

Communication

Seismogenic-Triggering Mechanism of Gas Emission Activizations on the Arctic Shelf and Associated Phases of Abrupt Warming

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Abstract: A seismogenic trigger mechanism is proposed to explain the abrupt climate warming phases in the Arctic as a result of strong mechanical disturbances in the marginal region of the Arctic lithosphere. Those disturbances might have been caused by great earthquakes in the Aleutian subduction zone, and slowly propagated across the Arctic shelf and adjacent regions, triggering the methane release from permafrost and metastable gas hydrates, followed by greenhouse gas emissions into the atmosphere. The proposed mechanism is based on the identified correlation between the series of the great earthquakes in the Aleutian island arc, which occurred in the early and middle of the 20th century, and the two phases of sharp climate warming, which began in 1920 and 1980. There is a 20-year time lag between these events, which is explained by the time of arrival of deformation waves in the lithosphere (propagating with a velocity of about 100 km per year) at the Arctic shelf and adjacent land from the Aleutian subduction zone, the region of their generation. The trigger mechanism causing the methane release from permafrost and metastable gas hydrates is related to the destruction of micro-sized ice films covering gas hydrate particles, the elements highly important for hydrate self-preservation, as well as destruction of gas-saturated micropores in permafrost rocks due to the slight additional stresses associated with deformation waves, and thus emergence of conditions favorable for gas filtration and its subsequent emission.

Keywords: abrupt climate warming; Arctic; great earthquakes; Aleutian subduction zone; tectonic waves; trigger mechanism; permafrost; metastable gas hydrates; gas hydrates self-preservation; gas filtration; methane emissions

1. Introduction

Among the general problems of civilization, the global climate warming on Earth has recently become one of the cutting-edge challenges. A huge amount of literature has been written about the causes of global warming, while its most common explanation is considered to be the anthropogenic factor causing the greenhouse effect through the increased carbon dioxide emissions into the atmosphere due to the accelerated development of world industry. A number of mathematical models exist, describing the effect of carbon emissions on climate warming. However, the reasons for the sudden onset of periods of sharp global warming on Earth, especially in the Arctic region, remain unclear. Figure 1 shows the well-known temperature variation curve for the Arctic, with clearly visible two phases of a fairly abrupt increase in the average temperature in contrast to the background interannual fluctuations. The first phase of a noticeable warming falls within period between 1920 and 1940, while the second phase began around 1980 and is ongoing nowadays. A similar temperature curve is observed for entire Earth. From the standpoint of the theory of anthropogenic global warming, it is

necessary to provide the evidence that carbon dioxide emissions into the atmosphere had increased significantly during the above periods of abrupt climate warming due to substantial rise of the industrial production. However, the measured data on carbon dioxide emission into the atmosphere associated with human activity in the 20th and 21st centuries display monotonic increase, which has no correlation with the sharp phases of climate warming, as shown in Figure 1.

