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20th Century Sea-Level Changes around the North of Ireland

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20th Century Sea-Level Changes around the North of Ireland

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20TH CENTURY SEA-LEVEL CHANGES AROUND THE NORTH OF IRELAND

FINAL REPORT

Research Contract: GPA 308-CON 466
Environment and Heritage Service (NI) and
The Queen's University, Belfast.

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SUMMARY

The physical record of sea-level change around the north of Ireland has been digitised to generate annual estimates of mean sea level position from Malin Head (1958-2001), and mean tidal level from Belfast Harbour (1918-2001). Both sites identify problems of datum consistency, while Belfast in particular shows evidence of gauge failure leading to record disruption. Both site's records have been checked and data gaps have been adjusted where possible. Both sites can be characterised by conservative data adjustments. The relative change in sea-level position for both sites has been determined by the use of linear regression on raw data and on nodal-tide detrended data. The use of quadratic polynomial regression has been used to check for signs of accelerated relative sea-level change in the latter part of the 20th century. Both sites exhibit overall negative tendency at a decade to sub-century scale (c. -0.2mm a^{-1}). Previous estimates of negative tendency tend to diminish at Malin Head, as the data window has been extended up to date. Both sites identify a sub-decadal oscillation in mean sea/tidal level that may account for the orientation of the significant ($p<0.05$) quadratic polynomial regression found for the detrended data from both sites. The differences in overall structure of the relative mean sea/tidal level during the 20th century at the two sites, is an unspecified combination of continuing Holocene isostatic land rise as well as recent eustatic sea level rise. The land rise appears to have been sufficient to mask any late 20th-century globally accelerated eustatic change (hence the negative tendency). The observed rise in the value of sea-level change rate, appearing to move towards a positive value over the latter half of the 20th century, may well reflect an accelerating eustatic sea-level change, which is likely to dominate over ongoing land elevation changes and result in a positive (transgressive) tendency within the next few decades. Such changes are currently identified on recently installed tide-gauges at Portrush and Bangor (c.7-8 year records). The strength of the signal is dependent on accurate determination of land change rates at both sites. The determination of Holocene isostatic signal at Belfast is further confused by localised land-sea relationships anthropogenically modified by continuing harbour developments through the last two centuries.

1 INTRODUCTION

1.1 Sea level change in the north of Ireland

Recent concern with the impacts of accelerated global changes has identified the specification of both secular sea-level change rates and their impacts along the world's shorelines, among the numerous needs of the environment to be faced in the 21st century (Houghton *et al.*, 1996). The global search for environmental change indications has been taken up as an element of national policy both at a regional and local level (cf. UK Climate Change Impact Studies). Figure 1.1 shows the annual mean sea level changes as reported from a number of British long-term (sub-century) records; trends that underlie the recent concern to specify future accelerations in sea-level change rate.

This report on the scale of relative sea-level change (RSLC) for the north of Ireland coast is undertaken as an aspect of this governmental concern into environmental change as a function of climate change. Published estimates of sea level change during the 20th century for the north of Ireland (Carter, 1982a) are now considered out-of-date, while NI's peripheral position to the GB remit (Woodworth *et al.*, 1999) and the neglected state of NI (and Irish sources generally: Fig.1.2) datasets of sea level position, means that more recent GB-orientated work tends to exclude NI. This position of relative neglect underlies this Environment and Heritage Service sponsored study into re-considering NI's sea-level history during the 20th Century.

Given that data sources are dependent on sites outside of Northern Ireland's territorial jurisdiction, it is more logical to consider the issues of sea level change through an island of Ireland perspective – hence the spatial aspect to the "north of Ireland" usage.

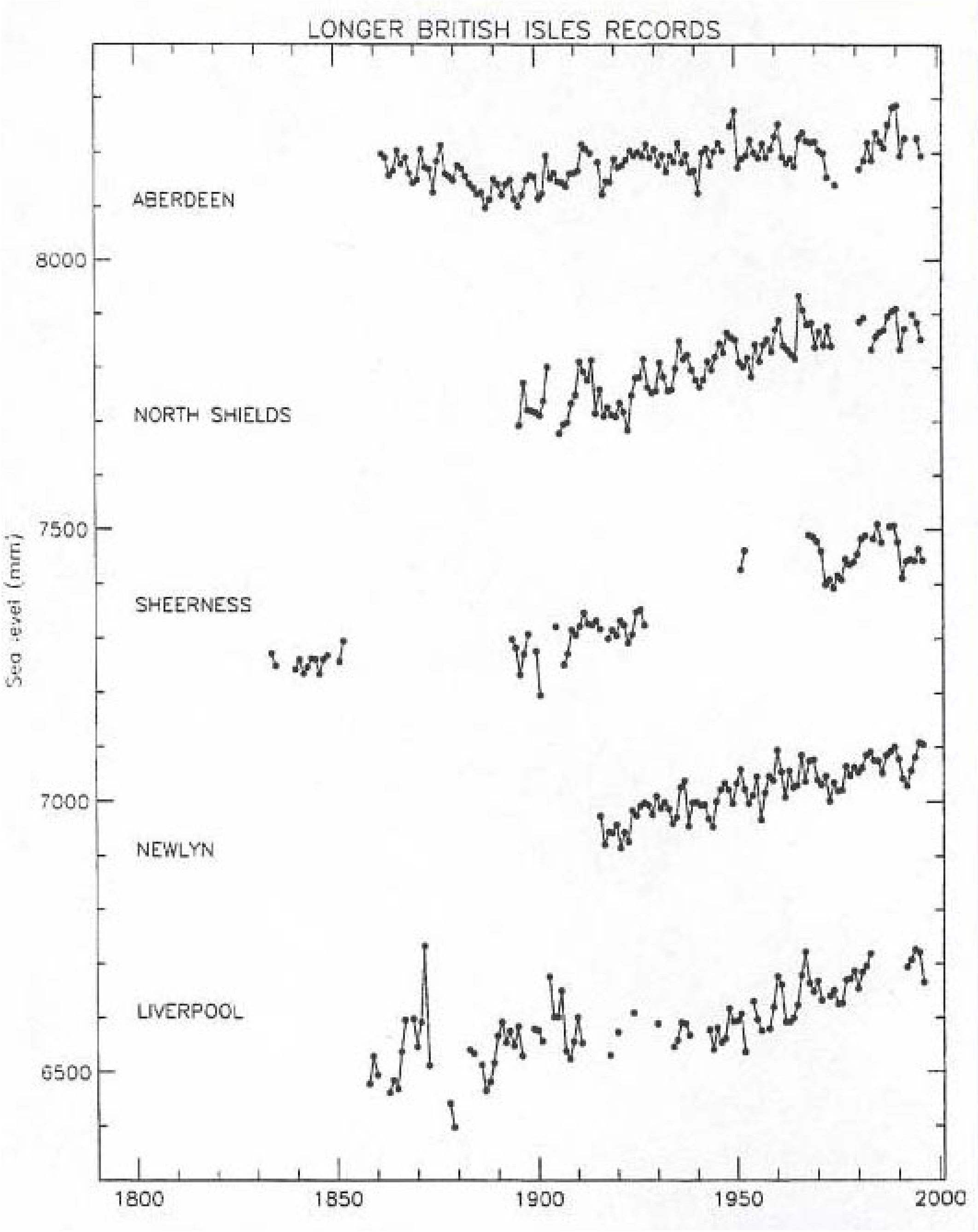


Fig 1.1: Rising annual mean sea-level as an indication of potential coastal hazard. Data from Proudman Ocenaographic Laboratory (see Section 3.1).

1.2 Causes of secular sea level change

The main forcing factor effecting the position of sea-level relative to a decade time scale is the change in *eustatic* sea level due to atmospheric warming or cooling, which gives rise to a change in the total volume of water in the oceans

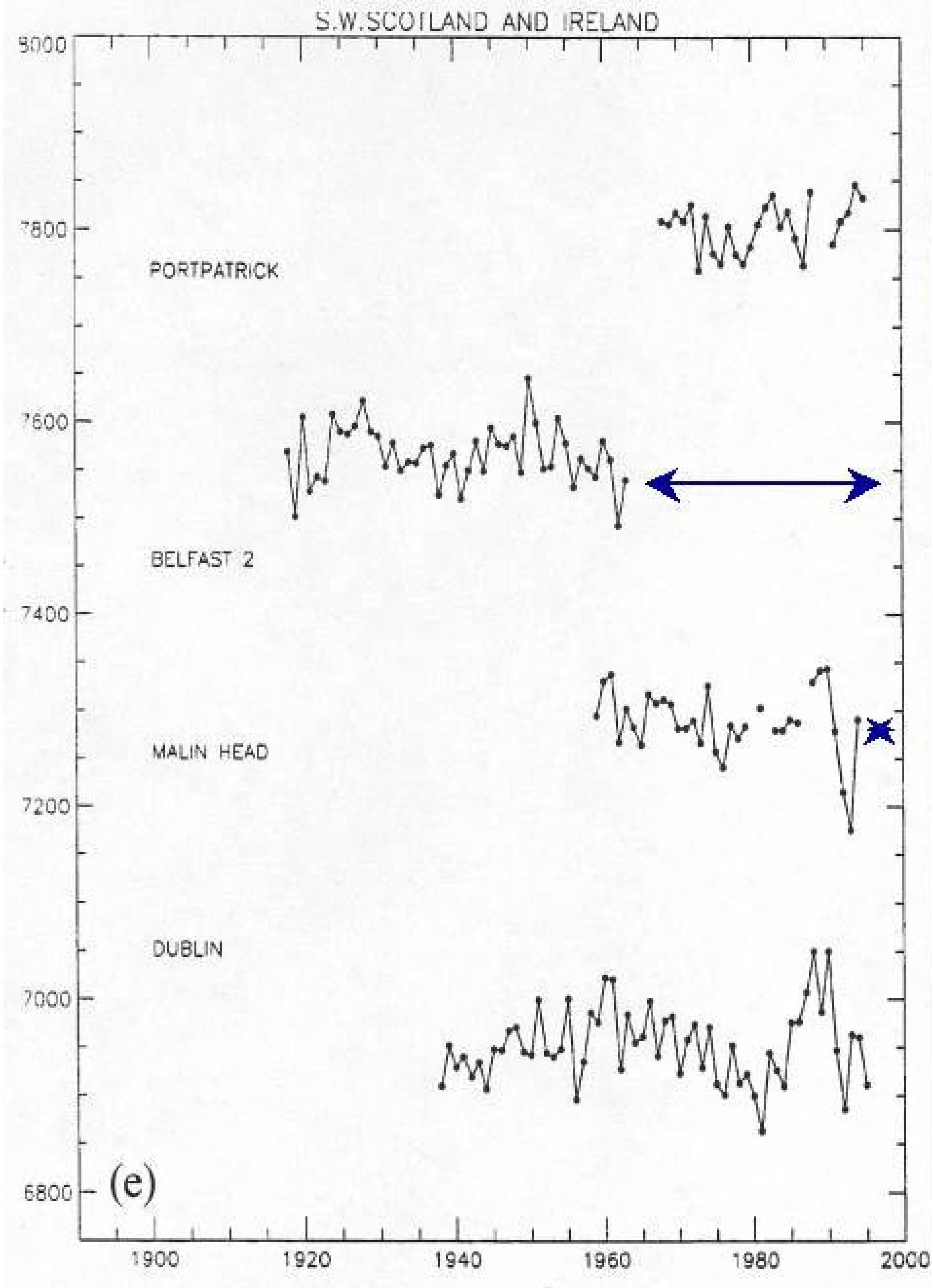


Fig.1.2: The Irish annual sea-level change record – note the gaps defined by arrows for stations in Ireland. Portpatrick is included as the nearest Scotland gauge to the north of Ireland. Vertical scale is in mm and is set to an arbitrary datum. Data from Proudman Oceanographic Laboratory.

causing a secular and persistent rise/fall in the average mean sea level (MSL) position. This type of change is one that has been gradual in the immediate historical past and scaled by a magnitude (<1m/century) that is often overlooked in its affects relative to human memory, though future sea-level changes may prove to be more memorable for coastal communities in its effect. The importance of sea-level position relative to the land is that it acts as the datum or level upon which the natural wave and tidal processes can operate. Thus we should recognise that rising sea-levels will both increasingly inundate low-lying land, as well as allow wave energy access to the terrestrial basement and its built environment. Periods of falling sea level present other opportunities for the environment (through extension of habitat diversity) given the possible emergence of low-lying land in a peri-marine position that can be the accommodation space for either terrestrially derived environments (eg wetlands) or, other coast-related environments (e.g. dunes). Sea level change is no more than a natural process, which *per se* is not an issue. It is the interaction of the sea and human activity that causes the problems.

Changes in eustatic sea level are driven principally by two climate-induced factors:

a) the expansion/contraction of sea water volume due to increased/reduced exchange of atmospheric heat to the upper oceans, and

b) an increase/reduction in sea water volume due to a persistent negative/positive budget in continental ice, i.e. melting/formation of land (glacier) ice.

Expansion of ocean water due to atmospheric-ocean exchange of heat (the steric effect) is thought to account for approximately half of the estimated future rise in 21st century MSL (Fig.1.3: Warrick & Farmer, 1990). The latest IPCC (2001) estimate follows that of Houghton *et al.* (1996) identifying a '"business as usual" scenario of c 49cm of sea-level rise over the next half century, but indicate an expansion of up to 80cm of mean sea level by 2100AD. Such global eustatic estimates are constrained by the local effects of crustal change (*isostatic* and *tectonic*) that may accelerate or decelerate MSL changes. This 21st century expansion is in marked contrast to eustatic rates of sea level change identified during the 20th century that were rarely more than 1mm a^{-1}. Woodworth *et al.* (1999) identified these scenarios through the lingering isostatic effects of land rise on northern UK and land subsidence on southern Britain, countering and enhancing, respectively, the affects of an atmospheric-oceanic driven c.1mm a^{-1} rise in MSL during the latter half of the 20th century.

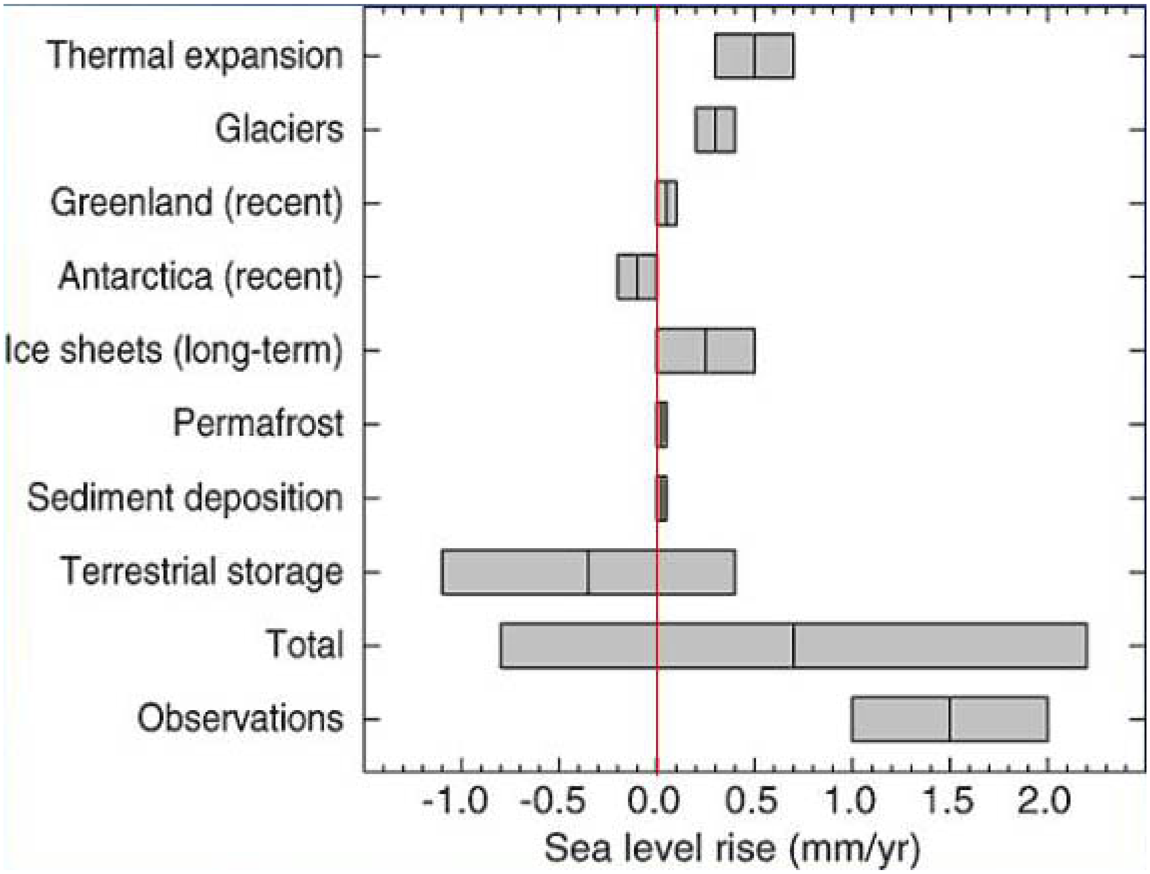
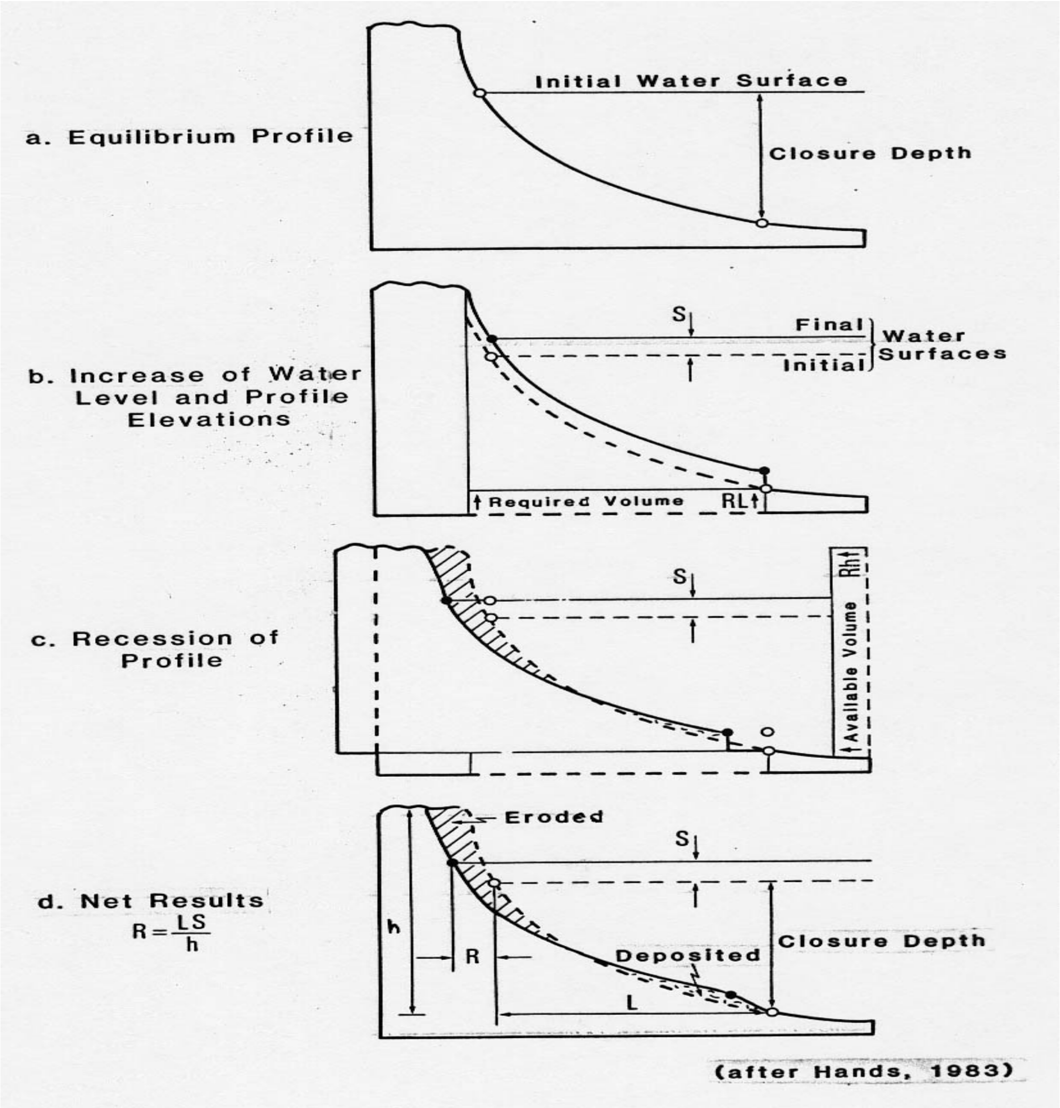


Fig.1.3: Sources and contributions to global mean sea-level rise (Warrick and Farmer 1990).

1.3 Why the concern with sea-level change?

A change in MSL is *per se* not an indicator of major coastal change, however MSL acts as the datum for wave and tidal activity that are the causes of coastal change. The geomorphology of the coast is a physical expression of mitigation of forcing energy expenditure: change the point of energy application and the configuration will change. Lifting the point of energy application through MSL change means that the coastal configuration will change. Rates of coastal change are often out of step with sea-level change, such lags making predictions of coastal change uncertain. Any MSL changes will be reinforced by any increase in wave energy or surge levels that are also associated with



(after Hands, 1983)

Fig1.4: The basis of the Bruun Rule by which a change in mean sea level translates into shoreline recession to allow the release of upper beach sediment to fill the nearshore accommodation space left by the rise in sea-level elevation and rebuild the beach profile (from Orford, 1987).

atmospheric changes. There is a widespread belief in the utility of the Bruun rule (Bruun 1962, 1989; SCOR, 1991) as a predictor of coastal response given any unit rise in sea level. Disregarding the finer points of this debate, the rule indicates through a simple budget of mass conservation, that an onshore and upwards shift in the beach profile under sea-level rise is associated with upper beach erosion, deriving the sediment required to keep the lower shoreface rising in step with the sea-level rise (Fig.1.4). In brief, sea-level rise leads to erosion of the back beach area beyond the scale of mere inundation. It has been estimated (for east USA coastal purposes – low lying sandy barriers) that for every unit mm rise in sea level there will be a concomitant onshore migration of the shoreline by around 7.5m, however the scale of erosion depends on the nature and height of the existing back beach (for derived sediment volume) and the height of the incident waves from the storm associated with a 10-year return period. The variations of these situations have been generalised by Carter (1991) into estimating annual retreat rates for the east, north-east and north coast of Ireland (Table 1 1) as a function of a 30cm increase in sea level by 2040AD, somewhat less than latest IPCC estimates identify. Although the Bruun rule is controversial, its implications for the impact of future sea-level rise offers some indication as to why society should be concerned with positive changes in MSL.

Location	**Low SLR (9cm)**			**Medium SLR (18cm)**			**High SLR (30cm)**		
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
West	0.64	0.60	0.47	1.28	1.20	0.14	2.14	2.00	1.58
North	0.96	0.84	0.56	1.92	1.68	1.12	3.21	2.81	1.87
Northeast	3.60	2.57	1.20	7.20	5.14	2.40	12.03	8.59	4.01
East	4.50	3.75	2.25	9.00	7.50	4.50	15.04	12.53	7.52
South	1.63	1.50	1.12	3.26	3.00	2.24	10.90	5.01	5.45
Southwest	0.88	0.75	0.37	0.76	1.50	1.74	2.95	2.50	1.25

Table 1.1: Potential coastal recession rates (m a^{-1}) based on the Bruun Rule as a function of varying RSL rise by AD2040 and coastal configuration of: 1=shoreline, 2= 2m high cliff and 3 = 10m high cliff (after Carter 1991)

The affects of future changes in MSL have been outlined for NI by Orford and McFadden (2002). A rise in RSL will lead to both increased inundation of low-lying coasts and erosion of soft coasts even before consideration of the effects of further increases in wave activity. The intertidal zone will be squeezed where the landward limit is constrained by a built-response. The loss of intertidal areas of open coasts, by coastal squeeze and increases in wave energy, will be seen in the stripping of sediment volume from beaches as well as a general coarsening of available sediment size. The loss of intertidal zones in estuaries will see a diminishment in protected habitats and a loss of marsh with its associated loss of bio-diversity. It is likely that dunes coasts will suffer non-sustainable beach and front-of-dune erosion. Soft and non-indurate cliff (glacial) coasts (Co Down) are likely to retreat with rates increasing well in excess of the contemporary average <0.3m a^{-1} recession rate. Hard rock coasts are unlikely to show any great change, though where hard rock has been a substantial foundation to soft glacigenic sediment perched above contemporary MSL (the Ards Peninsula), there may be a major retreat of the glacigenic cover.

