Cyclic Organization of Geological Environment: Permafrost Zone of Yakutia

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Abstract. High concentration of mining enterprises in cryolithozone in Yakutia can become the reason of economic loss because of climate warming anomalies. The paper deals with the investigation of the features of cryolithosystems reaction to climate change and search for a certain rhythmic ordering of climatic fluctuations and response to it of space-time shifts in cryolithosystems. According to the results of engineering and geological surveys carried out by the authors in 2001-2017, numerical modeling of series of average annual temperatures of the hydrometeorological station Yakutsk (Central Yakutia) was conducted by means of Fourier Analysis, wavelet Analysis and series autocorrelation analysis. Temperature fluctuations associated with 11, 22, 36, 48 and 72-year solar-conditioned cycles were detected. The wavelet analysis also showed the presence of less short-term periodic oscillations. A large cyclic temperature wave with a period of about 75 years is revealed. A forecast of the development of warming change in Yakutia for the coming decades is made. After a short decline in the rate of warming, intensification of its dynamics in the late twenties and during the thirties of this century, as well as in the second half of the current century cycle is predicted. Inertial processes in the permafrost zone will lead to its greatest destruction in 20-30 years after the accentuation of increased warming.

1. Introduction
Although the strategic mineral resources of Yakutia cryolithozone (including gold, diamonds, natural gas, oil, and coal) are now being intensely extracted, the prospects of developing the local mining sector for the 21st century are undefined. The reason for this is global warming. As of today, there is no reliable forecast regarding the mode of changes in the multi-meter layer of permafrost caused by the intensifying warming; moreover, there is no reliable substantiation of the warming trend itself. Some experts predict a warming followed by a flood of biblical proportions, while others expect a cold spell of the same scale followed by another ice age [1, 2].

2. Problem statement
As it is known, the functioning of cryolithosystems is determined by extreme climate indices, as well as by the presence in the layers of permafrost formations (PFs) of natural ice with its disposition to...
phase transformation. The instability and flexibility of these systems stimulate the development of a variety of natural processes that involve immense volumes of matter and energy, which may lead to dangerous and even catastrophic scenarios, also at mining sites. This is why primary focus must be on the climate and the particular aspects of reaction of cryolithosystems to its changes. There is a necessity to find an express rhythmic ordering of climate fluctuations and the response of the cryolithozone to this ordering in the form of space-time shift.

3. Materials and considerations
In accordance with the climatic pattern of Shender – Balobaev (1999-2009) [1, 3, 4], based on the results of harmonic analysis of average annual temperature series for Yakutsk, in this location in the current century we should expect an overall climate cooling and consequently the reduced risk of PFs thawing and hence development of hazardous geological processes and conditions. In the opinion of the authors, the climate changes taking place in Yakutsk are properly described by a constant component and three fundamental harmonics with the periods of 300, 110 and 75 years. The authors determined the end date of the current (2005 to 2017) climate warming when, as follows from their model, the average annual temperature in Yakutsk would reach minus 8.0°C. After that and up to 2054, in accordance with their forecast, there will follow an intensive cooling down to minus 11°C. Later, a period of warming is expected, lasting until 2088-2089, with average annual temperature increasing again to 8.5 to 9.0°C. The following century will be characterized by relatively constant air temperature, but towards the end of the 22\textsuperscript{nd} century it is supposed to decrease to minus 11.5°C [1].

However, today the validity of this forecast is not very high. For example, the average annual temperature of ground air in Yakutsk in 2005 to 2017 never increased (as the authors of the model had expected); just the opposite, in 2017 it showed the maximum of minus 6.6°C for the whole period of instrumental monitoring in Yakutsk. In addition to that, we can see two flaws in their study. First, the harmonic analysis the authors used while developing their model only allows to register harmonic motions in a steady-state regime, with time-constant parameters of amplitude, period and phase. However, natural processes are complex and they are not cyclic but rather rhythmical, since their parameters are subject to irregular changes in time within a certain range. These flaws are uncharacteristic for the wavelet analysis method, which features a self-adjusting sliding time-frequency interval, which properly reveals the low- and high-frequency behavior of the signal in different time scales. Second, talking about the graphical presentation of the model, at [1], questions arise regarding the derivation of harmonics with the periods of 300 and 110 years. The fact is that in harmonic analysis of any series of numerical values the length of period of the harmonics that represent the structure of the series cannot exceed the length of the series under investigation.

Another problem is that “without using the data about the solar nature of climate change the “tendency-based” forecasts are at best nothing but guesses and pure extrapolation from observation, which is always likely to lead the researcher to an erroneous conclusion” [5].

4. Results
We have used the materials of numerical modeling of average annual temperature series for hydrometeorological station Yakutsk (Central Yakutia) as well as the results of engineering and geological surveys carried out by the authors in 2001 to 2017.

The series of hydrometeorological station Yakutsk is the longest and the most representative one for the territory of Yakutia, embracing the last 187 years (starting from 1829), with non-stop monitoring done for 135 years (1882 to 2017). In addition to that, the runs of the curve for the Yakutsk series are in good agreement with the runs of the curve for the global temperature of the Earth, which gives the series a supra-regional status [6].

