***Original Research Article***

**Climate Change Impacts: Glacial Melt, Sea Level Rise, Water Salinization, and Emergent Pathogen Risks**

**ABSTRACT**

A pressing global threat, the accelerating rise in oceanic water levels, is unequivocally linked to the ongoing transformations in our climate, a connection substantiated by a considerable body of scientific evidence. Projections suggest that the sustained discharge of atmospheric pollutants throughout the present century will further exacerbate these planetary climate shifts, thereby jeopardizing the stability of a diverse array of ecological systems, spanning vast marine environments to critical tropical rainforests. Notably, the increasing elevation of sea levels stands as a highly probable and significant consequence of anthropogenic climate change. Beyond the direct impacts of rising seas, the diminishing of polar ice caps and high-altitude glaciers, a direct outcome of global warming and escalating global temperatures, presents a complex set of challenges. As seawater progressively inundates coastal regions, the freshwater resources vital for numerous communities face a heightened risk of saline contamination. Furthermore, recent scientific investigations have brought to light the existence of previously unidentified viral agents within these frozen environments, some possessing ancient genetic lineages and a potential for future infectivity. The accelerated ablation of these glacial stores increases the likelihood of these dormant microorganisms being introduced into wider ecological networks, thereby posing a potential threat of novel pandemics affecting both human and animal populations – a serious concern often referred to as a ‘permafrost pandemic.’ The pervasive influence of global warming is also instigating widespread glacial melting across the globe, posing a substantial risk to millions through amplified instances of drought, increased frequency and intensity of inundation events, and reduced accessibility to safe drinking water supplies. Recent decades have witnessed rates of glacial ice loss that deviate markedly from established historical patterns. This research endeavors to comprehensively address the far-reaching impacts of climate change, with a specific focus on the salinization of essential water sources, the potential for the emergence of pathogenic hazards, and the interconnected phenomena of glacial melt and sea level rise, ultimately underscoring the imperative for thorough understanding and robust mitigation strategies.

**KEYWORDS**

Climate Change, Drinking Water, Global Warming, Glacial Melt, Impact, Pathogen Risks, Sea Level Rise, Virus, Water Salinization.

**INTRODUCTION**

Greenland has seven meters of ice, Antarctica has sixty meters, and the world's glaciers and ice caps have half a million [31]. These 27 ice sheets and glaciers are now melting, causing the sea level to rise. The sea level increased by 20 centimeters over the last century. As of right now, the sea level is rising 35 cm every century [06]. According to Oppenheimer (2020) [31], the total sea level change will surpass one meter (m) by the end of the century. Paleoclimate records suggest a significant correlation between global warming and sea level rise, indicating an approximate 20-meter increase for each degree Celsius of warming, or a 50-meter rise for a 2.5-degree Celsius increase above pre-industrial levels [35]. However, the delayed response of ice sheets to climatic shifts means we're unlikely to observe such dramatic sea level changes within this century. Nonetheless, historical data reveals that sea levels have experienced rates of increase exceeding 3.5 millimeters per year in the past. Such a rapid acceleration in sea level rise strongly implies a swift breakdown of ice sheets. While the primary source is often attributed to the melting of Northern Hemisphere ice sheets, a contribution from Antarctica cannot be discounted. Today, we are witnessing an unprecedented surge in greenhouse gas emissions, a forcing of the Earth system unlike any seen in the past million years. It's important to recognize that the physical mechanisms responsible for those past instances of rapid sea level rise remain relevant in our current climate scenario. The Intergovernmental Panel on Climate Change (IPCC, 2007) [18] indicated that even with immediate stabilization of greenhouse gas emissions, sea levels would continue to rise for many decades. Prior to recent findings, sea level rise projections for the 21st century typically ranged from zero to one meter [07]. The IPCC's Fourth Assessment Report (AR4) forecasts a sea level increase of 0.18 to 0.59 meters by the close of the 21st century, across a variety of emission scenarios. Emerging measurement data on the rates of ice loss in Greenland and West Antarctica [13]- [14]; Helsen et al., 2008) [16] raises concerns about the possibility of surpassing a critical threshold, potentially leading to a multi-meter rise in sea levels well before the end of the current century. Icebergs originate at the intersection of glaciers and the sea. These ice formations are immense, often spanning several kilometers in width and length, and reaching thicknesses of up to one kilometer. Consequently, their mass is measured in gigatons, representing billions of tons. To provide a sense of scale, a major city like Los Angeles in the United States or Moscow in Russia consumes approximately one gigaton of water each year [35].

Analysis of temperature data since the 1890s reveals a notable clustering of record-breaking heat in the early 21st century, with the five hottest years observed being 2005, 1998, 2002, 2003, and 2004, in order of decreasing warmth. Looking towards the future, scientists project a considerable rise in Earth's average temperature by the end of this century, with predictions indicating a potential increase ranging from a lower bound of 2 degrees to an upper bound of 10 degrees. Satellite observations indicate that Greenland is presently experiencing an annual mass loss of approximately 300 gigatons [35]. This translates to the equivalent of losing a substantial iceberg into the ocean daily, exceeding the mass required for the Greenland Ice Sheet to maintain equilibrium with snowfall. However, iceberg calving represents only a fraction of the overall picture. More profound alterations are taking place hundreds of meters below the surface, at the interface between the cold interior ice and the warmer, saline ocean waters. Reduced freshwater flows can facilitate the inland movement of seawater [09]. However, seawater intrusion is not the sole cause of salinization. Increasing salinity in inland water bodies, across both arid and humid climates, is also attributed to human-induced salt sources, including road de-icing agents, wastewater discharge, and mining activities, as well as natural salt sources from adjacent bedrock [12]-[19]-[47]. This degradation of freshwater quality is challenging the achievement of water quality targets outlined in the UN's Sustainable Development Goal 6.3 [12]. The existing salinization issue is being exacerbated by the added salinity input from rising sea levels [20]. Climatic shifts are linked to the emergence of both novel and previously known viruses, leading to increased discussions regarding climate change-induced viral infections. The Intergovernmental Panel on Climate Change (IPCC) in its Sixth Assessment Report projects that global temperatures will exceed the 1.5-degree Celsius threshold by 2030 [02]. This warming trend is expected to result in extended summers and an Arctic Ocean free of sea ice by 2030. Research indicates that for each degree Celsius of global temperature rise, the tundra is projected to thaw by approximately 25%. Furthermore, Earth's multi-year layered ice experienced a decline of over 90% between 1976 and 2018. Considering the world's history of viral pandemics, such as malaria, the Spanish flu, and the recent COVID-19 outbreak, it is essential to address the close relationship between melting ice and the potential for viral emergence. Viruses, particularly infectious ones, are preserved within glaciers and ice formations across the Arctic and high-altitude tundra, posing a potential risk of future viral pandemics or epidemics. Some of these viruses may be entirely novel to the global population. The rapid thawing of permafrost soils, where these viruses have remained frozen for extended periods, releases meltwater that can transport them into rivers, seas, oceans, and other water systems. The critical concern lies in the potential for these ancient viruses to become reactivated.

