

A century of sea-level change in Ireland (1925–2024)

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Abstract. Understanding long-term sea-level 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 relative mean sea-level (RSL) change across the country. Modelled RSL rates were obtained from the rate field of the hierarchical Bayesian reconstruction. Mean modelled RSL rates over 1925–2024 ranged from 0.74 mm yr^{-1} at Belfast to 1.43 mm yr^{-1} at Tarbert in southwest Ireland, reflecting the combined influence of the shared regional signal, site-specific linear Glacial Isostatic Adjustment (GIA)-related contributions, and local effects. The network-mean modelled RSL rate for Ireland was 1.21 mm yr^{-1} (95 % CI: 0.90–1.55) over 1925–2024, increasing from 0.59 mm yr^{-1} (95 % CI: 0.19–1.02) during 1925–2000 to 3.13 mm yr^{-1} (95 % CI: 2.45–3.81) during 2000–2024, indicating a substantial acceleration in recent decades. These historical records provide a robust basis for reconstructing regional RSL rise and contextualising future coastal risk.

1 Introduction

Mean Sea Level (MSL) 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 and Woodworth, 2014). Globally, MSL has risen at approximately $3\text{--}4 \text{ mm yr}^{-1}$ over recent decades, with satellite altimetry showing $\sim 3.3 \text{ mm yr}^{-1}$ over 1993–2021, while shorter-term estimates of $\sim 4 \text{ mm yr}^{-1}$ over 2006–2016 reflect, in part, interannual variability (Hamlington et al., 2024; Llovel et al., 2023). Evidence further indicates an accelerating trend, from $\sim 2.1 \text{ mm yr}^{-1}$ in the early 1990s satellite record to $\sim 4.5 \text{ mm yr}^{-1}$ 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 (Oelmann et al., 2024). Understanding long-term sea-level changes from tide-gauge and archival data is essential for quantifying 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 vulnerable to flooding. In 2009 a major flood event in Cork led to

around EUR 100 million of damages to commercial and residential property (Olbert et al., 2017). Annual economic damages from coastal flooding in Britain are currently estimated at approximately GBP 360 million and are projected to increase two- to threefold by the end of the century (Haigh et al., 2022). Approximately 40 % of Ireland’s population lives within 5 km of the coast, including major cities (Wall et al., 2020), making coastal areas highly vulnerable. Given Ireland’s similar coastal exposure and geographical position, it is also likely to face significant costs and challenges.

Ireland has a modern network of over 40 tide gauges through the National Tide Gauge Network (NTGN), installed in the 2000s and managed by the Office of Public Works (OPW) and the Marine Institute (MI) (Cámaro García et al., 2021). However, only a few sites, including Malin Head, Dublin Port, and Belfast Harbour, provide long-term (> 40 years) 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 (1901–2010; Murdy et al., 2015, Fig. 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 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 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, yielding robust long-term RSL reconstructions, reduced uncertainties, and improved detection of long-term accelerations (Hogarth et al., 2021). Similar historical data rescue efforts across multiple Irish sites are therefore required to improve spatial and temporal coverage of sea-level observations.

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 and 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 GIA (Bradley et al., 2011). During the Last Glacial Maximum, the thickest ice extended from Scotland into Northern Ireland, thinning toward the southwest (Scourse et al., 2021). Following deglaciation, collapse of the forebulge caused land subsidence in the southwest and uplift in the northeast, producing spatial contrasts in RSL trends, including localized sea-level fall in parts of the northeast. Quantifying these impacts is complicated by the range of outputs among available GIA models, including variability within individual subfamilies. Understanding past ice-sheet dynamics is therefore critical not only for explaining histori-

cal 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, use physics-based, glaciologically self-consistent ice-sheet simulations (Tarasov et al., 2012), whereas the ICE-6G GIA model is tuned to fit global RSL and crustal motion observations (Peltier et al., 2015). Regional Bradley-type GIA models, including those based on the BRITICE-CHRONO ice-sheet reconstruction of the British–Irish Ice Sheet, are specifically calibrated to British–Irish RSL and GNSS (Global Navigation Satellite System) datasets (Bradley et al., 2023). These differences strongly influence predicted VLM rates, as demonstrated by studies showing high sensitivity to upper-mantle viscosity and uncertainties in deglaciation histories (Bradley et al., 2011, 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 integrate sea-level records from across Ireland, including the south and west where observations are sparse, to improve understanding of 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 non-linear local variability.

The objectives are to:

- i. Integrate and analyse new records from the south and southwest to investigate regional RSL variability in areas with limited long-term observations.
- ii. Reconstruct historical RSL changes across Ireland using quality-assured sea-level data.
- iii. Assess reconstructed spatial patterns of RSL trends considering the influence of GIA.
- iv. Contextualize historical RSL changes across Ireland and evaluate their implications for vulnerable coastal areas.

2 Data Collection, 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

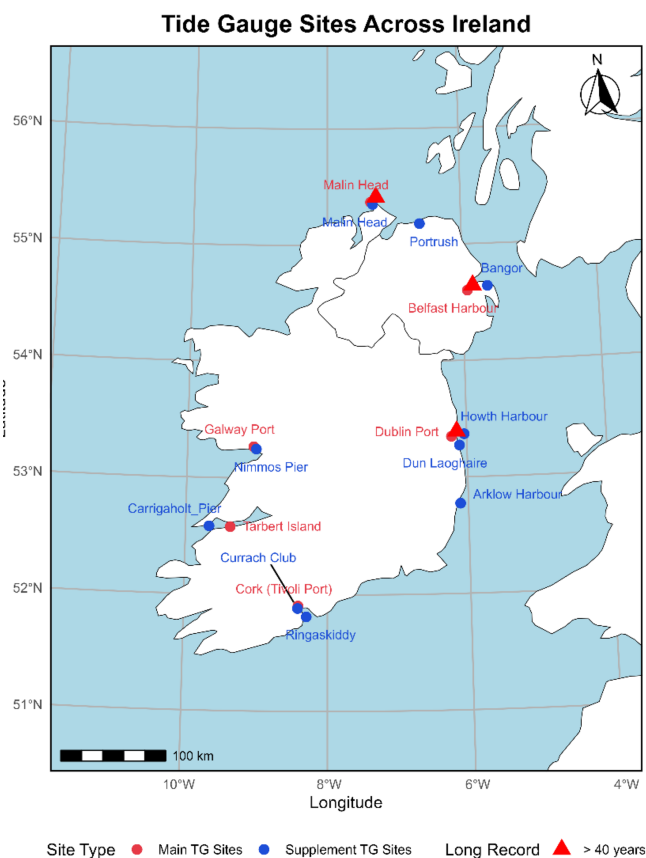


Figure 1. The six primary tide-gauge (TG) sites analysed in this study are shown in red. Supplementary TG sites, shown in blue, are located near the primary sites and are used to fill gaps or improve record quality where available. Belfast, Dublin Port, and Malin Head have long records spanning approximately 60–100 years and are indicated by red triangles.

Island (hereafter Tarbert) (Fig. 1). Supplementary records from nearby gauges were also included where available, including records from Bangor (near Belfast), Portrush (near Malin Head), Arklow, Howth and Dún Laoghaire harbours (near Dublin Port), Cork (Ringaskiddy and Currach Club, used to supplement Tivoli), Carrigaholt Pier (near Tarbert), and Rossaveel (near Galway).

Existing tide-gauge data were obtained from the Permanent Service for Mean Sea Level (PSMSL, Holgate et al., 2013). 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 were included:

- Malin Head (1958–1997).
- Portrush (1998–2015).
- Dublin Port (1938–2001).

PSMSL data for Malin Head were combined with modern observations from the Office of Public Works (OPW; 2004–2008; OPW, 2025) and the Marine Institute (MI; 2009–2024; Marine Institute, 2025). The PSMSL holds a Mean Tide Level (MTL) record for Belfast, but it does not extend beyond 1979. For this study, we used the Belfast dataset digitized by Murdy et al. (2015), which provides high-resolution 10 min 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 (British Oceanographic Data Centre, 2026).

PSMSL data from Dublin port were combined with data for Dún Laoghaire (formerly called Kingstown) from 1925–1931 and were obtained from McLoughlin et al. (2024). Additional data for 1932–1933 were recovered from raw mari-grams following the same methodology; further details are provided in the Supplement. For this study, we used the Dublin Port record spanning 1938–2001 obtained from the PSMSL. Observations after 2001 show considerable 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, including Arklow (2003–2006; OPW) and Howth (Dublin, 2007–2024; NTGN/MI).

