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Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	CAO-IRL: Coupled Atmosphere Ocean Wave forecast for Ireland
Lead Grantee (Organisation)	University of Galway
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Report Submission Date	23rd December 2022

	Name	**Organisation**
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Collaborators	N/A	

Project Summary (max 500 words)
Seamless weather prediction is an opportunity and a challenge facing the world meteorological community. Globally, all major weather forecasting agencies (e.g., ECMWF, NCEP, Met Office) use Coupled Global Circulation Models (CGCM) to solve weather for global forecasts. When it comes to meso-scale weather prediction, one needs to solve these very high spatial and temporal resolutions with better physical parameterizations (surface, radiation, turbulence, and boundary thermals). The current weather forecasting model used by Met Éireann is the non-hydrostatic convection permitting HARMONIE-AROME regional atmospheric forecast model. HARMONIE-

AROME is forced with ECMWF coupled global model output as initial and boundary conditions. Similarly, the Marine Institute uses the Simulating WAves Nearshore (SWAN) wave model for forecasting wave parameters forced by NCEP GFS Global model winds and WAVEWATCH III (WW3) Global model spectral boundary conditions. Apart from wave forecasts, the Marine Institute is using the Regional Ocean Modelling System (ROMS) for ocean state forecast parameters such as ocean temperature, salinity, sea level and ocean currents. ROMS is a free-surface, terrain following, primitive equations ocean model used by the Marine Institute for an area which covers Irish waters and the northeast Atlantic. All these models (Ocean, Atmosphere and Wave) are run every day independently with different model initial and boundary conditions. These varied initial and boundary conditions lead to variation in the forecast. Like CGCMs, regional coupled (Atmosphere-Ocean-Wave) models can enable regional weather to be forecast more accurately. Following on from the literature survey carried out during this project, it was decided a coupled model using HARMONIE-AROME (atmosphere), WW3 (wave) and ROMS (ocean) for Ireland should be developed using OASIS3-MCT coupler to share weather fields between the individual models. Regional coupled models are proven to be more accurate than its standalone counterpart in various studies highlighted in the literature review report. This is especially true for major/anomalous weather events such as storms and high impact weather events, which have been shown to be well predicted by coupled models in terms of intensity and direction. Despite the benefits of coupled models, their usage in real time forecasting is rare for reasons that are many folds. One important factor is that coupled models require substantially more computing power, with dedicated high-performance computation to run a coupled model with the required very high spatial and temporal resolution.

To begin with, WW3 was forced with operational HARMONIE-AROME forecasted winds and an extensive verification completed for three different physics schemes of WW3. Furthermore, WW3 is running operationally in three nested domain setups for Ireland on the Met Éireann research HPC server. HARMONIE-AROME and WW3 coupled (atmosphere-wave) model was implemented to predict wave parameters and winds over Ireland and the surrounding ocean. This two-way coupled model (HARMONIE-AROME-WW3) was validated with different observation datasets along with their stand-alone model counterpart. Further, the ROMS stand-alone ocean model was tested for ocean state forecast. This coupled forecasting system is a first for Ireland and will have important implications for renewable energy applications by providing improved weather forecasts and an integrated solar, wind (onshore & offshore) and wave energy forecasting system. The research outputs will greatly improve wind, wave and solar renewable energy forecasting in Ireland.

Keywords (min 3 and max 10)	Coupled, atmosphere, ocean, wave, renewable energy, forecasts, regional downscaling, NWP

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

The research goal of the project is to develop a coupled Ocean-Atmosphere-Wave weather forecasting model for Ireland. To begin with, a detailed literature survey was completed, and a report generated. The report conclusions recommended using the HARMONIE-AROME (atmosphere), ROMS (ocean), and WW3 (wave) models as components of a coupled model with the OASIS3-MCT coupler to exchange required parameters among these models during runtime. The PI has set-up the WW3 wave model for Ireland with three nested domains (Figure 1) and forced with HARMONIE-AROME operational wind forecast data. The WW3 system is currently running operationally at Met Éireann and generating 54-hour wave forecasts every day at 00GMT. Furthermore, these forecasts were validated with wave buoy observations around the coasts of Ireland. As a next step of the project, WW3 was coupled with the HARMONIE-AROME model using OASIS3-MCT. This atmosphere-wave coupling involved generating the remapping and weather files during runtime to exchange the parameters in real-time. Hence, a two-way coupled model consisting of HAMONIE-AROME and WW3 is successfully implemented and running. This atmosphere-wave coupled model is using IFS and WAM Global model initial and boundary conditions from ECMWF. The coupled model exchanges 10m wind speed from the atmospheric model to the wave model and in-turn, the wave model passes the sea surface roughness parameter to the atmospheric model. These exchanges occur during runtime and are controlled by a *configure file* during every model coupling time step. This is the first atmosphere-wave (HARMONIE-AROME and WW3) coupled model developed and validated for Ireland. A detailed verification of the coupled atmosphere-wave model outputs with observations and its stand-alone counterpart was completed. The coupled atmosphere-wave model results shown improved skill in the forecast of wave height and weather parameters as compared to its standalone counterpart. Furthermore, ROMS ocean model is tested for ocean-state forecast in a stand-alone mode.

Operational Wave Forecast Model: The Wave Watch III wave model is currently running at Met Éireann every day in operational mode. Every morning the WW3 model is run to produce a 54-hour operational wave forecast. The WW3 model is forced by hourly 10m wind speed and direction from the HARMONIE-AROME atmospheric model (00GMT run), and wave spectral data from the ECMWF-WAM model. Every day, plots are generated for Significant Wave Height (SWH) and wave direction from the post-processed output of WW3 and are automatically transferred to a server for the guidance of forecasters (figure 2). The details of the system configuration, model domain, bathymetry and initial conditions (figure 1) were discussed in the earlier annual report. To make this forecast more accurate and usable for forecasters, the PI has completed extensive verifications of the different physics schemes of the WW3 wave model.

Wave Watch III nested domain setup.

- Gridgen used for grid generation
- Emodnet high resolution bathymetry
- Harmonie-Arome forecasted winds as input
- Ifremer run WW3 global spectral conditions as boundary data
- Generated spatial Plots and extracted for Buoy locations

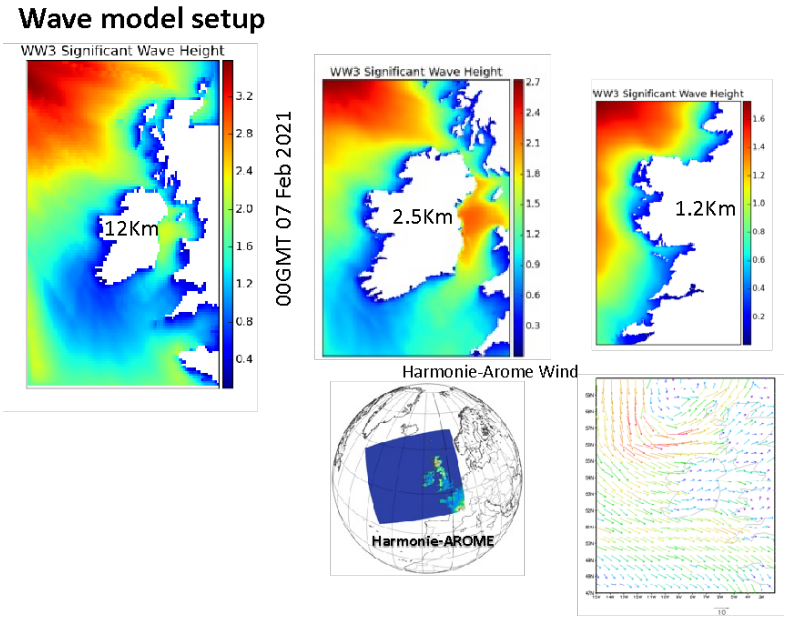

Figure 1: Wave model setup for operational run at Met Éireann

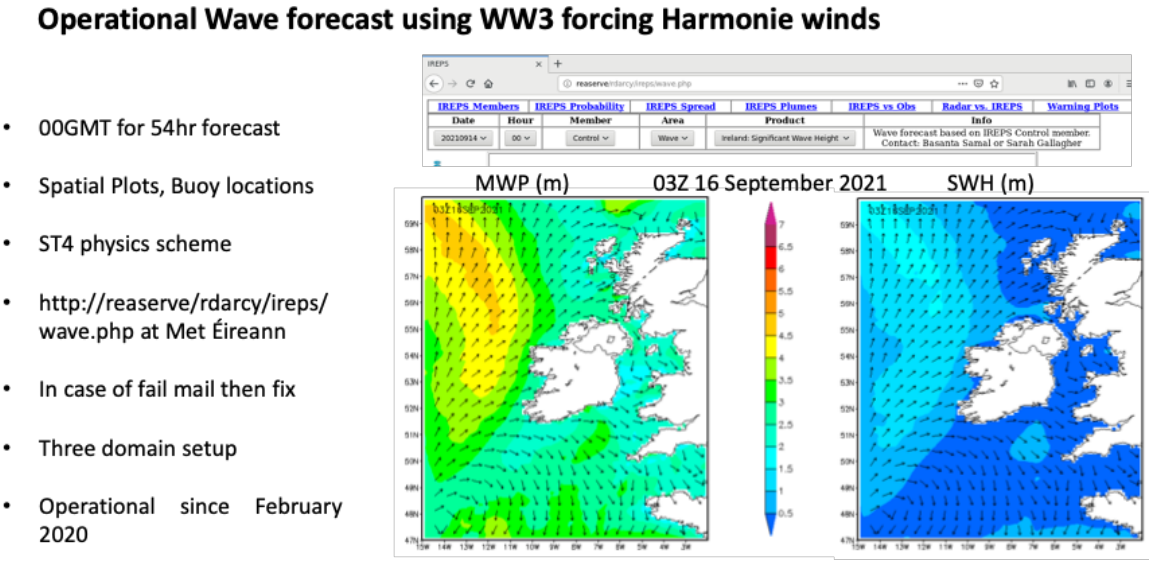

Figure 2: Wave model operational run at Met Éireann

Wave height verification: Significant Wave Height (SWH) is the average wave height, from trough to crest, of the highest one-third of the waves. The model post-processed SWH output were compared with wave buoy measured SWH every hour. Wave forecast for next 54 hours were generated every day. The first 24 hours of hourly forecast were validated and consolidated as Day1 forecast verification results. Similarly, 25-48 hours of hourly forecast were validated with corresponding observations and reported as Day2 forecast verification results. A total of three physics schemes were tested to determine the most accurate for the Irish domain. The three physics schemes are as follows:

- ST4 (Ardhuin et al., 2010) correction reduces the wind input for high frequencies and high winds
- ST3 (ECWAM) considers a stronger gustiness in unstable atmospheric conditions
- ST6 (Rogers et al. 2012 & Zieger et al. 2015) includes wind input source terms, and sink terms due to negative wind input, white capping dissipation and wave-turbulence interactions (swell dissipation).

