SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2022
Project Title:	Coupled Atmosphere Ocean Wave Forecasts for Ireland
Computer Project Account:	spiesama
Principal Investigator(s):	Basanta Kumar Samala
Affiliation:	ICHEC, University of Galway
Name of ECMWF scientist(s) collaborating to the project (if applicable)	…… ……
Start date of the project:	June 2021
Expected end date:	June 2026

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	35000000		35000000	
Data storage capacity	(Gbytes)	50000		50000	

Summary of project objectives (10 lines max)

The research goal of the project is to develop a regional coupled weather forecasting system (Ocean-Atmosphere-Wave) for Ireland. To begin with literature survey was completed and report suggested the atmosphere model HARMONIE-AROME used by Met Eireann currently and ROMS ocean model and WW3 wave model used by Marine Institute for their ocean state forecast are the components of the proposed coupled model with the OASIS3-MCT coupler used to exchange required parameters among these three models during runtime. The aim is to develop and validate fully coupled ocean-atmosphere-wave forecasting system for Ireland. This coupled forecasting model will provide improved weather forecasts, as well as integrated solar, wind and wave energy forecasting system which would significantly benefit the renewable energy sector. This research will involve short simulations and case studies using the coupled model to understand the coupled model response to different physics options in ocean and wave model specific to Ireland observations.

Summary of problems encountered (10 lines max)

PI has faced many problems during this model development to list a few. The complexity of ecFlow. The directory structures during the job submission and storing in different directories like ecgate, cca, SCRATCH and PERM, furthermore many log files. OASIS3-MCT related issues were difficult to trace and fix the error. Compiling all three models and ocasis3-mct with same set of compilers. Migrating from ECserver to Atos. PI could not port the coupled code and make it work on new HPC Atos server. Atos directory structure and ecFlow handling is different in latest version of Harmonie model.

Summary of plans for the continuation of the project (10 lines max)

PI has tried to compile and run the old version of working code of Harmonie-WW3-ROMS coupled code from ECserver to Atos. It was very time consuming and difficult task to port the old version of Harmonie in Atos. Hence PI has started the coupling of models from the beginning with the new version of Harmonie (cy43h22_bf). PI has started compiling WW# wave model, ROMS ocean model and OASIS3-MCT on atos server. The changes required for coupling is completed for all the models. The compilation of all the code is successful. Now the task of debugging and generating the remapping file for all the models remained as next task to be completed. Once all the developments completed then test run for the coupled model is to be conducted. While considering the new version of Harmonie, PI has implemented a new version of WW3 (v6.07) wave model has been implemented.

List of publications/reports from the project with complete references

- Attended online project progress meetings with Met Éireann on a regular basis.
- The PI attended the Hirlam NWP surface working week from time to time every year. PI is presenting his work in thee meetings to a wider community of Hirlam and Accord.
- PI is in regular touch with Met Norway, Meteo France and the Swedish Meteorological and Hydrological Institute (SMHI) during the coupled model development.
- PI has submitted annual report to SEAI, Dublin. PI has attended the meeting with SEAI, Met Éireann and Marine Institute on the progress of the project.
- PI has presented this work at European Meteorological Society symposium.

Summary of results

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.

