An Analysis of Global Warming by Comparison of Mean Sea Level Rise in Cities

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PART 1 - RATIONALE

Literature Review

At the moment, climate change is a largely debated issue with many different approaches and perspectives. Some people believe that it is something that can be prevented with a collective effort, but others argue that it is out of the average citizens' control. Climate change can have drastic effects on health, housing, safety, and work, but one of the most urgent aspects is seen in the change of water distribution across the globe (Mimura, 2013). As temperatures rise, thermal expansion causes sea levels to rise as well (Munk, n.d.). The IPCC concluded that the sea level rise was largely due to "the concurrent increase in global temperature over the last hundred years" (Munk, n.d.). The rest of the sea level rise is expected to come from the loss of mass from ice sheets; however, the exact contributions are unclear (Rowley et al., n.d.).

Although it is typical for temperature, climate, and sea levels to fluctuate naturally, there has never been an acceleration as severe as the one recorded throughout the 20th century (Church & White, 2006). For the past 100 years, scientists have been analyzing data from 1900 tide gauges in nearly 200 countries (Mimura, 2013). One main statistic is the global mean sea level, which is defined as the "height of the sea surface averaged over a period of time, such as a month or a year, long enough that fluctuations caused by tide and waves are largely removed" (Mimura, 2013). From 1870 to 2004, there was a rise of 195mm at the rate of 1.7 ± 0.3 mm/yr and an acceleration of 0.013 ± 0.006 mm/yr (Church & White, 2006). However, between the years 1993 and 2009, the rate was 3.2 ± 0.4 mm/yr (Church & White, 2006; Mimura, 2013). The magnitude of this difference is a clear confirmation of climate change, where there is clearly a magnitude of acceleration that had not previously been observed. If this acceleration continues, then the 1990 to 2100 sea level rise is projected to range between 280 and 340 mm, which could lead to flooding of low-lying coastal areas, coastal erosion, harmful effects on coastal ecosystems such as salt marsh, mangroves and coral reefs, salt water intrusion into estuaries and aquifers, and removal of residential areas (Mimura, 2013). In fact, Kulp and Strauss state that 190 million people—a confidence interval of 150-250 million—are occupying land projected to be below high tide lines by 2100 as a best case scenario (2019). If carbon emissions are greater than expected, a potential 630 million people could be affected (Kulp & Strauss, 2019).

Looking closer at the sub data set, Dublin recorded a mean sea level data set between the years 1938 and 2016 (Nejad et al., 2021). The data sites are located at Dublin Port and two tide gauges at Arklow and Howth Harbor (Nejad et al., 2021). Nejad and his team estimate that there was a rise at the rate of 1.1 ± 0.5 mm/yr between 1953 and 2016 and 7 ± 1.9 mm/yr between 1997 to 2016 (2021). These drastic numbers are a clear indication of a difference between early and current sea level rise rates that could potentially show a correlation with the global sea levels.

Purpose

The purpose of this study was for the authors to understand the relevant changes caused by global warming (e.g. rising sea levels) and understand their impact on the environment of coastal cities. Climate change itself is an extremely well-researched area, but more concerning are the devastating future projections made by leading scientists about the extent of Earth's lifeline. Rising sea levels could put thousands of cities underwater in a matter of years, including areas near the coast like Fairfax, Virginia, our study location. As members of Generation Z, it's important for us to engage in research about rising sea levels to add more information to the current trends that may define the next few decades of our lives. We hope that conducting this research may serve as a first step to environmental understanding and a foundation for future efforts of environmental protection and conservation.

Research Question

1) Is there a statistically significant difference between the pattern in mean sea level rise for Dublin, Ireland and the mean global sea level rise from 1993-2016?
2) Is there a strong correlation in mean sea level rise vs. year (1993-2016) or mean sea level rise between Dublin and global data?

PART 2 - DESIGN

Participants/Sample:

The researchers utilized a meta-analysis systematic census sampling method by incorporating water level information from a multitude of datasets. The samples utilized in this study included all data on mean sea levels in Dublin Port, Ireland, from the year 1938-2018. These measurements were recorded from tidal gauges and tidal charts. Procedures for selecting participants included those from readily accessible sea level datasets during the time period of the longitudinal study. These measurements were collected from 5 main source demographics with the following procedures:

1. Annual high and low water from Woodworth et al. (1991); PSMSL (2020) for the period 1938–2001 from the Port Authority annual dataset
2. Monthly values of mean high water (MHW) and mean low water (MLW) for the period of 1987–2001
3. High-frequency (10 min) data supplied by the Permanent Service for Mean Sea Level (PSMSL, 2020; Holgate et al., 2013) for the period 2002–2009.
4. High-frequency (5 min) data for the period 2007–2018 from the Irish National Tide Gauge Network (NTGN)
5. High water levels for the period 1968–2015 from the Greene Dataset

Measures

The researchers compiled mean high water, low water, mean tide level, and mean sea level for Dublin Port on the datasets mentioned above in Participants/Sample.

