Intro in Ice properties and BIO-factor

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Abstract. Microorganisms could play a significant role in shaping the properties of ice. This overview examines the existing knowledge on the influence of microorganisms on ice, focusing on glacial, polar, and marine ice systems. The interaction between microorganisms and ice mechanics is complex and multifaceted. Studies have shown that microbial activity, including biofilm formation, enzymatic processes, and ice nucleation, can impact ice strength and int interaction with structures. Microbial colonization has been found to weaken ice structures, alter ice permeability, and influence ice deformation behavior. Additionally, microbial communities associated with ice surfaces have been shown to enhance ice adhesion and frictional properties. Understanding the role of microorganisms in ice mechanics is crucial for comprehending the dynamics of frozen environments and their response to environmental changes. Further research in this field will contribute to improved predictions of ice behavior and its implications for climate, engineering, and environmental processes.

1 Introduction

Microorganisms play a crucial and intricate role in shaping the mechanical properties of ice across a wide range of environments, thereby influencing the behavior of frozen systems. This overview delves into the existing body of research to provide an in-depth exploration of the multifaceted influence of microorganisms on ice strength, with a specific focus on glacial, polar, and marine ice systems.

The interaction between microorganisms and ice mechanics encompasses a diverse array of processes, each contributing to the overall understanding of how microorganisms shape ice properties. Through the formation of biofilms, microorganisms create intricate communities that adhere to ice surfaces, altering its structural integrity and affecting its mechanical behavior. Enzymatic processes carried out by microorganisms introduce chemical modifications to the ice matrix, leading to changes in its strength and stability.

Ice nucleation, another pivotal process influenced by microorganisms, can impact the formation and growth of ice crystals, subsequently affecting the overall strength and structure of the ice. Microbial colonization has been found to weaken ice structures, potentially leading to increased susceptibility to mechanical stresses and fracturing. Additionally, the presence of microbial communities on ice surfaces can significantly alter ice permeability, affecting the movement of fluids and gases within the ice matrix.

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The influence of microorganisms on ice mechanics extends beyond structural aspects to encompass adhesion and frictional properties. Microbial communities associated with ice surfaces can enhance ice adhesion, facilitating the attachment of ice to other surfaces and influencing ice formation dynamics. Moreover, the presence of microorganisms can modify the frictional properties of ice, potentially impacting the movement and behavior of ice masses in different environmental conditions.

Understanding the intricate role of microorganisms in ice mechanics is crucial for comprehending the complex dynamics of frozen environments and their response to environmental changes, including climate variations and engineering activities. Further research in this field is of paramount importance to advance our knowledge and refine predictive models of ice behaviour [1-6]. This interdisciplinary exploration will contribute to improved insights into the implications of ice mechanics for climate studies, engineering applications in cold regions, and the functioning of polar ecosystems. By embracing the complexities of microbial-ice interactions, we can unravel the profound influence of microorganisms on ice properties and their broader implications for various environmental processes, including possible alteration of mechanical properties [7-9].

2 Ice properties dependence on microorganisms overview

EPS *(extracellular polymeric substances)* produced by ice-associated diatoms can reinforce local mechanical strength of matter. EPS are complex polymers secreted by diatoms, which are microscopic algae commonly found in polar and subpolar regions (fig 1). Some ways in which EPS contribute to enhancing the mechanical properties: EPS act as a natural binder, promoting the cohesion between grains. They form a matrix of sticky substances that help bind crystals together, increasing the overall strength and stability of the matter. EPS facilitate the bonding between adjacent grains, strengthening the connections and reducing the likelihood of grain detachment or breakage. This could enhance the overall structural integrity of the grained sea ice. A certain quantity of EPS could alter mechanical stresses more uniformly throughout the matter, reducing the concentration of stress and ability for brittle behaviour. This property inhibits crack propagation and fracture development, making the ice more resistant to impact strength. EPS increase the flexural strength of sea ice, allowing it to withstand bending or deformation without breaking. This property is especially important in dynamic ice environments where sea ice is subjected to various forces and movements.

Fig. 1. Example microorganisms in the climate of the North [https://sciencealert.com/snow-is-blooming-green-in-antarctica-as-global-temperatures-climb]

