

EMI R&D PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Irish storms: a storyline approach to future post-tropical cyclones
Computer Project Account:	spiekoki
Start Year - End Year :	2025 – 2025
Principal Investigator(s)	Tatjana Kokina
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Other Researchers (Name/Affiliation):	Colm Clancy (Met Eireann/UCD) John Hanley Met Eireann

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The objective of this project is to investigate the effect of climate change on extreme post-tropical cyclones affecting Ireland using a storyline framework. High-resolution HARMONIE-AROME simulations are used to recreate historical storms, including Storm Ophelia (2017), and examine how these events would evolve under modified environmental conditions representative of past and future climates. The project looks at perturbations to sea-surface temperature, air temperature and humidity, to assess impacts on storm intensification, track, peak intensity, wind speeds and precipitation. By combining high-resolution modelling with ensemble approaches and alternative boundary conditions, the project aims to provide physically consistent estimates of future changes in the impacts of post-tropical cyclones on Ireland.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

No significant issues were encountered with ECMWF computing infrastructure or the Atos HPC system.

The principal challenge during the reporting period was the implementation of archived NCEP GFS data as lateral boundary conditions for HARMONIE-AROME simulations of Storm Ophelia (2017). While recent GFS datasets could be processed successfully, historical GFS files from 2017 contained differences in GRIB encoding and parameter definitions that were incompatible with the standard workflow. In particular, issues were identified in soil parameter definitions and SURFEX initialisation fields, leading to failures during boundary interpolation and model initialisation.

Considerable effort was devoted to diagnosing and resolving these issues. Modifications to the preprocessing workflow and data handling procedures were developed, enabling successful multi-day HARMONIE-AROME simulations driven by archived GFS boundary conditions. These developments provide a robust framework for future IFS–GFS comparison experiments and subsequent climate-change sensitivity studies.

Experience with the EMI R&D Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The application process was straightforward. No issues were encountered during the year, in any administrative aspect of the project.

Summary of results (This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

The project started with identifying Storm Ophelia (2017) as the first test candidate. As the first step a custom domain was developed (see figure 1) – the extent of the domain allowed to capture all critical points of the Storm Ophelia evolution.

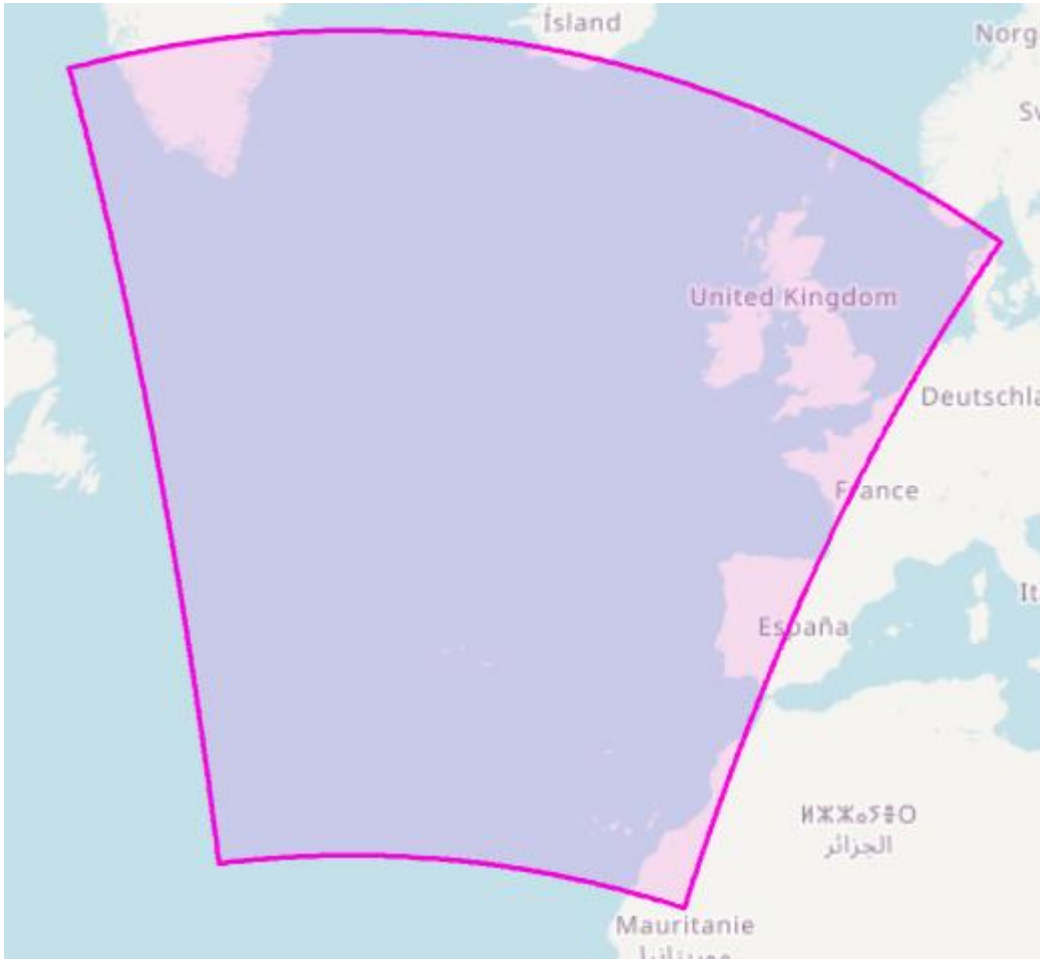


Figure 1 - HARMONIE-AROME domain used for Storm Ophelia simulations.

