EFFECTS OF GLOBAL WARMING ON THE FREQUENCY OF EARTHQUAKES IN THE NORTHERN AREAS OF PAKISTAN

Muhammad Usman, Shahid Nadeem Qureshi** and Najeeb Ahmad Amir****

ABSTRACT

As reflected in this paper, an attempt has been made to establish a correlation between temperature increase and increase in frequency of earthquakes in the Northern Areas of Pakistan. The data utilized contains decadal averages (1961-2000) and a six-year average (2001-2006) of temperature. Temperature observations are taken from the Gilgit, Skardu, Chitral and Islamabad-based observatories. The seismic block lies between latitude and longitude 29°-37.2° and 65°-77°, respectively. The seismic data being used for this study is for the years 1961-2005.

The study has shown that there exists a correlation between temperature increase and frequency of earthquakes. As the study area contains numerous glaciers, the increase of temperature causes these glaciers to melt thus releasing pressure on earth below and, as a result, the earth possibly rebounds causing earthquakes. This increases in frequency of earthquakes, in correlation with the temperature, lies in the magnitude ranging from 3.0 to 3.9. Similarly, depth study indicates that increase in the frequency of shallow-level (0-80km) earthquakes can be correlated with temperature. The month-wise study has shown that this continuous increase in earthquake frequency occurs in the months of October, November, December and February.

Keywords: *Global Warming, Glacier Melting, Isostatic Rebound, Gradual Increase in Seismic Activity.*

1. INTRODUCTION

The increasing temperature is very hazardous to life on Earth. There are various theories to explain it but the fact that cannot be denied is that the temperature of Earth is rising. Global Warming is not only changing our world's climate but, it is also causing direct and indirect changes on the surface as well as within the surface of Earth. This effect is no less threatening for Pakistan that has glaciers spreading over vast area in the North, which is also our study- area for this paper (Figure-1). As this region contains many active faults (Figure-2) (Kazmi and Jan, 1997) like Reshun Fault (RF), Upper Hunza Fault (UHF), Main Karakoram Thrust (MKT), Hamran Fault (HF), Main Mantle Thrust (MMT), Raikot-Sassi Fault, Kund Fault (KF), Harban Fault, Sassi-Dassu Fault, Shinkiari Fault, Indus (Darband) Fault, Nawshera Fault, Kund (Manki) Fault, Peshawar Basin Fault and Main Boundary Thrust (MBT) (ibid).

Due to these faults, this zone is seismologically very active and earthquakes occur more frequently here than anywhere else in Pakistan. This zone is also sensitive to changes that are caused by Global Warming, like receding of glaciers. As glaciers weigh billions of tons, their melting can cause the crust of Northern Areas to relax and rebound. As wasting ice-sheets and ice-caps unload the solid earth, stresses released both deform the Earth's surface (Pagli and Sigmundsson, 2008) and decompress the Earth's mantle (Sigvaldason, Annertz and Nilsson, 1992). If erosion or melting ice reduces load, the crust slowly rises by isostatic rebound (Wicander and Monroe, 2006).

In the last twenty years, there has been significant increase in the number of earthquakes that have been located each year. This increase in the number of earthquakes is partially due to the fact that there has been a tremendous increase in the number of seismograph stations in the world and many improvements in global communications have taken place (Alternat1ve, 2008).

In high mountain environments, geotechnical hazards are being increasingly considered in relation to the possible interaction with changing glacial and permafrost conditions (Harris, 2005) and (Huggel, 2008).

In response to increasing temperature over past 100 years, glaciers have gradually underwent thinning, loss of mass and retreat (Singh, Arora, and Goel, 2005). Although other factors like precipitation and cloud cover also affect the retreat of glaciers, air temperature is considered the most important one (ibid).

Global annual mean surface temperature of the globe has increased by 0.6 ± 0.2 °C between 1860 and 2000 (IPCC, 2001). Extent of snow-cover has been decreased by about 10% on average in the northern hemisphere since late 1960s (ibid). It has been said that Himalayan glaciers will melt away within 40 years leading to drastic reduction in river flow and widespread water-shortage (Pearce, 1999; and WWF, 2005).

* Earth and Environmental Sciences Department, Bahria University, Islamabad . Email: usman727@yahoo.com
** Earth Science Department, Quaid-e-Azam University, Islamabad. *** Pakistan Meteorological Department, Islamabad.

Figure - 1: (Taken from Google Earth) The location of seismic block. The area bounded within blue line is our study area. The place marks in above map shows the locations from where the observatories for temperature are taken.

