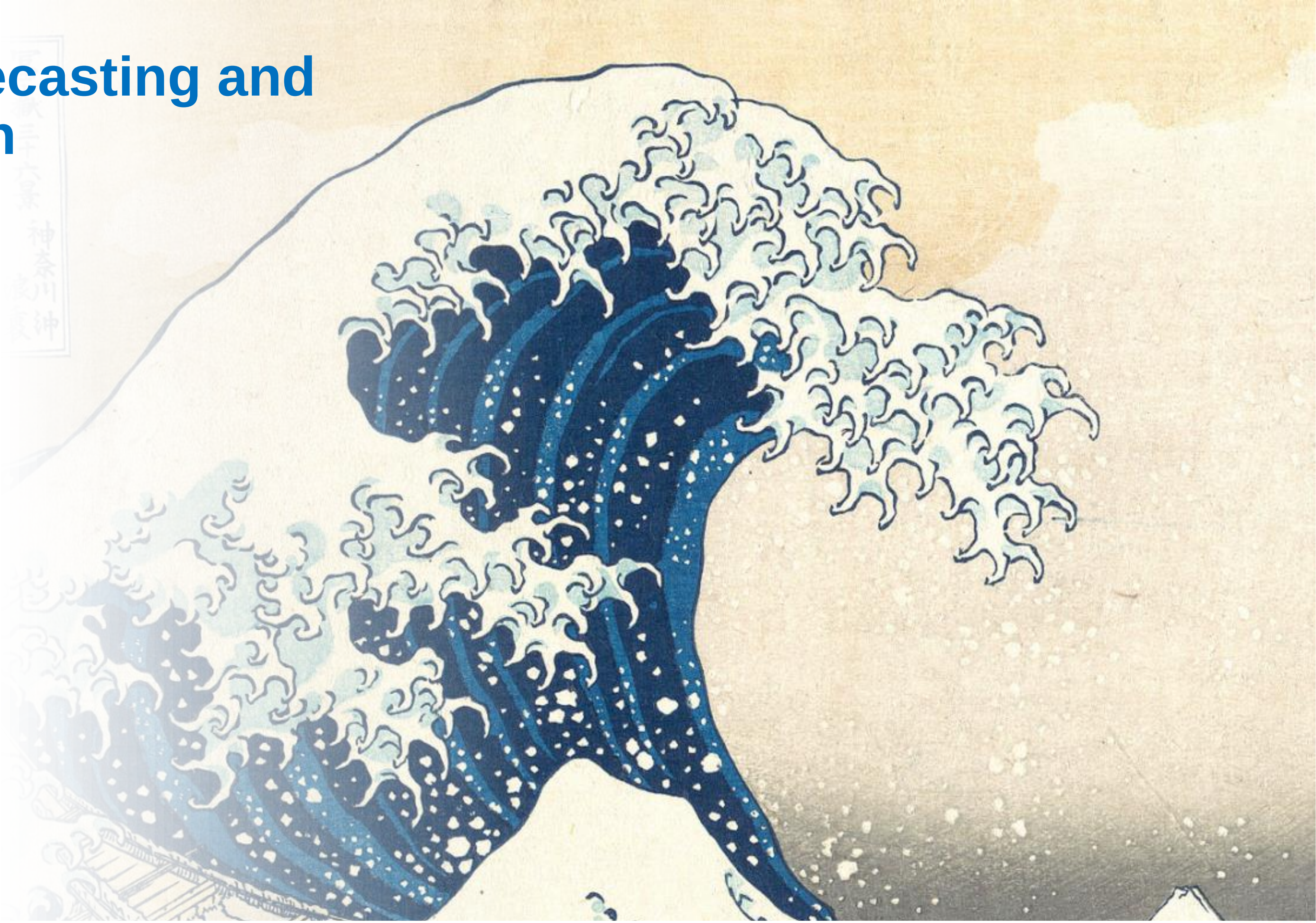
WP3: Sea State Forecasting and Resource Evaluation

3rd Advisory Board Meeting



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WP3: Progress and current work

- Resourse characterisation
  - SmartWave wave prediction (collaboration with Dr. Evdokia Tapoglou, *European Commission*) – a research article draft is to be submitted
  - Wave power resource evaluation in Atlantic Europe’s NorthWest seas (collaboration with Dr. Charikleia Oikonomou, *Hellenic Centre for Marine Research*) – a conference paper is under preparation
  - Wave prediction via Machine Learning (collaboration with Prof. Carrie Hall, *Illinois Institute of Technology*) – the dataset is in preparation
  - Wave climate dynamics in Atlantic Europe’s NorthWest seas (incl. Machine Learning) – design and theoretical part completed, numerical calculations are under preparation
  - SAR imaging of sea waves: Theoretical analysis of Sentinel 1 imagery – future work

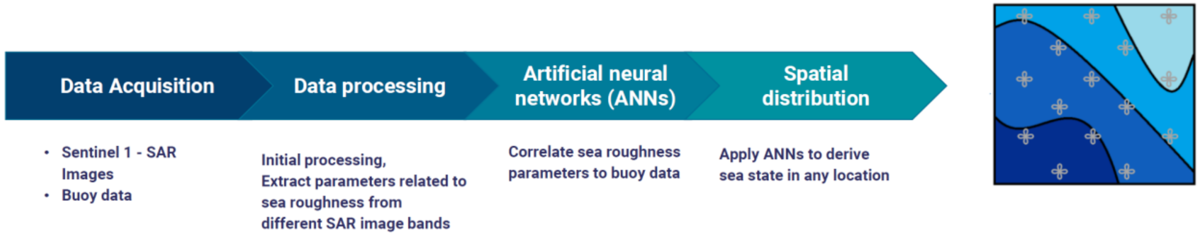
- WEC efficiency calculations in wave tanks – a TEAMER funding application (*collaboration with National Renewable Energy Laboratory NREL*) – has been submitted

- Array effects – future work

SmartWave – High accuracy & high spatial fidelity wave prediction

Motivation: Development of SmartWave to simulate parameters useful for marine renewables.

