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An Enhanced Seismic Activity Observed Due To Climate Change: Preliminary Results from Alaska

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Abstract. The impact of human induced climate change on the rising temperature cannot be neglected. According to the Intergovernmental Panel on Climate Change (IPCC) 2012 report, the mean temperature roughly rises up to 3 ℃ relative to 1990. Permafrost in Siberia and Alaska has started to thaw for the first time since it formed 11,000 years ago, has caused by the recent rise in temperature over the past six decades. The melting rate of glaciers has become significantly higher, causing a noticeable rise (0.19meters) in the sea level globally. Climate change can trigger catastrophes such as earthquakes, volcanic eruptions, tsunamis and landslides due to melting glaciers and rising in sea level. The melting of glaciers driven by global warming warns us of a seismically turbulent future. When glaciers melt, the massive weight on the Earth's crust reduces and the crust bounces back in what scientists call an "isostatic rebound". The process can reactivate faults and lift pressure on magma chambers that feed volcanoes, hence increases seismic activity. The paper discusses the correlation between rise in temperature due to global warming and earthquake frequency using Pearson's correlation coefficient and regression analysis based on a case study from Alaska.

1. Introduction

The global warming is not restricted to climate change, the entire planet is experiencing the consequences of disturbed energy balance. When we expand our context, it turns out that the dangers of global warming are far greater for humanity than implied by climate change. This disturbed energy balance could be in the form of an isostatic rebound, a volcanic activity or an earthquake.

The rise in mean surface temperature of air has become significant since at least the early 20th century globally, indicating the Earth surface is getting warmer [1]. According to NASA and NOAA most of the warming occurred in the past 35 years, with 15 out of the 16 warmest years on record have occurred since 2001 [2]. Since 1950 the warming rate of Alaska has reached to an alarming level of +5.3 ℉ per century which is faster than any other state in United States of America, by keeping margin of almost a full degree-per-century with the second place holder Minnesota's +4.4°F [3]. The warming rate of Alaska is more than double against the warming seen in the rest of United States. Warming in the winter has increased by an average of 6 ℉ [4] and has led to changes in ecosystems like, earlier breakup of river ice in the spring. As the climate continues to warm, average annual temperature in Alaska is projected to an additional 2 to 4 ℉ further increase by the middle of 21st century reported by U.S. Global Change Research Program [4].

The consequences of climate change lead to a lower sea ice extent (or area of ocean covered by ice) on record. For example according to National Snow and Ice Data Center 2014 report sea ice extent recorded in September 2014 was nearly 700,000 square miles which was less than the historical 1979-2000 average for that month - the difference is more than twice the size of Texas [5]. According to US

EPA 2015 annual report decline in the thickness and age of sea ice throughout the Arctic has been witnessed, with recent measurements indicating a loss of 50% of sea ice since 1979.

An enhanced volcanic activity has been observed due to deglaciation in Arctic has led to a hypothesis that the unloading of the glaciated ice in a volcanic terrains can increase volcanism through decompression melting in the shallow mantle or storage time reduction in crustal magma. Recently, the enhanced deglacial volcanic activity in Southeast Alaska sourced from Mount Edgecumbe Volcanic field has been correlated with the rapid isostatic adjustment, occurred following a retreat of regional glaciers [6]**.** The finding is consistent with the hypothesis that isostatic rebound is associated with ice-unloading which increases the volcanism [6], that can possibly influence the frequency of the earthquakes as well.

A certain earthquake is related to climate change? Surely not, but the earthquake activity can be linked to climate change, at least in a mountainous region where glaciers form and later they melt. The process introduces isostatic uplift and then will be a feedback between these processes [7]. Glaciation of mountainous areas introduce extra load on Earth's crust, which introduces stress in the crust. Depending on the rate of the isostatic uplift due to melting glacier and the composition of the underlying strata, these stresses can be released as landslides, ductile deformation and also as earthquakes. It may look ridiculous that climate change can affect the tectonic plate moment beneath the crust, but scientists like McGuire argue that it cannot just intensify disastrous events like cyclones, volcanoes, tsunamis but can trigger earthquakes as well.

2. Methods and study area

The work includes Alaska’s 42 years average temperature and earthquake data starting from 1974 to 2016 (Table 1). The annual temperature data in Table 1 is provided by *Alaska Climate Research Center*. The temperature data in Table 1 is an average of temperature data gathered from 250 different stations in Alaska. Whereas the earthquake data is obtained from USGS earthquake catalogue and have been categorized on the basis of magnitude (M_w) in Table 1.

