Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

Geological Survey
Suirbhéireacht Gheolaíochta
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Research Programme
- Short Call 2020, Final Report -

Lead Applicant Name	Prof. Christopher Bean
Host Organisation name	Dublin Institute for Advanced Studies
Project Title	Mapping weather & climate indices using seismic data (SeisStorm)
Contract Number	2020-sc-040

This report covers the period 1st December 2020 to project end date 30th November 2021

2. (a) Project information:

Final project report (*max 2500 words, excluding figures and headings*):

Executive summary (lay abstract, approx. 250 words):

The wind and wave climate of the NE Atlantic is very variable and energetic, exposing Ireland to potentially more extreme conditions with the changing climate but at the same time offering huge potential for renewable energy extraction. Global atmospheric circulation patterns and the ocean wave climate are deeply connected through the role of surface winds in the generation of ocean waves. At the same time, wind-driven ocean-wave-generated continuous Earth vibrations are produced at the seafloor and observed all over the world, defining a complex atmospheric coupling, via the oceans, with the solid Earth. The SeisStorm project aims to uncover the seismic signature associated with the North Atlantic storm tracks that fluctuate with the North Atlantic Oscillation (NAO). To do so, two methodologies have been investigated to extract long-term weather information from seismic data by mapping the fluctuations of the "seismic" storm track in the NE Atlantic. First, the storm driven changing wavefield of the continuous ocean seismic noise (~18 months) recorded on the seafloor during the SEA-SEIS experiment is investigated. Then a network of land seismic stations in Ireland is used in an attempt to reconstruct the ocean seismic storm track directly from land. In the context of a changing climate, the outcomes of the project benefit research on NE Atlantic storm track dynamics, for an alternative evaluation of likely more frequent extreme sea states affecting the Irish western coastline.

(i) Results, scientific/engineering targets reached beyond the state of the art and conclusions

The SeisStorm project exploits the mechanism behind the generation of secondary microseisms in order to extract valuable information on the storm track variability in the North Atlantic, fluctuating with the NAO. Secondary microseisms (3-10s) originates from pressure fluctuations at the seafloor, independent of the water depth, as a result of non-linear interactions of opposing ocean wave fronts (Longuet-Higgins, 1950). Therefore, in the North Atlantic, secondary microseism sources are expected to fluctuate with the changing storm track in response to variations in the NAO.

The results and scientific targets achieved through the project are developed below, looking at the outcomes of two approaches to extract storm track and climate variability information from NE Atlantic from Ocean Bottom Seismometer (OBS) data and a network of land seismic stations in Ireland.

NAO index extraction from the SEA-SEIS seismic data

Previous Ocean Bottom Seismometer (OBS) data recorded offshore Ireland have shown strong indications that the signature of the North Atlantic Oscillation (NAO) is ubiquitous in the Earth's background seismic wavefield (Le Pape and Bean, 2021). However, this work only considered 6 months of OBS data, which is quite limiting for a more long-term validation of the observations. The SEA-SEIS (www.sea-seis.ie) project (Prof Sergei Lebedev, DIAS, is the PI) covers a large swath of the NE Atlantic with Oceans Bottom Seismometers (OBS), and has generated an extensive seismic dataset recorded at the NE Atlantic seafloor for 18 months. Therefore, the SEA-SEIS data offers a unique opportunity to clearly differentiate seasonal effects from more long-term climate variations on the ocean seismic wavefield recorded at the seafloor.