A detailed description of these schemes is available in the Wave Watch III technical note (https://polar.ncep.noaa.gov/waves/wavewatch/manual.v5.16.pdf). The model runs with multi nested domains (12km, 2.5km and 1.2km). For verification, the PI collected quality controlled Marine wave buoy data from Met Éireann for six locations and wave height observations at two locations from the Marine Institute. From the 54-hour forecast, Day1 (24 hour) and Day2 (25-48hr) forecasts are compared. Forecasted 24- and 48-hour SWH data for the three domains of different resolution, and the three different physics schemes, were compared with observational data. In total, validations were made at eight locations: three on the East coast (Dublin, M2, and M5), one in the South (Kinsale) and four in the West (BerthB, SmartB, M4 and Ballybunion) (figure 3). For all these buoy locations, hourly observations were matched with hourly forecasts of all three physics schemes for the day1 and day2 forecasts. Furthermore, line plots, scatter and box plots, and verification statistics (e.g., RMSE, standard deviation, mean error) were calculated (figure 4). These results were discussed and presented at Met Éireann and in a symposium (EMS-2020 and Hirlam Surface week-2021). From this verification, results show that the day2 forecast is nearly as good as the day1 forecast. As expected, the higher resolution inner domain forecasts are slightly better than the low-resolution outer domains. Among the three physics schemes, the ST4 scheme performed consistently better for the full range of wave heights at all buoys (figure 5). It is noted that the models are unbale to capture a small number of high (> 8m) wave events. The validation results informed the decision to use the ST4 physics scheme in the operational WW3 model configuration currently running at Met Éireann.

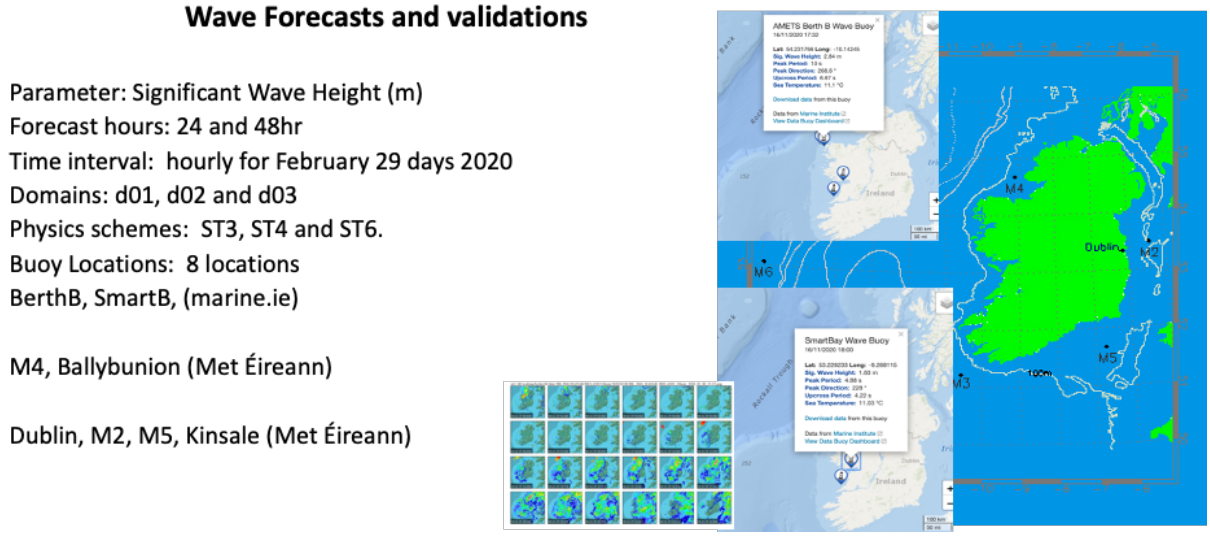

Figure 3: Wave forecast and validation location details

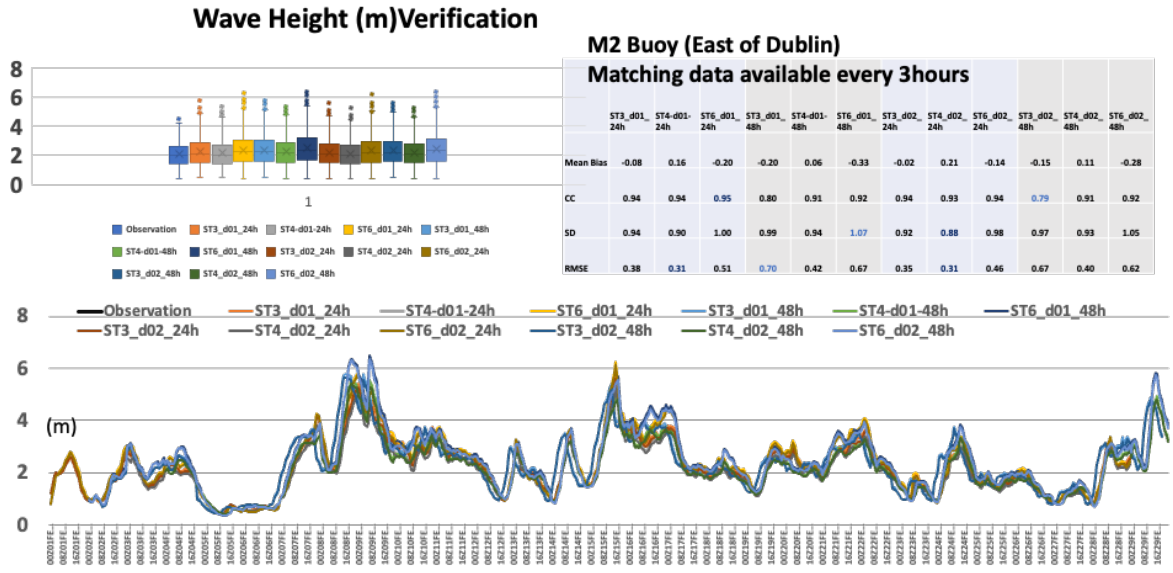

Figure 4: Significant wave height verification statistics for M2 buoy

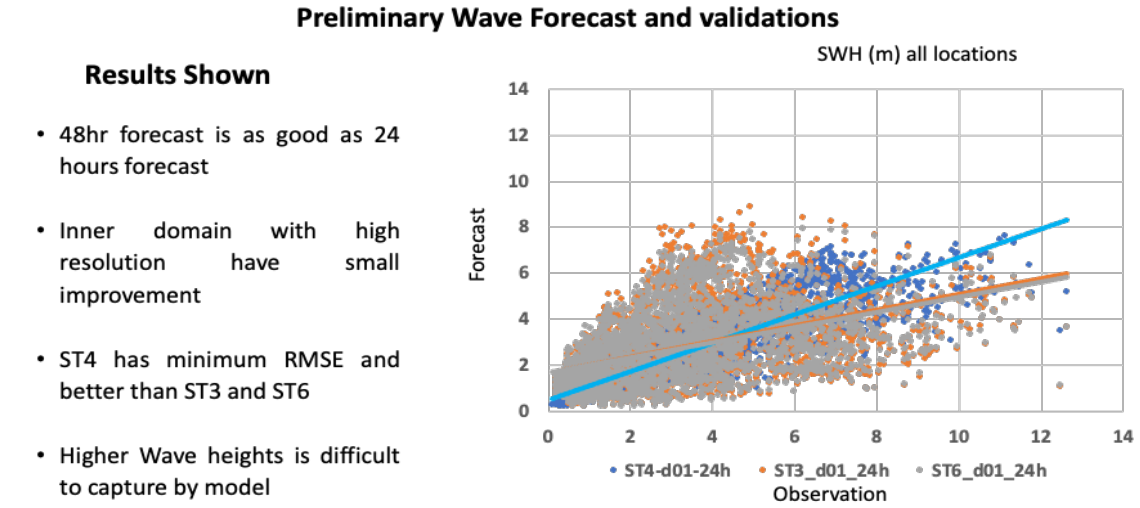

Figure 5: ST4 physics scheme forecasts closure to observation as compared to ST3 and ST6

HARMONIE-AROME-WW3 atmospheric-wave coupled model: HARMONIE-AROME is a more complex model as compared to WW3 with more routines and schemes, hence WW3 model was integrated inside the HARMONIE-AROME model. The coupled model is controlled by HARMONIE-AROME configuration and submit scripts. The PI successfully implemented the HARMONIE-AROME-WW3 coupled model with the required Ireland domain setup. In a coupled atmosphere-wave model the interactions at the atmosphere-ocean boundary need to be resolved in real-time. To develop this coupled model, the SURFEX routines were used from HARMONIE-AROME. SURFEX is the surface modelling platform and is composed of various physical models for natural land surface, urbanised areas, lakes, and oceans. SURFEX interacts with OASIS3-MCT to exchange coupling parameters between HARMONIE-AROME and WW3. The first step was to compile the OASIS3-MCT library along with all models by modifying the HARMONIE-AROME compilation scripts. The paths and libraries of OASIS3-MCT are included in the wave model during compile time. On the first time compilation of the code, a remapping file is generated which guides the parameters from one model to the other with different model grids. Every model makes calls to OASIS3-MCT functions (e.g., *send* and *receive*) to couple the various fields at the required timestep. *Prep* is the program which generates the initial surface

files. SURFEX routines and namelist files are modified to include WW3 routines in the coupled model. The *Config* file of HARMONIE-AROME has the control switches for coupling periodicity, restart file writing, and stand-alone HARMONIE-AROME run. HARMONIE-AROME shares 10m u and v components of the wind and are used to force WW3. WW3 in-turn shares sea surface roughness (also called Charnock parameter) with HARMONIE-AROME. The HARMONIE-AROME-WW3 coupled model was extensively tested and can be run in forecast mode. Forecasts are generated for six hours from 00 to 21 GMT in every three-hour interval. Furthermore, the coupled model can be run in stand-alone mode (HARMONIE-AROME) by switching off WW3 (set *two_way_couple* as *NO*). The coupled model (HARMONIE-WW3) and stand-alone models (HARMONIE-AROME and WW3) were validated for February 2020 to verify the benefits of coupling. Model simulation details are presented below.

