Case Study

Estimation of Glacial Rebound Effect by Vertical Velocity Analysis Method

Buzul Geri Çekilme Etkisinin Düşey Hız Analiz Metodu ile Tahmin Edilmesi

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Abstract

The physical phenomena occurring on the Earth, which has continous dynamic structure, changes slowly. Glacial withdrawal movements variations may also result from geodetic changes such as instabilities in the angular velocity of the world. Glacial Isostatic Adjustment models can be used to estimate gravitational field of earth and oceans' response to the growth and decay cycle of ice sheets. However, big data requirements of these models and approaches in their mathematical analysis, reveal the need for a simplified and less demanding model. The aim of this paper was to estimate the post glacial rebound effect by means of Global Positioning System campaign and positioning techniques. In this study, the linear trend of vertical velocity component was observed and the solid earth rises were estimated after ice sheet mass loss was investigated. In this direction, position time series of 34 International GNNS Service for Geodynamics stations with 24-hours period of 1995-2017 were used. By means of the MATLAB program, R^2 of velocities' vertical component were calculated by the least squares method. After this process, the spatial representation of the R^2 values on the earth was figured with "ordinary kriging" which is a geostatistics technique by using ArcGIS program. The generated map was compared with the map obtained by Milne's glacial isostatic adjustment model and the results were interpreted. The results present us that the post glacial rebound rates appears to be 88% compatible with the R^2 values.

Keywords: Glacial Isostatic Adjustment (GIA), ordinary kriging, Coefficient of Determination (R^2), Global Positioning Ssystem (GPS), glacial rebound effect

Öz

Sürekli dinamik yapıya sahip Dünya üzerinde oluşan fiziksel olaylar yavaşça değişim göstermektedir. Buzul geri çekilmeden kaynaklı hareketler dünyanın dairesel hızının değişimi gibi jeodezik değişimler neticesinde ortaya çıkabilmektedir Buzul İzostatik Dengeleme modelleri sayesinde yeryüzü yerçekim alanının ve okyanusların buzul tabakalarının büyümesine ve erimesine verdiği tepki net bir şekilde olmasa da hesaplanabilmektedir. Ancak söz konusu modellerin fazla veri ihtiyacı ve matematiksel analizindeki yaklaşımlar, daha basitleştirilmiş, daha az veriye ihtiyaç duyan bir model ihtiyacını ortaya koymaktadır. Çalışmanın amacı, Küresel Konumlama Sistemi kampanyası ve ölçüm değerlendirme yöntemleri ile buzul sonrası geri çekilme etkisinin tahmininin gerçekleştirilmesidir. Bu çalışmada, düşey hız bileşeninde gözlenen doğrusal eğilimin, buzul sonrası geri çekilmeden kaynaklı kabuk yükselişi ile korelasyonunun olup olmadığı araştırılmıştır. Bu doğrultuda, 1995-2017 yıllarına ait 24 saat oturum süreli 34 adet uluslararası GPS servisi istasyonuna ait hız zaman serilerinin kullanılarak MATLAB programı aracılığıyla en küçük kareler yöntemi ile R^2 değerleri hesaplanmıştır. Bu işlem sonrasında ise ArcGIS programı ile jeoistatistik tekniği olan "sıradan kriging" ile mekânsal ara kestirim yapılarak R^2 değerlerinin yeryuvarı üzerinde konumsal gösterimi elde edilmiştir. Elde edilen harita, Milne tarafından oluşturulan buzul izostatik ayarı modeli sonucunda elde edilen harita ile kıyaslanarak, sonuçlar yorumlanmıştır. Sonuçlar, buzul sonrası geri tepki oranlarının R^2 değerleriyle %88 uyumlu olduğunu göstermektedir.

Anahtar kelimeler: Buzul İzostatik Ayarı, sıradan kriging, Belirleme Katsayısı (R^2), Küresel Konum Belirleme Sistemi (KKS), buzul sonrası geri çekilme

Introduction

The Earth is constantly on the move and the physical events on it are slowly changing. For a several-thousand-year, the great mass of ice has pushed soil underneath the ice for half a mile in some parts of the Earth, so soil around the glacier has risen up to several hundred meters. Additionally, melting of ice sheets has increased the level of oceans. As a result of this phenomenon called post glacial rebound, soils under the ice have begun to rise again. The effects of glacial withdrawal are summarized in Figure 1. Although the large ice sheets in the Northern Hemisphere melt for a long time ago, the Earth's response to this event has been continuing even today. The rises of land masses after glaciers retreat in the East Coast and Great Lakes of the United States can be clearly observed.