Existing beaches and dunes are likely to be under great pressure. East coast beaches with backshore sediment deposits are generally of late-Holocene age (c.3ka: Murdy, 2001) and are not being renewed at a constant rate to match current sea-level rise. This may be reflected in recent media concern for diminishing Ulster beaches as a tourist attraction (eg Newcastle beaches, Co Down.). Sea-level rise associated with any increase in storminess will also result in diminishing beach volumes. The likelihood of increased erosion of adjacent glacigenic coasts (even if allowed by reducing coastal defences) is unlikely to be sufficient to replace this beach volume over the next century. The current practice of defending dunes (often due to the presence of golf courses) is only adding to this depleted beach budget, though the likelihood of such courses retaining their coherency via engineering defence is also debatable.

It is also important to appreciate the effect of increasing RSL on return periods of extreme water levels associated with storms and surges. Unfortunately extreme water levels for Belfast are uncertain, but analysis of analogous situations in north-west UK (Barkham *et al.*, 1992) show that with a sea-level rise of c 50cm by 2030AD, the return period of the current 100-yr extreme water level falls to 1 in 45 (for Glasgow) and 1 in 25 (for Silloth, Cumbria). UK ports in west Wales show alarming reductions in the current 100 year return period extreme water level, reducing to 1 in 22 yr for Holyhead and 1 in 3.5yr for Milford Haven. It is unlikely that east coast Ireland will experience the same return period reduction given the asymmetry of surge flow heights between eastern and western Irish Sea (Orford, 1989), however coastal infrastructures currently set to specific extreme tidal exceedence levels will come under pressure.

Much of this analysis is pertinent for future sea-level change, but 20th century sea level change will have already set in motion geomorphological trends that are likely to be challenged in scale terms, by changes of the next century. It is one of the unresolved issues of modern coastal geomorphology that we know little about the course of such changes. The specification of 20th century sea-level changes is a major step towards calibrating these type of relations as well as calibrating the baseline to future change.

1.4 Aims of the study

Specifically this study will:

- Outline the Holocene changes that are regarded as setting the regional context for 20th century sea-level changes in Northern Ireland.

- Create digital databases through which determination of 20th century sea level change for NI can be made. Such databases to be drawn from digital transformation of the two principal analogue tide gauge records: Malin Head (record length: 1953-2001) and Belfast Harbour (record length: 1918-2002).

- Consider the recent sea-level history of the north of Ireland, in the context of available studies in Ireland and Britain.

1.5 Objectives of the study

To achieve these aims the following objectives have to be met and represent the main activity of the project.

- To derive digital values of hourly observed water levels for Malin Head and semi-diurnal high and low water elevations for Belfast Harbour.

- To set all data to a consistent relative datum within the availability of tide-gauge history logs: Ordnance Datum (Malin Head) and Ordnance Datum (Belfast) to be used where feasible.

- To reduce raw data into annual estimates that will facilitate subsequent data manipulation for RSLC rate assessment.

- To derive decadal-century estimates of RSLC based on annual mean-sea position determined by regression analysis of annual mean-sea level values (detrended for nodal-tidal effects).

1.6 Conclusions

Sea-level change will be a major environmental concern in the 21st century for the island of Ireland. Planning for future changes is hedged by major uncertainty given our poor database with respect to 20th century trends of mean sea-level change. There is need to consolidate our analysis of existing long-term sea level data, drawn solely from tide gauge records at Malin Head and Belfast Harbour, and establish best estimates of 20th century relative sea-level change. These estimates and their contexts should enable governmental debate/action to move forward concerning the rate at which society will need to consider and adopt mitigation and adaptation practices in the face of this global challenge

2 DATA SOURCES AND METHODS

2.1 Measuring sea-level position

Any quantitative statement on sea-level change has to be constrained by a consistent definition of sea level, as well as by consistent methodology of measurement (van de Plassche, 1986). Sea level can be determined by either instrumental based recordings of actual water level variation, or in the absence of instruments, proxy determinations of water level from *in situ* or living position organic faunal/ floral remnants, whose shoreline living position are dependent on the degree to which they are immersed during the semi-diurnal tidal cycle. These so-called sea-level indicators are prone to a vertical elevation range and hence are variable in their precision and accuracy of interpretation for indication of past sea-level elevation. They are our only way of obtaining reliable information on past sea-level positions prior to the actual recording of tidal position by gauges, which generally started in the early 20th century around the north Atlantic apart from a few notable exceptions (e.g. Amsterdam in the 17th century and Brest in early 19th century).

2.2 Definition of MSL and SLC

All instrumental studies of sea level *per se* are implicitly referring to a mean value of sea level recorded over a unit time period. The latter has come by tradition to be taken as the chronological year, while the characteristic estimate of sea level position is its recorded mean (statistical average) position during the year. The mean is required given the rise and fall of sea level driven by tidal forces (in NI essentially the twice daily or semi-diurnal tidal excursion) and other atmospheric and linked oceanographic forcing. Mean sea level (MSL) is a statistical statement of the most typical value of still-water level elevation observed at one site over a chronological year. Therefore MSL has come to be defined as the mean of hourly still-water elevations recorded at one site (Pugh, 1987). Still water level assumes that there are no other influences on water motion so that any instantaneous water level disturbance due to wave activity is filtered out of the record by the insensitivity of measuring instrument to such short-term changes.

An alternative methodology, which is quicker and less prone to error of timing differences, is the use of the semi-diurnal high and low water elevations as a measure of tidal excursion. The annual average of semi-diurnal tidal maximum and minimum elevations (MTL) is taken as a surrogate for annual mean sea level, though usually there is a small difference between the two with MSL being higher than MTL. Fig 2.1 identifies the differences in annual elevations between MSL and MTL methodologies for a short temporal section of the Belfast Harbour tide-gauge record. This difference reflects the statistical sampling range on elevation forcing. These two indices of sea level position are used synonymously in some reporting. The sense of change in MSL over two or more annual estimates allows a specification of sea-level change (SLC). The slope of any linear trend line fitted to a time series of annual MSL values determines the rate of SLC. A positive trend equals a rise in MSL or sea-level rise (SLR), sometimes

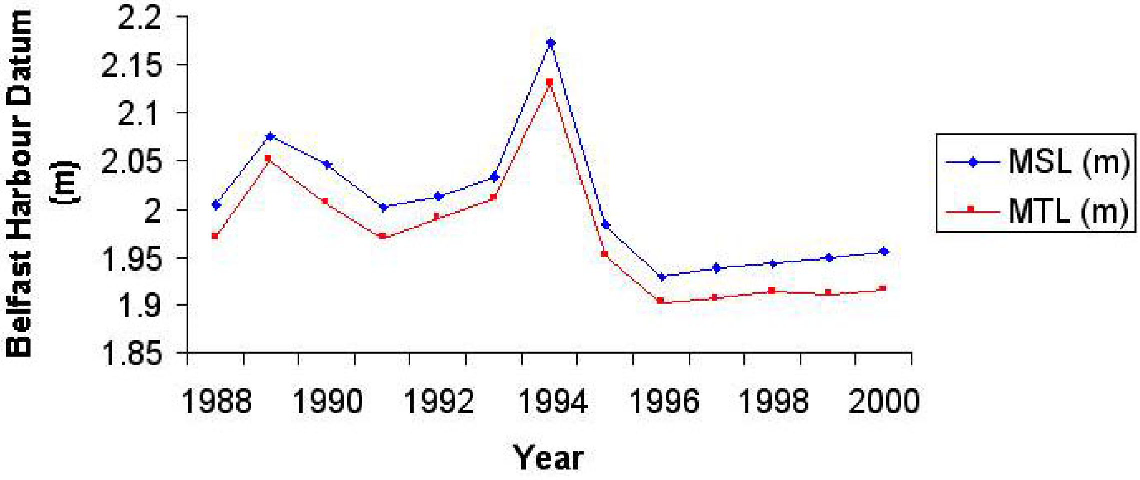


Fig.2.1: Difference between MSL and MTL for Belfast Harbour.

referred to as a transgressive sea level. A negative trend equals a fall in MSL, or sea level fall (SLF), sometimes referred to as a regressive sea level.

2.3 Problems in determining SLC and RSLC

It has been past practice that a zero datum used as a baseline for topographic mapping would be set to MSL. The Ordnance Survey in the United Kingdom thus defined its base datum (Ordnance Datum: OD) as the MSL drawn from the Newlyn, Cornwall gauge. Pre-Irish partition and prior to Newlyn's ascendancy, Ordnance Datum for Ireland was set at an arbitrary position marked out at Poolbeg (Dublin) that was c 2.7m below the now accepted MSL position. This Poolbeg datum was used until Partition (1922) when the Ordnance Survey (Northern Ireland) drew its OD from the Belfast tide gauge's defined MSL. The Irish Ordnance Survey continued with Poolbeg until the early 1960's, when the MSL datum at Malin Head tide gauge was specified. There has been no actual geodetic levelling of the land surface to connect OD Belfast and OD Malin, though they are regarded as being virtually synonymous. Neither has either value been connected with Great Britain's OD, though differential GPS now allows a technique that could accomplish this. Therefore Malin and Belfast tide gauges are not as yet linked with a consistent datum, so local MSL is used as an effective 0mOD. This specification does not account for any change in MSL since the gauges were established and a sufficient run of data could be established for statistical reduction of uncertainty.

The dominant problem in SLC studies is ensuring that there is a common consistent elevation (datum) used for all measurements at one site. The consistency of datum control is essential for any trend determination over the run of a time series. The failure to maintain datum consistency in instrumental records from gauging stations, especially if the gauge is moved or the type of gauge is changed, is a common detraction to the value of harbour tide gauge records for SLC determination, and in this respect Belfast Harbour proves to be a challenging gauge site.

A further problem for SLC determination is that any gauge statement can only be relative; hence studies of SLC are usually studies of relative sea-level change (RSLC). Relative sea-level change (RSLC) reflects the outcome of sea-level rise/fall (eustatic causes) in combination with land's rise/fall (isostatic causes). This means that the stability of the measuring instrument must be questioned regardless of water movement *per se*. The combined eustatic and land movement rates at any one position at the coastline generate the relative sea-level (RSL) change rate. Whereas eustatic effects are global in scale and in theory can be interpreted from a number of gauges, isostatic and neo-tectonic effects are regional at best, and require local specification and interpretation, and are harder to measure. The last major isostatic forcing for the north of Ireland was related to the extension of ice cover during the last glaciation (>18k years ago), which lead to a downward deformation of the upper crust and a consequent upwards crustal movement during the post glacial and Holocene periods. The issue for NI gauges is, given its past ice cover, whether isostatic effects are still exerting an influence on RSLC in the 20th century.

Confident RSLC determination requires;

i) long term continuous sea-level data from stable sites. Most harbour tide gauges that have a long history (decade to century scale) are likely to be attached to infrastructure support that has been open to vertical movement due to building/construction settlement. It has been assumed that this would be very small compared to eustatic sea level, but this is an assumption that is probably erroneous for ports during the 20th century. Some large fluctuations in RSLC from USA East coast tide gauges in deposition-dominated estuaries are thought to be due to sinking – i.e. estuary sediment compaction and neo-tectonics, as well as MSL rising due to a global eustatic component;

ii) stable and consistent recording instruments (usually tide gauges), each held to a common datum during its record (see Fig 2.2 for UK-considered system of such stations);

iii) and a spatial system of recording gauges that can act as cross-control for local affects on RSLC, i.e. isostatic, oceanographic, atmospheric and anthropogenic controls. Such stations are required by common practice to be within a 40km distance (IOC, 1994).

Raw data for modern (i.e. post-19th Century) RSLC determination are virtually always obtained from tide-gauges. Such data were usually recorded on paper charts as an analogue signal, then reduced to either;

a) an averaging of semi-diurnal high and low water elevations for one year, based on n=c.112 values. This value is thought to approximate to mean sea level though technically it is defined as Mean Tidal elevation

or;

b) an annual averaging of tidal levels for statistical statement of MSL (Mean Sea Level). This has often been at an hourly interval starting at the beginning of a chronological year. Values do not reflect high and low tidal positions *per se*, but is a better statistical characterisation of mean sea level with n= 8760 observations (8784 in a leap year). A recent trend is to digitally encode measurements on site, observing tidal level at c>15 minute intervals.

Given an annual MSL time series, then a trend line fitted via linear least-squares regression specifies a value of RSLR rate from the slope regression coefficient (ß1). The value of the trend line as a stable estimate for future change depends on the length of the time series. Woodworth *et al*. (1999) argued that a record >30 years is required before a stable estimate is supplied, but this is highly dependent upon the linearity of the time series. Evidence of decadal-scale periodicity in MSL is often observed in UK MSL series, likewise there may be other periodicities associated with oceanographic and atmospheric forcing. Woodworth *et al.* (1991) have supplied a master curve of UK forcing (Fig.7.1) that can be used to support the validity of major trends in MSL, though

Fig.2.2: The potential UK and Ireland net of tide gauges for determination of relative mean sea level changes over the 20th century (From POL). This does not indicate that all stations are at equal levels of gauge accuracy and consistency.

differences with the master curve may also be reflective of sub-regional differences in forcing. The curve does allow some validation of MSL in shorter series.

A major problem in analysing RSLC rate is the fitting of linear trends to over-narrow windows of multi-cyclic data. This aliasing can rapidly shift identified sea-level tendency, depending on window length and phase. It is essential that a long-term window of observed data is available to scale short-term data. The latest published account of RSLC for the north of Ireland during the 20th-Century is that of Carter (1982a) who used tidal elevation data sets terminating in 1980 (32 years). Orford (2001) queried whether the limited window and lack of long-term tidal de-trending of these data sets gave an enhanced magnitude to the RSL rate quoted by Carter (that of -2.5mm a^{-1}). Therefore, it is essential that the long-term window of observed data is available to establish best estimates as well as to scale other short-term data sources within the north of Ireland (eg Portrush and Bangor, both starting in the mid 1990s).

A long data set covering multiple decades allows evidence of major oceanographic (ocean-current fluctuations, sea-surface temperature variation) and atmospheric (North Atlantic Oscillation) forcing to be analysed (Goodwin *et al*., 2000). These causes of non-stationary variability in elevation need to be de-trended to reduce the statistical confidence band around the RSLC rate estimate. Excessive rhythmicity or oscillation will also force a wide confidence band around the RSLC rate estimate. Regression estimates are often tied to confidence via reduced sum of squares explanation, i.e. if the variance explained is high, the slope regression coefficient may carry greater confidence. In RSLC studies, the trend's importance is often in the sense of the regression trend rather than the percentage reduction in sum of squares (%RSS) associated with the regression, as the coefficient sense indicates a rise or fall in RSL trend.

It is also usual practice to use a data record in excess of 30 years to allow adequate smoothing of the 18.6 year Nodal tidal elevation changes (Lisitzin, 1974), which can generate decade-plus variation in MSL. Technically this tidal force tends to amplify the tidal range and though its amplification is as much for both tidal rise and fall, (such that MSL should remain consistent), inevitably the interactions with bottom bathymetry usually means that the HW is amplified more than LW, and MSL appear to rise. There is a need to detrend the RSL record, in order to remove the influence of the nodal tide. A simple smoothing using an un-weighted moving average term of 19 years helps to reduce the effect of this forcing. A trend line fitted to the resulting nodal detrended MSL series has been used to produce a conservative estimate of RSLC. This detrending has the advantage of reducing extremes as well as reducing the variation for %RSS explanation by the trend line.

2.4 Conclusions

Measurement of sea-level change requires consistent tidal level measurements obtained from harbour-based tide-gauges. Either statistical averaging of hourly measurements, or averaging of high and low tidal elevations determines annual value of mean sea level. Trend analysis in MSL requires at least 30 years of date so as to nullify nodal tide affects. Varying periodic trends have to be considered as being responsible for century-scaled sea-level change.

3 DATA SOURCES AND CONDITIONS: AVAILABILITY PRIOR TO STUDY

3.1 Tidal elevation sources

Northern Ireland has a poor and incomplete tide-gauge system by which RSLC can be determined. Tidal data in the province are recorded by a variety of agencies and with varying degrees of reliability. The most obvious data are those held by port authorities such as Belfast Harbour Commissioners. Other water level recorders are located at fluvial discharge positions in the inter-tidal zone that can offer some indication of tidal change, though their record can be also distorted by the fluvial discharge and hence are not a first-line record (e.g. the Rivers Agency water level recorder on the Quoile Drainage, Co Down). Tide gauge records in harbours are notorious for being distorted by water level disturbance (harbour settling, basin siltation, dredging, and ship wakes), at the mercy of physical damage and prone to repositioning around the port due to commercial infrastructure changes in the port.

Data from these sources may be transmitted to the Proudman Oceanographic Laboratory (POL), Bidston, (located at Liverpool Univ from summer 2003), which acts as a depository for tidal data that can be used for the determination of MSL. POL as a government agency (NERC supported) aim to maintain a digital data set of those stations defined as a Class A, which have stable datums and consistent records for long periods (c >30years). Although data for Malin Head and Belfast Harbour were nominally held by POL, the nature and structure of data support meant that both series were digitally incomplete and are not defined as Class A stations. There have been some attempts to set up such a station with Malin Head the most likely candidate.

Table 3.1 indicates the various constraints on available data sources from 4 tidal gauging stations in the north-east of Ireland as of 2000, i.e. prior to this project.

Tide-Gauge Location and Data Source[1]	**Start**	**Finish**
Malin Head Numerous gaps in period 1988-97 (RLR[2] on basis of MTL[3])	1958	1997
Portrush[1]	1995	2000
Belfast Harbour		
a) Belfast.Harbour Commissioners (BHC) (MTL)[4]	1918	1963
b)On-going tidal records from BHC. Passed to POL for storage only.	1980	2000
Bangor[1]	1996	2000

Table 3.1: Tidal level data availability in the north of Ireland in AD2000

Notes

1. Source: Data from Proudman Oceanographic Laboratory, Bidston (POL).

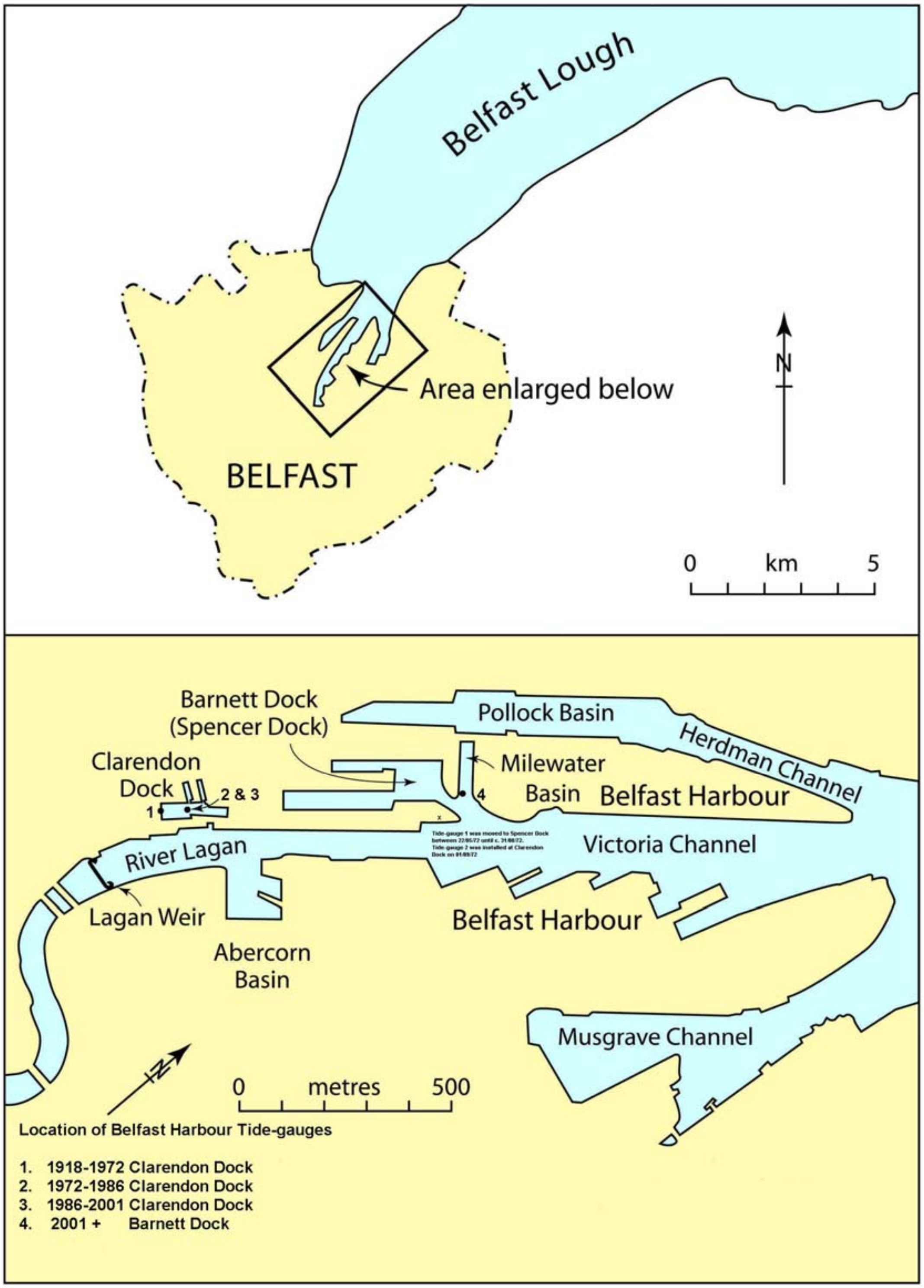
2. RLR: Revised Level Reference: an adjusted datum set for all data by POL, set at 7000mm and at a specific year datum (Malin 1976).

3. MTL: Mean Tide Level based on annual average of semi-diurnal high and low tide elevations.

4. Record supplied by Carter (Univ. Ulster) from BHC sources. Carter (1982a) identifies data for 1918-1980, but POL has only 1918-63 as verified and digitally available.

3.2 Belfast Harbour tide gauge (BHTG) record

Belfast Harbour tide gauge (Fig. 3.1) installed in 1918 is the only north of Ireland tide gauge of any potential long-term measurement length sufficient for determining multi-decade RSLC periodicities. However this gauge has been moved several times (see below) and the gauge type changed, as especially in the 1990s when standard float/ stilling well gauges were exchanged for variably performing pressure gauges. The tide gauge position was thought to be prone to land subsidence and anthropogenic affects (Carter 1982a). This chequered history has mitigated any consistent policy of analysis, such that only 1918-63 data (MTL) were electronically held before the this project, while later records are somewhat prone to gaps. This earlier data were compiled by Todd (1981) and



Tide-gauge 1 was moved to Spencer Dock between 22/05/72 until c. 31/08/72.
Tide-gauge 2 was installed at Clarendon Dock on 01/09/72

Location of Belfast Harbour Tide-gauges

1. 1918-1972 Clarendon Dock
2. 1972-1986 Clarendon Dock
3. 1986-2001 Clarendon Dock
4. 2001 + Barnett Dock

Fig. 3.1: Belfast Harbour and the various locations of tide gauges (1918-2001

although 1964-81 data were reported in his MSc thesis, the digital version of the last 18 years data were not transmitted to POL, so at the start of the project only the 1918-63 data were available.