**MATERIALS AND METHODS**

A comprehensive literature review was conducted, utilizing databases such as Scopus Index, PubMed, Academia, ResearchGate, and Google Scholar, to identify relevant research. This study relies on secondary data, gathered through an extensive online and offline review of sources including books, governmental and international reports, scientific journals, newspapers, and reputable websites.

**MOUNTAIN GLACIERS MELTING**

The swift melting of mountain glaciers across the globe, a direct outcome of climate change, generates considerable dangers for natural environments, sources of drinking and irrigation water, and the possibility of extreme flooding events. The fundamental reason for this accelerated loss of glacial ice is the persistent increase in worldwide temperatures, predominantly attributable to human activities, especially the combustion of fossil fuels. Higher atmospheric concentrations of greenhouse gases lead to a greater retention of heat, causing temperatures to rise and, as a result, glaciers to melt at a progressively faster rate. Worryingly, the speed at which the world's glaciers are shedding ice has doubled over the past two decades, highlighting a significant escalation of this critical issue. As glaciers serve as a vital natural storage of freshwater, their increasing rate of melting can lead to reduced water availability for industrial processes, agricultural irrigation, and human consumption, especially in regions with a strong dependence on glacial meltwater runoff. Changes in temperature and the amount of available water can disrupt ecological systems, affecting the plant and animal species that rely on water sources originating from glaciers. Moreover, the pooling of water from melting glaciers can form large lakes in natural depressions. These lakes are frequently held in place by potentially unstable ice dams or accumulations of rock and debris (moraines), and the collapse of these natural barriers can result in catastrophic and sudden flooding events. Finally, the contribution of melting glaciers to rising global sea levels can exacerbate coastal erosion, increase the frequency and severity of flooding in coastal zones, and necessitate the relocation of people living in vulnerable coastal communities. The melting of glaciers is also causing frozen ground, called permafrost, to thaw. This thawing can release trapped gases that contribute to global warming, making climate change even worse. Additionally, the lakes that form from melting glaciers can be very unstable. They can suddenly burst, causing huge and destructive floods that can lead to a lot of damage and even deaths. For instance, the glaciers in the Himalayas are a growing threat to South Asia because they could cause major floods and landslides of rock and ice. In Europe, the Alps and Pyrenees lost a significant amount of ice – 40% of their total glacier size – between the years 2000 and 2023. Glaciers in western North America also experienced a record loss of ice thickness, about 3 meters. In the year 2023, the world's glaciers lost the most ice in a single year ever recorded – a massive 600 gigatonnes of water. This amount of melting contributed about 1.7 millimeters to the overall rise in sea levels around the world.

Glaciers are massive accumulations of ice that act as natural storage for freshwater, releasing it over time through melting. They hold a vast amount of freshwater, and as they melt, these icy stores are decreasing. In some regions of the world, glaciers have shrunk by over 30% in less than 50 years. Mountain glaciers are particularly significant, as they contain more than two-thirds of all the freshwater on Earth. To illustrate their importance, consider the glaciers in the Himalayas. They feed seven major rivers in Asia, providing a vital water source for nearly two billion people – that's more than one-third of the world's population. Therefore, gaining a clear understanding of the consequences of glacier melt on a worldwide scale and attempting to predict these effects is crucial. While the last decade and a half has seen significant advancements in data collection, particularly through satellite technology, these modern tools cannot entirely substitute for established field observation methods, such as physically marking glaciers to track their movement, or newer technologies like drones.

The genesis of glaciers occurs under conditions where winter snowfall surpasses the ablation experienced during summer months, allowing for a net accumulation of snow. Over successive seasons, this accumulated snow undergoes a transformation into glacial ice through compaction and recrystallization. The immense pressure exerted by the overlying mass of snow and ice causes the basal layers to deform and flow, resulting in the formation of a dynamic ice stream that slowly traverses the landscape, progressively eroding and sculpting the terrain into characteristic glacial landforms. Conversely, a sustained period where ablation exceeds accumulation leads to a reduction in the glacier's mass, causing its terminus to recede up-valley. Given the direct and sensitive response of glacial advance and retreat to fluctuations in temperature and precipitation regimes, the observation of these changes serves as a straightforward yet potent indicator of ongoing climate change.



Figure 01: Himalayan and Patagonian projection year versus percentage of remaining ice (Figure Source: [25]- [26].)

