



Ireland's EU Structural Funds Programmes 2007 - 2013

Co-funded by the Irish Government and the European Union


# A 34-Year Nearshore Wave Hindcast for Ireland (Atlantic and Irish Sea coasts): Wave Climate and Energy Resource Assessment

Sarah Gallagher[1], Roxana Tiron[1], Frédéric Dias[1,2]

[1] School of Mathematical Sciences, UCD
[2] Centre de Mathématiques et de Leurs Applications, Ecole Normale Supérieure de Cachan and CNRS

*13th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazards Symposium, Banff, Canada, October 27 - November 1, 2013.*

# Summary

# Context and motivation

The Irish wave climate:

- Ireland located in Northeast Atlantic
- An energetic wave climate: Atlantic versus Irish Sea
- A potential for both wind and wave renewable industry
- An energetic wave climate: a potentially harsh environment!

Is there a gap in our knowledge of Ireland's wave climate?

- Lack of regional/local long term wave climate studies – climate variability
- Buoy observations sparse (from 2001)
- Nearshore wave buoys (from 2008)

# Methodology

## Local area / regional wave model approach:

- WaveWatch III alpha version with an unstructured grid
- Focus on Irish coastal waters
  - Saves on computational resources
- High-resolution into the nearshore
  - Examination of intermediate depths
- Regional area wave model boundary forcing fields:
  - Global wave model data forces model boundaries in deeper water
  - 10m wind data over entire domain
  - High-quality global / regional models available – ERA-Interim reanalysis

# Conclusions

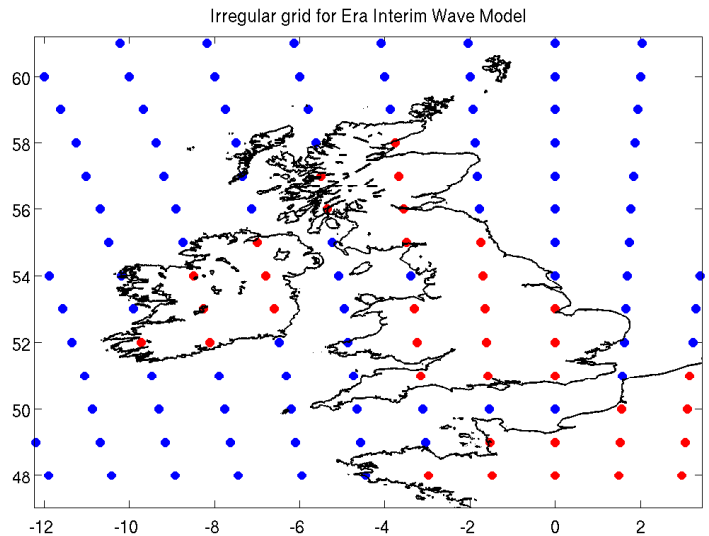
- A 34 year, high-resolution, nearshore wave hindcast was performed for Ireland: Atlantic and Irish Sea Coasts;
- The model was validated with observations from 17 wave buoys around Ireland: comparison between the observations and the model was found to be excellent;
- A strong spatial and seasonal variability was found for both significant wave heights and the wave energy flux;
- A strong correlation between the NAO teleconnection pattern and wave heights, wave periods and peak direction in winter and also to a lesser extent, in spring was also found on the west coast.

- 13 year hindcast using ERA-Interim wave data and high-resolution HARMONIE downscaled winds (2.5km) - SEAI project in collaboration with Met Éireann also under way.

# Boundary forcing fields

ERA-Interim Reanalysis:

