

The Physics of Glaciers

Fourth Edition

K. M. Cuffey

W. S. B. Paterson



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Butterworth-Heinemann is an imprint of Elsevier



Contents

<i>Preface to Fourth Edition</i>	<i>xi</i>
<i>Preface to First Edition</i>	<i>xii</i>
Chapter 1 Introduction	1
1.1 Introduction	1
1.2 History and Perspective	2
1.3 Organization of the Book	6
Further Reading	9
Chapter 2 Transformation of Snow to Ice	11
2.1 Introduction	11
2.2 Snow, Firn, and Ice	11
2.2.1 Density of Ice	12
2.3 Zones in a Glacier	13
2.3.1 Distribution of Zones	15
2.4 Variation of Density with Depth in Firn	16
2.5 Snow to Ice Transformation in a Dry-snow Zone	19
2.5.1 Processes	19
2.5.2 Models of Density Profiles in Dry Firn	22
2.5.3 Reduction of Gas Mobility	25
2.6 Hoar Layers	26
2.7 Transformation When Meltwater Is Present	27
Further Reading	28
Chapter 3 Grain-Scale Structures and Deformation of Ice	29
3.1 Introduction	29
3.2 Properties of a Single Ice Crystal	30
3.2.1 Structure	30
3.2.2 Deformation of a Single Crystal	32
3.3 Polycrystalline Ice: Grain-scale Forms and Processes	33
3.3.1 Orientation Fabrics: Brief Description	33
3.3.2 Impurities and Bubbles	33
3.3.3 Texture and Recrystallization	35
3.3.4 Formation of C-axis Orientation Fabrics	43
3.3.5 Mechanisms of Polycrystalline Deformation	48
3.4 Bulk Creep Properties of Polycrystalline Ice	51
3.4.1 Strain Rate and Incompressibility	51
3.4.2 Deviatoric Stress	52
3.4.3 Bench-top Experiments: The Three Phases of Creep	52
3.4.4 Isotropic Creep Behavior	54
3.4.5 Controls on Creep Parameter A	64

3.4.6	Recommended Isotropic Creep Relation and Values for A	72
3.4.7	Anisotropic Creep of Ice	78
3.5	Elastic Deformation of Polycrystalline Ice	88
	Appendix 3.1	88
	Appendix 3.2: Data for Figure 3.16	89
Chapter 4 Mass Balance Processes: 1. Overview and Regimes		91
4.1	Introduction	91
4.1.1	Notes on Terminology	94
4.2	Surface Mass Balance	96
4.2.1	Surface Accumulation Processes	96
4.2.2	Surface Ablation Processes	99
4.2.3	Annual (Net) Balance and the Seasonal Cycle	100
4.2.4	Annual Glacier Balance and Average Specific Balances	102
4.2.5	Variation of Surface Balance with Altitude	102
4.2.6	Generalized Relation of Surface Balance to Temperature and Precipitation	104
4.2.7	Relation of Glacier-wide Balance to the Area-Altitude Distribution	108
4.3	Mass Balance Variations of Mountain Glaciers	109
4.3.1	Interannual Fluctuations of Balance	109
4.3.2	Cumulative Balance and Delayed Adjustments	111
4.3.3	Regional Variations of Mass Balance	113
4.4	Englacial Mass Balance	115
4.4.1	Internal Accumulation	115
4.4.2	Internal Ablation	115
4.5	Basal Mass Balance	116
4.5.1	Basal Accumulation	116
4.5.2	Basal Ablation	118
4.6	Mass Loss by Calving	121
4.6.1	The Calving Spectrum	122
4.6.2	Calving from Tidewater Glaciers	123
4.6.3	Calving from Ice Shelves	124
4.6.4	Calving Relations for Ice Sheet Models	127
4.7	Methods for Determining Glacier Mass Balance	127
4.8	Mass Balance Regimes of the Ice Sheets	131
4.8.1	Greenland Ice Sheet	131
4.8.2	Antarctic Ice Sheet	134
	Further Reading	136
Chapter 5 Mass Balance Processes: 2. Surface Ablation and Energy Budget		137
5.1	Introduction	137
5.1.1	Radiation	138
5.1.2	Energy Budget of Earth's Atmosphere and Surface	138
5.2	Statement of the Surface Energy Budget	140
5.2.1	Driving and Responding Factors in the Energy Budget	141
5.2.2	Melt and Warming Driven by Net Energy Flux	141

