Recent mean sea level changes around the UK

Variação recente do nível do mar ao redor do Reino Unido

Carmo, F. W.
Faculty of Science and Engineering, University of Brighton Brighton BN2 4GJ. UK
fepeblue@gmail.com

Resumo

Há uma grande preocupação no Reino Unido com o aumento do nível relativo do mar e, consequentemente, com inundações em regiões costeiras principalmente no sul da Inglaterra. Por outro lado, acidentes geográficos que cobrem parte da Escócia refletem processos de soerguimento curstal devido ao efeito de glacioestasia, mantendo o Nível Relativo do Mar (NRM) mais baixo da Grã-Bretanha. Este trabalho fez uso de registros atualizados do nível do mar a partir de 8 marégrafos compreendendo o litoral Sul e Norte da Grã-Bretanha ao longo dos últimos 22 anos. As informações sobre movimentos verticais da crosta foram extraídos a partir da literatura mais recente disponível. Para o período de 1990 a 2012, a taxa de aumento do NRM encontrada nesta investigação é de 2,496 mm ano^{-1} ao redor do Reino Unido e, os maiores registros de NRM em todas as estações foram encontradas durante a segunda década apesar do período indicar um declínio se comparada com a primeira década.

Variação do nível do mar; glacio estasia; Reino Unido

Abstract

There is a great concern in the UK about relative sea level rising, consequently coastal flooding, especially in South England. On the other hand, the landforms of much of Scotland reflect crustal uplift due to glacio-isostasy process, which keeps the Relative Mean Sea Level (RMSL) to the lowest record in Britain. This work has made use of updated sea level records from 8 tide gauges covering South and North of Britain's coastline, relating to vertical crustal movement, which were extracted from recent literature available. This investigation finds the rate of sea level rise in the UK, for the period 1990 and 2012, is 2.496 mm yr-1 and that the highest years of recorded RMSL in all stations was in the second decade in this period. This is despite the fact the second decade showed an average decline in sea level when compared to the first.

Sea level change; glacio-isostasy; United Kingdom

Introduction

Sea level changes have been a critic scientific issue, closely related to studies of climate change, solid Earth processes and geodetic science (Woodworth *et al*., 2009), and the impact of changes in relative sea level (RSL) on coastal erosion and flooding has long been perceived (Lamb, 1991; Nicholls *et al*., 1999; Nicholls, 2002).

In the United Kingdom around 10 million people living in 5.5 million properties live in flood risk areas in England and Wales, with 2.6 million of those properties at direct risk of flooding from rivers or the sea (EA,2009); In England the cost of claims from flooding in June and July 2007 exceeded £3.5 bn (Runcie, 2009).

Although, only recently the increase in the rate of sea level change and the resultant coastal erosion has become attributed to the forcing effect of global climate (Parry *et al*., 2007).

Sea level has been always changing along the geological time, globally and locally rapidly or slowly for many different reasons, depending on the process that is causing the sea level variation. The last decades have gone through great advances in the development of geodetic techniques for measuring vertical land movements at tide gauges (IOC. 2006), regarding mainly the Global Positioning System (GPS) and Absolute Gravity (AG). In the case of the UK, the two techniques have been used in combination (Teferle *et al*. 2006). Continuous Geographic Positioning Systems (CGPS) now provides the longstanding land-level changes known from the Holocene geomorphological record to be placed into perspective. This allows land-level change to be integrated with the eustatic sea level change to better constrain the RSL trends over the most recent decades. With the advanced of digital technology, the accuracy, reliability, distribution and workability of the data to the final user in real time, has been enhanced (IOC, 2006).

Vertical land movements are usually linked to many different natural processes such as post-glacial rebound known as well as Glacial Isostatic Adjustment (GIA), earthquakes, plate tectonics and anthropogenic activities, such as ground pumping. Eliminating vertical land movement signals from mean sea level trends at tide gauges are important when estimating climate related changes in MSL (Neilan *et al*., 1998).

Global mean sea level change results from 2 major processes, mostly related to recent climate change, that alter the volume of water in the global ocean: a) thermal expansion; and b) the exchange of water between oceans and other reservoirs (glaciers and ice caps, ice sheets), other land water reservoirs - including through anthropogenic change in land hydrology, and its interaction with the atmosphere (Cazenave *et al.*, 2000).

The key objective of the present study is to determine and analyze the recent rates of relative sea level changes, by tide gauges measurements, between Southern and Northern of the British Isle in 8 different sites around the UK coastline. Relating the Mean Sea Level (MSL) data to vertical crustal movements, based on literature review on up-to-date crustal movements in the UK, the outcoming will be the RSL. A second aspiration is to understand and discuss decadal variation on sea level trends.

Methods

Study area

8 different tide gauge records along the United Kingdom coastline (Fig 1), 4 sites in the South (Dover, Portsmouth, Weymouth and Newlyn) and 4 in Scotland (Aberdeen, Lerwick, Wick and Stornoway).