1. Mean tide level (MTL) was calculated by averaging the mean high and low waters. Quality control measures for the digitisation included automatic comparison and checking of the calculated and recorded mean levels.
2. Mean sea level (MSL) data from 1938-1977 are relative to Port Datum. Data after 1978 are relative to the LAT, 20 cm above Poolbeg Datum. Quality control measures for the digitisation included automatic comparison and checking of the calculated and recorded mean levels.
3. Mean high water (MHW): Prior to 2003, high water values for each day were extracted from the tidal charts. Quality control measures for the digitisation included automatic comparison and checking of the calculated and recorded mean levels.
4. Mean low water (MLW) data from the period 1968–1976 were converted from feet and inches to meters. Quality control measures for the digitisation included automatic comparison and checking of the calculated and recorded mean levels.

Procedures

The following procedures for standardizing data were performed:

1) Researchers utilized a newly collated sea level record for Dublin Port, consisting of measurements from two tide gauges at Arklow and Howth Harbor.
2) For global mean sea level data, data quality checks and calibration were performed. Any biased high water levels were adjusted during digitization and recalibration.
3) For measurements involving mean sea levels, researchers created a novel Bayesian linear regression. This was utilized to correct mean sea levels, and the model contained mean

low water values as a predictor.

4) The re-created mean sea level dataset containing mean high water, low water, mean tide level, and mean sea level for Dublin Port was validated against other nearby tide gauge datasets set up in Howth Harbor.

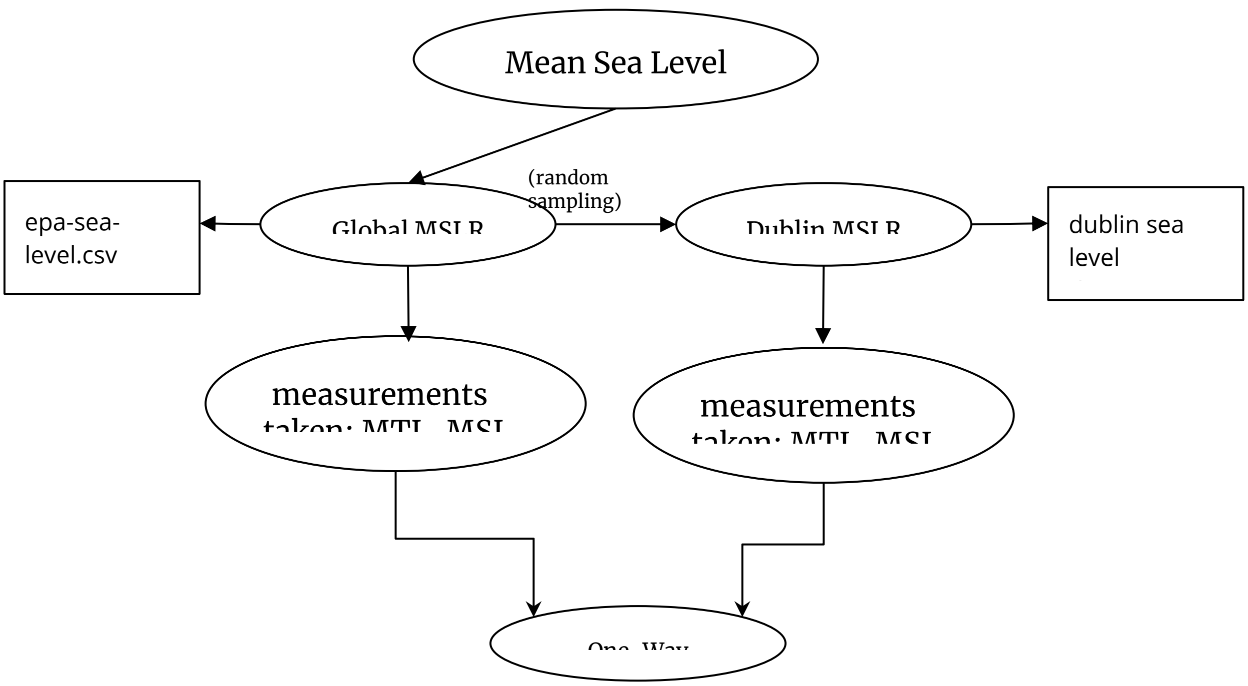
Analysis

In this study, we plan to analyze data from two datasets: the longitudinal Dublin mean sea level data and the global mean sea level data from concurrent periods. To test our first research question about the existence of a statistically significant difference between the two datasets, we plan to use a One-Way ANOVA test for difference in mean between groups. To test our second research question about the existence of a trend in sea level over time, we plan to use Multiple and Single Linear Regressions on both datasets compared to time.

The correct data analysis procedures will be performed on both datasets. This includes comparison of sample size, time frame measurements were taken, analysis of power based on previous literature, and verification of sampling procedures. In addition, we will be conducting a descriptive SOCCS analysis on both datasets (see Results section).

We will now explain the statistical methodology for the aforementioned inference tests. Conditions for linear regression include LINER: linearity, independence, normality, equal variances, and randomization. The correct condition protocols will be verified utilizing Minitab's Descriptive Data section, Residual Plots, and Normal Probability Plot on residuals. If necessary, transformations such as the log transformation for curvature or heteroscedasticity will be applied to one or both datasets. Conditions for ANOVA include independence, normality, and equal variances. Once again, correct condition protocols will be verified utilizing Minitab's Descriptive Data section, Residual Plots, and Normal Probability Plot on residuals for a One-factor ANOVA. All inference tests will be performed in Minitab.

