Effects of Recent Environmental Changes on Global Seismicity and Volcanism

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Received 10 February 2008; accepted 2 March 2009

ABSTRACT: A covariation of recent global environmental changes and seismicity on Earth is demonstrated. Presently, rising concern about anthropogenic activities and their consequences on the cryosphere and environment have always overlooked changes related to future tectonic activity. Possible factors affecting an increase in the number of earthquakes and volcanic eruptions are reviewed and discussed.

KEYWORDS: Seismicity; Tectonics; Sea level rise; Glacier retreat; Environmental changes; Volcanism

1. Introduction

The geological system represents the unity of lithosphere, hydrosphere, and atmosphere. A holistic view of nature’s complex systems today is inseparable from profound human effects on these systems. Presently, rising concern about anthropogenic activities and their consequences on the cryosphere and environment has always overlooked changes related to future tectonic activity. This paper attempts to illustrate briefly that there is enough evidence and known causative mechanisms with a rapid or a delayed response suggesting that present global environmental changes (viz., glaciers’ retreat and sea level rise under global warming)

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DOI: 10.1175/2009EI262.1
can be a strong triggering factor for occurrence of earthquakes and volcanic eruptions. A wide variety of examples are known and cannot be described within one paper, so this review discusses some of these, showing that even small stress perturbations produced by modern environmental changes can induce seismicity and volcanism. On the basis of the empirically and theoretically proven fact that Earth’s crust must be close to the earthquake failure threshold everywhere (e.g., Ruff 2002; McGarr et al. 2002), the present paper covers various contributing factors of stress changes related to ice, water, and tectonics.

2. Planetary redistribution of masses and stresses

Today, it is widely accepted that global warming is the cause for a powerful planetary redistribution of water masses from the polar regions to lower latitudes. A huge release of ice from polar and mountain regions is occurring (e.g., Figure 1). At the same time, a water loading of the equatorial region of the Earth is taking place because of the changes of circulation of the atmosphere, the ocean, and the specific spatial characteristics of the ocean. Also, one additional process here is the flow of water away from Greenland or Antarctica, which occurs when the gravitational pull of the ice sheet is reduced (Mitrovica et al. 2001).

As a result of the reduction of the water resources of the continents, they have become lighter by 11 000 km$^3$ for the past few centuries; the decrease of water masses in polar regions as result of glaciers shrinking was more than 15 000 km$^3$ (Klige and Evseeva 2006). All these masses have been discharged into the ocean and distributed equally on its surface. But, if we take into consideration that 70% of the ocean area is between 0° and 40°N–S latitudes, we can calculate that only within these limits has water mass increased by 20 000 km$^3$ (Figure 2). Hence, water phase transition and its displacement from polar and midlatitudes to equatorial regions during warming periods occurs unequally and produces lightening of high latitudes and weighting of low latitudes (Klige and Evseeva 2006).

This water displacement leads to a disturbance of the mass balance between the land and the ocean, and it changes characteristics of the Earth’s rotation (Kasimov and Klige 2006). Rising of the sea level, which is progressing at the rate of 3.1 mm yr$^{-1}$ (Solomon et al. 2007), results in accumulation of potential energy in the
ocean (7.2 × 10^{19} \text{ J yr}^{-1}) (Kasimov and Klige 2006). Its geophysical realization can have huge effects and induce an increase of earthquakes and the frequency of volcanic eruptions (as it was shown by, e.g., Cirel 2002; Kennett and Thunell 1975; McGuire et al. 1997) (Figure 3). As early as 1975 it was suggested by Kennett and Thunell that the periods of active volcanism seem to be well correlated with those for transgression in paleo–sea level changes (Kennett and Thunell 1975). This correlation may be reasonable if the additional crustal stresses for the water loading are not negligibly small compared with the crustal stress level before water loading. Kennett and Thunell thus suggested that the stress accumulation caused by surface mass redistribution may become a trigger and/or accelerator of geological phenomena such as volcanism and movement of active faults.