The research adopts the following methodologies: a regional study; selecting the study region and information collection. For the purpose of this research, published reports and news articles, along with journal publications were the major sources of information. Initially *stacked line graph* was constructed using Microsoft Excel to look for trends and patterns in the earthquake data set, further, *Pearson correlation* was employed to verify the correlation between variables (temperature and earthquake frequency) according to the proposed hypothesis that the increased earthquake activity can be correlated to rising temperature. Pearson correlation is used to predict the causality between two variables based on correlation coefficient value r.

Alaska is located in the far northwest of North America. It shares border with Canada to the east, the Arctic Ocean to the north and Pacific Ocean to the south and west as shown in Figure 1. Alaska is known for its largely undeveloped land, mountains, glaciers, harsh climate, seismic activity and biodiversity. A recent research findings by Alaska Climate Research Center (ACRC) show that there’s some additional warming recorded in Alaska after 1976, marking a phase change of pacific decadal oscillation from negative to positive phase (Figure 2) [8]. Taking a linear trend in figure 2, an annual average temperature variations can be seen over the last 6 decades.

According to Alaska Volcanic Observatory (AVO) Alaska makes up about 80% of all active volcanoes in United States. Since 1760, 30 Alaskan volcanoes have had more than 240 confirmed eruptions with an average of 1 event per year. However for the past 40 years in Alaska on average more than two eruptions per year have been recorded [9].

Unluckily Alaska is an earthquake prone region and has more coastline than any other state in U.S. Reports suggest that around 75% of all major events recorded in United States of magnitude 5 and above on Richter scale happen in Alaska [10]. In fact, magnitude 6 and 7 can nearly happen anywhere (figure 3), whereas the most destructive events – magnitude 8 on Richter Scale and above primarily occur in shallow part of the subduction zone, where dense oceanic rocks of the Pacific thrust sink under the continental rocks of the Alaska. Figure 3 presents the historical earthquake record from 1970 to 2012, while other examples of high magnitude earthquakes happened in Alaska before 1970 include the most powerful and worst earthquakes ever hit North America named “1964 Good Friday

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Earthquake" of magnitude $9.2M_w$ and "Rat Islands Earthquake" of magnitude $8.7M_w$ in 1965, both have been categorized as second and eighth largest earthquakes respectively, ever recorded worldwide by USGS.