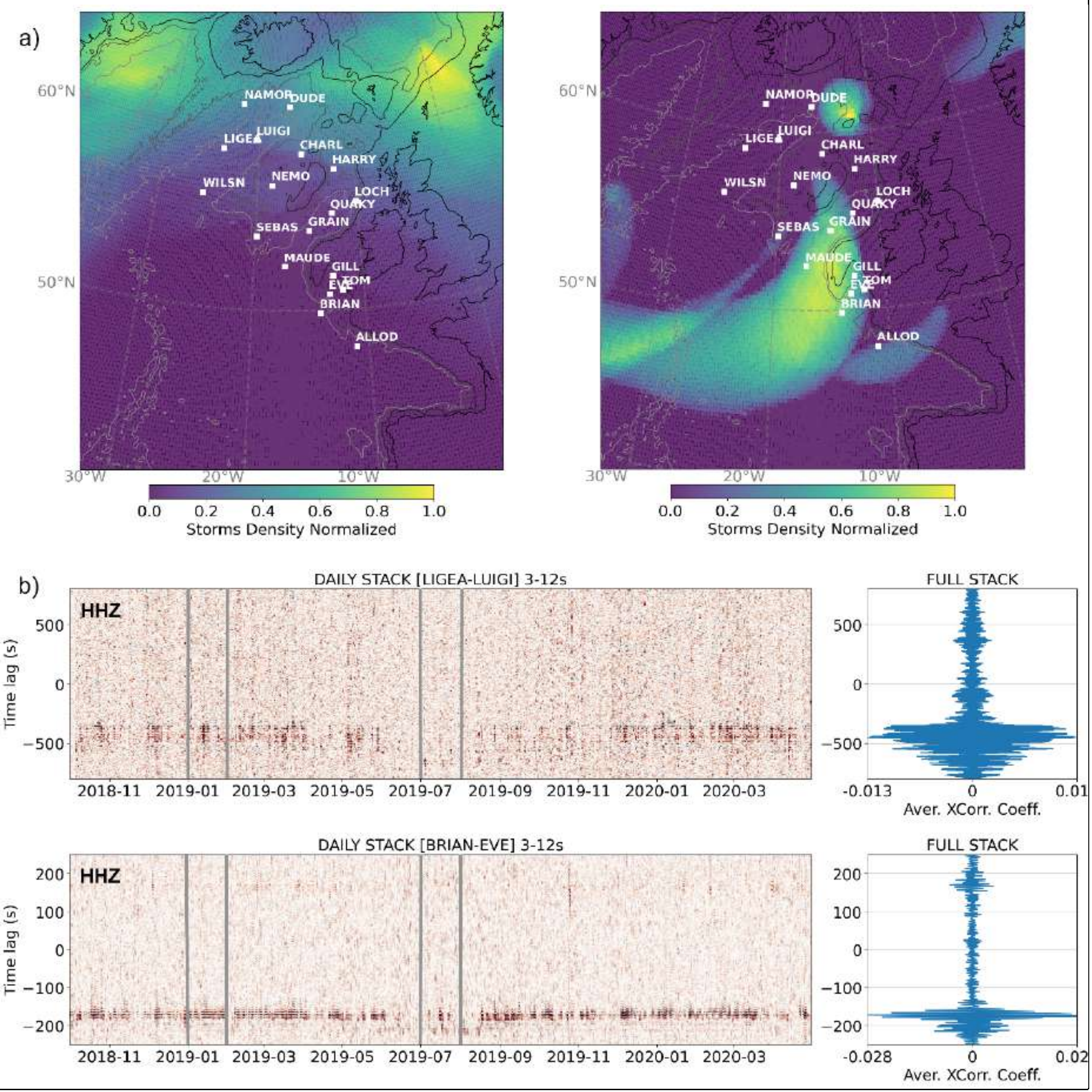

Figure 1 – Storm track influence on the SEA-SEIS seismic wavefield - a) *Monthly storm density for January 2019 and July 2019 derived from ERA5 mean sea level (MSL) pressure reanalysis. The "storm criteria" used to generate the density maps only consider locations with MSL below 995hPa.* ***b)*** *Daily cross-correlations for two seismic stations pairs (vertical component): LIGEA-LUIGI and BRIAN-EVE. The two months windows highlighted correspond to January and July 2019 for comparison with Figure 1a.*

Through the project we aimed to validate further the approach described in Le Pape & Bean (2021) consisting on linking daily variations in OBS cross-correlation coefficients of seismic Rayleigh modes' excitation with changing secondary microseisms source locations. Here, multiple stations pairs from SEA-SEIS data with relatively short interstation distances have been investigated. However, not all daily cross-correlograms are even as some pairs appeared noisier compared to others. In addition, four stations from the SEA-SEIS survey (HARRY, ALLOD, SEBAS & NEMO) have not been recovered yet, creating some gaps in the possible combinations of station pairs with short interstation distances. However, the cross-correlograms with good daily signal to noise ratio still exhibit very interesting fluctuations in Rayleigh phases arrivals. Figure 1 compares the position of storm densities for two particular months compared with seismic vertical component cross-correlations for two OBS pairs located at different latitudes: LIGEA-LUIGI (60°N) and BRIAN-EVE (50°N). The storm densities are estimated monthly based on ERA5 mean sea level (MSL) pressure data reanalysis. ERA5 represents the fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for the global climate and weather. In this example, we can see that, compared to January 2019, for the month of July 2019 a second slower phase becomes more apparent on both pairs cross-correlations. A trend that extends for the other months. In fact, for further comparisons, the ERA5 derived storm track maps have been added as supplementary material in section 4 below derived for all months covering the SEA-SEIS survey. As discussed in Le Pape & Bean (2021) this behaviour is likely due to a change in the regional storm distribution that excites Rayleigh modes differently. Deep water seismometers located on top of a thick sedimentary basin offshore Ireland can highlight significant excitation of Rayleigh higher mode seismic energy as secondary microseism sources become more common on top of the basin.

The fluctuations in SEA-SEIS data daily cross-correlations appear even clearer for the station pair QUAKY-LOCH, when comparing both hydrophone and vertical seismic components cross-correlograms. For most station pairs, the cross-correlograms for vertical seismic and hydrophone channels are quite similar. This is expected since the Rayleigh surfaces waves highlighted by the noise cross-correlation technique are coupled between the water column and the Earth's structure below the seafloor for periods associated with secondary microseisms (3-12s). However, the stations pair QUAKY-LOCH shows a completely opposite behaviour. Whereas, the dominant seismic phase on the vertical seismic cross-correlations occurs for negative time lags, the dominant phase on the hydrophone cross-correlations occurs at positive time lags but is also characterized by a faster apparent velocity. In addition, those two phases seem to be out of synchronization through the months. As discussed above, this observation very likely correlates with a change in storm locations (Fig. 1a). Based on the OBS results from Le Pape & Bean (2021) in the Rockall Trough, we interpret the dominant phase on the vertical component as the Rayleigh fundamental mode and the faster phase seen on the hydrophone component as a Rayleigh higher mode.

