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Excerpt
More Information

1 Why study glaciers?

Before delving into the mathematical intricacies with which much of this book is concerned, one might well ask why we are pursuing this topic – glacier mechanics? For many people who would like to understand how glaciers move, how they sculpt the landscape, how they respond to climatic change, mathematics does not come easily. I assure you that all of us have to think carefully about the meaning of the expressions that seem so simple to write down but so difficult to understand. Only then do they become part of our vocabulary. Only then can we make use of the added precision which mathematical analysis, properly formulated, is able to bring. Is it worth the effort? That depends upon your objectives; on why you chose to study glaciers.

There are many reasons, of course. Some are personal, some academic, and some socially significant. To me, the personal reasons are among the most important: glaciers occur in spectacular areas, often remote, that have not been scarred by human activities. Through glaciology, I have had the opportunity to live in these areas; to drift silently in a kayak on an ice-dammed lake in front of our camp as sunset gradually merged with sunrise on an August evening; to marvel at the northern lights while out on a short ski tour before bedtime on a December night; and to reflect on the meaning of life and of our place in nature. Maybe some of you will share these needs, and will choose to study glaciers for this reason. I have found that many glaciologists do share them, and this leads to a comradeship that is rewarding in itself.

Academic reasons for studying glaciers are perhaps difficult to separate from socially significant ones. However, in three academic disciplines, the application of glaciology to immediate social problems is at least one step removed from the initial research. The first of these is glacial geology. Glaciers once covered 30% of the land area of Earth, and left deposits of diverse shape and composition. How were these deposits formed, and what can they tell us about the glaciers that made them? The second discipline is structural geology; glacier ice is a metamorphic rock that can be observed in the process of deformation at temperatures close to the melting point. From study of this deformation, both in the laboratory and in the field, much has been learned about the origin of metamorphic structures in other crystalline rocks that were deformed deep within the Earth. The final discipline is paleoclimatology.

Glaciers record climatic fluctuations in two ways: the deposits left during successive advances and retreats provide a coarse record of climatic change which, with careful study, a little luck, and a good deal of skill, can be placed in correct chronological order and dated. A more detailed record is contained in ice cores from polar glaciers such as the Antarctic and Greenland ice sheets. Isotopic and other chemical variations in these cores reflect past atmospheric circulation patterns, changes in temperature, and changes in the composition of the atmosphere. Changes during the past several centuries to several millennia can be quite precisely dated using core stratigraphy. Those further back in time are dated less precisely using flow models and proxy measures of other well-dated phenomena such as Earth's orbital variations.

Relatively recent changes in climate and in concentrations of certain anthropogenic substances in the atmosphere are attracting increasing attention as humans struggle with problems of maintaining a healthy living environment in the face of overpopulation and the resulting demands on natural resources. Studies of ice cores and other dated ice samples provide a baseline from which to measure these anthropogenic changes. For example, levels of lead in the Greenland ice sheet increased about 4-fold when Greeks and Romans began extracting silver from lead sulfides in ~500 BCE (Hong *et al.*, 1994). Then, after dropping slightly in the first millennium AD, they increased to more than 80 times natural levels during the industrial revolution and to more than 200 times natural levels when lead additives became common in gasoline in ~1940 (Murozumi *et al.*, 1969). These studies are largely responsible for the fact that lead is no longer used in gasoline. Similarly, measurements of CO_2 and CH_4 in ice cores have documented levels of these greenhouse gases in pre-industrial times.

Other applications of glaciology are not hard to find. Some people in northern and mountainous lands live so close to glaciers that their lives would be severely altered by significant ice advances. Tales from the seventeenth and eighteenth centuries, a period of ice advance as the world entered the Little Ice Age, tell of glaciers gobbling up farms and farm buildings. Buildings were crushed into small pieces and mixed with "soil, grit, and great rocks" (Grove, 1988, p. 72). The Mer de Glace in France presented a particular problem, and several times during the seventeenth century exorcists were sent out to deal with the "spirits" responsible for its advance. They appeared to have been successful, as the glaciers were then near their Little Ice Age maxima and beginning to retreat. Increasing amounts of industrial black carbon, an aerosol, were falling on glacier surfaces then, absorbing solar radiation and increasing melt rates (Painter *et al.*, 2013)

Retreat may also present a problem. In many places, melting glacier ice provides a steady source of water for irrigation and other uses during the summer months. Glacier retreat reduces this flow and may divert it to a different valley. In the western Himalaya, such a diversion forced the inhabitants of Kumik to move their village to a new location and dig a 7 km canal to provide water (Mingle, 2015).

Retreat of the Greenland and Antarctic Ice Sheets, together with that of numerous mountain glaciers world-wide, is also raising sea level. This retreat is expected to continue and to accelerate (Straneo and Heimbach, 2013) as global warming, exacerbated by black carbon from forest fires and burning of fossil fuels, increases melting. In the Admundsen Sea sector of West Antarctica, retreat of Thwaites and Pine Island glaciers could trigger collapse of the West Antarctic Ice Sheet, raising sea level ~3 m during the coming centuries to millennia (Park *et al.*, 2013; Feldmann and Levermann, 2015). In short, sea-level rise will increasingly impact our coastal infrastructure. Some political jurisdictions have had the foresight to begin planning for this eventuality.

Other people live in proximity to rivers draining lakes dammed by glaciers. Some of the biggest floods known from the geologic record resulted from the failure of such ice dams, and smaller floods of the same origin have devastated communities in the Alps and Himalayas. Somewhat further from human living environments, glaciologists may study the possibility of extracting economically valuable deposits from beneath glaciers, or how to curb the discharge of icebergs into shipping lanes.

Glacier ice itself is an economically valuable deposit; glaciers contain 60% of the world's fresh water, and peoples in arid lands have seriously studied the possibility of towing icebergs from Antarctica to serve as a source of water. People in mountainous countries use glacier meltwater not only for drinking, but also as a source of hydroelectric power. By tunneling through the rock under a glacier and thence up to the ice–rock interface, they trap water at a higher elevation than would be possible otherwise, and thus increase the energy yield. Glaciologists provide advice on the activity of the glaciers and where to find streams beneath them.

Lastly, we should mention a proposal to dispose of radioactive waste by letting it melt its way to the base of the Antarctic Ice Sheet. How long would such waste remain isolated from the biologic environment? How would the heat released affect the flow of the ice sheet? Might it cause a surge. In the end, this project was abandoned, not on glaciological grounds but, rather, because there seemed to be no risk-free way to transport the waste to Antarctica.

A good quantitative understanding of the physics of glaciers is essential for rigorous treatment of many of these academic problems, as well as for accurate analysis of various engineering and environmental problems involving glaciers and of concern to humans. The fundamental principles upon which this understanding is based are those of physics and, to a lesser extent, chemistry. Application of these principles to glacier dynamics is initially straightforward, but, as with many problems, the better we seek to understand the behavior of glaciers, the more involved, and often the more interesting the applications become.

So we have answered our first question; we study glaciers for the same reasons that we study many other features of the natural landscape, but also for a special reason which I will try to impart to you, wordlessly, if you will stand with me looking over a glacier covered with a thick blanket of fresh powder snow to distant peaks, bathed in alpine glow, breathless from a quick climb up a steep slope after a day of work, but with skis ready for the telemark run back to camp. “Mäktig,” my companion said – powerful.