ANN based system

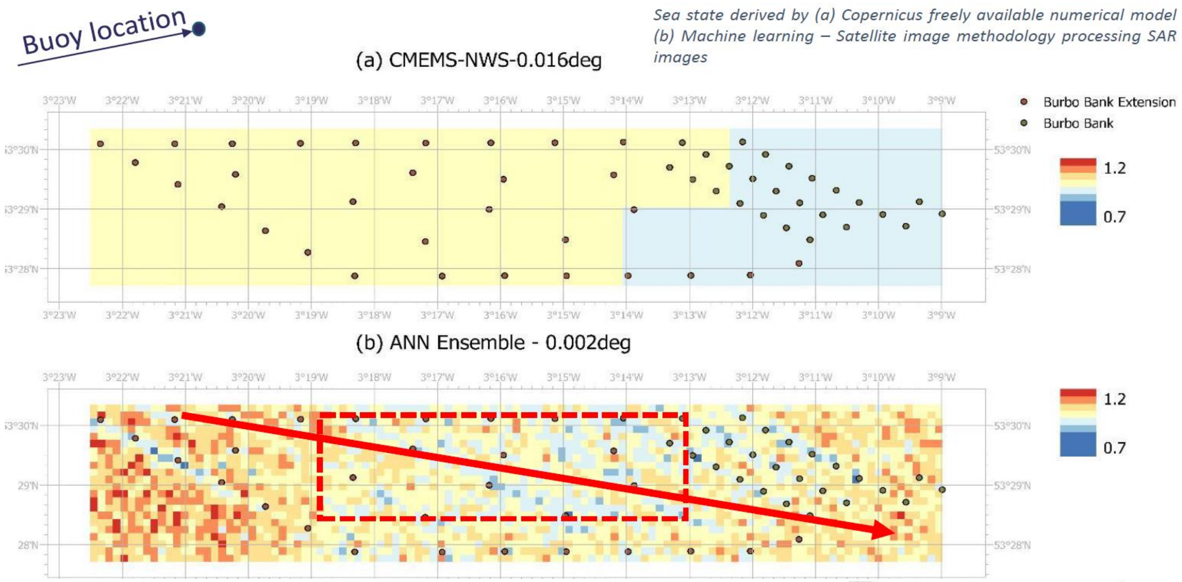


Comparison of Sea state conditions at 2/4/2019 06:32:16am

Buoy data: 0.89m (6:30am) – 1.07m (7:00am)	Numerical model at the buoy: 0.92m	ANN Ensemble: 0.95m

Example results – Burbo Bank

- Same trend of significant wave height for both hindcasts
- Higher resolution for machine learning-satellite image methodology
- Possible to identify pattens like sheltering in the inner wind turbines compared to the ones that are at the edge of the wind farm.



Tapoglou, E., Forster, R. M., Dorrell, R. M., & Parsons, D. (2021).
Machine learning for satellite-based sea-state prediction in an offshore windfarm.
Ocean Engineering, 235, 109280.

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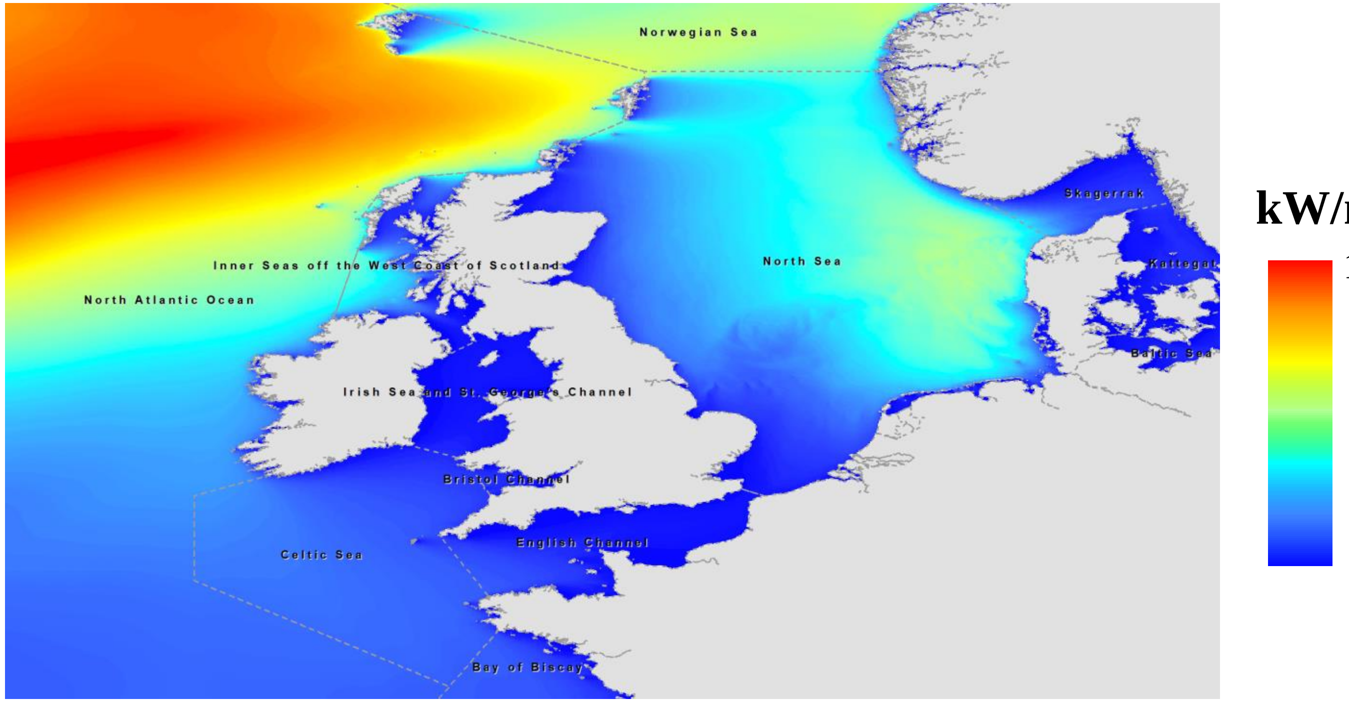
Wave power resource evaluation in Atlantic Europe's NorthWest seas

