https://doi.org/10.5194/egusphere-2025-6404
Preprint. Discussion started: 13 January 2026

A Century of Mean Sea-Level Change in Ireland (1925-2024)

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Abstract. Understanding mean sea level (MSL) change is crucial for assessing coastal vulnerability and guiding adaptation planning, particularly by identifying regions most at risk. Central to this understanding is the availability of long-term sea-level data. In Ireland, digitized records longer than 40 years are rare and mostly confined to the northeast; however, data archaeology—including the digitization of historical marigrams—can fill spatial and temporal gaps where undigitized records exist. Previous studies have focused primarily on individual sites in the north and east. Here we show that integrating previously undocumented records from the southwest with well-documented datasets provides a comprehensive assessment of MSL change across the country. We find clear regional variability, with the highest mean rates in the south and west. Long-term mean instantaneous rates—representing the modelled rate of sea-level change at each site—vary systematically between regions, reflecting coherent spatial patterns. Rates range from ~1.07 mm yr^{-1} in the north to 2.48–2.74 mm yr^{-1} in the south and west, with the highest observed at Cork (2.74 mm yr^{-1}). The regional mean is 1.96 ± 0.1 mm yr^{-1} for 1925–2024, decreasing to 1.88 ± 0.1 mm yr^{-1} after accounting for Glacial Isostatic Adjustment (GIA). Annual rates increased from below 1 mm yr^{-1} during 1925–2000 to above 4 mm yr^{-1} during 2000–2024, peaking at ~6 mm yr^{-1} in 2024, highlighting pronounced 21st-century acceleration. After applying atmospheric and datum adjustments and accounting for GIA within a Bayesian framework, these historical records provide a robust basis for reconstructing regional sea-level rise and contextualizing future coastal risk, with implications for coastal planning and adaptation strategies globally.

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1 Introduction

Mean Sea Level (MSL) is the long-term average height of the sea surface at a given location, calculated over a period sufficient to smooth out short-term variations such as tides, storm surges, and weather (Hünicke et al., 2015). Globally, MSL is rising at 3–4 mm yr^{-1}, with satellite observations showing ~3.3 mm yr^{-1} from 1993–2021 and ~4 mm yr^{-1} from 2006–2016, and more recent estimates of ~4.5 mm yr^{-1} in 2023 compared to 2.1 mm yr^{-1} in 1993 (Llovel et al., 2023). If this trend continues, an additional ~169 mm of global sea-level rise could occur over the next three decades, consistent with mid-range projections from IPCC AR6 (Hamlington et al., 2024). Understanding MSL changes from tide-gauge and archival data is essential for quantifying long-term trends and interactions with tides, storm surges, and extreme events, providing critical information for coastal planning and adaptation at global and local scales (Talke et al., 2018). However, the magnitude and expression of these changes are strongly influenced by regional and local factors. In Ireland, coastal cities such as Cork and Galway are highly vulnerable to flooding. In 2009 a major flood event in Cork led to around €100 million of damages to Commercial and Residential property (Olbert et al., 2017). Annual economic damages from coastal flooding in Britain are currently estimated at approximately £360 million and are projected to increase two- to threefold by the end of the century (Haigh et al., 2022). Approximately 40% of Ireland's population lives within 5 km of the coast, including major cities (Wall et al., 2020), making coastal areas highly vulnerable. Given Ireland's similar coastal exposure and geographical position, it is also likely to face significant costs and challenges.

Ireland has a modern network of over 40 tide gauges through the National Tide Gauge Network (NTGN), installed in the 2000s and managed by the Office of Public Works (OPW) and the Marine Institute (MI) (Cámaro García et al., 2021). However, only a few sites, including Malin Head, Dublin Port, and Belfast, provide long-term (>40 years) continuous records, which are incorporated into the Permanent Service for Mean Sea Level (PSMSL). Digitized historical series are concentrated in the north and east of the island, including Malin Head (1958–2002; Holgate et al., 2013, extended to the present with MI and OPW data), Dublin Port (1938–present), and Belfast (1901/1902–2010; Murdy et al., 2015, Figure 1), whereas records along the south and west coasts are sparse and often of relatively short duration. This uneven geographic coverage makes it difficult to detect regional trends in MSL, as large portions of

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the coast remain unmonitored. A minimum of 40 years is generally required to robustly determine trends in MSL (Hogarth et al., 2021). Recent work in Britain shows the benefits of systematically recovering and integrating historical tide-gauge data into a unified framework, which yielded a robust two-century MSL curve, reduced uncertainties, and revealed long-term accelerations (Hogarth et al., 2021). Similar historical data rescue and integrated analyses across multiple Irish sites are needed to overcome the limited spatial and temporal coverage of existing records.

Across Ireland, relative sea-level (RSL) change varies markedly, with lower rates in the northeast and higher rates in the southwest, primarily due to Glacial Isostatic Adjustment (GIA) (Bradley et al., 2011). During the Last Glacial Maximum, the thickest ice extended from Scotland into Northern Ireland, thinning toward the southwest (Scourse et al., 2021). Following deglaciation, collapse of the forebulge caused land subsidence in the southwest and uplift in the northeast, producing spatial contrasts in RSL trends, including localized sea-level fall in parts of the northeast. Quantifying these impacts is complicated by differences among available GIA models, which yield different outputs even within their own subfamilies. Understanding past ice-sheet dynamics is therefore critical not only for explaining historical RSL variations across Ireland but also for refining GIA models, thereby enhancing predictions of future sea-level rise (Clark et al., 2022; Bradley et al., 2023). This is particularly important on the island of Ireland, where regional differences in land movement and sea-level response make accurate projections essential for coastal planning. GIA models differ due to variations in ice-sheet histories, Earth rheology assumptions, and differences in spatial and temporal resolution and calibration approaches (Bradley et al., 2023). GLAC1D uses physics-based, glaciologically self-consistent ice-sheet simulations (Tarasov et al., 2012), whereas ICE6G models are tuned to fit global relative sea-level (RSL) and crustal motion observations (Peltier, 2015). Regional Bradley-type models, including those based on BRITICE-CHRONO reconstructions, are specifically calibrated to British–Irish RSL and GPS datasets (Bradley et al., 2023). These differences strongly influence predicted vertical land motion, as demonstrated by studies showing high sensitivity to upper-mantle viscosity and uncertainties in deglaciation histories (Bradley et al., 2011; Bradley et al., 2023). Consequently, modelled uplift rates can vary substantially, meaning the choice of GIA model can affect corrected sea-level trends.

In this paper, we aim to gather sea-level data from across Ireland, including the south and west where records are sparse, to improve understanding of both Mean Sea Level (MSL) changes and the influence of Glacial Isostatic Adjustment (GIA). The objectives are to:

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i) Integrate and analyse new records from the south and southwest to investigate MSL changes in regions with limited long-term observations.

ii) Reconstruct the historical MSL for Ireland using quality-assured sea-level data.

iii) Assess the influence of GIA on regional sea-level trends.

iv) Contextualize historical MSL changes across Ireland and evaluate their implications for vulnerable coastal areas.

2. Data Collection and Digitization

The sites analysed in this study are Belfast Harbour, Malin Head, Dublin Port, Cork, Galway, and Tarbert (Figure 1). Supplementary records from nearby gauges were also included where available—for example, Bangor (supplementing Belfast), Portrush (supplementing Malin Head), Kilrush Lough (supplementing Tarbert), Galway (supplementing Galway Harbour for 1967–1970), and Arklow Harbour, Howth Harbour, and Dún Laoghaire Harbour (supplementing Dublin Port). By integrating data from multiple sources, this study fills key gaps and provides new insight into spatial variability in sea-level trends.

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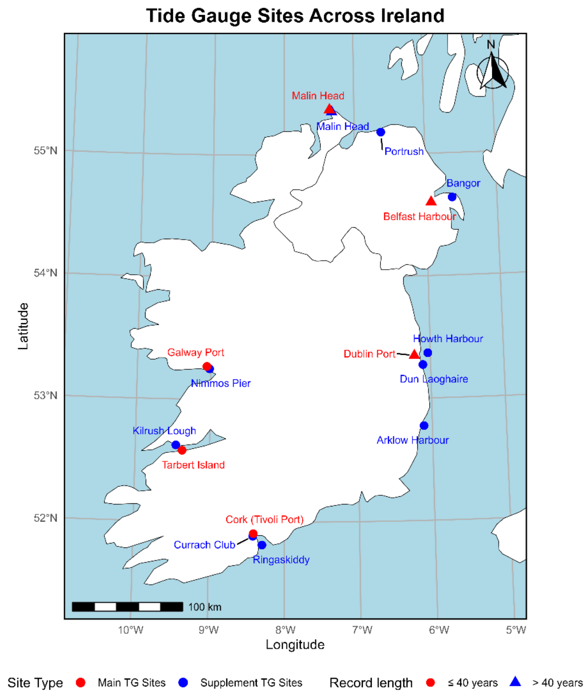

Figure 1. The six primary tide-gauge (TG) sites are shown in red. Supplementary TG sites, shown in blue, are nearby gauges (modern or historical) used to fill gaps or improve record quality. Belfast Harbour, Dublin Port, and Malin Head are long-record sites (>40 years), with records spanning 60–100 years.

Tide-gauge data were obtained from the Permanent Service for Mean Sea Level (PSMSL, Holgate et al., 2013), a key global repository of sea-level observations. Mean Tide Level (MTL) records were obtained from the PSMSL repository for the following sites, covering only the periods used in this study:

- Malin Head (1958–1995); higher-resolution data are available in the GESLA database, but their quality has not been independently verified.
- Bangor (2011–2015).
- Portrush (1996–2015).
- Dublin Port (1938–2001).

Modern data for Malin Head were obtained from the OPW (2004–2008) and the MI (2009–2024) (MI, 2025; OPW, 2025).

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The PSMSL holds a Mean Tide Level (MTL) record for Belfast Harbour, but it does not extend beyond 1963. For this study, we used the 1902–2010 Belfast dataset digitized by Murdy et al. (2015), which provides high-resolution 10-minute intervals for most of the record, except for 1990–2000, which is provided at hourly intervals.

Historical data for Dún Laoghaire Harbour (formerly Kingstown) spanned 1925–1931 and were obtained from McLoughlin et al. (2024). Data for two additional years (1932–1933) were recovered from raw marigrams; however, these records are less reliable due to thicker, less accurate traces—particularly in 1933, when frequent clock stoppages affected the data. Only the months of June to August in each year were digitized. Marigrams were digitized at hourly intervals using WebPlotDigitizer (Rohatgi, 2024), employing the full-grid method described by McLoughlin et al. (2024) for severely distorted images, achieving an estimated accuracy of approximately 1 cm.

Data for Dublin Port, updated and corrected for bias in modern observations, were available as yearly means (Shoari Nejad et al., 2022). For this study, we used the Dublin Port record spanning 1938–2001. Tide-gauge observations after 2001 exhibit considerable divergence, suggesting potential instrument malfunction and reduced reliability. To ensure continuity and extend spatial coverage, modern sea-level data from the NTGN were added to the Dublin Port record, comprising measurements from Arklow (2003–2006; managed by the OPW) and Howth (Dublin, 2007–2024; MI).

In the far west of Ireland, tidal records for Galway (1967–1970), near Nimmo's Pier, were obtained from the British Oceanographic Data Centre (BODC) archive (BODC, 2025). The dataset contained both Julian Day and human-readable calendar dates (yyyy-mm-ddThh:mm:ss) at hourly intervals; these were converted to a standard datetime format for analysis. Data for 1967 and 1970 were incomplete. Tide-gauge data for Galway Port were obtained from the NTGN (MI; 2007–2024).

For all sites, all datasets except the PSMSL MTL monthly means were extracted at hourly intervals for consistency, and all digitized data originally in feet were converted to metres.

2.1 Cork Harbour

To the southwest of Ireland, tide-gauge data for Cork Harbour were obtained from Port of Cork engineers and archival reports. The dataset includes measurements from Tivoli Port for 1974–1976/1977, 1984–1985, and more recent records from a modern tide gauge for 2001–2005 and

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2010–2012. The 2001–2005 and 2010–2012 Tivoli records were already available digitally and therefore did not require manual digitization. The 1970s and 1980s records were in marigram (pencil trace) format (Figure 2), with measurements spanning 06:00–06:00 the following day, and were digitized at hourly intervals using WebPlotDigitizer (Rohatgi, 2024) with the reduced grid method described by McLoughlin et al. (2024), achieving an accuracy of approximately 1 cm (0.01 m) per measurement.

Complementing these data, tide-gauge measurements spanning several months, from October 1976 to January 1977, were obtained from a Cork Harbour pollution report for Monkstown (O'Sullivan, 1977). These pen-trace records were digitized at hourly intervals, with a time axis ranging from 00:00–24:00. All data were standardized to hourly intervals for consistency. Modern OPW tide-gauge measurements from Ringaskiddy (2012–2021) and Currach Club (2022–2024) were included in the record.

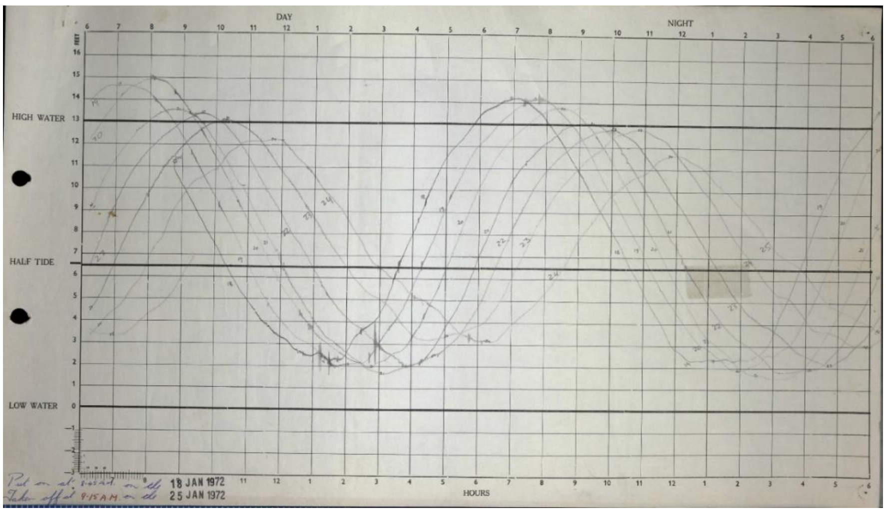

Figure 2. Example of a Cork marigram with a pencil trace. The X-axis represents time from 06:00–06:00 the following day, and the Y-axis shows water level in feet relative to chart datum. Dates are indicated above the pencil traces. Data courtesy of Port of Cork engineers (personal communication, 2022).

