WHAT CAN THE LOCAL GPS NETWORK TELL US ABOUT THE GLACIAL ISOSTATIC ADJUSTMENT OF LONG ISLAND, NY?

Moore, M [1] **, Brown, R.** [1] **, Thomas, M.** [1] **, Santella, K.** [1] **, Ballato, B.**[1] **, Marsellos, A.E.** [1] **, Tsakiri, K.G.**

[2] [1]*Dept. Geology, Environment and Sustainability, Hofstra University, NY, USA,*
[2]*Department of Information Systems, Analytics, and Supply Chain Management, Rider University, NJ, USA*

Abstract

Long Island, NY has a low-topographic relief of large residential areas along the coastline, and a relative subsidence or uplift of areas may elevate the risk of flooding. Utilizing GPS data, the movement of Long Island was analyzed to determine the presence of any glacial isostatic adjustment and positional change. Although Long Island is not in a tectonically active region nor is it directly connected to rebound by changes in mantle viscosity, subsidence or uplift is expected to occur due to glacial isostatic adjustment. Other studies have used models dependent on the last glacial maximum and ice mass change for estimating the severity of global warming and understanding the impact of the relative sea-level change. In our paper, we applied a statistical methodology focused on local changes in elevation and plate positioning. We used an R programming language to statistically analyze the relationship between four GPS sites out of the fourteen on Long Island, specifically their north, east, and up components, to identify any glacial isostatic adjustment that may affect Long Island's topography. A low-pass (KZ) filter has also been applied to remove high-frequencies, allow a higher signal-to-noise ratio, and reveal a long-term trend. The results of this study are consistent with those of previous studies, such as the relative northwestern velocity of the northeastern region of North America, and we have concluded that the four GPS sites with the greatest extended time duration of data show a very prominent and continuous subsidence of the Long Island, NY, with the exception of a short interval of uplift (2013-2015).

Keywords: GPS data, glacial isostatic adjustment, Long Island in New York

Introduction

Long Island in New York is subject to many hazards and has subsequently been the topic of numerous studies with the intention of interpreting them. One of these hazards is the potential of the island subsiding, uplifting, and/or drifting away from the mainland of New York state. This could be an effect of glacial isostatic adjustment, or the movement of a landmass that had once been subject to ice-age glaciers. Long Island is no stranger to the effects of glaciation as it was formed by glacial deposits. However, to ensure the safety of coastal residents and to better understand the tectonic movements of the northeastern coast, it is important to research what geological events are taking place and what potential future events may change the position of the region.

Our study was conducted with the objective of observing whether or not glacial melting is shown as an isostatic rebound of Long Island by analyzing GPS data through the R programming language and RStudio software. There are several scientific papers on the isostatic rebound and glacial isostatic adjustment of other areas including but not limited to noise-removal filtering methods (Bogusz et al., 2019), but none focused on Long Island. The authors of a paper completed in the New England region used an "S transform filter", which is a time-frequency filter, to analyze their data (George et al., 2011). Unlike our research, however, they chose to focus on the plate's latitudinal and longitudinal movement, rather than vertical up and down motions. Other scientific articles stand out in their analysis of glacial isostatic rebound (Sella et al., 2004; 2007). The authors researched the North American GPS sites to measure and analyze surface velocity fields of the region, as well as glacial isostatic adjustment and plate motions. They used GIPSY-OASIS software to collect and analyze these velocities, as well as the post-glacial rebound of North America.

Our analysis focuses on the plane's vertical position, with reference to its longitudinal and latitudinal positions as well. To compare these positions over time, we used the Kolmogorov-Zurbenko (KZ) filter for both spectral analysis and the application of the moving average. The KZ function was key to this analysis because it has been previously observed that a low signal-to-noise ratio may mask significant trends and in various time scales (Zurbenko and Sowizral, 1999). The low signal-to-noise ratio does not necessarily consist mostly of noise, but components such as other physical phenomena with significant variance. An application of a low-pass filter may eliminate such interferences to reveal the existence of trends over different time scales (Marsellos et al., 2020). The time series decomposition using the Kolmogorov–Zurbenko (KZ) filter provides adequate separation of frequencies in the time series data, and it has been applied in many environmental applications (Eskridge, et al., 1997; Ward, 2007; Tsakiri & Zurbenko, 2011; Tsakiri & Zurbenko, 2013). The KZ filter provides a simple design and allows a physical interpretation of all the time series components (Zurbenko, 1986; Wikipedia KZ Filters). The KZ filter provides the best and closest results to the optimal mean square of error. Also, it allows effective separation of frequencies for application directly to datasets with missing data (Close & Zurbenko, R-CRAN package "KZ").

