
References Cited or Recommended

- Abe-Ouchi, A. 1993. *Ice sheet response to climatic changes: a modelling approach*. Zürcher Geographische Schriften No. 54. Geographical Institute, ETH Zurich, Switzerland.
- Abramowitz, M. and I. A. Stegun. 1970. *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*. Dover Publications, New York, NY, USA.
- Alexiades, V. and A. D. Solomon. 1993. *Mathematical Modeling of Melting and Freezing Processes*. Hemisphere Publishing Corporation, Washington, DC, USA.
- Alley, R. B. 2000. *The Two-Mile Time Machine. Ice Cores, Abrupt Climate Change and Our Future*. Princeton University Press, Princeton, NJ, USA and Oxford, UK. ISBN 0-691-00493-5.
- Alley, R. B., I. Joughin, H. J. Horgan, T. K. Dupont, B. R. Parizek, S. Anandakrishnan and K. M. Cuffey. 2007. A first calving law for ice shelves: spreading-rate control of calving rate. Abstract #C43A-01, American Geophysical Union Fall Meeting, San Francisco, CA, USA, 2007.12.10–14.
- Aschwanden, A. and H. Blatter. 2005. Meltwater production due to strain heating in Storglaciären, Sweden. *Journal of Geophysical Research*, **110** (F4), F04024. doi:10.1029/2005JF000328.
- Aschwanden, A. and H. Blatter. 2009. Mathematical modeling and numerical simulation of polythermal glaciers. *Journal of Geophysical Research*, **114** (F1), F01027. doi:10.1029/2008JF001028.
- Azuma, N. 1995. A flow law for anisotropic polycrystalline ice under uniaxial compressive deformation. *Cold Regions Science and Technology*, **23** (2), 137–147.
- Bader, H. 1954. Sorge's law of densification of snow on high polar glaciers. *Journal of Glaciology*, **2**, 319–323.
- Bahr, D. B., W. T. Pfeffer and M. F. Meier. 1994. Theoretical limitations to englacial velocity calculations. *Journal of Glaciology*, **40** (136), 509–518.
- Bamber, J. L. 1988. Internal reflecting horizons in Spitsbergen glaciers. *Annals of Glaciology*, **9**, 5–9.

- Benn, D. I., N. R. J. Hulton and R. H. Mottram. 2007a. 'Calving laws', 'sliding laws' and the stability of tidewater glaciers. *Annals of Glaciology*, **46**, 123–130.
- Benn, D. I., C. R. Warren and R. H. Mottram. 2007b. Calving processes and the dynamics of calving glaciers. *Earth Science Reviews*, **82**, 143–179.
- Bentley, C. R. 2004. Mass balance of the Antarctic ice sheet: observational aspects. In: J. L. Bamber and A. J. Payne (Eds.), *Mass Balance of the Cryosphere. Observations and Modelling of Contemporary and Future Changes*, pp. 459–489. Cambridge University Press, Cambridge, UK and New York, NY, USA.
- Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C. K. Shum, L. D. Talley and A. Unnikrishnan. 2007. Observations: Oceanic climate change and sea level. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 385–432. Cambridge University Press, Cambridge, UK, and New York, NY, USA. URL <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>.
- Blatter, H. 1987. On the thermal regime of an arctic valley glacier, a study of the White Glacier, Axel Heiberg Island, N.W.T., Canada. *Journal of Glaciology*, **33** (114), 200–211.
- Blatter, H. 1995. Velocity and stress fields in grounded glaciers: a simple algorithm for including deviatoric stress gradients. *Journal of Glaciology*, **41** (138), 333–344.
- Blatter, H. and G. Kappenberger. 1988. Mass balance and thermal regime of the Laika Ice Cap, Coburg Island, N.W.T., Canada. *Journal of Glaciology*, **34** (116), 102–110.
- Bond, G., H. Heinrich, S. Huon, W. Broecker, L. Labeyrie, J. Andrews, J. McManus, S. Clasen, K. Tedesco, R. Jantschik, C. Simet and M. Klas. 1992. Evidence for massive discharges of icebergs into the glacial Northern Atlantic. *Nature*, **360** (6401), 245–250.
- Bond, G. C. and R. Lotti. 1995. Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. *Science*, **267** (5200), 1005–1010.
- Breuer, B., M. A. Lange and N. Blindow. 2006. Sensitivity studies on model modifications to assess the dynamics of a temperate ice cap, such as that on King George Island, Antarctica. *Journal of Glaciology*, **52** (177), 235–247.
- Bronshstein, I. N., K. A. Semendyayev, G. Musiol and H. Muehlig. 2004. *Handbook of Mathematics*. Springer, Berlin, Germany etc., 4th ed.
- Brotchie, J. F. and R. Silvester. 1969. On crustal flexure. *Journal of Geophysical Research*, **74** (22), 5240–5252.
- Buckingham, E. 1924. Dimensional analysis. *Philosophical Magazine*, **48** (283), 141–145.

- Budd, W. F. and T. H. Jacka. 1989. A review of ice rheology for ice sheet modelling. *Cold Regions Science and Technology*, **16** (2), 107–144.
- Bueler, E. 2003. Construction of steady state solutions for isothermal shallow ice sheets. Tech. Rep. 03-02, Department of Mathematics and Statistics, University of Alaska, Fairbanks.
- Bueler, E., C. S. Lingle, J. A. Kallen-Brown, D. N. Covey and L. N. Bowman. 2005. Exact solutions and verification of numerical models for isothermal ice sheets. *Journal of Glaciology*, **51** (173), 291–306.
- Calov, R. 1994. *Das thermomechanische Verhalten des Grönländischen Eisschildes unter der Wirkung verschiedener Klimaszenarien – Antworten eines theoretisch-numerischen Modells*. Doctoral thesis, Department of Mechanics, Darmstadt University of Technology, Germany.
- Calov, R. and R. Greve. 2006. ISMIP HEINO. Ice Sheet Model Intercomparison Project – Heinrich Event INterCOmparison. Online publication. URL <http://www.pik-potsdam.de/~calov/heino.html>.
- Church, J. A., J. M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M. T. Nhuân, D. Qin and P. L. Woodworth. 2001. Changes in sea level. In: J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (Eds.), *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 639–693. Cambridge University Press, Cambridge, UK and New York, NY, USA.
- Classen, D. F. and G. K. C. Clarke. 1971. Basal hot spot on a surge type glacier. *Nature*, **229**, 481–483.
- Colinge, J. and H. Blatter. 1998. Stress and velocity fields in glaciers: Part I. Finite difference schemes for higher-order glacier models. *Journal of Glaciology*, **44**, 448–456.
- Colinge, J. and J. Rappaz. 1999. A strongly nonlinear problem arising in glaciology. *Mathematical Modelling and Numerical Analysis*, **33** (2), 395–406.
- Dansgaard, W. and S. J. Johnsen. 1969. A flow model and a time scale for the ice core from Camp Century, Greenland. *Journal of Glaciology*, **8** (53), 215–223.
- de Berg, M., O. Cheong, M. van Kreveld and M. Overmars. 2008. *Computational Geometry. Algorithms and Applications*. Springer, Berlin, Germany etc., 3rd ed.
- Debnath, L. and P. Mikusiński. 1993. *Introduction to Hilbert Spaces and Applications*. Academic Press, San Diego, CA, USA.
- Durand, G., O. Gagliardini, T. Zwinger and E. Le Meur. 2009. Full-Stokes modeling of marine ice sheets: influence of the grid size. *Annals of Glaciology*, **52**. In press.
- Eisen, O., A. Bauder, M. Lüthi, P. Riesen and M. Funk. 2009. Deducing the thermal structure in the tongue of Gornergletscher, Switzerland, from radar surveys and borehole measurements. *Annals of Glaciology*, **50** (51), 63–70.