Since the station pair QUAKY-LOCH exhibits the clearer variations in cross-correlations for different Rayleigh modes, a daily higher mode or HM index is extracted following the method presented in Le Pape & Bean, (2021). Here, the approach is used to derive a seismic HM index from daily difference between the cross-correlations coefficients of fundamental (here from the vertical component) and higher seismic modes (here from the hydrophone channel). This seismic HM index is then plotted against the daily NAO index for the recording period of the SEA-SEIS data. The "raw" HM index appears relatively noisy but once processed through a median filer, to attenuate some of the daily outliers, the NAO trend starts to reveal itself more clearly through the OBS data. Both HM and NAO indices are not perfectly correlated but do show some striking similarities that highlight a clear connection between climate variability associated with the NAO and ocean induced Earth's vibrations over the whole SEA-SEIS acquisition period.

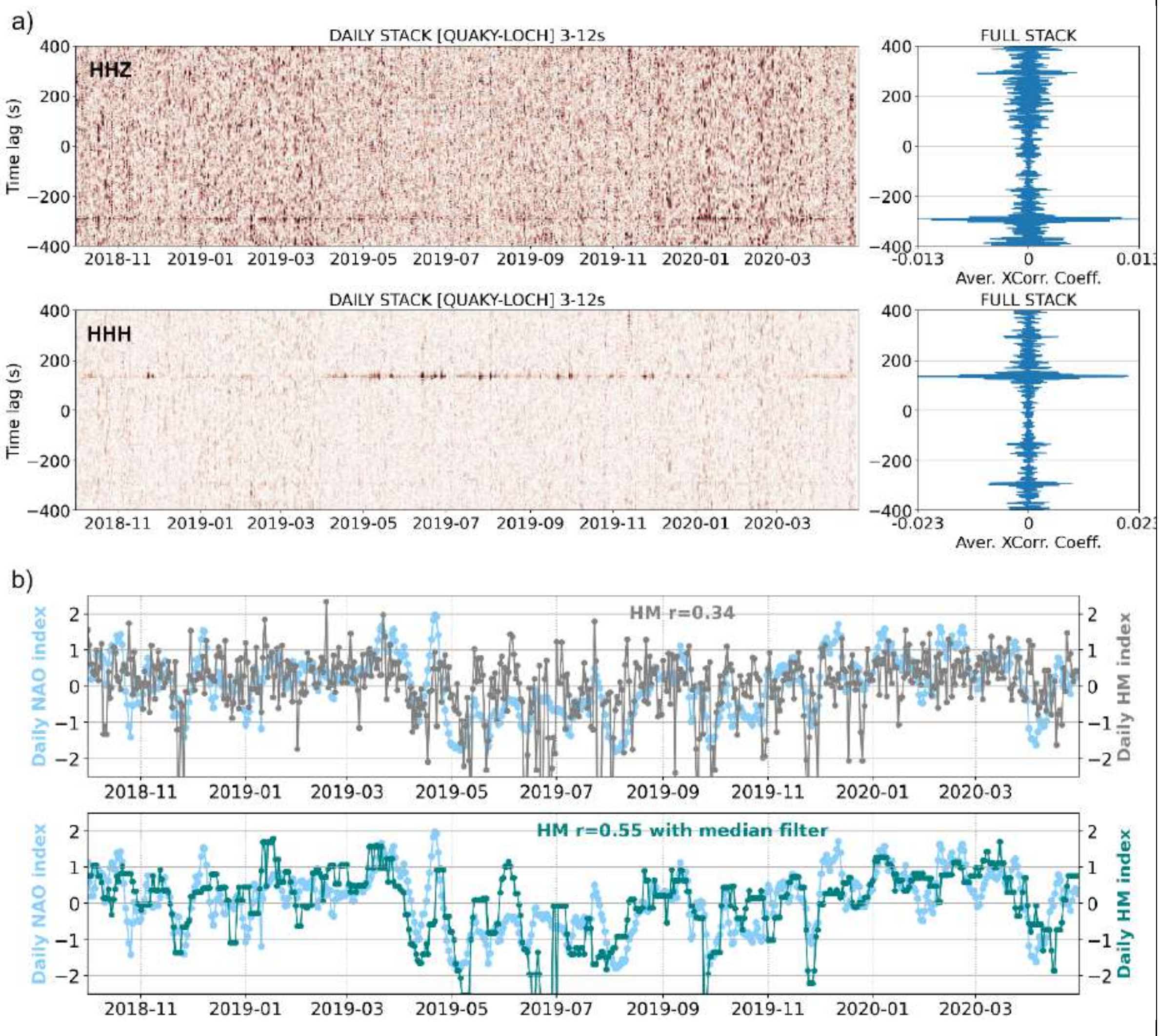

Figure 2 – NAO connection to the SEA-SEIS seismic wavefield - a) *Daily cross-correlations for seismic stations pair QUAKY-LOCH for seismic vertical (HHZ) and hydrophone (HHH) channels.* ***b)*** *Daily NAO index compared with OBS derived HM index. Pearson correlation coefficients between the two indices are shown for the "raw" and median filtered HM index.*

The SEA-SEIS data is a huge dataset and clearly more work is needed to explore further the noise properties and the link with the changing storm track through the months. However, the close connection behind the seismic HM index and daily NAO index confirms the tight NAO influence on the secondary microseism wavefield recorded as the seafloor. The observed trends in Rayleigh variations are definitely not only due to seasonal changes in storm intensity but the influence of the NAO in shifting the NE Atlantic storm track northward or southward through months depending on its index values. However, some station pairs are easier to decipher than others in term of their connection with the NAO. This will depend on the station locations, including interstation distance, but also the subsurface structure and bathymetry at the stations. For instance, similar to the OBS data used in Le Pape & Bean (2021), the SEA-SEIS OBS data shows again that the Rockall Trough basin's location and its underlying geological structure is quite a unique feature of the NE Atlantic for monitoring the seismic noise wavefield's response to weather changes. The station pair QUAKY-LOCH shows that a clearer Rayleigh mode separation is more apparent in the Rockall Trough.