Rampino et al. (Rampino et al. 1979) suggested that the redistribution of water that accompanies glaciations and deglaciation gives rise to both hydroisostatic and glacioisostatic readjustments. Asymmetric mass loading, as on Greenland, requires that the global spin axis adjusts to the new symmetry of mass. During the last century, the mean pole displacement was 6 cm yr\(^{-1}\) along the meridian 77°W. Realignment of the geoid (or perturbation in the rotational parameters of the planet) will then lead to worldwide stress that might trigger global seismic activity (Anderson 1974) and eruptions (Rampino et al. 1979). Rampino et al. suggested that crustal adjustment will be more active along the plate margins and major intersections of lineaments and faults.

Chappel (Chappel 1975) noted that the stress gradients associated with the mantle flow beneath continental margins in response to glacial loading and unloading could

![Figure 2. Water distribution on different latitudes as a result of the global climate warming (adapted from Klige and Evseeva 2006).](image-url)
be $10^5$ times larger than the tidal loading of continental shelves associated with
Earth tides, which are known as possible triggers for earthquakes (e.g., Tsuruoka
et al. 1995) and volcanic eruptions (McNutt 2002; Ruff 2002). It is interesting to
note here that, as tide levels grow, presently (Kasimov and Klige 2006) the loading
amplitudes should be growing as well.

Recently, ideas about glacial loading and tectonic activity interaction were
supported by observations and modeling (e.g., Pagli and Sigmundsson 2008; Pagli
et al. 2007; Jellinek et al. 2004; Sigvaldasson et al. 2002; Larsen et al. 2005). For
example, Pagli and Sigmundsson (Pagli and Sigmundsson 2008) investigated the
influence of glacioisostatic stresses on seismic and volcanic activity in Iceland and
calculated that thinning of Vatnajokull ice cap (the largest ice cap in Iceland, laying
over the mid-Atlantic plate boundary) is causing a pressure decrease of about 1700
Pa yr$^{-1}$ in the mantle beneath the ice and can be related to “anomalous sequence of
reverse faulting earthquakes (which are favored by glacio-isostatic stress) from
1974 to 1996 in Bardarbunga.” The same authors quote Jull and McKenzie (Jull and
McKenzie 1996), who have shown that during the deglaciation of Iceland within
Pleistocene–Holocene ice sheet melting decreased the pressure in the mantle (up to
19 000 Pa yr$^{-1}$) and increased melt production by a factor of about 30.

Figure 3. Global changes. 1: Sea level rise at Brest (northern Atlantic), 2: number of
volcanic eruptions, 3: number of earthquakes (adapted from Kasimov and
Klige 2006).
By projecting the above-mentioned examples on to the present global retreat of glaciers it is possible to suggest that many regions of the Earth’s crust are experiencing pressure decreases and can be subjected to significant stress changes leading to higher seismic and tectonic activities.

3. Hydroengineering and transgression of the sea

The process of increasing normal stress-inducing seismicity has numerous well-studied examples, showing that on a local scale humankind has already faced the phenomenon many times.

For the last 70 years, it has been well known that large-scale hydroengineering causes local seismicity magnification even at nonseismic areas (e.g., Gupta 1992; McGarr et al. 2002). And, as history shows, it is the most frequent reason for powerful earthquakes induced by human activities. For example, a reservoir filled with water on the Koyna River, India (1967), caused an earthquake with a magnitude 6.4 and resulted in a death toll of about 200 (Gupta and Rastogi 1976; Narain and Gupta 1968). There have been more than 100 earthquakes induced by hydroengineering (with magnitudes of 2.0–6.5). In Table 1 we name nine earthquakes (Adushkin and Turunaev 2005), induced by filling reservoirs with water, with a magnitude of more than 5.3 that occurred over the last 50 yr.

Earthquakes caused by the filling of reservoirs are the first and the most well-studied type of induced seismicity and the most frequent one. This is so because of the huge number of reservoirs on the planet. In the last 100 yr there were about 45 000 dams built in the world. In one case, because of induced seismicity, a construction of the Auburn Dam in California was stopped. Even for the Sichuan earthquake a human trigger related to water level change at a nearby reservoir was named as a possible causative factor (Kerr and Stone 2009). Not all reservoirs induce seismicity because it is determined by tectonic and stress environments, reservoir volume, depth, area, rate of water level change, and other factors (e.g., for dams exceeding a height of 90 m, 10% show induced seismicity, and for 140 m, 21% accordingly; Adushkin and Turunaev 2005).