Model Simulation details

- ✓Models used: WW3 (standalone), Harmonie (standalone), Harmonie-WW3 (two-way coupled)
- ✓Forecast hours: 24 hour from 00GMT
- ✓Time interval: hourly for 02-17 (16days) February 2020
- ✓Verifications: Observation with Coupled and uncoupled model
- ✓Station observations (met.ie) and spatial (satellite and ERA5)
- ✓Horizontal resolution: 2.5km (Ireland25 domain)
- ✓Resources used: CCA on Ecserver
- ✓Parameters: SWH, WS, Temp., Pressure, RH and Rainfall

The verification results show that the coupled model improves the forecast of significant wave height and out-performs the uncoupled WW3 model (figure 6). These improved results of SWH are seen for point observations as well as spatial plots. Like wave height, other parameters from the HARMONIE-AROME atmospheric model are slightly improved when forecast by the coupled model as compared to uncoupled. The parameters are validated with available location specific observations (20 locations around Ireland) and spatially with available satellite data and reanalysis dataset (figure 7). The following parameters were validated rainfall, wind speed, pressure, temperature and relative humidity. Rainfall validations were considered in terms of different categories of rainfall (light, moderate and heavy) and Yes/No categories (rain or no rain). It is noticed that correct hits in each category of rainfall are improved in the coupled model forecasts. In general, the coupled model showed slight improvements in forecast by decreasing the bias and increasing the corelation coefficients in all variables analysed. The coupled (atmosphere-wave; HARMONIE-AROME-WW3) model is fully developed for operational use.

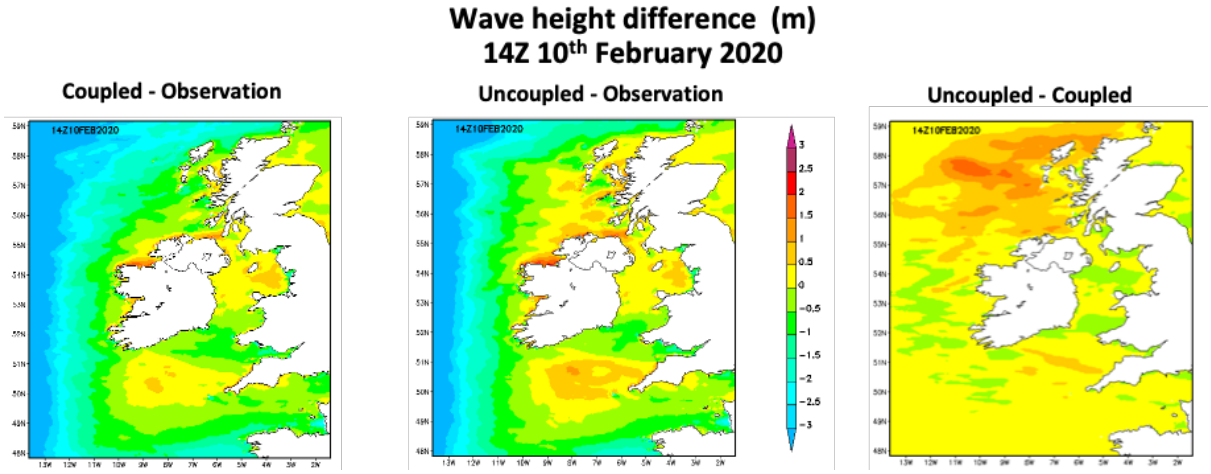

Figure 6: Bias of Coupled (HARMONIE-AROME-WW3) and uncoupled WW3 model SWH forecast

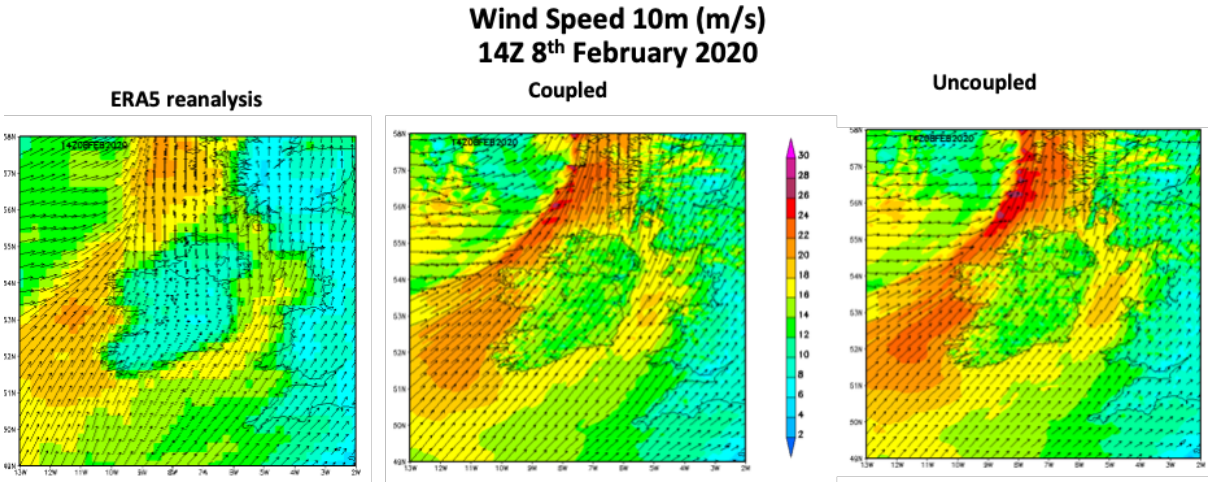

Figure 7: Wind speed from coupled (HARMONIE-AROME-WW3) and uncoupled HARMONIE-AROME model

HARMONIE-AROME-WW3-ROMS, atmospheric-wave-ocean fully coupled model:

The Regional Ocean Modelling System (ROMS) ocean model is a free surface, terrain-following primitive equation model widely used by the scientific community. From the literature study, it was decided to couple ROMS ocean model with HARMONIE-AROME atmosphere and WW3 wave model. The ROMS stand-alone model was implemented on ecgate supercomputer systems. Furthermore, the domain files were generated with EMODNET high resolution bathymetry data using the *gridpak* tool. The next step was to create initial and boundary conditions for the ROMS model using ERA5 reanalysis data and the *ERA5-ROMS-Master* python tool. ROMS standalone model was simulated for few days. The next step was creation of remapping files for HARMONIE-AROME and ROMS i.e., ocean2atmosphere and atmospher2ocean weight files which transfer the exchange files between models. Similarly, remapping files were created for ROMS and WW3. Finally, the necessary exchange files were created for the first-time step and changes for *namelist files* for all three models were written accordingly. The test run of the fully coupled model (ocean-atmosphere-wave) didn't succeed after the first-time step. After extensive debugging, it was decided to complete three experiments to find the bug, the results of which showed that the remapping file for ROMS and HARMONIE-AROME was not appropriate and was not transferring the exchange files. The probable reason of failing was mismatch of OASIS3-MCT with SCRIP. At present the fully coupled model is not tested for ROMS-HARMONIE-AROME. Very recently, we have re-generated the remapping file for HARMONIE-AROME and ROMS using a different tool (same as HAMRONIE-NEMO coupling by Meteo France; https://doi.org/10.5194/acp-2021-239). Recently the ECMWF ecgate and cca supercomputers were phased out so the fully coupled system (Figure 8) needs to be implemented and re-tested on the new supercomputer (Atos).

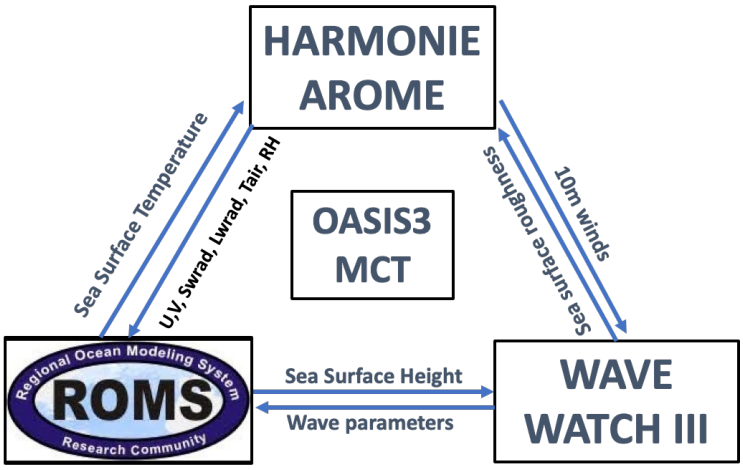

Figure 8: Schematic diagram of coupled (Atmosphere-Ocean-Wave) model using OASIS3-MCT coupler and the required exchange of parameters from one model to the other.

2.2 Introduction to Project

The first regional coupled atmosphere-ocean models were developed in the 1990s with the primary purpose of improving weather forecasting and the prediction of extreme events (e.g., Bender et al., 1993; Gustafsson et al., 1998; Hodur, 1997; Xue et al., 2000). These developed from early approaches using hybrid models involving simplified atmosphere or ocean components (e.g., Bender et al., 1993; Gustafsson et al., 1998) to coupled 2D models (Wang et al. 1995; Xue et al., 2000) and finally to coupled 3D models by the early 2000s (e.g., Hodur, 1997; Rinke et al. (2003); Aldrian et al. (2005); Mikolajewicz et al. (2005)). The first 3D two-way coupled regional atmosphere-ocean model, which also incorporated sea ice dynamics was presented by Schrum et al. (2001, 2003) for the North Sea and Baltic Sea region.