The Earth's glaciers and the seasonal accumulation of snowfall represent indispensable sources of freshwater, sustaining the domestic, agricultural, and industrial needs of at least three billion individuals across the globe. It is a matter of significant concern, however, that for several decades consecutively, virtually all of the world's glacial ice reserves have been undergoing a process of net loss, a trend that, for many glaciers, extends back to the nineteenth century. Notably, glaciers situated at extreme elevations, predominantly those within the High Mountain Asia region, encompassing the Himalayas, alongside glaciers located at high latitudes or within polar environments, have historically posed considerable logistical and scientific challenges for comprehensive study [26]. While these high-altitude and high-latitude ice masses initially appeared less susceptible to the impacts of contemporary global warming, recent evidence now indicates a discernible and accelerating decline even within these previously more stable glacial systems. While it's true that mountains actually hold much more water seasonally in the form of snowpack compared to glaciers, the patterns of snowfall in many mountainous regions have become increasingly erratic. We're seeing a shift towards greater unpredictability, with periods of very heavy snowfall followed by severe and prolonged dry spells. This kind of fluctuation increases the danger of both floods and avalanches. What's also concerning is that, much like the glaciers, snowpack in many mountain systems seems to be on a downward trend: we're getting less snow overall, and in some cases, precipitation that used to fall as snow is now falling as rain. This shift has significant economic consequences, negatively impacting both farming and tourism. Furthermore, major urban populations, such as those in the southwestern United States where rising temperatures and reduced snowpack have together led to increasingly intense drought conditions, are facing less reliable access to the water they need [26].

**THE CRITICAL IMPORTANCE OF GLACIERS IN A CHANGING CLIMATE**

Carbon dioxide represents a significant greenhouse gas, integral to the planet's thermal regulation. Greenhouse gases facilitate the passage of solar radiation into Earth's atmosphere while subsequently trapping a portion of that energy, thereby maintaining a habitable temperature. In their absence, the Earth's mean temperature would approximate -15°C. However, an increase in greenhouse gas concentrations leads to enhanced heat retention within the atmosphere, resulting in global warming. This phenomenon is primarily driven by anthropogenic industrial activities, which generate elevated emissions of gases such as carbon dioxide, methane, nitrous oxide, and carbon monoxide, thereby inducing climatic shifts.

Glaciers, in contrast to seawater, are primarily composed of freshwater. Consequently, they serve as a vital source of pure meltwater, originating from high-altitude regions, and possess the capacity to sustain approximately one-third of the global population, representing 2.4 billion individuals [11]. Furthermore, glaciers play a critical role in regulating the Earth's climate system by sequestering greenhouse gases, including methane, which contributes to global warming. Beyond their current ecological roles, glaciers represent a critical archive of past climatic conditions. By analyzing oxygen isotopes within deep ice layers, scientists are able to reconstruct Earth's temperature records spanning hundreds of thousands of years. Furthermore, the presence of glaciers significantly mitigates current sea levels; their absence would result in widespread inundation of heavily populated coastal regions. Studies indicate that the complete ablation of the Earth's approximately 5 million cubic kilometers of land-based ice would transpire over a period of nearly 5,000 years, culminating in a sea level rise of approximately 65 meters.

**GLOBAL WARMING CAUSES GLACIERS TO MELT AND SEA LEVELS TO RISE**

Water exists ubiquitously across the Earth in its various phases-vapor, liquid, and solid-with ice formations covering a substantial portion of the planet's surface. These ice bodies are predominantly located in proximity to the polar regions, where ambient temperatures facilitate the sustained solid state of water. While the ocean's surface is largely characterized by liquid water, the Arctic Ocean and select Antarctic areas exhibit sea ice cover, often overlaid with snow. The landmasses of Greenland and Antarctica are largely enveloped by extensive ice sheets. These formations are characterized by substantial ice plates, reaching thicknesses of several thousand meters. Notably, the Greenland ice sheet, spanning approximately 1.7 million square kilometers, covers a significant proportion, roughly seven-eighths, of the island's total area. Conversely, the Antarctic ice sheet covers an area of approximately 13 million square kilometers, exceeding the Greenland ice sheet in both size and thickness, reaching up to 4,000 meters [28]. Antarctica currently represents the planet's largest freshwater reservoir. Both ice sheets, situated at high latitudes, have developed over extensive, elevated landmasses. Similarly, the North Pole is encapsulated by ice, floating upon the expansive Arctic Ocean. Sea ice typically measures up to 5 meters in thickness, while icebergs can extend to hundreds of meters [28].

The prevailing consensus attributes global warming to a substantial alteration of the atmospheric greenhouse effect, driven by the augmented concentrations of greenhouse gases, notably carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), and chlorofluorocarbons (CFCs), observed throughout the 20th century. This hypothesized global warming, particularly its impact on high-latitude regions where the majority of Earth's ice is located, raises concerns about potential sea level rise. The observed intensification of the greenhouse effect is attributed to anthropogenic influences. The combustion of fossil fuels, including oil, coal, and natural gas, alongside other human activities, has resulted in elevated greenhouse gas emissions, particularly since the onset of the Industrial Revolution in the mid-18th century. The global average annual temperature of the Earth and its atmosphere exhibited an increase of approximately 0.5°C throughout the 20th century. Projections regarding sea-level rise present a range of scenarios, with some experts positing that extreme cases could materialize within the 21st century. Certain models suggest a potential eustatic sea-level rise of up to 4.5 meters by the year 2100. Conversely, more conservative, yet still uncertain, estimates project a sea-level increase of 1.2 meters by 2100 and roughly one meter by 2050 [28].

**THE IMPACT OF GLACIER MELT AND SEA LEVEL RISE ON THE ENVIRONMENT AND HUMAN SOCIETY**

The thawing of glaciers exerts a significant influence on both human society and the natural world, contributing to a cascade of effects including escalating sea levels, diminished freshwater resources, and modifications in atmospheric circulation patterns. These changes carry substantial implications for coastal populations, ecological systems, and the overall stability of the global climate. The contribution of melting glaciers to rising sea levels exacerbates coastal erosion and amplifies the impact of storm surges. Furthermore, the increasing temperatures of both the atmosphere and oceans contribute to the heightened frequency and intensity of coastal storms, such as hurricanes and typhoons.



Figure 02: The Antarctic Thwaites glacier's edge (Figure Source: [52]).

While the precise total volume of glaciers and ice caps globally remains under investigation, complete melting of these ice reserves would result in an estimated sea level rise of approximately 70 meters (around 230 feet), leading to the inundation of every coastal urban center worldwide. The survival of ice-dependent fauna is intrinsically linked to the presence of sea ice. Across the polar food web, the loss of sea ice and warming ocean temperatures are instigating profound transformations. Many species are experiencing the disappearance of their food sources, the loss of essential habitat, and widespread disruptions to their established life cycles.

