

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

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Abstract. Understanding ~~mean~~long-term 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~~relative mean sea-level (RSL) 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 Mean modelled rate of sea-level change at each site—vary systematically between regions, reflecting coherent spatial patterns. Rates range~~RSL rates were derived from -1.07 mm yr^{-1} in the north to $2.48\text{--}2.74\text{ mm yr}^{-1}$ in the south and west, with the highest observed at Cork (2.74 mm yr^{-1}). The regional mean is $1.96 \pm 0.1\text{ mm yr}^{-1}$ for the rate field of the hierarchical Bayesian reconstruction. Mean modelled RSL rates over 1925–2024, decreasing to $1.88 \pm 0.1\text{ mm yr}^{-1}$ after accounting for ranged from 0.71 mm yr^{-1} at Belfast to 1.32 mm yr^{-1} at Tarbert in southwest Ireland, reflecting the combined influence of the shared regional signal, site-specific linear Glacial Isostatic Adjustment (GIA). Annual rates increased from below 1 mm yr^{-1} —related contributions, and local effects. The network-mean modelled RSL rate for Ireland was 1.11 mm yr^{-1} (95% CI: $0.78\text{--}1.45$) over 1925–2024, increasing from 0.41 mm yr^{-1} (95% CI: $-0.01\text{--}0.88$) during 1925–2000 to above 4 mm yr^{-1} 3.27 mm yr^{-1} (95% CI: $2.61\text{--}3.93$) during 2000–2024, peaking at $\sim 6\text{ mm yr}^{-1}$ in 2024, highlighting pronounced 21st-century indicating a substantial acceleration in recent decades. The reconstructed regional

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component, representing the shared signal across the tide-gauge network, has a mean rate of 1.01 mm yr^{-1} (95% CI: 0.19–1.84) over 1925–2024. 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 RSL rise and contextualizing contextualising future coastal risk, with implications for coastal planning and adaptation strategies globally.

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1 Introduction

Mean Sea Level (MSL) ~~is~~ represents 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); Pugh & Woodworth, 2014). Globally, MSL ~~is rising~~ has risen at approximately 3–4 mm yr⁻¹, mm yr⁻¹ over recent decades, with satellite observations altimetry showing ~3.3 mm yr⁻¹ mm yr⁻¹ from over 1993–2021 and 4 mm yr⁻¹ from 2006–2016, and more recent, while shorter-term 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 mm yr⁻¹ over 2006–2016 reflect, in part, interannual variability (Hamlington et al., 2024); Llovel et al., 2023). Evidence further indicates an accelerating trend, from ~2.1 mm yr⁻¹ in the early 1990s satellite record to ~4.5 mm yr⁻¹ in recent years (Hamlington et al., 2024), although short-term variability contributes to interannual fluctuations. However, tide-gauge sea-level observations are influenced not only by changes in ocean volume but also by regional processes and vertical land motion (VLM). They therefore record relative sea level (RSL), representing changes in sea level relative to the local land surface rather than absolute ocean volume changes (Oelsmann et al., 2024). Understanding MSL long-term sea-level changes from tide-gauge and archival data is essential for quantifying long-term RSL 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

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vulnerable to flooding. In 2009 a major flood event in Cork led to around €100 million of damages to ~~Commercial~~commercial and ~~Residential~~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~~García et al., 2021). However, only a few sites, including Malin Head, Dublin Port, and Belfast ~~Harbour~~, provide long-term (>40 years) ~~continuous~~ records, which are incorporated into the Permanent Service for Mean Sea Level (PSMSL) ~~dataset~~ (Holgate et al., 2013). 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 ~~Harbour~~ (1901/4902–2010; 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~~tide-gauge-derived MSL and RSL, as large portions of the coast remain unmonitored. A minimum of 40 years is generally required to robustly determine trends in ~~MSL~~tide-gauge-derived sea-level records (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~~yielding robust ~~two-century MSL curve~~long-term RSL ~~reconstructions~~, reduced uncertainties, and ~~revealed~~improved detection of long-term accelerations (Hogarth et al., 2021). Similar historical data rescue ~~and integrated analyses~~efforts across multiple Irish sites are ~~needed~~therefore required to ~~overcome the limited~~improve spatial and temporal coverage of ~~existing records~~sea-level observations.

~~Across Ireland, relative sea level (RSL)~~Tide-gauge-derived RSL changes are influenced by variations in both ocean level and VLM. Land levels can change due to geological processes, of which Glacial Isostatic Adjustment (GIA) is the primary globally modelled component (Tamisiea & Mitrovica, 2011; Bradley et al., 2011). Across Ireland, 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,

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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 the range of outputs~~ among available GIA models, ~~which yield different outputs even including variability~~ within ~~their own individual~~ 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). ~~GIA models, such as~~ GLAC1D ~~uses, use~~ physics-based, glaciologically self-consistent ice-sheet simulations (Tarasov et al., 2012), whereas ~~ICE6G models are the~~ ICE-6G GIA model is tuned to fit global ~~relative sea-level (RSL)~~ and crustal motion observations (Peltier, 2015). Regional Bradley-type GIA models, including those based on ~~the~~ BRITICE-CHRONO ~~reconstruction~~ ice-sheet reconstruction of the British-Irish Ice Sheet, are specifically calibrated to British-Irish RSL and ~~GPSGNSS (Global Navigation Satellite System)~~ datasets (Bradley et al., 2023). These differences strongly influence predicted ~~vertical land motion~~ VLM rates, 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~~ integrate sea-level ~~data~~ records from across Ireland, including the south and west where ~~records~~ observations are sparse, to improve understanding of ~~both Mean Sea Level (MSL) historical RSL changes~~. In this study, long-term RSL variations are reconstructed from tide-gauge observations using a hierarchical framework that separates ~~regional signals, site-specific linear components (including GIA-related effects), and the influence of Glacial Isostatic Adjustment (GIA) non-linear local variability~~.

The objectives are to:

- i) Integrate and analyse new records from the south and southwest to investigate ~~MSL~~

~~changes regional RSL variability in regions areas~~ with limited long-term observations.

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

iii) Assess reconstructed spatial patterns of RSL trends considering the influence of GIA ~~on regional sea-level trends~~.

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

2. Data Collection and Digitization and Datum Standardisation

2.1 Data Sources

The six primary tide-gauge sites analysed in this study are Belfast Harbour, ~~(hereafter Belfast)~~, Malin Head, Dublin Port, Cork, Galway, Harbour (hereafter Galway), and Tarbert Island (hereafter Tarbert) (Figure 1). Supplementary records from nearby gauges were also included where available ~~for example, including records from~~ Bangor ~~(supplementing near~~ Belfast), Portrush ~~(supplementing near~~ Malin Head), ~~Kilrush Lough (supplementing Tarbert)~~, Galway ~~(supplementing Galway Harbour for 1967–1970)~~, and Arklow ~~Harbour~~, Howth ~~Harbour~~, and Dún Laoghaire ~~Harbour (supplementing harbours (near~~ Dublin Port). ~~By integrating data from multiple sources, this study fills key gaps and provides new insight into spatial variability in sea-level trends).~~ Cork (Ringaskiddy and Currach Club, used to supplement Tivoli), Carrigaholt Pier (near Tarbert), and Rossaveel (near Galway).

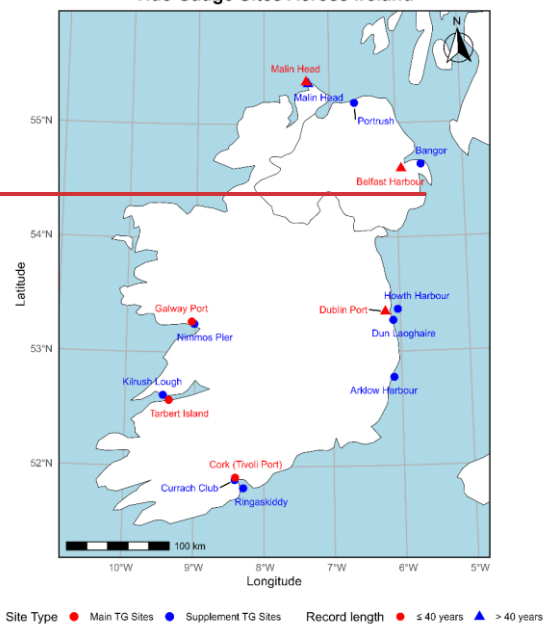
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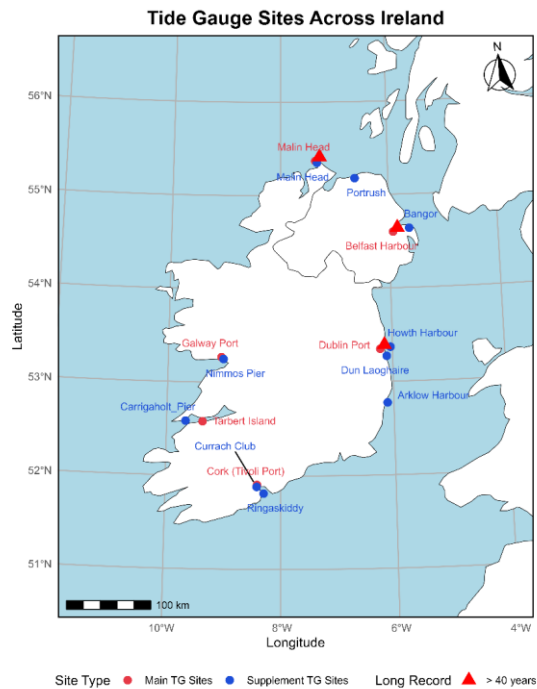
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Tide Gauge Sites Across Ireland





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~~Tide~~Existing 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 periods used in this study. MTL is defined as the average of Mean High Water (MHW) and Mean Low Water (MLW) and can differ slightly from Mean Sea Level (MSL) (Woodworth, 2017). For the purposes of this study, MTL is treated as an approximation of MSL. As these records are derived from tide gauges, they represent RSL observations referenced to local land benchmarks and therefore contribute to the reconstruction of historical RSL changes. The following sites, ~~covering only the periods used in this study~~ were included:

- Malin Head (1958–1995); higher resolution data are available in the GESLA database, but their quality has not been independently verified.
- Banger (2011–2015/1997).
- Portrush (1996/1998–2015).
- Dublin Port (1938–2001).

Modern PSMSL data for Malin Head were obtained combined with modern observations from the Office of Public Works (OPW; 2004–2008; OPW, 2025) and the Marine Institute (MI; 2009–2024; MI, 2025). The PSMSL holds a Mean Tide Level (MTL) record for Belfast Harbour, but it does not extend beyond 1963/1979. 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. The analysis period was restricted to 1925 onward to maintain consistency with the integrated Dublin Port sea-level record, for which the early Dún Laoghaire component begins in 1925. Previous work has identified step-like discontinuities and non-linear behaviour in the PSMSL Belfast record (Hogarth et al., 2020), indicating potential datum inconsistencies. The Murdy et al. (2015) dataset was therefore used as a higher-resolution alternative for this study. Data from the BODC for Bangor (2011–2022) were used to supplement the Belfast record (BODC, 2025).

Historical PSMSL data from Dublin port were combined with data for Dún Laoghaire Harbour (formerly called Kingstown) spanned from 1925–1931 and were obtained from McLoughlin et al. (2024). Data Additional data for two additional years (1932–1933) were recovered from raw marigrams; however, these records following the same methodology; further details are less reliable due to thicker, less accurate traces—particularly provided 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), Supplementary Material. For this study, we used the Dublin Port record spanning 1938–2001. Tide gauge observations obtained from the PSMSL. Observations after 2001 exhibit show considerable divergence, suggesting potential instrument malfunction and reduced reliability deviation from the preceding Dublin Port record.

suggesting increased uncertainty in the post-2001 observations. To ensure continuity and extend spatial coverage, modern sea-level data from the NTGN were added ~~to the Dublin Port record, comprising measurements from, including~~ Arklow (2003–2006; ~~managed by the~~ OPW) and Howth (Dublin, 2007–2024; NTGN/MI).

~~In~~To the ~~far~~southwest of Ireland, where no long-term PSMSL data exist, tide-gauge data for Cork Harbour were obtained from Port of Cork engineers and archival records, covering multiple periods between 1971 and 2024. The record includes historical observations from Tivoli Port (1971–1974, 1976/1977, 1981–1984) and modern tide-gauge measurements from Ringaskiddy (2012–2021) and Currach Club (2022–2024). Additional data for 2001–2005 and 2010–2011 were also incorporated from existing Tivoli records. Digitization procedures and quality control for the 1970s and 1980s are provided in the Supplement (see Figure S1).

The Tarbert tide-gauge record (1964–1986) was digitized from OPW archives and includes observations in both imperial and metric units referenced to OD Poolbeg, an interchangeable name for Ordnance Datum Dublin that was in use prior to the establishment of the national datum at Malin Head. The dataset represents the longest continuous tide-gauge record from southwest Ireland used in this study. Digitization procedures and quality control are provided in Supplement S1 (see Figure S2). Additional tide-gauge data for Tarbert were obtained from the NTGN (OPW), with the record extended using observations from the Carrigaholt tide gauge for 2019–2024 to provide an updated modern continuation.

To the west of Ireland, ~~tide~~tide-gauge records ~~for~~from Galway (1967–1970), near Nimmo’s Pier, and from Rossaveel (1973–1974) 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 the years 1967, 1970, 1973, and ~~1970~~1974 were incomplete. Tide-gauge ~~data~~records for Galway ~~Port~~ were obtained from the National Tide Gauge Network (NTGN-~~MI~~, 2007–2024).

~~For all sites, all datasets except~~Table 1 summarises 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, origin, temporal coverage, and supplementary datasets used for each of the six primary 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 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.

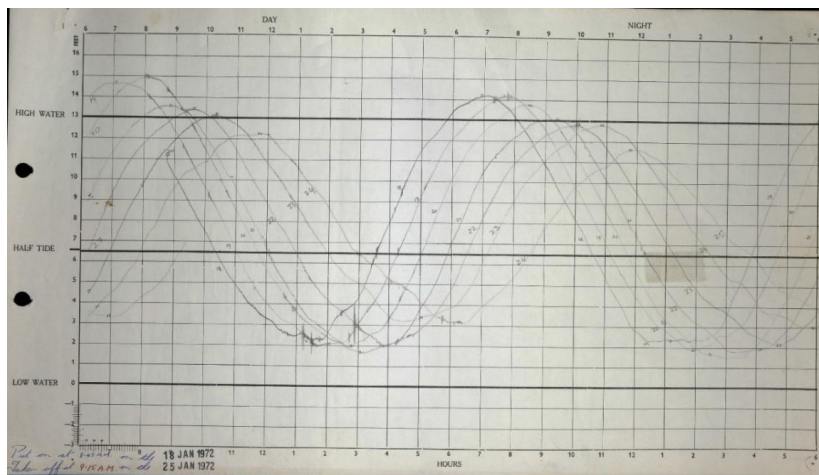


Figure 2. Example of a Cork marigram with a pencil trace. The X-axis represents time from 06:00–06:00 the following day, and the Y-axis shows water level in feet relative to chart datum. Dates are indicated above the pencil traces.

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 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.

Table 1. Summary of tide-gauge records, data sources, and periods used in this study prior to quality control and processing.

Site	Period	Primary data source	Additional data sources and extensions
Belfast	1925–2024	Murdy et al. (2015)	Bangor (2011–2022; BODC; extension/gap-filling)
Malin Head	1958–2024	PSMSL / OPW / MI	Portrush (1998–2003, 2015; PSMSL), NTGN records from OPW (2004–2008) and MI (2009–2024)
Dublin Port	1938–2024	PSMSL	Dún Laoghaire (1925–1931; McLoughlin et al., 2024; 1932–1933 digitized marigrams); Arklow (2003–2006), Howth (2007–2018, 2019–2024; NTGN/MI)
Cork Harbour	1971–2024	Port of Cork / OPW / MI	Tivoli historical records (digitized); Ringaskiddy (2012–2021), Currach Club (2022–2024; NTGN/OPW data)
Tarbert Island	1964–2024	OPW archives	Historical Tarbert records (digitized); Carrigaholt (2019–2024; NTGN/OPW data)
Galway	1967–2024	BODC (1967–1970, 1973–1974); MI (2007–2024)	Galway Harbour supplementation (2007–2024; NTGN/MI)

2.2. Datum Conversions

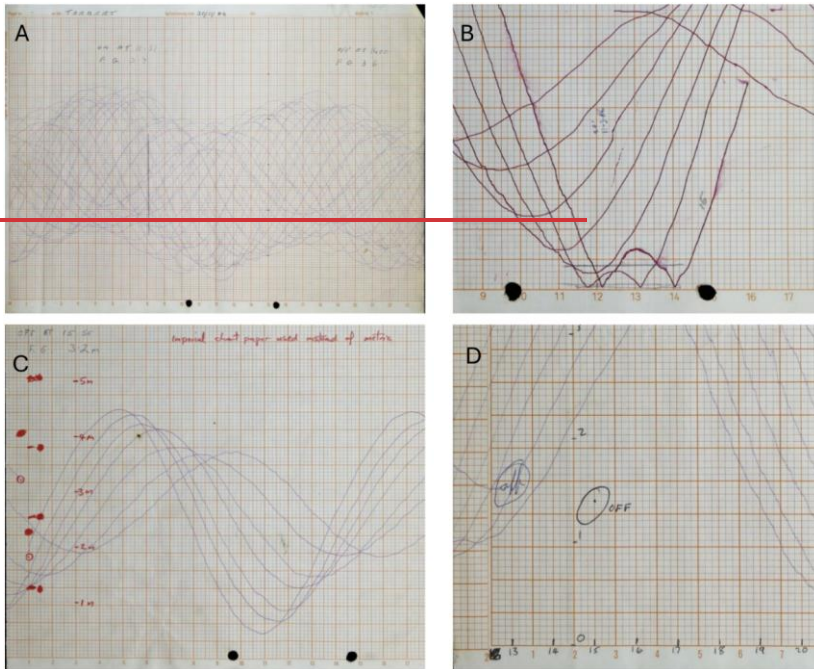


Figure 3. Examples of marigrams requiring careful digitization: (A) A Tarbert marigram spanning nearly one month, making accurate digitization nearly impossible. (B) Daily low tides intercepting or approaching the X-axis, requiring manual correction. (C) Variations in graph paper type and unit scaling, 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.

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; MI, 2025) 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 Sea-level data for all sites were adjusted to Ordnance Datum Malin (OD Malin; sometimes referred to as ODM). Records reported relative to Ordnance Datum Belfast (ODBOD Belfast) or Ordnance Datum Dublin (ODD₂; i.e., OD Poolbeg) were converted to ODM.

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 (PSMSL, 2025) and 0.037 m, was added to reference ODM. Similarly, Bangor data were adjusted by subtracting 10.500 m, adding 3.582 m (PSMSL, 2025), 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, siteusing station-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).
- 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 benchmarks, published or documented datum information, and archival metadata sources. 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). Based on this consistency, a correction of 2.705 m was applied to convert the Tarbert data to m_ODM.

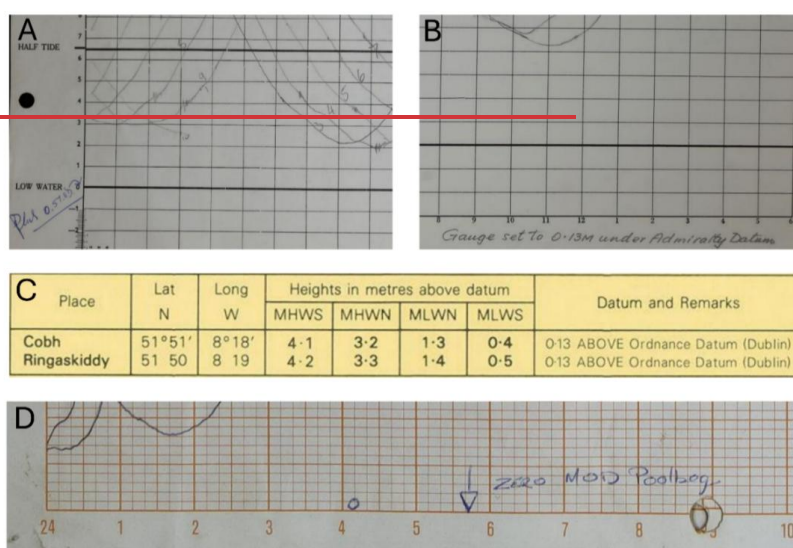


Figure 4. Datum adjustments applied to Cork (Tivoli) and Tarbert sea-level records at different periods: (A–C) Tivoli data—(A) 1970s corrected by +0.174 m (0.57 ft), (B) 1980s corrected by –0.13 m, consistent with gauge documentation and regional tide alignment, (C) early 2000s adjusted by +0.13 m to 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.

For Galway, the Galway Harbour datum used to convert data from ODD to ODM is 2.732 m (OPW, personal communication). BODC data adjustments and conversion procedures for all stations are documented in the Supplement, with Figure S3 showing Cork and Tarbert and Table S1 providing details 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; Figure 5). After applying this adjustment, the 2.732 m datum was subtracted to reference all values to ODM.

Galway (Eire) Site History

~~Fell 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

~~3. Figure 5. 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.~~

~~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 oee 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.

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 6) 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

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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 6) 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 6.

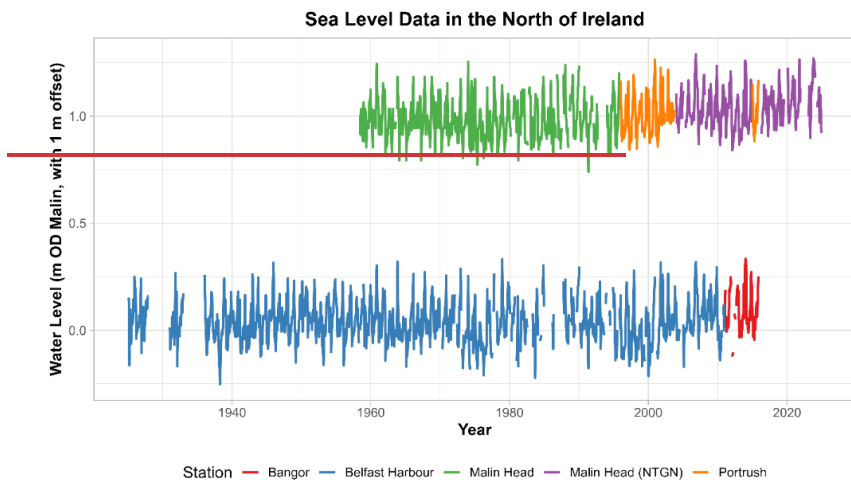


Figure 6. Mean Sea Level (MSL) for Northern Ireland tide gauges. Belfast and Malin Head have been offset by 1 m for clarity. All data are referenced to Ordnance Datum Malin (ODM). Bangor and Portrush records were used to supplement Belfast and Malin Head.

The Dublin Port tide gauge on the east coast (PSMSL, 1938–2001; PSMSL, 2025) exhibits unusual variations from the 1970s to early 1990s (Shoari Nejad et al., 2022). The timeseries for 1938–2001 is shown in Figure 7. 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.

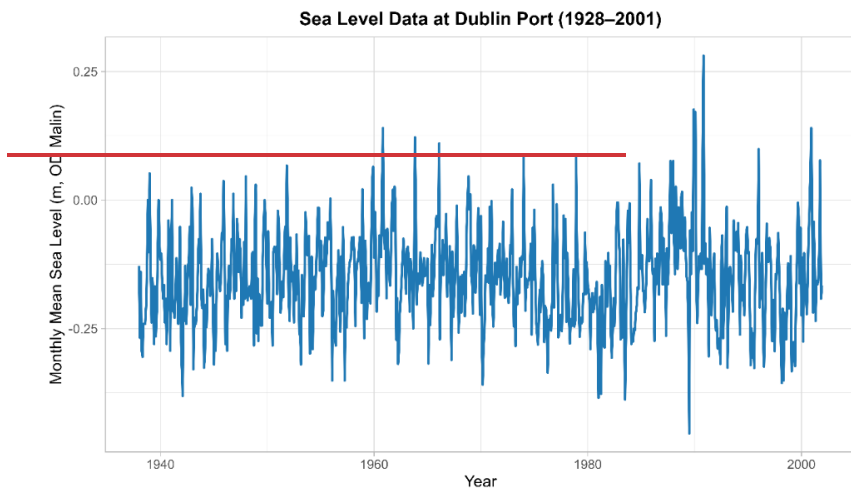


Figure 7. Monthly mean sea level measurements at Dublin Port (1938–2001), highlighting periods with consistently lower or higher monthly means, particularly from the mid-1970s to early 1990s.

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 reconstruction, 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 ($\sim 150.3^\circ$ – 160.2°). Outliers included 2001 ($>185^\circ$ phase lag) and slightly elevated 2002/2005 phase lags ($\sim 165.4^\circ/162.5^\circ$), 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 Curraeh Club (2022–2024) data were incorporated to further complete the Cork record. M2 amplitudes ranged ~ 1.40 – 1.49 m and phase lags $\sim 144.6^\circ$ – 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 8.

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 $\sim 145.9^\circ$ – 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 $\sim 144.6^\circ$ – 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 8. For Kilrush Lough, three months in 2024 (February, September, and October) were omitted following M2 corrections and statistical outlier detection.

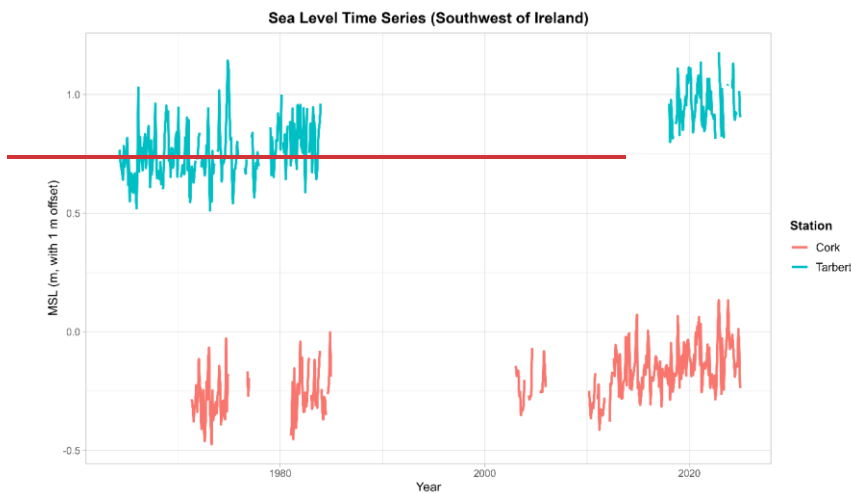


Figure 8. Sea level data for Tarbert (1964–1983), Kilrush Lough (2018–2024), and Cork sites—including Tivoli (1970s–1980s and 2000s), Currach Club, and Ringaskiddy—adjusted to Ordnance Datum Malin (ODM) and vertically offset by 1 m for clarity.