Methodology

To complete our research, we used R programming language to assess the Nevada Geodetic Laboratory's Global GPS Network. We retrieved data of all GPS sites (MNP1, MOR6, NYBK, NYBR, NYCI, NYCO, NYDP, NYEL, NYJM, NYQN, NYRH, QYNS, SG06, ZNY1) in Long Island. Out of all the GPS sites on Long Island, as seen in Figure 1, four GPS sites (NYCI, NYQN, NYRH, and ZNY1) were the only ones that spanned approximately the past 15 years other than MOR6. Despite the fact that MOR6 fit the desired time frame, we did not utilize it because there was a significant number of missing data. The locations of the GPS sites can be

seen in Figure 2, and the sites we used are shown in red. The software RStudio was used to run the data as explained below.
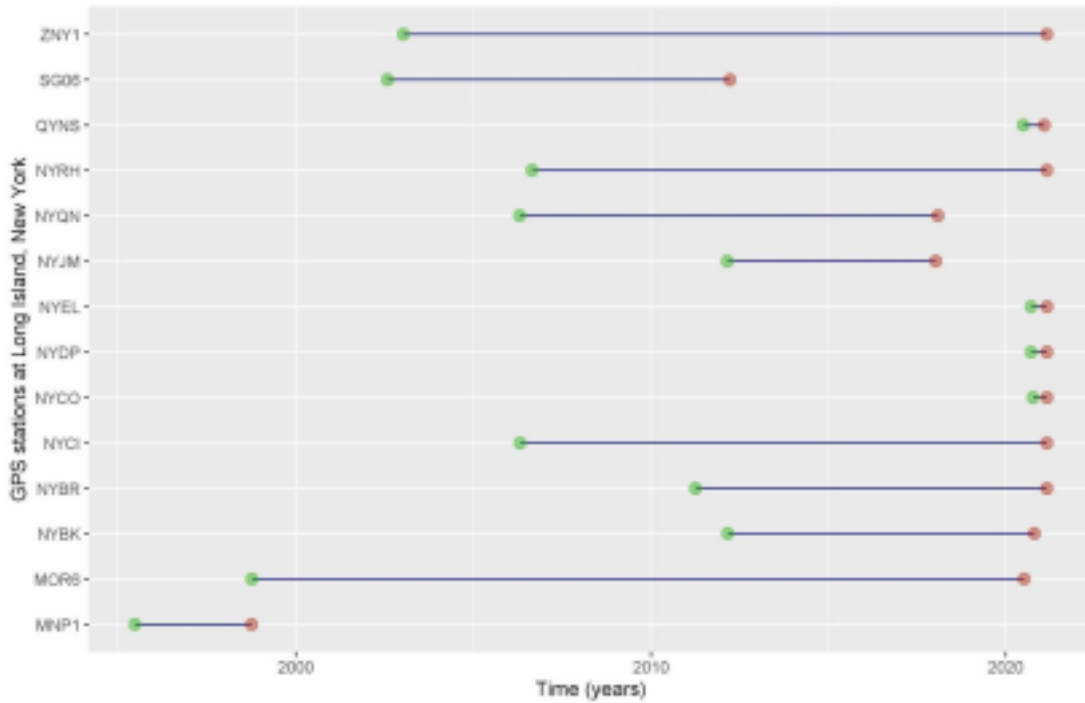