Mapping of shallow, intermediate, and deep-water areas

122,728 modeled wave measurements ranging from 1980 to 2021

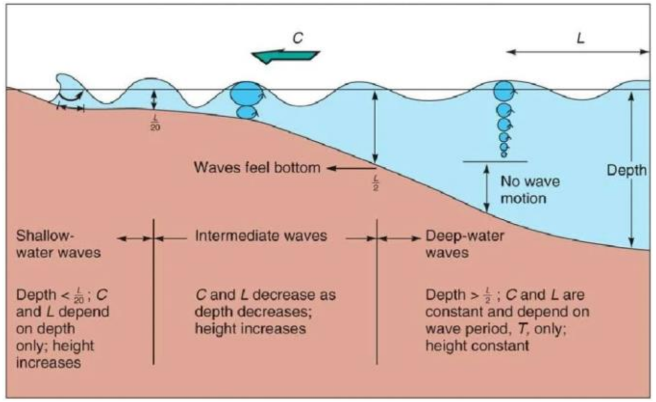


Daily mean wave power density (28.01.2022)

Bathymetry (EMODnet and GEBCO)

Atlantic- European NorthWest Shelf- Wave Physics Reanalysis NWSHELF_REANALYSIS_WAV_004_015 (Copernicus)

Relationship between wavelength and water depth



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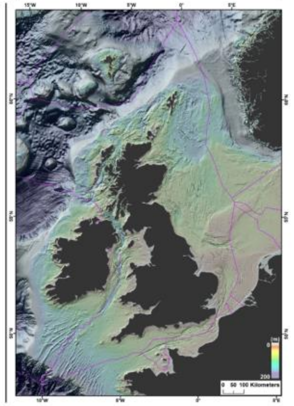
Wave climate dynamics in Atlantic Europe's NorthWest seas

Bathymetry offshore model of the UK (EMODnet and GEBCO)



Determination of uniform waves zones

Dove, D., Bradwell, T., Carter, G., Cotterill, C., Gafeira Goncalves, J., Green, S., ... & Ottesen, D. (2016). Seabed geomorphology: a two-part classification system.

VARIABLES
sea_surface_wave_significant_height (SWH)
sea_surface_wave_mean_period_from_variance_spectral_density_second_frequency_moment (MWT)
sea_surface_wave_period_at_variance_spectral_density_maximum (MWT)
sea_surface_wave_mean_period_from_variance_spectral_density_inverse_frequency_moment (MWT)
sea_surface_wave_from_direction (VMDR)
sea_surface_wave_from_direction_at_variance_spectral_density_maximum (VMDR)
sea_surface_wave_stokes_drift_x_velocity (VSDXY)
sea_surface_wave_stokes_drift_y_velocity (VSDXY)
sea_surface_wind_wave_significant_height (WW)
sea_surface_wind_wave_from_direction (WW)
sea_surface_wind_wave_mean_period (WW)
sea_surface_primary_swell_wave_significant_height (SW1)
sea_surface_primary_swell_wave_mean_period (SW1)
sea_surface_primary_swell_wave_from_direction (SW1)
sea_surface_secondary_swell_wave_mean_period (SW2)
sea_surface_secondary_swell_wave_from_direction (SW2)
sea_surface_secondary_swell_wave_significant_height (SW2)

TEMPORAL COVERAGE — from 1980-01-01 to present
TEMPORAL RESOLUTION — 3 hourly instantaneous
SPATIAL RESOLUTION — 0.017° × 0.017°

Wave type dominance → Map of waves based on simulation

- Torsethaugen's method
- Swell energy weight method

Map of waves based on simulation
- JONSWAP for deep water
- TMA for shallow water
- peak enhancement factor
- Wave steepness method
- Goda's method

