Evolution and origin of global glaciers and their impacts on the environment

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Abstract—Glacier is one of the most important freshwater resources. However, the situation of glaciers is changed nowadays because of global warming. This study aimed at two types of glaciers, and analyzed their evolution, origin and impacts on the environment. As for typical melting glaciers, the Vatnajökull glacier and Urumqi Glacier No.1, Tianshan Mountains gradually melt over time. Their causes are related to atmospheric River events, black carbon pollutants, ice recycling, global warming, and human activities. The impacts of glacier retreat mainly include sea-level rise and can alleviate global warming and cause surface deformation. However, there are some “weird” glaciers because they are expanded in the past few years rather than shrinking. Those glaciers are highly concentrated in the Karakoram, Pamir Mountains, Svalbard, the Canadian Arctic islands, Alaska, and Iceland, which are called surged-type glaciers. Hydrological control, thermal regime, deformable bed hypothesis, and critical mass are reasons for glacier expansion. There is no clear and unified opinion on the advantages or disadvantages of glacier expansion.

1. Introduction

Glacier is one of the most important freshwater resources. There are a total of sixteen million square kilometers, and are concentrated in the Arctic, Antarctica, Karakoram Mountain, Greenland, and Alaska. Based on data, those glaciers are about 11 percentages of the land area of the earth. However, the situation of glaciers is changed nowadays because of global warming, which is one of the most serious problems that all modern humans face.

Over the past century, climate warming has been significant and the warming trend has intensified, so the elements of the glacier circle are in a state of continuous retreat and threaten the safety of water resources, causing a series of problems. First, sea-level incredibly increases at least 68 meters, and all coastal cities, including London, Los Angeles, Shanghai, Sydney, will be completely flooded. It produces huge impacts on global economics. Second, atmosphere heat balance, hydrosphere, and ecological system are broken. Extreme weather, such as heavy downpours, hurricanes, and tsunami, will be normal because ocean currents are changed due to glacier melting. Third, plenty of scientists are concerned that prehistoric virus will be released once all glaciers are melting. In addition, those
prehistoric viruses in the permafrost would spread worldwide as the ocean current moves, and it would result in some unnamed and weird diseases that we cannot be healed by medical science.

Many studies focus on the impact of glacier melting on the environment; however, glacier expansion is another important phenomenon, which is less studied. Therefore, Vatnajokull glacier, Urumqi Glacier No.1, Tianshan Mountains and Karakoram mountain are selected as examples to compare and discuss the two situations of glacier melting and expansion. Quantum GIS(QGIS) and ArcGIS software are used to study their causes and effects.

2. Methods

As for glacier melting, the analysis and processing data used in the study area are from the USGS website. The downloaded data include Urumqi Glacier No.1, Tianshan Mountains satellite data in Landsat 8 OLI/TIRS C1 Level-1 data set in September 2013 and September 2021, Vatnajokull glacier satellite data in Landsat 8 OLI/TIRS C1 Level-1 data set in 2015-2021, and Digital Elevation Model(DEM) data in 2005 and 2014. The meteorological data are from the NOAA website. The downloaded data include the annual average temperature, annual precipitation and other meteorological data monitored by 8 meteorological stations around Tianshan Mountain in China from 1951 to 2021.

QGIS is used to process and analyze the satellite data by RGB comparison setting and Normalized Difference Vegetation Index(NDVI) which highlights the snow cover in the image by using the combination of visible light (mainly green light) and short-wave infrared band, to obtain the comparison of glacier area and height in different years. As for the glacier, RGB = band7 / band5 / band3 (this RGB is mainly used to remove atmospheric effects and highlight natural surfaces) and RGB = band5 / Band6 / Band4 (this RGB is mainly used to distinguish land and water) are selected in this study. It is found that the results obtained by the two RGBs are almost the same, so the results obtained by RGB = band7 / band5 / band3 are finally selected for analysis. Through the comparison between band ratios and NDVI, it is found that the results of NDVI are clearer. Finally, the results of NDVI are selected for comparative analysis.

The spatial interpolation analysis of the Inverse Distance Weighted(IDW) method is carried out on the meteorological data of meteorological stations around the study area by using ArcGIS software, so as to obtain the meteorological data such as annual average temperature and annual precipitation in the study area.