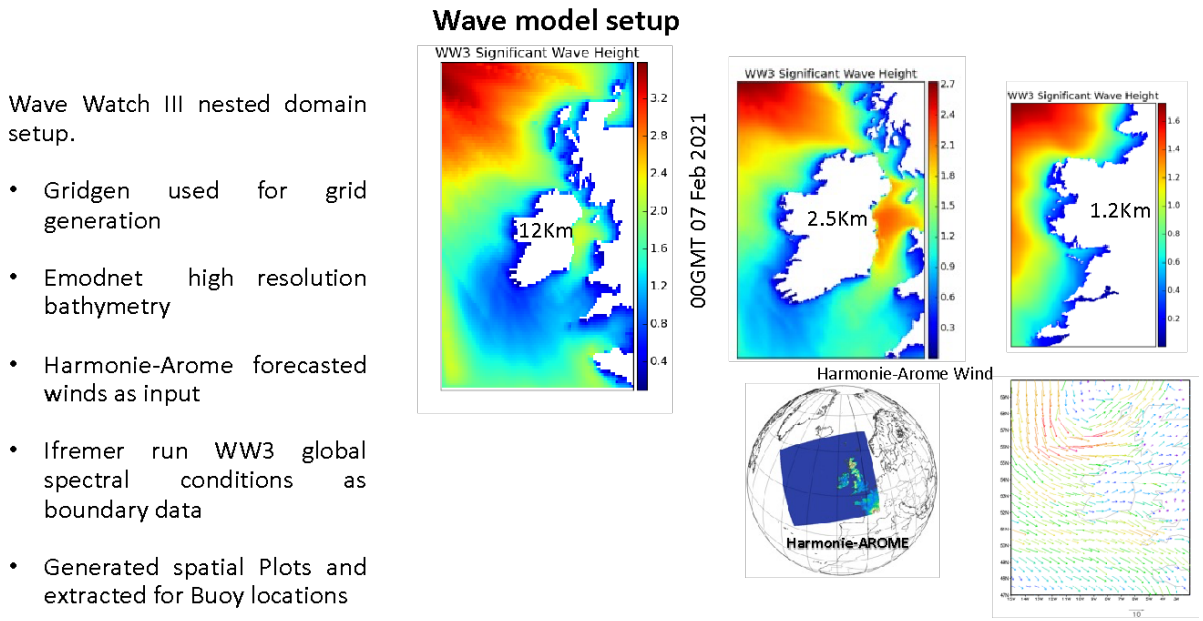

Figure 1: Wave model setup for operational run at Met Éireann

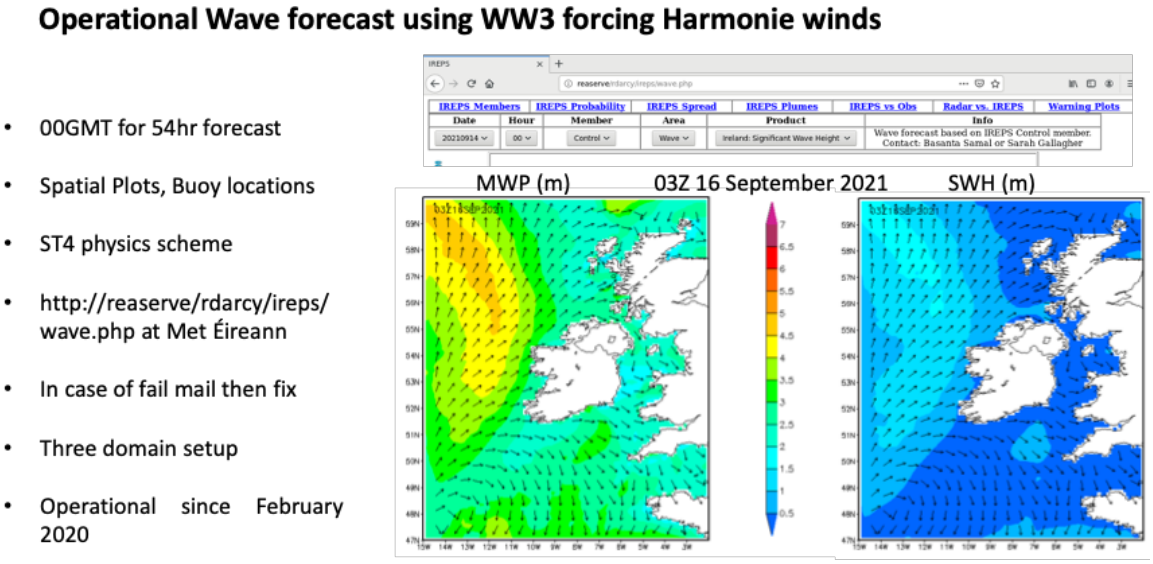

Figure 2: Wave model operational run at Met Éireann

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.