Figure 1. Regional map of Alaska

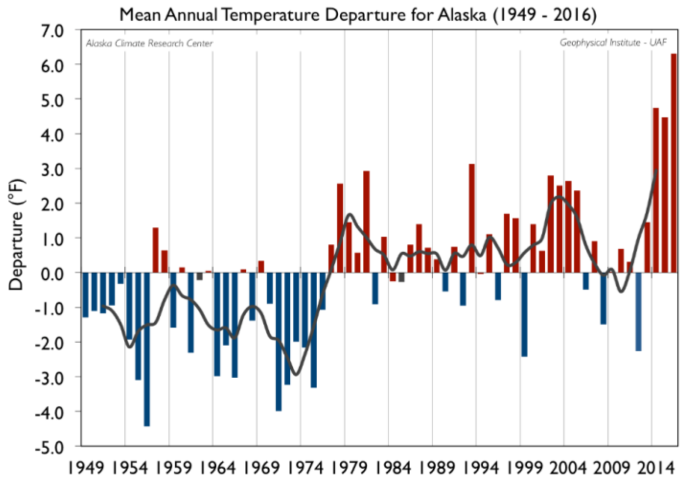

Figure 2. Mean annual temperature of Alaska Source: ACRC

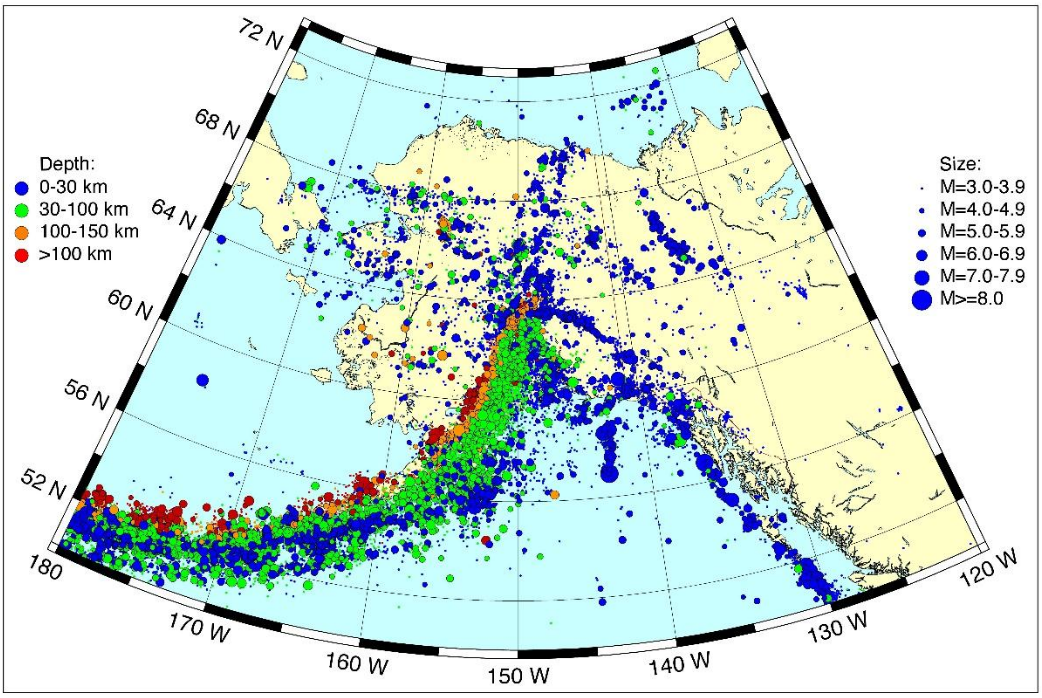

Figure 3: Historical map of earthquakes occurred in Alaska reported from 1970-2012, Source: AEC

3. Climate change and projected potential for seismic response

Climate change deserves a credit for its versatility. Global warming is not merely a fraction rise in the temperature over time, but these few degrees are and will continue affecting our human society and natural environment in the form of droughts, sea level rise, and floods if temperature continue to rise, however now seems it can influence another extreme class of events known as earthquakes.

U.S. Artic Research Commission reported [11] that the consistent rise in the temperature is a serious concern in Alaska and Arctic because often melting of glaciers and permafrost due to air and surface warming lead to ground destabilization as well as ecosystem changes. According to Sujib Kar [12] seismicity has been increasing due to global warming. Kar in an interview [13] said that "If you look at the number of earthquakes of magnitude 5 or more in Richter scale from 2001 to 2015 in earthquake-prone areas, you will be able to comprehend the dynamics. The rise of global temperature was phenomenal during this period". He further added that the total number of earthquakes recorded in 2001 with magnitude 5 or more on Richter scale across the globe were merely 157, whereas the numbers for same type of events occurred in 2015 were nearly ten times higher – 1556 [13]**.** The trend according to the proposed hypothesis shows that rising temperature due to global warming in Alaska might have contributed to the sharply increased cumulative earthquake frequency in recent decades.

Bill McGuire, a professor of geophysical and climate hazards at University College London, in his book entitled "Waking the Giant" argues that, if the present trend of climate change driven by human continue, the temperature and sea level will rise as compared to post-glacial period, it would be a surprise if some of the countless faults under the subsurface did not respond to the new distribution of global water certain to occur as world continue to heat up. He told India Climate Dialogue that "it's not a theory anymore, there is huge amount of evidence for the clear relationship between climate change and earthquakes particularly in Scandinavia and North America at the transition from the last Ice Age. The seismic response of ice unloading can clearly be seen in Alaska" [13]**.** McGuire [14] argues that when climate changed naturally in the past and planet emerged from an ice age, large ice sheets covering in much of the planet retreated. They were so heavy that the resulting release of pressure on the earth's crust caused it to '*bounce back*' triggering earthquakes, tremors and even volcanic activity [15] along preexisting fault lines. The last ice age occurred 20,000 years ago when temperature started rising caused large ice sheets to retreat, our earth is still responding to that ice age and the crustal bounce back rate has been modelled [16].

Earthquake and active volcanoes are interrelated for their same origin – tectonic disturbance. Generally when a volcano erupts it is very common for an earthquake to ensue. One can source the other, or both can occur at the same time because earthquakes are common around an active volcano and are usually triggered either by the moment of the magma beneath the earth surface or in response to strain exerted in an area of weak faults due to magma exclusion during volcanic activity. However such earthquakes in most cases are not of very high magnitude thus do not cause much damage directly.