- Eisen, O., I. Hamann, S. Kipfstuhl, D. Steinhage and F. Wilhelms. 2007. Direct evidence for continuous radar reflector originating from changes in crystal-orientation fabric. *The Cryosphere*, **1** (1), 1–10. URL <http://www.the-cryosphere.net/1/1/2007/>.
- Ekman, M. 1991. A concise history of postglacial land uplift research (from its beginning to 1950). *Terra Nova*, **3**, 358–365.
- EPICA Community Members. 2006. One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature*, **444** (7116), 195–198. doi: 10.1038/nature05301.
- Faria, S. H. 2003. *Mechanics and thermodynamics of mixtures with continuous diversity*. Doctoral thesis, Department of Mechanics, Darmstadt University of Technology, Germany. URL <http://tuprints.ulb.tu-darmstadt.de/307/>.
- Forsström, P.-L., O. Sallasmaa, R. Greve and T. Zwinger. 2003. Simulation of fast-flow features of the Fennoscandian ice sheet during the Last Glacial Maximum. *Annals of Glaciology*, **37**, 383–389.
- Fowler, A. C. 1984. On the transport of moisture in polythermal glaciers. *Geophysical and Astrophysical Fluid Dynamics*, **24**, 99–140.
- Gagliardini, O., F. Gillet-Chaulet and M. Montagnat. 2009. A review of anisotropic polar ice models: from crystal to ice-sheet flow models. In: T. Hondoh (Ed.), *Physics of Ice Core Records Vol. 2*. Yoshioka Publishing, Kyoto, Japan. In press.
- Gagliardini, O. and J. Meyssonier. 1997. Flow simulation of a firn-covered cold glacier. *Annals of Glaciology*, **24**, 242–248.
- Glen, J. W. 1955. The creep of polycrystalline ice. *Proceedings of the Royal Society London A*, **228** (1175), 519–538. doi:10.1098/rspa.1955.0066.
- Greve, R. 1994. Zwischenbericht zur Dissertation “Thermomechanisches Verhalten polythermer Eisschilde”. Unpublished report, Department of Mechanics, Darmstadt University of Technology, Germany.
- Greve, R. 1997. A continuum-mechanical formulation for shallow polythermal ice sheets. *Philosophical Transactions of the Royal Society London A*, **355** (1726), 921–974. doi:10.1098/rsta.1997.0050.
- Greve, R. 2000. *Large-scale glaciation on Earth and on Mars*. Habilitation thesis, Department of Mechanics, Darmstadt University of Technology, Germany. URL <http://tuprints.ulb.tu-darmstadt.de/816/>.
- Greve, R. 2005. Relation of measured basal temperatures and the spatial distribution of the geothermal heat flux for the Greenland ice sheet. *Annals of Glaciology*, **42**, 424–432.
- Greve, R., L. Placidi and H. Seddik. 2009. A continuum-mechanical model for the flow of anisotropic polar ice. In: T. Hondoh (Ed.), *Physics of Ice Core Records Vol. 2*. Yoshioka Publishing, Kyoto, Japan. In press, preprint at arXiv:0903.3078 [physics.geo-ph].
- Greve, R. and S. Sugiyama. 2009. Decay of the Greenland Ice Sheet due to surface-meltwater-induced acceleration of basal sliding. arXiv:0905.2027 [physics.geo-ph]. URL <http://arxiv.org/abs/0905.2027>.

- Greve, R., R. Takahama and R. Calov. 2006. Simulation of large-scale ice-sheet surges: The ISMIP HEINO experiments. *Polar Meteorology and Glaciology*, **20**, 1–15.
- Griffiths, D. F. 1997. The ‘no boundary condition’ outflow boundary condition. *International Journal for Numerical Methods in Fluids*, **24**, 393–411.
- Gudmundsson, G. H. 1994. *Glacier sliding over sinusoidal bed and the characteristics of creeping flow over bedrock undulations*. Mitteilungen No. 130. Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Switzerland.
- Gudmundsson, G. H. 1997a. Basal-flow characteristics of a linear flow sliding frictionless over small bedrock undulations. *Journal of Glaciology*, **43** (143), 71–79.
- Gudmundsson, G. H. 1997b. Basal-flow characteristics of a non-linear flow sliding frictionless over strongly undulating bedrock. *Journal of Glaciology*, **43** (143), 80–89.
- Heinbockel, J. H. 1996. *Introduction to Tensor Calculus and Continuum Mechanics*. Trafford Publishing, Victoria, BC, Canada and Oxford, UK. ISBN 1-55369-133-4. Free online version available at <http://www.math.ou.edu/~jhh/counter2.html> (retrieved 2009-03-11).
- Heinrich, H. 1988. Origin and consequences of cyclic ice rafting in the North-east Atlantic Ocean during the past 130,000 years. *Quaternary Research*, **29** (2), 142–152.
- Hindmarsh, R. C. A. 2004. A numerical comparison of approximations to the Stokes equations used in ice sheet and glacier modeling. *Journal of Geophysical Research*, **109** (F1), F01012. doi:10.1029/2003JF000065.
- Hofmann, W. 1974. Die Internationale Glaziologische Grönland-Expedition EGIG. *Zeitschrift für Gletscherkunde und Glazialgeologie*, **5**, 217–224.
- Holmlund, P. and M. Eriksson. 1989. The cold surface layer on Storglaciären. *Geografiska Annaler*, **71A** (3-4), 241–244.
- Hooke, R. L. 2005. *Principles of Glacier Mechanics*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2nd ed.
- Hubbard, A., I. Willis, M. Sharp, D. Mair, P. Nienow, B. Hubbard and H. Blatter. 2000. Glacier mass-balance determination by remote sensing and high-resolution modelling. *Journal of Glaciology*, **46** (154), 491–498.
- Humbert, A., R. Greve and K. Hutter. 2005. Parameter sensitivity studies for the ice flow of the Ross Ice Shelf, Antarctica. *Journal of Geophysical Research*, **110** (F4), F04022. doi:10.1029/2004JF000170.
- Hundsdorfer, W. and J. G. Verwer. 2003. *Numerical Solution of Time-Dependent Advection-Diffusion-Reaction Equations*. Springer, Berlin, Germany etc.
- Hutter, K. 1983. *Theoretical Glaciology; Material Science of Ice and the Mechanics of Glaciers and Ice Sheets*. D. Reidel Publishing Company, Dordrecht, The Netherlands.
- Hutter, K. 1993. Thermo-mechanically coupled ice-sheet response – cold, polythermal, temperate. *Journal of Glaciology*, **39** (131), 65–86.

- Hutter, K. and K. Jöhnk. 2004. *Continuum Methods of Physical Modeling*. Springer, Berlin, Germany etc.
- Huybrechts, P., J. Gregory, I. Janssens and M. Wild. 2004. Modelling Antarctic and Greenland volume changes during the 20th and 21st centuries forced by GCM time slice integrations. *Global and Planetary Change*, **42** (1-4), 83–105. doi:10.1016/j.gloplacha.2003.11.011.
- Huybrechts, P., A. J. Payne and EISMINT Intercomparison Group (including R. Greve). 1996. The EISMINT benchmarks for testing ice-sheet models. *Annals of Glaciology*, **23**, 1–12.
- Huybrechts, P., O. Rybak, F. Pattyn, U. Ruth and D. Steinhage. 2007. Ice thinning, upstream advection, and non-climatic biases for the upper 89% of the EDML ice core from a nested model of the Antarctic ice sheet. *Climate of the Past*, **3** (4), 577–589. URL <http://www.clim-past.net/3/577/2007/>.
- Jania, J., D. Mochnacki and B. Gadek. 1996. The thermal structure of Hansbreen, a tidewater glacier in southern Spitsbergen, Svalbard. *Polar Research*, **15** (1), 53–66.
- Jänich, K. 1994. *Linear Algebra*. Springer, New York, NY, USA. ISBN 0-387-94128-2.
- Kundu, P. K. and I. M. Cohen. 2004. *Fluid Mechanics*. Elsevier Academic Press, San Diego, CA, USA etc., 3rd ed.
- Le Meur, E. 1996. Isostatic postglacial rebound over Fennoscandia with a self-gravitating spherical visco-elastic Earth model. *Annals of Glaciology*, **23**, 318–327.
- Le Meur, E. and P. Huybrechts. 1996. A comparison of different ways of dealing with isostasy: examples from modelling the Antarctic ice sheet during the last glacial cycle. *Annals of Glaciology*, **23**, 309–317.
- Liu, I.-S. 2002. *Continuum Mechanics*. Springer, Berlin, Germany etc.
- Lliboutry, L. A. and P. Duval. 1985. Various isotropic and anisotropic ices found in glaciers and polar ice caps and their corresponding rheologies. *Annals of Geophysics*, **3**, 207–224.
- Lunt, D. J., G. L. Foster, A. M. Haywood and E. J. Stone. 2008. Late Pliocene Greenland glaciation controlled by a decline in atmospheric CO₂ levels. *Nature*, **454** (7208), 1102–1105. doi:10.1038/nature07223.
- Lüthi, M. and M. Funk. 2001. Modelling heat flow in a cold, high altitude glacier: interpretation of measurements from Colle Gnifetti, Swiss Alps. *Journal of Glaciology*, **47** (157), 314–324.
- Marguerre, K. and H.-T. Woernle. 1969. *Elastic Plates*. Blaisdell Publishing Company, Waltham, MA, USA etc.
- Meehl, G. A., T. F. Stocker, W. D. Collins, F. P., A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver and Z.-C. Zhao. 2007. Global climate projections. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment*

