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A retrospective look at coupled ice sheet–climate modeling

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Since its inception, numerical climate modeling has evolved along with available computer power. Limitations in computer power quickly led to distinct types of models, with relatively simple models capable of long integrations, versus complex models suitable for short-duration detailed snapshots. Recognizing these computing limitations, strategies to combine and enhance knowledge from the different model types were conceived, and Schneider and Dickinson (1974) were early proponents of interactive "hierarchies" of models. In that framework, numerical climate models of different complexities, ranging from energy balance models (EBMs) for long-term simulations, through zonal statistical-dynamic models and nowadays, Earth models of intermediate complexity (EMICs), to general circulation (or global climate) models (GCMs) for short-term weather details, are used in combination with each other. For instance, the GCM is used to determine key sensitivities (to orbital perturbations, for example), and then the EBM is tuned to have the same sensitivities. Knowledge and experience at each level of the hierarchy is applied interactively at other levels. Climate-model hierarchies have also been discussed by Henderson-Sellers and McGuffie (1987), Claussen et al. (2002) and Bartlein and Hostetler (2004), with Claussen et al. (2002) distinguishing between integration of components vs. detail of description, and proposing the term "spectrum" to avoid any suggestion that one hierarchical level is better than another (Fig. 1).

This paper briefly surveys how these ideas have found form over the last several decades, in the area of coupled ice sheet–climate modeling. To some extent the original concept of hierarchies has been realized, but mostly it has been adapted in different ways than originally envisioned, driven by the need to address the very

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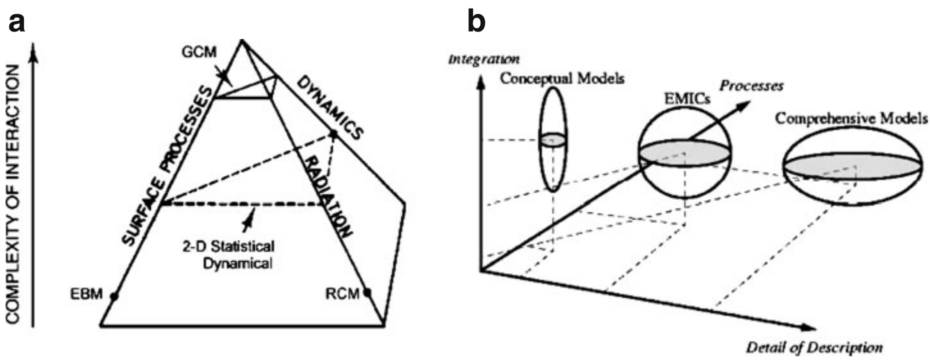

Fig. 1 **a** Climate-modeling pyramid, adapted from Henderson-Sellers and McGuffie (1987). **b** Spectrum of climate models, from Claussen et al. (2002)

different temporal and spatial scales of synoptic meteorology (days, $\sim 10^3$ km) and ice sheets (10^3 to 10^5 years, 10's km near their margins; Saltzman 1984, 1990). Techniques addressing the time-scale mismatch are described first, followed by a shorter discussion of spatial downscaling methods. The last section summarizes other types of hierarchical interactions and future directions.

1 Multiple time scales

Since the early studies of causes of the ice ages in the nineteenth and early twentieth centuries, a tight connection between ice cover and climate was realized, and the need to involve meteorologic forcing by orbital perturbations (Adhémar, Croll, Milankovitch, described in Imbrie and Imbrie 1979). As data and theories became more refined in the late 20th century, the need to represent climate with more robust models emerged. However, the mismatch between "fast" weather/climate variations and much slower ice-sheet variations is a fundamental problem for numerical modeling; on the one hand, there is a need to accurately simulate weather over an ice sheet to provide its annual surface mass balance, but doing so straightforwardly with full GCMs driving ice sheet models over million-year time scales would take prohibitively long even on today's computers.

Nevertheless, long-term simulations are needed to address many ice-age questions. Continental-scale ice sheets typically vary on time scales of 10^4 years or more, and the fastest large-scale fluctuations such as the final collapse before interglacials still take several 1,000's of years. These fluctuations occur repeatedly throughout ice ages of 10^6 to 10^7 years extent, such as Neoproterozoic Snowball Earth events (Hoffman and Shrag 2000), sudden growth of major Antarctic ice and subsequent oscillations in the Cenozoic, $\sim$34 Ma to the present (Zachos et al. 2006, 2008), and Quaternary Northern Hemispheric glacial/interglacial cycles of the last $\sim$3 Myear (Imbrie et al. 1993).

Progress in understanding these events requires the ability to drive prognostic models of the long-term components (ice sheets, sediment and bedrock, deep oceans, biogeochemical carbon cycles) continuously for O(10^4 to 10^7) years. Since the 1970s, numerical ice sheet models have been developed that are capable of simulating the long-term evolution of kilometers-thick ice cover in three spatial dimensions on regional or continental scales (e.g., Andrews and Mahaffy 1976; Jenssen 1977; Budd and Smith 1979; Oerlemans 1982; Huybrechts 1990; Fastook and Prentice 1994; Greve 1997; Ritz et al. 1997; Verbitsky and Saltzman 1997; Bueler and Brown 2009; Rutt et al. 2009). These models use scaled (approximate) equations of the slow flow of ice deforming under its own weight, and solve for the changing ice thickness and internal ice temperatures on a regular grid, accounting for ice advection, surface snow accumulation minus summer melt, freezing or melting at the ice base, and vertical depression or rebound of the bedrock below the ice. The horizontal grid size in these models is typically 10 to 50 km, with ∼10 or more vertical layers to keep track of internal temperatures.

Given forcing fields of surface mass balance and sub-ice shelf melting, it is quite feasible to run 3-D ice sheet models over continental domains through 10^4 to 10^7 years, typically taking a few days to weeks of wall-clock time on modern computers. The main impediment to long-term runs is the provision of the forcing fields: net annual mass balance over the ice sheet surface, and rates of oceanic sub-ice-shelf melt, as these vary through the run due to ice-sheet extent and elevations, orbital variations, atmospheric CO_2, sea level and other forcing. At a minimum two climate fields are needed for the surface budget: seasonal cycles of air temperature and precipitation. Other atmospheric fields such as wind speed and cloudiness can enter into boundary-layer treatments, but their long-term variations tend not to be as important (Pollard and PMIP Participating Groups 2000). The modeling of ocean circulation below ice shelves and sub-ice-shelf melting is challenging and in early stages of development (Beckmann and Goosse 2003; Dinniman et al. 2007; Holland et al. 2008a), and is not discussed here, but could be amenable to some of the temporal methods described below. In the rest of this section, four different approaches are described that provide air temperatures and precipitation over long time scales, roughly in the order they appeared in the literature since the 1970s.

1.1 Energy balance models

The Earth's climate can be crudely approximated as horizontal diffusion of heat, transporting net radiative input from the warm tropics to the cold polar regions, with the transport depending only on the horizontal gradient of a single-level temperature. Ice extent is included implicitly, by increasing solar reflectivity where temperatures are below some value (0 to −5°C).The resulting one-equation Energy Balance Models (EBMs, otherwise known as Simple Climate Models, e.g., Budyko 1969; Sellers 1969; North 1975; cf. Eriksson 1968) are simple enough to be run for millions of years.

In the 1970s, climate models of this kind were coupled with explicit ice-sheet models and applied to the Quaternary ice ages. An even simpler variant is to represent climate by a prescribed snowfall-minus-melt pattern versus height and latitude (Weertman 1976), but the results are very similar if a seasonal EBM is used with ice melt dependent on the EBM's summer temperature (Pollard 1978). In this way, 1-D to 3-D Northern Hemispheric ice-sheet models were driven for 10^5 to 10^6 years though the Quaternary, with the climate component forced primarily by orbital perturbations and sometimes a long gradual cooling representing a presumed decline in CO_2 (e.g., Oerlemans 1980; Sergin 1980; Birchfield et al. 1982; Pollard 1982, 1983; Hyde and Peltier 1987; Neeman et al. 1988; DeBlonde and Peltier 1993; Mudelsee and Schulz 1997; Tarasov and Peltier 1997, 1999).

More recently, the EBM–ice sheet genre has been applied to earlier glaciations of the Phanerozoic and Precambrian (Hyde et al. 1999, 2000, 2006; Crowley et al. 2001), and to the Cenozoic with climate box-models or inversions (Langebroek et al. 2009; de Boer et al. 2010). An "anomaly" method was introduced, in which only the EBM *differences* from the modern simulated climate are used, and superimposed on modern observed climatology (e.g., Tarasov and Peltier 1997, 1999, for Quaternary cycles). In this method, it is hoped that climate model biases remain the same as for modern, and so cancel to yield more accurate paleoclimate results.

Even using the anomaly method, Energy Balance Models with their simple diffusive heat transport can only crudely capture the largest-scale variations in air temperatures, and offer no information on precipitation changes, or only a little with diffusive moisture-latent heat extensions (Chu and Ledley 1995; Bendtsen 2002; Pollard and Kasting 2005). Although these models have provided important insights and successfully simulated basic ~20 and 40 kyear fluctuations in response to orbital forcing, they leave important questions unanswered, such as the causes of the 100,000 year cycle, Mid-Pleistocene Transition, and rapid initiation of ice sheets at the end of interglacials. Some of the shortcomings might be due to the omission of other long term processes and components (sediment, deep ocean variations, carbon cycling), but they could also be due to oversimplified climate forcing. To test the latter possibility, ice sheet models need to be coupled with more comprehensive climate GCMs or EMICs.

1.2 Basic asynchronous with GCMs and EMICs

For most researchers, the longest full-GCM integrations that are practical for individual experiments are hundreds to several thousand years (Kiehl and Shields 2005; Kahana and Valdes 2009; Liu et al. 2009). For $O(10^6)$-year ice-age timescales, continuous GCM integrations through the entire time span are currently infeasible, and GCM applications have been limited to (1) snapshots of individual times, and (2) sub-samples of climate states used creatively to drive the ice sheet model through long periods.

Since the 1980s, many GCM snapshots have been used to deduce mass balance on prescribed North American, Eurasian and Antarctic ice sheets at specific times, mainly ice inception at the end of the last interglacial ~116 ka, the Last Glacial Maximum ~21 ka, and the present to next few hundred years. As well as testing net mass balance, these studies have quantified important forcing and feedback factors such as orbital perturbations, atmospheric pCO_2, biosphere–atmosphere and ocean–atmosphere interactions.

The problem of Northern Hemispheric ice-sheet initiation at the end of the last interglacial is amenable to just one climate snapshot, looking at areas with net annual snow accumulation and/or driving nascent ice sheets with an invariant climate, and has received considerable attention (e.g., Royer et al. 1983; Rind et al. 1989; Syktus et al. 1994; Dong and Valdes 1995; DeNoblet et al. 1996; Gallimore and Kutzbach 1996; Pollard and Thompson 1997a; Vettoretti and Peltier 2004).