To the 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 assessment of digitization accuracy for the 1970s and 1980s are provided in the Supplement (see Fig. 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 assessment of digitization accuracy are provided in Supplement S1 (see Fig. 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-gauge records from Galway (1967–1970), near Nimmo’s Pier, and from Rossaveel (1973–1974) were obtained from the British Oceanographic Data Centre (BODC) archive (British Oceanographic Data Centre, 2026). The dataset contained both Julian Day and human-readable calendar dates (yyyy-mm-dd, hh:mm:ss) at hourly intervals; these were converted to a standard datetime format for analysis. Data for the years 1967, 1970, 1973, and 1974 were incomplete. Tide-gauge records for Galway were obtained from the National Tide Gauge Network (NTGN; MI, 2007–2024).

Table 1 summarises the origin, temporal coverage, and supplementary datasets used for each of the six primary tide-gauge records in this study.

2.2 Datum Conversions

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 (OD Belfast) or Ordnance Datum Dublin (ODD; i.e., OD Poolbeg) were converted to OD Malin using station-specific benchmarks, published or documented datum information, and archival metadata sources. Site-specific datum adjustments and conversion procedures for all stations are documented in the Supplement, with Fig. S3 showing Cork and Tarbert and Table S1 providing details for Galway.

3 Validation of Tide Gauge data

All sea-level datasets underwent rigorous validation prior to inclusion in the sea-level reconstruction. To ensure methodological consistency, observations from modern datasets were assessed for data completeness and gaps, with the quality-control approach informed by procedures used within the UK tide-gauge network. UKCMF methodology identifies gaps greater than 4.1 hours in the primary observation channel and recommends excluding months with substantial data gaps from monthly mean sea-level calculations (UK Coastal Monitoring and Forecasting, 2014). Informed by these quality-control principles, the study-specific methodology used in this analysis was as follows: observations were assessed on an hourly basis to identify missing hours. Days with more than 4 missing hours were excluded from monthly calculations, and months with 15 or more such days were omitted. For months passing these quality-control criteria, daily mean sea levels were calculated from the avail-

able observations on valid days, and the monthly mean was calculated as the mean of the valid daily means.

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 and 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 time-series 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

Table 1. Summary of tide-gauge records, data sources, and periods used in this study prior to quality control and processing. Records contain gaps at many stations.

Site	Period	Primary data source	Additional data sources and extensions
Belfast	1925–2022	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)

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 (Fig. 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 (Fig. S12 and Table S3).

4 Data Processing and Sea-Level Modelling

4.1 Atmospheric Adjustments

In the processing of the RSL data, two reanalysis products were used to correct for atmospheric effects: the NOAA/CIRES/DOE 20th Century Reanalysis Version 3 (20CRv3; NOAA/CIRES/DOE, 2025; Slivinski et al., 2019) and ERA5 reanalysis (Hersbach et al., 2023) to cover the full time period of this study. These atmospheric predictors were incorporated into a regression-based correction to account for atmospheric influences on the observed RSL variability and facilitate estimation of longer-term sea-level trends.

20CRv3 reanalysis provides a continuous record from 1806 to 2015 at 1 m spatial resolution, making it well suited to 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.

To cover the modern period, ERA5 reanalysis was employed. ERA5 reanalysis extends from 1940 to the present, with higher resolution (0.25 m). 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 masks from the 20CRv3 reanalysis and the ERA5-Land monthly reanalysis product (NOAA/CIRES/DOE, 2025; Hersbach et al., 2023). Together, these complementary reanalyses provide the atmospheric forcing fields required to correct both historic and modern records.

Surface pressure anomalies were calculated to account for atmospheric contributions to sea-level variability, following the general approach of Frederikse and Gerkema (2018). Land points were masked using the native land-sea mask, and the remaining ocean pressure values were averaged with cosine-latitude weighting to compute a weighted mean ocean pressure, which was then subtracted from each grid point to obtain anomalies. This ensures that the anomalies reflect ocean pressure variations relevant to sea-level changes near tide-gauge stations, avoiding contamination from continental pressure variations.

Concurrent 10 m zonal (*u*) and meridional (*v*) wind components were extracted from the corresponding reanalysis fields and converted to zonal and meridional wind stress using the approach of Smith (1980). Atmospheric predictors were extracted using station-specific spatial sampling procedures appropriate to each reanalysis product; for 20CRv3, atmospheric fields were spatially averaged within the predefined local search window, whereas for ERA5, the grid point exhibiting the strongest correlation with the observed sea-level record within the predefined local search region was selected. Atmospheric variables, together with seasonal terms,

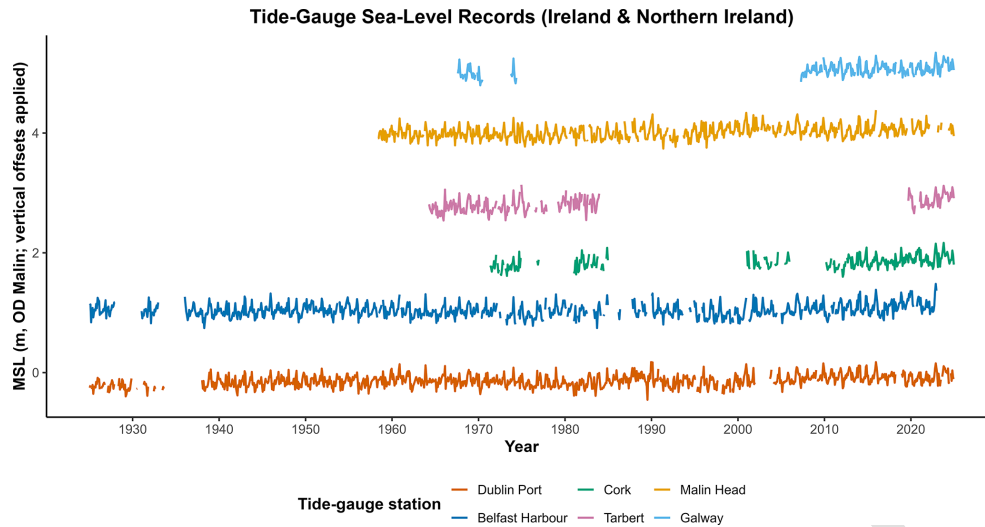


Figure 2. Tide-gauge records for Ireland and Northern Ireland. The six records combine historical PSMSL data with modern NTGN observations and, where required, nearby auxiliary stations to improve temporal continuity. Station-specific quality control was applied, including removal of outliers, datum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

were initially included as predictors in the regression, with statistically insignificant predictors omitted from the final model. Further details on predictor selection and regression model formulation are provided in the Supplement. Annual mean values were calculated from all available monthly MSL values. Although a minimum of 11 months is generally used for annual mean calculation (Permanent Service for Mean Sea Level, 2025), this criterion could not be applied consistently to the historical tide-gauge records because some years contained substantial gaps. Therefore, years were retained where at least three consecutive months of valid observations were available, with all valid monthly observations in those years included in the annual mean calculation.

The processed tide-gauge records used as input for the sea-level reconstruction are shown in Fig. 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.

4.2 Incorporating Glacial Isostatic Adjustment into RSL Reconstruction

It is important to understand the role of 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 VLM, we applied corrections from 16 GIA models, including 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;

Peltier et al., 2015), and GLAC1D variants (BC hybrid – hybrid boundary condition, VM5a – viscosity model; Tarasov et al., 2012). These models differ in their ice-sheet history reconstructions, Earth rheology assumptions, and regional calibration strategies, resulting in spatially variable predictions of uplift and subsidence across Ireland. The ICE-5G model (Peltier, 2004) was excluded from 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 preferred model defined as that which produced the smallest residual inter-site dispersion among the corrected site-specific trends. This provides a data-driven measure of the extent to which each GIA model reduces residual inter-site 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, with sites retained where observations spanned at least 20 years within this interval; gaps within the observation period were permitted. The analysis used monthly mean RSL observations