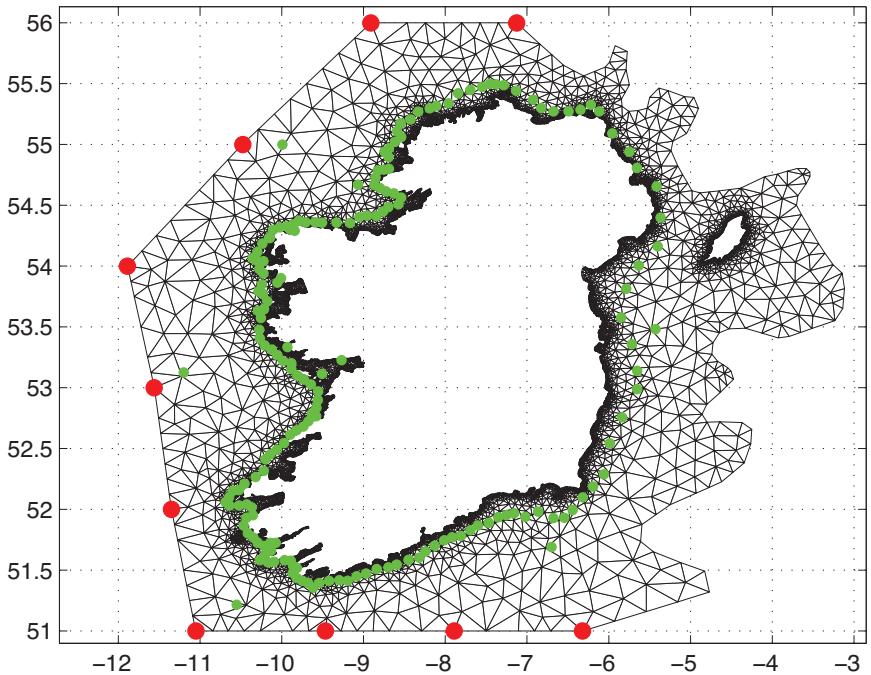
- Most recent global atmospheric reanalysis from the ECMWF
  - ECMWF (European Centre for Medium-Range Weather Forecasts)
- Reanalysis available from 1979 to present
- 79km resolution
- Assimilates satellite data:
  - altimeter wave-heights
  - scatterometer ocean surface winds




ERA-Interim wave model grid points: blue - sea point, red - land point.

# Grid Construction

- An unstructured grid approach:
- Components
  1. Unstructured mesh
  2. Variable resolution depending on depth and depth gradient:
     - 250m in nearshore locations
     - 10km offshore
  3. 15,000 sea points
  4. Computational resources (regular versus irregular grid)
  5. Explicit scheme - CFL
- Grid boundary based on GSHHS vector shoreline dataset
  1. Landsat imagery used to correct shoreline
  2. Boundary created using:
     - UK east coast shoreline
     - ERA-Interim boundary feeding points in Atlantic