The tide gauge is still operated by the Belfast Harbour Commissioners and data passed for storage to POL. Given the lack of Class A designation for Belfast Harbour gauge, POL's operational resource availability meant that these analogue gauge records are not analysed and merely stored at POL (Bidston, Merseyside). Even later digital recording gauge records were only providing hard copy as the data source. Some digital work has been undertaken by POL on a few individual years in the 1970s and 1980s, but a lack of POL resource means that the Belfast Harbour data set had yet to be digitally completed.

3.2.1 History and Quality of the BHTG Data

The Belfast Harbour tide-gauge was installed during 1917, to celebrate the seventieth anniversary year of the establishment of the Harbour Commission. The purpose of this tide-gauge was to monitor the level of semi-diurnal tide and generate reliable annual tide-tables for Belfast Lough, which was then described as the chief port in Ireland and one of the front ranking ports in the UK. Accurate tidal information was an important requirement for the increasingly busy harbour, aiding the precise timing of ships sailing to and from the port as well as defining the most propitious time for ship-launching from the Harland and Wolff yard. The tide-gauge was set at harbour datum, which is equal to the level of Clarendon Dry Dock Sill. Belfast Harbour datum is equivalent to Admiralty Chart Datum (ACD) (Commander John Page *pers com*).

Although, the Belfast Harbour tide-gauge was first set-up at Clarendon dock, it is currently located within the Milewater Basin. Throughout its long history the tide-gauge has been moved on several occasions, the most recent installation was established in March 2001 (Fig. 3.1). Indeed, because the tide-gauge has been moved on several occasions, the quality of the data that the tide-gauge produced is questionable, with the consistency of the tide-gauge datum being open to question (Fig.3.2). Through an effort to track down the tide-gauge history, it was revealed that no gauge log-book was kept, instead comments were added to the gauge paper. However, the Hydrographic Office stated that the Belfast tide-gauge benchmark had remained consistent for at least forty years (Commander John Page *pers com*).

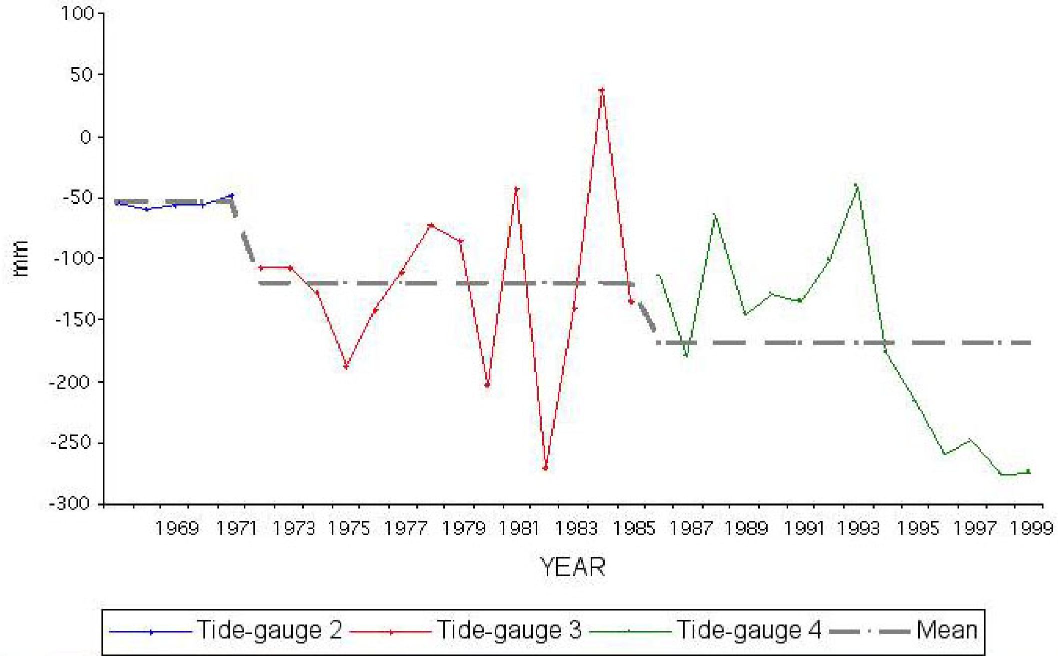


Fig. 3.2: Discrepancies in the various datums used by different tide gauges in Belfast Harbour between 1960 and 2002, identified by a first pass on determining annual MSL.

Earlier investigations (Carter 1982a) identified a connection between relative sea-level (RSL) trends and the development of Belfast Harbour and infilling of Belfast Lough. Carter (1982a) recognised a regressive RSL trend (at a rate of -2.1mm a^{-1}) following the 1950's and concluded that this behaviour was probably related to the rapid development and reclamation of Belfast Harbour and Belfast Lough following the Second World War. In essence, Carter (1982a) thought that the infilling of the adjacent parts of Belfast Lough for land reclamation and development had affected the tidal curve within the vicinity of the gauge, hence influencing the results.

Other factors that have probably influenced the BHTG results have been land subsidence. Land subsidence in Belfast is a phenomenon that is not uncommon. Indeed, the presence of the so-called ‘Belfast Sleech’ (a sub-surface, Holocene soft estuarine silty clay) has been the cause of much concern for developers for over a century. Around the Harbour and within Belfast city centre, there are numerous buildings that float on this bed of ‘sleech’ supported by pilings, indeed the recently restored Albert Clock being just one of them. Within the Belfast Harbour area, it is estimated that a road built during the 1970’s sank as much as c.60cm (c. 2cm a^{-1}) in places. This has caused numerous problems, such as the displacement of storm drains (Ray Howie *pers* com). Given that the BHTG, has always been situated within the area of Clarendon dock, the oldest dock in Belfast, it has been an assumption that contemporary settlement has been minimal. Since Belfast Harbour is a busy port, dredging activities have to occur on a regular basis. Dredging activities occur within a minimum of one year to a maximum of five years (Ray Howie, *pers* com) and dis-equilibrium imposed on main channels is going to diffuse into surrounding berths and may cause adjustment to accommodation of the tidal prism allowed into the vicinity of the gauge. Without detailed dredging logs it is not feasible for this aspect to be considered further.

3.2.2 BH Tide-gauge 1 (1918-1972)

Evidence of the earliest tide-gauge that operated within the Belfast Harbour was an electrically operated automatic AGA tide-gauge that was sited at Clarendon dock (Todd 1981, p16). Todd, (1981) used the high and low tide readings from 1917 to 1963, and 1972 to 1975 that the Harbour Commission Engineers abstracted from the original marigrams. He justified using this information by claiming that the original marigrams were no longer available (Todd, 1981, p16). However, in conflict with this information, POL stated that a Lege tide-gauge operated from 1958 until 1972 (www.pol.ac.uk/ psmsl/pubi/docu.psmsl/170271.docu). The marigrams associated with this tide-gauge (1958-1972), were very well maintained and the annual record was almost complete until the early 1970's. The individual record sheets contained daily records that were all appropriately dated and rarely contained discontinuous records, except with some weekends and public holidays. The quality of these records meant that they were easy to follow accurately and convert into a digital format.

Due to harbour reclamation (1965-1967) this tide-gauge was moved in 1966 to the north side of Clarendon dock. During May 1972 the tide-gauge was temporarily moved to Spencer dock (renamed Barnett dock). The tide-gauge was moved to allow for the partial infilling of the North end of Clarendon dock and quay re-facing. Although, it is known from a note attached to the original marigram that the gauge was moved to Spencer dock on the 22/05/1972, it is also known that it was moved back to Clarendon and replaced by 01/09/1972. On further examination, all the OS maps revised between 1963 and 1970 have indicated that the tide-gauge was located at Clarendon dock, whereas the OS map revised in 1975 has illustrated the absence of a tide-gauge at Barnett dock.

3.2.3 BH Tide-gauge 2 (1972-1986)

The faulty tide-gauge was replaced with a Lege stilling gauge in September 1972. This tide-gauge was positioned at Clarendon dock and remained operational until November 1986. As evident from the notes attached to the original marigrams, this tide-gauge was fraught with difficulties. Shortly after its installation, and during its second year of operation, this tide-gauge was breaking down on a regular basis. It has been deduced from the availability of several attached notes, that regular siltation appeared to be the main problem. It is possible that the partial infilling of the North end of Clarendon dock (near to the tide-gauge position); between 1973 and 1974 may have been responsible for this problem.

The individual record sheets associated with this tide-gauge, often contained multiple records. It is possible that the individual A3 sheets needed by this tide-gauge were probably expensive, hence justifying the running of several days on one sheet. Considering that these individual sheets contained multiple records (up to ten days), it was often difficult to follow the readings. However, with care readings can be followed over multiple tidal cycles.

3.2.4 BH Tide-gauge 3 (1986-2001)

During 1986, the Lege tide-gauge was replaced with a Valeport Marine Scientific pressure tide-gauge. According to the marigrams, it is evident that this tide-gauge was positioned at Clarendon Dock. The marigrams associated with tide-gauge 3, displayed a reading of the tidal elevation on an hourly and daily basis. The tide-gauge records associated with this tide-gauge were clearly dated and did not contain any multiple records. This tide gauge stopped operating during March 2001 and was replaced by the most recent installation.

3.2.5 BH Tide-gauge 4 (2001-2002)

This tide-gauge is a Valeport BTH 700 and is the most recent installation made by the Harbour Commissioners. It started recording water level in Milewater Basin on the 16th March 2001 at 1310. The data output from this tide-gauge are in digital form and no marigrams exist. This tide-gauge recorded the water level (air-water interface) via a transducer at ten-minute intervals, which are converted digitally. The only problem associated with this tide-gauge data, has been the omission of several readings at the end of the daily record. Shortly after 2300 hours (between March and November 2001), the tide-gauge stopped recording until 0000 the following day. However, this timing error was rectified and described as being caused by software problems (Harbour Commissioners *pers com*).

3.3 Malin Head tide gauge record

The other consistent long term record for the north of Ireland record comes from the Malin Head tide gauge (Fig 4.1 and Fig.3.3: 1958 to 2002) that is located at Port More harbour on the north Co. Donegal coast. The gauge is supported by the Ordnance Survey of Ireland, and used to determine MSL

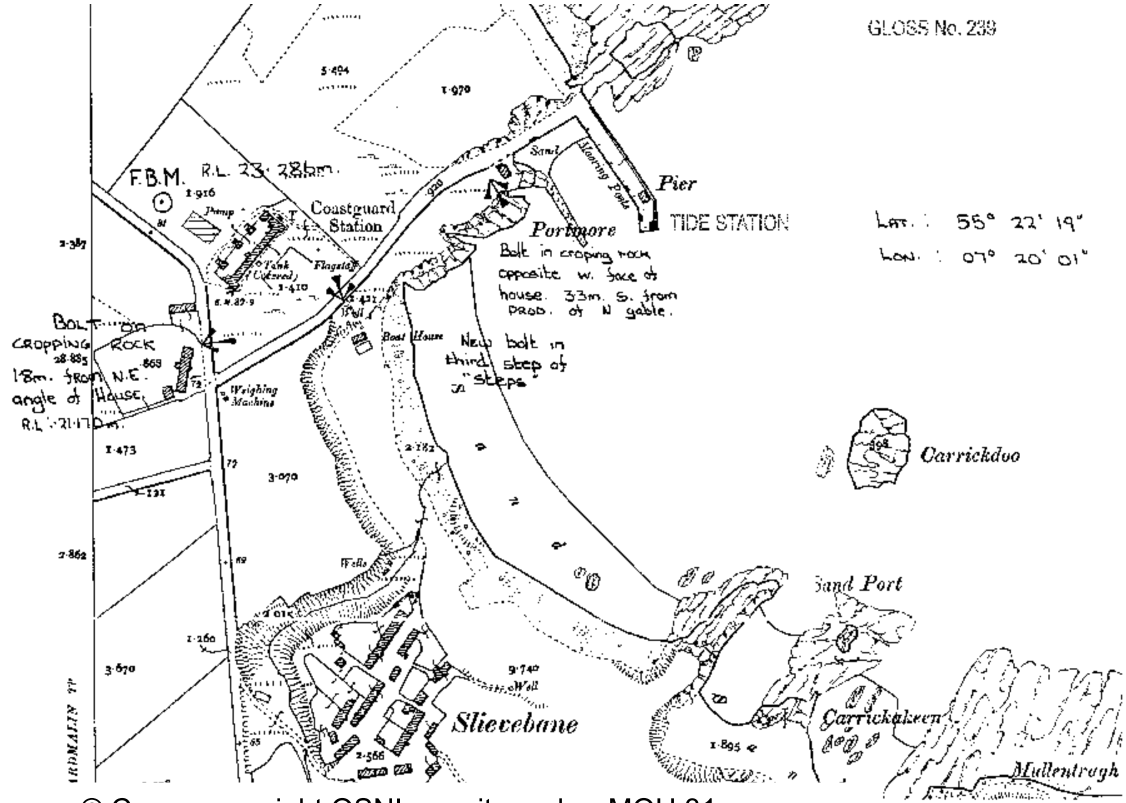


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Fig 3.3: Location of Malin Head tide-gauge at Port More harbour (after POL).

position in order to define a datum for terrestrial geodetic levelling. The gauge is physically run by staff from the Irish Met Office who have a station at Port More, who send the physical records (analogue chart) to OSI (Phoenix Park, Dublin) for analysis.

The tidal records are analysed by MTL methodology, and sent onto POL for storage. POL posted this data set on its website, as a Revised Level Referenced set (i.e. a consistent datum: see note 2 Table 3.1), but only reports data up to the end of 1997. Nothing further has been sent to POL from OSI (this appears due to the retirement of the person dealing with the data derivation in 1997). The lack of subsequent data and the fact that OSI are actively considering the cessation of the gauge due to lack of recording paper is somewhat disconcerting as this site is by far the best maintained and least disturbed gauge in Ireland.

That stated, there are numerous hiatuses in the data and a sudden unexplained shift in the datum of the records in 1993 casts doubt on the integrity of values in the 1990s. In recognition of the primacy of this data set for MSL studies in Ireland, Geography, Queen's University, Belfast has been undertaking (through EU research contracts) an electronic transformation of the data. At the start of this EHS project 1953-1988 data had been digitised, and verified (though timing errors needed to be checked); 1989-1994 data were in need of verification, while 1995-2000 data were yet to be digitised. OSI supplied QUB with all of the charts since 1958 and a major programme of checking and verification of data had to be undertaken. The 1958-1997 data resident on POL website as of 2001 is based on numerous data omissions which were reconsidered by this project.

3.4 Short term tide gauge records: Portrush and Bangor

In an effort to develop the recording network, POL set up two further tide gauges: Portrush (1995) on the north coast, and Bangor (1996) on the east coast of Ulster. Though both of these have suffered from minor interruptions (Bangor offline during 2001-2) with pier restructuring) they are digitally recording tidal levels every 15 minutes. The shortness of the records means that the only available near-immediate RSLC determinations for NI are of limited value and must be analysed in the context of temporal MSL variability exposed on Malin Head and Belfast Harbour records.

3.5 External tide gauge records

It is POL practice to relate tide gauge records to external buddy or spatial adjacent records for comparison and confirmation of trends. Portpatrick is the closest mainland station and has been considered as a comparison for Belfast Harbour. This tempered by the possible differing isostatic responses of NI from Scotland due to intervening tectonic boundaries

3.6 Objectives of the project: Extension of data sources

The project has supported the following data developments:

- The extension of the hourly digital record (1988-2001) for Malin Head
- The verification and creation of an hourly tidal elevation data set for Malin Head on a unified datum (as far as the gauge maintenance log allowed) for 1958-2001.

- Creation of a "useful" Malin Head database that allows data smoothing and RSLC estimation to be undertaken for as much of the data set as possible. "Useful" in this sense means that interpolation of missing data has been undertaken in line with POL recommendations
- The digitisation of HW and LW positions for Belfast harbour (1960-2001) as an extension to the existing digital MTL set held by POL (1918-1963). The overlap of 4 years (1960-63) was used to check for methodological consistency between Todd's data set and the latest QUB data set.
- Given the four gauge changes between 1960 and 2001 in Belfast Harbour, there were likely to be major difficulties in establishing a consistent datum across the time period, so an extra objective was defined by which a "useful" data set for Belfast Harbour was developed.
- The problems presented by record breaks means we have set up a series of data sets for Belfast: *raw* (all data), *adjusted* (regulated to POL data standards) and a *useful* series (interpreted with Buddy station help) for RSL trend definition.

3.3 Conclusions

Prior to the commencement of this study, existing primary data in digital form for Malin Head was incomplete (1992-2001 missing) and had not been verified for timing, omissions and datum stationarity. Belfast Harbour tide gauge data were still in analogue form for 1960-2001, with contentious datum stationarity. Problems with missing Belfast data means that a unified data series useful for RSL change determination will require interpolation using buddy station help.

4 PAST RELATIVE SEA-LEVEL CHANGE (RSLC) IN THE NORTH OF IRELAND

4.1 Holocene-scale RSLC and its consequences in the north of Ireland

The ice sheet of the Last Glacial Maximum (LGM c.22ka) extended south beyond the north of Ireland and was of sufficient thickness for an isostatic element to be a major part of the dynamics of shoreline positions in this region during the subsequent post-glacial (18k-10ka) and Holocene (10ka to present day) periods. Carter (1982) in a comprehensive review of the structure of RSLC for Northern Ireland based on dated post-glacial and Holocene sea-level indicator positions recognised two spatial provinces (north and north-east Ireland) with differential RSLC (Fig.4.1). Carter carefully reviewed all palaeo SL indicators and showed that the best estimate of RSLC over the last 18ka was set within a vertical elevation band of about 25m centred on present OD. This RSLC reflects both eustatic and isostatic forces working together. It has to be remembered that the terrestrial surface has also been moving upwards with an absolute upward change in sea-level position at about 4-5 times the relative range. The greater the past ice thickness the greater the postglacial crustal rise, and given the north of Ireland as an individual ice producer even before Scottish ice spread across, it is only to be expected that Ireland would show major and persistent post-glacial isostatic response to major ice-induced crustal depression.

The cross-province RSLC differences relate to both the timing and vertical extent of two processes:

a. the relative sea-level maximum position which occurred after a rapid mid-Holocene transgression (thought due to major global eustatic changes between 10ka and 6ka);

b. the subsequent deceleration of RSL (after 5-6ka) caused by a possible remnant isostatic element still working for NI and Scotland, (but not evident in England), common to both sides of the NI province.

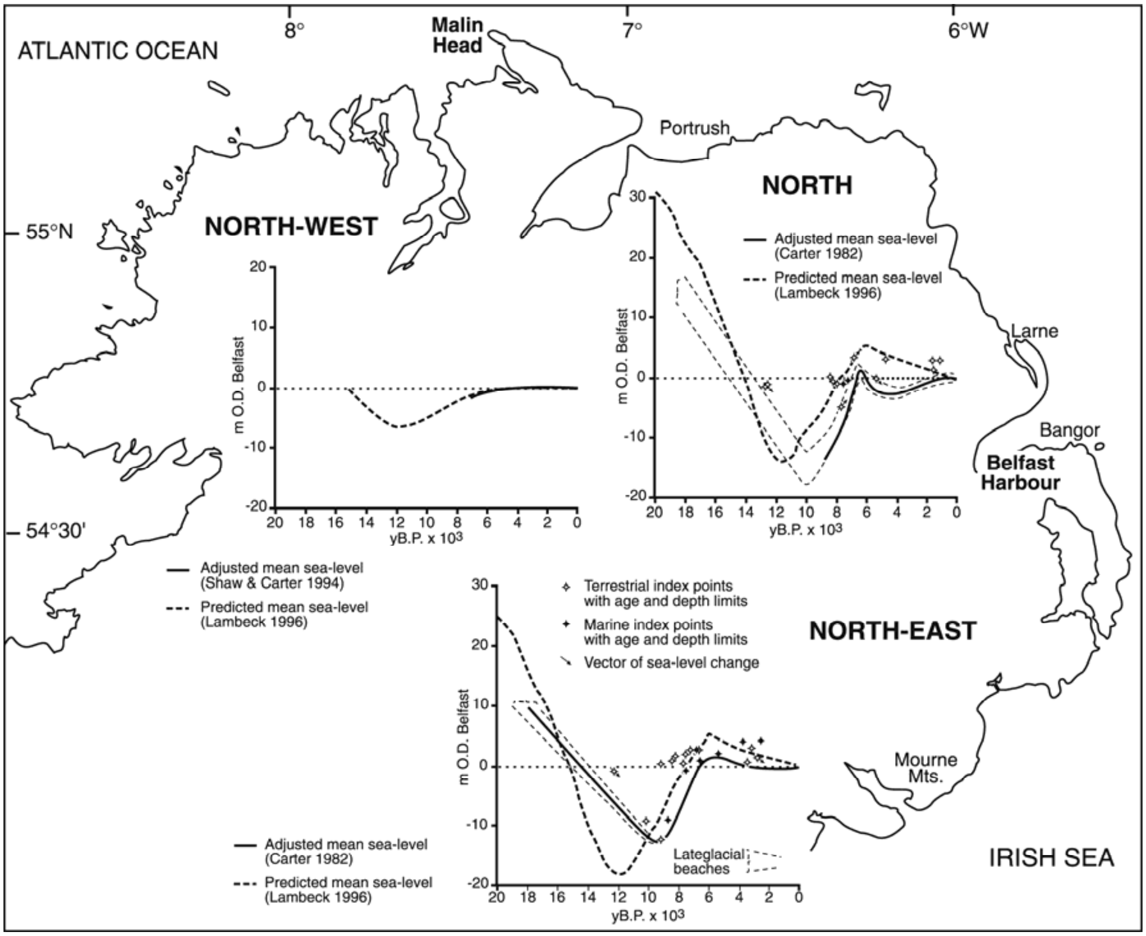

Fig. 4.1: Variation in Holocene RSL change across the north of Ireland (after Orford *et al.*, 2003).

In both province cases, Carter recognised that RSL achieved a peak position between 2-3 m above modern ordnance datum (OD) at c.6.8ka on the north coast and c. 5.5ka ago on the northeast coast (ages in un-calibrated radiocarbon years). Carter also observed that the lack of sea-level index points in the last 3ka, made the timing and position of any regressive shoreline from this peak to present-day OD only speculative for the north of Ireland seaboard.

Subsequent field investigations of RSLC around the west (Carter *et al.*, 1989) and north–west (Shaw and Carter, 1994) Irish coast have only confirmed the general gradient of RSL identified by Carter (1982a). The relative elevation of mean sea level achieved at the time of the mid-Holocene deceleration event (c 6ka) appears to fall towards the west of Ireland, to a position that is below present OD in northwest Ireland (Co. Donegal). There is also an inferred structural change in the nature of the RSL following the mid-Holocene deceleration. Whereas in northeast Ireland, there is a distinctive maximal sea-level peak and inferred regressive phase, in the west there is no maximal sea-level peak, rather only a deceleration in the transgressive tendency after c.6ka, which appears to have persisted to the present-day. Thus the presence of a Holocene higher-than-present MSL (high stand) was restricted to northeast Ireland.

In the past decade, the crustal modelling work of Lambeck (1996) has re-opened the issue of the high stand's presence in the north of Ireland. His geophysical model of earth crust deformation with and then without ice presence specifies a distinctive mid-Holocene highstand (Fig.4.1) for both north and northeast Ireland peaking between 5-6m OD, c. 6000 years ago. The RSL regression from this modelled highstand persists in time beyond that of Carter's extrapolation, and thus could be a more prominent forcing component of late-Holocene coastal deposition.

