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Methodology for determining climate change by analysis of impurity concentrations in the glacier

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Abstract. The work contains the analysis of possible distributions of aerosol impurities through the glacier depth in those regions of Antarctica, where synoptic maps have shown stabilization of cyclones; and based on this analysis a methodology has been proposed for the determination of climatic parameter changes (average temperature and atmospheric precipitation amount) over a long time period. The main sources of the impurities in the glaciers of Antarctica are marine and continental aerosols, carried by meridional circulation of air masses. The annual concentration of chemical impurities, carried from both ocean and continent, and fallen on the glacier with rain or snow, is approximately the same over a long time period, if the glacier is located in a region of stable cyclonic activity. In this case, for the analysis, ice cores are taken continuously through the glacier depth. Linear sizes of all samples are similar. The quantity of annual layers in the sample is determined based on the age of the lower and upper levels in the glacier, from where the sample is taken. The thickness of the annual ice layer in the glacier is determined by the amount of fallen atmospheric precipitation and ablation processes. Consequently, all samples correspond to the periods of both equal and different durability. The quantity of annual layers in the sample (n) characterizes the amount of atmospheric precipitation of the corresponding period. Changes in the impurity concentrations from sample to sample are connected with the relative change in temperature of the corresponding periods. Then the two parameters, the number of annual layers, n, and the layer impurity content, C, have been determined experimentally in each sample. Based on these two parameters, a new technique has been proposed that allows determination of approximate temperature and precipitation changes over the time period, equal to the age of the studied glacier.

Keywords: aerosol, glacier, ice age.

INTRODUCTION

One of the best practices to identify patterns of climate change and to predict its trends in the future may be the analysis (reproduction and reconstruction) of the features of past climate changes. Both short term and long term climate changes should be analyzed (Aristarain et al., 1986; Schneider, Noone, 2007).

Sedimentary accumulations at the bottom of seas and lakes, as well as ice cores are the natural sources of information about climate change in the past. The analysis of heavy oxygen isotopes content along the ice thickness from 5 deepest wells in Antarctica and Greenland has let to establish a single chronological scheme of climate change on the Earth. According to EPICA, 2004, during the last 500,000 years, average global temperature cycles of 100,000 years period

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have been clearly defined in the Earth's atmosphere. The epochs of cold and warm climates in the past have been established and the periods of their alternation, corresponding to four cycles: 19, 23, 41 and 100 thousand years have been identified.

The analysis of the movement of the Earth along elliptical orbit around the Sun and the laws of celestial mechanics provide theoretical explanation of warm and cold climatic periods, as well as their duration, which corresponds to the time periods of the cycles predicted (calculated) by M. Milankovich: 19, 23, 41 and 100 thousand years respectively.

So-called small Ice Ages also exist next to the cold Ice Age mentioned above. Thus an interglacial warming before 1300 AD was found, as well as a significant cooling up before 1900. However, the details of "small Ice Ages" have not been sufficiently studied in the past.

Budnik et al. (2011—2012), determined the concentrations of Al and Si in ice samples of different ages. The samples were selected from a glacier located near Akademik Vernadsky station. A high concentration of Al and Si is observed in those ice samples that correspond to a warmer period during their formation. These results lead to the aim of finding new methods for determining the relative changes in average temperatures and precipitation accumulation changing the concentration of chemical impurities along the depth of the glacier respectively.

The purpose of this work is to propose a new methodology for determination of climate change chronological scheme.

Over the last years of the XX century and beginning of the XXI century, a large number of studies devoted to glacial cores from various horizons of Antarctic glaciers were performed (Capron et al., 2010; Dahl-Jensen et al.,1998). According to the results of occlusive air studying in the ice samples, the model of ancient atmosphere complex composition was obtained.

Many publications have analyzed chemical impurities composition in Antarctic glaciers. The sources of these impurities are different types of aerosols: space, volcanic, marine (Cl, Mg, Na, K, SO_4) and continental dust (Al, Ca, Si, ...). Thus, Barnes, Wolf, (2004) showed ice samples taken from different depths of the Dome C glacier within first 500 m. Also this work has shown that marine aerosols include many salts that mainly concentrate at the boundaries of ice grains (salts of Na(NaCl), Mg, S).

Barletta et al. (2012) have determined the concentration of nitrates and sulfates located in the grooves (veins) of Antarctica glaciers, which is a breeding ground for primitive bacteria, viruses, etc. The role of biological activity in reducing the albedo of Antarctic glaciers was investigated in Musilova et al. (2016). The authors (Castebrunet et al., 2006) investigated the role of the dimethyl sulfide concentration, secreted by phytoplankton during its life. With marine aerosols the dimethyl sulfide enters the Antarctic ice, which allows tracking the climate changes in glacial and interglacial periods. Price (2007) devote the study to ice channels with a diameter of microns and a water film around aerosols, which includes dissolved ionic impurities that support the life of microorganisms. Based on conductivity examination of Antarctic ice samples, the concentration of SO_4^{--}, Cl^-, NO_3^- ions in different glacier horizons between 26 and 71 meters of depth was determined (Moore et al., 1990). It is interesting to study the dependence of chemical elements concentration on the glacier depth (layer) from which the sample was selected.