Coupled models typically outperform uncoupled models, particularly under extreme marine weather conditions (e.g., Aldrian et al., 2005; Bender & Ginis, 2000; Gröger et al., 2015; Lynn et al., 2015; Pullen et al., 2006; Seo et al. 2007A). Sea waves play a key role in the exchange of momentum, heat, and turbulent kinetic energy at the air–sea interface. Wind waves, once generated, extract energy and momentum from the atmosphere so the atmospheric drag over the oceans becomes sea-state dependent. Furthermore, ocean waves affect the mixing of heat and momentum in the upper ocean layers. In this context, only a real-time coupled model can fully represent all the forces and feedbacks that contribute to air–sea interactions. Highly energetic phenomena are strongly controlled by air-sea interactions, and so simulating these accurately is crucial. For tropical cyclones, the use of coupled models is already standard in research, forecast, and climate assessments (e.g., Bender et al., 2010; Bernadet et al., 2015; Knutson et al., 2013). Numerous studies have demonstrated improved skill in the simulations of storms when using coupled atmosphere-ocean-wave models in place of standalone atmosphere models (e.g., Chen et al., 2007, Warner et al., 2010, Liu et al., 2011, Renault et al., 2012, Zambon et al., 2014, Zhao et al. 2017, Pianezze et al., 2018). Studies such as Lee et al. (2012), Süld et al. (2015), Staneva et al. (2016) and Wahle et al. (2016) have demonstrated that surface wind speeds, waves and storm surges provide a closer match to observations when simulated with a coupled atmosphere-wave model. Numerous international studies have demonstrated the advantages of using coupled atmosphere-ocean simulations in place of atmosphere-only simulations for the study of high impact weather, and of seasonal and intra-seasonal oscillations which are largely dependent on ocean boundary conditions. Regional coupled models are also proven to better represent air-sea

interaction during high-impact weather events such as cyclones and depressions (Ratnam et al, 2009; Samala et al, 2013).

Coupled Modelling Systems:

The number of convection-resolving coupled atmosphere-ocean-wave models currently in operation is limited. One of the most widely used is the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modelling System developed by the United States Geological Survey (USGS), comprising of (i) the Weather Research and Forecast (WRF v3.9.1.1) atmospheric numerical weather prediction model, (ii) the Regional Oceanic Modelling System (ROMS svn 885), (iii) the Simulating WAve Nearshore (SWAN v41.20) wave model, (iv) the WAVEWATCHIII (WW3 v5.16) wave model, (v) the Infra-gravity wave model (InWave v1.0) and (vi) the National Community Sediment Transport Model (NCSTM). These model components are coupled together using the Model Coupling Toolkit (MCT) and the Spherical Coordinate Remapping and Interpolation Package (SCRIP). Both static and dynamic high-resolution nested domains can be configured for both WRF and ROMS.

Numerous international studies have demonstrated the advantages of using COAWST in place of uncoupled models. For example, COAWST was used at high resolutions (up to 3 km for the atmosphere and up to 1 km for the ocean and wave models) in the Mediterranean region (Renault et al., 2012; Carniel et al., 2016; Ricchi et al., 2016). These studies highlight that high-resolution coupling significantly improves the simulation results. Olabarrieta et al., (2012) used COAWST to simulate hurricane Ida and demonstrated substantial improvement in accuracy over uncoupled model systems. Zambon et al. (2014) used COAWST to simulate hurricane Ivan and compared the results with those from WRF atmosphere-only simulations. The results show a drastic improvement by the COAWST coupled model in the simulation of ocean and atmosphere parameters during and after the hurricane. Olabarrieta et al. (2011) simulated a large storm event affecting Willapa Bay (Washington State) during 22 to 29 October 1998 using the 'vortex-force' method to represent the interaction between waves and currents, and achieved very good agreement with observed water elevations, currents and wave measurements. Another notable fully coupled system is the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) developed by the Naval Research Laboratory (NRL) and used operationally by the U.S. Department of Defence. The non-hydrostatic atmospheric component is coupled with the hydrostatic, mesoscale version of the NCOM ocean model using the ESMF coupler (Doyle et al., 2014). Compared to non-coupled simulations the system demonstrated improved skill in the forecasting of strong winds and storms (Small et al., 2011, Doyle et al., 2014).

Andreas et al. (2017) used the OASIS3- MCT (Valcke et al., 2013) coupling system to couple the COSMO-CLM atmosphere model (Rockel et al., 2008; Baldauf et al., 2011) with the NEMO ocean model (Madec et al, 2011). Long-term validation simulations over the European region demonstrated improved skill in the simulation of surface temperatures (Pham et al., 2014), wind speeds, storm tracks and extreme winds (Akhtar et al. 2014). Wahle et al. (2016) coupled the COSMO-CLM model with the WAM wave model and found that the two-way coupling improved the accuracy of simulated winds and waves thus justifying the use of the approach for both operational and climate simulations. The UK Environmental Prediction Prototype project implemented an atmosphere–land–ocean–wave modelling system (UKC2) focused on the United Kingdom and surrounding seas at km-scale resolution. The UKC2 incorporates models of the atmosphere (Met Office Unified Model), land surface with river routing (JULES), shelf-sea ocean (NEMO) and ocean waves (WAVEWATCH III) coupled with OASIS3-MCT. Validation experiments comparing the skill of the UKC2 system with that of the individual components demonstrated improvements in the simulation of air temperature, sea surface temperature, wind speed, significant wave height and mean wave period (Lewis et al., 2018).

In many European countries, including Ireland, the convection-permitting HARMONIE–AROME numerical weather prediction model is used for operational short range weather forecasts. It is developed, maintained, and validated as part of the shared ALADIN–HIRLAM system by a collaboration of 26 countries in Europe and northern Africa. To extend HARMONIE–AROME towards a more complete regional modelling system, and therefore improve the accuracy of the forecasts, developments are under way to implement coupling between ocean and wave models. Within the HARMONIE–AROME and ALADIN communities, developments are underway to improve the accuracy of forecasts by coupling the atmospheric model with ocean and wave components to simulate more realistic interactions between the atmosphere and ocean. In Slovenia, the ALADIN atmosphere model (4.4km resolution) has been coupled with the Princeton Ocean Model (POM) using the OASIS3-MCT toolkit on a domain including the Adriatic Sea. Comparison of the performance of a two-way coupled atmosphere–ocean system and one-way coupled ocean model showed superior performance by the two-way coupled model for both air and ocean temperatures (Ličer et al, 2016a). The team plan to improve their system with the addition of a coupled wave component (WAM) and the replacement of POM with NEMO (Ličer et al, 2016b). Researchers at Météo-France are coupling HARMONIE-AROME-France to the NEMO ocean model using the OASIS3-MCT coupler which exists within SURFEX from version 8.0 (Voldoire et at., 2017). Preliminary experiments in Norway have indicated that coupling HARMONIE– AROME with the wave model WAM reduces near-surface wind bias for strong winds (Süld et al. 2015). In a similar manner to the French, the team used OASIS3-MCT (via SURFEX v8.0) to create a fully coupled system consisting of HARMONIE-AROME cy43, NEMO and WAM. A recent study by César Sauvage et al., (2021) concluded that a coupled model (HARMONIE-AROME-NEMO-WW3) could improve the air-sea interaction in a Mediterranean heavy precipitation event.

2.3 Project Objectives

The aim of the current project is to develop a fully coupled regional atmosphere-ocean-wave model for Ireland using HARMONIE-AROME, WW3 and ROMS. This is a first-of-its-kind development anywhere in Europe by using these three (HARMONIE-AROME, WW3 and ROMS) models. Figure 8 shows a schematic overview of the prototype coupled model structure in which multi-directional coupling is implemented (atmosphere-ocean yet to be fully completed/tested) between the three models. A brief introduction to the three component models, the coupler and the coupled system is presented below.

HARMONIE-AROME is based on the HARMONIE-AROME-France model developed within the ALADIN consortium. It solves for the standard governing equations of mass, momentum, energy, and humidity using appropriate physical models to simulate the effects of clouds, pollutants, earth rotation, and other processes. The model is non-hydrostatic, with a dynamical core based on a two-time level, semi-implicit, semi-Lagrangian discretisation of the fully elastic equations, using a hybrid coordinate system in the vertical direction. The HARMONIE framework facilitates observation handling, climate generation, lateral boundary coupling and postprocessing. HARMONIE-AROME parameterizes radiation using a two-stream approximation in model columns and the effects of surface slopes are accounted for. Shortwave and longwave spectral computations follow Fouquart and Bonnel (1980) and Mlawer et al. (1997), respectively, and cloud optical properties for liquid clouds are derived from Morcrette and Fouquart (1986), and from Ebert and Curry (1992) for ice clouds. HARMONIE-AROME uses a mixed-phase microphysics scheme, the ICE3 scheme (Pinty and Jabouille 1998), wherein cloud water and ice as well as rain, snow, and graupel are prognostic variables. Hail is assumed to behave as large graupel particles. The

turbulence parameterization was developed by Cuxart et al. (2000) and is based on a prognostic TKE equation combined with a diagnostic mixing length L.

WaveWatch III solves the random phase spectral action density balance equation giving the wave energy spectrum as a function of location, frequency, and direction of the waves. The model includes options for shallow-water (surf zone) applications, as well as to permit the wetting and drying of grid points. Propagation of a wave spectrum can be solved using regular (rectilinear or curvilinear) and unstructured (triangular) grids. The PI has used Gridgen, an opensource grid/bathymetry generation tool written in matlab and Python to create domains for the WW3 Ireland model which match the current operational HARMONIE-AROME forecast, and testing domains implemented at Met Éireann. The European Marine Observation and Data Network (EMODnet) Digital Terrain Model (DTM) data with a resolution of 1/16 arc minute grid was used to create the bathymetry for the WW3 Ireland model Winds forecast by HARMONIE-AROME and wave spectra from the Global WAM model run by ECMWF are provided as initial and boundary conditions.

ROMS is a 3D, free surface, terrain-following primitive equation ocean model which solves for tidal height, ocean currents, temperature and salinity. The code can be run in serial or parallel mode and uses a coarse-grained parallelization paradigm which partitions the computational 3D grid into tiles. Each tile is then operated on by different parallel threads. ROMS allows for a nested domain configuration to focus on a particular region with very high resolution. The ROMS model has no integral modules or tools to create the grid/bathymetry and forcing files. Using the gridpak opensource tool, the PI has generated three ROMS domains to conform with the operational HARMONIE-AROME forecast and testing domains currently in use at Met Éireann. For generating forcing data such as initial, boundary and climatology files for ROMS, the PI used the model2roms python tool. Once these files are prepared, a namelist file is configured to choose the required parametrisations, time step and other run-time options. For compiling ROMS, one needs fortran and C compilers, and NetCDF, HDF libraries.