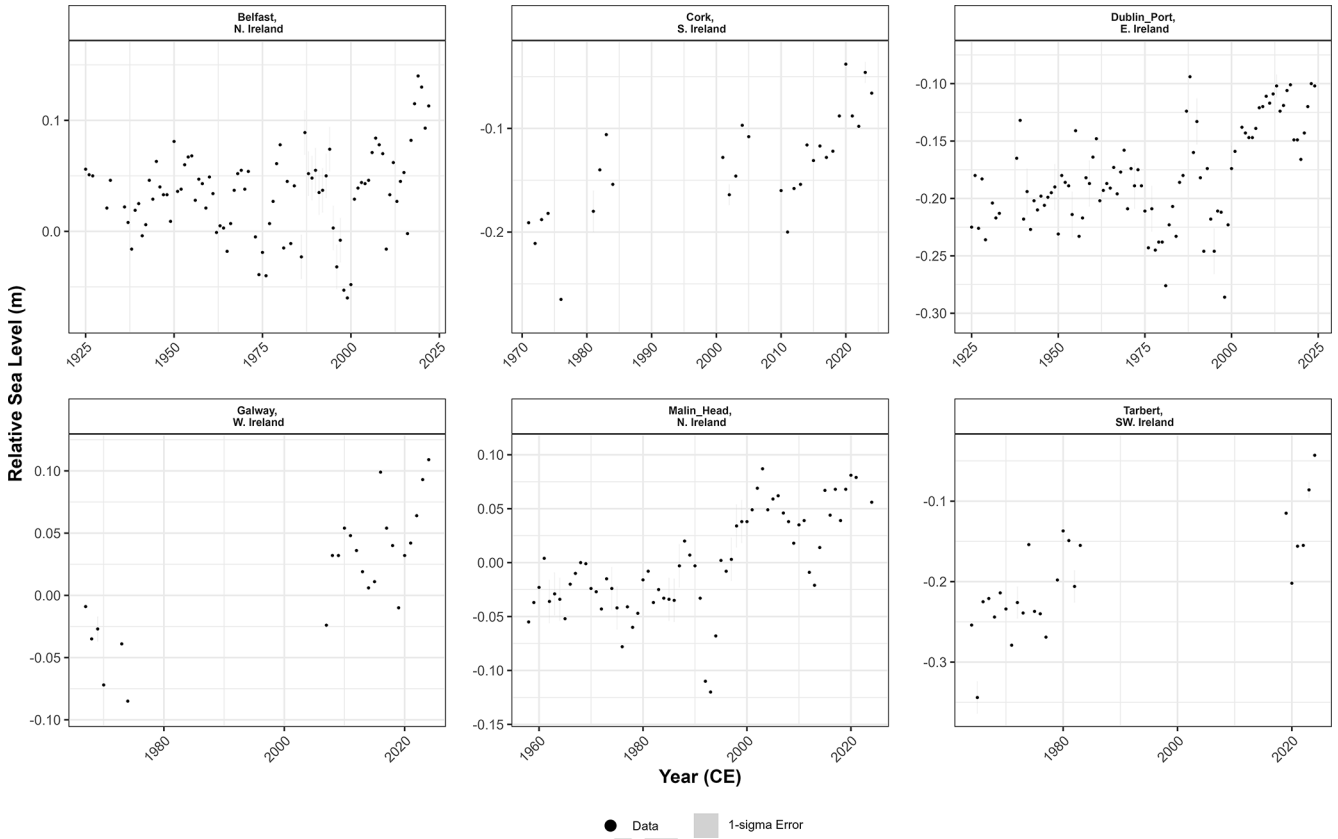


Figure 3. Tide-gauge records used as input to the RSL reconstruction model (datum: OD Malin, metres), showing spatial coverage, record length, and temporal gaps.

from each tide-gauge station. 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 inter-site 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 Fig. 4.

4.3 Statistical Sea-Level Modelling

The longer tide-gauge timeseries, extending back ~ 100 years, often contain gaps and observational noise, requiring a flexible statistical approach to their modelling. Long-term RSL variability was modelled using the Noisy Input Generalised Additive Model using the *reslr* package (Upton et al., 2024, Upton et al., 2025). This model uses a Bayesian hierarchical framework with random effects and a spatio-temporal

Generalised Additive Model (GAM) to examine RSL change and corresponding rates of change. It accounts for measurement uncertainty in observations and incorporates age uncertainty through the Noisy Input method (McHutchon and Rasmussen, 2011). These uncertainties were assigned according to the characteristics of each data source, incorporating known sources of temporal, measurement, and processing uncertainty.

The data level for the Noisy Input Generalised Additive Model (NI-GAM; Upton et al., 2024) is given by (Eq. 1):

$$y = f(x, t) + \epsilon_y, \epsilon_y \sim N(0, \sigma^2 + s_y^2) \quad (1)$$

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 h), digitized historical tide-gauge records an uncertainty of 0.002 years (~ 0.7 d), and monthly PSMSL tide-gauge records an uncertainty of 0.004 years (~ 1.5 d) to reflect increasing uncertainty associated with timing, digitization, and temporal

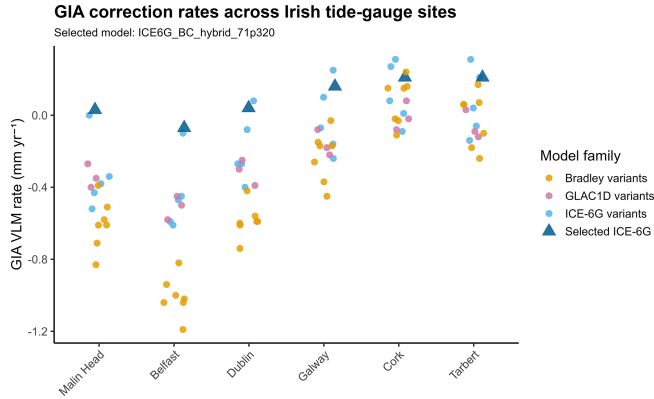


Figure 4. Modelled GIA VLM rates (mm yr^{-1}) at six Irish tide-gauge sites. Dark blue triangles indicate the selected ICE6G_BC_hybrid_71p320 model. Other symbols represent alternative GIA model families (ICE6G variants, Bradley-type variants, and GLAC1D). The ICE6G_BC_hybrid_71p320 model was selected because it produced the smallest 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.

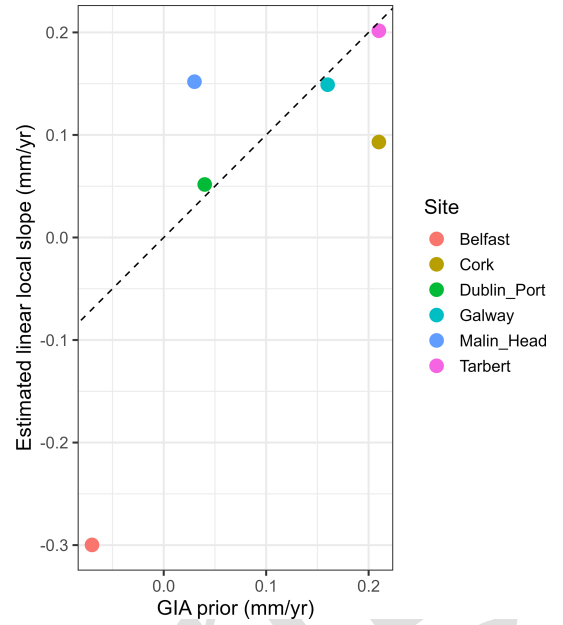


Figure 5. Comparison between prescribed GIA prior rates and estimated linear local trends from the NI-GAM inversion.

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):

$$f(x, t) = r(t) + g(z_x) + h(z_x) + l(x, t) \quad (2)$$

where $r(t)$ is the regional time-varying component across all sites, $g(z_x)$ is a linear term for each site, $h(z_x)$ is a vertical offset for each site, and $l(x, t)$ is a residual term for each site. The regional term $r(t)$ represents temporal processes that are common across all sites (Upton et al., 2024).

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 constrained to reproduce the prescribed GIA values (Fig. 5). Tarbert and Galway show the closest agreement with their respective GIA priors, with estimated slopes of approximately 0.20 and 0.15 mm yr^{-1} compared with prescribed values of 0.21 and 0.16 mm yr^{-1} , respectively. In contrast, Dublin Port exhibits a positive estimated trend of approximately 0.05 mm yr^{-1} compared with its relatively small GIA prior of 0.04 mm yr^{-1} . Cork also shows a marked departure, with an estimated slope of approximately 0.09 mm yr^{-1} compared with the prescribed GIA rate of 0.21 mm yr^{-1} , although the inferred trend remains positive. Belfast shows the largest departure from the 1:1 relationship, with a slope of -0.30 mm yr^{-1} versus a GIA prior of -0.07 mm yr^{-1} . Malin Head shows a notable departure, with an estimated slope of approximately 0.15 mm yr^{-1} compared with a positive GIA prior of 0.03 mm yr^{-1} . These differences demonstrate that, while the GIA priors provide a first-order representation of the expected spatial pattern in VLM, the inferred linear local component retains substantial site-specific variability, including both amplification and attenuation of the prescribed trends.

