International Training Course on Cryosphere Observation, Monitoring, and Research along the Belt and Road

Cryospheric Chemistry

Key Processes and environmental impacts

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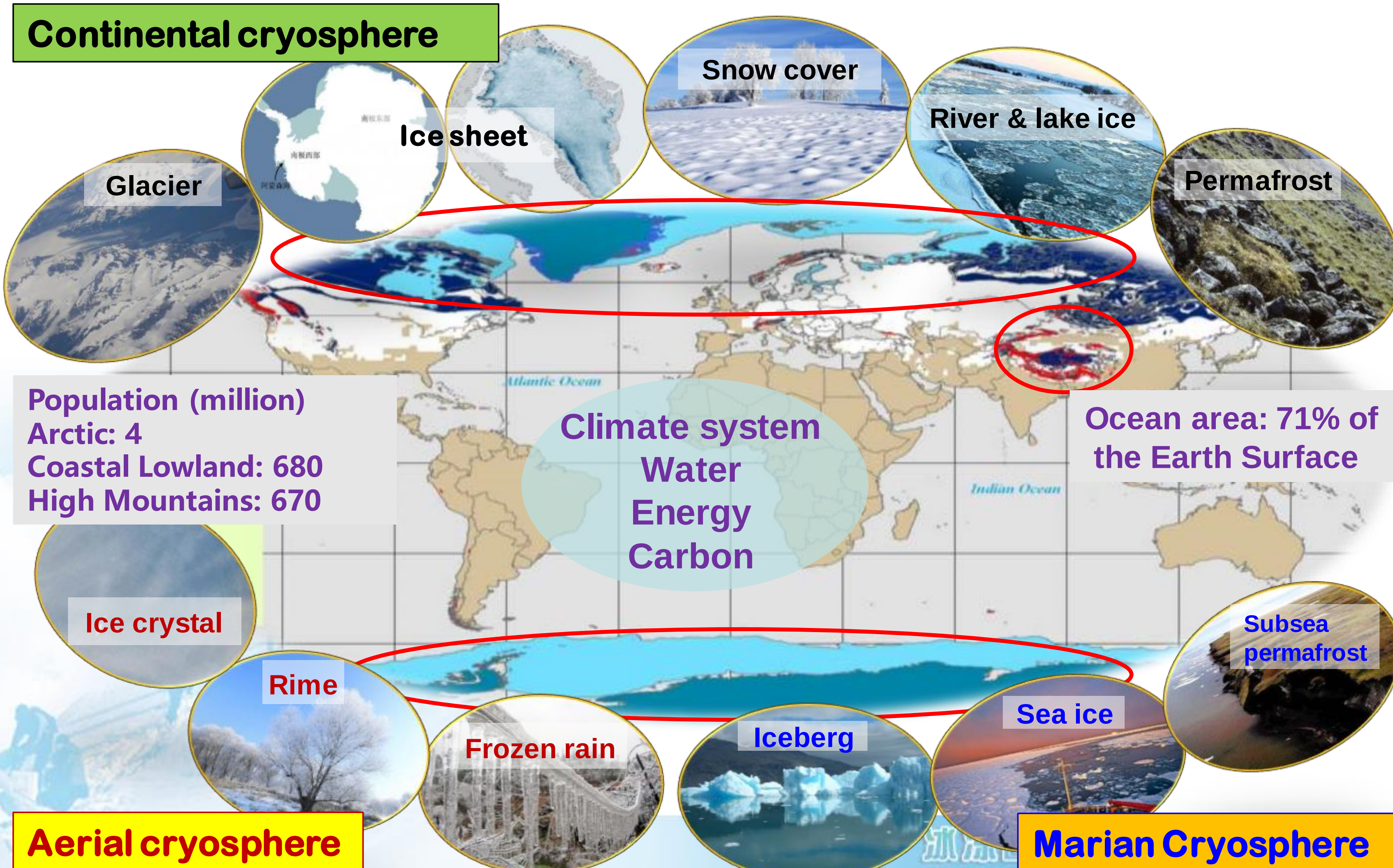
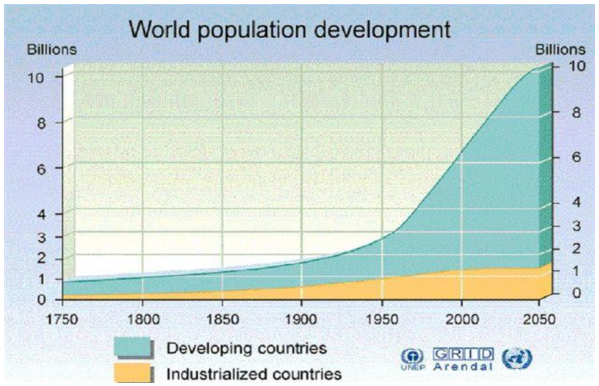
Background: Cryosphere



The cryosphere is experiencing rapid Change

Anthropogenic activities VS cryosphere environment

Population increasing



Urbanization acceleration

- **1972: Declaration on Human Environment**
- **1992: Rio Declaration on Environment and Development**
- **2015: The Paris Agreement**
- **2024: Mitigate climate change, restore nature and land, and create a pollution-free world**

Industry development

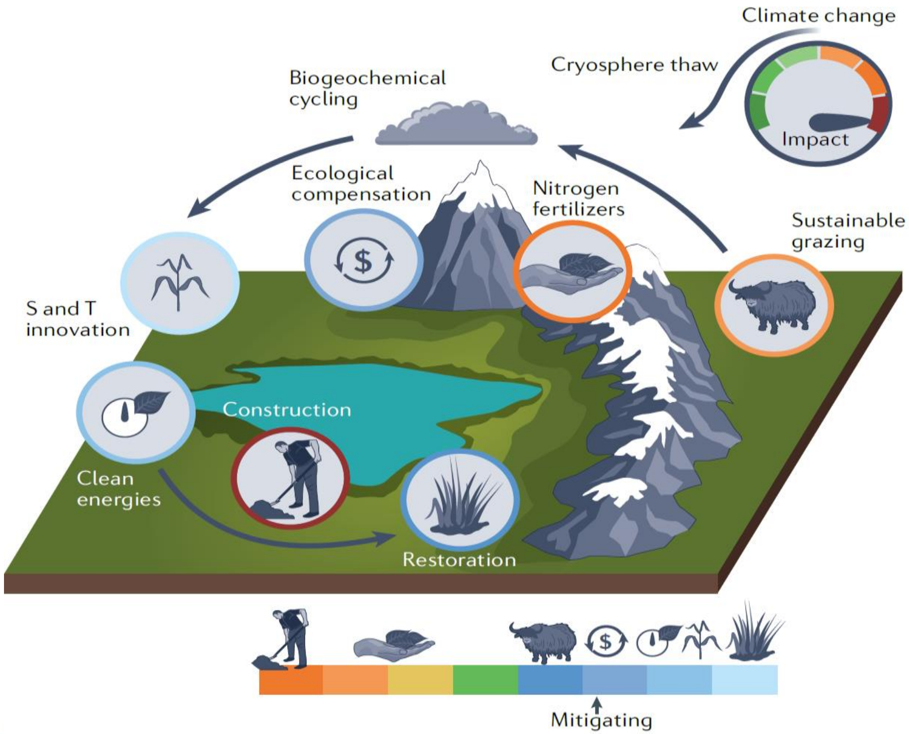
Fossil fuels use

The cryosphere environment is significantly affected by human activities

SKLCS

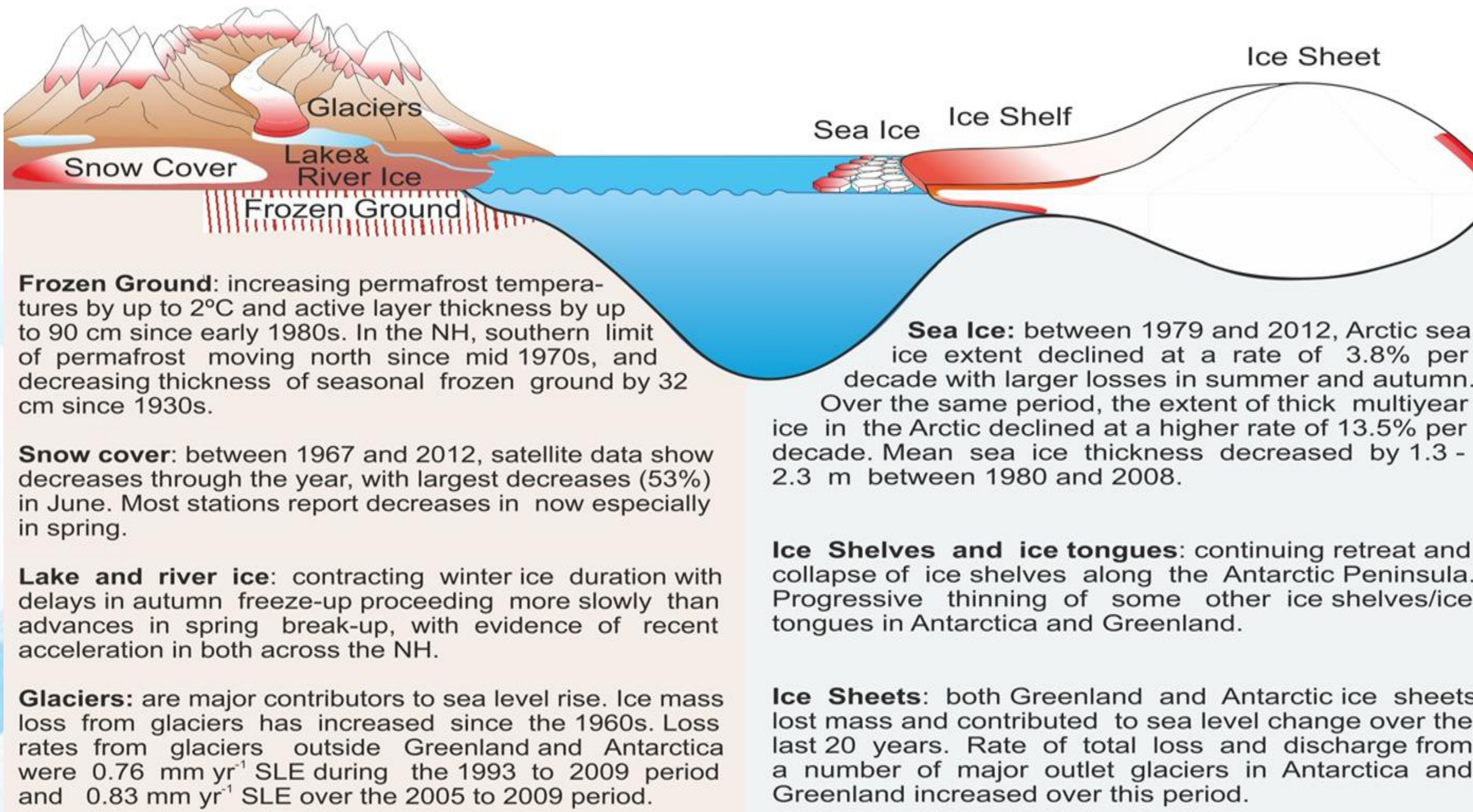
Glacier melting

The climate and environmental effects of biogeochemical cycles in the cryosphere are changing under a warming climate.



Cryospheric chemistry

- mainly investigate the relevant components of the cryosphere, their spatiotemporal distribution, potential sources, migration and transformation processes, fate and climate & environmental effects.



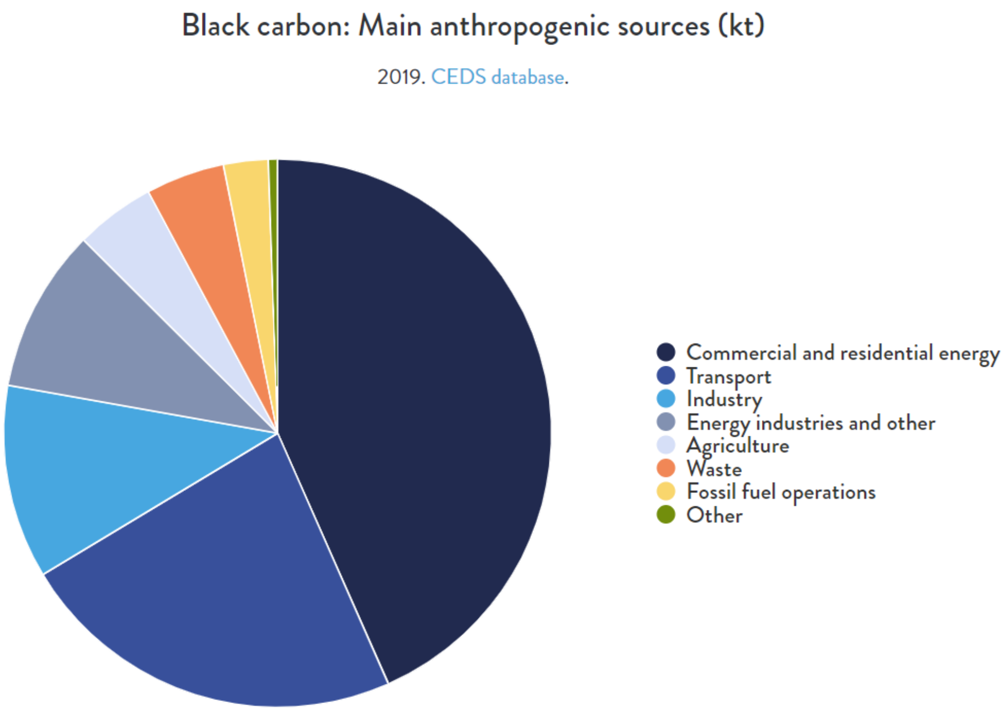
1. Potential source and processes of cryospheric chemicals

1.1 Major sources

- Emissions from various physical, chemical, and biological processes in nature, such as volcanic activity, sandstorms, waves, lightning, emissions from land and marine flora and fauna, and dust from outer space;
- Various emissions from human industrial and agricultural production and daily activities.

1.1 Major sources

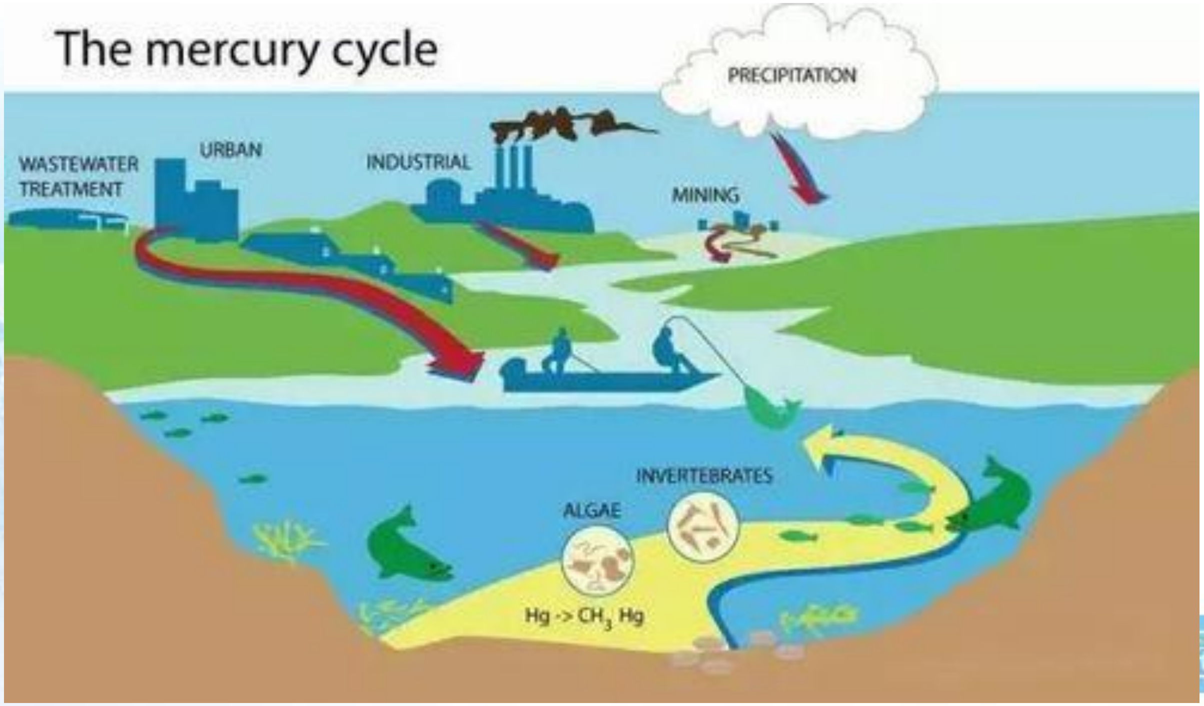
Black carbon, commonly known as soot, is a component of fine particulate air pollution ($PM_{2.5}$). It is formed by the incomplete combustion of wood and fossil fuels, a process which also creates carbon dioxide (CO_2), carbon monoxide, and volatile organic compounds.



- Sources differ significantly region to region. In Asia and Africa **residential solid fuels** contribute 60-80% of emissions, whereas in Europe and North America **diesel engines** contribute about 70% of emissions.

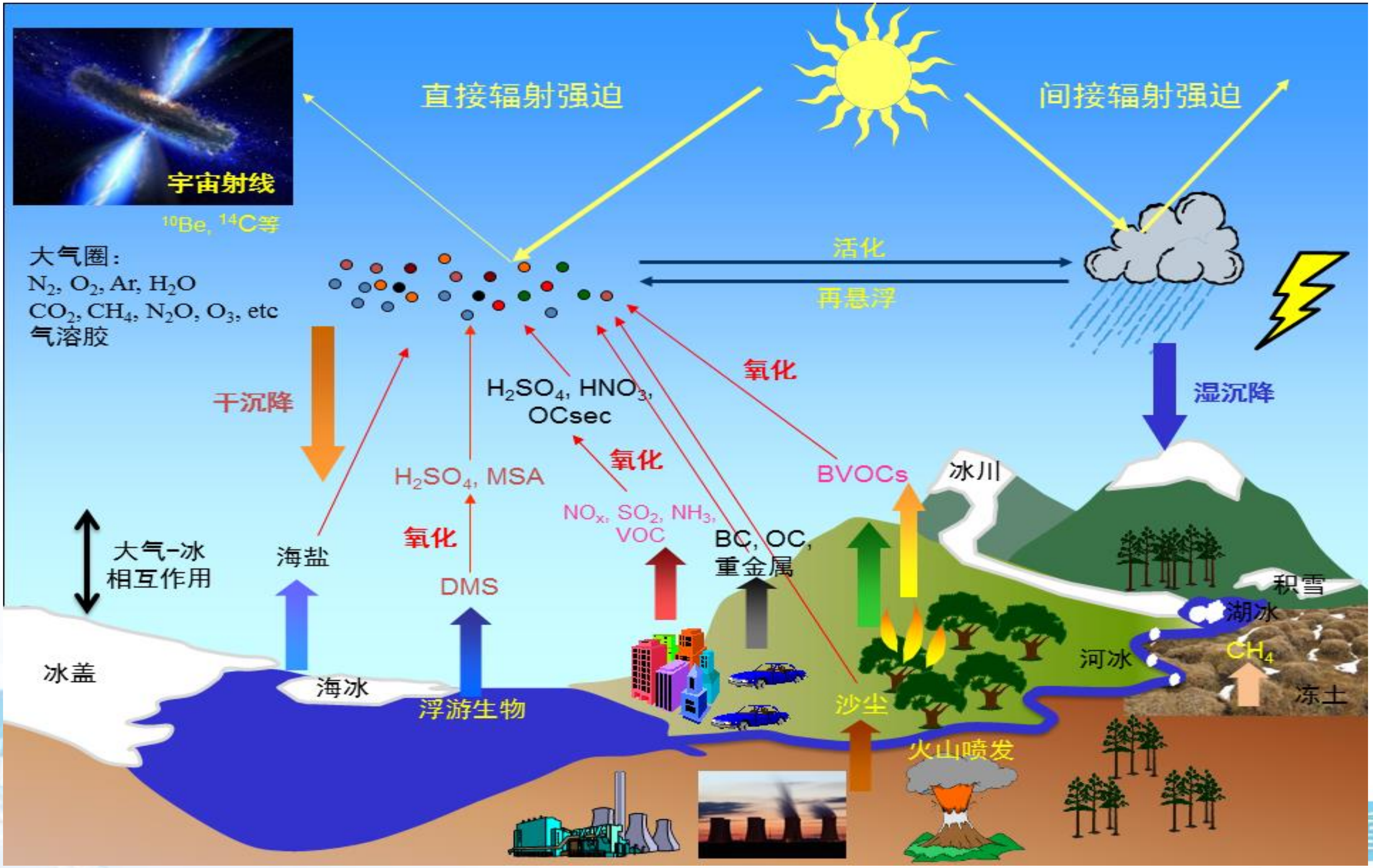
1.1 Major sources

- Natural levels of mercury exist in soil, air, and water around the world.
- Mercury can enter the environment through human activities such as the burning of coal, the extraction of metals from ore, the manufacturing of cement, and the use and disposal of products containing mercury, such as fluorescent lights and some types of batteries. In certain regions of the world, small-scale gold mining processes using mercury are also a significant source of mercury pollution.



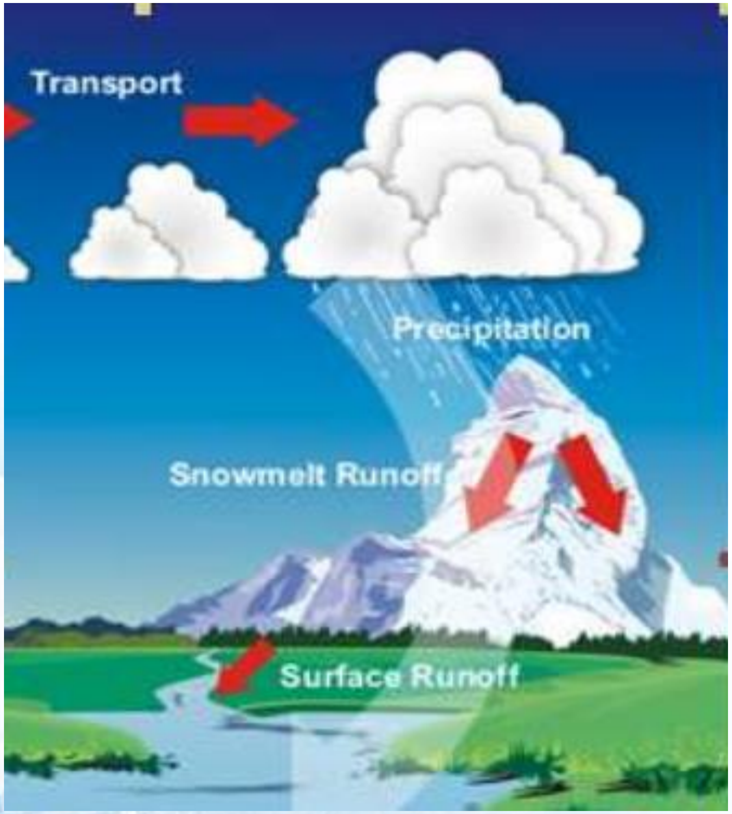
1.2 The deposition of atmospheric chemical components into the cryosphere and their main processes after deposition

Physical-Chemical-Biological processes



1.2.1 Physical processes of cryospheric chemicals

Mainly including atmospheric dry and wet deposition, interface exchange, snow and ice melting and ion pulse, leaching process of permafrost active layer, sea ice salt discharge process, etc

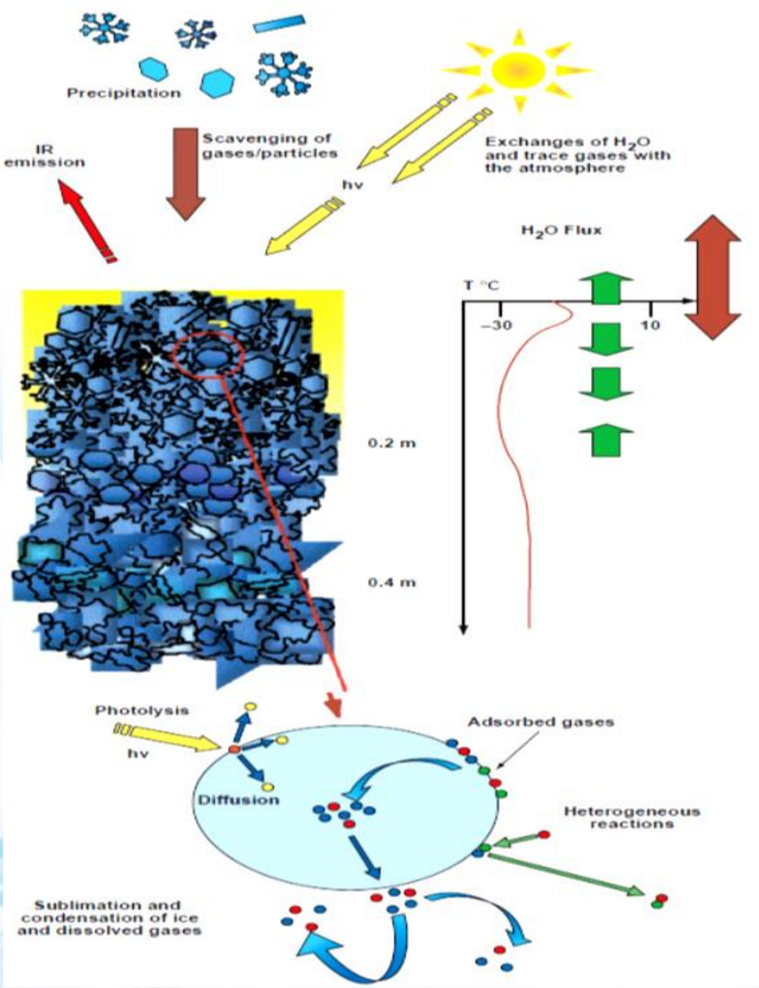


dry wet sedimentation and interface exchange

- **Taking the example of dry and wet deposition of atmospheric chemical components entering the cryosphere:**

- **Dry deposition refers to the transport of atmospheric chemical components to the surface of the cryosphere medium in the absence of precipitation, while wet deposition refers to the process of chemical components settling together with precipitation when precipitation occurs.**

The basic principles and influencing factors of snow air interface exchange:



◆**Snow absorbs various gaseous and particulate substances during its formation and snowfall process. After settling into the snow, temperature and radiation changes cause the water vapor flux to vary with vertical depth, determining the deformation and metamorphism process of snow.**

◆**The density of surface snow is between approximately 0.01-0.5 g cm-3, therefore, most of the snow space is filled with pore air that can freely exchange with the atmosphere. The chemical composition changes are controlled by many physical processes, including absorption, solid-state diffusion, and copolymerization, as well as chemical processes such as photochemical reactions and temperature controlled reactions.**

1.2.2 Chemical processes of cryospheric chemicals

SKLCS

Chemical processes mainly include isotope fractionation, photochemical reactions, redox reactions, etc.

- The chemical reaction process is a transfer phenomenon that involves not only chemical phenomena but also physical properties, including momentum, heat, and mass transfer.
- Chemical reaction refers to the process in which molecules break down into atoms, which then rearrange and combine to form new molecules.
- Chemical components undergo various chemical reaction processes in the cryosphere, and the changes in the chemical forms of each component in the cryosphere profoundly affect the biogeochemical cycling processes, thereby having important impacts on the climate and environment of the cryosphere.

1.2.2 Chemical processes of cryospheric chemicals

- ✓ **Isotope fractionation:** The phenomenon in which the isotopes of a certain chemical element are distributed in different proportions among two or more substances during physical, chemical, and biological processes.

- ✓ **Photochemical reaction:** A chemical reaction that occurs when light energy is absorbed under visible light or ultraviolet radiation.

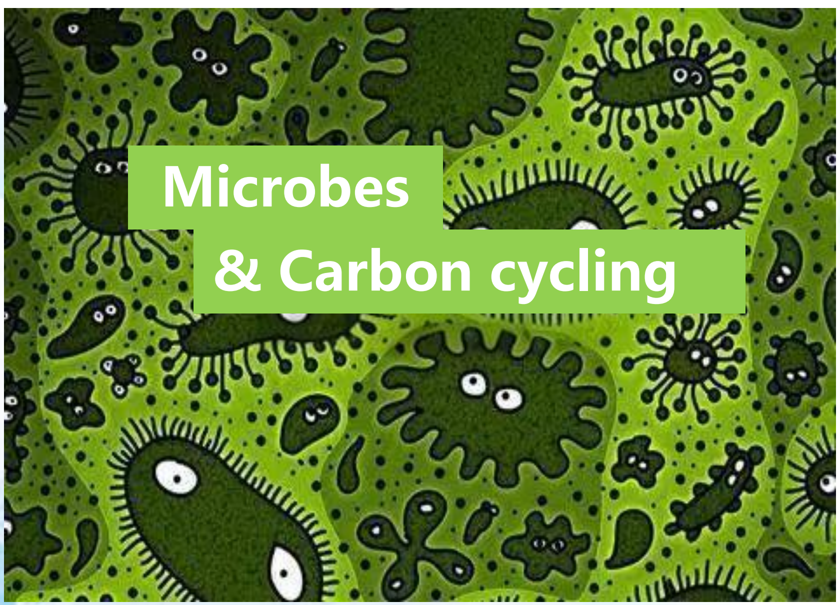
Biological processes mainly include methane production and oxidation, methylation, nitrification and denitrification, etc.

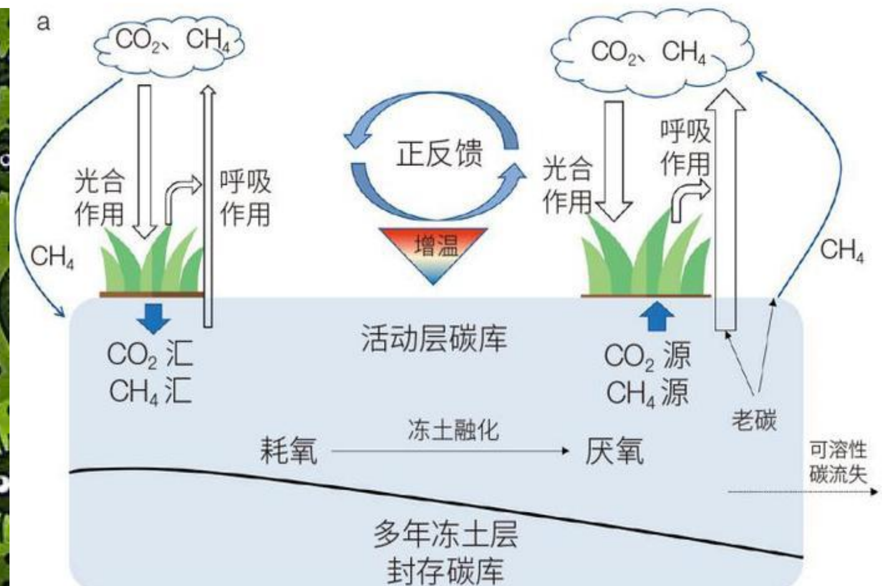
- The characteristic of organisms is **metabolism**, and the entire metabolic process is the absorption and transformation of environmental substances by organisms from a microscopic perspective, all of which are chemical reactions and changes that occur at the molecular level. Therefore, many macroscopic manifestations of organisms are caused by **microscopic chemical changes** within the body, and cryosphere chemistry is closely related to microbial activity.

- Microbial activity profoundly affects the chemical cycling changes in the cryosphere, and is one of the key processes that play an important role in the chemical changes of glaciers, permafrost, and sea ice.

Methane production and oxidation:

- **Methane is produced through hydrogen reduction of CO2 and acetic acid fermentation under anaerobic conditions by methanogenic bacteria;**
- **Methane oxidizing bacteria oxidize and digest methane under aerobic conditions.**



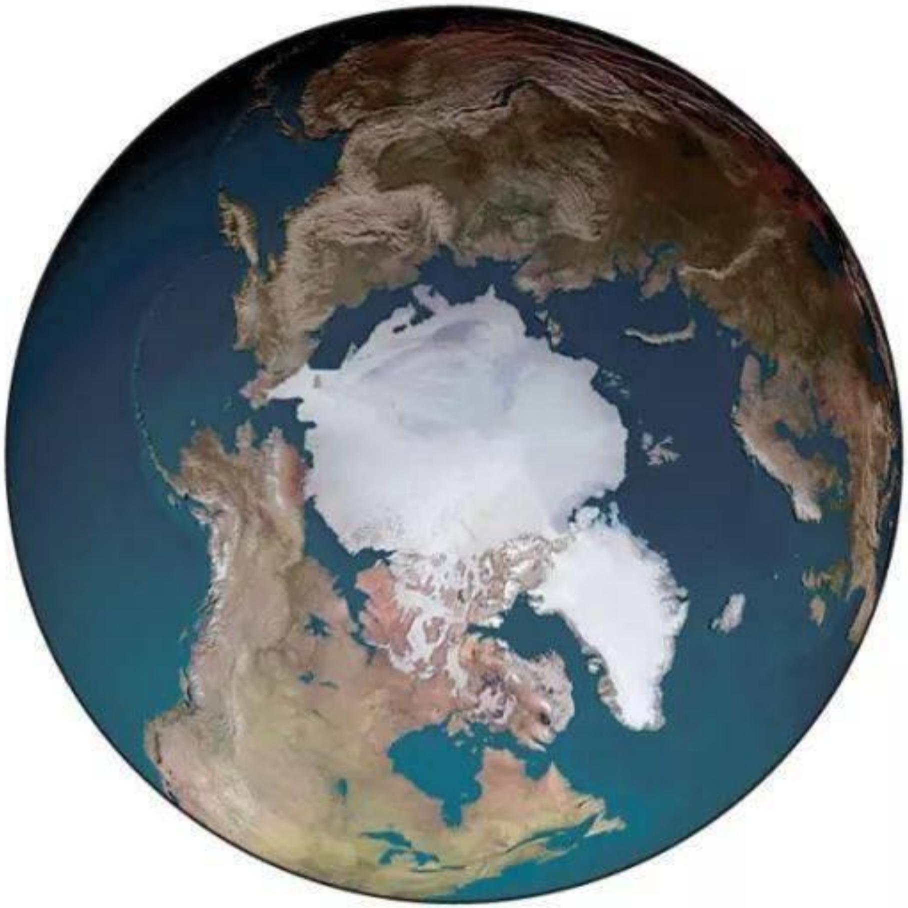


1.2.3 Biological processes of cryospheric chemicals

- **Methylation:** refers to the process of catalyzing the transfer of methyl groups from active methyl compounds to other compounds, which can form various methyl compounds, or chemically modify certain proteins or nucleic acids to form methylation products.