Many GCM snapshots have also been performed for the Last Glacial Maximum (LGM), looking at the effects of the ice sheets on climate and taking advantage of abundant proxy climate data and reliable ice-sheet reconstructions (e.g., Gates 1976a, b; Manabe and Broccoli 1985; Hall et al. 1996; Fabre et al. 1997; Pollard and Thompson 1997b; Broccoli 2000; Kageyama and Valdes 2000; Hewitt et al. 2003; Kim et al. 2003, 2008; Braconnot et al. 2007). Some of these studies compute the mass balance over the Northern Hemispheric ice sheets, sometimes using the same anomaly method with respect to modern climate as mentioned above for EBMs, and/or interpolating to the finer ice-sheet grids to account for the mismatch in spatial scales as described below (e.g., Charbit et al. 2002, 2007; Zweck and Huybrechts 2005). A few studies have simulated times during the last deglaciation between the LGM and the early Holocene (e.g., Kutzbach and Guetter 1986; Mitchell et al. 1988; Kutzbach et al. 1998; Carlson et al 2009). Many GCM simulations of modern and future greenhouse climate have been performed, and some GCMs have been used to drive the Greenland and Antarctic ice sheets over the next hundreds to few thousands of years (Huybrechts et al. 2004; Alley et al. 2005; Ridley et al. 2005; Vizcaino et al. 2008).

Deeper-time applications with ice-sheet models driven by one or a few GCM climate solutions include the Cenozoic (DeConto et al. 2007, 2008), Ordovician (Herrmann et al. 2004), Permo-Carboniferous (Horton et al. 2007) and Neoproterozoic Snowball Earth (Baum and Crowley 2001; Donnadieu et al. 2003; Pollard and Kasting 2004).

Since the late 1990s, a few groups have made use of GCMs in longer-term ice-age simulations, using a basic asynchronous method. The ice-sheet model is run continuously, but the GCM is run only a few decades at a time, at several-thousand year intervals using the current orbit and ice sheet size, to provide the mass balance forcing over the ice sheets. The most recently computed mass balance is used to drive the ice sheet model through the next several-thousand-year asynchronous period. Each snapshot requires a few decades of GCM integration to spin up the upper ocean and to average out interannual variability (Pollard et al. 1990). This technique was used by Charbit et al. (2002) to simulate the last Northern Hemispheric deglaciation since 21 ka, and by Horton and Poulsen (2009) in Permo-Carboniferous ice-age experiments. However, the computational expense of the GCM integrations has limited this technique to O(10^4 to 10^5) year intervals. Another kind of scheme with accelerated orbital variations was used by Jackson and Broccoli (2003) to simulate Northern Hemispheric mass balance in a GCM for the past 165,000 years, but is only applicable for models with no long-term prognostic components, and not for coupling with ice-sheet models.

GCMs with deep-ocean components are needed to test hypotheses concerning interactions with thermohaline circulation and deep-ocean carbon storage (e.g., Imbrie et al. 1992; Toggweiler and Lea 2010). However, this presents a complication for the asynchronous method, because deep-ocean-adjustment time scales are a few thousand years, intermediate between those of the near-surface climate and the ice sheets. Spinning up the deep ocean to equilibrium at each GCM synchronous phase would greatly increase the CPU time required, and may not be realistic. Running the deep ocean using asynchronous and/or acceleration techniques (e.g., Hewitt et al. 2003; Kim et al. 2003) may be feasible, but with more frequent atmospheric updates than for the ice sheets (c.f., Lunt et al. 2006; Timm and Timmermann 2007).

Recently, EMICs (Earth models of intermediate complexity) have been used in basic asynchronous or fully synchronous mode, allowing longer coupled ice-sheet integrations than are possible with GCMs. The atmospheric components in EMICs range from EBMs, statistical-dynamical (zonally averaged eddy) or quasi-geostrophic models to very coarse-resolution GCMs, and are coupled in some cases to relatively sophisticated ocean and other component models (Claussen et al. 2002). Many such studies have been applied to the Quaternary with runs ranging from $\sim 10^4$ to $\sim 10^6$ years, focusing on glacial inception (e.g., Wang and Mysak 2002; Kageyama et al. 2004; Calov et al. 2005, 2009), millennial-scale interactions between ocean thermohaline circulation and ice sheets (e.g., Schmittner et al. 2002; with meltwater experiments intercompared in Rahmstorf et al. 2005), all or part of the last ~100 kyear glacial cycle (Gallee et al. 1992; Calov et al. 2002; Charbit et al. 2005; Philippon et al. 2006; Ganopolski et al. 2010), and the last 3 Myear (Berger et al. 1999). They have also been applied to the future (Loutre and Berger 2000; Berger and Loutre 2002; Swingedouw et al. 2008), and deeper-time ice ages (e.g., Donnadieu et al. 2004). However, it is unclear whether the atmospheric dynamics of EMICs are always sufficient for ice-age problems. The representations of atmospheric dynamics and precipitation in some of the simpler EMICs are based empirically on modern climatology, and their skill is likely to decay once they are applied to different boundary conditions, especially over the flanks of past continental ice sheets.

1.3 GCM lookup table

An alternative to the basic asynchronous-GCM method in long-term ice-age experiments is the use of a lookup-table of stored GCM climate solutions. In a preparatory step before long ice-sheet integrations, a collection of GCM snapshots is assembled, forming a look-up table of climates with specified external conditions and ice sizes that span the space of all possible states expected during the long-term runs. Then at any point in a long-term ice sheet run, current temperature and precipitation fields are interpolated appropriately from the appropriate GCM lookup-table members.

The lookup table can consist of just two extreme climate members, often modern and Last Glacial Maximum, that are weighted together in proportion to an empirical "glacial index" such as Greenland ice-core $\delta^{18}O$ over the last ~120 kyears, to drive Northern Hemispheric ice sheets (e.g., Marshall and Clarke 1999a, 2002; Rodgers et al. 2004; Zweck and Huybrechts 2005; Charbit et al. 2007). This is a useful way of investigating processes and testing ice-sheet models, but has the drawback of imposing the Greenland ice-core fluctuations (millennial, orbital and 100,000 yr) directly on the ice-sheet results, so is not ideal for investigating fundamental causes of these variations.

An extension of this method is to build a multi-dimensional matrix of GCM snapshots. Given that (1) there are a limited number of degrees of freedom in the important long-term determinants of climate (orbit, ice-sheet size, and atmospheric CO_2 level), and (2) each determinant is more or less one-dimensional (summer insolation at mid latitudes for orbits, total ice volume for ice-sheet configuration), then a matrix of generic GCM simulations can be assembled with orbits ranging over hot–medium–cold summers, with prescribed ice sheets ranging from none through intermediate to maximum sizes, and with several levels of CO_2. At any point in a long-term ice-sheet simulation, the climate can be interpolated from members of this matrix based on the current orbit, overall ice-sheet volume and CO_2 level. A preliminary version of this method was used by DeConto and Pollard (2003) and Pollard and DeConto (2005) to simulate major growth of Cenozoic Antarctic ice at the Eocene–Oligocene boundary ~34 Ma. The full matrix method is currently being applied to Cenozoic Antarctica using a $3 \times 3 \times 3$ matrix with three orbital configurations, three prescribed ice sheet sizes, and three CO_2 levels (Wilson et al. 2009).

However, practical limits on the number of GCM matrix members introduce problems for this method, because orbital configurations and ice-sheet configurations are not really one-dimensional, and need many more than three cases each to fully describe their effects on climate. For instance, the pattern of upslope intensification of precipitation on ice-sheet flanks cannot simply be interpolated from those of two GCM solutions with larger and smaller ice-sheet sizes. Other drawbacks are that (1) other long-term determinants of climate may be important, such as ocean gateway openings, and (2) feedbacks such as meltwater caps and shutdowns of the North Atlantic thermohaline circulation are not readily captured. These drawbacks may be ameliorated by using matrices with more dimensions and elements, but then the number of GCM simulations required may approach or exceed that required by the simpler basic asynchronous method.

1.4 Climate parameterization

Another technique, used from the first long-term ice sheet studies, is simply parameterizing climate over ice sheets. This can be as simple as a zonally symmetric snowfall-minus-snowmelt pattern versus height and latitude, as mentioned in Section 1.1. With two horizontal dimensions, this approach has been limited mostly to Plio-Pleistocene and future Antarctica, with East Antarctic ice sheet (EAIS) configurations similar to present. Modern precipitation and temperature are either taken from climatologic datasets, or parameterized simply in terms of geographic variables. For past times, the modern temperature is perturbed simply in proportion to geologic time series reflecting regional climate, such as Vostok ice core δD or deep-sea-core δ^{18}O records, plus a lapse-rate correction for elevation changes and a Clausius-Clapeyron relation for precipitation shifts (Huybrechts 1998, 2002; Ritz et al. 2001; Pollard and DeConto 2009). Future projections using this method include Huybrechts and Oerlemans (1990) and Huybrechts et al. (1991), but have been superseded in recent years by GCMs and EMICs (Section 1.2).

The simple parameterizations of modern Antarctic temperature and precipitation are based on regression analyses of modern Antarctic climatology, which relate temperature and precipitation over the EAIS to surface elevation, latitude, surface slope, distance to coast, etc. (Musynski and Birchfield 1985; Fortuin and Oerlemans 1990; Giovinetto et al. 1990). Basic univariate or bivariate regression works quite well for modern EAIS, in part because the ice approximates a single dome centered near the South Pole, and the dependent and independent variables are more or less zonally symmetry. But for earlier Cenozoic ice sheet configurations with non-zonal smaller ice sheets or multiple ice caps, more sophisticated methods would be needed, based possibly on multivariate regression or artificial neural nets (Reusch et al. 2005) and trained by discrete GCM/RCM snapshots of past times. A first step towards this approach in principle was taken by Abe-Ouchi et al. (2007), who forced a Laurentide ice-sheet model through the last 120 kyears with climate parameterizations adjusted beforehand according to a few discrete GCM snapshots.

2 Multiple spatial scales

2.1 Interpolation from coarse GCM and EMIC grids

The techniques described in the previous section address the *temporal* mismatch between climate and ice sheets. Another problem in all applications using coarse-grid climate models is the mismatch in *spatial* scales. Horizontal grid sizes in GCMs and EMICs are typically several hundred km, and are inadequate to resolve the steep topography around ice-sheet margins that are important in determining ablation. Hence, many studies use straightforward interpolation techniques to derive the mass balance on a much finer-scale ice-sheet model grid.