The model was run at 2.5 km resolution, originally driven by IFS boundary conditions. In addition, tests with HARMONIE-CLIMATE ('HCLIM') driven by ERA5 boundary conditions and separately IFS boundary conditions were completed.

However, because ERA5 is produced using a version of the ECMWF IFS and associated data-assimilation framework, it is not an independent source of large-scale forcing relative to IFS. Initial tests suggested limited additional benefit from an ERA5–IFS comparison. Consequently, ERA5 was not pursued further as a separate experimental branch within the project.

The track and minimum pressure for these tests are shown in figures 2 and 3 respectively.

Ophelia 14-16 October 2017 HCLIM ERA5, HCLIM IFS and Harmonie IFS at 2.5km

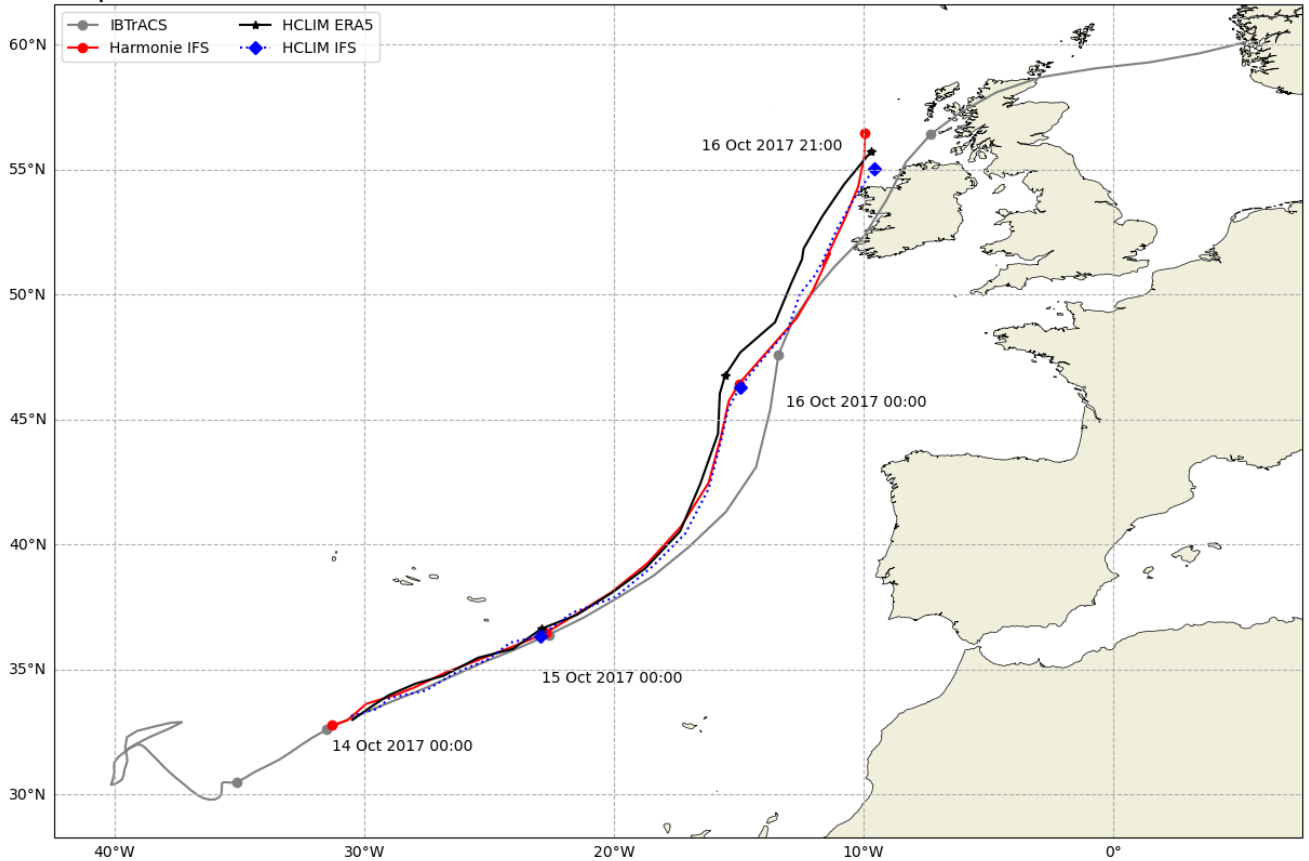


Figure 2 - Storm Ophelia track comparison from simulations performed with HCLIM at 2.5 km resolution on a large North Atlantic domain using IFS boundary conditions. For reference, the observed IBTrACS track and a corresponding HCLIM simulation driven by ERA5 are also shown. While small differences are evident, the IFS- and ERA5-driven simulations produce broadly similar storm tracks, suggesting limited sensitivity to the choice of forcing dataset in this configuration.