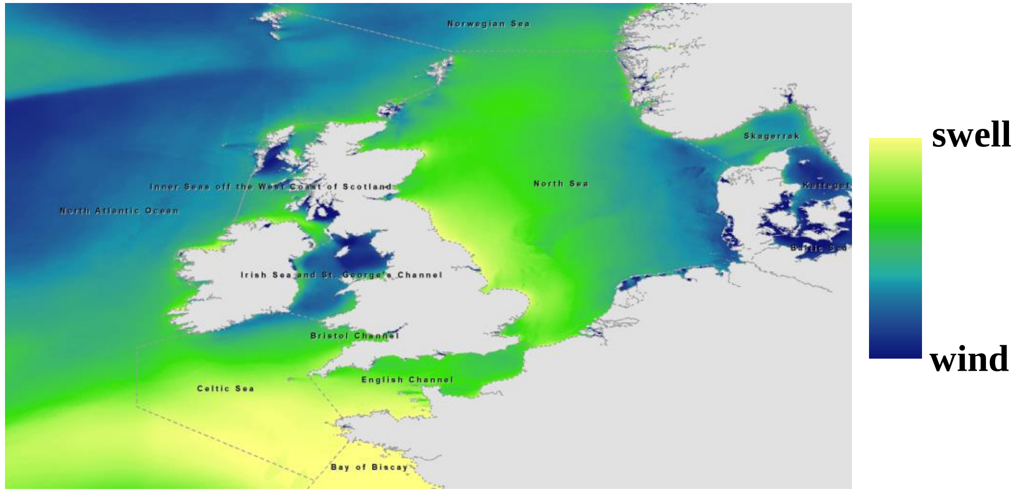
Hindcast wave parameters (1980-2022)
Total: Hs, Tp, Tz, Dp
Components: Tm_w, Tm_s1, T_ms2, Dw, Ds1, Ds2

Sea level anomaly (1993-2021)

GEBCO bathymetry

Wave power
- Model of wavelength
  - Deep
  - Intermediary
  - Shallow
  - Tm based on partitioned components

Long-term trends
- WP
- SLA
- SLT decomposition
- Climate Toolbox
- Mann–Kendall and Wang Swail method
- Multiscale analysis
  - Months (January, July)
  - Climatological mean
  - Annual
- Correlation
- Moving window correlation
  - Local variance



Daily mean sea state dominance (28.01.2022)

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SAR imaging of sea waves: Theoretical analysis of Sentinel 1 imagery

SLC products are generated for all acquisition modes:

- StripMap SLC
- Interferometric Wide swath SLC
- Extra Wide swath SLC
- Wave SLC

Stripmap SLC

Beam	S1	S2	S3	S4	S5	S6
Spatial Resolution rg x az m	1.7 x 4.9	2.0x4.9	2.5x4.9	3.3x4.9	3.3x3.9	3.6x4.9
Pixel spacing rg x az m	1.5x3.6	1.8x4.2	2.2x3.5	2.6x4.1	2.9x3.6	3.1x4.1
Incidence angle °	22.3	25.6	31.2	36.4	41.0	43.8

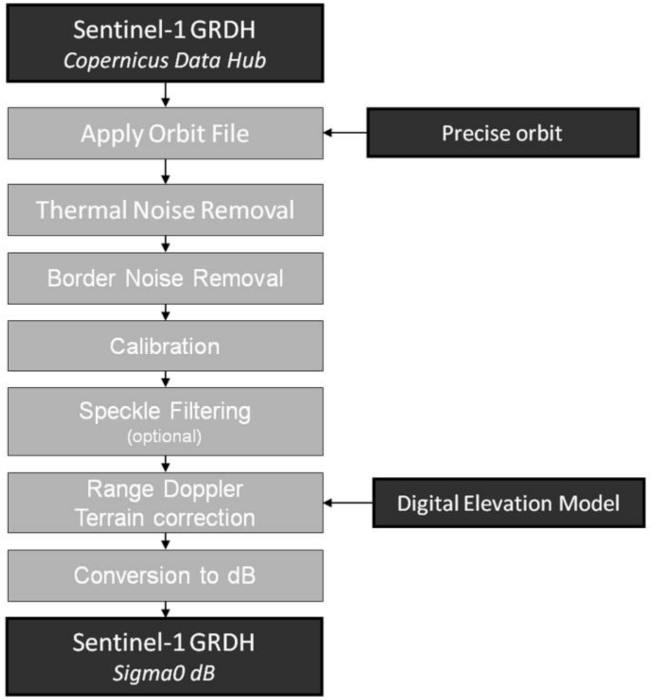
Interferometric Wide Swath SLC

Beam ID	IW1	IW2	IW3
Spatial Resolution rg x az m	2.7x22.5	3.1x22.7	3.5x22.6
Pixel spacing rg x az m	2.3x14.1	2.3x14.1	2.3x14.1
Incidence angle °	32.9	38.3	43.1

Wave SLC

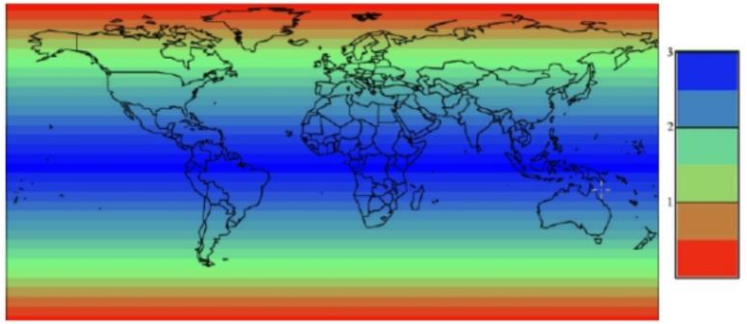
Beam ID	WV1	WV2
Spatial Resolution rg x az m	2.0x4.8	3.1x4.8
Pixel spacing rg x az m	1.8x4.1	2.7x4.1
Incidence angle °	23.4	36.4