OASIS3-MCT (coupler) is a coupling software developed primarily for use in the climate and weather forecasting community. It provides the ability to couple different models with low implementation and performance overhead. The latest version of OASIS3-MCT includes elimination of a separate hub coupler process, parallelization of the coupling communication and runtime grid interpolation, and the ability to easily reuse mapping weight files. OASIS3-MCT includes the ability to couple between components running sequentially on the same set of tasks as well as to couple within a single component between different grids or decompositions such as physics, dynamics, and I/O. OASIS3-MCT has been tested with different configurations on up to 32,000 processes, with components running on high-resolution grids with up to 1.5 million grid cells, and with over 10,000 2-D coupling fields.

The Coupled Model (HARMONIE-AROME-ROMS-WW3): HARMONIE-AROME is a significantly more complex model than WW3, with more complicated routines and schemes. Hence the WW3 configuration is integrated into HARMONIE-AROME scripts instead of the other way round. Similarly, the ROMS model was also integrated into the HARMONIE-AROME scripts. In the coupled model, this is achieved using the surface modelling platform SURFEX developed by Meteo-France which is composed of various physical models for natural land surface, urbanised areas, lakes, and oceans. SURFEX interacts with OASIS3-MCT to exchange coupling parameters between HARMONIE-AROME, ROMS and WW3.

As shown in Figure 8, HARMONIE-AROME coupling with WW3 is complete and extensive validations of this coupled (atmosphere-wave) model show improvements over the uncoupled counterparts. ROMS standalone model tested. Although the changes for coupling of all three models was completed, the remapping file between ocean-atmosphere did not work during the test run. ROMS-WW3 coupling worked fine with the exchange of files to each other. Unfortunately, the ECMWF ecgate and cca supercomputers were phased out and the fully coupled model could not be fully tested.

2.4 Summary of Key Findings/Outcomes

Current practice:

- Met Éireann runs the HARMONIE-AROME atmospheric model operationally four times a day, but the resulting model winds are not used for running an in-house wave model. The Marine Institute runs the SWAN wave model with NCEP forced winds. The ROMS ocean model is run semi-operationally at the Marine Institute. All three models run independently with different initial and boundary conditions from different global models.
- Marine Institute, Galway is using SWAN wave model for near shore wave forecasts. They plan to upgrade and implement WW3 wave model for the same.
- Marine Institute is running ROMS ocean model for their ocean state forecast operationally. They use NCEP initial and boundary conditions to run ROMS.
- All these models are running as standalone models with very different initial and boundary conditions, which leads to increased forecast error. There is a need for a coupled model comprising of all three atmosphere (HARMONIE-AROME), ocean (ROMS) and wave (WW3) models in Ireland for integrated forecast of ocean, wave and weather. The objective of this project is to develop a regional coupled Ocean-Atmosphere-Wave model consisting of HARMONIE-AROME, ROMS and WW3 model for accurate weather, ocean state and wave forecasts for Ireland.

Project Achievements:

- The WW3 wave model with multi domain set-up is running in operational mode at Met Éireann every day. The model is forced with HARMONIE-AROME operational forecast winds and ECMWF Global WAM model wave spectra data.
- A detailed verification of the WW3 forecast system was completed, the results of which informed the choice of WW3 model setup to implement in the coupled model (outcome of this project).
- The WW3 wave forecasting system was validated by comparing forecast data (for various physics schemes) with the observation data at buoys surrounding Ireland.
- Various test simulations were conducted using the HARMONIE-AROME model along with all dependent software and tools on *EC-Server*. The code (version cy43) was run successfully with Ireland150 (toy) domain, operational Ireland25 (2.5km) domain, and larger domain of ireland25_090.
- Enabled OASIS3-MCT coupler in HARMONIE-AROME and coupled the required parameters with WW3.

- Developed HARMONIE-AROME-WW3 two way coupled model with real-time exchange of parameters between models. Winds (10m) from HARMONIE-AROME passing to WW3 and in return WW3 is passing wave induced stress (Charnock parameter) to HARMONIE-AROME.
- The two-way coupled Atmosphere-Wave model is ready and tested for different initial conditions for operational run.
- For the first time, the HARMONIE-AROME-WW3 (atmosphere-wave) two-way coupling model is implemented and tested on the Irish domain, where both models exchange respective parameters at assigned time steps. The present model domain and initial and boundary conditions are the same as the operational atmosphere-only HARMONIE-AROME national forecasts.
- The PI has developed HARMONIE-AROME-WW3 two-way coupled model for Ireland on the supercomputer at ECMWF (courtesy of Met Éireann for providing the facility and support to PI).
- The HARMONIE-AROME-WW3 coupled code is running with single domain wave model set-up and using ECMWF wave spectral boundary conditions as input.
- The required software, tools and scripts for HARMONIE-AROME and WW3 are implemented on the ECMWF supercomputer (ecgate and cca) including modifications and additions to the OASIS3-MCT coupler.
- From the WW3 verification study with different physics schemes, it was concluded that the ST4 physics scheme works well for the Irish coast, hence the same setup is implemented in the coupled model.
- A detailed verification of the HARMONIE-AROME-WW3 coupled model was completed, which demonstrated that the coupled model forecast performs slightly better than the uncoupled counterpart for wave and weather parameters.
- ROMS stand-alone ocean model was setup with EMODENET bathymetry and ERA5 reanalysis for initial boundary conditions. The required OASIS3-MCT and namelist changes for coupling were implemented in the ROMS ocean model. External tools like gridpak and ERA5-ROMS-Mater tools are implemented on ecgate supercomputer to generate bathymetry and initial boundary conditions for ROMS.
- ROMS ocean model integrated in HARMONIE-AROME-WW3 coupled model. The necessary changes for coupling completed in all three models. Remapping files created using SCRIP.
- During testing of the coupled model ROMS-WW3 coupling worked fine along with Harmonie-WW3.

2.5 Project Impact

This research provided a coupled atmosphere-wave forecasting model for operational forecast use. The PI has developed and implemented atmosphere-wave and ocean-wave coupling systems for Ireland. The coupled systems are implemented within an atmosphere-ocean-wave environment, with the choice to run individual components or coupled systems. The final atmosphere-ocean-wave system is near complete and requires further development and testing. This coupled forecast system is a first for Ireland will have important implications for renewable energy applications by providing improved weather forecasts and an integrated solar, wind (onshore & offshore) and wave energy forecasting system. The research outputs will greatly improve wind, wave and solar renewable energy forecasting in Ireland, which has been proven

by results of coupled model versus uncoupled model. The research will provide robust and reliable renewable energy forecasts and will encourage the foundations for transitioning Ireland to a low carbon, climate resilient and environmentally sustainable economy. The solar and wave energy forecasts resulting from the proposed research will inform the emerging ocean and solar energy market in Ireland and encourage an uptake in these renewable energy technologies. This coupled system is expected to improve the skill of weather forecasts in general including renewable energy forecasts in Ireland. In particular, the coupled system is expected to provide more accurate forecasts of extreme events such as flooding and storms. Such extreme events are likely to be a critical issue for Ireland due to climate change. In addition, Ireland faces increased threats from high-impact weather events such as prolonged dry periods, heavy rain episodes and prolonged warm spells.

The improved forecasts will provide a direct benefit to Irish society which is increasingly vulnerable to the impact of weather due to both climate change and increasing urbanisation. Weather-related hazards such as flooding and wildfires have the potential to cause personal injury or loss of life, and to damage property, infrastructure and the environment. Met Éireann (2017) have identified fisheries, the built infrastructure, agriculture, water resources, forestry, energy and transport infrastructure to be among the most vulnerable sectors to extreme weather within our economy. The improved forecasts resulting from this project will allow planners, policy makers and emergency services to make informed decisions based on accurate and robust weather forecasts. In addition, the research will inform national projects such as the national flood forecasting department at Met Éireann in support of the OPW (Met Éireann, 2017).

Forecasts of ocean and wave conditions are important to all who live, work or travel on or near sea and ocean, and the economic impact is significant for end-users in harbour and coastal monitoring, dredging, offshore design and operations, wave and wind energy, maritime traffic control and the Navy. For example, improved forecasts of strong waves/storms will yield direct economic benefits by providing information to sea transportation and port management (if strong wave conditions are forecasted, ships can slow down and save on fuel, instead of waiting outside of the harbour) and there is additional economic benefit in providing improved knowledge of wave environments for facilities situated near coasts. There is also indirect economic benefit in defining the wave resource for optimal implementation of wave energy parks to provide alternative electricity sources. The societal benefits of improved ocean/wave forecasting include improving safety conditions for ocean workers, reduced loss of life, public access to better wave forecasts for recreational activities and enhanced environmental protection.

2.6 Recommendations

The PI has developed and implemented atmosphere-wave and ocean-wave coupling systems for Ireland. The coupled systems are implemented within an atmosphere-ocean-wave environment, with the choice to run individual components and/or coupled systems. A detailed validation was completed which demonstrated the improvements in skill of the coupled systems. The final atmosphere-ocean-wave system is near complete and requires further development and testing. Furthermore, the ocean-wave coupling system, while working, needs to be further tested and validated. It is recommended that once the final coupling step is complete, a detailed validation experiment is completed to quantify the added valued of a fully coupled system over the individual model components. Further, the coupled system should be updated by inclusion of the latest versions of HARMONIE-AROME, ROMS and WW3, and ported to the new ECMWF supercomputer.

