Review

GREVE, R. and H. BLATTER. 2009. *Dynamics of ice sheets and glaciers*. Berlin, Springer. 301pp. ISBN-10: 3-642034-14-4, ISBN-13: 978-3-642-03414-5, hardback, US$159.

Teaching a quantitative glaciology class I have often found myself relying on some combination of Hooke's *Principles of glacier dynamics* (Hooke, 2005), Cuffey's recent update of Paterson's classic *The physics of glaciers* (Cuffey and Paterson, 2010) and Van der Veen's slightly dated but still eminently practical *Fundamentals of glacier dynamics* (Van der Veen, 1999). I have occasionally directed the more mathematically inclined students to sections of Hutter's more difficult, but rewarding, *Theoretical glaciology* (Hutter, 1983). The recent monograph *Dynamics of ice sheets and glaciers* by Ralf Greve and Heinz Blatter is a welcome addition to the canon, slotting into the more advanced end of the spectrum. Unlike the other books mentioned, it is focused exclusively on the dynamics of ice sheets and glaciers, so several notable glaciological topics are not covered or are mentioned only briefly. For example, ice–ocean interaction is omitted, though it has become a necessary component of any modern discussion of ice sheets and climate. With its narrow focus and hefty price tag, one would not recommend this book as the primary textbook for either an introductory or advanced glaciology course. However, teachers will do well to have a copy placed on reserve at the library, and researchers will want to have a copy on their bookshelf (next to their worn copy of Paterson), because the topics covered are covered extremely well, with a wealth of detail and rigor not present in any of the alternatives.

After a brief introduction in which the cryosphere, ice sheets, glaciers and ice shelves are defined, chapters 2 and 3 introduce readers to the mathematical and physical background needed to understand glacier flow. Both chapters provide concise reviews that serve to remind students about vectors and tensors (chapter 2) and continuum mechanics (chapter 3). They also introduce the notation conventions used throughout the book. I particularly like the way vectors and tensors are defined by the way they transform, and the final section in chapter 3, where the simple problem of gravity-driven laminar thin-film flow is explored. This simple problem foreshadows the development of glacier dynamics that follows in chapters 5 and 6, and provides a conceptually simple example to which students can return when pondering the complexities of the shallow-ice approximation. I suspect that students who have never seen a tensor before or have never been exposed to continuum mechanics may find this rapid-fire introduction overwhelming and may need a more extended introduction. However, with a little coaching and external reading assignments, most advanced undergraduate students and beginning graduates should be able to bring themselves up to speed.

In chapter 4 we learn a little about the crystal structure of ice and are introduced to Glen's flow law and the nonlinear rheology of ice. While the presentation is clear, a disappointment of this chapter is a lack of empirical data to support the rheology. Much of the observational evidence that led to, and has pointed towards the limits of, Glen's flow law appeared in the pages of the *Journal of Glaciology*. Without observational evidence, students must take the author's word that Glen's flow law is an appropriate description for ice.

The real strength of the book lies in chapters 5 and 6 wherein the full Stokes-flow problem of ice-sheet dynamics in all of its splendor is first revealed and then the shallow-ice and shallow-shelf approximations are derived using scaling arguments. The notation is clean and the exposition describing the scale analysis is unusually clear, making the scaling arguments easy to follow. They appear to be designed to appeal to those with backgrounds in geophysical fluid dynamics, going to the extreme of copying the nomenclature of geophysical dynamicists to describe the various approximations as 'hydrostatic' or 'non-hydrostatic'. Also included is a valuable discussion of the implementation details of finite-difference methods (for the shallow-ice approximation) and finite-element methods (for the shallow-shelf approximation). An ice-sheet modeler will eventually need a more in-depth introduction to numerical methods, but these sections provide the hints necessary for someone with a little experience with numerical methods to get started writing their own ice-sheet model.

Chapter 7 expands the treatment from ice sheets to glaciers, providing one of the best descriptions of how glaciers differ dynamically from ice sheets. Hidden within this chapter is the authors' short treatment of sliding. The approach to sliding uses dimensional analysis along with some modest physical intuition to guess the form that the sliding law must take for hard- and soft-bedded glaciers. This is a refreshing approach and will be appreciated by readers with a physics background. It is, however, unfortunate that basal sliding does not receive more space and attention since specifying appropriate basal boundary conditions, especially in regions with active basal hydrology, remains one of the most challenging problems faced by numerical modelers and field glaciologists alike.

Chapter 8 introduces glacial isostasy, a subject crucial to accurately modeling past ice ages, while chapter 9 includes a discussion of anisotropy with a focus on the CAFFE model (Continuum-mechanical Anisotropic Flow model based on an anisotropic Flow Enhancement). The discussion of the CAFFE model is one of the clearest I have come across. However, unlike the discussion of dynamics, the authors do not go through the general case in which one starts with 21 degrees of freedom in the anisotropy tensor and then uses symmetries to simplify until only a handful of the most important degrees of freedom remain. This is admittedly tedious to perform, but students do benefit from seeing the contraction so that they can better appreciate the maximum simplicity of the CAFFE model. Beyond anisotropy, chapter 10 also discusses compressible firn and temperate and polythermal glaciers.

Space constraints and the reality that glacier dynamics is a rapidly evolving field inevitably lead to the selective inclusion or exclusion of topics. I was nonetheless disappointed that inverse methods were discussed only in passing. Inverse methods have played a prominent role in modern ice-sheet models as a means of avoiding initialization problems and better understanding basal processes. The ability to not only solve the forward problem but also fashion a reasonable inverse model is something that any budding ice dynamicist must have in their bucket of tools. Nonetheless, readers will want this book on their shelf for what it does provide, a thorough and rigorous introduction to ice-sheet and glacier dynamics; that is, after all, what the book is about.

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