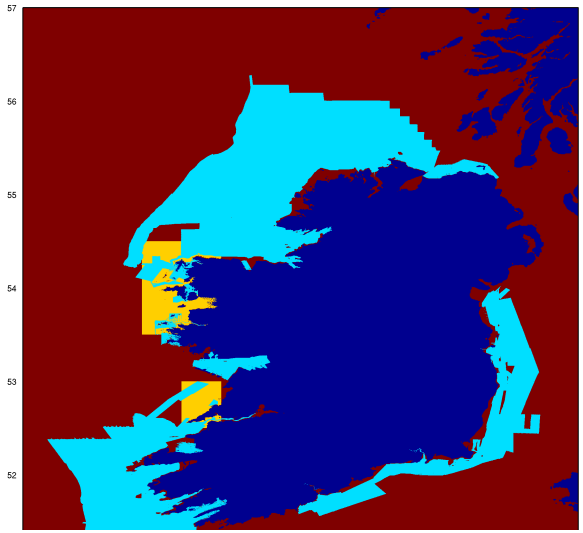


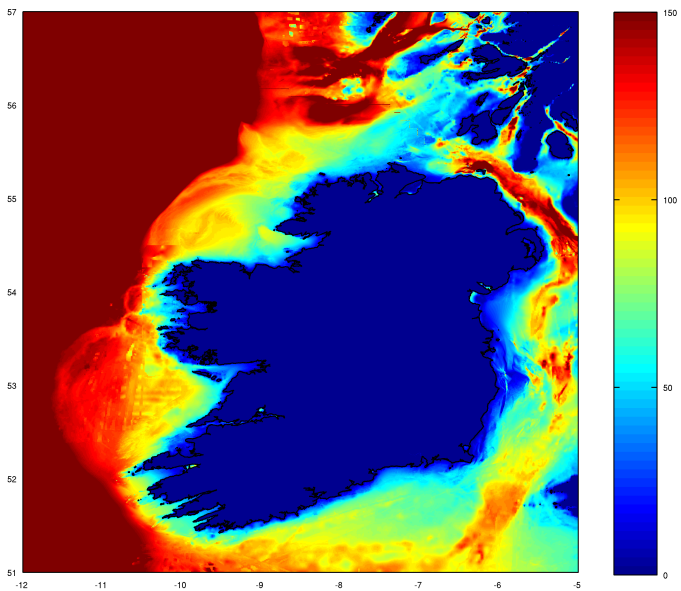

Unstructured grid and bathymetry depth for 34 year wave hindcast model run.

Red circles: ERA-Interim grid points.

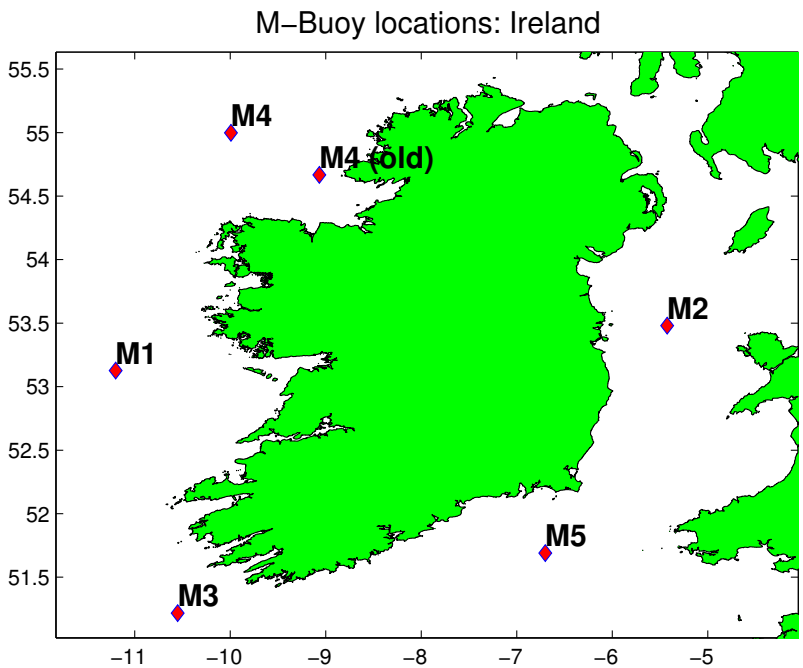
# Bathymetry - Construction of DEM

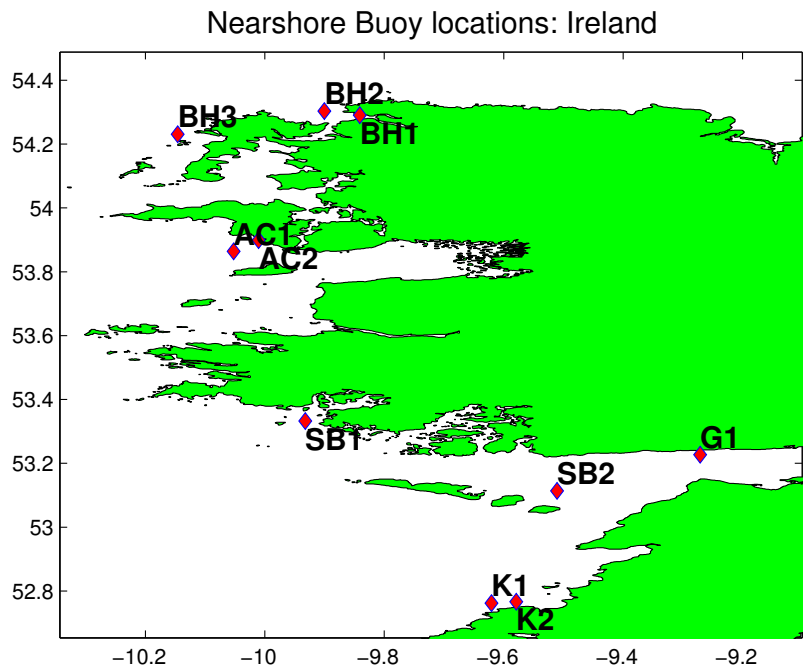
- INFOMAR: Integrated Mapping for the Sustainable Development of Ireland's Marine Resource
  1. Joint venture of GSI and Marine Institute
  2. High resolution data:
     - LiDAR: 2 to 5m resolution
     - Multi-beam echo-sounder (MBES): 10 to 80m resolution
- EMODnet (European Marine Observation and Data Network) and Oceanwise:
  1. To fill the missing areas in INFOMAR dataset
  2. 250m resolution (15")
- Bathymetry blended and smoothed - weightings (INFOMAR has priority)
- Creation of a "Master Grid" - artificial ridges from mismatches smoothed out