2.2 Tarbert Island

An additional dataset spanning 1964–1986 for Tarbert Island, Kerry, representing the longest tide gauge record from the southwest of Ireland included in this study, was provided in feet (1964–1977) and metres (1979–1986) relative to OD Poolbeg, with data from 1978 omitted

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due to continuous gaps and poor quality. Timing offsets were noted throughout the digitization process but were generally minor and tended to balance out overall. Some handwritten notes were difficult to interpret and were left unchanged; as they appeared in only one or two images per year, their impact on the dataset was negligible. In rare cases of duplicate-dated traces where uncertainty existed regarding the correct trace, only one was retained. Additionally, some dates were estimated when information was absent. While these instances could affect dataset accuracy, they are fully documented for transparency (Figure 3A–D). Figure 3A shows marigrams spanning up to one month, an issue also reported by Latapy et al. (2023) when tide sheets were not changed regularly; such records were excluded from digitization.

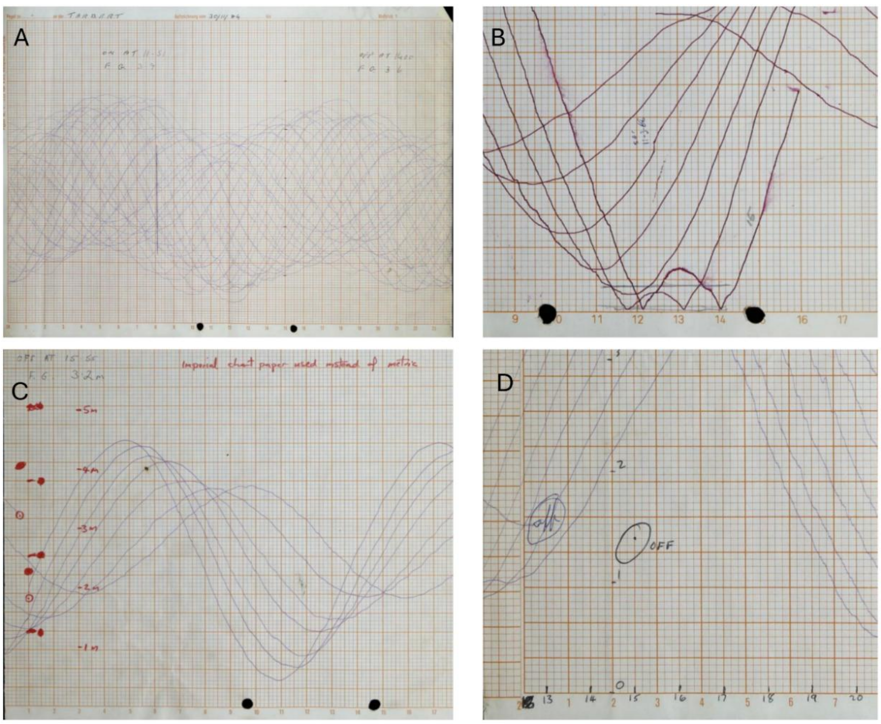

Figure 3. Examples of marigrams requiring careful digitization: A) A Tarbert marigram spanning nearly one month, making accurate digitization nearly impossible. (B) Daily low tides intercepting or approaching the X-axis, requiring manual correction. (C) Variations in graph paper type and unit scaling, with conversion factors indicated (e.g., one metre = four or 3.2 grid boxes). (D) Visible timing offsets requiring alignment corrections based on handwritten X-axis annotations. Data courtesy of the OPW (personal communication, 2024).

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The Tarbert dataset presented significant challenges, particularly timing offsets and related errors. Traces at the beginning or end of marigrams were occasionally discarded if severely misaligned with the hourly grid, even when the opposite end aligned correctly. Testing marigrams from 1964 and 1965 revealed deviations from the correct hourly intervals; however, the mean offset per marigram was typically within 1 cm.

Marigrams from the 1960s and 1970s often exhibited low tides that touched or nearly touched the X-axis before rebounding upward (Figure 3B). In these cases, manual correction was applied: the difference between the rebound peak and the base point on the X-axis was measured and subtracted to improve tidal estimates. This issue was absent after 1979, when data were digitized in metres relative to Ordnance Datum Dublin (ODD) rather than feet. On imperial chart paper, one metre was represented by four grid boxes, whereas on metric chart paper, the spacing of the grid resulted in roughly 3.2 boxes per metre (Figure 3C). This difference reflects the design of the chart grids, not a scaling error.

Timing offsets between the recorded hour and the digitized hourly grid occasionally caused recorded times to deviate by up to ~30 minutes (Figure 3D). Analysis of each marigram showed that the corresponding mean water-level offset remained well within 20 mm, within the allowable margin between digitization and instrumentation. Because MSL is computed as a temporal average over the full tidal cycle, these temporal misalignments have a negligible effect on MSL calculations, rendering the dataset suitable for MSL analysis.

The tidal images were generally of excellent quality and were digitized using WebPlotDigitizer (Rohatgi, 2024). Although some manual adjustments were necessary where handwritten notes or other anomalies occurred, most of the data—despite bends in the images—could be digitized directly without employing the grid or reduced grid method described by McLoughlin et al. (2024). The digitization process itself introduced an uncertainty of approximately 1 cm; however, accounting for additional factors such as timing offsets and necessary adjustments, an overall uncertainty of ±2 cm was assigned to the Tarbert dataset. For Tarbert, nearby Kilrush Lough data (2018–2024) were incorporated into the record to provide modern observations, owing to the close proximity and similar tidal characteristics.

3.0 Datum Conversions

For all sites, sea-level data were adjusted to Ordnance Datum Malin (ODM). Records reported relative to Ordnance Datum Belfast (ODB) or Ordnance Datum Dublin (ODD, i.e., OD Poolbeg) were converted to ODM.

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For Malin Head, the PSMSL Revised Local Reference (RLR) data were first converted from millimetres to metres. The standard PSMSL RLR datum offset of 3.977 m was applied, followed by an additional datum correction of 3.136 m based on Office of Public Works (OPW) OD Malin datum information valid up to 2018. The commonly cited Malin Head benchmark offset of 3.06 m was not used, as it aligns the series only to the local benchmark and not fully to the national OD Malin vertical datum. These corrections, with a total adjustment of 7.113 m, align the RLR series with both the local tide-gauge benchmark and the OD Malin datum, bringing the data accurately to ODM.

In Belfast, the standard datum of −2.01 m (National Tidal and Sea Level Facility, 2025) brings data from Chart Datum (CD) to OD Belfast (ODB). To convert from ODB to Ordnance Datum Malin (ODM), an additional 0.037 m was applied, reflecting the average difference between Malin Head and Belfast (Prendergast, 2004). For Portrush, 8.600 m, with an additional 1.604 m and 0.037 m, was added to reference ODM. Similarly, Bangor data were adjusted by subtracting 10.500 m, adding 3.582 m, and adding 0.037 m to convert to ODM.

To the east of Ireland, the Dún Laoghaire sea-level data were adjusted following McLoughlin et al. (2024). The local datum of 2.722 m, minus the chart datum of 1.75 ft (0.533 m), results in a 2.189 m correction to convert the data to Ordnance Datum Malin (ODM). This correction is applied to all available Dún Laoghaire records. Similarly, the Dublin Port PSMSL data (1938–2000) were converted to ODM using benchmark adjustments: subtracting 6.017 m from 10.594 m below the primary benchmark (BM, TGZ 1978), adding 0.238 m (difference between BM 1895 and TGZ port datum 1977), subtracting 0.436 m (1938–1977 relative to Port Datum, 0.436 m above Poolbeg OD), and adding 2.722 m (Dún Laoghaire datum). These steps resulted in a final correction of 7.101 m, applied to bring the PSMSL data to m_ODM.

All Cork data were adjusted to Ordnance Datum Malin (ODM) following the procedure outlined below. Historic records at Tivoli and Monkstown, originally tied to Ordnance Datum Dublin (OD), were converted to ODM using the 2.752 m datum established by Pugh et al. (2021), which links ODD values to ODM through nearby benchmark levelling. Prior to conversion, site-specific adjustments were applied:

- For the 1970s Tivoli records, a correction of +0.174 m (0.57 ft) was applied based on contemporary notes (Figure 4A).

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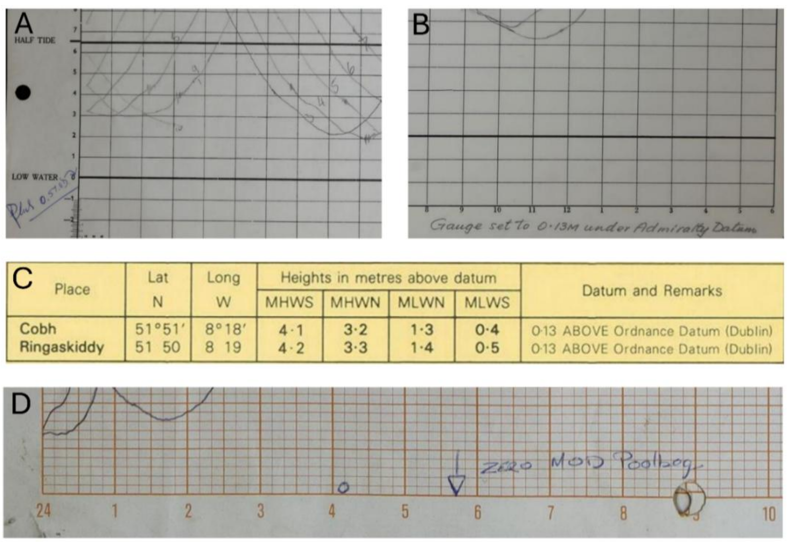
- For the 1980s Tivoli data, a correction of –0.13 m was applied, consistent with gauge documentation indicating the instrument was set 0.13 m below Admiralty Datum; this offset provided the best alignment with regional tide records (Figure 4B).

Modern Tivoli data from the early 2000s were adjusted by +0.13 m to bring values to OD, following recommendations from the UK National Tidal and Sea Level Facility (Irish Water, 2005) (Figure 4C). After these corrections, all Cork datasets were successfully adjusted to ODM.

In the absence of a site-specific datum for Tarbert, the records indicate that the data are assumed to be referenced to ODD (Ordnance Datum Poolbeg; Figure 4D). Using this assumption, nearby datums were considered: Shannon is 2.705 m above ODD and Ballybunion is 2.704 m above ODD (OPW, personal communication, 2024). Based on this consistency, a correction of 2.705 m was applied to convert the Tarbert data to m_ODM.



C Place	Lat N	Long W	Heights in metres above datum MHWS	MHWN	MLWN	MLWS	Datum and Remarks
Cobh	51°51′	8°18′	4·1	3·2	1·3	0·4	0·13 ABOVE Ordnance Datum (Dublin)
Ringaskiddy	51 50	8 19	4·2	3·3	1·4	0·5	0·13 ABOVE Ordnance Datum (Dublin)

Figure 4. Datum adjustments applied to Cork (Tivoli) and Tarbert sea-level records at different periods: (A–C) Tivoli data—(A) 1970s corrected by +0.174 m (0.57 ft), (B) 1980s corrected by −0.13 m, consistent with gauge documentation and regional tide alignment, (C) early 2000s adjusted by +0.13 m to Ordnance Datum (Irish Water, 2005); (D) Tarbert records shown relative to ODD (0 m, OD Poolbeg). Note: 1964–1977 data were originally in feet relative to OD Poolbeg. (A–B, courtesy of Port of Cork engineers, personal communication, 2022; C, Irish Water, 2005; D, data courtesy of the OPW, personal communication, 2024.)

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For Galway, the Galway Harbour datum used to convert data from ODD to ODM is 2.732 m (OPW, personal communication, 2024). BODC data for Galway, adjacent to Galway Harbour, show that the 1967 and 1968 records were reported in metres relative to ODN and can be directly referenced to ODM by subtracting 2.732 m. In contrast, the 1969 and 1970 records, also reported in metres, appeared higher than the 1967 and 1968 values. Metadata indicate that these records required a 3.048 m adjustment to align with the benchmark (TGZ; Table 1). After applying this adjustment, the 2.732 m datum was subtracted to reference all values to ODM.

Table 1. BODC metadata table showing datum relationships for Galway (BODC, 2025). Values from 1967–1968 are aligned with ODM (0.000 m offset). For 1969–1970, TGZ was −3.048 m; subtracting 3.048 m aligns these years with the earlier records.

Galway (Eire) Site History

Full site history and benchmark not yet available.

Datum Information

Year	Data rel to ACD	Data rel to ODN	Data rel to TGZ	TGZ rel to ODN	TGZ rel to TGBM	ACD rel to ODN
1967	0.201	0.000	0.000	0.000	not available	-0.201
1968	0.201	0.000	0.000	0.000	not available	-0.201
1969	-2.847	-3.048	-3.048	0.000	not available	-0.201
1970	-2.847	-3.048	-3.048	0.000	not available	-0.201

All modern sea-level data from the NTGN (OPW and MI) for the available sites were already fully referenced to Ordnance Datum Malin (ODM).