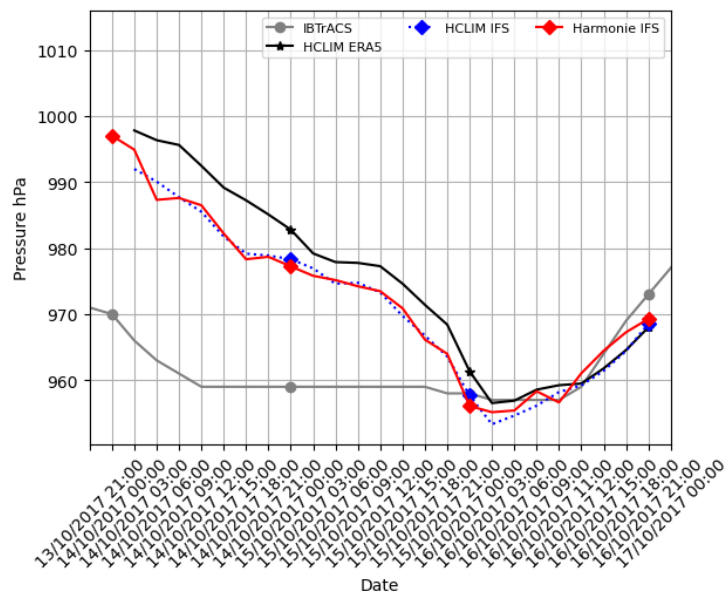


Figure 3 - Minimum central pressure evolution of Storm Ophelia from HCLIM simulations driven by IFS and ERA5 boundary conditions, with IBTrACS included for reference. The two simulations show very similar behaviour throughout the storm lifecycle, with differences generally small and a maximum deviation of approximately 3 hPa.

The model shows limited skill in reproducing the early evolution of Storm Ophelia prior to approximately 14 October 2017. However, from 14 October onwards the simulated track and intensity compare more favourably with observations, particularly during the approach towards Ireland.

To complement the large-scale evaluation based on storm track and central pressure, we also compared the simulations against selected local observations. These included minimum pressure measurements at Valentia Observatory (Figure 4) and wind speed observations from Roches Point (Figure 5).

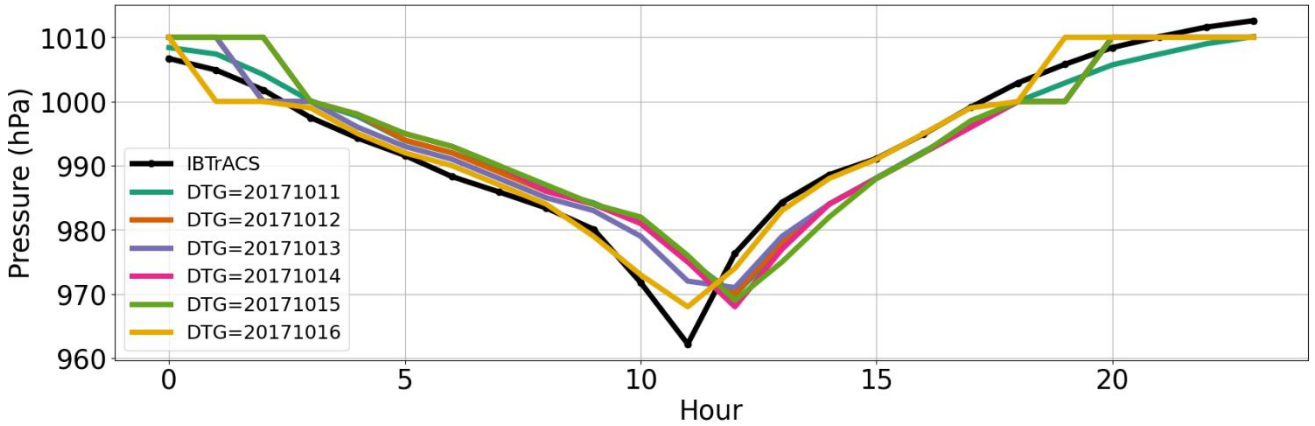


Figure 4 - Pressure recorded at Valentia observatory compared to the pressure produced in HARMONIE – AROME simulations, with different start dates.

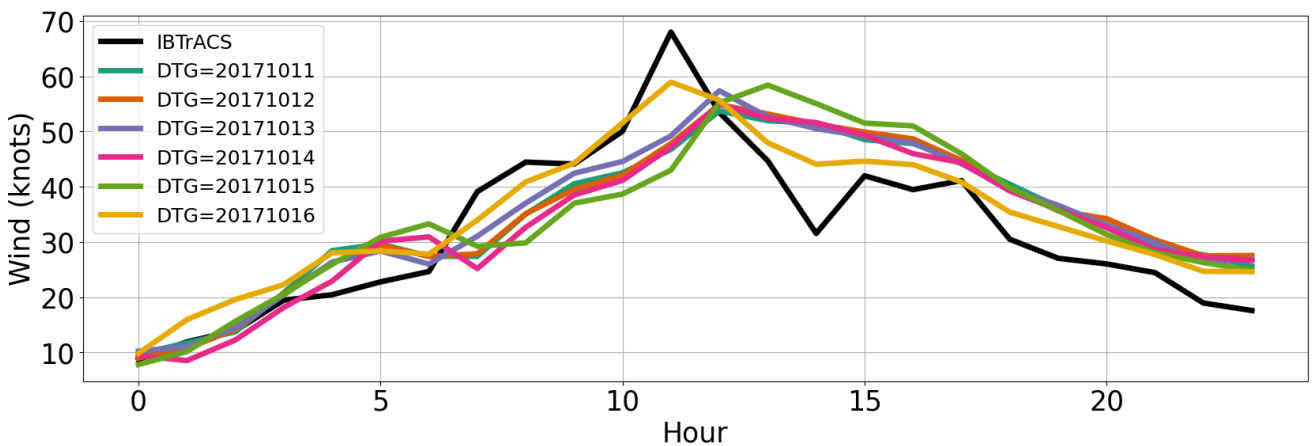


Figure 5 - Wind speed recorded at Roches Point compared to the wind produced in HARMONIE – AROME simulations, with different start dates.