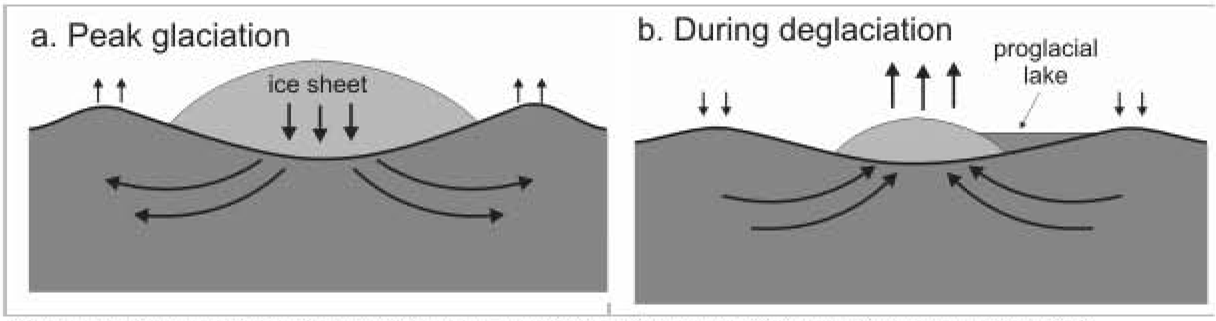


Figure 1. Glacier withdrawal (Courtesy of Tom James at Natural Resources Canada).

Glacial Isostatic Adjustment (GIA) refers to the response of the earth to the gravitational field and the oceans to the growth and melting of ice layers. The widely studied component of GIA is rising of the solid earth after the melting of ice layers. GIA, which is a relatively fast process, triggers up to100 m changes on earth and sea from sea level.

Changes caused by glacial movements can be monitored by GIA models. Global Positioning System (GPS), a geodetic dataset, Interferometric Synthetic Aperture Radar (InSAR) Altimeter and tide indicator data are used to measure surface deformation associated with GIA (King et al., 2010). The Earth's crust, oceans and ice sheets are considered as three main components of model calculations on a global scale. GIA models are designed for solving the classical geodynamic problems of solid earth responses against to the ocean and ice loading. The models also determine self-consistent redistribution of meltwater gravitationally in the ocean throughout the world.

Many GIA models have been developed by prominent researchers in this field. Peltier was at the forefront of developing the GIA's theory in the late 70s and early 80s. He has pioneered the development of finite element analysis and numerical analysis solutions to sea level equality (Peltier et al.,1976). Shennan and Milne have developed highly accurate methods to solve the sea level equation. Methods were used to investigate and explain various geophysical phenomena (Milne et al.,2013). Lambeck also developed a model for solving the sea level equation of coastal line calculation, which is a more complex process, as well as ice and ocean loading (Lambeck et al.,1998). Wu used the finite element method for modeling isostatic deformation and sea level changes associated with GIA. His studies were generally conducted on the effects of observed GIA, and the structure and rheology of Earth (Wu et al.,2005). Kaufman investigated the Earth's crustal movements, the effects of this movement and GIA observations. Those observations were used to predict the viscosity of the Earth's layers (Kaufmann et al.,1998). The German Geological Research Center in Potsdam pioneered the development of spectral finite differences. The viscoelastic response of the earth was investigated by using the finite element methods to calculate the 3-D viscosity structure of the surface loading. Additionally, Zong, Paulson and Wahr analyzed the rebound after the glacial, examined the viscous mantle convection problems using the finite element model (Zong et al.,2003). Sabadini, Gasperini, Giunchi, and Spada investigated the effects of GIA on the lateral structure of the Earth's crust (Gasperini et al., 1990; Giunchi et al., 1997). Vermeersen has developed “Analytical Normal Mode” method for viscoelastic loosening in the Earth's crust due to surface loading (Vermeersen et al., 1996). Fjeldskaar used the Fourier Transformation Method with a realistic glacier melt model to calculate the loading response against surface loading. He used the simple half space model, consisting of a viscous mantle covered by an elastic lithosphere. (Fjeldskaar et al., 1997).

