The influence of topographic parameters coupled with increasing surface temperatures and anthropogenic activity are melting the Himalayan glaciers; Khumbu glacier with debris cover, Nepal.

PHOTO COURTESY: WILFRIED HAEBERLI

2. Predicting Future Pathways: Permafrost, Sea ice and Glaciers

The chapter discusses the impacts of climate change on the cryosphere, which includes the earth's glaciers, ice sheets, permafrost, and sea-ice. The melting of these components of the cryosphere is caused by the rise in global temperatures and the subsequent increase in greenhouse gas emissions. The melting of the Arctic sea ice will have a severe impact on the Arctic environment, including its biodiversity and habitat, which will affect the livelihood of the indigenous population. Moreover, the loss of multiyear sea ice is contributing to Arctic amplification, leading to a significant increase in surface air temperature. This chapter also highlights the teleconnections between Arctic sea-ice and regional monsoons and how the melting of ice can affect the ocean circulation. The changes in temperature gradient between mid-latitudes and the Polar region can cause weather extremes such as heat waves. Finally, it discusses the impacts of climate change on permafrost, which contains almost twice the amount of carbon than the atmosphere. The thawing of permafrost releases carbon along with methane, another greenhouse gas, into the atmosphere, contributing to further rise in global temperatures.

2.1 Introduction

Climate change is no longer a myth or mere speculation. It is impacting lives and livelihoods in all spheres be it onshore or offshore, mountainous, coastal areas or plains. The cryosphere and oceans support unique habitats and are interconnected with other components of the climate system through global exchange of water, energy and carbon dioxide (Krishnan, 2023). Around 10 per cent of earth's land area is covered by glaciers or ice sheets which are sensitive to climate change processes. The projected responses of the cryosphere to the global warming and climate change, accelerated by the human induced greenhouse gas emissions, has led to widespread shrinking of the cryosphere, with mass loss from ice sheets and glaciers, vanishing sea ice in Arctic both in extent and thickness, melting of ice sheets in Greenland, West and Peninsular Antarctica and the high mountain glaciers of Himalaya. The permafrost in the Arctic, highland of Tibet and Himalaya and elsewhere in the cold regions of the earth is thawing due to this rise in temperature.

mass loss

2.2 Arctic Sea ice

The Arctic occupies an area of about 40 million sq km that is three times larger than Europe and represents about eight per cent of the earth, housing four million people. The rise in the global temperatures and consequent melting of Arctic sea-ice will adversely impact the Arctic environment including the biodiversity and the habitat, impacting the livelihood of the population, especially the indigenous people that constitute about 15 per cent of the population.

2.2.1 Impact of Global Warming on Sea ice

The spatial pattern of the warming of the surface temperatures is not uniform. Some regions, such as the Arctic, are warming at alarming rates, nearly four times higher than the global average. The temperature in 2022 was almost 1.2 degrees warmer than the pre-industrial climate. With the increase in the greenhouse gases, Arctic sea-ice is projected to further decrease.

greenhouse gas

Arctic sea-ice extent has recorded a decreasing trend for all months of the year. The extreme warming of the Arctic has been well recognized more so after the year 2000. The rate of warming is much higher and this is leading to increased melting of sea-ice as also the ice sheets of Greenland where extreme melting was only observed in the years 2019 and 2021. The trends in the Arctic sea-ice cover in March show a decline of about 2.6 per cent per decade. The month of September, which is the end of summer season in the northern hemisphere, records minimum sea ice. Between 1979 and 2018, the rate of reduction is 12.8 ± 2.3 per cent per decade during this month. The Arctic sea-ice has thinned, with loss of multiyear sea ice amounting to nearly 90 per cent loss of five-year-old ice. The loss of sea ice contributes to the Arctic amplification with surface air temperature increasing by more than double the global average over the last two decades. The model (SSP 245) predicts the future projection of melting, under medium median emission scenario, to reach about 15 per cent. Models capture that under these scenarios the Arctic may be sea ice free by 2050 unless emissions are brought down considerably with grave consequences (Krishnan, 2023).