- Report of the Intergovernmental Panel on Climate Change*, pp. 747–845. Cambridge University Press, Cambridge, UK, and New York, NY, USA. URL <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>.
- Miyamoto, A. 1999. *Mechanical properties and crystal textures of Greenland deep ice cores*. Doctoral thesis, Hokkaido University, Sapporo, Japan.
- Moran, M. J. and W. N. Shapiro. 2000. *Fundamentals of Engineering Thermodynamics*. Wiley, New York, NY, USA.
- Morland, L. W. 1984. Thermomechanical balances of ice sheet flows. *Geophysical and Astrophysical Fluid Dynamics*, **29**, 237–266.
- Morland, L. W. 1987. Unconfined ice-shelf flow. In: C. J. van der Veen and J. Oerlemans (Eds.), *Dynamics of the West Antarctic Ice Sheet*, pp. 99–116. D. Reidel Publishing Company, Dordrecht, The Netherlands.
- Morton, K. W. and D. F. Mayers. 1994. *Numerical Solution of Partial Differential Equations*. Cambridge University Press, Cambridge, UK and New York, NY, USA.
- Müller, I. 1985. *Thermodynamics*. Pitman Advanced Publishing Program, Boston, MA, USA etc.
- Nedjar, B. 2002. An enthalpy-based finite element method for nonlinear heat problems involving phase change. *Computers and Structures*, **80** (1), 9–21.
- Nye, J. F. 1957. The distribution of stress and velocity in glaciers and ice sheets. *Proceedings of the Royal Society London A*, **239** (1216), 113–133. doi:10.1098/rspa.1957.0026.
- Paterson, W. S. B. 1971. Temperature measurements in Athabasca Glacier, Alberta, Canada. *Journal of Glaciology*, **10** (60), 339–349.
- Paterson, W. S. B. 1994. *The Physics of Glaciers*. Pergamon Press, Oxford, UK etc., 3rd ed.
- Pattyn, F., L. Perichon, A. Aschwanden, B. Breuer, B. de Smedt, O. Gagliardini, G. H. Gudmundsson, R. Hindmarsh, A. Hubbard, J. V. Johnson, T. Kleiner, Y. Konovalov, C. Martin, A. J. Payne, D. Pollard, S. Price, M. Rückamp, F. Saito, O. Souček, S. Sugiyama and T. Zwinger. 2008. Benchmark experiments for higher-order and full-Stokes ice sheet models (ISMIP-HOM). *The Cryosphere*, **2** (2), 95–108. URL <http://www.the-cryosphere.net/2/95/2008/>.
- Pedlosky, J. 1987. *Geophysical Fluid Dynamics*. Springer, New York, NY, USA etc., 2nd ed.
- Petrenko, V. F. and R. W. Whitworth. 1999. *Physics of Ice*. Oxford University Press, Oxford, UK etc.
- Pettersson, R., P. Jansson and H. Blatter. 2004. Spatial variability in water content at the cold-temperate transition surface of the polythermal Storglaciären, Sweden. *Journal of Geophysical Research*, **109** (F2), F02009. doi:10.1029/2003JF000110.
- Pham, Q. T. 1995. Comparison of general-purpose finite-element methods for the Stefan problem. *Numerical Heat Transfer, Part B*, **27**, 417–435.
- Pimienta, P., P. Duval and V. Y. Lipenkov. 1987. Mechanical behaviour of anisotropic polar ice. In: E. D. Waddington and J. S. Walder (Eds.), *The*

- Physical Basis of Ice Sheet Modelling*, IAHS Publication No. 170, pp. 57–66. IAHS Press, Wallingford, UK.
- Placidi, L. 2004. *Thermodynamically consistent formulation of induced anisotropy in polar ice accounting for grain-rotation, grain-size evolution and recrystallization*. Doctoral thesis, Department of Mechanics, Darmstadt University of Technology, Germany. URL <http://tuprints.ulb.tu-darmstadt.de/614/>.
- Placidi, L., R. Greve, H. Seddik and S. H. Faria. 2009. Continuum-mechanical, anisotropic flow model for polar ice masses, based on an anisotropic flow enhancement factor (CAFFE). *Continuum Mechanics and Thermodynamics*. Submitted, preprint at arXiv:0903.0688 [physics.geo-ph].
- Pralong, A. and M. Funk. 2005. Dynamic damage model of crevasse opening and application to glacier calving. *Journal of Geophysical Research*, **110** (B1), B01309.
- Pralong, A. and M. Funk. 2006. On the instability of avalanching glaciers. *Journal of Glaciology*, **52** (176), 31–48.
- Pralong, A., K. Hutter and M. Funk. 2006. Anisotropic damage mechanics for viscoelastic ice. *Continuum Mechanics and Thermodynamics*, **17** (5), 387–408.
- Press, W. H., S. A. Teukolsky, W. T. Vetterling and B. P. Flannery. 1996. *Numerical Recipes in Fortran 77*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2nd ed.
- Reddy, J. N. 2006. *An Introduction to the Finite Element Method*. McGraw-Hill, Boston, MA, USA etc., 3rd ed. International edition.
- Reeh, N. 1968. On the calving of ice from floating glaciers and ice shelves. *Journal of Glaciology*, **7** (50), 215–232.
- Ridley, J. K., P. Huybrechts, J. M. Gregory and J. A. Lowe. 2005. Elimination of the Greenland ice sheet in a high CO₂ climate. *Journal of Climate*, **18** (17), 3409–3427.
- Ritz, C. 1987. Time dependent boundary conditions for calculation of temperature fields in ice sheets. In: E. D. Waddington and J. S. Walder (Eds.), *The Physical Basis of Ice Sheet Modelling*, IAHS Publication No. 170, pp. 207–216. IAHS Press, Wallingford, UK.
- Russell-Head, D. S. and W. F. Budd. 1979. Ice sheet flow properties derived from borehole shear measurements combined with ice core studies. *Journal of Glaciology*, **24** (90), 117–130.
- Saito, F. and A. Abe-Ouchi. 2004. Thermal structure of Dome Fuji and east Dronning Maud Land, Antarctica, simulated by a three-dimensional ice-sheet model. *Annals of Glaciology*, **39**, 433–438.
- Saito, F., A. Abe-Ouchi and H. Blatter. 2006. European Ice Sheet Modelling Initiative (EISMINT) model intercomparison experiments with first order mechanics. *Journal of Geophysical Research*, **111** (F2), F02012. doi:10.1029/2004JF000273.