As mentioned above, many models in the literature have been used to monitor the glacial withdrawal effects. In order to collect data and operate these models effectively, there is a need to establish fixed base stations where glacial retreat can be observed. Financing these type of investments with high cost is not always possible. Also operation of these establisments needs so much money and time.

In the current situation, the stations for monitoring of the GIA effects are constructed only at the designated points where have a high probability of glacial movement. Thus, GIA models may not model glacial effects for other points on the Earth efficiently. In addittion some parameters can not be clearly defined in models. For example, horizontal speeds at GPS receivers are more accurate than vertical ones, but it is necessary to remove the plate movement value from the speed outputs of the GIA model. Neither the plate movement nor the GIA effects can be fully calculated. Hence this issue can not be grasped so easily (King et al., 2010).

This study’s aim was to establish a simple method not to use large amount of data on same scale as the models really need and to monitor glacial effects with the minimum cost. In this study, the regions where glacial effects can be observed, are modeled with minimum data by using the vertical speed analysis method.

Research and Method

Satellite technologies and Global Navigation Satellite System (GNSS) are used commonly for areas where surface displacement and strain due to tectonic movements are detected. One of the most effective method to monitor crust displacements and movement is using permanent stations which can measure the surface movement continuously. It is not always possible to access to fixed ground-based stations’ data, therefore campaign measurements are usually made at regular intervals. The speed vectors are obtained by evaluating these GPS campaigns. The velocity vectors provide information to interpret crustal movements of the region (Baysal et al., 2010).

International GNNS Service for Geodynamics (IGS), which provides high quality data and products in the GNSS standard, supports world science researches and multi-disciplinary applications. In this study, it was aimed to estimate the rise of the Earth’s crust due to glacial rebound with using position time series of IGS stations by GPS campaigns. In GPS observations high accuracy of positioning is important concept. Therefore, position time series of IGS stations are obtained by Precise Point Positioning technique (PPP) which removes GNSS system errors to provide high level of position accuracy up to 3 centimeters.

Figure 2 showed the IGS stations, chosen for the operation of this study. GPS vertical component time series data of thirty four IGS stations with 24-hours period were used in the study for years between 1995-2017.

Figure 2. IGS points (prepared by author).

Geodetic point velocity information with high accuracy has of great importance in studies such as modeling of crust movements, fault systems and tectonic movements deformation. For coordinate time series analysis there is a need to have accurate speed estimation. Many different mathematical models are used in coordinate time series analysis. The mathematical model, shown in equation 1, is used in this study. This equation is a simplified version of annual signal dominant equation. The explicit form of equation was shown in equation 2 & 3. For the velocity estimations, "Multiple Linear Regression Analysis" method was used. The unknowns in the mathematical model were obtained by the Least Squares Method taking into account the annual linear trend and seasonal periodic effects. The MATLAB program was used for the evaluation of the mathematical method.

The most common mathematical model;

$$y(t) = y_0 + v(t - t_0) + \sum g(t, y) + \varepsilon(t) \quad (1)$$

$y(t)$: time series observation vector,
t_0 : initial observation epoch of time series,
y_0 : initial coordinate value of time series at time t_0,
$v(t)$: other geophysical factors that affect the station linear velocity g (t, y) station speeds,
$\varepsilon(t)$: error term,
$g(t, y)$: periodic and non-periodic effects, where

$$\sum g(t, y) = \sum_{j=1} a_j \sin(2\pi f_j t_i) + b_j \cos(2\pi f_j t_i) + \varepsilon_j(t_i) \quad (2)$$

f_j : seasonal effect

a_j, b_j : coefficient amplitudes of seasonal effect

When seasonal effects are taken into account, equation 1 transformed to equation 3,

$$y(t_i) = y_0 + vt_i + \sum_{j=1} a_j \sin(2\pi f_j t_i) + b_j \cos(2\pi f_j t_i) + \varepsilon(t_i) \quad (3)$$