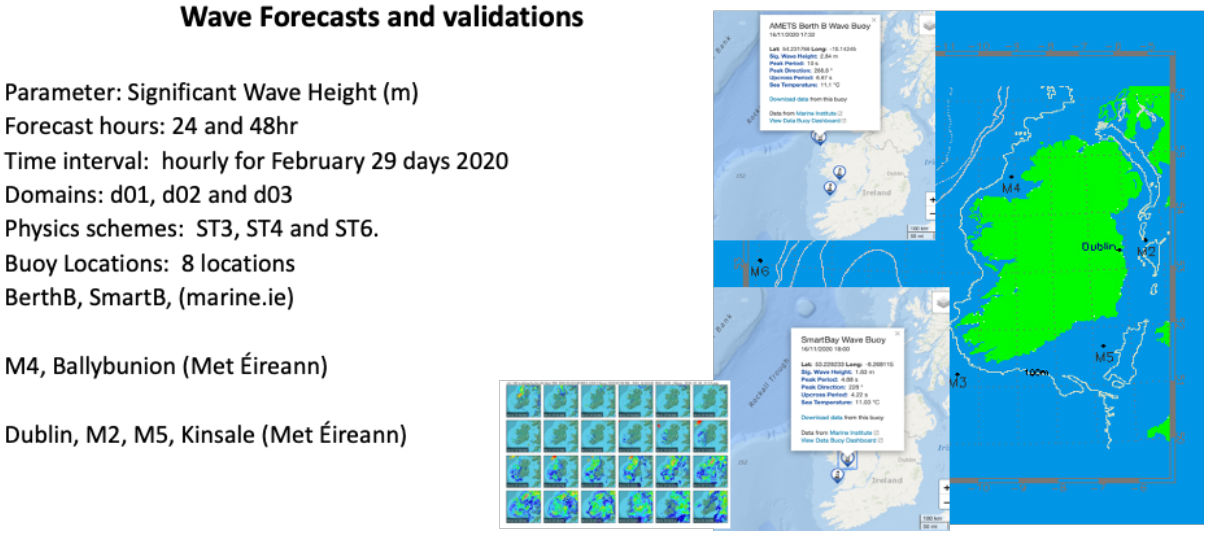

Figure 3: Wave forecast and validation location details

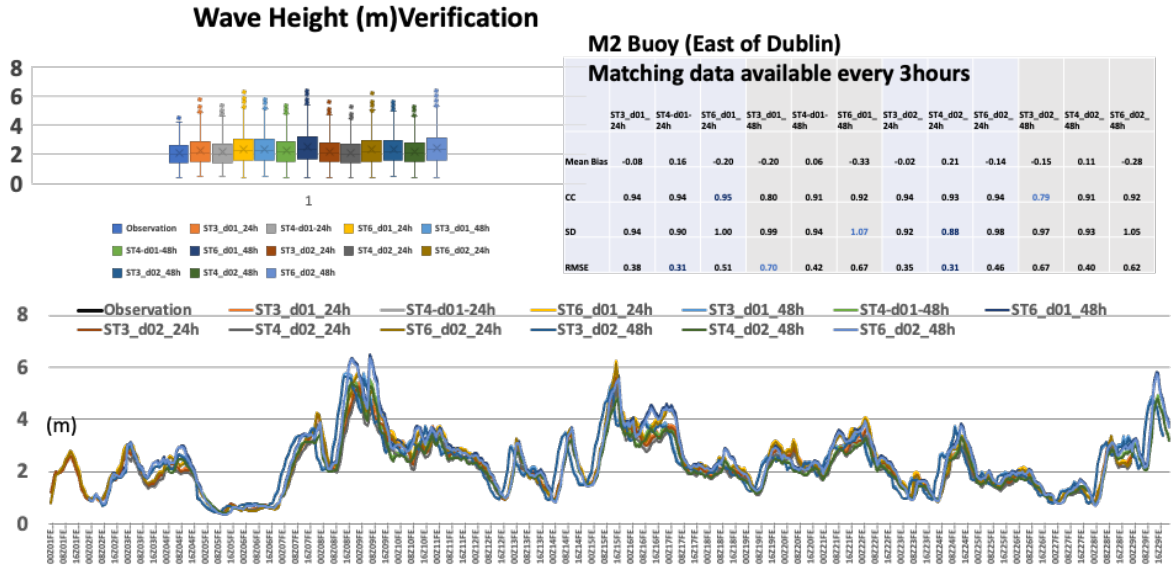

Figure 4: Significant wave height verification statistics for M2 buoy

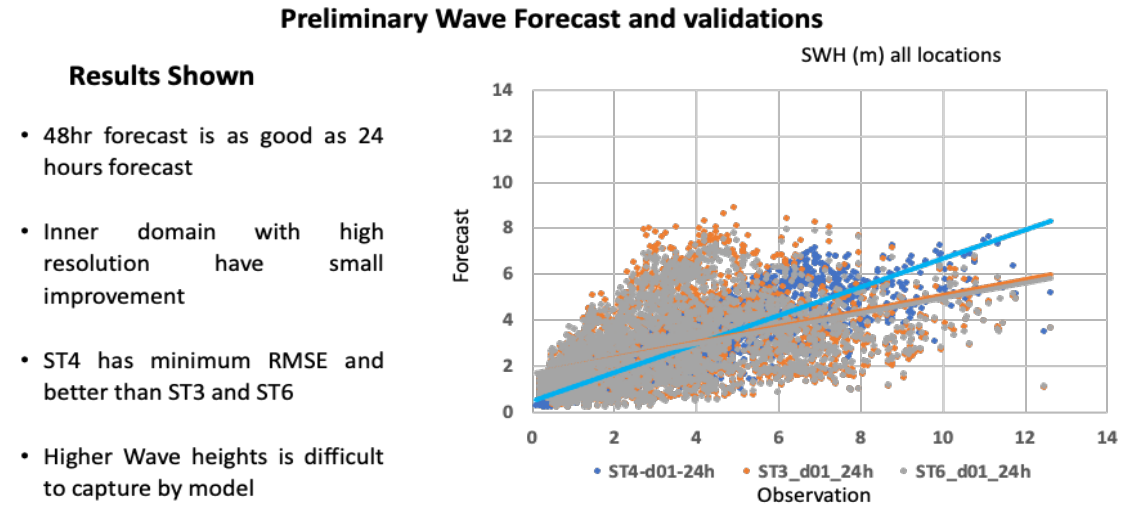