5.3	Components of the Net Energy Flux	142
5.3.1	Downward Shortwave Radiation	143
5.3.2	Reflected Shortwave Radiation	145
5.3.3	Longwave Radiation	148
5.3.4	Field Example, Net Radiation Budget	148
5.3.5	Subsurface Conduction and Radiation	150
5.3.6	Turbulent Fluxes	152
5.4	Relation of Ablation to Climate	160
5.4.1	Calculating Melt from Energy Budget Measurements	160
5.4.2	Simple Approaches to Modelling Melt	162
5.4.3	Increase of Ablation with Warming	165
5.4.4	Importance of the Frequency of Different Weather Conditions	168
5.4.5	Energy Budget Regimes	169
	Further Reading	173
Chapter 6 Glacial Hydrology		175
6.1	Introduction	175
6.1.1	Permeability of Glacier Ice	176
6.1.2	Effective Pressure	177
6.2	Features of the Hydrologic System	177
6.2.1	Surface (Supraglacial) Hydrology	178
6.2.2	Englacial Hydrology	179
6.2.3	Subglacial Hydrology	181
6.2.4	Runoff from Glaciers	185
6.3	The Water System within Temperate Glaciers	194
6.3.1	Direction of Flow	194
6.3.2	Drainage in Conduits	197
6.3.3	Drainage in Linked Cavities	205
6.3.4	Subglacial Drainage on a Soft Bed	209
6.3.5	Summary of Water Systems at the Glacier Bed	212
6.3.6	System Behavior	214
6.4	Glacial Hydrological Phenomena	216
6.4.1	Jökulhlaups	216
6.4.2	Antarctic Subglacial Lakes	220
	Further Reading	222
Chapter 7 Basal Slip		223
7.1	Introduction	223
7.1.1	Measurements of Basal Velocity	224
7.1.2	Local vs. Global Control of Basal Velocity	226
7.2	Hard Beds	229
7.2.1	Weertman's Theory of Sliding	229
7.2.2	Observations at the Glacier Sole	233
7.2.3	Improvements to Weertman's Analysis	234
7.2.4	Discussion of Assumptions	236
7.2.5	Comparison of Predictions with Observations	237
7.2.6	How Water Changes Sliding Velocity on Hard Beds	238

7.2.7	Sliding of Debris-laden Ice	250
7.2.8	Sliding at Sub-Freezing Temperatures	253
7.2.9	Hard-bed Sliding: Summary and Outlook	254
7.3	Deformable Beds	255
7.3.1	Key Observations	256
7.3.2	Till Properties and Processes	257
7.3.3	Constitutive Behaviors	264
7.3.4	Slip Rate u_b on a Deformable Bed	269
7.3.5	Large-scale Behavior of Soft Beds	273
7.3.6	Continuity of Till	277
7.3.7	Additional Geological Information	279
7.4	Practical Relations for Basal Slip and Drag	280
	Further Reading	283
Chapter 8 The Flow of Ice Masses		285
8.1	Introduction	285
8.1.1	Ice Flux	286
8.1.2	Balance Velocities	288
8.1.3	Actual Velocities	289
8.1.4	How Surface Velocities Are Measured	293
8.2	Driving and Resisting Stresses	295
8.2.1	Driving Stress and Basal Shear Stress	295
8.2.2	Additional Resisting Forces and the Force Balance	299
8.2.3	Factors Controlling Resistance and Flow	301
8.2.4	Effective Driving Force of a Vertical Cliff	307
8.3	Vertical Profiles of Flow	309
8.3.1	Parallel Flow	309
8.3.2	Observed Complications in Shear Profiles	311
8.4	Fundamental Properties of Extending and Compressing Flows	315
8.4.1	General Concepts	315
8.4.2	Uniform Extension or Compression	317
8.5	General Governing Relations	319
8.5.1	Local Stress-equilibrium Relations	320
8.5.2	General Solutions for Stress and Velocity	321
8.5.3	Vertically Integrated Force Balance	322
8.5.4	General Mass Conservation Relation (Equation of Continuity)	330
8.5.5	Vertically Integrated Continuity Equations	331
8.6	Effects of Valley Walls and Shear Margins	338
8.6.1	Transverse Velocity Profile Where Basal Resistance Is Small	339
8.6.2	Combined Effects of Side and Basal Resistances	340
8.7	Variations Along a Flow Line	346
8.7.1	Factors Controlling Longitudinal Strain Rate	346
8.7.2	Local-scale Variation: Longitudinal Stress-gradient Coupling	347
8.7.3	Large-Scale Variation	351
8.8	Flow at Tidewater Margins	353
8.8.1	Theory	353
8.8.2	Observations: Columbia Glacier	355