# Validation: wave buoy locations




Left: Location of the M-buoys. Right: Location of the nearshore buoys.

- The wave model hindcast will be validated against available buoy data:
  - M-buoys as part of the Irish Marine Buoy Network provided by Met Éireann
  - Nearshore buoys provided by the Marine Institute, ESB and Shell

# Validation: Duration of buoys observations

Table: Buoy location depth and duration of time series used in comparison with model data. Buoys listed in order of depth.

| *Buoy* | *Location* | *Depth* $(m)$ | *Period* $(mm/yy)$ |
|---|---|---|---|
| M3 | SW of Mizen Head | 155 | 01/03 - 12/12 |
| M1 | W of Aran Isl. | 140 | 03/01 - 12/07 |
| BH4 | W of Belmullet | 100 | 05/12 - 12/12 |
| M2 | E of Lambay Isl. | 95 | 05/03 - 12/12 |
| M4 | Donegal Bay | 72 | 04/03 - 11/12 |
| M5 | SE Coast | 70 | 10/04 - 12/12 |
| BH3 | W of Belmullet | 56 | 12/09 - 01/12 |
| K1 | Killard Point | 51 | 11/11 - 01/12 |
| AC1 | Achill Isl. | 43 | 11/11 - 08/12 |
| BH1 | Broadhaven Bay | 38 | 01/09 - 10/09 |
| K2 | Killard Point | 36 | 08/12 - 12/12 |
| SB2 | E of Aran Isl. | 28 | 01/10 - 06/10 |
| G1 | Galway Bay | 22 | 05/08 - 01/12 |
| AC2 | Achill Isl. | 21 | 11/11 - 01/12 |
| SB1 | Mace Head | 18 | 04/09 - 09/09 |
| BH2 | Broadhaven Bay | 11 | 06/06 - 07/09 |

# Comparison between the wave model and buoy observations:

## Deep water (depths > 70m)

| | Significant wave height | | | | Period | | | | Direction | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Buoy* | *Bias* (*cm*) | *RMSE* (*cm*) | *R* | *SI* (%) | *Bias* (*s*) | *RMSE* (*s*) | *R* | *SI* (%) | *Bias* (*deg*) | *RMSE* (*deg*) | *R* | *SI* (%) |
| M3 | -4 | 45 | 0.95 | 16 | 0.3 | 0.8 | 0.87 | 11 | 5 | 13 | 0.95 | 15 |
| M1 | -15 | 46 | 0.96 | 16 | 0.3 | 0.9 | 0.86 | 12 | - | - | - | - |
| BH4 | 5 | 38 | 0.96 | 13 | 0.2 | 0.6 | 0.92 | 8 | 9* | 20 | 0.7 | 29 |
| M2 | 15 | 31 | 0.94 | 25 | 0.9 | 1.2 | 0.65 | 26 | -15 | 24 | 0.77 | 14 |
| M4 | -1 | 39 | 0.97 | 13 | 0.2 | 0.7 | 0.98 | 19 | 2 | 13 | 0.94 | 15 |
| M4(old) | -24 | 55 | 0.94 | 23 | 0.3 | 0.9 | 0.84 | 13 | - | - | - | - |
| M5 | -3 | 38 | 0.94 | 21 | 0.1 | 0.8 | 0.82 | 15 | -6 | 18 | 0.84 | 14 |