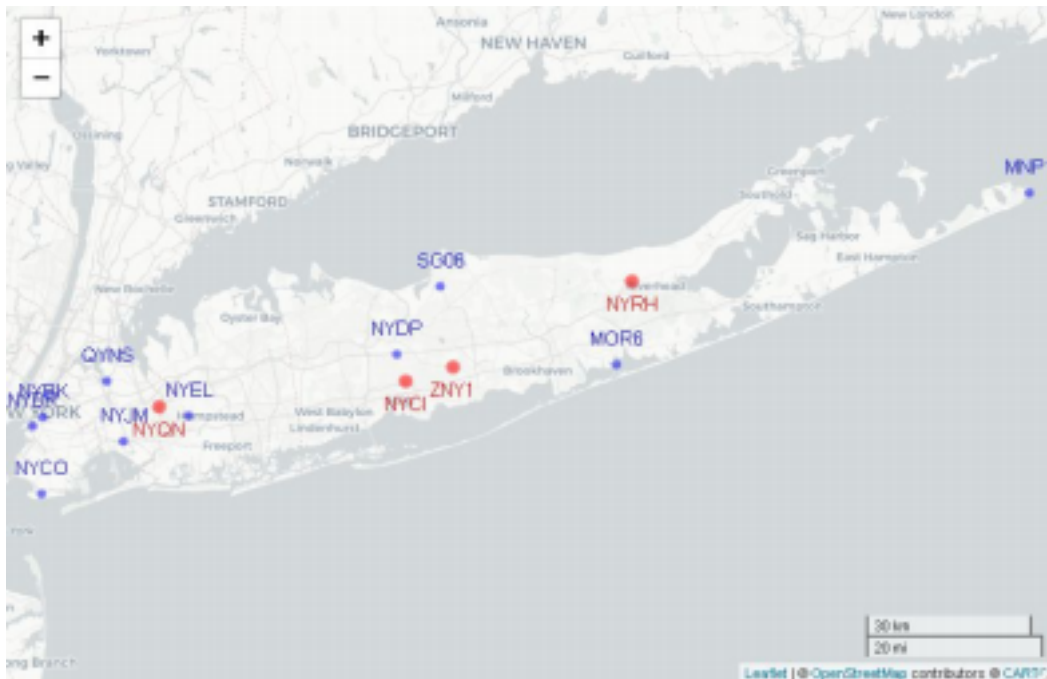*Figure 1: Span of all GPS sites' data in Long Island, NY*

Figure 2: Map of GPS sites on Long Island, NY (the red represents the GPS sites that were used in our

research while the blue are the sites that had a shorter span of data or too many holes and were therefore not used)

We first created a data set of the northward, eastward, and upward movement of all four GPS sites. There were outliers in all the individual data sets, which were removed using the z-score function in R with a range of -3.0, 3.0. The formula applied to find the z-score is as seen in expression (1):

$$Z = \frac{x - \mu}{\sigma}$$

(1)

Periodograms were developed using the raw data from each GPS site and the "periodogram" function of the TSA package, and the highest observed period was selected to eliminate the higher frequencies. The higher frequencies were removed using the moving average function (KZ).

To decide on the size of the moving average window, we performed a spectral analysis of the sites using periodograms of the raw data from each GPS site to find the cycles or noise created by atmospheric and ionospheric interference. We used the periodograms to identify the high and low frequencies and to determine the size of the moving average window size and filter out everything but the low frequencies. We then normalized the data and applied a KZ filter using this window. The KZ filter is a low-pass filter, and has been applied with three repeated iterations (p) of a simple moving average of (m) points. The moving average of the KZ filter is provided by expression (2):

$$Y_t = \frac{1}{m} \sum_{j=-k}^{k} (X_{t+j})$$

(2)

where $m = 2k + 1$. The output of the first iteration becomes the input for the second iteration, and so on. The time series is produced by p iterations of the filter described above, and it is denoted by the following expression (Eq. (3)):

$$Y_t = KZ_{m,p}(X_t)$$

(3)

The filtered and standardized data can be seen below the "normalize()" function was used with the method as the new standard data for each of the GPS sites. Since we are focusing on the vertical movement of Long Island and what may be contributing to it, we need to see how closely correlated movement up, north, and east are to one another. To do so we created a basic correlation matrix for each of the GPS sites that focused on the vertical, longitudinal, and latitudinal movement of Long Island. Table 1 shows the correlation matrix of each of the sites. Additionally, we used simple linear regression with the "east" and "up" values to check the p-values and the coefficient determination (R^2) between each component (north, east, up) of the

sites.