- **Nitrification and Denitrification:** Nitrification refers to the process in which organisms convert organic nitrogen into ammonium ions through microbial decomposition and mineralization; Denitrification refers to the anaerobic respiration process in which nitrate or nitrite is reduced to N2O-NO-NH3 by denitrifying bacteria under anaerobic conditions.

2. Climate and environmental effects of cryospheric chemistry



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Climate and environmental effects of cryospheric chemistry

- **Cryospheric chemistry can play important roles in the climate system at different time scales (daily, seasonal, interannual, decadal, and centennial).**

- **These effects are mainly achieved by affecting the Earth's surface energy water cycle processes, such as influencing radiation balance processes (such as snow ice albedo feedback mechanisms), and the exchange of chemical components between the cryosphere and other layers.**

- **The spatiotemporal changes of glaciers (ice sheets), snow cover, river and lake ice, and sea ice significantly affect global energy balance, water cycle, and environmental processes, which in turn affect climate and environmental change.**

Mainly including the following climate and environmental effects:

- Climate effects of ice nuclei
- Climate and environmental effects of sea ice
- Climate effects of carbonaceous aerosols
- Climate and environmental effects of dust
- Climate and environmental effects of carbon sources and sinks in the cryosphere
- Environmental risks associated with rapid changes in the cryosphere

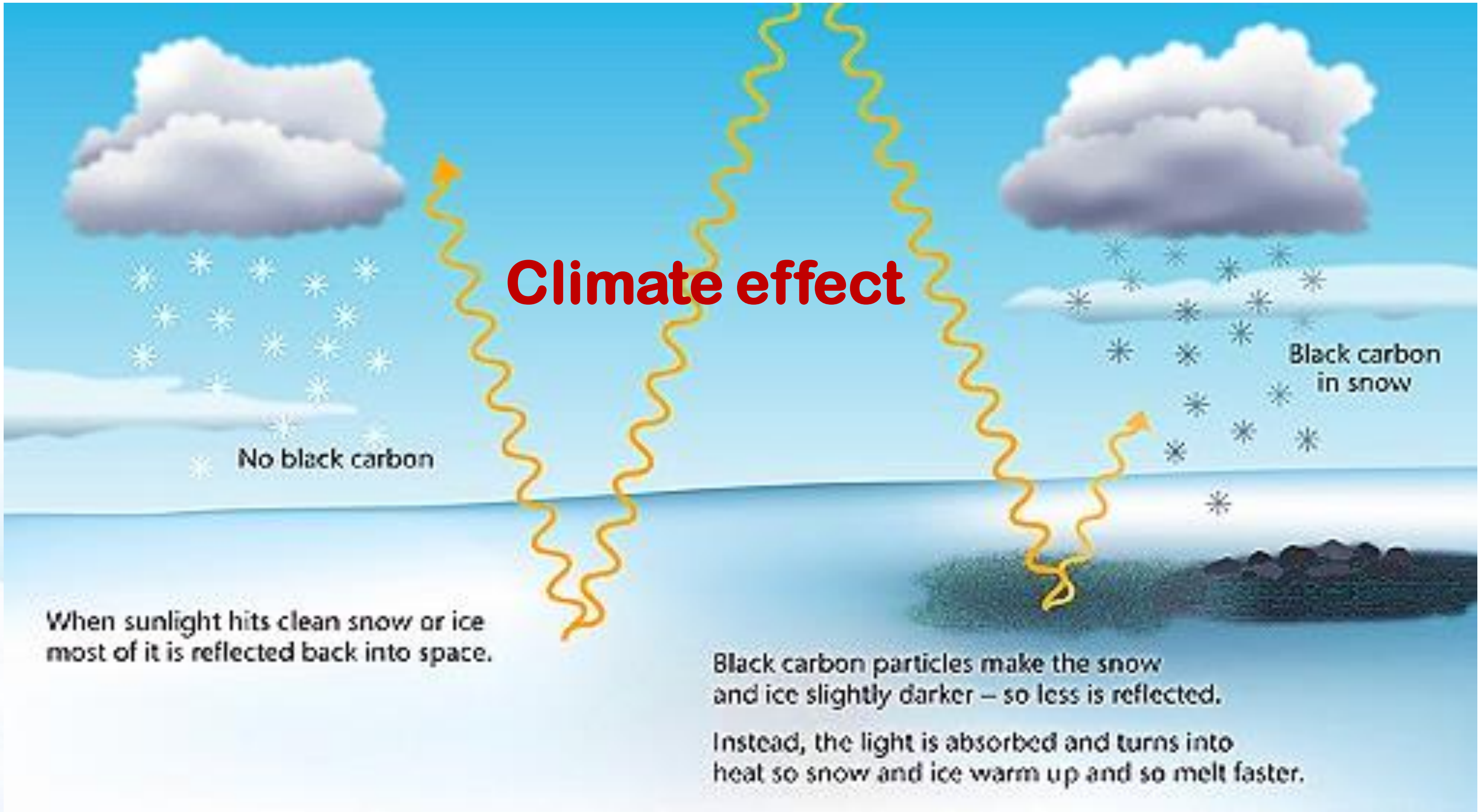
2.1 Climate effects of ice nuclei

Ice nuclei refer to solid particles in the atmosphere that can cause water vapor to condense or supercooled water droplets to freeze and form ice crystals.

- **Ice nuclei mainly come from atmospheric aerosol particles, but only a small portion of aerosol particles can become ice nuclei. The ratio of ice nuclei to aerosols is 10^{-3}-10^{-6}, and the nucleation efficiency varies with temperature and the supersaturation state of ice. Both natural and human activities can produce ice nuclei, and the sources of atmospheric ice nuclei include dust particles, mineral dust, industrial smoke, volcanic ash streams from volcanic eruptions, and meteor dust.**

- Ice nuclei may have significant impacts on the macroscopic and microscopic structure, radiation characteristics, and physical properties of clouds. Ice nuclei play an important role in many physical processes, and are equally important as cloud condensation nuclei.

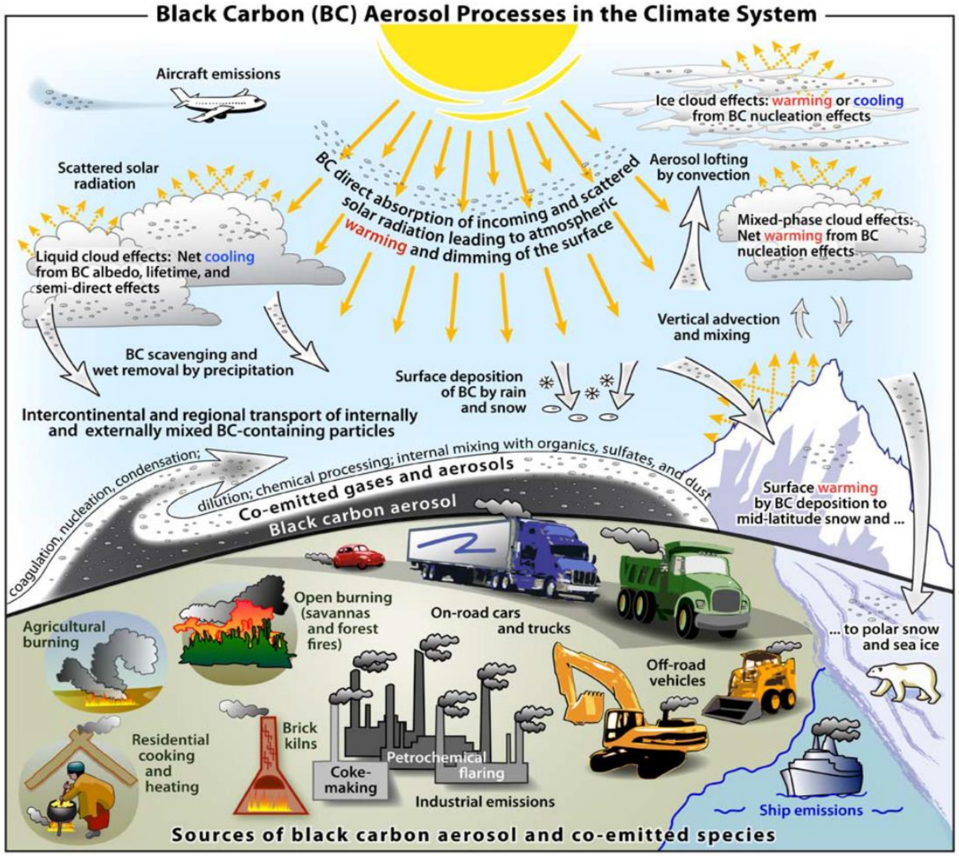
2.1 Climate effects of ice nuclei



Ice nuclei (such as SO_4^{2-} aerosol particles, black carbon, etc.) have a profound impact on global climate change.

2.2 Climate effects of carbonaceous and dust aerosols

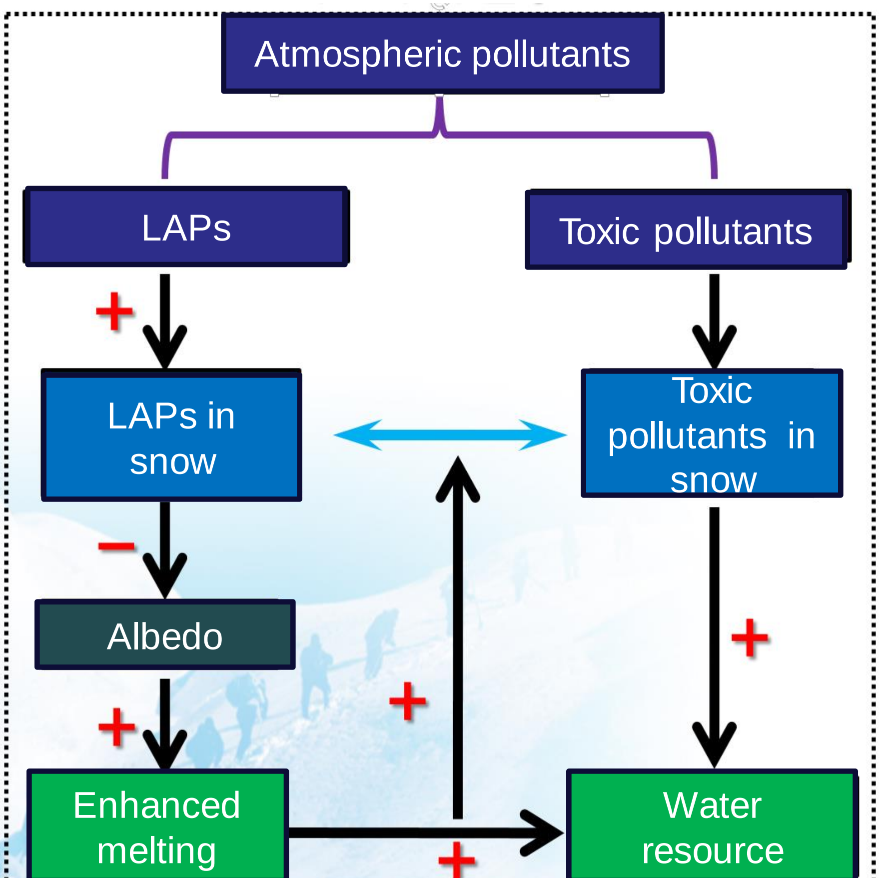
◆ **Carbonaceous aerosols are an important component of atmospheric aerosols, which can affect global climate change, atmospheric visibility, regional air quality, and human health**



◆ **If carbonates are not considered, carbon in aerosols can be divided into two categories: organic carbon (OC) and elemental carbon (EC), which are important components of atmospheric aerosols.**

Bond et al., 2013

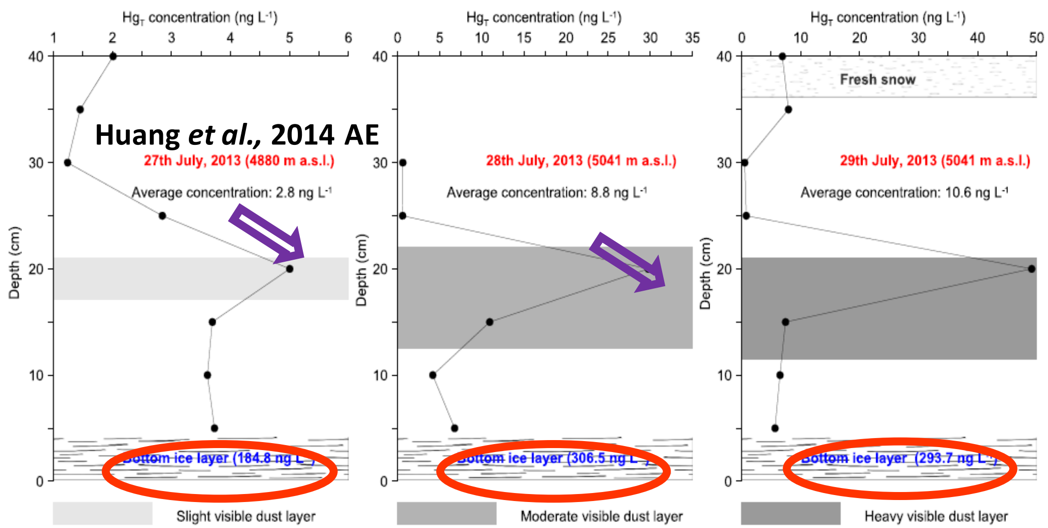
2.2 Climate effects of carbonaceous and dust aerosols

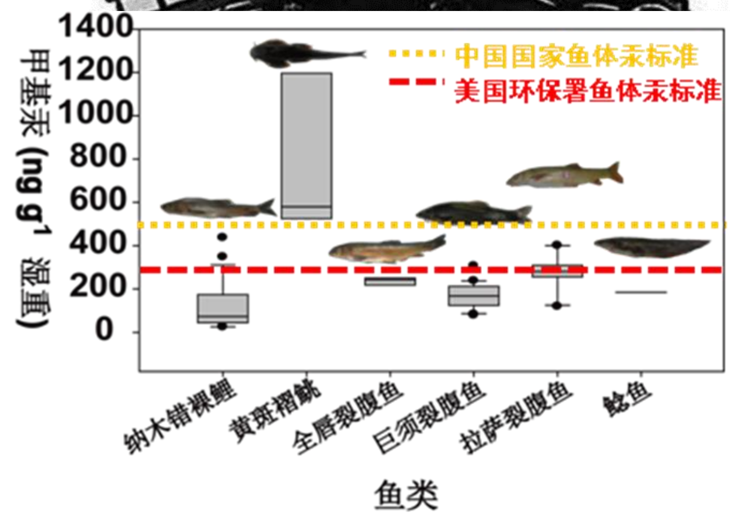


Black carbon can substantially enhance snow and glacier melting.

2.3 Environmental risks due to rapid cryospheric change

Cryosphere is a pool for atmospheric mercury pollutants



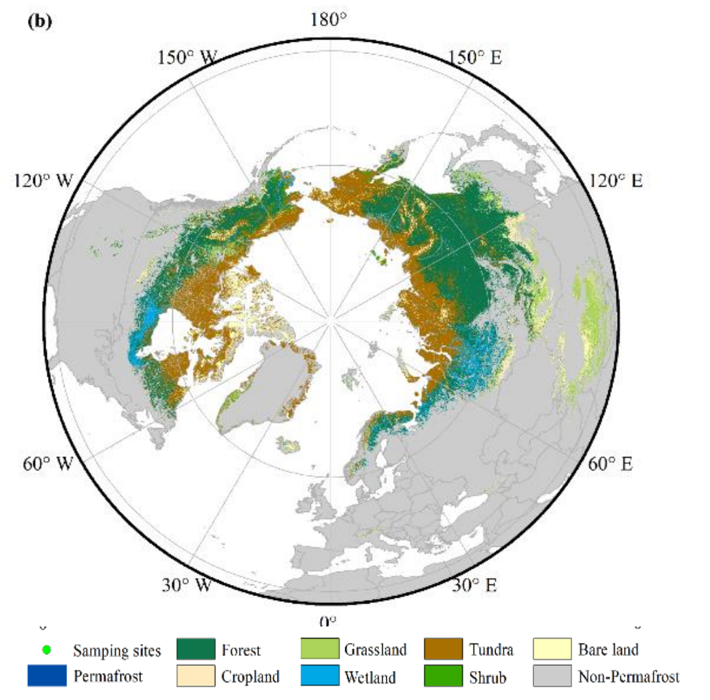


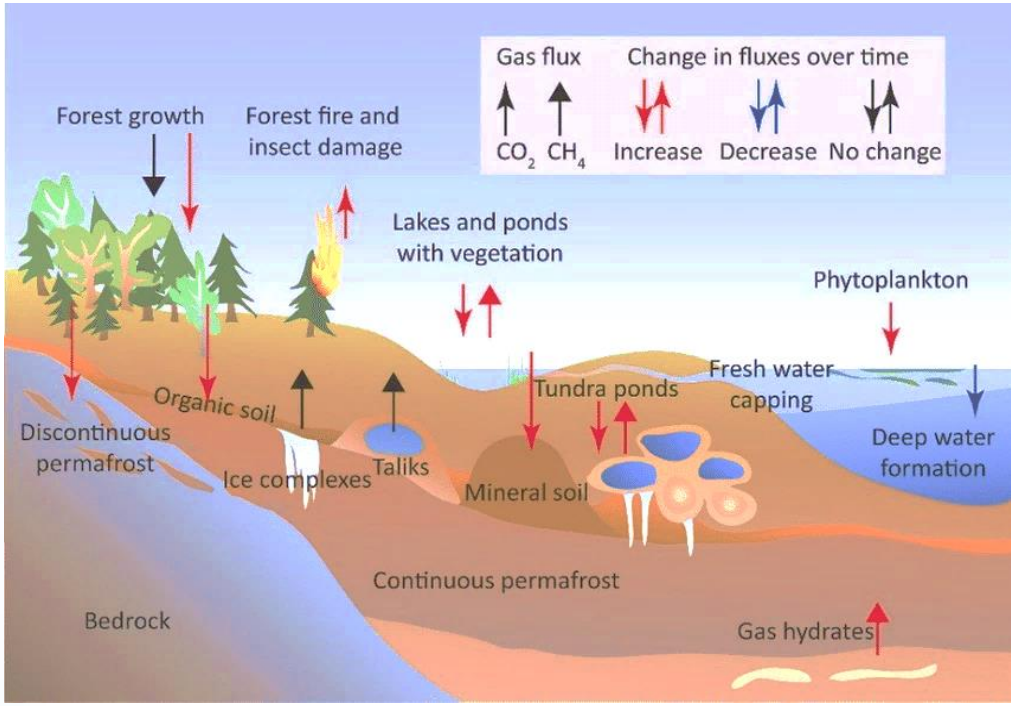
The condensation capture effect of the cryosphere on mercury.

The second release of mercury

- **Feedback effect of permafrost carbon cycle and climate warming**

The long-term accumulation of organic carbon storage in soils of permafrost regions in the northern hemisphere reaches 1466~1672 Gt C

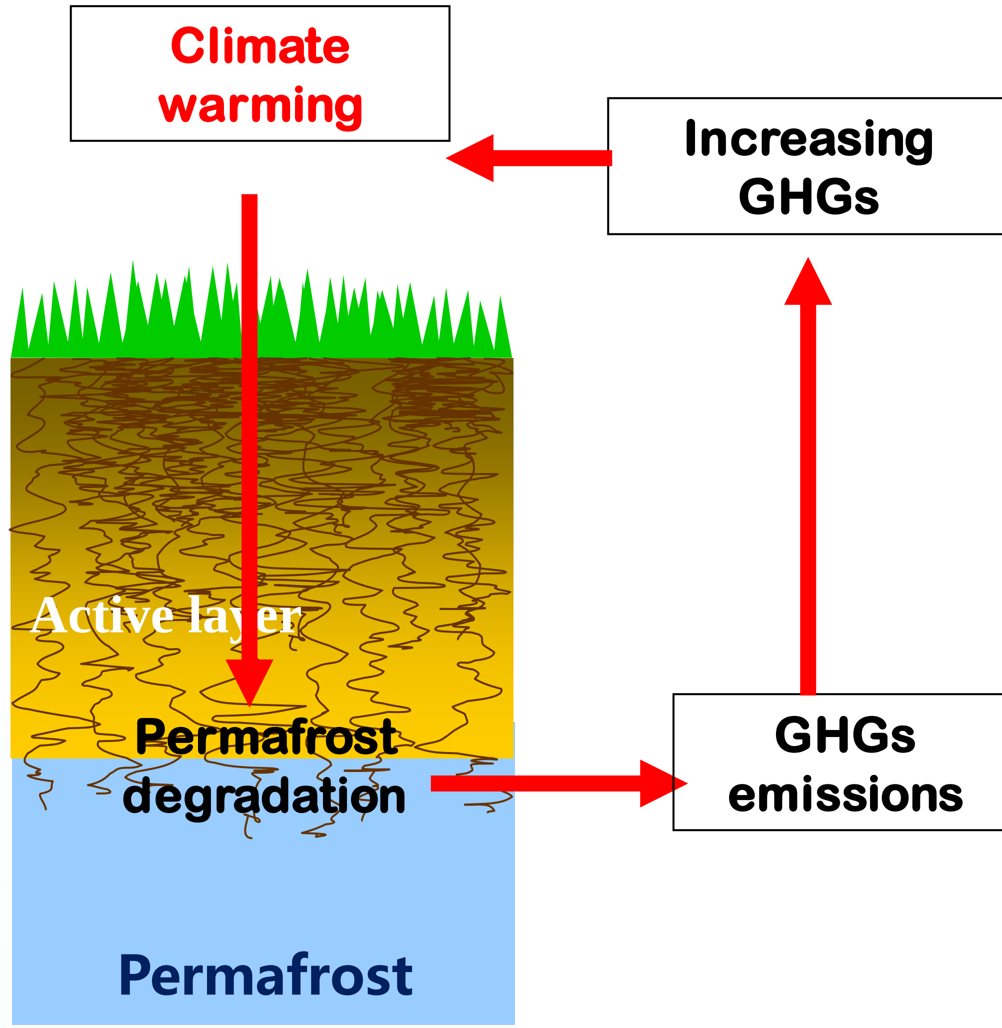




Wu et al., 2022 SOTE; Tarnocai et al., 2009 GBC

2.4 Climate and environmental effects of carbon sources and sinks

The rapid degradation of permafrost regions, the melting of underground ice, and the significant changes in carbon release caused by permafrost thermal karst landforms have led to the loss of carbon reservoirs.



2.5 Climate and environmental effects of sea ice

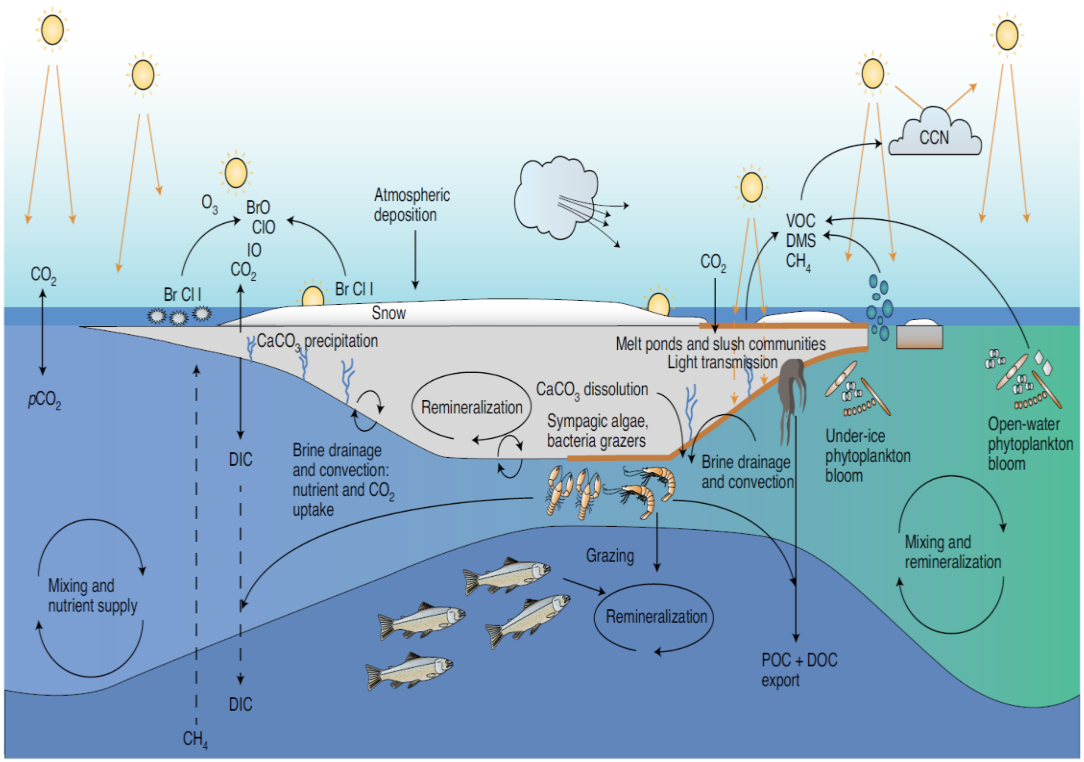


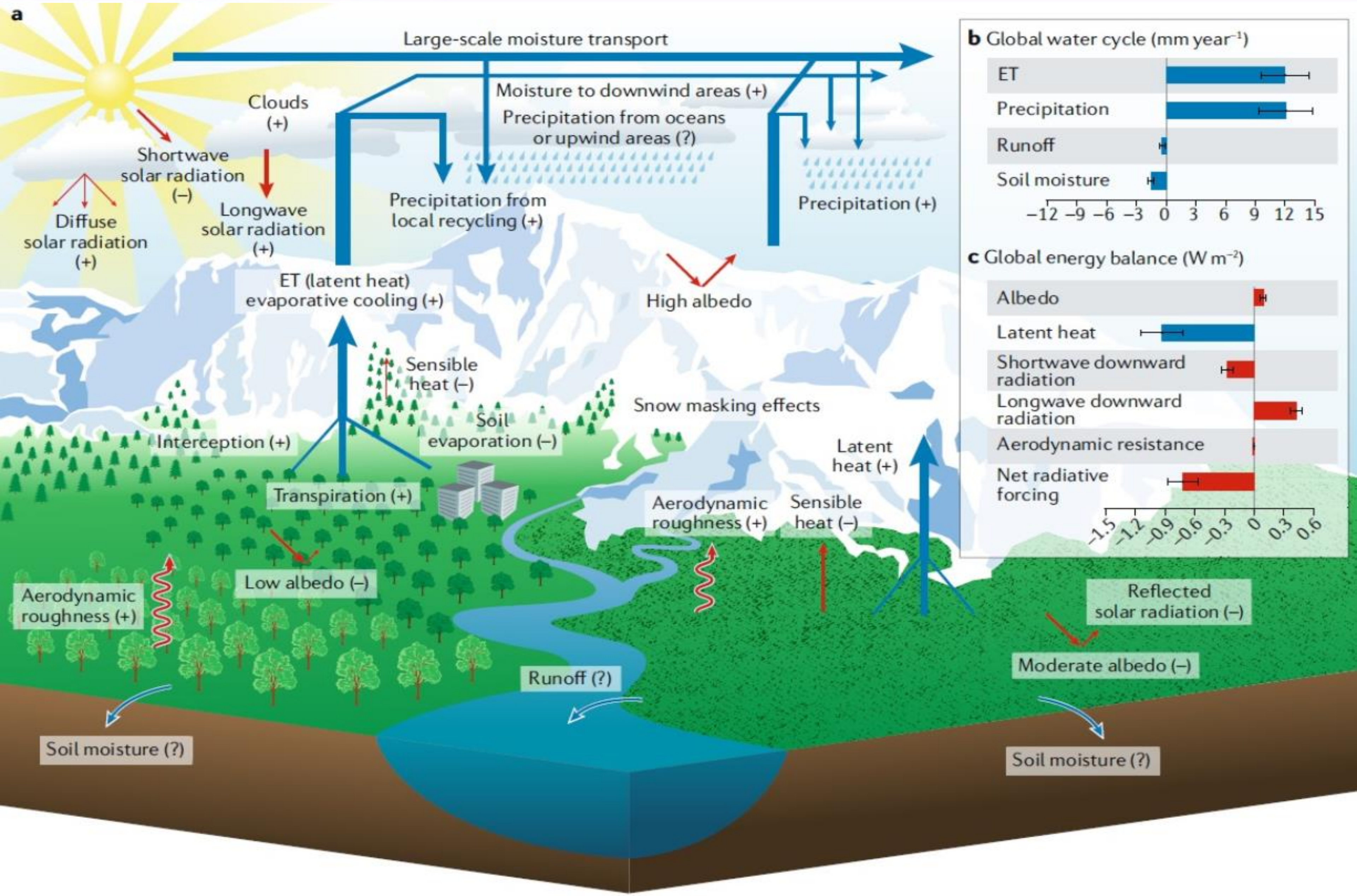
Fig. 1 | Schematic of seasonal sea-ice biogeochemical processes in the Arctic Ocean. Black arrows represent the directionality of biogeochemical exchanges; for example, across an interface (such as CO_2 efflux from the ocean to the atmosphere and release of reactive halogen species from the ice surface) or throughout an interval (such as brine drainage and convection along the ice-water interface, and heterotrophic remineralization of organic material throughout the brine network). Dashed lines illustrate diffusive gradients, such as that of dissolved inorganic carbon (DIC). Yellow arrows indicate solar radiation. Ice-associated and pelagic microalgal communities and their grazers are represented by orange shading and symbols. The biological carbon pump links carbon exchange processes in the surface to sequestration at depth through POC and dissolved organic carbon (DOC) export, illustrated by arrows penetrating below the mixed layer (darker shading). Surface processes further impact climate active gases, such as DMS and CH_4 as well as volatile organic compounds (VOC), which can contribute to the formation of cloud condensation nuclei (CCN). Figure adapted from ref. [109].

Lannuzel et al., 2020, NCC

Rapid retreat of sea ice:

- Seasonal primary productivity advances, leading to an increase in the abundance of ice algae and plankton;
- The release of dimethyl sulfide DMS increases, and the capture of CO2 increases;
- The reduction of sea ice animal communities, endemic fish and animals in the region;
- CH4 release increases, halogen components decrease, and ozone depletion decreases

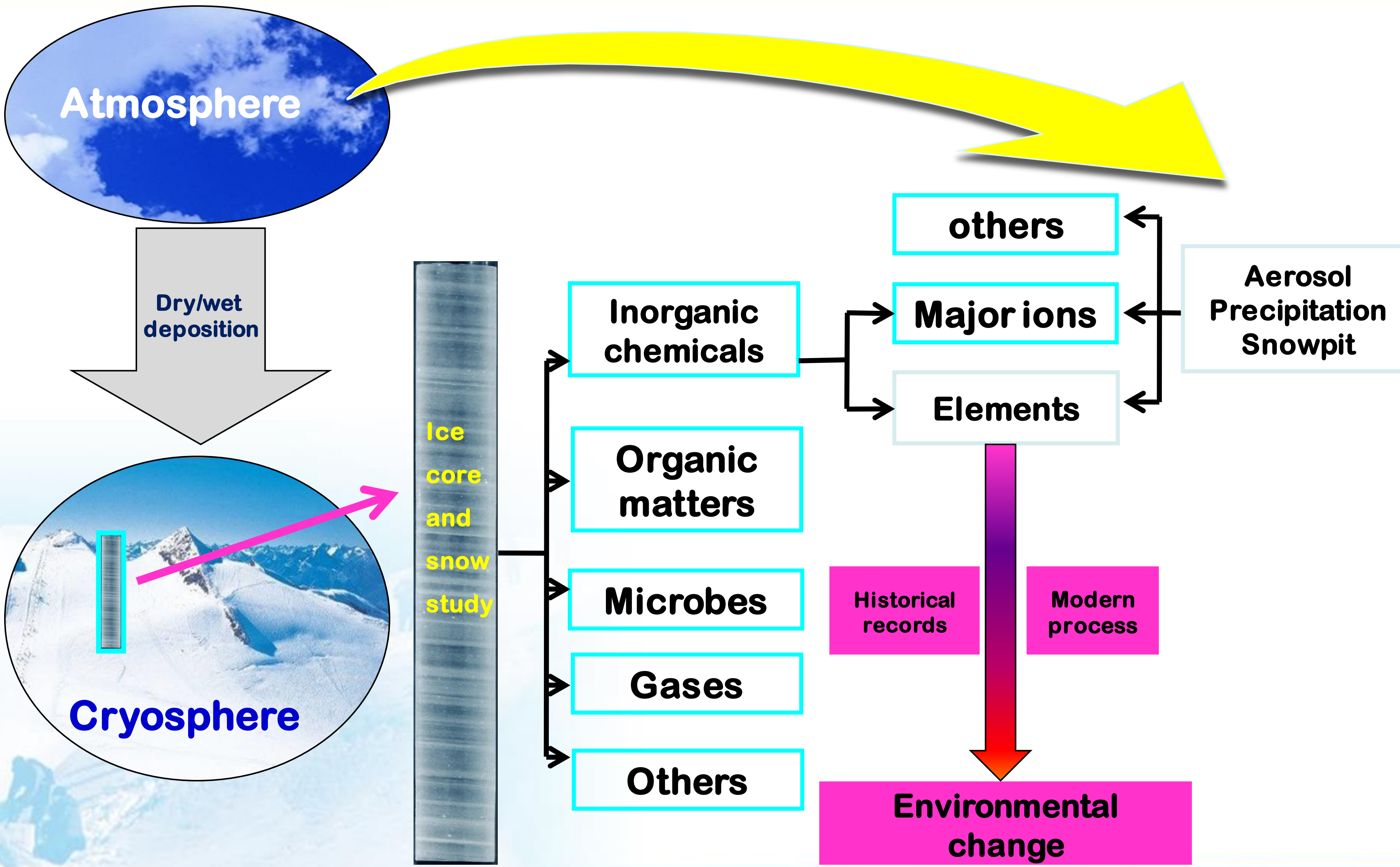
Summary



a
Large-scale moisture transport
Moisture to downwind areas (+)
Precipitation from oceans or upwind areas (?)
Clouds (+)
Shortwave solar radiation (–)
Longwave solar radiation (+)
Diffuse solar radiation (+)
Precipitation from local recycling (+)
Precipitation (+)
ET (latent heat) evaporative cooling (+)
High albedo
Sensible heat (–)
Soil evaporation (–)
Snow masking effects
Interception (+)
Transpiration (+)
Latent heat (+)
Aerodynamic roughness (+)
Sensible heat (–)
Low albedo (–)
Aerodynamic roughness (+)
Reflected solar radiation (–)
Runoff (?)
Moderate albedo (–)
Soil moisture (?)
Soil moisture (?)
b Global water cycle (mm year⁻¹)
ET
Precipitation
Runoff
Soil moisture
−12 −9 −6 −3 0 3 6 9 12 15
c Global energy balance (W m⁻²)
Albedo
Latent heat
Shortwave downward radiation
Longwave downward radiation
Aerodynamic resistance
Net radiative forcing
−1.5 −1.2 −0.9 −0.6 −0.3 0 0.3 0.6

3. Glacier chemistry

Research framework for snow and ice recording of atmospheric components



Monitoring

- Ice core
- Snowpit
- Surface snow

Keep clean !!!

