Bentley, C. R., and J. M. Wahr. "Satellite Gravity and the Mass Balance of the Antarctic Ice Sheet." *J. Glaciol.* 44 (147) (1998): 207–213.

Bolzan, J. F., and K. C. Jezek. "Accumulation Rate Changes in Central Greenland from Passive Microwave Data." *Polar Geography* 24 (2) (1999): 98–112.

Budd, W. F., and R. C. Warner. "A Computer Scheme for Rapid Calculations of Balance Flux Distributions." *Ann. Glaciol.* 23 (1996): 21–27.

Church, J. A., and J. M. Gregory. "Changes in Sea Level." In *Climate Change 2001: The Scientific Basis,* edited by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson. Cambridge: Cambridge University Press, 2001, pp. 639–693.

Cuffey, K. M., and G. D. Clow. "Temperature, Accumulation, and Ice Sheet Elevation in Central Greenland Through the Last Deglacial Transition." *J. Geophys. Res.* 102 (C12) (1997): 26,383–26,396.

Hamilton, G. S., I. M. Whillans, and P. J. Morgan. "First Point Measurement of Ice-Sheet Thickness Change in Antarctica." *Ann. Glaciol.* 27 (1998): 125–129.

ISMASS Committee. "Recommendations for the Collection and Synthesis of Antarctic Ice Sheet Mass Balance Data." *Global and Planetary Change* 42 (2004), 1–15.

Jacobs, S. S., H. H. Hellmer, and A. Jenkins. "Antarctic Ice Sheet Melting in the Southeast Pacific." *Geophys. Res. Letters* 23 (9) (1996): 957–960.

Kapsner, W. R., R. B. Alley, C. A. Shuman, S. Anandakrishnan, and P. M. Grootes. "Dominant Control of Atmospheric Circulation on Snow Accumulation in Central Greenland." *Nature* 373 (1995): 52–54.

Le Meur, E., and P. Huybrechts. "A Comparison of Different Ways of Dealing with Isostasy: Examples from Modelling the Antarctic Ice Sheet During the Last Glacial Cycle." *Ann. Glaciol.* 23 (1996): 309–317.

Lythe, M., D. G. Vaughan, and the Bedrock Consortium. "BEDMAP: A New Ice Thickness and Subglacial Topographic Model of Antarctica." *J. Geophys. Res.* 106 (B6) (2001): 11,335–11,352.

Mayewski, P. A., and I. D. Goodwin. *International Trans-Antarctic Scientific Expedition (ITASE)*. PAGES/SCAR Workshop Report Series, 97-1. Bern, Switzerland, 1997.

Polar Research Board. *Glaciers, Ice Sheets, and Sea Level: Effect of a CO2-induced Climatic Change*. Report of a Workshop held in Seattle, Washington, September 13–15, 1984. U.S. DOE/ER/60235-1, 1985.

Rignot, E. "Mass Balance of East Antarctic Glaciers and Ice Shelves from Satellite Data." *Ann. Glaciol.* 34 (2002): 217–227.

Rignot, E., and R. H. Thomas. "Mass Balance of Polar Ice Sheets." *Science* 297 (5586) (2002): 1502–1506.

Shepherd, A., D. J. Wingham, and J. A. D. Mansley. "Inland Thinning of the Amundsen Sea Sector, West Antarctica." *Geophys. Res. Lett.* 29 (10) (2002): 2-1 to 2-4.

Winebrenner, D. P., R. J. Arthern, and C. A. Shuman. "Mapping Greenland Accumulation Rates Using Observations of Thermal Emission at 4.5 cm Wavelength." *J. Geophys. Res.* 106 (D24) (2001): 33,919–33,934.

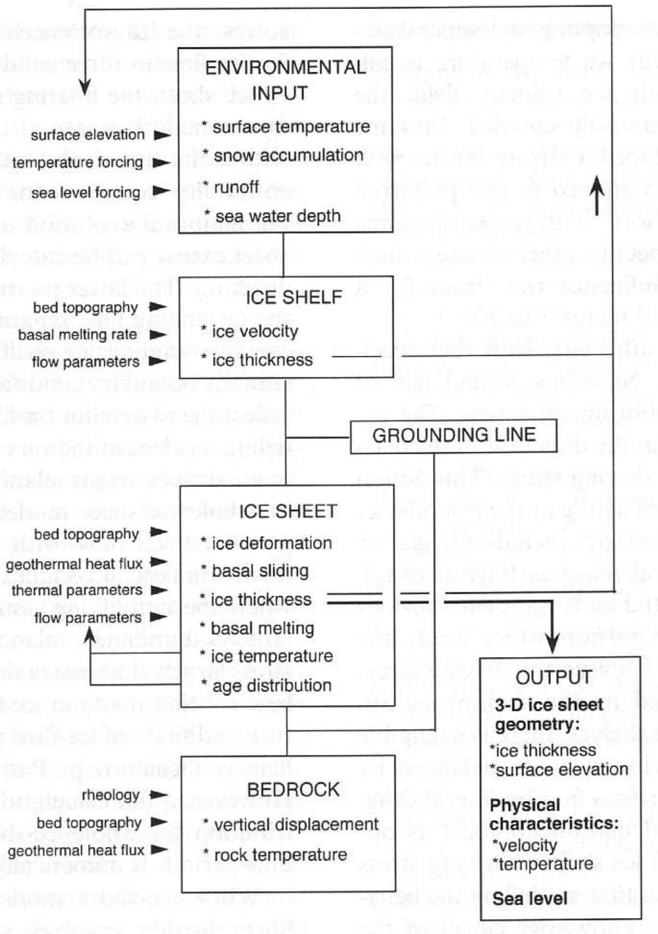
Zwally, H. J., B. Schultz, W. Abdalati, J. Abshire, C. Bentley, A. Brenner, J. Bufton, J. Dezio, D. Hancock, D. Harding, T. Herring, B. Minster, K. Quinn, S. Palm, J. Spinhirne, and R. Thomas. "ICESat's Laser Measurements of Polar Ice, Atmosphere, Ocean, and Land." *J. Geodynamics* 34 (2002): 405–445.