- Sammonds, P. R. 1999. Understanding the fundamental physics governing the evolution and dynamics of the earth's crust and ice sheets. *Philosophical Transactions of the Royal Society London A*, **357** (1763), 3377–3401.
- Schoof, C. 2007a. Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *Journal of Geophysical Research*, **112** (F3), F03S28. doi: 10.1029/2006JF000664.
- Schoof, C. 2007b. Marine ice-sheet dynamics. Part 1. The case of rapid sliding. *Journal of Fluid Mechanics*, **573**, 27–55. doi:10.1017/S0022112006003570.
- Schwerzmann, A. A. 2006. *Borehole analysis and flow modeling of firn-covered glaciers*. Ph.D. thesis, ETH Zurich, Switzerland. URL <http://e-collection.ethbib.ethz.ch/view/eth:28327>.
- Seddik, H., R. Greve, L. Placidi, I. Hamann and O. Gagliardini. 2008. Application of a continuum-mechanical model for the flow of anisotropic polar ice to the EDML core, Antarctica. *Journal of Glaciology*, **54** (187), 631–642.
- Seibert, P. 1993. Convergence and accuracy of numerical methods for trajectory calculations. *Journal of Applied Meteorology*, **3**, 558–566.
- Smith, G. D. and L. W. Morland. 1981. Viscous relations for the steady creep of polycrystalline ice. *Cold Regions Science and Technology*, **5**, 141–150.
- Straughan, B., R. Greve, H. Ehrentraut and Y. Wang (Eds.). 2001. *Continuum Mechanics and Applications in Geophysics and the Environment*. Springer, Berlin, Germany etc. ISBN 3-540-41660-9.
- Sugiyama, S., A. Bauder, M. Funk and C. Zahno. 2007. Evolution of Rhone-gletscher, Switzerland, over the past 125 years and in the future: application of an improved flowline model. *Annals of Glaciology*, **46**, 268–274.
- Thoma, M. and D. Wolf. 1999. Bestimmung der Mantelviskosität aus Beobachtungen der Landhebung und Schwere in Fennoskandien. Scientific Technical Report STR99/02, GeoForschungsZentrum Potsdam, Germany.
- Thomas, R. H. 2004. Greenland: recent mass balance observations. In: J. L. Bamber and A. J. Payne (Eds.), *Mass Balance of the Cryosphere. Observations and Modelling of Contemporary and Future Changes*, pp. 393–436. Cambridge University Press, Cambridge, UK and New York, NY, USA.
- Thomas, R. H., D. R. MacAyeal, D. H. Eilers and D. R. Gaylord. 1984. Glaciological studies on the Ross Ice Shelf, Antarctica, 1973-1978. In: C. R. Bentley and D. E. Hayes (Eds.), *The Ross Ice Shelf: Glaciology and Geophysics*, Antarctic Research Series No. 42, pp. 21–53. American Geophysical Union, Washington DC, USA.
- Truffer, M. 2004. The basal speed of valley glaciers: an inverse approach. *Journal of Glaciology*, **50** (169), 236–242.
- Turcotte, D. L. and G. Schubert. 2002. *Geodynamics*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2nd ed.
- van der Veen, C. J. 1999. *Fundamentals of Glacier Dynamics*. A. A. Balkema, Rotterdam, The Netherlands.
- Vialov, S. S. 1958. Regularities of glacial shields movement and the theory of plastic viscous flow. In: *Physics of the Motion of Ice*, IAHS Publication No. 47, pp. 266–275. IAHS Press, Wallingford, UK.

- Vieli, A., M. Funk and H. Blatter. 2000. Tidewater glaciers: frontal flow acceleration and basal sliding. *Annals of Glaciology*, **31**, 217–221.
- Vieli, A., M. Funk and H. Blatter. 2001. Flow dynamics of tidewater glaciers: a numerical modelling approach. *Journal of Glaciology*, **47** (159), 595–606.
- Vieli, A. and A. J. Payne. 2005. Assessing the ability of numerical ice sheet models to simulate grounding line migration. *Journal of Geophysical Research*, **110**. doi:10.1029/2004JF000202.
- Weis, M. 2001. *Theory and finite element analysis of shallow ice shelves*. Doctoral thesis, Department of Mechanics, Darmstadt University of Technology, Germany. URL <http://tuprints.ulb.tu-darmstadt.de/171/>.
- Wilson, R. C. L., S. A. Drury and J. L. Chapman. 2000. *The Great Ice Age. Climate Change and Life*. Routledge, London, UK and New York, NY, USA. ISBN 0-415-19842-9.
- Zotikov, I. A. 1986. *The Thermophysics of Glaciers*. D. Reidel Publishing Company, Dordrecht, The Netherlands.
- Zwally, H. J., W. Abdalati, T. Herring, K. Larson, J. Saba and K. Steffen. 2002. Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, **297** (5579), 218–222. doi:10.1126/science.1072708.
- Zwinger, T., R. Greve, O. Gagliardini, T. Shiraiwa and M. Lyly. 2007. A full Stokes-flow thermo-mechanical model for firn and ice applied to the Gorshkov crater glacier, Kamchatka. *Annals of Glaciology*, **45**, 29–37.

List of Symbols

Only the principal symbols are listed. A scalar is indicated by italics type, a vector by bold face upright type and a tensor by sans serif upright type.

| | |
|-------------------|--|
| 0 | zero vector |
| 1 | unit tensor |
| a | acceleration ($= d\mathbf{v}/dt = d^2\mathbf{x}/dt^2$) |
| a_b | basal melting (-freezing) rate in the vertical direction |
| a_b^\perp | basal melting (-freezing) rate |
| a_m^\perp | volume flux through the CTS |
| a_s | accumulation-ablation function (surface mass balance) in the vertical direction |
| a_s^\perp | accumulation-ablation function (surface mass balance) |
| b | z -coordinate of the ice base |
| b_0 | isostatically relaxed value for b without ice load |
| c | (1) specific heat in general (2) specific heat of ice [$= (146.3 + 7.253 T[\text{K}]) \text{J kg}^{-1} \text{K}^{-1}$] (3) specific heat of firn (Sect. 9.2) |
| c^\perp | calving rate |
| d_e | effective strain rate |
| \mathbf{e}_i | set of orthonormal basis vectors (in the present configuration κ_t) |
| \mathbf{e}_t | tangential unit vector |
| f | volume force |
| $f(\sigma_e)$ | creep function |
| $f^*(\mathbf{n})$ | orientation distribution function [$= \rho^*(\mathbf{n})/\rho$] |
| \mathbf{g}, g | gravitational acceleration ($= 9.81 \text{ m s}^{-2}$) |

| | |
|----------------------------|---|
| g | density of arbitrary physical quantity |
| g_s | arbitrary physical quantity per unit mass (“specific ...”) |
| h | (1) z -coordinate of the ice surface (2) specific enthalpy ($= u + p/\rho$; Sect. 9.3) |
| \mathbf{j} | diffusive water mass flux in temperate ice |
| k | enthalpy diffusivity |
| \dot{m}_b^w | water mass flux into the base |
| \mathbf{n} | (1) unit normal vector (2) orientation (direction of the c -axis; Sect. 9.1) |
| n | stress exponent ($= 3$) |
| p | (1) pressure (2) production density of arbitrary physical quantity (Chapter 3) |
| $p(\rho, T)$ | thermodynamic pressure |
| p_{visc} | viscous pressure |
| p_{tot} | total pressure [$= p(\rho, T) + p_{\text{visc}}$] |
| p_{sw} | hydrostatic pressure of sea water |
| p_{sea} | hydrostatic pressure of sea water at the ice-sea interface |
| p, q | basal sliding exponents |
| \mathbf{q} | heat flux |
| $\mathbf{q}^*(\mathbf{n})$ | orientation flux |
| \mathbf{q}_l | latent heat flux in temperate ice |
| \mathbf{q}_s | sensible heat flux in temperate ice |
| q | load per unit area |
| q_{geo}^\perp | geothermal heat flux |
| q_{sea}^\perp | heat flux on the sea side of the ice-sea interface |
| r | specific radiation power |
| s | supply density of arbitrary physical quantity |
| \mathbf{t} | Cauchy stress tensor |
| \mathbf{t}^D | Cauchy stress deviator [$= \mathbf{t} - (\frac{1}{3} \text{tr } \mathbf{t}) \mathbf{1}$] |
| \mathbf{t}_{lith} | stress at the lithosphere side of the ice-lithosphere interface |
| \mathbf{t}_{sea} | stress at the sea side of the ice-sea interface |
| \mathbf{t}_n | stress vector |
| t | time |
| $[t]$ | typical time-scale |
| \mathbf{u} | displacement |
| $\mathbf{u}^*(\mathbf{n})$ | orientation transition rate |
| u | specific internal energy |
| \mathbf{v} | velocity ($= d\mathbf{x}/dt$) |