Using a network of land seismic data to map offshore storm tracks

The use of OBS data to extract storm track information and associated fluctuations following the NAO is very informative. However, the approach remains logistically challenging for long-term applications in monitoring seismic storm track and associated climate variability. In addition, applying the OBS cross-correlation methodology on land data is more complex. One of the main reasons being the occurrence of Rayleigh mode conversions as the seismic noise generated by storms propagates to land, burying deeper in the data that information on the source origin. The use of time reversal or reversed in time (RT) simulations can help overcome this limitation and hopefully not only reconstruct the original secondary microseism source location but also monitor its fluctuation as it respond to the changing storm track. The time reversal localisation technique consists on backpropagating the signal measured at a network of receivers into a 3D model as realistic as possible, re-creating the original wave and untangling distortions created by the scattered medium along the way and refocusing at the original source point. That way, the receivers define some kind of "time-reversed mirror" sending the signal back to its origin (Fink at al. 1999). Mainly developed for acoustics, the technique has been investigated in seismology for earthquake location (Larmat et al. 2016) but also to locate volcanic tremors (Lokmer et al. 2009). However, it has not been applied yet on ocean secondary microseisms localisation. One of the main drawbacks is the need for a relatively large and complex 3D model for signal backpropagation. In addition, the source area associated with secondary microseisms is expected to be relatively sparse and therefore tricky to differentiate from the presence of multiple scatters along the signal propagation path.

We decided to test and investigate that approach on a regional 3D seismo-acoustic model of the Irish offshore (Le Pape et al., 2021). The model comprises the water column (acoustic) and 3 elastic domains defined by sediments, crust and mantle. The model needs to be complex enough to be able to reproduce *in situ* signal scattering necessary for time-reversal applications. On Figure 3, some preliminary synthetic tests were performed on the 3D model for signal point sources. This work has been supported with additional communication with Mathias Fink from ESPCI Paris on the use of time reversal mirrors. In our test, we first performed two forward simulations for two different point source locations S1 and S2, where the source time function is injected as vertical pressure 15m below the sea surface. The signal propagating through the model is recorded on multiple land stations located in Ireland. The station locations are actually real station locations from June 2012 combining DIAS Ireland Array and UCD WaveObs projects. For each stations the recorded 3-component signal is then reversed in time and backpropagated in the model for reversed in time (RT) simulations. The RT simulations results plotted on Figure 3 represent an "image stack" over multiple time steps, showing the back-tracing of the max amplitude of the wavefield to its original source. That way the path of the original signal from the source to the stations can be highlighted as well as the original source location. As seen on the RT simulations results, for synthetic noise both point source locations can be recovered relatively well with the use of that particular distribution of stations. However, it is worth noting that here the synthetic backpropagated signal was generated by the same model used in the RT simulation, defining an optimum set-up for the method.