Note: The blue line boundary is an estimated boundary it does not show the exact location of study area

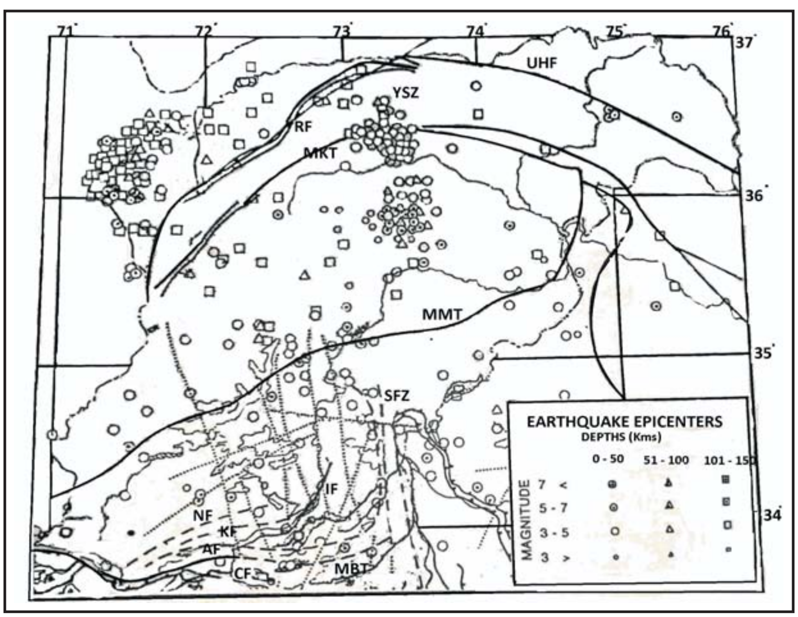

Figure - 2: Seismotectonic map of study area

Note: the location of Yasin (YSN) and Hamran (HSZ) Seismic zones. Faults UHF=Upper Hunza Fault, RF=Reshun Fault, MKT=Main Karakoram Thrust, MMT=Main Mantle Thrust, NF=Noushera Fault, KF=Kund Fault, AF=Attock Fault, IF=Indus Fault, MBT=Main Boundary Thrust

Accelerated glacier retreat has occurred in Nepal and Bhutan over the last two decades of 20th century (Kadota, et. al., 2000; Ageta, et. al., 2001; and Fujita, et. al., 2001). Since 1840, most of the Himalayan glaciers have retreated more than 1200m (Ahmed and Rais, 1998). Individually, Pindari has retreated 3500m in 139 years, Gangotri has retreated 35m in 34 years, Snatopath, 50m in 30 years, Milam 35m in 55 years, Bara Singri, 55m in 90 years. Parbati glacier in Beas valley, Sona Pani glacier in Chenab valley have been retreating (ibid). In this zone most of the glaciers are covered with debris eventhough they are receding (ibid).

Projections from Earth-climate Model suggest that global surface air temperature will increase substantially in future due to radiative effects of enhanced atmospheric concentrations of gases (Delworth, Mahlman and Knutson, 1999).

2. AIM OF THE PRESENT STUDY

The aim of our study is to find the correlation between temperature-increase and frequency of earthquakes in the Northern Areas of Pakistan. This study will hopefully help to predict frequency of earthquakes in future for taking various preventive measures.

3. MATERIAL AND METHODS

The data utilized contains decadal average of temperature (1961-2000) and six-year average of temperature (2001-2006). For recording temperatures, the observatories established at Gilgit, Skardu, Chitral and Islamabad. The temperature data of Chitral observatory starts from 1971. The seismic block lies between latitude 29°-37.2° and longitude 65°-77°. The period of seismic data utilized for this study is 1961-2005. The temperature and seismic data for the study has been provided by Pakistan Meteorological Department (PMD).

Selection of Study-Area: For study, the Northern Areas of Pakistan have been selected, as this region contains a number of glaciers. The duration of study is 1961-2005, during which:

- i PMD (Pakistan Meteorological Department) was only source for monitoring earthquakes;
- ii No new seismic stations were developed by PMD;
- iii No new sensitive instruments were installed.

Temperature study: A network of four observatories has been used (Figure-1). The average increase in temperature has been shown in Table-1. As ten hottest years ever measured in the history of Earth i.e., 1991, 1995, 1997, 1998, 1999, 2001, 2002, 2003, 2004 & 2005 (Al Gore, 2006) lie within the time-span 1991-2006, which means that the said span will show a sudden rise in average temperature compared to that of 1961-1990. Considering this fact, calculations have been made to show the average increase of temperature in the two following spans:

Span 1: It contains average increase of temperature during 1961-1990. Span 2: It contains average increase of temperature during 1991-2006 (Table-2).