Results

Outliers appear to occur at a very short time, specifically at GPS sites NYCI in 2011, 2012, and 2014, NYQN in 2014, 2015, and 2017, NYRH in 2014, 2015, 2016, and 2017, and ZNY1 in 2004 and 2007 (Figure 3). Those outliers are eliminated as explained in Methodologies. As can be seen in Figure 4, we only eliminated the necessary data points.
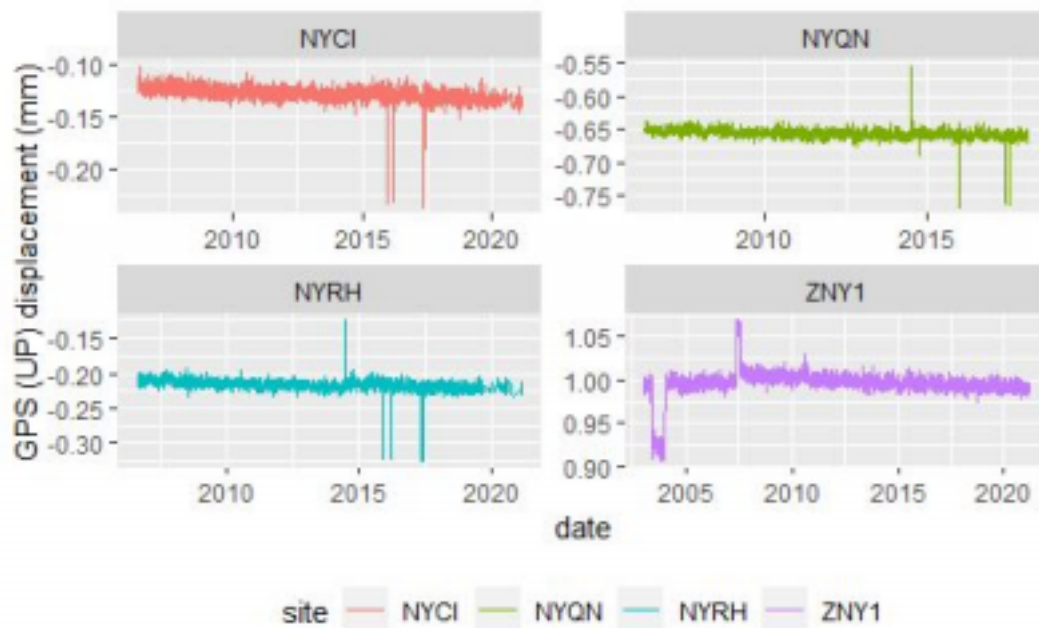

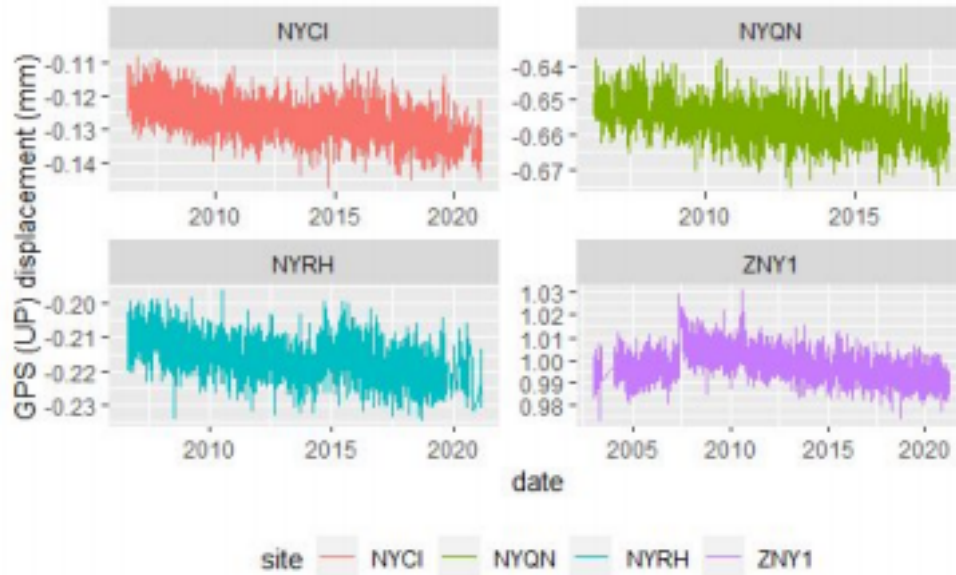*Figure 3: Raw data of displacements (in mm) from the selected GPS sites that include outliers*

Figure 4: Raw data of displacements (in mm) from the selected GPS sites in which outliers have been excluded using a z-score (-3,3).