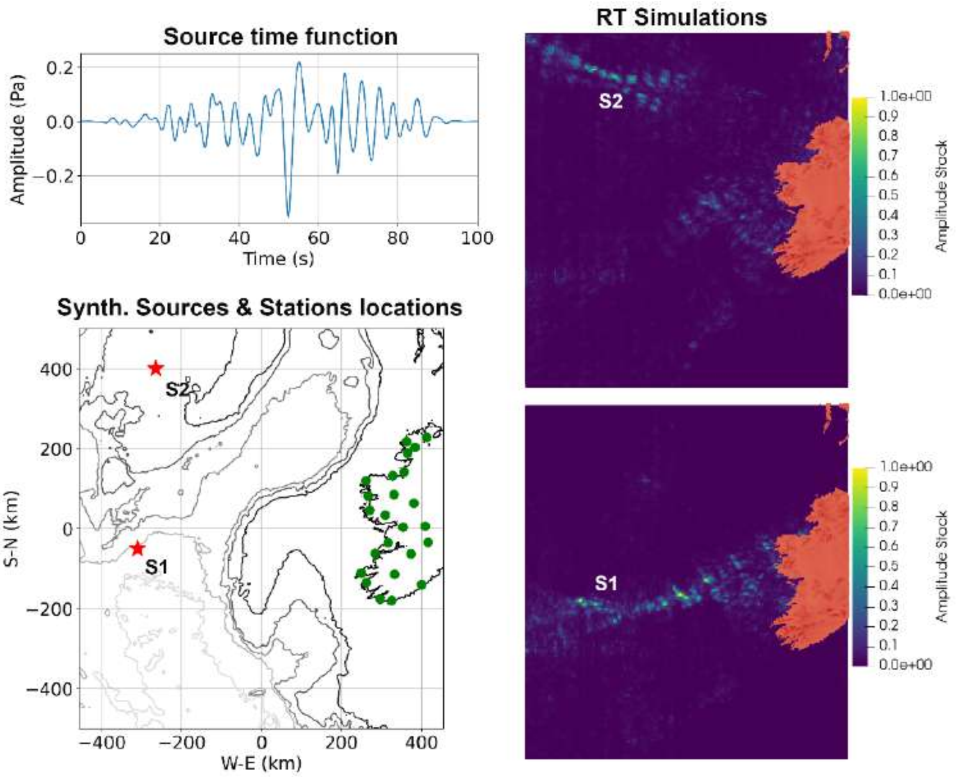

Figure 3 – RT simulations capacity test – *Synthetic data generated by two points source (red stars) and recorded at real stations locations in Ireland (green dots) and backpropagated across a seismo-acoustic 3D model of the Irish offshore. The source time function for those tests was generated using the amplitude spectrum of a 5s Ricker wavelet, converted back to a 100s long time signal after introducing a random phase. The RT simulation plots represent the max amplitude stack of the backpropagated wavefield over multiple time steps.*

We then looked a backpropagating real time seismic "noise event" extracted from ocean microseism data recorded at those same stations. Two main challenges were expected: (i) the model is only an approximation of the real Earth structure and therefore it is not optimum anymore, (ii) the noise source for the ocean secondary microseisms recorded at the stations is more widespread. Due to the limited spatial coverage of the model, we tried to focus on storms that appeared relatively small in extension and close enough to Ireland. Figure 4 and 5 show the RT simulations results for two storms passing by Ireland on 14^{th}-15^{th} June 2012 and 28^{th}-29^{th} June 2012 respectively. The RT simulations results are compared with surface winds highlighting the storm distribution at the time of the "noise event" but also with the expected seismic noise source location derived from Ifremer's ocean wave model for the same time considered in the RT simulations.

The results are quite complex to interpret in details and more time windows need to be investigated in order to further understand and characterize the observations. But still those simulations show some very promising results. In both cases, both storms are evolving from SW Ireland towards NE Ireland. As the storms slightly shift to the east, opposing wind waves generated around the low-pressure system likely interact together producing secondary microseisms that can explain the strong SE-NW orientated source direction observed for storm #1 and #2. In addition, for storm #2 as the storm move further north, the noise starts to be located further to the north of Ireland. In addition, some of the simulated source locations and directions match with the expected seismic sources from the ocean wave model. However, there are some discrepancies which can be explained by multiple factors. The ocean wave model seismic source is only representative of a 3h time window whereas RT results are representative of a 2min noise window. Both results are also derived from two different models and we look here at the whole spectrum noise spectrum (3-10s) which leads to more complex results too. A bigger model and a sparser distribution of stations would also likely benefit an improved characterisation of the seismic noise sources and associated storm locations.