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 1.

Table 1. 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).	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 detected 3 SD from mean); Arklow Nov 2022 and July 2024 (used only in the full record to adjust Howth baseline offset with Howth).	Monthly means 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.	Tivoli 2003–2005; Ringaskiddy 2012–2021; Currane 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; monthly means deviating by more than three standard deviations from the mean.	Due to the extremely close proximity, all data were checked together across the full time series.	Galway Harbour 2007–2024.

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 9).

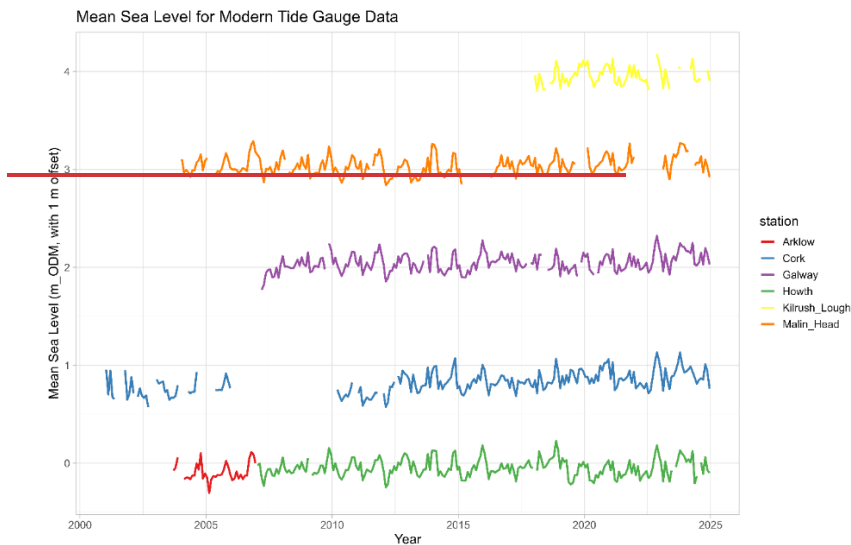


Figure 9. Tide-gauge records (2000s) for Arklow, Howth, Galway, Kilrush Lough, and Malin Head. Series are vertically offset by 1 m for clarity, except Arklow and Howth, which are shown together after applying a fixed datum offset to align them.

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 observations were extracted from modern datasets. Following standard validation practices, months with more than 15 missing days or days with more than 4 missing hours Months were excluded from monthly averages for all datasets, except for the PSMSL records, which when 15 or more days were either completely missing or contained more than four missing hourly observations. 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 MSL values are not computed calculated for months with more than 15 missing days, and where gaps exceeding ~4 hours in the primary channel are treated as missing when

calculating insufficient daily averages observations during quality assessment (UK Coastal Monitoring and Forecasting [UKCMF], 2014).

Tidal constituents were analysed for all high-resolution datasets where temporal resolution allowed, with particular focus on the dominant semi-diurnal M2 component. M2 amplitude and phase lag were used as primary indicators of record quality, as they are highly sensitive to timing errors, datum inconsistencies, and instrument-related issues, and therefore provide a robust measure of consistency in long tide-gauge series (Pugh & Woodworth, 2014). The M2 tidal constituent amplitude and phase were recomputed using the oce package (Kelley et al., 2022). Where M2 amplitudes or phase lags deviated from the rest of the dataset, monthly M2 values were inspected to identify and flag poor-quality observations. In addition, interannual variability in M2 parameters was assessed, with temporal evolution of both amplitude and phase used to assess datum stability and instrumental consistency across the record. At Belfast, as an example, values falling outside the observed M2 amplitude range (~1.13–1.24 m) were flagged as potential data-quality issues. Similar station-specific assessments were undertaken for the other records. Clearly erroneous spikes (i.e., physically unrealistic or corrupted values) were first identified and removed from the monthly MSL records. A subsequent quality-control step applied a threshold of ± 4 standard deviations (SD) from the station mean to identify potential outliers within the monthly MSL values. Values exceeding this threshold were assessed before exclusion across all sites. Such exceedances were rare and were interpreted as likely instrumentation or data-quality issues rather than physically plausible meteorological variability (e.g., storm surges), allowing removal of gross observational errors while preserving realistic variability within the records.

In addition to the procedures described above, selected records required station-specific corrections, including adjustment of timing offsets, removal of poor-quality intervals, and supplementation with nearby tide-gauge records where appropriate. These procedures were undertaken to maximise record continuity while maintaining consistency in datum and tidal characteristics. Full details of station-specific quality-control decisions, omitted periods, and supplementary datasets are provided in the Supplement. Corrected timeseries plots and quality control assessments for the principal tide-gauge records are presented in Figures S4–S11, while Table S2 summarises omitted periods, incorporation of supplementary records, and exclusion of potentially erroneous data. Harmonic tidal analysis (including M2 amplitude and phase) is

also used as a quality-control metric for assessing record consistency. Modern tide-gauge datasets obtained from the NTGN (MI and OPW) underwent additional quality control, including assessment of M2 tidal characteristics, statistical outlier detection, and evaluation of datum consistency between overlapping records. Further information on these procedures, including the Arklow–Howth datum adjustment and validation of modern datasets, is provided in the Supplement. The six composite tide-gauge records, supplemented by nearby modern stations, provide the longest continuous observational coverage in northern and eastern Ireland (Malin Head, Belfast, and Dublin Port), whereas the south-western records (Cork, Tarbert, and Galway) consist of more sporadic timeseries that include data gaps (Figure 2). Independent validation of the tide-gauge records against satellite altimetry was also performed to assess consistency over the satellite era (1993–present); these comparisons are shown in the Supplement (Figure S12 and Table S3).

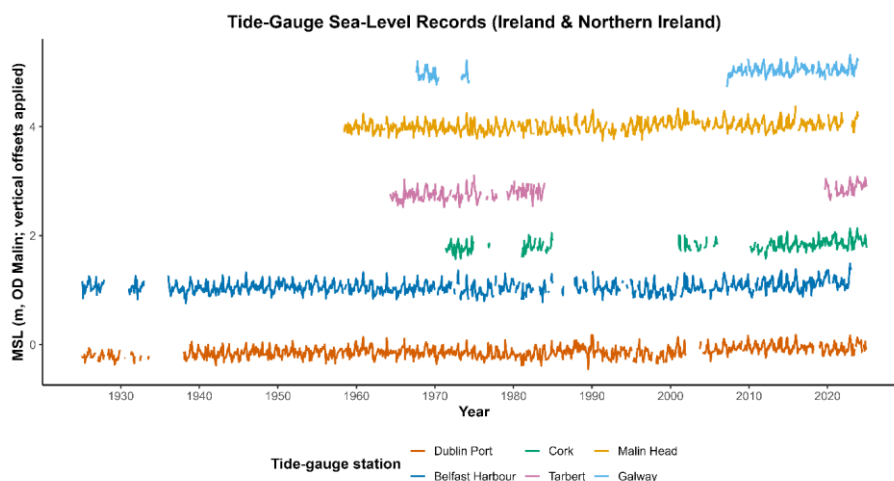


Figure 2. Tide-gauge records for Ireland and Northern Ireland. The six records combine historical PSMSL data with modern NTGN observations and, where required, nearby auxiliary stations to improve temporal continuity. Station-specific quality control was applied, including removal of outliers, datum consistency checks, and exclusion of unreliable periods as described in the text. Vertical offsets (1 m increments) are applied to individual stations for clarity.

5.4 Data Processing and Sea-Level Modelling

5.4.1. Atmospheric Adjustments

In the processing of the ~~MSL~~RSL 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 reanalysis (Copernicus Climate Change Service, 2025). ~~to cover the full time period of this study. These corrections, including surface pressure and wind forcing, reduce high-frequency atmospheric predictors were incorporated into a regression-based correction to account for atmospheric influences on the observed RSL variability and facilitate the identification estimation of long longer-term sea-level trends in MSL.~~

20CRv3 reanalysis provides a continuous record from 1806 to 2015 at 1° spatial resolution, making it well suited to ~~historie~~historical 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 reanalysis was employed. ERA5 reanalysis 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~~masks from the 20CRv3 reanalysis and the ERA5-Land monthly reanalysis 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 using a method adapted from~~ Frederikse & Gerkema (2018). ~~who accounted for atmospheric contributions to seasonal sea-level deviations.~~ Land points were masked using the native land-sea mask ~~of each dataset, setting,~~

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and the remaining ocean pressure values ~~over land~~ were averaged with cosine-latitude weighting to ~~missing~~ compute a weighted mean ocean pressure, which was then subtracted from each grid point to obtain anomalies. This ensures that ~~the~~ anomalies reflect ~~oceanic~~ ocean 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):

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

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):

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

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 $\pm 0.25^\circ$ (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):

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

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

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

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

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

where $\rho_{air} = 1.225 \text{ kgm}^{-3}$ 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.

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

WaterLevel(t)

$$= \beta_0 + \beta_1 P'(t) + \beta_2 \tau_x(t) + \beta_3 \tau_y(t) + \beta_4 \sin\left(\frac{2\pi t}{365.25}\right) + \beta_5 \cos\left(\frac{2\pi t}{365.25}\right) + \beta_6 \sin\left(\frac{2\pi t}{182.63}\right) + \beta_7 \cos\left(\frac{2\pi t}{182.63}\right) + \epsilon(t) \quad (6)$$

Here, t is time in days since the start of the year. For each tide-gauge record, β_0 is the intercept, β_1 , β_2 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. $\epsilon(t)$ 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 $P'_t(t)$, $\tau_x(t)$, $\tau_y(t)$) 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 variability in the observed sea-level record within a predefined local search region. Atmospheric variables, together with 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 terms, were incorporated as predictors. Consequently, all predictors that were statistically significant in the multiple regression were retained (Table 2).

Table 2. 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	$P'_t(t)$	$\tau_x(t)$	$\tau_y(t)$	$\sin\left(\frac{2\pi t}{365.25}\right)$	$\cos\left(\frac{2\pi t}{365.25}\right)$	$\sin\left(\frac{2\pi t}{182.63}\right)$	$\cos\left(\frac{2\pi t}{182.63}\right)$	Notes / Supplement
Malin Head	Included	Included	Included	Included	Omitted	Included	Omitted	—
Portrush	Included	Included	Included	Included	Included	Included	Omitted	—
Belfast	Included	Included	Included	Included	Included	Included	Omitted	Supplemented — by Banger 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	—

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 3. The in 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.

Table 3. 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	0.1	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 10 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.

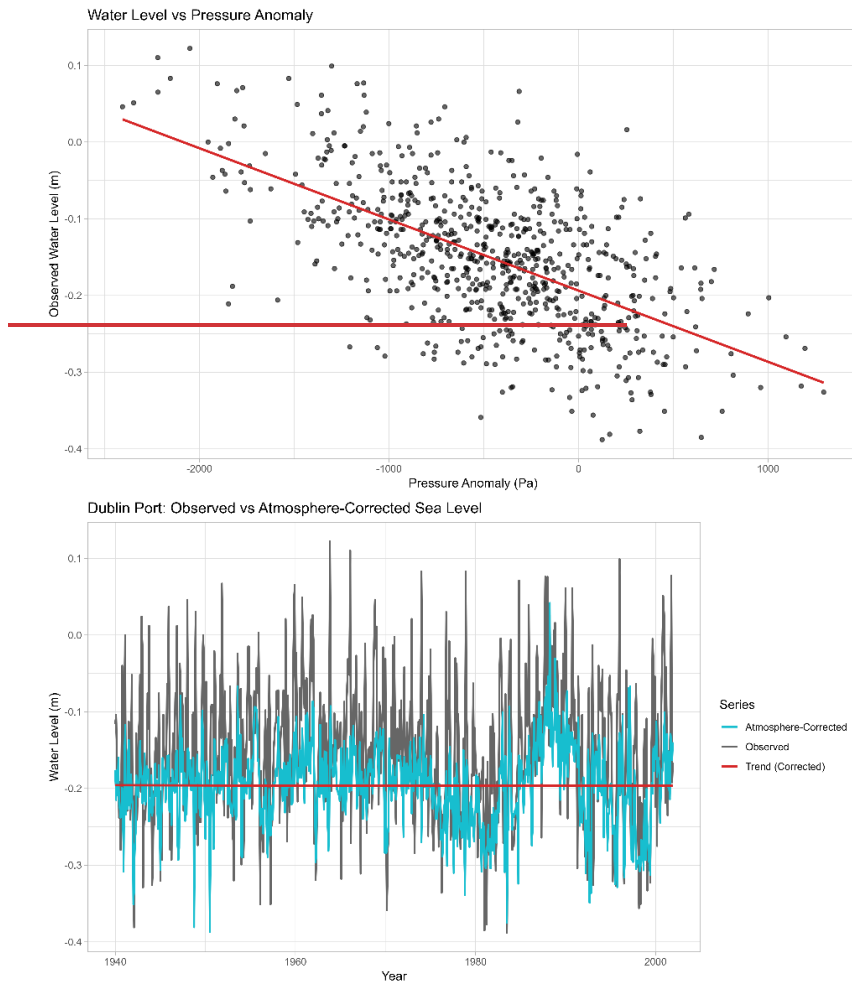


Figure 10. Atmospheric correction workflow at Dublin Port. Top: observed water level versus pressure anomaly, showing a strong negative correlation ($r = -0.599$, $p < 0.001$). Bottom: observed versus atmosphere-corrected water level, with a linear trend fitted. The regression removes atmospheric pressure 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 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 $\pm 1^\circ$ 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 ($-0.00130 \text{ m yr}^{-1}$), Dublin Port ($-0.000036 \text{ m yr}^{-1}$), and the combined record ($-0.000041 \text{ m yr}^{-1}$) agree within uncertainty. Bootstrap slope difference estimates (95 % CI: -0.000193 to $0.000205 \text{ m yr}^{-1}$) 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 11).

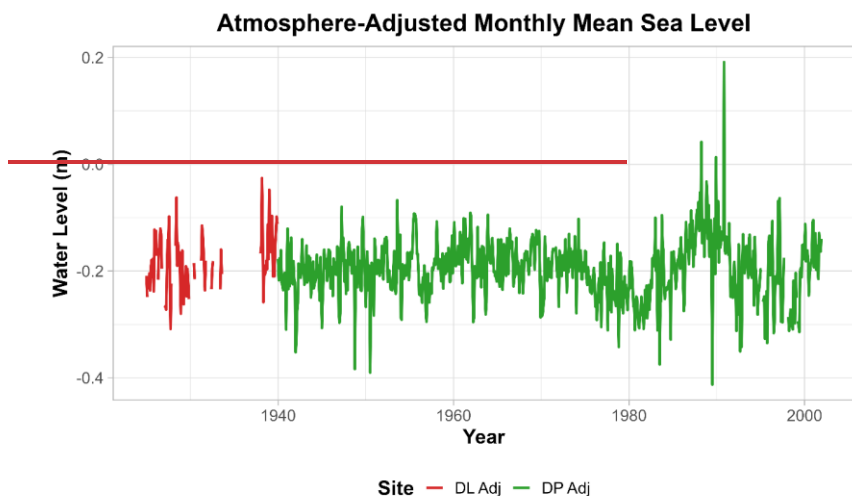


Figure 11. Time series of atmosphere-adjusted monthly mean water levels at Dún Laoghaire (DL Adj, red) and Dublin Port (DP Adj, green). There is no discontinuity between the 20CRv3 (DL Adj) and ERA5 (DP Adj) data. Atmospheric adjustments reduce high-frequency variability, emphasizing long-term sea-level trends.

Mean sea level (MSL) was then calculated over full years or using a minimum of 11 monthly mean values, following months is generally used for annual mean calculation (PSMSL, 2025), to avoid spurious this criterion could not be applied consistently to the historical tide-gauge records because some years contained substantial gaps. Years with fewer than three consecutive months of data were excluded. Therefore, years were retained where at least three consecutive months of data were excluded. valid observations were available, with all valid monthly observations in those years included in the annual mean calculation.

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5.3 GIA Corrections and The processed tide-gauge records used as input for the sea-level reconstruction are shown in Figure 3. The figure illustrates the spatial distribution of the selected tide-gauge sites, the temporal coverage of each record, and the remaining gaps in the observational datasets.

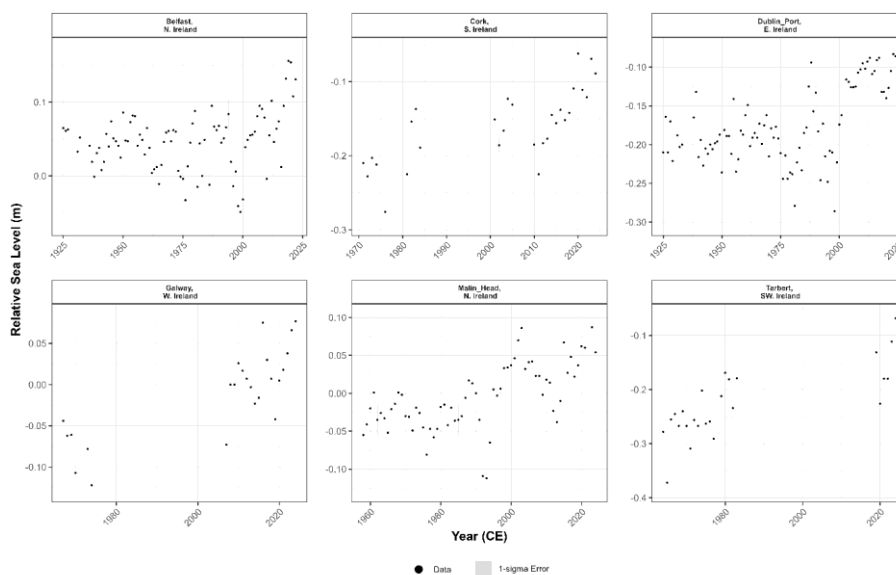


Figure 3. Tide-gauge records used as input to the RSL reconstruction model (datum: OD Malin, metres), showing spatial coverage, record length, and temporal gaps.

4.2 Incorporating Glacial Isostatic Adjustment into RSL Reconstruction

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, with the southwest generally experiencing greater subsidence relative to the northeast due to ongoing post-glacial adjustment. To account for the isostatic component of vertical land motion (VLM), we applied corrections from 1816 GIA models, including an ICE5G model and ICE6G Bradley-type models (thick, thin, hybrid, North Sea; Bradley et al., 2011, 2023), ICE-6G variants (standard, BC hybrid – hybrid boundary condition, VM5a – viscosity model; Peltier, 2004, 2015), and GLAC1D variants (BC hybrid – hybrid boundary condition, VM5a – viscosity model; 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/strategies, resulting in spatially variable predictions of uplift and subsidence across Ireland. By incorporating multiple GIA The ICE-5G model families and variants, we account for structural

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uncertainty in vertical land motion, enabling robust estimation of absolute sea-level rise (with site-specific GIA removed)(Peltier, 2004) was excluded from tide-gauge records the model evaluation owing to its older-generation ice-history reconstruction and Earth rheology assumptions, and because more recent GIA models provide improved calibration against contemporary observational constraints.

The aim was to identify the GIA model that minimised the inter-site spread of GIA-corrected RSL trends across Ireland. Model performance was assessed using the inter-site standard deviation of GIA-corrected RSL rates, with the optimal model defined as that which produced the smallest residual spatial dispersion among the corrected site-specific trends. This provides a data-driven measure of the extent to which each GIA model reduces residual spatial variability in the observed RSL trends prior to integration into the RSL reconstruction framework. Site-specific RSL records were therefore corrected using all 16 candidate GIA models, and the resulting inter-site spread in robust linear RSL trends was calculated for each model. The ICE6G_BC_hybrid_71p320 model produced the lowest residual inter-site spread among the candidate GIA corrections evaluated and was therefore selected as the GIA correction applied in the RSL reconstruction framework. The comparison was performed over 1973–2022, providing a common assessment interval that included observations from all sites within the available Irish tide-gauge network. Records were not required to be continuous over the full assessment period, and model evaluation was based on all available observations within this interval, including records with temporal gaps. This selection represents a data-driven optimisation of residual spatial dispersion among corrected tide-gauge trends rather than an assertion that ICE6G_BC_hybrid_71p320 provides the uniquely most physically realistic representation of GIA. The selected model reduces residual regional differences among corrected tide-gauge trends but should be interpreted within the broader uncertainty associated with alternative GIA reconstructions. Differences between candidate GIA models in predicted VLM rates (mm yr^{-1}) across the six Irish tide-gauge sites are shown in Figure 4.

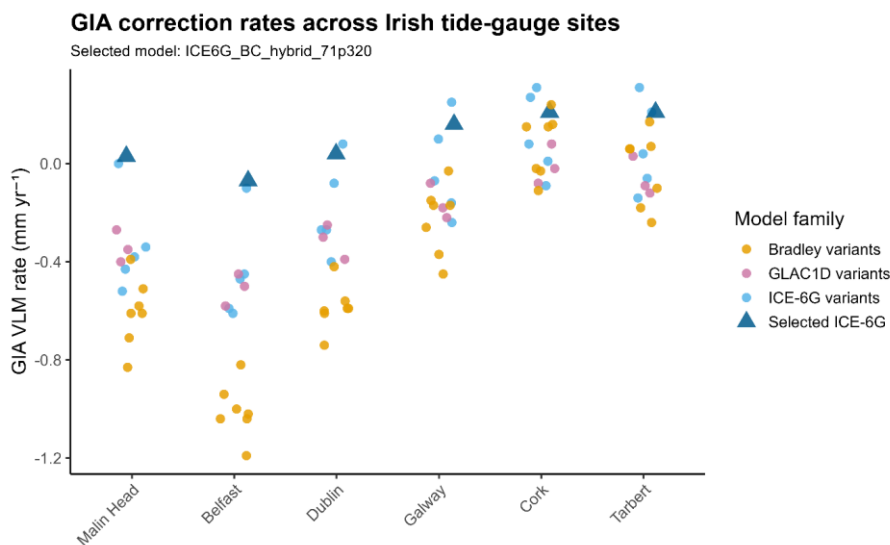


Figure 4: Modelled GIA VLM rates (mm yr^{-1}) at six Irish tide-gauge sites. Dark blue triangles indicate the selected ICE6G BC hybrid 71p320 model. Other symbols represent alternative GIA model families (ICE6G variants, Bradley-type variants, and GLAC1D). The ICE6G BC hybrid 71p320 model was selected based on its ability to minimise the residual inter-site spread in GIA-corrected RSL trends among the candidate models evaluated. This selection reflects improved spatial consistency of the corrected tide-gauge trends rather than the absolute magnitude of the predicted GIA VLM rates.

4.3. Statistical Sea-Level Modelling

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 12). 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.

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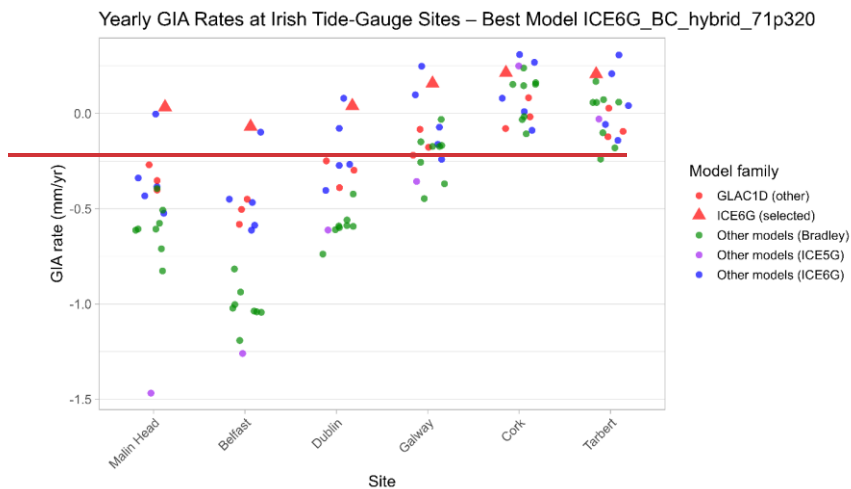


Figure 12. Yearly GIA rate corrections at six Irish tide-gauge sites. Red triangles indicate the selected ICE-6G-BC-Hybrid-71p320 model among the other model families.

The longer tide-gauge timeseries, extending back ~100 years, often contain gaps, nonlinear fluctuations, and observational noise, requiring a more-flexible statistical 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 $<0.25 \text{ mm yr}^{-1}$, 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.

to their modelling. Long-term sea-level RSL variability was then modelled using the Noisy Input Generalised Additive Model using the reslr package (Upton et al., 2024), which implements, Upton et al., 2025). This model uses a Bayesian hierarchical framework with random effect terms, spline-based smooths, and effects and a spatio-temporal Generalised Additive Models (GAMs) to represent nonlinear trends. Model (GAM) to examine RSL change and corresponding rates of change. It accounts for measurement uncertainty in both sea-level observations and corresponding incorporates age inputs using uncertainty through the Noisy Input method (McHutchon & Rasmussen, 2011), producing posterior distributions for sea level and its rates of change). These uncertainties were assigned according to the characteristics of each data source, incorporating known sources of temporal, measurement, and processing uncertainty.

The ~~relative sea data~~ level (RSL) field was modelled using a non-linear mixed effects Generalized for the Noisy Input Generalised Additive Model (NI-GAM; Upton et al., 2024) to account for long term trends, site specific deviations, and observational uncertainty is given by (Eq.71):

$$y_{ij} = y = f(x_j, t_i) + \epsilon_{yx}, t) + \epsilon_{yL} \epsilon_y \sim N(0, \sigma^2 + \frac{\sigma^2}{s_y^2} s_y^2) \quad (71)$$

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): where y is the response data, RSL, at site j and time i , $f(x, t)$ is the process mean that depends on location x and time t , and ϵ_y is the error term, where σ^2 is the residual variance and s_y is the known measurement uncertainty. Age uncertainties are required in the reslr package and were assigned according to data source. Modern tide-gauge observations were assigned an age uncertainty of 0.00023 years (~2 hours), digitized historical tide-gauge records an uncertainty of 0.002 years (~0.7 days), and monthly PSMSL tide-gauge records an uncertainty of 0.004 years (~1.5 days) to reflect increasing uncertainty associated with timing, digitization, and temporal aggregation. RSL observational uncertainties were assigned according to data source. A baseline uncertainty of 1 cm was applied to modern tide-gauge observations to account for potential instrumental and datum-related uncertainties. For Galway, this uncertainty was applied to the tide-gauge record from 1967 onwards, as the record was available in recorded form rather than requiring digitization. For Bangor, an exception was made for the modern data, with an uncertainty of 2 cm applied from 2011 onwards, reflecting greater uncertainty in data quality from 2016 and maintaining consistency with the conservative 2 cm uncertainty applied to Belfast. Digitized historical tide-gauge records were assigned a total uncertainty of 2 cm to account for additional digitization and processing uncertainties. Monthly PSMSL records were assigned a conservative vertical uncertainty of ± 2 cm to account for potential uncertainties associated with instrumental measurements, digitization, and data processing. The decomposition of the MSL process in reslr is given by (Eq.2):

$$f(x, t) = r(t) + g(z_x) + h(z_x) + l(x, t) \quad (82)$$

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where $r(t)$ is the regional time-varying component across all sites, $g(z_x)$ is a linear term for each site-specific slope (e.g., GIA), $h(z_x)$ is a site-specific vertical offset for each site, and $l(x, t)$ captures non-linear local spatio-temporal deviations. is a residual term for each site. 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 represents temporal 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 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 13 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 common across all sites (Upton et al., 2024).