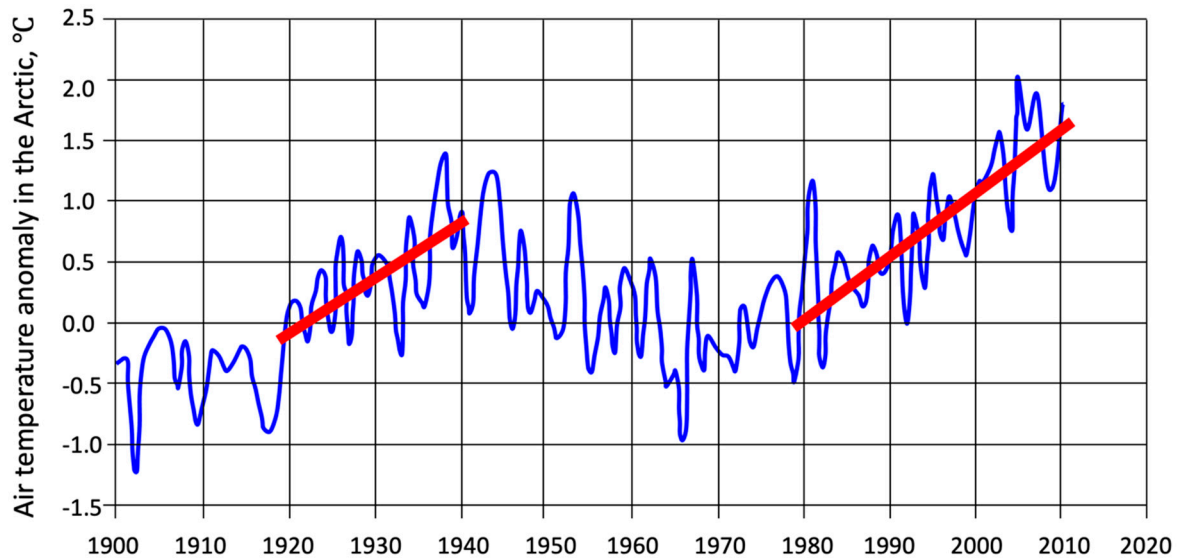


Figure 1. Arctic air temperature anomaly variation since 1900 (data compiled by Arctic and Antarctic Research Institute). Thick red lines indicate the phases of abrupt warming.

Along with the widespread anthropogenic global warming theory, the possible effect of natural mechanisms on the present-day climate of Earth is also being considered. In particular, for the Arctic, which is experiencing the most intense warming, methane emissions are believed to be a major factor. As proposed by a number of researchers [1–4], these may be caused by the permafrost thawing and gas hydrate degradation, resulting in a mass release of methane, which is a potent greenhouse gas. In this case, the cause of permafrost thawing and gas hydrates decomposition is considered to be a background increase in Earth’s surface temperature due to various factors, for example, a Holocene transgression of the Arctic Ocean shelf, etc. Besides, the numerous studies suggest that seismotectonic activity is also an important contributor to this process [5–9]. Without going deep into the discussion and analysis of different thermal models here, we rise one fundamental question: what is the probability that the slow natural process of heating, involving a large region of the Earth’s surface, with the time scale of tens or hundreds of thousands of years, might have caused such intense permafrost thawing and hydrate degradation that led to methane emissions and abrupt warming in the Arctic in exactly our time? The likelihood of such a scenario seems to be extremely low. Hence, there is a need for a search for other, alternative natural mechanisms explaining rapid climate warming in the Arctic, in contrast to purely thermal ones. One of such possible mechanisms, the first ever proposed in the author’s talk at a meeting of the Presidium of the Russian Academy of Sciences on 10 March 2020 [10], is presented in this paper.

2. Evidence for the Seismogenic Origin of Climate Changes in the Arctic

It is clear that such natural mechanisms, theoretically capable of causing abrupt climate warming in the Arctic region, must meet two main criteria. First, they must have an abrupt manifestation and, second, have a sufficiently large power and large-scale (regional) impact. If we look at the endogenous geodynamic processes taking place in the Earth’s subsurface that meet the above criteria, then we find that the most obvious candidate for this role is the great mega-earthquakes occurring in subduction zones. These are characterized by enormous energy and produce a large-scale regional impact to

the surrounding lithosphere. The subduction zone closest to the Arctic region is the Aleutian island arc, which forms its southeastern margin. Here, the northwestern part of Pacific lithospheric plate is being immersed in the mantle, the process which largely determines the geological evolution of the Arctic [11,12]. The Aleutian arc is located at a distance of 2000–3000 km from the eastern part of Arctic shelf and in this connection three main questions arise, the answers to which should be given within the framework of the proposed seismogenic mechanism of abrupt warming in the Arctic region. The first question concerns the correlation between the phases of rapid warming and the periods of the great earthquake's occurrence in the Aleutian subduction zone. The second question is related to the mechanism of transmission of lithospheric disturbances caused by great earthquakes from the Aleutian region to the Arctic shelf, consistent with the observed spatiotemporal patterns. Finally, the third issue is the mechanism itself, through which the seismogenic disturbance affects the gas-saturated permafrost rocks and gas hydrates of the Arctic shelf, leading to the methane release and its emissions into the atmosphere.