4. Validation of Tide Gauge data

All sea-level datasets underwent rigorous validation prior to inclusion in the MSL analysis. Monthly means for all non-PSMSL datasets were recomputed using the oce package (Kelley et al., 2022), ensuring consistent processing across the network. M2 tidal amplitudes and phase lags were calculated for all high-resolution datasets where temporal resolution allowed. Statistical outlier detection was systematically applied across all sites by removing values exceeding ±3 standard deviations from the mean. Both M2 tidal constituents (amplitudes and phase lags) and z_0 (mean sea level) values were examined to identify and flag poor-quality observations, ensuring that all datasets incorporated into the MSL analysis were robust.

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4.1. Validation of Tide Gauge Data: Historical and Modern Records

For the Belfast record, 1925 was chosen as the starting point instead of 1901–1902, providing a 100-year overlap with the Dublin (Dún Laoghaire) record. The tidal record (Murdy et al., 2015; Figure 5) was generally consistent from 1925 to 1988, with M2 tidal amplitudes within ±0.1 m of 1.2 m and phase lags mostly between 325° and 326°. In contrast, the period 1989–2000 contained a higher proportion of poor-quality and missing data, which may have affected measurements associated with tide gauge 4 (TG4) operations at Milewater Basin during harbour redevelopments. However, after omitting poor-quality or missing data, the dataset for this period was generally of good quality. Timing offsets were also identified and, where possible, corrected by adjusting certain years by one hour in specific months to improve temporal consistency.

The Bangor record (2011–2015; Figure 5) was used to fill gaps in the Belfast dataset due to the proximity of the stations. Months with M2 tidal amplitudes exceeding 1.2 m by more than 0.1 m were removed. Statistical outlier detection further excluded monthly means exceeding three standard deviations from the overall mean, identifying December 1985 and February 1990 as outliers. Although no individual month in 1985 exceeded the 3-SD threshold, the annual mean was ~0.2 m above all other years, indicating data quality issues; consequently, 1985 was excluded from further analysis.

The Malin Head record contains known data issues in the early 1990s (1992–1993), as documented by PSMSL. Hogarth et al., (2020) suggested that the Portrush record could serve as a more robust replacement for portions of the Malin Head data. Specifically, all of 1993 and the last three months of 1992 (October–December) were omitted from the Malin Head record, and Portrush data were used for 1996–2003 and 2015. Modern NTGN data for Malin Head (OPW, 2004–2008; MI, 2009–2024) completed the record. After removing the end of 1992 and 1993, statistical outlier detection was applied to further validate the data, excluding monthly mean values exceeding three standard deviations from the overall mean. This led to the removal of February 1990 and April 2024. The verified Malin Head record is shown in Figure 5.

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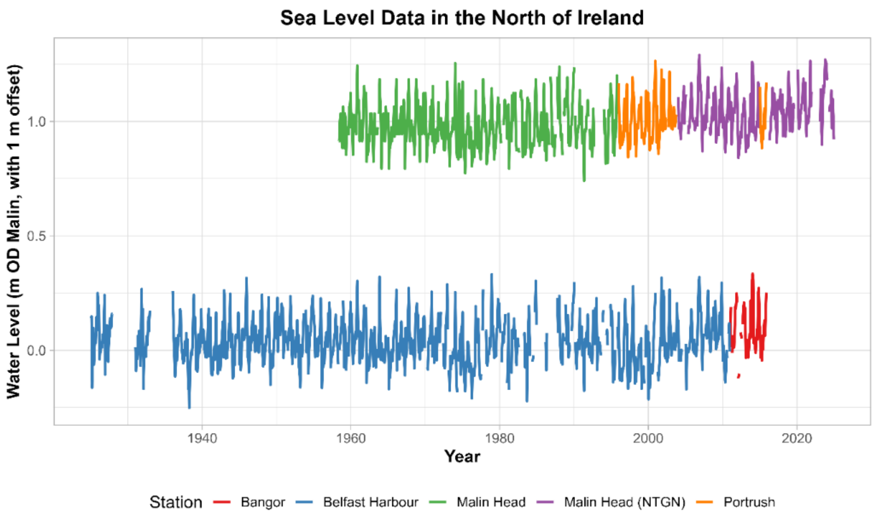

Figure 5. Mean Sea Level (MSL) for Northern Ireland tide gauges. Belfast and Malin Head have been offset by 1 m for clarity. All data are referenced to Ordnance Datum Malin (ODM). Bangor and Portrush records were used to supplement Belfast and Malin Head.

The Dublin Port tide gauge on the east coast (PSMSL, 1938–2001) exhibits unusual variations from the 1970s to early 1990s (Shoari Nejad et al., 2022). The timeseries for 1938–2001 is shown in Figure 6. Statistical outlier detection identified several potentially erroneous mean sea-level months—November 1960, July and December 1989, February and November 1990, and December 2000—which were subsequently removed from the analysis.

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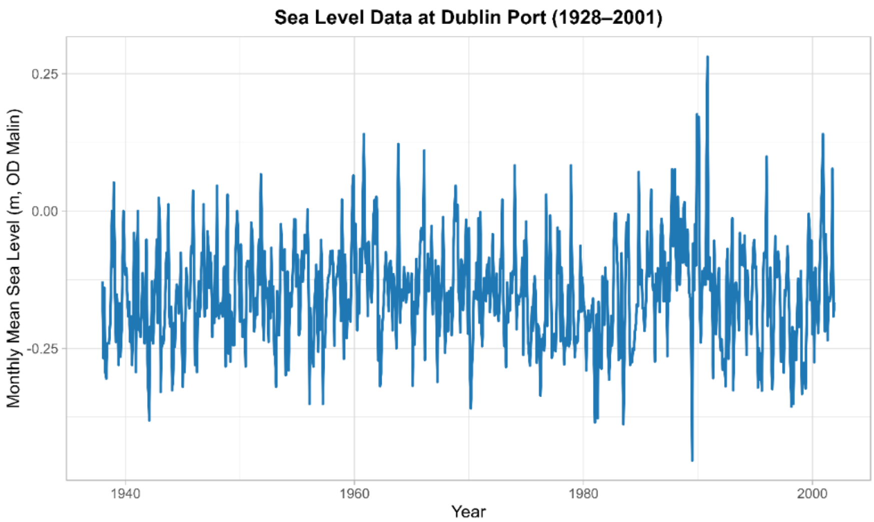

Figure 6. Monthly mean sea-level measurements at Dublin Port (1938–2001), highlighting periods with consistently lower or higher monthly means, particularly from the mid-1970s to early 1990s.

Digitized Dún Laoghaire data for June–August 1932 and 1933 were of good quality, with amplitudes of 1.25 m and phase lags of 326.7° (1932) and 324.6° (1933), closely aligning with McLoughlin et al. (2024). No monthly mean exceeded three standard deviations from the overall mean.

To construct a near-continuous century-long record, modern sea-level data from NTGN OPW Arklow (2003–2006) and MI Howth (2007–2024) were integrated with the historical Dún Laoghaire (1925–1933) and Dublin Port (1938–2001) datasets. Monthly means were largely consistent across the combined series, with only July 2024 from Howth omitted due to a deviation exceeding three standard deviations from the mean.

For the south-west coast, the Cork dataset required several adjustments during validation, including computation of M2 amplitudes and phase lags. At Monkstown, only 1976 had a phase lag (153.1°) within the expected 144.4–154.1° range (Pugh et al., 2021). Tivoli initially showed phase lags of 167–175°, indicating a systematic DST-related offset, which was corrected by shifting timestamps back 1 h during late-March to October periods. Post-correction, Tivoli phase lags ranged ~150.9–153.8°, closely matching reference values. Only November and December 1982 were excluded, as their amplitudes fell outside the expected ~1.37–1.49 m range.

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Modern Tivoli data (2001–2005, 2010–2011) generally agreed in amplitude (~1.37–1.49 m) and phase lag (~150.3°–160.2°). Outliers included 2001 (>185° phase lag) and slightly elevated 2002/2005 phase lags (~165.4°/162.5°), which were retained because their amplitudes fell within the expected range after exclusion of poor-quality months, leaving MSL unaffected.

NTGN OPW Ringaskiddy (2012–2021) and Currach Club (2022–2024) data were incorporated to further complete the Cork record. M2 amplitudes ranged ~1.40–1.49 m and phase lags ~144.6°–152.2°, consistent with Monkstown and Tivoli.

After initially checking the M2 amplitudes and phase lags to address any poor-quality data in the Tivoli and Monkstown datasets, and performing statistical outlier detection on all data up to 2024, no further potentially erroneous observations were identified, with all monthly means remaining within three standard deviations of the overall mean. The rectified Cork dataset is shown in Figure 7.

To assess tidal characteristics in the south-west of Ireland, two nearby sites, Tarbert and Kilrush Lough, were compared. Tarbert exhibited M2 amplitudes of ~1.55–1.66 m with phase lags of ~145.9°–156.2°, while Kilrush Lough (NTGN MI modern data, 2018–2024), located less than 11 km across the estuary, showed amplitudes of ~1.48–1.64 m and phase lags of ~144.6°–147.8°. Individual months or years with amplitudes outside these ranges were excluded from the analysis.

Prior to direct comparison, the Tarbert dataset (1964–1986) exhibited systematic timing offsets, including a recurring one-hour discrepancy between late March and October, consistent with uncorrected daylight saving time (DST), and a persistent one-hour offset from 1968 to 1970 due to missing DST adjustments. Timestamps were corrected by shifting back one hour during DST periods and for the full years 1968–October 1971, resulting in the exclusion of approximately one hour of data per year.

Data from 1984–1986 were omitted because M2 amplitudes consistently fell below the expected range of 1.55–1.66 m, reaching 1.3–1.50 m; the corrected Tarbert time series is shown in Figure 7. For Kilrush Lough, three months in 2024 (February, September, and October) were omitted following M2 corrections and statistical outlier detection.

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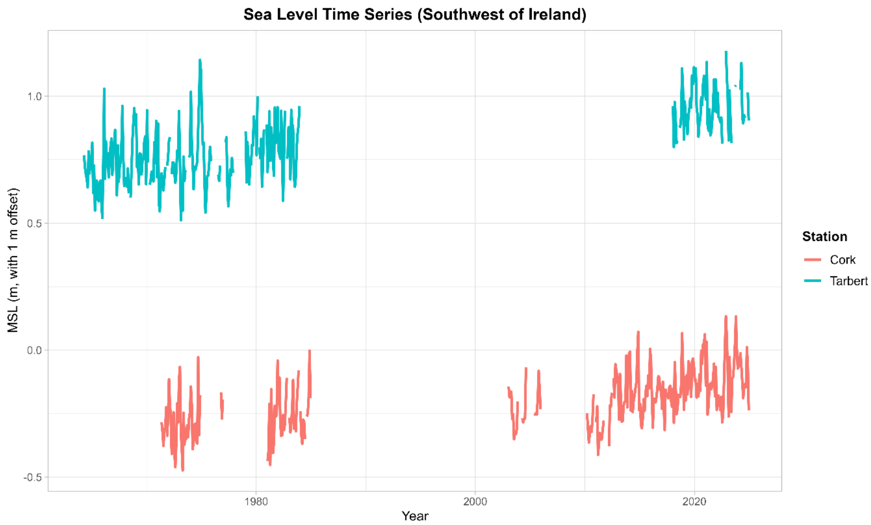

Figure 7. Sea-level data for Tarbert (1964–1983), Kilrush Lough (2018–2024), and Cork sites—including Tivoli (1970s–1980s and 2000s), Currach Club, and Ringaskiddy—adjusted to Ordnance Datum Malin (ODM) and vertically offset by 1 m for clarity.

In western Ireland, the Galway record was assessed using both historical and modern datasets. The BODC data from Galway (1967–1970) were largely complete, with only a few hours missing on select days in 1968 and 1970; these were flagged as unreliable and excluded from the analysis. Modern Galway Port data (2007–2024) were supplemented with NTGN MI observations to fill gaps and ensure continuity in the historical record. Comparison of tidal harmonics between the 1967–1970 BODC dataset and modern Galway Port observations revealed only minor differences. M2 tidal amplitudes are slightly higher in the modern record (~1.46–1.59 m) than in the BODC data (~1.45–1.48 m), and phase lags differ slightly (~137.2°–142.3° vs. ~126.4°–128.8°), but overall the values remain in close agreement.

A summary of all tide gauges for which data were omitted due to poor quality and where supplementary data were incorporated is provided in Table 2.

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Table 2. Summary of tide gauges with data omitted due to poor quality and where supplementary data were incorporated. Note: Years with fewer than three consecutive monthly observations were automatically discarded and may not all be explicitly listed.