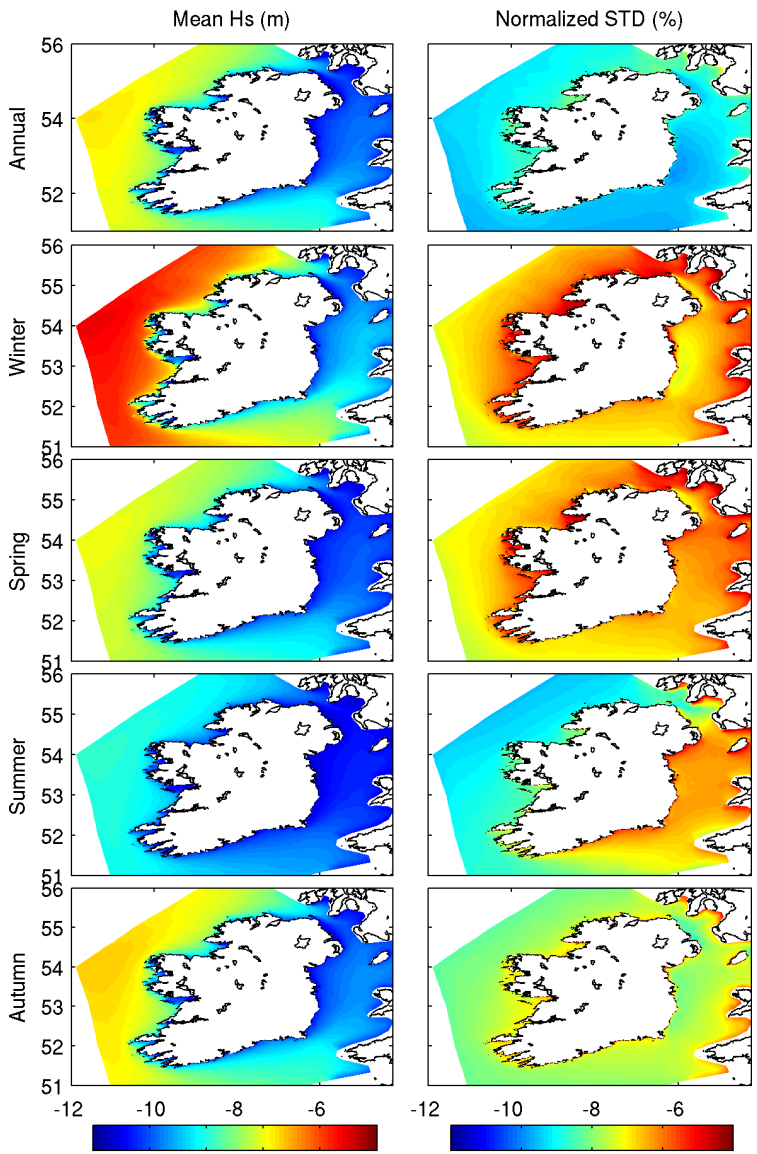
# Comparison between the wave model and buoy observations:

## Moving towards the nearshore (depths < 56m)

| | Significant wave height | | | | Period | | | | Direction | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Buoy* | *Bias* (*cm*) | *RMSE* (*cm*) | *R* | *SI* (%) | *Bias* (*s*) | *RMSE* (*s*) | *R* | *SI* (%) | *Bias* (*deg*) | *RMSE* (*deg*) | *R* | *SI* (%) |
| BH3 | 11 | 40 | 0.97 | 15 | 0.2 | 0.7 | 0.89 | 10 | 7* | 16 | 0.69 | 25 |
| K1 | 31 | 53 | 0.97 | 12 | 0.0 | 0.7 | 0.88 | 7 | 4* | 9 | 0.74 | 13 |
| AC1 | -14 | 34 | 0.98 | 15 | -0.1 | 0.7 | 0.91 | 11 | 5* | 13 | 0.68 | 14 |
| BH1 | 2 | 31 | 0.97 | 16 | 0.1 | 0.9 | 0.86 | 14 | 4 | 11 | 0.83 | 25 |
| K2 | 20 | 40 | 0.96 | 16 | 0.0 | 0.7 | 0.90 | 11 | -0.5* | 9 | 0.75 | 13 |
| SB2 | -5 | 17 | 0.89 | 27 | -0.4 | 1.9 | 0.61 | 43 | 12 | 29 | 0.65 | 29 |
| G1 | 7 | 18 | 0.94 | 25 | -0.3 | 1.5 | 0.60 | 6 | - | - | - | - |
| AC2 | -6 | 43 | 0.95 | 11 | -0.5* | 1.5 | 0.76 | 12 | 6* | 12 | 0.45 | 12 |
| SB1 | -36 | 44 | 0.95 | 52 | -0.4 | 1.1 | 0.71 | 23 | 6 | 12 | 0.70 | 9 |
| BH2 | 1 | 8 | 0.97 | 15 | - | - | - | - | - | - | - | - |