The projected impacts of sea-level rise on both ecological systems and human societies remain subject to considerable uncertainty. This unpredictability stems largely from the inherent complexities in forecasting the consequences of global warming, a challenge that can be attributed to a multitude of factors, including the limitations of **General Circulation Models (GCMs).** Despite the considerable uncertainties surrounding the precise consequences of global warming, and consequently, sea-level rise, this issue remains a focal point of intense scrutiny. While the assessment of the impacts of sea-level rise on ecosystems and human settlements is subject to inherent limitations, it is anticipated that numerous socio-economic, political, and environmental consequences will be experienced worldwide, with coastal zones on every continent facing heightened vulnerability [28]. Regardless, the diverse components of the global economy will experience these socio-economic, political, and environmental impacts in varying ways. For instance, while sea-level rise may generate comparable biophysical effects in both industrialized and developing nations, the capacity to respond to this challenge will differ significantly between wealthy and less affluent states within the global political economy. Developing nations, often lacking adequate resources to manage even existing environmental problems, will face substantial difficulties in securing the necessary means to mitigate the risks associated with sea-level rise. Barring the improbable scenario of substantial sea-level rise occurring in the distant future, the aforementioned challenges are likely to persist for these governments. While developed nations may have reached a stage where implementing mitigation strategies has minimal repercussions on their economic performance, such a situation is far from the reality for developing countries. In a global context where a nation's economic productivity is often equated with its political influence, this disparity is further entrenched. Given the prevailing debt crises and the fragile economic conditions of many developing nations, the prospect of them readily securing resources for sea-level rise mitigation currently appears highly unlikely [28].

**FRESHWATER AND GLACIERS**

The seemingly vast oceans that dominate our planet's surface belie the scarcity of usable water. The great majority of Earth's liquid is too high in salinity for consumption by plants, animals, and humans alike. Freshwater reserves account for only around 2.5 percent of the total global water, and a very small fraction of this, less than 0.1 percent, represents the accessible drinking water that is naturally renewed through annual rainfall [42]. Glaciers play a crucial role in safeguarding ecosystems against the impacts of climate change by acting as natural reservoirs, storing approximately 70% of the planet's freshwater and releasing it during periods of drought or seasonal aridity. In tropical regions, the continuous melting of glaciers sustains streamflow and often represents the exclusive water source for both human populations and wildlife throughout the dry seasons. Given that freshwater is already a limited resource for a significant portion of the globe, projected population growth over the next three decades is anticipated to substantially exceed any potential increases in water availability [42].

A considerable portion of Earth's freshwater is sequestered in glaciers, underscoring their role as essential freshwater reservoirs. The meltwater originating from these ice formations is crucial for sustaining numerous ecosystems and supporting human endeavors such as hydroelectricity production, agriculture, and drinking water provision. Approximately 68.7% of the world's freshwater is stored within glaciers and ice caps, rendering glacial meltwater a vital freshwater source, particularly in dry climates. Functioning as natural "water towers," glaciers accumulate water in cold seasons and release it during dry ones, a process essential for global water security. The Antarctic and Greenland ice sheets collectively hold more than 99 percent of the planet's freshwater ice.

The Himalayan glaciers, vital sources of year-round water for two billion people and the headwaters of seven of Asia's major rivers-the Ganga, Indus, Brahmaputra, Salween, Mekong, Yangtze, and Huang He-are diminishing at an alarmingly accelerated rate. The anticipated two-thirds reduction in July-September flows in the Ganga River, resulting from the loss of glacial meltwater, would lead to water scarcity for 500 million individuals and 37% of India's irrigated land. In Kazakhstan's northern Tien Shan mountains, where over 90% of the water is utilized for agricultural purposes, permafrost and glaciers, which are experiencing accelerated melting, contribute 75–80% of the river runoff. In the arid Andes region, glacial meltwater exerts a more significant influence on river flow than precipitation, even during the wet season. The majority of major urban centers in Ecuador, Peru, and Bolivia rely on meltwater from rapidly shrinking glaciers for both their water supply and hydroelectric power generation; consequently, numerous communities are already facing water scarcity and conflicts over resource allocation [42]. The swift melting of glaciers can not only elevate river flood risks but also lead to the formation of potentially perilous glacial meltwater lakes. The ongoing ice melt or the breaking off of large ice chunks into these lakes can trigger devastating glacial lake outburst floods. According to a recent United Nations Environment Programme (UNEP) report, climate change has created an imminent threat of overflow for 44 glacial lakes situated in Nepal and Bhutan. Over the course of the 1900s, global mean sea level ascended by 1-2 mm each year, a trajectory expected to continue, with melting glaciers projected to add 0.2-0.4 mm to the annual increase. However, recent investigations indicate a more substantial contribution from glacial melt in areas such as the Patagonia Icefields and Alaska since the mid-1990s, now totaling 0.375 mm annually. This implies a potential underestimation of the role of glaciers in sea level rise. Consequently, coastal environments worldwide will be subject to the impacts of rising sea levels, including amplified erosion, more frequent flooding events, and the encroachment of saltwater into freshwater ecosystems and aquifers. The Mississippi River Delta in the United States witnessed a substantial annual decline of 100 square kilometers in its wetland extent, a direct consequence of the erosion driven by the relatively small sea level rise experienced in the 20th century [42].

**COASTAL AQUIFER SALINIZATION**

The confluence of marine and terrestrial freshwater sources, occurring in unconfined aquifers or estuarine environments, creates brackish water zones characterized by a mixture of saline and freshwater. The dynamic interplay between the hydraulic pressure exerted by these distinct water bodies results in a perpetually shifting boundary of the brackish water region. Periods of substantial freshwater discharge from the land, whether originating from recent precipitation events, snowmelt, or controlled releases from dams, exert pressure that displaces seawater seaward. Conversely, phenomena such as inland drought conditions, unsustainable rates of water extraction, reductions in land cover permeability, elevated sea levels during high tides, or the broader impacts of climate change can drive a landward intrusion of seawater. A substantial body of research has investigated the extent and underlying factors contributing to salinization in unconfined coastal aquifers globally. A comprehensive review and synthesis of many of these investigations is presented by Ketabchi et al. [21], who also explore the interrelationships between groundwater recharge rates, local topographic and geological characteristics, and the phenomena of seawater intrusion and sea level rise.