The review made by Korkina (1978) showed the analysis of peculiarities distribution of different impurities along the glacier depth. However, both increase and decrease in sets of glaciers impurities concentration were determined depending on the depth, i.e. the age of the sample. This change in concentration of impurities in the ice cores selected from different depths may relate to the climatic conditions of the period when the sampled ice was formed (Budnik et al., 2011—2012).

RESULTS AND DISCUSSION

We propose a new approach for determining the duration and alternation of warm and cold periods during the formation of a glacier based on two parameters: change in average temperature and accumulation of precipitation. The transition from one period

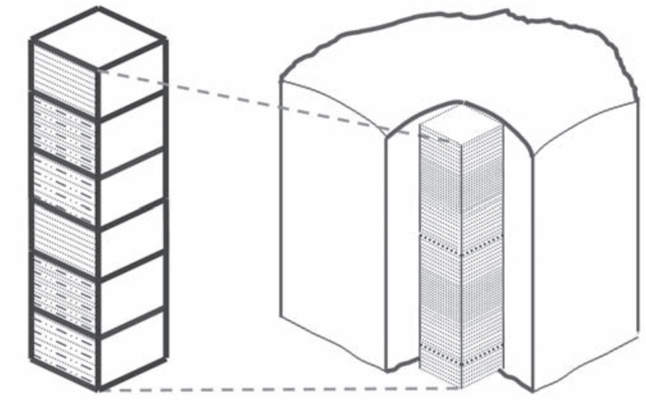


Figure. Sampling along the depth of the glacier

to another is determined by the number of annual layers in the sample — ***n*** and the amount of chemical elements in it — ***C***. The proposed method can be used for glaciers located in the Antarctic region, where O.G. Krychak and other researchers (Petrov, 1975) identified seven cyclone stabilization areas along the mainland coast based on synoptic maps: Weddell Sea, Queen of Maud Land, western Antarctic Peninsula, etc. Then the total annual concentration of impurities transported from both the ocean and the continent over a long time will be approximately the same.

A complete analysis of glacier ice samples includes 4 stages.

Stage I: equal in volume and linear size ice samples are selected continuously along the depth of the glacier (see Figure).

Stage II: dating of upper and lower layers of each sample. Currently, there are a number of techniques for dating Antarctic glacier cores based on the determination of cosmogeneous isotope concentrations, such as Ar^{40}, C^{14}, Pb^{210} and others (Field et al., 2006; Huber et al., 2006; Taylor et al., 2004). The difference in obtained values determines the formation period of each sample (this should correspond to the number of annual layers in it). The number of annual layers in the sample can also be determined by ultrasonic laser sounding. This method provide accuracy within 1 mm for the measurement of glacier layer thickness (Mikesell et al., 2017). The thickness itself depends on the amount of precipitation and the intensity of ablation (melting and evaporation) processes during the year. Large thickness of the layers consequently causes small number of layers in the sample, and therefore such case corresponds to high precipitation period. A lower thickness corresponds to time with low amount of precipitation, respectively.

Stage III: determination of chemical impurities concentration in each sample. For the analysis of impurities concentration in the samples it is first necessary to make a selection of typical chemical elements, that are present in continental aerosols (Al, Ca, Si, ..., etc.), since these salts are the least soluble in water, they are less susceptible to migration, which allows them to accumulate in the respective layers of the glacier. High sensitive equipment usually provides determination accuracy of chemical composition in the range of 10^{-9} g / g in samples.

Stage IV: classification performance. Each sample is described by the number of annual layers — ***n***, and its impurities concentration — ***C***. They change from sample to sample in accordance to the average temperature — $\boldsymbol{T_{ave}}$ and the precipitation amount — $\boldsymbol{m_{ave}}$ within the period. For determination of climatic characteristics of the entire set of samples, four samples with extreme values of the annual layer numbers and impurities concentrations should be taken. Other samples are considered as intermediate cases. The criteria and corresponding climatic performance are given in the Table.

In the first case, the minimum number of annual layers in the sample indicates relatively large amount of precipitation and a cold period.

In the second case, the number of annual layers is greater and ablation processes are less intense. Actually the total precipitation amount in both cases is the same, and the ablation processes in the first case are more intense, as the equal impurities concentrations are reached in a shorter time. Therefore, the average temperature in the second case should be lower than in the first case. The amount of precipitation should be lower than in the fourth case, since the concentration of impurities in the last case is higher, due to more intensive ablation processes in the given period.

