over an area
- Two methods: Phase-resolving (computation of surface elevation) or phase-averaged (spectral) models delivering only statistical parameters
- Output is spatial and temporal mean, e.g. for global scale wave models over grid spacing 0.5 to 3° and time step 3 to 6 hours

Wave rose (power weighted)



Hindcast data from Taylor and Motion (2005)

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Methods to evaluate the resource: Numerical modelling

Numerical modelling

Advantages:
- Can be applied at any location (also at location of device)
- Data are mainly of hindcasting nature (wind measurements as input)

Disadvantages:
- Require calibration with satellite altimeter and in-situ measurements
- Accuracy affected by numerics (temporal and spatial discretisation etc.)

Ideal for:
- Long-term prediction of resource
- Local transformation of waves from deep- to shallow-water
- Site specific wave climate

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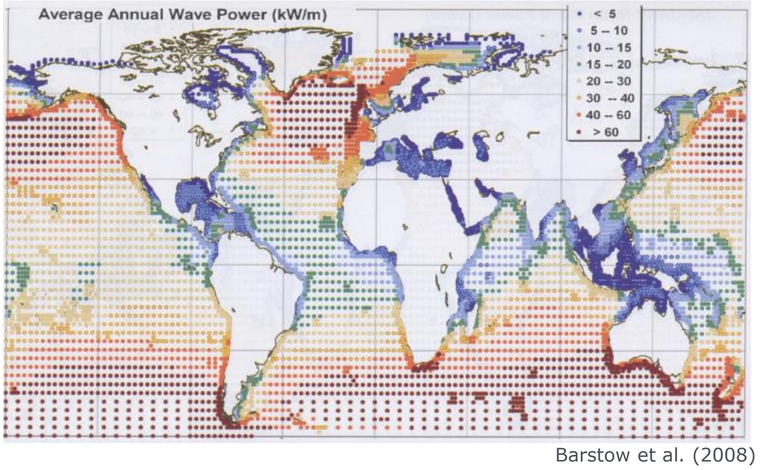
Methods to evaluate the resource: Numerical modelling

10-year mean annual wave power based on 6 hourly WAM data calibrated and corrected against buoy and satellite altimeter data



Barstow et al. (2008)

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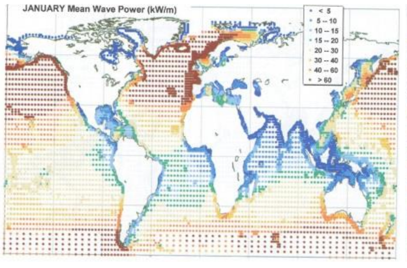
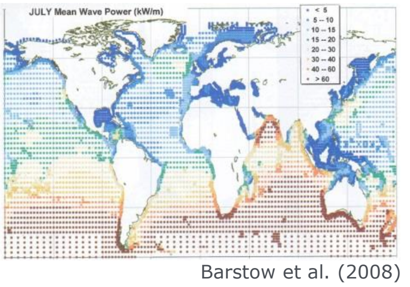
Methods to evaluate the resource: Numerical modelling

10-year mean wave power based on 6 hourly WAM data calibrated and corrected against buoy and satellite altimeter data

January



July



Barstow et al. (2008)

→ Similar conclusions as for summer and winter data of Satellite Altimetry

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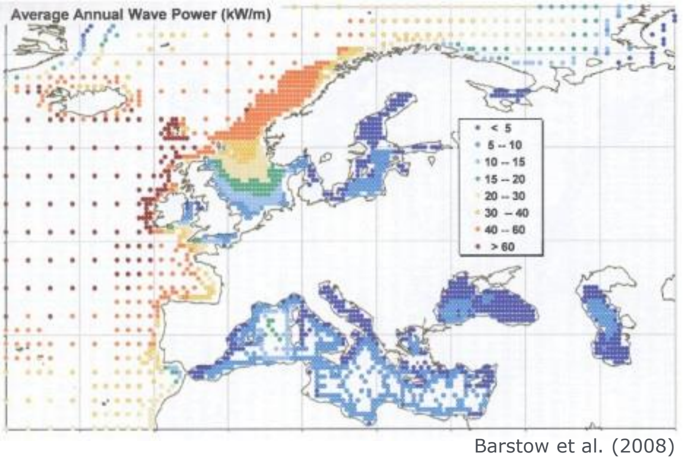
Methods to evaluate the resource: Numerical modelling