The first step is to horizontally interpolate the GCM temperature and precipitation fields to the ice-sheet grid, often using simple bilinear interpolation. Simple vertical corrections to air temperature are then applied, to correct for the difference between the GCM-interpolated topography and the actual ice surface elevation, assuming a constant lapse rate (e.g., Thompson and Pollard 1997; Fabre et al. 1998; although it is not clear what this lapse rate should be; see also Greuell et al. 1997). In some cases, a similar vertical correction to precipitation is also applied (elevation-desert effect). If only the monthly means of GCM temperature and other meteorologic variables are saved, then the non-linear effects of diurnal cycles and synoptic variability on melt can be imposed in the calculation of mass balance (see below; Marshall et al. 2004; Zweck and Huybrechts 2005).

Statistical hypsometric corrections to net mass balance for nascent ice caps have been proposed, that account for small-scale topographic variability not even resolved by the ice-sheet grid. This allows for extra melting in deep valleys vs. accumulation on mountain plateaus, but has been used in relatively few long-term studies to date (Walland and Simmonds 1996; Marshall and Clarke 1999b; cf. Kotlarski et al. 2010).

Precipitation is less amenable to simple topographic corrections than air temperature, because it can be affected by forced orographic uplift and descent, resulting for instance in enhanced snowfall on the windward flanks of ice sheets. Air-parcel schemes are available that capture these effects given large-scale incoming winds, temperature, humidity and finer-scale topography (Sanberg and Oerlemans 1983; Fortuin and Oerlemans 1990; Leung and Ghan 1998), but they or simpler versions have been used in only a few ice-sheet studies (Hulton et al. 2002; Calov et al. 2005; van den Berg et al. 2008).

The two main methods used in calculating net annual mass balance at each ice-sheet grid point from seasonal temperature and precipitation are the empirical positive degree days (PDD) parameterization (e.g., Braithwaite 1981; Marshall et al. 2004; Hock 1999 including radiation), and the more physically based surface energy balance model (SEBM; e.g., van de Wal and Oerlemans 1994; Pollard and PMIP Participating Groups 2000; Anslow et al. 2008). Debate continues on the relative merits of these two methods (van de Wal 1996; Bougamont et al. 2007). If not included in the mass-balance model, allowance can be made for partial retention of meltwater by refreezing in the underlying firn, which significantly modifies the net surface balance (Pfeffer et al. 1991; Thompson and Pollard 1997; Jannssens and Huybrechts 2000; Marshall et al. 2004) and can produce a surprising variety of stratified sequences in nature (Shumskii 1964; Paterson 1994). Refreezing is an example of ice-sheet-specific surface physics at the interface between climate and ice sheet models; another example that has not been included in dynamical ice-sheet models to date is the formation and drainage of supraglacial lakes observed on Greenland (Luthje et al. 2006; Box and Ski 2007; Das et al. 2008; Sundai et al. 2009), but such processes are beyond the scope of this paper.

2.2 Regional climate models, and stretched-grid GCMs

Some ice-age problems may require not just smooth interpolation from GCM grids, but explicit modeling of dynamic meteorology over the ice sheets, for instance upslope precipitation and downslope katabatic winds on steep ice-sheet margins. To achieve this, GCM simulations can be enhanced by the use of atmospheric regional climate models (RCMs) on limited domains over a particular ice sheet, driven at their lateral boundaries by GCM meteorology. Several groups have applied RCMs over modern Antarctica and Greenland (e.g., Hines et al. 1997; Bailey and Lynch 2000; Fettweis et al. 2005; van den Broeke et al. 2006; Ettema et al. 2009). Others have used RCMs to investigate details of the mass balance over Northern Hemispheric ice sheets at LGM (Bromwich et al. 2004, 2005) and other times, including the effects of proglacial lakes (Hostetler et al. 2000).

Alternatively, a single GCM can be used with stretched-grid capability, i.e., with a region of finer grid spacing over the area of interest. This technique has been applied to the Eurasian Ice Sheet and proglacial lakes early in the last glacial-interglacial cycle, using the LMDZ GCM (Krinner et al. 2004; Peyaud et al. 2007; see also Colleoni et al. 2009).

In principle, all of the temporal methods described in Section 1 for using GCMs in long-term ice-sheet experiments can be augmented by embedded RCM simulations, by performing one RCM run for each GCM snapshot. This has not yet been attempted, probably due to the computational expense of the RCM (which is comparable to GCMs, given that multiple years of RCM integration would be needed for each snapshot to average out interannual variability).

3 Discussion

In summary, substantial progress has been made since the 1970s in coupled ice sheet–climate modeling techniques, especially in

1. temporal techniques to address the mismatch between time scales (days to years for meteorology and climate, 10^4 to 10^6 years for ice sheets), and
2. spatial techniques to address the mismatch in model grid resolutions (100's km for global climate models, 10's of km for ice-sheet ablation zones).

One aspect of long-term coupled ice sheet–climate simulations that is sometimes overlooked is the need to achieve the correct ice-sheet mass balance not just for one time or interval, but for multiple stages of an ice-age cycle. The interpolation schemes and PDD or SEBM models connecting the GCM climate with ice-sheet mass balance have uncertain parameters that can be tuned to achieve a desired average mass balance for a particular ice sheet at a particular time (for instance, the Laurentide at LGM). If no such tuning is done, there is wide scatter in whole-ice-sheet mass balances predicted by different GCMs, even though their seasonal climates differ by only a few °C (due to the strong sensitivity of summer melt to air temperatures in ablation zones; Pollard and PMIP Participating Groups 2000). Thus the sign and rate of ice-sheet change can be readily adjusted to a desired value for one particular time, or for a limited unidirectional interval such as the last deglaciation. A much greater challenge is to achieve the right signs and rates of ice-sheet growth and decay through several or all stages of a 100,000 year glacial-interglacial cycle.

The climate and ice-sheet models developed since the 1970s have huge ranges in complexity, and there has been some "vertical" interaction between hierarchical levels (Schneider and Dickinson 1974), mostly for climate models alone. For instance, atmospheric GCM results have been compared and interpreted using single-column radiative–convective models (Henderson-Sellers and McGuffie 1987), EBM ice-age climate sensitivity (Hyde et al. 1989), and conceptual vegetation feedbacks (Brovkin et al. 1998). There have also been some hierarchical studies for ocean models alone (Hirschi and Stocker 2002; Dijkstra and Weijer 2003; cf. Schneider and Thompson 1981).

In the ice sheet–climate arena, hierarchical interactions have mainly been between ice flowline models (with 1 horizontal dimension) and analogous behavior in 3-D models. Lessons learned from 1-D flowline models about Snowball-Earth transitions (Budyko 1969; Sellers 1969; North 1975), Small Ice Cap Instability (SICI, due to albedo feedback; North 1984, Lee and North 1995), Small Ice Sheet Instability and hysteresis (SISI, due to height-mass-balance feedback; Weertman 1961, 1964; Abe-Ouchi and Blatter 1993; Oerlemans 2002), and both SICI and SISI (MacAyeal 1979), helped to interpret tipping points in long-term 3-D model simulations of past and future Greenland and Antarctica (Huybrechts 1993; Crowley and Yip 1994; Crowley and Baum 1995; Cuffey and Marshall 2000; Toniazzo et al. 2004; Pollard and DeConto 2005; Vizcaino et al. 2008) and Neoproterozic Earth (Donnadieu et al. 2003, 2004; Poulsen 2003; Pollard and Kasting 2004).

Other examples for coupled ice-climate modeling are few. For instance, 0-D conceptual models have explored long-term interactions between global ice volume, temperature and/or carbon dioxide (Saltzman and Verbitsky 1993; Paillard 1995; Parrenin and Paillard 2003), but interactions with 3-D modeling have been sparse, probably due to the gulf in complexity and the difficulty in matching the 0-D model terms with 3-D model processes (although explicit physical processes are identified in Paillard and Parrenin 2004). Similarly, studies using 0-D stochastic resonance models (Benzi et al. 1981; Matteucci 1989) and fundamental analysis of degrees of freedom and free vs. forced variability (Vautard and Ghil 1989; Yiou et al. 1994) have seen little expression in 3-D modeling to date. On the other hand, recent theories and simple models that consider seasonal and interhemispheric aspects of orbital insolation variations and the consequences for ice-sheet cycles (Raymo et al. 2006; Huybers and Denton 2008; Huybers and Tziperman 2008; Huybers 2009) translate more readily to 3-D modeling, and testing them with 3-D ice sheet–climate models will be more straightforward.

Instead of "vertical" interactions in the hierarchical pyramid, much effort in recent years has been directed along the "integration" axis of Claussen et al. (2002), combining ice sheet–climate models with other long-term components important to ice-sheet evolution, like the evolution of GCMs and EMICs towards comprehensive Earth systems models. These components and processes, with very incomplete modeling references, include:

- Ice stream/shelf flow, grounding-line migration, higher-order flow equations (Weertman 1974; Hughes 1981; MacAyeal 1989; MacAyeal et al. 1996; Hubbard 2000; Pattyn 2002; Bennett 2003 (review); Hindmarsh 2004, 2006, 2009; Payne et al. 2004, 2007; Dupont and Alley 2005; Vieli and Payne 2005; Pollard and DeConto 2007, 2009; Schoof 2007; Bueler and Brown 2009; Hughes 2009; Joughin et al. 2009; Nick et al. 2009)
- Basal hydrology, aquifers, effect on basal stress (Flowers and Clarke 2002; Johnson and Fastook 2002; Parizek and Alley 2004; Clarke 2005 (review); Carlson et al. 2007; Creyts and Schoof (2009)
- Oceanic circulation under ice shelves, oceanic melting/freezing at their base, meltwater/sea-ice feedbacks (Nicholls 1997; Dinniman et al. 2007; Holland et al. 2008a, b; Swingedouw et al. 2008; Thoma et al. 2008; Vizcaino et al. 2008; Walker et al. 2009; Little et al. 2010)
- Ice-shelf and tidewater calving (van der Veen 1996; Doake et al. 1998; Kenneally and Hughes 2002; Benn et al. 2007 (review); Alley et al. 2008; Scambos et al. 2009; Parizek et al. 2010)
- Supraglacial lakes and hydrofracture (Luthje et al. 2006; Box and Ski 2007; Das et al. 2008; Krawczynski et al. 2009; Sundai et al. 2009)
- Subglacial lakes, outburst floods: physical models (Shoemaker 1991; Clarke et al. 2004; Pattyn et al. 2004; Alley et al. 2006; Evatt et al. 2006; Pattyn 2008; Carter et al. 2009)
- Marine bathymetric landforms, interaction with grounding-line advance and retreat (Alley 1991; Anderson 1999; Dahlgren et al. 2002; Alley et al. 2007; Nick et al. 2007)
- Tidal effects on ice streams, stick-slip motion (Bindschadler et al. 2003; Winberry et al. 2009)
- Deformable sediment and till, long-term distribution, effect on basal stress (MacAyeal 1992; Boulton 1996; Alley et al. 1997; Clark and Pollard 1998; Licciardi et al. 1998; Tulaczyk et al. 2000, 2001; Kamb 2001; Bougamont and Tulaczyk 2003; Pollard and DeConto 2007; Hildes et al. 2004)
- Supraglacial debris, stagnation (Vacco et al. 2010)
- Aeolian dust, effects on and of ice sheets (Peltier and Marshall 1995; Overpeck et al. 1996; Mahowald et al. 1999; Krinner et al. 2006; Sugden et al. 2009; Ganopolski et al. 2010)
- Proglacial lakes (Andrews 1973; Pollard 1982; Marshall and Clarke 1999a; Tarasov and Peltier 2005; Peyaud et al. 2007)
- Water isotopic ratios within the ice (Clarke and Marshall 2002; Clarke et al. 2005; Lhomme et al. 2005; Sima et al. 2006)
- Bedrock deformation (Le Meur and Huybrechts 1996; Peltier 2004; Tarasov and Peltier 2004; Lambeck et al. 2006)
- Terrrestrial landforms, erosion, landscape evolution (Hindmarsh 1999; Alley et al. 2003; Tomkin 2003; Anderson et al. 2006; Kite and Hindmarsh 2007; Hooke and Fastook 2007; Hindmarsh and Stokes 2008; Jamieson and Sugden