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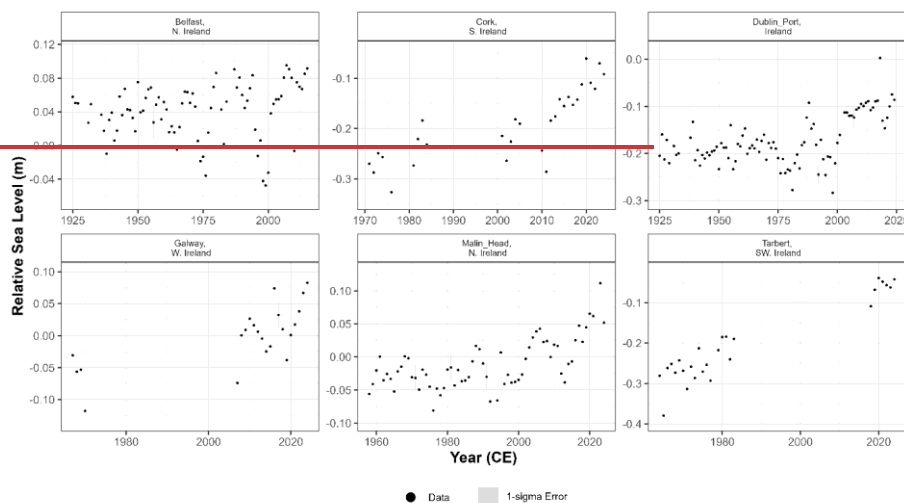


Figure 13. Tide-gauge sites used as input in the reslr package (datum: m_ODM). Annual relative sea level records are shown for each site, illustrating the spatial coverage, record length, and gaps in the dataset.

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The linear local component was modelled as an unstructured random effect for each site, constrained by site-specific GIA rates used as informed priors in the Bayesian framework. A corresponding linear-rate uncertainty of $\pm 0.3 \text{ mm yr}^{-1}$ was assigned to these GIA priors, providing a balanced prior that constrains physically plausible VLM while allowing the RSL observations to inform site-specific trends.

Overall, the estimated trends retain some broad correspondence with the spatial pattern represented by the GIA priors, but several sites show substantial departures from the 1:1 relationship, indicating that the inferred local linear component is not fully explained by the prescribed GIA correction (Figure 5). Galway and Tarbert show the closest agreement with their respective GIA priors, with estimated slopes of approximately 0.17 and 0.19 mm/yr compared with prescribed values of 0.16 and 0.21 mm/yr, respectively. In contrast, Dublin Port exhibits a substantially larger positive estimated trend (approximately 0.17 mm/yr) than its relatively small GIA prior of 0.04 mm/yr. Cork also shows a marked departure, with the estimated slope reduced to approximately 0.07 mm/yr relative to the prescribed GIA rate of 0.21 mm/yr, although the inferred trend remains positive. Belfast shows the largest absolute departure from the 1:1 relationship, with an estimated slope of approximately -0.22 mm/yr

compared with a GIA prior of -0.07 mm/yr, indicating a substantially more negative local linear component than prescribed by the GIA prior. Malin Head shows a smaller but notable departure, with the estimated slope changing sign from a positive GIA prior of 0.03 mm/yr to a slightly negative estimated trend of approximately -0.01 mm/yr. These differences demonstrate that, while the GIA priors provide a useful first-order representation of the regional pattern in VLM, the inferred linear local component retains substantial site-specific variability, including both amplification and attenuation of the prescribed trends and, at Malin Head, a reversal in sign.

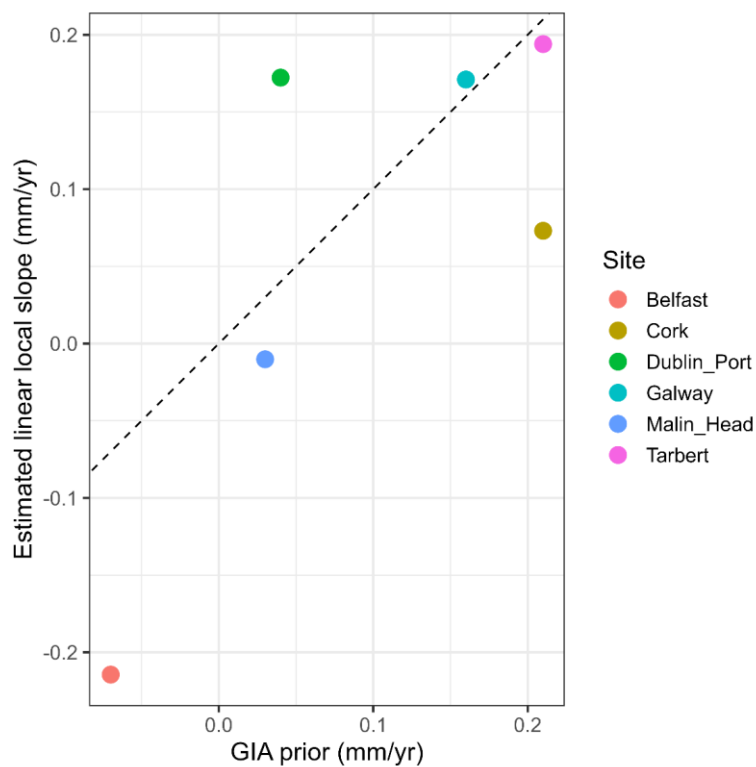


Figure 5. Comparison between prescribed GIA prior rates and estimated linear local trends from the NI-GAM inversion.

The reslr NI-GAM framework decomposes the RSL signal into regional, linear site-specific, site-level offset, and residual non-linear components, allowing both long-term trends and local deviations to be represented within a single hierarchical structure.

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Spline complexity in the reslr framework controls the flexibility of the regression splines used within the spatio-temporal Generalised Additive Model (GAM) to represent RSL variability (Upton et al., 2024, 2025). The parameter `spline_nseg_t` controls temporal spline complexity, determining how flexibly the model can represent changes through time, whereas `spline_nseg_st` controls the complexity of spatio-temporal variation between sites. Lower values produce smoother model behaviour, whereas higher values allow more complex temporal and spatial patterns but increase the potential for overfitting. In this study, spline complexity was intentionally restricted (`spline_nseg_t = 2`, `spline_nseg_st = 1`) to capture broad century-scale variability while avoiding overfitting, given the approximately 100-year reconstruction period, limited spatial coverage of tide-gauge sites, and heterogeneous temporal coverage of the observational records. Belfast and Dublin Port provide the strongest long-term constraints, whereas shorter and more discontinuous records from Malin Head, Cork, Galway, and Tarbert provide less information on long-term variability. Long-term sea-level trends generally require multi-decadal observations (e.g. ~40 years) to be estimated robustly (Hogarth et al., 2021). 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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Therefore, the selected spline complexity reflects the temporal and spatial information available within the tide-gauge network and avoids resolving higher-frequency variability that is not supported by the observations.

RSL rates for each site were obtained from posterior samples of the NI-GAM modelled rate of change (`mu_pred_deriv`), representing the posterior distribution of RSL rates (mm yr^{-1}) evaluated across the extended prediction grid. Prediction grids for each site were extended to cover 1925–2024, providing a common temporal framework for estimating and comparing site-specific rates. The RSL rate combines the shared regional component, site-level linear trends

informed by prescribed GIA estimates, and local deviations captured by the model. Extending the prediction grid beyond the temporal range of observations allows rate estimates to be evaluated over a common time interval across sites; however, uncertainty increases where estimates extend beyond direct observational constraints.

Yearly instantaneous RSL rates represent the derivative of the reconstructed RSL curve and describe the modelled rate of RSL change at individual years. Long-term mean modelled RSL rates were calculated by averaging these annual rate estimates over the specified time interval within each posterior draw. The resulting posterior distributions were summarised as posterior mean rates with 95% credible intervals (CI).

4.4. Model Validation

~~We assessed the~~The predictive performance of the NI-GAM model ~~was assessed~~ using 403-fold cross-validation ~~with the cross_val_check() function from the implemented in the reslr package (Upton et al., 2024).2024). Three-fold cross-validation divides the observations into three subsets, with each subset used once for model evaluation against predictions generated from the remaining data. Three-fold cross-validation was selected because the tide-gauge dataset contains a limited number of observations and uneven temporal coverage among sites, ensuring that sufficient observations remained within each training subset to constrain the spatio-temporal model structure. In this procedure, the dataset is repeatedly split into training and testing subsets to evaluate model accuracy. 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~~ages up to 2024 were included. 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.~~

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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 4). Narrow and consistent prediction intervals indicate that observational uncertainty is well captured.

The NI-GAM produced predictive intervals with coverage close to the nominal 95% level, achieving an overall coverage of 91.19%. Site-specific coverage ranged from 0.800 at Tarbert to 0.958 at Galway, reflecting differences in predictive performance among sites (Table 2). Prediction interval widths were highly consistent across the network (0.123–0.127 m), suggesting broadly consistent model-derived uncertainty estimates across the study region. Error metrics further support model performance, with an overall mean error (ME) effectively zero (<0.001 m), indicating minimal systematic bias. Mean absolute error (MAE) and root mean squared error (RMSE) remained low, with overall values of 0.028 m and 0.036 m, respectively. Site-specific RMSE values ranged from 0.032 to 0.048 m, with the largest errors observed at Tarbert, potentially reflecting greater uncertainty associated with the historical record and increased local variability.

Table 42. Cross-validation performance metrics for each site. Coverage shows represents the proportion of observed RSL values contained within the 95% posterior predictive interval; while PI width gives represents the interval width of this interval. ME, mean error; MAE, mean absolute error; RMSE, root-mean-square error.

Site	Coverage (95 % PI)	PI Width (m)	ME (m)	MAE (m)	RMSE (m)
Malin Head	0.926	0.123	0.001	0.025	0.034
Belfast	0.940	0.123	<0.001	0.029	0.036

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Dublin Port	0.926936	0.133123	-0.001	0.028	0.035
Cork	0.931862	0.135125	<0.001	0.027	0.035
TarbertGalway	0.962958	0.138126	<0.001	0.026	0.032
GalwayTarbert	0.955800	0.137127	<0.001	0.038	0.048

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 5), demonstrating strong predictive performance even for sparser records.

Table 5. 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 14. Most points closely follow the 1:1 line, and the narrow, consistent prediction intervals indicate that the NI-GAM effectively captures long-term trends. The NI-GAM captures the broad range of observed RSL variability while representing site-specific differences across the Irish tide-gauge network. Prediction intervals remain relatively narrow and consistent among sites, consistent with the similar uncertainty estimates obtained from cross-validation. Galway shows particularly strong agreement between observed and predicted values, with the highest predictive interval coverage (0.958) and a low RMSE (0.032 m). Cork and Malin Head also show relatively close agreement, with predictions capturing the main pattern of observed RSL variability. Greater departures from the 1:1 relationship are evident at Belfast and Dublin Port, while Tarbert shows the largest

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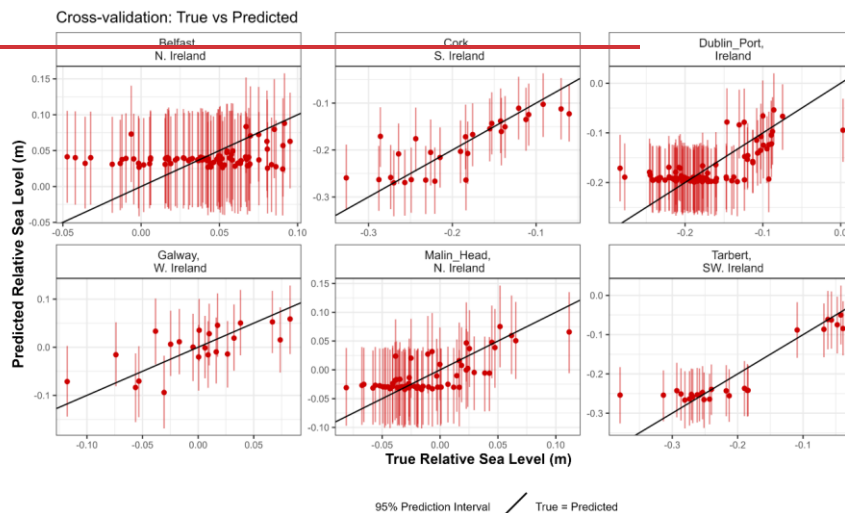
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deviation, consistent with its lowest predictive interval coverage (0.800) and highest RMSE (0.048 m). Overall, cross-validation indicates that the NI-GAM provides generally good predictive performance across the network, while also highlighting differences in predictive performance associated with site-specific variability, and measurement uncertainty. Model performance is strongest at Malin Head, Galway, and Tarbert, while Belfast exhibits slightly wider intervals and greater scatter, reflecting higher and uncertainty in the 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.

records.

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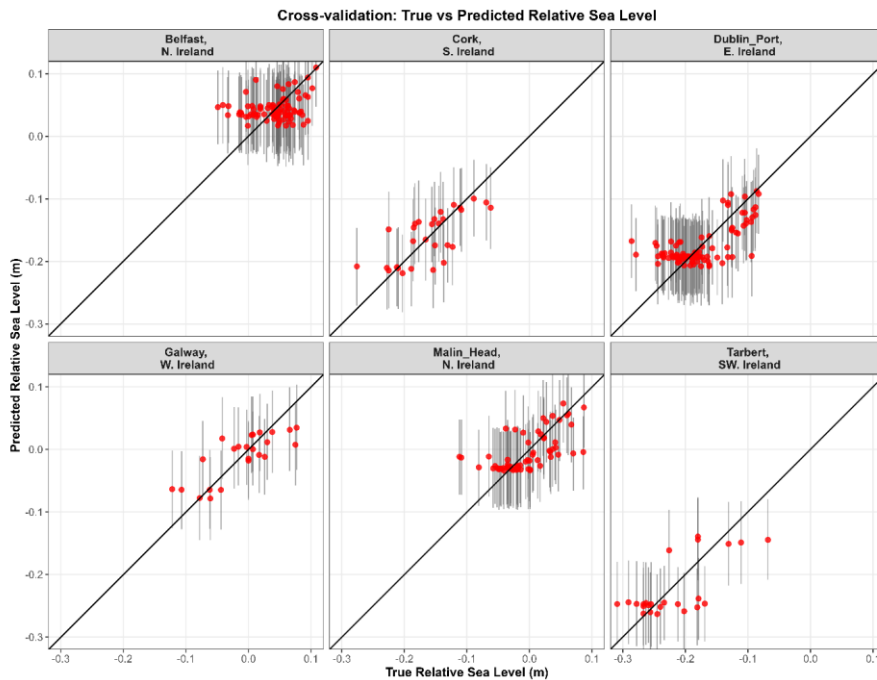


Figure 146. True versus predicted **relative sea level (RSL)** from **103-fold NI-GAM cross-validation** across all tide-gauge sites. Red points show posterior predictive means with **95 %95% predictive intervals**, and the black diagonal line represents the 1:1 reference; points **nearcloser to** the line indicate **strongstronger** predictive agreement.

An evaluation of the cross-validation residuals over time further clarifies this site-specific variability (Figure 7). Belfast and Dublin Port display temporal structure in their residuals, with periods of positive and negative deviations from zero rather than a consistently centred residual distribution. At Belfast, residuals are generally distributed around zero, although periods of predominantly positive and negative deviations are evident throughout the record, including more negative residuals around the late 1990s and early 2000s. Residual variability also appears greater in the most recent observations, with both positive and negative departures evident after approximately 2015, including several notable positive residuals. At Dublin Port, residuals show periods of predominantly negative values during parts of the 1970s–1990s, followed by generally more positive residuals during the 2000s and 2010s. The apparent flattening of the residual pattern may partly reflect the model capturing longer-term RSL

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variability, although some observational departures are not fully reproduced. Given the limited number of observations during some intervals, however, it is not possible to determine whether these deviations reflect persistent changes in RSL behaviour or shorter-term variability.

In contrast, residuals for Malin Head remain relatively well centred around zero throughout much of the record, although some temporal variability is evident. A positive excursion is evident approximately between 1998 and 2003 relative to the surrounding period. This interval coincides with the inclusion of additional historical observations from Portrush and may therefore partly reflect differences associated with combining the supplementary record segment. However, the deviation is localized and transient and does not provide strong evidence of persistent model bias or a long-term shift in the residuals.

The residual patterns at Cork, Galway, and Tarbert should be interpreted in the context of their lower data density and incomplete temporal coverage. Cork and Galway contain observations concentrated within particular periods, while Tarbert has particularly sparse observations and a substantial gap between historical and more recent measurements. The limited number of recent observations at Tarbert also constrains interpretation of its recent residual behaviour. Consequently, model performance at these sites reflects validation against discontinuous observations rather than continuous long-term historical variability, making direct comparison with longer records such as Belfast and Dublin Port more limited.

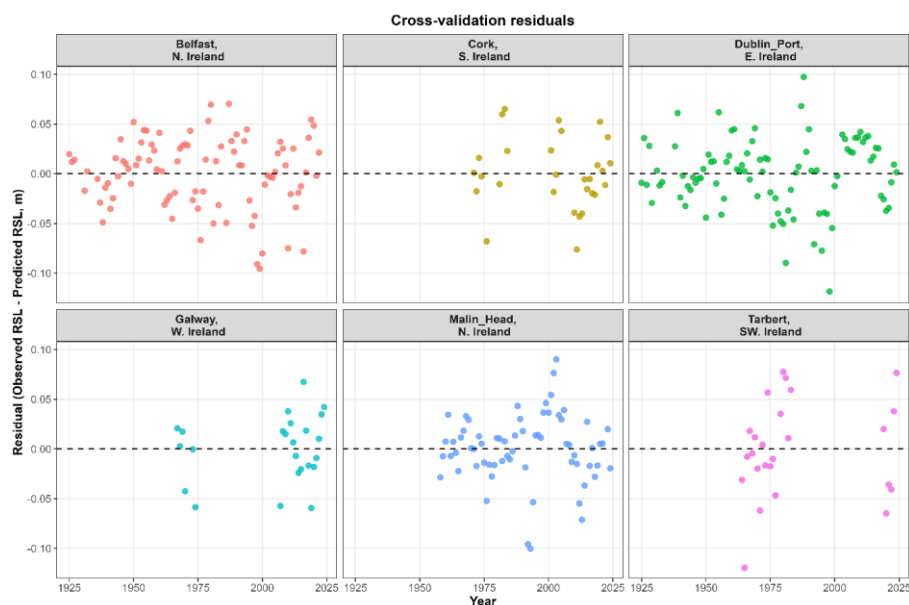


Figure 7. Cross-validation residuals (Observed – Predicted RSL, m) plotted against time (Year) for each tide-gauge station. The dashed horizontal line indicates zero error. The plots reveal site-specific temporal structures and variations in historical data density across the Irish coastline.

7.5 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 $\pm$ standard error (SE) derived from the posterior distribution, unless otherwise stated. Because the annual rate curves are smoothed, instantaneous rates may differ from raw year-to-year estimates by up to $\sim 1 \text{ mm yr}^{-1}$. 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 within typical interannual variability ($\sim 1 \text{ mm yr}^{-1}$), and do not materially affect the overall trends or spatial patterns

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(Figure 15). Figures 15–17 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 15). 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 ($2.14 \pm 0.23 \text{ mm yr}^{-1}$, 1958–2024), whereas Belfast shows the lowest ($1.07 \pm 0.14 \text{ mm yr}^{-1}$, 1925–2015), illustrating regional differences. Along the east coast, Dublin Port exhibits a mean rate of $1.57 \pm 0.18 \text{ mm yr}^{-1}$ (1925–2024). In the south and southwest, Cork shows a higher mean rate of $2.74 \pm 0.26 \text{ mm yr}^{-1}$ (1971–2024), with Tarbert at $2.48 \pm 0.25 \text{ mm yr}^{-1}$ (1964–2024), and along the west coast, Galway records $2.53 \pm 0.25 \text{ mm yr}^{-1}$ (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 $0.87 \pm 0.11 \text{ mm yr}^{-1}$ (1958–2000), Belfast at $0.56 \pm 0.09 \text{ mm yr}^{-1}$ (1925–2000), and Dublin Port at $0.67 \pm 0.09 \text{ mm yr}^{-1}$ (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.

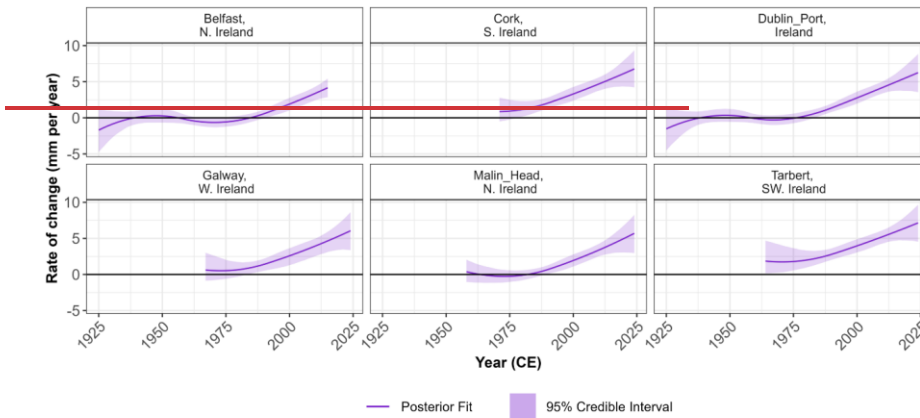


Figure 15. Modelled instantaneous sea-level rates across Irish tide gauge sites (1925–2024). The purple line shows the NI-GAM-derived instantaneous rate with site-specific GIA contributions removed, representing absolute (GIA-free) sea-level rates. Shaded regions indicate the 95% credible interval of 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 6. 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.

~~Table 6. 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.~~

The reconstructed relative sea level (RSL) record (Figure 8) reflects the combined influence of the regional signal, site-specific linear GIA-related contributions, and non-linear local variability across the Irish tide-gauge network. The regional component represents the dominant contribution to the network-mean RSL signal, while the non-linear local component remains comparatively small, indicating that site-specific departures from the broader spatio-temporal pattern are limited. The linear GIA-related component introduces spatial variability between sites consistent with the applied GIA priors, with inferred deviations reflecting differences between the prescribed GIA rates and the modelled site-specific trends.

Sites with shorter observational records, particularly Tarbert, Cork, and Galway, show increased uncertainty when the reconstruction is extended back to 1925, as reflected by wider Bayesian credible intervals (CIs). All sites show evidence of increasing RSL rates throughout the reconstruction period, with acceleration becoming apparent after approximately 1975 and particularly pronounced during the 2000s.

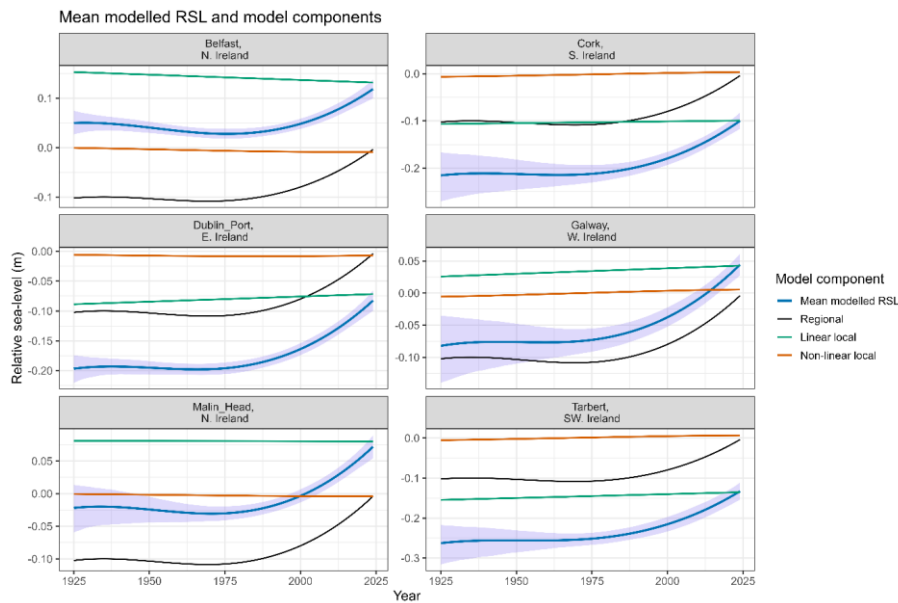


Figure 8. Mean modelled RSL (blue; sum of the three component contributions) and credible interval (blue ribbon), with decomposition into regional (black), linear local (GIA-related, green), and non-linear residual (red) components for Irish tide-gauge sites.

Mean modelled RSL rates across the Irish tide-gauge network show an overall increase from the late twentieth century into the 2000s, indicating acceleration in RSL change in recent decades. Here, mean modelled RSL represents the combined influence of the regional, linear GIA-related, and local model components. Instantaneous rates represent the modelled temporal rate of change in the smoothed NI-GAM RSL reconstruction and are reported for individual modelled years. In contrast, period-mean rates represent the average rate of change over a specified interval. The 95% CI widens towards the end of the modelled period (Figure 9), reflecting reduced observational constraints near the temporal boundaries of the reconstruction. For 2024, instantaneous RSL rates are estimated at 4.19 mm yr^{-1} (95% CI: 2.54–5.80) for Belfast, 4.37 mm yr^{-1} (95% CI: 2.76–5.99) for Malin Head, 4.63 mm yr^{-1} (95% CI: 2.99–6.26) for Dublin Port, 4.50 mm yr^{-1} (95% CI: 2.89–6.12) for Cork, 4.61 mm yr^{-1} (95% CI: 3.01–6.25) for Tarbert, and 4.59 mm yr^{-1} (95% CI: 2.98–6.22) for Galway.