ICE SHEET MODELING

Ice sheet modeling underpins much of our understanding of the Antarctic Ice Sheet. A primary motivation for developing mathematical models of ice flow is to gain better insight of the key processes controlling ice-sheet behaviour and to predict the ice sheet's response to external forcing. Modeling necessarily implies a simplified description of reality, however analytical methods can only be used for the most simple problems. Therefore, ice-dynamic models use numerical methods to solve continuous equations on a numerical grid with the aid of a computer. Ice-flow models are commonly based on fundamental physical laws and assumptions thought to describe glacier flow.

Models can be separated into two categories, namely diagnostic and prognostic models. A diagnostic model describes a certain process while a prognostic model predicts how a quantity or process evolves with time. Diagnostic ice-sheet models often isolate a small part of the ice sheet in great detail or consider the physics of a specific process in a schematic way. They are useful to highlight the importance of certain mechanisms and provide insight in key processes governing ice flow. Prognostic models mostly predict the evolution of ice thickness and thus glacier geometry over time. Such models often attempt to be comprehensive in the number of processes taken into account, however sometimes at the expense of a rigorous consideration of the full details of a particular component.

A further distinction can be made on how models embody horizontal space: either they study the dynamics of selected one-dimensional flowlines within the ice sheet or they study the ice sheet in the full two-dimensional horizontal plane. The former type is often referred to as flowline or flowband model and the latter as planform model. Planform models often average processes over the vertical extent, in which case these models are referred to as two-dimensional planform or vertically integrated models. Otherwise they incorporate vertical processes explicitly. Examples of such vertical processes are ice temperature, stress, and velocity components, as well as ice crystal fabric and water content. Such models are called three-dimensional thermomechanical models and are at the top end of the class of ice-sheet models. They are able to describe the time-dependent flow and shape of real ice sheets, and are akin to general circulation models developed in other branches of climate science. Their development closely follows technical process in such fields as computer power, ice-core and sediment drilling, remote sensing, and geophysical dating techniques, which are both providing the required calculating means and the necessary data to feed and validate such models.



Structure of a comprehensive three-dimensional ice-sheet model applied to the Antarctic ice sheet. The inputs are given at the left-hand side. Prescribed environmental variables drive the model, which has ice shelves, grounded ice, and bed adjustment as major components. The position of the grounding line is not prescribed, but internally generated. Ice thickness feeds back on surface elevation, an important parameter for the calculation of the mass balance. The model essentially outputs the time-dependent ice-sheet geometry and the coupled temperature and velocity fields. (From Huybrechts 2004.)

Historically, planform time-dependent modeling of ice sheets largely stems from early work by Mahaffy (1976) and Jenssen (1977), extending on the pioneering "Derived Physical Characteristics of the Antarctic Ice Sheet" of W. F. Budd and colleagues at the Australian National Antarctic Research Expeditions published in 1971. These landmark studies introduced many concepts and techniques that are still used in glaciology today. The most important concept made use of the fact that the horizontal extent of an ice sheet is large compared with its thickness. In what became known as the shallow-ice approximation (Hutter 1983), longitudinal derivatives of stress, velocity, and temperature are assumed small compared to vertical derivatives. This greatly simplifies the numerical solution. Although the assumption is only fully satisfied over inland portions of continentally based ice, it has shown general applicability in large-scale ice-sheet modeling as long as surface slopes are evaluated over horizontal distances at least an order of magnitude greater than ice thickness.

The core of an ice-sheet model calculates how ice flows downhill in response to stresses set up by gravity. This ice flow results from internal deformation and from ice sliding over its bed where the basal temperature has reached the melting temperature and a lubricating water-saturated layer has formed. Whereas basal sliding depends to a large extent on the properties of the bed under the ice, internal deformation is the inherent manifestation of individual ice crystals subjected to stress. This deformation is reasonably well understood on the macro scale and can be reliably modelled taking into account Glen's flow law. That is an empirical relation derived from laboratory tests, which is most commonly used in ice flow modeling. It considers ice as a nonlinear viscoelastic fluid, relating strain rates to stresses raised mostly to the third power. The rate of deformation for a given stress also depends on the temperature of the ice and the fabric of the ice. The warmer the ice, the easier it deforms. For the temperature range encountered in the Antarctic Ice Sheet, three orders of magnitude are involved. In the flow law, this temperature effect