2008; Jamieson et al. 2008; Kessler et al. 2008; Boulton et al. 2009; Sugden 2009 (review); Vacco et al. 2009; Stokes and Tarasov 2010)

These modeling studies provide a rich framework to embed ice-sheet models more realistically into their surrounding environment. The first five to seven on the list are considered to be particularly important for possible fast drawdown through Greenland and West Antarctic ice streams in future decades to centuries, and may be coming into play sooner than was expected a few years ago (e.g., Rignot and Kanagaratnam 2006; Bell 2008; Holland et al. 2008b; Rignot 2008; Vaughan 2008; Pritchard et al. 2009). There is an urgent need to develop more realistic and reliable models of each of them, and much current work in ice sheet–climate modeling is directed to that end.

References

Abe-Ouchi A, Blatter H (1993) On the initiation of ice sheets. Ann Glaciol 18:203–207

Abe-Ouchi A, Segawa T, Saito F (2007) Climatic conditions for modelling the Northern Hemisphere ice sheets throughout the ice age cycle. Clim Past 3:423–438

Alley RB (1991) Sedimentary processes may cause fluctuations of tidewater glaciers. Ann Glaciol 15:119–124

Alley RB, Cuffey MK, Evenson EB, Strasser JC, Lawson DE, Larson GJ (1997) How glaciers entrain and transport basal sediment: physical constraints. Quat Sci Rev 16:1017–1038

Alley RB, Lawson DE, Larson GJ, Evenson EB, Baker GS (2003) Stabilizing feedbacks in glacier-bed erosion. Nature 424:758–760

Alley RB, Clark PU, Huybrechts P, Joughin I (2005) Ice-sheet and sea-level changes. Science 310:456–460

Alley RA, Dupont TK, Parizek BR, Anandakrishnan S, Lawson DE, Larson GJ, Evenson EB (2006) Outburst flooding and the initiation of ice-stream surges in response to climatic cooling: a hypothesis. Geomorph 75:76–89

Alley RB, Anandakrishnan A, Dupont TK, Parizek BR, Pollard D (2007) Effect of sedimentation on ice-sheet grounding-line stability. Science 315:1838–1841

Alley RB, Horgan HJ, Joughin I, Cuffey KM, Dupont TK, Parizek BR, Anandakrishnan S, Bassis J (2008) A simple law for ice-shelf calving. Science 322:1344

Anderson JB (1999) Antarctic marine geology. Cambridge Univ. Press, 289 pp

Anderson RS, Molnar P, Kessler MA (2006) Features of glacial valley profiles simply explained. J Geophys Res 111:F01004. doi:10.1029/2005JF000344

Andrews JT (1973) The Wisconsin Laurentide ice sheet: dispersal centers, problems of rates of retreat, and climatic implications. Arct Alp Res 5:185–199

Andrews JT, Mahaffy MAW (1976) Growth rate of the Laurentide Ice Sheet and sea level lowering (with emphasis on the 115,000 BP sea level low). Quat Res 6:167–183

Anslow FS, Hostetler S, Bidlake WR, Clark PU (2008) Distributed energy balance modeling of South Cascade glacier, Washington and assessment of model uncertainty. J Geophys Res 113:F02019. doi:10.1029/2007JF000850

Bailey DA, Lynch AH (2000) Development of an Antarctic regional climate system model. Part I: sea ice and large scale circulation. J Clim 15:1337–1350

Bartlein PJ, Hostetler SW (2004) Modeling paleoclimates. In: Gillespie AR, Porter SC, Atwater AF (eds) The quaternary period in the United States, vol 1. Developments in Quaternary Science, Elsevier Publ., pp 565–584

Baum SK, Crowley TJ (2001) GCM response to late Precambrian (∼590 Ma) ice-covered continents. Geophys Res Lett 28:583–586

Beckmann A, Goosse H (2003) A parameterization of ice shelf–ocean interaction for climate models. Ocn Model 5:157–170

Bell RE (2008) The unquiet ice. Sci Am 298:60–67

Bendtsen J (2002) Climate sensitivity to changes in solar radiation on a simple coupled climate model. Clim Dyn 18:595–609

Benn DI, Warren CR, Mottram RH (2007) Calving processes and the dynamics of calving glaciers. Earth-Sci Rev 82:143–179
Bennett MR (2003) Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. Earth-Sci Rev 61:309–339
Benzi R, Pandolfo JP, Sutera A (1981) Further application of the theory of stochastic perturbation of deterministic systems to simple climate models. Quart J R Met Soc 107:549–559
Berger A, Loutre MF (2002) An exceptionally long interglacial ahead? Science 297:1287–1288
Berger A, Li XS, Loutre MF (1999) Modelling northern hemisphere ice volume over the last 3 Ma. Quat Sci Rev 18:1–11
Bindschadler RA, King MA, Alley RB, Anandakrishnan S, Padman L (2003) Tidally controlled stick-slip discharge of a West Antarctic ice stream. Science 301:1087–1089
Birchfield GE, Weertman J, Lunde AT (1982) A model study of the role of high-latitude topography and the climate response to orbital insolation anomalies. J Atmos Sci 39:71–87
Bougamont M, Tulaczyk S (2003) Glacial erosion beneath ice streams and ice-stream tributaries: constraints on temporal and spatial distribution of erosion from numerical simulations of a West Antarctic ice stream. Boreas 32:178–190
Bougamont M, Bamber JL, Ridley JK, Gladstone RM, Greuell W, Hanna E, Payne A, Rutt I (2007) Impact of model physics on estimating the surface mass balance of the Greenland ice sheet. Geophys Res Lett 34:L17501. doi:1029/2007GL030700
Boulton GS (1996) Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. J Glaciol 42:43–62
Boulton GS, Hagdorn M, Maillot PB, Zatsepin S (2009) Drainage beneath ice sheets: groundwater-channel coupling, and the origin of esker systems from former ice sheets. Quat Sci Rev 28: 621–638
Box JE, Ski K (2007) Remote sounding of Greenland supraglacial melt lakes: implications for subglacial hydraulics. J Glaciol 53:257–265
Braconnot P et al (2007) Results of PMIP2 coupled simulations of the mid-Holocene and Last Glacial Maximum—Part 1: experiments and large-scale features. Clim Past 3:261–277
Braithwaite RJ (1981) On glacier energy balance, ablation, and air temperature. J Glaciol 27:381–391
Broccoli AJ (2000) Tropical cooling at the Last Glacial Maximum: an atmospheric-mixed layer ocean model simulation. J Clim 13:951–976
Bromwich DH, Toracinta ER, Wei H, Oglesby RJ, Fastook JL, Hughes TJ (2004) Polar MM5 simulations of the winter climate of the Laurentide Ice Sheet at the LGM. J Clim 17:3415–3433
Bromwich DH, Toracinta ER, Oglesby RJ, Fastook J, Hughes TJ (2005) LGM summer climate on the southern margin of the Laurentide ice sheet: wet or dry? J Clim 18:3317–3338
Brovkin V, Claussen M, Petoukhov V, Ganopolski A (1998) On the stability of the atmosphere–vegetation system in the Sahara/Sahel region. J Geophys Res 103:31613–31624
Budd WF, Smith IN (1979) The growth and retreat of ice sheets in response to orbital radiation changes. In: Sea level, ice and climatic change. Int Assoc Hydrol Sci Publ 131:369–409
Budyko MI (1969) The effect of solar radiation variations on the climate of the Earth. Tellus 21: 611–619
Bueler E, Brown J (2009) Shallow shelf approximation as a “sliding law” in a thermomechanically coupled ice sheet model. J Geophys Res 114:F03008. doi:10.1029/2008JF001179
Calov R, Ganopolski A, Petroukhov V, Claussen M, Greve R (2002) Large-scale instabilities of the Laurentide Ice Sheet simulated in a fully coupled climate-system model. Geophys Res Lett 29:2216–2219
Calov R, Ganopolski A, Claussen M, Petoukhov V, Greve R (2005) Transient simulation of the last glacial inception. Part I: glacial inception as a bifurcation in the climate system. Clim Dyn 24:545–561
Calov R, Ganopolski A, Kubatzki C, Claussen M (2009) Mechanisms and time scales of glacial inception simulations with an Earth system model of intermediate complexity. Clim Past 5: 245–258
Carlson AE, Jenson JW, Clark PU (2007) Modeling the subglacial hydrology of the James Lobe of the Laurentide Ice Sheet. Quat Sci Rev 26:1384–1397
Carlson AE, Anslow FS, Obbink EA, LeGrande AN, Ullman DJ, Licciardi JM (2009) Surface-melt driven Laurentide ice sheet retreat during the early Holocene. Geophys Res Lett 36:L24502. doi:10.1029/2009GL040948
Carter SP, Blankenship DD, Young DA, Peters ME, Holt JW, Siegert MJ (2009) Dynamic distributed drainage implied by the flow evolution of the 1996–1998 Adventure Trench subglacial lake discharge. Earth Planet Sci Lett 283:24–37