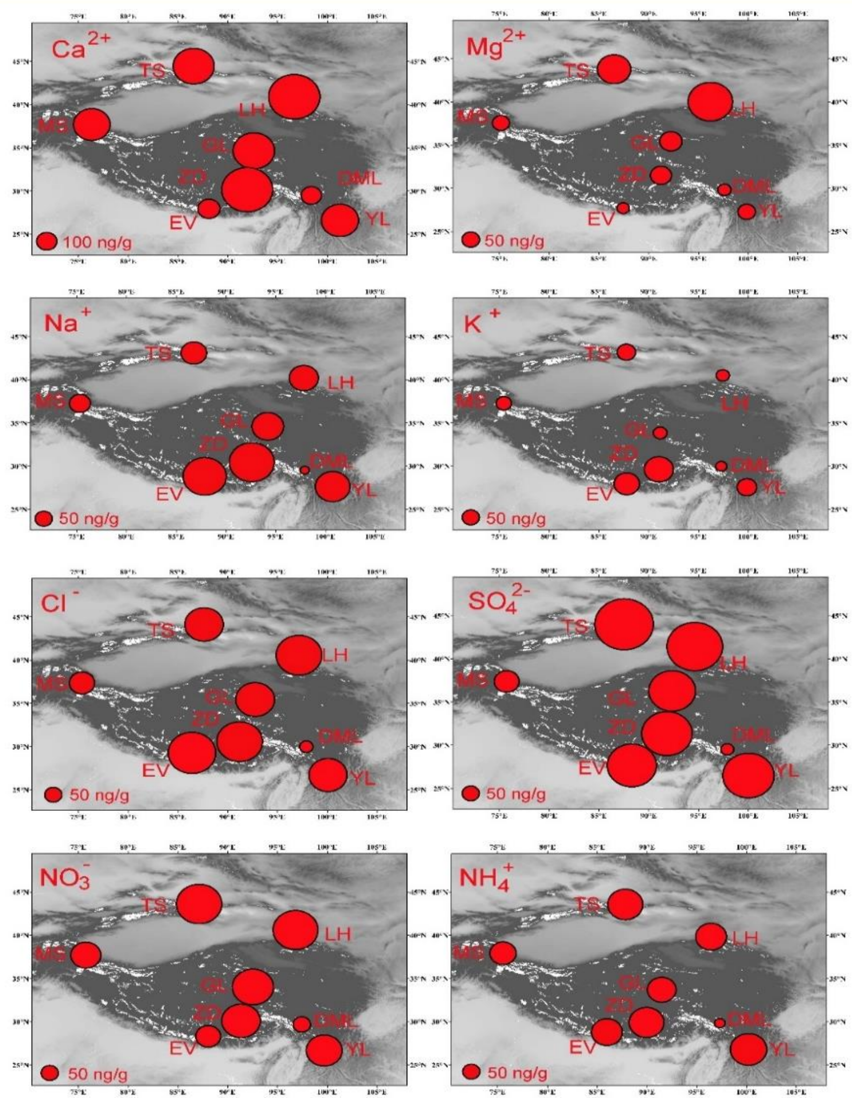
3.1 Inorganic chemicals

Main sources:

- ✓ **Crustal chemical composition**
- ✓ **Sea salt**
- ✓ **Natural events (volcanic eruptions, forest fires)**
- ✓ **Human activity emissions**

➢ **To determine the contribution of different sources of chemical ions, it is usually assumed that all Na+ in snow and ice comes from the ocean. The contribution of sea salt (ss) and non sea salt (nss) can be distinguished based on the ratio of snow and ice ions to Na+ in standard seawater:**

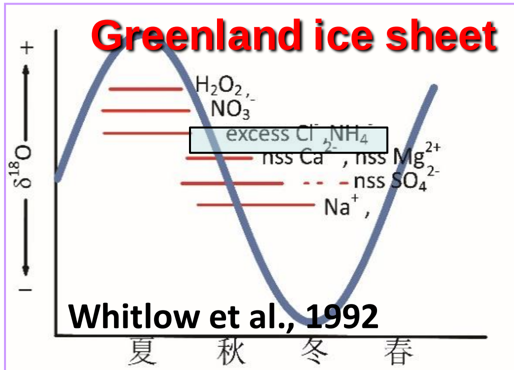
nssA = A – Na (ssA/ssNa)



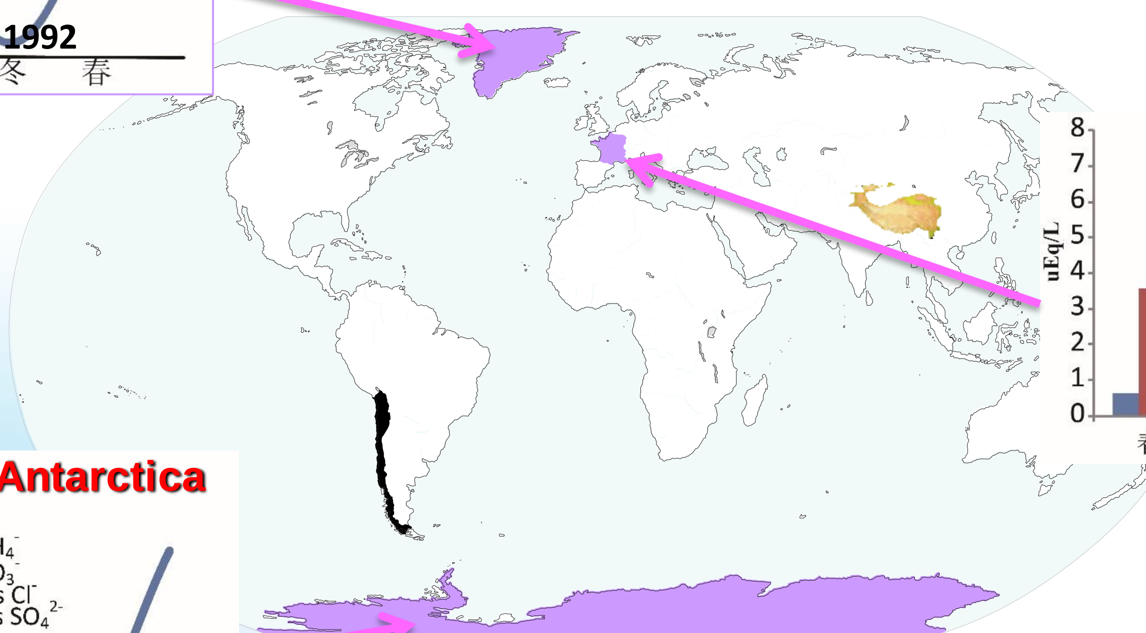
Major ions in snowpit of west China

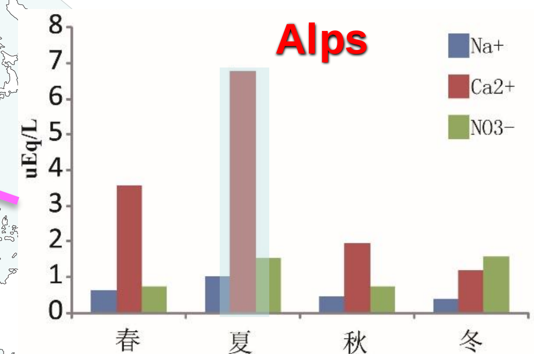
3.1 Inorganic chemicals

◆ There are significant differences in seasonal variations of chemical ions in global snow and ice.

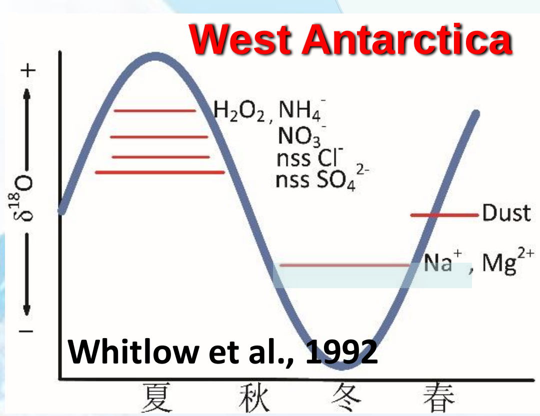


Arctic: Na+ from sea salt sources peaks in autumn and winter





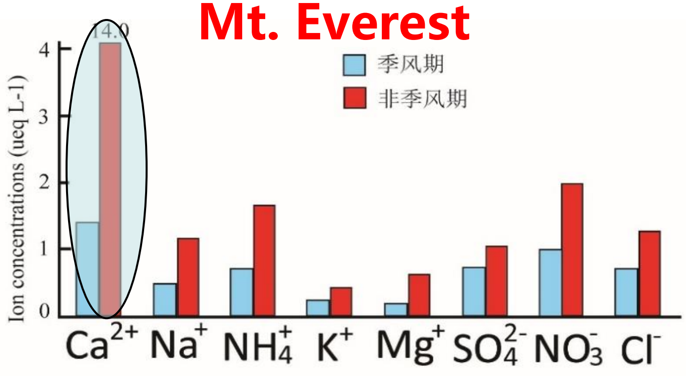
Maupetit et al., 1995

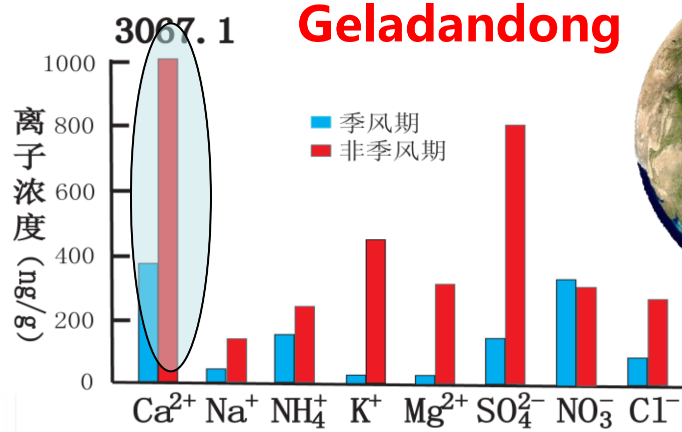


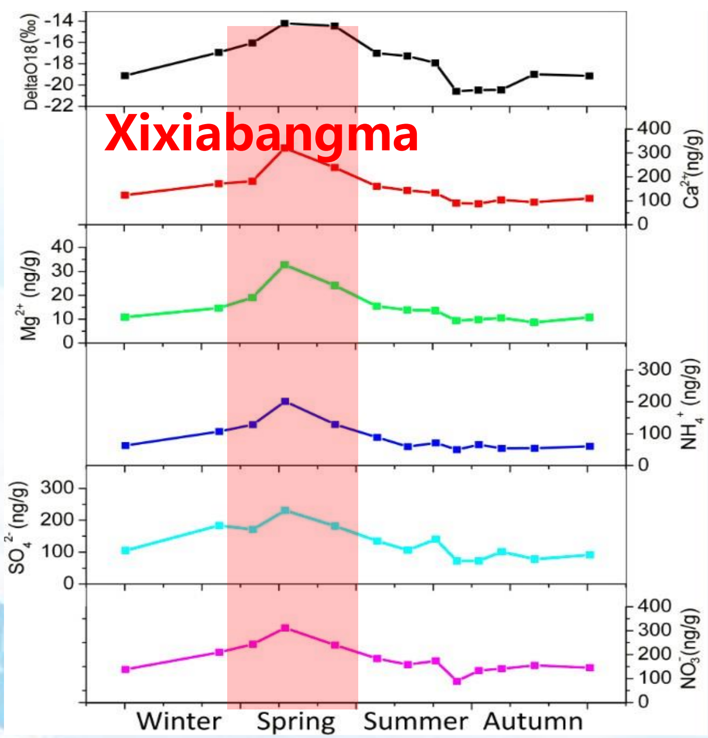
Antarctica: High values of Na+ from sea salt sources during winter

Alps: Terrestrial sourced Ca2+ peaks in summer

3.1 Inorganic chemicals







- **The non monsoon period (winter and spring) is high, while the monsoon period (summer) is low, reflecting the impact of sandstorms in winter and spring and the South Asian summer monsoon on the atmospheric environment.**

3.1 Inorganic chemicals

- **Conductivity and pH value: Conductivity is a comprehensive indicator of the total ions contained in snow and ice, mainly reflecting the chemical characteristics and components of snow and ice. The relationship between different ions in snow and ice and conductivity reflects the dominant factor affecting conductivity. The correlation between conductivity and acidity pH also indicates the dominant ions in snow and ice.**

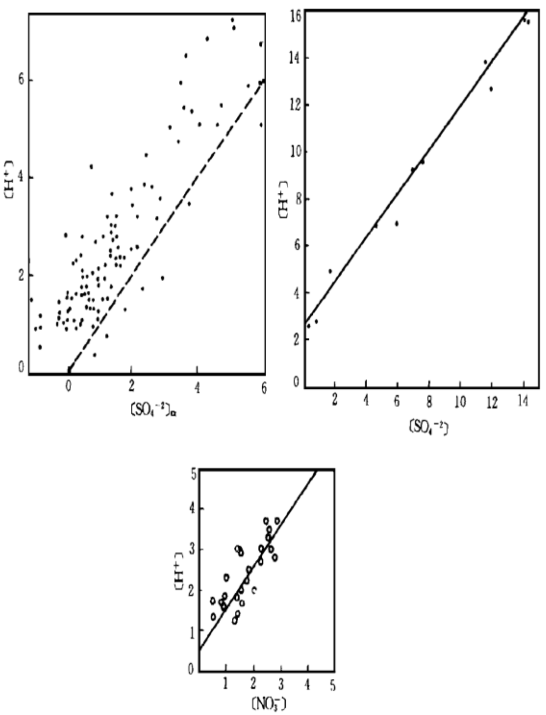


图1 南极冰盖中 H与 SO_4^{2-}, NO_3^- 及 nss SO_4^{2-} 的关系 (引自 Legrand *et al*., 1987)

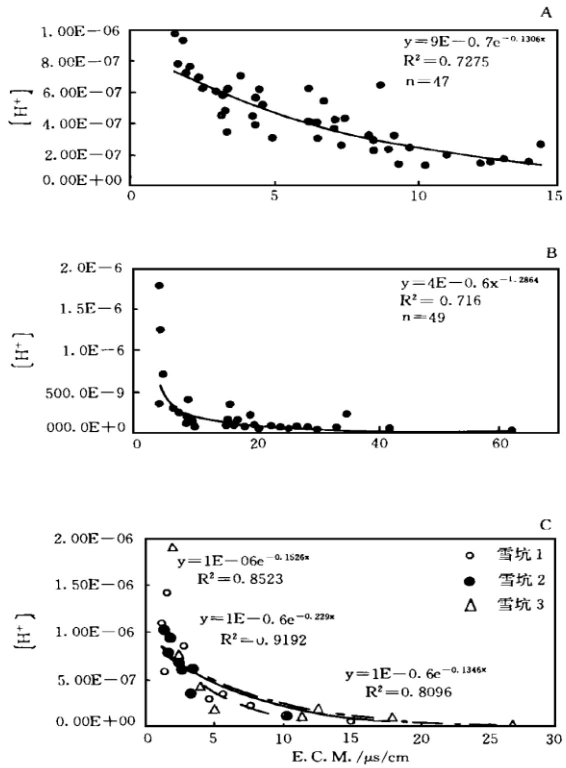


图2 青藏高原雪冰电导率与 H 的关系

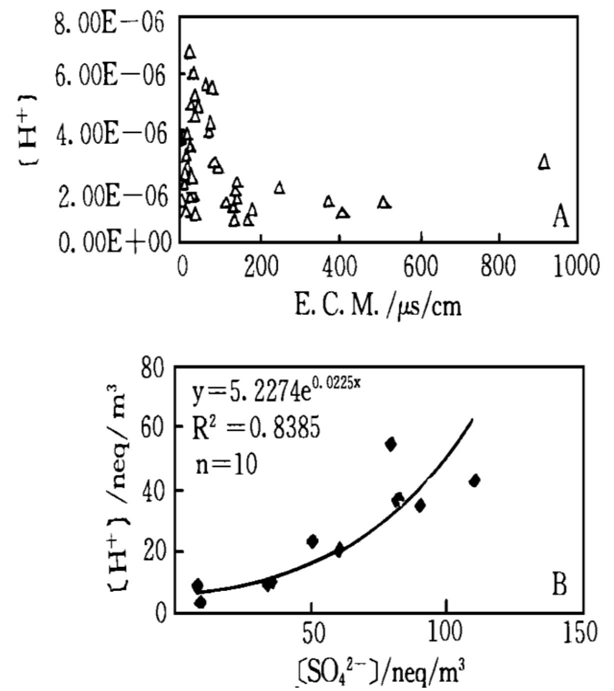
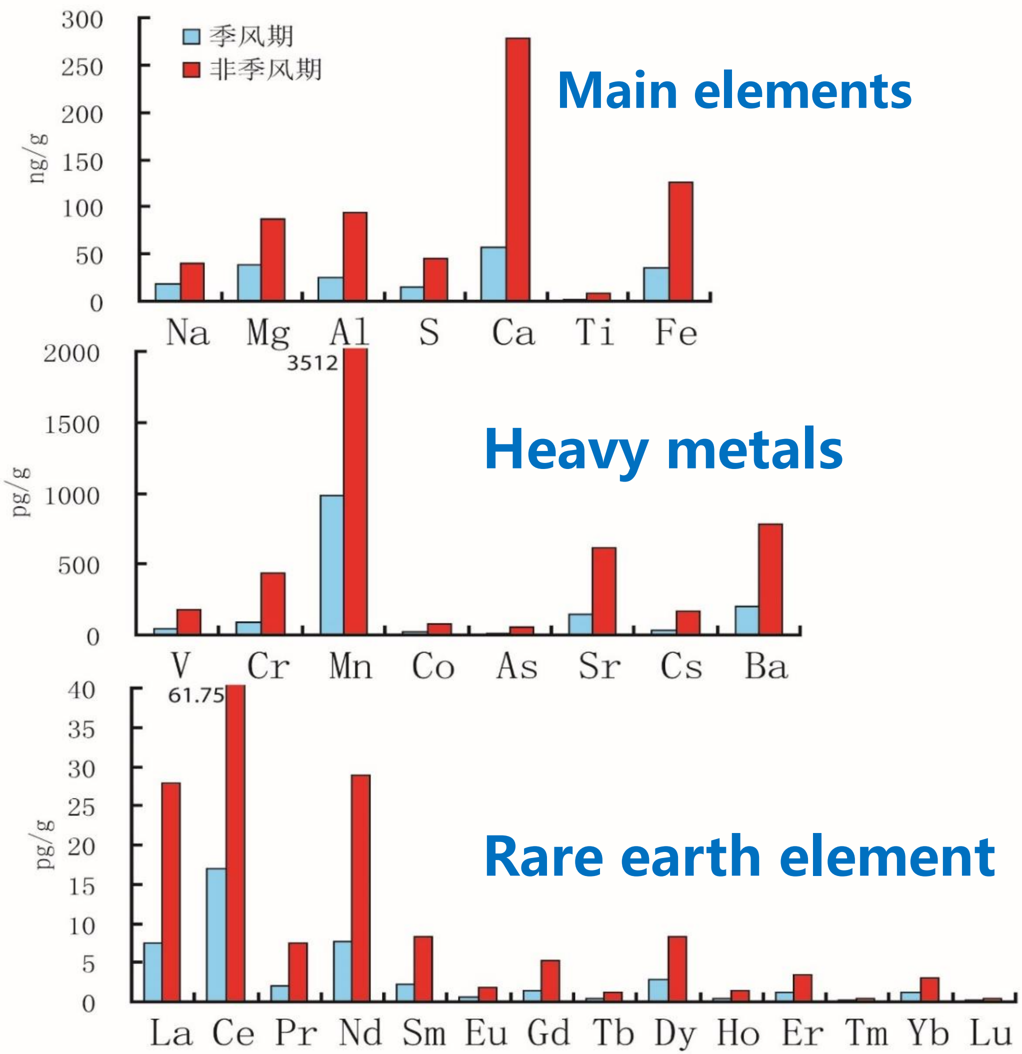


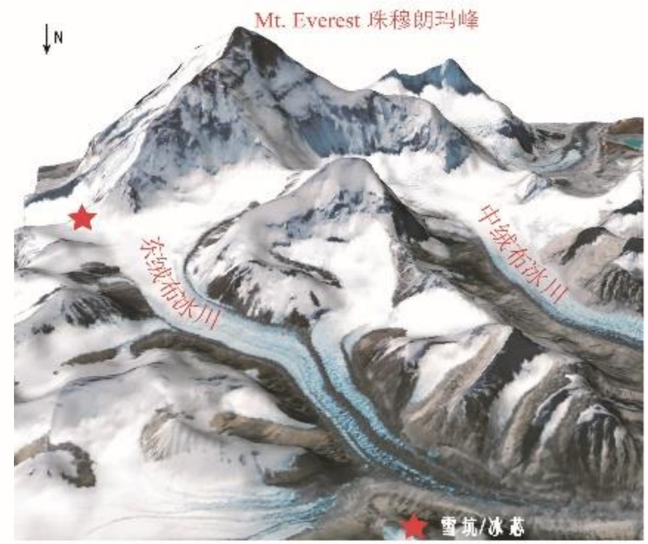
图4 A北冰洋中心地带积雪内电导率与 H 散点关系图; B北极霾气溶胶中 SO_4^{2-} 与 H 相关曲线 (据 Lazrus and Ferek, 1984)

3.1 Inorganic chemicals

Elements

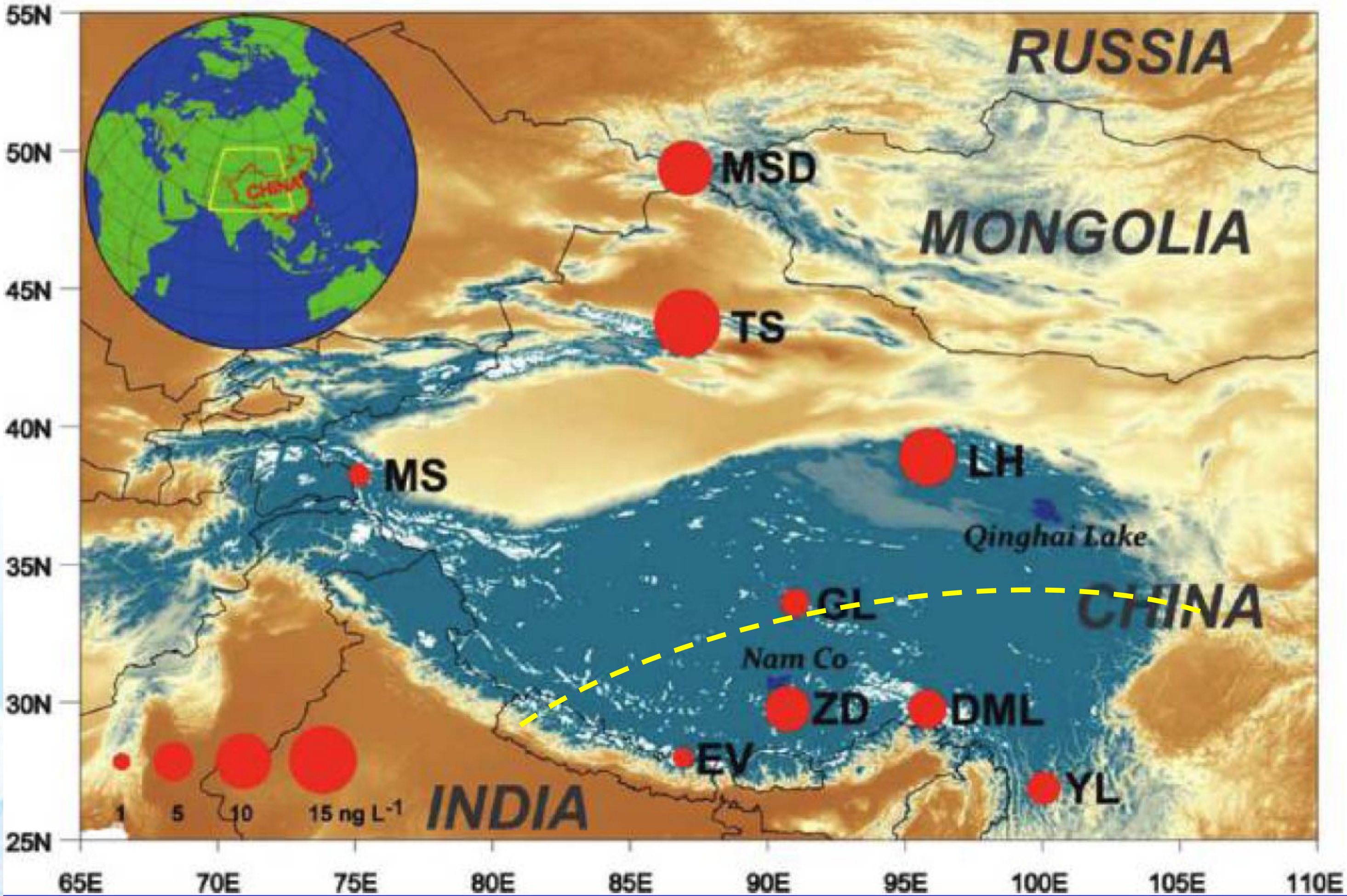


Mt. Everest



- **The element content in snow and ice is high during non monsoon periods and low during monsoon periods.**

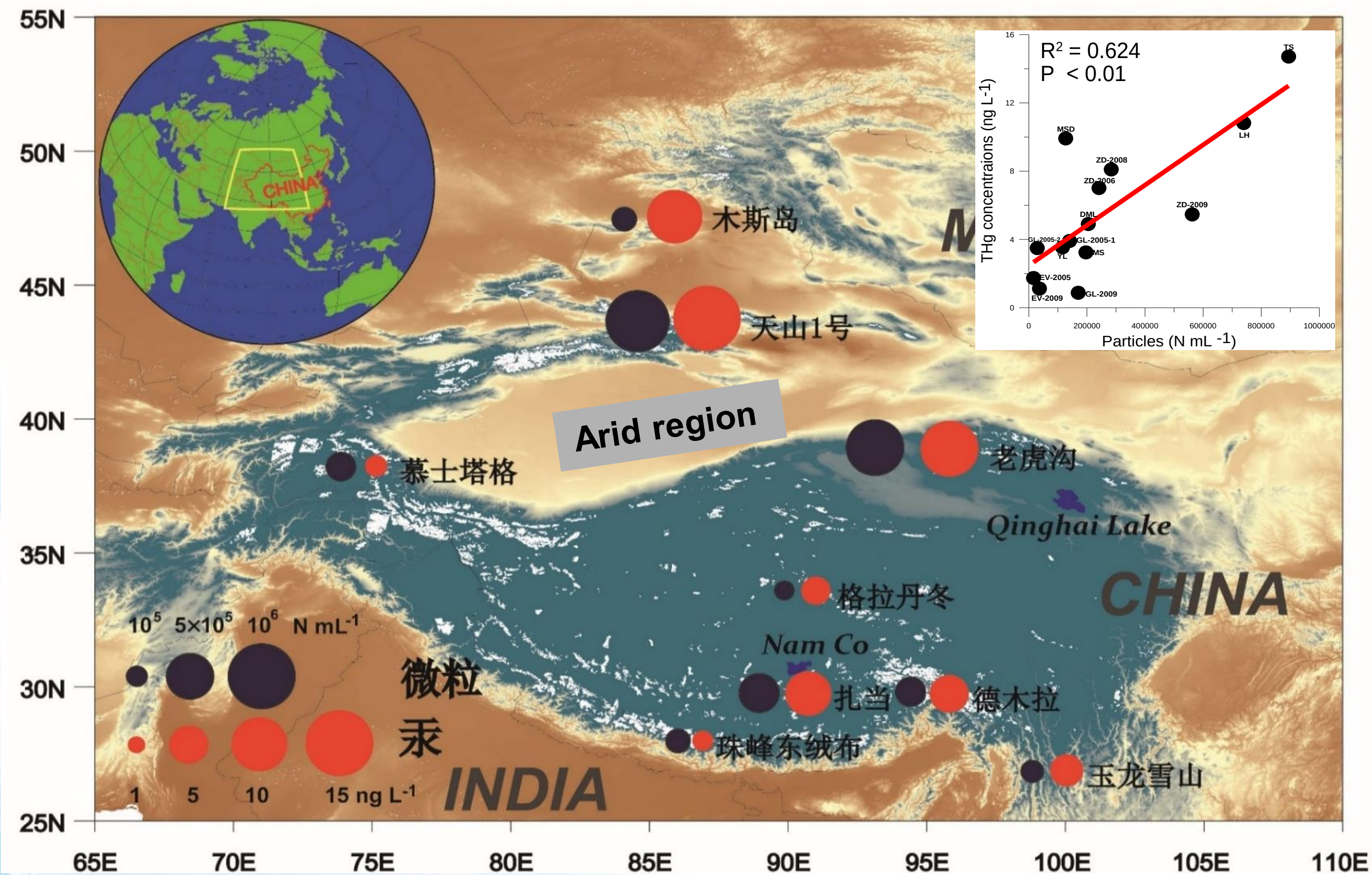
3.1 Inorganic chemicals



- **The seasonal distribution of mercury is generally characterized by high non monsoon periods and low monsoon periods, and this pattern is more significant in the South Asian summer monsoon affected area**

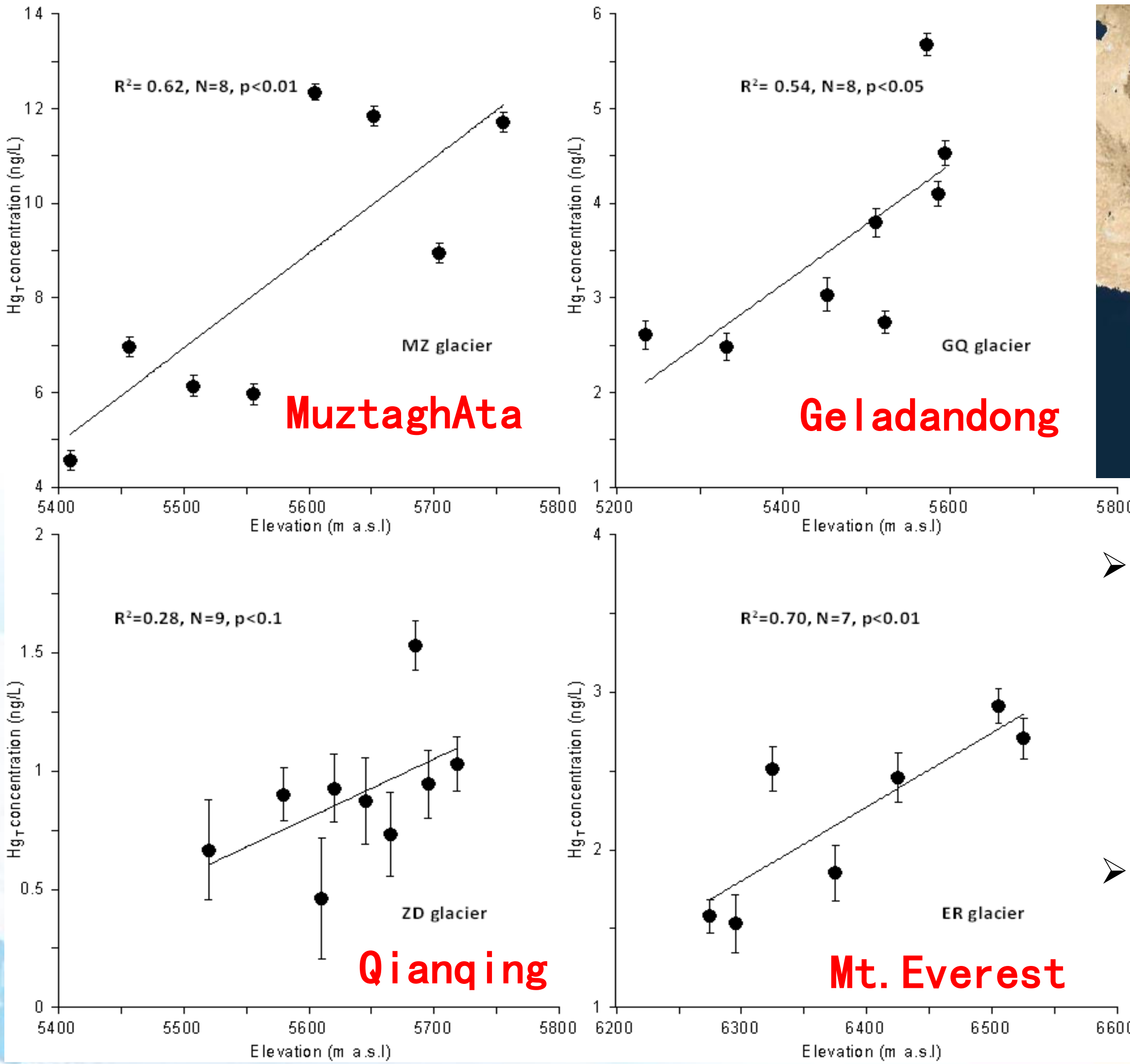
3.1 Inorganic chemicals

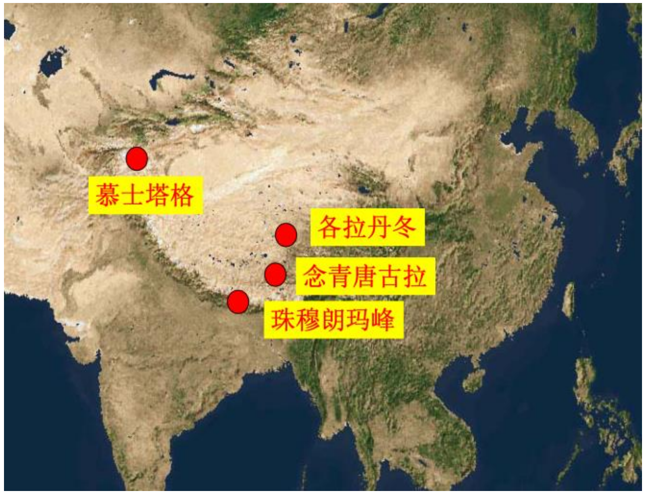
➢ **The spatial distribution of total mercury in snow and ice is generally controlled by atmospheric dust**