# Analysis: Significant wave height

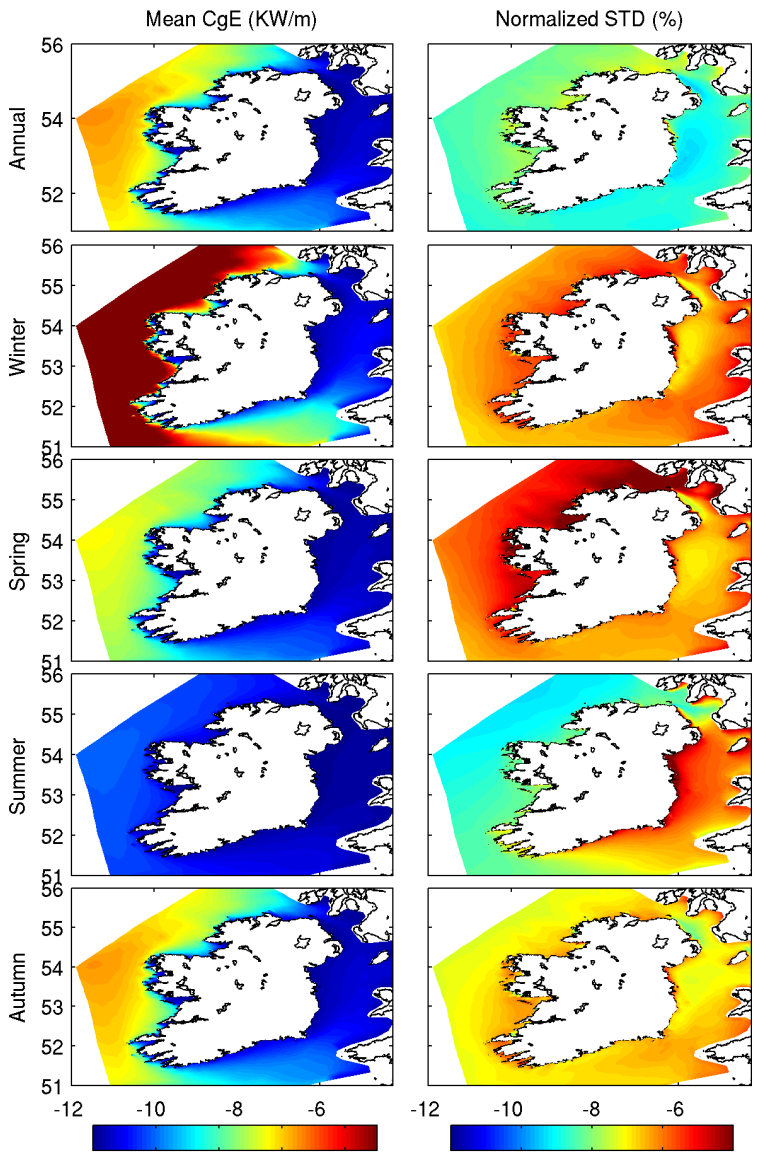
- In winter, the Atlantic coast is exposed to highly energetic sea states – mean Hs close to 5m;
- In contrast, mean Hs values do not exceed 2m on the Irish Sea coast in any season;
- Significant interannual variability of Hs:
  - up to 15% for the annual means
  - over 25% in winter and spring;
- On the Atlantic coast the interannual variability more pronounced in the nearshore.




Left panels: annual and seasonal mean significant wave height (Hs). Right panels: normalized standard deviation of the means (%), which quantifies the interannual variability.