As for the glacier expansion in Karakoram Mountain Range, two datasets are used in this study, obtained from two different times in the USGS website. This study selects a date in the year of 2021 and 2013, and make sure both of them are in the same season. Inaccuracy will be produced if the study chooses one date in summer and another in winter. Using QGIS to and analyze the same region to compare glacier changes. Then, the study chooses RGB in order to discover glacier change. The first RGB is 5:4:3 which is natural color.

Figure 1(a) shows the glacier situation in 2013, and Figure 1(b) shows the glacier situation in 2021. It is obvious that the “white area” in Figure 1(b) is slightly more than the “white area” in Figure 1(a). This white area includes snow and ice. Glacier is made of ice, rather than snow. So, this study used a new band combination in order to distinguish snow and ice. For the new band combination, the study used a raster calculator for calculating Band 2 divided by Band 7. This band composition, band 2 divided by band 7, is usually used for detecting water bodies, and it is still useful in this situation.

Figure 2(a) shows the glacier situation in 2013, and Figure 2(b) indicates the glacier situation in 2021. This band combination essentially helps use distinguish snow and ice. Based on images, crystal implies glacier. It is clear to see glacier coverage of Figure 2(b) in 2013 is larger than glacier coverage of Figure 2(a) in 2021.
Fig. 1 Satellite Image of Glaciers in Karakoram Mountain Range in (a) 2013; (b) 2021 with RGB 5:4:3
Fig. 2 (a)

Fig. 2 Satellite Image of Glaciers in Karakoram Mountain Range in (a) 2013; (b) 2021 with Band Combination (Band 2 divided by Band 7)
3. Glacier melting

3.1. Typical Glacier Evolution

3.1.1. Vatnajokull glacier
Vatnajokull glacier, located in the east-south coastal of Iceland, is one of the biggest glaciers in Europe. It is also one of the most vulnerable glaciers while facing global warming. In order to have a better understanding of the recession of the Vatnajokull glacier, we download remote-sensing its images between 2015 and 2021 from the website Earth Explorer. All these images are collected by Landsat 8 satellite. To highlight glaciers, NDSI is used to process the images. The definition of NDSI is ‘NDSI = (GREEN-SWIR) / (GREEN+SWIR)’.

As we can see from the chart below, the cover of Vatnajokull glacier shows a rapidly decreasing trend. Almost 50% of Vatnajokull glacier has melted in 5 years.

Through the classification method, researchers set training areas to study the image in 2015 and 2020 and combine the output results. Then we get the below image showing the glacier overall change between 2015 and 2020 (Figs. 3, 4).

Fig.3 Vatnajokull glacier change from (a) 2015; (b) 2016; (c) 2017; (d) 2018; (e) 2019; (f) 2020
3.1.2. Urumqi Glacier No.1, Tianshan Mountains
Urumqi Glacier No.1, Tianshan Mountains is located in Urumqi county, Xinjiang Uygur Autonomous Region, about 120 kilometers southwest of Urumqi city. It belongs to the source area of Urumqi River on the north slope of Tiangel mountain. Urumqi Glacier No.1, Tianshan Mountains was formed in the third glacial age, with a history of 4.8 million years. Due to the concentration of modern glaciers, typical glacier landforms and sediments, and complete and clear preservation of ancient glacier relics, it is known as a “glacier living fossil”, and has become the best place to observe and study modern glaciers and ancient glacier relics in China.

The image is processed by QGIS to obtain the glacier distribution map in 2013 and 2021 (Fig. 5). The blue area is the glacier; the green area is land and the white area is cloud. In the output results (Fig. 6), the part from glacier to the glacier is set to blue, and the part from glacier to land is set to red. It is obtained that the glaciers in 2013 are distributed in red and blue areas, and the glaciers in 2021 are distributed in blue areas. Therefore, it is obvious that the glacier melting area from 2013 to 2021 is large, and the glacier melting rate is very fast.
In addition, the NDSI method is used to observe the change of glacier area (Fig. 7). Finally, a large area of glaciers melting from 2013 to 2021 can be observed. This method is more comparative and clearer than band 2 / band 7, and can highlight the desired area.