Charbit S, Ritz C, Ramstein G (2002) Simulations of Northern Hemisphere ice-sheet retreat: sensitivity to physical mechanisms involved during the last deglaciation. Quat Sci Rev 21: 243–265
Charbit S, Kageyama M, Roche D, Ritz C, Ramstein G (2005) Investigating the mechanisms leading to the deglaciation of past continental northern hemisphere ice sheets with the CLIMBER–GREMLINS coupled model. Glob Planet Change 48:253–273
Charbit S, Ritz C, Philippon G, Peyaud V, Kageyama M (2007) Numerical reconstructions of the Northern Hemispheric ice sheets through the last glacial cycle. Clim Past 3:15–37
Chu S, Ledley TS (1995) Hydrologic cycle parameterization for energy balance climate models. J Geophys Res 10:16289–16303
Clark PU, Pollard D (1998) Origin of the mid-Pleistocene transition by ice-sheet erosion of regolith. Paleoceanogr 13:1–9
Clarke GKC (2005) Subglacial processes. Ann Rev Earth Planet Sci 33:247–276
Clarke GKC, Marshall SJ (2002) Isotopic balance of the Greenland Ice Sheet: modelled concentrations of water isotopes from 30,000 BP to present. Quat Sci Rev 21:419–430
Clarke GKC, Leverington DW, Teller JT, Dyke AS (2004) Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200 BP cold event. Quat Sci Rev 23 389:407
Clarke GKC, Lhomme N, Marshall SJ (2005) Tracer transport in the Greenland ice sheet: three-dimensional isotopic stratigraphy. Quat Sci Rev 24:155–171
Claussen M et al (2002) Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models. Clim Dyn 18:579–586
Colleoni F, Krinner G, Jakobsson M, Peyaud V, Ritz C (2009) Influence of regional parameters on the surface mass balance of the Eurasian ice sheet during the peak Saalian (140 kya). Glob Planet Change 68:132–148
Creyts TT, Schoof CG (2009) Drainage through subglacial water sheets. J Geophys Res 114:F04008. doi:10.1029/2008JF001215
Crowley TJ, Yip K-JJ (1994) Snowline instability in a general circulation model—application to Carboniferous glaciation. Clim Dyn 10:363–376
Crowley TJ, Baum SK (1995) Is the Greenland Ice Sheet bistable? Paleoceanogr 10:357–363
Crowley TJ, Hyde WT, Peltier WR (2001) CO_2 levels required for deglaciation of a "near-snowball" earth. Geophys Res Lett 28:283–286
Cuffey KM, Marshall SJ (2000) Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. Nature 404:591–594
Dahlgren KIT, Vorren TO, Laberg JS (2002) The role of grounding-line sediment supply in ice-sheet advances and growth on continental shelves: an example from the mid-Norwegian sector of the Fennoscandian ice sheet during the Saalian and Weichselian. Quatern Int 95–96:25–33
Das S, Joughin I, Behn MD, Howat IM, King MA, Lizzarralde D, Bhatia MP (2008) Fracture propagation to the base of the Greenland ice sheet during supraglacial lake discharge. Science 320:778–781
DeBlonde G, Peltier WR (1993) Late Pleistocene ice age scenarios based on observational evidence. J Clim 6:709–727
de Boer B, van de Wal RSW, Bintanja R, Lourens LJ, Tuenter E (2010) Cenozoic global ice volume and temperature simulations with 1-D ice-sheet models forced by benthic $\delta^{18}O$ records. Ann Glaciol 51:23–33
DeConto RM, Pollard D (2003) Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. Nature 421:245–249
DeConto R, Pollard D, Harwood D (2007) Sea ice feedback and Cenozoic evolution of Antarctic climate and ice sheets. Paleoceanogr 22:PA3214. doi:10.1029/2006PA001350
DeConto RM, Pollard D, Wilson P, Palike H, Lear C, Pagani M (2008) Thresholds for Cenozoic bipolar glaciation. Nature 455:653–656
DeNoblet NI, Prentice IC, Joussaume S, Texier D, Botta A, Haxeltine A (1996) Possible role of atmosphere–biosphere interactions in triggering last glaciation. Geophys Res Lett 23:3191–3194
Dijkstra HA, Weijer W (2003) Stability of the global ocean circulation: the connection of equilibria within a hierarchy of models. J Mar Res 61:725–743
Dinniman MS, Klinck JM, Smith WO (2007) Influence of sea ice cover and icebergs on circulation and water mass formation in a numerical circulation model of the Ross Sea, Antarctica. J Geophys Res-Oceans 112:C11013. doi:10.1029/2006JC004036
Doake CSM, Corr HFJ, Rott H, Skvarca P, Young NW (1998) Breakup and conditions for stability of the northern Larsen Ice Shelf, Antarctica. Nature 391:778–780

Dong B, Valdes PJ (1995) Sensitivity studies of Northern Hemisphere glaciation using an atmospheric general circulation model. J Clim 8:2471–2496
Donnadieu Y, Fluteau F, Ramstein G, Ritz C, Besse J (2003) Is there a conflict between the Neoproterozoic glacial deposits and the snowball Earth interpretation: an improved understanding with numerical modeling. Earth Plan Sci Lett 208:101–112
Donnadieu Y, Ramstein G, Fluteau F, Roche D, Ganopolski A (2004) The impact of atmospheric and oceanic heat transports on the sea-ice-albedo instability during the Neoproterozoic. Clim Dyn 22:293–306
Dupont TK, Alley RB (2005) Assessment of the importance of ice-shelf buttressing to ice-sheet flow. Geophys Res Lett 32:L04503. doi:10.1029/2004GL022024
Eriksson E (1968) Air–ocean–icecap interactions in relation to climatic fluctuations and glaciation cycles. Met Monogr 8:68–92
Ettema J, van den Broeke MR, van Meijgaard E, van de Berg WJ, Bamber JL, Box JE, Bales RC (2009) Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling. Geophys Res Lett 36:L12501. doi:10.1029/2009GL038110
Evatt GW, Fowler AC, Clark CD, Hulton NRJ (2006) Subglacial floods beneath ice sheets. Phil Trans R Soc A 364:1769–1794
Fabre A, Ritz C, Ramstein G (1997) Modelling of the Last Glacial Maximum ice sheets using different accumulation parameterizations. Ann Glaciol 24:223–228
Fabre A, Ramstein G, Ritz C, Pinot S, Fournier N (1998) Coupling an AGCM with an ISM to investigate the ice sheets mass balance at the Last Glacial Maximum. Geophys Res Lett 25: 531–534
Fastook JL, Prentice M (1994) A finite-element model of Antarctica—sensitivity test for meteorological mass–balance relationship. J Glaciol 40:167–175
Fettweis X, Gallee H, Lefebre F, van Ypersele J-P (2005) Greenland surface mass balance simulations by a regional climate model and comparison with satellite-derived data in 1990–1991. Clim Dyn 24:623–640
Flowers GE, Clarke GKC (2002) A multi-component coupled model of glacier hydrology. 1. Theory and synthetic examples. J Geophys Res 107:B11, 2287. doi:10.1029/2001JB001122
Fortuin JPF, Oerlemans J (1990) Parameterization of the annual surface temperature and mass balance of Antarctica. Ann Glaciol 14:78–84
Gallee H, van Ypersele JP, Fichefet T, Marsiat I, Tricot C, Berger A (1992) Simulation of the last glacial cycle by a coupled, sectorially averaged climate–ice sheet model. 2. Response to insolation and CO_2 variations. J Geophys Res 97:15713–15740
Gallimore RG, Kutzbach JE (1996) Role of orbitally induced changes in tundra area in the onset of glaciation. Nature 381:503–505
Ganopolski A, Calov R, Claussen M (2010) Simulation of the last glacial cycle with a coupled climate ice-sheet model of intermediate complexity. Clim Past Discuss 5:2269–2309
Gates WL (1976a) Modeling the ice-age climate. Science 191:1138–1144
Gates WL (1976b) The numerical simulation of ice-age climate with a global general circulation model. J Atmos Sci 33:1844–1873
Giovinetto MB, Waters NM, Bentley CR (1990) Dependence of Antarctic surface mass balance on temperature, elevation, and distance to open ocean. J Geophys Res 95:3517–3531
Greuell W, Knap WH, Smeets PC (1997) Elevational changes in meteorological variables along a midlatitude glacier during summer. J Geophys Res 102:25941–25954
Greve R (1997) Application of a polythermal three-dimensional ice sheet model to the Greenland ice sheet: response to steady-state and transient climate scenarios. J Clim 10:901–918
Hall NMJ, Valdes PJ, Dong B (1996) The maintenance of the last great ice sheets: a UGAMP GCM study. J Clim 9:1004–1019
Henderson-Sellers A, McGuffie K (1987) A climate modelling primer. John Wiley Publ., p 217
Herrmann AD, Patzkowsky ME, Pollard D (2004) The impact of paleogeography, pCO_2, poleward ocean heat transport and sea level change on global cooling during the late Ordovician. Paleogeogr Palaeoclimatol Palaeoecol 206:59–74
Hewitt CD, Stouffer RJ, Broccoli AZJ, Mitchell JFB, Valdes PJ (2003) The effect of ocean dynamics in a coupled GCM simulation of the Last Glacial Maximum. Clim Dyn 20:203–218
Hildes DHD, Clarke GKC, Flowers GE, Marshall SJ (2004) Subglacial erosion and englacial sediment transport modelled for North American ice sheets. Quat Sci Rev 2:409–430
Hindmarsh RCA (1999) Coupled ice-till dynamics and the seeding of drumlins and bedrock forms. Ann Glaciol 28:221–230

Hindmarsh RCA (2004) A numerical comparison of approximations to the Stokes equations used in ice sheet and glacier flow. J Geophys Res 109:F01012. doi:19.1029/2003JF000065

Hindmarsh RCA (2006) The role of membrane-like stresses in determining the stability and sensitivity of the Antarctic ice sheets: back pressure and grounding line motion. Phil Trans Roy Soc A-Math Phys Eng Sci 364:1733–1767

Hindmarsh RCA (2009) Consistent generation of ice-streams via thermo-viscous instabilities modulated by membrane stresses. Geophys Res Lett 36:L06502. doi:10.1029/2008GL036877

Hindmarsh RCA, Stokes CA (2008) Formation mechanisms for ice-stream lateral shear margin moraines. Earth Surf Process Landf 33:610:626

Hines KM, Bromwich DH, Liu Z (1997) Combined global climate model and mesoscale model simulations of Antarctic climate. J Geophys Res 102:13747–13760

Hirschi J, Stocker TF (2002) Rapid changes of the oceanic circulation in a hierarchy of ocean models. Tellus 54A:273–287

Hock R (1999) A distributed temperature-index ice and snowmelt model including potential direct solar radiation. J Glaciol 45:101–111

Hoffman PF, Shrag DP (2000) Snowball Earth. Sci Am 282:68–75

Holland PR, Jenkins A, Holland DM (2008a) The response of ice shelf basal melting to variations in ocean temperature. J Clim 21:2558–2572