2.1. Great Earthquakes in the World and Within the Aleutian Arc

Let us discuss the three above questions subsequently. The first question is whether correlation exists between the phases of abrupt warming in the Arctic and periods of the maximum seismic activity in the Aleutian island arc. The historical data of XX and XXI centuries on the great earthquakes in the World with magnitudes M exceeding 8.0 are shown in Figures 2 and 3 [13]. The great earthquakes that had occurred in the Aleutian subduction zone from the beginning of the XX century to the present day (Figures 2 and 3) indicates an unprecedentedly powerful series of three great earthquakes that occurred in a relatively short period of time between 1957 and 1965. These include an M 8.6 earthquake of 1957 that occurred in the central part of the Aleutian arc, an enormous M 9.3 earthquake of 1964 at the eastern margin of the arc, and, finally, M 8.7 earthquake of 1965, that hit the western part of the arc (Figure 3).

After this series of huge shocks, the Aleutian island arc has been in seismic “silence” until present time, with no earthquakes having magnitudes higher than 8.0, but the only exception—an M 8.0 event that took place in the central part of the arc in 1986. Thus, one can see there is a 15–20-year lag between the strongest shock series that hit the Aleutian arc, and the beginning of abrupt Arctic warming, which started in 1980. This means that in the framework of the proposed seismogenic mechanism of climate change in the Arctic, disturbances in the lithosphere caused by great earthquakes in the Aleutian arc had to propagate over a distance of more than 2000 km to reach the Arctic shelf in about 20 years, i.e., the average propagation velocity of such disturbances should be about 100 km per year.

Another issue that arises in connection with the proposed seismogenic trigger hypothesis relates to the earlier phase of abrupt warming in the Arctic, which began in 1920 and ended around 1940 (Figure 1). The time of its onset, like the one discussed above, correlates with an earlier series of great earthquakes in the Aleutian arc with approximately the same time lag. Indeed, in accordance with historical data on the great earthquakes [13], in 1899 the great earthquake with magnitude M 8.0 occurred in the eastern part of the Aleutian arc and later, in 1906 two great earthquakes with magnitudes M 8.3 and M 8.4 occurred in the western part of the Aleutian arc (Figure 2). Then, this subduction zone was in silence without great earthquakes (M more than 8.0) that lasted for more than 20 years.

Thus, the time between the earlier shock series of the great earthquakes in the Aleutian arc of 1899 and 1906 and the beginning of the first phase of abrupt warming in 1920 is about 15–20 years, which is very similar to the time lag between the shock series of 1957, 1964 and 1965 and the beginning of the second phase of abrupt warming in 1980. Therefore, both phases of abrupt warming in the Arctic, that started in 1920 and 1980, respectively, were preceded by great earthquakes' series in the Aleutian subduction zone, which occurred about 15–20 years prior to these climatic events.