10-year mean annual wave power based on 6 hourly WAM data calibrated and corrected against buoy and satellite altimeter data



Barstow et al. (2008)

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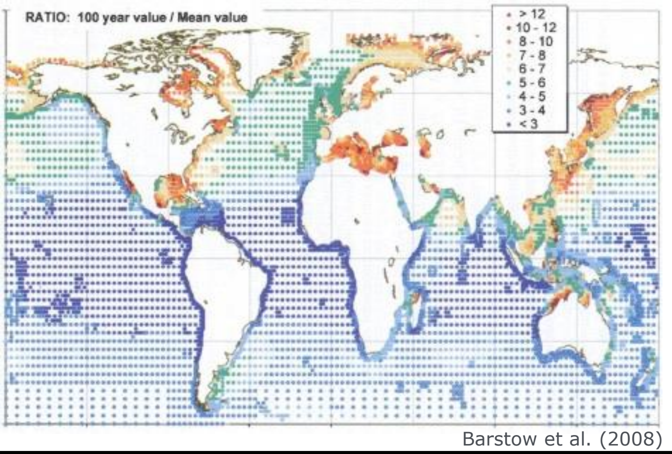
Methods to evaluate the resource: Numerical modelling

Ratio of maximum 100-year significant wave height to mean, based on 6 hourly WAM data

→ indication of design cost of a device relative to its income (resource)



Barstow et al. (2008)

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Data bases

Archived data (see Meyers et al. 2010 for more extensive list)

- **EuroWaves**: A tool based on the **model WAM/SWAN** which can be used for the evaluation of wave conditions at any European coastal location (deep- and shallow-water) calibrated by **in-situ** and **satellite altimeter** measurements.
- **GlobeWave**: The project provides free access to **satellite wave data** and products in a common format, both historical and in near real time from various European and American satellites. It also provides comparisons with **in-situ measurements** and interactive data analysis tools.
- **WERATLAS** (European wave energy atlas): It characterises wave climate and wave energy statistics in European seas at particular points in the offshore region based on **model predictions** and **in-situ** and **satellite altimeter measurements**.

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Data bases

Archived data

- **World Wave Atlas 2.0**: A *commercial* global **satellite altimeter** database and software package calibrated against **buoy data** delivering significant wave height at 1 s resolution with a monthly update and sorted globally in 10 × 10º areas provided global, region, by country and site-specific.

- **WorldWaves**: *Commercial* product from Fugro OCEANOR delivering world-wide offshore wave and wind time series at 10000 points on a 0.5º grid over 10 years of 6 hourly based on the **ECMWF database** including **modelling** in shallow waters with SWAN and further tools establishing computational grids and editing bathymetric data.

→ Data bases work with *two*, or even with *all three* methods

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Conclusions

- The European west coast offers an exceptional, but also variable wave energy resource
- The prediction of the wave energy resource is not trivial: it is based on past data and variable from wave-to-wave, synoptic (weather system), seasonal, inter-annual and climatic
- All three main categories to estimate the wave energy resource have their strengths and limitations:

  In-situ measurements: relatively accurate *point averages over time* but only at limited locations and over limited period of time

  Satellite Altimetry: measurements nearly over whole globe but only *instantaneous spatial averages* over 2-10 km with low repeat period

  Wave models: applicable to any location but delivers rather estimated *averages over grid space and time step*
- Specific projects are likely to start with a data base and then to go into more details with a combination of several methods, e.g. numerical long-term modelling validated with satellite and in-situ measurements

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There are many further case studies for particular countries or regions available.

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