Long-term mean modelled RSL rates vary geographically across the Irish tide-gauge network (Table 3). These rates allow comparison of spatial differences in long-term RSL change between sites. The mean modelled RSL rates are summarised in Table 3 for each tide-gauge site. Lower rates are observed in the north of Ireland, with Malin Head and Belfast exhibiting mean rates over 1925–2024 of 0.96 mm yr⁻¹ (95% CI: 0.54–1.39) and 0.71 mm yr⁻¹ (95% CI: 0.39–1.02), respectively. The lower rates are consistent with spatial variations in GIA-related vertical land motion across Ireland, with greater relative uplift in the north contributing to lower observed RSL rise. Dublin Port, located on the east coast, shows a mean rate of 1.17 mm yr⁻¹ (95% CI: 0.87–1.47) over 1925–2024, consistent with the broader regional pattern of higher rates along the east and south coasts compared with northern sites.

Higher mean rates are observed at the southern and western sites, with Tarbert showing the highest rate at 1.32 mm yr⁻¹ (95% CI: 0.79–1.92) over 1925–2024. Galway also exhibits a relatively high mean rate of 1.29 mm yr⁻¹ (95% CI: 0.80–1.90), while Cork shows a slightly lower rate of 1.18 mm yr⁻¹ (95% CI: 0.65–1.75). These higher rates likely reflect the combined influence of the regional sea-level signal and spatial variations in vertical land motion, with weaker GIA-related uplift and relative subsidence contributing to enhanced RSL change in parts of southern and western Ireland. Tarbert exhibits the highest long-term rate, indicating the strongest relative sea-level rise within the reconstructed network. Uncertainty is greatest for Galway, Cork, and Tarbert during the earlier part of the extended prediction period, with wider CI also evident at Malin Head (Figure 9). The increased uncertainty reflects reduced observational constraints during these periods, where the model relied more heavily on extrapolation beyond the available tide-gauge records. The extended prediction grid enables consistent rate estimates over 1925–2024, with greater uncertainty at sites having shorter observational records.

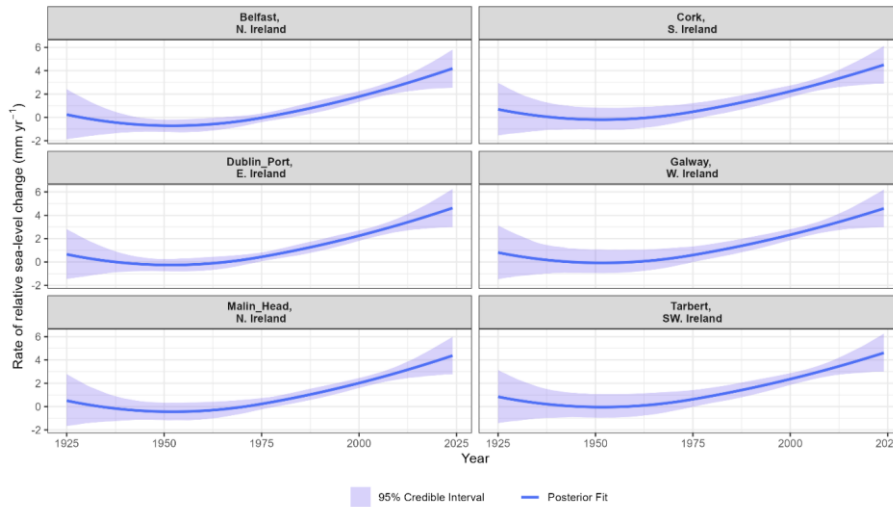


Figure 9: Modelled RSL rates (including regional, linear, and local components) across Irish tide-gauge sites (1925–2024). The figure highlights long-term trends and inter-site variability. Prediction grids were extended back to 1925 for all sites; increased uncertainty is evident at Cork, Tarbert, and Galway during periods without observations, reflecting reduced data constraints and greater uncertainty in the modelled rates.

Comparison with the earlier period (1925–2000) highlights the recent acceleration in modelled RSL change. During this earlier period, rates were generally low, with several sites showing values close to zero and substantial uncertainty. Belfast shows a mean rate of -0.01 mm yr^{-1} (95% CI: -0.36 to 0.34), Malin Head 0.26 mm yr^{-1} (95% CI: -0.24 to 0.78), and Dublin Port 0.45 mm yr^{-1} (95% CI: 0.10 – 0.80). Higher mean early-period rates were estimated at the western and southwestern sites, with Galway 0.61 mm yr^{-1} (95% CI: -0.01 to 1.41), Cork 0.49 mm yr^{-1} (95% CI: -0.16 to 1.23), and Tarbert 0.64 mm yr^{-1} (95% CI: -0.01 to 1.47), although uncertainty remained substantial. Across individual tide-gauge sites, the modelled rates shown in Figure 9 indicate higher rates during the early twenty-first century compared with the earlier twentieth-century period, consistent with a recent acceleration in RSL change across the tide-gauge network.

Table 3: Mean modelled RSL rates across Irish tide-gauge sites for the period 1925–2024. Rates are derived from the posterior total rate field and represent the combined contribution of the linear (GIA), regional, and local model components. Values are presented as posterior means with 95% CI.

Site name	Period (time span)	Mean instantaneous Rate (mm-yr ⁻¹)	Site-specific modelled linear GIA Contribution (mm-yr ⁻¹)	Mean GIA-free instantaneous sea-level RSL rate (mm-yr ⁻¹ , ± SE)	95% credible interval (CI)
Malin Head	1958–1925–2024	2.14 ± 0.23	0.03	2.11 ± 0.24	0.0354–1.39
Belfast	1925–2015–2024	1.07 ± 0.14	-0.07	1.14 ± 0.14	0.39–1.40
Dublin Port	1925–2024	1.57 ± 0.18	0.04	1.53 ± 0.18	0.87–1.84
Cork	1971–1925–2024	2.74 ± 0.26	0.00	2.74 ± 0.26	0.2165–1.75
Tarbert	1964–1925–2024	2.48 ± 0.25	0.00	2.48 ± 0.25	0.2179–1.92
Galway	1967–1925–2024	2.53 ± 0.25	0.00	2.53 ± 0.25	0.1680–1.90

To enable fair comparison across sites, mean modelled instantaneous rates were calculated over the overlapping period 1971–2024 (Table 7) 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 7. Comparison of mean modelled instantaneous sea-level rise rates ($\pm$ SE) across

aHThe regional modelled RSL signal confirms the acceleration observed at individual tide-gauge sites (Figure 10). The mean modelled RSL rate across the Irish tide-gauge network over 1925–2024 is 1.11 mm yr⁻¹ (95% CI: 0.78–1.45). When separated into earlier and more recent periods, the mean rate increases from 0.41 mm yr⁻¹ (95% CI: -0.01–0.88) during 1925–2000 to 3.27 mm yr⁻¹ (95% CI: 2.61–3.93) during 2000–2024, demonstrating a marked acceleration in RSL change. The instantaneous mean modelled RSL rate in 2024 reaches 4.48 mm yr⁻¹ (95% CI: 2.84–6.14), indicating continued acceleration in the rate of RSL change during the early twenty-first century. These mean modelled RSL rates incorporate the common regional sea-level signal together with site-specific GIA and local components, with GIA represented using the ICE6G_BC_hybrid_71p320 model.

The regional component exhibits a similar temporal pattern. Across the full model period (1925–2024), the posterior mean regional rate is 1.01 mm yr⁻¹ (95% CI: 0.19–1.84). The regional rate increases from 0.31 mm yr⁻¹ (95% CI: -0.58–1.25) during 1925–2000 to 3.16 mm yr⁻¹ (95% CI: 2.13–4.09) during 2000–2024, reaching an instantaneous regional rate of 4.37 mm yr⁻¹ (95% CI: 2.66–6.03) by 2024. The close correspondence between the mean modelled RSL rate and regional rate indicates that the common regional signal dominates the network-mean RSL evolution. The GIA-related and local components make comparatively small contributions to the network-mean rate, with the mean modelled RSL rate differing from the regional rate by only approximately 0.10 mm yr⁻¹.

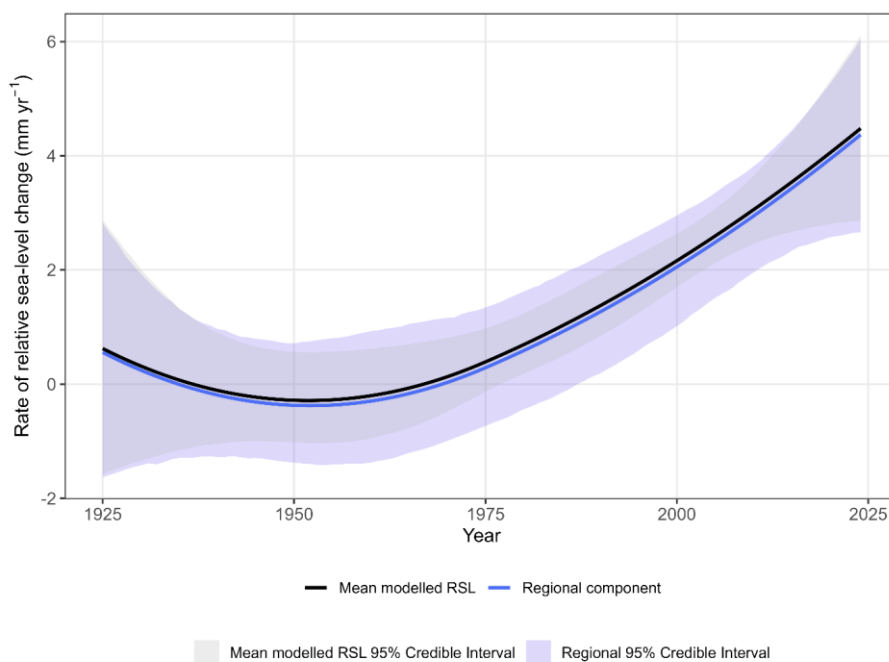


Figure 10: Mean and regional RSL rates (1925–2024) across the Irish tide-gauge network. Shaded areas indicate the 95% CI. The mean modelled RSL rate combines regional, GIA, and local components, while the regional rate represents the shared spatio-temporal signal. The close correspondence between the two rates indicates that the GIA and local components make only a small contribution to the network-mean modelled RSL rate.

The accumulated RSL change implied by the posterior RSL rate reconstruction was calculated by cumulatively summing annual posterior rate estimates through time. The mean accumulated RSL rise across the reconstructed Irish tide-gauge sites. **Note: Belfast record ends in 2015; all other sites extend to 2024. Note: $\pm$ SE as defined in Table 6.**

Site	Period	Modelled instantaneous Rate (mm yr ⁻¹ , $\pm$ SE)
Malin Head	1971–2024	2.56 $\pm$ 0.26
Belfast	1971–2015	1.86 $\pm$ 0.22
Dublin Port	1971–2024	2.57 $\pm$ 0.26
Cork	1971–2024	2.74 $\pm$ 0.26

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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 16, which shows the regional component. Between 1925 and 2024, the mean modelled instantaneous sea level rate, with the site specific GIA contribution removed, was $1.88 \pm 0.10 \text{ mm yr}^{-1}$. Including the ICE6G_BC_hybrid_71p320 GIA contribution, the mean modelled instantaneous rate increases to $1.96 \pm 0.10 \text{ mm yr}^{-1}$, 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 16), reflects the increase in instantaneous rates over 1925–2024. Between 1925 and 2024, sea level rose by 0.151 m (15.1 cm), based on the difference between the levels at the start and end years.

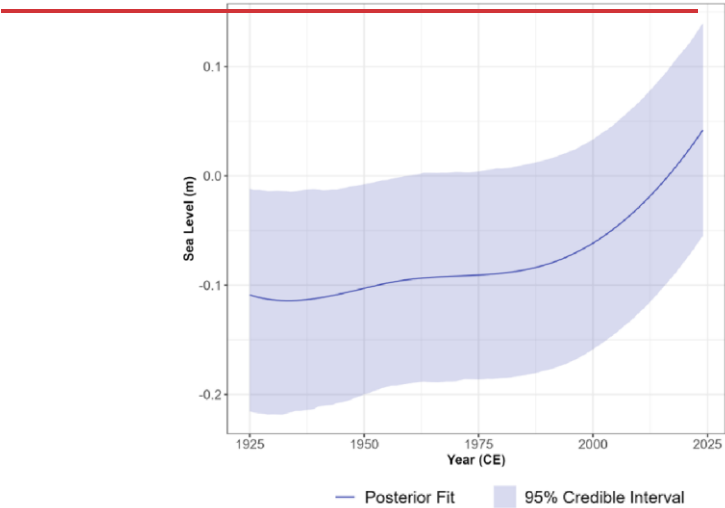


Figure 16. Smoothed regional sea level curve (1925–2024) across Irish tide gauges (GIA-free). Shaded areas show the 95 % credible interval. The curve represents the smoothed analysis of the tide gauge records, not raw annual observations, with of the regional sea-level signal, site-specific linear GIA contributions removed(GIA-related) components, and non-linear local variability.

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The yearly rates of sea level rise are shown in Figure 17 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 $0.84 \pm 0.05 \text{ mm yr}^{-1}$ (GIA-adjusted) and $0.77 \pm 0.04 \text{ mm yr}^{-1}$ (GIA-free) during 1925–2000 to $4.34 \pm 0.09 \text{ mm yr}^{-1}$ (GIA-adjusted) and $4.23 \pm 0.09 \text{ mm yr}^{-1}$ (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 (95 % CI: 6.15–6.15). These values represent the modelled derivatives of the smoothed fit, highlighting the pronounced acceleration in sea level rise during the 21st century.

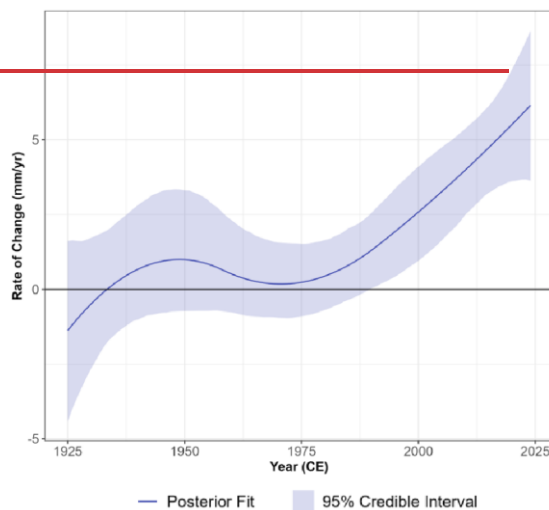


Figure 17. Regional GIA-free instantaneous sea level rates (1925–2024) derived from the posterior. Shaded areas indicate the 95 % credible interval. The curve represents smoothed instantaneous rates, not raw annual tide-gauge slopes.

8.6 Discussion

The results highlight spatial and temporal variability in sea level behaviour across Northern Ireland. This study presents an integrated view of modelled RSL change for the island of Ireland over the past century. By incorporating newly digitized records from the south and southwest of the country, the analysis provides estimates of both the common regional sea-

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level signal and site-specific deviations from this signal. We find a consistent pattern of RSL rise, with acceleration becoming particularly pronounced since the early twenty-first century and instantaneous sea-level rates from the posterior are $2.14 \pm 0.23 \text{ mm yr}^{-1}$ exceeding 4 mm yr^{-1} at the Irish tide-gauge sites in 2024. These recent rates are broadly consistent with the accelerated rates of global mean sea-level rise observed in recent decades.

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Results from the statistical modelling in this study are consistent with previous studies. Orford et al. (2006) reported RSL rates of $-0.20 \pm 0.37 \text{ mm yr}^{-1}$ for Belfast (1918–2002) and $-0.16 \pm 0.17 \text{ mm yr}^{-1}$ for Malin Head (1958–2024) and $1.07 \pm 0.14 \text{ mm yr}^{-1}$ at Belfast (1925–2015). Note the different end years. Modern modelled total (1998). For comparison, the NI-GAM reconstruction estimates a modelled RSL rate of -0.01 mm yr^{-1} (95% CI: -0.36 to 0.34 mm yr^{-1}) for Belfast over 1925–2000 and 0.52 mm yr^{-1} (95% CI: 0.10 – 0.93 mm yr^{-1}) for Malin Head over 1958–1998. The Belfast estimate is consistent with the near-zero rate reported by Orford et al. (2006), while the Malin Head estimate is higher than the earlier estimate, although differences in record composition and methodological treatment limit direct comparison. These differences likely reflect variations in the underlying observations, record composition, temporal coverage, and methodological treatment of long-term trends. In particular, the updated Malin Head record differs in composition from that used by Orford et al. (2006), incorporating observations from Portrush in 1998. Differences in the available observations and record processing may therefore influence the estimated trend over this multi-decadal interval. The higher 2024 values represent 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 rate estimates 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 15, indicating increased uncertainty in these periods. Both substantially exceed their earlier century rates of $0.87 \pm 0.11 \text{ mm yr}^{-1}$ at Malin Head (1958–2000) and $0.56 \pm 0.09 \text{ mm yr}^{-1}$ 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 $\pm 1 \text{ mm yr}^{-1}$. 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 1925–2015 NI-GAM reconstruction and, when considered alongside the temporal increase in modelled record, whereas our Malin Head rate (2.14 mm yr^{-1} , 1958–

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2024) closely matches the IPCC estimate, indicating broad consistency with our regionally averaged modelled rates. Rates are consistent with an acceleration in RSL change in recent decades.

To the east, Dublin Port exhibits a long-term ~~instantaneous sea level~~ mean modelled RSL rate of $1.57 \pm 0.18 \text{ mm yr}^{-1}$ (1925–2024), while pre-2000 rates were lower, around $0.67 \pm 0.09 \text{ mm yr}^{-1}$ (95% CI: 0.87–1.47). The estimated mean modelled RSL rate for 1925–2000, rising was lower at 0.45 mm yr^{-1} (95% CI: 0.10–0.80), increasing to $3.75 \pm 0.18 \text{ mm yr}^{-1}$ (95% CI: 2.47–3.51) for 2000–2016, and reaching 6.19 mm yr^{-1} (3.67–8.70). The instantaneous RSL rate in 2024 reached 4.63 mm yr^{-1} (95% CI: 2.99–6.26), indicating a substantial recent increase in the rate of RSL change. These results are generally consistent with previous tide-gauge estimates for overlapping periods. For example, Shoari Nejad et al. (2022) ~~report~~ reported a tide-gauge-derived MSL trend of 1.4 mm yr^{-1} (95% CI: 0.6–1.6 ~~mm yr~~ mm yr^{-1}) for Dublin Port during 1953–2016 based on using Bayesian linear regression applied to corrected data, whereas observations, compared with our mean modelled RSL rate is of 1.27 mm yr^{-1} (95% CI: 1.61 ~~mm yr~~ 1.02 – 1.53) for the same period. Although slightly higher, but both the two estimates show broad agreement and indicate an overall increase. Earlier in RSL rise. Previous analyses ~~show~~ have reported more modest and variable pre-2000 sea-level rates of RSL change around at Dublin Port prior to 2000, with modelled rates of -0.84 mm yr^{-1} for (1938–1961, declining to -0.32 mm yr^{-1} for ; 95% CI: -0.69 to 0.29 mm yr^{-1}) and 0.24 mm yr^{-1} (1961–1980; 95% CI: -0.17 to 0.64 mm yr^{-1}). These estimates are broadly consistent with historical estimates of 0.6 mm yr^{-1} (values reported by Carter (1982), who estimated MSL rates of 0.6 mm yr^{-1} for 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} modelled RSL rate of 0.37 mm yr^{-1} (95% CI: 0.09–0.65). Differences between studies are expected due to varying models likely reflect variations in data coverage, corrections, and data coverage; nevertheless, modelling approaches; however, all estimates indicate relatively little increase pre-modest rates of RSL rise before 2000, followed by a pronounced acceleration post 2000. Shorter term rates during 2000–2016 are $3.75 \pm 0.18 \text{ mm yr}^{-1}$, reflecting marked acceleration in the 21st century recent decades. Palaeo-reconstructions using saltmarsh foraminifera also indicate a similar century-scale comparable long-term RSL rate since the early 19th nineteenth century ($1.6 \pm 0.6 \pm 0.9 \text{ mm yr}^{-1}$; 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 $2.74 \pm 0.26 \text{ mm yr}^{-1}$ (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 $2.48 \pm 0.25 \text{ mm yr}^{-1}$ (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 $2.53 \pm 0.25 \text{ mm yr}^{-1}$ (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 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 ($1.86 \pm 0.22 \text{ mm yr}^{-1}$), Dublin Port ($2.57 \pm 0.26 \text{ mm yr}^{-1}$) and Malin Head ($2.56 \pm 0.26 \text{ mm yr}^{-1}$) had intermediate rates, and the highest rates occurred in the southwest, ranging from $2.69 \pm 0.26 \text{ mm yr}^{-1}$ at Galway to $2.74 \pm 0.26 \text{ mm yr}^{-1}$ at Cork and Tarbert.

The combined mean GIA free regional component across all tide gauge sites is shown in Figure 16. Between 1925 and 2024, the mean modelled instantaneous sea level rate, with GIA contributions removed, was $1.88 \pm 0.1 \text{ mm yr}^{-1}$, increasing to $1.96 \pm 0.1 \text{ mm yr}^{-1}$ when including the ICE-6G_hybrid_71p320 GIA contribution. The smoothed regional curve (Figure 16) 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 Higher RSL rates of rise are observed along the southern and western coasts of Ireland. Cork shows a long-term mean modelled RSL rate of 1.18 mm yr^{-1} (95% CI: 0.65–1.75; 1925–2024), with the instantaneous RSL rate reaching 4.50 mm yr^{-1} (95% CI: 2.89–6.12) in 2024. This differs from the MSL rate reported by Pugh et al. (2021), who estimated a rate of $2.2 \pm 0.2 \text{ mm}$

yr⁻¹ for Cork over 1842–2019/2020. Differences between these estimates likely reflect contrasting time periods, modelling approaches, record processing, and datum alignment. Pugh et al. (2021) aligned the Cork record to a datum of 2.752 m, whereas in this study the Cork reconstruction was aligned to the OPW datum of 2.69 m, with additional site-specific adjustments applied. Applying the 2.752 m datum results in a larger divergence between the Cork tide-gauge and satellite SSH trends, with a trend difference of -3.17 mm yr^{-1} (satellite minus tide gauge). In contrast, the OPW-sourced datum provides closer agreement with the satellite and modern Ringaskiddy and Currach Club observations, providing further support for the adopted datum correction. The selected adjustment produced close agreement with modern Ringaskiddy and Currach Club observations from 2012 onwards, providing support for the adopted datum correction. Tarbert exhibits the highest long-term mean rate among the analysed sites, with a mean modelled RSL rate of 1.32 mm yr^{-1} (95% CI: 0.79–1.92; 1925–2024). This rate is consistent with the broader pattern of higher RSL rise along southern and western Ireland but should be interpreted with some caution because the historical Tarbert record has greater datum uncertainty than other sites. The instantaneous RSL rate in 2024 reached 4.61 mm yr^{-1} (95% CI: 3.01–6.25). River discharge from the River Shannon may also influence observed sea-level variability at Tarbert, as shown in other estuarine systems (e.g., Piecuch et al., 2018). On the west coast, Galway exhibits a long-term mean modelled RSL rate of 1.29 mm yr^{-1} (95% CI: 0.80–1.90; 1925–2024), with the instantaneous RSL rate increasing to 4.59 mm yr^{-1} (95% CI: 2.98–6.22) in 2024, consistent with the broader regional acceleration in RSL change. The reconstructed Irish RSL record (1925–2024) was compared with global MSL reconstructions and observations, including the Palmer et al. (2021) global tide-gauge reconstruction (1925–2010) and the Copernicus Marine Service (CMS, 2026) satellite altimetry sea-surface height (SSH) record (1993–2024) (Figure 11). The Irish RSL reconstruction follows a broadly similar long-term pattern to the global records, with relatively modest changes through much of the twentieth century followed by increased rates of sea-level rise during recent decades. The Irish reconstruction begins with a higher reconstructed RSL value in 1925 than the global tide-gauge reconstruction. However, the global tide-gauge record exhibits a faster rise during the early-to-mid twentieth century, resulting in convergence of the two records by the late 1970s. From the mid-1990s to 2010, the Irish RSL record remains slightly below the global tide-gauge reconstruction, consistent with regional differences in the magnitude of recent sea-level change. During the satellite altimetry era (1993–present), the Irish RSL and global SSH records display comparable acceleration patterns, with the global SSH record remaining slightly higher.

The similarity in recent trends indicates that the acceleration observed around Ireland is consistent with the broader global sea-level signal.

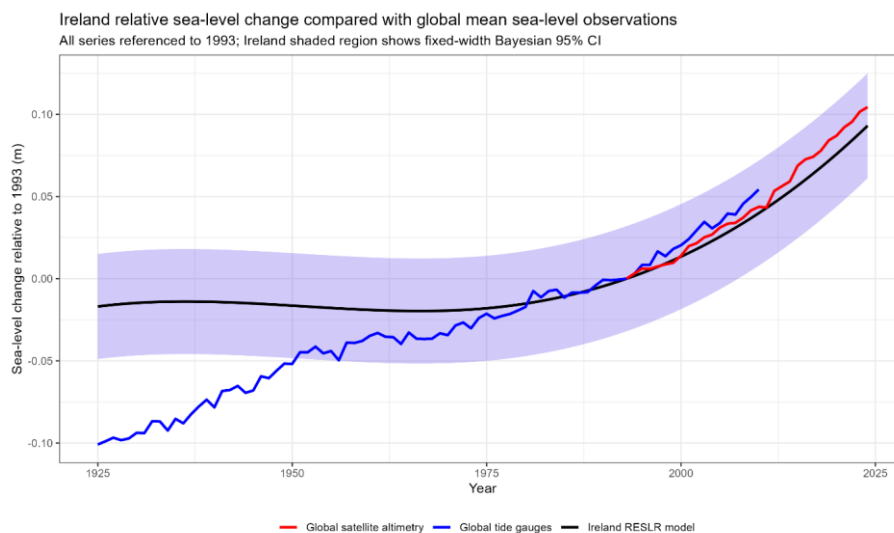


Figure 11. Comparison of the reconstructed Irish RSL record (1925–2024) with global MSL datasets. The Irish RSL reconstruction is shown alongside the Palmer et al. (2021) global tide-gauge reconstruction (1925–2010) and the Copernicus Marine Service (CMS) global mean sea-surface height (SSH) satellite altimetry record (1993–2024).