Figure 5: ST4 physics scheme forecasts closure to observation as compared to ST3 and ST6

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.

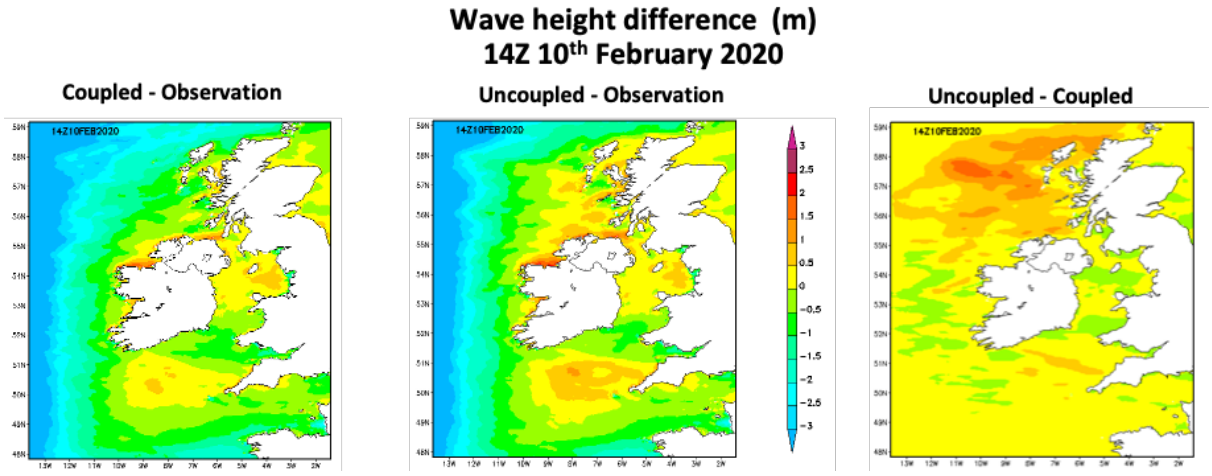

Figure 6: Bias of Coupled (HARMONIE-AROME-WW3) and uncoupled WW3 model SWH forecast