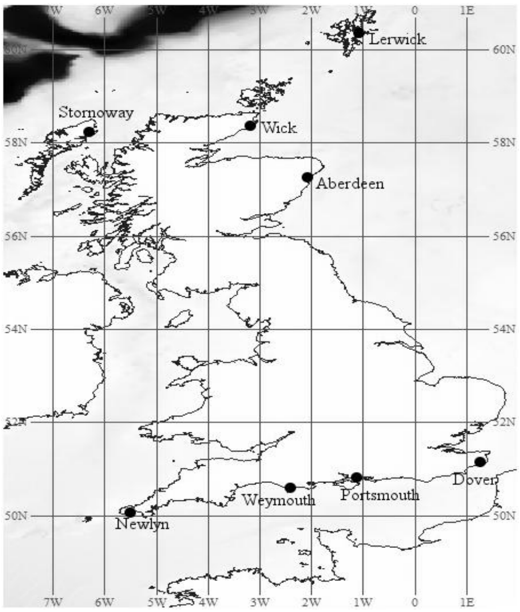

Figure 1: Map of Britain demonstrating the eight tide gauge locations studied.

For this investigation all the stations

provided 20 years or more of data, only in Portsmouth and Weymouth had the data started being taken in 1991, the others started in 1990. At the tide gauge of Lerwick, there is a gap in the year of 2012. However this station is at the best position to measure vertical sea level variances, due to the distance to the continentally effects such as ports and input of freshwater.

From 1997 to 2005, the Institute of Engineering Surveying and Space Geodesy (IESSG) and the Proudman Oceanographic Laboratory (POL) fixed Continuous Global Positioning System (CGPS) stations at 10 of the 44 tide gauges which form the national tide gauge network as part of the NTSLF (Bindoff *et al*., 2007). The GPSs are based on Tide Gauge Benchmarks (TGBM) that is a stable surface or mark near a gauge, to which the gauge zero is referred. It is connected to a network of local auxiliary benchmarks to check local stability and guard against accidental damage (Pugh, 2004).

There are many ways to calculate MSL, in order to avoid short-term changes of relatively large amplitude due to tides and surges. The most straightforward method is to sum all the values observed over one month or year and calculate the arithmetic mean (Pugh, 2004). The RMSL is perceived through difference in measurements by coastal tide gauges, simultaneously, with vertical changes of the land (newest literature revised) upon the area the gauge equipment is situated.

Averaging long periods of sea level, derived by analysis of sea level variations are the basis to define reference levels. These levels are often used for map or chart making or as a reference for subsequent sea levels measurements. For geodetic surveys the MSL is frequently adopted, being the average value of levels observed each hour over a period of at least a year and preferably over 19 years (Pugh, 2004).

Data processing

For this work the data were collected from the British Oceanographic Data Centre (BODC), provided at the web site: http://www.bodc.ac.uk/; and processed on Excel, the outcome of this process is the averaged yearly MSL, which.

Monthly MSL values are calculated at BODC from a filter working on quarter-hourly values derived from one or more cubic splines applied to the raw data. The filter is a convolution of the Vassie 03B filter (which converts 15-minute data to hourly values) and the Doodson X0 filter.

Results and Discussion

At Aberdeen (Fig 2 b) it is possible to observe a decreasing tendency of sea level from 1991 to 1993, when it gets at its minimum average sea level record of 2,481 m. After 1993 there has been an increase of sea level up to 2,600 m in 2006, although later records showed a slightly retraction up to 2010 when it stated to get higher records.