There is a heterogeneous and variable glacigenic cover across the Irish landscape. Extensive unconsolidated glaciogenic deposits both along past and present coastlines and across the inner shelf have been open to major wave reworking throughout the Holocene period. The present coast of north-west Ireland is storm-wave dominated, with significant wave heights (H_s) of <14m associated with extreme westerly moving storms (Orford *et al.*, 1999), although this wave height is considerably reduced within the enclosed waters of north-east Ireland where inshore storm H_s is <2m (Orford, 1989). Tidal activity shows a meso- to macro-tidal range (3-5 m), with macro-tidal restricted to the northeast coast of Ireland. The mid-Holocene RSL has acted as moving base level for an extensive reworking of shelf and nearshore glacigenic deposits that have provided a heterogeneous size range of coastal sediments (Carter and Wilson, 1993). The available inshore and cross-shore wave energy gradients are sufficient to decouple reworked glacial sediments and allow spatial separation of coarse and fine sediment. The strongly discordant and resistant surface geology of the Irish terrestrial basement has provided through the Holocene a coastline of headlands and bays that generate major gradients in breaking waves allowing a range of littoral morpho-sedimentary environments to develop based on this partitioning of sediment size.

A major element of these coastal assemblages is formed by extensive dune systems (Carter, 1982; Orford and Carter, 1988; Carter, 1990; Carter and Wilson, 1990; Wilson, 1990; Wilson and McKenna 1996). The depositional history of these dunes is punctuated by periods of vegetated surface stability from which *in situ* organic remnants have been dated to times since the mid-Holocene RSL deceleration. The initiation of primary dune emplacement has been inferred from the limited ^{14}C dating of these *in situ* organic rich dune horizons. Much of the coastal dune initiation in the north of Ireland is thought to have occurred during the transgressive to regressive switch of relative sea-level rise between 6ka and 5ka ago (Orford and Carter, 1988; Carter et al., 1989; Carter and Wilson, 1993; Shaw and Carter, 1994).

Over the last decade there have been more detailed developments of coastal morpho-stratigraphy around Ireland, including studies of a wide variety of dune types. Orford *et al.* (2003) has provided an outline of beach ridge and dune development at Murlough, Co Down, based on luminescence dating of sediment that enables a closer specification of the relationship between regressive sea-level position during the mid- to late-Holocene and sediment supply to the beach face to enable ridges and then dune development to take place. This type of analysis also shows that dune activity was enhanced during the Little Ice Age of the 14th-18th Centuries, but a lack of information on RSLC *per se* reflects that we are still missing out on an important control variable for coastal behaviour during the last Millennium. This means that the bridge between past and present RSLC is missing and that much of the trends between the two eras has to be speculative.

4.2 RCLC around the north of Ireland during the 20th century

As section 3 indicated, the RSLC data sources are small in number and limited by their extent and their available conversion to digital format. Figures 4.2 to 4.4 show the MSL variation for Belfast Harbour, Malin Head and Portrush plus Bangor, respectively.

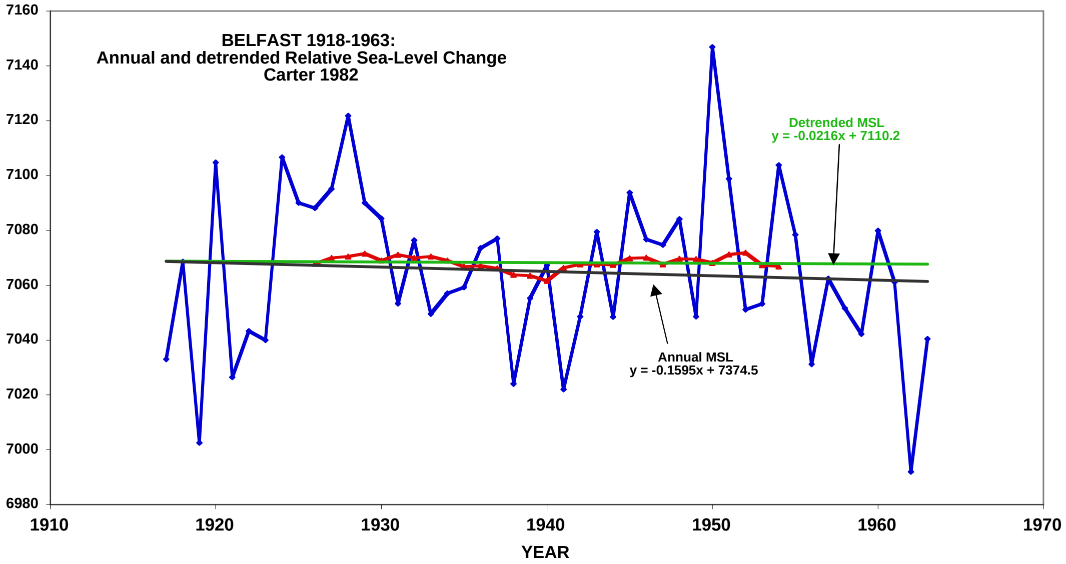

Fig. 4.2: RSL change based on Belfast Harbour tide-gauge 1918-1963 after Carter (1982).

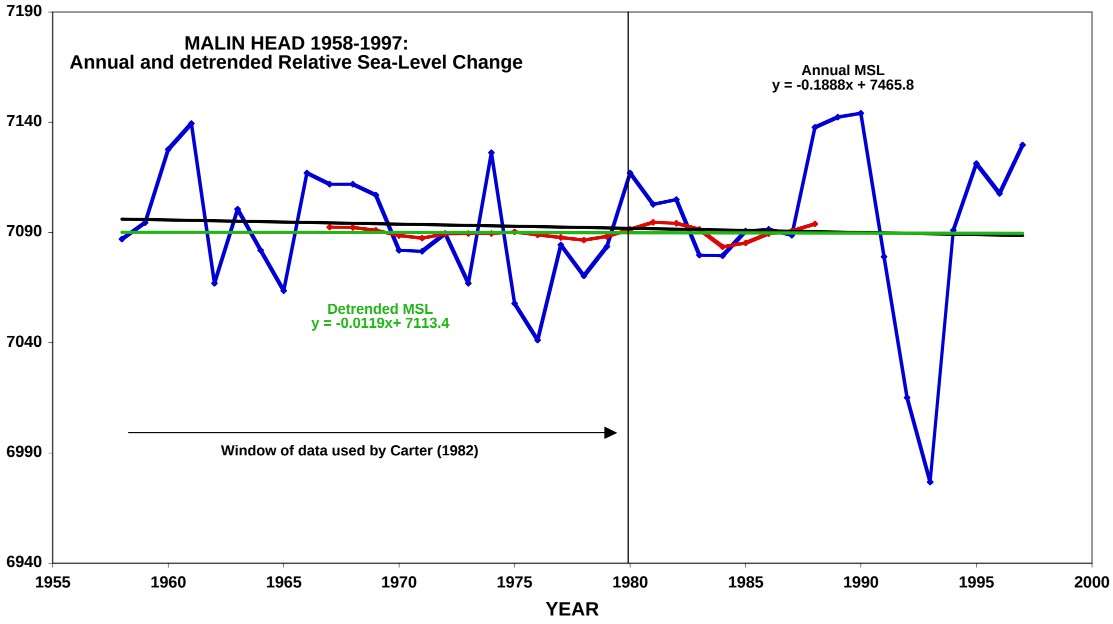

Fig.4.3: RSL change based on Malin Head tide-gauge 1958-1997 from POL

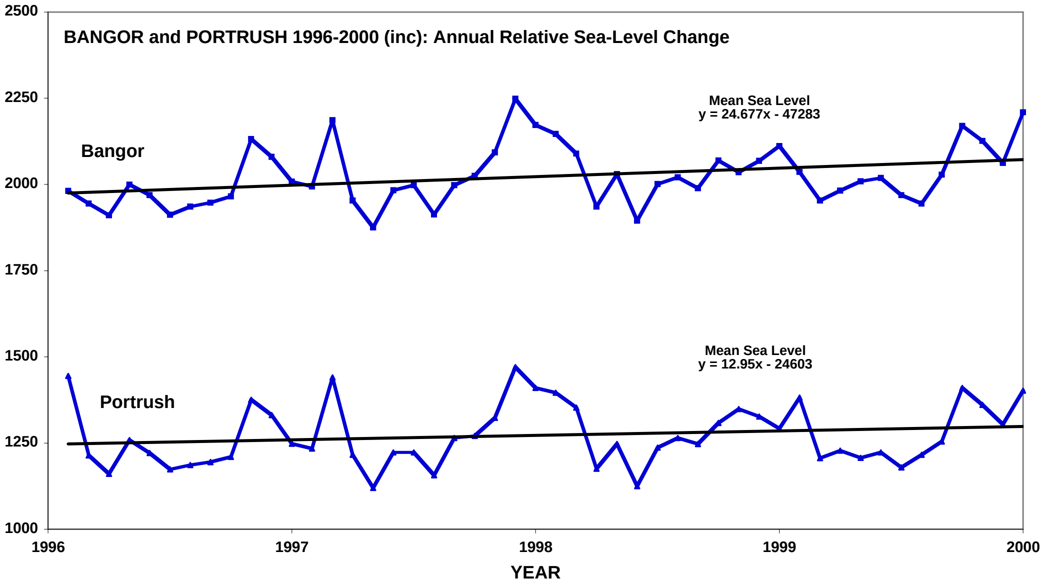

Fig. 4.4: Monthly mean sea-level variation from Portrush and Bangor tide gauges

Table 4.1 shows the RSLC rate changes (mm a^{-1}) that had been calculated for the four stations considered on the basis of the then current data record (Orford 2001).

Tide-Gauge Location and Data Source[1]	**Start**	**Finish**	**Annual RSLC rate[2]**	**Annual RSLC rate by seasonal detrend[5]**	**Annual RSLC rate by nodal detrend[6]**
Malin Head Numerous gaps in period 1988-97 (RLR[3] on basis of MTL[4])	1958	1997	**-0.19**	Not required	**-0.01**
Portrush	1995	2000	**+2.69[9]**	**+12.95** **+8.56[10]**	Not viable yet
Belfast Harbour Belfast.Harbour Commissioners (BHC) (MTL)[7]	1918	1963	**-0.16**	Not required	**-0.02**
Bangor	1996	2000	**+9.09[9]**	**+24.67** **+17.72[10]**	Not viable yet

Table 4.1: Data sources and relative sea-level change rates for specific tide gauges in north-east Ireland (mm a^{-1})

Notes

1. Source: Data from Proudman Oceanographic Laboratory, Bidston (POL) and QUB digital data set.
2. RSLC: Relative sea-level change rate based on Mean Sea Level from hourly or 15min records.
3. RLR: Revised Level Reference: an adjusted datum set for all data by POL, set at 7000mm and at a specific year datum (Malin 1976).
4. MTL: Mean Tide Level based on annual average of semi-diurnal high and low tide elevations.
5. Seasonal detrend: Analysis of monthly data using only12-monthlydata sets: Oct to following Sept.
6. Nodal: Use of 19 years smoothing to detrend major tidal cycle affect of 18.6 years (nodal tide). Accepted as best-estimate of overall long-term trend in relative sea level change.
7. Record supplied by Carter (Univ. Ulster) from BHC sources. Carter (1982a) identifies data for 1918-1980, but POL has only 1918-63 as verified and digitally available.
8. Rate over continuous monthly record that does not necessarily equate with an annual 12-month cycle specification.
9. Seasonal detrending by using annual average MSL.

Although contemporary annual RSL change rate varies from between c +1.5 and +2mm a^{-1} to between +0.5 and +1mm a^{-1}, on a south to north UK gradient (Woodworth *et al.*, 1999), there is no consistent equivalent estimate for

Northern Ireland in the last century. Carter (1982a) identified falling RSL trends of <2.5mm a^{-1}, over the 20th-century for Malin Head and Belfast Harbour, which he thought were due to a remnant isostatic signal from ice unloading post the last glacial maximum. Carter further identified the possible effects of Belfast harbour expansion affecting the declining RSL signal that he obtained for that site.

Orford (2001) specified the difficulties in estimating an overall Northern Ireland RSL change rate given the breaks in, and non-overlapping nature of tide-gauge data from the four data generating sites available. A key problem was the need to detrend the nodal tidal (18.6 years periodicity) signals from data series, which had not been undertaken by Carter. Further analysis of detrended data from Belfast (1918-63) and Malin Head (1958-1995) indicated only small RSL fall rates, suggestive of remnant isostatic uplift. This declining signal has low-amplitude decade-scale oscillations (Fig.4.2 & 4.3) that have major implications for estimates of RSLC dependent on data window length, and are thought to have affected Carter's 1982 analysis (Orford, 2001).

Analysis of recent (but not detrended) MSL data from Portrush and Bangor tide gauges (1996-2000: Fig. 4.4) identify positive trends in RSL of <+2.5mm a^{-1} at both sites (Orford, 2001). It is still uncertain whether these recent up-swings reflect eustatic acceleration of RSL, are part of the nodal tidal expansion, or relate to an upswing in the decade-scale oscillations running through NI data. Regardless of the origin of the upswing, there may be contemporary problems ensuing from this RSL rise in the present decade, regardless of any acceleration over the next 20-50 years. Such accelerations are likely to translate into an annual average RSLR of c.2 times the current extreme identified elsewhere in northern UK. The issue of variation around the decadal-century estimates of RSL is one still to be adequately specified, while clarification of RSL changes during the 20th-Century for the north of Ireland also remained a major research requirement.

4.3 Discussion

There is obvious non-linearity in MSL identified at the Belfast Harbour gauge (Fig.4.2) as well as at Malin Head (Figs. 4.3). Table 4.2 shows that the Malin Head record, once the nodal tide is detrended, is still experiencing a negative tendency, although its strength diminishes the further the time series used moves towards mid-1990s (<-1 mm a^{-1}). Whether this is the effect of a oceanographic factors is unknown, though Carter (1982) thought his estimate of –2.4 mm a^{-1} for Malin (Table 4.2) reflected the last vestiges of isostatic uplift from the last glacial maximum. Rates of Malin Head

	Belfast Harbour	**Period**	**Malin Head**	**Period**
Carter (1982)	**-0.20**	1918-1980	**-2.40**	1958-1980
Woodworth *et al* (1999)	**-0.25**	1918-1963	**-0.58**	1958-1994

Table 4.2: Published RSLC determinations (mm a^{-1}) for Belfast and Malin Head.

RSLC in Table 1 identify a possible lower isostatic trend when the rise in MSL recorded during 1980-1997, is included in the analysis. Woodworth *et al.* (1999) calculated Malin RSLC at –0.58 mm a^{-1}, confirming this reducing north coast MSL trend. The record at Malin is however clearly affected by the nodal tidal signal. When the longest record is detrended, the remaining RSLC signal (-0.01mm a^{-1}) shows a virtual absence of any negative tendency. This absence reflects either a loss of any further isostatic trend of the north coast, or the real possibility of a very reduced signal given a potentially longer time series window, or an indication of an accelerating rise in MSL that masks a consistent 20th-century isostatic signal.

Carter (1982a) also identified a RSLC of -0.2 mm a^{-1} for Belfast. This is bracketed both by the -0.25 mm a^{-1} estimate of Woodworth *et al*., (1999) and by the Orford (2000) analysis (-0.16 mm a^{-1}). Variation between these three estimates is probably within a sampling error band. Changes in MSL during recent years for NI gauges need to be compared with the Malin record, to see if gauge position eastwards from Malin shows a diminishing impact of the isostatic effect. Although the result of nodal detrending suggests that there is no long-term isostatic difference between Malin and Belfast MSL, the difference between Portrush and Bangor's MSL in the 1990s might indicate an isostatic differential is still working.

The most obvious point from this preliminary analysis was that RSLC time series in the north-east of Ireland over the 20th century were likely to be non-linear with major fluctuations (on a basic 19 year nodal tidal periodicity plus associated higher-order periods of c. 7 and 5 years (Todd, 1981 as reported by Carter, 1982a). RSLC is therefore highly variable when considered within subsets of these periodicities. Short-term RSLC rates in excess of +/-10-20mm a^{-1} were twice the magnitude of predicted MSL changes in the next century (Houghton *et al.*, 1996) and probably reflect the variance rather than the mean of future change. Of concern is whether the extreme rise in RSL of the last five years (+8 to +17 mm a^{-1}) is only the upswing of a decadal periodic limb, or a reflection of a major change in the long-term trend of MSL, i.e. acceleration. This question cannot be answered as yet. Until the time series for Malin is up-dated so that the Bangor/Portrush series can be matched against the longer trend, any view on the direction of recent (and future) MSL activity in NI will be severely constrained. The difference between Portrush and Bangor may show some north/east coast differential that is isostatic, plus a differential potential for oceanographic forcing through storm surge development in the Malin Sea compared to the enclosed North Channel.

4.4 Conclusions

Mesoscale estimates of RSL change for the north of Ireland at both Belfast Harbour and Malin Head prior to 2001 tend to indicate that there has been a 20th-century negative tendency (regressive phase), despite short-term positive changes identified at Portrush and Bangor. All of these RSL estimates are uncertain given reduced data windows, untransformed data and non-stationary datums. There is a need to open data windows to maximum available extent, confirm datum stability and detrend for nodal tidal activity before uncertainty of estimates can be reduced.

5 METHODOLOGY: TIDE GAUGE DATA DIGITISATION AND VERIFICATION

5.1 Principles of analogue to digital conversion

Data to be obtained (observed water level) are either, hourly-observed tidal values or, semi-diurnal high and low tidal level elevations. The choice depended on the state of the tide gauge record, the time frame in which data digitisation could be undertaken and compatibility with existing digital data to which these new data were to be added. The main methodological problem was whether to continue the measurement of Belfast Harbour on a semi-diurnal basis or attempt to produce an hourly data set. The hourly set is the standard for analysis of surge and related storm effects, but was not necessary *per se* for determination of annual RSLC (as required by EHS remit). Therefore the Belfast Harbour tide-gauge record (1963-2000) was digitised for semi-diurnal high and low tide elevations only.

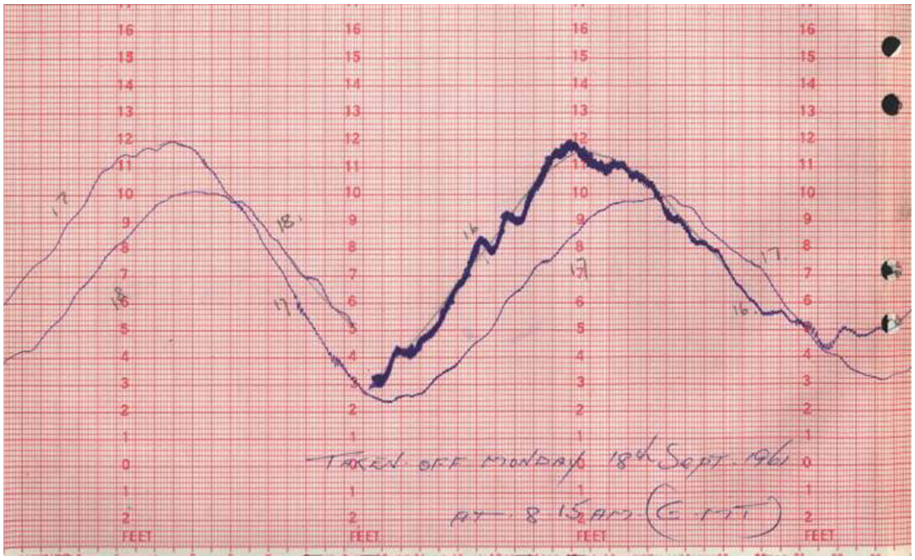

Fig.5.1 Example section of a weekly marigram from Belfast Harbour, where the sheet had been left on for two weeks.

Given the hourly basis of existing Malin Head digital data, the remaining years were digitised for hourly tidal levels. A constant stream method was used whereby the full analogue curve (usually week length, Fig.5.1) was reduced to x-y co-ordinates and concatenated to a full 24-hour x 7-day record length (to counter paper shrinkage and/ or over-run of the clock mechanism). Purpose written code (Basic) was used by which hourly values of water elevation were then estimated from the x-y stream. All values were adjusted for variation in datum that can be obtained from the gauge log. Validation of drum placement error/distortion had to be undertaken manually.

5.2 The digitising procedure

For most of the 20th Century, Ireland's tide gauges used the traditional method of a clock, a float, a pen and a weekly paper sheet. The first stage of data transformation is to convert the analogue records (Fig.5.1) into an accurate digital format. This part of the data assemblage process proved to be the most problematic and resulted in the time overshoot of this project. A customised GIS project was set up using ESRI ArcView 3.2 software. Six control points were identified on each weekly sheet and were used to develop a grid based on the x, y co-ordinates of the sheet (where x = time, y = water elevation). While a minimum of four points are required in digitising procedures to develop a grid (one control in each corner), six were used in order to account for and reduce any distortion which could result from chart quality due to folding and storage over the years. The complete water level curve was digitised (streamed) as a continuous line (made up of x, y nodes), before being converted to points (x, y). There were on average 40 points for the equivalent of every minute of the line, leading to a water level observation every 1.5 seconds. These points were then exported out of the GIS package and inserted into an Excel worksheet, where a validation process was carried out on each sheet independently.

5.3 Malin Head Tide Gauge record

Data from Malin Head used in this research covered the period 1958-2001 inclusive. The data set 1958-1990 was already available in digital format, meaning that the procedure outlined above only had to be applied to the remaining years 1991-2001. Although the period 1958-1990 had previously been converted to digital form, considerable effort was made on validating each year as parts of the data were missing, not in the correct order, or had extreme values included, due to human error in the original digitisation process.

5.3.1 Validation procedure

There were two major correction factors that were applied to the digitised tidal data. Firstly, timing problems (due to gauge clock inaccuracies) were corrected, and secondly, the water elevations were adjusted to that of the staff gauge datum.

5.3.2 Initial timing problems:

Each weekly tide gauge sheet came with the date, time and staff gauge reading indicative of when the record started and ended. This enabled the correct number of hours and minutes represented by each sheet to be calculated. Using a macro written in Visual Basic, and run in Microsoft Excel, the digitised line was then re-divided (along the x-axis) into the correct number of minutes for the period covered. The macro then searched through the new time series and identified the first hourly (x-axis) equivalent and read off the corresponding water elevation (y-axis). For example, if the record started at 10.45am, the first 15 minutes of data were overlooked by the macro and the 11am hourly water level was recorded. This eliminated the problem of having too many or too few observations in a weekly series, and resulted in the correct number of observations equally spaced at hourly intervals (60 minutes).

Timing problems became apparent at intervals throughout the Malin Head series. This was due to either clock inaccuracies in the gauge or the incorrect time being recorded on the tide gauge charts. For the Malin coverage, further validation was undertaken at POL, enabling all identifiable timing problems to be corrected, bringing them into line with the predicted series.

5.3.3 Staff gauge levels:

Once the correct number of observations was generated, the levels could be reduced to a common datum. The chart zero of each sheet is set at a certain elevation above that of the staff gauge. The first adjustment of the digitised data was then to pull down the observed levels to that of the staff gauge, so that they could later be corrected to OD Malin. At this point it is sometimes necessary to include the first and last observations of the streamed data, if these values are not already included (through ending on the hour). For instance, the sheet in Fig.5.1 was started and taken off at 9.30am. Therefore the hourly data extracted starts at 10am and ended seven days later at 9am (British Summer Time). However, the elevation on the staff gauge at these hourly intervals was not known, but the heights 30 minutes before and after (9.30am) were known. All of the observations were reduced by a correction factor, equivalent to the difference between the first reading on the chart and what it registered on the staff gauge at that time.

A second major problem stemmed from the fact that this difference was not always consistent through the record. Due to a slight slope in the way the paper had been fitted, at times the series ran at a slight angle. In this case the difference between the ‘on’ and ‘off’ correction factors reflected the degree of rise or fall in the chart. This difference was then divided by the number of minutes in the weekly series (hence the need for the odd minutes either side of the first and last hour), and an increment added or subtracted to each hourly extracted elevation.

Once the above procedures were complete, the hourly values were stored in an Excel file, until the year was complete. Each annual file has been adjusted to Greenwich Mean Time (GMT) and begins at midnight on 1st January, ending at 11pm on 31st December. Each file represents observed hourly water levels throughout the year – 8760 values, or 8784 values in a leap year.