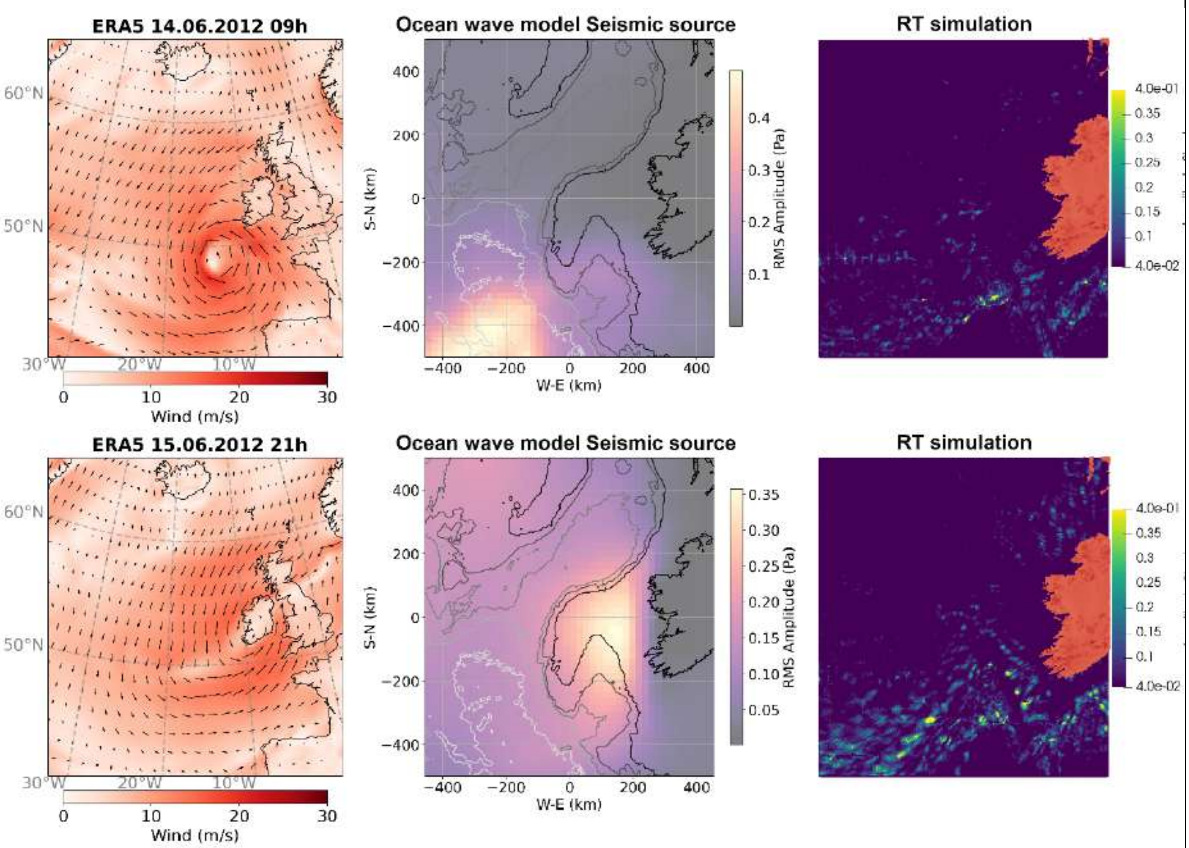

***Figure 4 – Storm #1:** RT simulation of seismic noise data from Ireland compared with the expected storm position (ERA5 reanalysis) and offshore seismic source location (Ifremer's ocean wave model) at the time of the recorded seismic signal. The backpropagated signal in each simulation corresponds to a continuous 2 min "noise event" window between 9h05 and 9h07 on 14/06/12 and 21h05 and*

21h07 on 15/06/2012. The RT simulation plot shows the stack of the maximum wavefield over multiple time steps.

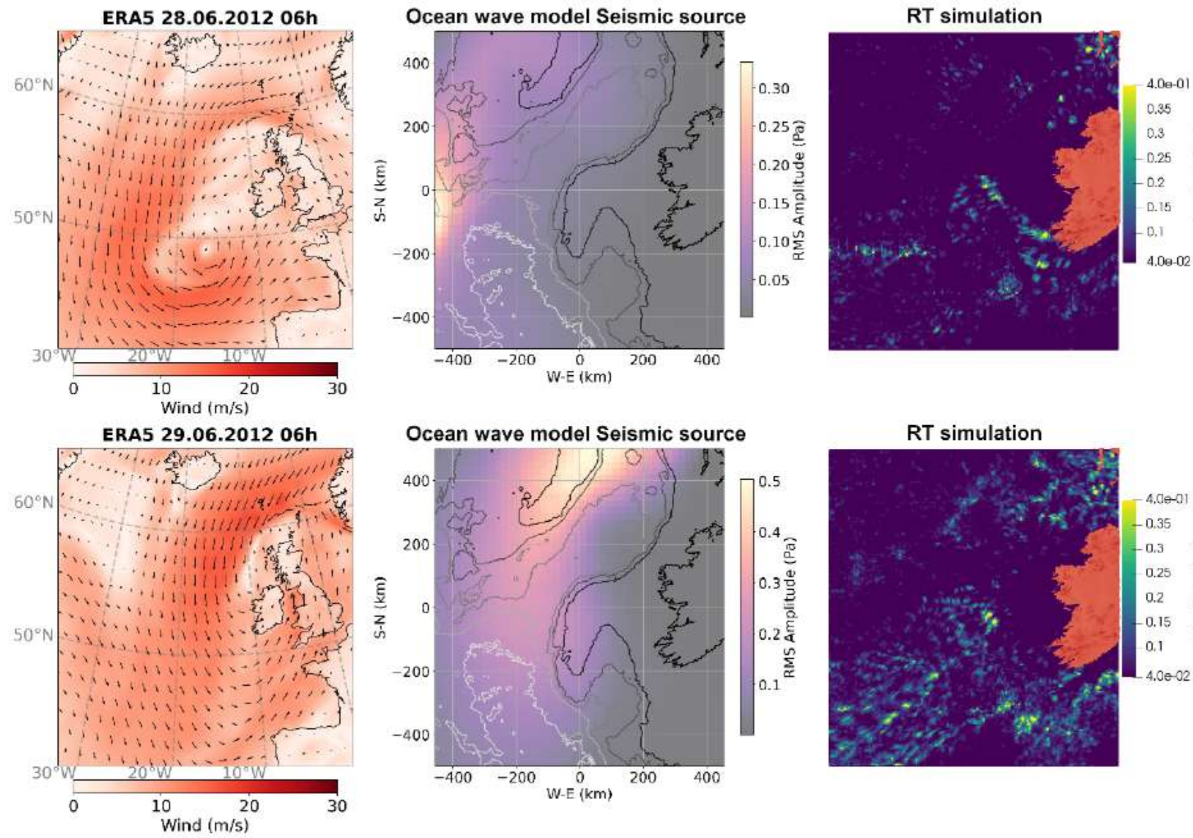

Figure 5 – Storm #2: *RT simulation of seismic noise data from Ireland compared with the expected storm position (ERA5 reanalysis) and offshore seismic source location (Ifremer's ocean wave model) at the time of the recorded seismic signal. The backpropagated signal in each simulation corresponds to a continuous 2 min "noise event" window between 6h05 and 6h07 on 28/06/12 and 6h05 and 6h07 on 29/06/2012. The RT simulation plot shows the stack of the maximum wavefield over multiple time steps.*

(ii) Implementation (milestones, deliverables, project management)

The first milestone of the project and associated deliverable on the "*Assessment of mapping NAO index using seismic data*" was achieved after month 3. Following the processing of the SEA-SEIS data and ERA5 reanalysis data, the recovery of the NAO trend for fall 2018 to spring 2020 was successfully derived from the OBS data.

The second milestone of the project and associated deliverable on a methodology to "*Map of Storm's tracks using seismic data*" was achieved at month 5. However, the application of time reversal mirrors for secondary microseisms localisation has been quite challenging. As mentioned above, the source distribution is very diffuse which leads to a broad distribution of scatters along the signal path that acts as secondary sources. Several tests have been performed on the real data in comparison with the single point source simulations in order to find a way to limit those effects from bathymetry and sedimentary basins' morphologies.