# Analysis: CgE

- In winter CgE over 130kW/m;
- Decrease in energy levels from winter to summer dramatic – West Coast energy levels of 20kW/m in summer months;
- Variability larger than Hs:
  - up to 25% in mean annual levels
  - well over 35% in mean CgE winter and spring levels on North and West Coast;
- Can this variability be linked to larger scale atmospheric circulation patterns such as the North Atlantic Oscillation NAO?




Left panels: annual and seasonal mean wave energy flux (kW/m of wave crest). Right panels: normalised standard deviation of the means (%) which is a measure of the interannual variability of the wave energy resource.

# Analysis: NAO

Table: Correlation between the 34 year hindcast results (1979-2012) and NAO seasonal averages for significant wave height, energy period and peak direction at the buoy locations.

| | Significant wave height | | | | Period | | | | Direction | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Buoy* | *DJF* | *MAM* | *JJA* | *SON* | *DJF* | *MAM* | *JJA* | *SON* | *DJF* | *MAM* | *JJA* | *SON* |
| M3 | **0.65** | 0.48 | - | - | **0.50** | **0.52** | - | 0.39 | **0.59** | 0.36 | - | - |
| M1 | **0.74** | **0.54** | - | - | **0.51** | **0.50** | - | - | 0.44 | - | - | - |
| BH4 | **0.79** | **0.57** | - | - | **0.53** | **0.53** | - | - | 0.39 | - | - | - |
| M2 | **0.54** | - | -0.4 | - | - | - | - | - | **0.71** | - | -0.4 | - |
| M4 | **0.8** | **0.58** | - | - | **0.59** | **0.56** | - | - | **0.53** | - | - | - |
| M4(old) | **0.81** | **0.58** | - | - | 0.48 | **0.52** | - | - | - | - | - | - |
| M5 | **0.50** | - | **-0.54** | - | - | - | - | - | **0.56** | - | - | - |
| BH3 | **0.81** | **0.58** | - | - | 0.39 | **0.50** | - | - | - | - | - | - |
| K1 | **0.81** | **0.63** | - | - | - | **0.51** | - | 0.37 | 0.46 | - | - | - |
| AC1 | **0.8** | **0.63** | - | 0.37 | - | 0.44 | - | - | 0.47 | **0.57** | **0.58** | - |
| BH1 | **0.76** | **0.51** | - | - | 0.49 | **0.53** | - | - | - | - | - | - |
| K2 | **0.80** | **0.63** | - | - | - | **0.50** | - | 0.37 | **0.5** | 0.39 | 0.41 | 0.36 |
| SB2 | **0.75** | **0.56** | - | - | - | - | - | - | **0.58** | - | - | - |
| G1 | **0.76** | **0.55** | - | - | - | - | - | - | **0.51** | - | - | - |
| AC2 | **0.75** | **0.60** | - | - | - | - | - | - | **0.52** | **0.62** | **0.63** | - |
| SB1 | **0.69** | **0.54** | - | - | - | - | - | - | **0.64** | 0.49 | - | - |
| BH2 | **0.84** | **0.66** | - | - | - | 0.47 | 0.36 | - | 0.37 | - | - | - |