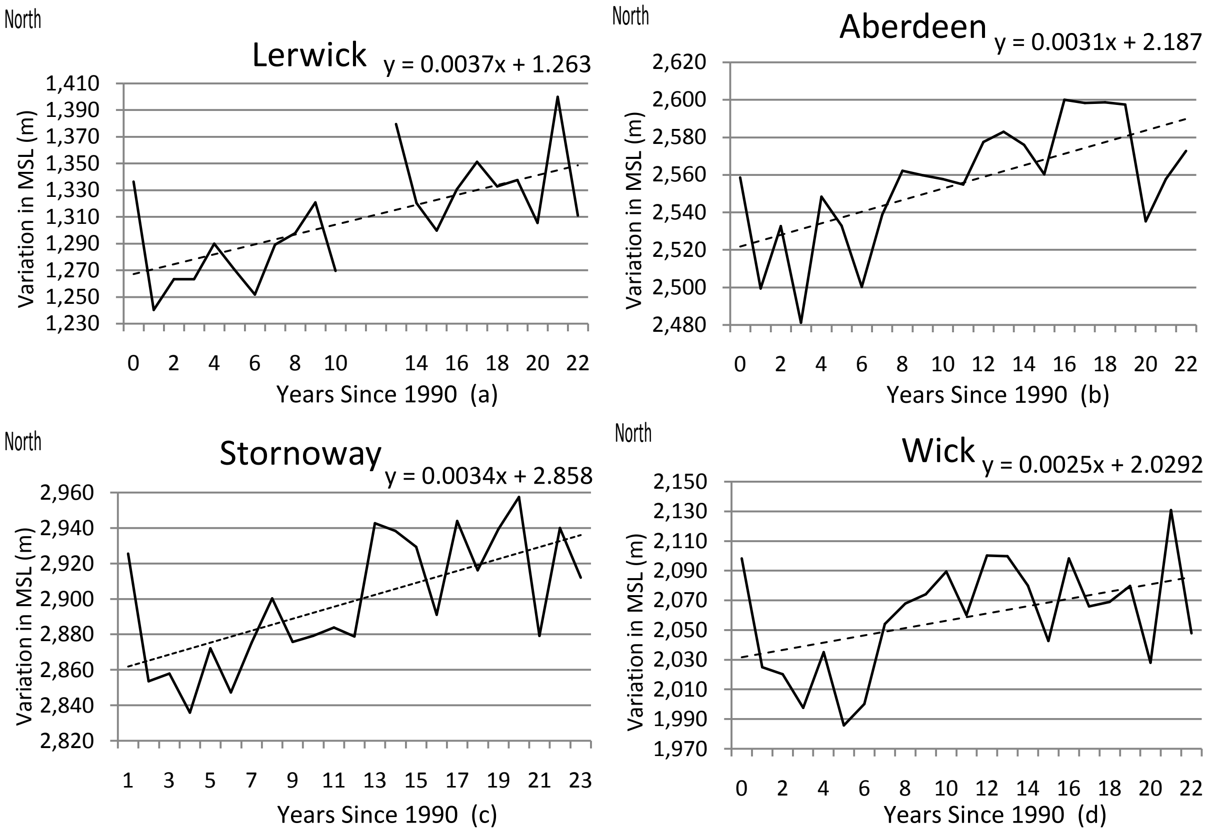

Figure 2: Variance and the trend line of sea level along 22 years from 1990 to 2012, at Aberdeen tide gauge.

The registers of the tide gauges at Wick (Fig 2d) presented a similar pattern to the other northern stations; however the decreasing in MSL goes up to 1995, when it shows a consistent increase in MSL. Portsmouth (graph 3e) is in contradiction to any other station, it started rising from the beginning of the records in 1991, reaching the highest mark in 2002 followed by three years of falling MSL. At Newlyn (Fig 3f) presented the highest rate, 3.9 mm/year, among all the locations; Portsmouth (Graph 3e) that is closest station to Newlyn and has shown a similar rate of 3.8 mm/year.

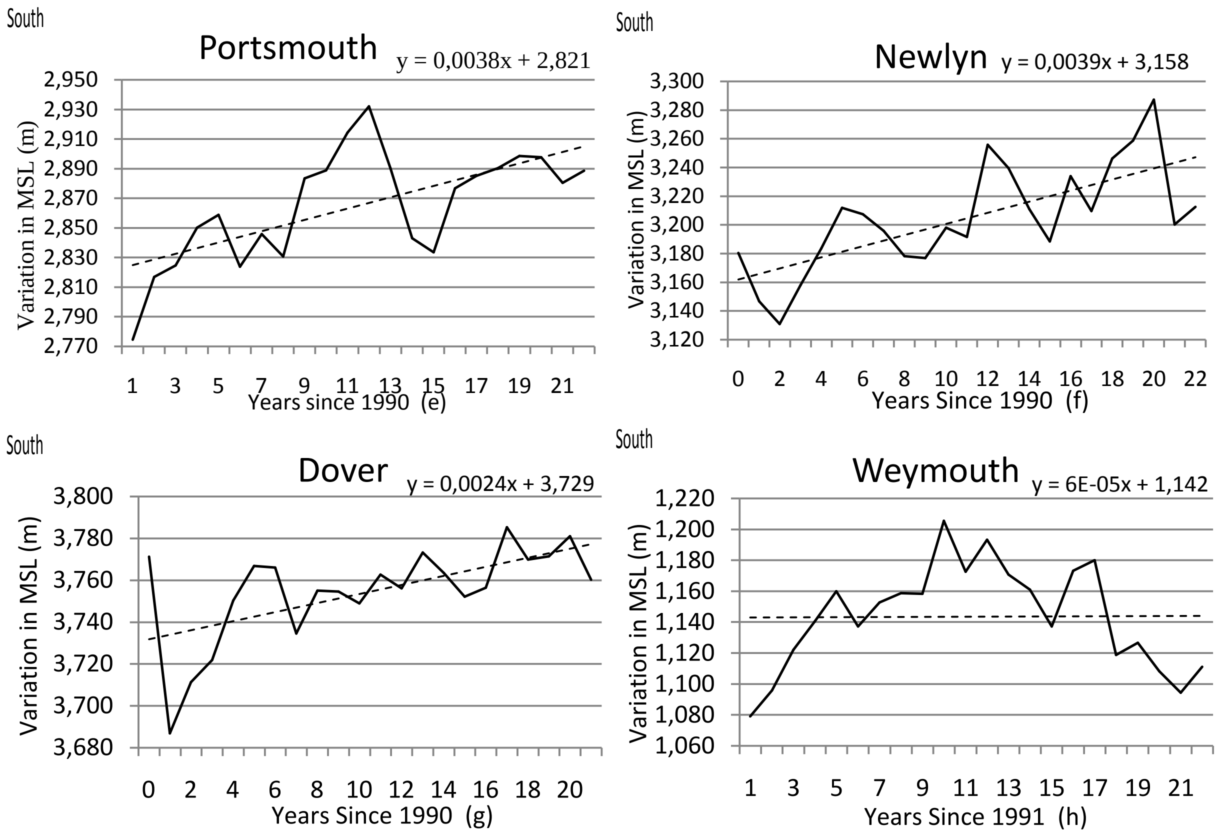

Figure 3: Variance and the trend line of sea level along 22 years from 1990 to 2012, at Newlyn tide gauge.