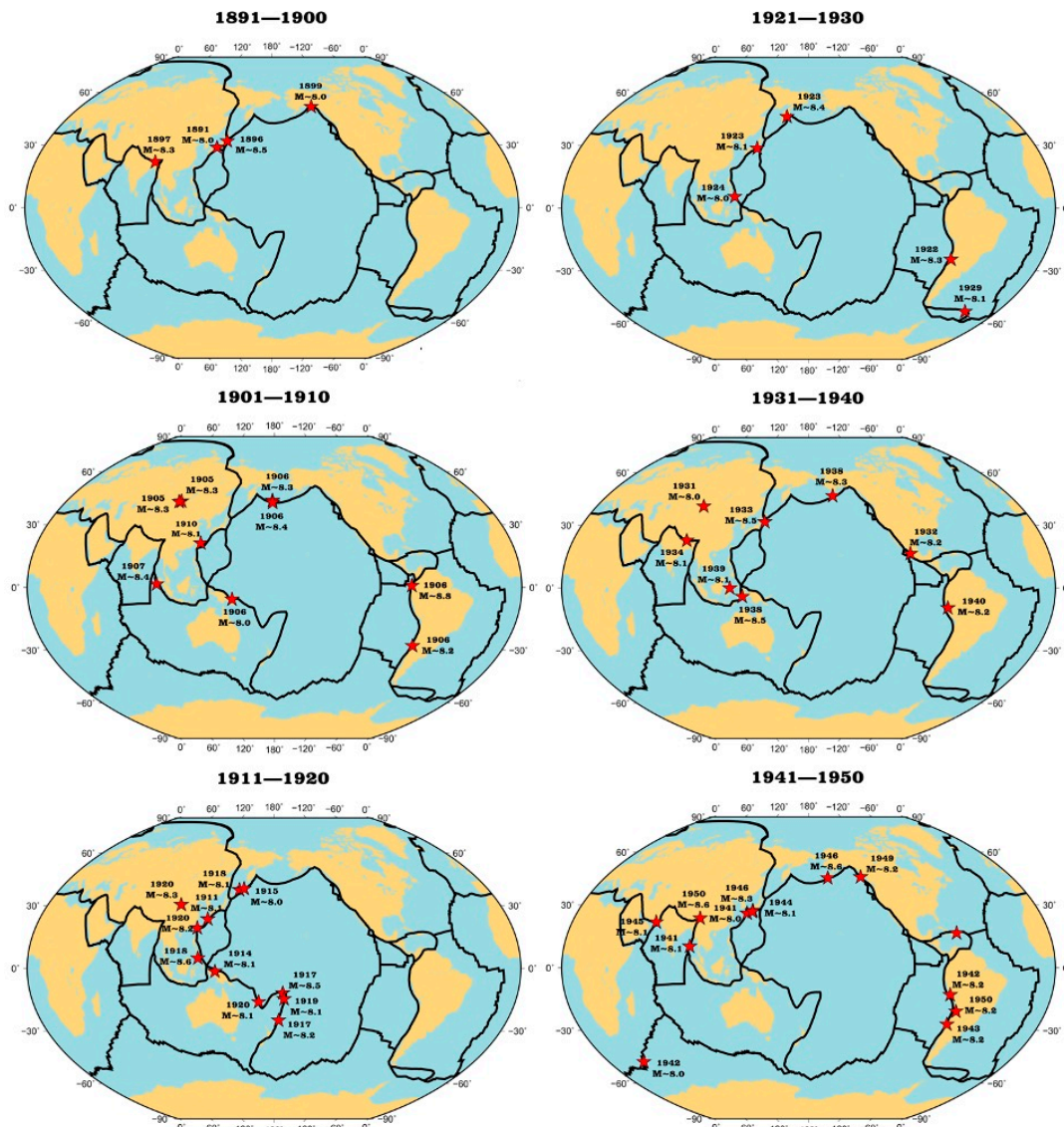


Figure 2. Global distribution of epicenters of the great earthquakes in 1891–1950. Plate boundaries according to NUVEL-1 model are shown as black lines; red stars indicate epicenters of earthquakes having magnitudes greater or equal to 8.0.

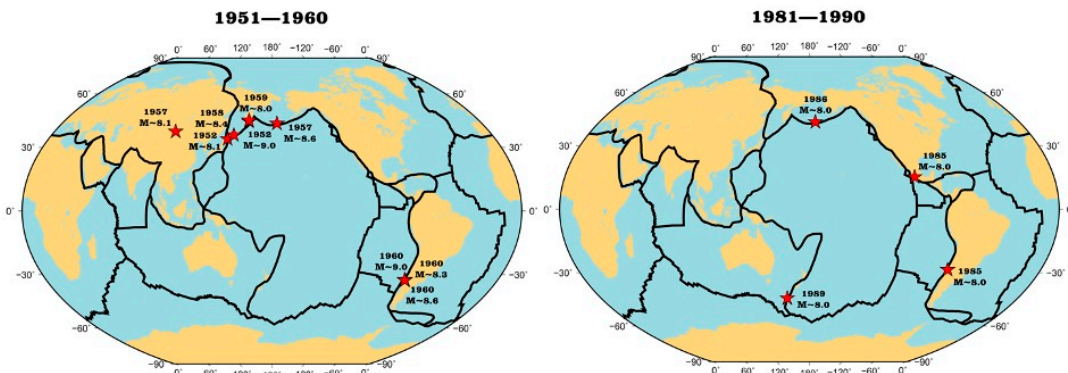


Figure 3. Cont.