Among possible seismicity-trigger mechanisms are a growth of elastic tension under the pressure of a reservoir, an increase of pressure inside underlying rocks caused by deformation of interstices and water migration, a decrease of the strength

<table>
<thead>
<tr>
<th>Name of dam</th>
<th>Country</th>
<th>Height (m)</th>
<th>Volume (km³)</th>
<th>Year of filling and year of max earthquake</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koyna</td>
<td>India</td>
<td>103</td>
<td>2.71</td>
<td>1964–67</td>
<td>6.5</td>
</tr>
<tr>
<td>Kremasta</td>
<td>Greece</td>
<td>165</td>
<td>4.75</td>
<td>1965–66</td>
<td>6.3</td>
</tr>
<tr>
<td>Hsinfengkiang</td>
<td>China</td>
<td>105</td>
<td>10.05</td>
<td>1959–62</td>
<td>6.1</td>
</tr>
<tr>
<td>Tsuruta</td>
<td>Japan</td>
<td>117</td>
<td>0.10</td>
<td>1964–68</td>
<td>6.1</td>
</tr>
<tr>
<td>Kuzuryu</td>
<td>Japan</td>
<td>128</td>
<td>0.35</td>
<td>1967–72</td>
<td>6.0</td>
</tr>
<tr>
<td>Oroville</td>
<td>United States</td>
<td>236</td>
<td>4.30</td>
<td>1968–75</td>
<td>6.1</td>
</tr>
<tr>
<td>Kariba</td>
<td>Zimbabwe</td>
<td>128</td>
<td>160.37</td>
<td>1959–63</td>
<td>5.8</td>
</tr>
<tr>
<td>Aswan</td>
<td>Egypt</td>
<td>110</td>
<td>150</td>
<td>1975–81</td>
<td>5.6</td>
</tr>
<tr>
<td>Makio</td>
<td>Japan</td>
<td>105</td>
<td>0.08</td>
<td>1961–76</td>
<td>5.3</td>
</tr>
</tbody>
</table>
of rocks after interaction with water, a decrease of friction between blocks due to infiltration of water to spaces between blocks, an increase of a level of underground waters, and the Rebinder effect (for more references and factors, please refer to Simpson 1986; McGarr et al. 2002; Adushkin and Turunaev 2005).

An interesting example is the Caspian Sea, which can be called “a natural laboratory,” where the consequences of rapid water level rise can be studied. This lake is the biggest (after oceans) water body with a cutoff basin. In some sense it can play the role of a model for the World Ocean (Dobrovolsky 2006).

A process of natural rapid water filling of the Caspian basin with seismic consequences has been observed here. The transgression of the Caspian Sea has caused a number of earthquakes on its coastline. The Caspian Sea’s volume, mass, and area increased significantly in a short period of time. This has changed the pressure and its spatial distribution on tectonic edifices and caused significant changes in groundwater. Additional water, which could penetrate into upper layers of the lithosphere near the coast line, could play the role of lubricator for some of the fault zones, where seismic events take place.

The level of the Caspian Sea rose 235 cm between 1978 and 1995 with an annual speed of about 12–30 cm. Evolution of this sea can be a natural model for a consideration of the world coastline development (over the last 60 000 yr, e.g., the Caspian Sea level has increased and decreased from 30 to 80 m above and 20 to 25 m below its present state; Korotaev 2006). Also, there was a speculative opinion (e.g., Aleksandrov et al. 2006) that seismicity occurs not only along the coastal zone, but at the Caucasus Mountains (neighboring the Caspian Sea) depending on sea level changes of the Caspian Sea. In Figure 4 there are time series of Caucasus seismicity and sea level change of the Caspian Sea (for Baku tide gauge station). Seismicity is an indicator of a region’s stress and intensity of Earth crust movements that is interconnected with the level of the Caspian Sea. It was conjectured (though time series are quite short) that the activation of seismicity at the Caucasus Mountains within certain limits was determined by water volume changes. The sea level rise here was equal to an additional pressure $-0.15$ bar ($15 000$ Pa). This value is 15 times bigger than pressure changes due to tidal forces, which, as was already mentioned, can also be a factor for earthquakes (Tsuruoka et al. 1995). It is important that changes are occurring on a very wide area and agreeably have an effect on significant depths of the Earth’s crust.