Their analysis reveals that the degree of seawater intrusion is fundamentally governed by two key parameters: the rate of groundwater recharge, which is modulated by local land cover, land use practices, and soil permeability; and the volume of freshwater discharging from the aquifer, which is influenced by precipitation patterns, the geological composition of the aquifer, and its hydraulic conductivity. Furthermore, Ketabchi et al. [21] observed that aquifers exhibiting a higher ratio of thickness to length demonstrate greater susceptibility to seawater encroachment. In instances of transient saline contamination resulting from acute events, aquifer remediation through flushing is often a viable option. For example, Xiao et al. [49] modeled the impact of a storm surge introducing saltwater into a coastal aquifer in south Florida, U.S., and determined that the time required for chloride flushing from the aquifer was approximately eight years. They noted that the duration of this process is contingent upon aquifer recharge rates and prevailing regional precipitation patterns. Similarly, Lui and Tokunaga [23] investigated aquifer flushing following tsunami-induced salinization on Niijima Island, Japan, which relies on groundwater resources. Their findings highlight that the thickness of the unsaturated zone overlying the aquifer plays a significant role in determining both the duration of aquifer contamination and the retention of saltwater over wash. Projections indicate that potable water resources could be compromised by overwash-driven salinization events as early as the 2030s under the RCP 8.5 climate scenario with the inclusion of ice sheet collapse, the 2040s for the RCP 8.5 scenario alone, and the 2060s for the RCP 4.5 scenario [43]. The emergence of consistent over wash events associated with altered, routine wave dynamics—rather than solely extreme occurrences—presents a significant threat to drinking water availability. These frequent inundations may not allow sufficient time for natural aquifer flushing processes to occur, despite potential local variations in vulnerability among atolls [05]. Quantifying and synthesizing the overall extent of persistent salinization poses a considerable challenge due to its substantial temporal and spatial variability, both horizontally and vertically. The susceptibility of aquifers to salinization and their capacity for natural flushing exhibit a wide range [01]. Some aquifers may experience rapid contamination and subsequent remediation, while others may undergo slower rates of salinization but prove more recalcitrant to natural flushing processes.



Figure 03: Resources and Recharge of Ground Water (mm/a), (Figure Source: [53]).

**ESTUARIES BECOMING SALINIZED**

While the relationship between estuary salinization and threats to drinking water supplies has received comparatively less research attention, the dynamic movement of the salt intrusion front is often more readily observable and trackable in estuarine systems than within subterranean aquifers. An exception to this trend is the work of Roehl et al. [36], who examined the interconnectedness of drinking water sources in the states of Georgia and South Carolina in the United States with estuarine salinization and the phenomenon of sea level rise. Roehl et al. [36] posit that seawater intrusion into the studied estuaries occurs when "two of the following three conditions—low stream flow, high tidal range, and/or high mean sea levels—are concurrently present." Their sea level rise projections (ranging from 0 to 1 meter) indicate that while the salinity at the water intake points does not consistently exceed drinkable limits, the frequency of days with elevated salinity levels increases. Under current sea level conditions (0 m scenario), the intakes experience saline water approximately 5% of the time. This frequency is projected to increase to 20% of the time under the 1-meter sea level rise scenario [01].

**EMERGING VIRUSES DUE TO MELTING GLACIER ICE**

Environments that remain frozen year-round, such as permafrost and glaciers, are believed to serve as natural reservoirs for an immense number of microorganisms. The majority of these microbes, including some that can cause human illnesses, exist in a state of inactivity. However, with the increasing rate of ice melt due to global warming, approximately 4×1021 of these dormant organisms are released from their frozen confinement each year and enter surrounding natural environments, sometimes near human settlements. Several studies have focused on regions with glaciers that are nearing retrieval, encompassing high-elevation tundra glaciers, such as those found on the Tibetan Plateau at approximately 22,000 feet above sea level, and deep Arctic zones, including the Canadian Arctic, the Norwegian Arctic, and Russian Siberia [22]. In a recent scientific endeavor, a collaborative team of Russian and French researchers successfully isolated a virus from a sample of Siberian permafrost estimated to be nearly 30,000 years old [02]. A 2014 study published in the Proceedings of the National Academy of Sciences described the discovery of one of the largest viruses ever documented. This virus exhibited significant structural distinctions compared to typical viruses and was reported to have a size of 1500 nanometers (one-billionth of a meter) [46]. Notably, this makes it ten times larger than the Human Immunodeficiency Virus (HIV) and visible using a standard light microscope. The virus, named Pithovirus sibericum, was successfully revived and demonstrated the ability to infect amoeba species [04].

Scientists say an old virus that had lain dormant for at least 30,000 years has "come back to life" (Figure 04). It melted and re-emerged contagious after being discovered frozen under a thick layer of Siberian permafrost. Although there is no risk to humans or animals from the epidemic, the French scientists warn that as the ground becomes exposed, new viruses may be released.



Figure 04: A giant virus 30,000 years old "comes back to life" (Figure Source: [04]).

In addition to Pithovirus sibericum, other viral entities, including Mollivirus sibericum and members of the Mimivirus genus, have also been identified within thawing permafrost samples [02]. In another noteworthy investigation, scientists successfully recovered genetic material from the Spanish flu and smallpox viruses from thawing permafrost. Intriguingly, these pathogenic viruses, despite being considered eradicated from natural circulation, were found preserved in a dormant state within the frozen ground. Glaciers exist even in high-altitude regions, such as the Tibetan Plateau, and these ice formations may harbor ancient viral agents. Research conducted on the Guliya Ice Cap, situated at an elevation of 22,000 feet above sea level, provides evidence for this possibility [22]. By drilling a 164-foot core sample from the ice cap, researchers identified the genetic sequences of 33 distinct viruses that had been entrapped within the ice. The estimated age of these viral entities was approximately fifteen thousand years. Notably, at least 28 of these viruses were found to be previously unknown, while the remaining 4 had been identified in prior studies [02].