Study Design Diagram



PART 3 - RESULTS

Data Analysis

Statistics

Variable	Total Count	Mean	StDev	Median	IQR	Skewness
MSL_m_ODM	76	-0.15810	0.04621	-0.16204	0.05837	0.40
CSIRO Adjusted Sea Level	76	5.442	1.732	5.366	2.514	0.37

Figure 1. Minitab Descriptive Statistics of both Dublin and Global MSLR datasets.

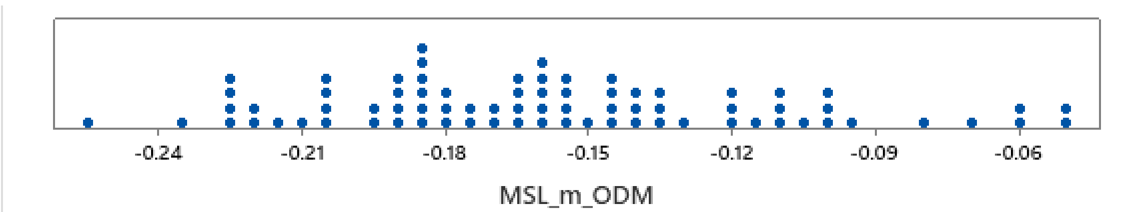


Figure 2. Minitab dotplot of Dublin MSLR dataset.

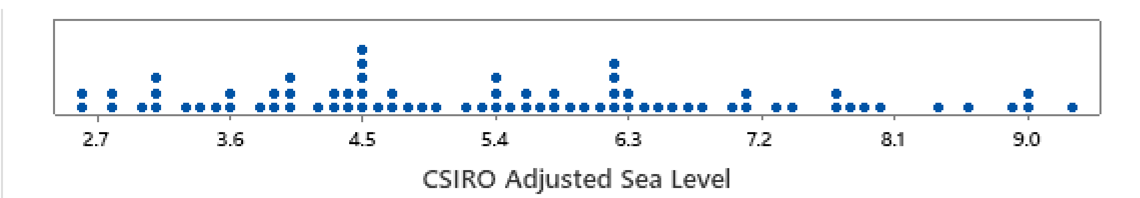


Figure 3. Minitab dotplot of Global MSLR dataset.

In the data processing of our two datasets, we chose selected measurements from 1938–2013 in order to ensure data was available from both sources for comparison. Therefore, we had n = 76 in each group, satisfying the Central Limit Theorem (n ≥ 30). The shape of the Dublin MSLR dataset is approximately symmetric and unimodal, with a peak (mean) at −0.1580 cm (Figure 2). From a comparison of the mean of −0.1580 cm and median of −.16204 cm, we see that they are approximately equal, and thus this dataset does not have any major skew besides a slight right skew. From the Descriptive Statistics, the spread of the Dublin dataset is .05837 cm (IQR), and this dataset does not have any significant outliers based on the 1.5 x IQR rule (Figure 1). The mean is a negative value because of its standardardization with global mean sea levels. The shape of the Global MSLR dataset is approximately symmetric and bimodal, with two peaks at 4.5 cm and 6.3 cm (Figure 3). The mean of this data is 5.442 cm and the median is 5.366 cm, showing that the dataset is approximately symmetric. From the Descriptive Statistics, the spread of the Global dataset is 2.514 cm (IQR), and this dataset does not have any significant outliers based on the 1.5 x IQR rule (Figure 1). Thus, from a preliminary analysis of our datasets, both sea level datasets satisfy the Large Sample Size conditions and the normality clause. However, we will need to conduct more in−depth analysis to verify this.