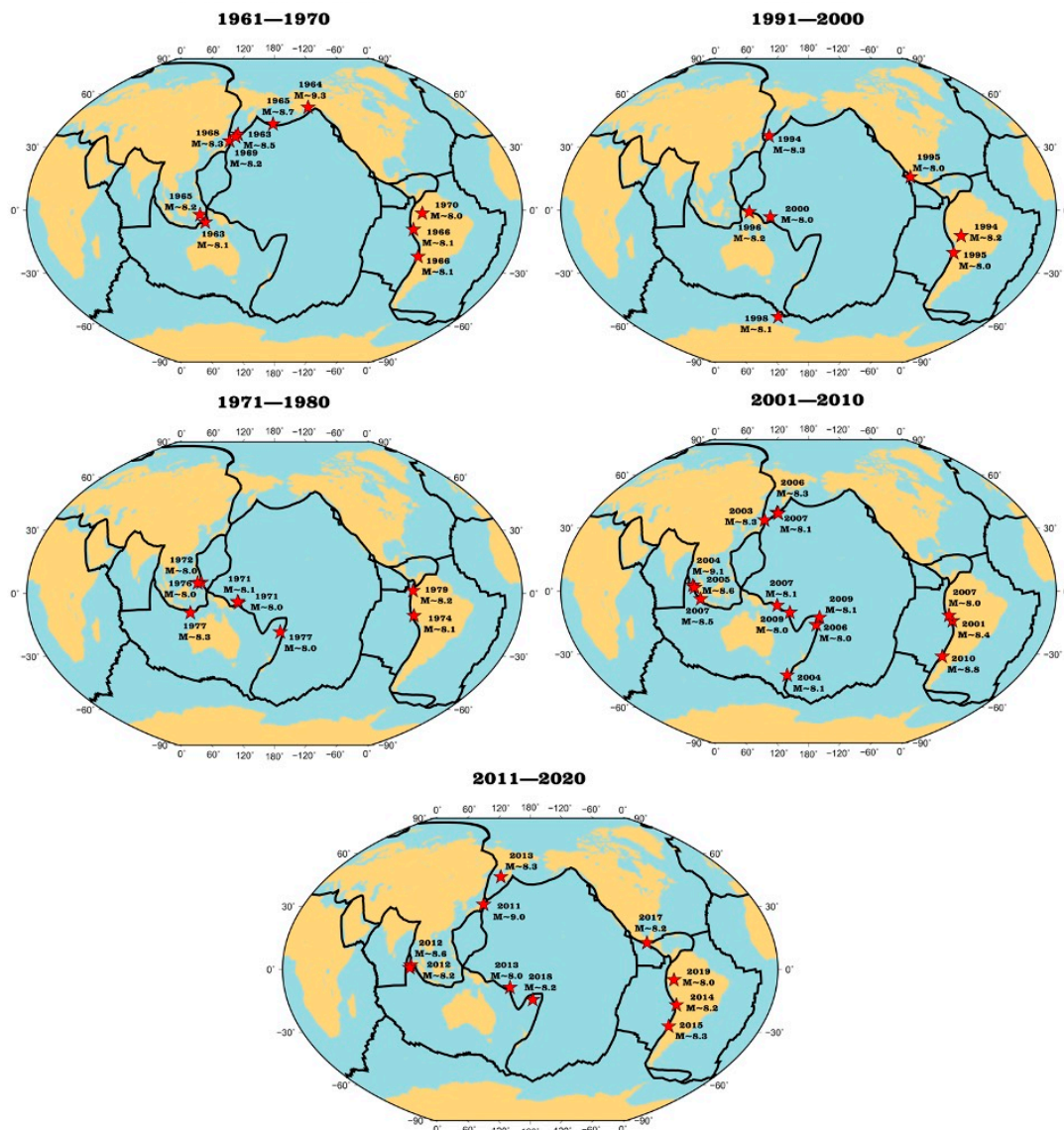


Figure 3. Global distribution of epicenters of the great earthquakes in 1951–2020. Plate boundaries according to NUVEL-1 model are shown as black lines; red stars indicate epicenters of earthquakes having magnitudes greater or equal to 8.0.