Prior to research uncovering ancient viral specimens, Antarctica, a continent characterized by limited biodiversity, was largely assumed to be devoid of viruses. However, a 2009 investigation of a frozen freshwater lake in Antarctica revealed the presence of DNA from nearly 10,000 previously uncharacterized viral species [29]. Subsequent studies of Antarctic permafrost have indicated a prevalence of DNA viruses, including bacteriophages, circular double-stranded DNA viruses, picornaviruses, virophages, and phycodnaviruses that infect algae, alongside the existence of quasi-species. The estimated age of these viral specimens is approximately 25 million years [48].

**MELTING GLACIERS COULD LEAD TO VIRUS OUTBREAKS IN SOME REGIOS**

In specific Arctic regions, populations residing near glaciers face an elevated probability of encountering novel viruses. For instance, Siberia contains burial grounds dating back to the 18th and 19th centuries situated near the Kolyma River, which potentially harbor nucleic acids of the smallpox virus. Furthermore, a Stone Age burial site was discovered in Gorny Altai, a region in close proximity to southern Siberia [02]. Additionally, the remains of individuals who succumbed to the Spanish flu were interred in the Alaskan tundra [08].

While locations of this nature are not expected to harbor eradicated live viruses, the accelerating melt of glaciers presents a potential pathway for their resurgence in a viable and infectious form. The circumstances surrounding an anthrax epidemic in Siberia offer a compelling illustration of this risk. Beyond hospitalizing close to a hundred individuals, the virus tragically led to the death of a young child. Subsequent inquiries determined that the anthrax outbreak stemmed from the exposure of lethal anthrax spores, which were released when the frozen remains of animals infected years earlier underwent a melt-thaw cycle [46]. These spores had remained in a state of inactivity within the intensely cold environment until they were freed by meltwater. Despite the fact that anthrax is bacterial in nature, a comparable scenario could unfold with viruses that are currently inactive within glacial ice [02].

**RECENT EVIDENCE OF CHANGE IN THE ANTARCTIC AND GREENLAND ICE SHEETS**

The existing ice supply and the amount of sea level rise it would cause if it melted completely are summarized in Table 1. Here, f= assuming a saltwater density of 1,028 kg/m3, an oceanic area of 3.62 × 108 km2, an ice density of 917 kg/m3, and the replacement of stranded ice below sea level by seawater.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Area****(106 Km2)** | **Volume of Ice****(106 Km3)** | **Possible rise in sea level, (m)f** |
| **Ice Caps and Glaciers** |
| **Smallest Estimate**Source: [30] | 0.51 | 0.05 | 0.15 |
| **Largest Estimate**Source: [10] | 0.54 | 0.13 | 0.37 |
| **Ice Sheets** | 14 | 27.6 | 63.9 |
| **Greenland**Source: [03] | 1.7 | 2.9 | 7.3 |
| **Antarctica**Source: [24] | 12.3 | 24.7 | 56.6 |
| **Snow on Land (Northern Hemisphere)** | 1.9-45.2 | 0.0005-0.005 | 0.001-0.01 |
| **Permafrost (Northern Hemisphere)**Source: [50] | 22.8 | 0.011-0.037 | 0.03-0.10 |

Table 01: Volume, Area, and Sea Level Equivalent of the Other Principal Sea Level Rise Contributing Factors (Source: [17]- [18]- [44]).

The possible significance of ice sheets, glaciers, and ice caps for future sea level rise is shown in Table 1. If all of the glaciers and icecaps melted, the sea level would rise by 0.05 to 0.13 meters. The current Antarctic and Greenland ice sheets hold enough water to increase the sea level by over 57 meters and 7 meters, respectively.

Considering the substantial volume of water held within the Greenland and Antarctic ice sheets, estimated to potentially raise global sea levels by approximately 70 meters (as detailed in Table 01), and acknowledging that the melting of these polar ice masses is the primary driver of future sea-level rise (SLR), even minor changes in their ice volume could lead to significant consequences.

1. **The Greenland Ice Sheet:**

The cyclical changes in temperature throughout the year in Greenland lead to widespread melting within the ice sheet, alongside the breaking off of icebergs and the disintegration of smaller floating ice platforms. Based on a longitudinal study by Tedesco (2007) [45], a notable trend of increasing snowmelt area has been observed over the past fourteen years, with an average annual expansion of 40,000 square kilometers. Additionally, investigations have documented considerable short-term instability in the amount of ice lost and the volume of ice discharged from Greenland's major glaciers that terminate in the sea [44].

1. **The Antarctic Ice Sheet:**

Although low temperatures in Antarctica create no surface runoff, recent satellite studies of ice discharge have challenged the concept that the ice sheet moves with everlasting slowness. The area around Pine Island Bay in West Antarctica is currently losing ice to the ocean at a much faster rate than it's gaining ice through snowfall inland. This imbalance is significant because this single region holds enough ice to potentially raise global sea levels by a meter and could lead to a widespread shrinking of the ice sheet in West Antarctica. Adding to this concern, the collapse of the less stable eastern ice shelf in this area could cause the neighboring Thwaites Glacier to become twice as large. Scientists suspect that a recent small warming of the ocean (about 0.3°C) in this area is a key reason for the widespread increase in ice flow, as the warmer water melts the underside of ice shelves, causing the grounded glaciers behind them to lift off the seabed and flow more quickly [44]. However, glaciers that are sheltered from these ocean changes by large and stable floating ice platforms contribute very little to the overall rise in sea levels. Based on standard methods for estimating runoff, the Antarctic Peninsula is currently contributing measurably to global sea-level rise as a direct and immediate consequence of climate warming. This contribution is estimated to be in the range of 0.008 to 0.055 millimeters annually. While it's challenging to precisely determine what fraction of the ice loss will become water runoff, this amount could potentially increase over the next 50 years if warming trends continue. Additionally, if the glaciers that carry ice away from the main ice sheet become unstable or flow faster, the amount of runoff, and therefore the contribution to sea-level rise, could also increase [44].