| | |
|----------------------------|---|
| $\mathbf{v}^*(\mathbf{n})$ | orientation-dependent velocity |
| \mathbf{v}_b | basal sliding velocity |
| \mathbf{v}_{gl} | velocity at the grounding line |
| \mathbf{v}_h | horizontal velocity |
| \mathbf{v}_i | ice velocity in temperate ice |
| \mathbf{v}_{sea} | velocity of subglacial sea water |
| \mathbf{v}_w | water velocity in temperate ice |
| \mathbf{w} | velocity of a singular surface |
| w | vertical displacement of the lithosphere |
| w_{ss} | steady-state value of w |
| \mathbf{x} | position vector (in the present configuration κ_t) |
| x, y | horizontal Cartesian coordinates |
| z | vertical Cartesian coordinate |
| z_l | z -coordinate of the lithosphere surface |
| z_m | z -coordinate of the CTS |
| z_{sl} | z -coordinate of the mean sea level |
| $A(T')$ | rate factor |
| $A_t(W)$ | rate factor of temperate ice |
| A | deformability of polycrystalline ice |
| $A^*(\mathbf{n})$ | crystallite deformability |
| A_0 | pre-exponential constant ($= 3.985 \times 10^{-13} \text{ s}^{-1} \text{ Pa}^{-3}$ for $T' \leq 263.15 \text{ K}$, $= 1.916 \times 10^3 \text{ s}^{-1} \text{ Pa}^{-3}$ for $T' > 263.15 \text{ K}$) |
| \mathbf{B} | left Cauchy Green tensor ($= \mathbf{V}^2$) |
| $B(T')$ | associated rate factor |
| \mathbf{C} | right Cauchy Green tensor ($= \mathbf{U}^2$) |
| C_b | basal sliding coefficient |
| C_{wi} | water-ice drag coefficient ($\approx 2.5 \times 10^{-3}$) |
| \mathbf{D} | strain-rate (stretching) tensor [$= (\mathbf{L} + \mathbf{L}^T)/2$] |
| \mathbf{D}^D | strain-rate (stretching) deviator [$= \mathbf{D} - (\frac{1}{3} \text{tr } \mathbf{D}) \mathbf{1}$] |
| D | diffusivity of the ice surface |
| D_a | diffusivity of the asthenosphere |
| \mathbf{E}_A | set of orthonormal basis vectors (in the reference configuration κ_r) |
| E | (1) flow enhancement factor (2) Young's modulus |
| $E(\mathcal{A})$ | anisotropic flow enhancement factor |
| E_s | stress enhancement factor |

| | |
|---------------------|--|
| F | deformation gradient ($= \text{Grad } \mathbf{x}$) |
| F_b | implicit representation of the ice base ($= b - z$) |
| F_{cf} | implicit representation of the calving front |
| F_{gl} | implicit representation of the grounding line |
| F_m | implicit representation of the cold-temperate transition surface ($= z - z_m$) |
| F_s | implicit representation of the ice surface ($= z - h$) |
| Fr | Froude number [$= [U]^2/(g[H])$] |
| H | displacement gradient ($= \text{Grad } \mathbf{u} = \mathbf{F} - \mathbf{I}$) |
| H | (1) thickness in general (2) ice thickness ($= h - b$) |
| H_a | thickness of the asthenosphere |
| H_l | thickness of the lithosphere |
| $[H]$ | typical vertical extent |
| J | Jacobian of the deformation gradient ($= \det F$) |
| K | flexural stiffness |
| K_l | flexural stiffness of the lithosphere ($\approx 10^{25} \text{ N m}$) |
| L | velocity gradient ($= \text{grad } \mathbf{v}$) |
| L | latent heat of ice ($= 3.35 \times 10^5 \text{ J kg}^{-1}$) |
| L_r | radius of relative stiffness [$= (K_l/(\rho_a g))^{1/4}$] |
| $[L]$ | typical horizontal extent |
| M | water mass production rate in temperate ice |
| N | membrane stress |
| \mathbf{N}_b, N_b | basal normal stress |
| $[P]$ | typical pressure |
| \mathcal{P}_m^w | water surface production rate at the CTS |
| \mathbf{Q} | horizontal volume flux |
| Q | activation energy ($= 60 \text{ kJ mol}^{-1}$ for $T' \leq 263.15 \text{ K}$, $= 139 \text{ kJ mol}^{-1}$ for $T' > 263.15 \text{ K}$) |
| R | rotation tensor ($= \mathbf{F} \cdot \mathbf{U}^{-1} = \mathbf{V}^{-1} \cdot \mathbf{F}$) |
| R | universal gas constant ($= 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$) |
| Ro | Rossby number [$= [U]/(2\Omega[L])$] |
| T | temperature |
| T_m | pressure melting temperature |
| T_0 | melting temperature at standard pressure ($= 273.15 \text{ K}$) |
| T' | temperature relative to the pressure melting point ($= T - T_m + T_0$) |
| T_{cf} | temperature at the calving front |
| T_{gl} | temperature at the grounding line |

| | |
|------------------------------------|--|
| T_s | ice surface temperature |
| T_{sea} | temperature of sea water at the ice-sea interface ($\approx -2^\circ\text{C}$) |
| \mathbf{U} | right stretch tensor [= $(\mathbf{F}^T \cdot \mathbf{F})^{1/2}$] |
| $[U]$ | typical horizontal velocity |
| \mathbf{V} | left stretch tensor [= $(\mathbf{F} \cdot \mathbf{F}^T)^{1/2}$] |
| V | activation volume |
| \mathbf{W} | spin tensor [= $(\mathbf{L} - \mathbf{L}^T)/2$] |
| W | water content of temperate ice (mass fraction) |
| W_s | water content at the ice surface |
| $[W]$ | typical vertical velocity |
| \mathbf{X} | position vector (in the reference configuration κ_r) |
| α | inclination angle |
| β | Clausius-Clapeyron constant (= $7.42 \times 10^{-8} \text{ K Pa}^{-1}$ for pure ice, = $9.8 \times 10^{-8} \text{ K Pa}^{-1}$ for air-saturated glacier ice) |
| γ_{ij} ($i \neq j$) | shear angle |
| $\dot{\gamma}_{ij}$ ($i \neq j$) | shear rate |
| $\delta(\cdot)$ | Dirac's delta function |
| δ_{ij} | Kronecker symbol |
| δ_{sea} | frictional dissipation at the sea side of the ice-sea interface |
| ϵ | infinitesimal strain tensor [= $(\mathbf{H} + \mathbf{H}^T)/2$] |
| ϵ^D | infinitesimal strain deviator [= $\epsilon - (\frac{1}{3} \text{tr } \epsilon) \mathbf{I}$] |
| ϵ | aspect ratio (= $[H]/[L] = [W]/[U]$) |
| ε_{ijk} | Levi-Civita symbol |
| ζ | (1) bulk viscosity (= $\lambda + 2\eta/3$) (2) vertical coordinate of the sigma transformation |
| η | shear viscosity |
| $\bar{\eta}$ | depth-integrated shear viscosity |
| ι | constitutive parameter for the orientation transition rate |
| κ | (1) bulk modulus (= $\lambda + 2\mu/3$) (2) heat conductivity in general (3) heat conductivity of ice (= $9.828 e^{-0.0057 T[\text{K}]} \text{ W m}^{-1}\text{K}^{-1}$) (4) heat conductivity of firn (Sect. 9.2) |
| κ_r | reference configuration |
| κ_t | present configuration |
| λ | (1) 1 st Lamé parameter (2) viscosity coefficient (3) orientation diffusivity (Sect. 9.1) |