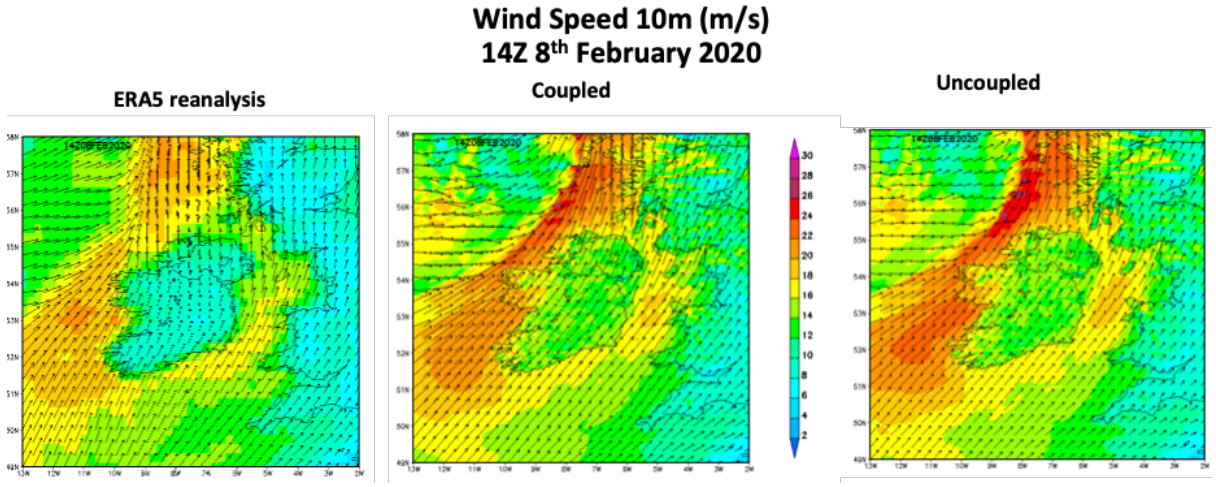

Figure 7: Wind speed from coupled (HARMONIE-AROME-WW3) and uncoupled HARMONIE-AROME model

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).

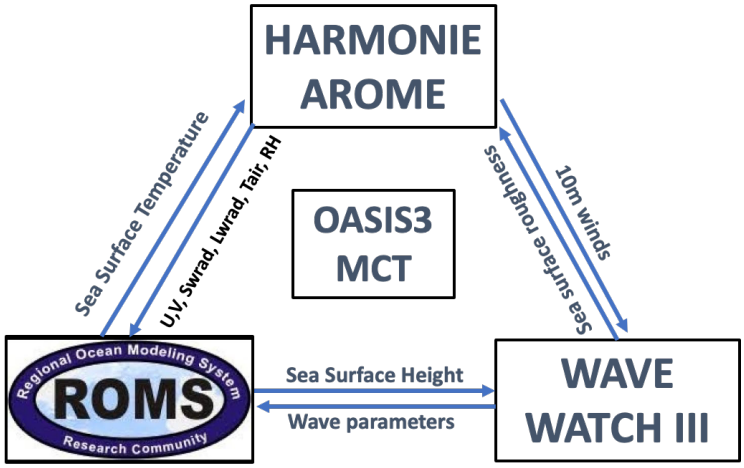

Figure 8: Schematic diagram of coupled (Atmosphere-Ocean-Wave) model using OASIS3-MCT coupler and the required exchange of parameters from one model to the other.

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.

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.

Summary of Key Findings/Outcomes

- 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.