Preprocessing



Using SAR images has benefits:

- Unaffected by weather
- Unaffected by cloud cover
- Larger datasets



Revisit frequency ~ 2 days (IW mode)

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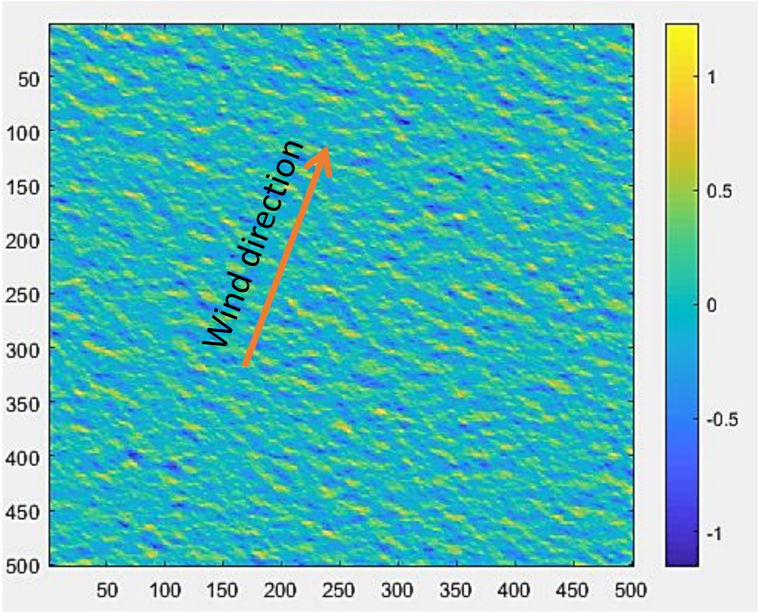
Sea Surface Modelling - Linear theory

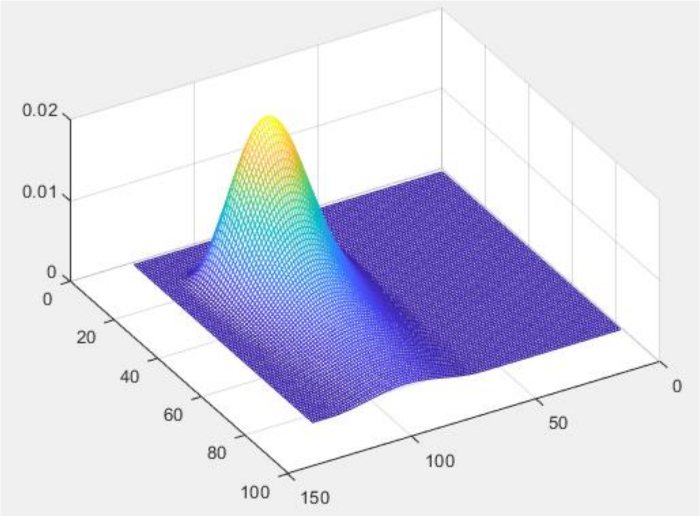
The irregular sea surface elevation model can be expressed as:

$$Z_{sea}(x, y, z, t) = \sum_i \sum_j A_{ij} \cos\left[k_i\left(x \cos\theta_j + y \sin\theta_j\right) - \omega_i t + r_{ij}\right]$$

$$A_{ij} = \sqrt{2S(k_i)D(k_i, \theta_j)dk_i d\theta_j}$$

Wind speed Vw = 7 m/s

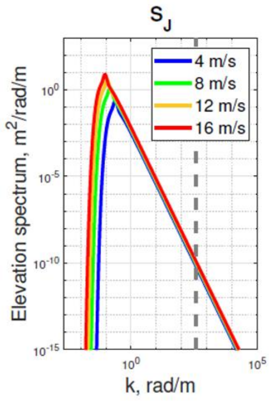




Omnidirectional spectrum

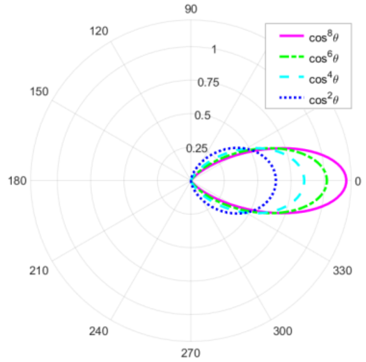
Joint North Sea Wave Project (JONSWAP)

$$S(k_i) = \frac{\alpha}{2} k_i^{-3} \exp\left[-1.25\left(\frac{k_i}{k_p}\right)^{-2}\right]$$
$$\exp\left\{\ln\gamma \exp\left[-\frac{\left(\sqrt{k_i/k_p} - 1\right)^2}{2\sigma^2}\right]\right\}$$



Directional spreading function

$$D(\theta_j) = \begin{cases} \frac{2}{\pi}\cos^2\theta_j & |\theta_j| \le 90^0 \\ 0 & |\theta_j| > 90^0 \end{cases}$$