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.

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). 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

The predictive performance of the NI-GAM model was assessed using 3-fold cross-validation implemented in the `reslr` package (Upton et al., 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 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 NI-GAM produced 95 % prediction intervals with an overall empirical coverage of 90.21 %, indicating reasonably good coverage, while also reflecting some under-coverage relative to the nominal 95 % level. Site-specific coverage ranged from 0.720 at Tarbert to 0.926 at Dublin Port, reflecting differences in predictive performance among sites (Table 2). Prediction interval widths were highly consistent across the network (0.122–0.125 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 (0.000 m), indicating minimal systematic bias. Mean absolute error (MAE) and root mean squared error (RMSE) remained low, with overall values of 0.028 and 0.036 m, respectively. Site-specific RMSE values ranged from 0.032 to 0.051 m, with the largest errors observed at Tarbert, potentially reflecting greater uncertainty associated with the historical record and increased local variability.

The comparison of observed and predicted RSL across all sites is presented in Fig. 6. The NI-GAM captures broad differences in observed RSL across the sites, although the degree of agreement varies among stations. Prediction intervals remain relatively narrow and consistent among sites, consistent with the similar uncertainty estimates obtained from cross-validation. Malin Head shows particularly strong agreement between observed and predicted values, with a high predictive interval coverage of 0.923, close to the highest value observed at Dublin Port (0.926), while Galway shows the lowest 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 deviation, consistent with its lowest predictive interval coverage (0.720) and highest RMSE (0.051 m). Overall, cross-validation in-

Table 2. Cross-validation performance metrics for each site. Coverage represents the proportion of observed RSL values contained within the 95 % posterior predictive interval, while PI width represents the width of this interval. ME, mean error; MAE, mean absolute error; RMSE, root-mean-square error. ME is reported to four decimal places to retain the small magnitude of site-specific bias; all other metrics are reported to three decimal places.

Site	Coverage (95 % PI)	PI Width (m)	ME (m)	MAE (m)	RMSE (m)
Malin Head	0.923	0.122	0.0002	0.026	0.035
Belfast	0.911	0.122	0.0006	0.029	0.035
Dublin Port	0.926	0.122	0.0003	0.026	0.034
Cork	0.897	0.124	−0.0004	0.027	0.036
Galway	0.917	0.124	−0.0003	0.027	0.032
Tarbert	0.720	0.125	0.0015	0.040	0.051

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 uncertainty in the observational records.

An evaluation of the cross-validation residuals over time further clarifies this site-specific variability (Fig. 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. The most recent observations also show both positive and negative departures from zero, including several notable positive residuals after approximately 2015. At Dublin Port, residuals fluctuate around zero throughout the observation period, with both positive and negative departures evident across the record. The apparent flattening of the residual pattern may be partly consistent with the model capturing longer-term RSL 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 in the underlying dataset 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 ob-

servations 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. Overall, the residual patterns do not indicate persistent systematic bias across the network, although site-specific departures and differences in data density contribute to variation in predictive performance.

5 Results

The reconstructed relative sea level (RSL) record (Fig. 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 increasing RSL rates throughout the reconstruction period, with the increase becoming increasingly evident after the 1970s and particularly pronounced during the 2000s.

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

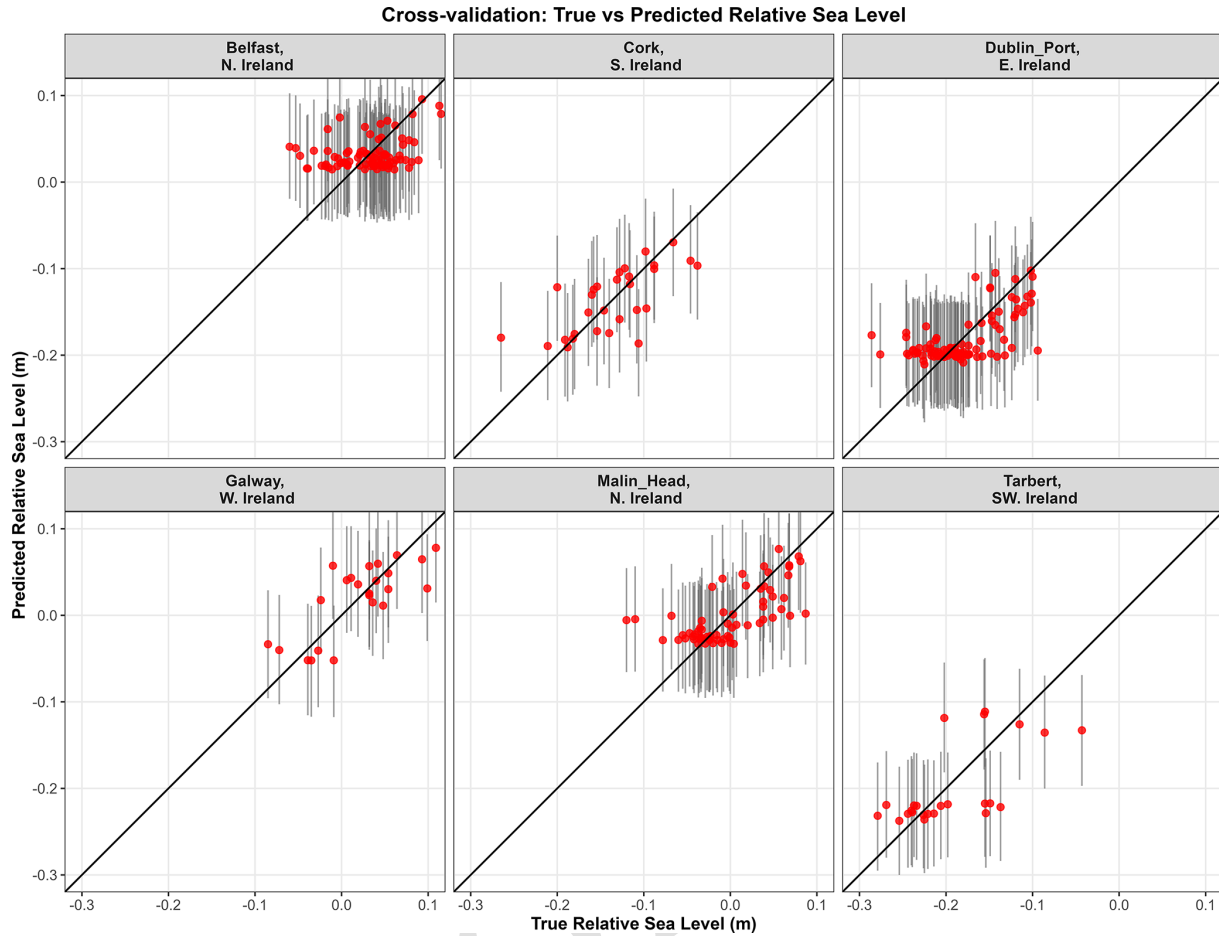


Figure 6. True versus predicted RSL from 3-fold NI-GAM cross-validation across all tide-gauge sites. Red points show posterior predictive means with 95 % predictive intervals, and the black diagonal line represents the 1 : 1 reference; points closer to the line indicate stronger predictive agreement.

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 (Fig. 9), reflecting reduced observational constraints near the temporal boundaries of the reconstruction. For 2024, instantaneous RSL rates are estimated at 3.89 mm yr^{-1} (95 % CI: 2.26–5.56) for Belfast, 4.38 mm yr^{-1} (95 % CI: 2.71–6.05) for Malin Head, 4.24 mm yr^{-1} (95 % CI: 2.65–5.86) for Dublin Port, 4.28 mm yr^{-1} (95 % CI: 2.66–5.88) for Cork, 4.41 mm yr^{-1} (95 % CI: 2.75–6.02) for Tarbert, and 4.37 mm yr^{-1} (95 % CI: 2.73–5.99) for Galway.

Long-term mean modelled RSL rates vary geographically across the Irish tide-gauge network. These rates provide a basis for comparing spatial differences in long-term RSL change between sites, with the mean modelled rates for each tide-gauge site summarised in Table 3. Rates vary across the northern sites, with Malin Head exhibiting a mean rate of 1.28 mm yr^{-1} (95 % CI: 0.86–1.73) and Belfast showing a lower mean rate of 0.74 mm yr^{-1} (95 % CI: 0.42–1.05) over

1925–2024. 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 1.12 mm yr^{-1} (95 % CI: 0.83–1.41) over 1925–2024.