The periodograms show a series of high frequencies and low frequencies. We haven't identified all the high frequencies due to the sheer amount, as well as the fact that they simply create noise that makes the overall trends unclear. Figure 5 shows that there is a pattern of periodicities in most of the GPS sites at around 183 days, 365 days, and 730 days in addition to the other numerous high frequencies. By making our moving average window for the KZ filter with a width of 730 days and 3 iterations, we filtered out everything but the low frequencies in order to see the long-term trends.
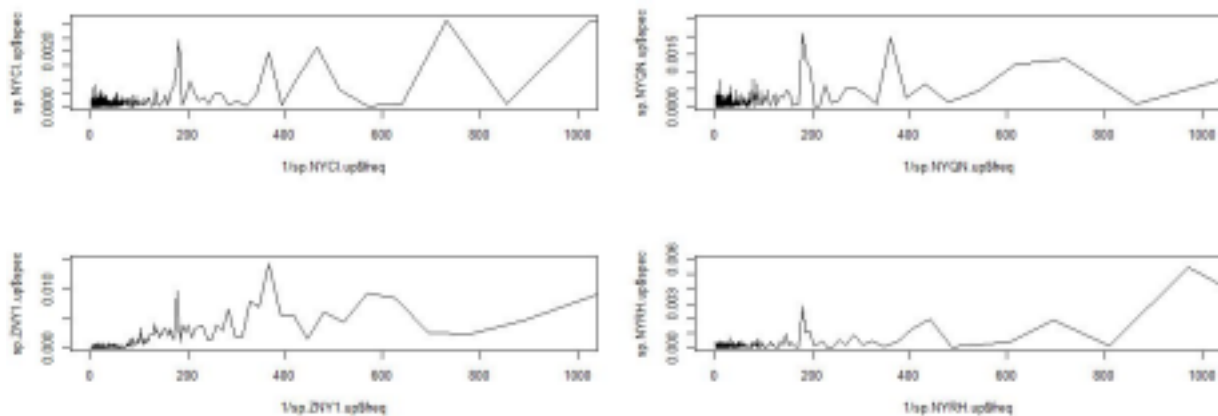

Figure 5: Spectral analysis of the selected GPS sites. The horizontal axis is the period in days.

All sites show a northwestern velocity consistent with the regional GPS velocity of the northwestern part of North America. The up component at all sites is weakly correlated with the east or north components, while the correlation between the east and north components is very

strong (Table 1).

Table 1: Correlation matrix of the components (north, east, up) for each GPS site

	site	ENU	Cor.east	Cor.north	Cor.up
	<chr>	<chr>	<dbl>	<dbl>	<dbl>
1	NYCI	east	1	-0.997	0.489
2	NYCI	north	-0.997	1	-0.491
3	NYCI	up	0.489	-0.491	1
4	NYQN	east	1.00	-0.992	0.372
5	NYQN	north	-0.992	1	-0.358
6	NYQN	up	0.372	-0.358	1
7	NYRH	east	1	-0.995	0.459
8	NYRH	north	-0.995	1	-0.454
9	NYRH	up	0.459	-0.454	1
10	ZNY1	east	1.00	-0.996	-0.111
11	ZNY1	north	-0.996	1	0.0692
12	ZNY1	up	-0.111	0.0692	1