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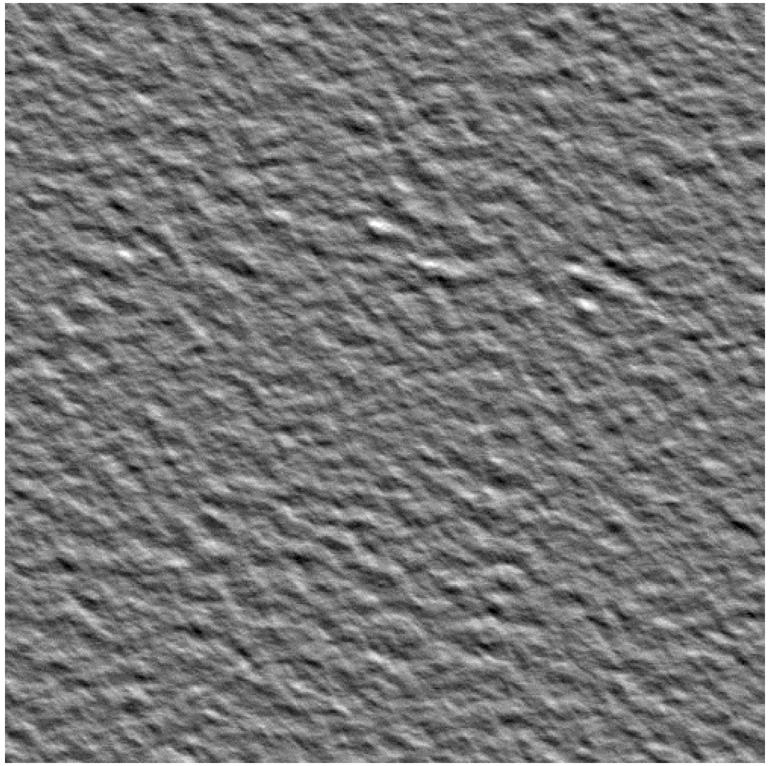
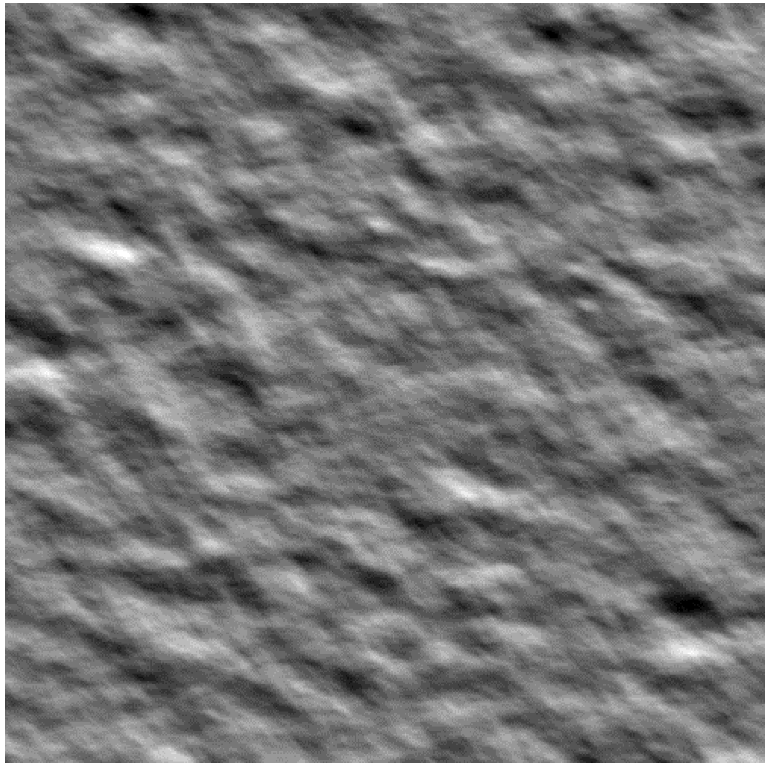
Sea Surface Modelling – Time domain

Vw = 7 m/s, F = 20 km



Vw = 7 m/s, F = 105 km



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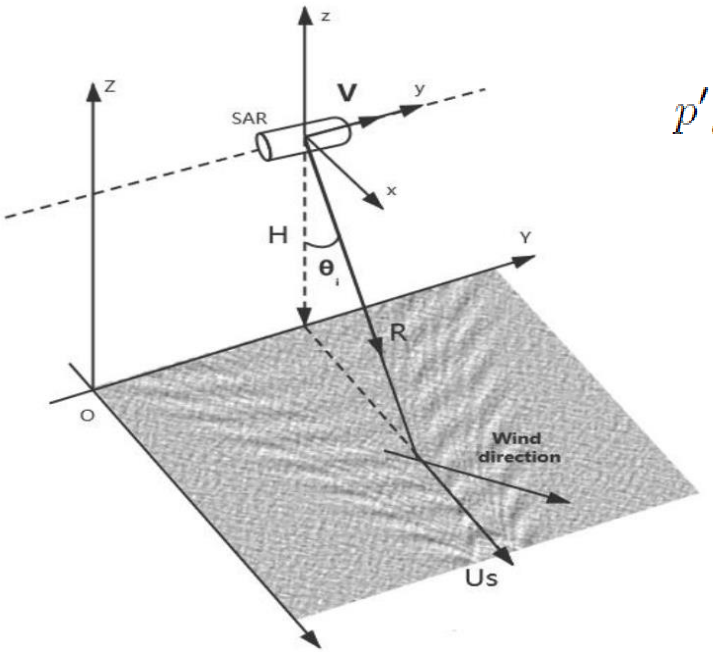
SAR image simulation – velocity bunching of gravity waves

$$I(x,y)=\frac{\pi T_i}{2V}\iint \delta(y-y_0)\frac{\overline{\sigma}(x_0,y_0)}{p_a^1(x_0,y_0)}\times \exp\left\{-\pi^2\left[\frac{x-x_0-\frac{R}{V}u_r(x_0,y_0)}{p_a^1(x_0,y_0)}\right]^2\right\}dx_0dy_0$$