The levels of mercury and dust particles in glacier snowpits

3.1 Inorganic chemicals





- **The concentration of mercury element increases with altitude, and the glacier area of the Qinghai Tibet Plateau is a globally important "mercury sink".**
- **Elevation amplification effect of mercury concentration in surface snow of glaciers.**

3.2 Organic matters

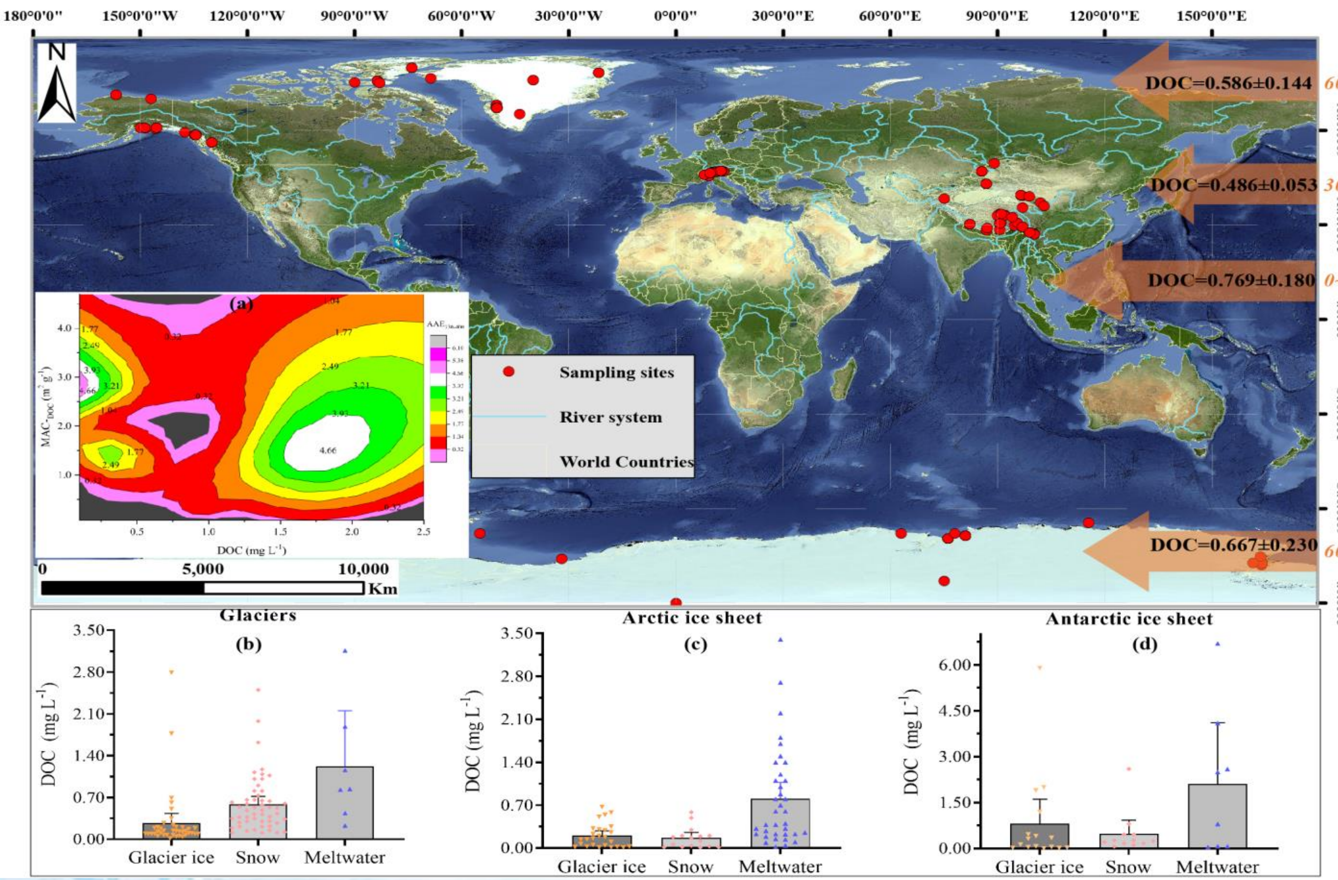
SKLCS

- **Organic matter:** Compounds containing carbon elements refer to compounds containing carbon elements other than carbon oxides, carbonates (hydrogen) salts, and metal carbides.

- The concentration of organic matter in glaciers is extremely low, but their research can not only provide information on climate change and biological activity, but also be used to indicate environmental change processes.

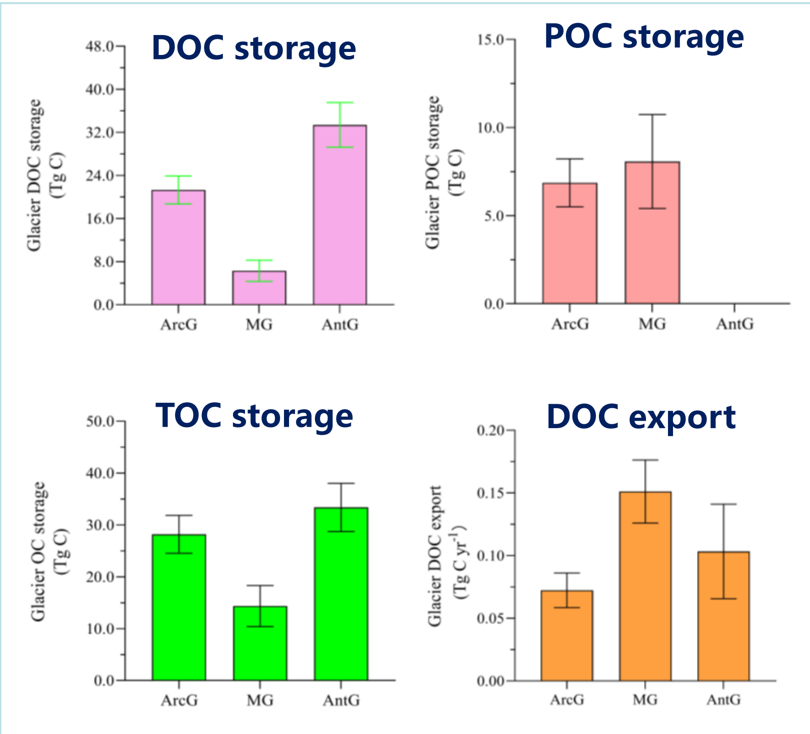
- The research on trace organic matter in glaciers mainly includes: By analyzing the composition, carbon number distribution, and odd even advantages of fatty acids of organic compounds mainly derived from natural sources, we can understand the sources and evolution of such organic compounds; Mainly organic pollutants generated by human activities, such as persistent organic pollutants (POPs) that are of global concern, including PAHs, PCBs, DDT, and HCH.

3.2 Organic matters

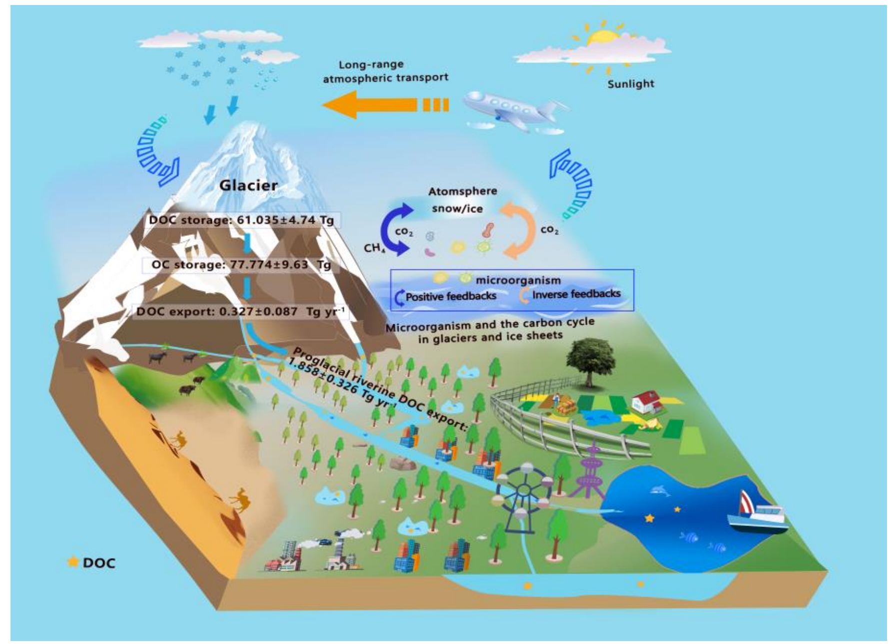


The distribution of organic carbon in global snow and ice (mainly including primary organic carbon directly emitted into the atmosphere from the combustion of fossil fuels and biomass, and low volatility products generated from the oxidation reaction of volatile organic compounds or secondary organic carbon generated from heterogeneous atmospheric reactions). Organic carbon in the atmosphere can alter solar radiation forcing, atmospheric visibility, and other factors through various physical and chemical changes, thereby affecting global climate change and also having significant impacts on human health.

3.2 Organic matters



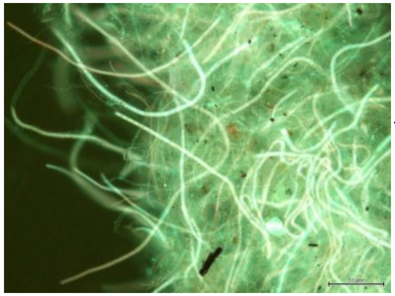
The role of glaciers and ice sheets in the global carbon cycle



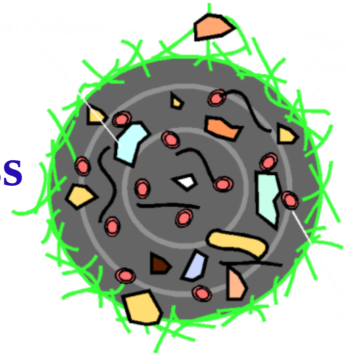
- ➢ **Ice caps store a large amount of organic carbon and are a component of the global carbon cycle.**
- ➢ **The estimated organic carbon storage in mountain glaciers and ice sheets is 75.97 ± 8.77 Tg C, with mountain glaciers containing approximately 14.37 ± 3.96 Tg C.**

3.2 Organic matters

- **The differences in dominant microbial communities and quantities in glaciers reflect the impact of different glacier environments on the structure and distribution of microbial communities.**
- **In the primary glacier ecosystem dominated by cold tolerant microorganisms, algae and fungi play the role of major producers. They rely on dust as nutrients and encapsulate dust particles for massive reproduction, ultimately forming cryoconite.**
- **Algae enriched on glaciers can produce a large amount of colored substances, which can significantly reduce the albedo of glacier surfaces and accelerate the melting process of glacier surfaces.**



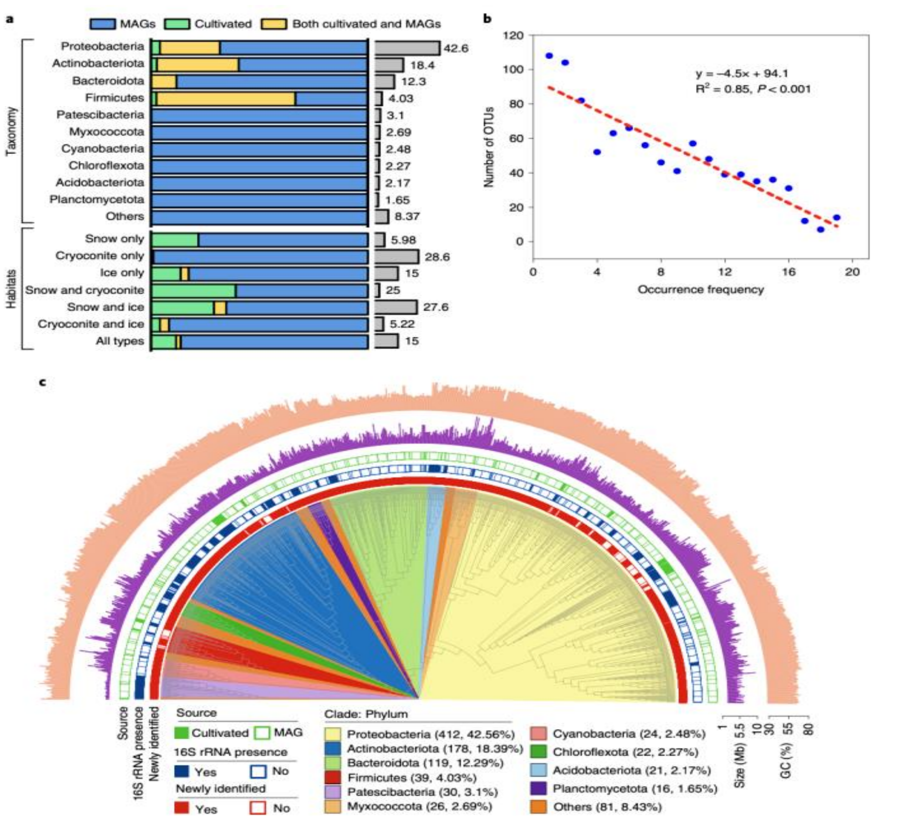
biomass



LIU Yongqin

3.2 Organic matters

- **The glaciers on the Qinghai Tibet Plateau are natural reservoirs for microorganisms, storing microorganisms from different historical periods. Microorganisms, as the main life group of glaciers, drive the carbon and nitrogen cycling of ecosystems and release downstream with glacier meltwater during glacier melting.**
- **Extreme environmental conditions such as low temperature and strong ultraviolet radiation have shaped the unique species types of glaciers. However, global warming has led to rapid melting of glaciers, reduced diversity of microorganisms adapted to glacier environments, and loss of glacier specific microbial resources.**



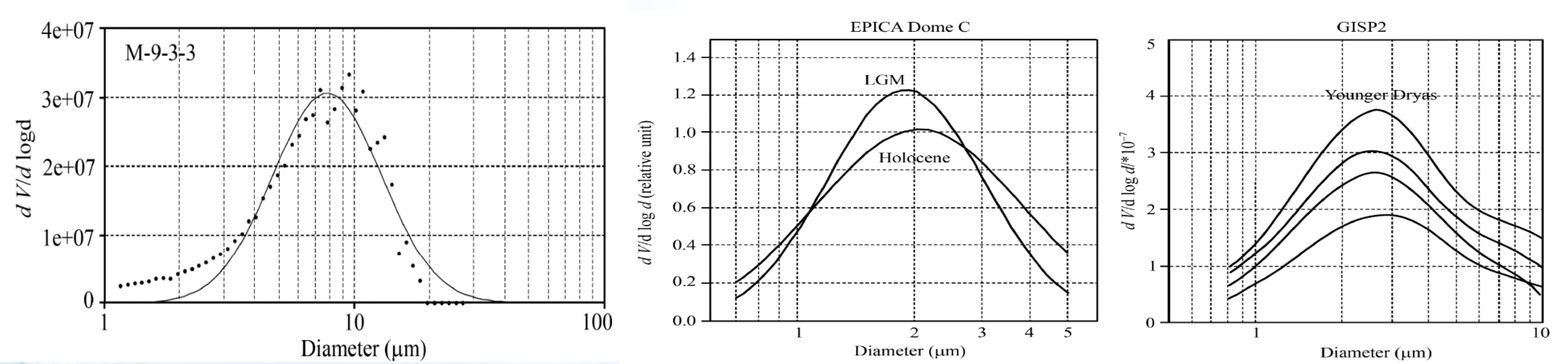
Based on 85 metagenomes from 21 glaciers on the Qinghai Tibet Plateau and 883 bacterial genomes isolated from glaciers on the Qinghai Tibet Plateau, the diversity and function of microorganisms in snow, ice, and ice dust (aggregates composed of minerals, organic matter, and microorganisms scattered on glacier surfaces) on the surface of glaciers on the Qinghai Tibet Plateau were revealed, and the first Qinghai Tibet Plateau glacier microbial genome and gene dataset (TG2G) was constructed.

Liu et al., 2022

3.3 Microparticles

- **Crustal dust:** Originating from arid and semi-arid regions, it changes the energy and material balance of glaciers by reducing their surface albedo, and has a significant impact on accelerating glacier melting. The study of dust in glaciers mainly involves the spatiotemporal patterns, physical and chemical properties (particle size, morphology, chemical composition), and sources of dust concentration and flux in snow and ice.

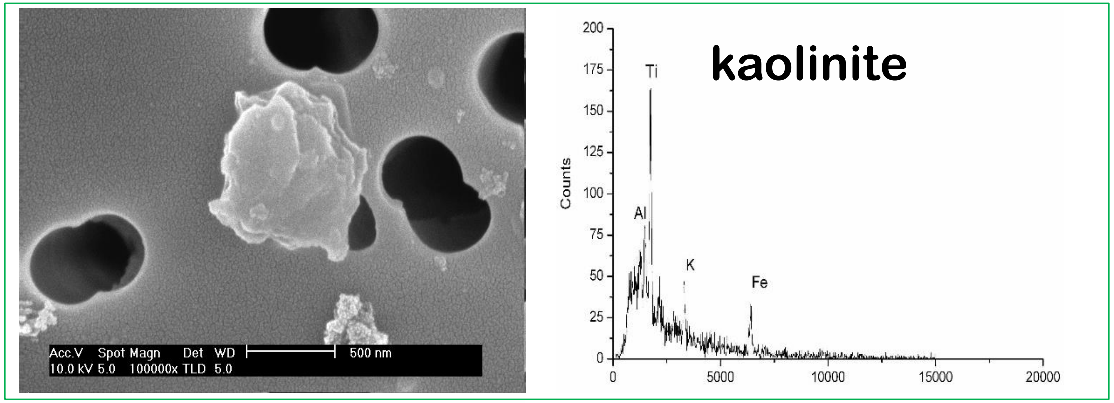
- The dust in the glacier area of western China has a large particle size distribution and a **single distribution mode**, which is significantly different from the particle size characteristics of snow and ice particles in the North and South Poles. For example, the particle size distribution range of particles in the glacier area of the Tibetan Plateau is 3~25 μ m, showing a unimodal distribution pattern; In the snow and ice of the North and South Poles, the particle size of dust is generally 1~2 μ m.

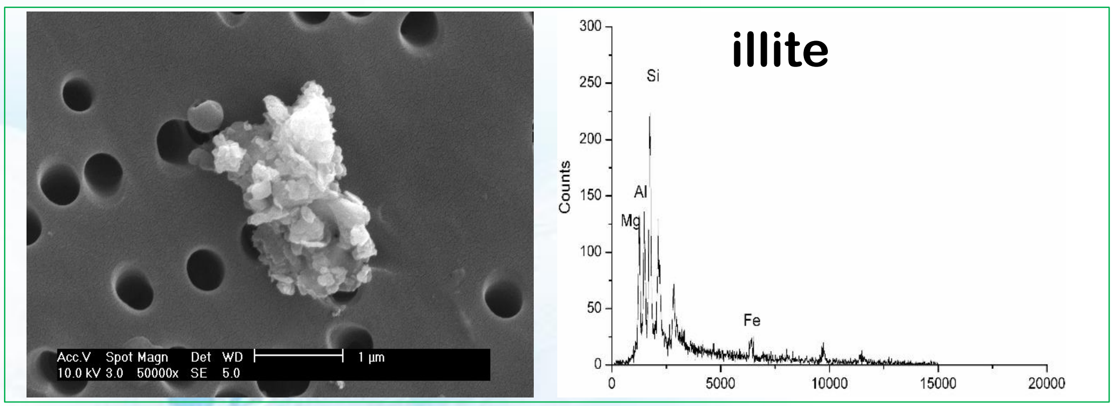


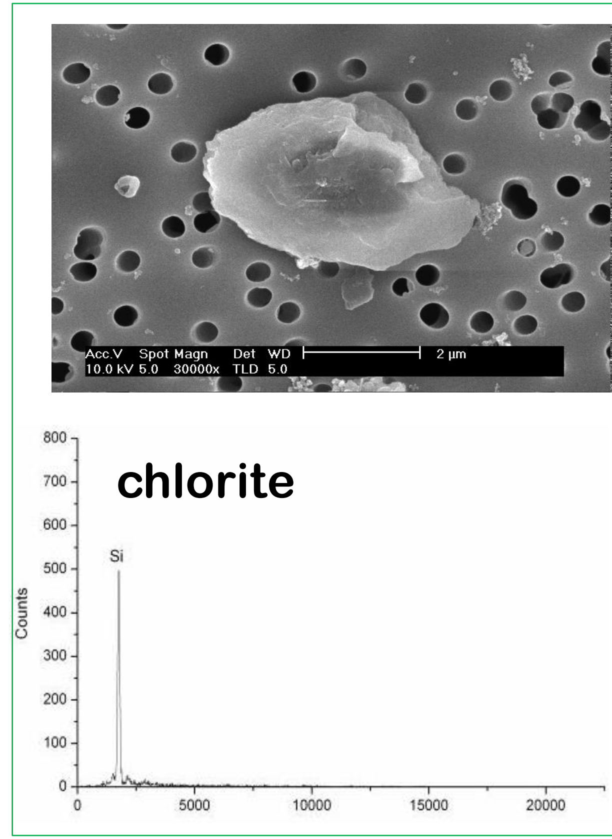
Wu et al., 2006

3.3 Microparticles

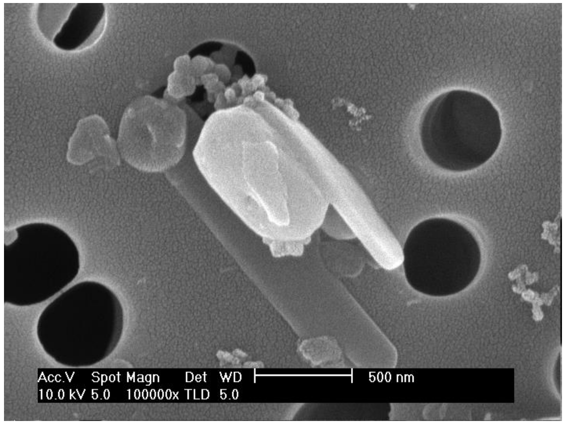
The morphology and energy spectrum of kaolinite, illite, and chlorite

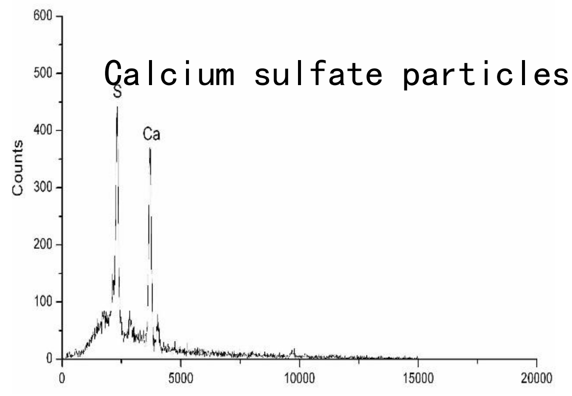


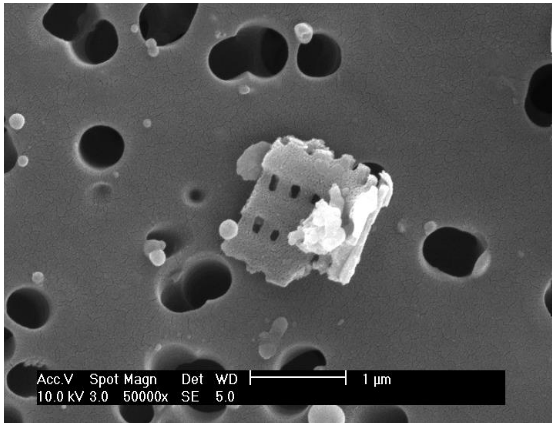


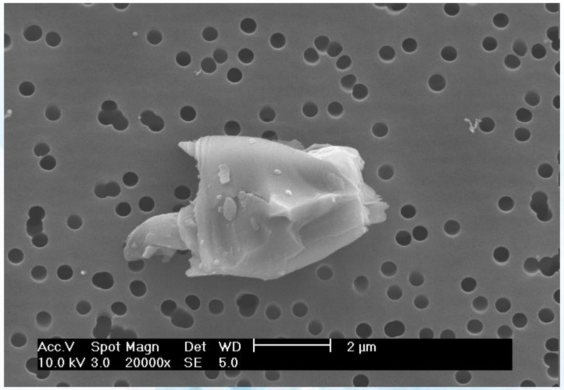


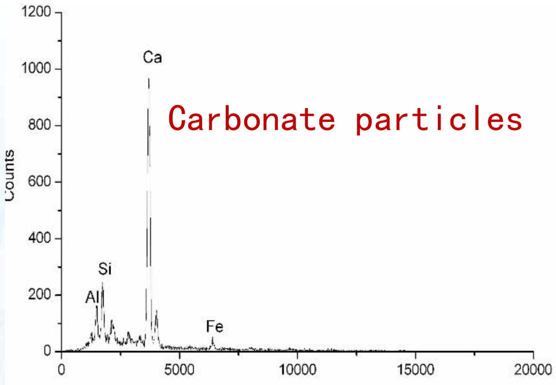
3.3 Microparticles

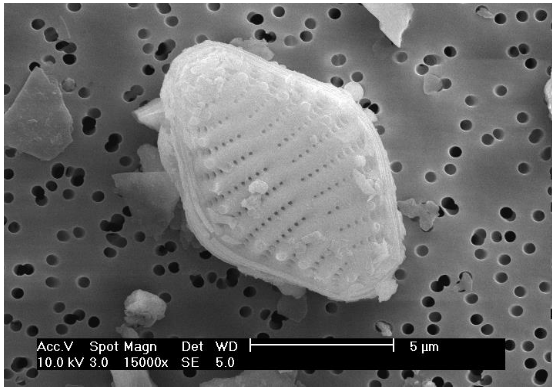








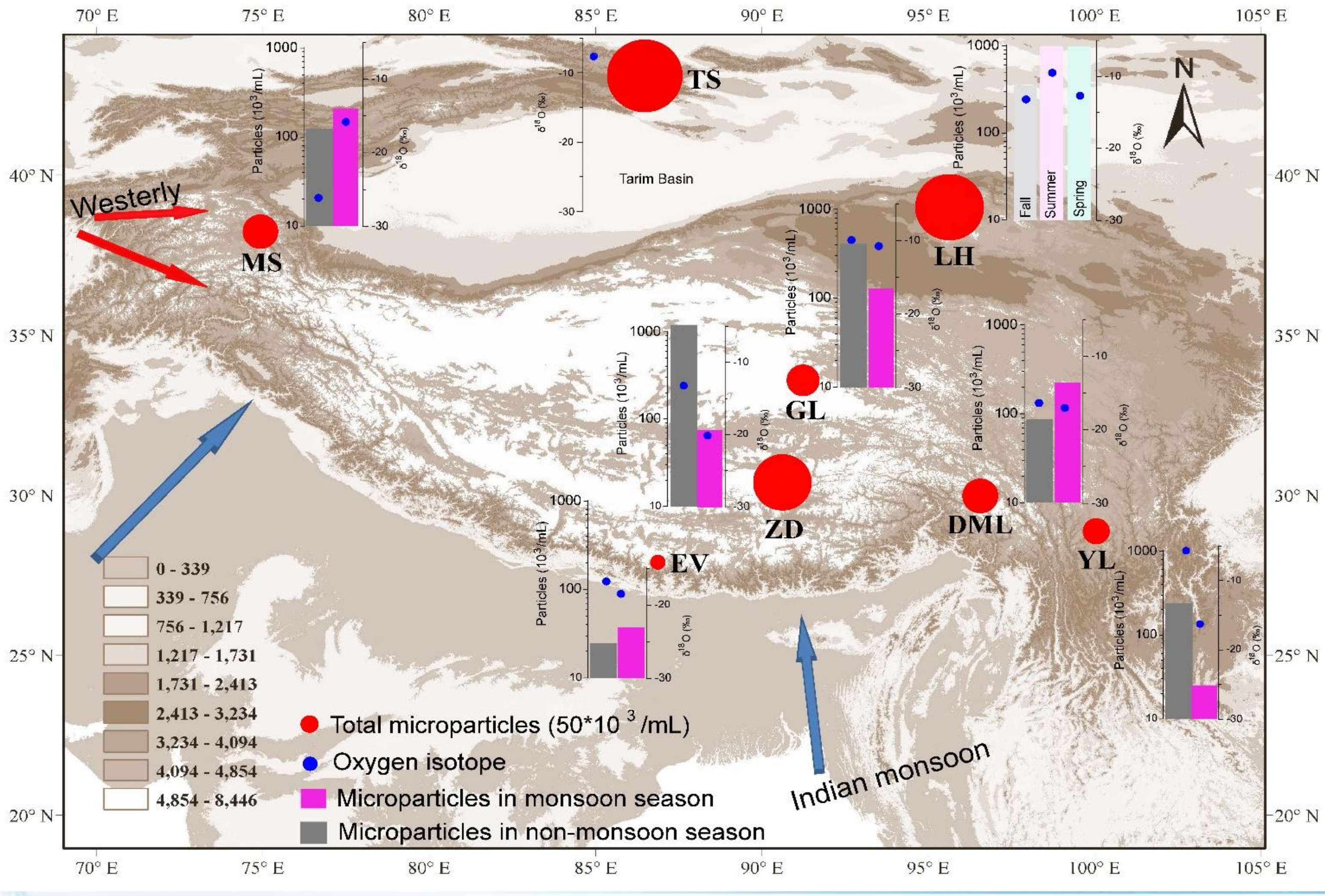




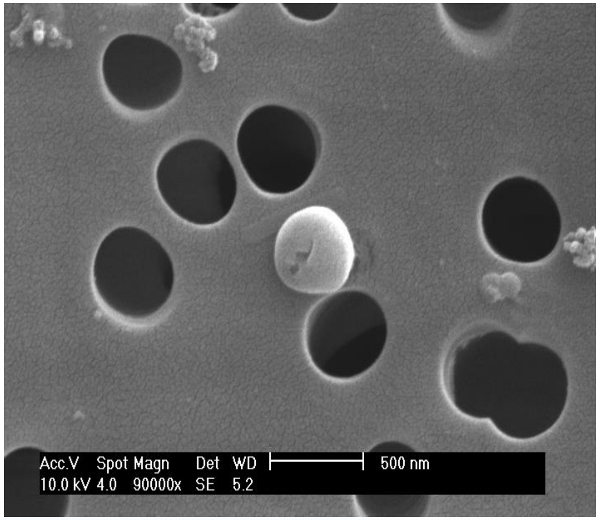
Biological particles mainly include bacteria, pollen, spores, plant or insect debris, etc.