Seismic study: The study has been made with seismic data for the period 1961-2005. The latitude & longitude of the seismic block are 29°-37.2° and 65°-77°, respectively. The seismic block contains Hindukush mountains, some parts of Afghanistan, Upper Punjab, Upper Balochistan, Tribal Areas, Northern Areas of Pakistan and Kashmir Region (Figure-1). For the purpose of study, the Northern Areas of Pakistan has been selected while other areas have been neglected as they either don't have glaciers or have different sources for monitoring earthquakes.

During the period of study, the frequency of earthquakes and average number of earthquakes per year has been shown in Table-3. To observe in which range this increase in earthquake-frequency lies, study has been made with respect to magnitude, depth and month-wise occurrence (Tables-6, 7 & 8, respectively). Like temperature, the seismic data has been studied in two time spans: Span 1: from 1961 to 1990 and Span 2: from 1991 to 2005 (Table-4).

4. RESULTS

Table-1 and Figure-19 show the increase in average temperature, while Table-2 shows span-wise increase in the average temperature of the study-area in the prescribed duration of study. Table-3 and Figure-20 show increase in earthquake-frequency in the study-area. Table-4 shows span-wise earthquake-frequency and average number of earthquakes per year. Table-5 shows span-wise earthquake frequency and average number of earthquakes per year by excluding the earthquakes of year 2005. Table-6 and Figure-3 and 4 show magnitude-wise; Table 7 and Figure-5 and 6 show depth-wise; and Table-8 and Figure-7 to 18 show month-wise frequencies of earthquakes that occurred during the period of study.

TEMPERATURE STUDY TABLES

Table - 1: Gradual Increase in Average Temperature of the Study-Area by Using Four Observatories

Stations / Duration	Islamabad	Chitral	Skardu	Gilgit	Average Temp. of the Study Area
1961-70	21.153		11.318	15.683	16.052
1971-80	21.383	15.9	11.482	15.783	16.137
1981-90	21.444	15.828	11.638	15.594	16.126
1991-00	21.562	15.858	11.885	15.685	16.248
2001-06	22.329	16.424	12.337	16.034	16.781

Table - 2: Average Increase in Temperature during Spans 1961-1990 and 1991-2006

Span Name	Duration	Increase in Temp. in ^{0}C
Span 1	**1961-90**	0.08
Span 2	**1991-06**	0.53

Note: During the span 1 there is small increase in average temperature, but Span 2 shows considerable increase in average temperature.

EARTHQUAKE STUDY TABLES

Table - 3: Earthquake Frequency and Average Earthquake in a Year during 1961-2005

Duration	No. of Earthquakes	Average Number of Earthquakes Per Year
1961-70	45	4.5
1971-80	121	12.1
1981-90	236	23.6
1991-00	395	39.5
2001-05	992	198.4
1961-05	**1,789**	**39.8**

Note: As we move down in this table, that is from 1961-70 to 2001-05, we find gradual increase from 1961-70 to 1981-90 and a sudden jump from 1991-00 to 2001-05, in earthquake frequency and average earthquake per year.

Table - 4: Earthquake Frequency and Average Earthquake a Year during 1961-1990 and 1991-2005

Span Name	Duration	No. of Earthquakes	Average Number of Earthquakes Per Year
Span 1	**1961-90**	402	13.4
Span 2	**1991-05**	1387	92.5

Note: This table shows that there is a sudden increase in earth earthquake frequency and average earthquake a year in span 1991-05 compared to span 1961-90.

Table - 5: Earthquake Frequency and Average Earthquake a Year in spans 1961-1990 and 1991-2004

Span Name	Duration	No. of Earthquakes	Average Number of Earthquakes Per Year
Span 1	**1961-90**	402	13.4
Span 2a	**1991-04**	761	54.3

Note: Here we have excluded year 2005 due to earthquake of 8 October 2005. But again the span 2a's average and frequency of earthquake is greater than span 1 average and frequency of earthquakes.

Table - 6: Magnitude-wise Frequency of Earthquakes

Duration \ Magnitude	2.0-2.9	3.0-3.9	4.0-4.9	5.0-5.9	6.0-6.9	Total
1961-70	0	2	35	8	0	45
1971-80	0	14	85	21	1	121
1981-90	0	65	156	11	1	233
1991-00	2	231	131	9	0	373
2001-05	2	492	411	45	1	951
1961-05	**4**	**804**	**818**	**94**	**3**	**1,723**

Note: As we move down in this table, that is from 1961-70 to 2001-05, we find that earthquakes of magnitude 3-3.9 are showing increase in their frequency in correlation with temperature. Earthquakes of magnitude 4-4.9 showing net increase and earthquakes of magnitudes 5-5.9 and 6-6.9 do not show any gradual increase in their frequency.