Holland DM, Thomas RH, de Young B, Ribergaard MH, Lyberth B (2008b) Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. Nature Geosci 1:659–664

Hooke RL, Fastook J (2007) Thermal conditions at the bed of the Laurentide ice sheet in Maine during deglaciation: implications for esker formation. J Glaciol 53:646–658

Horton DE, Poulsen CJ (2009) Paradox of late Paleozoic glacioeustacy. Geology 37:715–718

Horton DE, Poulsen CJ, Pollard D (2007) Orbital and CO_2 forcing of late Paleozoic continental ice sheets. Geophys Res Lett 34:L19708. doi:10.1029/2007GL031188

Hostetler SW, Bartlein PJ, Clark PU, Small EE, Solomon AM (2000) Simulated influences of Lake Agassiz on the climate of central North America 11,1000 years ago. Nature 405: 334–337

Hubbard A (2000) The verification and significance of three approaches to longitudinal stresses in high-resolution models of glacier flow. Geogr Ann 82A 471:487

Hughes TJ (1981) The weak underbelly of the West Antarctic Ice Sheet. J Glaciol 27:518–525

Hughes T (2009) Modeling ice sheets from the bottom up. Quat Sci Rev 28:1831–1849

Hulton MRJ, Purves RS, McCulloch DE, Sugden DE, Bentley MJ (2002) The Last Glacial Maximum and deglaciation in southern South America. Quat Sci Rev 21:233–241

Huybers P (2009) Pleistocene glacial variability as a chaotic response to obliquity forcing. Clim Past 5:481–488

Huybers P, Denton G (2008) Antarctic temperature at orbital timescales controlled by local summer duration. Nature Geosci 1:787–792

Huybers P, Tziperman E (2008) Integrated summer insolation forcing and 40,000-year glacial cycles: the perspective from an ice-sheet/energy-balance model. Paleoceanogr 23:PA1208. doi:10/1029/2007PA001463

Huybrechts P (1990) A 3-D model for the Antarctic ice sheet: a sensitivity study on the glacial-interglacial contrast. Clim Dyn 5:79–92

Huybrechts P (1993) Glaciological modeling of the late Cenozoic East Antarctic Ice Sheet: stability or dynamism? Geogr Ann 75A:221–238

Huybrechts P (1998) Report of the Third EISMINT Workshop on model intercomparison. European Science Foundation, Strasbourg, p 120

Huybrechts P (2002) Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles. Quat Sci Rev 21:203–231

Huybrechts P, Oerlemans J (1990) Response of the Antarctic ice sheet to future greenhouse warming. Clim Dyn 5:93–102

Huybrechts P, Letreguilly A, Reeh N (1991) The Greenland ice sheet and greenhouse warming. Palaeogeogr Palaeoclimatol Palaeoecol 89:399–412

Huybrechts P, Gregory J, Janssens I, Wild M (2004) Modelling Antarctic and Greenland volume changes during the 20th and 21st centuries forced by GCM time slice integrations. Glob Plan Change 42:83–105

Hyde WT, Peltier WR (1987) Sensitivity experiments with a model of the ice age cycle: the response to Milankovitch forcing. J Atmos Sci 44:1351–1374

Hyde WT, Crowley TJ, Kim K-Y, North GR (1989) Comparison of GCM and energy balance model simulations of seasonal temperature ranges over the past 18000 years. J Clim 2:866–887

Hyde W, Crowley TJ, Tarasov L, Peltier WR (1999) The Pangean ice age: studies with a coupled climate–ice sheet model. Clim Dyn 15:619–629
Hyde W, Crowley TJ, Baum SK, Peltier WR (2000) Neoproterozoic ‘snowball Earth’ simulations with a coupled climate–ice sheet model. Nature 405:425–429
Hyde WT, Grossman EL, Crowley TJ, Pollard D, Scotese CR (2006) Siberian glaciation as a constraint on Permian-Carboniferous CO_2 levels. Geology 34:421–424
Imbrie J, Imbrie KP (1979) Ice ages: solving the mystery. Enslow Publishers, Short Hills, p 224
Imbrie J et al (1992) On the structure and origin of major glaciation cycles: 1. Linear responses to Milankovitch forcing. Paleoceanogr 7:701–738
Imbrie J et al (1993) On the structure and origin of major glaciation cycles: 2. The 100,000 yr cycle. Paleoceanogr 8:699–735
Jackson CS, Broccoli A (2003) Orbital forcing of Arctic climate: mechanisms of climate response and implications for continental glaciation. Clim Dyn 21:539–557
Jamieson SSR, Sugden DE (2008) Landscape evolution of Antarctica. In: Cooper AK, Barrett PJ, Stagg H, Storey B, Stump E, Wise W (eds) Antarctica: a keystone in a changing world. 10th ISAES editorial team. Proceedings of the 10th international symposium on antarctic earth sciences. Acad Press, Washington, DC, pp 39–54
Jamieson SSR, Hulton NRJ, Hagdorn M (2008) Modelling landscape evolution under ice sheets. Geomorph 97:91–108
Jannssens I, Huybrechts P (2000) The treatment of meltwater retention in mass-balance parameterizations of the Greenland ice sheet. Ann Glaciol 31:133–140
Jenssen D (1977) A three-dimensional polar ice-sheet model. J Glaciol 18:373–389
Johnson J, Fastook JL (2002) Northern Hemisphere glaciation and its sensitivity to basal melt water. Quat Int 95–96:65–74
Joughin I, Tulaczyk S, Bamber JL, Blankenship D, Holt JW, Scambos T, Vaughan DG (2009) Basal conditions for Pine Island and Thwaites glaciers, West Antarctica, determined using satellite and airborne data. J Glaciol 55:245–257
Kageyama M, Valdes P (2000) Impact of the North American ice-sheet orography on the Last Glacial Maximum eddies and snowfall. Geophys Res Lett 27:1515–1518
Kageyama M, Charbit S, Ritz C, Khodri M, Ramstein G (2004) Quantifying ice sheet feedbacks during the last glacial inception. Geophys Res Lett 31:L24203. doi:1029/2004GL021339
Kahana R, Valdes PJ (2009) A transient simulation of the last deglaciation (21k–9k BP) using a fully coupled GCM. European Geosciences Union General Assembly, Vienna, Geophys Res Abstracts, vol 11, EGU2009-9302.
Kamb B (2001) Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion. In: Alley RB, Bindschadler RA (eds) The West Antarctic ice sheet: behavior and environment. Antarctic Research Series, vol 77. Amer Geophys Union, Washington, DC, pp 157–199
Kenneally JP, Hughes TJ (2002) The calving constraints on inception of Quaternary ice sheets. Quat Int 95–96:43–53
Kessler MA, Anderson RS, Briner JS (2008) Fjord insertion into continental margins driven by topographic steering of ice. Nature Geosci 1:365–369
Kiehl JT, Shields CA (2005) Climate simulations of the latest Permian: implications for mass extinction. Geology 33:757–760
Kim S-J, Flato GM, Boer GJ (2003) A coupled climate model simulation of the Last Glacial Maximum, Part 2: approach to equilibrium. Clim Dyn 20:635–661
Kim S-J, Crowley TJ, Erickson DJ, Govindasamy B, Duffy PB, Lee BY (2008) High-resolution climate simulation of the Last Glacial Maximum. Clim Dyn 31:1–16
Kite ES, Hindmarsh RCA (2007) Did ice streams shape the largest channels on Mars? Geophys Res Lett 34:L19202. doi:10.1029/2007GL030530
Kotlarski S, Jacob D, Podzun R, Paul F (2010) Representing glaciers in a regional climate model. Clim Dyn 34:27–46
Krawczynski MJ, Behn MD, Das SB, Joughin I (2009) Constraints on the lake volume required for hydro-fracture through ice sheets. Geophys Res Lett 36:L10501. doi:10.1029/2008GL036765
Krinner G, Mangerud J, Jakobsson M, Crucifix M, Ritz C, Svendsen JI (2004) Enhanced ice sheet growth in Eurasia owing to adjacent ice-dammed lakes. Nature 427:429–432
Krinner G, Boucher O, Balkanski Y (2006) Ice-free glacial northern Asia due to dust deposition on snow. Clim Dyn 27:613–625
Kutzbach JE, Guetter PJ (1986) The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 years. J Atmos Sci 43:1726–1759