Higher mean rates are observed at the southern and western sites, with Tarbert showing the highest rate at 1.43 mm yr^{-1} (95 % CI: 0.92–2.03) over 1925–2024. Galway also exhibits a relatively high mean rate of 1.38 mm yr^{-1} (95 % CI: 0.90–1.98), while Cork shows a slightly lower rate of 1.28 mm yr^{-1} (95 % CI: 0.80–1.85). 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 highest long-term RSL rate within the reconstructed network. Uncertainty is also greater at Cork, Galway, and Tarbert during the earlier part of the extended pre-

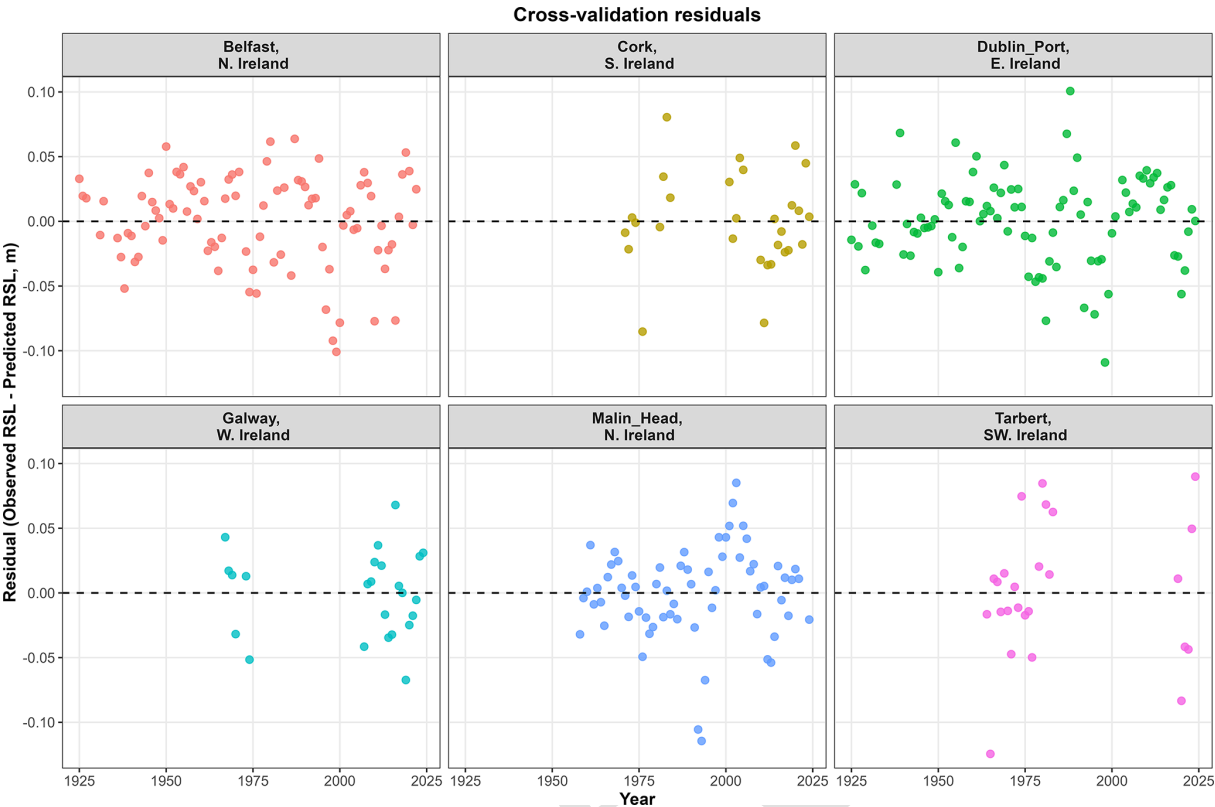


Figure 7. Cross-validation residuals (Observed – Predicted RSL, m) plotted against time (Year) for each tide-gauge station. The dashed horizontal line indicates zero error. The plots reveal site-specific temporal structures and variations in historical data density across the Irish coastline.

diction period, with wider CIs also evident at Malin Head (Fig. 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.

Comparison with the earlier period (1925–2000) highlights the recent acceleration in modelled RSL change. During 1925–2000, rates were generally low, with mean estimates ranging from 0.10 mm yr^{−1} (95 % CI: −0.26–0.44) at Belfast to 0.83 mm yr^{−1} (95 % CI: 0.21–1.64) at Tarbert. Malin Head, Dublin Port, Cork, and Galway showed rates of 0.65 (0.17–1.18), 0.49 (0.16–0.82), 0.67 (0.08–1.39), and 0.77 mm yr^{−1} (0.19–1.54), respectively. Across individual tide-gauge sites, the modelled rates shown in Fig. 9 indicate higher rates during 2000–2024 than during the earlier period, consistent with a recent acceleration in RSL change across the tide-gauge network.

The regional modelled RSL signal is consistent with the acceleration evident in the tide-gauge observations (Fig. 10). The mean modelled RSL rate across the Irish tide-gauge network over 1925–2024 is 1.21 mm yr^{−1} (95 % CI: 0.90–1.55). When separated into earlier and more recent periods,

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 RSL rate (mm yr ^{−1})	95 % credible interval (CI)
Malin Head	1925–2024	1.28	0.86–1.73
Belfast	1925–2024	0.74	0.42–1.05
Dublin Port	1925–2024	1.12	0.83–1.41
Cork	1925–2024	1.28	0.80–1.85
Tarbert	1925–2024	1.43	0.92–2.03
Galway	1925–2024	1.38	0.90–1.98

the mean rate increases from 0.59 mm yr^{−1} (95 % CI: 0.19–1.02) during 1925–2000 to 3.13 mm yr^{−1} (95 % CI: 2.45–3.81) during 2000–2024, indicating a marked increase in the rate of RSL change. The instantaneous mean modelled RSL rate in 2024 reaches 4.26 mm yr^{−1} (95 % CI: 2.68–5.84), indicating that the rate of RSL change remained elevated in 2024. These mean modelled RSL rates incorporate the common regional sea-level signal together with site-specific