Table - 7: Depth-wise Frequency of Earthquakes

Duration \ Depth	Shallow (0-80KM)	Intermediate (81-300KM)	Deep (Above 300KM)	Total
1961-70	22	21	1	44
1971-80	82	37	2	121
1981-90	115	121	0	236
1991-00	165	225	4	394
2001-05	828	164	0	992
1961-05	**1212**	**568**	**7**	**1,787**

Note: This table shows that the frequency of shallow level earthquakes has increased in correlation with temperature during the period of study. The earthquakes of intermediate level are also showing a net increase in their frequency.

Table - 8: Month-wise Frequency of Earthquakes

Duration \ Months	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1961-70	8	4	3	4	5	1	6	2	7	1	3	1	45
1971-80	7	6	13	11	9	2	8	8	35	9	3	10	121
1981-90	22	16	27	19	18	13	20	25	33	15	10	18	236
1991-00	30	30	39	39	50	32	43	33	18	23	24	34	395
2001-05	22	38	33	30	24	21	24	13	21	513	177	76	992
1961-05	**89**	**94**	**115**	**103**	**106**	**69**	**101**	**81**	**114**	**561**	**217**	**139**	**1789**

Note: There is increase in earthquake frequency in months of October, November, December and February in correlation with temperature, as we move from top to bottom that is from 1961-70 to 2001-05 in this table.

Magnitude-wise Earthquake Frequency

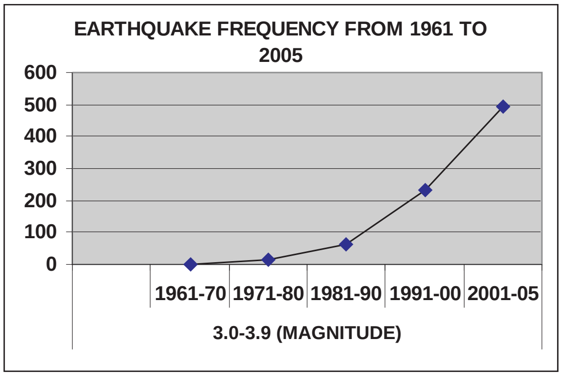

Figure-3: Earthquakes of magnitude 3.0-3.9 showing increase in their frequency in correlation with average temperature (Fig-19)

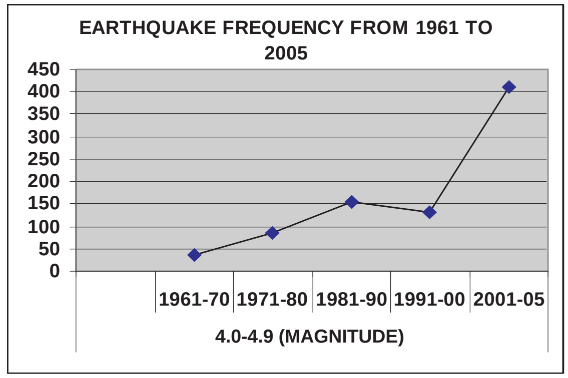

Figure-4: Earthquakes of magnitude 4.0-4.9 showing a net increase in the frequency

Depth-wise Earthquake Frequency

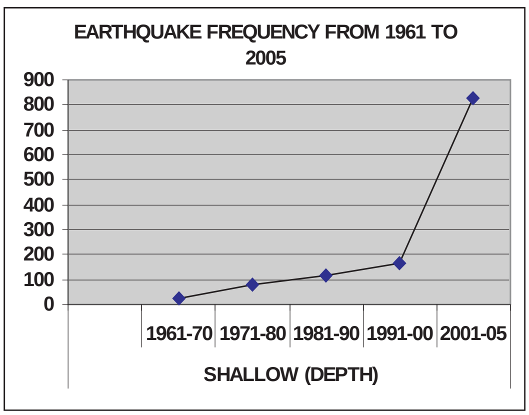

Figure-5: Shallow earthquakes (0-80km) showing gradual increase in there frequency correlation with average temperature (Fig-19)

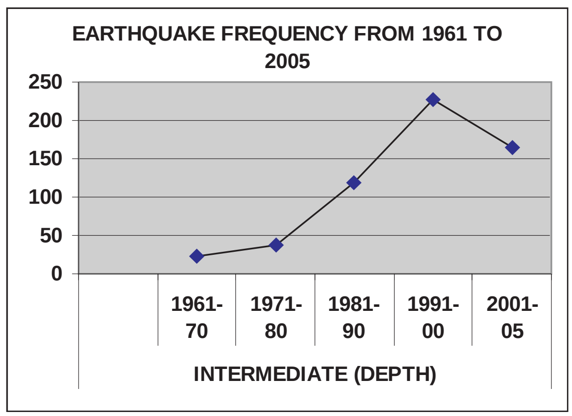

Figure-6: Intermediate earthquakes (81-300km) showing net increase in their frequency