Between 1925 and 2024, the mean modelled RSL rate across the Irish tide-gauge network was 1.11 mm yr^{-1} (95% CI: $0.78\text{--}1.45 \text{ mm yr}^{-1}$). The model indicates a clear acceleration through time, with the mean modelled RSL rate increasing from 0.41 mm yr^{-1} (95% CI: $-0.01\text{--}0.88 \text{ mm yr}^{-1}$) during 1925–2000 to 3.27 mm yr^{-1} (95% CI: $2.61\text{--}3.93 \text{ mm yr}^{-1}$) during 2000–2024. Integration of the posterior RSL rate field indicates a cumulative RSL rise of 11.1 cm (95% CI: $7.81\text{--}14.5 \text{ cm}$) between 1925 and 2024. This magnitude is broadly consistent with reported twentieth- and early twenty-first-century global MSL rise estimates of approximately 10–25 cm (IPCC, 2021; Mu et al., 2025), although regional differences arise from spatial variability in processes such as GIA, ocean dynamics, and local VLM.

Hogarth et al. relative sea-level tide-gauge data using a linear model is $1.90 \pm 0.60 \text{ mm yr}^{-1}$. 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.

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} relative to the GIA-free rate, 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 $-1.96 \pm 0.1 \text{ mm yr}^{-1}$ for the ICE6G_BC_hybrid_71p320-adjusted rate and $-1.90 \pm 0.60 \text{ mm yr}^{-1}$ 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 (2021) reconstructed long-term sea-level records for Great Britain using an extensively augmented and spatially clustered tide-gauge dataset, applying GIA corrections, and reported a post-1900 weighted linear rate of 2.12 mm yr^{-1} , with evidence of long-term acceleration from the nineteenth to twentieth century. The mean modelled RSL rate estimated here across the Irish tide-gauge network was 1.11 mm yr^{-1} (95% CI: $0.78\text{--}1.45 \text{ mm yr}^{-1}$) over 1925–2024, while the corresponding regional RSL component was 1.01 mm yr^{-1} (95% CI: $0.19\text{--}1.84 \text{ mm yr}^{-1}$). The lower mean modelled RSL rate estimated here for Ireland may partly reflect differences in regional sea-level response and GIA-related VLM, while differences in tide-gauge spatial coverage, record length, temporal periods analysed, and modelling approaches limit direct comparison. Earlier tide-gauge studies, as noted previously, reported near-zero to slightly negative RSL trends in Northern Ireland during the late 1990s and early 2000s (Orford et al., 2006). The present results are broadly consistent with these findings and with wider evidence indicating relative uplift in Northern Ireland, while southwestern Ireland experiences reduced uplift or subsidence (Bradley et al., 2011; Bradley et al., 2023; Kirby et al., 2023). These spatial differences reflect variations in GIA associated with former ice loading, with greater ice thickness and loading over Britain producing stronger GIA-related VLM responses, while thinner ice cover over Ireland resulted in comparatively smaller GIA effects (Shennan et al., 2018).

The GIA model ICE6G BC hybrid 71p320 was selected as the preferred model because it minimised the inter-site spread of GIA-corrected RSL trends and produced the lowest spatial variability across the Irish tide-gauge network. However, this selection should not be interpreted as indicating that it represents the uniquely optimal geophysical reconstruction of GIA. Rather, it represents the most suitable correction under the criterion adopted here, namely reducing spatial variability in observed RSL trends prior to integration into the RSL model, particularly between northern and southwestern Ireland. The inclusion of the modern Bangor

record, adjacent to the Belfast tide-gauge record, may contribute to the recent increase in northern RSL rates and reduce the apparent difference between northern and southern sites. Data gaps and differences in record quality were carefully considered during data preparation. To avoid potentially influential recent observations, the 2023–2024 Bangor data were excluded from the analysis because the apparent acceleration was considered potentially unreliable. Inclusion of these observations would increase the estimated Belfast rate over 1925–2024 from 0.71 mm yr⁻¹ to more than 0.9 mm yr⁻¹. During the earlier period, Belfast showed a slightly negative mean rate of -0.01 mm yr⁻¹ (95% CI: -0.36 to 0.34) over 1925–2000, compared with 0.23 mm yr⁻¹ (95% CI: -0.09 to 0.55) over 1925–2010. These earlier estimates indicate little net RSL rise, with substantial uncertainty, whereas inclusion of the modern Bangor observations results in a more pronounced recent acceleration in the Belfast record. This sensitivity highlights the influence that recent observations can have on estimated long-term rates and indicates that differences between sites should be interpreted cautiously. In the present analysis, ICE-6G variants generally produced the smallest spatial gradients across the Irish network, while GLAC1D variants produced intermediate gradients. Bradley-type models generally produced the largest spatial gradients, resulting in a stronger north–southwest contrast in modelled RSL trends.

Cross-validation of the NI-GAM model demonstrates generally reliable predictive performance for the reconstructed RSL time series, providing support for the robustness of the derived trends and instantaneous rate estimates. Three-fold cross-validation showed that 95% posterior predictive intervals captured 80.0–95.8% of held-out tide-gauge observations across sites, with an overall coverage of 91.19%. Prediction intervals were highly consistent across the network, with widths ranging from 0.123 to 0.127 m. Error metrics further support model performance, with an overall mean error (ME) effectively zero (<0.001 m), indicating minimal systematic bias. Mean absolute error (MAE) and root mean squared error (RMSE) remained low, with overall values of 0.028 m and 0.036 m, respectively, while site-specific RMSE values ranged from 0.032 to 0.048 m. Some variation is evident among sites, with Tarbert showing the largest residual errors and lowest predictive coverage, potentially reflecting greater uncertainty associated with the historical record, limited observational constraints, and increased local variability. Belfast and Dublin Port also showed modest departures from the 1:1 observed–predicted relationship, suggesting that some local multi-decadal variability may not be fully resolved within the model.

Although the tide-gauge records were represented as annual observations in the model inputs, a common observational uncertainty may not fully represent site- and time-dependent variability associated with the underlying measurements. Future work could investigate whether incorporating time-dependent and site-specific observational uncertainties, derived from the underlying tide-gauge records, improves uncertainty calibration and predictive agreement at locations with greater local variability. Overall, the cross-validation results indicate that the NI-GAM provides reliable predictions of regional RSL variability with well-characterised uncertainty, while highlighting locations where local variability and uncertainty representation may influence predictive performance.

Hogarth et al. (2021) at $1.96 \pm 0.1 \text{ mm yr}^{-1}$ including GIA contributions and $1.88 \pm 0.1 \text{ mm yr}^{-1}$ 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 ($0.84 \pm 0.05 \text{ mm yr}^{-1}$ GIA-adjusted, $0.77 \pm 0.04 \text{ mm yr}^{-1}$ GIA-free) and increased markedly between 2000 and 2024 ($4.34 \pm 0.09 \text{ mm yr}^{-1}$ GIA-adjusted, $4.23 \pm 0.09 \text{ mm yr}^{-1}$ GIA-free). Annual rates peaked in 2024 at 6.28 mm yr^{-1} (GIA-adjusted, 95 % CI: 6.19–6.36) and 6.15 mm yr^{-1} (GIA-free, 95 % CI: 6.15–6.15), explicitly highlighting the GIA-adjusted peak 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, particularly related to historical datum conversions, metadata limitations, and the interpretation of incomplete historical documentation. Although extensive datum adjustments and sensitivity assessments were

undertaken to standardise records to Ordnance Datum Malin, uncertainties in historical benchmarks, reference relationships, and undocumented changes in gauge configuration may influence long-term RSL estimates. Additional observational uncertainties include potential digitization ~~can occur~~ errors (McLoughlin et al., 2026), and tide gauge data may contain instrumentation ~~error~~ effects (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 ~~it~~, and residual high-frequency variability but do not eliminate all uncertaintynot fully removed by atmospheric corrections.

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 borrow information from the regional signal and other sites included in the model, providing continuous estimates across the full prediction period when prediction grids are extended. The conservative spline specification adopted in the NI-GAM prioritises estimation of long-term regional variability while limiting the representation of shorter-term variability that is not well constrained by the available tide-gauge observations.

For sites with limited observations, the model combines site-specific information with the regional signal and the linear (GIA-related) component to estimate RSL changes beyond the observed record. Estimates within the observation period are therefore most strongly constrained, whereas extrapolated estimates rely more heavily on model assumptions and regional information and should be interpreted with greater caution.

The Irish tide-gauge network analysed in this study shows evidence of accelerating RSL rise, with spatial differences reflecting local processes and higher long-term rates along the southern and western coasts. These regions, including 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 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 $2.5\text{--}3\text{ mm yr}^{-1}$, 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. may be particularly vulnerable due to higher RSL rates and limited observational coverage, especially within the Shannon Estuary. Projected long-term average rates towards the end of the century are highest in the southwest ($3.3\text{--}4.8\text{ mm yr}^{-1}$) and lower in the northeast ($2.2\text{--}3.7\text{ mm yr}^{-1}$) (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~~MSL (Wang et al., 2024).

9 **Conclusion**

A7 Conclusions

The key objective of this study was to ~~reconstruct~~estimate 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

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critical spatial gaps and situates Irish sea-level changes within a broader regional context, complementing previous studies in the UK.

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The overall regional modelled mean rate of sea level rise from 1925–In 2024 is $1.96 \pm 0.1 \text{ mm yr}^{-1}$. Removing the GIA contribution reduces this slightly to $1.88 \pm 0.1 \text{ mm yr}^{-1}$, representing the GIA free (absolute) rate. Rates of sea level rise reached $6.18\text{--}6.36 \text{ mm yr}^{-1}$ in 2024, with the highest mean instantaneous RSL rates observed in the southwest of were elevated across Ireland, where ranging from 4.19 to 4.63 mm yr^{-1} . Rates were broadly similar among sites such as Cork, with the highest estimated values occurring at Dublin Port and Tarbert, and followed by Galway exhibit elevated vulnerability to accelerated sea level rise and coastal flooding.

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Cork, indicating widespread acceleration in RSL rise across the Irish tide-gauge network. Adjustments for datums, atmospheric effects, seasonal cycles, and GIA were applied, incorporated into the analysis, with additional sensitivity testing used to assess the influence of GIA model choice. Under the chosen ICE-6G-ICE6G BC Hybridhybrid 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 the site-specific GIA rates were selected because this model produced the greatest reduction in inter-site differences, particularly in Northern Ireland in observed RSL trends when evaluated using a linear regression framework prior to integration into the reslr package. This selection does not indicate that it represents the definitive best GIA model. Future studies could further quantify the influence of GIA uncertainty and evaluate which GIA model provides the most physically plausible representation of VLM.

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Cross-validation confirms the robustness demonstrates generally good predictive performance of the regional reconstruction, demonstrating that even locations with shorter or sparse records can be reliably incorporated. Short predictive coverage close to the nominal 95% level, low overall error, and broadly consistent prediction-interval widths across the network. While short-term variability at individual sites is smoothed, emphasizing the strength the model captures the broad patterns 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 observed RSL variability 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, provides generally consistent uncertainty estimates. Performance varies among sites, with lower predictive coverage and urban exposure highlights the importance of targeted monitoring and adaptation planning.~~

~~higher errors at Tarbert, reflecting greater uncertainty associated with its sparse and discontinuous observational record.~~ 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 to reconstruct historical RSL change across Ireland. By synthesising available MSL observations from across the island, this study provides the first geographically balanced reconstruction of historical sea-level change in Ireland and strengthens~~ 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~~ Previous studies of MSL change in Ireland reported relatively low rates of rise (Carter, 1982; Woodworth et al., 1999; Orford et al., 2006), ~~and only while more~~ recent individual site studies have ~~shown identified~~ 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~~ This synthesis reveals a geographically balanced view, ~~clear acceleration in sea-level rise since the early 2000s, with the mean modelled RSL rate increasing from 0.41 mm yr⁻¹ (95% CI: -0.01–0.88) during 1925–2000 to 3.27 mm yr⁻¹ (95% CI: 2.61–3.93) during 2000–2024.~~ The results indicate that Ireland ~~now experiences recent~~ rates of sea-level rise in Ireland are broadly comparable to ~~or higher than~~ global averages, with ~~higher modelled RSL rates in the southsouthwest and west being more vulnerable east than in the east and north.~~ In ~~Given~~ the 21st century, ~~with accelerating observed recent acceleration in sea-level rise, Ireland's heavily and projected future increases, Ireland's~~ coastal population will need to adapt to the associated ~~higher frequency of increase in~~ coastal flooding and inundation.

~~Review statement. Review statement: Not yet peer-reviewed; to be updated upon submission to the journal.~~ Future work should focus on extending this reconstruction to additional sites and refining GIA corrections to improve understanding of regional sea-level change and support adaptation planning in vulnerable coastal areas.

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

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Dataset availability. Historical tide gauge records digitized as part of this study, together with ~~the Galway BODC~~ 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 ~~the modern~~ <https://www.digitalocean.ie/Data/DownloadTideData> (MI ~~data is available at:~~

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~~<https://www.digitalocean.ie/Data/DownloadTideData>~~ (Marine Institute, 2025), respectively. ERA5 and 20CRv3 reanalysis data used for atmospheric and seasonal corrections are available from ~~(<https://cds.climate.copernicus.eu/>)~~<https://cds.climate.copernicus.eu/> (Copernicus Climate Change Service, 2025) and ~~(https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html)~~https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html (NOAA PSL, 2025). Satellite altimetry sea-level data used for global comparisons are available from the Copernicus Climate Change Service (C3S, 2018) at <https://doi.org/10.24381/cds.4c328c78> and the Copernicus Marine Service (CMS, 2026) at <https://doi.org/10.48670/moi-00148>.

~~Code availability.~~ Code for all major components of this study ~~is~~will be made available on GitHub (~~<https://github.com/PatrickJMcLoughlin/Ireland-Sea-Level>~~<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; sea-level modelling; conceptualization. **R.E:** Writing – review and editing. **C. O'B:** Satellite data validation.

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Supplement of

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

McLoughlin et al.

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2. Data Collection and Digitization of Dún Laoghaire, Cork, and Tarbert Historical Records

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 Dun Laoghaire (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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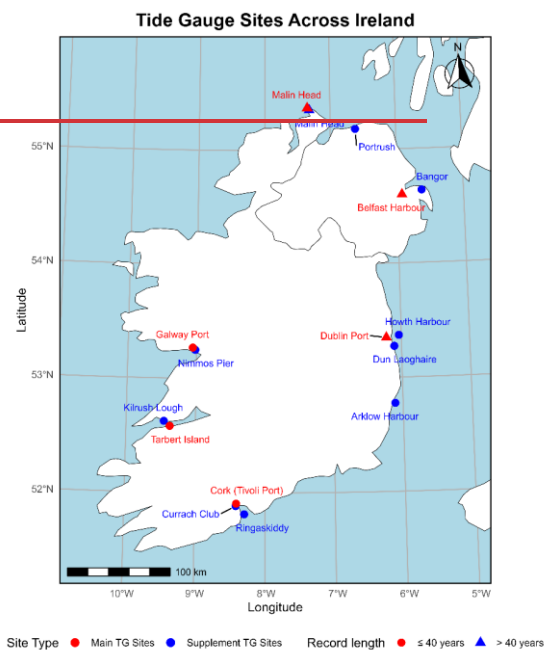


Figure 1. The six primary tide gauge (TG) sites are shown in red. Supplementary TG sites, shown in blue, are nearby gauges (modern or historical) used to fill gaps or improve record quality. Belfast Harbour, Dublin Port, and Malin Head are long-record sites (>40 years), with records spanning 60–100 years.

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).

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). Additional data for two additional years (1932–1933) were recovered from raw marigrams; however, these records are less reliable due to thicker, less accurate traces—complete because of degraded trace quality, particularly in 1933, when frequent clock stoppages affected the data record. Only the months of June to August in each were digitized for these years. This seasonal restriction may introduce sampling bias; however, because the analysis focuses on multi-year sea-level trends and tidal statistics, any seasonal signal is expected to have a limited influence on the results. 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 with an estimated positional 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. 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 1971–1974, 1976–1977, and 1981–1984–1985, and, together with more recent records from a modern tide gauge for 2001–2005 and 2010–2012–2011. The 2001–2005 and 2010–2012–2011 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 2S1), with measurements spanning 06:00–06:00 the following day, and in most images. They 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 (0.01–0.01 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 to 23:00 (i.e., 24 hourly values per day). 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.

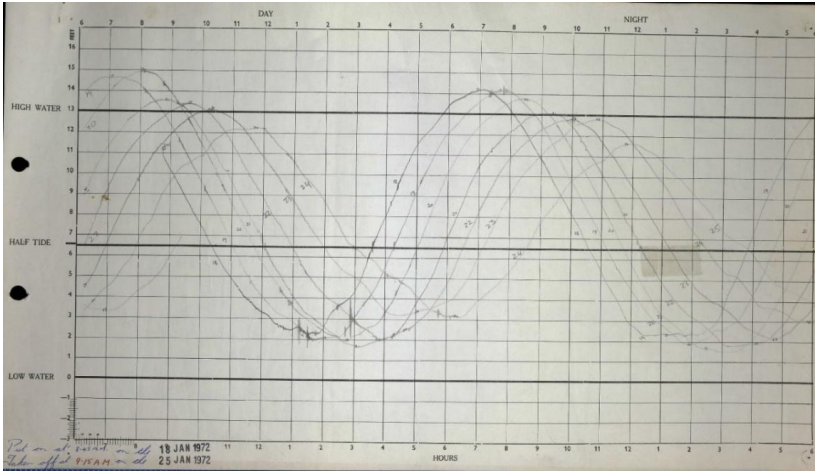


Figure 2S1. Example of a Cork marigram with a pencil trace. The X-axis represents time from 06:00–06:00 the following day, and the Y-axis shows water level in feet relative to chart datum- (CD). Dates are indicated above the pencil traces. Data courtesy of Port of Cork engineers (personal communication, 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 due to ~~continuous~~ extensive 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 the data were therefore 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 3AS2A–D). Figure 3AS2A 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.

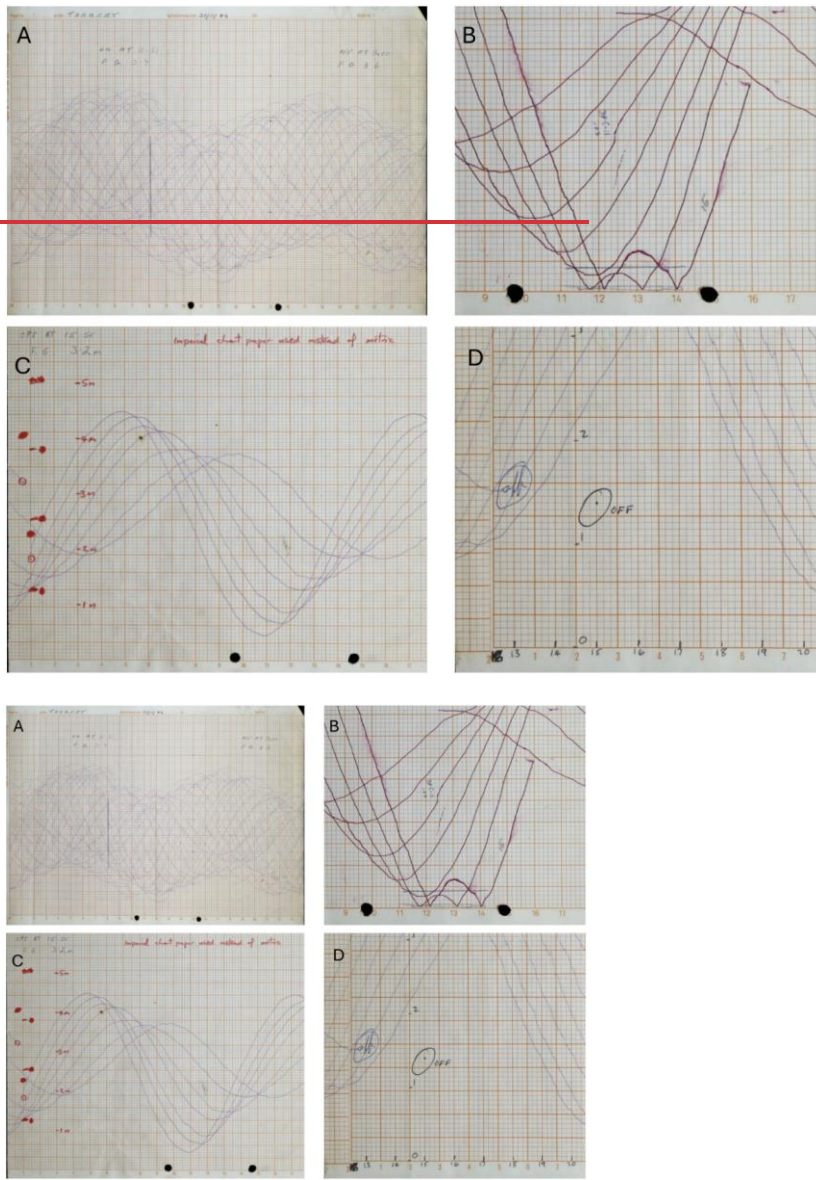


Figure 3S2. Examples of marigrams requiring careful digitization: (A)–(D) Tarbert marigram spanning nearly one month, making accurate digitization nearly impossible; (B) Daily low tides intercepting or approaching the X-axis, requiring manual correction; (C) Variations in graph paper type and unit scaling, 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).

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 S2B). 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~~ potential datum inconsistency was ~~absent~~ restricted to the earlier record, as observations after 1979, when data were digitized in metres relative to Ordnance Datum ~~Dublin (ODD) rather than feet~~. Poolbeg (OD Poolbeg). 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 Figure S2C). 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 S2D). Analysis of each marigram showed that the corresponding mean water-level offset remained ~~well~~ within 20 mm, within which was considered acceptable given the allowable margin between combined uncertainties associated with digitization and instrumentation. Because ~~MSL is~~ annual mean values are computed as ~~a~~ temporal averages over the full extended periods encompassing many tidal cycles, these temporal misalignments are expected to have a negligible effect on ~~MSL calculations, rendering the resulting sea-level record, and are therefore unlikely to materially affect the dataset suitable for MSL analysis~~ long-term RSL reconstruction.

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~~ was estimated to introduce 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; MI, 2025) were incorporated into the record to provide modern observations, owing to the close proximity and similar tidal characteristics.~~ Where historical notes or metadata provided clear evidence for corrections, these were applied transparently during digitization. Where annotations or potential adjustments could not be independently verified, the data were retained in their original digitized form to avoid introducing unsupported corrections. These potential sources of uncertainty are therefore incorporated into the assigned measurement uncertainty. For Tarbert, Carrigaholt data (2019–2024) were used to supplement the modern observations because of the proximity of the coastal tide gauge and its comparable tidal regime.

3.0-Datum ~~Conversions~~Adjustments

~~For all sites, sea~~Sea-level ~~data~~records were ~~adjusted~~standardised to Ordnance Datum Malin (OD Malin; also referred to as ODM). ~~Records reported relative~~Where necessary, records originally referenced to Ordnance Datum Belfast (~~OD~~BOD Belfast) or Ordnance Datum Dublin (ODD; i.e., OD Poolbeg) were converted to ~~OD~~MOD Malin using station-specific datum relationships and associated metadata.

For Malin Head, the PSMSL Revised Local Reference (RLR) data were first converted from millimetres to metres. ~~The standard~~A PSMSL RLR datum offset of 3.977 m was ~~then~~ applied; ~~followed by following the station-specific RLR procedure, and~~ an additional datum correction of 3.136 m ~~was applied~~ based on ~~Office of Public Works (the~~ OPW) OD Malin datum information ~~valid up to for the historical gauge datum established in 2004 and used until the 2018- datum update.~~ 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.~~113 m, align the RLR series with both the local tide-gauge reference and the OD Malin datum, bringing the data to OD Malin. These adjustments are critical for accurate sea-level reconstruction and rely on detailed historical datum documentation to ensure vertical consistency. For Portrush, following the PSMSL, 8.600 m was subtracted from the data, with an additional 1.604 m and 0.037 m (37 mm) added to reference the Ordnance Datum Malin Head (OD Malin). The additional adjustment of 0.037 m represents the mean vertical

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separation between Ordnance Datum Belfast (OD Belfast) and Ordnance Datum Malin (OD Malin), with OD Belfast being 37 mm below OD Malin (Prendergast, 2004).

In Belfast, the standard datum a separation of -2.01 m between Chart Datum (CD) and Ordnance Datum Belfast (OD Belfast) (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 (PSMSL, 2025) and 0.037 m , was added to convert elevations referenced to CD to reference ODM. Similarly, Bangor data OD Belfast. The resulting OD Belfast elevations were adjusted by subtracting 10.500 m , adding 3.582 m (PSMSL, 2025), and adding 0.037 m to convert to ODM subsequently transformed to Ordnance Datum Malin (OD Malin) by applying a $+0.037\text{ m}$ adjustment. The same vertical datum conversion procedure was applied to the Bangor BODC data, using the -2.01 m CD-to-OD Belfast adjustment (National Tidal and Sea Level Facility, 2025) and the $+0.037\text{ m}$ OD Belfast-to-OD Malin adjustment.

To the east of Ireland, the Dún Laoghaire sea-level data were adjusted following McLoughlin et al. (2024). The Dún Laoghaire local datum of 2.722 m , minus the chart datum is 2.722 m above OD Malin; subtracting the local Chart Datum (CD) offset of 1.75 ft (0.533 m), results in a -2.189 m gives a correction of 2.189 m to convert the data records to Ordnance Datum OD Malin (ODM). This correction is was applied to all available Dún Laoghaire records. Similarly, the Dublin Port PSMSL data (1938–2000) were converted to ODM OD Malin using a sequence of benchmark and datum adjustments. These comprised subtracting 6.017 m from the 10.594 m elevation below the primary benchmark (BM, TGZ 1978), adding 0.238 m (238 m to account for the difference between BM 1895 and the TGZ port datum Port Datum 1977), subtracting 0.436 m (436 m because the 1938–1977 relative records were referenced to a Port Datum; 0.436 m above Poolbeg OD), and adding 2.722 m (to account for the Dún Laoghaire datum). These steps resulted in a final. The resulting net correction of was 7.401 m 101 m , which was applied to bring convert the PSMSL data to m ODM metres above OD Malin.

All Cork data were adjusted to Ordnance Datum OD Malin (ODM) following the procedure outlined below. Historic records at Tivoli and Monkstown, originally tied referenced to Ordnance Datum Dublin (ODODD), were converted to ODM using the 2.752 m OD Malin using the Cobh Poolbeg–Malin Head transformation value of 2.69 m from the OPW vertical

datum transformation table (OPW, personal communication, 2024). This regional datum established transformation was chosen because it provides a consistent Cork-area conversion to OD Malin, whereas the 2.752 m adjustment reported by Pugh et al. (2021), which links ODD values to ODM through nearby represents a site-specific historical ODD–OD Malin relationship derived from the Passage West benchmark levelling network.

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 4A3A).
- 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 4B3B).

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 Malin (Irish Water, 2005) (Figure 4C3C). After these corrections, all Cork datasets were successfully adjusted to ODM–OD Malin.

