

REVIEWS

LLIBOUTRY, L.A. 1987. *Very slow flows of solids. Basics of modeling in geodynamics and glaciology*. Dordrecht, etc., Martinus Nijhoff Publishers.

OVER past years the gap between two types of glaciological modeller has widened; there now seems to be little communication between the specialists in continuum mechanics, determined to purify and reform mathematical techniques, and the physicists, struggling to represent the real world of ice and snow as best they may. Professor Lliboutry has written this book for all modellers: to help the physicist to become aware of modern mathematical methods and to help the mathematician to understand the fascinating and complex behaviour of rock and ice on all scales.

The book begins with a broad introduction to modelling. This is an unusual mixture of standard explanations of basic terms — elasticity, viscosity, stress — and penetrating comments on methodology. The section on boundary conditions could be read with profit by modellers in any field. There follows a chapter on the Laplace temperature equation. Here we begin to appreciate the characteristic method of the author. The nature and methods of solution of the equation are explained plainly as in many mathematical physics textbooks. What is different is the attention given to the examples. These are not only of geophysical interest in themselves — for example, Fourier's calculation of geothermal heat flux — but also show the reader how to think about physical problems.

Chapter 3 introduces stress, strain, and the basics of tensor calculus, but the reader is not allowed to proceed directly to the solution of flow equations. Faithful to his purpose, Lliboutry insists first on a thorough grounding in the material properties of the substances to be modelled. Chapter 4 reviews the microscopic processes of creep and chapter 5 the macroscopic constitutive laws for the rheological behaviour of ice and rocks. Both chapters are packed with fascinating material; rocks or ice, the author's enthusiasm knows no bounds.

The reader is then introduced to two classic flow problems which have been treated using the assumption of uniform viscosity, isostatic rebound, and glacier sliding. The required mathematical techniques (Navier–Stokes equations, bi-harmonic functions, and Fourier transforms) are explained simply and clearly, but the most valuable part of the chapter is the review of the basal sliding problem, which has by no means been solved, even in the case of no cavitation.

There is more on basal sliding, cavitation, and subglacial hydraulics in the chapter on temperate valley glaciers. Unfortunately, the discussion of surges is very brief, but there are enough references to lead the keen student into the literature. Points of mathematical interest are the introduction of kinematic waves and an inverse problem — how can the velocities at depth in a glacier be deduced from measurements at the surface?

Chapters 8 and 9 introduce the most complex modelling problems, in which velocity and temperature are coupled. For glaciologists, these are, above all, the inverse and forward problems for polar ice sheets: prediction of conditions below the surface of the ice sheet from surface measurements and modelling its evolution under changing climatic conditions. Professor Lliboutry does not attempt an exhaustive review of the forward problem but provides a useful summary. His distinction between the short-term response of the lower boundary layer and the long-term response of the whole ice sheet is helpful.

Throughout the book, and especially in chapter 10, the author produces finite-difference schemes for the equations

under discussion and shows how the stability of a given scheme can be determined. Chapter 13 introduces variational theorems and the finite-element method. It is rare to find this emphasis given to numerical methods but Lliboutry rightly wishes to deter the novice modeller from leaping in with home-made schemes. The sections on the propagation of errors in solution schemes for inverse problems are crucially important.

And so this astonishingly rich book continues; chapters on elasticity, perfect plastic behaviour, viscoelasticity, and transient creep; examples from plate tectonics (can we model the collision of India with Asia?); tantalizing references to key glaciological problems (how should we include the properties of "Wisconsin" ice in polar ice-sheet models?). There are even appendices with those odd bits of mathematics one always seems to need.

So are there no criticisms? No doubt, there will be lively disputes about some of the new material in the book. However, my impression is that the author has been very careful to warn the reader whenever he is about to propound theories which are not yet generally accepted. My only real regret is that the book has not been read by an editor with English mother tongue. Despite Professor Lliboutry's formidable grasp of the language, there are places where the inevitable errors are a bar to understanding. But I would not wish to lose some examples of the authentic tone of the author: "Singularities shall not be conjured away by avoiding placing a node at the singular point"; "One may request more thought and less computer"! There are a number of misprints, but these have already been identified in an erratum sheet and will no doubt be corrected in the next edition.

It must be admitted that this is a dense, allusive book; not easy reading even for those with experience in the field. It is the summation of a lifetime's work by a profoundly original scientist and cannot be fully appreciated without long and careful study. But, despite the difficulties, it is an essential text for all glaciologists. Let us hope that the publisher can be persuaded to produce a reasonably priced paperback version soon.

E.M. MORRIS

SWITHINBANK, C. 1988. *Satellite image atlas of glaciers of the world: Antarctica*. Washington, DC, United States Government Printing Office. (United States Geological Survey Professional Paper 1386-B.)

