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Comparison of cations recorded in Antarctica and the Qinghai-Tibetan Plateau ice core by using fuzzy cluster analysis

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Abstract A new approach of glacier classification is suggested on the basis of fuzzy cluster analysis of cations in ice cores. Cations in an ice core act as a synthetic index to refelect both the local and the global climate. Fuzzy cluster analysis of long time series data of cations in ice cores from five representative glacial ice cores (from south to north) has been used to create a similarity scale matrix ***R*** among these glaciers. Accordingly, any change in ***R*** represents a change in environment and climate. This type of analysis can determine the relativity of samples (glaciers) according to a cluster level (λ). Fuzzy cluster analysis of cations in ice cores collected from Antarctica and the Qinghai-Tibetan Plateau indicates drastic difference between glaciers of these two regions.
Key words fuzzy cluster analysis, cations, Antarctica, the Qinghai-Tibetan Plateau.

1 Introduction

Classification of glaciers has great significance for glaciological research. In 1964, the glaciers in China were firstly classified into continent and maritime by Shi and Xie(1964). In 1989, Lai and Huang classified the glaciers in Qinghai-Tibetan Plateau in terms of five physical indexes of the glacier equilibrium line(Lai and Huang 1989).

This article presents a model approach for classification of glaciers on the basis of fuzzy analysis of cation concentrations recorded in glacial ice cores. Accumulation and variation of cations in glacier are controlled by many factors. The cation concentrations in ice cores are influenced not only by local climate (such as precipitation) but also by global climate (such as diffusion and transport of the ions in the atmosphere), especially the atmospheric current which can make a glacier have relationship with one another. Thus, the cation concentrations in an ice core behave as a synthetic index to reflect not only the local climate but also the global climate. Thus, the fuzzy cluster analysis on long time series data of cations in ice core can be used to create a similarity scale matrix ***R*** among glaciers so that any change in the value of parameter ***R*** represents a change in the environment and climate.

2 Fuzzy classification of representative glaciers

A lot of information (data) from galcial ice core has been accumulated since the first ice core was drilled. In order to demonstrate the potential of fuzzy cluster analysis for glacier classification, U represents the five representative glacial ice cores collected northwards from Antarctica Nelson Station, the Hailuogou glacier, the Dasuopu glacier, the Guliya glacier and the Tuomufeng glacier.

Four indexes, namely: Na^+, K^+, Ca^{2+} and Mg^{2+}, which are easy to be determined in the laboratory and reflect the coexisting environment and the climate of a glacier, are used in this model study. Because the characteristic of K^+ and Na^+ are similar, these have been treated together (Na + K) in one group as an index. It is further assumed that the chosen indexes truely represent climatic and environmental characteristics of glaciers on yearly basis over a considerable period of time. Table 1 presents the normalized values of the indexes of (Na+K), Mg and Ca ions in ice cores collected from five glacial regions for sake of fuzzy cluster analysis.

Using the normalized data of the Table 1, the similarity scale matrix $\boldsymbol{R}$ among samples can be obtained by the way of exponential with ABS. Here $R(u_i, u_j) = r_{ij}$, and

$$r_{ij} = exp(-\sum_{k=1}^{m} |x_{ik} - x_{jk}|) \qquad (m=1,2,3)$$

Thus $\boldsymbol{R}$ is created and then square $\boldsymbol{R}$ till equivalent fuzzy relation matrix is reached.

Table 1. The normalized values of the cations in different glaciers

Information sources*	Location		$Na^+ + K^+$	Mg^{2+}	Ca^{2+}
Antarctic Nelson Station	62°17′S	59°03′W	0.904	0.064	0.032
Hailuogou glacier	29°35′N	101°56′E	0.65	0.03	0.32
Dasuopu glacier	28°24′N	85°46′E	0.52	0.05	0.43
Guliya glacier	35°2′N	81°30′E	0.23	0.06	0.70
Tuomufeng glacier	41°56′N	80°8′E	0.16	0.12	0.72

*: All the data are mean value. The data of the Hailuogou glacier come from Long Jiangping (1995) (Personal communication). The data of the Tuomufeng glacier come from Wang and Luo (1980). The data of Antarctica Nelson Station come from Wang Yongyan(1985). The data of the Guliya and Dasuopu glacier come from Yao Tandong (1995, 1996) (Personal communication).