Tide Gauge	Years/Months Omitted	Quality Issue	3-SD Outlier Detection Across Intervals	Supplement and Replacement Data
Malin Head	Feb 1990; Oct–Dec 1992 and 1993 omitted; 1996–2003 and 2015 replaced with Portrush data; Apr 2024 omitted (from 2003-2024 MI/OPW data). Portrush: Dec 2015.	Poor-quality data in the early 1990s; z_0 values exceeding three standard deviations from the mean.	PSMSL Malin Head (1958–2002); OPW Malin Head (2003–2008); MI Malin Head (2009–2024); Portrush (1996–2015).	Portrush PSMSL 1996–2003 and 2015; Malin Head OPW and MI 2003–2024.
Belfast Harbour	1985; Feb 1990; Dec 2015.	Amplitudes outside ±0.1 m of the M2 amplitude (1.2 m); z_0 values exceeding three standard deviations from the mean; potential datum control issues.	Belfast Harbour (1925–2010; outliers removed first); supplemented with Bangor (2011–2015) for final combined outlier detection.	Bangor PSMSL substituted for 2011–2015.
Dublin	Nov 1960; Jul and Dec 1989; Feb and Nov 1990; Dec 2000; Howth Jul 2024 (large spike, 3 SD from mean); Arklow Nov 2022 (used only to adjust Howth baseline in full record).	Monthly means (z_0) deviating by more than three standard deviations from the mean.	Dún Laoghaire (1925–1933); PSMSL Dublin Port (1938–2001); Arklow (2003–2006 used for MSL analysis; full 2003–2024 used for Howth offset correction); Howth (2007–2024).	Dún Laoghaire 1925–1933; Arklow 2003–2006 (full 2003–2024 used to compute Howth-baseline offset, but only 2003–2006 included in MSL analysis); Howth 2007–2024.
Cork (Tivoli)	1982 (Nov–Dec); 2001 (Jun–Sep); 2002 (Mar, Oct–Dec); 2004 (Mar); 2010 (Feb, Nov–Dec).	Monthly M2 amplitudes outside the yearly ranges were excluded: Tarbert 1.55–1.66 m; Kilrush Lough 1.48–1.64 m.	Due to the close proximity and similar tidal amplitudes, all stations were checked together.	Ringaskiddy 2012–2021; Currach Club 2022–2024.
Tarbert	1974 (Nov); 1976 (Oct, Nov); 1977 (Jun); 1978; 1979 (Jan–Feb); 1982 (Jan); 1984–1986. Kilrush Lough: Feb, Sept, and Oct 2024.	Monthly means causing yearly amplitudes to fall outside the ranges: Tarbert 1.55–1.66 m; Kilrush Lough 1.48–1.64 m.	Due to the close proximity, all data were checked together.	Kilrush 2018–2024.
Galway	1968–1970 (selected hours on some days omitted).	Unreliable data at Galway.	All data were checked together due to close proximity.	Galway Harbour 2007–2024.

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4.2. Modern Tide Gauge Data: Quality and Corrections

Modern tide gauges still produce raw records that may contain inaccuracies and require validation (Aarup et al., 2019). All modern datasets accessed from the NTGN (MI and OPW) included quality flags indicating good, poor, or cautionary data. The absence of a "good" flag does not necessarily imply that the data are erroneous; rather, it indicates that the data should be treated with caution. Independent quality checks were conducted, including computation of M2 tidal constituents and comparison with co-located records where available. Monthly mean outliers exceeding three standard deviations from the mean were identified and removed from each tide-gauge record.

A consistent datum offset between the overlapping Arklow and Howth series, likely due to geoid model differences, was quantified using the mean monthly discrepancy over the overlap period (2007–2024). This offset was applied to the full Arklow series (2003–2024) to align it with the Howth datum. Two outliers in the Arklow 2007–2024 portion—November 2022 and May 2024—exceeding three standard deviations from the mean—were removed. Only the 2003–2006 observations were used in the present analysis, with no outliers within this interval. The corrected Arklow series (2003–2006) was then employed to extend the Dublin Port record into the early 2000s. Following these procedures, all modern NTGN observations used in this study—including the previously uncovered Tivoli (Cork) data from the early 2000s—met quality and consistency criteria (Figure 8).

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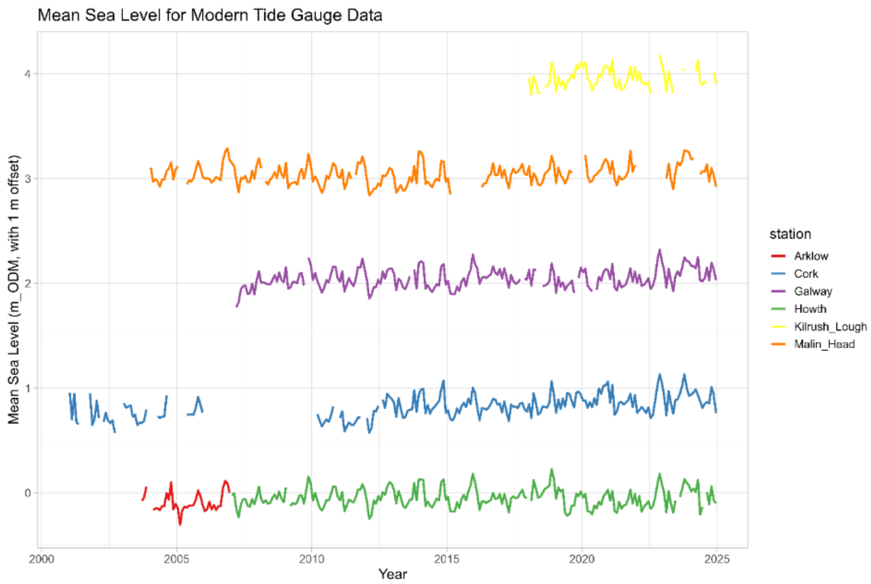

Figure 8. Tide-gauge records (2000s) for Arklow, Howth, Galway, Kilrush Lough, and Malin Head. Series are vertically offset by 1 m for clarity, except Arklow and Howth, which are shown together after applying a fixed datum offset to align them.

As a final validation, to ensure the Dublin Port dataset aligns with the modern Arklow and Howth datasets, comparison with Shoari Nejad et al. (2022) shows a mean difference of 0.021 m and a standard deviation of 0.017 m. No obvious jumps were observed, with a maximum year-to-year difference of 0.071 m, indicating no datum issues.

4.3. Data Quality Control and Standardization

To ensure methodological consistency, only hourly intervals were extracted from modern datasets. Following standard validation practices, months were excluded from monthly averages if the total number of days that were either fully missing or had more than four missing hours was 15 days or greater. PSMSL records were exempt, as they are already provided as monthly means. This approach is consistent with recommendations from the UK National Tide Gauge Network, where monthly mean sea level values are not computed for months with more than 15 missing days, and gaps exceeding ~4 hours in the primary channel are treated as missing when calculating daily averages (UK Coastal Monitoring and Forecasting [UKCMF], 2014).

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5. Data Processing and Sea-Level Modelling

5.1. Atmospheric Adjustments

In the processing of the MSL data, two reanalysis products were used to correct for atmospheric effects: the NOAA/CIRES/DOE 20th Century Reanalysis Version 3 (20CRv3; NOAA PSL, 2025; Slivinski et al., 2019) and ERA5 (Copernicus Climate Change Service, 2025). These corrections, including surface pressure and wind forcing, reduce high-frequency atmospheric variability and facilitate the identification of long-term trends in MSL.

20CRv3 provides a continuous record from 1806 to 2015 at 1° spatial resolution, making it well suited to historic tide gauge records such as Belfast (from 1925). Its extended temporal coverage and assimilation of historical observations allow long-term variability and trends to be assessed. However, the dataset terminates in 2015.

To cover the modern period, ERA5 was employed. ERA5 extends from 1940 to the present, with higher resolution (0.25°). Although not appropriate for pre-1940 applications, it is particularly valuable for correcting contemporary tide gauge data.

From both datasets, ocean surface pressure fields were used to compute anomalies, and 10 m u- and v-component winds were extracted for wind stress calculations. Land–sea masks were applied using the native mask from 20CRv3 and the ERA5-Land monthly product (Copernicus Climate Change Service, 2025). Together, these complementary reanalyses provide the atmospheric forcing fields required to correct both historic and modern records.

Atmospheric pressure contributions to the observed sea-level records were accounted for using monthly-mean surface pressure fields from the NOAA/CIRES/DOE 20th Century Reanalysis Version 3 (20CRv3; 1806–2015, 1° resolution) and ERA5 (1940–present, 0.25° resolution). Together, these datasets provide the historical (pre-1940) and modern (post-1940) coverage required for consistent atmospheric correction of tide-gauge records.

Surface pressure anomalies were calculated following Frederikse & Gerkema (2018). Land points were masked using the native land–sea mask of each dataset, setting pressure values over land to missing. This ensures that anomalies reflect oceanic pressure variations relevant to sea-level changes near tide-gauge stations, avoiding contamination from continental pressure variations.

To remove the global atmospheric mass signal and isolate local variability, a latitude-weighted global mean surface pressure was computed at each time step (Eq.1):

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$$P_{global}(t) = \frac{\sum_i P_i(t)\cos\varphi_i}{\sum_i \cos\varphi_i} \qquad (1)$$

where P_i(t) is the pressure at ocean grid point i and φ_i is its latitude. The cosine weighting accounts for the decreasing area of grid cells toward the poles, ensuring that the global mean accurately represents the mass-weighted atmospheric signal rather than a simple arithmetic mean.

The resulting surface pressure anomaly at each ocean grid point is given by (Eq.2):

$$P'_i(t) = P_i(t) - P_{global}(t) \qquad (2)$$

After removing the global atmospheric signal, the pressure anomalies were averaged locally around each station to represent site-specific conditions, before computing wind stress and applying the regression model.

For each tide-gauge station, the local pressure anomaly was calculated by averaging all ocean grid points within a 1° radius (20CRv3) or within ±0.25° (ERA5), ensuring that the anomaly represents the local conditions near each station. This ensures that the anomaly represents local atmospheric forcing conditions relevant to each tide-gauge site.

Concurrent 10 m zonal (u) and meridional (v) wind components were extracted from the same reanalysis fields and converted to wind stress. Wind speed magnitude was first computed using (Eq.3):

$$|U| = \sqrt{(u^2 + v^2)} \qquad (3)$$

The drag coefficient C_D was parameterized following Smith (1980) (Eq.4):

$$C_D = \begin{cases} 0.001 & if \ |U| < 7.5\ m/s \\ 0.00061 + 0.000063\,|U| & if \ |U| \geq 7.5\ m/s \end{cases} \qquad (4)$$

Wind stress components were subsequently calculated using (Eq.5):

$$\tau_x = \rho_{air}\, C_D\, |U|\, u, \qquad \tau_y = \rho_{air}\, C_D\, |U|\, v \qquad (5)$$

where $\rho_{air} = 1.225\ \mathrm{kg}m^{-3}$ is air density. This formulation ensures that both the magnitude and direction of the wind stress vector are physically consistent with the combined u- and v-components of the wind.

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Atmospheric corrections were applied by fitting a multiple linear regression model to the observed monthly sea-level records at each station (Eq.6):

$$\mathrm{WaterLevel(t)} = \beta_0 + \beta_1 P'(t) + \beta_2 \tau_x(t) + \beta_3 \tau_y(t) + \beta_4 \sin\left(\frac{2\pi t}{365.25}\right) + \beta_5 \cos\left(\frac{2\pi t}{365.25}\right) + \beta_6 \sin\left(\frac{2\pi t}{183.63}\right) + \beta_7 \cos\left(\frac{2\pi t}{183.63}\right) + \varepsilon(t) \quad (6)$$

Here, t is time in days since the start of the record. β_0 is the intercept. β_1–β_3 are the coefficients for the atmospheric terms: β_1 corresponds to the pressure anomaly $P'(t)$, β_2 to the zonal wind stress $\tau_x(t)$, and β_3 to the meridional wind stress $\tau_y(t)$. β_4–β_5 are the coefficients for the annual harmonic (sin and cos terms), and β_6–β_7 are the coefficients for the semiannual harmonic (sin and cos terms), which are included if statistically significant. ε(t) is the residual representing the portion of sea-level variability not explained by the model.

At some tide-gauge stations, correlations between observed water level and atmospheric predictors (pressure anomaly $P'_i(t)$, $\tau_x(t), \tau_y(t)$) were weaker than at others. These differences reflect variations in local geography, coastal orientation, and sheltering from prevailing winds (Pugh & Woodworth, 2014). Predictors that were weak in their simple correlation or statistically insignificant in the multiple regression ($p > 0.05$) were omitted from the final model. In a few cases, terms that were marginally non-significant in the regression or weak in simple correlation were retained at specific sites—such as the semiannual harmonic at Dún Laoghaire and Galway, which slightly improved R^2—where they represented physically meaningful seasonal effects, ensuring that the model captured known local variability in water level. Importantly, a weak simple (Pearson) correlation does not imply that a predictor is unimportant in a multivariate regression. For example, τ_x exhibits negligible correlation with water level at some sites, yet remains statistically significant when included alongside atmospheric pressure and $\tau_y(t)$ because it explains variance conditional on those predictors. Consequently, all predictors that were statistically significant in the multiple regression were retained (Table 3).

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Table 3. Regression terms included in atmospheric corrections for each tide-gauge site. Legend: Included = term included in the final regression; Omitted = term not included in the regression.

Site	$P'_i(t)$	$\tau_x(t)$	$\tau_y(t)$	$\sin\left(\frac{2\pi t}{365.25}\right)$	$\cos\left(\frac{2\pi t}{365.25}\right)$	$\sin\left(\frac{2\pi t}{182.63}\right)$	$cos\left(\frac{2\pi t}{182.63}\right)$	Notes / Supplement
Malin Head	Included	Included	Included	Included	Omitted	Included	Omitted	–
Portrush	Included	Included	Included	Included	Included	Included	Omitted	Supplement to Malin Head
Belfast	Included	Included	Included	Included	Included	Included	Omitted	Supplemented by Bangor data
Dublin Port	Included	Included	Included	Included	Omitted	Included	Omitted	–
Howth	Included	Omitted	Included	Included	Included	Included	Omitted	Supplement to Dublin Port
Arklow	Included	Omitted	Included	Included	Omitted	Omitted	Omitted	Supplement to Dublin Port
Dún Laoghaire	Included	Omitted	Omitted	Included	Included	Included	Omitted	Supplement to Dublin Port
Cork	Included	Included	Included	Included	Included	Included	Omitted	–
Tarbert	Included	Included	Included	Included	Included	Omitted	Omitted	Supplemented by Kilrush Lough data
Galway	Included	Omitted	Included	Included	Included	Included	Omitted	Supplemented by Galway Port data

To assess the effect of atmospheric adjustments on tide-gauge records, the mean and standard deviation (SD) of both the original and atmosphere-adjusted water levels were computed. These metrics provide a quantitative measure of the sub-annual variability removed by the regression model. Results for all stations are summarized in Table 4. The atmospheric correction consistently reduced variability across all tide-gauge sites, as indicated by decreases in SD, demonstrating successful removal of pressure- and wind-driven effects. Changes in the mean water level were generally small, reflecting the removal of atmospheric contributions, with slightly larger adjustments observed at Dublin Port.