Consequently, a start date of 14 October 2017 was selected for the baseline experiments, together with the chosen model domain and IFS boundary conditions, providing a consistent framework for the subsequent sensitivity studies.

Next, experiments with uniformly adjusted boundary conditions were completed. These experiments were in the range between -1 degree and +4 degrees adjustments. The air temperature on all levels was increased (or decreased uniformly), sea surface temperature was adjusted, and relative humidity kept constant. The resulting track and pressure profile can be seen in figures 6 and 7.

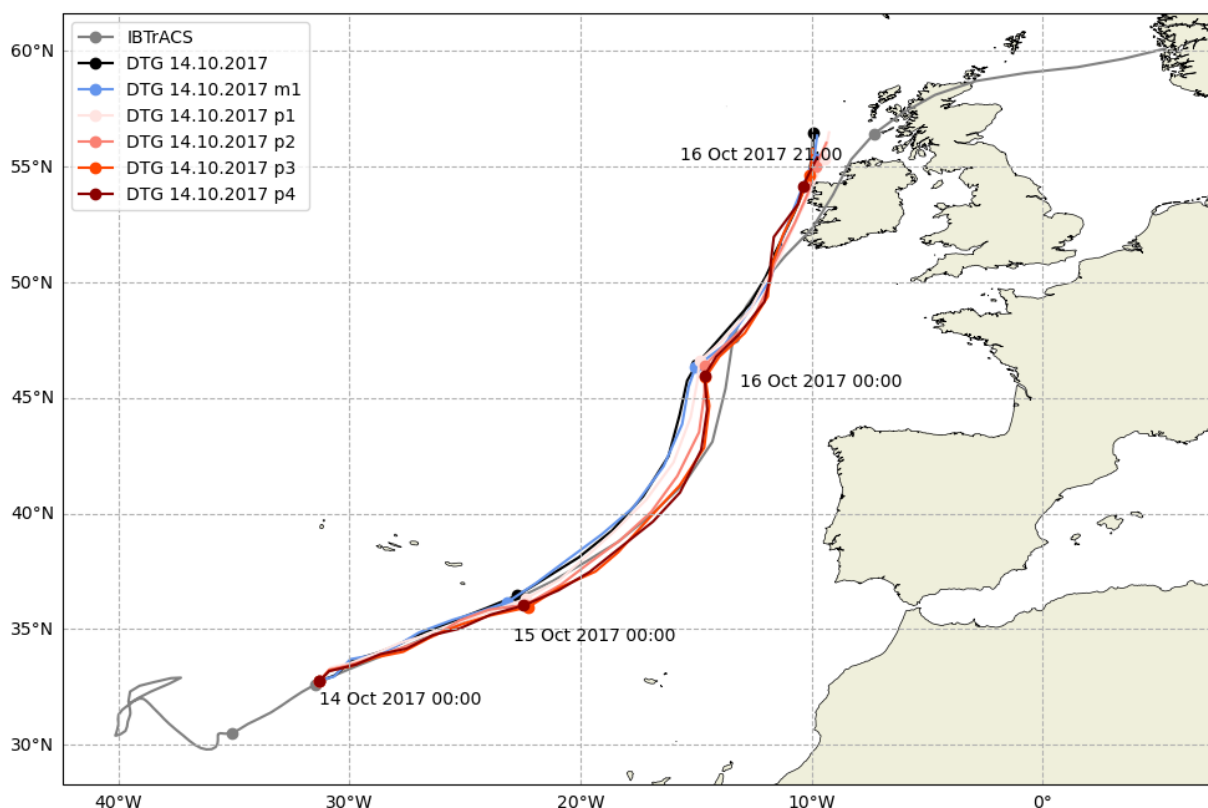


Figure 6 - Storm Ophelia track depending on the adjusted temperature. IBTrACS are presented in gray, HARMONIE-AROME hindcast in black, scenarios from -1 K to +4 K are indicated by colour lines, and denoted m1 for -1 K, p1 for +1 K, p2 for +2 K, p3 for +3 K, and p4 for +4 K.

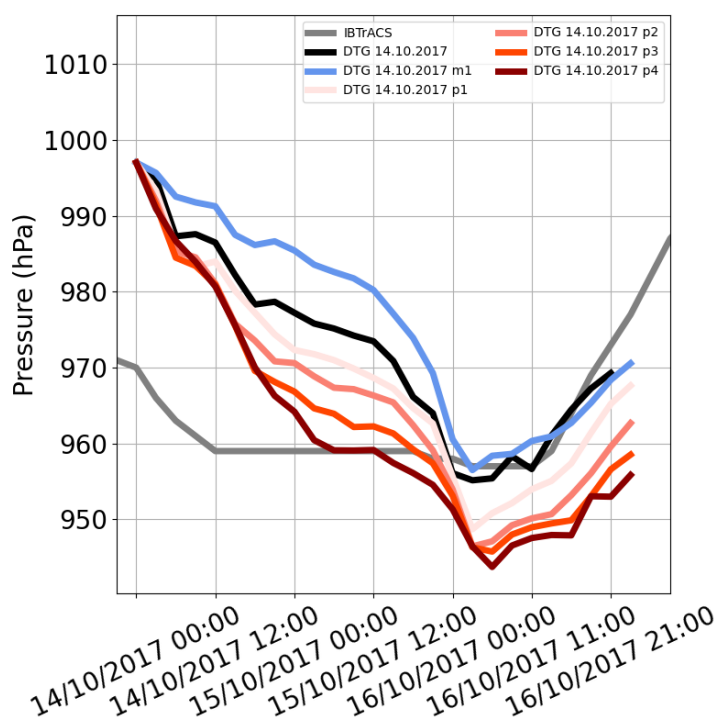


Figure 7 - Storm Ophelia minimum pressure depending on the adjusted temperature. IBTrACS are presented in gray, HARMONIE-AROME hindcast in black, scenarios from -1 K to +4 K are indicated by colour lines.