4. Results and discussion

For earthquake data minimum earthquake magnitude picked is 2.5 on Richter scale, below 2.5 no events were considered. Table 1 witnesses a prominent temperature change of over +5 ℉ during the study period in Alaska. In addition the average temperature during last 15 years (33.4 ℉ – 0.77 ℃) has risen half a degree Celsius more than the temperature during first 15 years (32.5 ℉ – 0.27 ℃) whereas for the years in-between (1989 –2001) the average temperature noted is 32.97 ℉ – 0.54 ℃ which confirms the alarming rate of consistent temperature rise in Alaska during last 42 years.

Due to the unexpected rapid melting of glaciers, Alaska has already lost almost a vertical kilometer of ice cover due to which stresses on the underneath rocks are being released [17]. This removal of load in return causes the earth crust to rise upward due to *isostatic rebound* [18], the released stresses could deform the earth surface [19] causing earthquakes. It is to be noted in Table 1 that temperature is consistently rising with over 13 times increased earthquake frequency (cumulative frequency) during the study period. Almost every sharp rise in temperature in Table 1 has consequently increased the total number of earthquakes recorded for the particular period.

Table 1. Total Number of earthquakes recorded based on the magnitude (M_w).

Years	Average Temp. (℉)	Minor EQs (2.5 – 4)	Moderate EQs (4 -5.9)	Major EQs (6 +)	Total Earthquakes	Cumulative Frequency
1974-77	30.02	259	224	0	483	161
1977-80	33.08	514	300	5	819	273
1980-83	32.6	373	306	3	682	227.3
1983-86	32.42	420	325	7	752	250.6
1986-89	34.36	646	424	9	1089	363
1989-92	33.3	1542	254	6	1802	600.6
1992-95	34.3	2415	304	4	2723	907.6
1995-98	32.2	2291	274	1	2566	855.3
1998-01	32.1	1896	302	9	2207	735.6
2001-04	34.96	3687	472	4	4163	1387.6
2004-07	33.43	3398	306	2	3706	1235.3
2007-10	32.2	3906	297	2	4205	1401.6
2010-13	31.4	4602	295	3	4900	1633.3
2013-16	35.03	5680	324	6	6010	2003.3

4.1. Earthquake frequency trend analysis

The stacked line graph plotted for the average frequencies of minor, moderate, major and cumulative frequency of earthquakes recorded allowing to easily identify and compare the trends in a time series data. It is understandable in Figure 4 that the average earthquake frequencies irrespective of the type of earthquakes follow an increasing trend. In fact minor, moderate and major earthquakes lines are almost overlapping, depict that frequencies of all types of earthquakes are indubitably increasing in a similar fashion during the study period.

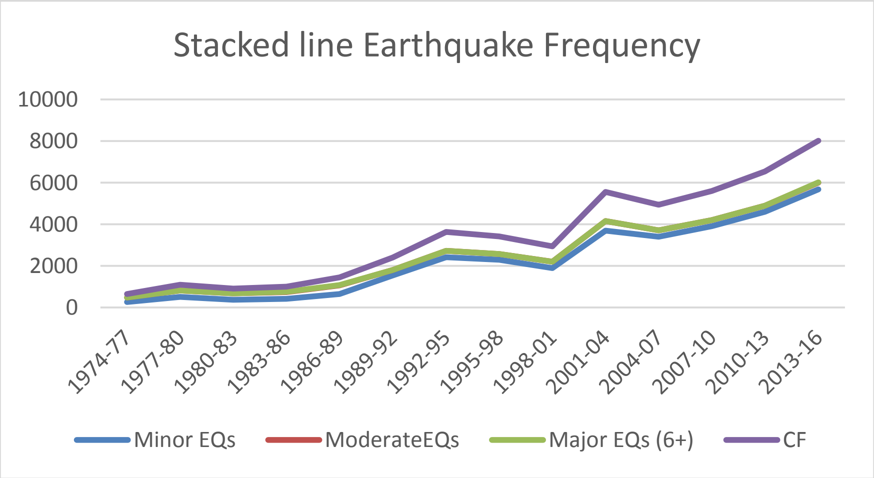

Figure 4. Stacked line graph for minor, moderate, major and cumulative earthquake frequencies (CF)