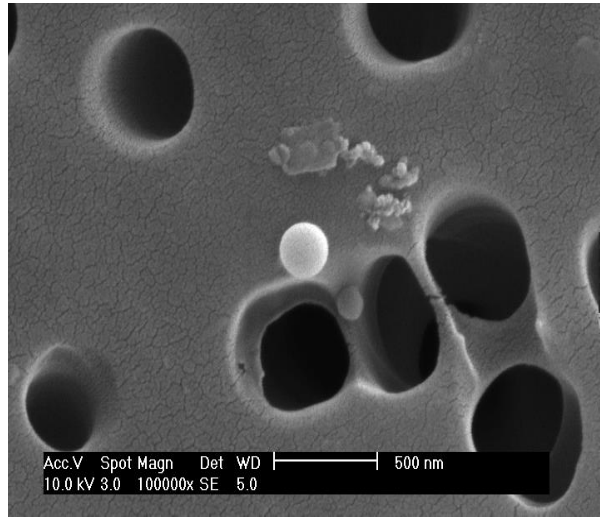
3.3 Microparticles

- **The variation of dust concentration in Tibetan Plateau is mainly controlled by distance from arid areas and altitude.**

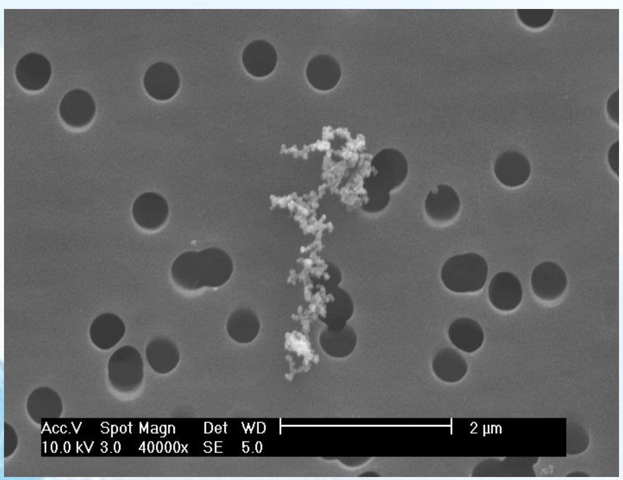


3.4 Black carbon (BC)

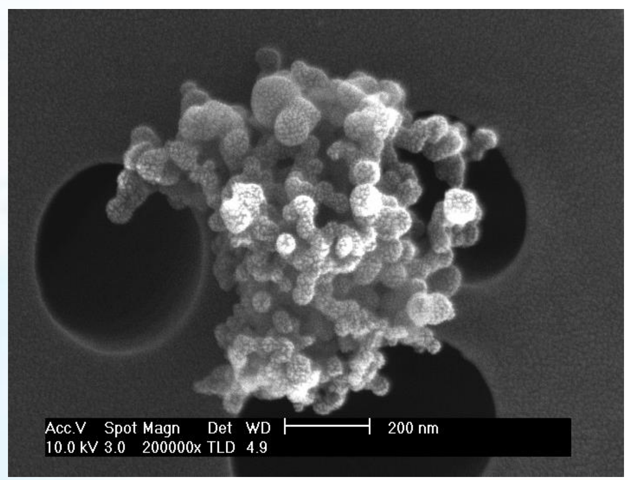




Tar ball



Chain like smoke particles



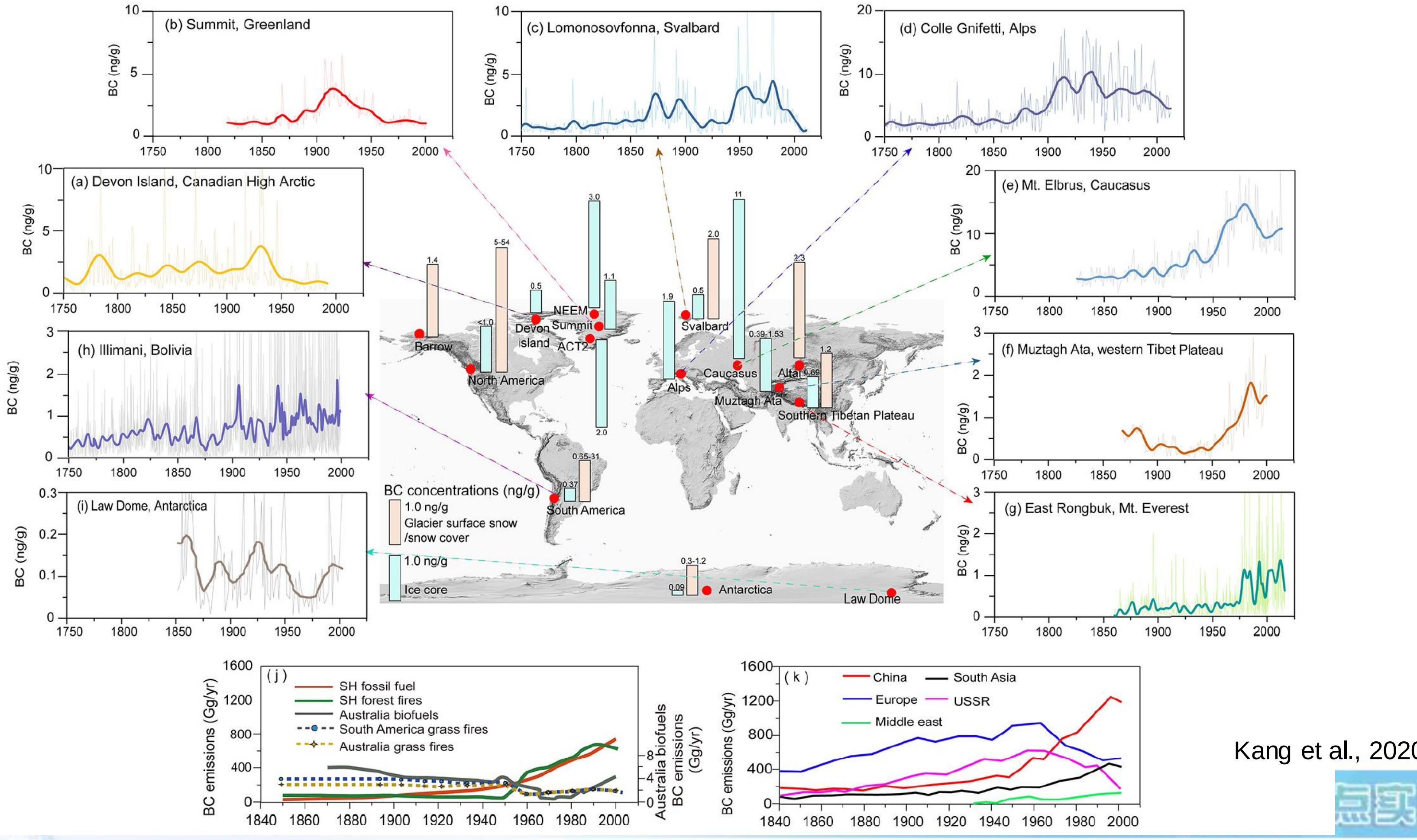
Accumulated smoke particles

Black carbon:

- mainly derived from incomplete combustion of fossil fuels and biomass;
- Not only does it absorb solar radiation in the atmosphere, causing it to warm up, but its deposition on glaciers can significantly reduce the albedo of glacier surfaces, thereby accelerating glacier melting.

3.4 Black carbon (BC)

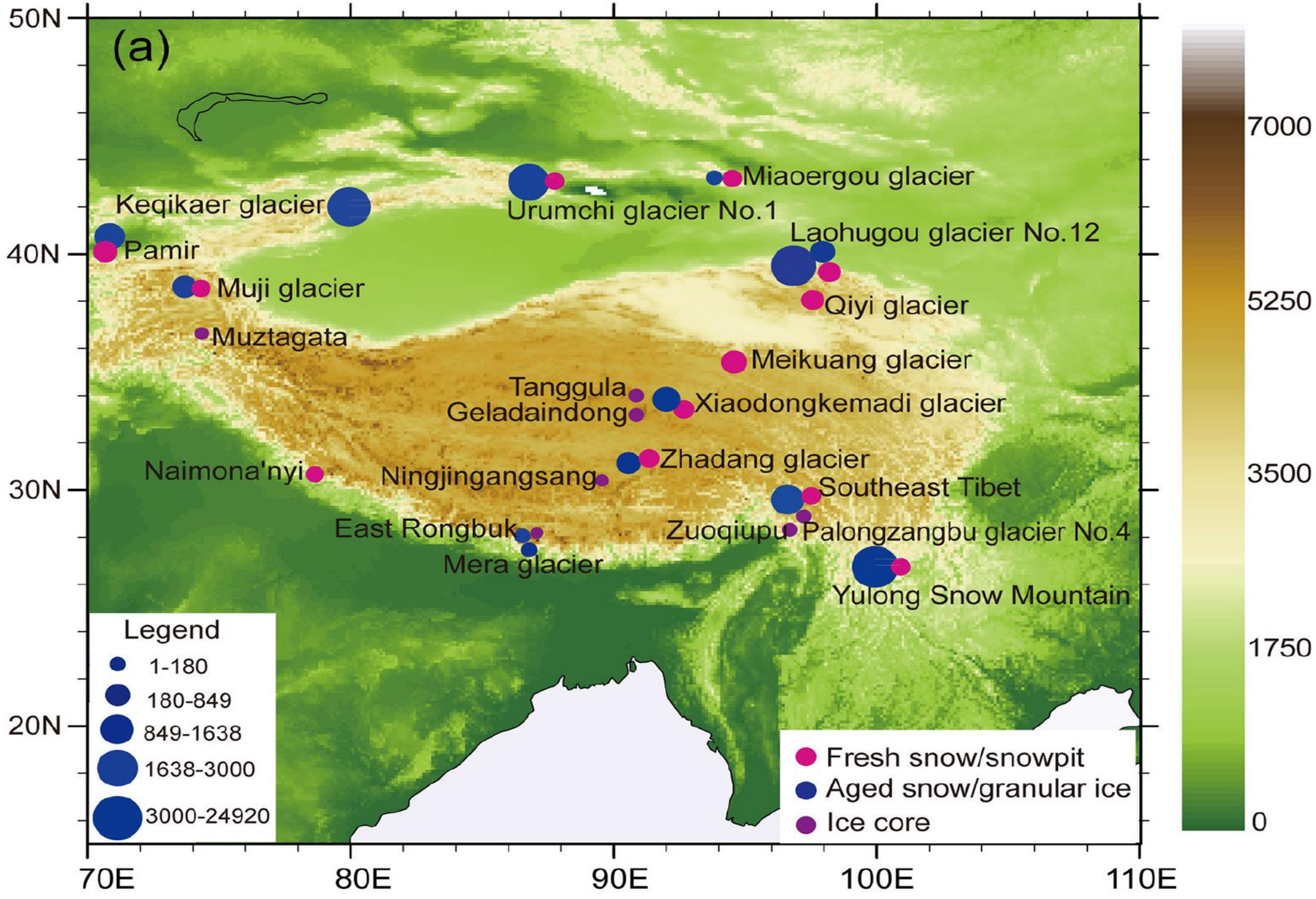
Changes of black carbon concentration in ice cores and modern snow and ice



Kang et al., 2020

3.4 Black carbon (BC)

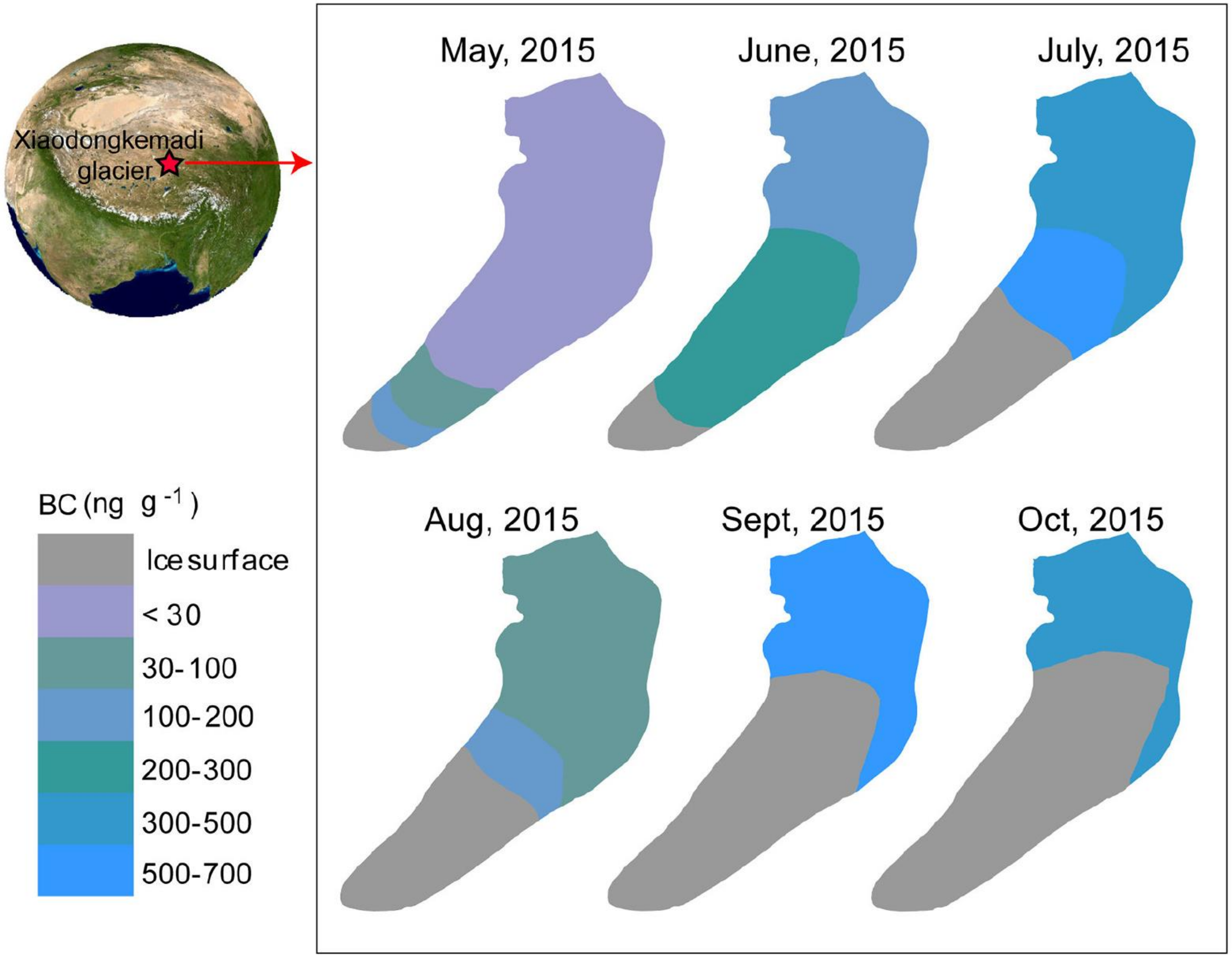
Distribution map of black carbon content in glaciers, snow and ice in the Qinghai Tibet Plateau and surrounding areas



Kang et al., 2020

3.4 Black carbon (BC)

Distribution of BC from Xiaodongkemadi Glacier in the central Tibetan Plateau

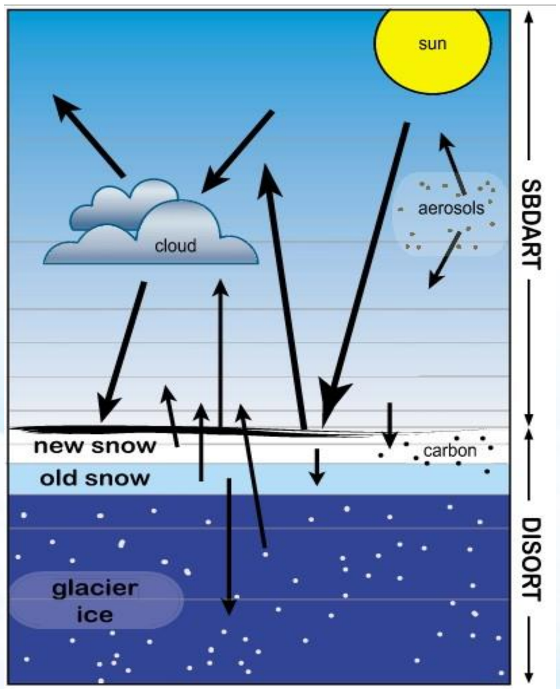


Kang et al., 2020

3.4 Black carbon (BC)

Radiative forcing of BC in global surface snow

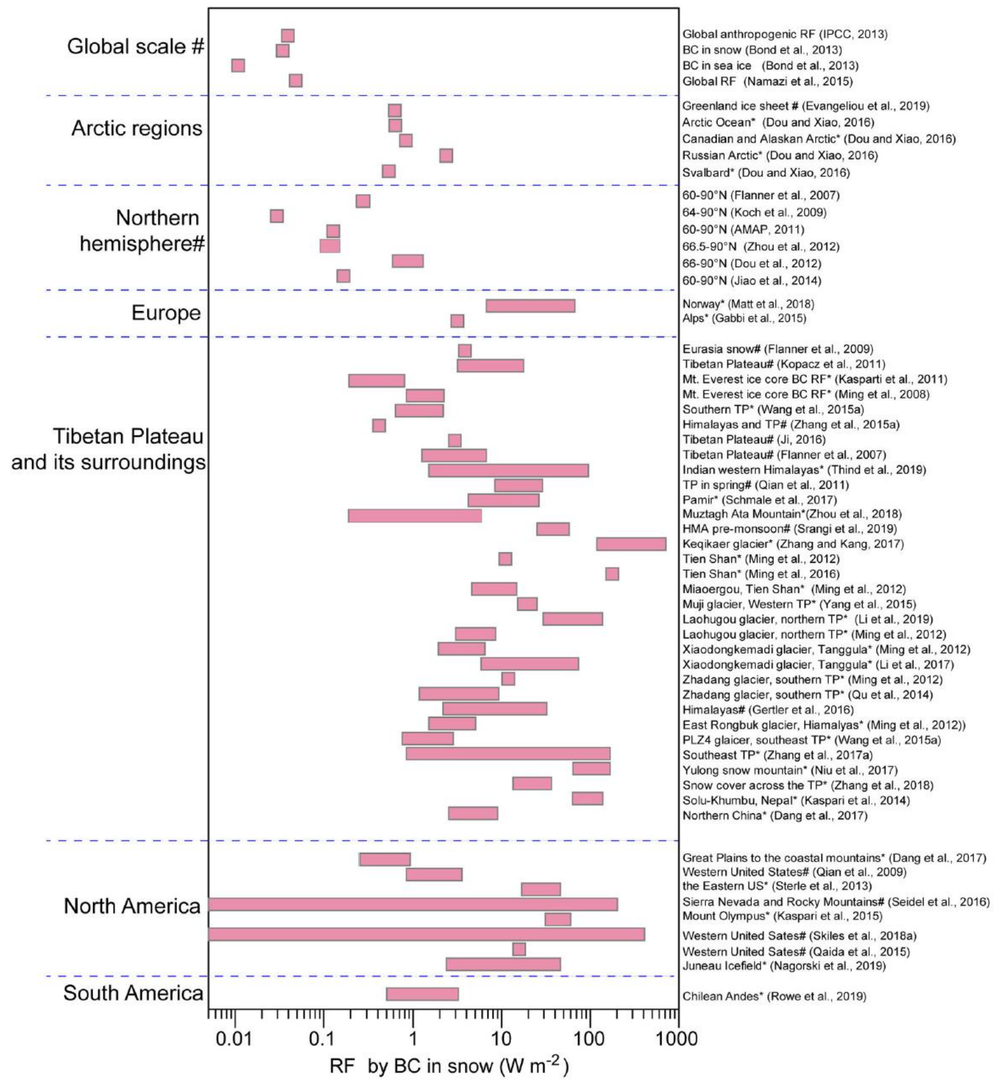
$$RF_x = R_{in\text{-}short} * \Delta\alpha_x$$



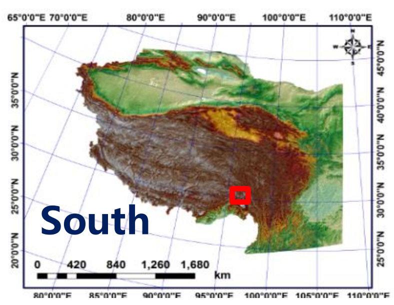
SNICAR

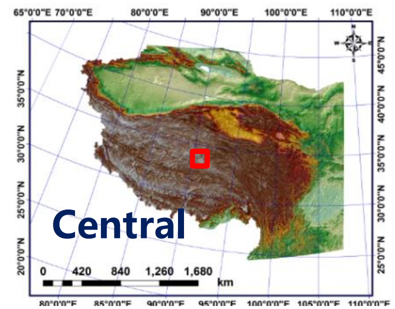
（SNow ICe Aerosol Radiative）

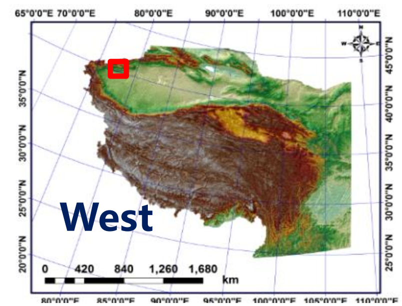
Flanner, 2007

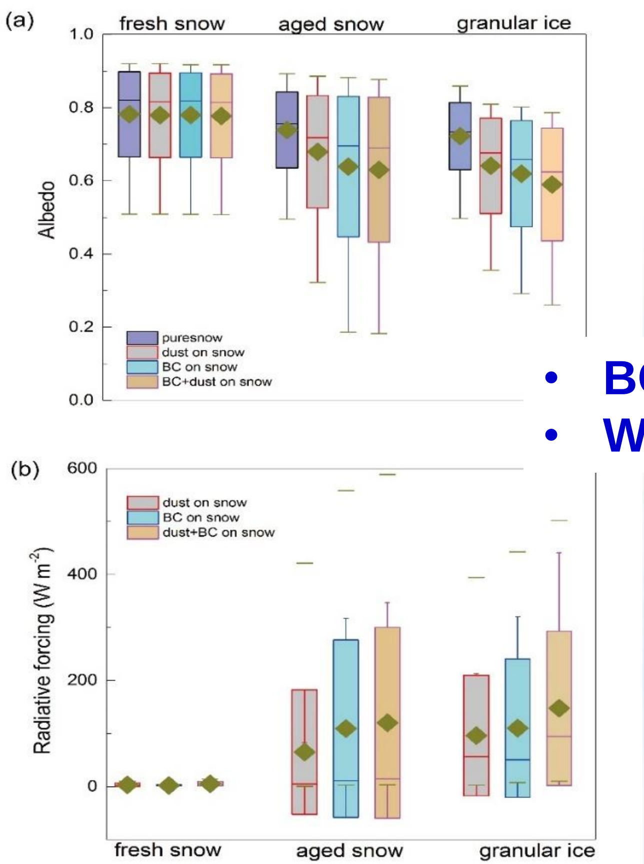


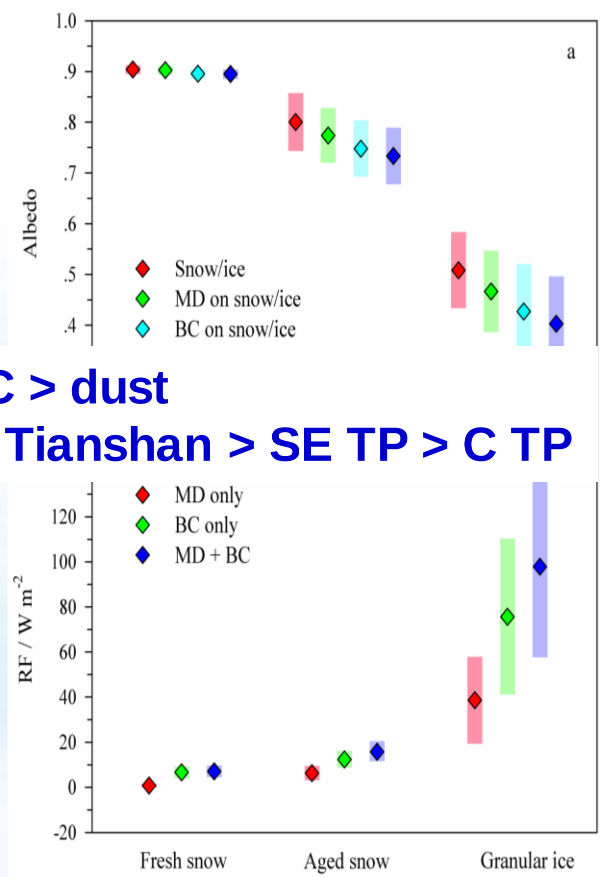
3.4 Black carbon (BC)

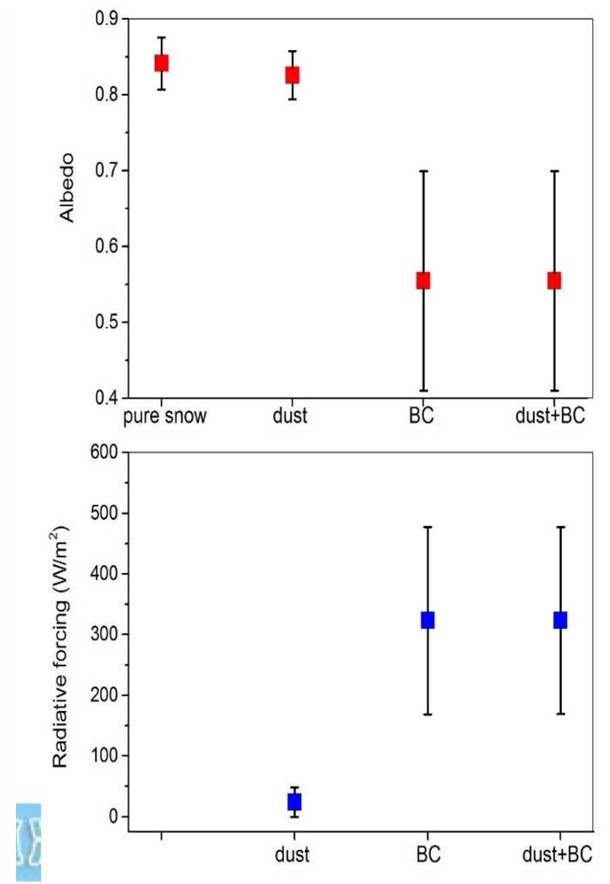








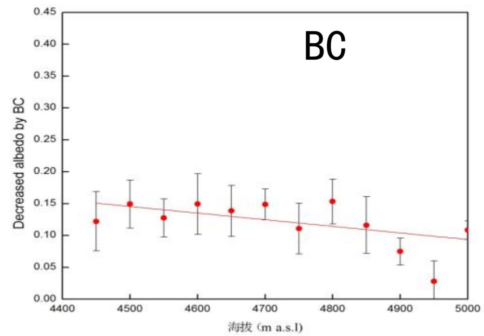


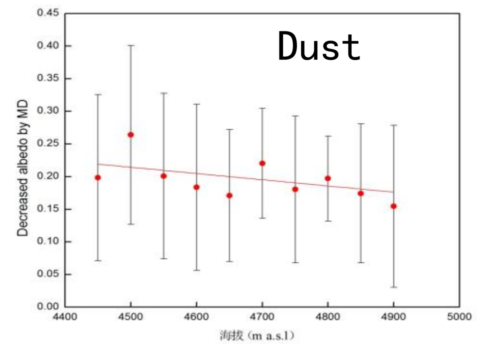


- **BC > dust**
- **W Tianshan > SE TP > C TP**

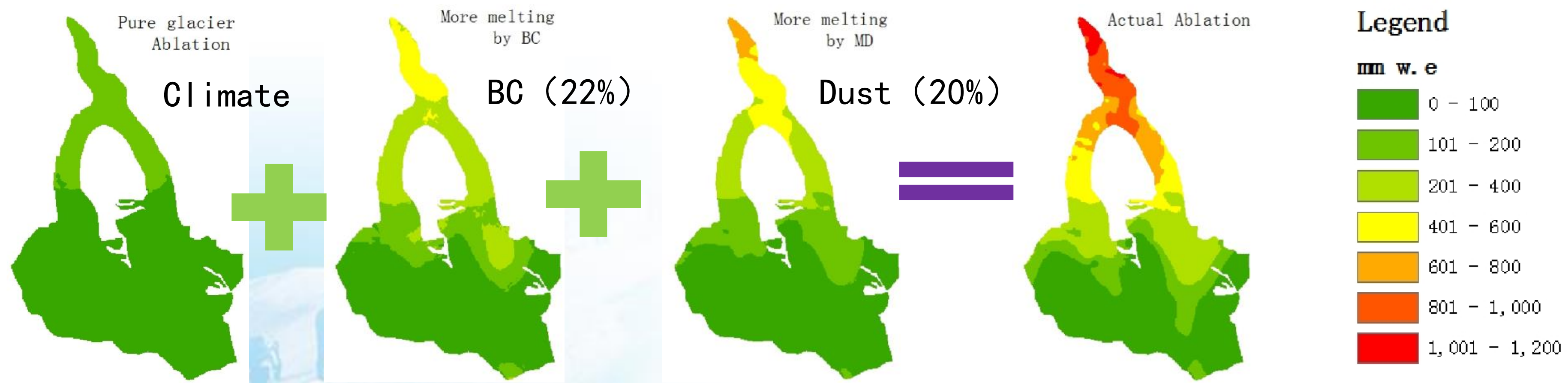
3.4 Black carbon (BC)

BC and dust can accelerate snow and ice melting together





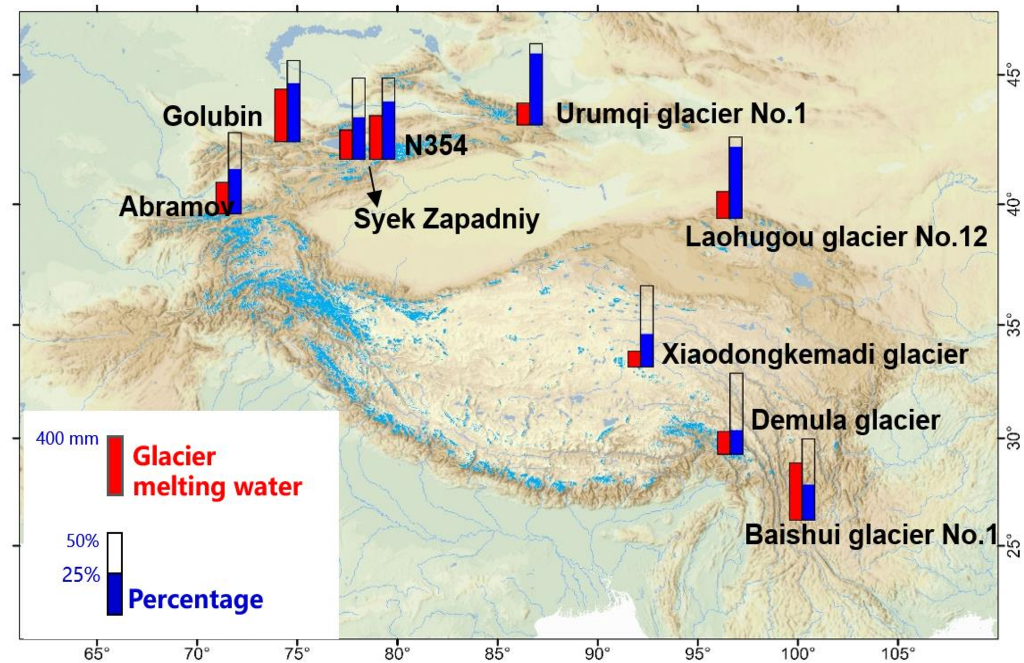
Summer（July-Aug.）



The Impact of Black Carbon and Dust on Glacier Melting in Laohugou Glacier No.12

3.4 Black carbon (BC)

The contribution of BC to glacier melting on the Tibetan Plateau



- **The contribution of black carbon to glacier melting is about 15-20%.**
- **The loss of water caused by the melting of snow and ice due to black carbon is approximately 4.6 Gt/year.**

- **Deepening our understanding of the rapid melting mechanism of plateau glaciers, it is proposed that snow ice black carbon is an important factor in accelerating glacier melting on the Qinghai Tibet Plateau.**

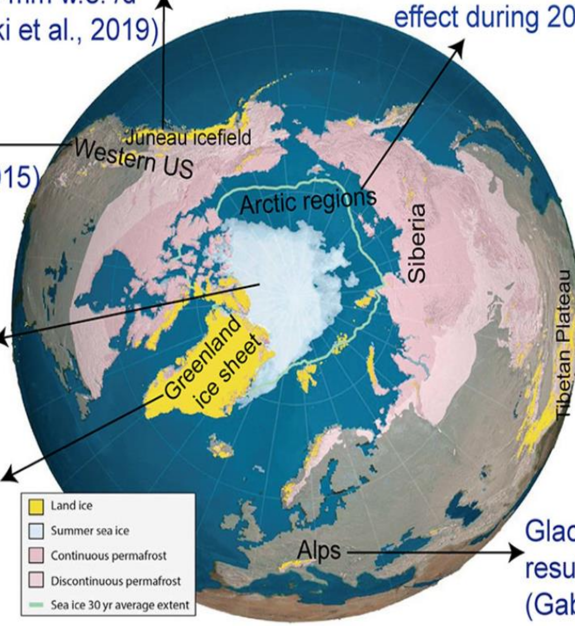
Zhang et al., 2017 JGR
Zhang et al., 2018 TC

3.4 Black carbon (BC)

Glacier melting increased in July by 10-18 mm w.e. /d (Nagorski et al., 2019)

About 14% of the Arctic warming and 20% of Arctic snow and ice loss due to BC albedo effect during 20th century. (Koch et al., 2011)

1. BC and other impurities lead to 6% albedo reduction, regional surface waming of 0.84 C, and snowpack reduction by 11 mm w.e. in springtime. (Oaida et al., 2015)
2. Increasing Hoh river discharge. (Kaspari et al., 2015)



July-September mean Arctic sea ice coverages reduced by 3% and 1% due to BC effect in 1998 and 2001. (Flanner et al., 2007)

Greenland mass loss increased by 6.8% due to BC deposition. (Li and Flanner, 2018)