Because no suitable DEM data in September 2021 was found, the DEM data in September 2005 and October 2014 were finally downloaded and 3D processed and analyzed. Finally, the 3D map of two years was obtained (Fig. 8). The high-altitude area is red and the low-altitude area is blue, which can see the altitude change in these two years. Figure 8 shows that the legend that the highest altitude decreased by 60 m from 2005 to 2014. Due to the missing data in 2005, the lowest altitude in the legend is 0 m, which cannot be compared with the lowest altitude in 2014. However, through the difference of the highest altitude, it can be concluded that icebergs are melting from 2005 to 2014, and the height of icebergs is decreasing, and the highest altitude decreases at the rate of 7.5 m/a.
3.2. Reasons for glacier melting

3.2.1. The effect of Atmospheric River Event on glacier melting
Atmospheric rivers, an elongated, narrow structures in the atmosphere, often happen in middle latitude with lots of moist air, which have impacts on coastal regions worldwide. This kind of climate phenomenon can cause high temperature, which is more apparent in the coastal area. Thus, it can trigger extreme glacier melting especially in the coastal area. In addition, the impinging warm and damp air may result in the air ascending the mountain instead of surrounding the mountain. This can cause cloud formation, leading to rainfall, on the windward slopes. Glacier ablation would happen during rainfall and condensation. [1]

3.2.2. Black carbon pollutants
Black carbon pollutants in glaciers accelerate the melting. Due to the incomplete combustion of fossil fuel and biomass, the level of black carbon in the ambient keeps increasing. Atmospheric black carbon, a kind of carbonaceous aerosols, has a strong effect on absorbing solar radiation. Some studies manifest that these light-absorbing aerosols may influence the monsoon, which is detrimental to the glacier located in the monsoon area. The Himalayan cryosphere is one of areas that is suffering from climate change the most. Based on observations, remote sensing, and atmospheric modeling, there is a higher melting rate in the Himalayan glacier. The reason behind it is much deeper beyond climate warming. The majority of the population of the world settle along the foothills of the Himalayas, which cause a great amount of black carbon. When deposited by snow, fully sun-absorbing black carbon becomes detrimental to the glacier. [2]

3.2.3. Recrystallization of ice
Recrystallization of ice enhances glaciers to creep and collapse. The warmer temperature and high strain rates activate migration recrystallization, resulting in larger ice grains size. The increase in grain size can soften the margins of fast-flowing glaciers and make glaciers more fragile to crack. According to research, the grain in areas of glacier being sheared has a similar phenomenon with physical properties of the crystalline microstructure. This means that larger and better-oriented grain can be observed in areas where ice is warm and being sheared. In conclusion, the increase of grain size caused by global warming enhance the glacier’s possibility to fracture and while glacier shearing, strain rate would increase causing the growth of grain. Owing to global warming, a vicious cycle forms. [3]

3.2.4. Climate change
The climate change in the glacier area directly affects the material melting and accumulation of glaciers, and the two climate elements of temperature and precipitation are most closely related to glacier change. The analysis shows that from 1960 to 2013, the temperature in the whole Xinjiang region changed from 6.2 to 9.0 °C, the climate tendency rate was 0.32 °C/10a, and the annual precipitation changed from 93.2 to 205.8 mm, showing an upward trend as a whole, and the climate tendency rate was 8.23mm/10a. According to the data of 14 meteorological stations in Tianshan area, the temperature and precipitation in Tianshan area showed an upward trend from 1960 to 2016, with an increased rate of 0.29°C/10a and 10.3 mm / 10a respectively [4]. The spatial and temporal characteristics of climate change have an important impact on the regional differences of glacier change [5]. The simulation of the material balance of No.1 glacier at the source of Urumqi River shows that the change of temperature ±1°C or precipitation ±35% has an impact on the height of the material balance line of 140±125m [6].