Deglaciation due to climate change promotes volcanism as discussed in section 1 which sources faults to reactivate. The effect of increased volcanic activity can be prominent in Alaska as most of the region is covered with glaciers melting at a high rate that can increase the frequency of earthquakes by reactivating pre-existing weak tectonic faults which makes the region sensitive to the changes like un-loading heavy ice cover. Thus a sharp increase in the frequency of earthquakes from 2001 – 2016 in figure 4 can be correlated to NASA reported 15 hottest years since 2001 [2] that has caused the glaciers and sea ice to melt at rapid pace and sea level to rise at a record rate of 85.5mm [20].

4.2. Correlation analysis

To get more insight into the data and to further verify the correlation between temperature and seismic activity Pearson's correlation coefficient was calculated at P < 0.01 i.e. with 99% confidence interval (chance of error is 1 out of 100) for minor, moderate, major and combined (moderate + major) earthquake data as shown in Table 2. As we are seeking a correlation between temperature and frequency of earthquake events, therefore, only temperature column is considered.

Table 2. Pearson's correlation coefficient (r), "r" is significant at P<0.01"*" and at P<0.12"**"

	Temperature	**Minor EQs**	**Moderate EQs**	**Major EQs**	**Combined (Mod+Maj) EQs**
Temperature	1				
Minor EQs	0.34	1			
Moderate EQs	**0.69***	0.17	1		
Major EQs	**0.44****	-0.15	0.42	1	
Combined (Mod+Maj) EQs	**0.70***	0.16	0.999	0.46	1

Earthquake behaviour is chaotic and skills for forecasting them are limited, however the rise in the frequency of small earthquakes is arguable as glaciers melt and sea level rises. Due to tremendous increase in the low magnitude earthquake records since 21st century beginning, the correlation coefficient between temperature and minor earthquakes was expected to be the strongest among all others presented in table 2, however interestingly, it is not even significant which reflects the technological progression of recent seismic station network expansion by USArray all over U.S. On the other hand, rise in temperature showed a strong positive correlation with moderate earthquake records, whereas its significant correlation with major earthquakes at P < 0.12 (medium confidence) was totally a surprise. Furthermore, a combined effect of both moderate and major earthquakes was also considered against the temperature variations that startlingly represented even greater correlation value r than its value for moderate earthquakes which warns that the rate of isostatic rebound driven by melting glaciers due to regional rise in temperature of Alaska has become high enough to influence the subsurface tectonic plates and can yield both moderate and major earthquakes by reactivating the subsurface faults.

To further validate our point and to testify the biasness of correlation coefficient, line graphs with linear regression trend for earthquakes of magnitude 4 and above versus temperature were plotted and set parallel in Figure 5 & 6 to visually examine the correlation between temperature and seismic activity in Alaska. Interestingly both presented analogous increasing trends. Although the earthquake regression line looks less steep as compared to temperatures', however the increase in the frequency of seismic records is evident. The sharp rise in average temperature of Alaska has not just escalated the frequency of earthquakes during particular periods such as 1986-89 and 2001-04, but each fluctuation either high or low in temperature graph seems influencing the earthquake frequency accordingly (Figure 5 & 6) is not merely a coincident, however, these frequent earthquakes most probably are the isostatic responses due to climate change in study region.

Adding carbon dioxide to the atmosphere inevitably causes the temperature to rise, and more you add, the greater the temperature rise [21]. No doubt GHG emission has made life possible, but the accumulation of greenhouse gases and particles such as inorganic black carbon soot due to enhanced anthropic activities has caused the Earth surface temperature to rise constantly according to IPCC 2014. According to USArray earthquake monitoring network –Transportable Array (TA) deployment of seismic stations expansion from 2004–2015 across 48 states including Alaska has enabled recording high quality data i.e. smaller subsurface movements are now recorded with precision, hence number of earthquakes recorded every year are increasing. Thus, technology advancement during recent decades might have contributed most likely to the low magnitude earthquake records in particular. The minor earthquakes listed in table-I confirms the sophistication of our capabilities of measuring earthquakes below magnitude 4 on Richter scale with time. Still, it seems that the technological progression perhaps have not affected the concerned seismic records of magnitude 4 and above because the tools used previously in 80s and 90s were able to record such events efficiently which table-I confirms.