Uniform warming experiments indicate that temperature perturbations have only a limited impact on the track of Storm Ophelia. While warmer scenarios show a modest increase in track displacement relative to the control simulation, the differences remain small compared with the overall uncertainty represented by the ensemble spread and are not substantially different from the observed IBTrACS track. (Ensemble simulations are not presented here, but discussed later in the report).

Additional sensitivity tests using different initialization dates (not presented here, but briefly discussed later) support the conclusion that the projected warming does not lead to a significant change in storm trajectory.

In contrast, storm intensity exhibits a clear sensitivity to warming. Increasing temperatures systematically deepen the cyclone, with the simulated minimum central pressure decreasing from 952.8 hPa in the control simulation to 943.7 hPa in the +4 K scenario. The rate of deepening also increases with warming, indicating that future environments may favour more intense Ophelia-like storms even where the storm track remains largely unchanged. These results suggest that future impacts are more likely to arise from changes in storm intensity and associated hazards than from substantial shifts in storm trajectory.

To assess whether the projected track changes remained within the range of forecast uncertainty, a six-member control ensemble was performed using the same model configuration as the deterministic simulation. Comparison of ensemble track spread with the temperature-perturbation experiments showed that the differences introduced by warming were generally comparable to, or smaller than, the natural variability represented by the ensemble. These results support the conclusion that changes in air and sea temperatures have only a limited influence on the track of Storm Ophelia, with the simulated trajectories remaining within the expected range of forecast uncertainty.

The sensitivity of the results to simulation initialization date was also investigated. As expected, simulations initialized closer to landfall generally produced more accurate storm evolution and reduced track variability. However, these experiments did not reveal any systematic relationship between temperature perturbations and track position. This provides further evidence that the modest track differences observed in the warming experiments are primarily attributable to forecast uncertainty rather than to the imposed temperature changes.

Given the limited sensitivity of storm track to warming, the potential impacts at landfall become the primary focus of the analysis. This is particularly important as the warming experiments indicate a systematic deepening of Storm Ophelia, suggesting the potential for more severe impacts even in the absence of substantial track changes.

To quantify these impacts, a Storm Severity Index developed by Klawns and Ulbrich (SSI; Klawns, M. and Ulbrich, U., 2003) was adopted as an integrated measure of wind-related damage potential. SSI maps were produced for each simulation using the Met Éireann ReAnalysis (MERA; Gleeson et al., 2017; Whelan et al., 2018). The MERA dataset was used to establish local wind climatology, from which SSI values were calculated to assess how changes in storm intensity may translate into changes in societal and infrastructural impacts.

The SSI maps reveal a clear increase in the spatial extent and magnitude of wind-related impacts with increasing temperature. In the control simulation, elevated SSI values are largely confined to parts of the southwest and west of Ireland, with relatively limited inland penetration. The -1 K experiment produces a similar or slightly weaker impact footprint. In contrast, the warming experiments show a systematic expansion of areas experiencing anomalously strong winds relative to the local climatology. The +1 K and +2 K scenarios lead to a broader corridor of elevated SSI extending from the southwest towards the north and northwest, while the +3 K and +4 K simulations produce the most widespread impacts, with enhanced SSI values affecting large portions of western, northern and central Ireland. The strongest signal is found in the +4 K scenario, where both the affected area and peak SSI values increase substantially relative to the control simulation.