Using this matrix a sample relation system diagram can be drawn. This type of analysis can determine the relativity of samples and cluster the samples according to a cluster level (λ) from large to small (He 1983). The results are deduced from cluster analysis of cations in the five representative ice cores of U are shown in Fig. 1.

Clustering can be visualized as follows:

(1) As $0 \leqslant \lambda < 0.56$, U can be divided into one type: {the Antarctic Nelson Station, Hailuogou, Dasuopu, Guliya, Tuomufeng};

(2) As $0.56 \leqslant \lambda < 0.57$, U can be divided into two types: {the Antarctic Nelson Station}, {Hailuogou, Dasuopu, Guliya, Tuomufeng};

(3) As $0.57 \leqslant \lambda < 0.77$, U can be divided into three types: {the Antarctic Nelson Station}, {Hailuogou, Dasuopu}, { Guliya, Tuomufeng};

(4) As $0.77 \leqslant \lambda < 0.86$, U can be divided into four types: {the Antarctic Nelson Station}, {Hailuogou}, { Dasuopu}, { Guliya, Tuomufeng};

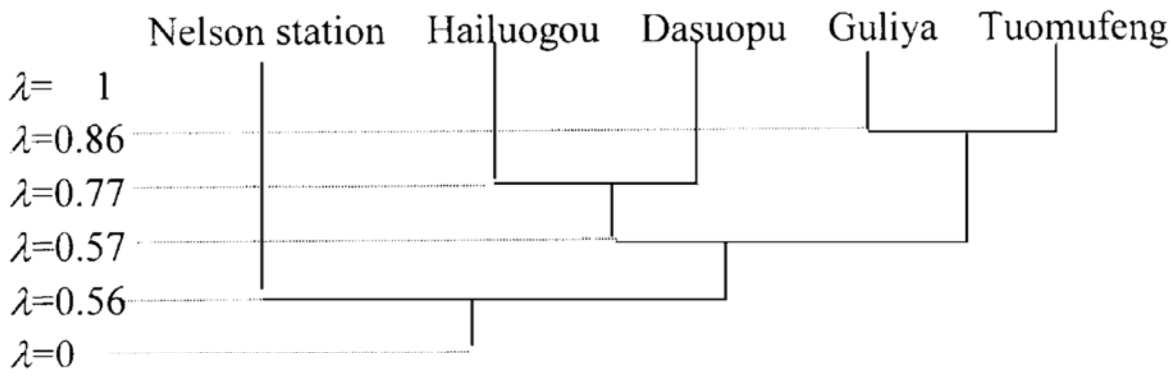

Fig. 1. Fuzzy cluster of 5 samples with different λ.

(5) As $0.86 \leqslant \lambda < 1$, U can be divided into five types: {the Antarctic Nelson Station}, {Hailuogou}, { Dasuopu}, { Guliya}, { Tuomufeng}.

3 Discussion

Glacier classifications are different in different levels of λ. As $0.86 \leqslant \lambda < 1$, U can be divided into 5 types. It means that every glacier has itself special character. As far as major cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) are concerned, the cation concentration change trends are different from one another. From the south to the north, concentration of Ca^{2+} increases quickly, which may directly indicate the gap between glacier and the Ocean. Fig. 2 shows the spatial variation of major cations from the south to the north. It is clear that from south to north, the Ca^{2+} and Mg^{2+} concentrations increase in the Qinghai-Tibetan Plateau. But the Mg^{2+} content in the Antarctic Nelson Station is higher than that in the Hailuogou, the Dasuopu and the Guliya glaciers. On the other hand, the content change trend of Na^{+} and K^{+} are just opposite to that of Ca^{2+}. This spatial variation of cations is expected due to both the local and global environment and climate. It is just this result that lead to different characteristics among glaciers under different λ. The difference are found not only in ion concentrations but also in precipitation, pH and conductivity, etc..