**SEA LEVEL RISE(SLR) PROJECTIONS**

The Intergovernmental Panel on Climate Change (IPCC) has faced criticism, notably from Hansen (2006, 2007) [15]- [13], who argued that their earlier projections for Sea Level Rise (SLR) were too low because they didn't fully factor in the possibility of substantial "ice sheet disintegration." Although predicting the precise timing of SLR is difficult due to the complex and often unpredictable nature of glacier breakdown, there are critical tipping points. If these points are surpassed, they could initiate a rapid increase in sea levels, potentially reaching several meters considerably sooner than the end of this century [44].

A major source of uncertainty in predicting future sea level rise stems from the various feedback mechanisms that can accelerate the disintegration of ice sheets, both on their surfaces, within their structures, and in the adjacent oceans. For instance, snow-covered ice is highly reflective, sending most sunlight back into space. However, as warming temperatures cause increased surface melting, the exposed, darker, and wetter ice absorbs more solar energy. Furthermore, much of the resulting meltwater flows to the base of the ice sheet, acting as a lubricant. It also carves channels through the ice, contributing to a faster rate of iceberg calving into the sea [51].

Recent satellite images have shown significant accumulations of meltwater on the Greenland ice sheet's surface. In a separate investigation, researchers analyzed satellite-derived data on the age and thickness of Arctic sea ice to generate a historical record dating back to 1982. Their findings indicated a considerable decrease in the extent of the oldest and thickest ice. This reduction in robust, older ice increases the likelihood of the ice-albedo feedback mechanism intensifying warming trends in the Arctic region [27].

Notwithstanding the challenges in precisely forecasting the various factors contributing to Sea Level Rise (SLR), recent satellite measurements indicate an accelerating trend in the rate of change across these components. Notably, Rahmstorf et al. (2007a) [34] have demonstrated that the rate of sea level increase since 1990 has exceeded the projections of the majority of climate models. In contrast to the Intergovernmental Panel on Climate Change's (IPCC) 2001 best estimate of an increase of less than 2 millimeters per year, satellite data spanning the period from 1993 to 2006 reveals a linear trend in SLR of 3.3 millimeters per year.

In their 2008 study, Pfeffer et al. [33] investigated potential future sea level rise (SLR) resulting from glacier contributions throughout the twenty-first century by positing target increases of 2 and 5 meters. Subsequently, they evaluated existing data on current rates of ice loss to ascertain the feasibility of these targets. Their findings indicate that a total SLR of approximately 2 meters by the year 2100 is achievable under physically plausible glacial conditions, but only in scenarios involving exceptionally rapid and extreme accelerations across all relevant variables. Under more probable, yet still accelerated, conditions, their projections suggest a sea level rise of roughly 0.8 meters by the end of the twenty-first century. Although they propose utilizing this 0.8-meter estimate as a foundation for future forecast revisions, they concede that a range of 0.8 to 2.0 meters remains within the realm of possibility when the complexities of ice flow dynamics are considered [44].

The Last Interglacial (LIG), or Eemian period, spanning roughly 129,000 to 116,000 years before the present, was a time of elevated global temperatures and sea levels. This era offers a significant comparative framework for understanding prospective changes in climate and ocean levels. During the LIG, the global average sea level is believed to have been 5 to 10 meters higher than what is observed today, a considerable difference. Concurrently, with diminished ice sheet extent, the Earth's climate was warmer than its current state. While reconstructions of global temperatures during the LIG vary, suggesting an increase of approximately 2°C above present-day values in some studies and negligible change in others, this period is garnering increasing scientific interest as a potential analog for a warmer planet. Otto-Bliesner et al. (2006) [32] conducted an analysis on how warming in the Northern Hemisphere influenced the Arctic ice fields during the Last Interglacial Period (LIG), spanning from approximately 116,000 to 129,000 years ago. Their methodology involved the use of a comprehensive global climate model, a dynamic model simulating ice sheet behavior, and data derived from past climate records. The integration of climate and ice-sheet modeling, grounded in physical principles and constrained by ice core data, indicates that the Greenland Ice Sheet, along with other ice masses surrounding the Arctic, likely contributed between 2.2 and 3.4 meters to the rise in sea levels during the LIG. Additionally, the climate conditions simulated in their study are consistent with paleoclimate evidence of prior warming events [44]. Utilizing a related methodology, Overpeck et al. (2006) [32] reached the conclusion that if current trends in greenhouse gas emissions persist without significant change, the warmer conditions of the future could induce melting across comparable regions of Greenland. They further suggest that such widespread melting has the capacity to cause a sea level rise of several meters by the end of the current century.

**RESULT AND DISCUSSION**

The synthesis of existing literature presented in this research unequivocally demonstrates the far-reaching and interconnected impacts of climate change on glacial environments and their downstream consequences. The accelerating rate of glacial melt, a direct response to rising global temperatures driven by anthropogenic greenhouse gas emissions, is not only a significant contributor to global sea level rise but also a catalyst for freshwater salinization and a potential trigger for the re-emergence of ancient pathogens. The evidence reviewed confirms a global acceleration in glacial ice loss, with rates doubling in recent decades. This meltwater directly contributes to the observed rise in sea levels, a trend projected to continue and potentially intensify throughout the 21st century. While smaller glaciers play a crucial role in regional water supplies, the massive ice sheets of Greenland and Antarctica hold the key to substantial future sea level rise. The observed instabilities and increasing rates of ice discharge from these Polar Regions, particularly in areas like West Antarctica, raise concerns that future sea level rise could exceed current IPCC projections. The complex interplay of feedback mechanisms, such as the ice-albedo effect and basal lubrication by meltwater, further complicates predictive modeling and suggests the potential for rapid and non-linear increases in sea levels. The comparison with the Last Interglacial period, characterized by significantly higher sea levels, serves as a critical analog for the potential magnitude of future sea level rise under sustained warming. This research highlights the dual pathways through which climate change exacerbates water salinization. Rising sea levels drive the inland intrusion of saltwater into coastal aquifers and estuarine environments, contaminating vital freshwater resources. Simultaneously, altered precipitation patterns and reduced freshwater discharge from glacial melt further diminish the hydraulic pressure needed to counteract this intrusion. Human activities, such as unsustainable water extraction and land-use changes, compound the problem. The projected timelines for the compromise of potable water sources in low-lying coastal areas due to increase over wash events are particularly concerning, posing immediate threats to human health and livelihoods. The dynamic and often less visible nature of subsurface aquifer salinization, compared to the more readily observable salinization of estuaries, underscores the need for comprehensive monitoring and management strategies.