From 1993 to the end of 2006, near-global measurements of sea level (between $65^\circ$N and $65^\circ$S) made by high-precision satellite altimeters indicate that global average sea level has been rising at $3.1 \pm 0.4$ mm yr$^{-1}$ (Nerem et al. 2006). This is twice as fast as the average rate of the twentieth century.

Sea level rose much more slowly over the past 6000 yr. The sea level 2000 yr ago can be deduced by examining fish tanks built by the ancient Romans. Because the tanks had to be at sea level for the sluice gates to function, one can precisely estimate sea level during the period of their use. Comparison of this level with historical records indicates that there has been little net change in sea level from 2000 yr ago until the start of the nineteenth century (Lambeck et al. 2004).

It is also interesting to add that, for global sea level rise and coast line changes, not only the absolute value of sea level rises but its accelerating rate is also important (Stoddart and Reed 1990). This is critical for the manner of response by coastal geomorphologic systems, which are not able to readjust to additional stresses quickly.
Past and ongoing transfers of mass from the ice sheets to the oceans result in changes in the gravitational field and vertical land movements and thus changes the height of the ocean relative to land. These large-scale changes, plus local tectonic movements, influence the regional impact of sea level rise (Lambeck and Johnston 1998; Mitrovica et al. 2001; Peltier 1998).

Future predictions of sea level rise published by the Intergovernmental Panel on Climate Change (IPCC) are 0.18–0.59 m (full range between B1 and A1FI scenarios) for the twenty-first century. But contributing authors have mentioned that “dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise” (Solomon et al. 2007).

Figure 4. Oscillation of 1) the Caspian Sea level, 2) an annual water increase, 3) maximum class earthquakes, and 4) number of earthquakes at the Caucasus (adapted from Aleksandrov et al. 2006).
This is a critical point. Behind it one can expect 5.0 m of sea rise instead of 0.59 m this century (Hansen 2007) (e.g., it is equal to a complete melting of Greenland). As early as 1978 Mercer (Mercer 1978) suggested that global warming from the burning of fossil fuels could lead to disastrous disintegration of the West Antarctic ice sheet, with a sea level rise of several meters worldwide. Now there is more evidence that it really may happen. This process is determined by specific ice sheet structure (Hughes 1973): the West Antarctic ice sheet is based on bedrock that is significantly below sea level (up to 420 m below the sea level; refer for the full review and references to Hansen 2007). Hansen wrote that, under “business-as-usual” forcing in the twenty-first century, the sea level rise surely will be dominated by ice sheet disintegration and that this latter accelerating component can contribute to sea level rise of about 5 m this century (Hansen 2007).

Sea level rise predicted by the maximum IPCC scenario (0.59 m; Solomon et al. 2007) corresponds to a 5.7-kPa pressure increase; 5 m of additional water mass can be equal to almost 50 kPa of additional pressure on the crust. Compared with the Caspian Sea case, such a dramatic scenario will be catastrophic in many ways as it will be increasing the misbalance between land and sea and growing seismicity around the globe. Seismicity associated with reservoirs and the Caspian Sea transgression can be named as small-scale examples showing how water level changes in the ocean can induce earthquakes. Such expectations do not have wide recognition nowadays despite the fact that as early as the 1970s such ideas appeared in print: “variations in climate lead to stress changes on the earth’s crust—for instance, by loading and unloading of ice and water masses and by axial and spin-rate changes that might augment volcanic (and seismic) potential” (Rampino et al. 1979).

4. Other stress perturbation factors

Among other stress perturbation factors on land, affecting seismic activity, the following can be named:

1) anthropogenic industrial activities (volume of rocks annually moved by humans is about 10 000 km³; i.e., bigger than the volume of materials coming naturally from the land to the ocean; Safyanov 2006);
2) changes of areas covered with snow and soil moisture distribution; and
3) abrupt movements of glaciers in Greenland and Antarctica.