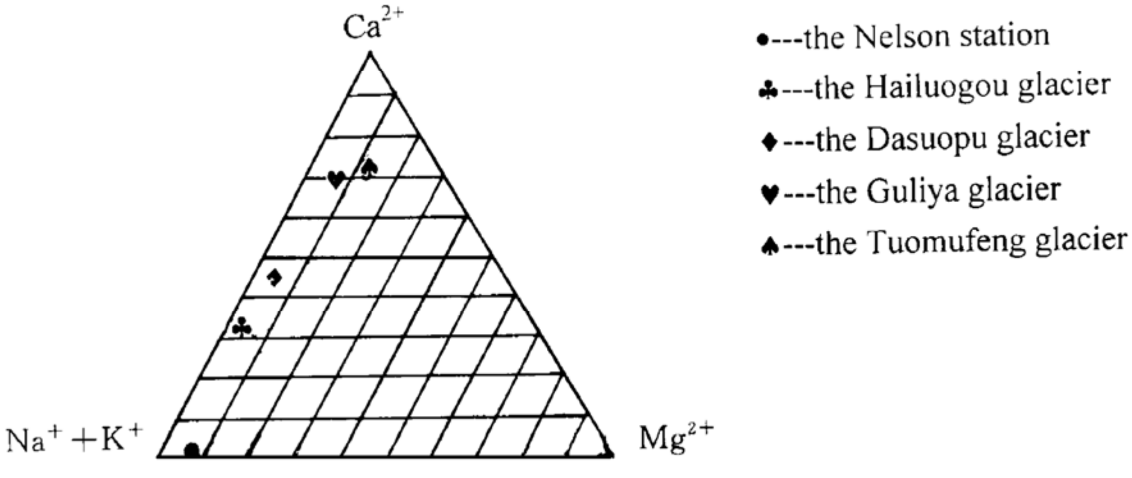

Fig. 2. The spatial variation of cations in different glaciers.

At 0.77≤λ<0.86, U can be divided into four types. Within this λ level, some common characteristics are observed for the Guliya and Tuomufeng glaciers; both of them are influenced by the westerly circulating current and the west airflow of the Mediterranean, and the airflow on the southeast and southwest margins also controlled the precipitation. Their common characteristics are that the distribution of precipitation is fairly even yearly, the precipitation is rather great both in spring and in winter. The other two types, the Hailuogou glacier and the Dasuopu glacier, are very different regardless of the fact that both of them are inluenced by the Southwest Monsoon. The Hailuogou glacier is typical maritime type glacier, its annual precipitation is 1800 mm (Su 1984), two times more than that of the Dasuopu glacier. Ion concentrations can reliably reflect their difference. Specifically, the concentration of Na^+ is higher than that of Ca^{2+} in the Hailuogou glacier and concentration of Ca^{2+} is higher than that of Na^+ in the Dasuopu glacier. What reason caused $Ca^{2+}>Na^+$ in the Dasuopu glacier is not still very clear, but from a study of the precipitation of the Dasuopu glacier, it can be obtained that its precipitation mass mainly comes from the Indian Ocean, however, the Dasuopu glacier lies at the south verge of the Qinghai-Tibetan Plateau. It is just its special site which caused its ions coming from many ways while its precipitation is mainly coming from the Indian Ocean. As compared with the Hailuogou glacier, the result is that the Dasuopu glacier is less influenced by the Southwest Monsoon than the Guliya glacier.

At 0.57≤λ<0.77, U can be divided into three types: {the Antarctic Nelson Station}, {the Hailuogou glacier, the Dasuopu glacier}, {the Guliya glacier, the Tuomufeng glacier}. In this λ level, the common characteristics of the Hailuogou and Dasuopu glaciers appear, both of them are influenced by the Southwest Monsoon in spite of the fact that they have other common characteristics, such as plentiful precipitation (mainly in summer but not in winter). Under this λ condition, they are very different from the Guliya glacier and the Tuomufeng glacier. The main difference is that the first two glaciers are mainly influenced by the Southwest Monsoon while the later two glaciers are mainly influenced by the west circulating current. Reflecting to ion concentrations, the difference is the ratio value between Ca^{2+} and Na^+. The ratios in the Hailuogou and the Dasuopu (1.14 and 1.30 respectively) are smaller than those in the Guliya and the Tuomufeng glaciers (3.48 and 6.33 respectively). From the above analysis, it may be seen that the relationship between the Guliya and the Tuomufeng are closer than that between the Hailuogou and the Dasuopu.