Averaging two decades

The data was also processed dividing the years available in two separate periods in order to analyse 11 years of variation each.

Once the time series were divided, two patterns became clear: first, at all stations there were up rising MSL independent of the region; the second is that six out of eight locations presented a decreasing in MSL, only Stornoway (Fig 4d) and Newlyn (Fig 3f) did not present the same pattern, although they show a very slight increase in MSL.

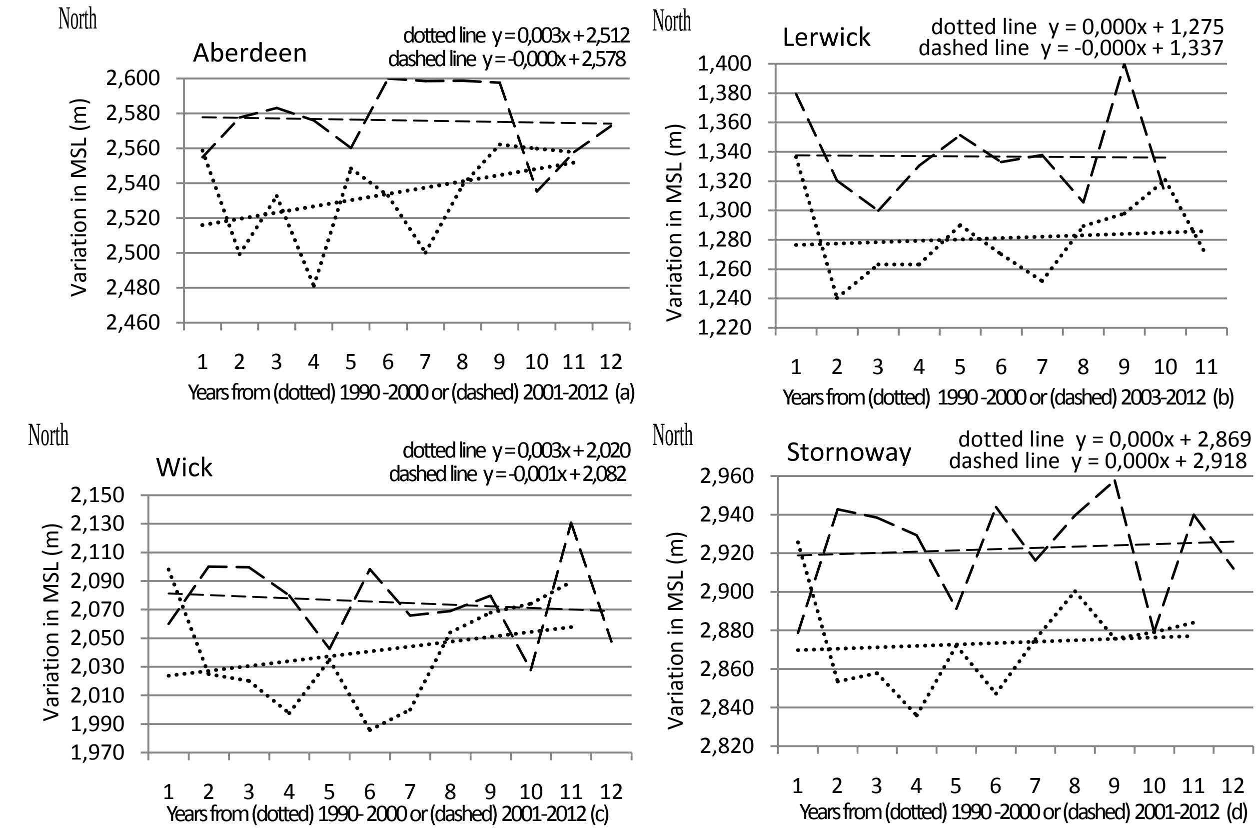

Figure 4: Variation in MSL in 2 different periods. Dotted line represents the 1990s; dashed line represents the period of 2001.

Aberdeen (Fig 4a) demonstrates a general pattern between the two periods. At the first there is an increase in MSL of 3.6 mm/year, while the decade started in 2001 presents a slight decline in MSL of -0.3 mm/year.