As a result of the evaluation of the equation 3 with the MATLAB program, R^2 values were obtained which give information about the linear trend in the vertical component. The R^2 value approaches "1" if the equation results are closer to observed values. The equation 4 of R^2 defined below.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \hat{v}_i^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} = 1 - \frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (4)$$

x_i : observed value
$\hat{x}_i$: value obtained from equation from regression equation
$\hat{v}_i$: residual value
$\bar{x}$: the average of the observed values

The IGS points shown in Figure 2 were spatially distributed over the entire Earth, but these points only give information about certain regions and positions. To define R^2 values for the entire Earth, "kriging" method as a geostatistical interpolation method has been used. It uses interpolation techniques for the non-measured points to define value from the measured points at the neighbouring locations by a linear combination. In the study, kriging method was used for transforming a continuous surface displacement by using a function that passes over or near the points representing tectonic movements. R^2 values were obtained by using ordinary kriging method on the ArcGIS® program. Mathematical formulation of ordinary kriging method is shown in equation 5.

$$Z(X_0) = \sum_{i=0}^{N} W_i \, x \, Z(x_i) \quad (5)$$

$Z(X_0)$: estimated Z value at X_0 point,
W_i : $Z(X_0)$'s weight values for each $Z(x_i)$ used in the calculation,
$Z(x_i)$: the empirical data used to estimate $Z(X_0)$
N : $Z(X_0)$ is the number of points used in the calculation.

Results and Discussions

R^2 values of the IGS stations' velocities' vertical components showed a constant trend over time. In the study, the trend component was important in terms of revealing the correlation between the rise of the shell and the glacial retrieval. The coefficient of determination values were interpreted as the ratio of changes in the prediction explained by the model. It has a value ranging from 0 to 1. R^2 value explains the variability of the predicted value (Y or Z) entirely by the model. Therefore it shows the suitability of the model for each measurement. In other words, if R^2 is 0, it indicates that the model does not disclose any variability in the estimation. The R^2 value greater than 0.50 is generally considered to be a significant correlation. Table 1 showed the R^2 values obtained from the Least Squares Method.

Table 1
R^2 Values Obtained From The Least Squares Method (Prepared By Author)

Station	City	Lat.	Lon.	R^2	Station	City	Lat.	Lon.	R^2
AIRA	Aira	31.82	130.60	0.81	**NKLG**	Libreville	0.35	9.67	0.08
ALRT	Alert	82.49	-62.34	0.94	**NYAL**	Ny-Alesund	78.93	11.87	0.98
AREQ	Arequipa	-16.47	-71.49	0.45	**ONSA**	Onsala	57.40	11.93	0.86
BAKE	Baker Lake	64.32	-96.00	0.98	**ORID**	Ohrid	41.13	20.79	0.1
BARH	Bar Harbor	44.40	-68.22	0.03	**PALM**	Palmer Station	-64.78	-64.05	0.94
BLYT	Blythe	33.61	-114.71	0.11	**PETS**	Petropavlovsk-Kamchatka	53.02	158.65	0.89
CEDU	Ceduna	-31.87	133.81	0.28	**QIKI**	Qikiqtarjuaq	67.56	-64.03	0.91
CHUM	Chumysh	43.00	74.75	0.38	**RABT**	Rabat	34.00	-6.85	0.49
CHUR	Churchill	58.76	-94.09	0.99	**RAMO**	Mitzpe Ramon	30.60	34.76	0.5
EBRE	Roquetes	40.82	0.49	0.12	**RESO**	Resolute	74.69	-94.89	0.96
HOFN	Hoefn	64.27	-15.19	0.98	**SALU**	São Luis	-2.59	-44.21	0.55
HOLM	Ulukhaktok	70.74	-117.76	0.8	**SCOR**	Scoresbysund	70.49	-21.95	0.85
IQAL	Iqaluit	63.76	-68.51	0.77	**SYOG**	East Ongle Island	-69.01	39.58	0.28
KOUG	Kourou	5.10	-52.64	0.46	**THU2**	Thule Airbase	76.54	-68.83	0.96
MAL2	Malindi	-3.00	40.19	0.4	**TIXI**	Tixi	71.63	128.87	0.32
MATE	Matera	40.65	16.70	0.53	**TRO1**	Tromsoe	69.66	18.94	0.89
NAIN	Nain	56.54	-61.69	0.91	**URUM**	Urumqi	43.59	87.63	0.63

The map in Figure 3 was generated with the R^2 values of the IGS stations in the Table 1. In the study, the accuracy of the findings compared with the map, which was published in the Quaternary Encyclopedia of Science (Milne, 2013), accepted by many researchers (Bell, M., 2014; Clark, P. U., 2002; Lambeck, K., 2002), and showed the regions affected by glacial retreat.