The response of glaciers to climate change involves a series of complex processes. Atmospheric conditions, solar radiation, temperature, precipitation, wind and cloud cover affect the mass and energy balance of glacier surface. The increase of annual precipitation in Tianshan area can not make up for the loss of glacier material caused by the rapid rise of temperature, which is the main reason for glacier retreat. Therefore, the increase of temperature is the main factor for the rapid retreat of glaciers in this area [7].
Studies have shown that the longer the time scale or the larger the spatial range, the more significant the influence of temperature on the advance and retreat of glaciers [8]. Precipitation usually only has a significant impact on the advance and retreat of glaciers on a short time scale (such as less than 10 years) and a small spatial scale. The glaciers in Tianshan area are continental glaciers. The accumulation and accumulation mainly occur in summer, which belongs to summer accumulation glaciers.

The analysis of meteorological data shows that in the recent 20 years, the temperature and precipitation in Tianshan mountain area have increased significantly in summer. Without considering the lag of glacier response, it is preliminarily considered that the melting caused by the significant rise of summer temperature is greater than the accumulation caused by precipitation in the year, which is the main reason for the retreat of Tianshan glacier. The general rise of temperature in the study area leads to the general rise of the snow line in the glacier area, especially after 2000, the rise of temperature in the glacier area leads to the rise of the overall snow line, which intensifies the retreat of glacier [7].

3.2.5. Human activities
In addition, human activities have also had an impact on the melting of glaciers in recent years. Human activities have accelerated the melting of the glacier. For example, the exhaust gas from large vehicles passing by the nearby roads and nearby factories has slightly increased the temperature around the glacier. The glacier is covered with a layer of ice dust, which affects the reflection of the glacier on light and heat and intensifies the retreat of the glacier. Another aspect is the grassland retreat and soil degradation caused by overgrazing, which are the incentives for the accelerated melting of glaciers.

3.3. Impacts of glacial ablation
The impacts of glacier melting are not only about the rise in sea level. Its impacts are various and complex, which refer to many aspects such as ecology, tectonics, environmental science. Here we list some of the latest research on glacier melting impacts. Hoping it will be helply for other research to have a deeper study in the glacier.

3.3.1. Crustal stress
Glacial ablation can cause surface deformation and the temporal and spatial variation of crustal stress and fault earthquake. Most of the glaciers spread over mountains with high elevation. And many mountains are located in tectonic belts. While glaciers melting, vertical pressure keeps decreasing. Under the corporate impression of decreasing glacier load and compression on both sides, the surface may lift up apparently. The higher the elevation, the more the glacier load will reduce, and the higher it would lift up. For some glaciers located in the fault zone, the reduction of glacier would make each main fault belt show different evolutionary trends, which may eventually have a different impact on the change seismic risk. [9]

3.3.2. Effect on carbon sequestration
Glacier retreats alleviate global warming and have a positive effect on the marine ecosystem. According to new research, the collapse of the marine glacier causes the increase the level of light and energy to enter the water and change alga bloom duration, timing and composition. Besides glacier melting can release many macronutrients and drop-stones onto the seabed, which may be important to the establishment of habitat and constructing seafloor biomass. Thanks to the bloom of alga, benthos can get more food. New life, measured as increased biomass of bottom dweller, emerging in the wake of glacier retreat, were found to now store 12-36 t C year-1 in each fjord, so the 216 retreating along the West-Antarctic Peninsula(WAP) may restore 3000-5000 t C year-1. [10]

3.3.3. Ecosystem impacts
The accelerating adaptation of glaciers makes lakes complex expand quickly and enlarge glacier run-off. Thus, water cycle balance maybe broken resulting in ice-fall, glade burst and ice-snow melting flood. In addition, the glacier melting is always accompanied with the degeneration of frozen earth which may
impact the water cycle such as underground water supply and run-off. This can reduce soil water content and the ability of the ecosystem to adjust run-off and kill short-rooted plants, causing the decrease of biodiversity making desertification more severe. [11]

4. Glacier Expansion

4.1. Karakoram Mountain Range Expansion:
No one can ignore it is a startling fact that a staggering 90 percentages of glaciers and ice fields are in retreat due to a rising surface and atmospheric temperature. However, some glaciers are surprisingly advancing/expanding at greater rates than even before climate change became noticeable by human. Glacier in Karakoram mountain range is a good example that has expanded in the past few decades [12]. Karakoram mountain range is located in the borders of China, India, and Pakistan. The average elevation of the mountain range is over 5,500 meters. The second highest peak, on the earth, K-2 is located in this mountain range. Results show that glaciers in Karakoram have expanded in the past eight years (Figs. 1, 2).