Biofilms can in influence the mechanical behavior of sea ice. Biofilms are complex communities of microorganisms that adhere to surfaces and form a slimy matrix of extracellular polymeric substances (EPS). Some key roles of biofilms in the mechanical behavior of sea ice [10-13]: Biofilms promote the adhesion of ice to various surfaces. The EPS matrix produced by microorganisms helps in binding ice crystals to the underlying substrate, enhancing ice adhesion. This adhesion can influence the stability of ice structures and their resistance to external forces. Biofilms contribute to the bonding between ice grains, improving the cohesion of the ice matrix. The EPS produced by microorganisms acts as a natural binder, facilitating the formation of strong bonds between adjacent ice grains. This bonding increases the overall strength and stability of sea ice. Biofilms can affect the permeability of sea ice. The EPS matrix can partially block the pore spaces within the ice, reducing the permeability and limiting the movement of fluids and gases through the ice matrix. This can have implications for processes such as nutrient transport, gas exchange, and biological activity within the ice. Biofilms can enhance the fracture resistance of sea ice. The cohesive nature of biofilms and their ability to bind ice grains together contribute to the prevention and propagation of cracks within the ice. By distributing mechanical stresses and reducing stress concentrations, biofilms can increase the resistance of sea ice to fracture. Biofilms can alter the mechanical properties of sea ice, including its strength, stiffness, and deformation behavior. The presence of biofilms within the ice matrix introduces additional complexities in terms of material behavior and response to external forces.

Microbial impacts on ***ice rheology*** refer to the influence of microorganisms on the flow and deformation behavior of ice. Here are some key aspects of microbial impacts on ice rheology [14-15]:

Microorganisms can alter the *viscosity of ice,* affecting its flow properties. The presence of microbial communities and their associated extracellular polymeric substances (EPS) can increase the viscosity of ice, making it more resistant to flow. This can have implications for the movement of ice masses and the overall dynamics of frozen environments.

Microorganisms can influence the *deformation behavior* of ice. The interactions between microorganisms and ice grains can modify the mechanical response of ice to external forces. This includes effects on the ice's ability to deform, undergo plastic flow, or exhibit brittle behavior.

Microbial activity can affect the *shear strength* of ice. The presence of biofilms and EPS can enhance the cohesion between ice grains, leading to increased shear strength. This can impact the stability of ice structures and their resistance to shear forces, such as ice floe collisions or ice deformation under ocean currents.

Microorganisms can influence the *creep behavior* of ice, which refers to its tendency to slowly deform over time under constant stress. Microbial activity, particularly through the production of EPS, can affect the rate of creep in ice, potentially altering its long-term deformation characteristics.

Microorganisms can induce changes in the *alignment of ice crystals*, impacting the anisotropic nature of ice rheology. The presence of microorganisms and their interactions with ice grains can lead to preferred crystal orientations and affect the overall mechanical response of the ice.

Microbial influence on ice ***permafrost environments*** is significant and plays a crucial role in various processes and dynamics. Some key aspects of microbial influence in ice permafrost environments:

Microorganisms in ice permafrost environments are involved in *carbon cycling*. They can degrade organic matter and release greenhouse gases such as carbon dioxide ($CO2$) and methane ($CH4$) through processes like microbial respiration and methanogenesis. These microbial activities contribute to the carbon balance and the release of greenhouse gases into the atmosphere.

Microbes in ice permafrost environments participate in *nutrient cycling*. They can mineralize organic compounds, releasing essential nutrients like nitrogen and phosphorus into the surrounding environment. This nutrient availability influences the growth and activity of other organisms in the permafrost ecosystem.

Methanogenic microorganisms are responsible for *methane production* in ice permafrost environments. As the permafrost thaws, microbial communities can access organic matter and produce methane as a metabolic byproduct. Methane release has implications for climate change, as it is a potent greenhouse gas.

Microbial activities can influence the stability of ice *permafrost*. Some microorganisms, such as methanotrophic bacteria, consume methane and help reduce its release into the atmosphere. This microbial methane oxidation can contribute to permafrost stability by reducing the pressure buildup caused by methane accumulation.

Microorganisms in ice permafrost environments are involved in various *biogeochemical cycles*, including nitrogen, sulfur, and iron cycles. They can transform and recycle these elements, influencing nutrient availability, geochemical processes, and the overall functioning of the permafrost ecosystem.

Microbial communities in ice permafrost environments exhibit unique *adaptations to extreme conditions*, such as low temperatures and limited nutrient availability. Understanding the composition, diversity, and dynamics of these microbial communities is essential for comprehending the ecological functioning of permafrost environments.

Biofilms can have an influence on ***ice adhesion***, affecting the bonding and attachment of ice to various surfaces. Some key aspects of biofilm influence on ice adhesion: Biofilms promote enhanced adhesion of ice to surfaces. The extracellular polymeric substances (EPS) produced by microorganisms within the biofilm form a sticky matrix that helps bind ice crystals to the underlying substrate. This increased adhesion can improve the stability and longevity of ice attachments. Biofilms can modify the surface roughness of substrates, which in turn affects ice adhesion. The presence of biofilms can introduce irregularities and micro-scale features on surfaces, creating more points of contact and increasing the surface area for ice bonding. This roughness enhances the mechanical interlocking between the ice and the substrate, enhancing adhesion. Biofilms can facilitate chemical interactions between the ice and the substrate, promoting adhesion. The EPS produced by microorganisms within the biofilm can act as an adhesive layer, capable of forming hydrogen bonds or other chemical bonds with the ice and the substrate. These chemical interactions strengthen the adhesion and improve the bonding between the surfaces. Biofilms can create a network of interconnected EPS, effectively bridging ice crystals and surfaces together. This bridging mechanism enhances the adhesion by providing additional contact points and promoting mechanical interlocking between the ice and the substrate. Biofilms can provide protection against shear forces that could otherwise detach or dislodge the ice. The cohesive nature of biofilms and their ability to bind ice crystals together reinforce the adhesion and make it more resistant to shear stresses, such as those caused by water flow or wind.