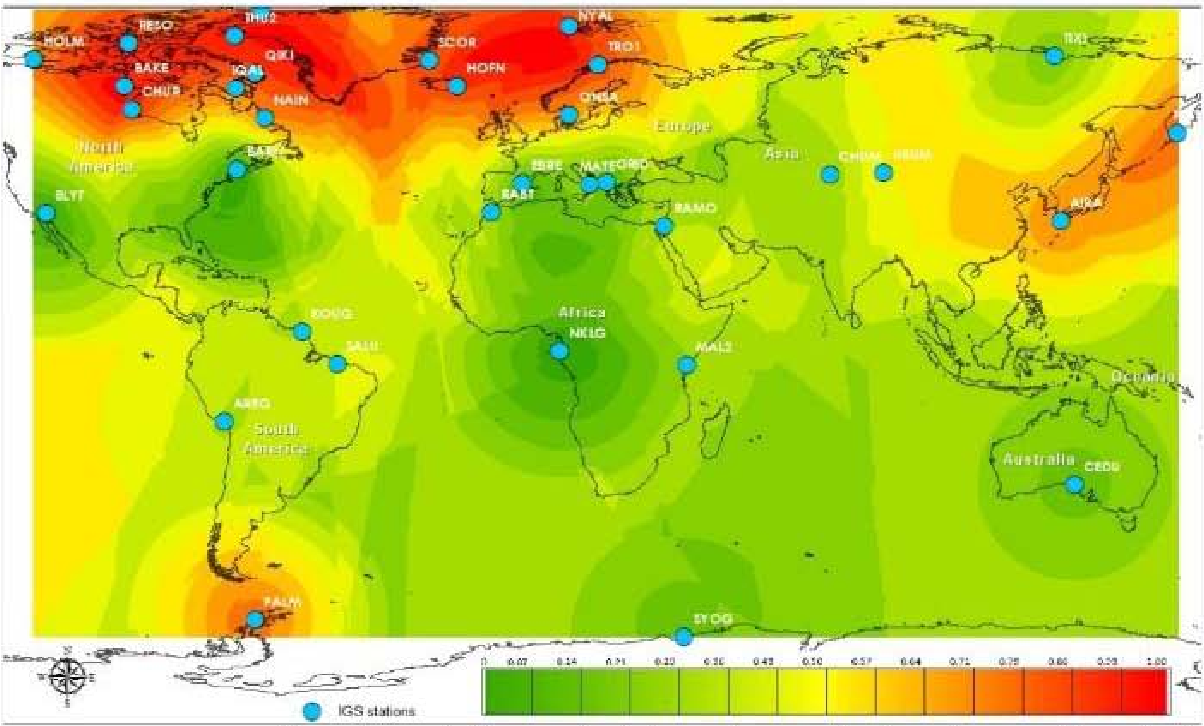


Figure 3. Map created by ordinary kriging method depending on R^2 values (prepared by author).

When the R^2 value were examined, it was found that the regions, R^2 values close to 1, were the continents of South America, Northern Europe and Antartica affected by glacial retreat. The map of Milne was used for the correctness of this inference. The regions in his map were coordinated by using Georeferencing Method (Figure 4) in ArcGIS Program. Glacial retreat rates of 34 IGS points were overlapped with the values in the his map. All R^2 values that corresponded with the rates, were found approximately (Figure 5).