Verifying Inference Conditions

1. **Linearity**

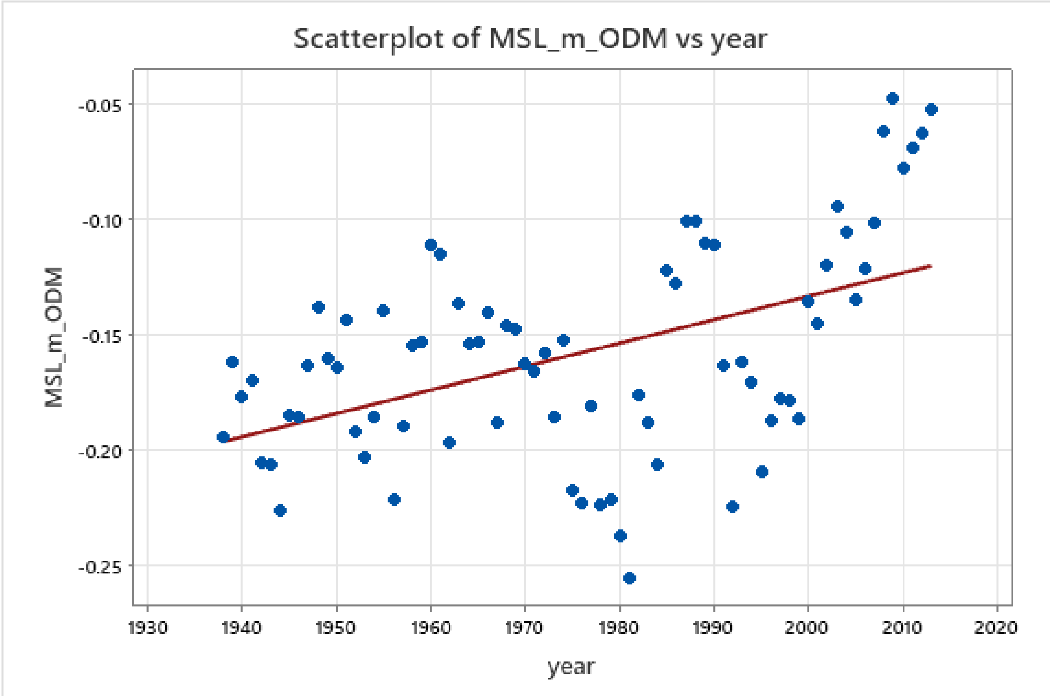


Figure 4. Scatter plot of Dublin means sea level vs. year from 1938-2013.

In this scatterplot of Dublin MSL vs. year in our given timeframe (Figure 4), we see that there is a positive trend between increasing year and MSLR that can be modeled by a linear regression line. The correlation coefficient seems moderately strong. Because the residuals are randomly distributed above and below the line, we conclude that the Linearity Condition is satisfied for this dataset.

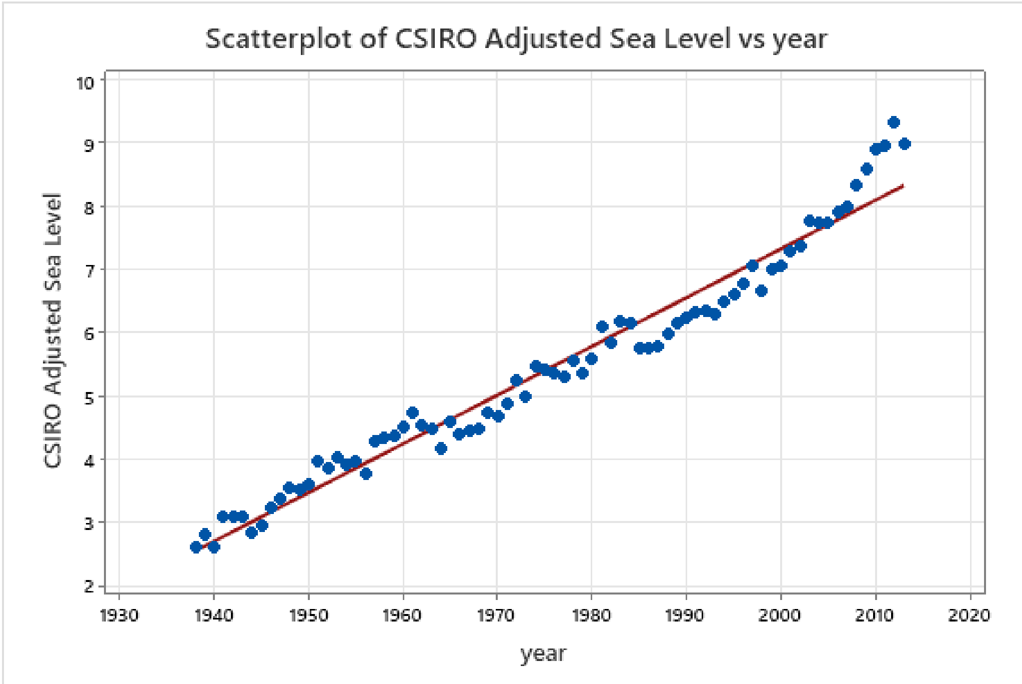


Figure 5. Untransformed scatterplot of global mean sea level rise vs. year from 1938-2013.

In this scatterplot of Global MSL vs. year in our given timeframe (Figure 5), we see that there is a positive trend between increasing year and MSLR that can be modeled by a linear regression line. In this scatterplot, the correlation coefficient seems to be very strong, and the data points majorly fall along the line. The residuals seem to be randomly distributed above and below the line, However, there is a clear issue of upward curvature in the years after 1990. In order to satisfy the Linearity Condition, we performed a logarithmic transformation on the Global dataset, with the results shown below.