THIS volume is the first published regional chapter of the USGS *Satellite image atlas of glaciers of the world*. The complete atlas, edited by Richard Williams and Jane Ferrigno, was formulated in 1979 to provide a Landsat image base line of global ice extent for the period 1972–82, and will include contributions from 50 scientists. This large project, originally to be published as one volume, has grown in scope, taken longer than planned, and is now being published as 11 separate chapters: one introductory chapter, nine regional chapters, and a topically oriented chapter. Antarctica (chapter B) is not only the first to be published but also possibly the most important in the series. This is not only because Antarctica contains the vast majority of glacier ice on Earth, but because at present less than 20% of the Antarctic ice sheet has been mapped at a scale of 1:250 000 or larger, and satellite imagery offers the potential of economically increasing this coverage and of monitoring any changes.

The Antarctica chapter can be divided into two sections of almost equal length. The first, written by Charles Swithinbank with a small contribution from Trevor Chinn on the Dry Valleys of Victoria Land, uses selected Landsat images to describe and qualitatively interpret glaciological features. The second half, prepared by Richard Williams and Jane Ferrigno, consists of tables identifying and qualifying the best available Landsat 1, 2, and 3 multi-spectral scanner (MSS) images for each of the 2514 nominal scene centres within Antarctica, and the useable images from the limited number of Landsat 3 return beam vidicom (RBV) images not over-exposed. Two 1:10 000 000 scale maps accompany the volume: one showing the location of the images discussed in detail, and the second an index map showing by coded key the quality of the optimum image available for each scene centre.

There can be little dispute that Charles Swithinbank is uniquely qualified to write the Antarctica chapter of the *Atlas*. His foresight and enthusiasm in identifying the potential of, at first meteorological satellites (in the late 1960s), and then the Landsat series for glaciological research, his prodigious and possibly unmatched first-hand knowledge of the geography of the Antarctic continent, and his broad familiarity with Antarctic literature provide an extremely sound base for the chapter.

Following an introduction, the descriptive part of the volume is divided into five geographical sectors (the Transantarctic Mountains, the Indian, Atlantic, and Pacific Ocean sectors, and the Antarctic Peninsula). Each of these is further divided into sub-sections based on geographical features such as mountain ranges, coastlines, or ice shelves. Sixty-one annotated figures (mostly at 1:1 000 000 or 1:500 000 scale and one-third of them in false colour) derived from carefully selected satellite imagery are used to describe the important glaciological features in each of the areas. The vast majority of available Landsat images prior to 1982 came from Landsat 1 during the 1972–73 and 1973–74 austral summers, and nearly 75% of the figures are from this spacecraft with only a few figures derived from Landsat 2 and 3 imagery (and one from Landsat 4). Several images from the NOAA/TIROS N series of meteorological satellites show that, because of the large scale of major Antarctic glaciological features, even a 1.1 km resolution is useful for mapping and monitoring.

The satellite images are supplemented by 40 photographs, mostly aerial obliques, used to define the different glaciological features discussed, to illustrate specific features identified in the satellite imagery, and to provide coverage of areas south of lat. 81°S. not imaged by Landsat satellites. In comparing the oblique aerial photographs and the satellite imagery, I was constantly reminded of the vast scale of Antarctic glaciological features. In a photograph, one Antarctic glacier or nunatak looks much like another (even with first-hand field knowledge): only at image scales in excess of 100 km do the features become geographically recognizable.

The majority of scenes discussed are in regions near the edge of the grounded ice, from ice shelves, or from regions with mountain ranges or nunataks. It is in these areas that the most recognizable features (e.g. bare rock, blue ice and melt features, ice-stream flow features, surface undulations and disturbances) occur, and it is also here that the dynamics of the ice is most varied. Only three images show the interior ice sheet of East Antarctica but even here some surface features are discernible. Swithinbank uses visible features and a wide variety of other data sources to interpret the dynamic regime of the glaciers (identifying the grounding-line position, drainage divides, strain configurations, iceberg-calving processes, etc.) and to estimate sub-ice topography and surface slopes. Other data used include surface elevations, radio echo-sounding thicknesses, measured ice velocities, and modelling results. These are all sourced in an impressive bibliography. However, most of the interpretations remain qualitative and some are purely speculative. For example, do faint features discernible on the interior ice sheet represent differences in surface slope or in surface-crystal structure? Crystal size might be expected to affect the snow albedo in Band 7 (0.8–1.1 μm) but not in Band 4 (0.5–0.6 μm). So, interpretation of such features requires quantitative assessment of the spectral signature of the different surfaces, probably coupled with

field investigations.

These points lead to my one major criticism of the volume. Nowhere is there any discussion or data on the spectral ranges of the Landsat bands, the relative value of the different bands for discriminating surface features, the effect of illumination angle (both elevation and azimuth), and intensity on the imagery, or on separation of different surface types and cloud on the basis of spectral signature, pattern recognition, etc. Some of these deficiencies may arise because chapter B (Antarctica) has been published before chapter A (Introduction) which may well contain some of this detail. Nonetheless, many of the images presented in the volume are either enhanced single-channel or false-colour MSS images and some information on the enhancement used and on the weighting given to different bands would have been valuable. In particular, Figure 24 shows two different false-colour enhancements of the one image of the lower Byrd Glaciers: one highlighting blue ice and melt water, and the other highlighting bare rock. I would far prefer to know what spectral reflectance classifications were used to generate these rather than the provided information on the trade names of the image-processing equipment used. I would also like to have seen solar elevation and azimuth included in the already lengthy caption to each image (although the former can be obtained from the table of optimum images).