8.9	Ice Sheets: Flow Components.....	356
	8.9.1 Flow at a Divide	357
	8.9.2 Ice Streams.....	360
	8.9.3 Ice Shelves	373
	8.9.4 Transition Zone Between Grounded and Floating Ice	384
	8.9.5 Flow Over Subglacial Lakes	385
8.10	Surface Profiles of Ice Sheets	385
	8.10.1 Profile Equations	385
	8.10.2 Other Factors Influencing Profiles	390
	8.10.3 Relation Between Ice Area and Volume.....	395
	8.10.4 Travel Times	396
	8.10.5 Local-scale Relation of Surface and Bed Topography	397
	Further Reading.....	398
 Chapter 9 Temperatures in Ice Masses.....		 399
9.1	Introduction	399
9.2	Thermal Parameters of Ice and Snow.....	400
9.3	Temperature of Surface Layers	401
9.4	Temperate Glaciers	405
	9.4.1 Ice Temperature	405
	9.4.2 Origin and Effect of Water	407
	9.4.3 Distribution of Temperate Glaciers	408
9.5	Steady-state Temperature Distributions	409
	9.5.1 Steady-state Vertical Temperature Profile	409
9.6	Measured Temperature Profiles	413
9.7	General Equation of Heat Transfer	416
	9.7.1 Derivation of Equation	416
	9.7.2 Boundary and Basal Conditions	419
9.8	Temperatures Along a Flow Line.....	420
	9.8.1 Observations	421
9.9	Time-varying Temperatures.....	423
9.10	Temperatures in Ice Shelves	426
 Chapter 10 Large-Scale Structures.....		 429
10.1	Introduction	429
10.2	Sedimentary Layers	430
10.3	Foliation.....	430
	10.3.1 Elongate Bubble Forms	434
	10.3.2 Finite Strain	434
10.4	Folds	436
	10.4.1 Folding in Central Regions of Ice Sheets.....	438
10.5	Boudinage.....	438
10.6	Faults	440
10.7	Implications for Ice Core Stratigraphy	441
10.8	Ogives and Longitudinal Corrugations	443
10.9	Crevasses.....	445
	10.9.1 Patterns and Conditions for Occurrence	445

10.9.2	Crevasse Depth and Propagation	449
10.9.3	Related Tensional Features	451
10.10	Structural Assemblages	452
	Further Reading	452
Chapter 11 Reaction of Glaciers to Environmental Changes		453
11.1	Introduction	453
11.2	Reaction to Changes of Mass Balance: Scales	454
11.2.1	Net Change of Glacier Length	455
11.2.2	Simple Models for Response	456
11.2.3	Simple Models for Different Zones	461
11.3	Reaction to Changes of Mass Balance: Dynamics	464
11.3.1	Theoretical Framework	464
11.3.2	Ice Thickness Changes	469
11.3.3	Relative Importance of Diffusion and Kinematic Waves	476
11.3.4	Numerical Models of Glacier Variation	477
11.4	Reactions to Additional Forcings	483
11.4.1	Response of Glaciers to Ice and Bed Changes	483
11.4.2	Factors Influencing the Reaction of an Ice Sheet to the End of an Ice Age	485
11.4.3	Ice Flow Increased by Water Input	490
11.5	Changes at a Marine Margin	494
11.5.1	Conceptual Framework	495
11.5.2	The Tidewater Glacier Cycle	500
11.5.3	Interactions of Ice Shelves and Inland Ice	503
11.5.4	Forcing by Sea-level Rise	508
	Further Reading	510
Chapter 12 Glacier Surges		511
12.1	Introduction	511
12.2	Characteristics of Surging Glaciers	513
12.2.1	Spatial Distribution and Relation to Geological Setting	513
12.2.2	Distribution in Time	514
12.2.3	Temperature Characteristics	515
12.2.4	Characteristics of Form and Velocity	516
12.3	Detailed Observations of Surges	517
12.3.1	Surges of Temperate Glaciers	517
12.3.2	The Role of Water: Variegated Glacier	520
12.3.3	Surges Where the Bed Is Partly Frozen	523
12.3.4	Surges of Polythermal Tidewater Glaciers	526
12.4	Surge Mechanisms	528
12.4.1	General Evidence Relevant to the Mechanism	528
12.4.2	The Mechanism for Temperate Glaciers	532
12.4.3	Polythermal Glaciers	536
12.5	Surging of Ice Sheets?	537
12.6	Ice Avalanches	538