Comparing the GPS data after it has been standardized and the KZ filter is applied reveals an overall pattern of subsidence taking place on Long Island (Figure 6). GPS sites NYCI, NYQN, NYRH, ZNY1 show a downtrend of 0.01 mm per decade. The east, north, and vertical components of Long Island GPS sites are shown to be behaving uniformly from a long-term perspective and any instances of uplift motion related to glacial melt and isostatic rebound were not present given the time series. However, all the analyzed sites show a significant temporal uplift during the 2013-2015 interval despite the overall downward trend.
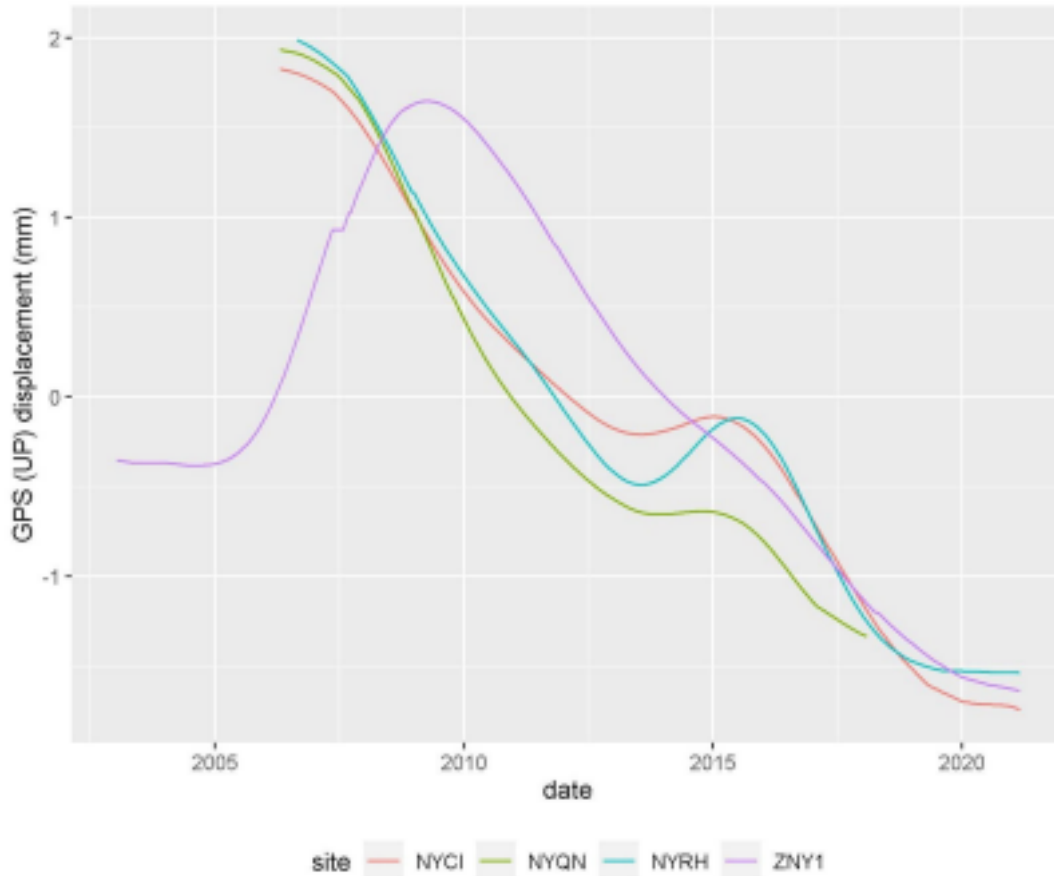
Figure 6: Displacements (in mm) of the up component from the GPS selected sites NYCI, NYQN, NYRH, and ZNY1 after being averaged by the KZ moving average function with a window size of 730 and 3 iterations. Data were standardized to fit at the same scale.

Discussion

Our study shows no evidence of a prevailing tectonic isostasy of uplift due to glacial melt. By eliminating the outliers, we precisely and accurately determined the long-term trends. External factors influenced the raw data, and the application of the moving average function (KZ) has eliminated the high frequencies from the long-term trends. The implications of the study are that Long Island's glacial isostatic adjustment has not applied during the GPS logged

interval, suggesting the end of such a process in comparison to the northern latitudes of North America as previous studies have shown (e.g., Sella et al., 2004).

Monitoring the glacial isostatic adjustment or any vertical displacement of the island is vital to understanding the relative impact of sea level rise. Utilizing GPS coordinates allows us to notice any significant patterns or changes. However, we have not proceeded to further decomposition of higher frequencies and related short-term patterns. Short-term variations of GPS data may include but are not limited to major causes of GPS outliers such as multi-paths,

non-line of sight signals, or overhead foliage. Therefore, while seasonal-term frequencies and/or short-term frequencies caused by moon cycles were erased using the KZ filter, there may be factors not discussed such as tectonic activity or sunspots that may have affected the trends of the data. The possible correlations between such factors and the movement of Long Island were not explored.