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Table 4. Mean and standard deviation of observed and atmosphere-adjusted monthly mean sea levels at all tide-gauge sites. SD = standard deviation.

Site	Mean Water Level OD Malin (m)	SD Water Level (m)	Mean Atmosphere-Adjusted (m)	SD Atmosphere-Adjusted (m)
Malin Head	0.00	0.10	-0.01	0.05
Belfast	0.04	0.10	0.040	0.05
Portrush	0.01	0.09	-0.02	0.03
Dublin Port	-0.15	0.09	-0.20	0.05
Howth	-0.05	0.09	-0.10	0.05
Arklow	-0.09	0.09	-0.12	0.02
Dún Laoghaire	-0.20	0.08	-0.18	0.05
Cork	-0.20	0.12	-0.18	0.08
Tarbert	-0.19	0.14	-0.20	0.12
Galway	0.03	0.10	0.00	0.06

Including the atmospheric pressure anomaly term enables the regression to capture the local expression of the inverted barometer effect, typically ~10 mm $mbar^{-1}$ (Pugh et al., 2021). The regression estimates site-specific sensitivity to atmospheric pressure and wind stress directly from observations. The resulting residuals represent sea-level variability with atmospheric effects removed. Figure 9 illustrates this atmospheric correction at Dublin Port, showing how the regression isolates true sea-level variability by removing the influence of pressure and wind stress.

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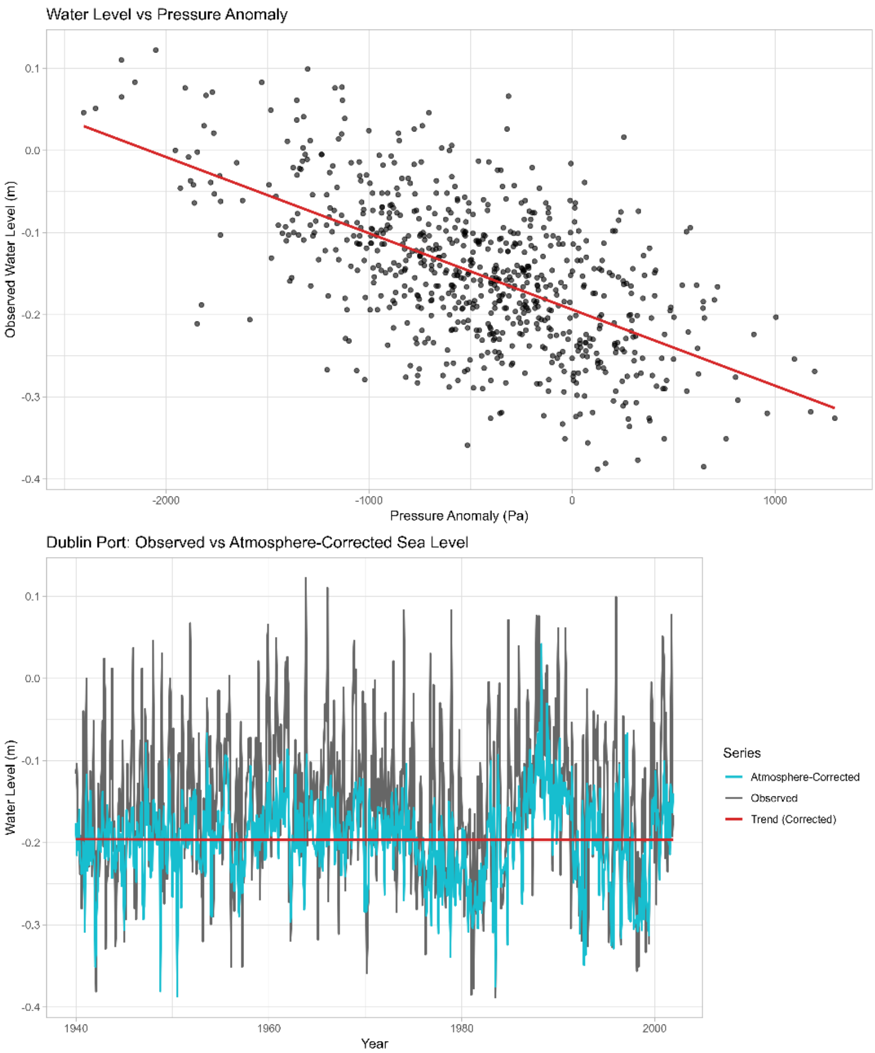

Figure 9. Atmospheric correction workflow at Dublin Port. Top: observed water level versus pressure anomaly, showing a strong negative correlation (r = -0.599, p << 0.001). Bottom: observed versus atmosphere-corrected water level, with a linear trend fitted. The regression removes atmospheric pressure effects, leaving residuals that reflect true sea-level variability.

5.2 Coordinate Selection for Atmospheric Adjustments

Atmospheric pressure corrections were applied selectively at tide-gauge sites across Ireland, depending on record length and data resolution. A strong relationship exists between sea level

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and atmospheric conditions (Johansson et al., 2022; Zubier & Eyouni, 2020), particularly between atmospheric pressure and sea-level variability (Pham et al., 2024; Dangendorf et al., 2024).

- Pre-1940 stations: Belfast (including Bangor) and Dublin Port (including Dún Laoghaire) were corrected using 20CRv3 (1° resolution), from which surface pressure and 10 m wind components were extracted. To account for coarse resolution near coastlines, all grid points within ±1° of each station were averaged to approximate local conditions. Record coverage: Belfast and Bangor (1925–2015), Dublin Port (1938–1939), Dún Laoghaire (1925–1933, merged with Dublin Port for 1938–1939).
- Post-1940 stations: Cork, Tarbert, Malin Head, Galway Port, Dublin Port, Arklow, Howth, and Portrush used high-resolution ERA5 (0.25°) for atmospheric correction. For each station, surface pressure and 10 m wind components were extracted from the ERA5 grid point previously identified as showing the highest correlation with the local sea-level record.

Atmospherically adjusted records from Dún Laoghaire (1925–1933) and Dublin Port (1938–2000) were tested for consistency. Linear trends for Dún Laoghaire (–0.00130 m yr^{-1}), Dublin Port (–0.000036 m yr^{-1}), and the combined record (–0.000041 m yr^{-1}) agree within uncertainty. Bootstrap slope-difference estimates (95 % CI: –0.000193 to 0.000205 m yr^{-1}) and segment–interaction tests ($p \approx 0.988$) indicate no significant site-specific differences. Accordingly, the Dún Laoghaire record was merged with Dublin Port with negligible effect on the long-term trend, enabling construction of a continuous Dublin series (Figure 10).

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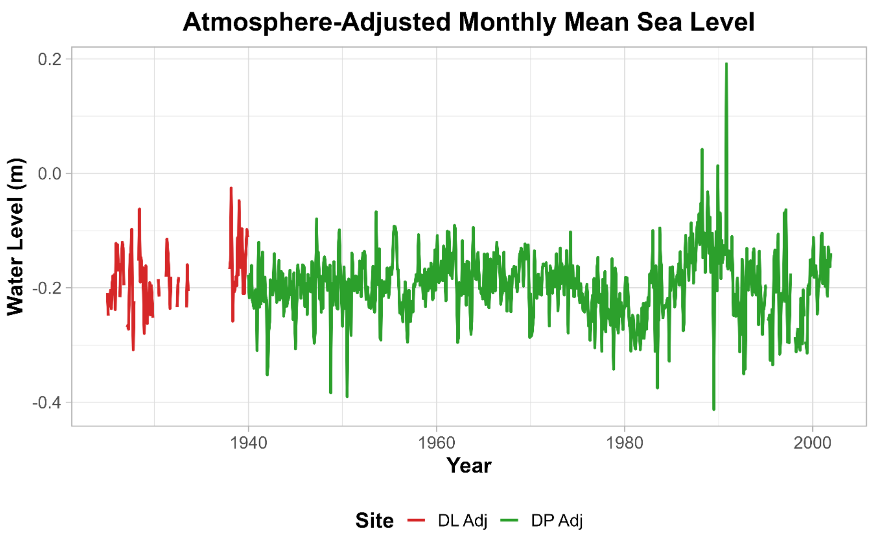

Figure 10. Time series of atmosphere-adjusted monthly mean water levels at Dún Laoghaire (DL Adj, red) and Dublin Port (DP Adj, green). There is no discontinuity between the 20CRv3 (DL Adj) and ERA5 (DP Adj) data. Atmospheric adjustments reduce high-frequency variability, emphasizing long-term sea-level trends.

Mean sea level (MSL) was then calculated over full years or using a minimum of 11 monthly mean values, following PSMSL (2025), to avoid spurious gaps. Years with fewer than three consecutive months of data were excluded.

5.3 GIA Corrections and Statistical Sea-Level Modelling

It is important to understand the role of Glacial Isostatic Adjustment (GIA) in shaping sea-level variability around Ireland, particularly due to regional differences between the northeast and southwest. To account for the isostatic component of vertical land motion (VLM), we applied corrections from 18 GIA models, including an ICE5G model and ICE6G variants (standard, BC hybrid, VM5a; Peltier, 2004, 2015), GLAC1D variants (BC hybrid, VM5a; Tarasov et al., 2012), and Bradley-type models (thick, thin, hybrid, North Sea; Bradley et al., 2011, 2023). These models differ in their ice-sheet history reconstructions, Earth rheology assumptions, and regional calibration approaches, resulting in variable predictions of uplift and subsidence across Ireland. By incorporating multiple GIA model families and variants, we account for

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structural uncertainty in vertical land motion, enabling robust estimation of absolute sea-level rise (with site-specific GIA removed) from tide-gauge records.

To evaluate the influence of Glacial Isostatic Adjustment (GIA) on relative sea-level (RSL) records, site-specific RSL data were corrected using 18 candidate GIA models, and the residual inter-site spread was computed for each model. The ICE-6G_hybrid_71p320 model produced the lowest spread and was selected as the optimal GIA correction based on this criterion (Figure 11). Differences among most models were small, although the ICE-5G model produced relatively large GIA rates at Malin Head and Belfast (~1.2–1.5 mm yr⁻¹). Overall, the impact of these variations on site-specific and national RSL rates was modest.

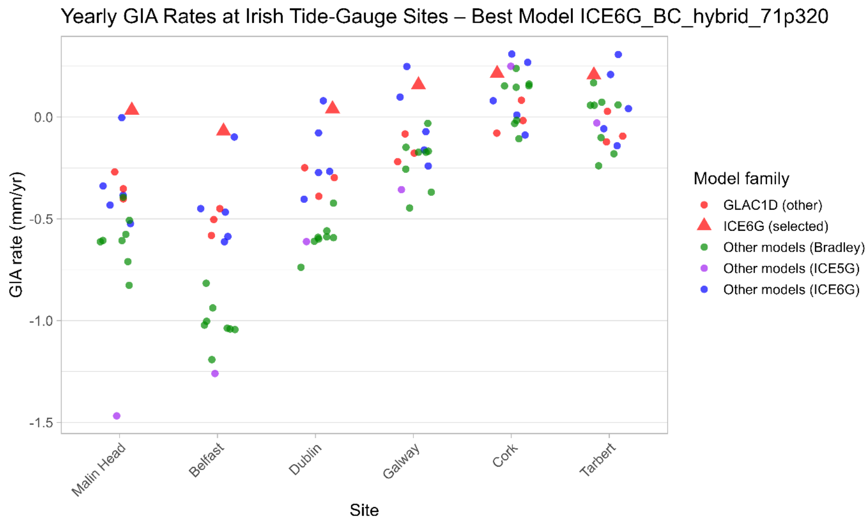

Figure 11. Yearly GIA rate corrections at six Irish tide-gauge sites. Red triangles indicate the selected ICE-6G BC_Hybrid_71p320 model among the other model families.

The longer timeseries extending back ~100 years often contain gaps, nonlinear fluctuations, and observational noise, requiring a more flexible approach. After applying atmospheric adjustments, nodal (18.6 yr) tidal-cycle effects (Pugh & Woodworth, 2014) were tested at Belfast, Dublin, and Cork—the only sites with sufficiently long, continuous records—and were found to alter long-term rates by <0.25 mm yr⁻¹, well below observational and model uncertainties. Because other sites were too short to resolve the nodal signal and its effect was negligible, nodal corrections were not applied in the final analysis.

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Long-term sea level variability was then modelled using the reslr package (Upton et al., 2024), which implements a Bayesian hierarchical framework with random effect terms, spline-based smooths, and spatio-temporal Generalised Additive Models (GAMs) to represent nonlinear trends. It accounts for measurement uncertainty in both sea level observations and corresponding age inputs using the Noisy Input method (McHutchon & Rasmussen, 2011), producing posterior distributions for sea level and its rates of change.

The relative sea-level (RSL) field was modelled using a non-linear mixed-effects Generalized Additive Model (NI-GAM; Upton et al., 2024) to account for long-term trends, site-specific deviations, and observational uncertainty (Eq.7):

$$y_{ij} = f(x_j, t_i) + \epsilon_y, \epsilon_y \sim N(0, \sigma^2 + s_{y_{ij}}^2) \quad (7)$$

where y_{ij} is the observed RSL at site j and time i, $f(x_j, t_i)$ is the underlying mean sea-level process, and ϵ_y is observation error.

The mean sea-level process was decomposed into regional and local components (Eq.8):

$$f(x,t) = r(t) + g(z_x) + h(z_x) + l(x,t) \quad (8)$$

where $r(t)$ is the regional component, $g(z_x)$ is a linear site-specific slope (e.g., GIA), $h(z_x)$ is a site-specific vertical offset, and $l(x,t)$ captures non-linear local spatio-temporal deviations. The regional term $r(t)$ was represented with cubic B-splines to capture long-term trends across all stations.