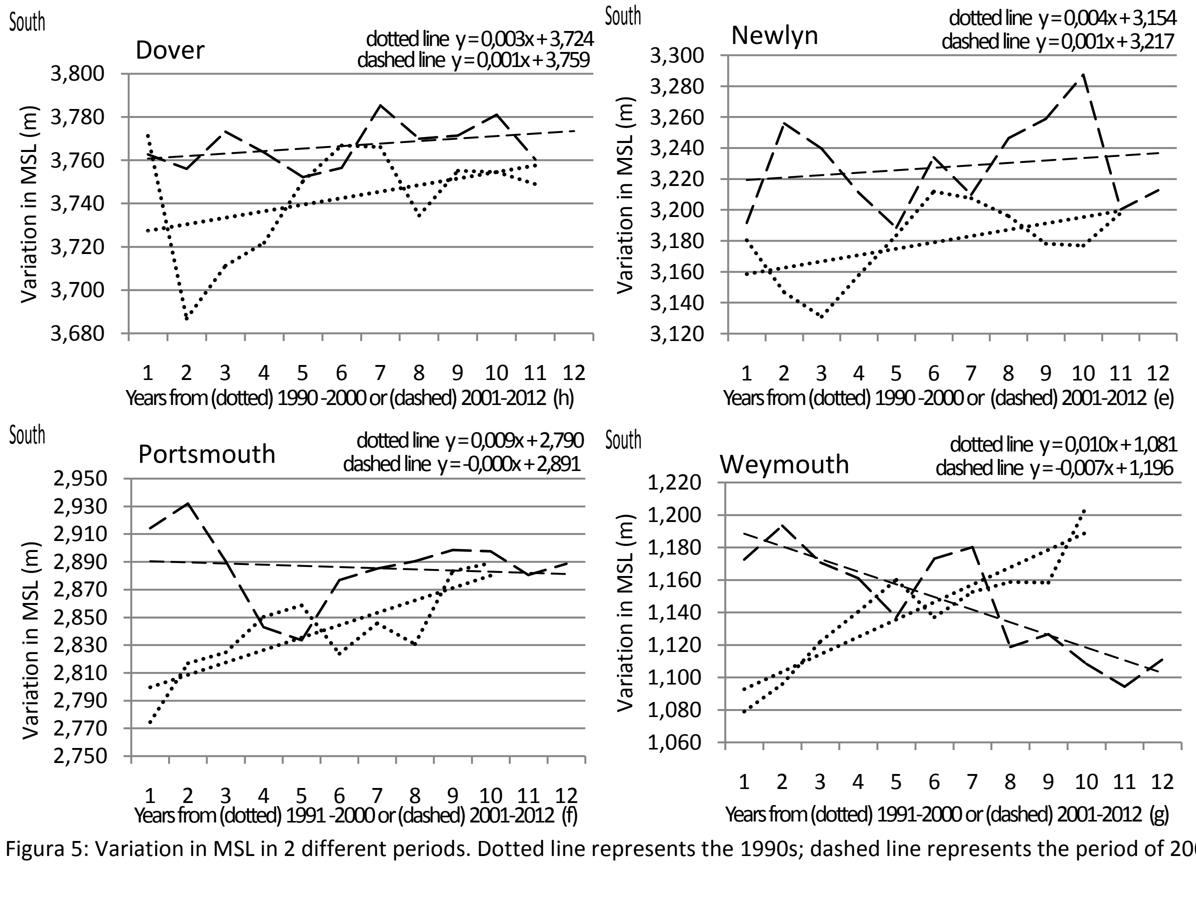

Figura 5: Variation in MSL in 2 different periods. Dotted line represents the 1990s; dashed line represents the period of 2001.

Wick station (Fig 4c) shows significant falling in MSL, perceptible from 1990 to 1996, when a uniform turned up happened until 2000. The decade starting at 2001 exhibits a

At Newlyn tide gauge (Fig 5e), the records showed an increase in mean sea level of 4.1 mm/year, in the first 10 years, in despite of the three first years of decaying in MSL. The 10 years from Portsmouth (Fig 5f) presents the second highest rising in MSL in first decade 9 mm/year, which reached 10.7 mm/year. Similar data maybe relate to the short

slightly decrease in MSL, only in 2011 a prominent rising appears but just in the next year the MSL falls again, giving to this decade an average of -1.1 mm/year.

2001, also shows a gain in MSL, but less steep of 1.6 mm/year. In this decade reached a positive vertical movement due to a consistent rising between 2007 and 2010.

distance of about 60 km to each other. In the second decade, Portsmouth presents a smooth MSL decrease of 0.8 mm/year.

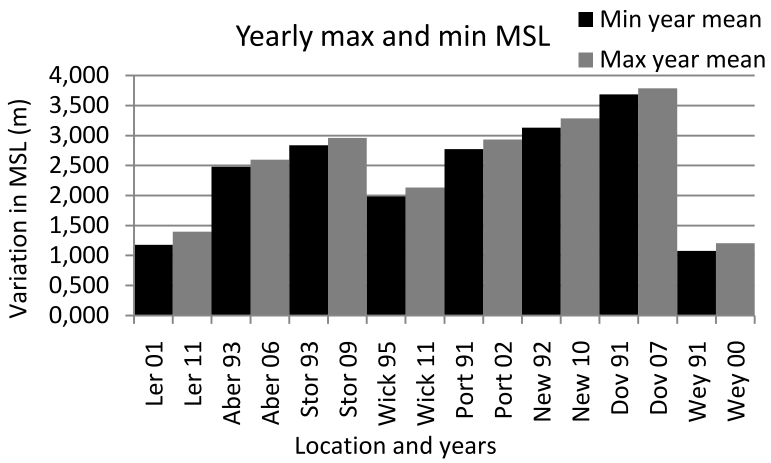

Figure 6: It shows maximum and minimum MSL in all locations and the year which they occurred.