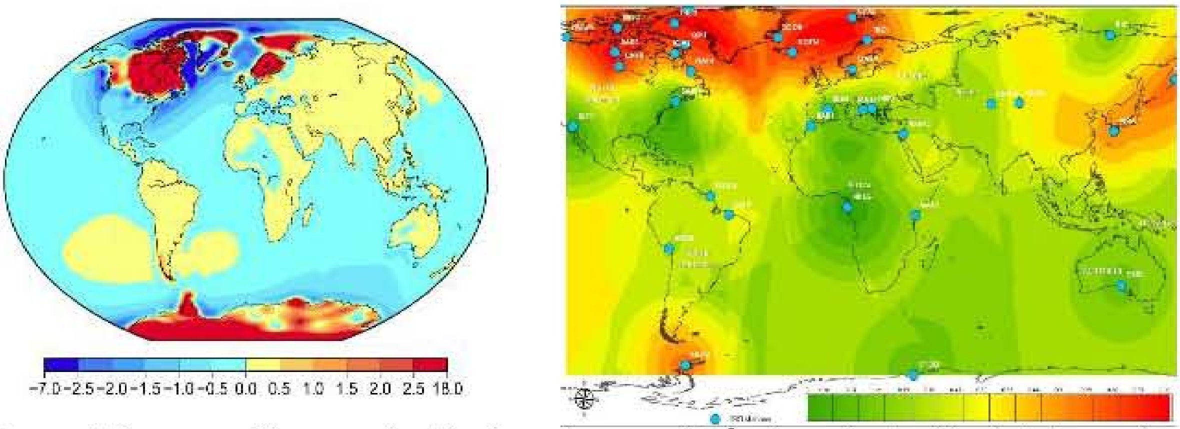
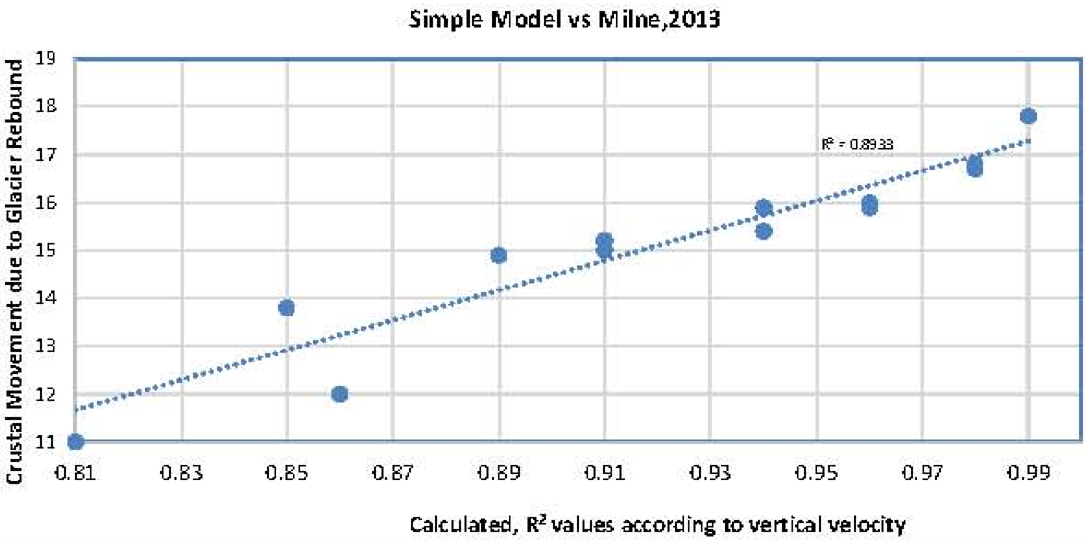


Figure 4. The map of the post glacial rebound rates and R^2 values obtained by kriging method (Milne, 2013).



Site	AIRA	ACRT	BAKE	CHUR	HOFN	NYAC	PALM	PETS	QIKI	RESO	SCOR	THU2	TROI	NAIN	ONSA
R2	0.81	0.94	0.98	0.99	0.98	0.98	0.94	0.89	0.91	0.96	0.85	0.96	0.89	0.91	0.86
glacial	11	15.9	16.8	17.8	16.8	16.7	15.4	14.9	15	16	13.8	15.9	14.9	15.2	12

Figure 5. Map created by Milne 2013 with using GIA models (prepared by author).

The model proved that the IGS stations which have high R^2 values for velocity component was compatible with post glacial rebound in the study of Milne. It was calculated that the similarity of maps was close to 88%. This result showed that it is possible to detect and investigate glacial effects in any region on the Earth with monitoring only vertical speed.