| | |
|----------------------------|---|
| μ | 2 nd Lamé parameter (shear modulus) |
| ν | (1) Poisson's ratio (2) water diffusivity in temperate ice (Sect. 9.3) |
| ξ, φ | horizontal coordinates of the sigma transformation |
| ρ | (1) density in general (2) density of ice ($= 910 \text{ kg m}^{-3}$) (3) density of firn (Sect. 9.2) |
| $\tilde{\rho}$ | relative density of firn ($= \rho/\hat{\rho}_i$) |
| $\rho^*(\mathbf{n})$ | orientation mass density |
| ρ_a | density of the asthenosphere ($= 3300 \text{ kg m}^{-3}$) |
| ρ_i | partial density of ice in temperate ice |
| $\hat{\rho}_i$ | bulk density of ice ($= 910 \text{ kg m}^{-3}$) |
| ρ_{sw} | density of sea water ($= 1028 \text{ kg m}^{-3}$) |
| ρ_w | partial density of water in temperate ice |
| $\hat{\rho}_w$ | bulk density of water ($= 1000 \text{ kg m}^{-3}$) |
| σ_e | effective stress |
| σ_0 | residual stress |
| τ | time coordinate of the sigma transformation |
| τ_a | time lag of the relaxing asthenosphere ($\approx 3000 \text{ a}$) |
| $\tau_b, \bar{\tau}_b$ | basal drag (shear stress) |
| τ_d | driving stress |
| τ_{sea} | basal drag (shear stress) induced by circulating sea water |
| ϕ | flux density of arbitrary physical quantity |
| ψ | arbitrary scalar, vector or tensor field |
| ω | material volume in the present configuration κ_t |
| Γ | constitutive parameter for the orientation production rate |
| $\Gamma^*(\mathbf{n})$ | orientation production rate |
| $\Delta\zeta$ | spacing of vertical coordinate ζ |
| $\Delta\xi, \Delta\varphi$ | spacing of horizontal coordinates ξ and φ , respectively |
| $\Delta\tau$ | spacing of time coordinate τ |
| $[\Delta T]$ | typical temperature variation |
| Φ_n | set of basis functions |
| $\Omega, \bar{\Omega}$ | angular velocity of the Earth ($= 7.2921 \times 10^{-5} \text{ s}^{-1}$) |
| $\bar{\Omega}$ | material volume in the reference configuration κ_r |

List of Acronyms

| | |
|-----------|--|
| AGCM | Atmosphere General Circulation Model |
| AMSL | Above Mean Sea Level |
| CAFFE | Continuum-mechanical, Anisotropic Flow model, based on an anisotropic Flow Enhancement factor |
| CTS | Cold-temperate Transition Surface, |
| DA | Diffusive Asthenosphere |
| EAIS | East Antarctic Ice Sheet |
| EDML | EPICA ice core in Dronning Maud Land |
| EGIG | Expédition Glaciologique Internationale au Groenland |
| EISMINT | European Ice Sheet Modeling INiTiative |
| EL | Elastic Lithosphere |
| ELDA | Elastic Lithosphere / Diffusive Asthenosphere |
| ELRA | Elastic Lithosphere / Relaxing Asthenosphere |
| EPICA | European Project for Ice Coring in Antarctica |
| ETH | Eidgenössische Technische Hochschule (Swiss Federal Institute of Technology) Zurich |
| FESSACODE | Finite Element Shallow Shelf Approximation Code |
| FOA | First Order Approximation |
| FS | Full Stokes |
| GCM | General Circulation Model |
| GPS | Global Positioning System |
| GRIP | Greenland Ice Core Project |
| HEINO | Heinrich Event INtercOmparison |
| IAI | International Antarctic Institute |
| IPCC | Intergovernmental Panel on Climate Change |

| | |
|-----------|---|
| ISMIP | Ice Sheet Model Intercomparison Project |
| LGM | Last Glacial Maximum |
| LL | Local Lithosphere |
| LLDA | Local Lithosphere / Diffusive Asthenosphere |
| LLRA | Local Lithosphere / Relaxing Asthenosphere |
| MODIS | MODerate-resolution Imaging Spectroradiometer |
| NADW | North Atlantic Deep Water |
| NASA | National Aeronautics and Space Administration |
| ODE | Ordinary Differential Equation |
| ODF | Orientation Distribution Function |
| OGCM | Ocean General Circulation Model |
| OMD | Orientation Mass Density |
| QED | Quod Erat Demonstrandum (which was to be demonstrated) |
| RA | Relaxing Asthenosphere |
| RIGGS | Ross Ice Shelf Geophysical and Glaciological Survey |
| SGVE | Self-Gravitating, spherical, Visco-Elastic multi-layer |
| SIA | Shallow Ice Approximation |
| SICOPOLIS | SIMulation COde for POLythermal Ice Sheets |
| SSA | Shallow Shelf Approximation |
| WAIS | West Antarctic Ice Sheet |

Index

- ablation, 66, 104, 179
- acceleration, 21, 63, 73, 193
- accumulation, 1, 66, 104, 179
- accumulation area, 174, 224
- accumulation-ablation function, 66, 71, 82
- activation energy, 52, 54
- activation volume, 52
- additivity, 26
- advection, 22, 26, 27
- AGCM, 109
- air bubble, 226
- Alaska, 253
- albedo, 4
- alternator, 10
- Amery Ice Shelf, 2, 111
- AMSL, 2, 105, 224
- Andes, 2, 4
- angular momentum, 33
- angular momentum density, 33
- angular velocity, 62
- anisotropic enhancement factor, 205, 207, 208, 213, 215, 217
- anisotropic fabric, 203, 204
- anisotropy, 50, 203
- Antarctic Ice Sheet, 1, 3–5, 61, 109, 158, 185, 192, 199, 220, 222, 253
- Antarctic ice shelves, 111
- Antarctic Peninsula, 253, 262
- antisymmetric tensor, 12, 23
- Arakawa C grid, 97
- Arrhenius law, 52–54
- arrow, 7
- aspect ratio, 63, 78, 111, 117
- associated rate factor, 56
- asthenosphere, 188
- Atlas Mountains, 4
- atmosphere, 61
- atmospheric circulation, 6
- Austfonna, 3, 192
- balance equation, 27, 30
- balance of angular momentum, 33
- balance of internal energy, 36, 37, 64
- balance of kinetic energy, 35
- barycentric velocity, 238
- basal drag, 68, 79
- basal melting, 2
- basal melting rate, 68, 71, 82, 240
- basal melting-freezing rate, 112
- basal plane, 49
- basal sliding, 68, 79, 157, 261
- basal sliding exponent, 69
- basal sliding velocity, 69, 79, 158, 163, 178
- basis, 9
- basis function, 135
- Bessel function, 191
- biharmonic equation, 42, 190
- biharmonic operator, 43
- binary mixture, 237
- body, 17
- British Isles Ice Sheet, 4
- Bueler profile, 88, 89
- bulk modulus, 39
- bulk viscosity, 44