Two latter points have recently been changing very rapidly because of accelerating rates of temperature increase. Because of industrial expansion of human activity it is possible to expect further aggravation of anthropogenic seismicity and deformational processes caused by engineering activities. Some examples are provided below to illustrate the second and third points and to show that an exponentially growing technocratic society produces a broad spectrum of stress changes inducing seismicity with a rate uncommon for most geologic processes.

1) Oil mining was a reason for very strong earthquakes [Gazli, Uzbekistan: 7.6 magnitude (1976); Coalinga field, California: 6.5 magnitude (1983); Kumdagskoe, Turkmenistan: 5.7 magnitude (1983)] (Adushkin and Turunaev 2005). Now, for example, Sakhalin Island is one of the most rapidly
developing centers of oil industry expansion. On 29 May 1995 there was one of the most severe earthquakes in the Russian Federation in the twentieth century—the Neftegorsk city (“City of Oil” in Russian) was totally destroyed by a strong earthquake (7.6 magnitude). The death toll was more than 2000 people. This event occurred in the northern part of Sakhalin Island in a region considered to be a fairly inactive plate boundary between the North American and Eurasian plates (Arefiev et al. 2000). Some scientists suggested that this was caused by intensive oil pumping in the region (Adushkin and Turunaev 2005; Nikolaev 1995).

The next frequently observed example of technogenically induced seismicity is a rock burst associated with stress changes produced by mining and surface unloading. For example, 50% of all Russian mines have this phenomenon. The strongest rock burst in Russia occurred at the Khibiny Mountains (the Kola Peninsula) on 16 April 1989 (5.0 magnitude) (in the world—Ernst Thaelmann, Germany, 1989, 5.4 magnitude; Solvey, United States, 1995, 5.3 magnitude) (Adushkin and Turunaev 2005; McGarr et al. 2002).

2) Annual vertical crustal motions were analyzed by Mangiarotti et al. (Mangiarotti et al. 2001). They describe these displacements by seasonal changes in snowpack thickness and soil moisture. It is projected that during this century summer soil moisture will be reduced in many regions. Displacement amplitudes, associated with the annual interhemisphere movements of water mass and ocean–continent water mass exchange, may reach 10 mm. The general pattern is a compression of the Northern Hemisphere (with peak in February–March) and its expansion (August–September), while the Southern Hemisphere behaves conversely, when the ocean mass reaches a maximum in late August (Mason et al. 2004).

Nowadays the snow area extent in the world is shrinking significantly, producing mass changes on land. Mean monthly snow-cover extent in the Northern Hemisphere has decreased at a rate of 1.3% decade$^{-1}$ during the last 40 yr, with greatest losses in the spring and summer months. Maximum mean area covered by snow in the Northern Hemisphere is 45.2 million km$^2$; minimum is 1.9 million km$^2$. Climate models project significant decreases in snow cover by the end of this century, with reductions of 60%–80% in snow water equivalent in most midlatitude regions. Increases are projected for the Canadian Arctic and Siberia (Barry et al. 2007). To emphasize the importance of such changes and the magnitude of annually oscillating normal pressure produced by snow and its effects on crust deformation described by Mangiarotti et al. (Mangiarotti et al. 2001), it is interesting to consider the following example. For heavy snow regions of central Japan maximum snow depth reaches 4–20 m. This is equal to a pressure of 13.7–68.6 kPa (assuming average density of snow as 350 kg m$^{-3}$) or to a gravitational load of a 1.4–7.0-m-tall column of water or a 0.56–2.8-m rock column. Presently, such dynamic loading variations in normal pressure are rapidly changing and cannot be ignored.
(e.g., even atmospheric pressure variation shows some evidence of induced microseismicity; Ruff 2002).

3) The last reason for an increased number of seismic phenomena caused by changes in the cryosphere, which needs to be mentioned here, is a new class of earthquakes—glacial earthquakes. Such glacial earthquakes, represented by rapid (30–60 cm) ice-mass movement (unknown till 2003) on Greenland show a strong seasonality as well as doubling of their rate of occurrence over the past 5 yr because of accelerating rates of summer melting (Ekström et al. 2006).