Kutzbach J, Gallimore R, Harrison S, Behling P, Selin R, Laarif F (1998) Climate and biome simulations for the past 21,000 years. Quat Sci Rev 17:471–506
Lambeck K, Purcell A, Funder S, Kjaer KH, Larsen E, Moller P (2006) Constraints on the Late Saalian to early Middle Weichselian ice sheet of Eurasia from field data and rebound modeling. Boreas 35:539–575
Langebroek PM, Paul A, Schulz M (2009) Antarctic ice-sheet response to atmospheric CO_2 and insolation in the middle Miocene. Clim Past 5:633–646
Le Meur E, Huybrechts P (1996) A comparison of different ways of dealing with isostacy: examples from modelling the Antarctic ice sheet during the last glacial cycle. Ann Glaciol 23:309–317
Lee WH, North GR (1995) Small ice cap instability in the presence of fluctuations. Clim Dyn 11: 242–246
Leung LR, Ghan SJ (1998) Parameterizing subgrid orographic precipitation and surface cover in climate models. Mon Weather Rev 126:3271–3291
Lhomme N, Clarke GKC, Ritz C (2005) Global budget of water isotopes inferred from polar ice sheets. Geophys Res Lett 32:L20502. doi:10.1029/2005GL023774
Licciardi JM, Clark PU, Jenson JW, MacAyeal DR (1998) Deglaciation of a soft-bedded Laurentide Ice Sheet. Quat Sci Rev 17 427:448
Little CM, Gnanadesikan A, Oppenheimer M (2010) How ice shelf morphology controls basal melting. J Geophys Res 114:C12007. doi:10.1029/2008JC005197
Liu Z, Otto-Bliesner BL, He F, Brady EC, Tomas R, Clark PU, Carlson AE, Lynch-Stieglitz J, Curry W, Brook E, Erickson D, Jacob R, Kutzbach J, Cheng J (2009) Transient simulation of last deglaciation with a new mechanism for Bølling–Allerød warming. Science 325: 310–314
Loutre MF, Berger A (2000) Future climatic changes: are we entering an exceptionally long interglacial? Clim Change 46:61–90
Lunt DJ, Williamson MS, Valdes PJ, Lenton TM, Marsh R (2006) Comparing transient, accelerated, and equilibrium simulations of the last 30000 years with the GENIE-1 model. Clim Past 2: 221–235
Luthje M, Pedersen LT, Reeh N, Greuell W (2006) Modelling the evolution of supraglacial lakes on the West Greenland ice-sheet margin. J Glaciol 52:608–618
MacAyeal DR (1979) A catastrophe model of the plaeoclimate. J Glaciol 24:245–257
MacAyeal DR (1989) Large-scale ice flow over a viscous basal sediment: theory and application to Ice Stream B, Antarctica. J Geophys Res 94:4071–4087
MacAyeal DR (1992) Irregular oscillations of the West Antarctic ice sheet. Nature 359:29–32
MacAyeal DR, Rommelaere V, Huybrechts P, Hulbe CL, Determann J, Ritz C (1996) An ice -shelf model test based on the Ross Ice Shelf, Antarctica. Ann Glaciol 23:46–51
Mahowald N, Kohfeld KE, Hannson M, Balkanski Y, Harrison SP, Prentice IC, Schulz M, Rodhe H (1999) Dust sources and deposition during the last glacial maxima and current climate: a comparison of model results with paleodata from ice cores and marine sediments. J Geophys Res 104:15895–15916
Manabe S, Broccoli AJ (1985) The influence of continental ice sheets on the climate of an ice age. J Geophys Res-Atmos 90:2167–2190
Marshall SJ, Clarke GKC (1999a) Modeling North American freshwater runoff through the last glacial cycle. Quat Res 52:300–315
Marshall SJ, Clarke GKC (1999b) Ice sheet inception: subgrid hypsometric parameterization of mass balance in an ice sheet model. Clim Dyn 15:533–550
Marshall SJ, Clark PU (2002) Basal temperature evolution of North American ice sheets and implications for the 100-kyr cycle. Geophys Res Lett 29:24, 2214. doi:10.1029/2002GL015192
Marshall SJ, Pollard D, Hostetler S, Clark PU (2004) Coupling ice-sheet and climate models for simulation of former ice sheets. In: Gillespie AR, Porter SC, Atwater AF (eds) The quaternary period in the United States, vol 1. Developments in Quaternary Science, Elsevier Publ., pp 105–126
Matteucci G (1989) Orbital forcing in a stochastic resonance model of the late-Pleistocene climate variations. Clim Dyn 3:179–190
Mitchell JFB, Grahame NS, Needham KJ (1988) Climate simulatrions for 9000 years before present: Seasonal variations and effect if the Laurentide ice sheet. J Geophys Res 93:8283–8303
Mudelsee M, Schulz M (1997) The Mid-Pleistocene climate transition: onset of 100 ka cycle lags ice volume build-up by 280 ka. Earth Planet Sci Lett 151:117–123
Musynski I, Birchfield GE (1985) The dependence of Antarctic accumulation rates on surface temperature and elevation. Tellus 37A:204–208

Neeman BU, Ohring G, Joseph JH (1988) The Milankovitch theory and climate sensitivity 2. Interactions between the northern hemispheric ice sheets and the climate system. J Geophys Res 93:11175–11191

Nicholls KW (1997) Predicted reduction in basal melt rates of an Antarctic ice shelf in a warmer climate. Nature 388:460–462

Nick FM, van der Veen CJ, Oerlemans J (2007) Controls on advance of tidewater glaciers: results from numerical modeling applied to Columbia Glacier. J Geophys Res 112:F03S24. doi:10.1029/2006JF000551

Nick FM, Vieli A, Howat IM, Joughin I (2009) Large-scale changes in Greenland outlet dynamics triggered at the terminus. Nature Geosci, 2, 110:114

North GR (1975) Theory of energy-balance climate models. J Atmos Sci 32:2033–2043

North GR (1984) The small ice cap instability in diffusive climate models. J Atmos Sci 41:3390–3395

Oerlemans J (1980) Model experiments on the 100,000-yr glacial cycle. Nature 287:430–432

Oerlemans J (1982) A model of the Antarctic ice sheet. Nature 297:550–553

Oerlemans J (2002) On glacial inception and orography. Quat Int 95–96:5–10

Overpeck J, Rind D, Lacis A, Healy R (1996) Possible role of dust-induced regional warming in abrupt climate change during the last glacial period. Nature 384:447–449

Paillard D (1995) The hierarchical structure of glacial climatic oscillations: interactions between ice-sheet dynamics and climate. Clim Dyn 11:162–177

Paillard D, Parrenin F (2004) The Antarctic ice sheet and the triggering of deglaciations. Earth Planet Sci Lett 227:263–271

Parizek BR, Alley RB (2004) Implications of increased Greenland surface melt under global-warming scenarios: ice-sheet simulations. Quat Sci Rev 23:1013–1027

Parizek BR, Alley RB, Dupont TK, Walker RT, Anandakrishnan S (2010) Effects of orbital-scale climate cycling and meltwater drainage on ice sheet grounding line migration. J Geophys Res-Earth Surf 11:F01011

Parrenin F, Paillard D (2003) Amplitude and phase modulation of glacial cycles from a conceptual model. Earth Planet Sci Lett 214:243–250

Paterson WSB (1994) The Physics of Glaciers, 3rd edn. Butterworth-Heinemann Publ., Oxford, p 481

Pattyn F (2002) Transient glacier response with a higher-order numerical ice-flow model. J Glaciol 48:467–477

Pattyn F (2008) Investigating the stability of subglacial lakes with a full Stokes ice-sheet model. J Glaciol 54 353:361

Pattyn F, De Smedt B, Souchez R (2004) Influence of subglacial Vostok lake on the regional ice dynamics of the Antarctic ice sheet: a model study. J Glaciol 50 583:589

Payne AJ, Vieli A, Shepherd AP, Wingham DJ, Rignot E (2004) Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans. Geogr Res Lett 31:L23401. doi:10.1029/2004GL021284

Payne AJ, Holland PR, Shepherd AP, Rutt IC, Jenkins A, Joughin I (2007) Numerical modeling of ocean–ice interactions under Pine Island Bay's ice shelf. J Geophys Res 112:C11019. doi:10.1029/2006JC003733

Peltier WR (2004) Global glacial isostasy and the surface of the ice-age earth: the ICE-5G (VM2) model and GRACE. Ann Rev Earth Planet Sci 32:111–149

Peltier WR, Marshall S (1995) Coupled energy-balance/ice-sheet model simulations of the glacial cycle—a possible connection between terminations and terrigenous dust. J Geophys Res-Atmos 100:14269–14289

Peyaud V, Ritz C, Krinner C (2007) Modelling the early Weichselian Eurasian ice sheets: role of ice shelves and influence of ice-dammed lakes. Clim Past 3:375–386

Pfeffer WT, Meier MF, Illangasekare TH (1991) Retention of Greenland runoff by refreezing: implications for projected future sea-level change. J Geophys Res 96:22117–22124

Philippon G, Ramstein G, Charbit S, Kageyama M, Ritz C, Dumas C (2006) Evolution of the Antarctic ice sheet throughout the last deglaciation: a study with a new coupled climate–north and south hemisphere ice sheet model. Earth Planet Sci Lett 248:750–758

Pollard D (1978) An investigation of the astronomical theory of the ice ages using a simple climate–ice sheet model. Nature 272:233–235

Pollard D (1982) A simple ice sheet model yields realistic 100 kyr glacial cycles. Nature 296:334–338

Pollard D (1983) A coupled climate–ice sheet model applied to the Quaternary ice ages. J Geophys Res 88:7705–7718

Pollard D, DeConto RM (2005) Hysteresis in Cenozoic Antarctic ice sheet variations. Glob Planet Change 45:9–21

Pollard D, DeConto RM (2007) A coupled ice-sheet/ice-shelf/sediment model applied to a marine-margin flowline: forced and unforced variations. In: Hambrey MJ, Christoffersen P, Glasser NF, Hubbard B (eds) Glacial sedimentary processes and products, vol 39. Int Assoc Sedimentol Special Publication , Blackwell Publ., pp 37–52

Pollard D, DeConto RM (2009) Modelling West Antarctic ice sheet growth and collapse through the past five million years. Nature 458:329–332

Pollard D, Kasting JF (2004) Climate–ice sheet simulations of Neoproterozoic glaciation before and after collapse to Snowball Earth. In: Jenkins G, McMenamin M, McKay C, Sohl L (eds) The Extreme Proterozoic: Geology, Geochemistry and Climate, vol 146. Geophysical Monograph, American Geophysical Union, Washington, DC, pp 91–105

Pollard D, Kasting JF (2005) Snowball Earth: a thin-ice solution with flowing sea glaciers. J Geophys Res-Oceans 110:C07010. doi:10.1029/2004JC002525

Pollard D, Thompson SL (1997a) Driving a high-resolution dynamic ice-sheet model with GCM climate: ice-sheet initiation at 116 Kyr BP. Ann Glaciol 25:296–304

Pollard D, Thompson SL (1997b) Climate and ice-sheet mass balance at the Last Glacial Maximum from the GENESIS version 2 global climate model. Quat Sci Rev, 16:841–864

Pollard D, Muszynski I, Schneider SH, Thompson SL (1990) Asynchronous coupling of ice sheet and atmospheric forcing models. Ann Glac 14:247–251

Pollard D, PMIP Participating Groups (2000) Comparisons of ice-sheet surface mass budgets from Paleoclimate Modeling Intercomparison Project (PMIP) simulations. Glob Planet Change 24: 79–10

Poulsen CJ (2003) Absence of a runaway ice-albedo feedback in the Neoproterozoic. Geology 31:473–476

Pritchard HD, Arthern RJ, Vaughan DG, Edwards LA (2009) Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. Nature 461:971–975

Rahmstorf S et al (2005) Thermohaline circulation hysteresis: a model intercomparison. Geophys Res Lett 32:L23605. doi:1029/2005GL023655

Raymo ME, Lisiecki LE, Nisancioglu N (2006) Plio-Pleistocene ice volume, Antarctic climate, and the global delta O-18 record. Science 313:492–495

Reusch DB, Hewitson BC, Alley RB (2005) Towards ice core-based synoptic reconstructions of West Antarctic climate with artificial neural networks. Int J Clim 25:581–610

Ridley JK, Huybrechts P, Gregory JM, Lowe JA (2005) Elimination of the Greenland ice sheet in a high CO_2 climate. J Clim 18:3409–3426

Rignot E (2008) Changes in West Antarctic ice stream dynamics observed with ALOS PALSAR data. Geophys Res Lett 35:L12505. doi:10.1029/2008GL033365

Rignot E, Kanagaratnam P (2006) Changes in the velocity structure of the Greenland Ice Sheet. Science 311:986–990

Rind D, Peteet D, Kukla G (1989) Can Milankovitch orbital variations initiate the growth of ice sheets in a general circulation model? J Geophys Res 94:12851–12871

Ritz C, Fabre A, Letreguilly A (1997) Sensitivity of a Greenland ice sheet model to ice flow and ablation parameters: consequences for the evolution through the last climatic cycle. Clim Dyn 13:11–24