2.2. Slow Tectonic Diffusion as Possible Stress Disturbance Transmission Mechanism

Now we move to the second question—the mechanism of slow transmission of lithospheric disturbances, having the characteristic velocity consistent with the above value. It should be emphasized here that, in contrast to elastic seismic waves that propagate rapidly in the lithosphere with velocities of about 8 km per second, in our case we consider totally different so-called “tectonic waves” or “deformation waves”, representing large-scale mechanical perturbations of the lithosphere, a solid elastic plate underlain by a highly viscous asthenospheric layer. For the first time, the problem of the possibility of slow propagation of deformations in the lithosphere, treated as a quasi-homogeneous elastic layer lying on a viscous basement, was analyzed by W. Elsasser in 1967 [14]. He has shown that, in the simplest case of horizontal deformations in the lithospheric layer, the perturbation caused by the discontinuous initial displacement is described by a regular diffusion equation. In later studies, it was shown that tectonic diffusion of stresses in the lithosphere can explain the migration of seismic activity following the great earthquakes, for example, the aftershock migration following the earthquake in the Aleutian arc of 1965 (M 8.7) over a distance of about 300 km along the Pacific plate with an velocity

of about 100 km per year [15]. Thus, it can be stated that, in principle, there is a mechanism for the slow transmission of stress–strain disturbances along the lithospheric layer, which propagate at about 100 km/year, although those disturbances experience strong attenuation and slow down as they travel further from the source in accordance with the Elsasser diffusion mechanism modelled for purely horizontal displacements in the lithosphere–asthenosphere system. A much lower attenuation of perturbations and a greater distance of their propagation in the lithosphere is obtained if we apply the oscillation model from [16] with its generalization to the case of elastic–flexural deformations of the lithosphere, including both horizontal and vertical displacements, which allows us to describe the wave mode of distant propagation of perturbations with only minor attenuation and velocities of the order of 100 km/year (Figure 4). The deformation disturbance wave travelling from the Aleutian arc is over a thousand kilometers wide; it covers all areas of the Arctic shelf and adjacent land. Therefore, the proposed trigger mechanism applies wherever the settings are suitable, i.e., in the presence of permafrost and metastable gas hydrates, including the Kara Sea as well as the northern parts of the Western and Eastern Siberia.