The weak association of the up component with both east and north GPS components may be associated with noise caused by atmospheric, ionospheric or other geological and atmospheric phenomena causing interferences. However, the application of a moving average eliminates those high-frequency interferences. Our research has primarily focused on long-term trends, consequently, a moving average of a large window is more useful. A large moving average window is necessary for eliminating higher frequencies and increasing signals on the long-term trends of this glacial isostatic adjustment study. We chose 730 day intervals over 365 day intervals because the lowest frequency detected by the spectral analysis was 730 days. However, the spectral analysis has indicated few low frequencies with periods of less than 730 days such as 365 days and 183 days.

Conclusion

Applying a low-pass filter has facilitated the deletion of high-frequency GPS oscillations caused by either atmospheric, ionospheric, gravitational effects or other exogenic factors. Long-term variations of the vertical GPS component shows a consistent downtrend, and implies the subsidence of the Long Island region, while also confirming no presence of an uplift caused by glacial isostatic adjustment. All GPS sites show a consistent northwestern motion and a vertical component being weakly related to east and north components. The elimination of higher frequencies on the vertical component has revealed a continuous downtrend implying a subsidence at the region with an intermittent single interval of an uplift during the 2013-2015.

Credit authorship contribution statement

Moore, M.: R coding, conceptualization, writing- Methodology plus part of References and Results, editing, data curation and analysis; Brown, R.: Abstract writing, results writing, conceptualization; Thomas, M.: R coding, editing, data analysis, writing- Discussion, part of References; Santella, K.: R coding, data curation and analysis, conceptualization, writing -

Introduction, part of Abstract, part of Results, part of References, editing; Ballato, B.: conceptualization, writing, editing, part of abstract, part of introduction, part of conclusion, R coding; Marsellos, A.: Supervision, Conceptualization, R coding, editing, writing; Tsakiri, K.G.: R coding, writing - Methodology

References

Bogusz, J, Klos, A, Pokonieczny, K, 2019. Optimal Strategy of a GPS Position Time Series Analysis for Post-Glacial Rebound Investigation in Europe, Remote Sensing 11, no. 10: 1209.

Close, B.; Zurbenko, I. Kolmogorov-Zurbenko Adaptive Filters. Available online: http://cran.r-project.org/web/packages/kza/index.html. March 16, 2021.

George, N.V., Tiampo, K.F., Sahu, S.S., Mazzotti, S., Mansinha, L., Panda, G., 2012. Identification of Glacial Isostatic Adjustment in Eastern Canada Using S Transform Filtering of GPS Observations, Pure and Applied Geophysics, 169 (2012), pp. 1507-1517.

Marsellos, A.E., Hantzis, K.D., Tsakiri, K.G., 2020. How to remove the seasonal atmospheric effect: An application on a surface volcanic temperature at Nisyros active volcano, Hellenic Volcanic Arc, Journal of Volcanology and Geothermal Research, Volume 407.

Sella, G., Stein, S., Wdowinski, S., Dixon, T., Dokka, R., 2004, GPS observation of glacial isostatic adjustment in North America, *Cah. Cent. Eur. Geod. Seismol.*, 23, 105– 110. Sella, G., Stein, S., Dixon, T., Craymer, M., James, T., Mazzotti, S., Dokka, R., 2007. Observation of glacial isostatic adjustment in "stable" North America with GPS, Geophysical Research Letters, Volume 34, Issue 2.

Tsakiri, K.; Zurbenko, I.G., 2013. Explanation of fluctuations in water use time series. Environ. Ecol Stat. 20, 399–412.

Tsakiri, K.G.; Zurbenko, I.G., 2011. Prediction of ozone concentrations using atmospheric variables. Air Qual. Atmos. Health, 4, 111–120.

Wikipedia. Kolmogorov-Zurbenko Filters. Available online: http://en.wikipedia.org/wiki/Kolmogorov%E2%80%93Zurbenko_filter. March 16, 2021. Yang, W., Zurbenko, I., kzft: Kolmogorov–Zurbenko Fourier transform and application. R package, 2006.

Zurbenko, I.G., M. Sowizral, 1999. Resolution of the destructive effect of noise on linear regression of two time series, Far East J. Theor. Stat., 3, pp. 139-157.

Zurbenko, I.G. The Spectral Analysis of Time Series; Amsterdam North Holland Series in Statistics and Probability; Elsevier North-Holland: New York, NY, USA, 1986.