Despite glacial movements modeling is popular subject among researchers, the glacial withdrawal effect cannot be easily predicted still. As it is well known, the basic approach of modeling is that the simple model is the best model. We can evaluate the model of the study as the best one, as it gives a chance to researchers to follow the post glacial rebound effect in a short period of time with low cost.

There is a need to carry out further comprehensive studies on the measurement of post glacial rebound effects such as vertical crustal motion, global sea levels which are substantial terms of any study. Acknowledgement

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Extended Turkish Abstract
(Genişletilmiş Türkçe Özet)

Buzul Geri Çekilme Etkisinin Düşey Hız Analiz Metodu ile Tahmin Edilmesi

Dünya sürekli hareket halindedir ve üzerinde oluşan fiziksel olaylar yavaşça değişim göstermektedir. En son buzul çağında Dünya'nın bazı kısımlarında oluşan milyon tonluk buzul tabakaları buzulların altındaki toprakları yarım kilometreye kadar iterken buzul çevresindeki toprakların da birkaç yüz metre yükselmelerine neden olmaktadır. Buz tabakalarının erimesiyle oluşan su okyanuslara akarak deniz seviyesini yükseltmekte, bunun neticesinde buzul geri çekilme etkisi olarak adlandırılan olay oluşmakta, buzun altındaki topraklar tekrar yükselmektedir. Kuzey Yarımküredeki büyük buzul tabakaları uzun zaman önce erimelerine rağmen, yerkürenin bu olaya tepkisi, bugün bile devam etmekte,. Kuzey Amerika'da da bu etki net bir şekilde gözlemlenmektedir. Özellikle, Amerika Birleşik Devletleri'nin doğu kıyısı ve Büyük Göller bölgesinde buzul etkisi ile kabaran topraklarda, çökme hareketinin devam ettiği net bir şekilde tespit edilmiştir.

Buzul İzostatik Dengeleme (Glacial Isostatic Adjustment-GIA) yeryüzü yerçekim alanının ve okyanusların buzul tabakalarının büyümesine ve erimesine verdiği tepkiyi ifade etmektedir. GIA'nın yaygın olarak incelenen bileşeni, buzul erimesini takiben arazi yüzeyinin tekrar yükselerek eski seviyesine gelmesi ile ilgili olan "buzul sonrası geri çekilme" dir. Nispeten hızlı bir süreç olan GIA, okyanus seviyesinde 100 m lik değişimleri ve yeryüzünün deformasyonunu tetiklemektedir.

Buzul geri çekilme etkisinin izlenmesi için kullanılan birçok model literatürde yer almaktadır. Bu modellerin etkin çalışabilmesi için birçok veriye ve tepkinin net bir şekilde ölçülebilmesi içinde buzul etkisinin gözlemlenebileceği yerlere istasyon kurulma ihtiyacı bulunmaktadır. Söz konusu ihtiyaçların giderilmesi ise uzun bir zaman dilimi ve fazla mali kaynak harcanmasını gerektirdiğinden, bu modellerin her zaman kullanılması mümkün olamamaktadır. Mevcut durumda GIA etkisini izleyen istasyonlar sadece buzul hareketleri belirlenen noktalarda kurulduğundan, modeller farklı noktalarda buzul etkisinin olup olmadığı konusunda net bir sonuç verememektedir. Ayrıca modellerde bazı hususlar tam olarak ortaya konamamaktadır. Örnek vermek gerekirse, yatay Küresel Konum Belirleme Sistemi (KKS) hızları düşey hızlardan daha hassastır fakat GIA modelinin hız çıktıları ile karşılaştırıldığında GIA'nın hesaplanabilmesi için plaka hareketinin çıkartılması gerekmektedir. Ayrıca ne plaka hareketi ne de GIA tam olarak hesaplanamadığından kavranması güç bir durum olarak da karşımıza çıkmaktadır.