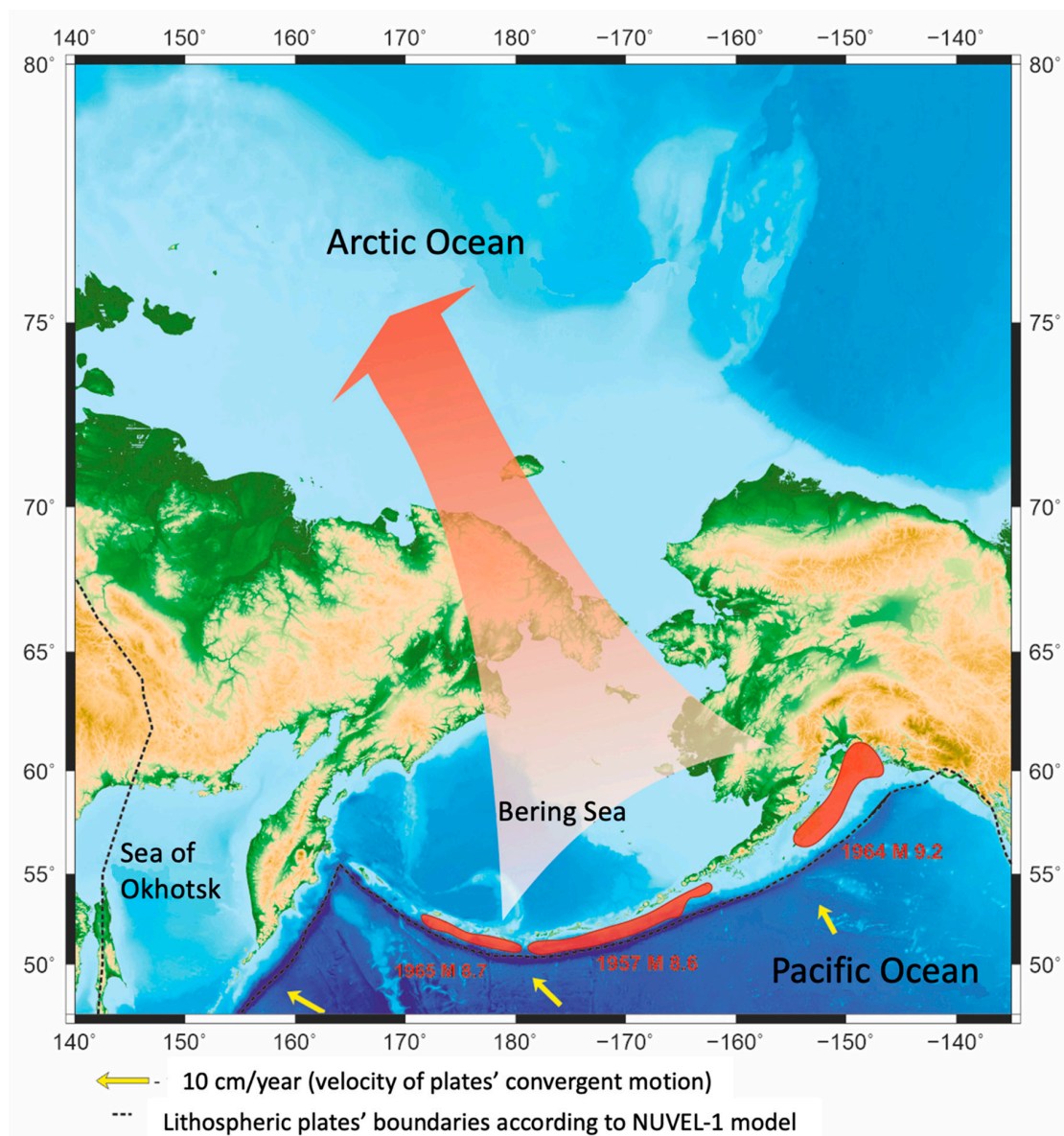


Figure 4. Locations of the great earthquakes in the Aleutian subduction zone in the second half of the 20th century and tectonic disturbance propagation towards Arctic.

2.3. Methane Release Due to Stress Propagation

Finally, let us consider the third of the above questions concerning the hypothesis of the seismogenic effect of mega-earthquakes in the Aleutian arc on the climate in the Arctic. Here, we mean a possible trigger effect of the lithospheric stress–strain state disturbances that spread across the Arctic shelf and adjacent areas, leading to a sharp increase in methane emissions from gas-saturated permafrost, containing metastable gas hydrates. In order for the trigger mechanism causing methane release from permafrost and gas hydrates and associated with lithospheric deformation waves to become physically possible, one needs to assume that the gas-saturated medium is in a metastable critical state, which can be easily disturbed by relatively weak stress perturbations. The numerous sources of data suggest that the Arctic zone is characterized by the presence of metastable gas hydrates occurring at much shallower depths than it is required for their thermodynamic stability [17]. This phenomenon was explained on the basis of the so-called gas hydrate self-preservation effect, which was confirmed by laboratory experiments [17–23]. The effect of gas hydrate self-preservation has the meaning as following. At negative temperatures, violation of the hydrate stability conditions (due to a decrease in pressure or an increase in temperature) causes its dissociation accompanied by the release of gas and water. The dissociation process soon stops due to the formation of thin ice films around the particles of dissociating gas hydrate because of the rapid freezing of water; these thin ice films block the released gas and the remaining hydrate mass, preventing its further dissociation [17,21] (Figure 5).

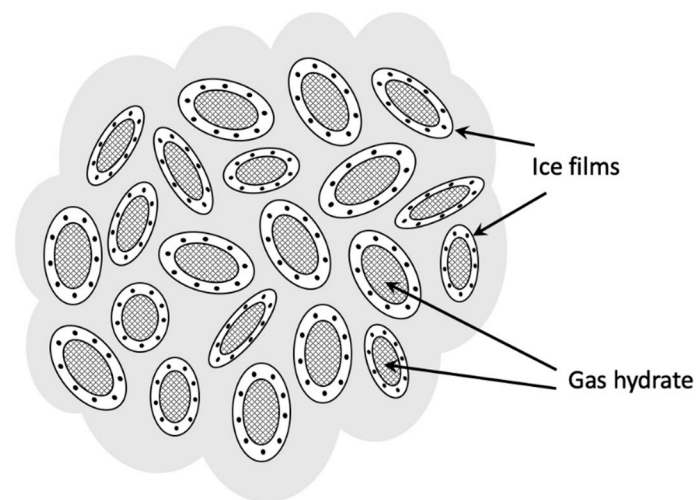


Figure 5. Metastable gas hydrate structure.