At 0.56≤λ<0.57, U can be divided into two types: {the Antarctic Nelson Station}, {the Hailuogou, the Dasuopu, the Guliya, the Tuomufeng}. Within this λ level, the Antarctic Nelson Station is essentially distinct from the glaciers of the Qinghai-Tibetan Plateau. The ocean separates the Antarctica far from the other continents, and the resource of ions in the Antarctica is far different from that in the Qinghai-Tibetan Plateau. Ca^{2+} in the Antarctica ice-snow is the typical representative impurity from the mainland crust, and the increasing concentration of Ca^{2+} in the Antarctic ice-snow is a signal of increasing impurity in the atmosphere (Qin 1995). Table 1 shows that the content of Ca^{2+} in the Nelson Station is much less than that in the glaciers of the Qinghai-Tibetan Plateau. This is because the Antarctica is far away from the other continents. On the other hand, the concentration of $Na^{+}+K^{+}$ is much higher than that in the glaciers of the Qinghai-Tibetan Plateau. As far as the sites of glacier are concerned, we can see that the content of $Na^{+}+K^{+}$ in glacier is directly connected with the gap between the glaciers and the ocean. The bigger the gap is, the larger the content of $Na^{+}+K^{+}$ and vice versa. However, the variation of Ca^{2+} content with the gap is just opposite to that of $Na^{+}+K^{+}$, namely, the smaller the gap is, the lower the content of Ca^{2+} and vice versa.

The value of Ca^{2+}/Na^{+} is an important parameter, it can be defined as continent degree. The value of Ca^{2+}/Na^{+} is high while the continent degree is large and vice versa. In Table 2, the values of Ca^{2+}/Na^{+} are nearly the same for the Nelson Station and the ocean, but that in the Nelson Station is much lower than that in the glaciers of the Qinghai-Tibetan Plateau. The continent degree in the Qinghai-Tibetan Plateau increases step by step from the south to the north. Table 2 shows that the continent degree in the Nelson Station is the smallest one and in the Tuomufeng it is the largest one. Generally, Na^{+} and Ca^{2+} in the Antarctic verge mainly come from the ocean, but in the inland of Antarctica Ca^{2+} mainly comes from the earth crust (Qin 1995). That is to say, in Antarctica there are different continent degrees for different region. The continent degree increases gradually as the distance between the region and the ocean increase. The Nelson Station is very close to the ocean, so its continent degree is far smaller.

Table 2. The values of Ca^{2+}/Na^{+} in different glaciers

	Sea water	Nelson Station	Hailuogou	Dasuopu	Guliya	Tuomufeng
Ca^{2+}/Na^{+}	0.038	0.032	1.141	1.30	3.486	6.33

At $0\leqslant\lambda<0.56$, U can be divided into one type only. Within this λ level, all difference among the glaciers are omitted.

By the analysis, the characteristics among glaciers are closer under large λ level than under small λ level. In Fig. 1, the common feature between the Guliya and the Tuomufeng glaciers appear as λ is equal to 0.86, whereas, the common feature between the Nelson Station and the glaciers of the Qinghai-Tibetan Plateau appear as λ already decreases to 0.56. On the other hand, glaciers are more similar as their λ levels are closer. In Fig. 1, the gap of λ between the Nelson Station and the Hailuogou glacier is 0.21 while that between the Nelson Station and the Guliya glacier is 0.3. That means that the relationship between the Nelson Station and the Hailuogou glacier is closer than that between the Nelson Station and the Guliya glacier. It is apparent that the Nelson Station and the Hailuogou are mainly influenced by the ocean while the Guliya glacier is mainly influenced by the continent. In short, it is a gradually changing trend from maritime glaciers to continental glaciers. A maritime glacier is always characterized by some typical characters of the continent glaciers. So it is very difficult to classify glaciers in a specific way.

4 Conclusion

In this article, five representative glaciers are studied. Each target glacial ice core has three indexes of $Na^{+}+K^{+}$, Ca^{2+} and Mg^{2+}, for fuzzy cluster analysis we can study them. And the results indicate that the relation among the glaciers changes with the λ level. As the λ level gets high, each glacier attaches itself to a typical character which has no relation with others. With the decrease in λ level, the common character between the Guliya glacier and Tuomufeng glacier appears. With a further decreasing of λ, the common character between the Hailuogou glacier and the Dasuopu glacier appears. With a further decrease in λ level, the glaciers can be divided into two parts: the Antarctic Nelson Station and the Qinghai-Tibetan Plateau glaciers. This indicates that the environment and climate in the Antarctic Nelson Station is different from that in the Qinghai-Tibetan Plateau. As λ decreases more, the boundaries among the glaciers become indistinct. They can be put in one type.

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