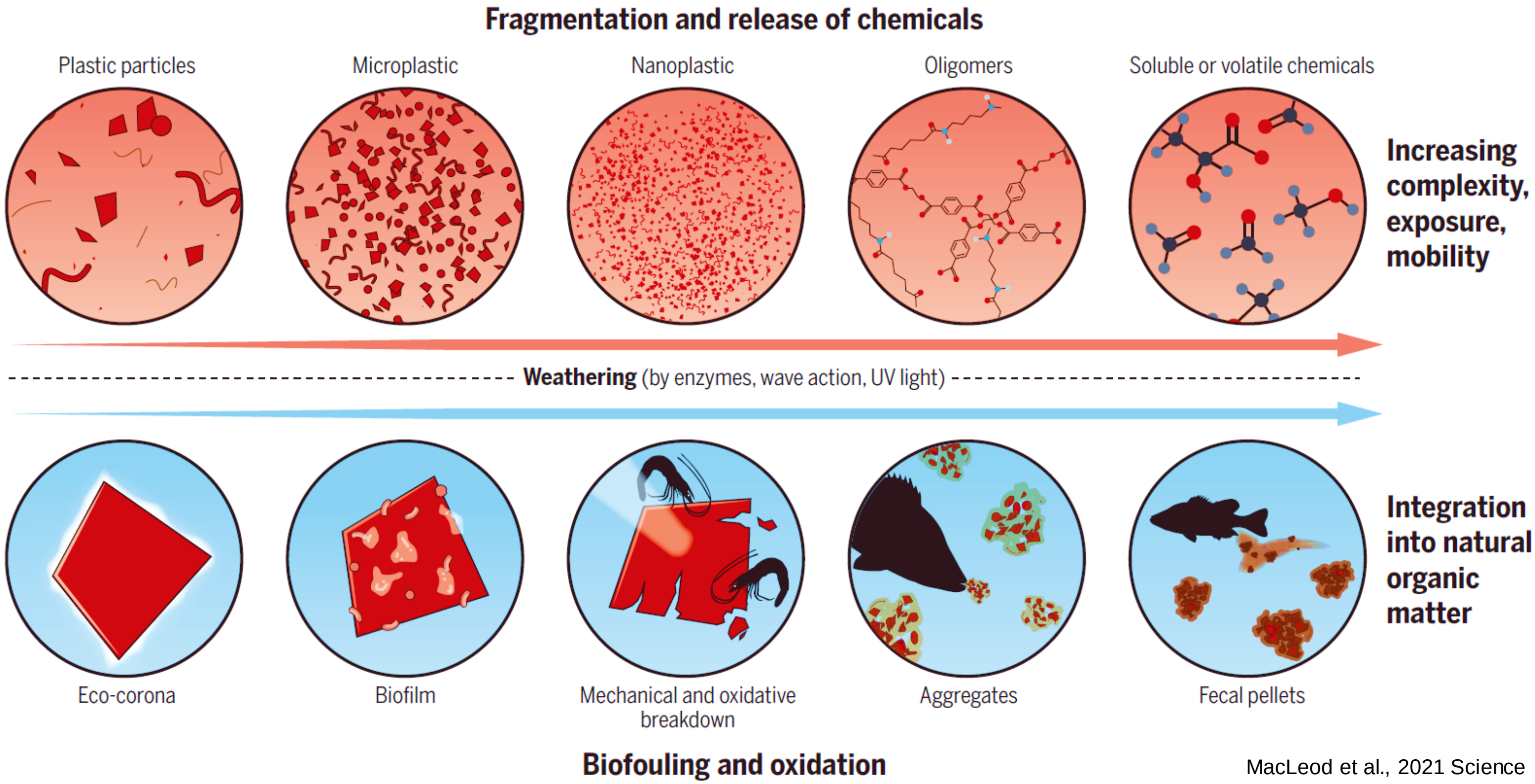
1. Snow cover duration reduction by 3-6 days. (Zhang et al., 2018)
2. Snow depth decrease by 5-25 mm w.e. (Ji, 2016)
3. Glacier melt enhanced by 5-20% in summer, equally to about 100-350 mm w.e. (Zhang et al., 2017a)

Glacier mass balance reduced by 280-490 mm w.e., resulting to increase in discharge of 2.5-21.4%. (Gabbi et al., 2015)

Kang et al., 2020

3.5 Microplastics

◆ **Plastic is widely used due to its excellent properties. However, due to improper management, a large amount of plastic waste continues to accumulate in the environment, endangering the ecosystem. Plastic weathering in the environment forms microplastics.**



MacLeod et al., 2021 Science

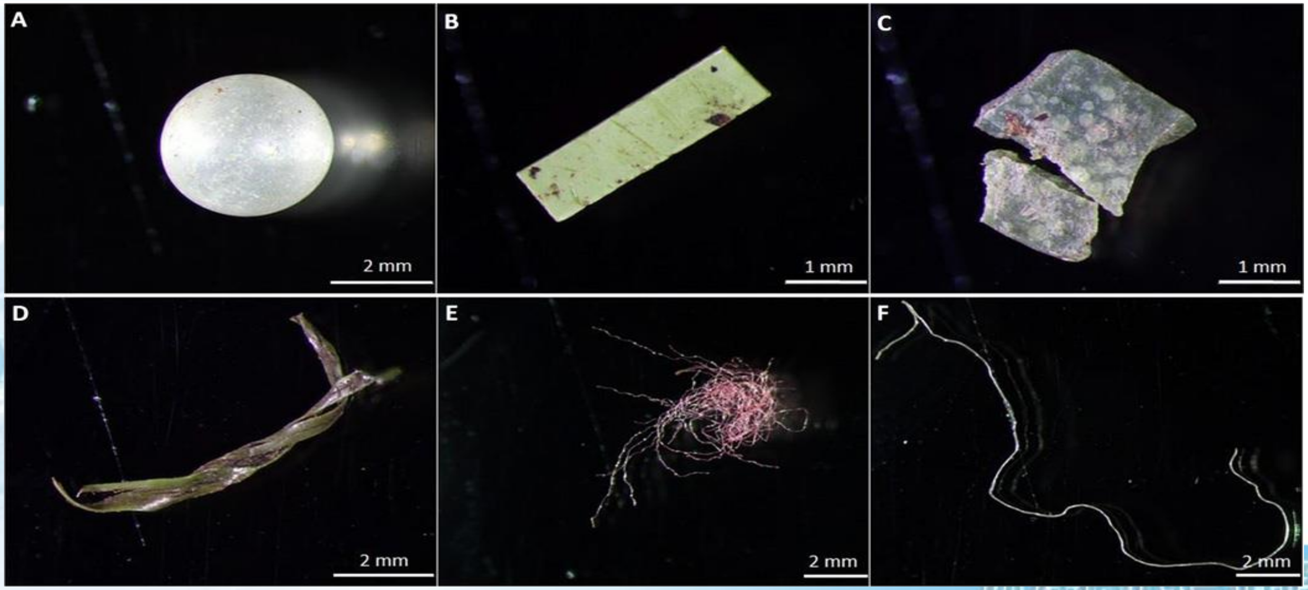
3.5 Microplastics

◆ Definition: Microplastics generally refer to plastic fragments, fibers, films, and pellets less than 5 mm.

◆ According to different sources, microplastics are divided into **primary microplastics** and **secondary microplastics**.

✓ Primary microplastics: Small particle industrial plastic products produced during industrial production processes, often used in frosted skincare and pharmaceutical products.

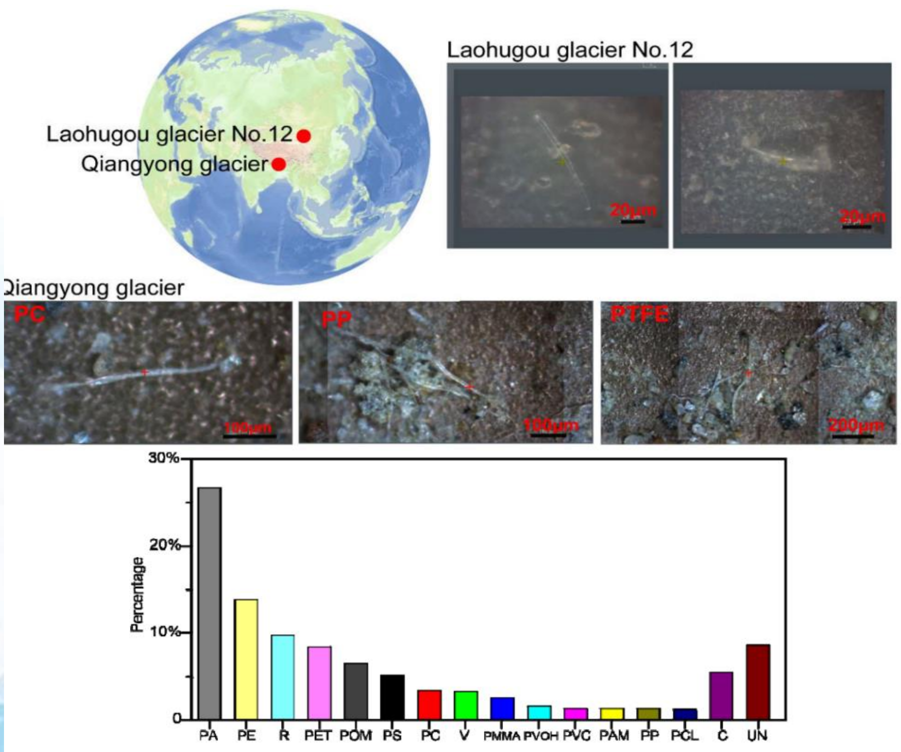
✓ Secondary microplastics: Small particle plastics formed by the decomposition and rupture of plastic products through physical, chemical, and biological processes.

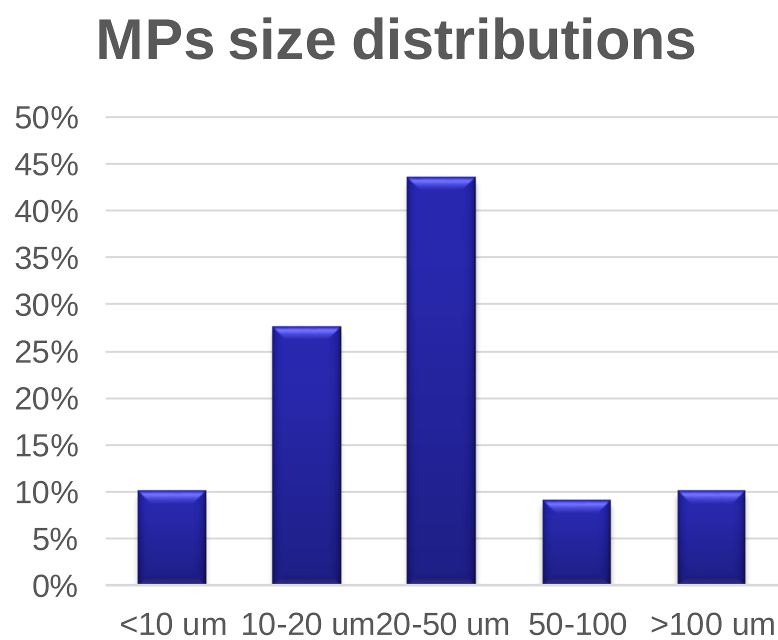


(Weithmann et al., 2018, Science)

3.5 Microplastics

◆ **Microplastics, including various types such as PC, PE, PP, etc., have been detected in the snow and ice of glaciers on the Tibetan Plateau. Fibers plastics dominate, with over 80% being smaller than 50 μ m.**

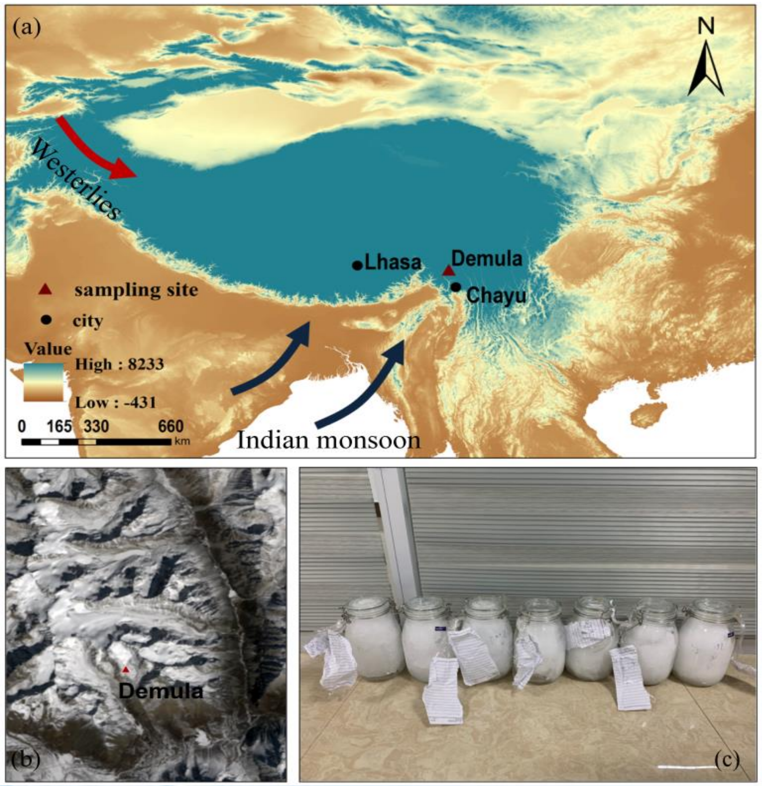


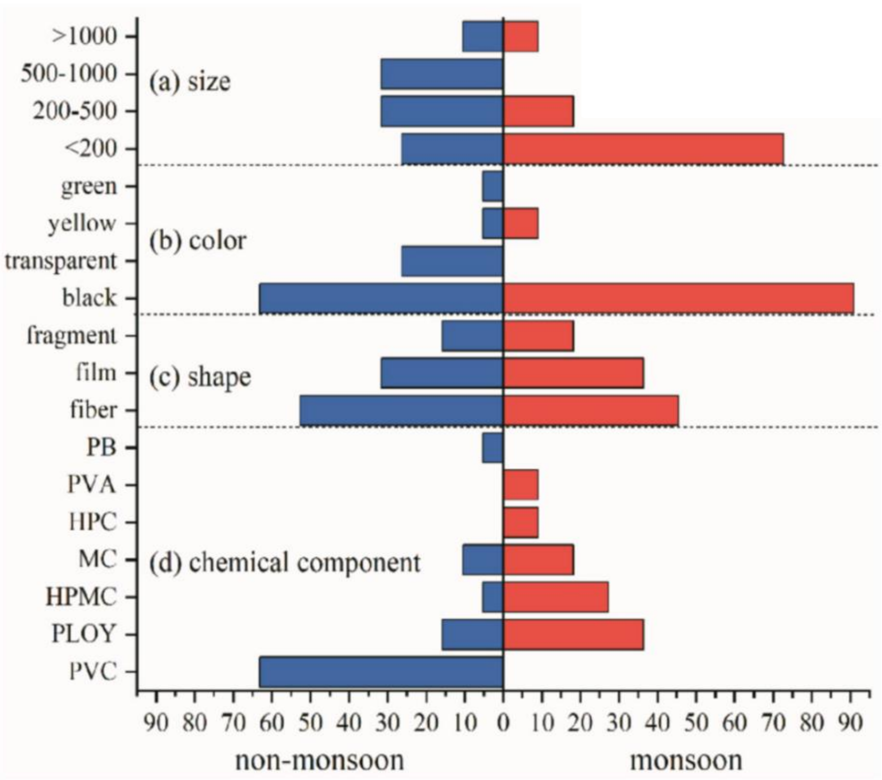


Zhang et al., 2021 SOTE

3.5 Microplastics

Microplastics in glaciers exhibit distinct seasonal variations

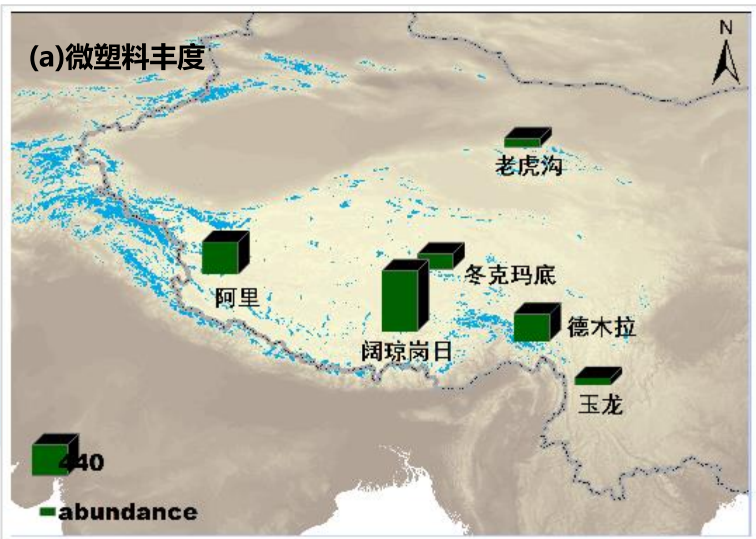


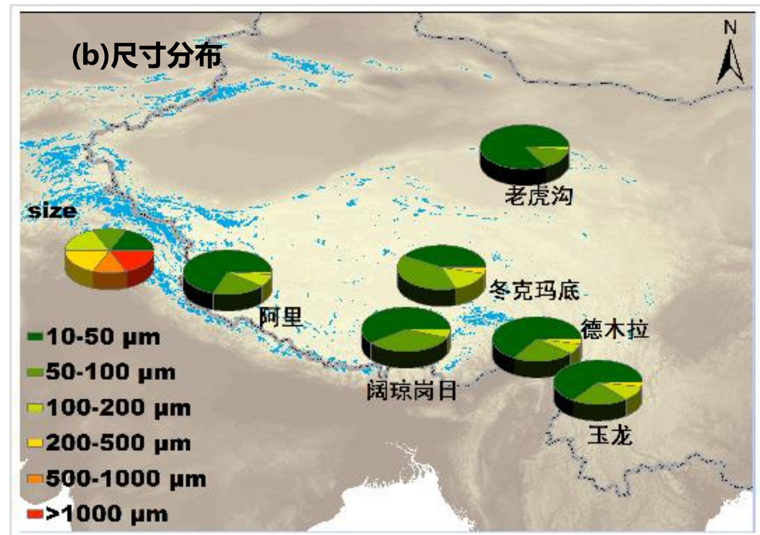


Wang, Zhang* et al., 2022 EP

3.5 Microplastics

◆ Distributions of microplastics in glaciers



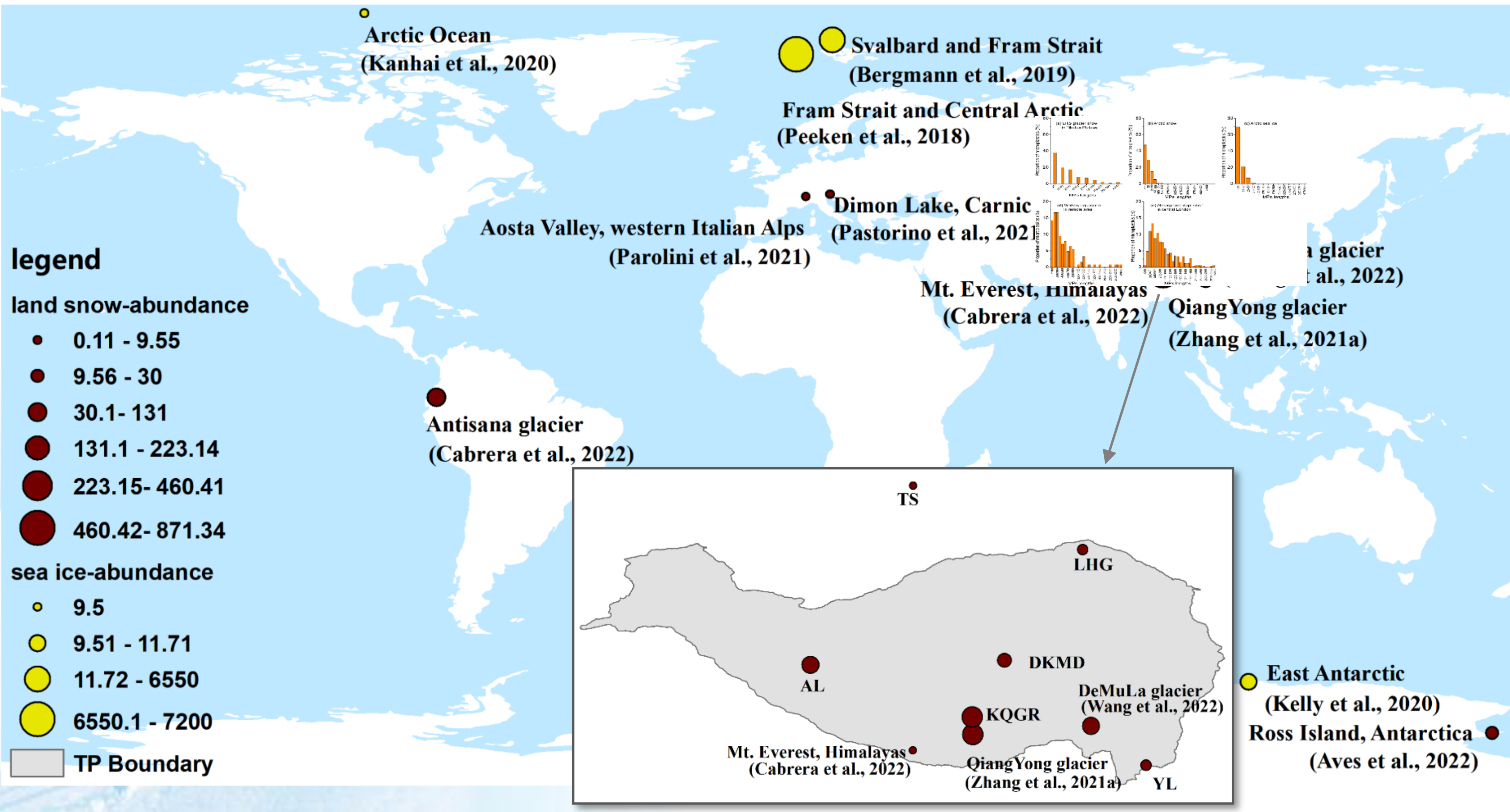


- Average abundance:~360 N L^{-1}
- Small sized microplastics dominated

For the first time, the spatial distribution characteristics of glacier microplastics with "High in the south & Low in the north" have been systematically revealed.

Zhang et al., 2021 SOTE
Wang&Zhang* et al., 2022 EP

3.5 Microplastics



Zhang et al., 2022 ESR
Wang, Zhang* et al., 2024 preparation

3.6 Stable isotopes

SKLCS

Traditional Stable Isotope Ratio

- When water evaporates from the ocean surface, lighter water molecules composed of ^{16}O and H are more likely to leave the water surface and enter the atmosphere. When water vapor in the atmosphere condenses, heavy water molecules composed of ^{18}O and D preferentially descend, resulting in differences in the spatial and temporal distribution of stable isotope ratios in natural water bodies (including snow and ice). The isotope ratio is generally expressed as the difference between the heavy isotope concentration and the light isotope concentration ratio (R_0) in the "standard average ocean water":

$$\delta = \frac{R - R_0}{R_0} \times 1000$$

- The main factors affecting the stable isotope ratios in snow and ice include **temperature effects, water vapor sources, latitude effects, altitude effects, and continental degree effects**.

3.6 Stable isotopes

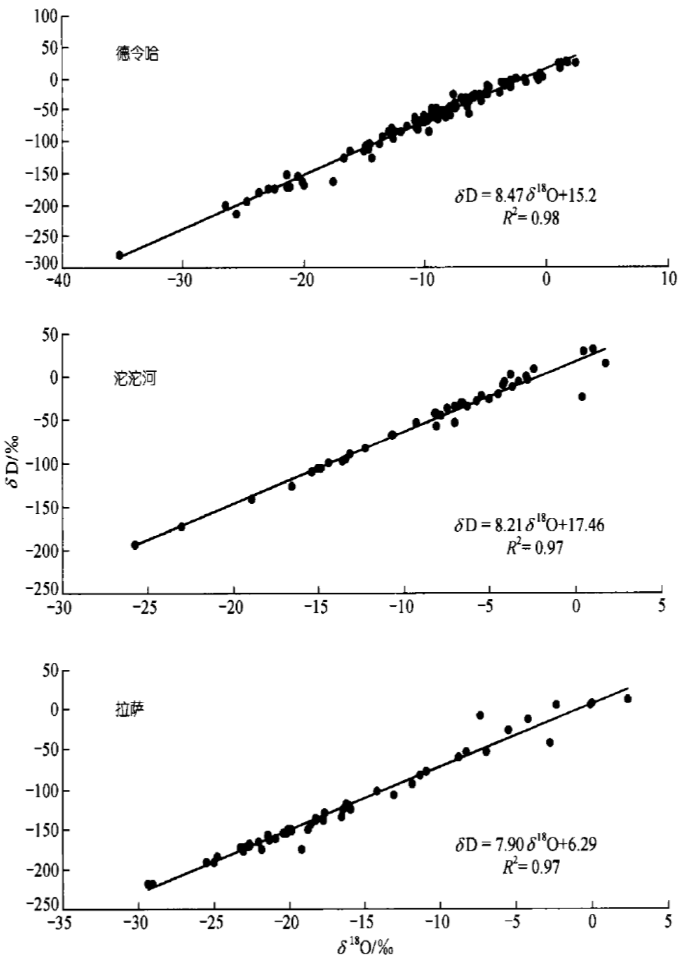


图 1 青藏高原从南到北降水中大气水线

Tian et al., 1998

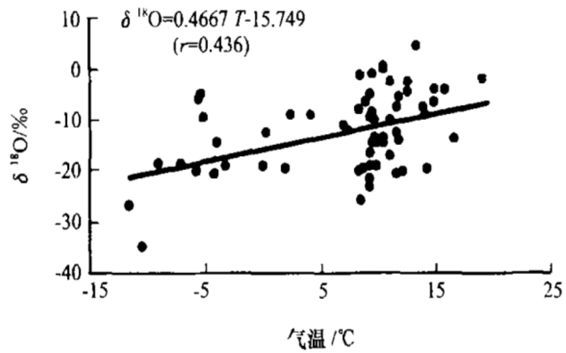


图 2 狮泉河 1999—2002 年历次降水中的 δ^{18}O 和降水时气温的散点分布图

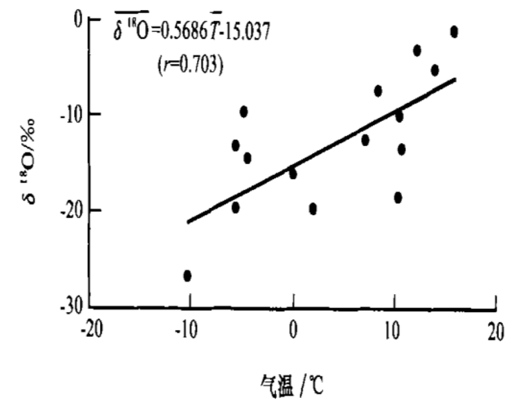
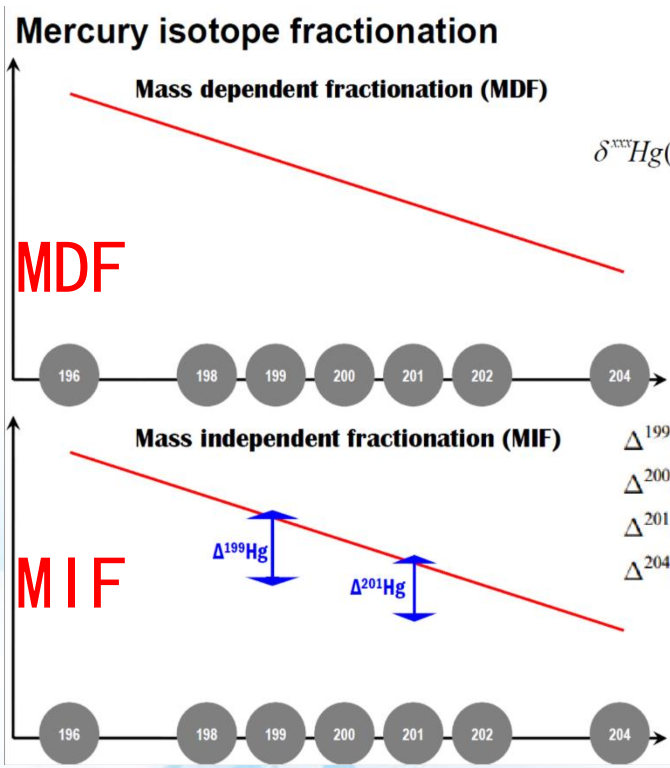


图 4 狮泉河 1999—2002 年月平均 δ^{18}O 与月平均降水温度关系

- **The stable isotope ratio has a good positive correlation with temperature, so the stable isotope ratio in ice cores can be used to reconstruct ancient temperature changes.**

3.6 Stable isotopes

Non-traditional stable isotopes



$$\delta^{xxx}Hg(‰) = \left(\frac{\left(\frac{^{xxx}Hg}{^{198}Hg}\right)_{sample}}{\left(\frac{^{xxx}Hg}{^{198}Hg}\right)_{SRM3133}} - 1 \right) \times 1000$$

where xxx is ^{199}Hg, ^{200}Hg, ^{201}Hg, ^{202}Hg, ^{204}Hg

$$\Delta^{199}Hg = \delta^{199}Hg - (\delta^{202}Hg \times 0.2520)$$
$$\Delta^{200}Hg = \delta^{200}Hg - (\delta^{202}Hg \times 0.5024)$$
$$\Delta^{201}Hg = \delta^{201}Hg - (\delta^{202}Hg \times 0.7520)$$
$$\Delta^{204}Hg = \delta^{201}Hg - (\delta^{202}Hg \times 1.493).$$

Arctic snow -Hg

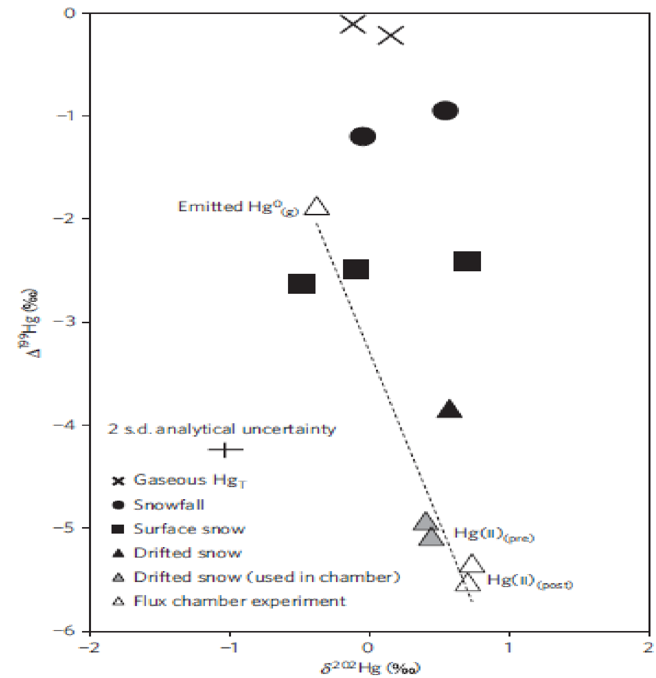
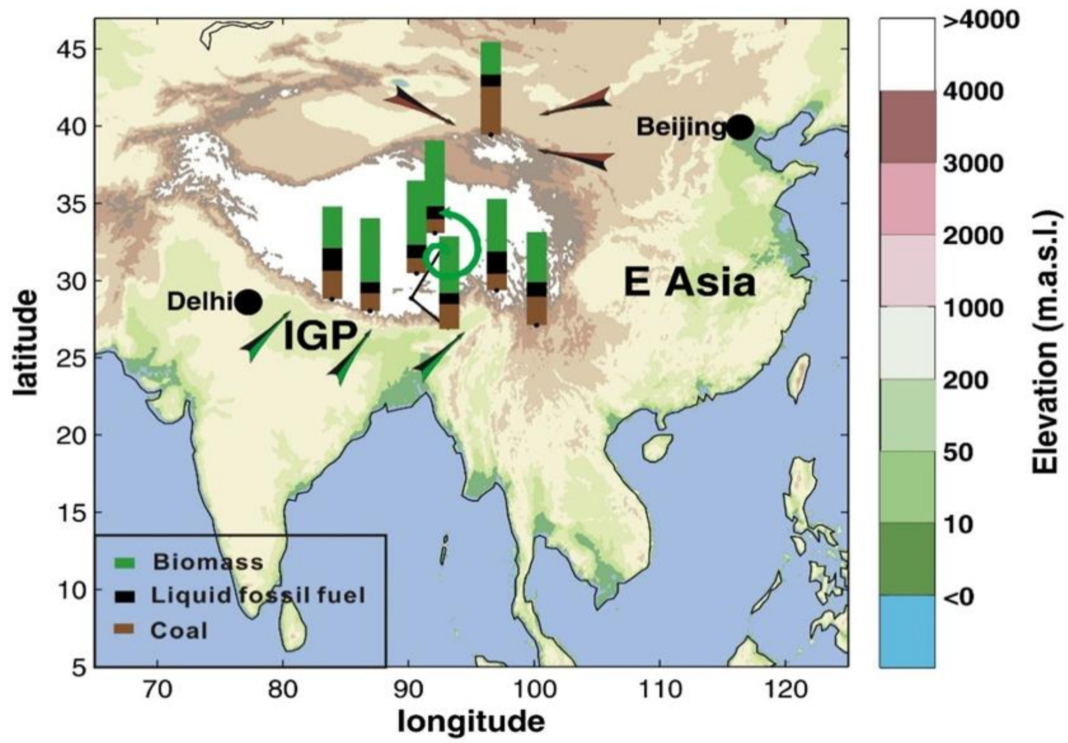


Figure 1 | Mass-dependent and mass-independent mercury isotope compositions of snow samples, chamber experiment samples and gaseous samples. Snowfall, surface and drifted snow samples are

Sherman et al., 2010 NG

- **Using the mass fractionation (MDF Hg) and non-mass fractionation (MIF Hg) signals of mercury isotopes to characterize the changes after atmospheric mercury depletion events (AMDEs).**

- **The contributions of carbonaceous aerosols from different sources in glaciers in western China is determined by radioactive carbon isotopes (^{14}C) calibration.**

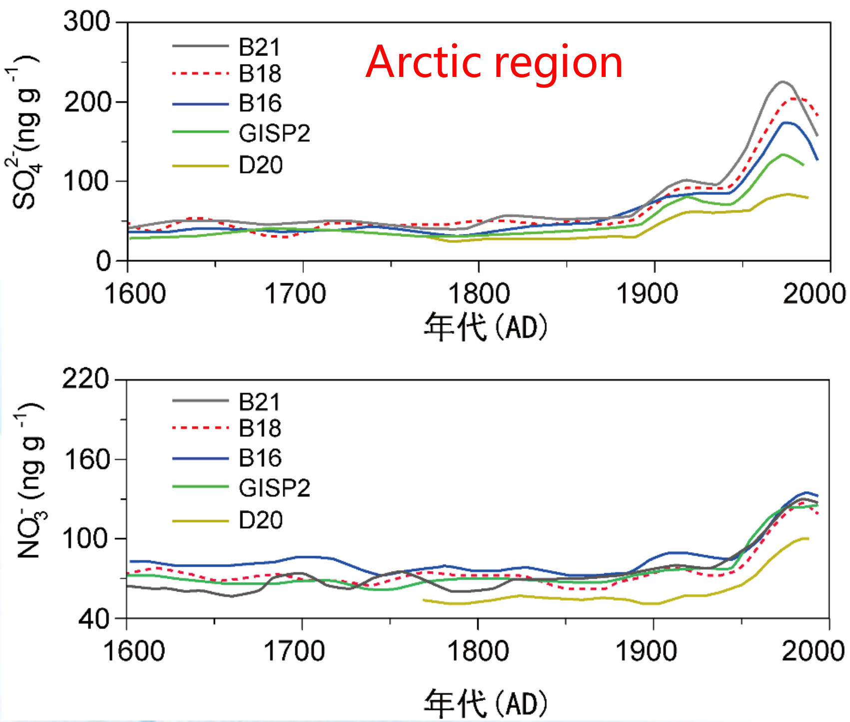


Relative contributions of biomass fuel, coal, and liquid fuel combustion emissions to black carbon in glaciers on the TP
(Li et al., 2016 Nature communications)