Month-wise Earthquake Frequency

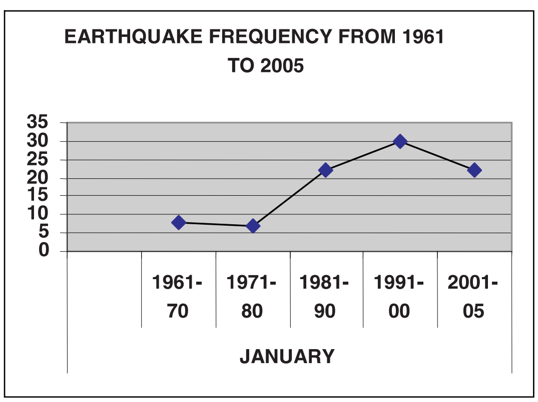

Figure-7: This figure shows a net increase in month-wise frequency of earthquakes

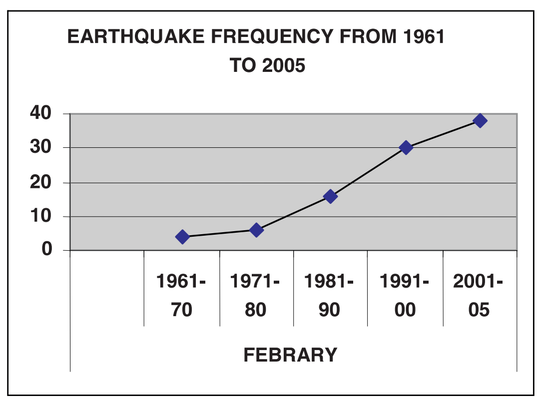

Figure-8: This figure shows increase in month-wise frequency of earthquakes in correlation with temperature (Fig-19)

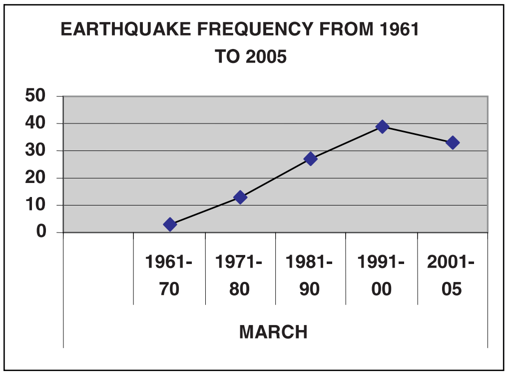

Figure-9: This figure shows a net increase in month-wise frequency of earthquakes

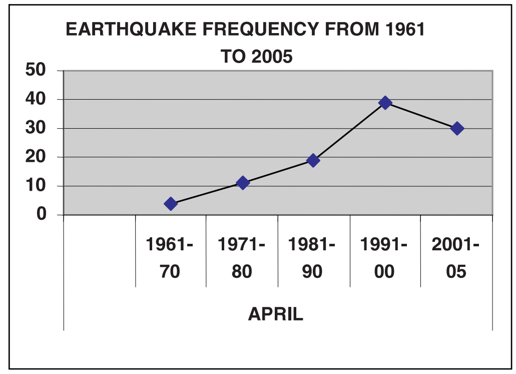

Figure-10: This figure shows net increase in month-wise frequency of earthquakes

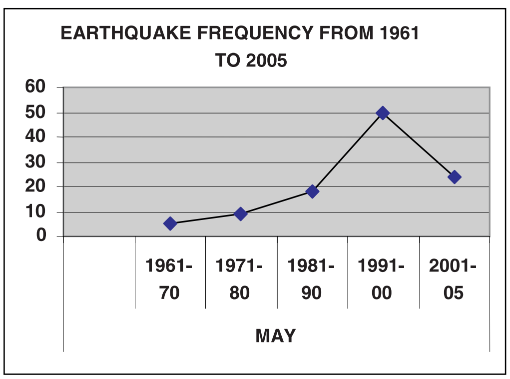

Figure-11: This figure shows net increase in month-wise frequency of earthquakes

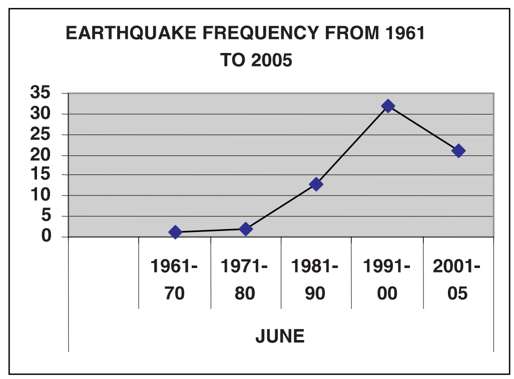

Figure-12: This figure shows a net increase in month-wise frequency of earthquakes