5.3.4 Malin Head: treatment of previously reported errors

Previous analysis of these data (Carter, 1982) was based on observations taken from the charts by eye, on a 3-hourly basis provided by OSI (Rossiter, 1961; Pugh, 1987). Hourly data collected in this project were used to calculate annual MSL positions through the record. These positions were then plotted as a time-series (Fig. 4.3). From this first plot a substantial drop (c. 10 cm) in MSL is evident in 1992 & 1993. This dip in MSL was identified by Woodworth *et al*. (1999) as due to instrumental error. A calibration check carried out in late August 1993 revealed that the chart readings were 6 cm low, but it was unknown when the error occurred (Woodworth *et al*., 1999). Including such an error in regression analysis data would generate an inaccurate predictor equation for determining RSL change.

A review of the tide gauge charts covering this period identifies that the error occurred in mid-December 1991. During stormy weather it appears that the ‘bubble pot’ started to come adrift, which was associated by spurious pen recordings on the chart. This fixture had become completely dislodged by 16th January 1992 (by which time the gauge had become non-operational). This pot was replaced on 16th January, when the gauge resumed observing continuous sea level. The calibration check, which followed in August 1993, identified the 6 cm shortfall and in order to correct it, the bubble pot was re-fitted at its correct level on 1st September 1993. To adjust this error on the hourly extractions, a 6cm elevation has been added to each recorded observations between 16th January 1992 (when the records started) and 1st September 1993. This adjusted data is shown in Fig. 4.3, which still identifies a dip in the RSL trend for 1993, despite this 6 cm correction.

Dips in trend (up to 10 cm) can also be picked up in the period 1999-2001, when the record dips off without recovering. Whilst a low position *per se* can never be ruled out, this particular drop is a cause for concern, as it has not been picked up at the nearby gauges of Portrush or Bangor (Fig.4.4). Rather, these gauges show a gradual rise in relative sea-level through this period (Orford, 2001). Due to this fact, it is unlikely that such a major opposite trend could be occurring at Malin Head. Whilst initially it was thought that this dip was caused by instrumental error as in 1992, the drop does not appear consistent or linear through these years.

A gap in the record also exists between 16th April and 3rd June 1998, where there are no charts available. It is not known whether these charts have been lost or where never recorded due to a malfunction of the gauge, as no official logbook is kept.

To test for mechanical malfunction of the gauge, MSL values were calculated for the period 1st January – 16th April, and 3rd June – 31st December (hence cutting out the period with no data in 1998) for the years 1994 – 2001. A consistent difference in these calculated values should identify a problem caused by an instrumental error in the operation of the tide gauge, such as the 6 cm shortfall above (1992). However, the MSL values of these two periods were not consistent (January – April mean difference: 0.1759 m; June – December mean difference: 0.0955 m)) to represent a constant underestimation of hourly water levels, so daily mean values for the years 1997 – 2001 were calculated (Fig. 5.2-5.6). In these figures 1997 is considered an error free year, and is used as the baseline to compare daily means with subsequent years as it represents the year with a complete coverage that is closest to this latest dip in RSL trend, 1993 is also included. The first obvious anomaly can be seen in Fig.5.2 (1993 & 1997), where in 1993 the month of February has consistently lower daily mean tidal levels than 1997. This is unexpected as the higher sea levels are found in the stormier winter months, with the lower values expected in the calmer (fair-weather) summer months. This period aside, an association is evident between the remaining months, with the exception of late April. Figure 5.3 shows that there is no substantial difference between daily MSL in 1997 and 1998. The dip in MSL for 1998 is within natural variability (one standard deviation of the mean of the time series) and the drop does not appear to have been initiated during the period of no observations in 1998.

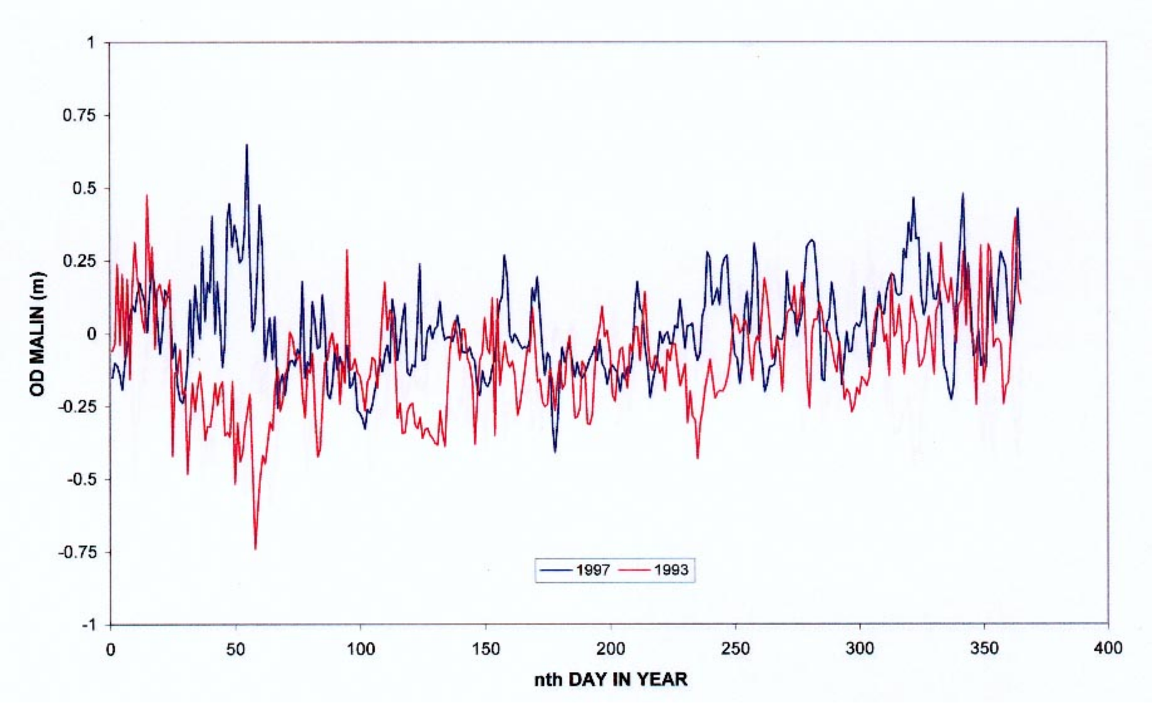

Fig 5.2: Daily mean tidal elevation from Malin Head 1993 and 1997

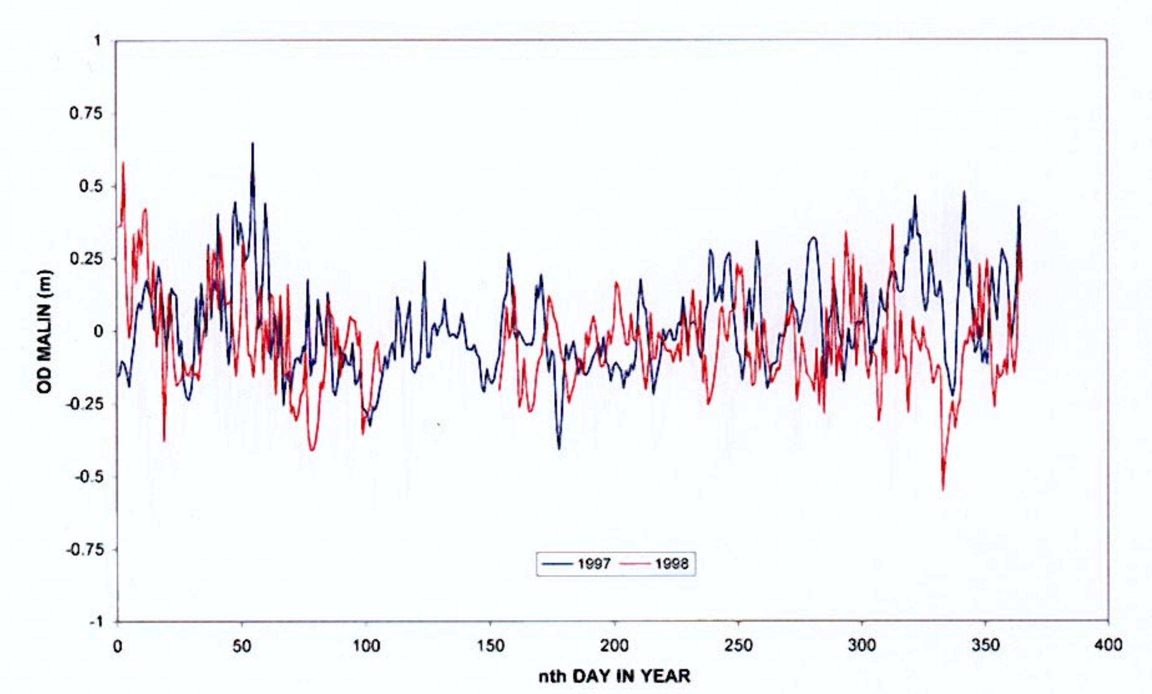

Fig 5.3: Daily mean tidal elevation from Malin Head 1997 and 1998

Like 1993, 1999 (Fig. 5.4), 2000 (Fig. 5.5) and 2001 (Fig. 5.6) all demonstrate a lower daily MSL position around February, with 2000 also experiencing a similar

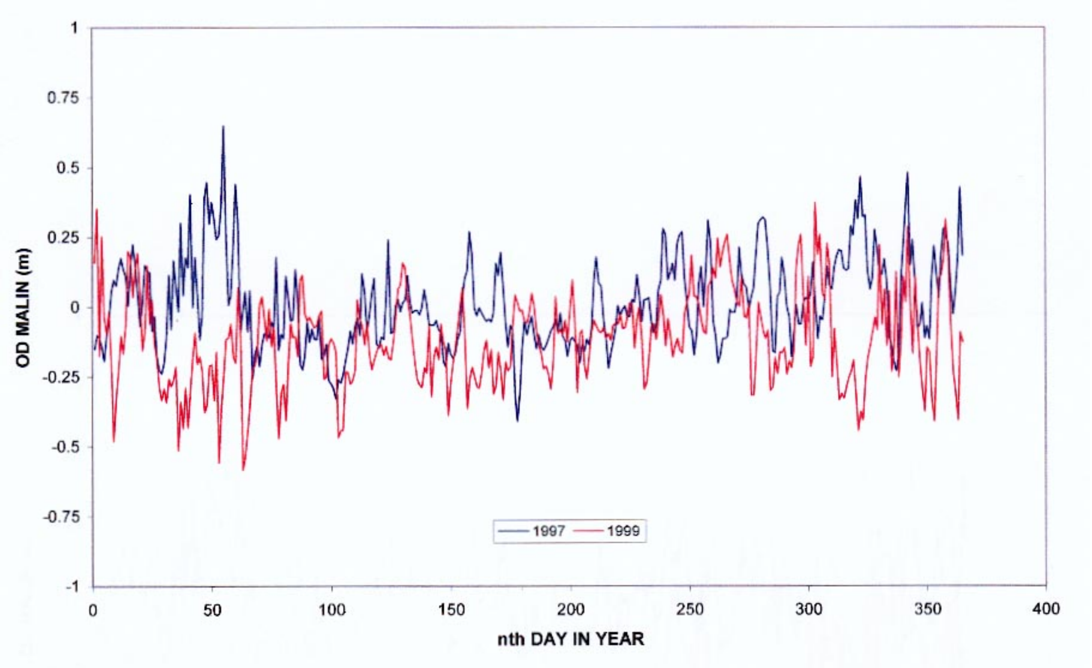

Fig 5.4: Daily mean tidal elevation from Malin Head 1997 and 1999

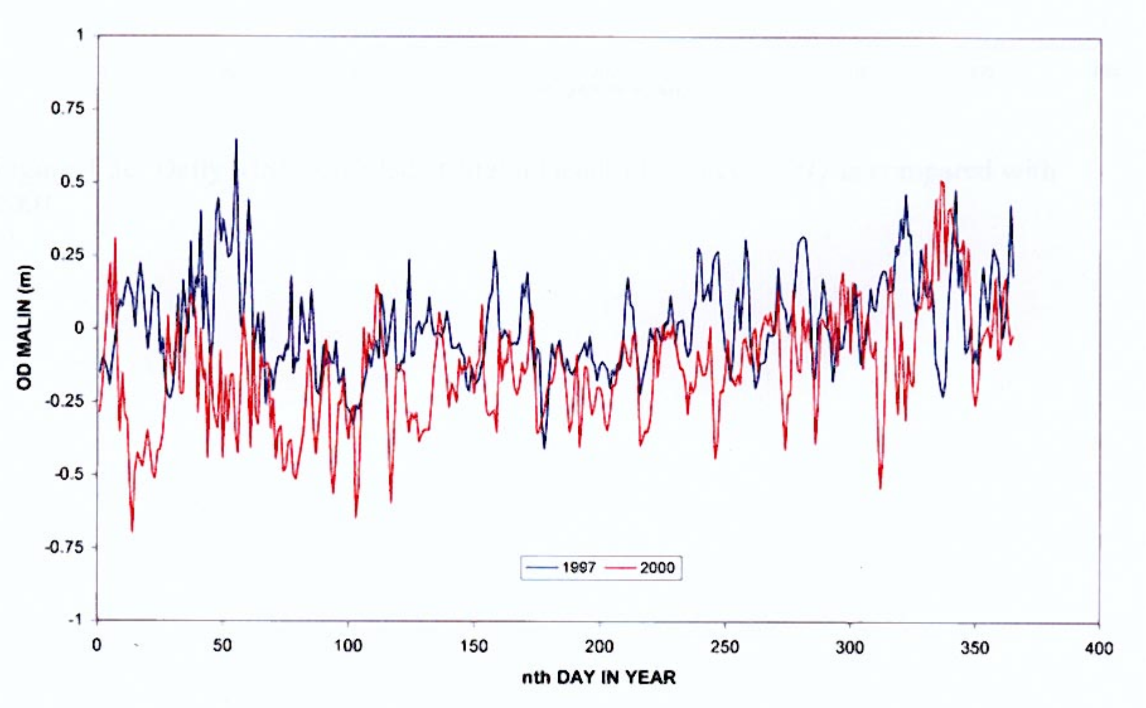

Fig. 5.5: Daily mean tidal elevation from Malin Head 1997 and 2000

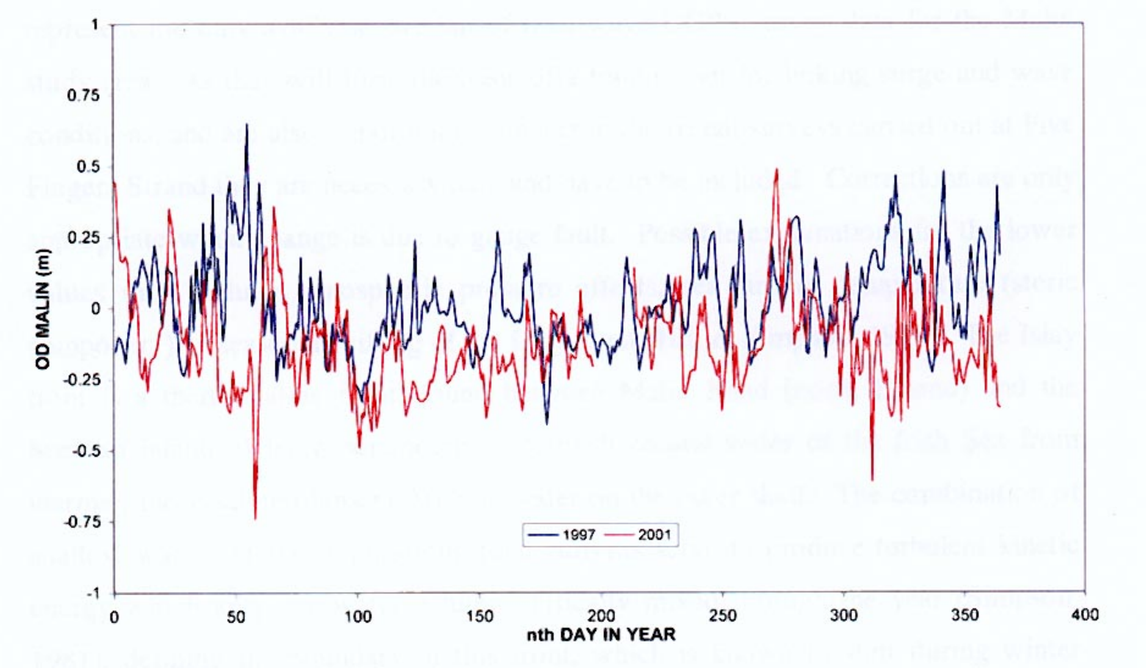

Fig.5.6: Daily mean tidal elevation from Malin Head 1997 and 2000

trend in January. Both 1999 (Fig. 5.4) and 2001 (Fig. 5.6) also dip in November. In contrast, the summer months in all years do not experience any consecutive drops, which rules out the possibility of a linear gauge problem as any potential distortion only becomes variably apparent during winter months.

As no consistent error can be found with the gauge record from Malin Head, which would indicate a mechanical fault, and given an opposite trend (Orford, 2001) is recorded at both Portrush and Bangor (Fig. 4.4), the period 1999-2001 should be treated with caution. Corrections are only appropriate when change is due to gauge fault. Possible explanations for the lower values may include atmospheric pressure effects, sea surface temperature (steric component) or seasonal shifting of the Islay front (Hill & Simpson, 1989). The Islay front is a thermohaline front, found between Malin Head (north Ireland) and the Scottish Island of Islay, separating cold, fresh coastal water of the Irish Sea from warmer, more saline (denser) Atlantic water on the outer shelf. The combination of shallow water together with strong tidal currents serve to produce turbulent kinetic energy which keep the water column vertically mixed through the year (Simpson, 1981), defining the boundary of this front, which is known to shift during winter months (Hill & Simpson, 1989). Due to resource constraints it has not been possible to explore these potential causes.

5.5 Belfast Harbour Tide Gauge record

5.5.1 Data extension and verification

Prior to this investigation, sea level data relating to Belfast Harbour in digital format only extended from 1918-1963. In order to extend the record, the tide-gauge marigrams held in storage by POL were digitised at QUB. Consequently, the Belfast Harbour database has now been extended by approximately forty years, bringing the record up to 2001. The Mean Tide Level

(MTL) method of extracting the daily high and low water levels was used (IOC, 1994). Ideally, the Mean Sea-Level (MSL) method of extracting hourly values has been favoured (Pugh, 1987). However, due to the nature of the Belfast Harbour marigrams, it was difficult to digitise the complete tidal curve (streamed), since the daily tidal curve was often discontinuous. To stream the Belfast tidal data would mean setting each marigram up on the digitiser on several occasions, which would make this project time consuming. As Todd (1981) used the MTL method, it was decided to continue to keep the time-series consistent. Although, Woodworth (1987) noted that MTL differs slightly from MSL, due to shallow water effects, it was calculated from those years when hourly water levels were available for Belfast (1988-2000) that a difference of approximately 30mm exists between the two methods (Table 5.1). This supports the (IOC, 1994) conclusion that there is little difference in the results generated between the MTL and MSL methods.

Year	**MSL (m)**	**MTL (m)**	**Difference (m)**
1988	2.004673	1.96881	0.034792
1989	2.075316	2.068534	0.006782
1990	2.047501	2.005374	0.042127
1991	2.000802	1.96921	0.031592
1992	2.012571	1.990809	0.021762
1993	2.031815	2.024602	0.007213
1994	2.172377	2.130604	0.041773
1995	1.984286	1.951588	0.032698
1996	1.929299	1.900963	0.028336
1997	1.938693	1.905386	0.033307
1998	1.942706	1.914048	0.028658
1999	1.948678	1.911312	0.037366
2000	1.956319	1.916142	0.040177
Mean difference			**0.029737**

Table 5.1 Comparison of MTL and MSL methodologies
(Belfast Harbour tidal data 1988-2000)

5.5.2 Data Checking Procedures (Quality Control)

In order to check that the original tide-gauge marigrams were digitised correctly, the digital data was checked thoroughly before any statistical parameters (mean and standard deviation) were calculated. In order to ensure accuracy, the digitised figures were broken up into monthly intervals and checked against the original analogue records. This way it was easier to physically identify any problems. For example if a point (spikes) or a set of wrong points (glitches) were identified (projecting too high or low) by cross-checked with the analogue tide-gauge sheets, they could be corrected. In the majority of cases such spikes were not caused by human error, but were present in the original gauge data and often represented distinct episodic oceanographic forcing, i.e. surges (Fig 5.7).

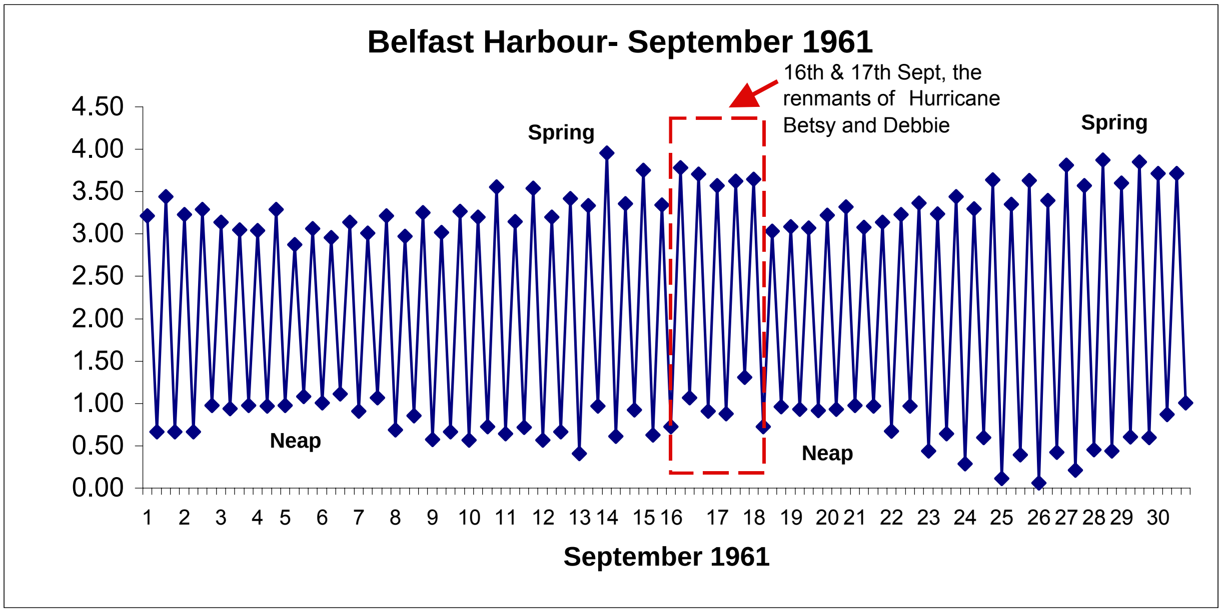

Fig. 5.7 Effect of ex- hurricane Betsy and Debbie is raising extreme water levels above expected elevations (spike effect) Note LW as well as HW were raised

5.5.3 Data gaps and processes of interpolation

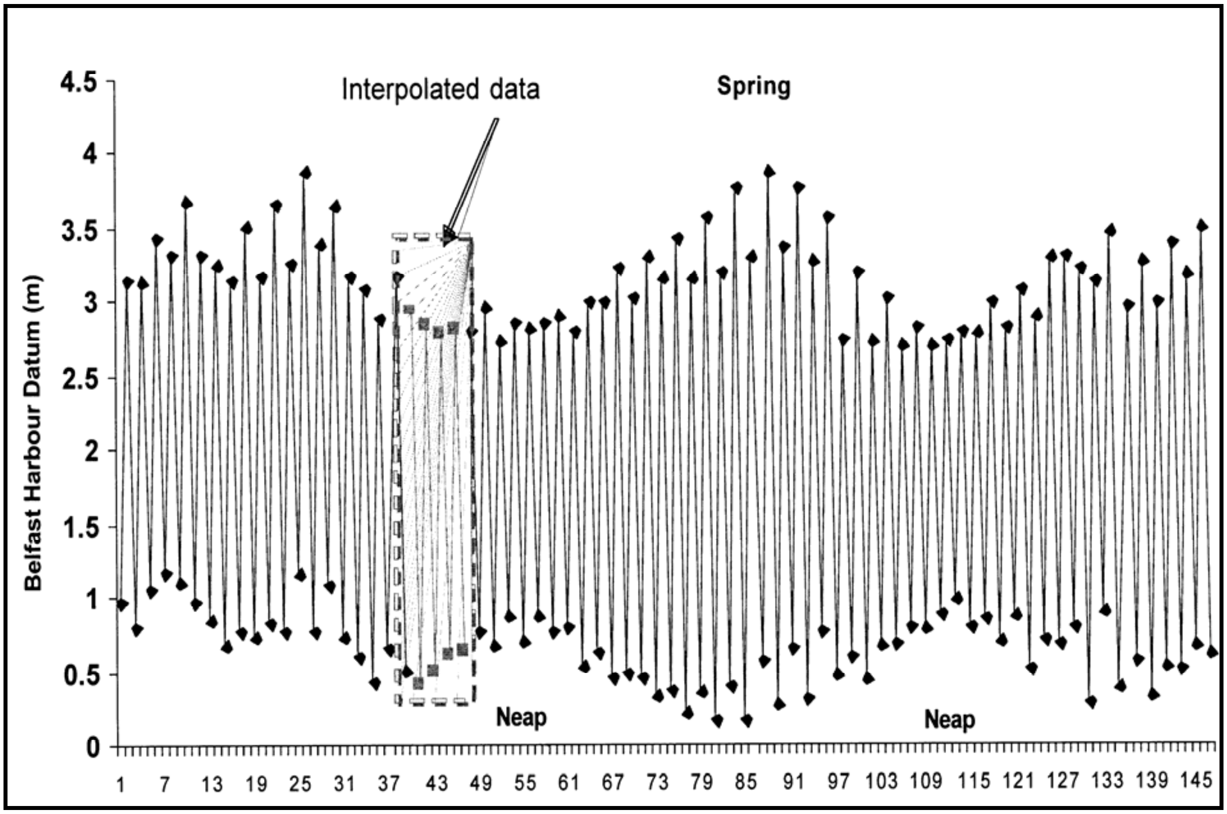

Fig.5.8: Example of interpolation in Belfast harbour record

Too often, data gaps were present in the Belfast Harbour data set, mainly as the result of tide-gauge faults. In order to fill out these gaps, data interpolation was conducted. However, since it is recommended that data gaps greater than twenty-four hours (4-5 points) should not be interpolated (IOC, 1994) then interpolation was not conducted for periods greater than that specified time. In order to interpolate missing data gaps, monthly cycles were plotted on MS Excel and the tidal cycle pattern was investigated, subsequently missing data was manually fitted to this tidal cycle (Fig.5.8). It should be noted that this is a crude method of interpolation, since the filled data gaps may omit meteorological influences, such as surges.