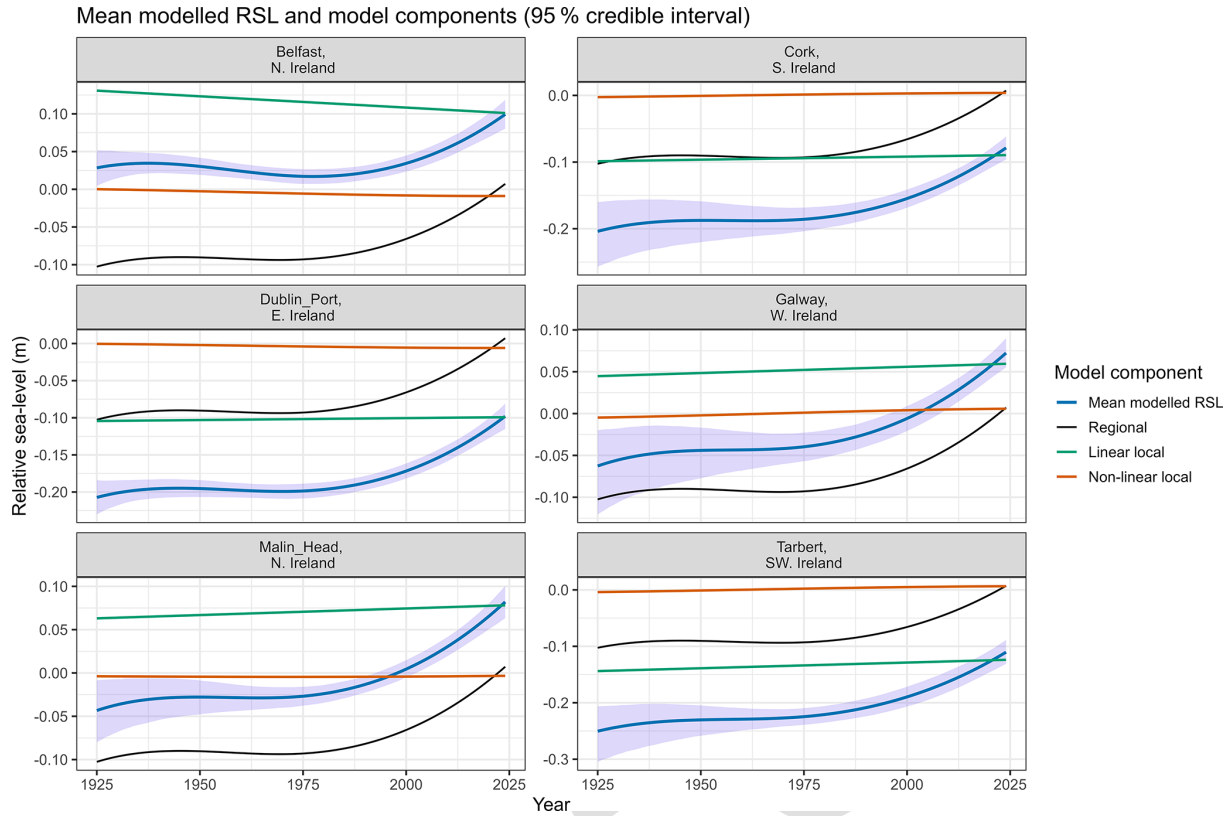


Figure 8. Mean modelled RSL (blue; sum of the three component contributions) and credible interval (blue ribbon), with decomposition into regional (black), linear local (GIA-related, green), and non-linear residual (red) components for Irish tide-gauge sites.

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 1.13 mm yr^{-1} (95 % CI: 0.36–1.98). The regional rate increases from 0.51 mm yr^{-1} (95 % CI: -0.34 – 1.45) during 1925–2000 to 3.04 mm yr^{-1} (95 % CI: 2.06–3.94) during 2000–2024, reaching an instantaneous regional rate of 4.18 mm yr^{-1} (95 % CI: 2.48–5.82) 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 $< 0.10 \text{ mm yr}^{-1}$.

The accumulated RSL change was calculated from the difference between the posterior total modelled RSL estimates at the beginning and end of the reconstruction period. The mean accumulated RSL rise across the six reconstructed Irish tide-gauge sites was 11.8 cm (95 % CI: 8.78–15.1 cm) between 1925 and 2024.

6 Discussion

This study presents an integrated view of 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-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, with instantaneous RSL rates exceeding 4 mm yr^{-1} at five of the six Irish tide-gauge sites in 2024. These recent rates indicate substantial acceleration in RSL rise around Ireland and are broadly consistent with the recent acceleration observed in global sea-level rise.

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 (1958–1998). For comparison, over the corresponding periods, the NI-GAM reconstruction estimates a modelled RSL rate of 0.10 mm yr^{-1} (95 % CI: -0.26 – 0.44) for Belfast over 1925–2000 and 0.72 mm yr^{-1} (95 % CI: 0.31–1.15) 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

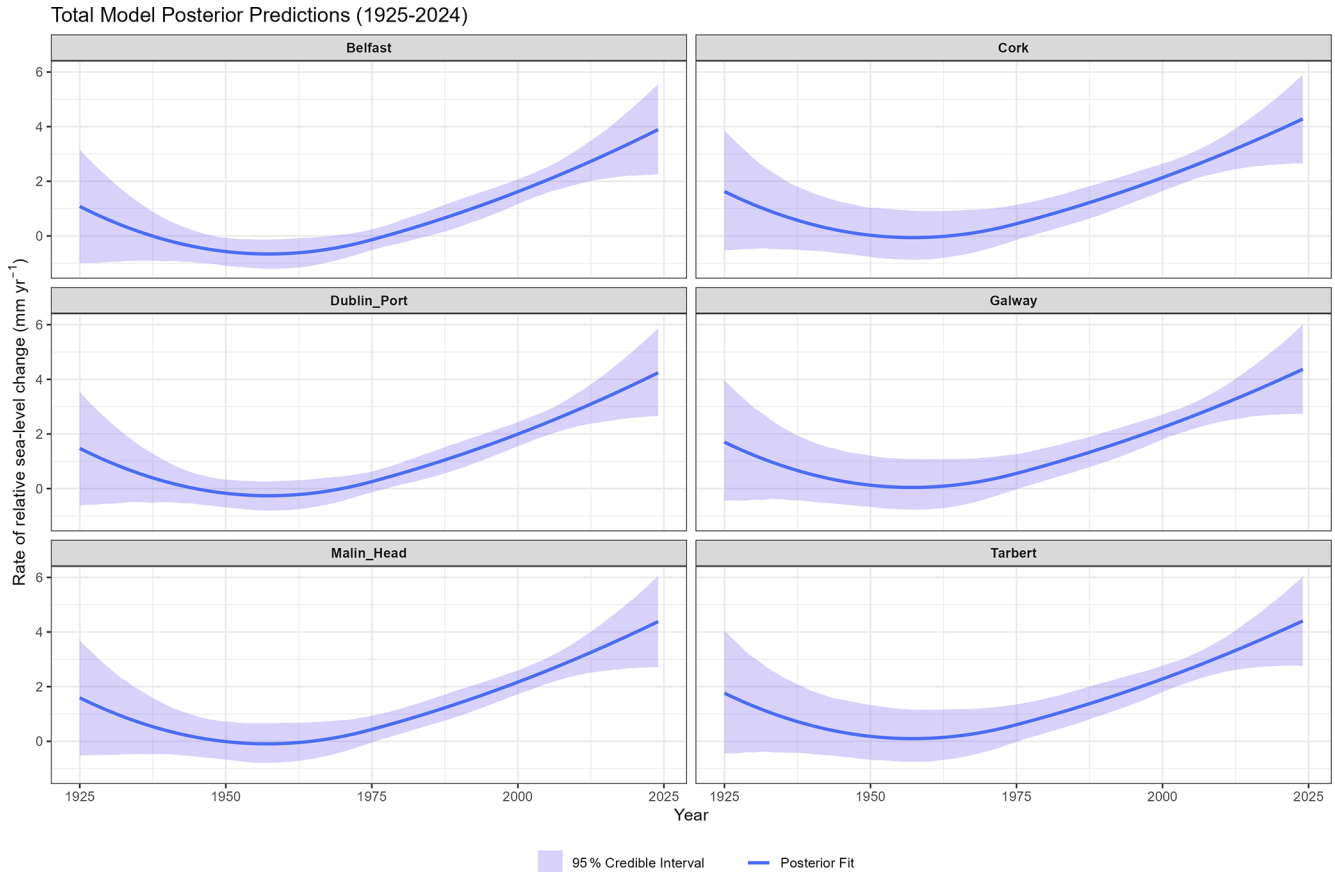


Figure 9. Modelled RSL rates (including regional, linear, and local components) across Irish tide-gauge sites (1925–2024). The figure highlights long-term trends and inter-site variability. Prediction grids were extended back to 1925 for all sites; increased uncertainty is evident at Cork, Tarbert, and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

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 long-term mean rate at Malin Head is higher than at Belfast and broadly comparable to the rates observed at the southern and western sites, indicating that Malin Head exhibits relatively high RSL rates.

To the east, Dublin Port exhibits a long-term mean modelled RSL rate of 1.12 mm yr^{-1} (1925–2024; 95 % CI: 0.83–1.41). The estimated mean modelled RSL rate for 1925–2000 was lower at 0.49 mm yr^{-1} (95 % CI: 0.16–0.82), increasing to 2.69 mm yr^{-1} (95 % CI: 2.16–3.23) for 2000–2016. The instantaneous RSL rate in 2024 reached 4.24 mm yr^{-1} (95 % CI: 2.65–5.86), indicating a substantial recent increase in the rate of RSL change. These results are generally consis-

tent with previous tide-gauge estimates for overlapping periods. Shoari Nejad et al. (2022) reported a tide-gauge-derived MSL trend of 1.1 mm yr^{-1} (95 % CI: 0.6–1.6 mm yr^{-1}) for Dublin Port during 1953–2016 using Bayesian linear regression applied to corrected observations, compared with our modelled RSL rate of 1.08 mm yr^{-1} (95 % CI: 0.83–1.32) for the same period. The two estimates are very similar and show broad agreement, providing consistent evidence of the long-term rate of RSL change at Dublin Port. At Dublin Port, our reconstruction indicates relatively modest and variable rates of RSL change prior to 2000, with modelled rates of -0.08 mm yr^{-1} (1938–1961; 95 % CI: -0.57 to 0.39 mm yr^{-1}) and 0.08 mm yr^{-1} (1961–1980; 95 % CI: -0.33 to 0.48 mm yr^{-1}). These estimates can be compared with historical 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. Over 1938–1996, Woodworth et al. (1999) reported a long-term trend of 0.2 mm yr^{-1} , compared with our modelled RSL rate of 0.30 mm yr^{-1} (95 % CI: 0.03–0.57). Differences between studies likely reflect variations in data coverage, corrections, and modelling ap-