It is worth noting on (Fig 6), that all of the highest rates in MSL were achieved in the second decade despite having the lowest average in sea level between the two decades. It may be correlated with the increase of stochastic event caused by climate change.

In order to help visualization of the crustal up-lifting in a national-scale analysis for Britain, Fig 7 shows the ellipse of present-day relative uplift (relative sea-level fall), -1.2 mm yr^{-1}, mostly centred on the deglaciated mountains of Scotland (Shennan, 2012). However, for crustal movement data CGPS and AG based on work of Bingley (2001), Teferle, *et al* (2006) & (2007), Wahl *et al*., (2013), Woodworth *et al*., (2009) and Shennan (2012) were used in the equation in order to give the

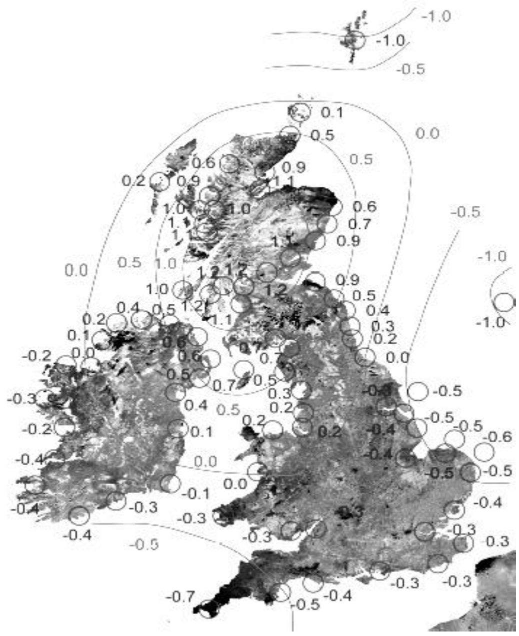

Figure 7: Rate of relative land-level change 1 ka to the present day in the British Isles (Ireland and the UK) (mm yr-1). Relative land uplift is shown as positive and relative subsidence as negative, (Shennan, 2012).

Relative Mean Sea Level (RMSL). Moreover, the seas around the UK are relatively shallow leading to tide-surge interaction processes that affect sea-level, principally along the North Sea coastline (Prandle and Wolf, 1978).

Following the standards outlined by Mitrovica and Milne (2003), for each geographical location (φ) and time (t), sea level (SL) is the difference between the geoid and the solid surface of the Earth. The calculation is done in millimetres per year (mm yr^{-1}) the data about land movement is taken from the latest literature available.

$$SL(\varphi, t) = G(\varphi, t) - R(\varphi, t)$$

Relative Mean Sea Level (RMSL)

Sites	1990-2012 trend line (mm yr^{-1})	1990-2000 trend line (mm yr^{-1})	2001-2012 trend line (mm yr^{-1})
Lerwick	2.7	-0.1	-0.8
Wick	2	2.9	-1.6
Aberdeen	2.41	2.6	-1.6
Stornoway	2.9	0.2	-0.1
Dover	1.76	2.56	-1.87
Portsmouth	3	8.2	0
Weymouth	0.8	9.9	-8.6
Newlyn	4.4	3.6	2.1
Mean RMSL	2.496	3.733	-1.559

Figure 8: It presents the relative mean sea level at the 8 locations, the first column shows the trend of RMSL during the 22 years analyzed, while the second and third column demonstrates the rates of each decade.

The results obtained by this investigation (Fig 8) are corroborated by Bindoff *et al*. (2007); Bingley (2001); Rennie, *et at*. (2011), however, the methodology applied in this work was much simpler.

The average RMSL found at the 8 station around Britain in this work is 2.496 mm yr^{-1}, which is in the range of confidence with Bindoff *et al*. (2007), increased by the rate of 3.1 mm yr^{-1} between 1993 and 2001. The most plausible explanation comes also from Bindoff *et al*. (2007): for the period 1993 to 2003, for which the observing system is much better, the contributions from thermal expansion (1.6 ± 0.5 mm yr^{-1}) and loss of mass from glaciers, ice caps and the Greenland and Antarctic Ice Sheets together gave 2.8 ± 0.7 mm yr^{-1}.

Bindoff *et al*. (2007), also investigated land movements through combined CGPS and AG, estimating changes in land level correlate with long term geological and geophysical evidence for the 'tilt' of Great Britain, which has Scotland rising by 1 to 2 mm yr^{-1} and the South of England subsiding by up to 1.2 mm yr^{-1}.

Regional variability in sea level is principally because of thermal expansion and salinity (Kohl and Stammer 2008). Other phenomena as changes in circulation because of polar ice melt (Stammer *et al*. 2011) or gravitational effects and visco-elastic response of the solid Earth to last deglaciation and ongoing land ice melt are also reasons from regional variability in MSL (Milne *et al*. 2009).