5.5.4 Data Comparison with Buddy gauges

To ensure that the Belfast Harbour data was of the highest quality, the monthly averages were compared with Buddy gauges. Buddies are tide-gauge stations that are located nearby, generally less than 40 km away. For this investigation, the tide-gauges located at Portpatrick (Scotland), Bangor and Larne were selected, since they are approximately 40 km from Belfast. It is unfortunate that the Malin Head and Portrush tide-gauges lay too far outside this recommended 40km boundary and hence cannot be compared with Belfast Harbour. However, as the distance between stations increases then differential oceanographic sea-level variations should be considered.

A brief description of these buddy tide-gauges is outlined in Fig.5.4. The monthly values for these stations were downloaded from the internet via the Permanent Service for Mean Sea Level (PSMSL) site

www.pol.ac.uk/psmsl/psmsl_individual_stations.html

and exported onto MS Excel, subsequently each year was compared with the Belfast raw data and analysed. It is necessary that this type of data comparison is conducted so that MSL variability due to oceanographic and meteorological forcing can be identified. Furthermore, as with the Belfast Harbour tide-gauge, the influence of land subsidence, siltation and dredging activities might be identified. It is expected that if the observed values are above the expected values, then this might indicate subsidence or siltation, alternatively if they appear too low this might indicate evidence of harbour dredging.

Table 5.2: Position and type of the Buddy Tide-Gauges

Location	**Portpatrick**	**Larne**	**Bangor**
Grid-reference	54 51 N 05 07 W	54 51 N 05 47 W	54 40 N 05 40 W
No. of years	34 (1968-2001)	14 (1959-1980)	8 (1994-2001)
Tide-gauge type	Lea Stilling Well (After 1990) A class bubbler	Lege Gauge	
Approximate distance from Belfast Harbour (km)	42	20.2	15.1

5.5.5 Description of the Belfast Harbour Data Series

Three data sets were produced for analysis of RSL, in an effort to deal with missing data and corrections of datums. These data series are identified as;

- Raw
- Useful
- Adjusted

The **raw** data is as identified from the original marigram tidal levels corrected for as many levelling inconsistencies and timing difficulties that could be obtained via the actual statements written on the charts and Belfast Harbour commissioners commentaries. Once the raw data relating to Belfast Harbour were checked for accuracy, the monthly and annual mean and the standard deviation were calculated and used as a verification cross check. These data (1960-2002) was then linked up with the existing POL data (1918-1963). The monthly and annual values (1918-1963), for Belfast were downloaded from the internet via the Permanent Service for Mean Sea Level (PSMSL) web site. Once this data was downloaded, the *Revised Local Reference* (RLR) subset was converted back to harbour datum and then Belfast OD (m) in order to keep the data series consistent. In accordance with PSMSL terminology, the RLR is the data set for which the full benchmark datum history is available.

Following the guidelines outlined by (IOC, 1994) it is recommended that the mean and standard deviation should only be calculated if there are 15 or more days of raw data (≥60 observations) available. Furthermore, the annual mean should only be calculated if there are eleven or more monthly mean values available. In order to fulfil the (IOC, 1994) guidelines, the tide-gauge data was filtered for each year. If the raw data did not meet up to the guidelines it was not accepted, and subsequently classified as useless. This treatment of the raw data produced the second series known as the **useful** or POL transformed series.

Finally, the third data series was derived from the comparison checks made with the buddies. The monthly means relating to the raw series were plotted and compared against the monthly means for Portpatrick, Larne and Bangor. The average differences between the raw data and the buddies were calculated and hence the raw data was adjusted accordingly, producing the **adjusted** series. This series is an intuitive approach to present a corrected series that fills the gaps as left by the POL-IOC analysis. Clearly this is biased to what other stations might indicate as well as being a conservative perspective in that it assumes tidal behaviour that both echoes other adjacent sites as well as implying some past stationary memory process. This is a constraint but given the requirement for a trend line (RSL assessment) its is one way to move the analysis over the majority of data gaps.

5.6 Conclusions

Tide gauge data from both Malin Head (hourly elevation values: 1958-2001) and Belfast Harbour (high and low tidal elevations: 1918-2001) have been digitally transformed and verified for timing and datum. The difficulties of datum changes and data omissions necessitated the interpolation of an adjusted annual series for Belfast Harbour. Un-resolvable problems of extreme annual MSL have raised uncertainty about recent years (1998-2001).

6 RESULTS: MSL/MTL AND RSLC DETERMINATION

6.1 Malin Head

Relative sea level change can be determined, based on either the annual raw (total series) or nodal-detrended data. Due to the uncertain state of the 1999-2001 data, several alternative predictor equations were calculated which could be used to represent RSL change for the duration of the tide gauge record. Figure 6.1 is based on RSL from 1958 to 1998, and therefore excludes the years of concern (1999-2001).

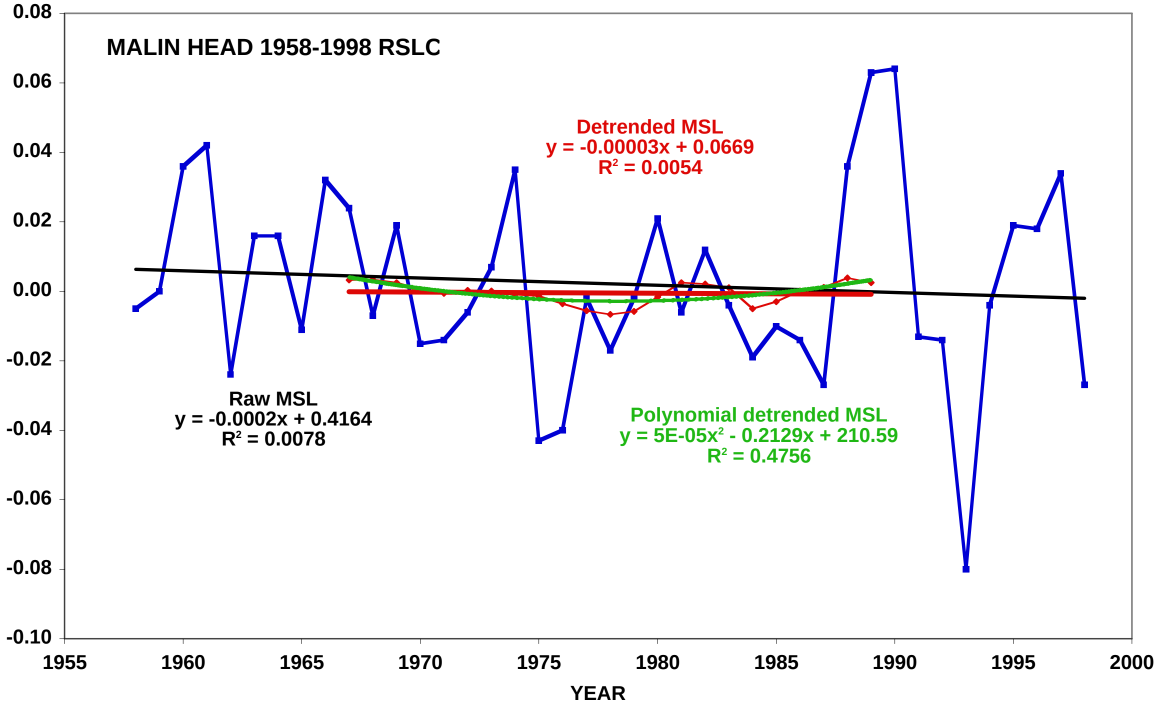

Fig.6.1: RSL determinations from Malin Head (1958-1998)

The second set (Fig. 6.2) shows regression equations and coefficients based on the entire data set, including 1999-2001. Each of these two data sets generate predictor equations based upon best-fit linear regression together with

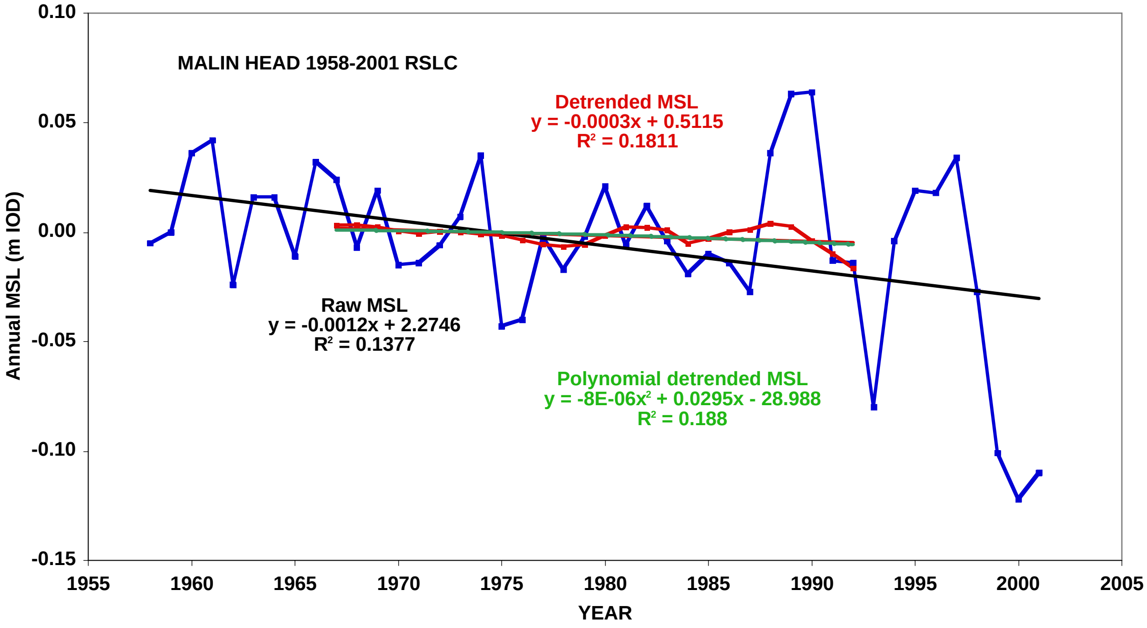

Fig.6.2: RSL determinations from Malin Head (1958-2001)

second-order (quadratic) polynomial regression analysis for indication of acceleration terms. The quadratic equation is only cited if this predictor leads to a significant ($p>0.05$) increase in %RSS over the linear term. In this respect, the curvilinear predictor for the 1958-2001 data set is visually indistinguishable from the linear trend (Fig.6.2) and should not be used to characterise the nodal detrended data. It is not straightforward to identify RSL variation in terms of a predicted annual rate of change (mm a^{-1}) generated by polynomial regression analysis, as this rate prediction varies over time. The overall sense of RSLC for Malin Head in the 20th century is regressive, though the absolute values and the range of change rates regardless of data window are small and close to zero. Table 6.1 specifies the slope regression coefficients for the various combinations of data and treatments. From Table 6.1, the influence of the nodal tide can be seen in that by not removing its influence, the rate of regressive RSL variation throughout both sets of time periods is exaggerated. Furthermore, by including the years 1999-2001, the overall raw data trend generated by the predictor equation is greatly changed, by almost 1 mm a^{-1}, while the detrended linear rate estimate is increased by an order of magnitude. Due to the concern surrounding the period 1999-2001, but given the importance of them in future analyses, it was decided as a precautionary measure to specify the regression coefficients of the RSL predictor equations for the years 1958-1998 as well as 1958-2001, thus specifying the later years non-conservative influence in the overall regression trend established. The effect of including 1999-2001 on the detrended data sets is noticeable, with the regressive slope estimate steepening by an order of magnitude. The polynomial-based regression models of the detrended MSL series indicate for both data sets an overestimate projected future sea-level rise for the 21st century. The difference between the linear and quadratic equations is negligible in the 1958-1998 data set and as such the linear model is the best predictor of this time series. The inclusion of the 1999-2001 data leads to a distinctive extension of the nodal-detrended data and increases the quadratic explanation significantly above the linear predictor by over 47% ($p<0.05$)

Duration of coverage	**Linear RSL change based on raw data (mm a^{-1})**	**Linear Nodal-detrended RSL change (mm a^{-1})**	**Polynomial justification %RSS**
1958-1998	-0.2	-0.03	47.02%
1958-2001	-1.2	-0.3	0.01%

Table 6.1: RSL variation obtained from Malin Head tide gauge analysis.

6.2 Belfast Harbour

Figures 6.3 to 6.5 show the various data sets developed from the BH tide gauge record over 1918-2001. To reiterate the raw MTL data (Fig.6.3) identifies all corrected values available; the useful data set (Fig.6.4) is generated via POL protocols and is a restricted data set; the adjusted data set (Fig.6.5) attempts to

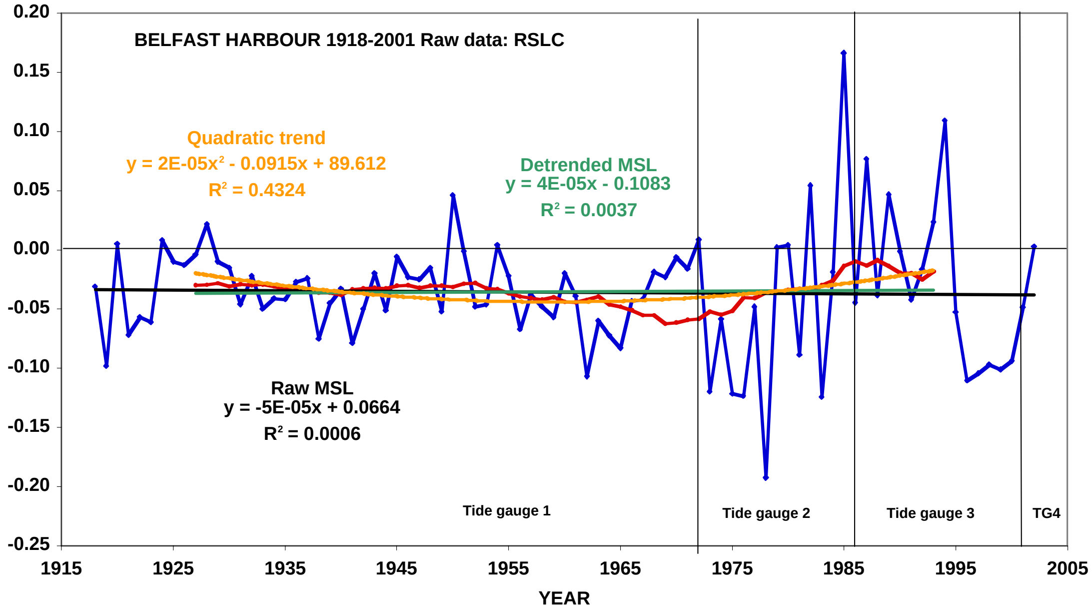

Fig.6.3: MTL (~MSL) from Belfast Harbour tide-gauge based on raw data. Annual MTL is not adjusted for missing data between 1960 and 2002. Raw MSL = linear regression of raw MTL data. Detrended MSL = linear regression of nodal detrended MTL. Quadratic trend = second order polynomial regression of nodal detrended MTL.

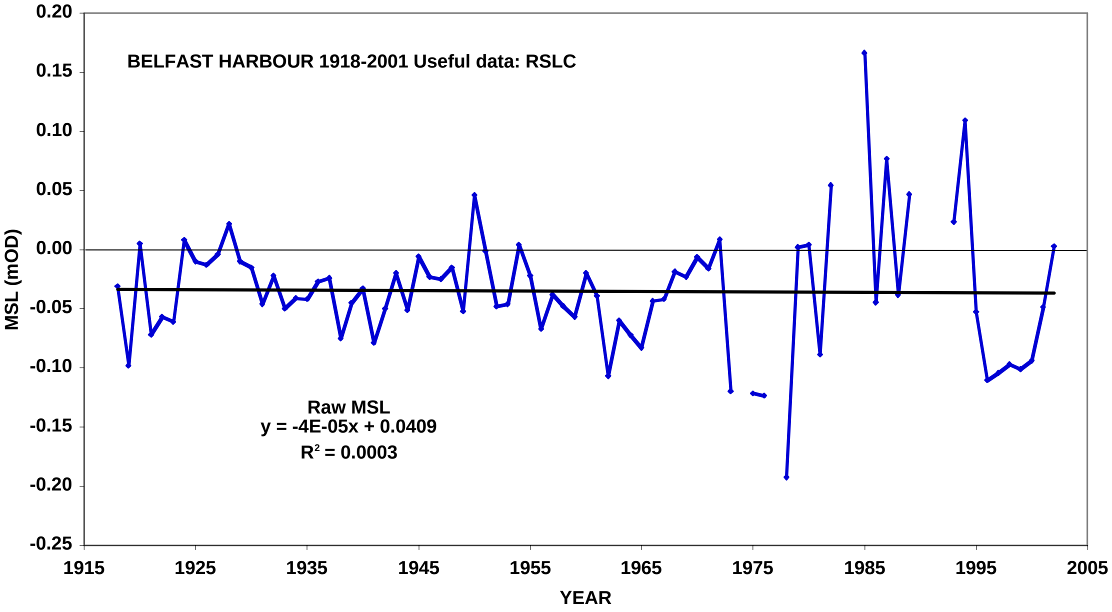

Fig.6.4: MTL from Belfast Harbour tide-gauge based on a POL verification of the data series between 1960 and 2002. Raw MSL = linear regression of raw MTL data.

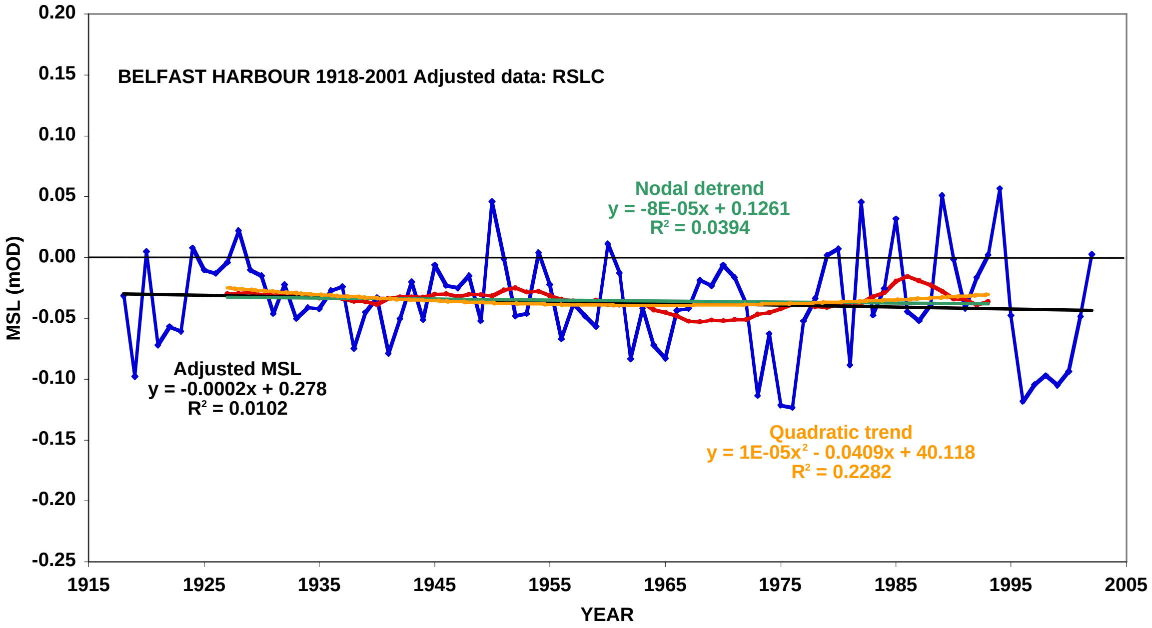

Fig.6.5: MTL (~MSL) from Belfast Harbour tide-gauge based on adjusted data. Annual MTL is adjusted using interpolation for missing data between 1960 and 2002. Raw MSL = linear regression of raw MTL data. Detrended MSL = linear regression of nodal detrended MTL. Quadratic trend = second order polynomial regression of nodal detrended MTL.

fill the gaps of the raw data set by interpolation and comparison with buddy gauges. The raw and adjusted data set deliver a notional annual MTL position and thus has a continuous data series that can be detrended for the nodal tide affect. These detrended data and associated linear trend lines are shown on the appropriate figure. The useful data set (Fig 6.5) has several annual MTL gaps and due to the 19 year term require in nodal detrending, any annual break stops detrend estimation for 9-years either side of the break. Therefore only a linear trend has been calculated for this series.

The obvious difference between the raw and adjusted data sets is the reduced variance of the post-1960 data in the adjusted set. This excludes the sudden drop in MTL in the mid-90s that is seen in both data sets. This reduction brings the adjusted data set variance comparable to variance observed in the 1918-1960 data set. Given the earlier data set is a more stable record (less gaps) it is likely to be a reputable template for the expected variance term in the later years. This helps to lower the uncertainty of accepting the adjusted set as the basis for a deriving a working estimate of RSLC (~RTLC).