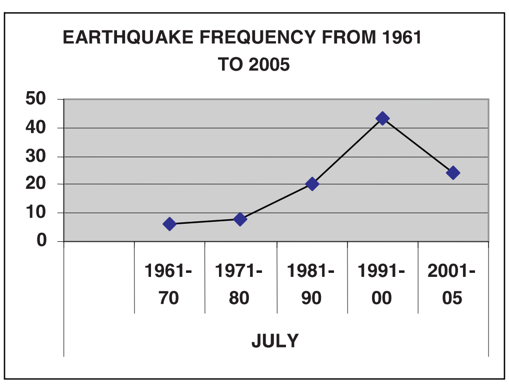

Figure-13: This figure shows a net increase in month wise frequency of earthquakes

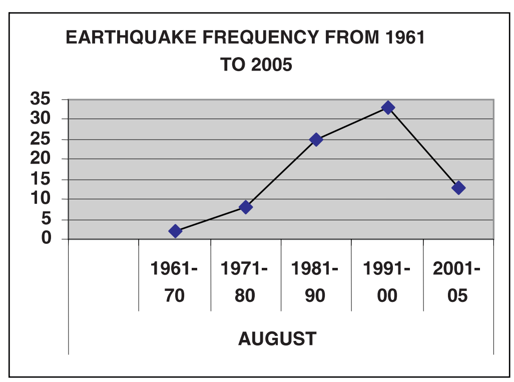

Figure-14: This figure shows net increase in month-wise frequency of earthquakes

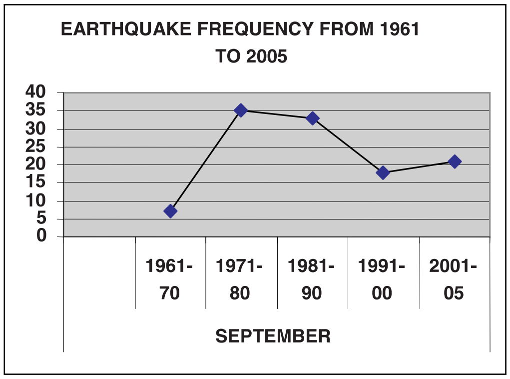

Figure-15: This figure shows a net increase in month wise frequency of earthquakes

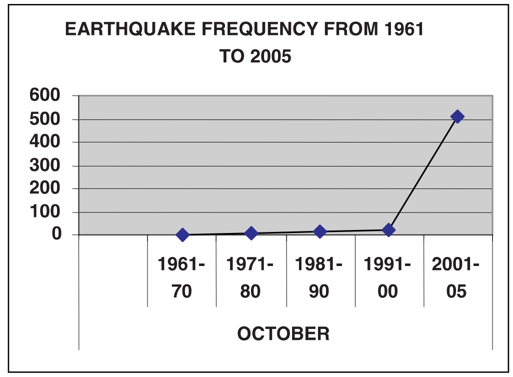

Figure-16: This figure shows increase in month wise frequency of earthquakes in correlation with temperature (Fig-19)

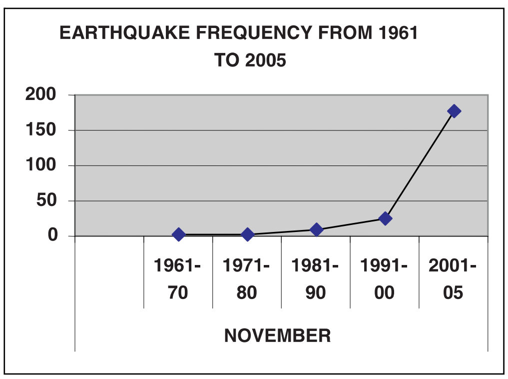

Figure-17: This figure shows increase in month wise frequency of earthquakes in correlation with average temperature (Fig-19)

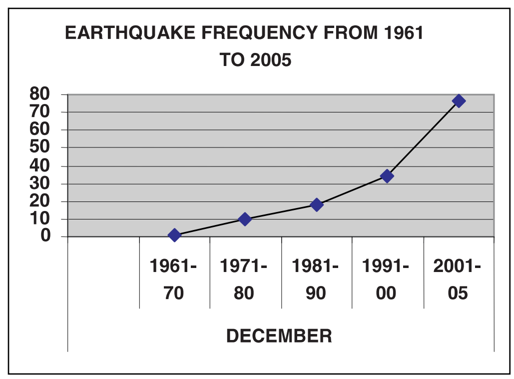

Figure-18: This figure shows increase in month wise frequency of earthquakes in correlation with average temperature (Fig-19)