Site-specific GIA rates from the ICE-6G_hybrid_71p320 model were included as linear components in the NI-GAM decomposition. Here, “absolute” (GIA-free) rates refer to NI-GAM-derived rates with the site-specific linear GIA slope removed; they do not account for non-linear GIA components or other geophysical processes. Measurement uncertainty in both RSL and age inputs was incorporated using the Noisy Input method, yielding posterior distributions for RSL and its rates of change.

The NI-GAM decomposition separates the mean sea-level process into regional, linear local (e.g., GIA), vertical offset, and non-linear local components, capturing both long-term trends and site-specific deviations. This approach produces an integrated regional component synthesizing information from all sites, capturing overall rates of sea-level change over time as well as instantaneous rates and short-term variability that simple yearly linear regressions may overlook. It also resolves long-term accelerations that linear approaches cannot detect. The

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hierarchical framework allows sites with sparse or short records to leverage information from the full network of tide-gauge sites, improving estimates of long-term sea-level trends even where individual records are limited. Annual records were compiled with associated metadata (site, region, year, latitude, longitude). A conservative age uncertainty of 0.004 yr was assigned to reflect minimal dating imprecision, and a relative sea level error of 2 cm was applied to account for all instrumental, tide-gauge, and digitization uncertainties in the compiled datasets. Figure 12 shows all sites used as input in the reslr package. The linear rate of error was set to a default of 0.03 cm (0.3 mm yr^{-1}) which was the same as the rate used by Upton et al. (2024).

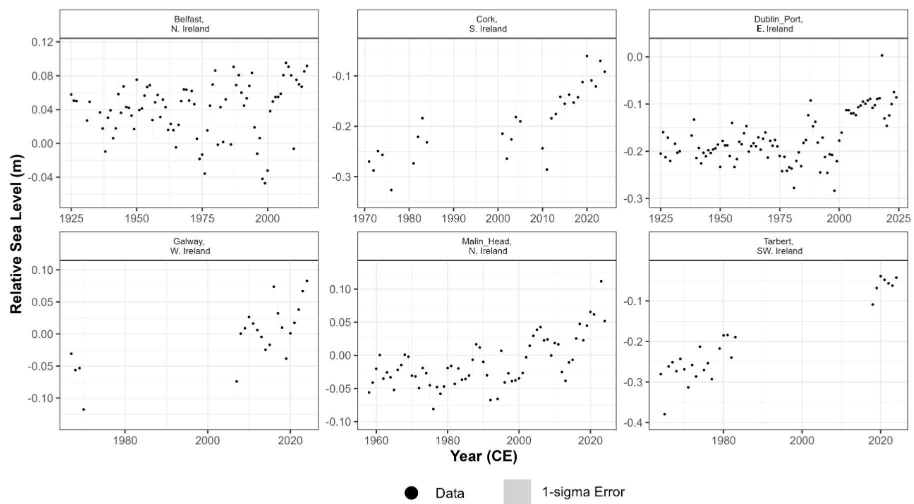

Figure 12. Tide-gauge sites used as input in the reslr package (datum: m_ODM). Annual relative sea-level records are shown for each site, illustrating the spatial coverage, record length, and gaps in the dataset.

The NI-GAM model was fitted using reslr_mcmc(), which performs Bayesian MCMC sampling of the posterior distributions for spline coefficients and random effects (Upton et al., 2024). The arguments spline_nseg_t = 3 and spline_nseg_st = 2 set the number of segments for temporal (regional) and spatio-temporal (local) B-splines, controlling the flexibility of the model in capturing nonlinear trends over time and space. Longer, more consistent datasets (>40 years) would ideally support spline_nseg_t = 4; however, a value of 3 better accommodates gaps in sparser records, especially at Galway, Cork, and Tarbert, providing a more robust fit.

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6. Model Validation

We assessed the predictive performance of the NI-GAM model using 10-fold cross-validation with the cross_val_check() function from the reslr package (Upton et al., 2024). Site-specific RSL records with Age ≤ 2025 were used, including site-specific linear GIA rates (linear_rate) and associated uncertainties (linear_rate_err = 0.3). For each fold, the Bayesian NI-GAM decomposition (model_type = "ni_gam_decomp") was fitted with 5,000 MCMC iterations per chain (1,000 burn-in, thinning = 5) across three chains. Temporal and spatio-temporal B-splines were parameterized with spline_nseg_t = 3 and spline_nseg_st = 2 to capture nonlinear trends over time and across sites. Predictive performance was evaluated using out-of-sample empirical coverage, prediction interval widths, and error metrics—including mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE)—as well as by comparing predicted versus observed values.

The predictive performance of the NI-GAM model was evaluated across all site-specific relative sea-level (RSL) records, incorporating site-specific linear GIA rates from the ICE-6G_hybrid_71p320 model. The Bayesian NI-GAM decomposition captured nonlinear trends while accommodating gaps in shorter records.

The NI-GAM produced well-calibrated predictive intervals. The overall coverage of the 95 % posterior predictive intervals was 95 %, close to the nominal value, with site-specific coverage ranging from 0.926 (Dublin Port) to 1.000 (Malin Head), and all sites within ±5 % of the expected 95 % coverage (Table 5). Narrow and consistent prediction intervals indicate that observational uncertainty is well captured.

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Table 5. Cross-validation performance metrics for each site. Coverage shows the proportion of observed RSL within the 95 % posterior predictive interval; PI width gives the interval width.

Site	Coverage (95 % PI)	PI Width (m)
Malin Head	1.000	0.133
Belfast	0.940	0.133
Dublin Port	0.926	0.133
Cork	0.931	0.135
Tarbert	0.962	0.138
Galway	0.955	0.137

Error metrics further support the model's accuracy. Mean errors (ME) were near zero for all sites, indicating negligible bias, while mean absolute errors (MAE) and root-mean-squared errors (RMSE) remained low (Table 6), demonstrating strong predictive performance even for sparser records.

Table 6. Cross-validation error metrics by site. ME: mean error; MAE: mean absolute error; RMSE: root-mean-squared error.

Site	ME (m)	MAE (m)	RMSE (m)
Malin Head	−0.000534	0.0202	0.0250
Belfast	−0.000104	0.0246	0.0319
Dublin Port	−0.000260	0.0285	0.0366
Cork	0.000087	0.0282	0.0394
Tarbert	0.000177	0.0281	0.0389
Galway	0.000284	0.0305	0.0354

The comparison of observed and predicted RSL across all sites is presented in Figure 13. Most points closely follow the 1:1 line, and the narrow, consistent prediction intervals indicate that the NI-GAM effectively captures long-term trends, site-specific variability, and measurement uncertainty. Model performance is strongest at Malin Head, Galway, and Tarbert, while Belfast

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exhibits slightly wider intervals and greater scatter, reflecting higher observational uncertainty. Overall, cross-validation confirms that the NI-GAM provides accurate, well-calibrated predictions of RSL and instantaneous rates, supporting its use for assessing regional sea-level trends and accelerations across Ireland.

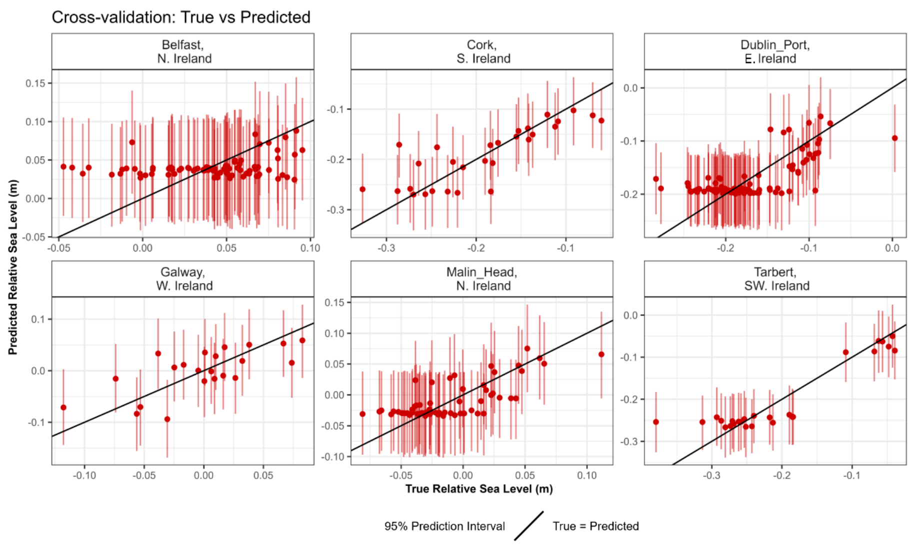

Figure 13. True versus predicted relative sea level (RSL) from 10-fold NI-GAM cross-validation across all tide-gauge sites. Red points show posterior predictive means with 95 % intervals, and the black diagonal line represents the 1:1 reference; points near the line indicate strong predictive agreement.

7 Results

In these results, we report instantaneous sea-level rates calculated as the first derivative of the smoothed NI-GAM posterior curve for each year, reflecting modelled changes rather than simple year-to-year differences in the raw tide-gauge data. Year-specific instantaneous rates are reported with 95 % credible intervals (CI), while period-mean instantaneous rates are reported as mean ± standard error (SE) of the temporal mean of instantaneous rates over the period, unless otherwise stated. Because the annual rate curves are smoothed, instantaneous rates may differ from raw year-to-year estimates by up to ~1 mm yr^{-1}. For visualization, site-specific linear GIA contributions (ICE-6G_hybrid_71p320) were removed to show GIA-free instantaneous sea-level rates. These corrections are small (−0.07 to 0.21 mm yr^{-1}), remain

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within typical interannual variability (~1 mm yr⁻¹), and do not materially affect the overall trends or spatial patterns (Figure 14). Figures 14–16 present the GIA-free instantaneous rates, while the text reports the total modelled instantaneous rates, including site-specific GIA.

Observed sea-level rates of rise show an apparent acceleration into the 2000s, although the confidence intervals (CI) for yearly rates increase substantially toward 2024, reflecting greater uncertainty in individual years (Figure 14). Including site-specific linear GIA contributions, instantaneous rates at Belfast peaked at 4.66 mm yr^{-1} (95 % CI: 3.16–6.05) in 2015, the final year of the record. In 2024, the smoothed instantaneous sea-level rates at all sites with records extending to 2024 reached approximately 6 mm yr^{-1} and above: Malin Head, Dublin Port, Cork, Tarbert, and Galway reached 6.18 mm yr^{-1} (95 % CI: 3.66–8.69), 6.19 mm yr^{-1} (3.67–8.70), 6.36 mm yr^{-1} (3.84–8.87), 6.36 mm yr^{-1} (3.84–8.87), and 6.31 mm yr^{-1} (3.79–8.82), respectively, indicating sustained high rates consistent with recent acceleration. These rates correspond to the first derivative of the smoothed posterior, with 95 % credible intervals representing uncertainty in observations.

Long-term mean modelled instantaneous sea-level rates vary geographically. With site-specific linear GIA contributions from ICE6G_BC_hybrid_71p320 included, Malin Head exhibits the highest mean rate (2.14 ± 0.23 mm yr^{-1}, 1958–2024), whereas Belfast shows the lowest (1.07 ± 0.14 mm yr^{-1}, 1925–2015), illustrating regional differences. Along the east coast, Dublin Port exhibits a mean rate of 1.57 ± 0.18 mm yr^{-1} (1925–2024). In the south and southwest, Cork shows a higher mean rate of 2.74 ± 0.26 mm yr^{-1} (1971–2024), with Tarbert at 2.48 ± 0.25 mm yr^{-1} (1964–2024), and along the west coast, Galway records 2.53 ± 0.25 mm yr^{-1} (1967–2024).

Consistent with the regional component, long-term rates were comparatively stable through most of the 20th century. Modelled instantaneous sea-level rates generally remained near ~0.56–0.87 mm yr^{-1} (SE 0.09–0.11 mm yr^{-1}) prior to 2000. For example, site-specific reconstructions indicate Malin Head at 0.87 ± 0.11 mm yr^{-1} (1958–2000), Belfast at 0.56 ± 0.09 mm yr^{-1} (1925–2000), and Dublin Port at 0.67 ± 0.09 mm yr^{-1} (1925–2000). These lower early-century rates contrast sharply with the substantially higher modelled instantaneous rates observed over the past two decades, reflecting the recent acceleration in sea-level rise.

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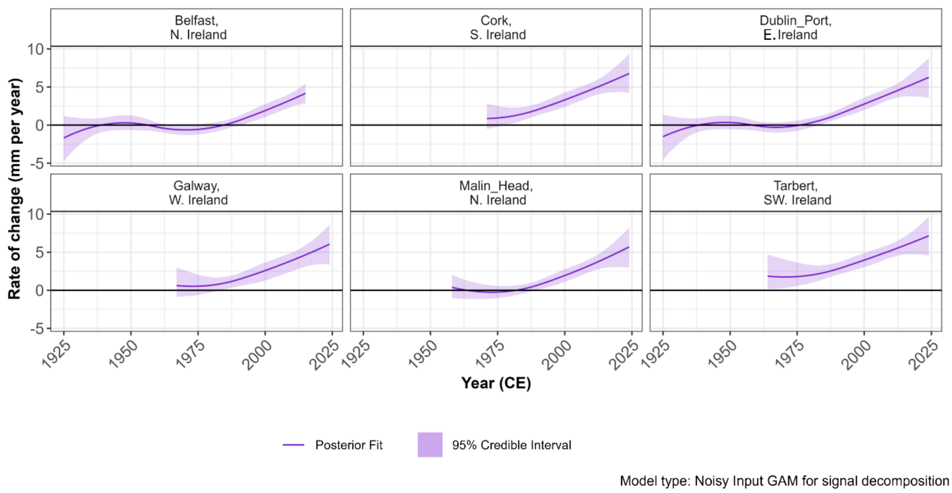

Figure 14. Modelled instantaneous sea-level rates across Irish tide-gauge sites (1925–2024). The purple line shows the NI-GAM-derived instantaneous rate with site-specific GIA contributions removed, representing absolute (GIA-free) sea-level rates. Shaded regions indicate the 95 % credible interval of the posterior distribution. All sites contribute to the regional curve, illustrating long-term trends and inter-site variability.