The best approach appears so far to mainly focus on extracting images from the backpropagating seismic wavefield in the deeper end of the 3D model for depths below 8km.

The seismic data were handled and processed using the python toolbox ObsPy (Beyreuther et al., 2010). Numerial computations for the RT simulations were achieved with the use of SPECFEM3D (Komatitsch & Tromp, 1999) and have been performed using the Kay cluster at the Irish Centre for High-End Computing (ICHEC). The SPECFEM3D Cartesian software is freely available via https://geodynamics.org/cig/software/specfem3d/. Visualization and processing of the RT simulation images was achieved with the software Paraview.

The daily NAO data are available through the Climate Prediction Center, NOAA at https://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml. The seismic source derived from the Ifremer's ocean wave model was access via the IOWAGA project (Rascle & Ardhuin, 2013; https://wwz.ifremer.fr/iowaga/Links) accessible via ftp in the folder /ifremer/ww3/HINDCAST/. The ERA5 reanalysis data was accessed from the Copernicus Climate Data Store (ERA5 hourly data on pressure levels from 1979 to present (copernicus.eu)).

As part of the project two SSD storage disks were purchased under the consumables budget of the project in order to store and rapidly access the processed SEA-SEIS and ERA5 data but also for storing the RT simulations results which are also very demanding in storage space.

Publication submission in an international peer-reviewed journal is expected for the first quarter Q1 of 2022.

The management of the project was performed through formal monthly meetings between the PI and his research group.

(iii) Outputs to date

The main outputs of the project to date are the validation of two methodologies that show promising potential in monitoring fluctuations in secondary microseism sources in the changing storm track in NE Atlantic.

- *Ocean methodology* – The method simply uses daily cross-correlations of between OBS stations located at the seafloor to monitor climate variability, and in particular the NAO and associated storm track variations. However, the method is highly depending on the station pair location, the interstation distance but also the water column and geological structure beneath the stations which controls the seismic Rayleigh modes excitation.

- *Land methodology* – The method is based on time reversal localisation of seismic sources and storm tracking based on a network of land station. As discussed in the result section, the outcomes remain constrained by the size of the 3D model and station distributions but are quite promising. For instance, exploring the use of a bigger model and sparser stations distribution would potentially benefit a better mapping of the NE Atlantic storm track based on seismic noise.

- These outputs will be stored in DIAS on its data servers.

(iv) Impact

- Relevance/application to GSI programmes, where applicable

The outcomes of the project are clearly highlighting Ireland's excellent geographical location in an effort to make ground breaking discoveries in our understanding of the NE Atlantic weather and storm activity, increasing the impact of GSI based research. By mapping Ireland's seabed seismic response to atmospheric processes, the project has shown potential crossover with the INFOMAR program on sea bed mapping, funded by the Department of Communications, Climate Action & Environment (DCCAE) and operated by the GSI and Marine Institute. With increasing engagement from the public towards climate change topics, this project's outcomes have potential to partner with public perception work (although not yet specifically planned here) on the role and potential of seismology in Ireland through the INSN, by highlighting how solid Earth, ocean and atmospheric processes are all connected.

- Other impacts

The study of long-term weather and climate input through ocean seismic noise is significant as it brings additional data (e.g. training data for machine learning schemes) for more robust sea state and weather models, with hopefully great benefit in the future for international and national weather organisations such as Met Eireann (Irish Met Service). Climate action, sustainability, monitoring & managing our oceans are recognised priorities for EU Horizon Europe funding schemes. The outcomes of the project, although preliminary, are building and maintaining capacity in this research area as a springboard to further funding applications. A better understanding of storm track dynamics would lead to an improved prediction of extreme sea states and weather across Ireland which is also of direct interest to state agencies in addition to the media, schools outreach, and the general public. At longer time scales improving our understanding of the wave climate could have a substantial impact on Irish coastal communities, who are increasingly vulnerable to storm surges from sea level rise.

The investigation of ocean seismic noise sources and their changing locations with storm activity using time reversal looks promising and can widely benefit the passive seismic imaging and monitoring applications. In addition, the use of seismic noise for passive and 'greener' seismic data acquisition is key for monitoring the Earth in a sustainable way on both land and in the marine environment. Hence any work that leads to a better understanding of microseisms adds to that effort. The outcomes of this project provide some first steps in the generation of reference information on the NE Atlantic seismic noise wavefield to the scientific community and industry for the development of passive offshore imaging methods (e.g. for estimating geomechanical properties of the near sea floor – important for communications cables, wind turbine foundations and geohazard monitoring). This also benefits Irish organisations such as the Sustainable Energy Authority of Ireland (SEAI) involved in the development for sustainable ocean energy.

This project was key to pilot development work that led to a successful application to the SFI-IRC fellowship programme 2021.

References:

Beyreuther, M., Barsch, R., Krischer, L., Megies, T., Behr, Y., & Wassermann, J. (2010). ObsPy: A python toolbox for seismology. *Seismological Research Letters*, *81*(3), 530–533.

Fink, M., (1999). Time-reversed acoustics, *Scientific American*, vol. 281, issue 5, pp. 91-97.

Komatitsch, D., & Tromp, J. (1999). Introduction to the spectral element method for three-dimensional seismic wave propagation. *Geophysical Journal International*, *139*(3), 806–822.