Terms of quick surface warming tended to be pursuit by increased thermal expansion and increases the rates of global sea-level rise. A possible link between global sea-level acceleration and temperatures was addressed in a semi-empirical study by Rahmstorf (2007). He parameterized the rate of change of sea level in terms of global mean surface temperature above a pre-industrial threshold (Bindoff *et al*., 2007).

Since 1993 thermal expansion of the oceans has contributed about 57% of the sum of the estimated individual contributions to the sea level rise, with decreases in glaciers and ice caps contributing about 28% and losses from the polar ice sheets contributing the remainder (Bindoff *et al*., 2007).

Church *et al*. (2001) regarded that Greenland was melting at an average rate of between 0.0 and 0.1 mm yr^{-1} between 1910—1990 (considering 20th century effects only). The IPCC Fourth Assessment (Lemke *et al*. 2007) suggested that the Greenland ice sheet had lost mass at rates equivalent to 0.05 ± 0.12 mm yr^{-1} of sea level rise during 1961–2003 and 0.21 ± 0.07mm yr^{-1} in 1993–2003. One factor that could be responsible for the lower UK MSL trend than the global-average IPCC values concerns melting of the Greenland ice sheet during the 20th century.

However, behind these general trends lies considerable uncertainty over regional variation in sea level, since strong basin-scale polarities, pronounced inter-decadal variability (Beckley *et al*., 2007).

The results reached by this study at Lerwick 2.7 mm yr^{-1} and Wick 2 mm yr^{-1}, of RMSL for the past 22 years are in agreement with Wahl *et al*., (2013), intervals of RMSL 4.1- 2.3 mm yr^{-1} at Lerwick, and 4-1.7 mm yr^{-1} at Wick for approximately the same period. The RMSL results at Dover's location reached by this work, 1.76 mm yr^{-1}, also corroborates with the result found by Wahl *et al*., (2013) that is between 1.8-0.9 mm yr^{-1}.

Stornoway can be attributed to a systematic increase in MSL rather than changes in the magnitude of tidal surges. Elsewhere on the Scottish coast, tide gauge data between 1957 and 2007 mainly show RSL rises of 1.5–4.6 mm yr^{-1}, (Rennie, *et al*, 2011). In despite the time series presented in this study are much shorter than the Rennie, *et al*. (2011), this confirms the result of 2.9 mm yr^{-1} for the 22 years. The correlation is slightly weaker, but still statistically significant, for the UK east coast sites (Lerwick to Dover). The sites in the English Channel are also significantly correlated to each other but are not significantly correlated with most North Sea sites (Wahl *et al*., 2013)

Lerwick is exceptional as the tide gauge measurements still suggest a fall in sea level in both periods (1990-2000; 2001-2012) presented in this work -0.1 and -0.8 mm yr^{-1}, respectively.

The acceleration recorded in MSL between the 19th and the 20th centuries, probably, has happened in North West European sea level, on the basis of the small number of very long sea-level records available (Woodworth, 1999), with the most plausible outcome being that the acceleration first became apparent in the latter part of the 19th century, although Jevrejeva *et al*., (2008) suggested an even earlier appearance of the acceleration. However, weak evidence has been found in individual tide gauge records for an ongoing positive acceleration of the sort suggested for the 20th century itself by climate models (Church *et al*., 2001). That is in part due to the hardness in characterizing such a low-frequency signal over a relatively short period in the presence of a large inter-annual and decadal variability in individual records (Douglas, 1992).

Conclusion

The linear trends demonstrated in this work, along the sites studied, despite the short period analyzed, showed a consistent increase in mean sea level, mainly because of the first period analyzed, which raised the rate of RSL more steeply. The variation among the station is coherent with the most recent literature, only Weymouth exhibited a very steep trends for both decades, the first (1990-2000) was highly positive and the second (2001-1012) presented a very high negative trend. However, nothing in the literature was found to corroborate or to deny the results found.

This work highlighted that the highest records of MSL were achieved in the second "decade" despite having the lowest average records in sea level between the two periods.

The impacts of physical changes can be estimated at all levels of the marine ecosystem, from plankton to fisheries. Although, it is hard to isolate, the climate affects upon the complex nature of the marine ecosystem, from others human impacts on coastal zone. In order to help coastal planners and managers to mitigate and adapt the coastal zone for flood, studies must be carried out regarding sea level changes as a factor of climate change, trying to understand and determine the anthropogenic pressure as well as non-climate contribution vertical land movement and glacial isostatic adjustment. This will lead to better estimates of changes in mean sea level around the UK, which is one of the most prepared for these challenges than most countries (Tol *et al*., 2008).

Reference

Beckley, B. L. (2007). A reassessment of global and regional Mean Sea Level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits. *Geophysical Research Letters 34* , 1-5.

Bindoff, N. J. (2007). *Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning,*. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

Bingley, R. D. (2001). Monitoring the Vertical Land Movement Component of Changes in Mean Sea Level Using GPS. *esults from Tide Gauges in the UK Journal of Geospatial Engineering. VOL 3(PART 1)* , 9-2.