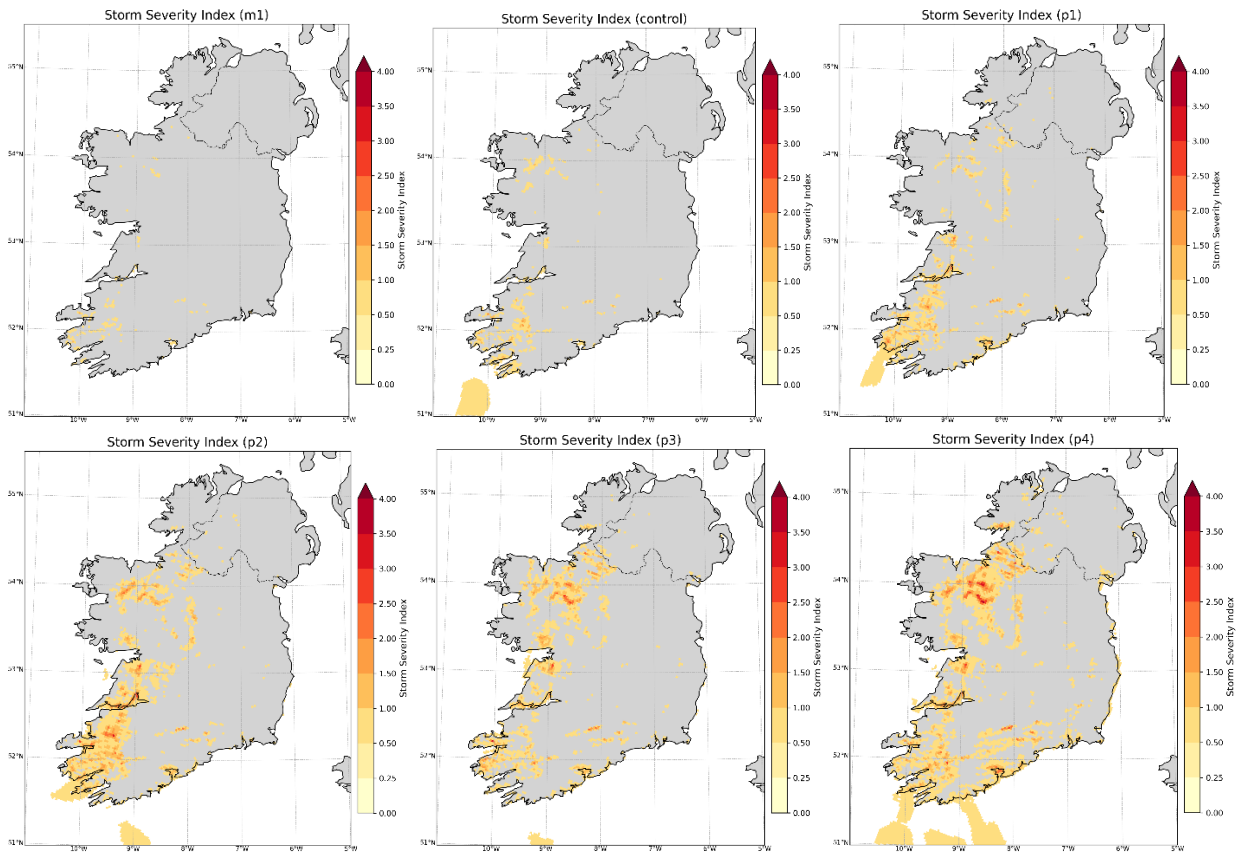


Figure 8 Storm Severity Index (SSI; Klawa and Ulbrich, 2003) calculated for Storm Ophelia under the control simulation and temperature perturbation experiments (-1 K to +4 K). SSI values are computed relative to the local wind climatology derived from the Met Éireann ReAnalysis (MERA). Warmer scenarios exhibit progressively larger areas exceeding climatological wind thresholds and higher SSI values, indicating an increase in the potential severity of wind-related impacts across Ireland.

The response is notably non-linear, with the largest increase in SSI occurring between the +3 K and +4 K scenarios. Furthermore, the expansion of elevated SSI values is not confined to exposed Atlantic coastal regions but extends well inland. As SSI is calculated relative to the local wind climatology derived from MERA, this indicates an increasing potential for damaging winds in regions that are less frequently exposed to extreme wind events. These results are consistent with the earlier finding that warming primarily influences storm intensity rather than track, suggesting that future Ophelia-like storms may produce substantially greater wind impacts at landfall even if their trajectories remain broadly unchanged.

GFS Boundary Conditions

Ribberink et al. (2026) highlighted differences between GFS and IFS in their representation of Storm Ophelia's early development, with GFS showing a closer correspondence to the observed tropical intensification. This provided additional motivation for investigating the sensitivity of HARMONIE simulations to the choice of driving model.

As with IFS approach, we first set out to produce a hindcast of Storm Ophelia, using HARMONIE-AROME set up, at 2.5km resolution, in the same set up as before.

We ran into some technical issues with HARMONIE ingesting GFS files as boundary conditions. Initial work involved adapting developments provided by AEMET colleagues to enable the use of GFS lateral boundary conditions within HARMONIE-AROME cycle 46h1.1.

Following the successful implementation of GFS boundary conditions, a series of hindcast experiments were performed with initialization dates ranging from 12 to 15 October 2017, see figure 9. All simulations completed successfully and reproduced the development of a deep cyclone consistent with the observed intensification of Ophelia. However, despite the realistic storm intensity, most simulations exhibited notable track errors, with Ophelia failing to follow the observed north-eastward trajectory towards Ireland. These results suggest that, while GFS boundary conditions provide a viable framework for simulating Ophelia, additional investigation was required to understand the source of the track discrepancies.

As a first step we have compared GFS, IFS and IBTrACS, assuming IBTrACS to be the ‘ground’ truth. The comparison is presented in figure 10.