Ekström et al. (Ekström et al. 2006) have analyzed long periods of seismic surface waves (1993–2005) on a global scale and found 182 previously unknown earthquakes located in glaciated areas; 136 of the earthquakes (4.6 < M < 5.1) are located beneath Greenland, an area otherwise known for its low level of seismicity. Other earthquakes are located in Alaska and on the Antarctic coast (Ekström et al. 2003). The authors suggest that the increase in number of glacial earthquakes over time appears to be a response to large-scale processes affecting the entire ice sheet (Joughin 2006).

5. General remarks

The previously mentioned nonuniform distribution of masses (with its maximum close to low latitudes) interestingly overlays with a distribution of natural catastrophes. Most major catastrophes of the twentieth century (70%) happened between the equator and 20° of the northern latitude (Shnyparkov 2006). In general they mostly happen on plate boundaries, which are occasionally situated in low latitudes. Also, there was a significant general increase of a number of hazardous events in the world during the twentieth century. The total reported global costs due to damage rose 15 fold over the last 50 yr, while the number of people affected tripled between the 1970s and 1990s. This was partly accounted for by exponential growth of population; additionally, a possible increase of seismic activity suggests further growth of a number of hazard events.

The general trend for the number of earthquakes in the world, suggested as having been steadily growing from the 1750s by some authors (e.g., Eiby 1980; Kasimov and Klige 2006), is extremely complex and can be partly explained by the U.S. Geological Survey’s (USGS) (http://earthquake.usgs.gov/learning/topics/increase_in_earthquakes.php) suggestion regarding the tremendous increase in the number of seismograph stations in the world (in 1931 there were about 350 stations; presently, there are more than 8000) and the larger amount of small events undetected in earlier years. The centennial catalog of global seismicity is now under development and is assumed to be complete only for events with a surface-wave magnitude of 7.0, but smaller magnitudes are still unclear for particular historical periods (Engdahl and Villasenor 2002).

Some authors suggest (Golubov and Gevorkyan 2006) that the contrast between seismicity at the Northern and Southern Hemispheres should be growing because of significant differences between scales of anthropogenic effect on the lithosphere.
Before 1930 seismicity was almost equal at both hemispheres, but it has changed significantly since then. After 1940 there was an increase of frequency of earthquakes within a period of 2 yr in the Northern Hemisphere. During 1963–79 the average growth of earthquakes with a magnitude more than 5.0 was 7% yr\(^{-1}\) for the whole Earth. The interior of the Northern Hemisphere was exposed to more long-term and intense technogenic impacts by the development of oil, gas, and mineral resource industries. After the 1940s the Northern Hemisphere was exposed to numerous nuclear tests and all of Earth was exposed to a global climate cooling. The most abrupt changes of seismicity happened in 1964—the year with a maximum number of underground nuclear tests (Golubov and Gevorkyan 2006). Golubov (2002) suggests that the second half of the twentieth century was characterized by activation of modern shearing of the Earth’s crust in limits of ancient platforms of the Northern Hemisphere and its frames.

6. Summary

Upper layers of the lithosphere, traditionally considered as an inertial part of ecosystem, actually take an active part in global deformational process and are able to react even to small external effects (Adushkin and Turunaev 2005) produced by natural or anthropogenic forces. All the above-mentioned mass-balance
and stress-disruption-related facts (simplified schematic summary presented in Figure 5) are important for seismic problems in terms of increasing the probability of such types of natural phenomena as earthquakes and volcanic eruptions and thus cannot be overlooked. In conclusion, the effect of industrial expansion on the environment can result in a greater number of seismic catastrophes in the near future.

Acknowledgments. The author would like to express gratitude to Dr. D. A. Short (HyARC, Nagoya University) for his help with polishing the English. The author is grateful to Prof. K. Nishimura (Nagoya University) for the time to write; for help with processing the paper to Dr. R. Avissar, present EI chief editor (Duke University); Dr. G. Bonan, interim EI chief editor (National Center for Atmospheric Research); and Prof. J. Foley, former EI chief editor (Institute on the Environment, University of Minnesota); finally—present work was supported by the Ministry of Education, Culture, Sports, Science and Technology, Japan—this support is greatly appreciated.

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