The tables of optimum images forming the second half of the volume are an extremely valuable resource for future workers. They represent a considerable achievement: 10 000 Band 7 images were examined and assessed. Of these, 44.6% were judged good to fair, providing acceptable Landsat images between 1972 and 1982 for 70% of Antarctica north of lat. 81°S. or 55% of the total area. An additional variable that could usefully have been included in the table is the availability of digital data for each image.

The production of the volume is generally very professional. The text is well written and readable with little undefined technical jargon (but I remain uncertain what a "deconvoluted cross-sectional area" is) and the image reproduction quality is adequate to show most of the features discussed. A minor irritation in reading the volume is that image descriptions may be several pages away from the relevant figure, although it is difficult to see how this could be avoided. There are few glaring editorial errors, some exceptions being that Figures 92 and 98 are Band 7, not enhanced false colour, and that Borg Massif is discussed in a different sub-section from that entitled "Borg Massif, Riiser-Larsen Ice Shelf, and Shackleton Range". More importantly, there are few major factual errors and the interpretations that are speculative are clearly identified as such. I disagree, however, that shuga formation resulting from the deposition of drift snow in open sea-water can contribute to the formation of Antarctic bottom water (p. B57). The necessary densification to form bottom water can only be initiated by a salinity increase, not simple surface cooling.

During 1987–88 and 1988–89, a considerable number of Antarctic images were collected by Landsat 4 and Landsat 5 as part of a co-operative acquisition program between SCAR countries and EOSAT, so publication of the compilation of imagery available for comparison from the earlier Landsat series is indeed timely. Landsat 4 and 5 have a slightly different orbit and repeat cycle than the earlier satellites, and also carry the thematic mapper (TM) sensor with a 30 m resolution and seven spectral bands (nothing dates more quickly than space technology). Additional Antarctic imagery is available from the French SPOT satellite (10 and 20 m resolution) and from the high-quality Soviet Soyuz Karta space photography (6 and 20 m resolution). Techniques have also been developed to determine digitally glacier-velocity fields by tracing the movement of fine-scale surface features on images collected several years apart, and we can expect increasingly quantitative uses of Landsat data in future. The USGS *Satellite image atlas* chapter on Antarctica will however remain a valuable base-line data source.

Despite some criticisms, I cannot but recommend this volume as essential to a wide audience. This audience includes armchair glaciologists requiring a new coffee-table book to replace Bentley and Humphries (*Snow crystals*) or Post and LaChapelle (*Glacier ice*), students requiring an

excellent description of Antarctic ice forms and processes, general Antarctic scientists and specialist Antarctic climatologists, remote-sensing experts, and glaciologists. It will also probably be in wide demand from Antarctic field scientists planning a suitably scenic location for their next grant application. For, despite Swithinbank's accurate assessment that we can now monitor Antarctic glacier changes without ever going into the field, there will always be a requirement for field researchers and, without the experience of these, volumes like the present could not be as authoritative.

It is hoped that future chapters in the USGS *Satellite image atlas of glaciers of the world* can maintain the high standard set by this one.

IAN ALLISON

Additional comments

This huge undertaking is an example of the kind of laborious effort which is a fundamental requirement for providing basic data and yet which is not spectacular, and which often needs further analysis to bring out quantitative information. Possibly such reasons, and probably others with which I am not familiar, explain why this volume, and its companions, have been much delayed. It is unfortunate that the text has not been brought up to publication date;

the references show a sharp cut-off after 1985, with only three from 1986 and none thereafter. Yet, the last 3 years have seen many relevant advances in the analysis of satellite images, including results reported at the International Glaciological Society's Second Symposium on Remote Sensing in Glaciology (*Annals of Glaciology*, 9) held in 1986, and the SCAR/IGS Fourth Symposium on Antarctic Glaciology (*Annals of Glaciology*, 11) held in 1987.

Over the past months, the future of the Landsat programme has seemed to be in doubt. At the same time, data from Soviet satellites and from Système Probatoire d'Observation de la Terre (SPOT) have become commercially available, although the improved resolution in the visible and near-infrared of the latter cannot replace the hitherto mostly untapped glaciological information available from the higher TM bands of Landsat. To support Landsat, it will therefore be important that glaciologists show that they derive benefit from images covering these wavelengths.

Analysis of digital satellite data offers, in my opinion, the best prospects for rapid and cost-competitive analysis of a number of glaciological phenomena, including detection of climatic change. The simplicity of Antarctica in terms of slopes and albedos means that this may be the area where workable algorithms can be most easily produced. Most of the problems with "automatic" digital analysis lie ahead, but I believe that this volume has helped to point the way, and it will provide nourishment as we travel this difficult route.

OLAV ØRHEIM