Increase in Earthquake Frequency with the Increase in Temperature during Period 1961-2005

Average Temperature

1961-70	16.051
1971-80	16.137
1981-90	16.126
1991-00	16.248
2001-06	16.781

Earthquake Frequency

1961-70	45
1971-80	121
1981-90	236
1991-00	395
2001-05	992

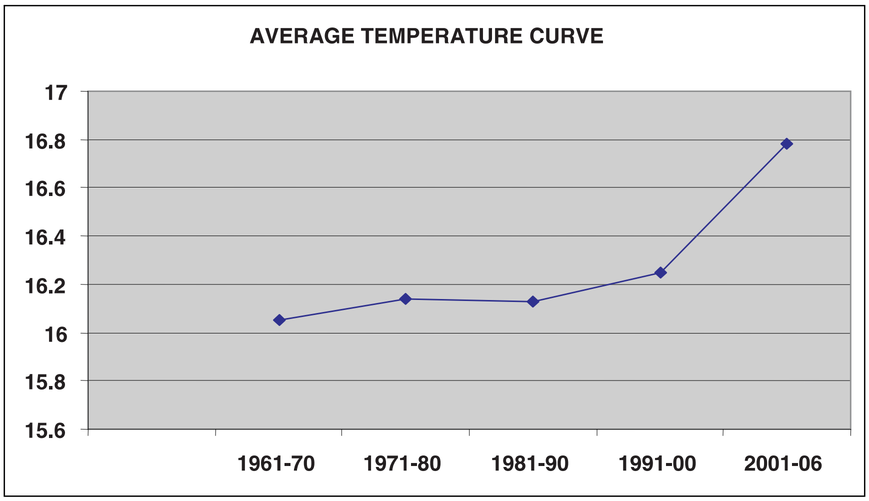

Figure-19: This figure shows average surface temperature of study area in duration 1961-06

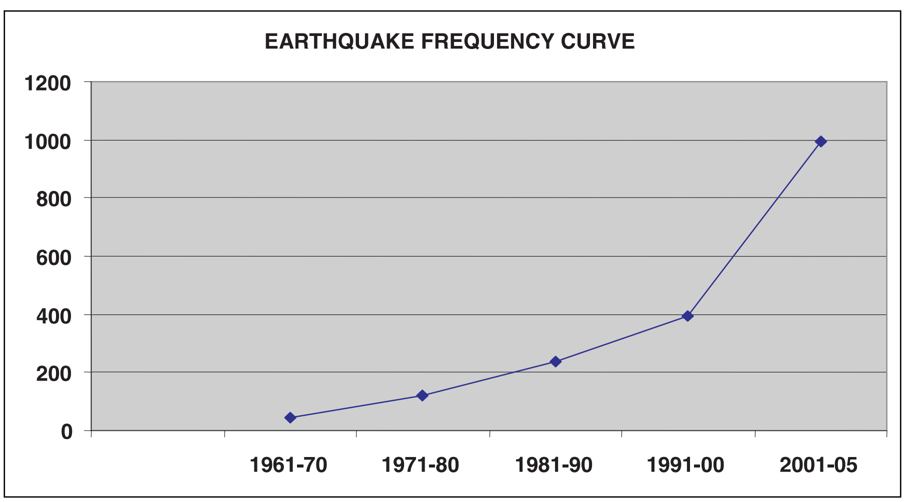

Figure-20: This figure shows earthquake frequency in study area in duration 1961-05

5. DISCUSSION

During the last twenty years, there has definitely been an increase in the number of earthquakes that have been located each year. This is because of the tremendous increase in the number of seismograph stations in the world and many related improvements in global communications (Alternat1ve, 2008)

As, in our study-area, during the period of study, the source, stations and instruments for monitoring earthquakes have remained the same. It means, if there is any increase in earthquake-frequency during the period of study, it can be explained by isostatic rebound of earth resulting from glacial retreat. The main cause for this glacial retreat is Global Warming. So, temperature can also be a cause for enhanced seismic activity.