To examine GIA-free instantaneous sea-level rates, we removed the site-specific GIA component from the modelled rates, as summarized in Table 7. Removing the GIA contribution brings site-level rates closer together and highlights the underlying absolute (GIA-free) sea-level change. The magnitude of these corrections is relatively small, ranging from a slight reduction of −0.07 mm yr^{-1} in the north, where land uplift reduces relative sea-level rise, to 0.21 mm yr^{-1} in the southwest, where land subsidence enhances relative sea-level rise.

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Table 7. Modelled instantaneous relative sea-level (RSL) rates at each site, including ICE-6G_hybrid_71p320 GIA contributions and corresponding GIA-free rates. Values are derived from the smoothed posterior distributions, not raw tide-gauge trends. Note: The reported standard errors represent uncertainty in the posterior mean instantaneous rate over the specified period, rather than interannual variability in raw observations.

Site	Period	Mean modelled instantaneous Rate (mm yr^{-1}, ± SE)	Site-specific linear GIA Contribution (mm yr^{-1})	Mean GIA-free instantaneous sea-level rate (mm yr^{-1}, ± SE)
Malin Head	1958–2024	2.14 ± 0.23	0.03	2.11 ± 0.23
Belfast	1925–2015	1.07 ± 0.14	−0.07	1.14 ± 0.14
Dublin Port	1925–2024	1.57 ± 0.18	0.04	1.53 ± 0.18
Cork	1971–2024	2.74 ± 0.26	0.21	2.53 ± 0.26
Tarbert	1964–2024	2.48 ± 0.25	0.21	2.27 ± 0.25
Galway	1967–2024	2.53 ± 0.25	0.16	2.37 ± 0.25

To enable fair comparison across sites, mean modelled instantaneous rates were calculated over the overlapping period 1971–2024 (Table 8) and are derived from the smoothed posterior distributions rather than raw annual observations. Over this interval, rates range from 1.86 ± 0.22 mm yr^{-1} at Belfast to 2.74 ± 0.26 mm yr^{-1} at both Cork and Tarbert, highlighting the spatial variability in long-term sea-level rise across Ireland, with the southwest exhibiting the highest overall rates.

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Table 8. Comparison of mean modelled instantaneous sea-level rise rates (± SE) across all Irish tide-gauge sites. Note: Belfast record ends in 2015; all other sites extend to 2024.
815 **Note: ± SE as defined in Table 7.**

Site	Period	Modelled instantaneous Rate (mm yr^{-1}, ± SE)
Malin Head	1971–2024	2.56 ± 0.26
Belfast	1971–2015	1.86 ± 0.22
Dublin Port	1971–2024	2.57 ± 0.26
Cork	1971–2024	2.74 ± 0.26
Tarbert	1971–2024	2.74 ± 0.26
Galway	1971–2024	2.69 ± 0.26

The combined mean GIA-free instantaneous sea-level rate across all tide-gauge sites is summarized in Figure 15, which shows the regional component. Between 1925 and 2024, the mean modelled instantaneous sea-level rate, with the site-specific GIA contribution removed,
820 was 1.88 ± 0.10 mm yr^{-1}. Including the ICE6G_BC_hybrid_71p320 GIA contribution, the mean modelled instantaneous rate increases to 1.96 ± 0.10 mm yr^{-1}, reflecting the combined effect of vertical land motion and sea-level change. The accelerated component of sea-level rise, shown in the smoothed regional curve (Figure 15), reflects the increase in instantaneous rates over 1925–2024. Between 1925 and 2024, sea level rose by ~0.151 m (~15.1 cm), based
825 on the difference between the levels at the start and end years.

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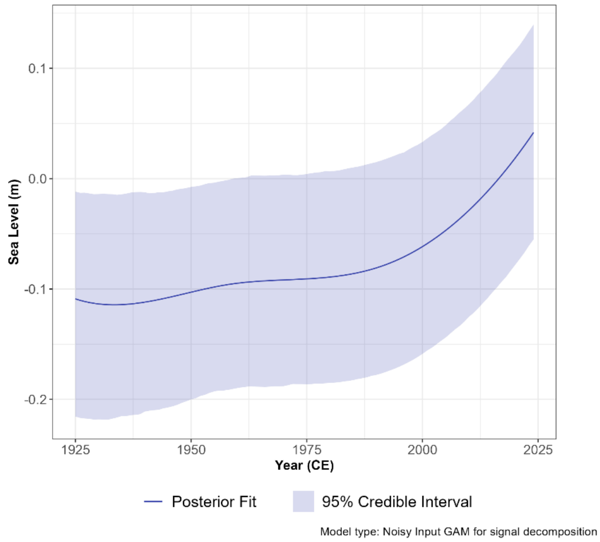

Figure 15. Smoothed regional sea-level curve (1925–2024) across Irish tide gauges (GIA-free). Shaded areas show the 95 % credible interval. The curve represents the smoothed analysis of the tide-gauge records, not raw annual observations, with site-specific linear GIA contributions removed.

The yearly rates of sea-level rise are shown in Figure 16 for all sites in the regional rate plot. The plot reveals fluctuations, including a slight decline from the 1950s to the 1970s, followed by a pronounced increase from around 1975. Annual instantaneous mean sea-level rates increased from 0.84 ± 0.05 mm yr^{-1} (GIA-adjusted) and 0.77 ± 0.04 mm yr^{-1} (GIA-free) during 1925–2000 to 4.34 ± 0.09 mm yr^{-1} (GIA-adjusted) and 4.23 ± 0.09 mm yr^{-1} (GIA-free) during 2000–2024, reaching 6.28 mm yr^{-1} in 2024 for GIA-adjusted rates (95 % CI: 6.19–6.36). The corresponding GIA-free rates rose to 6.15 mm yr^{-1} in 2024. These values represent the modelled derivatives of the smoothed fit, highlighting the pronounced acceleration in sea-level rise during the 21st century.

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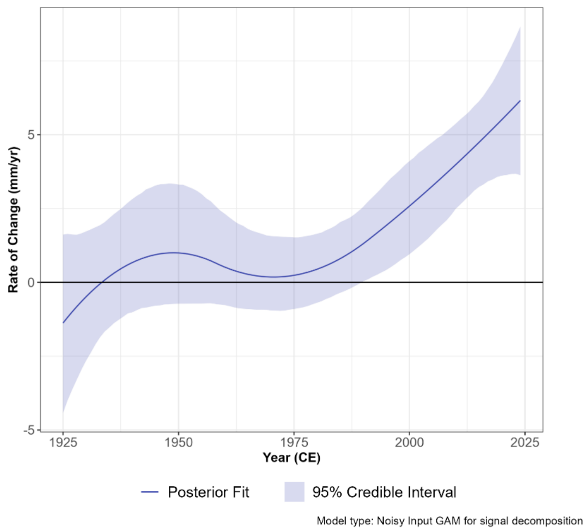

Figure 16. Regional GIA-free instantaneous sea-level rates (1925–2024) derived from the posterior. Shaded areas indicate the 95 % credible interval. The curve represents smoothed instantaneous rates, not raw annual tide-gauge slopes.

8. Discussion

The results highlight spatial and temporal variability in sea-level behaviour across Northern Ireland. Modelled instantaneous sea-level rates from the posterior are 2.14 ± 0.23 mm yr⁻¹ at Malin Head (1958–2024) and 1.07 ± 0.14 mm yr⁻¹ at Belfast (1925–2015). Modern modelled total instantaneous rates at Malin Head in 2024 reach 6.18 mm yr⁻¹ (95 % CI: 3.66–8.69), while at Belfast in 2015 they reach 4.66 mm yr⁻¹ (95 % CI: 3.16–6.05). It should be noted that these instantaneous rates are derived from the smoothed posterior and may slightly exaggerate peak values at the start and end of the record; this is reflected in the wider 95 % credible intervals in Figure 14, indicating increased uncertainty in these periods. Both substantially exceed their earlier-century rates of 0.87 ± 0.11 mm yr⁻¹ at Malin Head (1958–2000) and 0.56 ± 0.09 mm yr⁻¹ at Belfast (1925–2000) respectively. These differences illustrate the marked acceleration in regional sea level since the early 2000s. The higher rates reflect derivatives of the smoothed posterior rather than long-term averages, with smoothing potentially altering year-to-year estimates by ±1 mm yr⁻¹. The IPCC AR6 projection tool reports total rates of 2.2 mm yr⁻¹ (Malin Head) and 2.4 mm yr⁻¹ (Belfast) for 2020 under SSP3-7.0 (NASA, 2025); the higher Belfast rate reflects the later year (2020) compared with our

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1925–2015 modelled record, whereas our Malin Head rate (2.14 mm yr^{-1}, 1958–2024) closely matches the IPCC estimate, indicating broad consistency with our regionally averaged modelled rates.

To the east, Dublin Port exhibits a long-term instantaneous sea-level rate of 1.57 ± 0.18 mm yr^{-1} (1925–2024), while pre-2000 rates were lower, around 0.67 ± 0.09 mm yr^{-1} (1925–2000), rising to 3.75 ± 0.18 mm yr^{-1} (2000–2016), and reaching 6.19 mm yr^{-1} (3.67–8.70) in 2024. These results are generally consistent with previous tide-gauge estimates for overlapping periods. For example, Shoari Nejad et al. (2022) report 1.1 mm yr^{-1} (95 % CI: 0.6–1.6 mm yr^{-1}) for 1953–2016 based on Bayesian linear regression–corrected data, whereas our mean rate is 1.61 mm yr^{-1} for the same period—slightly higher, but both indicate an overall increase. Earlier analyses show modest and variable pre-2000 sea-level change around Dublin, with modelled rates of 0.84 mm yr^{-1} for 1938–1961, declining to 0.32 mm yr^{-1} for 1961–1980. These are broadly consistent with historical estimates of 0.6 mm yr^{-1} (1938–1961) and −0.3 mm yr^{-1} up to 1980 (Carter, 1982). Over 1938–1996, Woodworth et al. (1999) reported a long-term trend of 0.2 mm yr^{-1}, compared with our mean of 0.78 mm yr^{-1}. Differences between studies are expected due to varying models, corrections, and data coverage; nevertheless, all indicate relatively little increase pre-2000, followed by pronounced acceleration post-2000. Shorter-term rates during 2000–2016 are 3.75 ± 0.18 mm yr^{-1}, reflecting marked acceleration in the 21st century. Palaeo-reconstructions using saltmarsh foraminifera indicate a similar century-scale rate since the early 19th century (1.6 ± 0.9 mm yr^{-1}; Roseby et al., 2023).

Across Ireland's south to west coasts, the highest modelled instantaneous sea-level rates are observed. Cork Harbour shows a long-term mean rise of 2.74 ± 0.26 mm yr^{-1} (1971–2024), with instantaneous rates reaching 6.36 mm yr^{-1} (3.84–8.87) in 2024. These values exceed the longer-term historical linear trend of 2.2 mm yr^{-1} reported by Pugh et al. (2021) for 1842–2019, providing a robust baseline for comparison, corresponding to a cumulative rise of over 40 cm (Cubie, 2024). Tarbert similarly shows elevated rates, with a long-term modelled smoothed sea-level mean rate of 2.48 ± 0.25 mm yr^{-1} (1964–2024) and recent smoothed rates reaching 6.36 mm yr^{-1} (3.84–8.87). River discharge from the River Shannon may also influence the observed sea-level rates at Tarbert and Kilrush, as shown in studies of other estuarine systems (e.g., Piecuch et al., 2018). On the west coast, Galway Harbour exhibits a mean instantaneous sea-level rate of 2.53 ± 0.25 mm yr^{-1} (1967–2024), reflecting substantially higher rates in the 21st century, reaching 6.31 mm yr^{-1} (3.79–8.82) in 2024, consistent with the strong regional acceleration. In the absence of long historical records, it is difficult to accurately ascertain

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early-century rates for Cork, Tarbert, and Galway; however, the results indicate substantially lower rates prior to 2000, followed by marked acceleration post-2000.

Comparison of mean instantaneous rates across all sites over the overlapping period 1971–2024 revealed that Belfast had the lowest overall rate (1.86 ± 0.22 mm yr^{-1}), Dublin Port (2.57 ± 0.26 mm yr^{-1}) and Malin Head (2.56 ± 0.26 mm yr^{-1}) had intermediate rates, and the highest rates occurred in the southwest, ranging from 2.69 ± 0.26 mm yr^{-1} at Galway to 2.74 ± 0.26 mm yr^{-1} at Cork and Tarbert.

The combined mean GIA-free regional component across all tide-gauge sites is shown in Figure 15. Between 1925 and 2024, the mean modelled instantaneous sea-level rate, with GIA contributions removed, was 1.88 ± 0.1 mm yr^{-1}, increasing to 1.96± 0.1 mm yr^{-1} when including the ICE-6G_hybrid_71p320 GIA contribution. The smoothed regional curve (Figure 15) highlights the accelerated component of sea-level rise between 1925 and 2024. Over this period, sea level rose by ~0.151 m (~15.1 cm), based on the difference between the levels at the start and end years. This reflects the contribution from acceleration rather than total cumulative relative sea level and aligns broadly with global twentieth-century estimates of 10–25 cm (IPCC, 2021; Mu et al., 2025). For comparison, the rate estimated directly from raw relative sea-level tide-gauge data using a linear model is 1.90 ± 0.60 mm yr^{-1}. The difference of less than 0.1 mm yr^{-1} indicates good agreement between approaches. A linear GIA rate was used as an anchor to estimate instantaneous rates, since relative sea level alone is insufficient. Different GIA estimates produce slight variations and should be acknowledged. The ICE-6G_hybrid_71p320 model, which produced the lowest residual inter-site spread, was therefore identified as the optimal GIA correction.