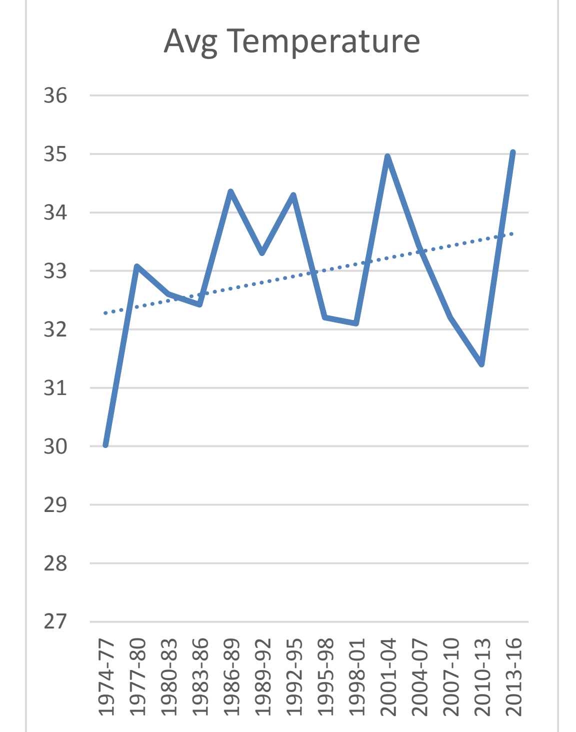

Figure 5. Average temperature graph

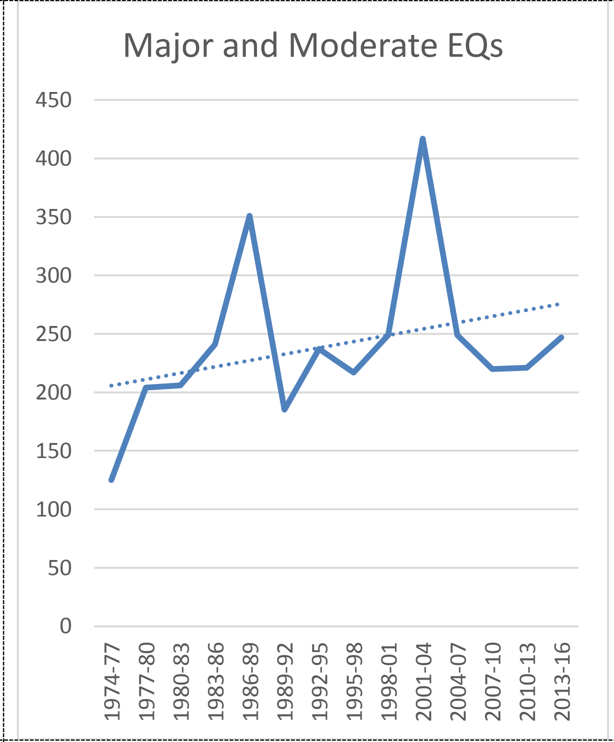

Figure 6. Combined (moderate and major) EQs

A total of 4468 earthquakes of magnitude above 4 on Richter scale have been reported from the study area including 61 major seismic events during the study period. The preliminary results by means of stacked and regression line graphs along with Pearson's correlation coefficient suggest that even though the postglacial stress due to rapid shrinkage of sea ice cover and melting glaciers has not yet started influencing the major earthquakes of magnitude 6 or more on Richter scale much, however the noticeable rise in the frequency of moderate earthquakes of magnitude ranging from 4 to 5.9 points to a seismically turbulent future, if the present trend of glaciers and sea ice melting due to rise in temperature driven by anthropogenic activity remains the same, soon many of the countless subsurface faults will start responding in the form of major earthquakes.

5. Conclusion

Temperature is rising globally due to global warming, particularly in Alaska it may result in a handful of benefits in terms of longer growing season for agricultural crops, tourism attraction and access to natural resources which are currently inaccessible due to the thick ice covers. However, the study conducted has used stacked line graph, Pearson's correlation coefficient and linear regression line graph to show that it can significantly influence the subsurface tectonic plate moments through accelerated seismic activity as well. It seems that rise in regional temperature due to global warming causing the glaciers to melt, which in turn depressurizing the underlying rocks, hence affecting the earth to rebound and faults to reactivate, therefore labeling the region seismically active with obvious increase in the frequency of volcanoes and earthquakes. The results presented are preliminary therefore further research will be conducted.

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