2.7 Conclusions and Next Steps

The PI implemented the WW3 wave forecast model in operational mode at Met Éireann. The system was carefully optimized to minimize HPC resources and forecast time. A careful validation experiment was completed to determine the optimal setup (e.g., model resolutions, domains, nesting strategy, physics options), the results of which demonstrated the skill of the model to forecast wave parameters out to 54 hours. The ROMS ocean model was implemented as a standalone model to forecast ocean parameters for the usage of different sectors. The PI developed a coupled atmosphere-wave 2-way coupled system by coupling the HARMONIE-AROME atmosphere model with the WW3 model. A detailed verification of the HARMONIE-AROME-WW3 system was completed, which demonstrated an improvement in the forecasts (both wave and atmospheric variables) using the coupled model. Furthermore, the PI integrated the ROMS ocean model into the HARMONIE-AROME-WW3 coupled system. All the necessary coupling changes such as namelist for exchange of parameters between models and remapping files were generated. While testing the fully coupled model, it was noticed that HARMONIE-AROME-WW3 and ROMS-WW3 worked fine, whereas the HARMONIE-AROME-ROMS coupling failed to exchange files. During different debugging experiments, it was concluded that the remapping file is unable to convert the model exchange files. Unfortunately, the ECMWF supercomputer was phased out which caused serious delays and prevented completion of the final coupling step.

Once the coupled system is implemented on the new ECMWF supercomputer, the HARMONIE-AROME-ROMS remapping files will be re-generated, thus completing the final step of developing a fully ocean-atmosphere-wave coupled model. It is recommended that a detailed validation experiment is completed to quantify the added valued of the fully coupled system (particularly in the simulation of high-impact weather events such as storms) over the individual model components. Furthermore, the coupled system should be updated by inclusion of the latest versions of HARMONIE-AROME, ROMS and WW3.

Note - Both Section 3 and Section 4 of this Final Report are required for SEAI review purposes only and will not be made publicly available.

SECTION 3: COMMUNICATION & DISSEMINATION (max 3 pages)

3.1 Communication, Dissemination and Exploitation

To facilitate collaboration with domain experts, the PI regularly visited (once a week prior to COVID-19 lockdown) Met Éireann. During the COVID restrictions, the PI regularly met with Met Eireann experts online. The PI joined the Hirlam, OASIS3-MCT, SURFEX, and *esm_coupling* community. The PI has closely collaborated with the HARMONIE-AROME consortium and participated in European conferences/workshops during the project duration to communicate results and get feedback from the community. An essential component of the research is the verification results from the coupled and uncoupled models. The PI presented the results of the WW3 wave model verification results and Harmonie-WW3 coupled model results with the relevant national and international researchers. In particular, the operational WW3 system provides wave forecasts to the forecast department at Met Éireann, providing another high-resolution wave height forecast along the coast of Ireland. The PI attended training courses and workshops relevant for the project (listed in table section 3.2). The PI attended regular steering group meetings with participants from SEAI, Met Éireann, and Marine Institute. The PI reported the progress of the project regularly with Met Éireann and Marine Institute.

The PI implemented various model components and coupled systems on the ICHEC and ECMWF (ecgate, cca and new atos system) supercomputers. The PI secured the required compute and storage resources by applying for an ECMWF special project. In addition, the PI implemented the WW3 model in operational mode on the research server at Met Éireann. The PI submitted annual reports to ECMWF regarding the usage of SBUs and progress of the project. The PI presented verification results of atmosphere-wave coupled model as compared to their uncoupled counterparts. The WW3 wave model is implemented in semi-operational mode at Met Eireann, and the forecasts are visualised and presented on a webpage (http://reaserve/rdarcy/ireps/wave.php). This webpage updates the wave forecast every day for the forecasters' consideration. The PI is currently preparing a user guide with technical description for the fully coupled model to submit to Met Éireann along with the coupled code.

3.2 Intellectual Property Management & Exploitation

All data resulting from the project will be made publicly available. The Offshore Renewable Energy Development Plan, published in February 2014, identifies Ireland's significant potential to generate offshore wind and ocean energy. The development opportunity for offshore wind is particularly in the context of exports to the UK in the first instance, with the possibility to participate in the future North West European energy market. The EU Blue Growth Study identifies offshore wind (€2.4bn and recent growth 21.7%) and ocean renewable energy (€<0.25bn and recent growth) as promising activities. The Irish plan includes provision for environmental monitoring to ensure potential impacts continue to be assessed. This opportunity to commercialise the datasets will be discussed with SEAI, Met Éireann and Marine Institute and the final decision will be left at their discretion.

Table 3.1 – List of Scientific Publications

Title	Main Author	Journal Title	Number, Date or Frequency	Publisher	Year of Publication	Is/Will open access be provided? If you marked "will", provide an estimate of the date	Peer-reviewed (Y/N)?
Verification of wave forecast using WW3 for Ireland: A test case	Basanta Kumar Samala	Yet to decide	Yet to decide	Yet to decide	Under preparation	Will (2023)	Y
Development of a coupled atmosphere-wave model for Ireland	Basanta Kumar Samala	Yet to decide	Yet to decide	Yet to decide	Under preparation	Will (2023)	Y

Table 3.2 – List of Dissemination Activities

Type of Activity	Main Leader	Title	Date/Period	Location	Type of Audience*	Size of Audience
Annual report	SEAI, Dublin	Progress of the project during 2019	February 2020	Pep.seai.ie	Researchers, Industry, Meteorologists	10
Harmonie- WW3 coupling	Met Norway, SMHI	Video conference and number of emails	~20/year	Virtual	Scientists	6
Weekly visit to Met Éireann	Met Éireann, Dublin	Collaborate and share results with Met Eireann experts	All Fridays until March 2020	Met Éireann, Dublin	Working and meeting with Dr. Saji Varghese, Dr. Sarah Gallagher, and Dr. Eoin Whelan	3
Weekly meeting with Met Éireann	Met Éireann, Dublin	Progress on project and ecgate access	Weekly virtual meeting	Virtual	Working and meeting with Dr. Ewa McAufield and Emily Gleeson	2
Bi-weekly meeting with Supervisor	ICHEC	Progress on project, guidance and help during work	Bi-weekly virtual meeting and discussion	Virtual	Working and solving technical issues with Dr. Paul Nolan	1

Type of Activity	Main Leader	Title	Date/Period	Location	Type of Audience*	Size of Audience
Progress meeting	Met Éireann, Dublin	Wave height verification, progress and future	18 December 2020	Virtual	meeting with Dr. Saji Varghese, Dr. Sarah Gallagher, Dr. Ewa McAufield and Dr. Paul Nolan	4
Accord surface week	ACCORD Group	Wave height verification and coupled model plan	20th October 2021	Virtual	Met Éireann, Accord group members	20
Workshop	Hirlam surface week	Verification results of WW3 Wave model	2020	Virtual	Hirlam community	40
Workshop	Hirlam surface week	Verification results of Harmonie-WW3 coupled model	2021	Virtual	Hirlam community	40
Workshop	Met Norway	Nordic coupled atmosphere-wave-ice-ocean modelling	2020	virtual	ESM coupling group	40
Symposium	European Meteorological Society	Coupled modelling work in Ireland	2020	virtual	Meteorological society	50
Regular communication	EU NWP community	Coupled modelling, OASIS3-MCT and Harmonie work	2019-2021	virtual	SMHI, Met Norway, AEMET, Meteo France, FMI, KNMI	30
Accord consortium meeting	Accord	Coupled modelling work progress and verification results	2021	virtual	Met Éireann, Accord group members	20
Quarterly meeting	ESM coupling group	Coupling work, Harmonie	2020, 2021	virtual	KNMI	10
Hirlam management group	Hirlam	Coupled modelling work progress and verification results	2021	virtual	Met Éireann	20

**Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible*

SECTION 4: PROJECT STATUS & WORK PLAN

4.1 Work Plan

Please provide your list of work packages in Table 4.1 below, as detailed in your original Application Form, and include a status update for each.

Table 4.1 – List of Work Packages

No.	Title	Status Update and Completion Status (%)
WP1	*Secure HPC compute and storage resources*	*Secured HPC resources at Kay (ICHEC resources), ECgate & cca (ECMWF resources) and Met Eireann server.* *Completed: 100%*
WP2	Comprehensive review of coupled systems • Detailed literature survey • Implement models on various HPC platforms • Investigate and test setups of various coupling strategies • Report on recommended coupled model setup Preliminary forecasts using modular setups	*Literature survey completed and report submitted* *Harmonie-AROME, WW3 and ROMS models implemented on ECMWF supercomputers* *Decision to use OASIS3-MCT for coupling* *Report generated on the atmosphere-ocean-wave model and coupling strategy* *WW3 wave forecasts implemented* *Completed: 100%*
WP3	Validation experiments and preliminary coupled systems • Validation of modular coupled setups • Semi-operational coupled model Technical report	*Validation of WW3 wave model with different physics schemes completed* *Harmonie-WW3 coupled model validations completed* *Harmonie-WW3 coupled model implemented for operational use* *Technical report submitted* *Completed: 100%*
WP4	Operational Atmosphere-Ocean-Wave coupled system • Fully coupled model setup • Forecasts visualisation • Technical report Peer-reviewed paper	*Fully coupled model failed to run, because of improper remapping file* *As fully coupled model is not ready so forecast visualisation is not done* *Technical report under preparation* *Paper: under preparation* *Completed: Incomplete 90%*
WP7	Communications / promotion of Renewable energy forecasts and Datasets • Presentation in conferences	*Presented in several workshops / working weeks/ coupling groups/ symposiums* *Peer-Review publication under preparation* *Completed :90%*

NOTE: By keeping in mind from the reviewer's comment, we have kept WP5 and WP6 for future research. We recognised the importance of developing a refined coupled modelling system rather than climate simulations.

In Table 4.2, please include details for each work package (copy and replicate the Table for each work package as required). Please provide an update on the progress, the specific milestones and deliverables achieved, and clearly identify any deviations from the original proposed work packages.