Arctic sea ice extent

emission

2.2.2 Teleconnections

regional monsoon teleconnection pattern thermohaline circulation

Arctic sea-ice can influence the regional monsoons through the teleconnection patterns. The melting of ice influences the ocean circulation. The contrast in the dense cold water columns of North Atlantic and the warm fresh water of lower latitudes establishes a density gradient which results in thermohaline circulation or overturning of the waters. With increased melting of the sea-ice, more fresh water will be introduced in the North Atlantic altering the tropospheric temperatures and weakening the thermohaline circulation. This in turn would affect the Indian summer monsoon adversely.

Arctic vortex heat wave radiative forcing

As the temperature increases and the Arctic ice melts, the Arctic vortex can break down and the Polar jet stream can weaken. The changes in the temperature gradient between the mid latitude and the Polar region can produce meanders in the jet stream, which can also influence the mid latitude and lead to weather extremes like heat waves as witnessed during the Russian heat wave in 2010 (Krishnan, 2023). The experiments have confirmed that when we increase long wave radiative forcing, the extent of the sea-ice decreases and with further increase in the radiative forcing the meandering starts. The assessment is that even the Gulf Stream will weaken.

2.3 Permafrost

Permafrost is defined as a frozen surface below the land which is typically frozen for about two years or more. It may occur in a continuous, discontinuous, sporadic or isolated form in nature. It is spread over in the Northern hemisphere for more than 20 million sq km. When it comes to the Himalayas, it has the largest area of mountain permafrost in the world.

loss of the permafrost

The loss of the permafrost in the Arctic and other cold and high mountain regions of the world such as Tibet and Hindukush Himalaya, as also in other areas, is driven by rise in surface air temperature, globalisation, infrastructure development, migration and tourism. The Permafrost temperatures have increased to record high levels when observed for the period from 1980s onwards to the present including the recent increase by 0.29°C ± 0.12°C (IPCC AR 6) from the year 2007 to 2016.

soil carbon

Arctic and boreal permafrost contain 1460–1600 Gt organic carbon, almost twice the carbon in the atmosphere. Preliminary computer analyses suggest that permafrost could produce carbon equal to about 15 per cent of today's emissions caused by human activities. Permafrost thaw and glacier retreat have decreased the stability of high mountain slopes with disruption in infrastructure (Goswami, 2023). Globally the permafrost has about 1,700 pentagram of carbon which is equal to about 1/4 of the total soil carbon. The soil carbon which gets frozen and trapped in the permafrost can be released on thawing. It warms the local climate, impacts the overall global climate and can have disastrous effects on roads, constructions and other infrastructures.

The studies on the permafrost areas in Himalaya have yet to gain momentum. However, some areas such as Lahaul and Spiti district in Himachal Pradesh and Tso Kar in Ladakh have been identified for detailed studies by Indian scientists where subsidence has been calculated in centimetres by using interferometry. The models suggest that southwest and northward monsoon rains and extreme events are likely to increase in Ladakh. This will cause permanent loss to the permafrost.