As noted previously, the ICE-5G Peltier and Bradley models show the largest GIA rates in Northern Ireland, reaching nearly −1.5 mm yr^{-1} at Malin Head and 1.26 mm yr^{-1} at Belfast (ICE-5G model). Earlier tide-gauge studies reported near-zero or slightly negative long-term relative sea-level trends in the northeast (−0.16 to −0.20 mm yr^{-1}), largely reflecting modest 20th-century sea-level rise offset by regional glacial-isostatic uplift (Orford et al., 2006). This contrasts with the modelled instantaneous rates but is consistent with observations that Northern Ireland is experiencing relative uplift, while the southwest shows slight subsidence (Bradley et al., 2011; Bradley et al., 2023; Kirby et al., 2023). GIA scenarios for the east, south, and west are less pronounced, with most south and western model rates generally showing slight subsidence.

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Applying the ICE-6G BC_Hybrid_71p320 GIA corrections, the GIA-adjusted mean sea-level rate at Belfast rises by 0.07 mm yr^{-1}, from 1.07 ± 0.14 mm yr^{-1} (GIA-free) to 1.14 ± 0.14 mm yr^{-1}, whereas Malin Head decreases by 0.03 mm yr^{-1}, highlighting the modest influence of GIA in Northern Ireland. These adjustments are small compared with the broader GIA range of −1.25 to −1.5 mm yr^{-1} in other models, particularly ICE-5G. At Dublin Port, the ICE-6G correction is minimal (−0.04 mm yr^{-1}), although alternative models such as ICE-5G could produce larger corrections (~−0.5 mm yr^{-1}). In the southwest, GIA adjustments indicate slight subsidence: Cork and Tarbert decrease by 0.21 mm yr^{-1}, and Galway by 0.16 mm yr^{-1}. Across all sites, ICE-6G corrections are modest and have a limited effect on long-term instantaneous mean sea-level rates.

While most GIA rates are small, they can meaningfully influence the overall national mean. For example, using the ICE-5G Peltier model—which produces the largest GIA-free contribution—the absolute instantaneous national rate would rise to ~2.53 mm yr^{-1}, compared with 1.96 ± 0.1 mm yr^{-1} for the ICE6G_BC_hybrid_71p320-adjusted rate and 1.90 ± 0.60 mm yr^{-1} from the linear RSL trend. Although the ICE-6G BC_Hybrid_71p320 model was selected as the best choice based on minimizing site-to-site variability and agreement with the linear rate (prior to GIA removal), uncertainties in GIA estimates remain. Direct comparisons between Ireland and Great Britain are complicated by differing glacial histories: the thicker Celtic Ice Sheet over Britain drove stronger glacial isostatic adjustment, whereas Ireland's thinner ice cover produced smaller relative sea-level changes (Shennan et al., 2018). For records spanning ~100 years, GIA has minimal impact on overall rates; nevertheless, for contextualizing sea-level changes and in reslr modelling, GIA should be acknowledged and incorporated.

The mean instantaneous rates are broadly consistent with historical British Isles estimates. Hogarth et al., (2021) reconstructed long-term tide-gauge records with GIA corrections (ICE-6G_C), reporting a weighted linear rate of 2.12 mm yr^{-1} for the 20th century, with acceleration in the late 19th and 20th centuries. Our mean modelled instantaneous sea-level rates for Ireland (1925–2024) are slightly lower than the 20th-century reconstruction of Hogarth et al. (2021) at 1.96 ± 0.1 mm yr^{-1} including GIA contributions and 1.88 ± 0.1 mm yr^{-1} for the GIA-free (absolute) rate, reflecting the relatively small GIA effect. Instantaneous mean sea-level rates were generally below 1 mm yr^{-1} prior to 2000 (0.84 ± 0.05 mm yr^{-1} GIA-adjusted, 0.77 ± 0.04 mm yr^{-1} GIA-free) and increased markedly between 2000 and 2024 (4.34 ± 0.09 mm yr^{-1} GIA-adjusted, 4.23 ± 0.09 mm yr^{-1} GIA-free). Annual rates peaked in

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2024 at 6.28 mm yr⁻¹ (GIA-adjusted, 95 % CI: 6.19–6.36) and 6.15 mm yr⁻¹ (GIA-free), with the GIA-adjusted value explicitly highlighted for completeness. Local variability differs between sites, reflecting regional differences in sea-level change, whereas British records benefit from longer and more continuous observations.

Cross-validation of the NI-GAM model demonstrates that the smoothing and hierarchical borrowing of information produce well-calibrated estimates of instantaneous sea-level rates. Mean rates across sites are generally stable, with 95 % posterior predictive intervals effectively capturing observed variability at most sites, except Belfast, which exhibits wider credible intervals due to higher observational uncertainty. Quantitative evaluation using 10-fold cross-validation shows site-specific coverage ranging from 0.926 to 1.000 and low root-mean-squared errors (0.025–0.039 m), indicating minimal bias and strong predictive skill. The smoothing process may slightly exaggerate apparent rates of rise during periods of rapid change, such as the 2000s and 2010s, but the model still effectively captures regional and site-specific trends, even in records with temporal gaps, meaning that peak instantaneous rates may be slightly overestimated relative to raw observations.

Some uncertainty remains in the observational data. Errors in digitization can occur (McLoughlin et al., 2026), and tide-gauge data may contain instrumentation errors (Gobron et al., 2019). While quality control reduces much of this noise, gaps in records—sometimes spanning several months or more—can still affect estimates. Atmospheric adjustments help reduce high-frequency variability but do not eliminate all uncertainty.

The reslr package produces robust regional estimates by integrating data from multiple sites (Upton et al., 2024). This hierarchical modelling approach allows sites with sparse records, such as Cork, Tarbert, and Galway, to benefit from information borrowed from neighbouring sites, resulting in continuous estimates even during periods of limited observations. A consequence of this strategy is that sites with short or incomplete records, such as Cork and Tarbert, may receive nearly identical instantaneous rates of rise during these intervals. While this reduces noise and increases the stability of the regional trend, it may smooth over real, site-specific variability. This approach highlights the ability to capture coherent regional trends, while emphasizing that caution is warranted when interpreting short-term or site-specific differences during periods of sparse data (Upton et al., 2024).

Coastal vulnerability is a key consideration when assessing rates of sea-level change across Ireland. Historical records indicate that sea level at Malin Head and Belfast has been rising

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since the early 2000s, despite earlier suggestions of a late-20th-century decline (Orford et al., 2006). Modern instantaneous sea-level rates in 2024 exceed ~6 mm yr^{-1} at Dublin Port, Galway, and other high-rate sites. These values correspond to the first derivative of the smoothed NI-GAM posterior and therefore reflect modelled acceleration rather than direct year-to-year changes in the raw tide-gauge observations. While such elevated end-of-record rates may partly reflect short-term variability and increased uncertainty toward the end of the record, they are coherent across multiple sites and are primarily associated with the recent steepening of the regional sea-level curve. These rates exceed long-term multi-decadal averages of approximately 2.5–3 mm yr^{-1}, highlighting pronounced temporal variability in relative sea-level change. Belfast, along with Dublin, Cork, and Galway, faces significant potential impacts due to dense urban populations and exposure to storm surges and coastal flooding (Department of the Environment and Local Government, 2001; Paranunzio et al., 2022).

The southwest and west, including Cork, Tarbert, and Galway, are particularly vulnerable due to local subsidence and sparse observational data. Limited tide-gauge coverage, notably in the Shannon Estuary, introduces uncertainty in local sea-level trends, complicating risk assessments. Projected long-term average rates towards the end of the century are highest in the southwest (3.3–4.8 mm yr^{-1}) and lower in the northeast (2.2–3.7 mm yr^{-1}) (MWP, 2024). Enhanced tide-gauge monitoring would improve understanding of local variability and support adaptation planning, particularly considering the projected acceleration in global mean sea level (Wang et al., 2024).

9 Conclusion

A key objective of this study was to reconstruct historical mean sea-level (MSL) change across Ireland, with particular focus on the south and southwest, where long-term observations have been limited. Accurate assessment of MSL change ideally requires long, continuous records, and the hierarchical framework applied to Irish tide-gauge data provides robust reconstructions of both long-term trends and recent accelerations. By integrating archival and modern tide-gauge data, including Cork, Tarbert, and Galway, this study fills critical spatial gaps and situates Irish sea-level changes within a broader regional context, complementing previous studies in the UK.

The overall regional modelled mean rate of sea-level rise from 1925–2024 is 1.96 ± 0.1 mm yr^{-1}. Removing the GIA contribution reduces this slightly to 1.88 ± 0.1 mm yr^{-1},

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representing the GIA-free (absolute) rate. Rates of sea-level rise reached ~6.18–6.36 mm yr^{-1} in 2024, with the highest mean instantaneous rates observed in the southwest of Ireland, where sites such as Cork, Tarbert, and Galway exhibit elevated vulnerability to accelerated sea-level rise and coastal flooding.

Adjustments for datums, atmospheric effects, seasonal cycles, and GIA were applied. Under the chosen ICE-6G BC_Hybrid_71p320 model, GIA corrections are generally small, with minimal impact at northern sites and slight contributions to sea-level rise in southwestern sites; however, alternative GIA models could produce larger differences, particularly in Northern Ireland.

Cross-validation confirms the robustness of the regional reconstruction, demonstrating that even locations with shorter or sparse records can be reliably incorporated. Short-term variability at individual sites is smoothed, emphasizing the strength of the regional trend.

These findings underscore the vulnerability of Ireland's coastal areas. Urban centres such as Cork and Dublin face heightened risk from rising seas and storm surges. Northern sites also remain exposed to flooding due to accelerated sea-level rise across all regions since the 2000s. The combination of accelerated sea-level rise, local subsidence, and urban exposure highlights the importance of targeted monitoring and adaptation planning.

Overall, this study demonstrates the value of integrating modern statistical frameworks with archival data, providing a comprehensive assessment of sea-level trends across Ireland and strengthening the foundation for scientific understanding and evidence-based policy development. Future work will focus on extending this reconstruction to additional sites and refining corrections to improve regional understanding of both GIA contributions and implications for policy implementation in vulnerable areas. Past studies of mean sea level in Ireland reported relatively low rates of rise (Carter, 1982; Woodworth et al., 1999; Orford et al., 2006), and only recent individual site studies have shown rates of sea-level rise consistent with climate change-driven trends (Pugh et al., 2021; Shoari Nejad et al., 2022). This study synthesizes all available mean sea-level data across the island of Ireland, presenting for the first time a geographically balanced view. The results indicate that Ireland now experiences rates of sea-level rise comparable to or higher than global averages, with the south and west being more vulnerable than the east and north. In the 21st century, with accelerating sea-level rise, Ireland's heavily coastal population will need to adapt to the associated higher frequency of coastal flooding and inundation.

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Competing interests. The lead author has declared that they, along with their co-authors, do not have any competing interests.

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Acknowledgements.

We sincerely acknowledge and thank the engineers of the Port of Cork for providing the Tivoli datasets, the Office of Public Works (OPW) for the Tarbert data, and Met Éireann for the use of their scanner. The records were kindly made available for borrowing and scanning, then digitized and uploaded as a corresponding dataset to this paper. This project (Grant-Aid Agreement No. CS/21/006) is carried out with the support of the Marine Institute and funded under the Marine Research Programme by the Irish Government. PM's work is supported under the same grant. GM is supported by the A4 Project (Aigéin, Aeráid, agus athrú Atlantaigh), with the support of the Marine Institute, under the Marine Research Programme, funded by the Irish Government grant no.: (PBA/CC/18/01) and iCRAG, with the support of Science Foundation Ireland (grant no. 13/RC/2092_P2).

Financial support. PM is funded (Grant-Aid Agreement No. CS/21/006) with the support of the Marine Institute and funded under the Marine Research Programme by the Irish Government. GM is supported by the A4 Project (Aigéin, Aeráid, agus athrú Atlantaigh), with the support of the Marine Institute, under the Marine Research Programme, funded by the Irish Government grant no.: (PBA/CC/18/01) and iCRAG, with the support of Science Foundation Ireland (grant no. 13/RC/2092_P2).

Dataset availability. Historical tide gauge records digitized as part of this study, together with Galway data from BODC (BODC, 2025, available at https://www.bodc.ac.uk/data/) and Belfast data (Murdy et al., 2015), will be deposited in a Zenodo repository and assigned a DOI upon publication. Data from the PSMSL are available at https://psmsl.org/data/obtaining/map.html#otherTab. Data from modern tide gauge stations maintained by the OPW and Marine Institute are available at https://waterlevel.ie/ (OPW, 2025) and https://www.digitalocean.ie/Data/DownloadTideData (MI, 2025), respectively. ERA5 and 20CRv3 reanalysis data used for atmospheric and seasonal corrections are available from https://cds.climate.copernicus.eu/ (Copernicus Climate Change Service, 2025) and https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html (NOAA PSL, 2025).

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Code for all major components of this study will be made available on GitHub (https://github.com/PatrickJMcLoughlin/Ireland-Sea-Level) upon publication.

Author contributions. **PM:** Conceptualization, data digitization of associated dataset; writing – original draft; software; writing – review and editing. **LS:** Data digitization of associated dataset, writing – review and editing. **GN:** Writing – review and editing. **KH:** Writing – review and editing. **GM:** Writing – review and editing; conceptualization. **M.U:** Writing – review and editing; conceptualization. **R.E:** Writing – review and editing.

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