Microbial activities can alter the ***permeability*** of sea ice, influencing the movement of fluids and gases through the ice matrix. Here are some key aspects of microbial alteration of sea ice permeability: Microorganisms associated with sea ice can produce extracellular polymeric substances (EPS), forming biofilms that contribute to alterations in permeability. EPS create a matrix of interconnected channels and voids within the ice, affecting the pathways available for fluid and gas transport. Microbial activity can modify the pore structure of sea ice. As microorganisms grow and metabolize within the ice, they can physically alter the size, shape, and connectivity of the pores. This modification affects the ability of fluids and gases to move through the ice and can lead to changes in permeability. Microorganisms and their byproducts can clog or block pores within the ice matrix. The accumulation of microbial biomass, EPS, or mineral precipitates can impede the flow of fluids and gases, reducing permeability. This microbial-induced clogging can have significant impacts on the transport of nutrients, dissolved gases, and other substances within the ice. Microbial alteration of sea ice permeability can influence the transport of nutrients. As sea ice acts as a habitat for various microorganisms, the movement of nutrients through the ice is vital for microbial growth and metabolism. Changes in permeability can affect the availability and distribution of nutrients within the ice, shaping microbial communities and their activity. The permeability of sea ice is crucial for gas exchange between the underlying seawater and the atmosphere. Microbial activities within the ice can affect the transport of gases, such as oxygen and carbon dioxide, across the ice-water interface. Changes in permeability due to microbial processes can influence gas exchange rates and impact biogeochemical cycles in sea ice environments.

Microbial impacts on ***ice friction*** refer to the influence of microorganisms on the frictional properties of ice surfaces. Here are some key aspects of microbial impacts on ice friction: Microorganisms can form biofilms on ice surfaces, leading to changes in friction. The presence of biofilms introduces a thin layer of extracellular polymeric substances (EPS) that can alter the surface properties of the ice, including its roughness and texture. These changes in surface characteristics can affect the frictional interaction between the ice and other materials. Microbial colonization on ice surfaces can modify the surface roughness, which influences the frictional behavior. Biofilms can create irregularities and micro-scale features on the ice surface, increasing the contact area and enhancing frictional forces between the ice and contacting materials. The EPS produced by microorganisms can act as a lubricant, affecting the frictional properties of ice. The slimy matrix of EPS can reduce the direct contact between the ice and other surfaces, resulting in lower friction coefficients. This lubricating effect can be particularly significant in the presence of water films or meltwater, where the EPS can enhance the lubrication between the ice and contacting materials. Microbial metabolic processes can generate byproducts that influence ice friction. For example, the production of extracellular enzymes by microorganisms can modify the chemical composition of the ice surface, affecting its frictional behavior. Microbes can also release substances that alter the viscosity or adhesion properties of the ice, thereby influencing friction. Microorganisms can influence the adhesion strength between the ice and other materials, which indirectly affects friction. By promoting the formation of biofilms or by altering the surface properties of the ice, microorganisms can enhance or reduce the adhesion strength, subsequently impacting the frictional behavior.

3 Conclusion

The influence of microorganisms on the mechanical properties of ice is a fascinating and complex field of research. Numerous studies have shown that microorganisms play a significant role in shaping the strength, stability, and behavior of ice in various environments, including glacial, polar, and marine ice systems.

Microbial activities, such as biofilm formation, enzymatic processes, and ice nucleation, have been found to impact ice strength and stability. Microbial colonization weakens ice structures, alters ice permeability, and influences ice deformation behavior. Additionally, microbial communities associated with ice surfaces can enhance ice adhesion and affect frictional properties.

Understanding the interplay between microorganisms and ice mechanics is crucial for comprehending the dynamics of frozen environments and their response to environmental changes. Such knowledge has implications for climate modeling, engineering applications in cold regions, and understanding the functioning of polar ecosystems.

Further research in this field is essential to gain a deeper understanding of the specific mechanisms through which microorganisms influence ice. Exploring microbial diversity, biofilm dynamics, and microbial-ice interactions will contribute to improved predictions of ice behavior and its implications for climate, engineering, and environmental processes.

Ultimately, investigating the role of microorganisms in ice mechanics provides valuable insights into the intricate connections between biological processes and the physical properties of ice. It highlights the importance of considering the biological component when studying the behavior and fate of ice in a changing world.

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