In the third case, the precipitation amount is greater than in the first case, since at the same number of annual layers, the impurities concentration is higher, what indicates more intensive ablation processes. Therefore, the average temperature of the period will be higher than in the first case.

In the fourth case, the amount of precipitation is greater than in the second case, as the ablation processes are more intense and the average temperature of the period is less than in the third case due to the equality of impurities concentration at different amounts of annual layers. It is similar to the temperature change between the first and second cases.

Similarly, it is possible to determine the climatic characteristics for all samples throughout the glacier depth and thus recover the change in mean temperature and precipitation throughout the life of the glacier according to the rules.

The accuracy of the proposed method is affected by the cores dating and determination of impurities concentrations in them.

1) Modern high-sensitivity equipment allows determining the chemical composition of ice samples with an accuracy of 10^{-9} g / g.

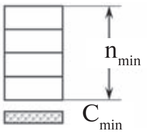
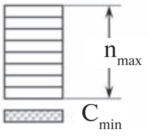
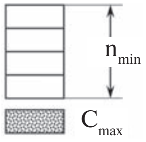
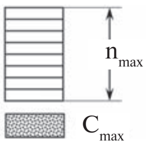
2) Generally, the accuracy of samples dating is determined by the error of chosen method (by radiocarbon C^{14}, by isotopes falling on the earth from aerosols Pb^{210}, Al^{26}, Be^{10}, Ar^{40}) (Field et al., 2006).

a) Dating of the upper annual layer of the sample from the "warm" glaciers is almost impossible, because in couple with evaporation, melting occurred also in the summer time, which leads to the mixing of the annual layers due to the infiltration of warm melt water. If the testing sample includes several tens of annual layers then the top layer dating error can reach 10—15%.

b) In case of "cold" glaciers, such an error may not happen due to the fact that ice melting is almost absent.

3) The layer of annual ice is affected by processes of plastic ice leakage starting from the depths of more than 50 meters. Therefore, adjustments to the thick-

Table. **Average temperatures, depending on the accumulation intensity of different precipitations**

№	View of sample	Annual layer numbers	m_{ave} — mean precipitation amount in the period	T_{ave} — mean temperature in the period
1		$n_{min} = 4$	Much	Low
2		$n_{max} = 8$	Very little	Very low
3		$n_{min} = 4$	Very much	Very high
4		$n_{max} = 8$	Little	High

1) $n_{min}C_{min}$; 2) $n_{max}C_{min}$; 3) $n_{min}C_{max}$; 4) $n_{max}C_{max}$.

ness of the annual layer should be made for these samples by calibration curves of viscous plastic ice displacement in the glaciers.

Thus, the proposed method allows investigating approximate changes in mean temperature and precipitation intensity within different periods over a time equal to the glacier age.

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Методика визначення зміни клімату за аналізом концентрацій хімічних домішок в льодовику

Реферат. В роботі проведено аналіз можливих комбінацій розподілу аерозольних домішок вздовж товщі льодовика в тих районах Антарктиди, де на основі синоптичних мап виявлена стабілізація циклонів, і на його основі запропонована методика зміни кліматичних параметрів (середня температура і кількість атмосферних опадів) протягом великого проміжку часу. Основними джерелами домішок в льодовиках Антарктиди є морські і континентальні аерозолі які переносяться меридіональною циркуляцією повітряних мас. Середньорічна концентрація хімічних домішок, які переносяться як з океану так і з материка і випадають на льодовик з дощем або снігом, буде приблизно однаковою протягом великого періоду часу, якщо льодовик розташований в районі зі стабільною циклонічною активністю. В цьому випадку для аналізу льодові керни вибираються безперервно вздовж глибини льодовика. Лінійні розміри всіх зразків однакові. Визначається число річних шарів в зразку, використовуючи вік нижнього і верхнього горизонтів в льодовику, звідки був відібраний зразок. Товщина річного шару льоду в льодовику визначається кількістю випадаючих атмосферних опадів і процесами абляції. Отже, всім зразкам відповідають періоди як однакової так і різної тривалості. Число річних шарів в зразку (n) характеризує кількість атмосферних опадів відповідного періоду. Зміна концентрації домішок від зразка до зразка пов'язана з відносною зміною температури відповідних періодів. Після цього експериментально визначаються два параметри: число річних шарів – n та вміст домішок у них – C в кожному зразку. На основі цих двох параметрів запропонована нова **методика**, яка дозволяє оцінити зміни середньої температури і кількості атмосферних опадів упродовж часу, рівного віку льодовика.

Ключові слова: аерозоль, льодовик, льодовиковий період.