Table 4.2 – Summary of Work Packages

WP1	**Secure HPC Compute and Storage Resources**		
Start Month No.	Prior to starting project	**Finish Month No.**	0
WP Lead:	Basanta Kumar Samala. NUIG		
WP Contributors	Paul Nolan, NUIG. Role: Assist with applications		
Objective(s)	*WP1-O1: Secure HPC Compute and Storage Resources (prior to starting project)* **Completion Update: Completed**		
Description (max 200 words)	To run and analyse the coupled forecasts, historical validations and climate simulations is a formidable computational task. To this end, we applied for an ICHEC "Class A", a PRACE "Project Access" and an ECMWF "Special Project" supercomputing project. These accounts have an estimated in-kind value of over €400,000 each. ICHEC has a successful track record of being awarded such HPC projects and porting climate and weather models to the various HPC platforms. ICHEC Class A projects provide 300TB of storage data. ICHEC have confirmed that if required, this limit can be raised by a further 300TB. These facilities will be utilised to store and share all forecast and historical data with national researchers and policy makers. These applications will be made prior to starting the project so that the PI can commence the research from day one.		
Milestones	*WP1-M1: Completed HPC Applications (prior to starting)* **Completion Status (%): 100%**		
Deliverables	*WP1-D1: Successful HPC Project Awards. Month 0* **Completion Status (%): 100%**		
Deviations from planned WP (if applicable)	N/A		
Key Outcomes	*HPC resources*		

WP2	**Comprehensive Review of Operational Atmosphere-Ocean-Wave Systems**		
Start Month No.	0	**Finish Month No.**	12
WP Lead:	Basanta Kumar Samala, NUIG		
WP Contributors	Paul Nolan, NUIG. Role: Assist in implementation of models and couplers. Assist with report writing		
Objective(s)	*WP2-O1: Complete Comprehensive Literature Review of Operational Atmosphere-Ocean-Wave Systems* **Completion Update: Completed** *WP2-O2: Determine the optimal and most computationally efficient coupler, ocean and wave models to implement* **Completion Update: Completed** *WP2-O3: First implementation of modular coupling components (e.g., ocean-wave, atmosphere-wave)* **Completion Update: Completed** *WP2-O4: Preliminary modular ocean/wave renewable energy forecasts* **Completion Update: Completed**		
Description (max 200 words)	The literature study in the initial stage of the project will decide on the models to use coupling and coupling strategy. The literature survey suggested to use HARMONIE-AROME (Atmosphere), WW3 (wave) and ROMS (Ocean) models and OASIS3-MCT as a coupler for developing the coupled model. The choice of models depends on several factors such as model skill, present operational models and computational efficiency. The PI investigated and tested a few coupling strategies including the SURFEX/OASIS3-MCT Interface and COAWST implemented MCT-SCRIP interface. The coupling system and choice of ocean and wave models is decided after a careful review process. To begin with atmosphere model which is involving communication and collaboration with the HARMONIE-AROME community, model validation and scale-testing. The PI was well versed with WW3 ocean model. To improve the wave model EMDONET high resolution bathymetry and WAM global boundary wave spectral data used during operational run of wave forecast. A detailed validation experiment was completed which covered spatial resolution impact and different physics options in wave model impacts in the forecast. The verification suggested ST4 physics option is best match for Irish coast. Hence, a semi-operational WW3 wave model run is setup to run at Met Eireann, which runs every morning by taking 00GMT data and forecast for next 54 hours. These forecasts are automated with the scripts. After forecast generation it generates visual plots for different wave parameters and send to an operational site for the usage of operational forecasters. Furthermore, the PI leveraged the experience and knowledge of Met Éireann and Marine Institute research staff who guided for this to achieve.		
Milestones	*WP2-M1: The PI will familiarise himself with the HARMONIE-AROME model and implement the model on the various HPC platforms.* **Completion Status (%): 100%** *WP2-M2: Complete Literature Review* **Completion Status (%): 100%** *WP2-M3: Complete investigation and test setups of various coupling strategies* **Completion Status (%): 100%** *WP2-M4: Implement preliminary modular components (e.g., ocean-wave)* **Completion Status (%): 100%** *WP2-M5: Complete review and make recommendations on choice of coupler, ocean and wave model(s)*		

	Completion Status (%): 100%
Deliverables	*WP2-D1: Internal Technical Report on recommended coupled-model setup* **Completion Status (%): 100%** *WP2-D2: Preliminary forecasts using modular setups (e.g., atmosphere-wave)* **Completion Status (%): 100%**
Deviations from planned WP (if applicable)	N/A
Key Outcomes	*Literature Review completed. It is concluded that HARMONIE-AROME atmosphere, WW3 wave and ROMS ocean models should be used for the coupled model using OASIS3-MCT coupler.* *Wave model forecast running in operational forecasting mode l at Met Éireann*

WP3	**Validation Experiments and Preliminary Coupled System**		
Start Month No.	12	**Finish** Month No.	26
WP Lead:	Basanta Kumar Samala, NUIG		
WP Contributors	Paul Nolan, NUIG. Role: Collaborate on validation experiments & assist with report writing		
Objective(s)	*WP3-O1: Validation of modular coupled setups* **Completion Update: Completed** *WP3-O2: First implementation and scale-testing of coupled system* **Completion Update: Completed** *WP3-O3: Validation of coupled model* **Completion Update: Completed for atmosphere-ocean & ocean-wave** *WP3-O4: Preliminary coupled atmosphere-wave renewable energy forecasts* **Completion Update: Completed** *WP3-O5: Peer-reviewed paper and Technical Report 2 on setup, implementation, computational efficiency and added skill of coupled models.* **Completion Update: Paper and Report is under preparation will complete soon**		
Description (max 200 words)	The HARMONIE-AROME atmosphere model coupled with WW3 wave model using OASIS3-MCT. This atmosphere-wave coupled model is tested and validated by performing short-term runs for several days. Observations from different sources are utilised according to both their availability and the model output tested for different weather and wave parameters. For instance, hourly wave buoy observations are available from the Irish Marine Weather Buoy Network and similarly weather station observations around Ireland are used during the validation of both meteorological (e.g., MSLP, wind speed/direction, air temperature, relative humidity and maximum gust) and oceanographic (e.g., significant wave height) outputs. Traditional statistical scores such as bias, standard deviation and correlation coefficient are calculated for each parameter to get a quantitative measure of the coupling-efficiency. Satellite-derived gridded observational datasets are also utilized during the validation process. For instance, ERA5 reanalysis and EUMETSAT online portal. The skill scores that will be examined include accuracy, frequency bias, hit rate, false alarm rate. The results suggest slight improved forecast by using coupled model both in weather and wave parameters. Basically, the higher bias in uncoupled model minimized in coupled model and correct hits are more in case of rainfall by using coupled model.		
Milestones	*WP3-M1: Short-term validation and scale-test experiments to further inform the coupling strategy* **Completion Status (%): 100%** *WP3-M2: Long-term validation experiments will inform the final choice of coupler, atmosphere and wave models for operational use* **Completion Status (%):100%**		
Deliverables	*WP3-D1: A semi-operational coupled atmosphere-wave model* **Completion Status (%):100%** *WP3-D2: Technical report 2 and one peer-reviewed paper on validations.* **Completion Status (%):80% (under preparation)**		
Deviations from planned WP (if applicable)	*Peer-reviewed paper is under preparation. Results were satisfactory and presented at ACCORD workshop and EMS 2020.*		
Key Outcomes	*Validation of wave model with buoy and observations completed* *Developed HARMONIE-AROME-WW3 coupled model using OASIS3-MCT*		

	coupler *Validations of HARMONIE-AROME-WW3 coupled model completed, results show improved forecast by coupled model.* *ROMS stand-alone model tested for few days and ready for use as an ocean state forecast* *ROMS model included in HARMONIE-WW3 coupled model* *ROMS-WW3 coupled model working fine within the fully coupled model*

WP4	**Operational Atmosphere-Ocean-Wave Coupled System**		
Start Month No.	20	**Finish** Month No.	36
WP Lead:	Basanta Kumar Samala, NUIG		
WP Contributors	Paul Nolan, NUIG. Role: Collaborate on development and implementation of operational system. Assist with webpage forecast visualizations and preparation of report and peer-review paper.		
Objective(s)	*WP4-O1: Operational and computationally efficient fully coupled atmosphere- ocean-wave system producing renewable energy forecasts* ***Completion Update: Not completed*** *WP4-O2: Operational forecasts visualized and presented on project webpage* ***Completion Update: Not completed; visualisation scripts and automatic run scripts from Wave model run will be useful to complete this after fully coupled model is ready***		
Description (max 200 words)	WP4 is the primary WP of the project to develop and implement a fully coupled atmosphere-ocean-wave forecasting system and working with researchers at Met Éireann, the wider HARMONIE–AROME community, the Marine Institute and SEAI to implement the system in operational mode. To implement this work package PI has coupled HARMONIE-AROME-WW3 atmosphere-wave coupled model and ROMS standalone model tested on supercomputer. Further the changes for coupling part also completed. While testing the fully coupled model it is noticed that HARMONIE-AROME and ROMS are not exchanging any parameters due to the improper remapping file. While other method of creating a remapping file is ready by that time the supercomputer is phased out for testing. The HARMONIE-AROME model version are very much dependent on the version of ecFlow and supercomputer directory structure and the latest versions are skipping / introducing new directory structure and various software libraries. It is difficult to implement again on a new supercomputer and with a latest version of HARMONIE-AROME atmospheric model. In this regard the fully coupled mode is incomplete by now and need further work on this. As this model could not get ready and tested hence further work of validation and operational implementation remained to be done.		
Milestones	*WP4-M1: Operational fully coupled model for testing* ***Completion Status (%): 90%*** *WP4-M2: Final operational fully coupled model(s) implemented* ***Completion Status (%): 80%*** *WP4-M3: Final operational fully coupled model(s) producing renewable energy forecasts* ***Completion Status (%): 80%*** *WP4-M4: Operational forecasts visualised and presented on project webpage* ***Completion Status (%): 70% (operational wave forecast scripts can be used for this purpose after fully coupled model is ready)***		
Deliverables	*WP4-D1: Final operational fully coupled atmosphere-ocean-wave system(s)* ***Completion Status (%): 90%*** *WP4-D2: Operational forecasts of renewable energy (and coastal weather) visualised and presented on project webpage* ***Completion Status (%): 70% (operational wave forecast scripts can be used for this purpose, further technical report and paper is under preparation)*** *WP4-D3: Final Technical Project Report outlining coupled system and*		

	improved skill ***Completion Status (%): 80% (under preparation)*** *WP4-D4: Peer-reviewed paper outlining coupled system and improved skill* ***Completion Status (%): 80% (under preparation)***
Deviations from planned WP (if applicable)	*Fully coupled model is not tested fully due to error in remapping files between ocean and atmosphere models. The ECMWF supercomputer was phased out which caused serious delays and prevented completion of the final coupling step*
Key Outcomes	*ROMS stand-alone model is ready for use* *Coupling changes required for HARMONIE-AROME, WW3 and ROMS are implemented in all three models and in OASIS3-MCT* *Remapping files are created for coupling HARMONIE-AROME and ROMS* *Remapping files are created for coupling WW3 and ROMS* *During test run it is noticed the coupling works fine for HARMONIE-AROME-WW3 and ROMS-WW3*