A critical and increasingly recognized consequence of glacial and permafrost thaw is the potential for the re-emergence of ancient microorganisms, including viruses. The identification of viable genetic material from long-dormant viruses, some dating back tens of thousands of years and previously unknown to science, within thawing ice cores is a significant finding. The Siberian anthrax outbreak, directly linked to the thawing of infected animal remains, provides a real-world illustration of the potential for such re-emergence to cause disease. As warming continues and more permafrost and glacial ice melts, the release of these potentially novel pathogens into water systems and surrounding environments increases the risk of exposure to both human and animal populations. The lack of prior exposure and potentially unique virulence of these ancient viruses raises serious concerns about the potential for future pandemics. The findings discussed underscore the intricate interconnectedness of Earth's systems. Glacial melt directly contributes to sea level rise, which in turn drives coastal salinization. The same warming trend responsible for ice melt also creates conditions conducive to the release and potential reactivation of ancient pathogens. The long timescales associated with these processes mean that even with immediate and drastic reductions in greenhouse gas emissions, the impacts of past warming will continue to unfold for centuries. The uncertainties surrounding the precise rates of ice sheet disintegration and the viability and infectivity of re-emerging pathogens highlight the urgent need for continued interdisciplinary research, combining glaciology, hydrology, microbiology, and climate science. This research synthesizes compelling evidence demonstrating that climate change is driving a cascade of critical impacts originating from glacial melt. These impacts extend beyond sea level rise to encompass the salinization of essential freshwater resources and the potential for the emergence of novel infectious agents. The scale and interconnectedness of these threats necessitate immediate and robust mitigation strategies to curb greenhouse gas emissions and proactive adaptation measures to safeguard water security, protect coastal communities, and prepare for potential public health challenges posed by re-emerging pathogens from the thawing cryosphere. The continued monitoring of glacial dynamics, coastal aquifers, and the microbial content of thawing ice is crucial for refining predictive models and informing effective responses to these escalating global challenges.

**CONCLUSION**

The accelerating pace of land ice melt is now surpassing earlier estimates, presenting a significant concern that, absent effective mitigation of climate change, the Earth's interconnected systems will experience a considerable elevation in sea levels, potentially reaching multiple meters. While a one-meter rise in global sea level within the current century is considered a highly likely outcome, the possibility of an even more rapid increase in subsequent decades cannot be dismissed. Although the underlying physical principles governing these transformations are largely established within the scientific community, the acquisition of further comprehensive observational data remains crucial. Such enhanced observations are necessary to more accurately incorporate the intricate dynamics of ice melt into the numerical models that serve as the foundation for generating dependable projections of future sea level change. The projected consequences of climate change extend to a significant inland encroachment of seawater across the majority of the planet's coastal regions. This phenomenon will inevitably induce fluctuations in the salinity levels of any municipality or settlement that relies on an unconfined aquifer or an estuarine ecosystem situated proximally upstream from the tidal saltwater limit for its potable water supply. Considering the considerable number of people residing in low-lying coastal zones- specifically, 230 million individuals living below an elevation of 1-meter relative to the present mean high tide line, and an additional 1 billion inhabiting areas below 10 meters- the likelihood of widespread drinking water salinization is substantial. Nevertheless, the necessary undertaking of relocating sources of potable water to mitigate this contamination will present formidable financial and logistical hurdles for a multitude of communities and nations globally. It turns out that glaciers might be holding onto more than just frozen water- they could also be reservoirs for ancient viruses. Scientists have discovered that some of these viruses trapped in the ice are very old and might have unique features we haven't seen before. As glaciers melt, this meltwater can carry these viruses into rivers and other water systems, potentially bringing them into contact with people and animals. This is a serious concern because these previously isolated viruses could pose a significant risk of causing new pandemics and widespread illnesses. To prevent the possible outbreak of novel viral diseases from this source, it's crucial that we take immediate and strong steps to tackle climate change and the melting of ice in polar regions and frozen landscapes.

It's important to understand that even if we managed to keep the amount of greenhouse gases in the air from increasing any further, the warming trend caused by human actions and the resulting rise in sea levels wouldn't just stop immediately. These are long-term processes that will continue to play out over centuries due to the way the climate system works and responds. Scientists anticipate that ice on land, like the massive ice sheets in Greenland and Antarctica, will keep melting at an accelerated rate. Additionally, as the oceans absorb heat, the water itself expands, which will also significantly contribute to higher sea levels. Right now, one of the biggest uncertainties and points of discussion among researchers is precisely how much ice the Antarctic and Greenland ice sheets are losing. Furthermore, the complex ways these ice sheets move and break off icebergs- processes that we still don't fully understand- make it challenging to accurately predict just how much they will contribute to sea level rise in the future. New data that scientists have gathered recently could have a really significant effect on our predictions for sea level rise. The reason for this is the sheer size of the ice sheets in Greenland and Antarctica. They contain so much frozen water that if they were to melt completely, the world's oceans would rise by over 70 meters. This means even relatively small changes in the amount of ice they lose can lead to substantial increases in sea level. To put it in perspective, if just the Greenland ice sheet melted entirely, the average sea level globally would go up by about 7 meters [44]. As we learn more about how rising temperatures are impacting these enormous ice masses through ongoing research, we'll be able to make more accurate predictions about the future. However, the information we have right now is raising some serious concerns. It suggests that we might be approaching a tipping point- a critical level of warming- that could trigger a rapid and substantial rise in sea levels, potentially by many meters, and this could happen much earlier than we previously anticipated, even before the end of this century.

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