In the absence of a site-specific datum for the Tarbert, the records indicate that the data are were assumed to be referenced to ODD (Ordnance Datum Poolbeg; Figure 4D3D). 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–metres above OD Malin.

Modern Kilrush Lough tide-gauge data (2018–2024; Marine Institute) are referenced to OD Malin; however, comparison with the datum-adjusted Tarbert record indicated a residual datum discrepancy of approximately 5–10 cm. Consequently, the Kilrush record was not incorporated into the extension of the Tarbert time series. Instead, Carrigaholt tide-gauge data (2019–2024) were used, as comparison with the overlapping Tarbert observations showed no evidence of a systematic datum offset.

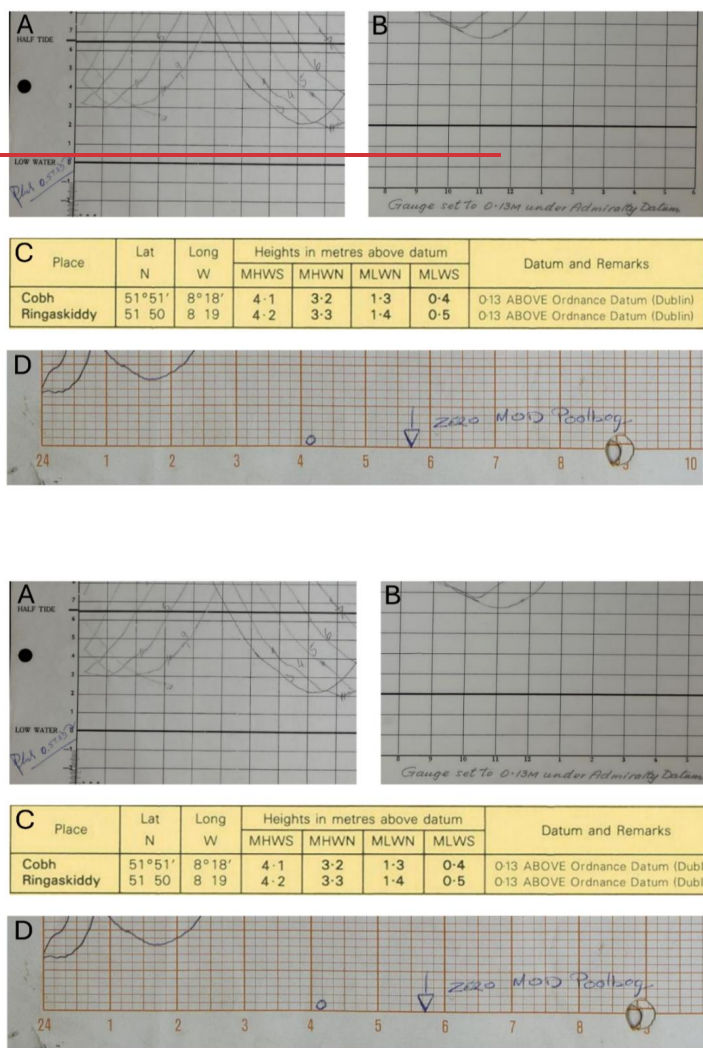


Figure 4.S3: Datum adjustments applied to Cork (Tivoli) and Tarbert sea-level records at different periods: (A–C) Tivoli data—(A) 1970s corrected by +0.174 m (0.57 ft), (B) 1980s corrected by –0.13 m, consistent with gauge documentation and regional tide alignment, (C) early 2000s adjusted by +0.13 m 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).

For Galway, the Galway Harbour datum used Datum corrections of 2.732 m for Galway (Nimmo's Pier) and 2.703 m for Rossaveel were applied to convert data from ODD to ODM is 2.732 m Ordinance Datum Malin Head (OD Malin) (OPW, personal communication, 2024). BODC data for Galway, adjacent to Galway Harbour, show indicate that the 1967 and 1968 records were reported in metres relative to ODN and can be directly are referenced to ODM Ordinance Datum Newlyn (ODN). These records were converted to OD Malin 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 be subtracted to align them with the benchmark (TGZ; Figure 5). After applying Table S1). Following this adjustment, the a further 2.732 m datum was subtracted to reference all values to ODM the records to OD Malin. The 1973 and 1974 records were converted to Ordinance Datum Malin (OD Malin) by applying a datum correction of 2.703 m.

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

Figure 5

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

Table S1. BODC metadata table showing datum relationships for Galway (BODC, 2025). Values from 1967–1968 are aligned with **ODMOD Malin** (0.000 m offset). For 1969–1970, TGZ was –3.048 m; subtracting 3.048 m aligns these years with the earlier records.

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

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 because the earlier observations contained frequent gaps and inconsistencies, while retaining an approximately 100-year overlap with the Dublin (Port (including Dún Laoghaire) record for comparison. Figures presented in this section show the raw monthly mean tide-gauge records used for quality control and validation. No atmospheric, seasonal, or long-term trend corrections were applied at this stage; these adjustments are introduced in the subsequent analysis section. The tidal-Belfast tide-gauge record (Murdy et al., 2015; Figure 6) was generally consistent from 1925 to 1988/2010, with M2 tidal amplitudes within ± 0.1 m of 1.2 m and phase lags mostly typically ranging between approximately 1.13 and 1.24 m. Phase lags occasionally fell outside the typical range (311.4° – 325° and 326° . In contrast, the 4°), but no sustained shifts were observed that would indicate datum instability or long-term timing errors. The period 1989–2000 contained a higher proportion of poor-quality and missing data, which may have affected measurements corresponds to the operation of the Valeport BTH 700 tide gauge (TG4) at Milewater Basin, Belfast Harbour, during harbour redevelopment (Murdy et

al., 2015), and was therefore examined in greater detail. Following the removal of missing and poor-quality data, the record for this period was retained for subsequent analysis. Timing offsets were identified in several years. Where consistent phase lag shifts were observed relative to other years, adjustments were applied to align the records temporally. These offsets were corrected by applying a one-hour time shift to segments of the record exhibiting timing misalignment. Most corrections occurred in data from the late 1980s to 2000, although occasional adjustments were also required in earlier parts of the record (e.g., 1963).

To assess the internal consistency of the Belfast tide-gauge record, annual M2 tidal amplitudes were estimated using harmonic regression and compared with a fitted 18.61-year lunar nodal cycle. The close correspondence between the observed annual M2 amplitudes and the expected nodal modulation indicates that the dominant tidal signal is generally preserved throughout the record, with no evidence of sustained major timing, processing, or data-quality inconsistencies. Annual M2 tidal amplitudes ranged between approximately 1.13 and 1.24 m over the record, showing a multi-decadal variability consistent with the expected 18.61-year lunar nodal cycle (Figure S4). Observed values closely follow the fitted nodal signal, with typical differences of only a few centimetres. Larger deviations occur mainly during periods of reduced data coverage, particularly in the mid-to-late 1980s, and do not persist over time. These periods coincide with operational changes at the Valeport BTH 700 tide gauge (TG4) at Milewater Basin, Belfast Harbour during harbour redevelopment (Murdy et al., 2015). The Belfast tide-gauge record shows no abrupt shifts or long-term departures, with only minor variability consistent with expected observational uncertainty. Overall, the record is suitable for tidal analysis and reconstruction of long-term sea-level changes.

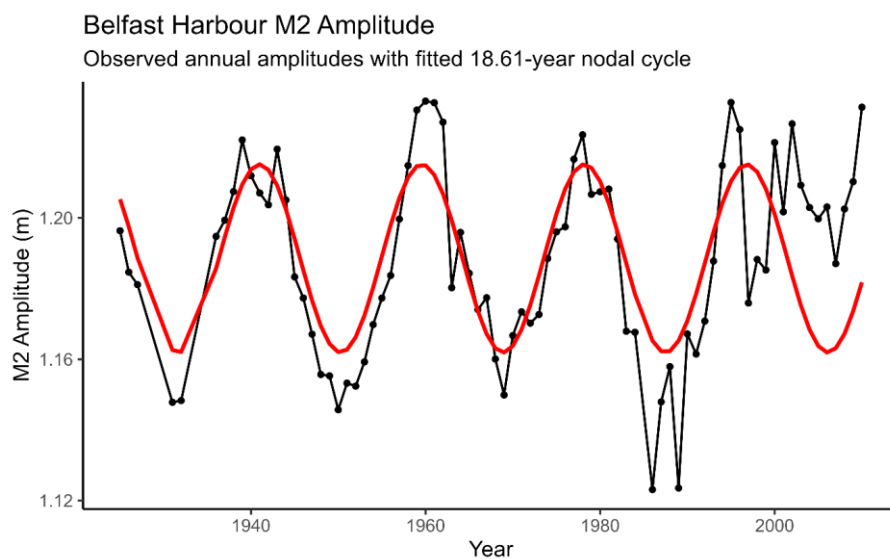


Figure S4. Annual M2 tidal amplitudes and phase estimates derived from harmonic analysis of the Belfast tide-gauge record (1925–2010), with the corresponding fitted 18.61-year lunar nodal cycle (nodal fit) shown for comparison.

Years in which Belfast M2 tidal amplitudes fell outside the 1.13–1.24 m range were examined at monthly resolution, including assessment of both individual months and consecutive multi-month periods exhibiting departures from this range. Individual months or periods were excluded only where additional evidence indicated reduced data reliability. In 1972, the combined August–September record produced an M2 amplitude below 1.1 m, falling outside the acceptance range (1.13–1.24 m), despite individual monthly analyses yielding amplitudes within the expected range. To maintain a consistent quality-control criterion based on the combined analysis period used for harmonic fitting, the August–September data were excluded from further analysis. In 1989, the combined October–December amplitude fell below 1.1 m, while individual monthly values remained above this threshold. Together with the missing July and August observations, this indicated reduced data reliability during the latter part of the year; therefore, only January–September data were retained for that year. Statistical outlier detection was performed jointly for the Belfast and Bangor records due to their close geographical proximity. Monthly mean values exceeding ± 4 standard deviations (SD) from the station mean were considered potential outliers and assessed before exclusion. Although individual months in 1985 did not exceed the ± 4 SD threshold for monthly MSL values, the

annual mean was notably elevated relative to surrounding years. Given this elevated annual behaviour, 1985 was conservatively excluded from the analysis as a potential data-quality issue. A summary of all periods omitted due to data-quality concerns, together with the rationale for their exclusion and any supplementary records incorporated, is provided in Table S2. The M2 phase lag and amplitude records (Panels A and B), following removal of potentially erroneous data, are shown in Figure S5. Period bins differ between tide-gauge plots and reflect differences in data availability and record length. The boxplots (Panel C) summarise variability within each data segment rather than applying identical time periods across stations.

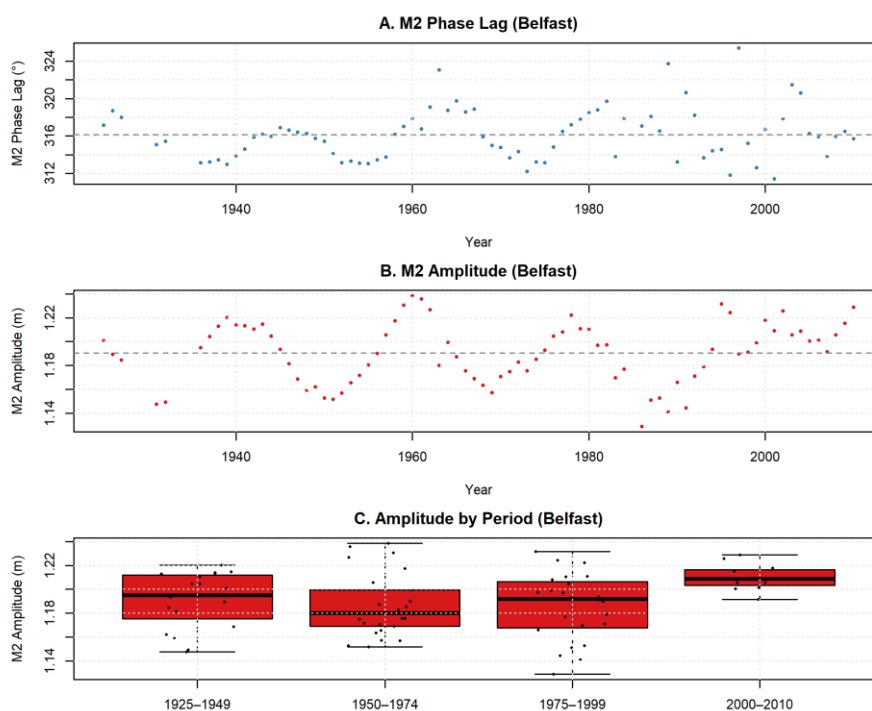


Figure S5. (A) M2 phase lag, (B) M2 amplitude, and (C) M2 amplitude by period (boxplot). Minor deviations are evident during the late 1980s, coinciding with the removal of low-quality data, intermittent data gaps, and operational changes associated with tide gauge 4 (TG4) operations at Milewater Basin during harbour redevelopments. However, after omitting poor quality or missing data Belfast Harbour redevelopment. Overall, the dataset for this period was generally of good quality. Timing offsets were also identified and, where

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~~possible, corrected by adjusting certain years by one hour in specific months to improve temporal consistency~~ **is considered suitable for RSL analysis.**

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The Bangor record (2011–2015; Figure 6) was used to ~~fill gaps in~~ extend the Belfast dataset ~~due to record beyond 2010 owing to the proximity of the stations. Months and their comparable tidal characteristics.~~ The Bangor dataset was obtained from the British Oceanographic Data Centre (BODC) for 2011–2024; however, only 2011–2022 were retained for the primary RSL analysis following quality control. Following consultation with BODC, we were advised that data from approximately 2016 onwards remained flagged as suspect and could potentially contain unresolved quality issues. Consequently, the hourly observations were independently inspected and quality-controlled before use (BODC, personal communication).

To assess the suitability of the hourly observations for use in this study, the record was inspected and compared across the full observation period. Most observations fell within the range -0.1 to 4.5 m relative to the unadjusted local datum prior to conversion to OD Malin. Following inspection of the hourly data, observations exceeding 4.5 m or below -0.1 m were removed as spurious values. This quality-control procedure identified 728 hourly observations requiring removal over the ~ 15 -year record, including isolated positive excursions exceeding 4.5 m (with maximum values exceeding 10 m) and 11 negative excursions below -0.1 m. A subsequent spot inspection of the monthly record identified March 2011 as having a tidal amplitude outside the expected range, and this month was therefore omitted from the analysis.

Despite the hourly quality-control results, the annual mean sea levels in the final years of the record were notably elevated. The annual mean increased from 0.117 m in 2021 to 0.239 m in 2023 and 0.267 m in 2024, with the latter two years showing a pronounced elevation relative to the preceding record. This represents an increase of approximately 15 cm between 2021 and 2024. Given the documented BODC warning that observations from approximately 2016 onwards remained potentially suspect, and the substantial influence of these recent observations on the estimated long-term RSL trend, 2023–2024 were conservatively excluded from the primary RSL analysis. This exclusion was treated as a precautionary data-quality decision rather than as evidence that the observations were statistical outliers.

Further validation of the resulting quality-controlled record was undertaken through harmonic analysis of the M2 tidal constituent. The resulting annual M2 phase lags showed a smooth temporal evolution, ranging from 315.30° to 319.90° (2011–2022). Annual M2 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, remained within the range 1.15–1.20 m (2011–2022), indicating data quality issues; consequently, 1985 was excluded from further analysis. The phase lags and M2 amplitudes show broad agreement with those observed at Belfast, supporting the suitability of the quality-controlled Bangor record.

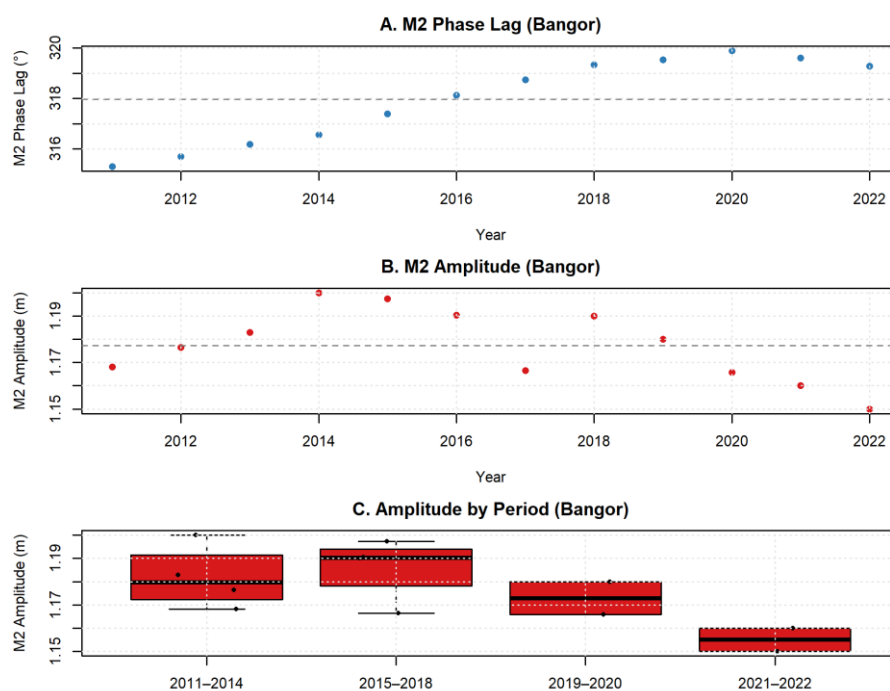


Figure S6. Annual M2 tidal constituent characteristics for the Bangor tide-gauge record (2011–2022): (A) M2 phase lag, (B) M2 amplitude, and (C) distribution of M2 amplitudes by period shown as boxplots. The consistent temporal behaviour of the M2 constituent provides an independent assessment of the stability and reliability of the record following quality control.

The Malin Head record contains known data issues in the ~~early~~late 1990s (~~1992–1993~~), as documented by PSMST and early 2000s. Hogarth et al. (2020) identified gauge malfunctions between 1998 and 2003 and suggested that the nearby Portrush record could serve as a more

~~robust replacement for~~ be used to replace problematic portions of the Malin Head ~~data~~. Specifically, all of 1993 and the last three months of 1992 (October–December) were omitted ~~from series~~. In addition, while the Malin Head ~~record, and~~ data used in this study were obtained from the PSMSL, BODC documentation for this tide gauge identifies instrument problems beginning in December 1991. These included inaccurate recordings following the detachment of the bubble-pot during a storm, a subsequent gauge breakdown in early 1992, and a 6 cm calibration offset identified in 1993 for which the timing of the error could not be established (BODC, 2025). Consequently, December 1991 was omitted, while February–August 1993 were excluded from the Malin Head record as a conservative quality-control measure in light of the documented calibration uncertainty in 1993 and the comparatively low monthly mean ~~sea-level values observed during this period~~. Portrush data were ~~therefore~~ used for ~~1996~~1998–2003 ~~and~~ to supplement the Malin Head record, together with data for 2015. Modern NTGN data for Malin Head (OPW, 2004–2008; MI, 2009–2024) ~~completed~~ were then used to complete the record. ~~After removing~~

A one-hour timing offset was identified in the ~~end of 1992~~ Malin Head OPW record between 2004 and ~~1993, statistical~~2006 and corrected by shifting timestamps by one hour to ensure consistency with the expected tidal phase lag. The Malin Head record was excluded for 2022 because insufficient observations were available. The Portrush record was not used as a supplement for this period, despite having several consecutive months of observations that could have allowed inclusion, because substantial data gaps remained throughout the year and the reliability of the record was uncertain. This decision was also supported by the presence of missing monthly observations in surrounding years within the PSMSL record. Statistical outlier detection was applied to further validate the data, ~~excluding monthly~~. Monthly mean values exceeding ~~three standard deviations~~ ± 4 SD from the overall station mean. This led to the removal of February–1990 were considered potential outliers and assessed before exclusion; however, no values exceeded this threshold. April 2024, was removed prior to statistical outlier detection because of an identified data spike. Statistical outlier detection was performed separately for the supplementary Portrush station because of its different geographical setting, and no outliers were identified. The verified Malin Head record, together with other tide-gauge records from Northern Ireland, is shown in Figure ~~6~~S7.

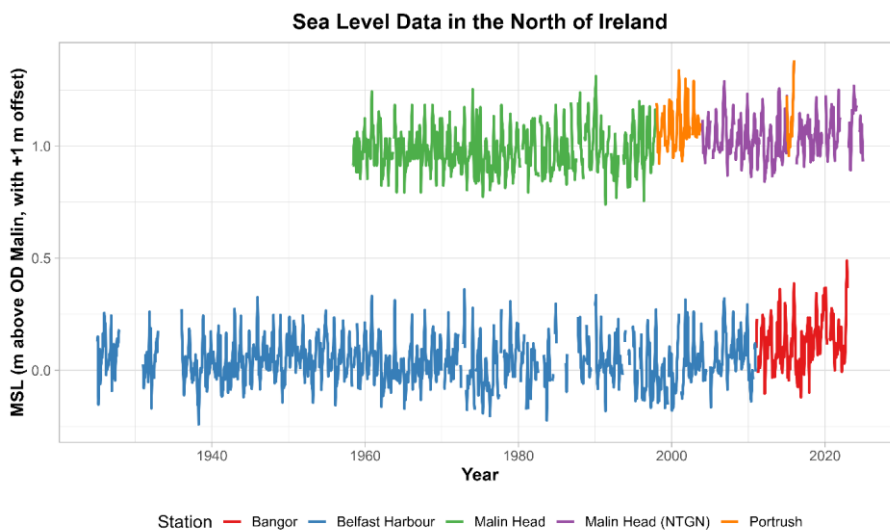
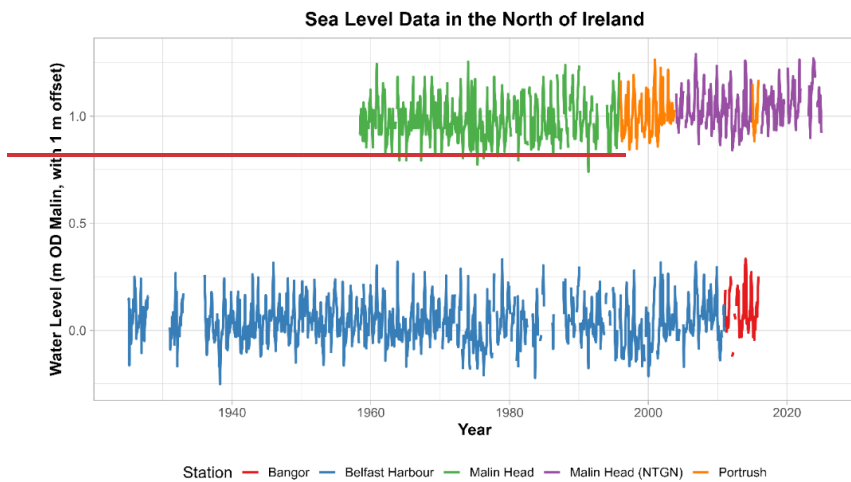


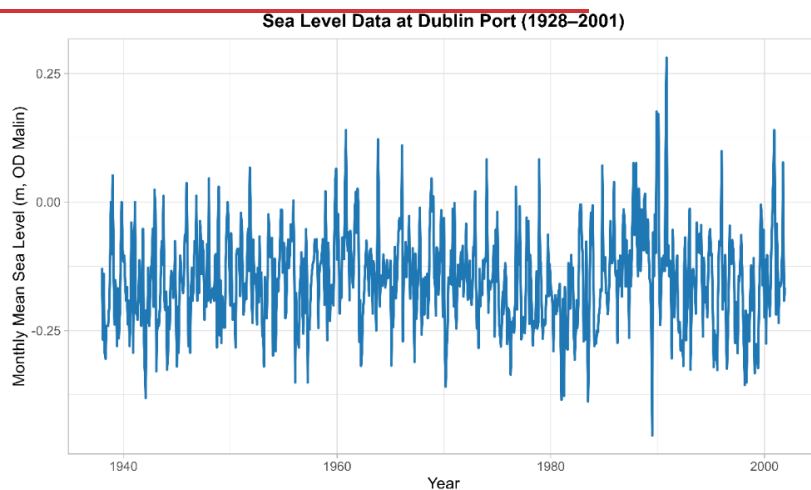
Figure 6. Mean Sea Level (S7. Monthly MSL) values for tide gauges in and around Northern Ireland tide gauges. Belfast and, divided into two groups as described in the text. For clarity, Malin Head and Portrush records have been offset by 1 m for clarity. +1 m relative to Belfast and Bangor. All data records are referenced to Ordnance Datum OD Malin (ODM), including Bangor and Portrush records, which were used to supplement the Belfast and Malin Head records.

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The Dublin Port tide gauge on the east coast (PSMSL, 1938–2001; ~~PSMSL, 2025~~) exhibits unusual variations from the 1970s to the early 1990s (Shoari Nejad et al., 2022). ~~The timeseries for 1938–2001 is shown in Figure 7.~~ Statistical outlier detection using a threshold of ± 4 SD from the station mean identified ~~several potentially erroneous mean sea level months—~~ November 1960, July and December 1989, February and November 1990, and December 2000 ~~—which were 1990 as a potential outlier, which was~~ subsequently removed from the analysis.

Figure 7. Monthly mean sea-level measurements at The updated time series for 1938–2001 is shown in Figure S8. Due to slight differences between the Dublin Port record and the supplementary harbour records, as well as potential site-specific variability, statistical outlier detection was performed independently for each station (Dublin Port, Dún Laoghaire, Howth, and Arklow).

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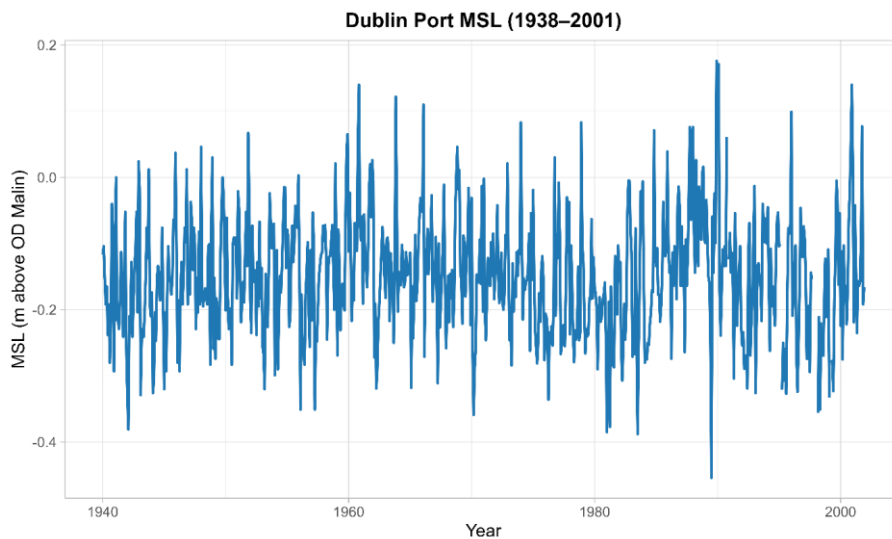


Figure S8. Monthly MSL values from the Dublin Port tide gauge (1938–2001), highlighting periods with consistently lower or higher monthly means, particularly from the mid-1970s to early 1990s.