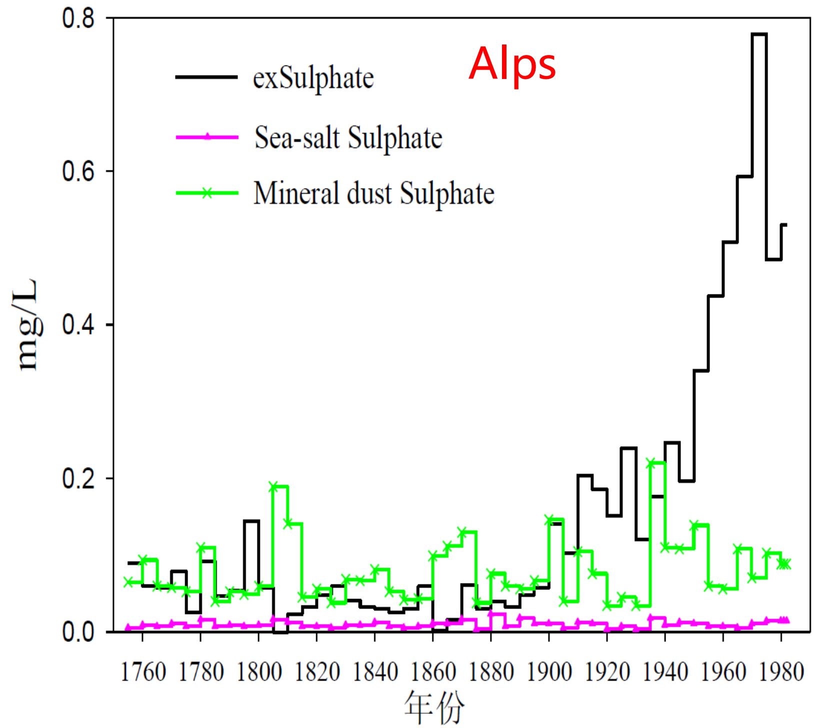
3.7 Historical reconstruction

major ions

- **Since the Industrial Revolution, the historical changes of chemical substances in snow and ice have been mainly controlled by the dual effects of global and local human activity emissions**



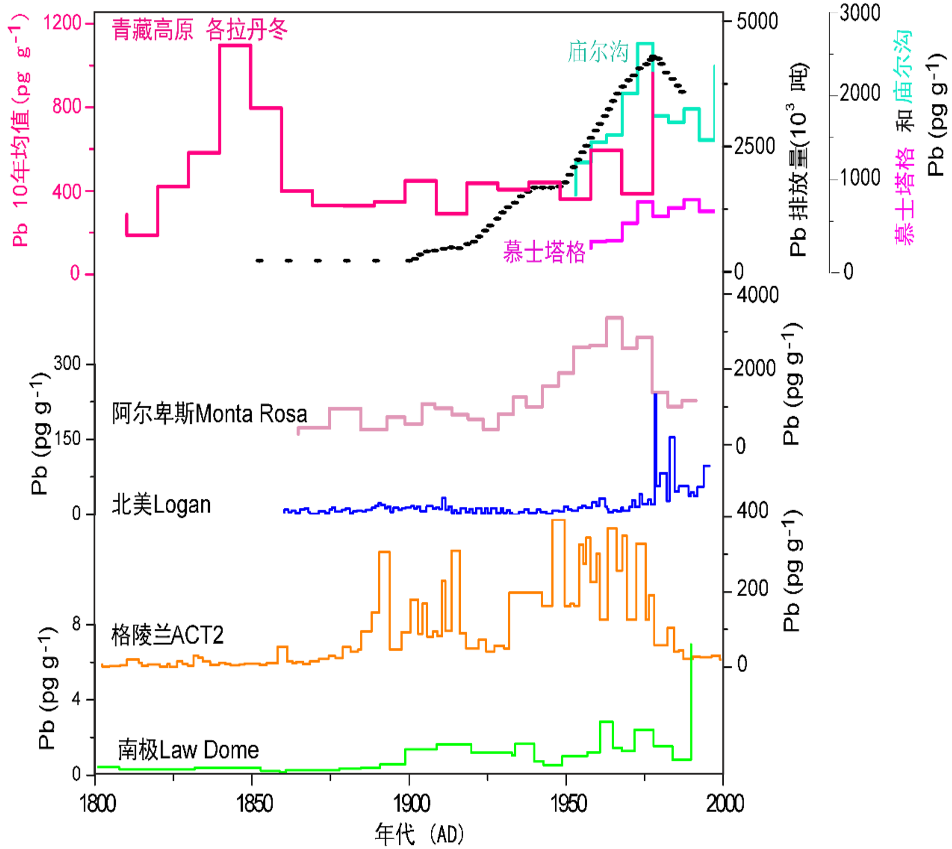
Historical records of SO_4^{2-} and NO_3^- in five ice cores from Greenland (Fischer et al., 1998)



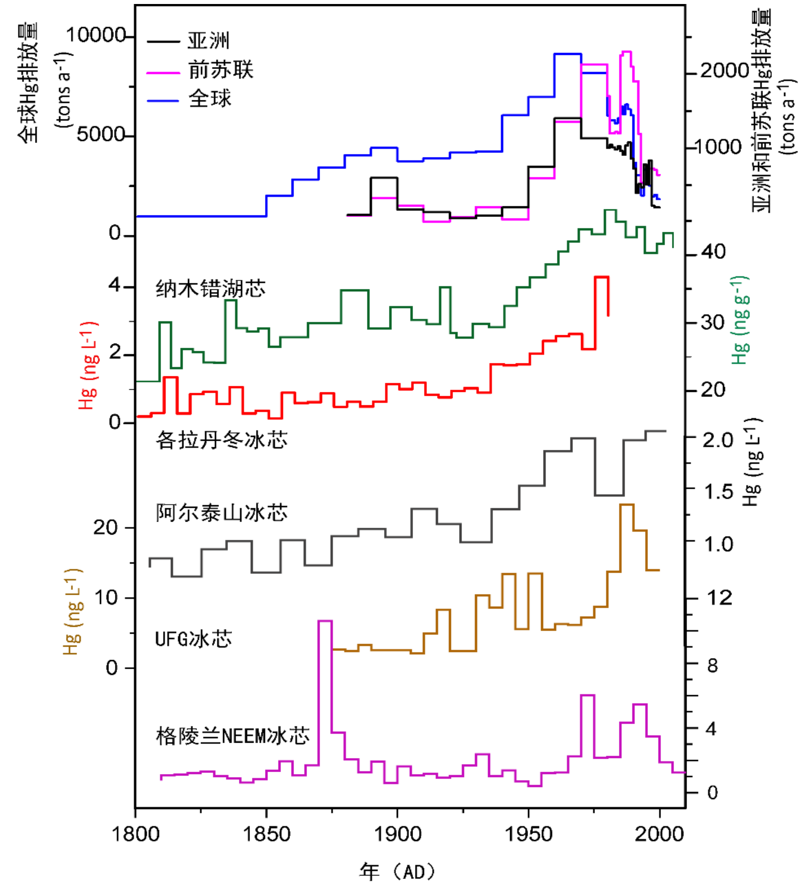
Average concentrations of $exSO_4^{2-}$, sea salt SO_4^{2-}, and continental SO_4^{2-} from Colle Gnifetti Ice Core at the Rosa Peak in the Alps (Schwikowski et al., 1999)

3.7 Historical reconstruction

- **Since the Industrial Revolution, the historical changes of chemical substances in snow and ice have been mainly controlled by the dual effects of global and local human activity emissions**



Historical records of Pb in ice cores from different regions around the world

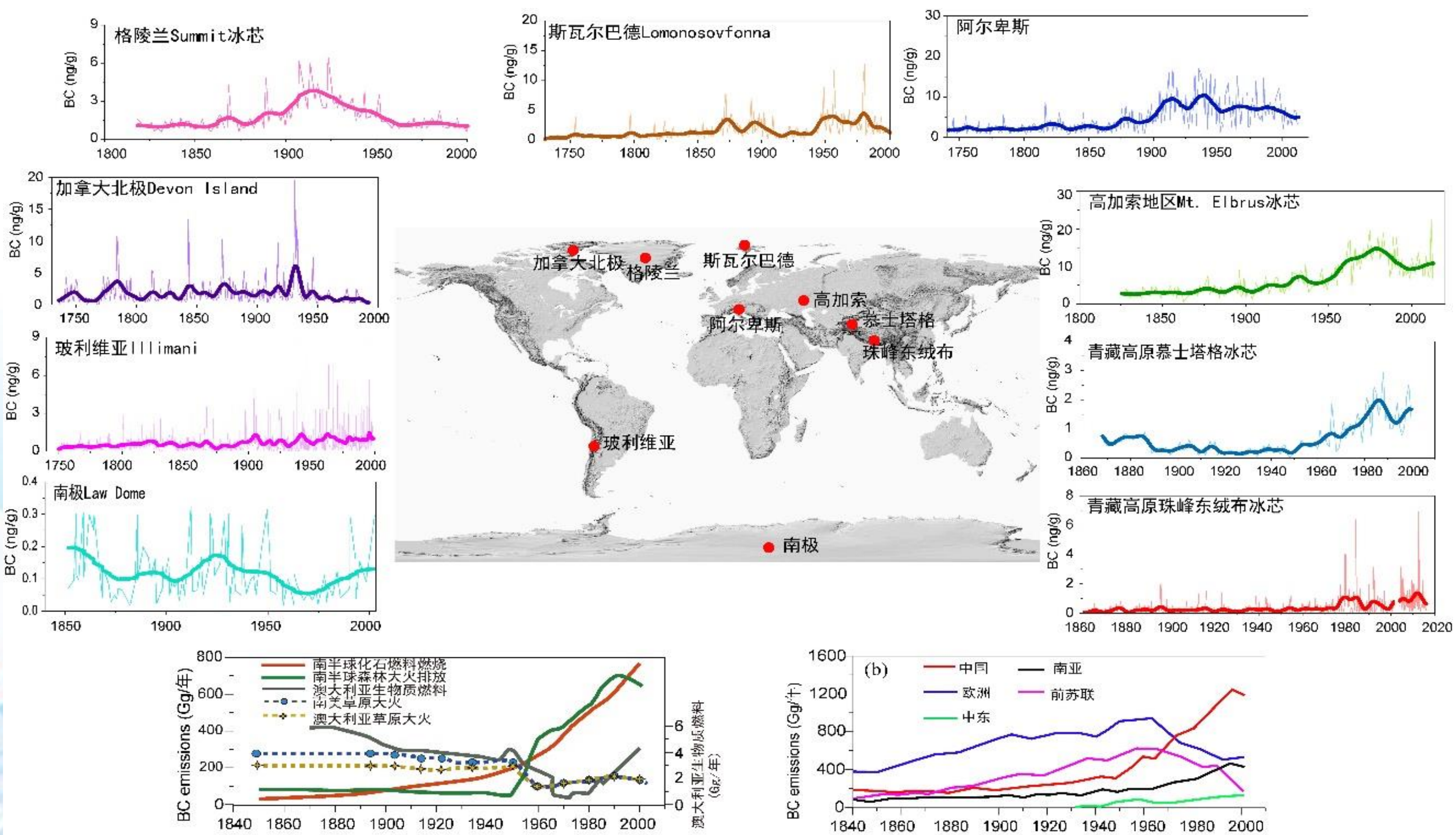


Historical records of Hg in global ice cores and Hg emission history

3.7 Historical reconstruction

Heavy metals

- **Since the Industrial Revolution, the historical changes of chemical substances in snow and ice have been mainly controlled by the dual effects of global and local human activity emissions**



Historical changes of black carbon in ice cores from different regions

4. Permafrost chemistry

Monitoring

- Soil temperature
- Depth of active layer
- Water content
- Ground ice content

- Carbon & Nitrogen
- Vegetation
- Microbes
- Pollutants

4.1 Chemical processes of permafrost

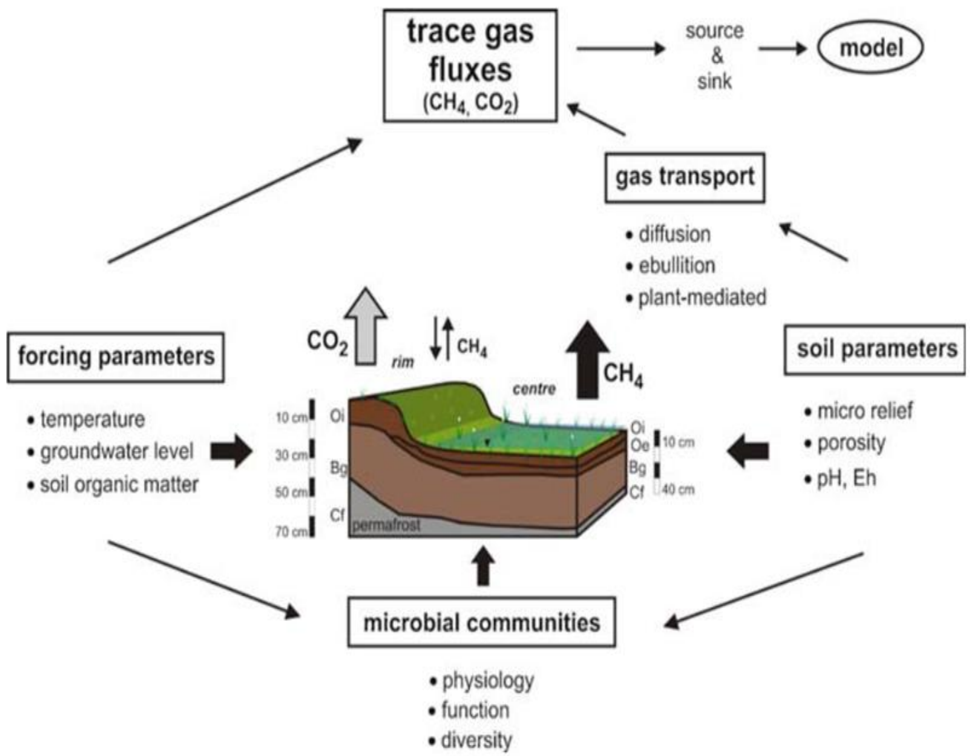
- **The chemical composition and processes (reactions) of permafrost:** Similar to soil, chemical reactions in permafrost include dissolution reactions, hydration reactions, substitution reactions, redox reactions, and ion exchange, but the chemical processes that occur in permafrost have unique characteristics.

- **The dissolution rate of some salts is slower** under low temperature conditions. Due to the low-temperature environment of permafrost, a large amount of chemical products such as hydrates and crystalline hydrates are produced through the reaction between soluble substances and water molecules.

- Due to the fact that **unfrozen water is equivalent to a concentrated solution**, its ions can quickly interact with ions on mineral surfaces, easily forming sol condensation and colloidal compounds. These processes are determined by **the phase transition of water (freezing or melting)**, which can lead to soil dehydration and cause organic-inorganic compound condensation (reaching the threshold for condensation).

- **Free water** only has a significant impact on seasonally frozen soil during warm seasons, and an important role of combined water (unfrozen state) is its reaction with ice and soil, maintaining dynamic balance.

4.1 Chemical processes of permafrost

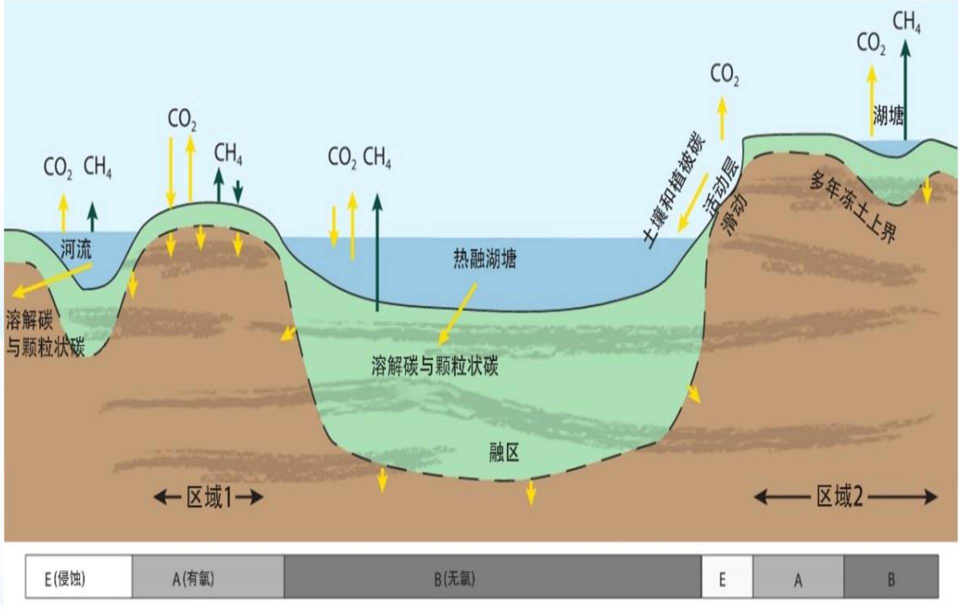


Schematic diagram of the processes affecting the formation, migration, and release of trace gases related in permafrost

- **Trace gases** from permafrost ecosystems are influenced by many **biotic and abiotic parameters**. The decomposition of soil organic matter and the production of greenhouse gases are caused by microbial activity, which is influenced by habitat and climate related characteristics. **The transport process of trace gases** determines the ratio of methane and CO2 emissions. However, the carbon release process, spatial pattern characteristics, and dependence on climate change related to permafrost have not yet been fully understood.

4.1 Chemical processes of permafrost

- **Thermokarst lakes** are one of the important characteristics of permafrost degradation over the years. They are formed by the melting of underground ice and surface subsidence due to rising temperatures. More organic carbon enters the lakes. The formation of thermokarst lakes transforms terrestrial ecosystems into aquatic ecosystems, which has a significant impact on **carbon cycling processes**.

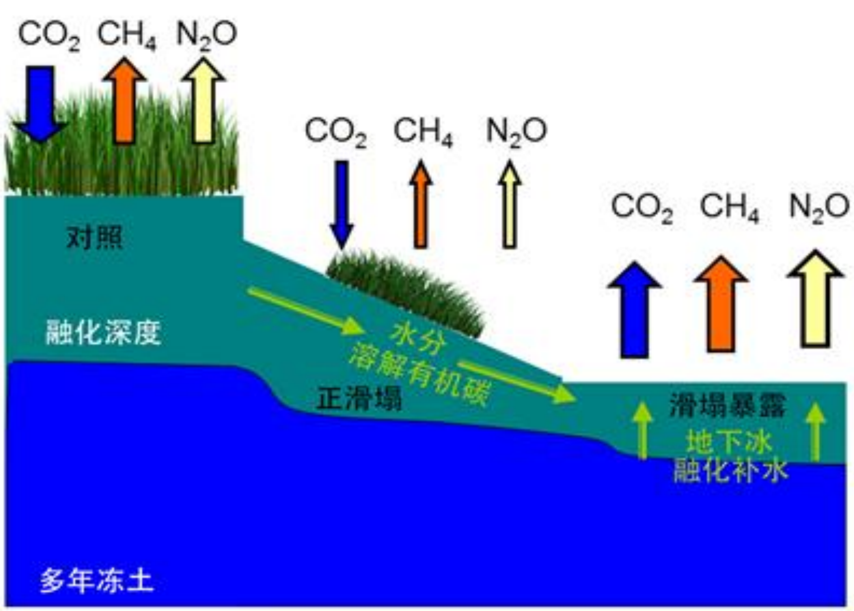


Schematic diagram of greenhouse gas emissions affected by thermokarst lakes in the Arctic permafrost region

- ✓ **Trace gas exchange** at the water-gas interface in permafrost regions mainly occurs in rivers and lakes. There are numerous rivers flowing into the sea in the entire Arctic region, all of which pass through vast permafrost areas and carry a large amount of organic carbon. This organic carbon will decompose in the water and be released into the atmosphere during transport, with methane being the most important gas. The methane emissions from newly formed thermokarst lakes are about 130~430 times higher than before the formation.

4.1 Chemical processes of permafrost

- The mineral soil at the bottom of the gully formed by **permafrost collapse** contains abundant dissolved organic carbon, which can provide electron acceptors for denitrification processes and **increase N_2O release**. At the same time, thermal melting landslides and gullies develop in permafrost regions rich in ice, where the moist and acidic soil contains a large amount of inorganic nitrogen, which can serve as substrates for microbial nitrification.



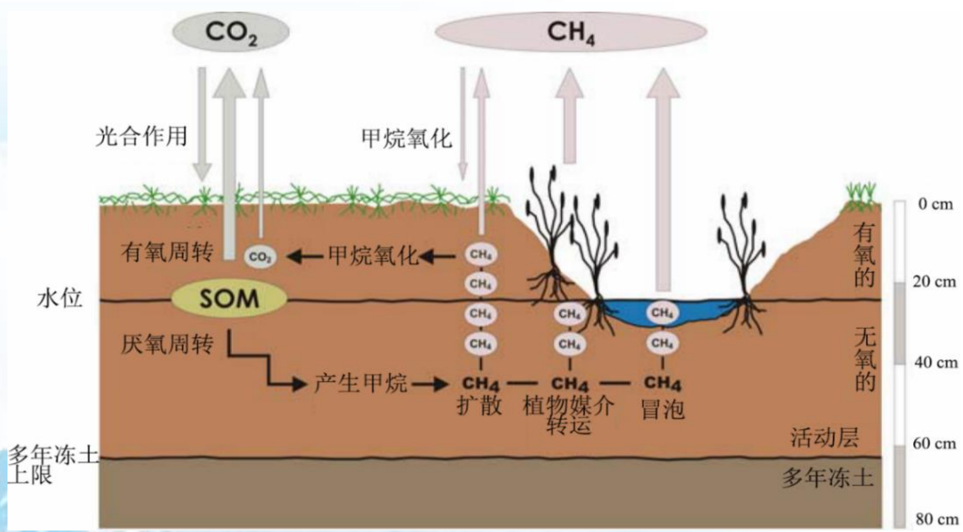
Schematic diagram of the carbon and nitrogen release process of permafrost thermokarst (Mu et al., 2017)

- ✓ **The nitrification process** refers to the process in which organisms convert organic nitrogen into NH_4^+ through microbial decomposition and mineralization. Most of the NH4+in the soil is oxidized into nitrite and nitrate under the action of nitrifying bacteria and aerobic conditions.

- ✓ **Biological denitrification** refers to the microbial process in which denitrifying bacteria reduce NO_3^- or NO_2^- to NH_3 under oxygen deficient conditions.

4.1 Chemical processes of permafrost

- There are **three main modes of methane transport** from anaerobic soil layers to the atmosphere in permafrost: **diffusion (slow), bubbling (fast), and plant mediated transport (by passing aerobic soil layers).** Vegetation is an important factor in microbial activity and methane transport, which can enhance or weaken methane emissions in different environments.
- Through the ventilation tissue of vascular plants, oxygen is transported from the atmosphere to the rhizosphere, thereby promoting **methane oxidation** in other hypoxic soil layers. On the contrary, the aeration tissue is the main pathway for methane to be transported from the anoxic layer to the atmosphere, by passing the **anaerobic/aerobic interface** where methane oxidation is most prominent in the soil.

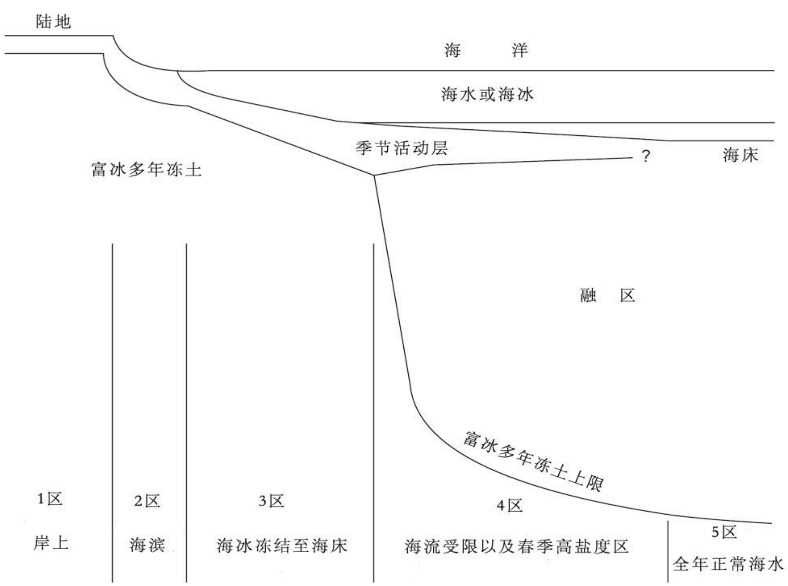


Schematic diagram of methane production and oxidation processes in permafrost regions (Wagner et al., 2009)

- ✓ Permafrost regions have low-temperature climatic conditions, but the abundance and composition of methane producing populations are similar to those of temperate soil ecosystems.
- ✓ About 68% of the methane released from humid permafrost environments is transported **through sedge plants** such as moss.
- ✓ In addition, vegetation provides a substrate for methane production, such as decaying vegetation branches and fallen leaves, and fresh root exudates, thereby promoting methane production.

4.2 Subsea permafrost

◆ **In general, the subsea permafrost is divided into five zones based on its distance from the coast and whether it is in the sea ice zone, namely the coastal zone (land area), the coastal zone, the area where the overlying ocean is constantly affected by sea ice and the sea ice freezes to the seabed, the area where the ocean currents at the bottom of the sea ice are restricted and the salinity of the seawater is high, and the open ocean zone.**



Schematic diagram of subsea permafrost zoning

- ✓ **The basic principles of biogeochemical processes in subsea permafrost are the same as those in terrestrial permafrost.**
- ✓ **The carbon cycle process of subsea permafrost is an international scientific hotspot under climate warming conditions. Currently, there is a lack of in-depth understanding of the distribution, mechanism, transformation, and estimation of subsea permafrost, which in turn affects the study of biogeochemical processes of subsea permafrost.**

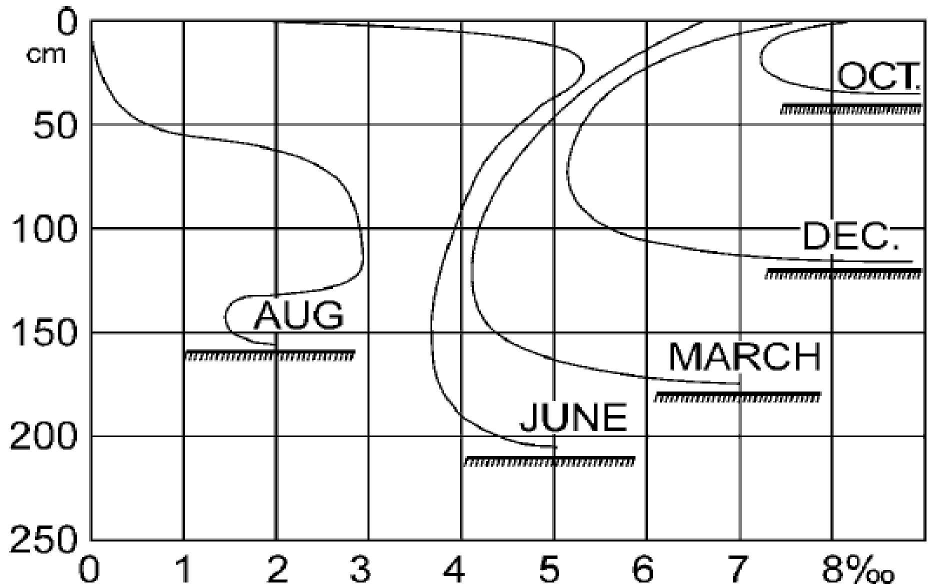
5. Sea ice chemistry

5.1 Overview of Sea Ice Chemistry

- Sea ice accounts for about 7% of the Earth's surface, and its chemical characteristics are largely a reflection of seawater chemistry, influenced by physical, chemical, and biological processes between water and ice, as well as river inputs. Sea ice salinity, major ions, nutrients, trace metals, dissolved gases, and organic matter are all research topics in sea ice chemistry, with sea ice salinity being the most extensively studied.

5.1 Overview of Sea Ice Chemistry

- **Ionic changes in sea ice:** During the freezing process of seawater, the ion composition changes, and there are differences in the temperature at which different salts precipitate in sea ice. The salinity in the ice changes in a **"C" shape** with depth throughout the year, and the surface salinity of sea ice decreases significantly during the melting season. At present, most large-scale sea ice models assume constant sea ice salinity, which cannot reflect the response of sea ice to atmospheric or oceanic boundary conditions. Temperature and salinity have a significant impact on ice porosity and pore microstructure.



The evolution of sea ice salinity profiles in the Arctic during winter and the melting season: processes such as ice water salt separation, gravity excretion, and brine expulsion lead to a "C" - shaped salinity profile of newly formed ice. （Thomas and Dieckmann, 2003）

5.1 Overview of Sea Ice Chemistry

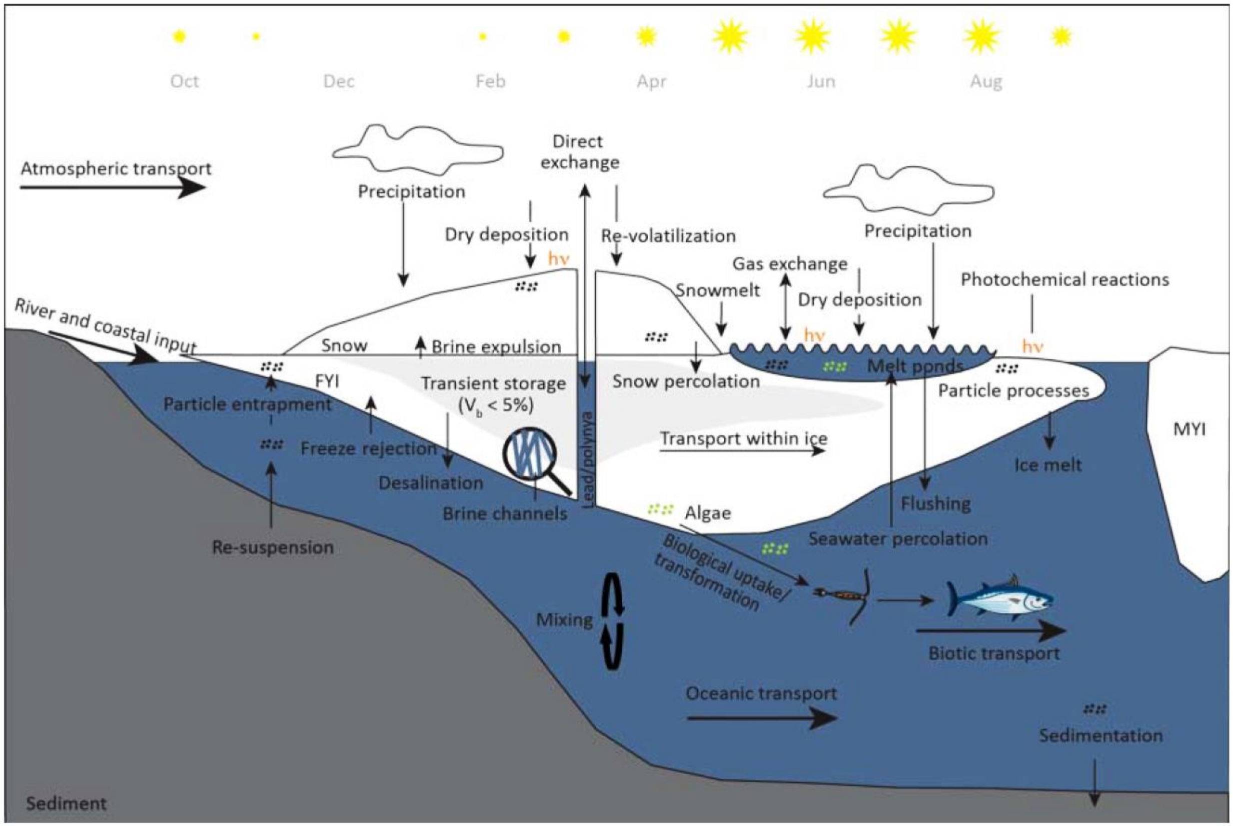
SKLCS

- **Organic matter in sea ice:** Algae that inhabit and grow in large numbers within the ice. The abundance of seaweed, bacteria, and other substances in sea ice has a significant impact on its chemistry through photosynthesis and anaerobic respiration. The absorption of carbon in photosynthesis leads to the biological isotope effect of stable isotopes, resulting in the enrichment of 12C in organisms.

- **Reactive bromine released by sea ice algae:** The high concentration of short-term BrO in the troposphere is due to the self catalysis of Br2 released by sea ice and sea salt. Arctic and Antarctic sea ice algae can also produce large amounts of brominated halogenated compounds such as bromoform, dibromomethane, bromochloromethane, methyl bromide, etc. These substances can be converted into active bromine through photochemistry, which is of great significance for the chemistry of polar regions.