SAR scanning geometry

$$p'_a(x,y)=N_l p_a\left[1+\frac{\pi^2 {T_i}^4}{{N_l}^2\lambda^2}\bar{A}_r(x,y)+\frac{1}{{N_l}^2}\frac{{T_i}^2}{{\tau_c}^2}\right]^{1/2}$$

Degraded azimuthal resolution

$$p_a=\frac{\lambda R}{2VT_i}$$

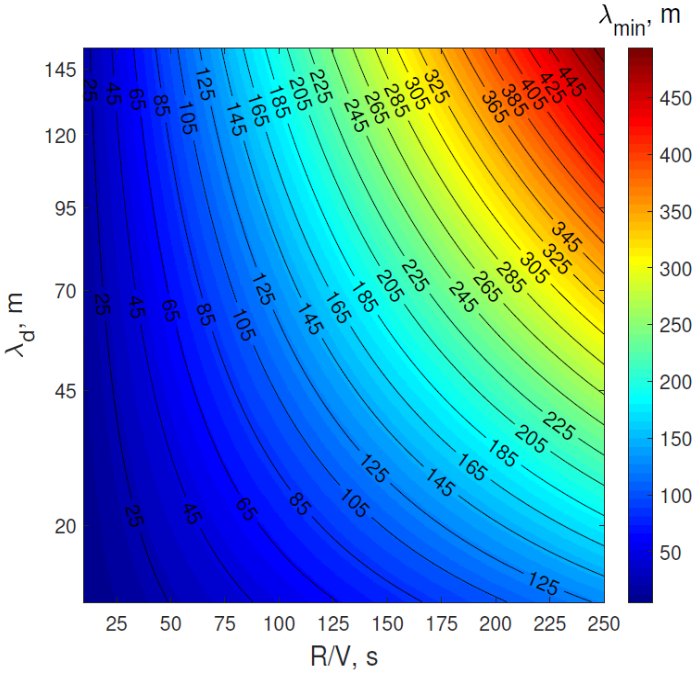
Single-look azimuthal resolution

R/V is the range-to-velocity ratio

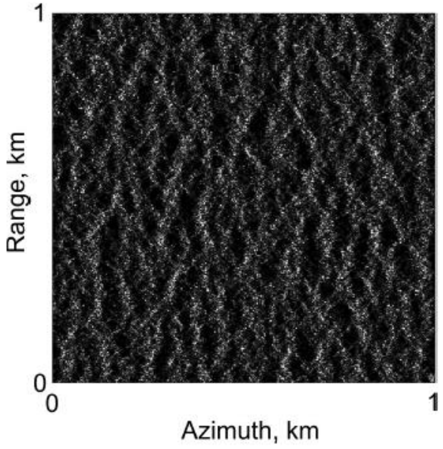
SAR simulation

The important limitation of SAR imaging of waves moving in flight direction which is associated with the velocity bunching is the azimuthal cut-off effect.

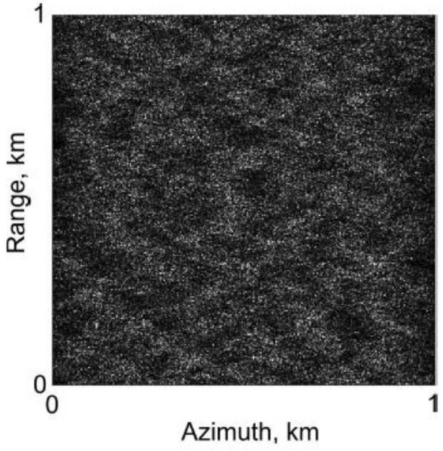
The minimal detectable wavelength of the surface waves can be approximated as $\lambda_{\min} = C_0 \frac{R}{V} \sqrt{H_s}$



(a)



(b)



(c)

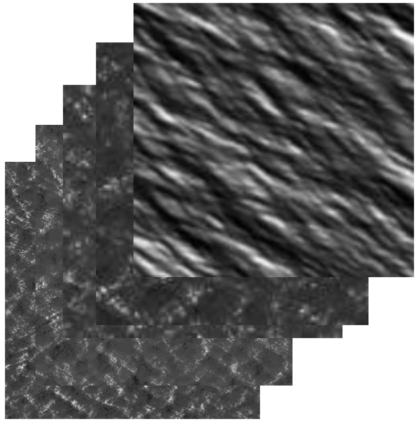
Simulated SAR images of the sea surface with Vw = 10.7 m/s and λd = 95.5 m for (b) airborne (R/V = 23.1 s) and (c) satellite (R/V = 107.1 s) platforms.

Rizaev, I. G., Karakuş, O., Hogan, S. J., & Achim, A. (2022). Modeling and SAR Imaging of the Sea Surface: a Review of the State-of-the-Art with Simulations. ISPRS Journal of Photogrammetry and Remote Sensing, 187, 120-140.