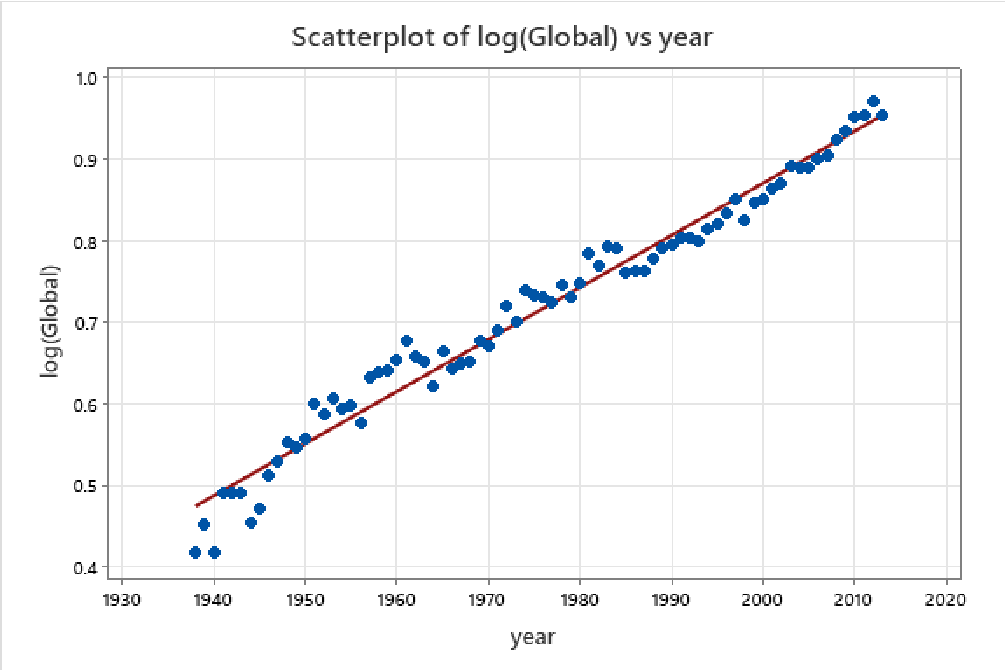


Figure 6. Log transformed scatterplot of global MSLR vs. year from 1938-2013.

The logarithmic transformation clearly addresses the issue of curvature in the years after 1990 (Figure 6). Although there is now more variation in the residuals of the years before 1965, they still fall both above and below the regression line, so we can conclude that the Linearity Condition is satisfied for the Global dataset.

2. Independence (& ANOVA)

We find it safe to assume, based on the procedures outlined in the Methods section, that all measurements taken by the ODM and CSIRO are independent of one another and independent between the two datasets. In addition, we assume that N > 10n (i.e. there are more than 760 population points of mean sea level measurements). Therefore, the Independence condition is satisfied for both datasets.

3. Normality (& ANOVA)

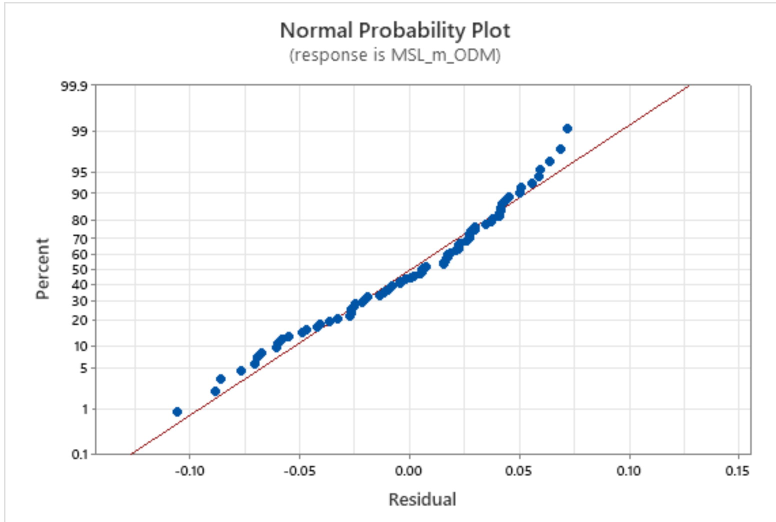


Figure 7. Normal Probability Plot of Dublin MSLR.

We plotted a Normal Probability Plot for the residuals of the Dublin MSLR (Figure 7). Despite a slight variation in the tail ends of the plot, the majority of the points fall on the line, and due to this linearity we can conclude the data satisfies the Normality Condition. This is also supported by our preliminary analysis of the Dublin MSLR dotplot, in which we concluded the dataset was approximately symmetric. Thus, the Normality Condition is satisfied for the Dublin dataset.

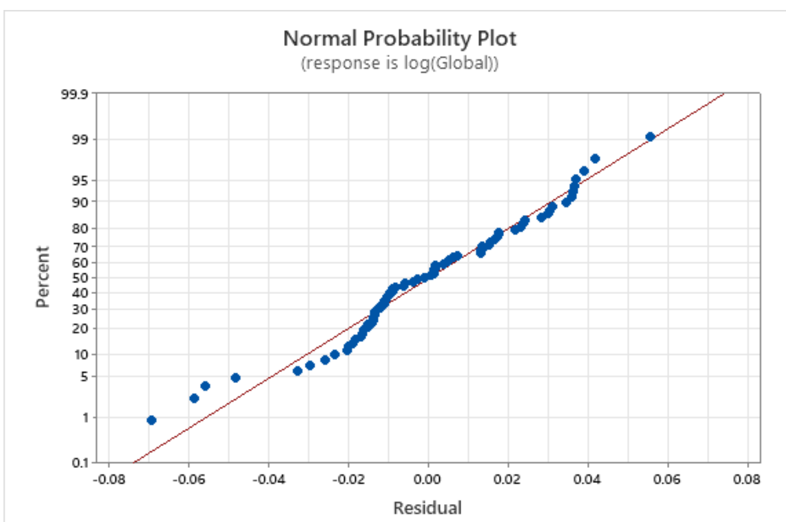


Figure 8. Normal Probability Plot of log(Global MSLR).