Ritz C, Rommelaere V, Dumas C (2001) Modeling the evolution of Antarctic ice sheet over the last 420,000 years: implications for altitude changes in the Vostok region. J Geophys Res-Atmos 106:31943–31964

Rodgers KB, Charbit S, Kageyama M, Philippon G, Ramstein G, Ritz C, Yin JH, Lohmann G, Lorenz SJ, Khodri M (2004) Sensitivity of Northern Hemispheric continental ice sheets to tropical SST during deglaciation. Geophy Res Lett 31:L02206. doi:10.1029/2003GL018375

Royer JF, Deque M, Pestiaux P (1983) Orbital forcing of the inception of the Laurentide ice sheet? Nature 304:43–46

Rutt IC, Hagdorn M, Hulton NRJ, Payne AJ (2009) The Glimmer community ice sheet model. J Geophys Res 114:F02004. doi:10.1029/2008JF001015

Saltzman B (1984) On the role of equilibrium atmospheric climate models in the theory of long-period glacial variations. J Atmos Sci 41:2263–2266

Saltzman B (1990) Three basic problems of paleoclimatic modeling: a personal perspective and review. Clim Dyn 5:67–78

Saltzman B, Verbitsky MY (1993) Multiple instabilities and modes of glacial rhythmicity in the Plio-Pleistocene: a general theory of late Cenozoic climatic change. Clim Dyn 9:1–15

Sanberg JAM, Oerlemans J (1983) Modelling of Pleistocene European ice sheets: the effect of upslope precipitation. Geologie en Mijnbouw 62:267–273

Scambos T, Fricker HA, Liu C-C, Bohlander J, Fastook J, Sargent A, Massom R, Wu A-M (2009) Ice shelf disintegration by plate bending and hydro-fracture: Satellite observations and model results of the 2008 Wilkins ice shelf break-ups. Earth Planet Sci Lett 280:51–60

Schmittner A, Yoshimori M, Weaver AJ (2002) Instability of the glacial climate in a model of the ocean-atmosphere-cryosphere system. Science 295:1489–1493

Schneider SH, Dickinson RE (1974) Climate modeling. Rev Geophys Space Phys 12:447–493

Schneider SH, Thompson SL (1981) Atmospheric CO_2 and climate: importance of the transient response. J Geophys Res 86:3135–3147

Schoof C (2007) Ice sheet grounding line dynamics: steady states, stability, and hysteresis. J Geophys Res-Earth Surface 112:F03S28. doi:10.1029/2006JF000664

Sellers WD (1969) A climate model based on the energy balance of the earth-atmosphere system. J Appl Meteorol 12:241–254

Sergin VY (1980) Origin and mechanism of large-scale climatic oscillations. Science 209:1477–1482

Shoemaker EM (1991) On the formation of large subglacial lakes. Canad J Earth Sci 28:1975–1981

Shumskii PA (1964) Principles of structural glaciology. Dover Publications, New York, p 497

Sima A, Paul A, Schulz M, Oerlemans J (2006) Modeling the oxygen-isotopic composition of the North America Ice Sheet and its effect ion the isotopic composition of the ocean during the last glacial cycle. Geophys Res Lett 33:L22710. doi:10.1029/2006GL026923

Stokes CR, Tarasov L (2010) Ice streaming in the Laurentide ice sheet: a first comparison between data-calibrated numerical model output and geological evidence. Geophys Res Lett 37:L01501. doi:10.1029/2009GL040990

Sugden D (2009) Ice sheets and ice caps. In: Slaymaker O, Spencer T, Embleton-Hamann C (eds) Geomorphology and global environmental change. Cambridge Univ. Press, pp 368–402

Sugden D, McCulloch RD, Bory AJM, Hein S (2009) Influence of Patagonian glaciers on Antarctic dust deposition during the last glacial period. Nature Geosci 2 281:285

Sundai AV, Shepherd A, Nienow P, Hanna E, Palmer S, Huybrechts P (2009) Evolution of supra-glacial lakes across the Greenland ice sheet. Remote Sens Environ 113:2164–2171

Swingedouw D, Fichefet T, Huybrechts P, Goosse H, Driesschaert E, Loutre M-F (2008) Antarctic ice-sheet melting provides negative feedbacks on future climate warming. Geophys Res Lett 35:L17705. doi:10.1029/2008GL034410

Syktus J, Gordon H, Chappell J (1994) Sensitivity of a coupled atmosphere–dynamic upper ocean GCM to variations of CO_2, solar constant, and orbital forcing. Geophys Res Lett 21:1599–1602

Tarasov L, Peltier WR (1997) Terminating the 100 kyr ice age cycle. J Geophys Res 102:21,665–21,693

Tarasov L, Peltier WR (1999) Impact of thermomechanical ice sheet coupling on a model of the 100 kyr ice age cycle. J Geophys Res 104:9517–9545

Tarasov L, Peltier WR (2004) A geophysically constrained large ensemble analysis of the deglacial history of the North American ice-sheet complex. Quat Sci Rev 23:359–388

Tarasov L, Peltier WR (2005) Arctic freshwater forcing of the Younger Dryas cold reversal. Nature 435:662–665

Thoma M, Jenkins A, Holl D, Jacobs S (2008) Modelling Circumpolar Deep Water intrusions on the Amundsen Sea continental shelf, Antarctica. Geophys Res Lett 35:L18692. doi:10.1029/2008GL034939

Thompson SL, Pollard D (1997) Greenland and Antarctic mass balances for present and doubled CO_2 from the GENESIS version-2 global climate model. J Clim 10:871–900

Timm O, Timmermann A (2007) Simulation of the last 21000 years using accelerated transient boundary conditions. J Climate 20:4377–4401

Toggweiler JR, Lea DW (2010) Temperature differences between the hemispheres drive ice-age climate variability. Paleoceanogr. doi:10.1029/2009PA001758

Tomkin JH (2003) Erosional feedbacks and the oscillations of ice masses. J Geophys Res 108:B10, 2488. doi:10.1029/2002JB002087

Toniazzo T, Gregory JM, Huybrechts P (2004) Climatic impact of a Greenland deglaciation and its possible irreversibility. J Clim 17:21–33

Tulaczyk S, Kamb WB, Engelhardt HF (2000) Basal mechanics of Ice Stream B, West Antarctica.1. Till mechanics. J Geophys Res 105:463–481

Tulaczyk SM, Scherer RP, Clark CD (2001) A ploughing model for the origin of weak tills beneath ice streams: a qualitative treatment. Quat Int 86:59–70

Vacco DA, Alley RB, Pollard D (2009) Modeling dependence of moraine deposition on climate history: the effect of seasonality. Quat Sci Res 28:639–646

Vacco DA, Alley RB, Pollard D (2010) Effect of rock avalanches and supraglacial debris on glaciers. Earth Planet Sci Lett (in press)

van de Wal RSW (1996) Mass-balance modelling of the Greenland ice sheet: a comparison of an energy-balance and a degree-day model. Ann Glaciol 23:36–45

van de Wal RSW, Oerlemans J (1994) An energy balance model for the Greenland ice sheet. Glob Planet Change 9:115–131

van den Berg J, van de Wal R, Oerlemans H (2008) A mass balance model for the Eurasian Ice Sheet for the last 120,000 years. Glob Planet Change 61:194–208

van den Broeke M, van de Berg WJ, van Meijgaard E, Reijmer C (2006) Identification of Antarctic ablation areas using a regional atmospheric climate model. J Geophys Res-Atmos 111:D18110. doi:10.1029/2006JD007127

van der Veen CJ (1996) Tidewater calving. J Glaciol 42:375–385

Vaughan DG (2008) West Antarctic Ice Sheet collapse: the fall and rise of a paradigm. Clim Change 91:65–79

Vautard R, Ghil M (1989) Singular spectrum analysis in nonlinear dynamics, with applications to paleoclimatic time series. Physica D 35:395–424

Verbitsky M, Saltzman B (1997) Modeling the Antarctic ice sheet. Ann Glaciol 25:259–268

Vettoretti G, Peltier WR (2004) Sensitivity of glacial inception to orbital and greenhouse gas climate forcing. Quat Sci Rev 23:499–519

Vieli A, Payne AJ (2005) Assessing the ability of numerical ice sheet models to simulate grounding line migration. J Geophs Res 110:F01003. doi:10.1029/2004JF000202

Vizcaino M, Mikolajewicz U, Groger M, Maier-Reimer E, Schurgers G, Winguth AME (2008) Long-term ice sheet–climate interactions under anthropogenic greenhouse forcing simulated with a complex Earth system model. Clim Dyn 31:665–690

Walker RT, Dupont TK, Holland DM, Parizek BR, Alley RB (2009) Initial effects of oceanic warming on a coupled ocean–ice shelf–ice stream system. Earth Planet Sci Lett 287:467–478

Walland DJ, Simmonds I (1996) Sub-grid scale topography and the simulation of Northern Hemisphere snow cover. Int J Climatol 16:961–982

Wang ZM, Mysak LA (2002) Simulation of the last glacial inception and rapid ice sheet growth in the McGill Paleoclimate Model. Geophys Res Lett 29:23, 2102. doi:10.1029/2002GL015120

Weertman J (1961) Stability of ice-age ice sheets. J Geophys Res 66:3783–3792

Weertman J (1964) Rate of growth or shrinkage of nonequilibrium ice sheets. J Glaciol 5:145–158

Weertman J (1974) Stability of the junction of an ice sheet and an ice shelf. J Glaciol 13:3–11

Weertman J (1976) Milankovitch solar radiation variations and ice age ice sheet sizes. Nature 261:17–20

Wilson DS, Pollard D, Luyendyk BP, DeConto R (2009) Ice volume at the Eocene–Oligocene transition predicted from restoration of West Antarctic topography. American Geophysical Union Fall Meeting, San Francisco, abstract PP41D-03

Winberry JP, Anandakrishnan S, Alley RB, Bindschadler RA, King MA (2009) Basal mechanics of ice streams: insights from the stick-slip motion of Whillans Ice Stream, West Antarctica. J Geophys Res 114:F01016. doi:10.1029/2008JF001035

Yiou P, Ghil M, Jouzel J, Paillard D, Vautard R (1994) Nonlinear variability of the climatic system from singular and power spectra of late Quaternary records. Clim Dyn 9 371:389

Zachos J, Pagani M, Sloan L, Thomas E, Billups K (2006) Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292:686–693

Zachos J, Dickens GR, Zeebe RE (2008) An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. Nature 451:279–283

Zweck C, Huybrechts P (2005) Modeling of the northern hemispheric ice sheets during the last glacial cycle and glaciological sensitivity. J Geophys Res 110:D07103. doi:10.1029/2004JD005489