5.2 Processes of Sea Ice Chemistry

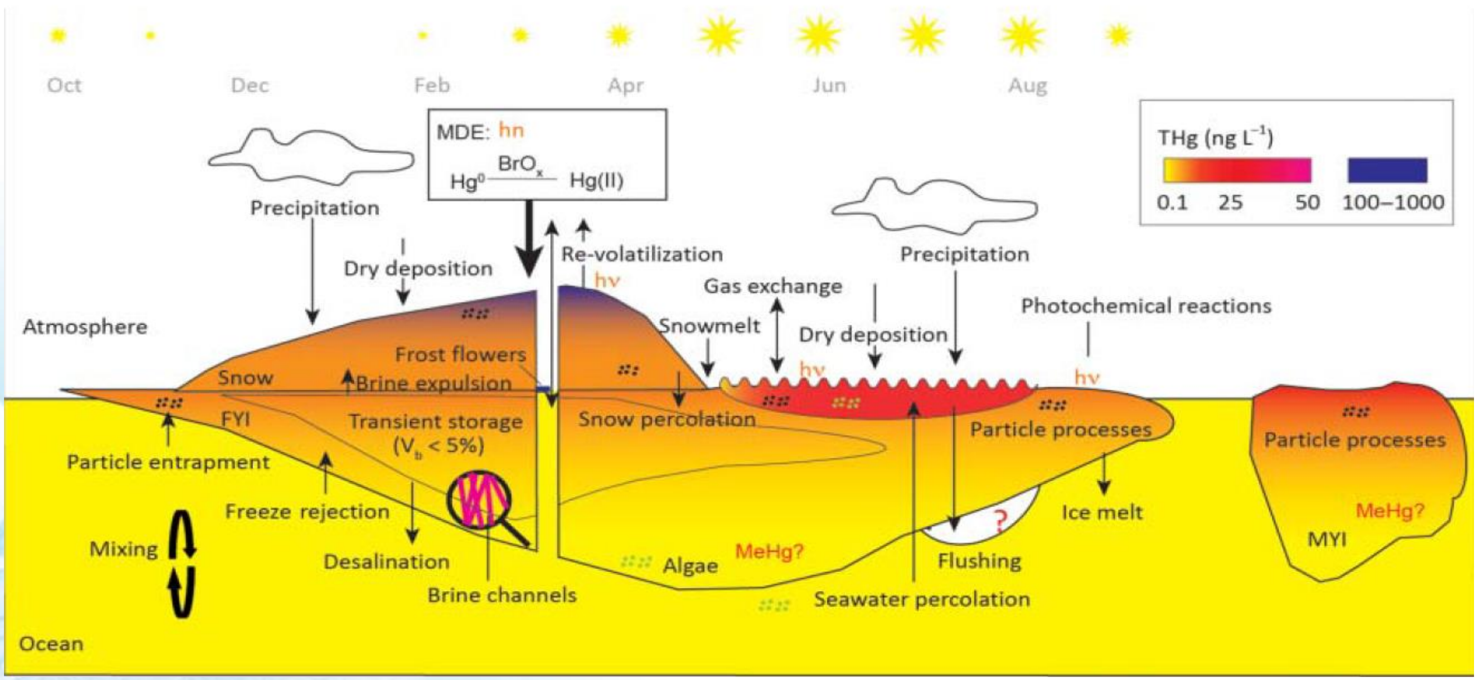
- During the formation and growth of sea ice, pollutants mainly enter the sea ice through freezing precipitation and particulate matter capture processes from lower seawater and sediments, or from overlying snow and atmospheric dry and wet deposition.



Major processes determining contaminant concentrations and bioaccumulation across the ocean–sea ice–atmosphere interface. FYI, first-year ice; MYI, multi-year ice; Vb, brine volume fraction; hν, solar radiation. *(Wang et al., 2017)*

5.2 Processes of Sea Ice Chemistry

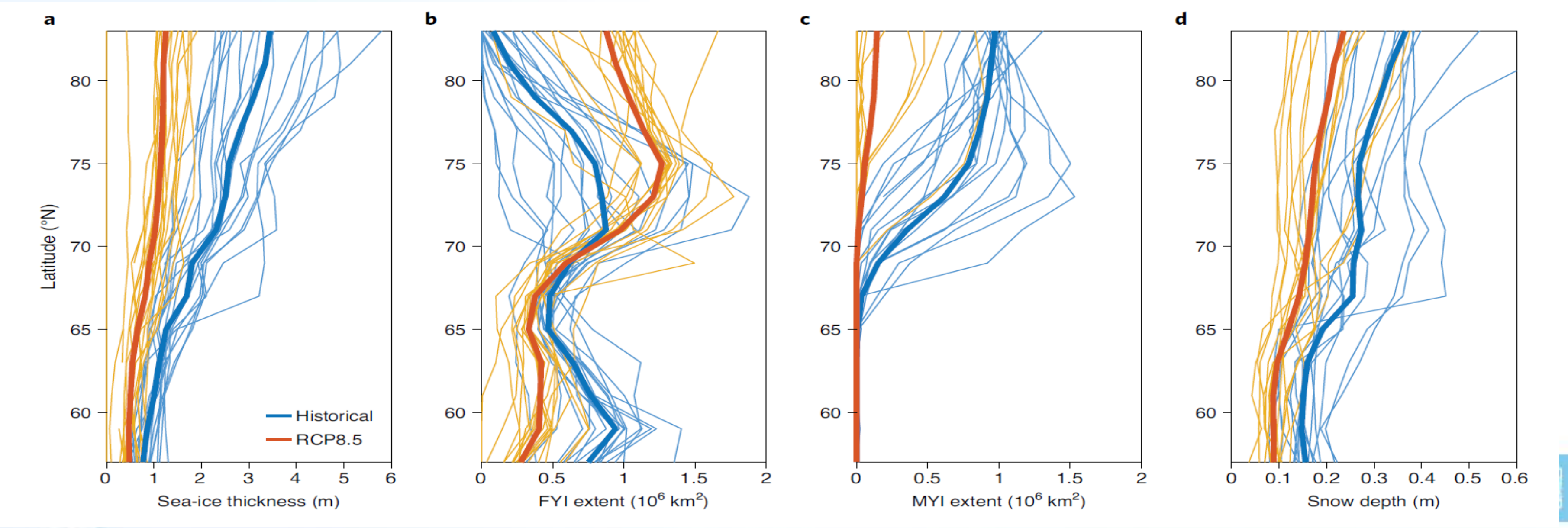
- **Mercury can significantly increase its flux during atmospheric mercury depletion events in spring. Only a small portion of pollutants cleared by snowfall directly enter the ocean through ice channels or ice lakes, while the vast majority of pollutants settle and remain on the surface of sea ice, and undergo post deposition transport and transformation processes to enter the interior of sea ice and seawater, or evaporate into the atmosphere. Dry deposition of pollutants can occur on snow cover, sea ice surface, ice channels, and melt pools.**



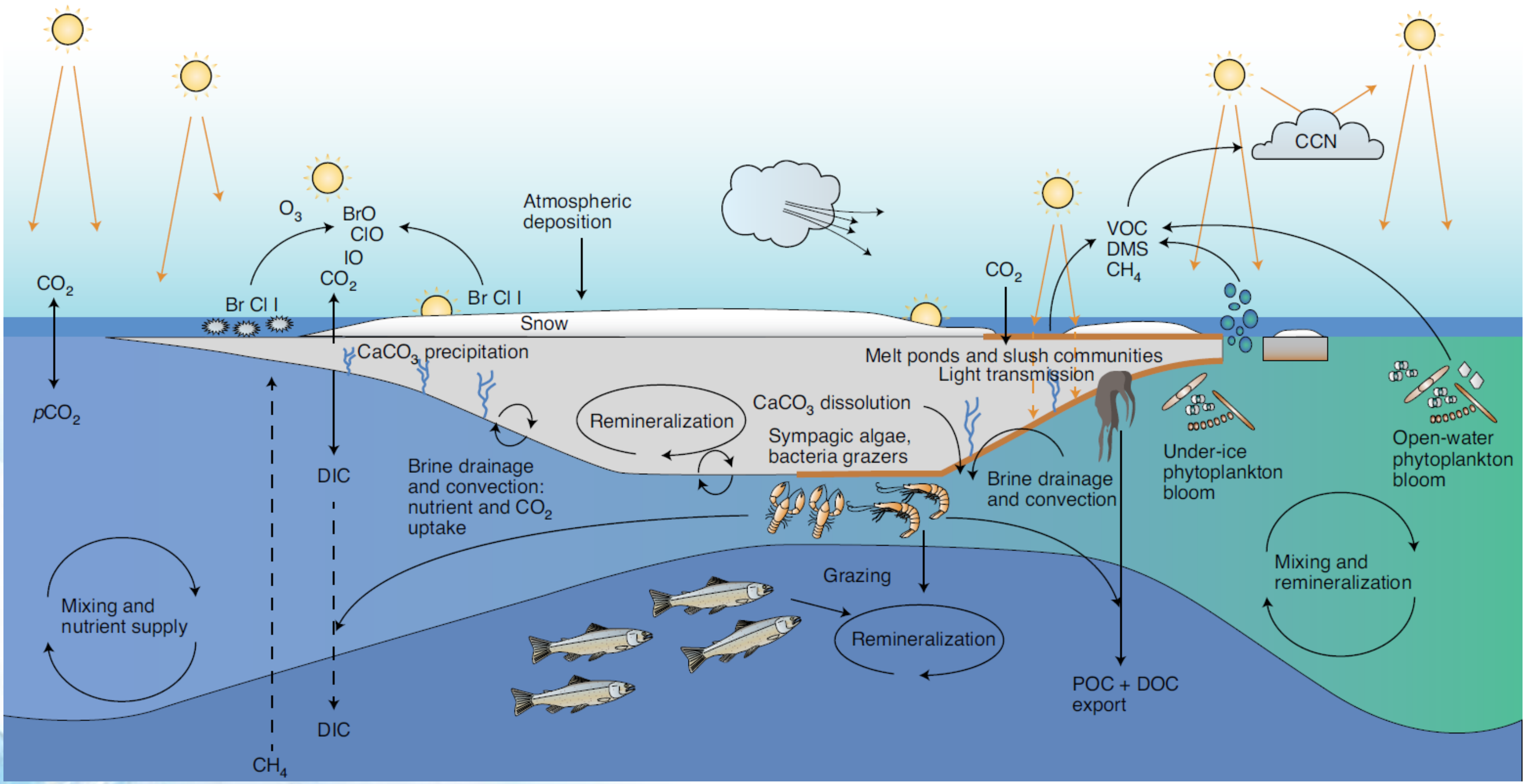
A simplistic schematic of mercury cycling in the Arctic sea ice environment. Colours denote approximate concentrations. HgT, total mercury; MeHg, methylmercury; MDE, mercury depletion events; BrOx, reactive bromine species (*x* = 0, 1); FYI, first-year ice; MYI, multi-year ice; Vb, brine volume fraction. ***(Wang et al., 2017)***

5.3 Arctic sea-ice biogeochemistry

- **The Arctic sea-ice-scape is rapidly transforming. Increasing light enetration will initiate earlier seasonal primary production. This earlier growing season may be accompanied by an increase in ice algae and phytoplankton biomass, augmenting the emission of dimethylsulfide and capture of carbon dioxide. Secondary production may also increase on the shelves, although the loss of sea ice exacerbates the demise of sea-ice fauna, endemic fish and megafauna. Sea-ice loss may also deliver more methane to the atmosphere, but warmer ice may release fewer halogens, resulting in fewer ozone depletion events. The net changes in carbon drawdown are still highly uncertain. Despite large uncertainties in these assessments, we expect disruptive changes that warrant intensified long-term observations and modelling efforts.**



The future of Arctic sea-ice biogeochemistry and ice-associated ecosystems



Schematic of seasonal sea-ice biogeochemical processes in the Arctic Ocean.

6. The climatic and environmental effects of cryospheric chemistry

6.1 Glacier retreat significantly alters carbon and nitrogen cycling

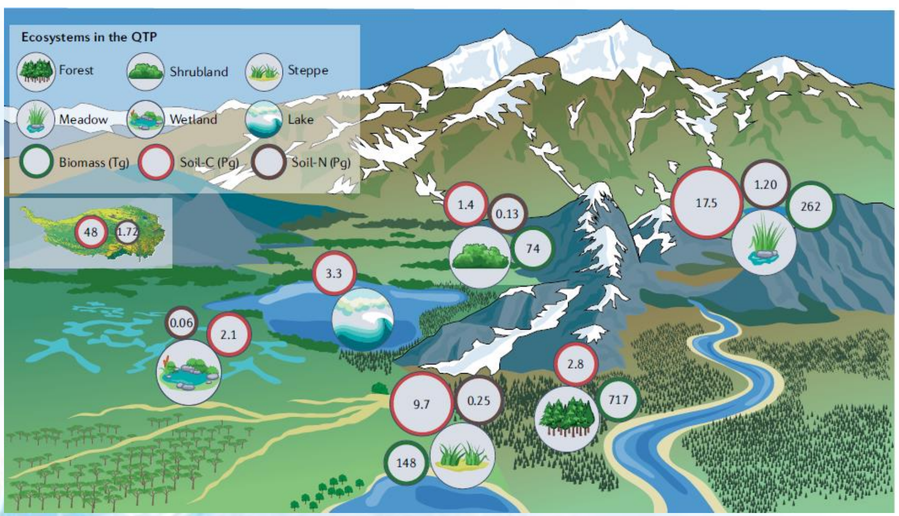
Impacts on hydrology, eco-systems and biogeochemical cycles

REVIEWS

Check for updates

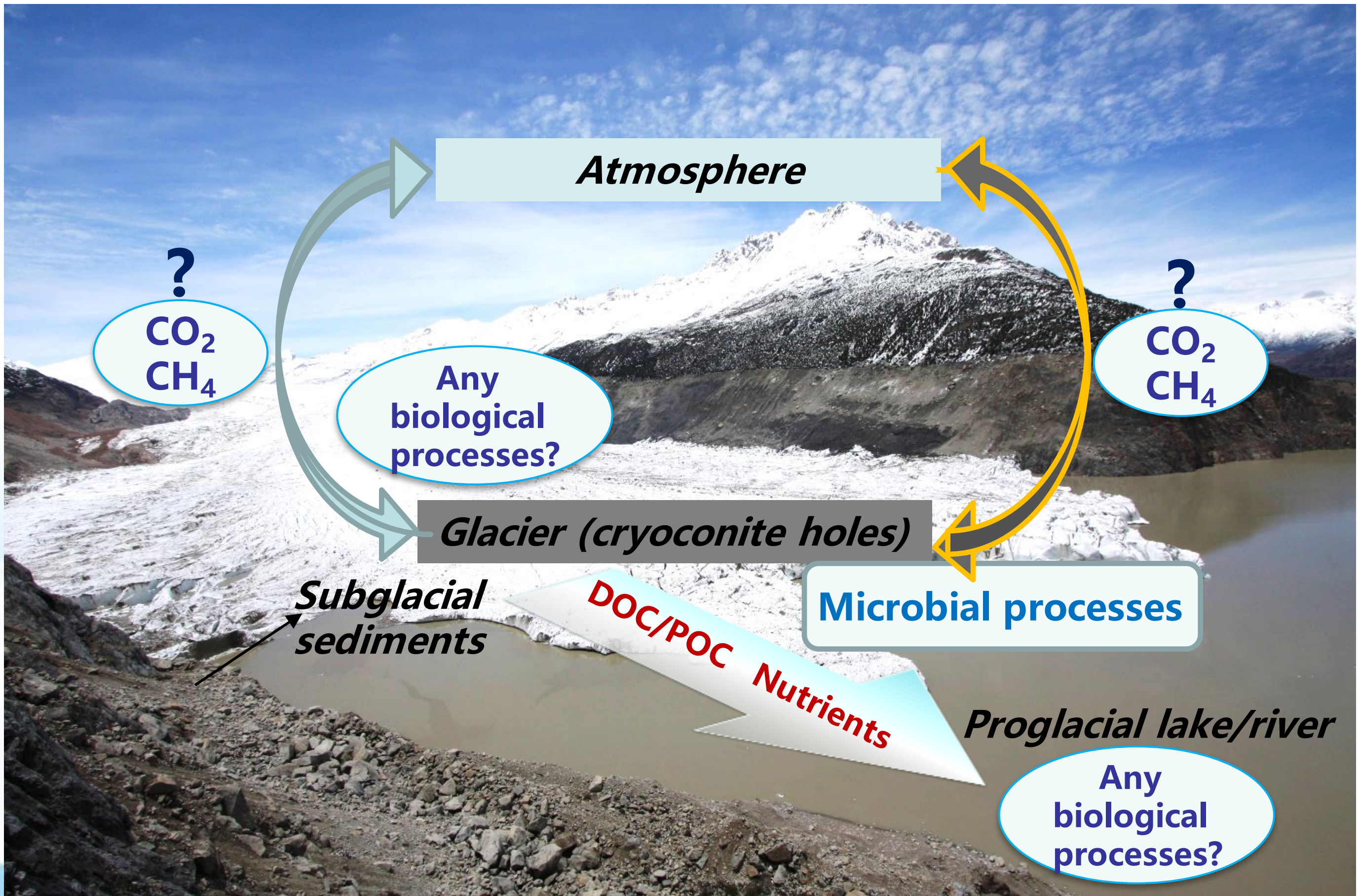
Carbon and nitrogen cycling on the Qinghai–Tibetan Plateau

Huai Chen[1]✉, Peijun Ju[1,2], Qiuan Zhu[3], Xingliang Xu[4], Ning Wu[1], Yongheng Gao[1], Xiaojuan Feng[5], Jianqing Tian[5], Shuli Niu[4], Yangjian Zhang[4], Changhui Peng[6,7] and Yanfen Wang[8,9]✉



- **TP as C sink: the net C absorption 44 Mt yr-1**
- **CH4 emission source since 2000s （0.96Tg yr-1）**
- **Warming, precipitation and nitrogen lead to increasing C absorption**
- **The above factors also lead to an increase in greenhouse gas emissions, an increase in soil respiration rate, and accelerated carbon mineralization in permafrost, resulting in increased carbon loss.**

6.1 Glacier retreat significantly alters carbon and nitrogen cycling



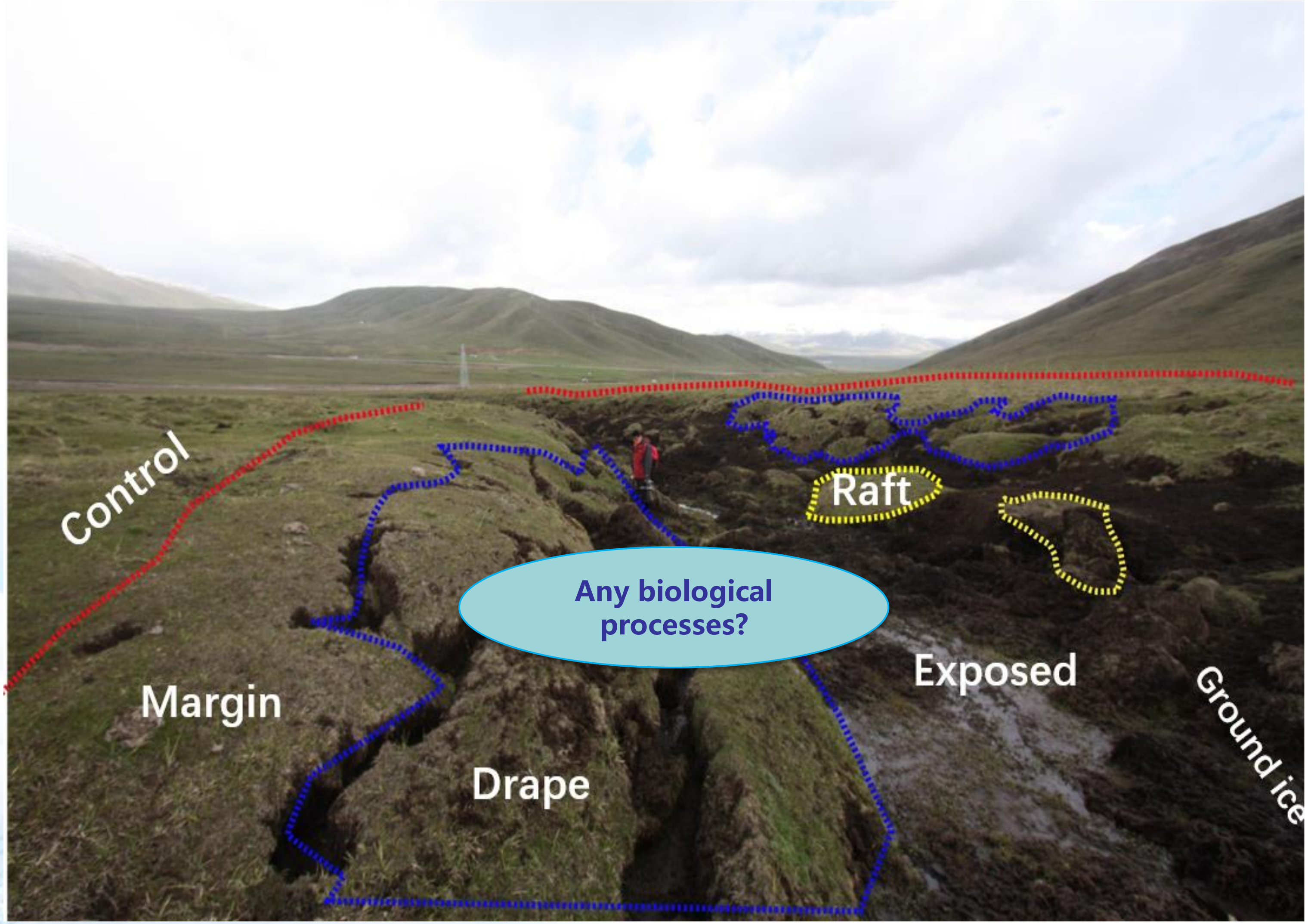
- Distributions of BC and OC
- Estimation of DOC/POC export
- TN or ON?
- Greenhouse gases emissions
- Biological process ???

Zhang et al., 2021 FR; Gao et al., 2024 submission

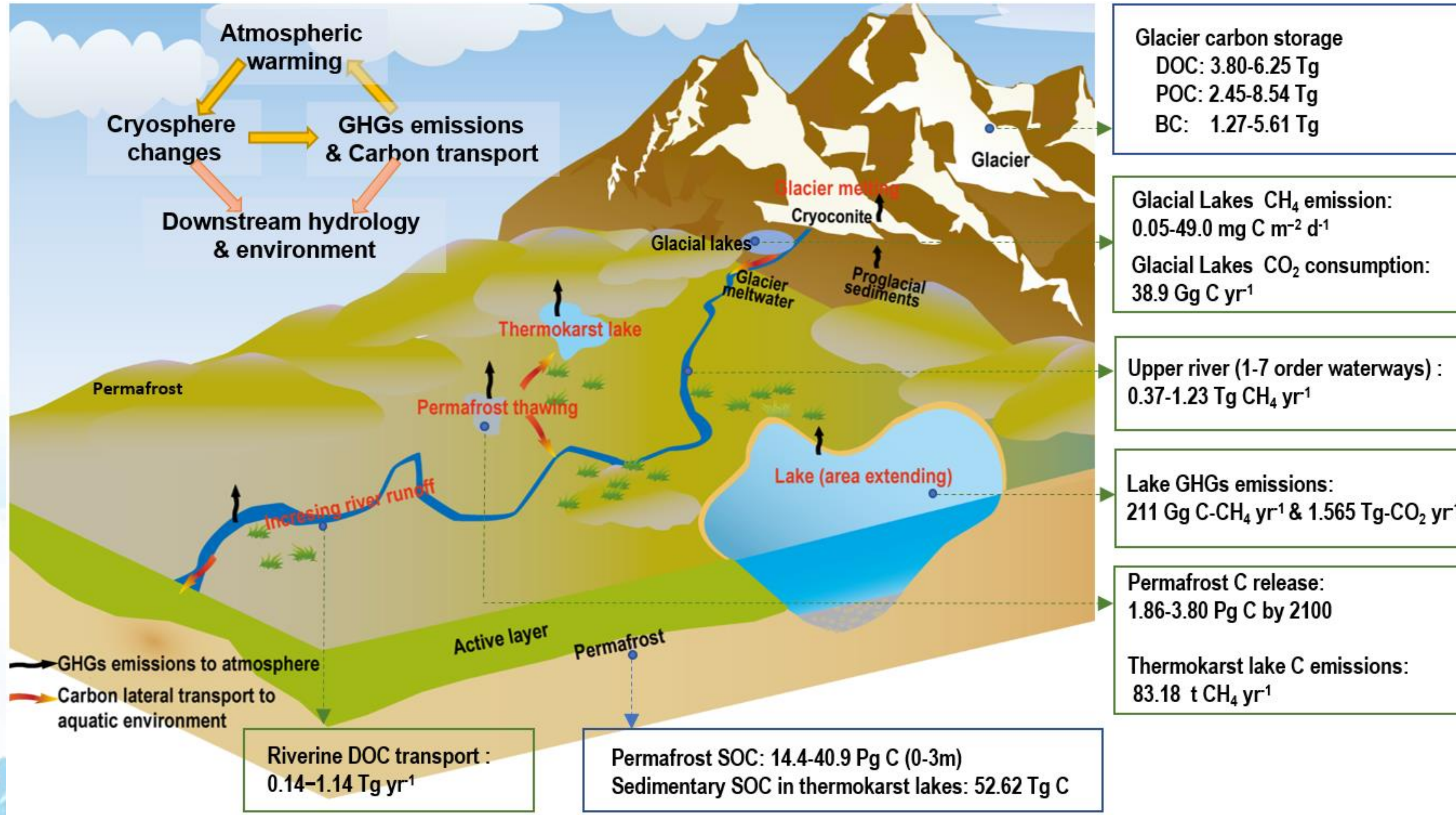
Greenhouse gas release mechanism in glacier areas: lacking

- Cryoconite holes
- Subglacial environment
- Glacial foreland
- Biological process

6.2 The degradation of permafrost significantly alters carbon and nitrogen cycling, as well as pollutant release



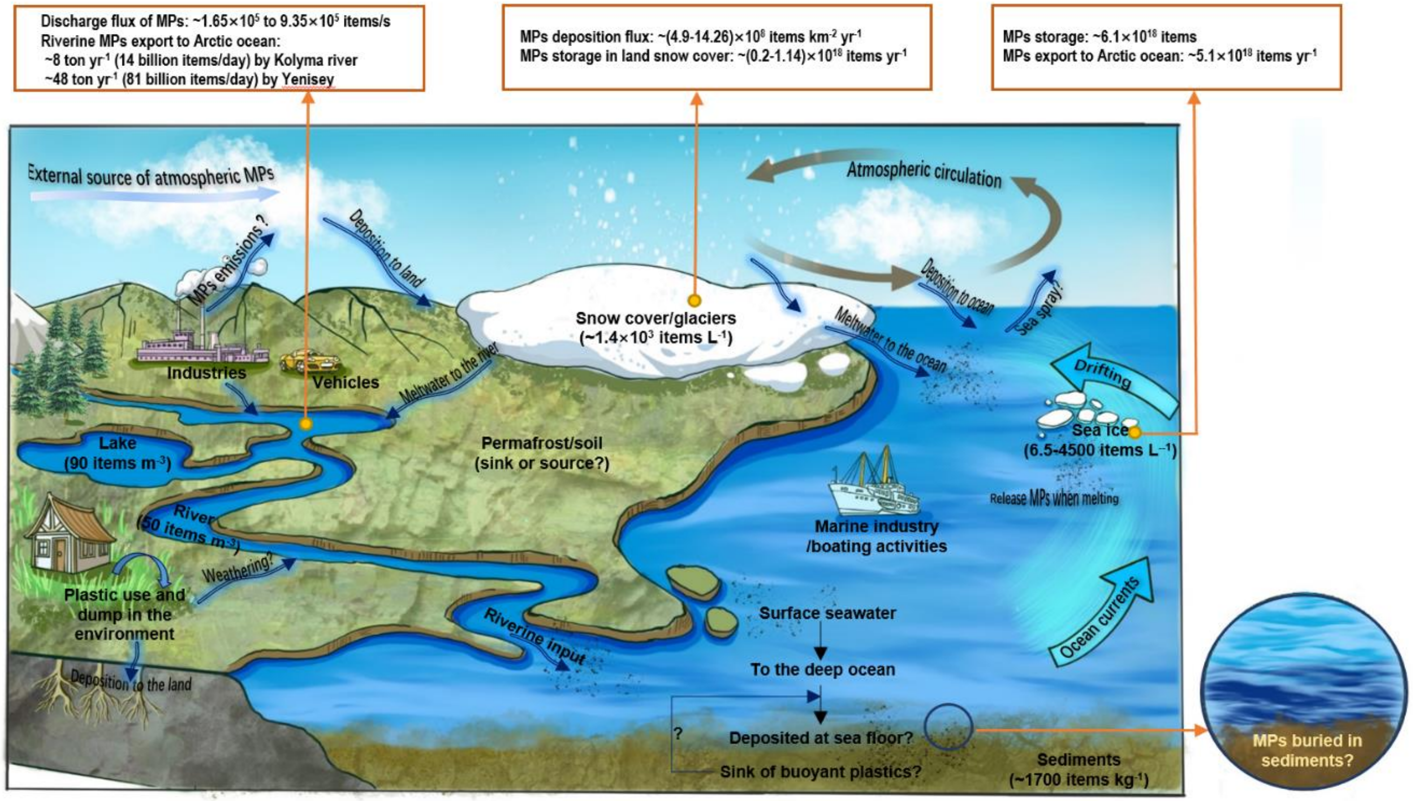
The impact of cryosphere retreat on carbon cycle



Gao TG et al., 2024 ESR

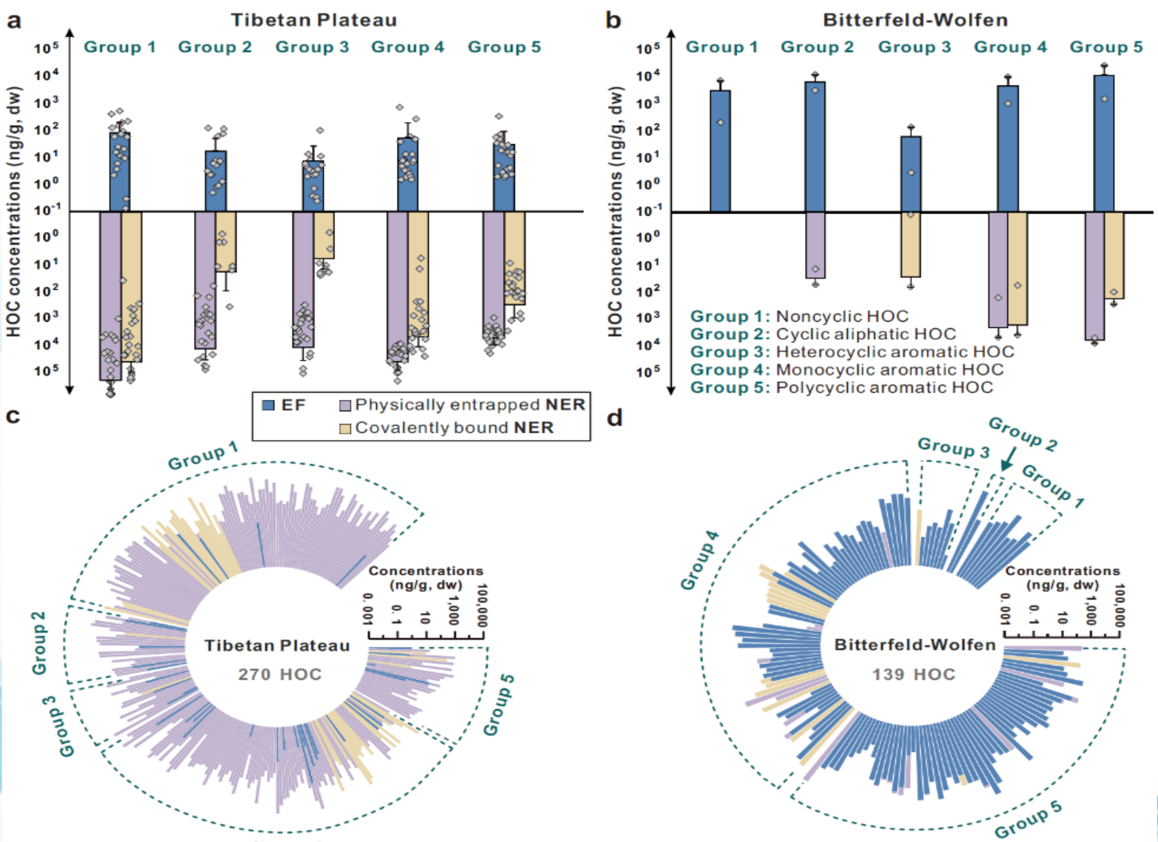
Shrinkage of the cryosphere leads to the release of pollutants

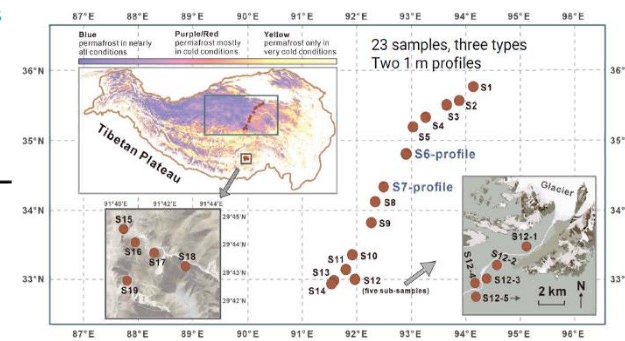
- **The melting of the cryosphere leads to the release of previously stored pollutants such as microplastics, indicating that the cryosphere is a temporary sink and possible source of release for microplastics and other pollutants**



Zhang et al., 2023 GSF

- There are a large number of hibernating halogenated organic compounds in permafrost regions, indicating that these substances pose significant environmental risks in the context of climate warming.





Zhu et al., 2023

Messages taking home:

1. What are the main sources of chemical components in glaciers?

2. What is the feedback effect of carbon cycle in permafrost regions on climate?

3. What are the microbial processes and their impacts caused by rapid shrinkage of the cryosphere?


THANKS！

Cryospheric hazards