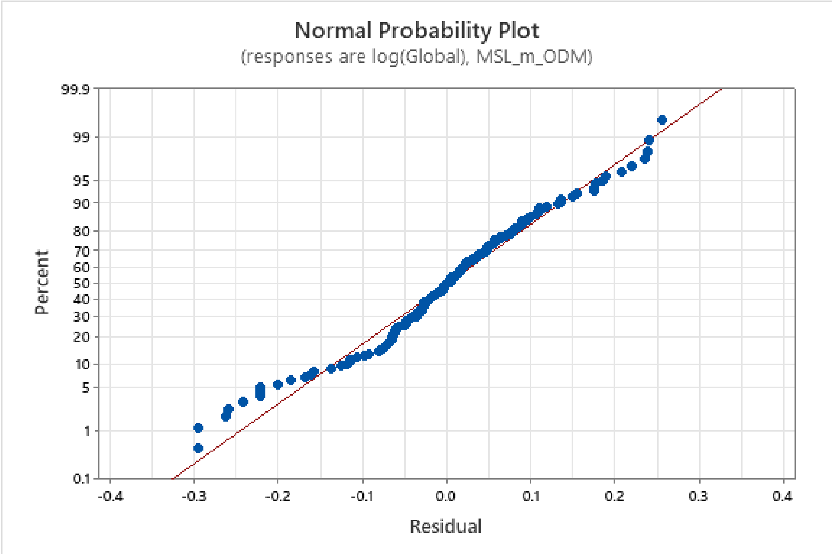


Figure 9. ANOVA Normal Probability Plot of log(Global MSLR) and Dublin MSLR.

We plotted a Normal Probability Plot for the residuals of the Global MSLR after the logarithmic transformation (Figure 9). Despite some slight curvature in the tail ends of the plot, we assume that the majority of the points follow a linear pattern. The original dataset showed an even stronger curvature in the NPP (Figure 8), so the transformation was a clear improvement. Due to this linearity, we can conclude the Global data satisfies the Normality Condition.

4. Equal Variances (& ANOVA)

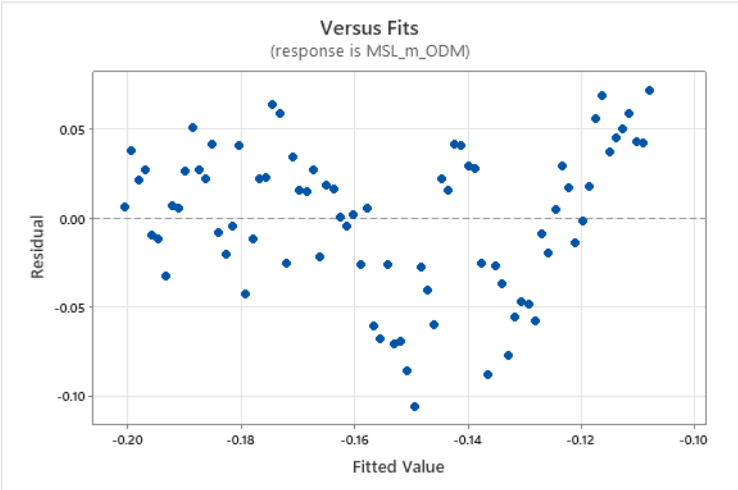


Figure 10. Residual Plot of Dublin MSLR based on Dublin scatter plot.

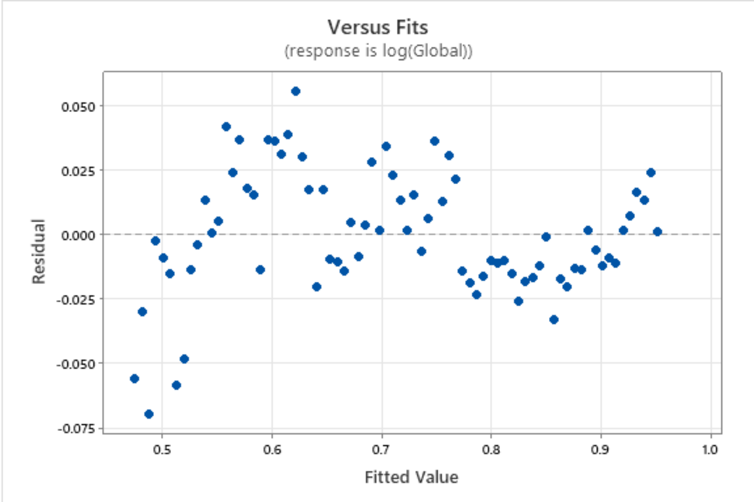


Figure 11. Residual Plot of log(Global MSLR) based on log(Global) scatter plot.

From this residual plot for Dublin MSLR (Figure 10) and Global MSLR (Figure 11), we see around equal variances above and below Residual = 0.00 line. Although there's a possibility of curvature for larger and smaller values, applied transformations were not able to successfully decrease homoscedasticity beyond this point. From our linear regression, we also saw clear support for a linear regression line on both datasets, especially the Global MSLR data. Thus, we can conclude that the Equal Variance Condition is satisfied for both datasets and proceed with caution.