The nodal detrended data reflect the periodic fluctuations identified in the Malin Head data, though the Belfast period appears to be twice that of the Malin trend. The Belfast amplitude increases in the latter half of the 20th century compared to the amplitude of the early/mid 20th-century. Both series show the early 1970 drop and 1985 peak (note that detrending shifts the relative fluctuations on in time. The relative excess of the 70s drop has been noted elsewhere (Woodworth *et al.*, 1999) and has been noted as a "one-off" event which possibly therefore over-accentuates the amplitude shifts of the later detrended series. It is difficult to draw comparisons between Malin and Belfast using the detrended data given the difference in data window length. RMTL change rate for the linear and polynomial predictors of detrended MTL are in Table 6.2. Both the raw and adjusted data sets show significant increases in %RSS in moving to the polynomial (quadratic) regression (42% and 21% respectively). Both polynomial equations identify minimal positions in the late 1950s to early 1960s and maximal RMTL (ie rising or accelerating RMTL) positions by the end of the 20th century.

Data Series	**Linear RSL change based on raw data (mm a^{-1})**	**Linear Nodal-detrended RSL change (mm a^{-1})**
RAW	-0.05	+0.04
USEFUL	-0.04	Not viable
ADJUSTED	-0.20	-0.08

Table 6.2: RSL change determinations for Belfast Harbour

6.3 Conclusions

The results illustrate that both Malin Head and Belfast Harbour records show evidence of marginal negative (regressive) mean sea-level trend. However, it is recognised that a number of issues still need to be considered before using these results as an estimator of the north of Ireland regional trend.

7 DISCUSSION: RSLC TRENDS FOR THE NORTH OF IRELAND

7.1 Malin Head

From the adjusted tidal gauge data now available, it appears that 20th century RSL at Malin Head still shows a very slight negative (regressive) tendency reinforcing Carter (1982), Woodworth *et al*. (1999) and Orford (2001) previous trend estimates (Table 4.3). These negative trends identified (Table 6.2) may be due in part to the window of data used in each analysis. As the window of data increases in each study, the strength of the negative tendency diminishes, especially true when the data includes the 1990's. It should be remembered that the contrary trend specified by Woodworth *et al*. (1999) also includes the uncorrected datum data of 1992-1993, forcing the regression predictor to a larger negative tendency.

Analysis	**RSLC** (mm a^{-1})	**Period**
Carter (1982)	**-2.40**	1958-1980 raw data
Woodworth *et al*. (1999)	**-0.58**	1958-1994 detrended
Orford (2001)	**-0.012**	1958-1997 detrended
This study: conservative estimate (2003)	**-0.03**	1958-1998 detrended
This study (2003)	**-0.3**	1958-2001 detrended

Table 7.1: RSL change determinations for Malin Head

However plausible the view that diminishing regressive trends are being conditioned by data window size, there is a further perspective that this diminishing regressive trend is, as suggested by Carter (1982a), the remnant affect of isostatic uplift. Alternatively, until there is a determination of actual crustal movement, the declining regressive tendency could reflect, in accordance with general UK trends, a possible acceleration of eustatic RSL due to global warming, which progressively masks and overcompensates a near consistent 20th century isostatic signal. It is unfortunate that although the uncertainty associated with determination of the trend is being reduced *per se*, there are still major uncertainties with the two input parameters of isostatic and eustatic rates

The RSLC record also identifies significant fluctuations in inter-annual and decadal variability. The nodal detrended MSL shows periodic fluctuations of the order of 7 years, which has been cited as being associated with increasing cyclonic activity in the eastern Atlantic (i.e. storminess: Orford *et al.*, 1996). This trend towards periodic fluctuations is typical of other sea level records in the British Isles (Woodworth *et al*., 1999) and globally (Meier & Wahr, 2002). Figure 7.1 is an attempt by Woodworth *et al*. to establish the typical fluctuations exhibited by most British tide gauges de trended for secular sea-level change. For example, the mid-1970's dip (Woodworth, 1987, Woodworth *et al.*, 1999) observed at Malin Head (Fig. 4.3) exists in all British records, while the apparent falls in the mid-late 1990s are also observed in the Malin data. Such inter-decadal variability identified in tide gauge records is reminiscent of that in other oceanographic and meteorological parameters in the north Atlantic, such as sea

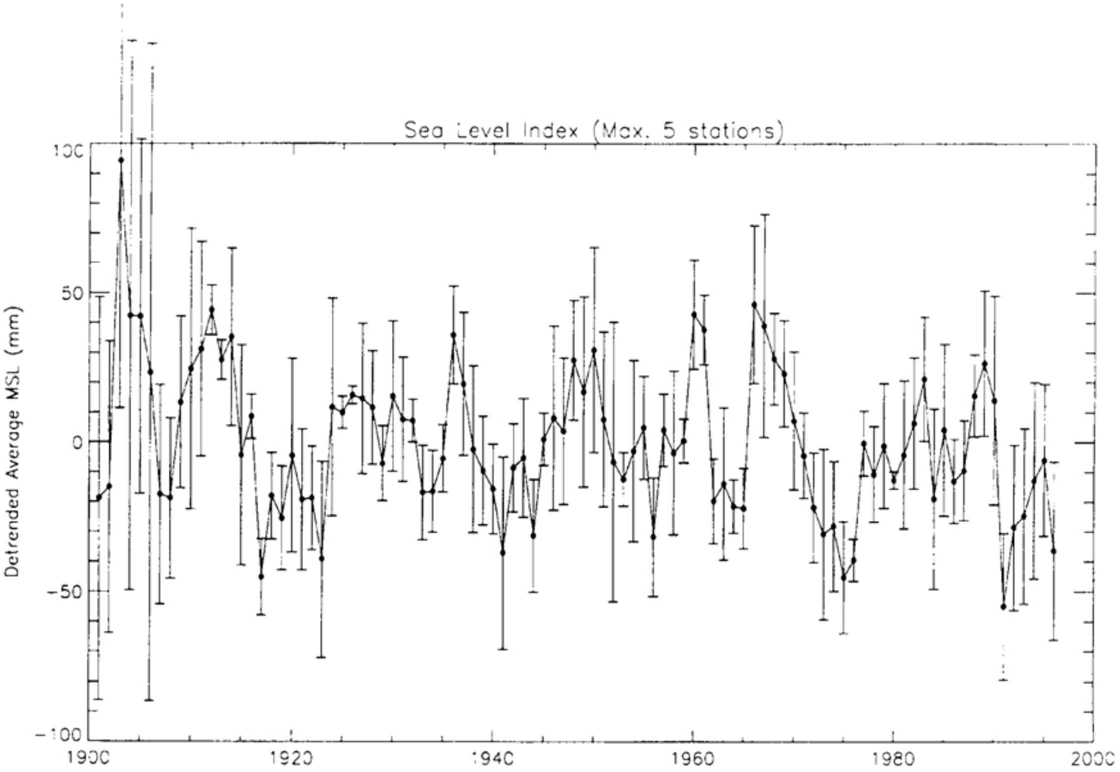

Fig 7.1: Standardised mean sea-level changes drawn from Woodworth et al., (1999) analysis of British tide-gauge records.

surface temperature (SST) (Sutton & Allen, 1997), storms (Schmith *et al*., 1998), NAO (Hurrell, 1995) and sun-spot activity (Currie *et al*., 1993). The periodicity of these environmental parameters may account for at least some of the decadal variation identifiable in these results.

7.2 Belfast Harbour

Table 7.2 identifies the rates of RMTL change identified in studies of Belfast Harbour over the last two decades. The general trend in MTL observed shows a marginally slightly negative (regressive) trend, though the raw data shows a slightly overall positive RMTL trend. The lengthening of the data window shows less, if any, effect on RMTL trend prediction. Despite the data problems experienced in the Belfast data of the late 20th century, it appears unlikely that the data window has any effect on this 80+ year record as opposed to the 40+ year record from Malin Head.

Data Series	**Linear RSL change based on raw data (mm a^{-1})**	**Linear Nodal-detrended RSL change (mm a^{-1})**	**Period**
Carter (1982)	-0.20	Not available	1918-1981
Woodworth *et al*., (1990)	-0.25	Not available	1918-1963
RAW: this study	-0.05	+0.04	1918-2002
USEFUL: this study	-0.04	Not viable	1018-2002
ADJUSTED: this study	-0.20	-0.08	1918-2002

Table 7.2: RSL change determinations for Belfast Harbour

However, caution is advised in dealing with the extended Belfast data series, since the quality of the raw Belfast record during the late 20th century is questionable. During the mid-1970s numerous mechanical faults were associated with tide-gauge 2. Consequently, the observed mid-1970s dip could be a reflection of poor data quality. Examination of the raw data series shows more negative mean sea-level values pre-1972 compared to post-1972. The data range is greater post-1972 (min -0.193; max 0.166) compared to pre 1972 (min -0.107; max 0.046). When comparing predictor equations applied to the raw Belfast data series, it is observed that the pre-1972 data generates a RMTL trend of -0.0049mm a^{-1}, whereas the post-1972 trend is 0.036 mm a^{-1}. (This may account for the significant quadratic regression explanation associated with the raw data. It is probable that the changing of the faulty AGA tide-gauge to a Lege stilling well gauge in August 1972 had an influence upon the results. It is unclear if a change in the recording method of the tidal level, or a lack of consistency in re-levelling the tide-gauge benchmark, or poor data quality has caused these results and hence the only positive RMTL trend observed so far.

In an attempt to track down the history of the tide-gauge benchmark the Hydrographic Office stated that the Belfast tide-gauge datum had remained consistent for at least forty years. Furthermore, the Harbour Commissioners had stated that every time the tide-gauge was moved the tide-gauge datum was re-surveyed (Ray Howdie, *pers com*). It is likely that the obvious pre- and post-1972 trend was caused by a faulty tide-gauge, since this tide-gauge was fraught with difficulties and broke down on a regular basis. It is also deduced that the stilling well tide-gauge that replaced the original AGA tide-gauge in 1972 was probably unsuitable for the naturally muddy estuarine environment of Belfast Lough. Several notes attached to the original marigrams indicate that siltation was a regular occurring problem associated with this gauge, while debris brought into Belfast Lough via the River Lagan (following heavy rain) may have become entangled within the stilling well causing blockage.

Before an attempt can be made to interpret the Belfast Harbour MTL signal, it is useful for the expansion history of the harbour to be considered. Over its long history from the 17th century, Belfast Harbour has experienced several phases of development and re-development. Carter (1982a) traced the subsequent infilling of Belfast Lough by the northwards expansion of harbour wharves and berths dating from 1835 until 1980 as identified from OS maps. This analysis revealed that the most active period of development occurred during the latter half of the 20th Century. Carter's examination of the Belfast tide-gauge data (cited as 1918-1981) revealed that mean tide level remained constant from the mid-1920's to the early 1950s, thereafter *falling* sharply at a rate of 2.1 mm a^{-1}. Carter initially made a connection between these tide-gauge trends, the development of the harbour and the probable alternation of the land/water level. It is known that the ground conditions within the Belfast Harbour area are unstable. If mean sea level is falling as indicated by Carter (1982a), then it is logical to presume that the land where the tide-gauge is positioned is rising rather than subsiding. It is presumed that the rapid development on the north-west and north-east side of Belfast Lough from the 1950's until the 1980's may have influence a general uplift on the inner west side via loading and unloading of the Holocene 'sleech' clays underlying Belfast Lough, thus accounting for the falling mean sea-level. However, evidence of subsidence (via the displacement of storms drains) on the west side of Belfast Harbour in the 1970s may undermine this argument.

The rapid development of the harbour and consequent modification of the configuration of the southern, upper, Belfast Lough may also have influenced the tidal prism (Carter, 1982a). However, at present no firm evidence exists to estimate if the tidal range has been augmented or diminished by harbour construction, even if the gauge's relative position has become slightly more reduced in exposure over the 20th century. With the establishment of the Lagan Weir during 1994, it is a suggestion that there has been some influence upon the natural tidal range of the estuary, by enhancing extreme tidal elevations that would have otherwise dissipated up-estuary. However, this 'weir-filter' is more likely to register as a rise in MTL, yet the 1990's raw data dip implies the reverse in that the overall influence of the Lagan Weir has been associated with a short-term regressive mean sea-level, despite overall the detrended signal identifies a long -term movement towards a near-static RMTL trend.

The Belfast record illustrates similar fluctuations in inter-annual and decadal variability as Malin Head, as is typical of other sea-level records around the British Isles (Woodworth *et al*., 1999). Woodworth (1987) and Woodworth *et al,* (1999) recognised a series of data dips in the UK record, in particular the deep dips of the mid 1970's and the 1990's. Investigating the mid-1970's dip Woodworth, (1987) stated that the amplitude of the nodal tide was too small to explain the large values relating to these dips and another explanation should be sought. Alternatively, (Woodworth, 1987) revealed that during the mid-1970s dip, sea-surface salinities (SSS) for the North Atlantic were anomalously low, indicating changes in circulation possibly connected to sea-level behaviour. However, the observed salinity variations were not accompanied by any large changes in sea-surface temperatures SST. There is no evidence to suggest that the mid-1970s dip is other than a temporary phenomenon. Indeed, Woodworth (1987) concludes that it would be irresponsible in view of the continuing global rise, and the apparent resumption of a rising trend to be seen in the majority of the UK records since about 1978, for these dips to be seen other than episodic.

Given the difficulties with the Belfast tide-gauge, it seemed justified to adjust the Belfast data using comparable data from other tide-gauges (buddies). Problems identified with the Belfast record (see Appendix !!) were rectified as appropriate. Consequently, the predictor equations generated from the adjusted data are probably more reliable than those generated from the raw data series. However, in all the series the dips of the mid 1970s and 1990s can still be observed. Although it is recognised that these low values or residues (dips) in the overall data series influence the regressive tendency in the trend-line down producing static to slightly negative predictor equations, it is thought like Woodworth et al. (1999) that it is unlikely that sea level is now rising on average less fast than over the base period; i.e. that is there has been an overall deceleration, rather than acceleration, in twentieth century MSL (cf. Woodworth, *et al.,* 1999).

7.3 Generalised trend for the north of Ireland

Figure 7.2 brings the two main detrended data sets from Malin and Belfast together for direct comparison. Note that the Belfast data datum is c 0.029m below the Malin datum. Table 7.3 shows the most likely RSL trends for the two sites with an overall regressive estimate of -0.2 mm a^{-1} for both sites, though at the detrended level there is a near order of magnitude reduction in the overall rate. The significant quadratic trend to the nodal detrended data suggest that the rate is likely to move towards a static or even positive relative sea-level tendency in future decades.

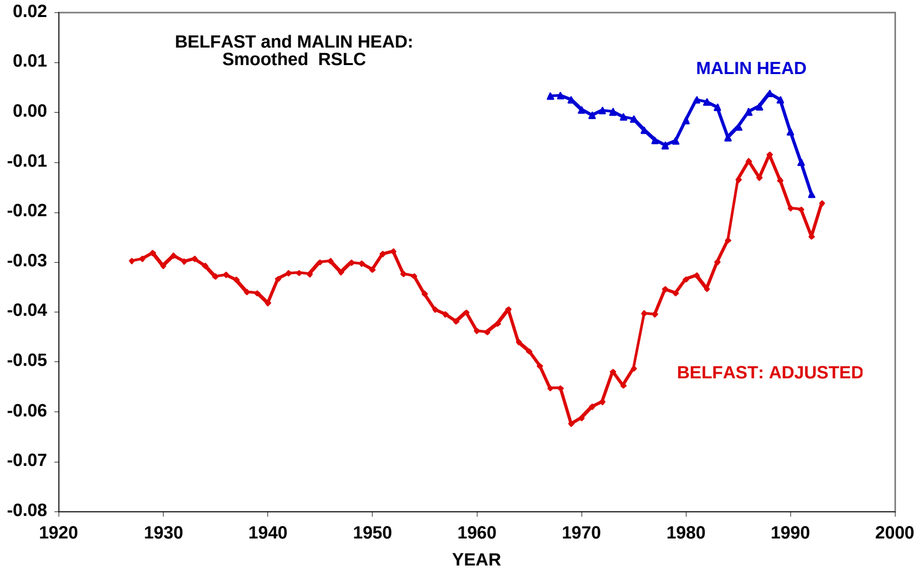

Fig 7.1: Comparison of detrended RSL and RMTL for the north of Ireland.

The question remains as to why the north of Ireland identifies a regional negative tendency as opposed to the wider British positive tendency of the last half of the 20th century. The decrease in the estimate of the regressive tendency

Site	RMSL/RMTL mm a^{-1}	Detrended RMSL/RMTL mm a^{-1}	Quadratic %RSS	Time period
Malin Head	**-0.20**	**-0.03**	**47.5%**	**1958-1998**
Belfast Harbour	**-0.20**	**-0.08**	**22.82%**	**1918-1998**

Table 7.3: Least biased estimators of RSLC and RTLC for the north of Ireland in the 20th century

at Malin Head over the last 20 years is likely to be due to some combination of the following three factors:

- the increasing data availability window that allows better trend estimation of sub-decadal sea-level fluctuation caused by atmospheric-ocean forcing;
- diminishing isostatic term as crustal movement reduces;
- accelerating eustatic sea-level rise component.

The first factor is probably loosing its impact in that we now appear to be working with a data window (using Belfast as a template) sufficiently long at Malin, that increasing the window is unlikely to alter the long-term prediction (assuming no further change in forcing processes).

An answer to the relative balance of isostatic and eustatic might be observed via observation of Belfast data. Even though Malin and Belfast are somewhat spatially apart, one would expect the two sites to show a similar RSLC trend at decade to sub-century scale. Figure 7.2 appears to show two differing sets of circumstances that by statistical chance show similar residual trend rates. There is a justifiable expectation for the eustatic component to be the same for two near-sites, so if there were an assumption that the eustatic term is similar to both sites, why would there be dissimilar land movement components? Belfast Harbour tide gauge may have exhibited relative displacement through harbour developments, but this is unlikely to account for the fall towards the episodic-forced low of the 1970s, nor the post-1970s rapid rise. One alternative way to account for the difference might therefore be for differing scales of isostatic readjustment between the two sites, with Malin feeling the full effects of a the residual crustal lift, while Belfast being further away from the centre of last glaciation ice unloading, exhibits a lesser trend. Therefore, given a similar eustatic trend, differing isostatic histories could account for the different 20th century MSL/MTL histories. This would require an assumption that the eustatic signal is the same for both sites. If this assumption is inappropriate, then Carter's analysis to explain this difference may be considered relevant. Carter's view of prism change due to harbour development could be the factor by which the long-term eustatic signal was depressed.

7.4 Conclusion

Although there is now some uniformity of annual MSL/RMTL change estimate for the north of Ireland (linear trend of -0.2mm a^{-1}), it is not yet feasible to specify the relative magnitude of the main components that contribute towards this sea-level change signal. The significant quadratic signatures for nodal detrended data suggest that recent and near-future trends may be steepening from the over-all linear trend estimate and that even long term trends may be switching into a positive (transgressive mode). If this is the case, then early warning signs may already be posted, with both Bangor and Portrush indicating positive trends (albeit only based on 6-7 years of data). It does appear that the long term isostatic component (millennia) is starting to be cancelled out by the eustatic component, and assuming no measurable change in the isostatic element over the next few decades, then the eustatic signal must be rising. This state can be supported by the last 20 years of Belfast data (Fig 7.2) that shows a steady transgressive signal. Regardless of whether this signal is only short term and capable of being reduced long-term by other periodic oceanographic factors, it will have an impact on the shoreline. There is some cause for concern that the current short-term steep rise in MSL/MTL (if persistent for a decade) will have a dramatic forcing effect on shoreline, back-beach and peri-marine environments, issues that need urgent consideration.

8 RECOMMENDATIONS

8.1 Introduction

The study has identified a number of consequences that need to be considered given the UK governmental strategic requirement of planning for mitigation and adaptation to climate change and its consequences. A number of recommendations are suggested to help move the process forward with respect to accurate specification of sea-level changes around the north of Ireland, and the consequences of such changes to the shoreline.

8.1 Support accurate tide gauge measurement

It is essential for the north of Ireland to have characteristic data on sea-level movement at a time when acceleration in the eustatic rate is widely predicted for Britain and Ireland. To support the measurement of sea level change there is a need for constant and reliable recording of tide gauge data. The provision of such gauges at Malin and Belfast Harbour is essential given the value of their long-term records and the past investment in the digital acquisition of such records. Their continuing support to the data record is required given that the alternative gauges at Portrush and Bangor are still too short in record length to provide stable and certain estimates of sea-level change.

8.2 Specify continuing land movement

The continuing problem of determining crustal movement of the north of Ireland needs to be resolved by direct measurement through satellite altimetry of a network of sites, so as to gain the first characterisation of land movement variation around the north of Ireland. Satellite altimetry would be a valuable tool enabling the decoupling of the sea and land movements, subsequently providing a more accurate estimation of future RSL behaviour from tide gauge record interpretation.

8.3 Specify ground conditions in Belfast Harbour

Given the instability of ground conditions at Belfast Harbour and its possible impact on tide-gauge stability, it is recommended that Global Positioning System (GPS) technology should be used to provide an independent monitoring of vertical land movements within the Harbour and upper Belfast Estuary.

8.4 Shoreline response to sea-level change

Emphasis has been placed on determining long-term scales of RSLC. The importance of such scaling has been considered in terms of the potential response time between sea-level change and shoreline response, however the lack of consistent shoreline monitoring at any scale in the north of Ireland means that this particular relationship can only be approached through reconstruction of shoreline histories for different depositional coastal environments by proxy measurements. Such proxies need investigation and development. Furthermore coastal change over the last century need to be assessed in the light of the fluctuations observed in the RSLC, both regressive and transgressive, to start to calibrate definitively sea level forcing - coastal response relationships.

9 ACKNOWLEDGEMENTS

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11 APPENDICES

Appendix I: Malin Head tide gauge (MSL record) 1958-2001 IOD datum = 0m

Year	Hours	MSL
1958	6950	-0.0050
1959	8448	0.0000
1960	7255	0.0360
1961	8370	0.0420
1962	8607	-0.0240
1963	8100	0.0160
1964	8629	0.0160
1965	8760	-0.0110
1966	8334	0.0320
1967	8569	0.0240
1968	5111	-0.0070
1969	7666	0.0190
1970	8754	-0.0150
1971	8651	-0.0140
1972	8765	-0.0060
1973	8442	0.0070
1974	8561	0.0350
1975	8736	-0.0430
1976	8565	-0.0400
1977	8760	-0.0020
1978	8760	-0.0170
1979	8760	-0.0020
1980	6313	0.0210
1981	8065	-0.0060
1982	7291	0.0120
1983	8387	-0.0040
1984	8280	-0.0190
1985	8424	-0.0100
1986	8042	-0.0140
1987	6953	-0.0270
1988	7695	0.0360
1989	8577	0.0630
1990	8337	0.0640
1991	8303	-0.0130
1992	8097	-0.0140
1993	8665	-0.0800
1994	8758	-0.0040
1995	8423	0.0190
1996	8459	0.0180
1997	8760	0.0340
1998	7609	-0.0270
1999	8760	-0.1010
2000	8784	-0.1220
2001	8094	-0.1100

Appendix II: List of Problems associated with the Belfast Tide-Gauge Records 1960-2000:

DATE	TIME	REASON GIVEN
1960		
12/01 - 15/01		Record missing
01/07 - 05/07		Tide-gauge broken
13/03	0900-2300	Pen not recording
14/07		Pen not recording
03/08	0000-0800	
04/08		Tide-gauge broken
09/09	0900-2300	Tide-gauge broken
10/09		
03/10	0000-0900	Pen not working
04/10		
02/11	1700-2300	Tide-gauge broken
03/11		
04/11	0000-0900	Record missing
	1000-2300	Record missing
	0000-0800	Record missing
	1000-2300	Record missing
	0000-2300	Record missing
	0000-1000	Record missing
1961		
27/05	1000-2300	No data no reason given
28/05		No data no reason given
29/05	0000-0820	Pen not working
1962		
7/03	1135	Attached note states that readings are 2”11’ high
1963		
13/01	0000-1400	No record due to ice in dock
24/01	0900-2300	No record due to ice in dock
19/06	0900-2300	Note stating that gauge registering 2" high on the morning of the 19th
15/08	0810-1515	Tide-gauge out of order 0810 until 1515 readings taken at 15mins intervals and plotted
20/08	1030 -1330	Launch of the Rinn Finn (80000 ton) at East Yard- unusual higher than normal waves
20/09	1130-1230	Launch of the Methane (East Yard) higher than normal waves- does not influence average reading.