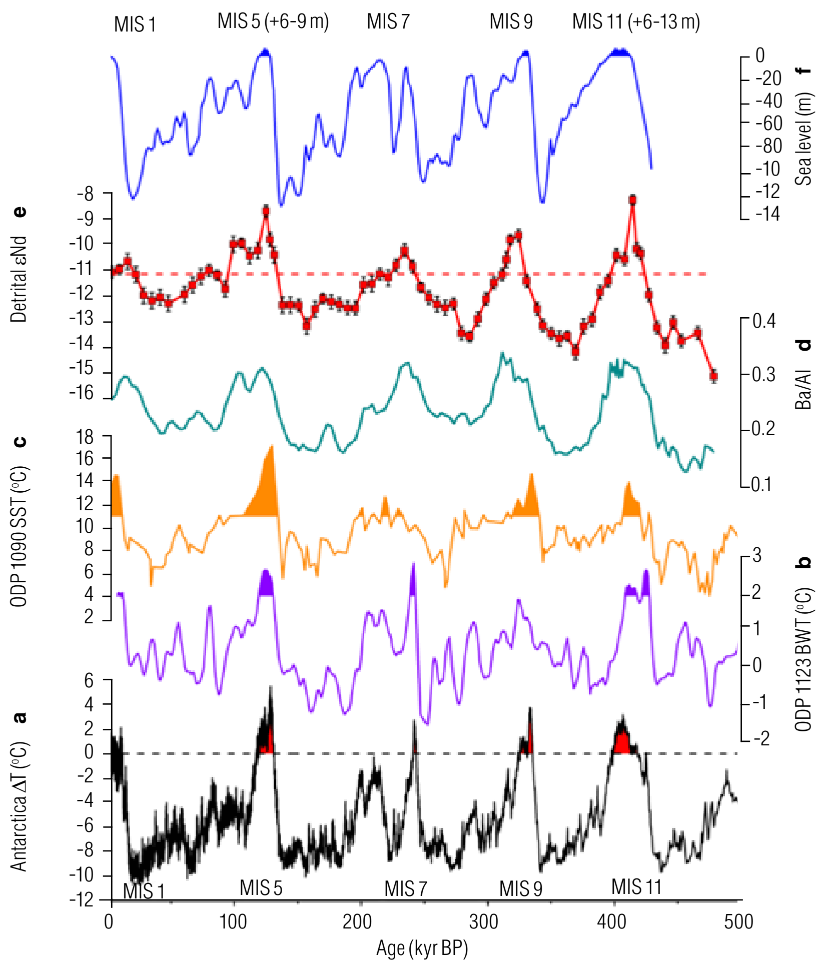
subsidence

2.4 The Antarctic Scenario

Antarctica is a unique continent, dominated by an ice sheet. With 98 per cent of the continent covered by permanent ice that accounts for 30 x 106 cu km of the ice. Antarctica is also the storehouse of 70 per cent of the earth's fresh water locked in its vast expanse of ice. The global rise in temperatures and climate change have also touched Antarctica which displays variable melt rates in different parts. The West Antarctica and Antarctic Peninsula are the worst affected, while the east Antarctic ice sheet has also

ice sheet

Fig. 2.1: Pliocene Greenhouse



Source: Rahaman, 2023

temporal variation
negative mass balance

started showing a negative mass balance (Kumar, 2023a). The Antarctic Sea ice expansion and recession are asymmetric with regional and temporal variation. While the sea ice was exhibiting a positive trend till 2015, the satellite data for subsequent years reveal that the years 2016, 2020, 2022 and 2023 have seen the lowest growth in Antarctic sea ice. The sea ice in the months of January and February in the Ross Sea Region too has recorded a drastic decline. The extent being 43 per cent lower than the mean extent of the previous years. The low sea ice significantly impacts the stability of the Antarctic ice shelves.

2.4.1 West Antarctic Ice sheet

risk
Pliocene

The West Antarctic Ice sheet is undergoing rapid mass loss currently and may collapse at some point of time with catastrophic consequences. A peep into the geological time scale when the CO_2 was very high along with high SST and atmospheric temperatures hints what we can expect with similar conditions in the present scenario. In one of the reconstructions for the last interglacial period in the Pliocene at 5.3 to 2.6 million years, CO_2 was 400 to 450 ppm and SST was two to three degree higher, and West Antarctica was completely free of ice. This particular interval is considered to be the best analogue for our near future climate. Two of the major glaciers in West Antarctica are undergoing rapid mass loss and most of the consequent rise in sea level, at approximately one cm per decade, is coming from the melting of land ice and glaciers of West Antarctica (Rahaman, 2023) leaving the coastal habitats worldwide, including India, at risk. The isotopic analyses of the sediments retrieved from this part have revealed a dynamic ice sheet situation in warm Pliocene to icehouse conditions in Pleistocene (Fig. 2.1).

2.4.2 Biogeochemical Changes

nutrient dynamics
carbon pump

The interaction of ice-ocean-atmosphere and ice-free high latitude ocean waters, have opened up new fields of research to understand the biogeochemical processes taking place under the climate change scenario. The Antarctic Sea ice is a substrate for algal growth that influences nutrient dynamics and water column stratification. Sea-ice melting gives rise to phytoplankton bloom which in turn controls the CO_2 draw-down as part of the carbon pump (George, 2023). A steadier mooring system has been set up in the sea ice with temperature sensors at 2 cm interval across the sea-ice.