- buoyancy, 188
- c-axis, 49, 50, 203, 204, 206
- CAFFE flow law, 207, 208
- CAFFE model, 204
- caloric equation of state, 59
- calving, 1, 2, 61, 184, 203, 261, 262
- calving front, 114, 117, 123
- calving rate, 87, 116
- Canadian Arctic, 253
- Canadian-type polythermal glacier, 253, 259
- Cartesian basis, 9
- Cartesian coordinates, 14, 61
- Cauchy Green tensor, 20
- Cauchy stress tensor, 31, 32, 34
- centrifugal force, 62
- clathrate, 226
- Clausius-Clapeyron constant, 53
- Clausius-Clapeyron gradient, 240
- climate system, 1
- closure of air bubbles, 226
- closure relation, 37
- coefficient of viscosity, 43
- cold base, 69
- cold glacier, 145, 237
- cold ice, 145, 183, 237
- cold-temperate transition surface, 183, 242
- column, 9
- compressibility of firn, 228
- compressible, 43, 228
- configuration, 17
- conserved quantity, 27
- constitutive equation, 37
- contact problem, 115, 123
- continuity equation, 29, 75
- continuum mechanics, 17
- core, 187
- Coriolis force, 62, 73, 112, 145, 193
- creep, 1, 50
- creep function, 52, 53
- cross product, 7, 10
- crust, 185, 187
- cryosphere, 1
- crystallite, 50, 203
- CTS, 242
- curl, 15
- curl theorem, 16
- damage mechanics, 262
- Darcy-type interaction force, 238
- debris layer, 183
- deformation, 17, 20
- deformation gradient, 18, 22
- Delaunay triangulation, 134
- densification of firn, 224
- density, 27, 29
- density of firn, 224, 227
- density of ice, 62, 225, 227, 232
- density of sea water, 112
- density of the asthenosphere, 188
- depth-integrated viscosity, 121
- determinant, 13
- diffusion equation, 82
- diffusive asthenosphere, 188, 195
- diffusive water mass flux, 238, 239, 241, 244
- dilatation, 38
- dilatation rate, 24, 130
- dimensional matrix, 159
- Dirac's δ function, 191, 211
- discontinuity, 183, 261
- dislocation, 50
- dislocation creep, 50
- displacement, 18
- displacement gradient, 38
- dissipation power, 35, 36
- divergence, 15
- divergence theorem, 16, 26, 27, 132
- dot product, 7, 10
- driving stress, 83
- Dronning Maud Land, 219, 220
- dual vector, 24
- dyadic product, 8, 10
- dynamic boundary condition, 67, 113
- dynamic recrystallisation, 51, 218, 219, 223
- East Antarctic Ice Sheet, 219
- eccentricity, 3
- EDML ice core, 219, 220
- effective pressure, 161
- effective strain rate, 55, 74
- effective stress, 53
- EGIG line, 103
- Einstein's summation convention, 9
- EISMINT model intercomparison, 86
- elastic body, 38

- elastic deformation, 51, 60
- elastic lithosphere, 188, 190, 195
- ELDA model, 188, 192, 195, 199
- elliptical boundary-value problem, 124
- ELRA model, 188, 199, 201
- emission scenario, 5
- energy, 35
- energy balance, 35, 45
- energy jump condition, 36, 69, 113
- enthalpy, 255
- enthalpy diffusivity, 257
- enthalpy gradient method, 256, 259
- EPICA, 220
- epsilon tensor, 14
- equation of motion, 63, 112, 229
- equilibrium line altitude, 104
- essential boundary condition, 133
- Euclidian space, 7
- Euler forward stepping, 100, 101
- Eulerian description, 18
- Eurasian Ice Sheet, 4, 109
- European Alps, 4
- evolution equation, 37

- fabric, 58, 203, 204, 206, 217
- FESSACODE, 141
- Fick's diffusion law, 239
- Fiescherhorn Glacier, 224
- Filchner-Rønne Ice Shelf, 2, 111, 199
- final stage of densification, 226
- finite difference, 164, 165
- finite difference method, 90, 131, 141
- finite difference scheme, 166, 168, 169, 181, 197
- finite element, 133
- finite element mesh, 133, 141
- finite element method, 131, 168
- firn, 224
- First Law of Thermodynamics, 36
- first order approximation, 76, 145, 153
- first order plane strain approximation, 156
- fixed point iteration, 166, 167, 172, 174, 180, 229, 236
- flexural stiffness, 42, 190
- floating condition, 120
- flow enhancement factor, 58, 203
- fluidity, 52, 53
- flux, 26
- flux density, 27
- force, 31
- force of gravity, 62
- forebulge, 191
- Fourier's law of heat conduction, 45, 59, 239, 257
- fracturing, 184, 262
- free surface, 61, 65, 112
- freeboard, 120
- freezing condition, 245, 248, 250
- frictional dissipation, 113
- front tracking, 255, 259
- Froude number, 64, 111, 145

- Galerkin finite element method, 137
- general balance equation, 27, 30
- general jump condition, 29
- geothermal heat flux, 61, 69, 242
- girdle fabric, 213, 221
- glacial, 3
- glacial cycle, 3, 104, 185
- glacial flow, 1
- glacial isostasy, 61, 82, 186
- glacier, 1, 2, 17, 48, 192, 237
- Glen's flow law, 54, 55, 204, 207, 208
- Global Conveyor Belt, 6
- global positioning system, 178
- global warming, 4, 261
- GPS, 178
- gradient, 15
- grain, 50, 183, 203
- grain boundary sliding, 54
- grain rotation, 204, 217, 219
- gravitational acceleration, 62
- Green's function, 191, 197
- greenhouse gas, 5
- Greenland Ice Sheet, 2–5, 86, 103, 109, 185, 192, 253
- GRIP ice core, 219
- ground ice, 1
- grounding line, 114, 117, 122, 262
- Gulf of Bothnia, 185
- Gulf Stream, 6

- hard bed, 157, 158
- Haut Glacier d'Arolla, 153, 182
- heat conductivity, 45, 59, 229
- heat flux, 35, 36, 59, 239
- hexagonal crystal, 49

- Holocene Epoch, 4
 homogeneous viscous thermoelastic body, 37
 Hooke's law, 39, 41, 60
 Hookean body, 38, 199
 horizontal velocity, 76, 80, 117, 122, 182
 hydraulic system, 183
 hydrology, 203, 261
 hydrostatic approximation, 75, 116, 145, 153
 hydrostatic pressure, 48, 161

 ice age, 3, 186
 ice base, 61, 67, 112, 183, 190
 ice cap, 1, 3, 192
 ice core, 141, 219, 220
 ice crystal, 50
 ice dome, 77
 ice Ih, 49
 ice load, 185, 188
 ice margin, 77
 ice sheet, 1, 61, 111, 185, 192, 237
 ice sheet model, 90, 103, 109
 ice shelf, 1, 60, 111, 262
 ice stream, 6, 203
 ice surface, 61, 65, 112, 183
 ice thickness equation, 71, 72, 81, 112, 125, 194
 ice-dynamic instability, 6
 identity transformation, 12
 incompressible, 30, 44, 52, 61, 149, 163, 192, 224
 index notation, 11
 inertial force, 62
 infinite viscosity, 56
 infinitesimal strain deviator, 39
 infinitesimal strain tensor, 38, 39
 initial stage of densification, 225
 inner core, 187
 inner product, 7
 interglacial, 3
 intermediate stage of densification, 225
 internal energy, 35, 255
 inverse problem, 179
 inverse tensor, 13
 IPCC, 4
 ISMIP model intercomparison, 108
 isostasy, 61, 82, 186
 isotropic fabric, 206, 207, 222

 isotropy, 38, 50, 203
 iteration method, 140

 Jacobian, 19, 23
 jump, 28
 jump condition, 29
 jump condition of angular momentum, 34

 Kelvin function, 191
 kinematic boundary condition, 66, 67, 112
 kinetic energy, 35
 kinetic energy density, 35
 Kohnen Station, 220
 Kronecker symbol, 9, 12

 Lagrangian description, 18
 lake ice, 1
 Lake Vostok, 158
 Lamé parameter, 39, 41, 60
 land ice, 1
 Laplacian, 15, 42
 large-scale surge, 107
 Larsen Ice Shelf, 262
 Last Glacial Maximum, 4, 185
 latent heat, 70, 256
 latent heat flux, 239
 Leibniz's rule, 70, 118
 Levi-Civita symbol, 10, 13, 14
 line integration, 167
 linear elastic solid, 38, 199
 linear transformation, 8, 10, 13
 linear viscous fluid, 43, 192
 lithosphere, 61, 188
 lithosphere surface, 61, 112, 116, 190
 LLDA model, 188, 192, 199
 LLRA model, 188, 190, 199
 local lithosphere, 188, 192
 local time derivative, 22
 localisation, 27

 mantle, 187
 Mars, 109
 mass, 29
 mass balance, 29, 37, 41, 44, 61, 112, 124, 228
 mass jump condition, 30, 113
 master element, 134

- material description, 18
- material equation, 37
- material quantity, 38
- material time derivative, 22
- material volume, 25, 26
- matrix, 11
- Mauna Kea, 4
- Maxwell fluid, 199
- mechanical ice shelf problem, 132
- melting, 1, 61, 104, 224
- melting condition, 245, 247, 249
- melting temperature, 53
- membrane stress, 119
- method of lines, 165
- migration recrystallisation, 51, 218, 219
- Milankovitch theory, 3
- mixture energy balance, 239
- mixture mass balance, 238
- mixture momentum balance, 238
- mixture theory, 237
- momentum, 30
- momentum balance, 31, 32, 37, 42, 44, 45, 63, 72, 76, 77, 117, 229
- momentum density, 30
- momentum jump condition, 32, 66, 68, 112
- motion, 17, 18
- motor oil, 54
- Mount Kilimanjaro, 3