Larmat, C., Montagner, J-P., Fink, M., Capdeville, Y., Tourin, A., & Clévédé, E., (2006). Time-reversal imaging of seismic sources and application to the great Sumatra earthquake, *Geophysical Research Letters*, vol. 33, L19312.

Longuet-Higgins, M. S. (1950). A Theory of the Origin of Microseisms. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *243*(857), 1–35.

Le Pape, F., Craig, D., & Bean, C. J. (2021). How deep ocean-land coupling controls the generation of secondary microseism Love waves. *Nature Communications*, *12*(1), 2332.

Le Pape, F., & Bean, C. J. (2021). North Atlantic Oscillation (NAO) climate index hidden in ocean generated secondary microseisms. *Geophysical Research Letters*, *48*, e2021GL093657.

Lokmer, I., O'Brien, G. S., Stich, D., & Bean, C. J. (2009), Time reversal imaging of synthetic volcanic tremor sources, *Geophysical Research Letters*, 36, L12308.

Rascle, N., & Ardhuin, F. (2013). A global wave parameter database for geophysical applications. Part 2: Model validation with improved source term parameterization. *Ocean Modelling*, *70*, 174–188.

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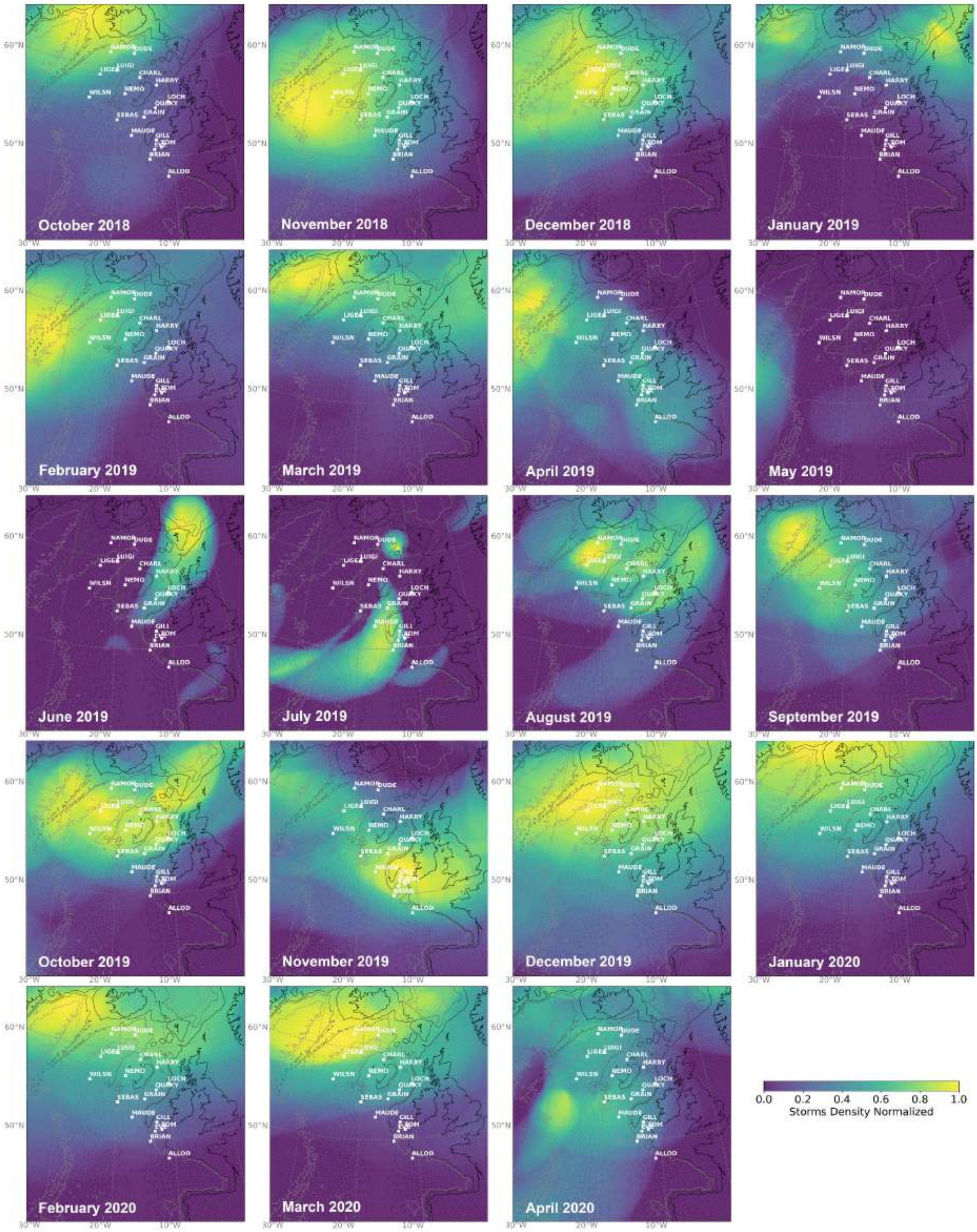
4. Supplemental information/datasets

Monthly storm density from October 2018 to April 2020 derived from ERA5 mean sea level (MSL) pressure reanalysis. The "storm criteria" used to generate the density maps only consider locations with MSL below 995hPa.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Storms Density Normalized
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