5. Randomization (& ANOVA)

Across a timespan of several decades, the CSIRO researchers used multiple randomly selected locations to collect and analyze sea level data. A similar random selection process was utilized for the Dublin researchers. Therefore, the Randomization Condition is satisfied for both datasets.

Linear Regression Statistical Inference

A. Dublin MSL

Regression Equation

MSL_m_ODM = -2.501 + 0.001187 year

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0414942	30.38%	29.48%	26.96%

Figure 12. Minitab Linear Regression equation for Dublin MSLR vs. year and model summary.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-2.501	0.405	-6.18	0.000	
year	0.001187	0.000205	5.80	0.000	1.00

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.05787	0.057866	33.61	0.000
year	1	0.05787	0.057866	33.61	0.000
Error	77	0.13258	0.001722		
Total	78	0.19044			

Figure 13. Minitab Regression Inference data and ANOVA Tables for Dublin MSLR vs. year.

Using Minitab, we conducted a single linear regression of Dublin MSLR vs. year of collection. Our model has an $R^2 = .304$, meaning that 30.4% of the variation in Dublin MSLR can be explained by the regression line (Figure 12). As hypothesized, there is a positive slope of 0.001187 cm/year, demonstrating that the mean sea level in Dublin has been steadily rising since 1938. The coefficient of -2.501 cm is insignificant due to extrapolation beyond given years (Figure 13). Based on a significance test for regression slope, we see the p-value for B is basically 0. Because the p-value is so low, we can reject the null hypothesis and have strong statistical evidence that the true slope for Dublin sea level rise is not 0, or that there is a positive correlation present. Because the VIF is 1.00, which is less than 5.00, we can conclude that multicollinearity is not a concern. In addition, Analysis of Variance for this regression line found that the regression line was highly significant in its predictive power, with a p-value of basically 0.00 (df = 77) (Figure 13).

B. Global MSL

Regression Equation

log(Global) = -11.860 + 0.006364 year

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0241639	97.17%	97.13%	96.99%

Figure 14. Minitab Linear Regression equation for Dublin MSLR vs. year and model summary.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-11.860	0.250	-47.51	0.000	
year	0.006364	0.000126	50.37	0.000	1.00

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	1.48152	1.48152	2537.31	0.000
year	1	1.48152	1.48152	2537.31	0.000
Error	74	0.04321	0.00058		
Total	75	1.52473			

Figure 15. Minitab Regression Inference data and ANOVA Tables for log(Global) MSLR vs. year.

Using Minitab, we then conducted a single linear regression of Global MSLR vs. year. This model has an $R^2 = .972$, meaning that 97.2% of the variation in Dublin MSLR can be explained by the regression line (Figure 14). This high R-sq and high correlation corresponds with the significant values for Constant and Year. As hypothesized, there is a positive slope of 0.006364 cm/year, demonstrating that the mean sea level globally has been steadily rising since 1938. The coefficient of -11.860 cm is insignificant due to extrapolation beyond given years (Figure 15). Based on a significance test for regression slope, we see the p-value for B is basically 0. Because the p-value is so low, we can reject the null hypothesis and have strong statistical evidence that the true slope for the global sea level rise is not 0, and that there is a positive correlation present. Because the VIF is 1.00, which is less than 5.00, we can conclude that multicollinearity is not a concern. In addition, Analysis of Variance for this regression line found that the regression line for global sea levels was once again highly significant in its predictive power, with a p-value of basically 0.00 (df = 74) (Figure 15).

One-Way ANOVA

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	$\alpha = 0.05$

Figure 16. Null and alternative hypotheses for One-Way ANOVA for Dublin and Global datasets.

Lastly, we conducted a One-Way ANOVA two compare the means of the Dublin and global mean datasets. Our null hypothesis was that the two groups had equal mean sea level rises, while our alternative hypothesis was that at least one of the groups had a different mean (Figure 16). All statistical inferences were conducted at a significance level of a = 0.05.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	28.859	28.8586	2569.16	0.000
Error	150	1.685	0.0112		
Total	151	30.543			

Figure 17. Minitab One-Factor ANOVA Table for Dublin vs. log(Global) MSL.

From the results of our ANOVA, we obtain an F-Value result of 2569.2, showing that the ratio of Mean Squared Error between groups is far, far greater than the Mean Squared Error within groups. Accordingly, the p-value is basically 0. Because the p-value is so low, we can reject the null hypothesis and have strong statistical evidence that the mean sea level rise between global sea level rise and Dublin, Ireland sea level rise are different.

Means

Factor	N	Mean	StDev	95% CI
log(Global)	76	0.7134	0.1426	(0.6893, 0.7374)
MSL_m_ODM	76	-0.15810	0.04621	(-0.18212, -0.13408)

Figure 18. Minitab Confidence Intervals for mean of Dublin and log(Global) MSL.