Due to the very small thickness of the ice shells (about one thousandth of a mm) and their limited strength, relatively small extra stresses are sufficient to break up these shells and release the trapped gas, making it possible for its filtration through the interconnected ice microcracks produced from the ice shells destruction. A somewhat similar pattern was observed in laboratory experimental studies of agglomerate rock samples, containing gas hydrates and gas-saturated ice blocks, conducted at the Department of Geocryology, Faculty of Geology, Moscow State University [17,22]. The microchannel failure process reported from these experiments, is accompanied by intense gas release, and suggests the physical mechanism of the ice-gas hydrate agglomerate degradation through the formation of a connected system of gas-filled micropores and microcracks as a result of the pressure gradient. The mechanism of zonal destruction of the ice-gas hydrate-gas-filled microchannels agglomerate can explain the process of de-preservation of metastable gas hydrates existing at low temperatures due to the emergence of a thin impermeable ice shell leading to hydrate self-preservation [17]. The described mechanism of zonal decomposition of the permafrost gas saturated rocks, containing ice and metastable gas hydrates under the influence of a slight changes in external pressure, leads to the conclusion that even small regional variations in the stress–strain state of the lithosphere and its sedimentary layer can

potentially release significant volumes of the trapped gas, and cause its flow through the system of microcracks, followed by the emissions into the water column and atmosphere.

The above considerations ultimately constitute the proposed physical mechanism, responsible for an abrupt warming in the Arctic as a result of high-energy mechanical disturbances in the marginal region of the Arctic lithosphere caused by great earthquakes in the Aleutian subduction zone and propagating across the Arctic shelf and adjacent territories. Reaching the accumulations of metastable gas hydrates, these disturbances trigger the methane release from permafrost sedimentary rocks. Based on the presented concept, it is straight forward to make a retrospective forecast that methane emission activity into the atmosphere should have arisen rapidly on the Arctic shelf and in adjacent regions just before the beginning of an abrupt warming in the Arctic in 1920 and 1980, which might be possible to reveal by historical data. In terms of impact on climate warming velocities of 100 km/year mean that the closer to the Aleutian seismic zone, the earlier will methane emission start, moving every year 100 km towards north-west. Verification of this retrospective forecast is necessary to confirm the hypothesis presented here.

3. Conclusions

In conclusion, we note that the seismogenic trigger mechanism of abrupt warming in the Arctic proposed here represents a novel view of the problem, which, of course, should undergo comprehensive verification and analysis, both in terms of consistency with observational data and detailed study of physical and mathematical basics of this new concept being developed.

Nevertheless, there is no doubt that the main initial premise of the proposed concept is the correlation between the two series of the great earthquakes in the Aleutian arc, which occurred in the early and middle of the 20th century, and two phases of sharp climate warming, which began in 1920 and 1980. These events of different nature are separated by a time gap of about 20 years, which is observed for both the 1st and the 2nd pairs of the events, which is hard to qualify as an accidental coincidence. A quite logical explanation of this time lag would be because of the arrival of lithospheric deformation waves from the Aleutian arc to the Arctic zone, with propagation velocity being about 100 km per year. As for the trigger mechanism describing methane release from a trapped state in micropores of the permafrost and metastable gas hydrate particles surrounded by ice films, special experiments and theoretical studies are required for more definitive judgement about the feasibility of the proposed concept.

The author is far from thinking that the observed climate changes in the Arctic and, moreover, the global warming, is determined exclusively by seismogenic triggering mechanism described here. The Earth's climatic system is complex and for its description it is quite natural to utilize coupled models involving geochemical, geophysical and meteorological factors, interacting with each other [24–28]. The mechanism of climate warming of geodynamic nature, discussed in this paper, is essentially an addition to the existing models, and is aimed primarily at explaining the reasons for the observed sharp change in climatic trends in the Arctic in the XX and XXI centuries.

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Conflicts of Interest: The author declares no conflict of interest.

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