- nabla operator, 15
- NADW, 6
- natural boundary condition, 133
- Navier equation, 42
- Navier-Stokes equation, 44–47, 193
- New Zealand, 4
- Newton's Second Law, 31
- Newtonian fluid, 43, 44, 56, 57, 149, 163, 192
- no-slip condition, 37, 46, 68
- non-material volume, 28
- norm, 7
- normal stress, 32
- North American Ice Sheet, 4, 109
- North Atlantic, 6
- North Atlantic drift, 6
- number triple, 9
- numerical grid, 91

- Nye's generalisation of Glen's flow law, 54

- obliquity, 3
- ocean, 61, 114
- oceanic tide, 60
- OGCM, 109
- Oligocene, 3
- optic axis, 49
- orthonormal basis, 9
- outer core, 187
- outer product, 8

- parallel sided slab, 146, 230, 246
- partial density, 238
- particle, 17
- Patagonian Ice Sheet, 4
- permafrost, 1, 5
- permutation tensor, 14
- Petterssen iteration, 174
- photogrammetry, 178
- plane strain, 46, 84, 126
- plate tectonics, 188
- Pleistocene, 3
- Pleistocene Glacial Epoch, 3
- Pliocene, 3
- plug flow, 117
- Poisson's ratio, 39, 60, 191
- polar decomposition, 19
- polar ice caps of Mars, 109
- polar stereographic projection, 61
- polycrystalline ice, 50, 203
- polygonisation, 217, 219
- polythermal glacier, 145, 237, 253
- porosity, 224
- position vector, 17
- positive definite, 19
- power law, 52, 53, 68
- power of stresses, 35
- power of volume forces, 35
- pre-exponential constant, 52, 54
- precession, 3
- present configuration, 17, 25
- pressure, 43–45
- pressure melting point, 54, 65
- primary creep, 51
- principal axis, 20
- prismatic plane, 50
- production, 26

- production density, 27
- proper orthogonal tensor, 19
- Puncak Jaya, 3
- pure shear, 222
- pyramidal plane, 50

- radiation power, 35
- radius of relative stiffness, 191
- radius of the Earth, 61
- rate factor, 52, 53
- recrystallisation, 204, 224
- rectangular grid, 91, 97
- reference configuration, 17, 25
- refreezing, 224
- regularised Glen's flow law, 56
- relative density, 227
- relaxation scheme, 140, 230
- relaxing asthenosphere, 188, 192
- residual stress, 56
- Reynolds' transport theorem, 26, 27
- Rhone Glacier, 177
- RIGGS campaign, 141
- rigid body rotation, 25
- river ice, 1
- Rocky Mountains, 253
- Ross Ice Shelf, 1, 111, 141, 199
- Rossby number, 64, 111
- rotation recrystallisation, 217, 219
- rotation tensor, 20
- Runge-Kutta scheme, 165

- scalar, 7
- scalar field, 14
- scalar invariant, 13, 53
- scalar multiplication, 7
- Scandinavia, 253
- Scandinavian Ice Sheet, 4, 109
- Scandinavian-type polythermal glacier, 253
- Schmidt diagram, 211, 214, 221–223
- sea ice, 1
- sea level, 4
- sea level rise, 2–4
- secondary creep, 51, 58
- seconds per year, 64
- sediment layer, 162
- settling of firn, 232
- SGVE model, 186, 199

- shallow ice approximation, 77, 125, 145, 152, 222, 262
- shallow shelf approximation, 117, 125
- shear, 38
- shear angle, 51
- shear experiment, 50
- shear modulus, 39, 60, 191
- shear rate, 24
- shear stress, 32, 50
- shear traction, 164
- shear viscosity, 44, 45, 52
- shooting, 166, 180
- SICOPOLIS, 90, 103, 255
- sigma transformation, 91
- simple shear, 52, 77, 207, 211, 216, 222
- single maximum fabric, 206, 207, 211, 216, 221, 222
- single shooting, 166, 180
- singular surface, 28
- sliding law, 68, 113
- small deformation, 38
- Smith-Morland flow law, 58
- snow, 1
- snowfall, 61, 104
- soft bed, 158
- solar insolation, 3
- Sorge's Law, 229, 230
- Southern Ocean, 2
- sparse matrix, 140
- spatial description, 18
- specific enthalpy, 255
- specific heat, 45, 59, 229, 256
- specific internal energy, 35, 36, 255
- specific kinetic energy, 35
- specific momentum, 32
- specific radiation power, 35, 36
- speed, 34
- spherical coordinates, 207, 213
- spin tensor, 23, 24
- staggered grid, 97
- standard parallel, 61
- stationary Rossby wave, 6
- steady state, 46, 84, 126, 222
- Stokes equation, 64
- Stokes flow, 64, 112, 145, 146, 153, 193
- Storglaciären, 153, 172, 174, 255
- strain-rate deviator, 43
- strain-rate tensor, 23, 52
- stress, 31

- stress deviator, 45, 52
 stress enhancement factor, 58, 141
 stress exponent, 52, 53
 stress tensor, 31, 32, 34
 stress vector, 31, 32
 stress-free condition, 46, 67, 78, 112
 stretch tensor, 20
 stretching tensor, 23
 subglacial hydrology, 203, 261
 sum of vectors, 7
 supply, 26
 supply density, 27
 surface mass balance, 66, 71, 104
 surface slope, 81
 surface temperature, 67, 83, 104
 surge, 107, 261
 Svalbard, 253
 Swiss Alps, 153, 177, 224
 symmetric tensor, 12, 19, 23
- Tasmania, 4
 temperate base, 69, 113, 240
 temperate glacier, 145, 237
 temperate ice, 145, 183, 237
 temperate surface, 240
 temperature, 38
 temperature evolution equation, 65, 75, 82, 112, 125
 temperature of sea water, 113, 141
 temperature relative to the pressure melting point, 54
 tensor, 10, 13
 tensor contraction, 14
 tensor field, 14
 tensor multiplication, 12
 tensor product, 8, 14
 terrain-following coordinate transformation, 91, 164, 233
- Tertiary, 3
 tertiary creep, 51
 thermal equation of state, 43
 thermal expansion, 5
 thermodynamic boundary condition, 67, 69
 thermodynamic pressure, 43, 44, 227
 thermomechanically coupled problem, 64
 thin channel, 192
 thin channel equation, 195
- thin elastic plate, 42, 190
 thin film, 46, 146
 time derivative, 22
 total pressure, 44
 trace, 13
 trajectory, 174
 transformed equations, 167
 transverse flow profile, 175
 triangulation, 134, 141
 tropical glacier, 2
 typical value, 63, 82, 111
- uniaxial compression, 207, 214, 216
 unit matrix, 12
 unit tensor, 12
 unit vector, 7
 universal gas constant, 52
 uplift, 185
 uplift rate, 199
 upper mantle, 55
- Vatnajökull, 3, 192
 vector, 7
 vector field, 14
 vector product, 7
 vector space, 7
 velocity, 21
 velocity gradient, 22
 vertical velocity, 76, 81, 125, 172, 182
 Vialov profile, 86, 89
 visco-elastic fluid, 199
 viscosity, 44, 45, 52, 54, 56, 64, 74, 76, 186, 192
 viscous material, 43
 viscous pressure, 44, 227
 volume flux, 71, 81
 volume force, 31, 62
 Vostok station, 2
- water flux, 244, 245
 water pressure, 161
 water-ice drag coefficient, 112
 weak formulation, 133
 Weertman-type sliding law, 68, 79, 106, 157, 161, 262
 weight function, 132
 West Antarctic Ice Sheet, 6, 262
 Wilkins Ice Shelf, 262
- Young's modulus, 39, 60, 191