4.2. Reason for expansion
The reason for glaciers expansion in Karakoram mountain range is that glacial surges. They are short-lived events, and surge glacier can move/expand sometimes. They can move in a faster speed than normal which is up to one hundred than normal. Surge-type glaciers are usually located in Karakoram, Svalbard, Arctic islands, Pamir, Iceland and Alaska. However, scientists estimated that only one percent of all the world’s glaciers ever surge. There are many concepts that glacial surges occur, such as Hydrological control, Thermal regime, Deformable bed hypothesis, and Critical mass.

Hydrological control is the transferring processions of melting water through ice masses. Tristram et al. (2016) argued that “the surface,” “interior,” and “ice-bed interface” are three core environments for a glacier’s hydrology. Depending on the volume of the glacier and the nature of the glacier bed, melting water at the ice-bed is a fast/slow flow path [13]. The thermal regime has an impact on the formation of ice-marginal moraines. Benedict et al. (2013) stated that “winter cold could penetrate through the ice margin(<10 m) and freeze these sediments to the glacier sole. Those sediments become elevated along the wedge-shaped advancing glacier snout before melting out and being deposited as asymmetrical edges during winter season [14].” Thus, the thermal regime is also a theory that explains why surge-type glacier and glacier advances. Deformable bed hypothesis is actually the geological conditions of the underlying surrounding rock may determine the frequency of surges, argued by Van der Meer et al. (2003). “Landslides” under ice may cause glaciers to slide [15]. This explains why turbulent glaciers tend to gather in certain areas. Critical mass is a procession of snow accumulation on the surface of the glacier. Vladimir argued that glaciers surge when there is a layer of snow, between 25-50 meters thick, on glaciers. Since snow accumulates over time, it will exceed the critical mass of a glacier and causing it to slide on a layer of water [16].

5. Conclusion
This study aims at global glaciers, analyses their evolution, impacts, and genesis.

Vatnjokull glacier and Urumqi Glacier No.1, Tianshan Mountains gradually melt over time. The causes are as follows: (1) the effect of Atmospheric River Event on glacier melting, (2) black carbon pollutants, (3) recrystallization of ice, (4) glaciers are melting continuously because the melting rate of glacial materials is higher than the accumulation rate due to the rise of global warming temperature, (5) human activities have also affected the melting of glaciers in recent years, and human activities promote the melting rate of glaciers faster and faster. For example, the exhaust gas from large vehicles passing on nearby roads and nearby factories makes the temperature around the glacier rise slightly. The glacier is covered with a layer of ice dust, which affects the reflection of the glacier on light and heat and intensifies the retreat of the glacier. As the main contributor to global warming, the elevation of temperature accelerates the growth of ice grain in glacier, which causes higher vulnerability of glaciers.
to collapse and fracture. In addition, atmosphere river events much more reinforced by global warming bring more heat and dampness, especially in monsoon areas. It can increase rainfall probability, thus rainwater absorbing heat accelerates glacier melting. The above situation can be detrimental to the glacier in the monsoon area. Besides, black carbon released by incomplete combustion of fossil fuel has a strong sun-absorbing ability. The heat gathering caused by this can be harmful to the glacier. Glacier retreats have complex impacts on the ecosystem, water cycle and underground stress. (1) The decrease of glacier reduces the ground surface stress, thus changing the balance between underground stress and surface pressure. For glaciers located in the tectonic shear zone, this may cause fault earth. (2) Vast nutrient substances which used to stay in the glacier are released into the surrounded bay. This causes the bloom of alga leading to mass propagation of benthos, which can be significant to carbon sequestration. (3) Speeding up glacier ablation means that more water enters run-off and the underground water cycle. This may ruin the water cycle, thus making frozen earth degenerate and influence biodiversity. (4) Sea level rise.