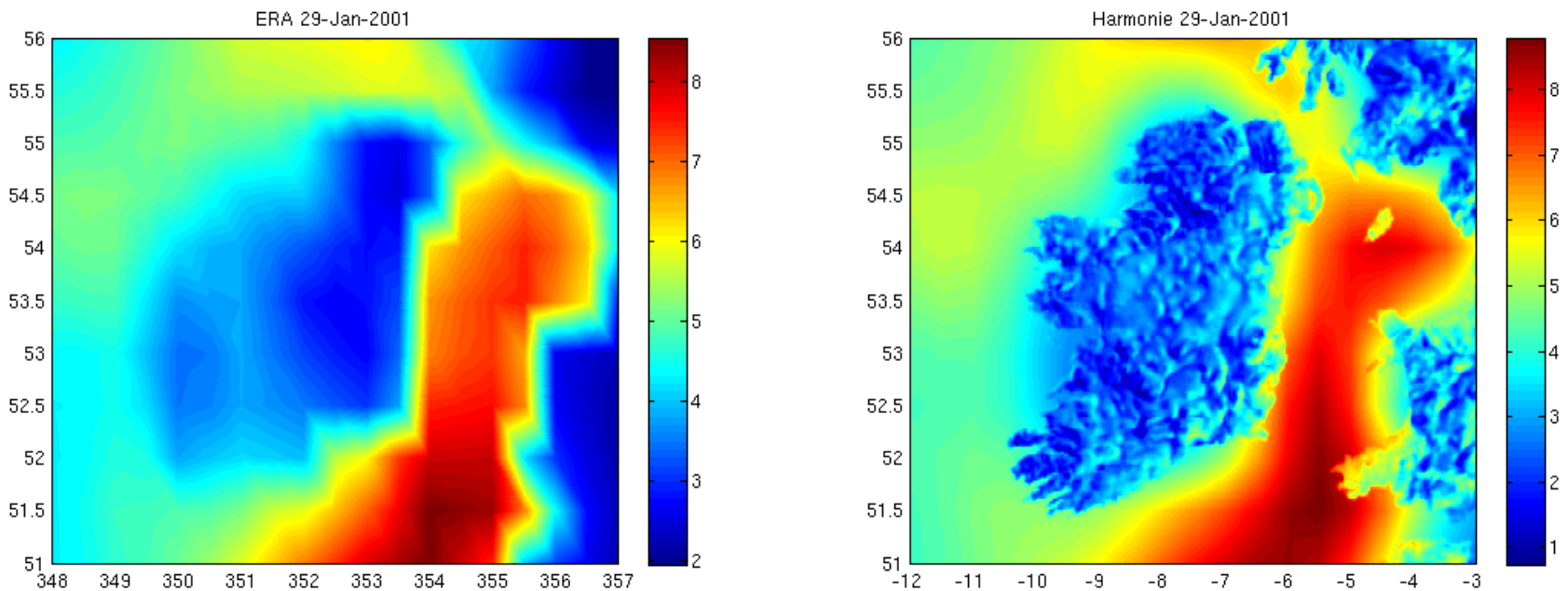
# Further work

SEAI project: "Nearshore Wave and Wind Climate on the West Coast of Ireland: Spatial and Seasonal Variability with Applications to the Renewable Energy Sector"

- Joint project in collaboration with Met Éireann
- ERA-Interim winds downscaled using HARMONIE model:
  1. Developed by HIRLAM (HIgh Resolution Limited Area Model) in close collaboration with the ALADIN consortium and ECMWF
  2. Non-hydrostatic mesoscale model with 2.5km resolution
  3. hourly outputs of U10 and V10
- Initially a 13 year wave and wind hindcast (2000 - 2012)
- This study will go beyond just marine renewable energy applications - marine applications
- Wind and wave resource - the first joint study for Ireland at high-resolution
- Weather window analysis

# Dynamical downscaling of winds

## ERA-Interim versus Harmonie 10m wind



# Acknowledgements


- This study was supported by the Sustainable Energy Authority of Ireland (SEAI) through the Renewable Energy Research Development & Demonstration Programme. SEAI is partly financed by Ireland's EU Structural Funds Programme co-funded by the Irish Government and the European Union;
- Additional funding was provided through the SFI project "High-end computational modelling for wave energy systems";
- Boundary forcing data (wave spectra and wind field data) provided by ECMWF through the MARS archive;
- Buoy data for validation was provided by ESB, Met Éireann and MI Ireland;
- The INFOMAR bathymetric datasets were provided by the GSI and MI;
- The VORF vertical datum software was provided by the GSI;
- Many thanks to M. Osborne (OCEANWISE) for his help with the UKHO bathymetry;
- The authors thank Dr. C. Sweeney and Prof. P. Lynch (UCD School of Mathematical Sciences) for helpful discussions and Dr. F. Ardhuin (Ifremer) for advice regarding the WAVEWATCH code;
- The numerical simulations were performed on the Stokes cluster at the Irish Centre for High-end Computing (ICHEC) and at the Swiss National Computing Centre under the PRACE DECI 10 project "Nearshore wave climate analysis of the west coast of Ireland".

# Thank you!

Aileen's wave at the Cliffs of Moher, Co. Clare.