2.5 The Himalaya

freshwater
discharge regime
glacial lakes

The glaciers all over the world are losing mass and the Himalaya is no exception when it comes to the impact of global warming and climate change on the cryosphere. The Himalaya stores the largest number of mountain glaciers with varying geometry that serve millions of people downstream as the source of freshwater for drinking and agriculture. Decline in the glacier mass eventually alters the local and regional hydrology by changing the discharge regime and also increasing the number and area of glacial lakes.

Though the direct field measurements of the glacier mass balance over Himalaya are limited, studies have shown that Himalaya has lost the ice mass in all its eastern, central and western sectors.

2.5.1 Kashmir Himalaya

Field studies coupled with remote sensing data in Jammu, Kashmir and Ladakh for over more than 12,000 glaciers occupying 19,727 sq km area, have revealed thinning during the period from 2000 to 2012 (Romshoo, 2023). During the last six decades glaciers have lost almost 25 per cent of the mass in the Upper Indus Basin. By the end of this century, the loss would amount to almost 47 to 67 per cent under these scenarios. The glaciers have receded and thinned with maximum thinning in the Pir Panjal Range and minimum in the Karakoram Range.

Indus Basin
Pir Panjal Range

2.5.2 Western Himalaya

The excessive melting of the glaciers in Chandra basin of Himachal Pradesh has resulted in an increase of the mean annual discharge by about 50 per cent during the last five decades (Sharma, 2023b). For example, in the Bhaga basin of Himachal Pradesh, glaciers have lost a huge ice mass equivalent -1.06 ± 0.3 m w.e/year. The rise in the melting and consequent spring runoff has changed the hydrological behaviour due to availability of water earlier on in the basin. The runoff, when constrained by moraines, gets stored in the form of glacial lakes and adds to the further ice loss due to calving. Glacial lakes in Samudra Tapu and Gepang Gath glaciers have shown 20 to 25 times expansion over the last five decades.

Chandra basin
Bhaga basin

2.5.3 Sikkim Himalaya

Compared to western Himalaya, the Sikkim Himalaya in eastern parts of the range present a different scenario due to being in different climatic and topographic zones. The glacier area loss in Sikkim ranges from 20 per cent to 30 per cent at different basins (Debnath, 2023). The exceptional and high recession has produced a number of glacial lakes which show 8 to 35 per cent of lake area expansion.

topographic zones
glacial lakes

The influence of topographic parameters coupled with increasing surface temperatures, low precipitation and anthropogenic activity are the main causes for the loss of glaciers. The debris cover or debris free glacier responds differently to the ablation, with clean glaciers suffering more loss than the others (Shukla, 2023). The melting glaciers have significant impact on water resources of Himalayan Rivers due to change in glacier basin hydrology, downstream water budget, impact on hydropower plants due to variation in discharge, flash flood (GLOF) and sedimentation.

Himalayan rivers
water budget
hydropower

2.6 Recommendations

i. Most of the models on Arctic sea-ice, especially the scenarios of the ER6 September Arctic ice, capture the free fall of sea-ice and predict that the Arctic will be free of sea ice by 2050. It is only in the low emission scenarios in the SSP 119 and 126 that the Arctic can be saved from the Arctic free ice condition (Krishnan, 2023).

ii. We need to advance capabilities in climate and earth system modelling and prediction systems, advance impact assessments, development of adaptation strategies to mitigate risk and for policy making, improve early warning systems and more importantly advance scientific research academic collaborations to complement and enhance in house R&D capabilities minimum climatologically (Krishnan, 2023).

iii. The data on permafrost area in Himalaya is constrained. There is a strong need to initiate a long term programme for mapping of such areas and collection of data on depth profile and extent of permafrost, especially in Lahaul and Spiti district of Himachal Pradesh and Ladakh region (Goswami, 2023).

iv. More glaciers in Himalaya need to be monitored for ice mass loss, recession and formation of glacial lakes. Space based observations need to be supplemented by field checks and ground surveys (Rahaman, 2023).