Global Navigasyon Uydu Sistemi (GNSS), nokta koordinatlarındaki değişim miktarının belirlenmesi, gerilimin tespit edilmesi ve tektonik hareketlere bağlı yüzey yer değiştirmesinin hesaplanmasındayaygın olarak kullanılmaktadır. Araştırma yapılacak alanda her zaman istasyon kurulması imkanı olmadığından Sabit Küresel Konumlama Sistemi (GPS) ile belli aralıklarla gerçekleşen kampanya ölçümleri, etkili bir araç olarak kullanılmaktadır. Bununla birlikte, GPS kampanyalarının değerlendirilmesiyle elde edilen hız vektörleri sayesinde yersel aktiviteler konusunda da bilgi elde edilebilmektedir.

Bu modellerin gereksinim duyduğu veri ihtiyacının minimize edilmesi, basit yöntemler ve minimum maliyetle buzul etkilerinin izlenmesi amacıyla bu çalışma ortaya konulmuştur. Bu çalışmada, seçilen örnek izleme noktaları sayesinde minimum veri ile buzul etkisinin ortaya çıkma ihtimalinin yüksek olduğu noktalar düşey hız analiz yöntemiyle modellenebilmektedir. Çalışmamızda, buzul geri çekilme etkisinden kaynaklı kabuk yükselişinin GPS kampanya ve ölçüm değerlendirme yöntemleri yardımıyla tahmini hedeflenmiştir. Örnek izleme noktalarının seçilmesinde Uluslararası GNNS Servisinden (*International GNNS Service for Geodynamics, IGS*) faydalanılmıştır. 1995-2017 yılları arasında yirmi iki yıllık zaman diliminde yirmi dört saat oturum süreli 34 adet IGS istasyonunun GPS düşey bileşenine ait zaman serisi verileri kullanılmıştır. Jet Propulsion Laboratory (JPL) tarafından değerlendirilerek GIPSYX yazılımı ile analizi yapılan ve yayımlanan bahse konu zaman serileri Hassas Nokta Konumlandırma (PPP) yöntemiyle elde edilmiştir. . Düşey hız öngörümünde: Yıllık doğrusal eğilim ve mevsimsel periyodik etkiler de hesaba katılarak "Çoklu Lineer Regresyon Analizi" ve "En Küçük Kareler" (EKK) yöntemi kulanılmış, değerlendirme ise MATLAB R2013a programı ile gerçekleştirilmiştir. IGS istasyonlarına ait R^2 değerlerinin zaman içinde sabit bir eğilim göstermesi, başka bir deyişle "doğrusal eğim bileşeni", buzul sonrası geri çekilmeden kaynaklı kabuk yükselişi arasındaki korelasyonun ortaya konması açısından önem arz etmektedir. Bu nedenle EKK yöntemi ile R^2 değerleri hesaplanmıştır. Sonrasında ise ArcGIS programı ile jeoistatistik teknik olan "sıradan kriging" ile mekânsal ara kestirim yapılarak R^2 değerlerinin yeryuvarı üzerindeki konumsal gösterimi elde edilmiştir. Elde edilen harita, Milen tarafından oluşturulan GIA modeli sonucunda elde edilen harita ile kıyaslanmıştır.

Ortaya konulan modelde R^2 değerlerinin yüzde 80 ve üzerinde olduğu bölgelerde, başka bir deyişle hızın sürekli olarak arttığı istasyonlarda, buzul geri çekilme ile R^2 değerlerinin %88 oranında uyumlu olduğu görülmektedir. Bu da sadece düşey hız izlenmesi ile dünya üzerindeki herhangi bir bölgede buzul etkileri tespit etmemize ve araştırmamıza imkan verecektir.

Buzul hareketleri modellemeleri çalışmaları yaygın olarak yapılmasına rağmen buzul çekilmesinin etkisi hala kolay bir şekilde hesaplanamamaktadır. Modelleme çalışmalarında temel kural en az veri ile en doğru sonuca yaklaştıracak modeli kurmak olduğundan, çalışmamızla elde ettiğimiz basit model ile araştırmacılar buzul sonrası geri tepme etkisini kısa sürede ve düşük maliyetle takip etmeleri mümkün olabilecektir. Düşey kabuk hareketi, manto taşınımı ve plaka tektoniği çalışmaları için önemli olan küresel deniz seviyeleri gibi buzul sonrası toparlanma etkilerini ölçmek içinse daha kapsamlı çalışmalar yapılması gerekmektedir.