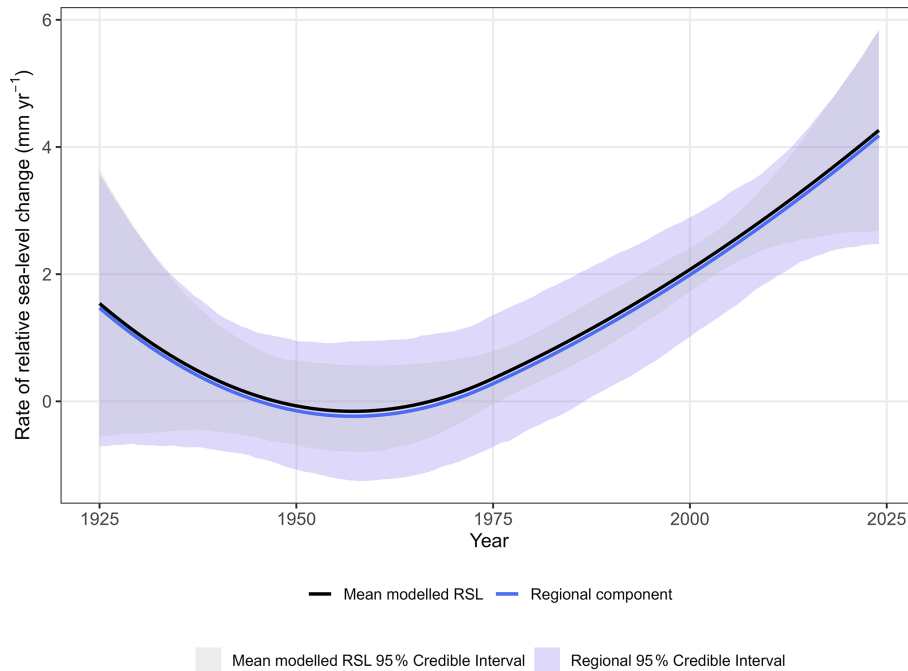


Figure 10. Mean and regional RSL rates (1925–2024) across the Irish tide-gauge network. Shaded areas indicate the 95 % CI. The mean modelled RSL rate combines regional, GIA, and local components, while the regional rate represents the shared spatio-temporal signal. The close correspondence between the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

proaches; however, all estimates indicate relatively modest rates of RSL change before 2000, followed by a pronounced acceleration in recent decades. Palaeo-reconstructions using saltmarsh foraminifera also indicate a comparable long-term RSL rate since the early nineteenth century ($1.6 \pm 0.9 \text{ mm yr}^{-1}$; Roseby et al., 2023).

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 1.28 mm yr^{-1} (95 % CI: 0.80–1.85; 1925–2024), with the instantaneous RSL rate reaching 4.28 mm yr^{-1} (95 % CI: 2.66–5.88) 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 differences in 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 approximately 2 mm yr^{-1} in magnitude (tide gauge minus satellite). 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 pro-

duced 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 1.43 mm yr^{-1} (95 % CI: 0.92–2.03; 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 4.41 mm yr^{-1} (95 % CI: 2.75–6.02). 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 1.38 mm yr^{-1} (95 % CI: 0.90–1.98; 1925–2024), with the instantaneous RSL rate increasing to 4.37 mm yr^{-1} (95 % CI: 2.73–5.99) in 2024, consistent with the broader regional acceleration in RSL change.

The reconstructed Irish RSL record (1925–2024) was compared with a global tide-gauge MSL reconstruction and a global satellite-altimetry SSH record, using the Palmer et al. (2021) global tide-gauge reconstruction (1925–2010) and the Copernicus Climate Change Service (C3S, 2018) satellite-altimetry sea-surface height (SSH) record (1993–2024) (Fig. 11). All three series were referenced to 1993 (1993 = 0), providing a common baseline for comparison of their tem-

poral evolution. Prior to the late twentieth century, the Irish and global tide-gauge series showed different temporal behaviour. While the global tide-gauge reconstruction exhibited an overall long-term rise, the Irish modelled RSL increased only modestly during the mid-twentieth century, rising by approximately 1.3 cm between 1925 and 1975. The two records became more closely aligned during the latter part of the twentieth century. From approximately the 1990s to 2010, the Irish modelled RSL followed a broadly similar upward trajectory to the global tide-gauge reconstruction, although the global series exhibited greater interannual variability and differences in magnitude occurred at various times.

During the satellite era (1993–2024), the Irish modelled RSL and global satellite-altimetry SSH record showed broadly similar upward trajectories. Both indicated substantial sea-level rise over this period, although the global satellite series rose somewhat more strongly, exceeding 0.10 m above the 1993 reference by 2024, compared with approximately 0.09 m for the Irish modelled RSL. The broadly similar late-period trajectories demonstrate that both the Irish reconstruction and the global satellite-altimetry record exhibit a pronounced rise in sea level during the satellite era.

Between 1925 and 2024, the mean modelled RSL rate across the Irish tide-gauge network was 1.21 mm yr^{-1} (95 % CI: $0.90\text{--}1.55 \text{ mm yr}^{-1}$). The model indicates a clear acceleration through time, with the mean modelled RSL rate increasing from 0.59 mm yr^{-1} (95 % CI: $0.19\text{--}1.02 \text{ mm yr}^{-1}$) during 1925–2000 to 3.13 mm yr^{-1} (95 % CI: $2.45\text{--}3.81 \text{ mm yr}^{-1}$) during 2000–2024. The cumulative RSL change, calculated from the difference between posterior total modelled RSL estimates in 1925 and 2024, was 11.8 cm (95 % CI: $8.78\text{--}15.1 \text{ cm}$). 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. (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 1.21 mm yr^{-1} (95 % CI: $0.90\text{--}1.55 \text{ mm yr}^{-1}$) over 1925–2024, while the corresponding regional RSL component was 1.13 mm yr^{-1} (95 % CI: $0.36\text{--}1.98 \text{ mm yr}^{-1}$). 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 because it produced the smallest inter-site spread in GIA-corrected RSL trends 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 according to the criterion adopted here, namely reducing spatial variability in observed RSL trends prior to integration into the reslr model. 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. While the Bangor observations were independently inspected and quality-controlled, the BODC warning that observations from approximately 2016 onwards remained potentially suspect indicates that residual uncertainty remains in the later Bangor record, and its data quality cannot be fully assured. 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 the current estimate of 0.74 to $\sim 0.96 \text{ mm yr}^{-1}$. During the earlier period, Belfast showed a near-zero mean rate of 0.10 mm yr^{-1} (95 % CI: $-0.26\text{--}0.44$) over 1925–2000, compared with 0.30 mm yr^{-1} (95 % CI: $-0.02\text{--}0.62$) over 1925–2010. Both estimates indicate relatively limited long-term RSL rise, although the 1925–2010 estimate is higher and remains associated with substantial uncertainty. These earlier estimates indicate relatively low rates of RSL rise, with substantial uncertainty, whereas inclusion of the modern Bangor observations results in a more pronounced recent acceleration in the Belfast record. The sensitivity of the estimated rates to the choice of GIA model highlights the importance of model selection 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 indicates generally good predictive performance for the reconstructed