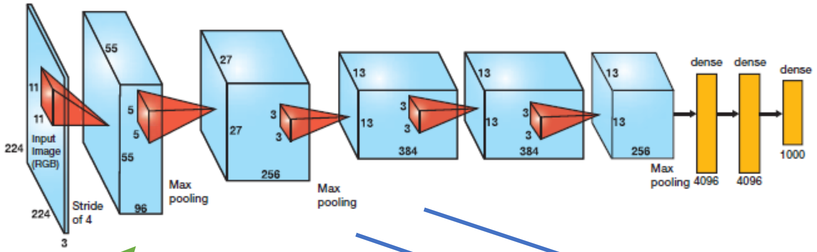
CNN based system

Deep learning

SAR imagery synthetic database creation
Different parameters:
wind directions
wind speeds
fetch size
incidence angles
polarizations

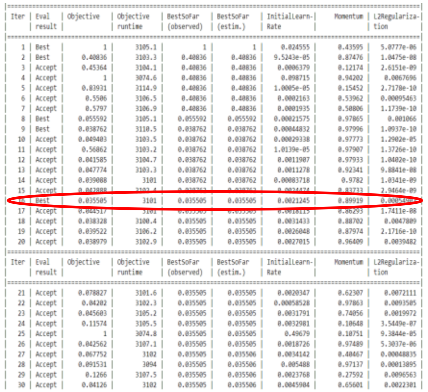


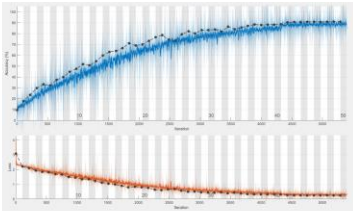
Training CNN (AlexNet)



Strategies:
Training from scratch
Transfer learning with real data

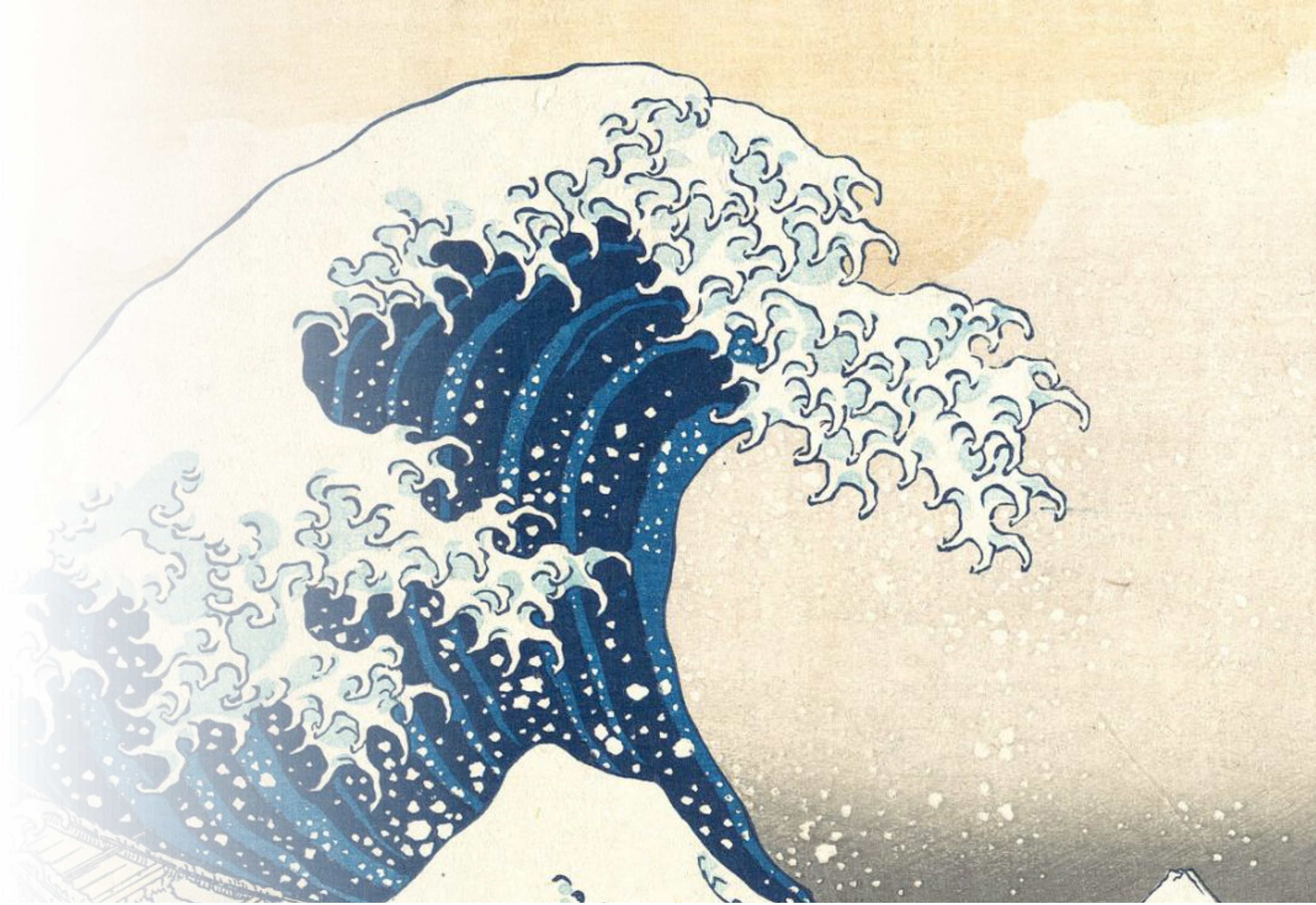
Automated classification and estimation of sea state parameters:
wave height
direction
frequency
speed





Bayesian optimization to find optimal network hyperparameters

Thank you!



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