Glaciers in Karakoram mountain range are expanded in the past few years. Hydrological control, thermal regime, deformable bed hypothesis, and critical mass are theories to cause glaciers expansion in Karakoram mountain range. Glacier expansion does not bring any advantage or disadvantage to our ecological system and environment so far, but it still needs to investigate in the future.

References
[1] Kropač, E., Mölg, T., Cullen, N. J., Collier, E., Pickler, C., Turton, J. V. (2021). A Detailed, Multi-Scale Assessment of an Atmospheric River Event and Its Impact on Extreme Glacier Melt in the Southern Alps of New Zealand. Journal of Geophysical Research: Atmospheres, 126(9): e2020JD034217.
[2] Negi, P. S., Pandey, C. P. (2021). Black carbon pollutants in pristine Himalayan ecosystem: a pilot study along Gangotri Glacier Valley. Environ Monit Assess, 193(11): 726.
[3] Ranganathan, M., Minchew, B., Meyer, C. R., Peč, M. (2021). Recrystallization of ice enhances the creep and vulnerability to fracture of ice shelves. Earth and Planetary Science Letters, 576.
[4] Maimaitiyiming, R., Yang, J.J., Liu, Y.Q., Guo, Y.C. He, X.M. (2016). Characteristics of Changes in Temperature and Precipitation in Xinjiang in Recent 54 Years. Research of Soil and Water Conservation, 23(02): 128-133.
[5] Shahgedanova, M., Nosenko, G., Khromova, T., Muraveyev, A. (2010). Glacier shrinkage and climatic change in the Russian Altai from the mid-20th century: An assessment using remote sensing and PRECIS regional climate model. Journal of Geophysical Research, 115(D16),
[6] Liu, S.Y., Xie, Z.C., Wang, N.L., Ye, B.S. (1999). Mass Balance Sensitivity To Climate Change: A Case Study Of Glacier No.1 At Urumqi Riverhead, Tianshan Mountains, China. Chinese Geographical Science, 9(2), 134-140.
[7] Xing, C.W. (2018). Study on temporal and spatial changes of glacier resources in Tianshan, China based on Landsat and ICESat data (Master’s thesis, Northwest Normal University).
[8] Gao, X.Q., Tang, M.C., Feng, S. (2000). Discussion on the relationship between glacial fluctuation and climate change. Plateau Meteorology, 19(01), 9-16.
[9] Meng, Q., HU, C.B.SHI, Y.L. (2021). Effects of glacier ablation on surface deformation, stress field, and seismic risk of main faults in Qilian Mountain area. Journal of University of Chinese Academy of Sciences, 38(05), 624-631.
[10] Barnes, D. K. A., Sands, C. J., Paulsen, M. L., Moreno, B., Moreau, C., Held, C., Downey, R., Bax, N., Stark, J. S., Zwerschke, N. (2021). Societal importance of Antarctic negative feedbacks on climate change: blue carbon gains from sea ice, ice shelf and glacier losses. Sci. Nat., 108(5), 1-14.
[11] Zou, M.J., Shao, C.K., Yang, K. (2021). 1979—2018 Changes in climate, glaciers and permafrost during 1979-2018 in Tibetan Autonomous Region and their potential impacts on renewable energy. Transactions Atmospheric of Sciences, (06), 980-991.
[12] Hewitt, K. (1969). Glacier surges in the Karakoram Himalaya (central Asia). Can. J. Earth. Sci.,
6(4): 1009-1018.

[13] Fynn, T. I., Hubbard, B. (2017). Glacier Hydrology and Runoff. https://www.researchgate.net/publication/310772674_Glacier_Hydrology_and_Runoff

[14] Reinardy, B. T. i., Leighton, L., Marx, P. J. (2013). Glacier Thermal Regime Linked to Processes of Annual Moraine Formation at Midtdalsbreen, Southern Norway.

[15] van der Meer, J. J., Menzies, J., Rose, J. (2003). Subglacial till: the deforming glacier bed. Quat. Sci. Rev., 22(15-17): 1659-1685.

[16] Kotlyakov, V (no published date). Global Warming and Surging Glaciers. https://www.un.org/en/chronicle/article/global-warming-and-surfing-glaciers