One-Way ANOVA can help us conclude that a difference exists between groups. However, a limitation is that ANOVA cannot quantify the amount of difference that exists between groups. In order to obtain a clear idea of just how large the difference is, we constructed a 95% Confidence Interval for the mean of both datasets. The confidence intervals do not overlap, supporting our ANOVA conclusion that there is a statistically significant difference between the mean sea level rise of Dublin, Ireland and globally.

Abridged Minitab Data

Year	**MSL_ODM**	**CSIRO Adj. Sea Level**
1938	-0.194282	2.62205
1939	-0.161499	2.82677
1941	-0.169893	3.09843
1942	-0.205599	3.09843
1943	-0.206429	3.09843
…		
1970	-0.162203	4.67717
1971	-0.165987	4.88189
1974	-0.152114	5.47244
1975	-0.217416	5.40945
…		
2010	-0.077851	8.90157
2011	-0.068897	8.96457
2012	-0.062403	9.32677
2013	-0.052292	8.98031

Minitab Code

```
WOPEN "C:\Users\1495333\Downloads\a_newly_reconciled_Dublin_msl_1938_to_2016.csv";

NOTE *** Data pane was used to change the worksheet

Save "C:\Users\1495333\Documents\Dublin.mpx";

Describe 'MSL_m_ODM' 'CSIRO Adjusted Sea Level'; Mean; StDeviation; Median; IQRange;
Skewness; Count.

Dotplot 'MSL_m_ODM'.

Dotplot 'CSIRO Adjusted Sea Level'.

Plot 'MSL_m_ODM'*'year' 'CSIRO Adjusted Sea Level'*'year'; Symbol; Regress.

Name C5 'log(Global)'

Let 'log(Global)' = LOGTEN('CSIRO Adjusted Sea Level')

Plot 'sqrt(Global)'*'year' 'log(Global)'*'year'; Symbol; Regress.

Response 'log(Global)' 'MSL_m_ODM'; GIntPlot; GHistogram; GNormal; GFits; TMethod;
TFactor; TANOVA; TSummary; TMeans;

OneWay; Response 'log(Global)' 'MSL_m_ODM'; GIntPlot; GHistogram; GNormal; GFits;
TMethod; TFactor; TANOVA; TSummary; TMeans;
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PART 4 - DISCUSSION

Using linear regression statistical inference, the correlation between the year and sea level rise was analyzed. For the Dublin data set, there was a correlation coefficient of $R^2 = .304$ and a regression equation of MSLR = -2.501 + 0.001187 (year). The slope is positive, which validates the assumption that sea levels are rising throughout the years. For the global data set, there was a correlation coefficient of $R^2 = .972$ and a regression equation of MSLR = -11.860 + 0.006364 (year). In comparison to the Dublin data, the slope has a greater magnitude and there is far more correlation globally. In order to test how similar these MSL rises are, a one-way ANOVA test was used. Since the F-value was 2569.16, and the p-value 0.000, the Mean Squared Error between groups is far greater than the Mean Squared Error within groups. Because the p-value is so low, we can confidently reject the null hypothesis and have strong statistical evidence that the mean sea level rise between global sea level rise and Dublin, Ireland sea level rise are different.

The results provided through this investigation reflect the global trends defined by Mimura, Church and White, and Nejad et al. by qualifying them. The data clearly shows that there is a trend of global sea level rise as described by Mimura and Church and White. In addition, the Dublin sea level rise described by Nejad et al. was also supported by the data. While the conjecture that sea levels have been rising globally is inexplicably supported by the evidence, the rates of change were massively different.

These results could be caused by the fact that Dublin experiences an elevation of 66 feet while the remaining 29 percent of the planetary surface has a mean elevation of about 840 meters (approximately 2,755 feet). This could lead to fluctuations in global sea level being reflected more greatly in Dublin. In addition, there were only three data sites included in this experiment.

In order to gather a more comprehensive set of data, perhaps more data sites could be added in future studies. In our studies we only analyzed data from Dublin, but there are many more possible coastal cities in different countries that experience varying tidal levels and sea level rises that can be utilized for further analysis. A Fisher LSD test could also be run as a measure of determining the direction of statistical difference. In this experiment, the goal was to understand the effects of climate change. The relationships studied are an addition to the ever-growing data produced by global organizations like CSIRO. The results of this experiment can be applied to future applications related to public policy and activism, as these results could lead to habitat and residential loss as mentioned by Kulp and Strauss, and serve as a foundational effort for environmental conservation and protection efforts.

PART 5 - REFLECTION

This project provided many opportunities for us to gain specific skills and knowledge and improve our research skills. First of all, because this research project served as a meta-analysis of studies that were already conducted, we had our first experience in dissecting and analyzing another researcher's work. This taught us some of the classically used sampling procedures and data processing techniques, such as digital recalibration and comparison with true parameters (tidal gauges), in professional research. In addition, despite already knowing how to conduct ANOVA and regression in Minitab, we now have the added benefit of applying the results of those inference tests to answer a research question that we created. In effect, we wanted to verify a hypothesis based on trends we saw, and we conducted all of our own analysis and calculations to do so. By also connecting this to previous research and our literature review, we've gained our first experiences in collaboration, a crucial part of research. All in all, the research experience we gained in this study have made us better researchers and can hopefully serve as the foundation for our future research endeavors.

PART 6 - REFERENCES

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