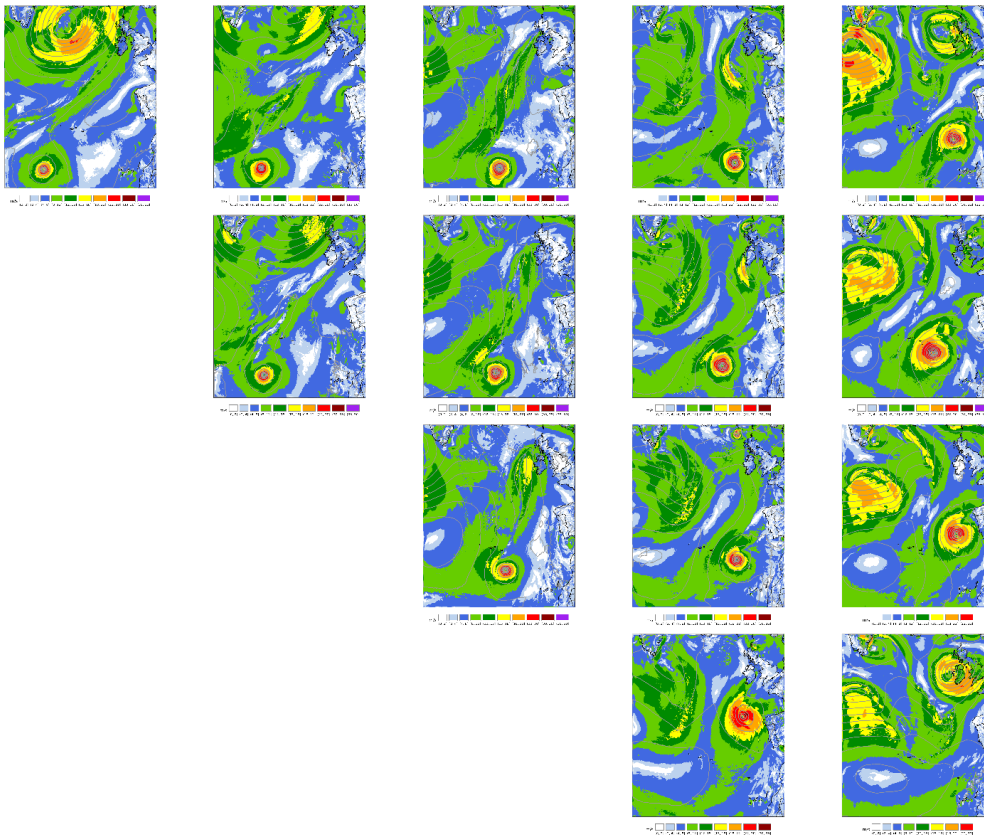


Figure 9 - Evolution of Storm Ophelia in HARMONIE-AROME simulations driven by GFS boundary conditions and initialized at 00 UTC on 12, 13, 14 and 15 October 2017. Each row represents a different initialization time, while columns show successive forecast lead times, with all simulations valid at 00 UTC on 17 October in the final column.

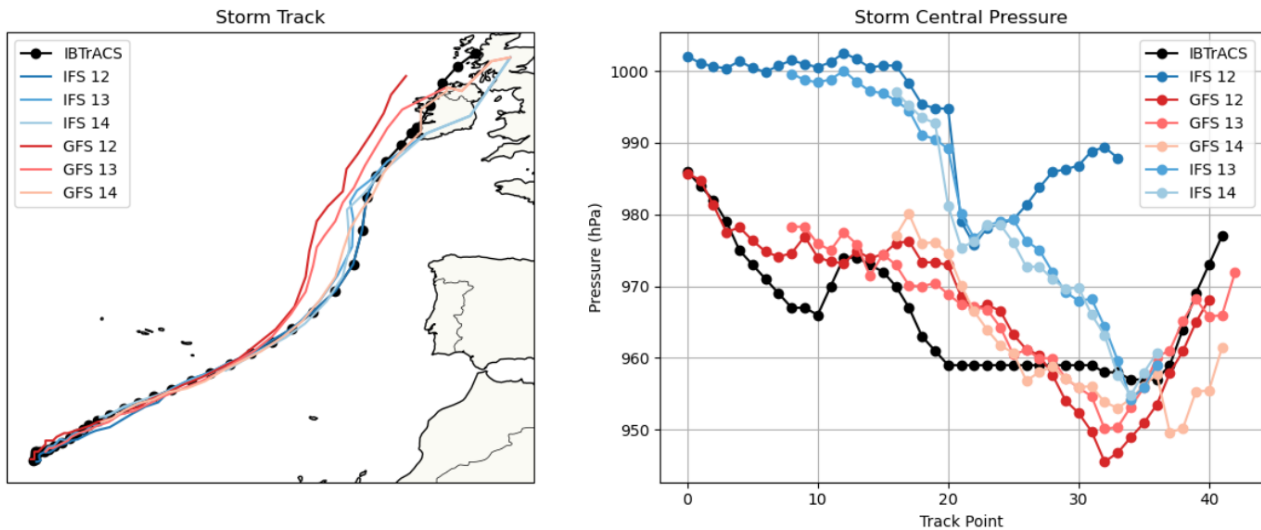


Figure 10 - Comparison of observed Storm Ophelia track and central pressure evolution (IBTrACS) with the corresponding large-scale boundary-condition fields from IFS and GFS, initialized at 00 UTC on 12, 13 and 14 October 2017. The left panel shows storm tracks, while the right panel shows minimum central pressure evolution.

The comparison highlights a clear difference between the two global models. While the GFS simulations generally reproduce Storm Ophelia's observed deepening and central pressure evolution reasonably well, the IFS simulations remain substantially weaker, with central pressures often 20–40 hPa higher than observed during the key intensification period. In contrast, both models produce similar storm tracks up to approximately 14 October, after which differences emerge, with the GFS tracks tending to deviate further west of the observed trajectory. Overall, GFS provides a more realistic representation of Ophelia's intensity, whereas neither model consistently captures the observed track evolution at later stages.

Once it was established that the boundary conditions were not responsible for the poor representation of Storm Ophelia, the HARMONIE model configuration was systematically investigated. Sensitivity experiments examined the effects of domain size, hydrostatic versus non-hydrostatic dynamics, horizontal resolution, spectral nudging, ensemble simulations, and the number of vertical levels.

Across all GFS-driven experiments, the results were remarkably consistent. Although Ophelia initially deepened, the storm subsequently failed to intensify further, deviated from the observed track, and dissipated before reaching Ireland. Changes to the model configuration, including horizontal resolution, the hydrostatic approximation, and vertical discretisation, had little influence on this behaviour.