WP7	**Communication and Promotion of Renewable Energy Forecasts and Climate Datasets**		
Start Month No.	1	**Finish** Month No.	36
WP Lead:	Basanta Kumar Samala, NUIG		
WP Contributors	Paul Nolan, NUIG. Role: Assist with workshops and writing of reports.		
Objective(s)	*WP7-O1: Communicate results and promote the forecast for renewable energy research applications in Ireland* ***Completion Update: nearly completed***		
Description (max 200 words)	This project started with a literature survey and finalization of models to couple and coupler. PI and supervisor attended a kick-off meeting at SEAI. PI had visited weekly once to Met Éireann, which helped in getting all the resources including supercomputer access. PI has become part of Hirlam community and got access to HARMONIE-AROME code. To start with WW3 wave model is implemented on operational run after validations. The necessary plots are generated and available for forecasters every day. From this PI has attended many workshops and working week meetings with EU group working on these models and coupled model. PI has presented many times this coupling work and results of validations with the wider community, SEAI, Met Éireann and Marine Institute throughout the project duration. Further PI has implemented atmosphere-wave coupled model and validated this model. Unfortunately, the final atmosphere-wave-ocean fully couple model could not test c and validated due to various reasons one among the supercomputer phased out and improper remapping file. PI supposed to organize a workshop at the end of this project after successful completion of fully coupled model and validation of it. This part could not happen as the fully coupled model is not ready.		
Milestones	*WP7-M1: Project kick-off meeting with partners (project partners, SEAI, Met Éireann and Marine Institute)* ***Completion Status (%): 100%*** *WP7-M2: Initial workshop* ***Completion Status (%): 100%*** *WP7-M3: First operational forecasts visualized and presented on project webpage* ***Completion Status (%): 100%*** *WP7-M4: Final Workshop attendee list* ***Completion Status (%): Cancelled due to COVID. The PI maintained continuous online communications with domain experts and relevant stakeholders***		
Deliverables	*WP7-D1: Initial Workshop* ***Completion Status (%): 100%*** *WP7-D2: Presentations at national & European conferences* ***Completion Status (%): 100%*** *WP7-D3: Operational forecasts of renewable energy (and coastal weather) visualized and presented on project webpage* ***Completion Status (%): 100%*** *WP7-D4: Long-term historical datasets stored and shared on ICHEC systems* ***Completion Status (%): Removed on the recommendation of the proposal review, as part of WP5 and WP6*** *WP7-D5: Euro-CORDEX contributions (1975-2100) under 4 IPCC RCP GHG scenarios (2.6, 6.0, 7.0, & 8.5) shared on CORDEX platforms* ***Completion Status (%): Removed as part of WP5 and WP6*** *WP7-D6: Final Workshop* ***Completion Status (%): Cancelled due to COVID restrictions***		
Deviations from planned WP (If applicable)	*Final workshop couldn't complete, as fully coupled model not yet operational in addition to COVID restrictions*		
Key Outcomes	*Excellent collaborations established with international communities including KNMI, SMHI, ECMWF, Hirlam, ACCORD, Met Norway and Meteo France.* *Presented and participated in many international conferences / workshops / working weeks during tenure of this project*		

	Operational website implemented for wave forecast at Met Eireann *Publication is under preparation on coupled model validation results, which shows improvement due to coupling* *Detailed user guide / technical report is under preparation*

ANNEX 1 – CASE STUDY TEMPLATE

Please complete the SEAI Case Study Template below. The details below may be used for SEAI promotional activities, e.g., project dissemination on SEAI Website or SEAI Twitter account.

Project Title	
CAO-IRL: Coupled Atmosphere Ocean Wave forecast for Ireland	
Project Summary – Please provide a brief and high-level summary of your project. (Max 3 sentences)	
For the first time in Ireland, The PI has developed and implemented atmosphere-wave and ocean-wave coupling systems for Ireland, validation results show that the coupled model is performing better than it's standalone counterparts. The coupled systems are implemented within an atmosphere-ocean-wave environment, with the choice to run individual components or coupled systems. The final atmosphere-ocean-wave system is near complete and requires further development and testing.	
What challenges did you face? Challenges can be technical (e.g., sensor failure), managerial (e.g., delay in the hiring process), financial (e.g., unexpected costs), etc.	
1. Complex models such as HARMONIE-AROME, ROMS and coupling took kit OASIS3-MCT were difficult to implement on the ECMWF supercomputer. 2. ecFlow the job submission way of HARMONIE-AROME and its complications on directory structure. 3. HARMONIE-AROME model is difficult to adapt in supercomputers particularly during COVID time.	
Three key statistics – If applicable, please provide three key statistics related to your RD&D Project: e.g. X kW generation capacity; X Papers Published; X Communities/Users involved; X potential energy/cost savings	
1.	Improved forecast of Winds and Waves using atmosphere-wave Coupled model
2.	HAMRONIE-AROME-WW3 (atmosphere-wave) coupled model is ready for operational use in Ireland. Validation results show improved forecast using this coupled model.
3.	Improved forecast during high impact weather events such as storms
What would you regard as the three most significant achievements or impacts enabled by this SEAI funding?	
1.	Atmosphere-Wave (HARMONIE-AROME-WW3) coupled model is available to run in operational mode at Met Eireann and results show improvements over the uncoupled components
2.	Operational wave forecast using WW3 are running in operational mode at Met Eireann. The ROMS ocean model is implemented and tested and is ready to run operational mode.
3.	Significant national progress towards the development of a fully coupled model, the results of which were shared and communicated with the EU community
Other	High impact weather events will be predicted more accurately using the developed forecasting systems of this project
How has this or will this research project be of benefit to Ireland?	
This research will improve the forecasting capacity for weather (Met Eireann), ocean waves (Marine Institute) and renewable energy (SEAI).	
What was the biggest learning outcome throughout the project?	
The biggest learning was to understand three different complex models and a complex coupler to develop a fully coupled system in collaboration with numerous communities who follow different coupling frameworks. The use of many different third-party software tools introduced further complications, to name a few ecFlow from Harmonie, different version of Harmonie, Harmonie data and directory structure in supercomputer, and finally migrating to new supercomputer Atos.	

What has this SEAI funding enabled for you/your organisation? (e.g. building capacity, developing a product, opening new markets, growth in revenue). Please be specific and quantify your responses where possible.
• This funding allowed to develop a coupled model for the first time in Ireland • Learning of new models, couplers and various tools • Enabled collaboration with many scientific organisations and consortium around Europe • Enabled access to ECMWF High Performance Computers and Met Éireann resources
What advice would you give to other researchers?
I would encourage other researchers to apply for funding from SEAI to conduct research on renewable energy
If you wish, please describe your overall experience working on this project (e.g. are you happy with its success, what was the highlight for you, and/or what do you have planned next)
The SEAI funding allowed me the opportunity to work/associate with the national and international weather forecasting community.. My plan is to continue this research to ensure uptake of the coupled models by end user applications.
***Please submit** a separate e-copy of any **pictures / maps / images / graphics** inserted into the text above, as individual .jpeg, .tiff, .csv files to ensure good quality printing.* *Please also submit 3 **research project cover pictures** (e.g., team photo, site photos, prototype photos, research lab photos etc). Please ensure the below picture requirements are met:* • *Pictures must be of high quality to ensure good quality printing* • *Layout: Landscape* • *Format: Jpeg* • *Size: Minimum 1200 x 1200 pixels*

ANNEX 2 – PROJECT COMPLETION SURVEY

Workforce Statistics *Please indicate in the table below the number of people who worked on this project within the Lead/Partner Organisation Types listed*		
Project Staff (By Lead/Partner Organisation Type)	**Number of Women**	**Number of Men**
Industry and SMEs (if applicable)	NA	NA
Academia or publicly funded research institutes (if applicable)	NA	NA
Of which, number of PhD Students	0	0
Other Public Sector or Semi-state Organisations (if applicable)	NA	NA
How many of the above staff were recruited specifically for this project?	0	0

Engagement – Civil Society and Policy Makers	
Did your project involve working with students and/or school pupils (e.g. open days, participation in science)?	
Yes – Please specify	
No	No
Did your project engage with societal actors beyond the research or industrial community?	
Yes – Please specify	
No	No

If yes, did you engage with citizens or organised societal groups (select from the below options)?	
No	No
Yes – in determining the research to perform	
Yes – while implementing the research	
Yes – in communication/dissemination of research results	
Did you engage with government / public bodies or policy makers (including international organisations)?	
No	
Yes – in framing the research	
Yes – while implementing the research	
Yes – in communication/dissemination of research results	Yes
If you marked yes above and engaged with international organisations, please specify which organisation and which country here:	Met Norway, KNMI-Netherlands, SMHI-Sweden, ECMWF-UK, Meteo France
Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?	
Yes – as a primary objective	
Yes – as a secondary objective	Yes
No	
If you marked yes above, please add details here	Decision making during high weather events such as storms
If yes, at which level?	
Local / Regional Level	Yes
National Level	Yes
European Level	
International Level	

Dissemination and Market Readiness	
How many articles were published/accepted for publication in peer-reviewed journals?	0
How many articles were presented and published in conference proceedings?	2
How many new patent applications have been made?	0
How many spin-off companies were created/ are planned as a direct result of this project?. If you marked “are planned”, please give an estimation of the date of creation.	0

Did the project result in a market ready solution (e.g. a product, a service)? (Yes/No)	No

Communication Statistics	
Which of the following have been used to communicate information about your project? (tick as appropriate)	
□ Press Release □ Communication via social media (Twitter, Linkedin, Applicant website, etc.) □ Media Briefing □ TV coverage / report □ Radio coverage / report □ Brochures / posters / flyers □ DVD / Film / Multimedia □ Other (please specify):	□ Coverage in specialist press □ Coverage in general press □ Coverage in national press □ Coverage in international press □ Website for the general public □ Event targeting general public (Festival, conference, exhibition) x□ Scientific conferences □ Other (please specify):

SEAI National Energy RD&D Funding Programme - Feedback
If you have any feedback or suggestions in relation to the SEAI National Energy RD&D Funding Programme, please provide below:

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