Bingley, R. M. (2007). Absolute Fixing of Tide Gauge Benchmarks and Land Levels. *Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme* .

Cazenave, A., Nerem, R., 2004. Present-day sea level change: observations and causes. Rev. Geophys. 42, 1–20.

Douglas B.C. (1992). Global sea level acceleration. *Journal of Geophysical Research 97* , 12699–12706.

Douglas B. C. (1997). Global sea level rise: a redetermination. *Surveys in Geophysics 18* , 279–292.

Environment Agency, National Flood Risk Assessment, 2009. http://publications.environment-agency.gov.uk/pdf/GEHO0609BQDS-E-E.pdf

IOC (2006). *Manual on sea-level measurement and interpretation. Volume 4 - An update to 2006. Intergovernmental Oceanographic Commission Manuals and Guides No. 14.* Paris: eds. Aarup, T., Merrifield, M., Perez, B., Vassie, I and Woodworth, P.

Jevrejeva S, M. J. (2008). Recent global sea level acceleration started over 200 years ago? *Geophysical Research Letters 35* .
Kohl A, S. D. (2008). Decadal sea level changes in the 50-year GECCO ocean synthesis. *J Clim 21* , 1876–1890.
Lamb, H., 1991. Historic Storms of the North Sea, British Isles and Northwest Europe. Cambridge University Press, Cambridge 204 pp.
Lemke, P. e. (2007). *Observations: changes in snow, ice and frozen ground, in Climate Change 2007: The Physical Science Basis (Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change) (Chapter 4),* . Cambridge, New York: eds Solomon.
Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Mitrovica J. X., M. G. (2003). On post-glacial sea level: I. General theory. *Geophysical Journal International 154* , 253–267.
Nicholls, R.J., Hoozemans, F.M.J., & Marchand, M. 1999. Increasing flood risk and wetland losses due to global sea-level rise: Regional and global analyses. *Global Environmental Change,* **9**, S69-S87.
Nicholls, R.J., 2002. Analysis of global impacts of sea-level rise: A case study of flooding. *Physics and Chemistry of the Earth*, 27, 1455-1466.
Parry, M. C. (2007). *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.
Prandle, D. W. (1978). The interaction of surge and tide in the North Sea and River Thames. *Geophys.J.R.Astron.Soc.* , 203–216.
Pugh, D. (2004). *Changing sea levels.* Cambridge University Press.
Rahmstorf S. (2007). A semi-empirical approach to projecting future sea-level rise. *Science 315* , 368–370.
Rennie, A. F., H. J. (2011). Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast. *Geomorphology 125* , 193-202.
Robert Runcie, Head of Flood Defence, Environment Agency in New Civil Engineer, August 2009. http://www.nce.co.uk/news/water/robert-runcie-spending-for-a-rainy-day/5206306.article
Shennan, I. &. (2002). Holocene land- and sea-level changes in Great Britain. *J. Quat. Sci., 17,* , 511–526.
Shennan, I. M. (2009). Late Holocene relative land - and sea-level changes: providing information for stakeholders. *GSA* , 52-53.
Shennan, I. M. (2012). Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. *S.Journal of Quaternary Science 27(1)* , 64-70.
Stammer D, A. N. (2011). Response of a coupled ocean-atmosphere model to Greenland melting. *Surv. Geophys* , 621–642.
Teferle, F.N., R.M. Bingley, S.D.R Williams, T.F. Baker, and A.H. Dodson (2006). Using continuous GPS and absolute gravity to separate vertical land movements and changes in sea-level at tide-gauges in the UK. *Phil. Trans. R. Soc.* , 917–930.
Teferle, F. N.; Bingley, R.; Waugh, A.I.; Dodson, A.H.; Williams, S. D. P.; Baker, T. F.. (2007) Sea level in the British Isles: combining absolute gravimetry and continuous GPS to infer vertical land movements at tide gauges. In: Tregoning, P.; Rizos, C., (eds.)

Dynamic planet monitoring and understanding a dynamic planet with geodetic and oceanographic tools. Berlin, Springer, 23-30.
Tol R.S.J., K. R. (2008). Towards successful adaptation to sea level rise along Europe's coasts. *Journal of Coastal Research 24(2)* , 432–442.
Wahl, T., Haigh, I.D., Dangendorf, S., and Jensen, J., 2013. Inter-annual and long-term mean sea level changes along the North Sea coastline. *In:* Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), *Proceedings 12th International Coastal Symposium* (Plymouth, England), *Journal of Coastal Research*, Special Issue No. 65, pp. 1987-1992, ISSN 0749-0208.
Woodworth P. L. (1999). High waters at Liverpool since 1768: the UK's longest sea level record. *Geophysical Research Letters, Volume 26* , 1589-1592.
Woodworth, P. L., Teferle, F. N., Bingley, R. M., Shennan, I., and Williams, S. D. P.: Trends in UK mean sea level revisited, Geophys. J. Int., 176(22), 19–30, doi:10.1111/j.1365- 246X.2008.03942.x, 2009b.