1964		
13/01	0000-1400	No record due to ice in dock
24/01	0900-2300	No record due to ice in dock
19/06	0900-2300	Note stating that gauge registering 2" high on the morning of the 19th
15/08	0810-1515	Tide-gauge out of order 0810 until 1515 readings taken at 15mins intervals and plotted
20/08	1030 -1330	Launch of the Rinn Finn (80000 ton) at East Yard- unusual higher than normal waves
20/09	1130-1230	Launch of the Methane (East Yard) higher than normal waves- does not influence average reading.
1965		
7/06 until 08/06	0930 -0930	Readings taken by observation
18/06	1500	Clocked stopped
19/06	1055	Clocked rewound
1966		
15/01-16/01	0800-1730	Record incomplete because of a fault
29/06	1100-2300	Record missing
30/06	0000-0720	Record missing
04/08	0800-2300	
05/08	0000-1300	Gauge out of order
05/08 until 08/08		Note attached stating that readings are 1ft too low- not reliable as gauge is under repair
03/11 until 04/11	0800-0800	Chart approximately 0.6” too high
12/12	0800-2300	
13/12	0000-0800	Note indicating that reading is 1.8ft above actual tide levels
15/12	0900-2300	Height of tide on card is approximately 1.3ft below actual levels

1967		
29/03	1228	HWL was read from the board
30/03	1430	HWL was read from the board
31/03 until 08/03		Record missing
06/12 until 10/12		Record missing
11/12		Reading missing
12/12 until 15/12		Readings doubtful
1968		
12/03	0700-2300	Record missing
13/03	0000-0700	Record missing

20/05 until 21/05		Record missing
10/06 until 12/06		Fault with the gauge
15/06 until 21/06		No record
10/11 until 11/11		No record
1969		
06/01	1600-2300	No record
07/01	0000-0600	Record missing due to faulty gauge clock
16/01	1800-2300	No record
17/01	0000-0600	Clockwork mechanism not wounded up has caused fault
24/01	2000-2300	No record
25/01	0000-0600	Clockwork mechanism not wounded up has caused fault
07/02	1600-2300	No record
08/02	0000-0600	Clockwork mechanism not wounded up has caused fault
18/03	0700-2300	No record
19/03	0000-2300	No record
20/03	0000-0900	No record, fault with gauge
23/10	0600-2300	Gauge not working, no reason given
27/10	0000-1300	Gauge not working, no reason given
17/12	0700-2300	No record
18/12		No record
19/15	0000-1200	No record
31/12	1100-2300	Clock mechanism is broken, no data
1970		
01/01 until 12/01		No record, fault with gauge
17/01	0900-1900	Faulty gauge
23/01	0800-2300	
24/01 until 26/03	0000-0700	No Record, fault with gauge
02/05	0800-2300	No Record.
03/05 until 05/05	1300	No Record, fault with gauge

23/08 until 26/08	0000-1000	HWL missing due to fault in gauge
07/09	0900-2300	No record
08/09 until 12/09	0000-0700	No record
05/10 until 12/10		Original values adjusted- as jump is detected
6/11 until 16/11	2100-2300	Record missing, clock unwound
19/12	0600-2300	Record missing
20/12		Record missing
21/12	0000-0900	Record missing
1971		
05/01 until 27/01		Section missing
03/05 until 04/05		Note attached to marigram stating that readings are 1’1” too high
18/06		Height adjusted
13/07		Clock stopped- no record
1972		
07/01 until 08/01	1000-0800	Record missing
18/02 until 21/02	1000-0900	Record missing
16/03 until 29/03	1600-1400	Record missing – faulty tide-gauge
11/04 until 16/05		Tide-gauge stopped due to a fault
16/05		Clock stopped- results unreliable
22/05		Note indicating that the tide-gauge is located at Spence Dock (Barnett Dock) entrance.
01/09		New tide-gauge in operation located at Clarendon dock
1973		
05/02 until 27/02		Record missing- no reason given
06/03 until 20/03		The readings appear faulty- a punch card was found that stated that the Belfast records were scrapped due to siltation
1974		
15/02		There is a physical drop in the data of 1m compared to the previous set of data
15/04 until 17/04		There appears to be a fault with the gauge- since the peaks and troughs are too smooth
10/05 until 16/05		Similar results as described above

13/05 until 31/05		No results due to strike
10/06 until 12/06		Note attached stating that the records on the sheet are not right, faulty gauge
15/07		Note attached stating that clock is failing to wind. Problem with tide-gauge float
24/09		There appears to be a physical drop with the data. However, no fault has been located, it is likely that this pattern has been caused by high pressure or just adjusted manually.
	1975	
07/04		Note attached stating that there has been a height shift
09/06 until 12/06		The data-sheet has been plotted and re-drawn from the original sheet which had an electrical fault plus a fault with the gauge
04/08	0500-1030	Thunderstorms cause irregular jumps in the graph
15/09		Mechanical fault
03/10 until 06/10		Chart slipping in the recorder
16/11 until 17/11		Ink has dried in holder
18/12 until 22/12		
	1976	
25/08 until 30/08		Record missing
	1977	
30/05 until 03/06		Silt in gauge
08/08 until 12/08		No record, faulty gauge
17/08 until 22/08		Record missing
22/08 until 01/09		No record, faulty gauge
05/09 until 12/09		Record missing
11/11		End of record for 1977
	1978	
06/02		Previous records lost due to faulty gauge
29/06	0900-2300	Faulty gauge
10/06 until 14/06		Problem with tide-gauge float
	1979	

26/01 until 29/01		Faulty gauge
13/04 until 18/04		Record incomplete
17/08 until 24/08		Faulty gauge
16/11 until 28/11		Fault associated with the tide gauge not recording low tide accurately
1980		
24/02 until 25/02		Faulty transmitter
07/03 until 10/03		Faulty gauge no record
10/03 until 21/03		No record
21/04 until 16/05		Problem with float
23/05 until 03/06		Faulty gauge
05/11 until 31/12		Faulty gauge
1981		
23/02 until 25/02		No record
22/04 until 23/04		No record
11/05 until 20/05		Faulty tide-gauge
08/06 until 18/06		Faulty tide-gauge
22/06 until 25/06		Faulty tide-gauge
22/08 until 23/08		Fading ink
24/08 until 27/08		Problem with ink
04/11 until 06/11		Problem with ink
1982		
07/01 until 11/01		No record due to water freezing in Clarendon Dock

22/03	0828	It appears as if the line has been physically moved up by 10cm (gauge calibration?)
22/03 until 24/03		No record
17/04 until 27/04		No record
02/06 until 04/06		No record
23/07 until 13/09		No record
15/10		No record until 11/01/83
1983		
11/01		Tide-gauge level re-set from 4.26m to 3.3m (1.16m) (previous values adjusted by 1.16m)
26/01 until 07/02		HWL does not extend beyond 3.36m- fault with the gauge
28/02 until 21/03		Data missing
13/04 until 20/04		Data missing
21/04		Level readjusted by 25cm- gauge calibration
26/07		Data missing
12/09 until 16/09		Faulty gauge, no record
12/10 until 14/10		Record missing
04/11 until 09/11		Record missing
16/12 until 20/12		Record missing
1984		
04/01		Record begins
13/01 until 17/01		Record missing
17/02 until 20/02		Record missing
02/03 until 05/02		Record missing
09/03 until 03/04		Record missing
30/04 until 07/06		Record missing
06/08 until 27/09		Record missing

01/10 until 05/10		Record missing
19/10 until 22/10		Record missing
09/11 until 12/11		Record missing
19/11 until 21/11		Record missing
26/11 until 30/11		Record missing
03/12 until 10/12		Record missing
1985		
03/01 until 07/01		Record missing
19/03 until 22/03		Record missing
28/10 until 13/11		Record missing
18/11 until 04/12		Record missing
23/12		Record missing
1986		
08/01		Although it is stated that the record began this date, it is difficult to pin-point where the record starts due to a fault with the gauge
24/01		Record restarts
05/02 until 21/02		Record missing
02/03 until 12/03		Record missing
28/04 until 30/04		Record missing
07/06 until 24/09		Record discontinues, fault with gauge
14/10		No record due to power failure
15/10 until 17/10		Record is discontinuous and difficult to follow with accurancy
01/11 until 05/11		Record missing, faulty gauge
15/11		Final reading taken. Although the record extends until 21/11- it is difficult to follow due to frequent brakes as a result of gauge failure
1987		
18/09		New gauge employed - Valeport
22/10		No record
23/10	0000-1200	Error with data

1989		
03/01		No record
05/02	1600	Section missing
16/02	1000-2300	Section missing
01/04		No record
06/04		No record
15/04		No record
21/05 until 01/06		No record
21/05 until 31/05	0100-2300	No record
02/06	0100-0800	No record
03/07 until 05/07		No record
09/07 until 01/09		No record- hand written note stating fault with gauge
		The results for September are questionable since there appears to be a fault with the gauge.
1990		
11/01 until 15/01	2100-0900	No record
18/01until 21/01		No record
31/01	1500-2300	No record
01/02		No record
04/02		No record
06/02	0000-0900	No record
01/04		No record
11/04	0100-0800	No record
21/04 until 22/04		No record
28/04 until 29/04	1200-2300	No record
12/05 until 17/05	1000-1600	No record
03/06	1300-2300	No record
04/04		No record
11/06	0000-0500	No record
20/06 until 21/06		No record

30/06	0600-1000	No record
13/07	2300	No record
14/07		No record
15/07	0000-0700	No record
17/07	0000-0700	No record
29/07	0000-0800	No record
31/07	0000-1200	No record
21/08-23/08	2000	No record
31/08	0000-0600	
08/09	0000-0600	No record
09/09	0000-0600	No record
16/09	0000-1300	No record
23/09	1900-2300	No record
29/09		No record
08/10	0000-1300	No record
22/10	1200-2300	No record
24/10		No record
04/11 until 05/11		No record
07/11 until 08/11		No record
10/11		No record
13/11 until 15/11		No record
20/11	0000-0800	No record
27/11	0000-1100	No record
16/12	0000-0800	No record
24/12		No record
1991		
02/01	0000-0800	No record
05/01	1500-2300	Section missing due to high tide of 4.9m
08/01	0300-0900	
31/01		No record
06/01	1100-1200	Data adjusted
07/02	0000-0800	No record

11/02 until 13/02	2200-0800	No record
17/02 until 18/02		No record
20/02		No record
21/02	0000-0800	No record
22/02		No record
13/03		No record
15/03 until 16/03		No record
21/03 until 24/03		No record
15/04	0000-0700	No record
24/04		No record
28/04		No record
30/04		No record
04/05	0000-0500	No record
06/05 until 07/05		No record
13/05 until 14/05		No record
24/05 until 30/05		No record
03/06	1500-2300	No record
09/06	0900-2300	No record
14/06 until 19/06	2200	No record
22/06 until 25/06	0000-0700	No record
30/06	0000-0700	No record
02/07	0000-0700	No record
04/07 until 07/07	0000-0500	No record
21/07 until 29/07		No record
03/08		No record
13/08		No record
15/08		No record
18/08		No record
24/08		No record
27/08		No record
02/09	0000-0700	No record
05/09	2200-2300	No record
08/09	0000-0600	No record
15/09		No record

22/09	1400-2300	No record
28/09	2300	No record
29/09		No record
05/10	2200-2300	No record
13/10	0000-0600	No record
28/10		No record
13/12	1000-2300	No record
14/12 until 15/12		No record
23/12		No record
1992		
10/01 until 12/01		No record
08/02 until 10/02		No record
22/02 until 23/02		No record
11/04 until 12/04		No record
13/06 until 15/06		No record
18/06	2300	No record
24/06 until 26/06	0100-0800	No record
29/06		No record
13/07 until 14/07		No record
18/07 until 19/07		No record
25/07	2000-2300	No record
28/07	1800-2300	No record
15/08 until 16/08		No record
30/08	1600-2300	No record
05/09 until 06/09	1800-2300	No record
02/11 until 08/11 09/11 until 10/11		No record
18/11		No record
26/11		No record
04/12		No record
06/12		No record

13/12		No record
1993		
09/01 until 10/01		No record
15/01 until 18/01		No record
30/01	0100-0800	No record
01/02		No record
05/02 until 08/02		No record
11/02		No record
14/02		No record
21/02		No record
28/02		No record
02/03	0900-2300	No record
07/03	0900-2300	No record
17/03	1300-2300	No record
12/04 until 14/04		No record
17/04 until 18/04		No record
03/05		No record
15/05 until 17/05		No record
31/05	0700-2300	No record
03/06 until 06/06		No record
19/06	2300	No record
20/06 until 22/06		No record
11/07		No record
15/07	0000-0700	No record
17/07 until 18/07		Timing problems
21/07	0800-2300	No record
26/07 until 28/07		No record
31/07		No record
01/08 until 02/08		No record
14/08 until 15/08		No record

18/08	0900-2300	No record
27/08 until 28/08		No record
02/09 until 05/09		No record
06/09 until 07/09		No record
11/09 until 22/09		No record
25/09 until 04/10		No record
09/10 until 12/10		No record
16/10 until 17/10		No record
19/10		No record
25/10 until 30/10		No record
02/11 until 04/11		No record
06/11		No record
08/11 until 09/11		No record
13/11 until 15/11		No record
21/11		No record
29/11		Timing problems
30/11		No record
10/12		No record
13/12		No record
18/12 until 19/12		No record
22/12 until 23/12		No record
25/12 until 29/12		No record
1994		
01/01	0100-0800	No record
03/01	0100-0800	No record
04/01	0100-0600	No record
08/01	0200-0800	No record

12/01 until 21/01		No record
01/02 until 28/02		No record
01/03 until 31/03		No record
22/04 until 30/04		No record
21/04	1600-2300	No record
29/04	1200-2300	No record
08/08	0100-0900	No record
12/08	0800-2300	No record
15/08	0800-2300	No record
16/08 until 31/08		No record
01/09 until 30/09		No record
01/10 until 31/10		No record
02/11 until 04/11		No record
05/11 until 21/11		Note attached to add 0.41 cm to high tide
1995		
26/02 until 28/02	1000-0800	No record
01/04		No record
11/07	0100-0800	No record
15/07		No record
19/07 until 27/07	1700-0600	Problem with gauge, not specified
04/08 until 14/08		No record
23/08	1100-2300	No record
28/08 until 20/10		No record
07/12	100-2300	No record
1996		
15/01		No record
01/03		No record
21/05 until 22/05	1000-2300	No record

17/06 until 18/06		No record
04/07 until 20/07		Problem with gauge although not specified
26/09	0100-1500	No record
28/09		Fault with gauge or datum adjusted?
01/10		Fault with gauge or datum adjusted?
29/11		Note attached stating that there is a transducer fault
10/12		Gauge working normally
20/12 until 23/12		No record
28/12 until 30/12		No record
1997		
02/01	1000-2300	No record
06/01	0100-0400	No record
14/01		Note attached stating add 0.3m to readings
17/01 until 20/01	1400-0700	No record
06/02	0100-2300	No record
17/01 until 20/01	1400-0700	No record
06/02	0100-2300	No record
22/02 until 24/02	1600-2300	No record
01/03	0900-2300	No record
24/03 until 25/03	0100-2300	No record
31/03	0100-0300	No record
05/04	0500-2300	No record
10/05	1000-2300	No record
30/07 until 31/07	2200-0300	No record
14/09 until 15/09	0100-0600	No record
1998		
08/06 until 23/06		Fault at low water possibly 0.40cm too high?
1999		
01/04		No record
29/06 until 02/08		No record

19/06 until 22/06		No record
28/06	0900-2300	No record
29/06 until 02/08		No record
2000		
01/01 until 10/01		No record
01/01 until 10/01		No record
15/02	0100-0800	No record
01/04		No record
15/11 until 22/11		No record
14/11	1700-2300	No record
2001		
01/01		Record missing
07/03		Data-set discontinues
16/03		New gauge in operation

Appendix III: Belfast Harbour tide gauge (MTL record) 1918-2001(OD Belfast)

Year	Raw mOD	Useful mOD	Adjusted mOD
1918	-0.0310	-0.0310	-0.0310
1919	-0.0980	-0.0980	-0.0980
1920	0.0050	0.0050	0.0050
1921	-0.0720	-0.0720	-0.0720
1922	-0.0570	-0.0570	-0.0570
1923	-0.0610	-0.0610	-0.0610
1924	0.0080	0.0080	0.0080
1925	-0.0100	-0.0100	-0.0100
1926	-0.0130	-0.0130	-0.0130
1927	-0.0040	-0.0040	-0.0040
1928	0.0220	0.0220	0.0220
1929	-0.0100	-0.0100	-0.0100
1930	-0.0150	-0.0150	-0.0150
1931	-0.0460	-0.0460	-0.0460
1932	-0.0220	-0.0220	-0.0220
1933	-0.0500	-0.0500	-0.0500
1934	-0.0410	-0.0410	-0.0410
1935	-0.0420	-0.0420	-0.0420
1936	-0.0270	-0.0270	-0.0270
1937	-0.0240	-0.0240	-0.0240
1938	-0.0750	-0.0750	-0.0750
1939	-0.0450	-0.0450	-0.0450
1940	-0.0330	-0.0330	-0.0330
1941	-0.0790	-0.0790	-0.0790
1942	-0.0500	-0.0500	-0.0500
1943	-0.0200	-0.0200	-0.0200
1944	-0.0510	-0.0510	-0.0510
1945	-0.0060	-0.0060	-0.0060
1946	-0.0230	-0.0230	-0.0230
1947	-0.0250	-0.0250	-0.0250
1948	-0.0150	-0.0150	-0.0150
1949	-0.0520	-0.0520	-0.0520
1950	0.0460	0.0460	0.0460
1951	-0.0010	-0.0010	-0.0010
1952	-0.0480	-0.0480	-0.0480
1953	-0.0460	-0.0460	-0.0460
1954	0.0040	0.0040	0.0040
1955	-0.0220	-0.0220	-0.0220
1956	-0.0670	-0.0670	-0.0670
1957	-0.0380	-0.0380	-0.0380
1958	-0.0480	-0.0480	-0.0480
1959	-0.0570	-0.0570	-0.0570
1960	-0.0200	-0.0200	0.0112
1961	-0.0390	-0.0390	-0.0129
1962	-0.1070	-0.1070	-0.0835
1963	-0.0600	-0.0600	-0.0415
1964	-0.0723	-0.0723	-0.0723
1965	-0.0831	-0.0831	-0.0831
1966	-0.0434	-0.0434	-0.0434
1967	-0.0418	-0.0418	-0.0418

1968	-0.0187	-0.0187	-0.0187
1969	-0.0232	-0.0232	-0.0232
1970	-0.0062	-0.0062	-0.0062
1971	-0.0161	-0.0161	-0.0161
1972	0.0086	0.0086	-0.0377
1973	-0.1197	-0.1197	-0.1137
1974	-0.0583		-0.0627
1975	-0.1215	-0.1215	-0.1215
1976	-0.1233	-0.1233	-0.1233
1977	-0.0479		-0.0522
1978	-0.1926	-0.1926	-0.0336
1979	0.0020	0.0020	0.0020
1980	0.0041	0.0041	0.0072
1981	-0.0887	-0.0887	-0.0887
1982	0.0545	0.0545	0.0457
1983	-0.1246		-0.0473
1984	-0.0186		-0.0253
1985	0.1663	0.1663	0.0320
1986	-0.0449	-0.0449	-0.0444
1987	0.0766	0.0766	-0.0518
1988	-0.0385	-0.0385	-0.0385
1989	0.0468	0.0468	0.0510
1990	-0.0015		-0.0015
1991	-0.0422		-0.0417
1992	-0.0164		-0.0164
1993	0.0235	0.0235	0.0023
1994	0.1092	0.1092	0.0566
1995	-0.0527	-0.0527	-0.0476
1996	-0.1105	-0.1105	-0.1183
1997	-0.1045	-0.1045	-0.1045
1998	-0.0971	-0.0971	-0.0971
1999	-0.1012	-0.1012	-0.1050
2000	-0.0939	-0.0939	-0.0939
2001	-0.0485	-0.0485	-0.0485
2002	0.0026	0.0026	0.0026

Appendix IV: Contents of CD **Belfast Tide-Gauge Data**

Location:	**Description:**
E:\Belfast Tide-gauge\Belfast1960 *.* \Belfast1986.xls	Belfast raw data (1960-1986)
Worksheets Include:	
E:\Belfast Tide-gauge\Belfast1960\data	Daily highs and lows
E:\Belfast Tide-gauge\Belfast1960\graph	High & low graph
E:\Belfast Tide-gauge\Belfast1960\mean-sd	Mean and standard deviation
E:\Belfast Tide-gauge\Belfast1960\monthly means	Monthly mean
E:\Belfast Tide-gauge\Belfast1960\interpolated	Interpolated data
E:\Belfast Tide-gauge\Belfast1987 *.* \Belfast2001	Belfast raw data (1987-2001)
E:\Belfast Tide-gauge\Belfast1960\data	Hourly readings
E:\Belfast Tide-gauge\Belfast1960\graph	Hourly graph graph
E:\Belfast Tide-gauge\Belfast1960\mean-sd	Mean and standard deviation
E:\Belfast Tide-gauge\Belfast1960\high&low	Daily highs and lows
E:\Belfast Tide-gauge\Belfast1960\H&LGraph	High & low graph
E:\Belfast Tide-gauge\Belfast1960\monthly means	Monthly mean
E:\Belfast Tide-gauge\Belfast1960\interpolated	Interpolated data
E:\Belfast Tide-gauge\Belmonthlys.xls	
Worksheets Include:	
E:\Belfast Tide-gauge\Belmonthlys\mean	Monthly means
E:\Belfast Tide-gauge\Belmonthlys\sd	Monthly standard deviation
E:\Belfast Tide-gauge\Belmonthlys\N=	No. of observations
E:\Belfast Tide-gauge\Belmonthlys\Graph	Tide-gauge means
E:\Belfast Tide-gauge\Belmonthlys\Smooth	19year run mean
E:\Belfast Tide-gauge\Belmonthlys\Raw1960	raw data 1960-2001
E:\Belfast Tide-gauge\Belmonthlys\Raw1918	raw data 1918-2001
E:\Belfast Tide-gauge\Belmonthlys\useful1960	useful 1960-2001
E:\Belfast Tide-gauge\Belmonthlys\useful1918	useful 1918-2001
E:\Belfast Tide-gauge\Belmonthlys\Summary	summary
E:\Belfast Tide-gauge\Belmonthlys\Graphs	

E:\Belfast Tide-gauge\Belfast1987\Buddies3.xls Data comparison checks

Worksheets Include:

E:\Belfast Tide-gauge\Belfast1987\Buddies3\Buddies	Comparison check
E:\Belfast Tide-gauge\Belfast1987\Buddies3\Rawvspp	Belfast vs PortPat
E:\Belfast Tide-gauge\Belfast1987\Buddies3\cal	Mean Calculation
E:\Belfast Tide-gauge\Belfast1987\Buddies3\adjusted	Applied 1
E:\Belfast Tide-gauge\Belfast1987\Buddies3\adjusted2	Applied 2
E:\Belfast Tide-gauge\Belfast1987\Buddies3\adjusted3	Applied 3
E:\Belfast Tide-gauge\Belfast1987\Buddies3\figure	Difference figure
E:\Belfast Tide-gauge\Belfast1987\Buddies3\adjusted4	Applied 4

E:\Belfast Tide-gauge\MLT&MSL.xls

Worksheets Include:

E:\Belfast Tide-gauge\MLT&MSL\compare	Comparison with MTL & MSL

E:\Belfast Tide-gauge\Summary.xls

Worksheets Include:

E:\Belfast Tide-gauge\Summary\data	Summary of all data

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Our aim is to protect and conserve the natural and built environment and to promote its appreciation for the benefit of present and future generations.

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