Digitized Dún Laoghaire data for June–August 1932 and 1933 were of good quality, with M_2 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 ± 4 SD from the overall mean.

To construct a near-continuous century-long sea-level record, modern sea-level tide-gauge data from NTGN OPW Arklow (2003–2006) and the earlier MI Howth series (2007–2018), as used by Shoari Nejad et al. (2022) and McLoughlin et al. (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. A later MI digital tide-gauge series provided additional Howth observations from 2018 onward. Comparison with the earlier Howth series indicated an apparent discontinuity around 2018. Consequently, the earlier Howth series was retained for 2007–2018, while the later MI digital series was incorporated from 2019–2024. This approach avoided introducing an apparent discontinuity into the combined series while maximising temporal coverage and maintaining consistency between the Howth observations. An isolated data spike in the Howth record in July 2024 was omitted prior to

statistical outlier detection. Statistical outlier detection was then applied to the monthly MSL record using a ± 4 SD threshold relative to the station mean. No outliers were identified.

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°) fell~~ within the expected M2 phase-lag range, with a phase lag of 153.1° compared with the expected range of 144.4 – 154.1° range (Pugh et al., 2021). The corresponding M2 amplitude for this year is 1.39 m; however, this estimate is based on a limited record covering only October–December and may therefore deviate slightly from nearby tide gauge records.

Tivoli initially showed phase lags of 167 – 175° , indicating a systematic daylight-saving-time (DST)-related offset, which was corrected by shifting timestamps back 1 h during late-March to October periods. Post-correction, Tivoli phase lags ranged ~~between 150.9° and 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.

Modern Tivoli data (2001–2005, 2010–2011) generally agreed in amplitude (~~~ 1.37 – 1.49 m~~) and phase lag (~~$\sim 150.3^\circ$ – 160.2°~~). ~~Outliers included 2001 ($>185^\circ$ phase lag) and slightly elevated 2002/2005 phase lags ($\sim 165.4^\circ/162.5^\circ$), which were retained because their amplitudes fell within the expected range after exclusion of poor quality months, leaving MSL unaffected.~~ 40 – 1.47 m) and phase lag ($\sim 150.3^\circ$ – 162.25°).

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 $\sim 144.61^\circ$ – 152.2° , consistent with Tivoli and Monkstown ~~and Tivoli~~.

~~After initially checking the~~ Following checks of 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 using a ± 4 SD threshold applied to all monthly mean observations up to 2024, no further observations were identified as requiring exclusion.~~ While the phase lags show some deviation in the 2000s for Tivoli, the M2 amplitudes remain in close agreement, ranging from approximately 1.39 to 1.49 m. This consistency suggests a stable tidal signal and supports the suitability of the dataset for reconstructing historical RSL changes. The M2 amplitudes and phase lags for the Cork dataset are shown in Figure S9. The M2 amplitude record exhibits multi-decadal variability consistent with the 18.6-year lunar nodal cycle where observations are available. However, because data gaps (particularly in the 1990s) prevent a continuous

time-series analysis, we rely on the observed timing of the data clusters to support nodal modulation as the primary driver rather than constructing a continuous nodal model.

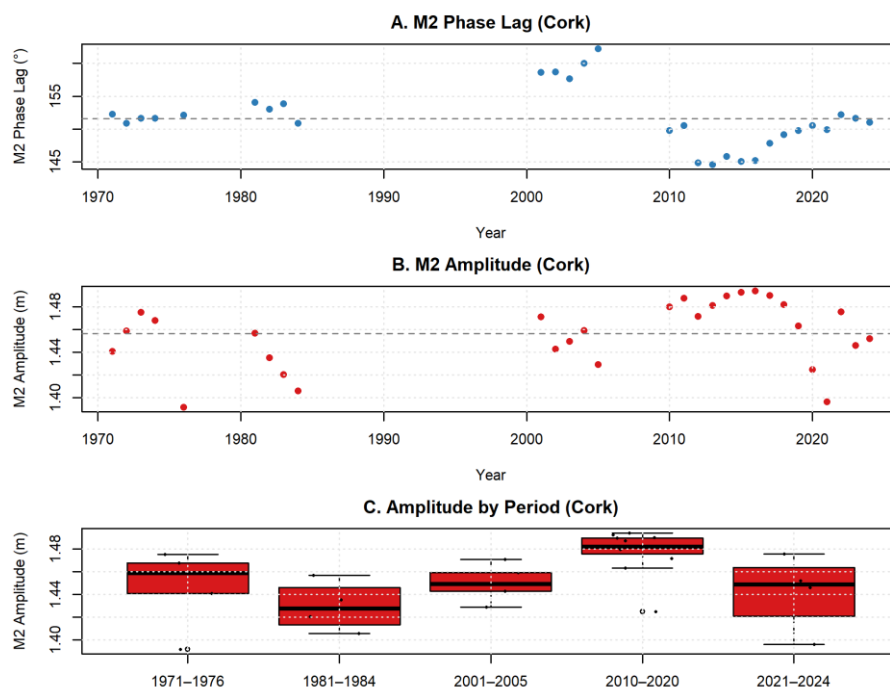


Figure S9. (A) M2 phase lag, and (B) M2 amplitude for the Cork dataset and, (C) M2 amplitude by period (boxplot). The largest deviations from the long-term mean occurred in the M2 phase lag record during the early 2000s, suggesting a small timing offset that remains after the removal of potentially erroneous observations were identified, with all monthly means remaining within three standard deviations of the overall mean. The rectified Cork dataset data. Nevertheless, M2 amplitudes remain relatively stable over the observation period. Overall, the dataset was retained and therefore included in the RSL reconstruction.

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The Cork record (combined stations Tivoli, Ringaskiddy, and Currach Club) referenced to Ordnance Datum Malin (OD Malin) is shown in Figure 8-S10. Months identified as poor quality based on erroneous M2 amplitudes were excluded prior to the final reconstruction (Table S2).

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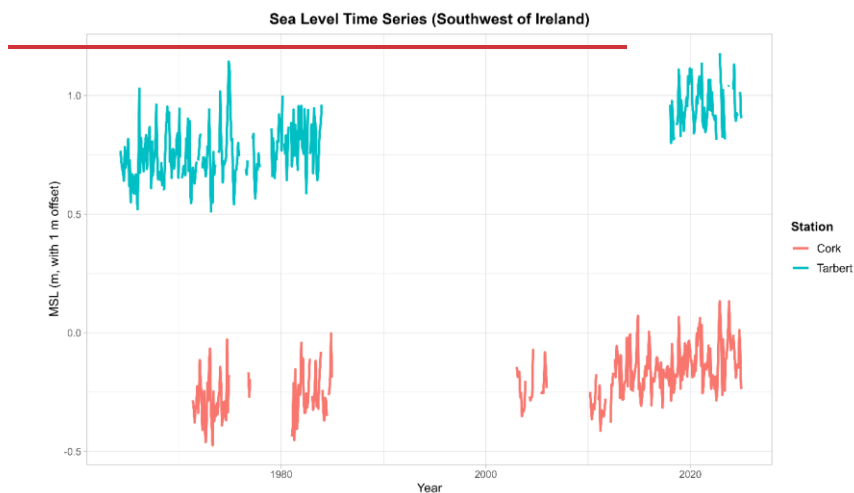
To assess tidal characteristics in the south-west of Ireland, ~~two nearby sites,~~ Tarbert and ~~Kilrush Lough Carrigaholt~~ were compared. Tarbert exhibited M2 amplitudes of ~ 1.55 – 1.66 ~~m~~ ^{66 m} with phase lags of $\sim 145.9^\circ$ – 156.2° , while ~~Kilrush Lough Carrigaholt~~ (NTGN ~~MOPW~~ modern data, 20182019–2024), located ~~less than 11 km~~ ^{22–23 km} across the estuary, showed comparable amplitudes of ~ 1.48 ~~43~~– 1.64 ~~m~~ ^{52 m} and phase lags of $\sim 144.6^\circ$ – 147.8° . ~~Individual months or years~~ ^{141.4°–143.3°}. The observed amplitude variability may reflect differences in hydrodynamic conditions within the Shannon Estuary system, as well as gaps in the observational records. Years with amplitudes outside these ranges were ~~excluded from the analysis~~ ^{inspected individually}. Months contributing to deviations outside the accepted range were excluded from the analysis, and where an entire year fell outside the accepted range, the full year was excluded. A localised datum issue affecting the Carrigaholt record during August–December 2020 was identified during routine quality-control assessment, and these data were excluded from subsequent analysis.

The comparable M2 amplitudes and phase lags indicate broadly consistent tidal characteristics between the sites, supporting the use of nearby records as supplementary observations where datum compatibility can be demonstrated. Although Carrigaholt is located closer to the estuary mouth and may therefore experience slightly different hydrodynamic conditions than Tarbert, it remained the most compatible supplementary record. Carrigaholt was therefore selected for extending the Tarbert time series because it provided a nearby record with no apparent systematic datum offset relative to Tarbert. More inland sites, including Foynes and Kilrush, were not incorporated because, despite being referenced to OD Malin, comparisons with the Tarbert record indicated relative datum differences that could not be confidently reconciled. Furthermore, monthly MSL comparisons showed closer agreement between Carrigaholt and Tarbert than with alternative nearby records, providing additional support for its selection.

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~~ ^{due to} uncorrected daylight saving time (DST), and a ~~persistent continuous~~ ^{one-hour} offset from 1968 to 1970 ~~due to missing DST adjustments,~~ ^{expressed in GMT}. Timestamps were corrected

by shifting them back one hour during DST periods and ~~for the full years from 1968– through~~ October 1971, resulting in the ~~exclusion/loss~~ of approximately one hour of ~~data per observations~~ in each year requiring correction.

Data from 1984–1986 were omitted because M2 amplitudes consistently fell below the expected range of 1.55–1.66 m, reaching between ~1.3–1.50 m; the corrected Tarbert time series is shown in Figure 8. ~~For Kilrush Lough, three months in 2024 (February, September, and October) were omitted following M2 corrections and statistical~~^{S10}. Statistical outlier detection- was performed separately for Tarbert and Carrigaholt due to the temporal separation between the records (Tarbert ending in 1983; Carrigaholt beginning in 2019) and potential site-specific differences in observed variability; no outliers were identified.



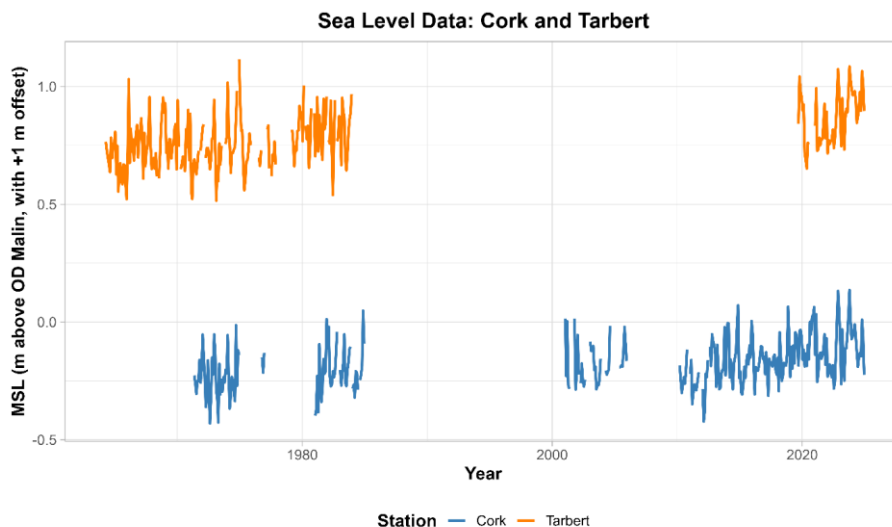


Figure 8S10. Sea-level data for records from the Tarbert (record (Tarbert, 1964–1983), Kilrush Lough (2018, combined with Carrigaholt, 2019–2024)) and from Cork sites—including (Tivoli (1970s–1980s and 2000s), Currach Club, and Ringaskiddy—adjusted), merged into continuous time series for display purposes. All records were referenced to Ordnance Datum Malin (ODM) and vertically OD Malin), with a 1 m vertical offset by 1 m applied to the Tarbert/Carrigaholt series for clarity visual separation.

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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 and Rossaveel (1973–1974) contained some missing on select days in 1968 and 1970; these were flagged as unreliable and excluded values, particularly in 1967, 1970, 1973, and 1974. However, only minimal poor-quality data required exclusion from the analysis records. Selected hourly observations from Galway during the 1968–1970 period were excluded on a small number of days where data-quality concerns were identified. Modern Galway Port data (2007–2024) were supplemented with NTGN MI observations to fill gaps and ensure continuity in extend the historical record. Comparison of tidal harmonics between the 1967–1970 BODC dataset, observations from Rossaveel (1973–1974), and modern Galway Port observations records revealed only minor differences. M2 tidal amplitudes were slightly higher in the modern record (~1.46–1.59 m) than in the BODC data (~1.45–1.48 m).

m), and phase lags differ slightly ($\sim 137.2^\circ$ – 142.3° vs. $\sim 126.4^\circ$ – 128.8°), but overall the values remain amplitudes remained in close agreement.

Phase lags differed more substantially ($\sim 137.2^\circ$ – 142.3° vs. $\sim 124.7^\circ$ – 128.9°); however, these differences were considered during tidal-quality assessment and did not provide evidence of a systematic issue affecting the MSL records. 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 4-S2. Given their geographic proximity and comparable tidal characteristics, the Galway and Rossaveel records were analysed together for statistical outlier detection, with no outliers identified.

Table 1. Summary of tide gauges with data omittedS2. Tide-gauge periods excluded due to poor data-quality concerns and where supplementary data wererecords incorporated. Note: Years with fewer into the analysis. Periods shorter than three consecutive monthly observations were automatically discarded and may not all be explicitly listedmonths are omitted.

Tide Gauge	Years/Months Omitted	Quality Issue	3 4-SD Outlier Detection Across Intervals	Supplement and Replacement Data
Malin Head	Feb 1990; Oct–Dec 1992 and December 1991; February–August 1993 omitted; 1996–2003 and 2015 replaced with Portrush data; Apr–April 2024 omitted (from the 2003–2024 MI/OPW data record)	Poor-quality data in the early 1990s; z_0 values exceeding three standard deviations from the mean. Potential poor-quality data. An isolated monthly MSL value was identified during visual and statistical quality control.	PSMSL Malin Head (1958–2002); OPW Malin Head (2003–2008); MI Malin Head (2009–2024); Portrush (1996–2015). No outliers detected	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	Belfast Harbour (1925–2010); outliers removed	Bangor PSMSL BODC substituted for 2011–2015.

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Tide Gauge	Years/Months Omitted	Quality Issue	4-SD Outlier Detection Across Intervals	Supplement and Replacement Data
	~~August–September 1972; 1985; October–December 1989; Bangor March 2011, 2023–2024~~	~~deviations from the mean; potential datum control issues; M2 amplitudes outside expected range; 1985: elevated annual MSL; 2023–2024: BODC quality warning and elevated MSL.~~	~~first; supplemented with Bangor (2011–2015) for final combined outlier detection; No outliers detected~~	~~2022~~
Dublin Port	Nov 1960; Jul and Dec 1989; Feb and Nov 1990; Dec 2000; Howth Jul 2024 (large spike detected 3 SD from mean); Arklow Nov 2022 and July 2024 (used only in the full record to adjust Howth baseline offset with Howth); Dublin Port: November 1990; Howth: 2018 from later MI digital series; July 2024	Monthly means deviating by more than three standard deviations from the mean. Dublin Port: monthly MSL > ±4 SD. Howth: apparent discontinuity around 2018 between series; isolated July 2024 spike	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); Dublin Port: November 1990.	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. Dún Laoghaire 1925–1933; Arklow OPW 2003–2006; earlier MI Howth series 2007–2018; later MI digital series 2019–2024 (Arklow 2003–2024 used for baseline offset)
Cork (Tivoli)	1982 (~~Nov–Dec~~ November–December); 2001 (~~Jun–Sep~~ June–September); 2002 (Mar, Oct–Dec; March, September–December); 2004 (Mar); March); 2010 (Feb, Nov–Dec; February, November–December)	Monthly M2 amplitudes outside the yearly ranges expected annual range (~1.39–1.49 m) 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; No outliers detected	Tivoli 2003–2005; Ringaskiddy OPW 2012–2021; Currach Club OPW 2022–2024.
Tarbert	1974 (~~Nov~~ November); 1976 (Oct, Nov–October–November); 1977 (Jun–June); 1978; 1979 (Jan–Feb–January–February); 1982 (Jan–January); 1984–1986–Kilrush Lough; Feb, Sept, and Oct 2024.; Carrigaholt August–December 2020	Monthly means causing yearly resulting in annual amplitudes to fall outside the ranges expected Tarbert range (1.55–1.66 m; Kilrush Lough 1.48–1.64 m) were excluded. Localised datum issue identified during quality control assessment in Carrigaholt.	Due to the close proximity, all data were checked together; No outliers detected	Kilrush 2018 Carrigaholt OPW 2019–2024.
Galway	1968–1970 (selected hours on some days omitted);	Unreliable data at Galway; monthly means deviating by more than three standard deviations from the mean. Poor quality observations identified	Due to the extremely close proximity, all data were checked together across the	Galway Harbour 2007–2024.

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Tide Gauge	Years/Months Omitted	Quality Issue	4-SD Outlier Detection Across Intervals	Supplement and Replacement Data
		through historical tide-gauge record quality flags; affected periods were excluded from analysis.	full-time-series; No outliers detected	

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~~4.2.~~ Given the length and complexity of the reconstructed records, occasional monthly-scale anomalies may persist despite the application of multiple independent quality-control procedures (Table S2). However, sensitivity checks and comparisons with overlapping records indicate that any remaining inconsistencies do not materially affect the resulting long-term RSL estimates.

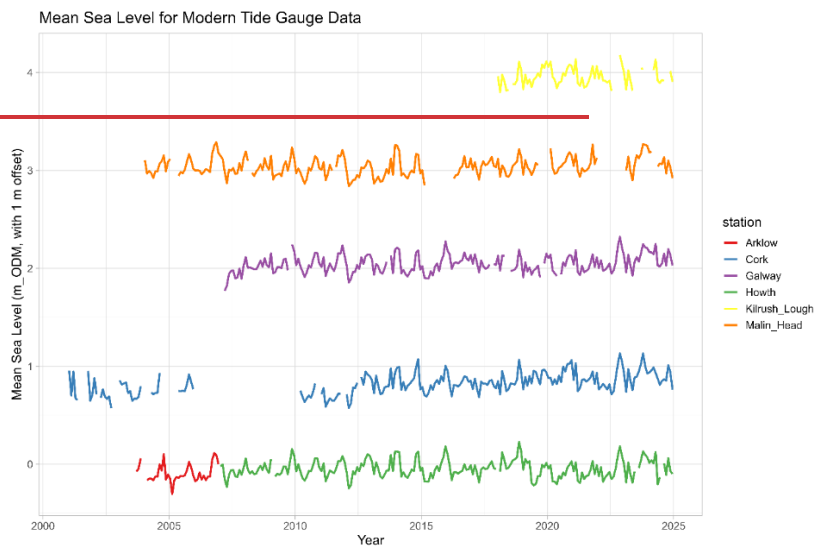
Modern **NTGN** Tide Gauge Data: Quality **Control** and Corrections

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Modern tide gauges still produce raw records that may contain inaccuracies and require validation (Aarup et al., 2019). All modern datasets ~~accessed~~ obtained 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~~ indicate erroneous observations; 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~~ ±4 SD from the station mean were assessed for each tide-gauge record. No statistical outliers were identified, aside from the previously noted data spikes in the Howth and modern Malin Head records, which were removed from each tide-gauge record prior to analysis.

A consistent datum offset between the overlapping Arklow and Howth series was identified, likely due arising from differences in vertical referencing (e.g., GNSS-derived heights relative to a geoid model differences, was rather than conventional levelling). The offset was quantified using the mean monthly discrepancy over the overlap period (2007–2024). ~~This offset was~~ and applied to the full Arklow series (2003–2024) to align it with the Howth datum. ~~Two outliers in~~ Statistical outlier detection was applied to the Arklow 2007–2024 portion— ~~November 2022 and May 2024—exceeding three standard deviations~~ record using a threshold of ±4 SD from the station mean—. ~~No outliers were removed~~ identified. 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 sea-level observations used/evaluated in this study/section—including the previously uncovered-identified Cork (Tivoli ~~(Cork)~~) data from the early 2000s—met the quality-control and consistency criteria applied in this study (Figure 9-S11).



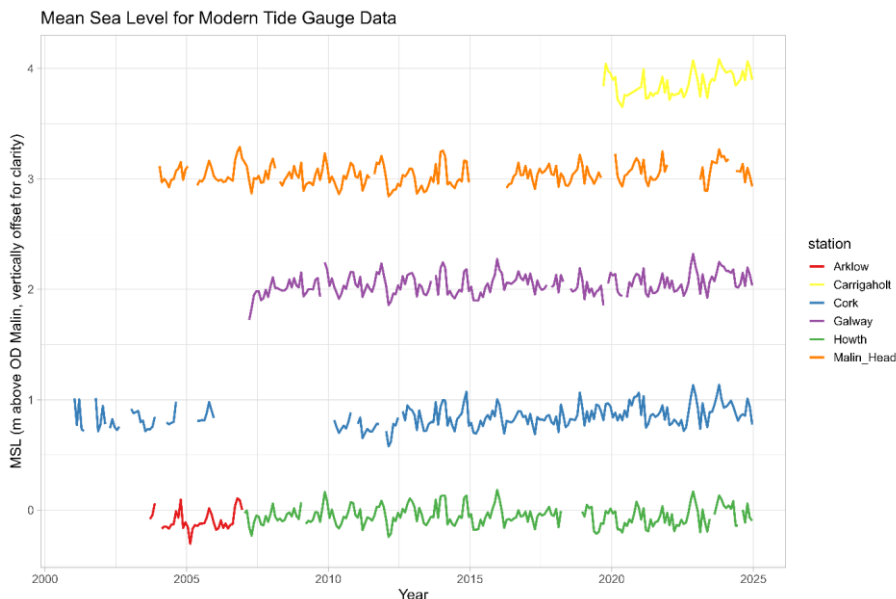


Figure 9S11. Tide-gauge records (2000s) for Arklow, Howth, Galway, ~~Kilrush~~ ~~Lough~~ Carrigaholt, and Malin Head. ~~Series are~~ Each time series has been vertically offset by 1 m for plotting clarity, ~~except;~~ Arklow and Howth, ~~which~~ are shown together after applying a fixed datum offset to align them.

As a ~~final~~ final ~~an additional~~ validation, to ensure step, the Dublin Port dataset ~~aligns with the modern~~ aligns with the modern ~~Arklow and Howth datasets, comparison was compared~~ with Shoari Nejad et al. (2022) ~~shows~~ (2022) to assess alignment with the corresponding historical record. The comparison ~~showed~~ a mean difference of 0.021 m 0.021 m and a standard deviation of 0.017 m 0.017 m. No obvious ~~jumps~~ discontinuities were observed, with ~~a maximum year to year difference of 0.071 m,~~ the largest change between consecutive overlapping observations being 0.072 m, providing no evidence of a systematic datum-related inconsistency.

Satellite Altimetry–Tide Gauge Comparison

For validation of the tide-gauge sea-level records, observations were compared with satellite altimetry (1993–present) from the Copernicus Climate Data Store (C3S, 2018). Following the Alt–TG comparison framework described by Ray et al. (2023), gridded sea-level anomaly data were used as an independent reference dataset to assess consistency in sea-level variability, trends, and potential reference-level instability through satellite altimetry–tide

gauge (Alt–TG) comparisons. Satellite altimetry values were extracted from the nearest available grid point to each tide-gauge location to provide a consistent spatial basis for comparison between the two observing systems. Validation was restricted to stations with sufficient temporal overlap with satellite altimetry, including Belfast, Malin Head, Dublin Port, Cork, the Carrigaholt (Tarbert extension), and Galway. For the Malin Head series, observations recorded at Portrush (1998–2003 and 2015) were excluded from the analysis because the change in measurement location introduced additional uncertainty when comparing the tide-gauge observations with the satellite altimetry grid point. Similarly, the Arklow record (2003–2006), although corrected for its baseline offset to Howth, was excluded from the Dublin Port series because of the separation between the measurement locations.

Across stations, the comparison showed generally good agreement in temporal variability between satellite altimetry and tide-gauge observations, with correlation coefficients ranging from approximately 0.55 to 0.76 and consistent temporal variability between the two observing systems (Figure S12). Alt–TG differences varied between stations, reflecting differences between geocentric satellite altimetry measurements and relative sea-level measurements from tide gauges, together with contributions from coastal ocean variability and spatial mismatch between gridded satellite observations and point-based tide-gauge measurements. These differences are expected when comparing satellite altimetry and tide gauges because the two observing systems sample sea level using different spatial scales and reference frameworks.

Differences between satellite altimetry and tide-gauge observations are expected because the two observing systems measure sea level within different reference frameworks. Satellite altimetry measures sea surface height relative to a geocentric reference frame, whereas tide gauges measure relative sea level with respect to local land-based benchmarks and are therefore sensitive to local VLM and datum definitions. Stations influenced by complex coastal geometry (e.g., estuarine and harbour environments) may exhibit reduced correlation compared with more open-coast sites, reflecting differences in spatial representativeness between gridded satellite observations and point-based tide-gauge measurements rather than necessarily indicating ~~no datum issues~~ errors in either dataset.

4.3. Data Quality Control and Standardization

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To ensure methodological consistency, only hourly intervals were extracted from modern datasets. Following standard validation practices, months with more than 15 missing days or days with more than 4 missing hours were excluded from monthly averages for all datasets, except for the PSMSL records, which 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).