The only modifications that produced noticeable improvements were adjustments to the model domain and the application of spectral nudging. Both improved the simulated storm track by constraining the large-scale circulation, bringing the cyclone closer to the observed trajectory. However, neither approach substantially improved the storm intensity, with the simulated minimum central pressure remaining significantly higher than observed.

Ensemble simulations produced very limited spread, indicating that the model response was highly deterministic under the imposed large-scale forcing, see figure 11. While spectral nudging improved the storm track, all ensemble members consistently underestimated Ophelia's peak intensity, suggesting that the primary limitation was not model uncertainty but the inability of the configuration to reproduce the observed intensification.

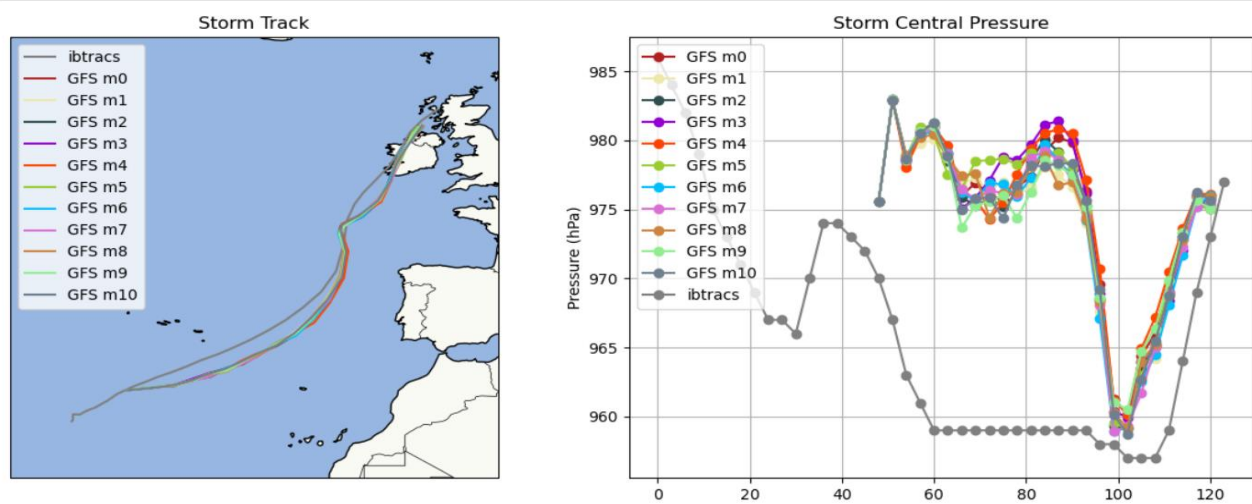


Figure 11 - Track (left) and central pressure evolution (right) for the GFS-driven ensemble simulations with spectral nudging, compared with the observed Storm Ophelia track and pressure from ITrACS (grey). Spectral nudging substantially improves the track representation, with all ensemble members following a similar trajectory close to the observed storm path. The ensemble spread remains small throughout the simulation, indicating that the large-scale circulation is effectively constrained by the nudging. While the pressure evolution is generally consistent across members, the simulations underestimate the depth of Ophelia during its peak intensity.

The similarity between the GFS- and IFS-driven simulations indicates that the persistent underestimation of Ophelia's intensity is unlikely to be explained by the lateral boundary conditions alone. Instead, it points towards a limitation within the HARMONIE-AROME modelling framework or its configuration that is common to simulations driven by both forcing datasets. The preliminary GFS experiments demonstrate that the representation of Storm Ophelia is sensitive not only to the choice of driving model but also to the interaction between the global forcing, the limited-area model, and the chosen simulation strategy.

While GFS appears to better capture the early stages of Ophelia's intensification than IFS, this improvement does not automatically translate into improved HARMONIE simulations. These results highlight the need for a dedicated investigation into the interaction between GFS, IFS, and HARMONIE boundary conditions, including the role of spectral nudging and initialization strategy. Given the scope of this work, such an investigation is best pursued as a separate methodological project, allowing the Future Weather project to remain focused on climate-change impacts once an optimal modelling framework has been established.

List of publications/reports from the project with complete references

Although the spiekoki finished, the parent Future Weather project is still ongoing, with future publications in preparation stage.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new EMI R&D Project.)

Following the return of the principal investigator in 2026, project activities have resumed fully. The technical developments completed during 2025 enabled the successful execution of an extensive suite of Storm Ophelia experiments using GFS boundary conditions.

The next phase of the project will focus on investigating the response of Storm Ophelia to non-uniform warming patterns, extending earlier work that examined uniform warming scenarios using IFS boundary conditions. These experiments will allow assessment of the sensitivity of storm evolution and impacts to more realistic future climate change signals.

References

- Gleeson, E., Whelan, E. and Hanley, J. (2017): *Met Éireann high resolution reanalysis for Ireland*. Advances in Science and Research, 14, 49–61. The paper describes the development of the 2.5 km Met Éireann ReAnalysis (MERA), a high-resolution regional reanalysis for Ireland.
- Klawa, M. and Ulbrich, U. (2003): *A model for the estimation of storm losses and the identification of severe winter storms in Germany*. Natural Hazards and Earth System Sciences, 3, 725–732.
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- Ribberink, M., de Vries, H., Bloemendaal, N., Baatsen, M., & van Meijgaard, E. (2026). *Tropical cyclone intensification and extratropical transition under alternate climate conditions: a case study of Hurricane Ophelia (2017)*. Weather and Climate Dynamics, 7, 37–64.
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