In view of the above, for the numerical modeling of the Yakutsk series we have used a set of mathematical methods, including Fourier analysis, wavelet analysis and series autocorrelation method. (figures 1 & 2) [7–10].
The harmonic analysis of the temperature series has shown that it includes a whole range of harmonics with periods close to the known solar-conditioned cycles. All the revealed modes of 11, 22, 36, 48 and 72 years are in line with the solar-conditioned oscillations of Schwabe-Wolf, Hall, Brickner, and with Brickner semi centennials and doubles.

The wavelet analysis has confirmed the harmonic structure revealed with the Fourier analysis method and completed it by showing the presence of a whole spectrum of shorter-term oscillations existing along with the long cyclical ones (72 and 36 years, 22 and 11 years).

The investigation of series autocorrelation has revealed the existence in the 12-87 lag range of a large cyclical temperature wave with a period of about 75 years. The points of extremum of the wave are at lags 37 (negative, at $r_{\text{max}} = -0.43$) and 72 (positive, at $r_{\text{max}} = 0.59$). In the structure of the 75-year cycle there appear 6 series of harmonics with periods close to 11 or 12 years. These harmonics, in their turn, consist of oscillations with the periods of 5 to 7 and 2 to 3 years.

The revealed deterministic component of the series does not allow to determine the period length of harmonics constituting its cyclical basis. Most likely, it is of dual character and is connected with the rhythms of a longer order known in geography, in particular, with the centennial and the 1500 to 1850 rhythms of Shnitnikov-Maksimov. In the more recent period, the influence of anthropogenic
constituent is also possible, not least due to the heating effect caused by urbanistic processes of the city of Yakutsk.

By now we have obtained a certain volume of observation materials for the dynamics of natural processes in Yakutian cryolithozone set against the warming in progress. They allow to a greater or lesser extent to estimate the response of cryolithosystems to the process of warming. In particular, with the increasing thawing of PFs and the rising of rock temperature on the bottom of the annual temperature transfer layer there has been observed the enhanced dynamics of exogenous geological processes and phenomena [6, 11]. In this context a special role is played by the abnormalities of atmospheric moistening, which are already likely to lay the groundwork for exogenous disasters, so far on a local scale [12–14].

With PF layers with high content of ice being quite common, especially on alluvial ice-bearing lowlands and mountain valleys of Yakutia (accounting for over 30% of the total area of the Sakha Republic), it is already a must to consider the potential hazards, including those related to the development of the extracting sector in the region. A strong example is the current ice melting in the Arctic, when after 30 years of warming the Arctic Ocean lost 25% of its ice cover in 2007 only. The process reached its critical point notwithstanding the long resistance of the Arctic, and after that it advanced at a rapid-fire pace. It should be borne in mind that the presence in the PF layers of natural ice with its disposition to phase transformation, huge mass, and inertness to thawing presents a major hazard that can become imminent at the worst possible time.

According to our observations, the first surge in the dynamics of exogenous processes in Central Yakutia took place just the same as in the Arctic, twenty-five years after the start of the major current heatwave in 1970s. It was registered in 2001 to 2003 in the valley of the Middle Lena river, where the thawing of PFs enhanced the dynamics of over-permafrost waters, which caused large-scale collapse of sedimentary sheath on the steep valley sides, with exposure of bedrock foundation. It also triggered the thermokarst on the open areas of ice-rich depositional planes and on the surfaces of ancient river terraces. This was most amply demonstrated in the vicinity of “Kangalassky Kamen’” area, on the south-east border of Kangalas brown coal deposit, the biggest one in Yakutia, located near the city of Yakutsk. The same happened in Erkeny area, 75 kilometers away from the Kangalas outshot.

Almost at the same time the motor roads of Yakutia were hit, including federal highways Lena (Yakutsk to Bol’shoy Never) and Kolyma (Yakutsk to Magadan). These are the roads that provide vehicle access to the gold fields of East Siberia and link the Sakha Republic (Yakutia) with the Far East of Russia, as well as Central Russia and Magadan Oblast, on the year-round basis.

Later, in 2013-2014, the exogenous expansion spread over the mountainous region of Eastern Yakutia. It showed most prominently in the area of Batagay tin ore deposit (Verkhoyansky region). Here, in the Batagayka river basin, emerged a giant heat erosion cave-in, which exposed the thick ice core of the cryolithozone, an ice bench up to 30 meters high and over a kilometer long.

The scale of cryolithozone destruction in the area of the Batagay cave-in clearly demonstrates both the enormity of the potentially hazardous ice morphology of the cryolithozone and the scale of the problem we are to face provided the warming builds up.

5. Conclusion

Visualizing the location of solar-conditioned temperature cycles we discovered on the time scale allowed us to revise the cyclical patterns of increasing warming in Yakutia for the coming decades. According to our forecast, the current century will see the continued increase (following a short-term decrease) in the dynamics of warming, especially in the late 2020s through 2030s, as well as in the second half of the current 100-year cycle. These periods may be regarded as potentially most hazardous for the stability of the cryolithozone. Considering the inert character of the process, the most severe destruction of cryolithozone is to be expected 20 to 30 years after the maximum increase in warming.

The most hazardous engineering-geological and geocological conditions are expected in the course of even 11-year solar cycles and of rising-stage and recession curves of the 100-year cycle.
It is at these periods that the increase of temperature will be accompanied by the abnormalities of atmospheric moistening capable of exacerbating and exponentially enhancing the dynamics of the destructive cryogenic processes [13].

6. References

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