5. Data Processing and Sea Level Modelling

5.1. Atmospheric Adjustments

In the processing of the MSL data, two

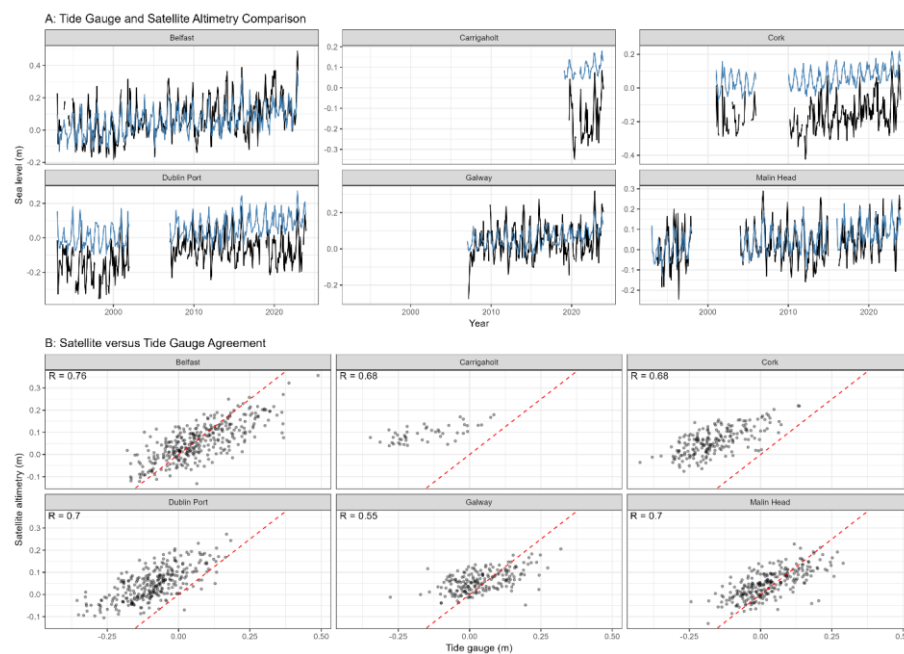


Figure S12. Comparison of in situ tide-gauge MSL records, adjusted to the Malin Head datum, and satellite altimetry observations at six Irish coastal stations (Belfast, Malin Head, Dublin Port, Cork, Galway, and Carrigaholt (Tarbert extension)). (A) Monthly tide-gauge MSL values (black) and nearest-grid-point satellite altimetry sea-level

anomaly estimates (blue) over the overlapping satellite altimetry period. (B) Corresponding scatter plots of satellite altimetry observations against tide-gauge MSL values, with the dashed line indicating the 1:1 relationship. Pearson correlation coefficients (R) are shown for each station.

The relative difference between satellite altimetry and tide-gauge trends (satellite – tide gauge) was calculated for each station to assess divergence between the two observing systems (Table S3). Differences were generally small across most stations, with the longer records showing differences ranging from -1.20 mm yr^{-1} at Belfast to $+1.09 \text{ mm yr}^{-1}$ at Galway. Close agreement was observed at Cork ($+0.42 \text{ mm yr}^{-1}$) and Dublin Port (-0.57 mm yr^{-1}), with Malin Head also showing a relatively small difference ($+0.86 \text{ mm yr}^{-1}$). Carrigaholt, used as an extension of the Tarbert record, showed the largest difference ($-11.86 \text{ mm yr}^{-1}$), reflecting the sensitivity of the short 2019–2024 overlap period rather than a long-term disagreement between the datasets. Despite this larger trend difference, Carrigaholt showed a moderate positive correlation between satellite altimetry and tide-gauge observations ($r = 0.68$), indicating that the two records captured comparable temporal variability over the overlapping period. However, this discrepancy is likely attributable to the short duration of the Carrigaholt record (September 2019–December 2024) rather than a systematic difference between the two observing systems. Sensitivity testing using equivalent short time windows at other stations produced similarly large trend differences; for example, restricting Malin Head to 2019–2024 resulted in a trend difference of approximately -8.30 mm yr^{-1} , while Galway showed a trend difference of approximately $-13.82 \text{ mm yr}^{-1}$ over the same period. These results indicate that short-term variability and limited record length can substantially influence trend comparisons over short intervals. The observed differences are consistent with the expected uncertainties associated with comparing point-based tide-gauge measurements and gridded satellite altimetry observations, particularly in complex coastal environments where local hydrodynamic variability, coastal proximity, and spatial sampling differences may influence agreement between the two observing systems. As emphasised by Ray et al. (2023), Alt–TG differences can arise from multiple non-instrumental sources, particularly near the coast where satellite and tide-gauge measurements represent different spatial scales.

Table S3. Comparison of linear sea-level trends from tide-gauge records and satellite altimetry over the overlapping satellite era. Differences are calculated as satellite altimetry trend minus tide-gauge trend.

<u>Tide-gauge station</u>	<u>Tide-gauge trend (mm yr⁻¹)</u>	<u>Satellite altimetry trend (mm yr⁻¹)</u>	<u>Difference (satellite – tide gauge) (mm yr⁻¹)</u>
Malin Head	2.19	3.05	0.86
Belfast	6.12	4.93	-1.20
Dublin Port	4.61	4.04	-0.57
Cork	4.13	4.55	+0.42
Carrigaholt (Tarbert extension)	23.00	11.14	-11.86
Galway	3.88	4.97	+1.09

The differences between altimetry-derived and tide-gauge trends were generally small across five of the six stations (-1.20 to +1.09 mm yr⁻¹) and are consistent with discrepancies expected from differences in coastal ocean dynamics, spatial sampling between gridded satellite observations and point-based tide gauges, and uncertainties associated with coastal altimetry (Ray et al., 2023).

Independent assessment of the Cork datum adjustment provides additional support for the adopted vertical referencing approach. Using the 2.752 m datum reported by Pugh et al. (2021) produces a Cork tide-gauge trend of 7.72 mm yr⁻¹ over the comparison period, compared with 4.55 mm yr⁻¹ from satellite altimetry, giving a trend difference of -3.17 mm yr⁻¹ (satellite minus tide gauge). In contrast, the OPW-sourced datum produces closer agreement with modern observations from Ringaskiddy and Currach Club, providing additional support for the adopted datum alignment.

Atmospheric Correction Model Selection and Validation

~~Predictors and their associated 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 grid points were accounted selected individually 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 each tide-gauge station to 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):

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

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):

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

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 $\pm 0.25^\circ$ (ERA5), ensuring that the anomaly represents the local conditions near each station. This ensures that the anomaly represents differences in 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):

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

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

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

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

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

where $\rho_{air} = 1.225 \text{ kg m}^{-3}$ 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.

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

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

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_5 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. $c(t)$ is the residual representing the portion of sea level variability not explained by the model.

At some tide gauge stations, correlations weather patterns and coastal geography. 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 varied among stations, reflecting differences in local geography, coastal orientation, and sheltering from exposure to prevailing winds (Pugh & Woodworth, 2014). Predictors that were weak in their simple correlation or statistically insignificant in the multiple regression analysis ($p > 0.05$) 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 S4).

Table 2-S4: 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	$P'_x(t)$	$\tau_x(t)$	$\tau_y(t)$	$\sin\left(\frac{2\pi t}{365.25}\right)$	$\cos\left(\frac{2\pi t}{365.25}\right)$	$\sin\left(\frac{2\pi t}{365.25}\right)$	$\cos\left(\frac{2\pi t}{365.25}\right)$	Notes / Supplement
Malin Head	Include	Include	Include	Included	Omitted	Included	Omitted	Supplement d by Portrush
Portrush	Include	Include	Include	Included	Omitted	Included	Omitted	Supplement to Malin Head
Belfast	Include	Include	Include	Included	Included	Included	Omitted	Supplement d by Bangor data
Bangor	Include	Omitte	Include	Included	Omitted	Omitted	Omitted	Supplement to Bangor
Dublin Port	Include	Include	Include	Included	Omitted	Included	Omitted	Supplement d by data from Dún Laoghaire, Arklow and Howth
Howth	Include	Omitte	Include	Included	Included	Included	Omitted	Supplement to Dublin Port
Arklow	Include	Omitte	Include	Included	Omitted	Omitted	Omitted	Supplement to Dublin Port
Dún Laoghaire	Include	Omitte	Omitte	Included	Included	Omitted	Included	Supplement to Dublin Port
Cork	Include	Include	Include	Included	Included	Included	Omitted	Supplement d by Ringaskiddy and Currach Club

Site	$P'_i(t)$	$T_x(t)$	$T_y(t)$	$\sin\left(\frac{2\pi t}{365.25}\right)$	$\cos\left(\frac{2\pi t}{365.25}\right)$	$\sin\left(\frac{2\pi t}{182.63}\right)$	$\cos\left(\frac{2\pi t}{182.63}\right)$	Notes / Supplement
Tarbert	Include	Include	Include	Included	Included	Omitted	Omitted	Supplemente d by Kilrush Lough dataCarrigah olt — Supplemente d by data from Rossaveel and Galway Harbour
Galway	Include	Omitte	Include	Included	Omitted	Included	Omitted	

- Note: Atmospheric corrections were calculated using the full Portrush record (1998–2015), whereas only the 1996–2003 and 2015 tide-gauge observations were used in the subsequent analysis.

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 on timescales shorter than one year (seasonal and monthly) removed by the regression model. Results for all stations are summarized in Table 3S5. The atmospheric correction consistently reduced variability across all tide-gauge sites, as indicated by decreases in SD, demonstrating successful, consistent with the removal of pressure- and wind-driven effects, variability captured by the regression model. Changes in the mean water level were generally small, reflecting the removal of atmospheric contributions, with slightly larger adjustments observed at Dublin Port.

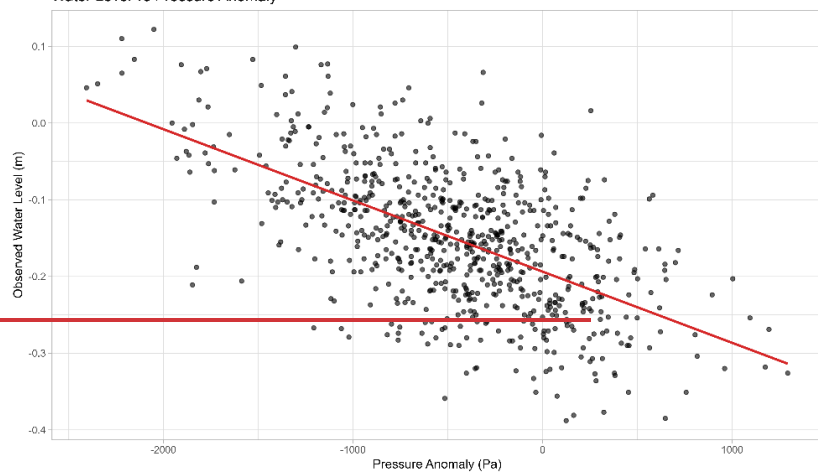
Table 3S5. Mean and standard deviation of observed and atmosphere-adjusted monthly mean-sea-MSL levels at all tide-gauge sites. SD = standard deviation.

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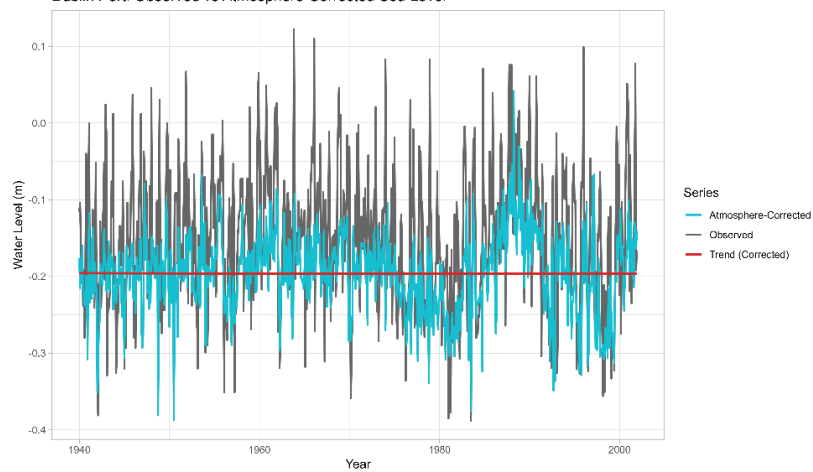
Site	Mean Water Level	SD Water Level	Mean Atmosphere-	SD Atmosphere-
	OD Malin (m)	(m)	Adjusted (m)	Adjusted (m)
Malin Head	0.00	0.10	-0.01	0.0506
Portrush	0.09	0.10	0.05	0.03
Belfast	0.04	0.10	0.04004	0.05
PortrushBangor	0.0413	0.0912	-0.0209	0.0307
Dublin Port	-0.15	0.09	-0.20	0.05
Howth	-0.05	0.09	-0.10	0.0504
Arklow	-0.09	0.09	-0.12	0.02
Dún Laoghaire	-0.20	0.08	-0.18	0.05
Cork	-0.2018	0.1210	-0.1816	0.0806
Tarbert	-0.1922	0.1412	-0.2023	0.1209
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, which typically alters water levels by ~10 mm per mbar⁻¹ (Pugh et al., 2021). The regression, resulting in broadly consistent reductions in short-term variability (SD) and slight changes in mean water level at most tide-gauge sites in this study. Similar to Thompson (1980), the regression estimates site-specific sensitivity to atmospheric pressure and wind stress directly from observations. The resulting residuals represent sea-level variability with the estimated atmospheric effects pressure effect removed. Figure 40S13 illustrates this atmospheric correction at Dublin Port, showing how the regression isolates true sea-level variability by removing reduces the influence of pressure and wind stress driven variability on observed water levels.

Water Level vs Pressure Anomaly



Dublin Port: Observed vs Atmosphere-Corrected Sea Level



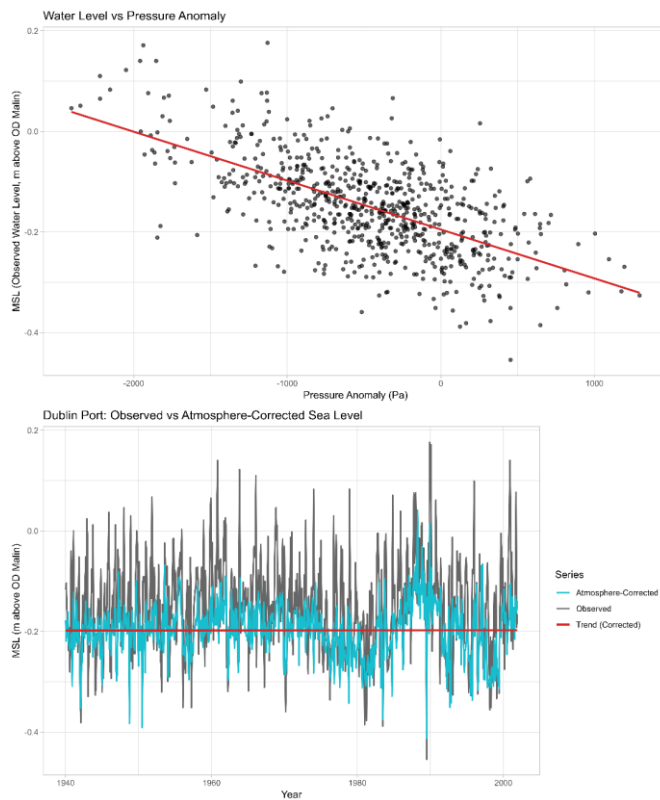


Figure 10S13. Atmospheric pressure correction workflow at Dublin Port. Top: ~~observed~~ **Observed monthly mean** water level versus **atmospheric** pressure anomaly, showing a ~~strong~~ negative correlation ($r = -0.599$, $p < 0.001$); ~~-0.613~~, $p < 2.2 \times 10^{-16}$), consistent with an inverse-barometer response in which higher atmospheric pressure is associated with lower sea level. The fitted linear regression shows the observed relationship between atmospheric pressure anomaly and sea level. Bottom: ~~observed~~ **Observed and atmosphere-corrected monthly mean** water level, with a linear trend fitted. The regression removes levels, illustrating the effect of removing the estimated atmospheric pressure effects, leaving residuals that reflect true sea-level variability contribution.

5.2 Coordinate Tide-Gauge Station Selection ~~for~~ and Atmospheric Adjustments Corrections

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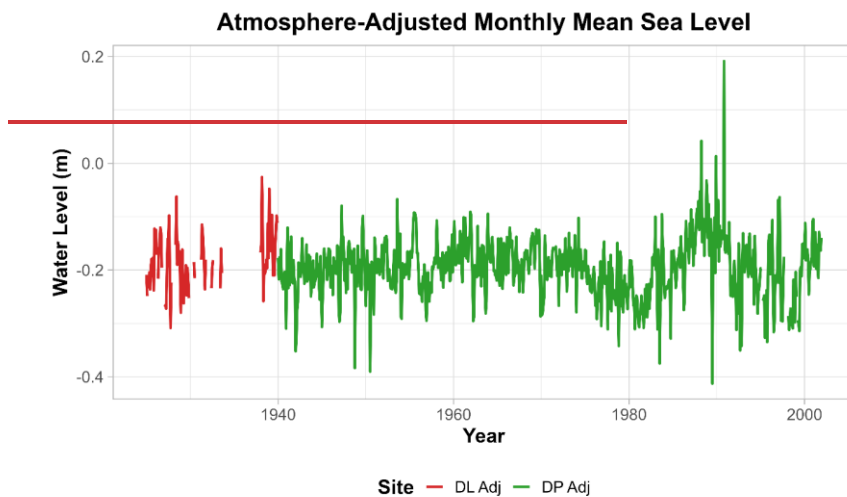
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Atmospheric pressure corrections were applied ~~selectively~~ at tide-gauge sites across Ireland, depending on record length and data resolution. ~~A strong relationship exists between sea-~~ Sea-level ~~and variability is strongly influenced by~~ atmospheric conditions, ~~particularly atmospheric pressure~~ (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 ~~the~~ 20CRv3 ~~reanalysis~~ (1° resolution), from which surface pressure and ~~10-m~~ 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.~~ Atmospheric variables were calculated as the unweighted spatial mean of all grid cells within a ±1° latitude/longitude window centred on each station to reduce grid-scale noise associated with coarse-resolution reanalysis fields and to provide a stable estimate of regional atmospheric forcing relevant to coastal sea-level variability. Record coverage: ~~was~~ Belfast ~~and Bangor~~ (1925–~~2015~~2010), Dublin Port (1938–1939), ~~and~~ Dún Laoghaire (1925–1933, merged with Dublin Port for 1938–1939).
- Post-1940 stations: ~~Bangor, Malin Head, Portrush,~~ Cork, Tarbert, ~~Malin Head,~~ Galway ~~Port,~~ ~~the post-1940 Dublin Port record,~~ Arklow, ~~and~~ Howth, ~~and Portrush used were~~ corrected using high-resolution ERA5 ~~reanalysis~~ (0.25°) ~~for atmospheric correction.~~ resolution). For each station, ~~surface~~ ERA5 reanalysis grid points within ±0.25° of the tide-gauge location were evaluated, and the grid point showing the highest correlation between pressure anomalies and the tide-gauge record over the common overlap period was selected. Surface pressure and ~~10-m~~ 10 m wind components were extracted from the ERA5 grid point previously identified as showing the highest correlation with the local sea-level record ~~this selected grid point, providing a site-specific representation of atmospheric forcing while maintaining consistency with the native spatial resolution of ERA5.~~

~~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 ≈ 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 11).



To assess the sensitivity of the derived relative sea-level (RSL) trends to atmospheric adjustment and the choice of atmospheric reanalysis dataset, a sensitivity analysis was undertaken. The Belfast record was evaluated using the 20CRv3 reanalysis for 1925–2010, with the Bangor extension evaluated using the ERA5 reanalysis for 2011–2022. The Dublin record was similarly evaluated using the 20CRv3 reanalysis for the early 1925–1939 segment and the ERA5 reanalysis for 1940–2024. The early 1925–1939 segment comprises the available Dún Laoghaire observations from 1925–1933, supplemented by Dublin Port observations from 1938–1939 for segment-consistency assessment. Simple linear trends were calculated for both the original and atmosphere-adjusted sea-level series to quantify the effect of these adjustments on the estimated RSL rates. No fixed offset was applied between records corrected using different atmospheric datasets, as differences between datasets were treated as a source of methodological uncertainty rather than a constant correction. The comparison therefore provides an assessment of the sensitivity of the calculated trends to the choice of atmospheric reanalysis dataset and atmospheric adjustment.

The results show that applying atmospheric corrections had a limited effect on the estimated Belfast trend, changing the rate by 0.09 mm yr^{-1} over 1925–2010. The shorter Bangor extension

showed a larger absolute difference of 1.17 mm yr^{-1} between uncorrected and corrected trends, with the trend increasing from 7.09 to 8.26 mm yr^{-1} . This larger change is associated with greater potential sensitivity to short-term variability and regression uncertainty. For the early Dún Laoghaire-based segment, comprising the available 1925–1933 Dún Laoghaire observations and the 1938–1939 Dublin Port observations, the 20CRv3-adjusted trend increased from 1.78 to 3.30 mm yr^{-1} ($+1.53 \text{ mm yr}^{-1}$). In contrast, the longer Dublin Port ERA5 period (1940–2024) showed little change, from 1.29 to 1.22 mm yr^{-1} (-0.07 mm yr^{-1}). The larger sensitivity during the shorter 20CRv3 period is consistent with greater sensitivity to short-term atmospheric variability and regression uncertainty over a shorter record. These differences reflect the sensitivity of the calculated trends to the atmospheric adjustment derived from the selected reanalysis dataset and the length of the observational record, rather than indicating the need for a systematic correction between datasets. The primary RSL trends therefore use the original sea-level records, with atmosphere-corrected trends retained as a sensitivity assessment (Table S6).

Table S6. Comparison of linear RSL trends before and after atmospheric adjustment for the Belfast, Bangor, and Dublin Port records, including the component tide-gauge records used during each period.

Station	Period	Dataset	Raw RSL trend (mm yr^{-1})	Atmosphere-corrected RSL trend (mm yr^{-1})	Difference (mm yr^{-1})
Belfast	1925–2010	20CRv3 reanalysis	-0.17	-0.08	$+0.09$
Bangor	2011–2022	ERA5 reanalysis	7.09	8.26	$+1.17$
Dún Laoghaire-based early segment	1925–1939	20CRv3 reanalysis	1.78	3.30	$+1.53$
Dublin Port	1940–2024	ERA5 reanalysis	1.29	1.22	-0.07

To further evaluate the influence of the early 1925–1939 period highlighted by the atmospheric-correction sensitivity analysis, the early and later Dublin records were analysed separately and subsequently compared with the combined stitched record (Figure S14). The early segment comprises the available Dún Laoghaire observations from 1925–1933, together with Dublin Port observations from 1938–1939 incorporated into the Dún Laoghaire-based early dataset, giving 10 available annual observations. The main Dublin Port segment extends from 1940 to

2001 and contains 62 observations. The 1938–1939 Dublin Port observations were therefore retained within the early segment for the purpose of the atmospheric-adjustment and segment-consistency analysis, before the early and later sections were merged into the stitched record. Linear trend estimates were $+3.30 \text{ mm yr}^{-1}$ for the early 1925–1939 segment, -0.03 mm yr^{-1} for the Dublin Port segment, and -0.12 mm yr^{-1} for the combined stitched record. The relatively large positive trend estimated for the early segment is associated with its short and discontinuous nature and was not statistically significant ($p = 0.085$). A bootstrap comparison of the stitched and Dublin Port-only trends gave a mean difference of approximately -0.08 mm yr^{-1} , with a 95% bootstrap percentile interval of approximately -0.31 to $+0.15 \text{ mm yr}^{-1}$. This interval spans zero, providing no evidence that inclusion of the early observations substantially alters the estimated long-term trend. A linear model including a segment $\times$ time interaction likewise found no statistically significant evidence of a difference in linear trend between the early and later segments (interaction $p = 0.159$). The early observations were therefore retained in the stitched record, as the sensitivity analyses provided no statistically significant evidence that their inclusion alters the estimated long-term linear trend.

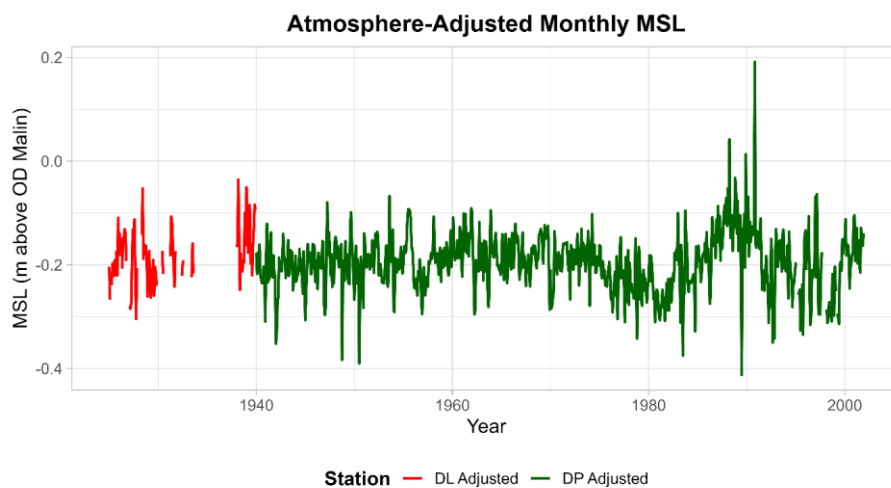


Figure 4S14. Time series of atmosphere-adjusted monthly mean water levels ~~at~~^{for the} early Dún Laoghaire-based segment (DL Adj Adjusted, red; 1925–1939, including Dublin Port observations for 1938–1939) and the subsequent Dublin Port record (DP Adjusted, green; 1940–2001). The early segment comprises the available Dún Laoghaire

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observations from 1925–1933, together with Dublin Port observations from 1938–1939, which were incorporated into the early dataset for segment-consistency assessment. Atmospheric adjustments were applied using 20CRv3 to the early 1925–1939 segment, including the 1938–1939 Dublin Port observations, and ERA5 to the Dublin Port record from 1940–2001. The merged records show no clear visual discontinuity between the 20CRv3 (DL Adj) and ERA5 (DP Adj) data. Atmospheric adjustments reduce, while atmospheric adjustment reduces high-frequency variability, emphasizing and allows the underlying long-term sea-level trends behaviour to be more clearly identified.

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.

The longer timeseries extending back 100 years often contain gaps, nonlinear fluctuations, and observational noise, requiring a more flexible approach. After applying atmospheric adjustments,

Sensitivity to the 18.6-Year Nodal Tidal Cycle

As a further sensitivity assessment, the potential influence of the 18.6-year nodal (18.6 yr) tidal cycle was also examined. Nodal effects (Pugh & Woodworth, 2014) were tested at Belfast, Dublin Port, and Cork Malin Head—the only sites records with sufficiently long, continuous records—and were found to alter observations. The inclusion of nodal variability altered long-term rates by $<0.25 \text{ mm yr}^{-1}$, well below observational and model uncertainties. Because Given that other sites were too short to resolve the nodal signal and its effect influence was negligible, nodal corrections were not applied in the final analysis. (Woodworth, 2012).

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