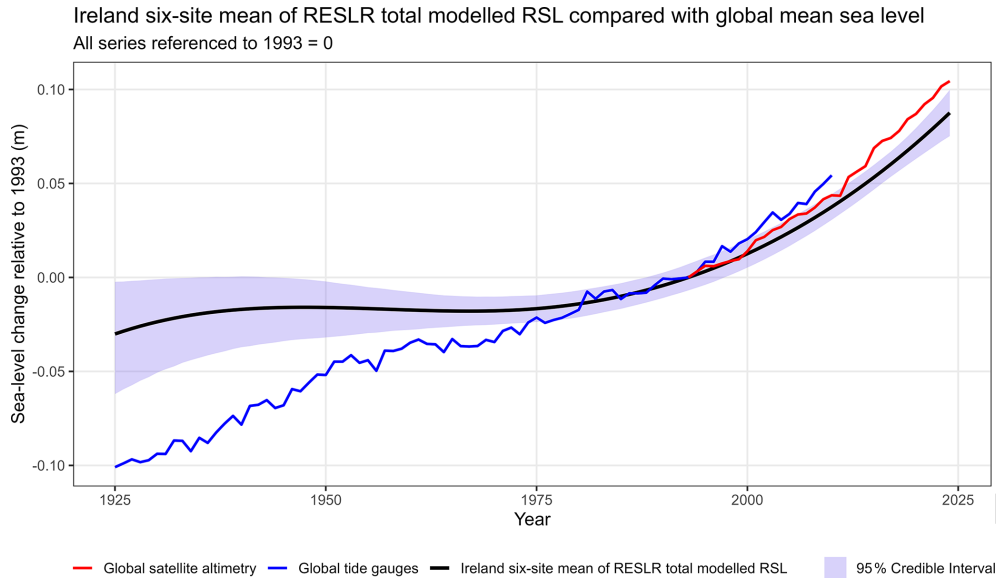


Figure 11. Comparison of the six-site mean reconstructed Irish RSL (1925–2024) with global sea-level datasets. The Irish RSL reconstruction (black line, with 95 % CI) is shown alongside the Palmer et al. (2021) global tide-gauge reconstruction (blue line; 1925–2010) and the Copernicus Climate Change Service (C3S, 2018) global mean sea-surface height (SSH) satellite-altimetry record (red line; 1993–2024). All three series are referenced to 1993 (1993 = 0) to facilitate comparison of their temporal evolution.

RSL time series. Three-fold cross-validation showed that the 95 % prediction intervals had empirical coverage of 72.0 %–92.6 % across sites, with an overall coverage of 90.21 %, indicating some under-coverage relative to the nominal 95 % level. Prediction intervals were highly consistent across the network, with widths ranging from 0.122 to 0.125 m. The near-zero overall mean error indicates limited overall bias in the model predictions. Mean absolute error (MAE) and root mean squared error (RMSE) were low, with overall values of 0.028 and 0.036 m, respectively, while site-specific RMSE values ranged from 0.0321 to 0.0510 m. Some variation is evident among sites, with Tarbert showing the largest residual errors and lowest predictive coverage, which likely reflects greater uncertainty associated with the sparse and discontinuous historical record and limited observational constraints. Belfast and Dublin Port also showed some departures from the 1 : 1 observed–predicted relationship, potentially indicating that some observed multi-decadal variability was not fully reproduced by the model at these sites.

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 generally good predictive performance across the network, while

highlighting locations where local variability and uncertainty representation may influence predictive performance.

Some uncertainty remains in the observational data, 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 errors in historical records (McLoughlin et al., 2026), instrumentation effects (Gobron et al., 2019), and residual high-frequency variability not fully removed by atmospheric corrections. For Belfast, additional uncertainty may arise from incomplete temporal coverage in the historical record digitized by Murdy et al. (2015). In some instances, observations were recorded or digitized a few minutes after the nominal hourly interval and were therefore not retained when the record was subsequently filtered to exact hourly timestamps. This can result in gaps in the standardized hourly series and may introduce uncertainty into daily, monthly, and annual mean estimates where temporal coverage is incomplete. Although atmospheric corrections accounted for pressure- and wind-driven variability, annual means based on incomplete records may not fully represent the seasonal cycle and could therefore introduce small positive or negative biases in individual years. The seasonal harmonic terms included in the regression remove the modelled seasonal component from the monthly records, but residual

seasonal variability may remain where observational coverage is incomplete.

The *reslr* package produces robust regional estimates by integrating data from multiple sites (Upton et al., 2024). This hierarchical approach allows sites with shorter or more incomplete 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, may warrant particular attention because they exhibit relatively high modelled RSL rates and, in some cases, limited observational coverage, particularly 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 MSL (Wang et al., 2024).

7 Conclusions

The key objective of this study was to estimate historical sea-level change across Ireland, with particular focus on the south and southwest, where long-term observations have been limited. By integrating archival and modern tide-gauge data, including Cork, Tarbert, and Galway, this study fills critical spatial gaps and situates Irish sea-level changes within a broader regional context, complementing previous studies in the UK.

In 2024, modelled instantaneous RSL rates were elevated across Ireland, ranging from 3.89 to 4.41 mm yr^{-1} . Rates were broadly similar among sites, with the highest estimated values occurring at Malin Head and Tarbert, followed by Galway, Cork, and Dublin Port, while Belfast exhibited the lowest estimated rate. These results indicate widespread acceleration in RSL rise across the Irish tide-gauge network, al-

though the 2024 Belfast estimate reflects modelled continuation beyond the end of its observational record in 2015. Adjustments for datums, atmospheric effects, seasonal cycles, and GIA were incorporated into the analysis, with additional sensitivity testing used to assess the influence of GIA model choice. Under the ICE6G_BC_hybrid_71p320 model, the site-specific GIA rates were selected because this model produced the smallest inter-site spread 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.

Cross-validation indicates generally good predictive performance of the regional reconstruction, with overall predictive coverage of 90.21 %, reasonably 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, the model captures the broad patterns of observed RSL variability and provides generally consistent uncertainty estimates. Performance varies among sites, with Tarbert showing the lowest predictive coverage (72.0 %) and highest prediction errors, which likely reflects greater uncertainty associated with its sparse and discontinuous observational record. Overall, this study demonstrates the value of integrating modern statistical frameworks with archival data 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. Previous studies of MSL change in Ireland reported relatively low rates of rise (Carter, 1982; Woodworth et al., 1999; Orford et al., 2006), while more recent individual site studies have identified rates of sea-level rise consistent with climate change-driven trends (Shoari Nejad et al., 2022). This synthesis reveals a clear acceleration in RSL rise since the late twentieth century, with the increase becoming particularly pronounced during the early twenty-first century. The mean modelled RSL rate increased from 0.59 mm yr^{-1} (95 % CI: $0.19\text{--}1.02$) during 1925–2000 to 3.13 mm yr^{-1} (95 % CI: $2.45\text{--}3.81$) during 2000–2024. The results indicate that the recent acceleration in RSL rise around Ireland is broadly consistent with the acceleration observed in global sea-level rise, with higher long-term modelled RSL rates generally occurring at southern and western sites, while lower rates are generally observed at northern sites. Given the observed recent acceleration in sea-level rise and projected future increases, Ireland's coastal population will need to adapt to the associated increase in coastal flooding and inundation. 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.

Code and data availability. Historical tide gauge records digitized as part of this study, together with Galway data from BODC (British Oceanographic Data Centre, 2026, available at <https://www.bodc.ac.uk/data/>) and Belfast data (Murdy et al., 2015), are available at <https://doi.org/10.5281/zenodo.17854748> (McLoughlin et al., 2025). Data from the PSMSL are available at <https://psmsl.org/data/obtaining/map.html> (last access: 9 May 2025). Data from modern tide gauge stations maintained by the OPW and Marine Institute are available at <https://waterlevel.ie/> (last access: 9 October 2025; OPW, 2025) and <https://www.digitalocean.ie/Data/DownloadTideData> (last access: 7 March 2025; Marine Institute, 2025), respectively. ERA5 and 20CRv3 reanalysis data used for atmospheric and seasonal corrections are available from the Copernicus Climate Change Service (Hersbach et al., 2023, <https://doi.org/10.24381/cds.f17050d7>) and the NOAA Physical Sciences Laboratory (NOAA/CIRES/DOE; https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html, last access: 19 October 2025), respectively. The 20CRv3 reanalysis is described by Slivinski et al. (2019). Satellite altimetry sea-level data used for validation (see Supplement) are available from the Copernicus Climate Change Service (Copernicus Climate Change Service (C3S), 2018) at <https://doi.org/10.24381/cds.4c328c78>. Code required for the main analyses and results of this study is available on GitHub (<https://github.com/PatrickJMcLoughlin/Ireland-Sea-Level>, last access: 1 October 2026) and is archived on Zenodo (<https://doi.org/10.5281/zenodo.23413431>, McLoughlin, 2026).

Supplement. The supplement related to this article is available online at [the link will be implemented upon publication].

Author contributions. PM: Conceptualization; data digitization of associated dataset; writing – original draft; software; writing – review and editing. LS: Writing – review and editing; data digitization of associated dataset – review and editing. GN: Writing – review and editing. KH: Writing – review and editing. GM: Writing – review and editing; conceptualization. MU: Writing – review and editing; sea-level modelling; conceptualization. RE: Writing – review and editing. CO'B: Validation of satellite data.

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