Global annual mean surface temperature has increased by 0.6 $\pm$ 0.2 ^{o}C between 1860 and 2000 (IPCC, 2001). Since 1840, most of the Himalayan glaciers have retreated more than 1200m (Ahmed and Rais, 1998). It means that the increase in temperature is causing Himalayan glaciers to retreat. In our study-area, the average temperature has gradually increased (Table-1). As this area contains numerous glaciers, so increase in temperature is causing these glaciers to retreat like other Himalayan glaciers. So, they are releasing stress on the crust below. If erosion or melting ice reduces load, the crust slowly rises upward by isostatic rebound (Wicander and Monroe, 2006). As wasting ice-sheets and ice-caps unload the solid Earth, stresses released both deform Earth's surface (Pagli and Sigmundsson, 2008) and decompress Earth's mantle (Sigvaldason, Annertz, and Nilsson, 1992). As the study area contains many active faults (Kazmi and Jan, 1997) the isosatic rebound of Earth resulting from glacial retreat due to increased average temperature can create movement along these faults to trigger earthquakes. If there are any dormant faults, they can become active. It means that with the gradual increase in average temperature in glacial zone, the earthquake frequency should also increase.

In study area during the period of 45 years, there have been 1789 earthquakes (Table-3). It is clear that with passage of time the frequency of earthquakes has increased (Figure-20). There is a clear correlation between average temperature increase and increase in earthquake frequency with respect to time (Figures-19 and 20). For more confirmation, when span-wise study has been made, (Table-2 and 4) we see that during the span 1961-90, there is a small increase in average temperature that is about 0.08 ^{0}C and the earthquake occur at average of about 13 earthquakes a year. But, when span 1991-2005 is studied, it is noted that there is a considerable increase in temperature that is 0.53 ^{0}C and the earthquakes occur at an average of about 93 earthquakes a year. The year 2005 alone has 626 earthquakes. They are the result of tremendous aftershocks produced by October 8, 2005 earthquake with its centre in Muzafarabad. So, there is a possibility that a sudden jump in earthquake frequency might be caused by October 8, 2005 earthquake. So the frequency of earthquakes and average earthquake a year has also been studied by excluding the earthquakes of the year 2005. Calculation of results, excluding the earthquakes of the year 2005, are: from 2001-2004 there are 366 earthquakes with the average of 92 earthquakes a year. Again, this result is greater than any previous yearly average of earthquakes as shown in Table-3. If the yearly average of earthquakes in span 1991-2004 is calculated we find average of 54 earthquakes a year, which is again far greater than span 1 average that has average of 13 earthquakes a year (Table-5). All these observations indicate an increasing tendency of earthquakes. As temperature of study-area is also increasing, so there seems to be a clear correlation between temperature increase and earthquake frequency.

To observe in which range the increase in earthquake frequency lies, the study has been made to observe the increase in earthquake frequency with respect to magnitude, depth and month-wise occurring.

For studying the magnitude of earthquakes, Mb scale (Body Wave Magnitude) has been used. Total Mb readings are 1728 (Table-6). It is found that the earthquakes of magnitude 3.0 to 3.9 have gradually increased during 1961-90 and considerably increased during 1991-05 (Figure-3), while the readings of earthquakes of magnitude 4.0 to 4.9 also show net increase in the occurrence (Figure-4).

The earthquake-study has also been made with respect to depth and total depth readings are 1787 (Table-7).The three divisions of depth are shallow (0-80km), intermediate (81-300km) and deep (above 300 km). The depth study indicates that frequency of shallow earthquakes has increased (Figure-5) in correlation with the average temperature (Figure-19), during the period of study. The intermediate earthquakes also show a net increase in their frequencies (Figure-6).

Month-wise study (Table-8) shows an increased frequency of earthquakes in October, November, December and February (Figures-16,17,18 and 8, respectively) in correlation with average temperature increase (Figure-19). The months January, March and April, May, June, July, August and September also show net increase in earthquake-frequency (Figures-7, 9, 10, 11, 12, 13 and 14, respectively).

6. CONCLUSIONS

This study shows that with the increase in temperature, the earthquake-frequency also increases. As in the study-area the analytical tools, such as source, stations and seismographs, have remained same during the period of study, it means that the main factor for increase in earthquake frequency can be temperature. Global warming is causing glaciers to melt thus releasing pressure on Earth below causing the Earth below to rebound that results in earthquakes. This increase in earthquake frequency, in correlation with temperature, lies in magnitudes ranging from 3.0 to 3.9. Depth study shows that the occurrence of shallow-level earthquakes has been increased during the period of study. The months of October, November, December and February also show increase in earthquake frequency in correlation with temperature.

The correlation between temperature increase and earthquake frequency is presently explained by glacier melting. Figure-19 gives clue that temperature of study area will increase rapidly in future. If the line of temperature (Figure-19) continues to rise, like from 2001-2006, than coming years can show extensive glacier melting, that may result in enormous flooding and earthquakes, which can be record breaking. The chances of various geological hazards (like land-sliding) relating to flooding and earthquakes should also increase.

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