Chapter 13	<i>Ice Sheets and the Earth System</i>	541
13.1	Introduction	541
13.2	Interaction of Ice Sheets with the Earth System	542
13.2.1	Processes Driving Ice Sheet Change	543
13.2.2	Feedback Processes	548
13.3	Growth and Decay of Quaternary Ice Sheets	555
13.3.1	Relation to Milankovitch Forcings	557
13.3.2	Climate Forcings at the LGM	561
13.3.3	Onset of Quaternary Cycles	563
13.3.4	Heinrich Events	563
13.4	Ice Sheet Evolution Models	565
13.4.1	Model Components	565
13.4.2	Model Calibration	569
13.4.3	Simulations of Quaternary Ice Sheets	569
	Further Reading	574
Chapter 14	<i>Ice, Sea Level, and Contemporary Climate Change</i>	575
14.1	Introduction	575
14.1.1	Equivalent Sea Level	576
14.1.2	Recent Climate and Sea-level Change	577
14.2	Global Warming and Mountain Glaciers	578
14.2.1	History of Glacier Lengths	579
14.2.2	Worldwide Mass Balance of Mountain Glaciers and Small Ice Caps	582
14.2.3	Sea-level Forecasts: Mountain Glaciers and Small Ice Caps	586
14.3	The Ice Sheets and Global Warming	590
14.3.1	Greenland	590
14.3.2	Antarctica	595
14.3.3	Model Forecasts of Ice Sheet Contributions to Sea-level Change	601
14.3.4	Simple Approaches to Forecasts for the Century Ahead	604
14.4	Summary	607
14.4.1	Recent Sea-level Rise	607
14.4.2	The Twentieth Century	608
14.4.3	This Century	608
Chapter 15	<i>Ice Core Studies</i>	611
15.1	Introduction	611
15.1.1	Some Essential Terms and Concepts	612
15.1.2	Delta Notation	612
15.2	Relation Between Depth and Age	614
15.2.1	Theoretical Relations	614
15.2.2	Determination of Ages	622
15.2.3	Difference of Gas and Ice Ages	630
15.3	Fractionation of Gases in Polar Firn	630
15.4	Total Air Content	634
15.5	Stable Isotopes of Ice	636

15.5.1	Conceptual Model	636
15.5.2	Interpretation of Records	644
15.6	Additional Techniques of Temperature Reconstruction	650
15.6.1	Borehole Temperatures	650
15.6.2	Melt Layers	651
15.6.3	Thermal and Gravitational Fractionation of Gases	652
15.7	Estimation of Past Accumulation Rates	652
15.8	Greenhouse Gas Records	654
15.8.1	Histories of Atmospheric Concentration	654
15.8.2	Isotopic Compositions of Greenhouse Gases	659
15.9	Gas Indicators of Global Parameters	659
15.9.1	Global Mean Ocean Temperature	659
15.9.2	Global Biological Productivity	660
15.10	Particulate and Soluble Impurities	660
15.10.1	Electrical Conductivity Measurement (ECM)	662
15.10.2	Primary Aerosols	662
15.10.3	Secondary Aerosols	664
15.11	Examples of Multiparameter Records from Ice Sheets	667
15.11.1	Deglacial Climate Change	667
15.11.2	A Long Record of Climate Cycling	667
15.12	Low-latitude Ice Cores	670
15.13	Surface Exposures in Ablation Zones	672
	Further Reading	674
	<i>Appendix: A Primer on Stress and Strain</i>	675
	<i>Index</i>	683