ICE-SHEET MODELLING CONTRIBUTION TO ANDRILL PROGRAMME

Nick Golledge[1], Andrew Mackintosh[1], Brian Anderson[1], Wolfgang Rack[2]

[1] Antarctic Research Centre, Victoria University of Wellington
[2] Gateway Antarctica, University of Canterbury

BACKGROUND

ANDRILL and earlier (Cape Roberts, CIROS 1 and 2) coring in the Ross Sea region of Antarctica (Barrett, 2009, Naish et al 2002, 2009), and associated ice sheet modelling (DeConto and Pollard 2003, Pollard and DeConto, 2009) have demonstrated East and West Antarctic ice sheet variability on orbital timescales since ice sheet inception at the Eocene/Oligocene boundary at around 35 Ma. Of direct societal relevance, interpretation of the ANDRILL 1B core suggests that repeated collapses of the West Antarctic Ice Sheet (WAIS) have occurred in the last 5 Ma, in both the Pliocene and during Pleistocene 'super' interglacials when temperatures and CO_2 levels were slightly higher than today (Naish et al. 2009, Pollard and DeConto 2009). In apparent conflict with these findings, moraine dating, survival of extreme polar desert landforms, ancient buried ice, and extinction of local temperate biota in the adjacent Dry Valleys region indicate stability of the East Antarctic Ice Sheet since the mid Miocene (the last 13 ma) (Sugden et al. 1995, Sugden and Denton 2004, Lewis et al. 2008). At present, it is not possible to discriminate between these seemingly divergent hypotheses, nor assess whether they are compatible, because the interpretation of geological evidence (both cores and onshore geomorphology) involve substantial extrapolation in both space and time, and ice sheet modelling lacks the appropriate spatial resolution for direct comparison to field evidence. As a consequence of these and other uncertainties, numerical modelling and empirical reconstructions differ vastly in their interpretation of the former ice volumes which resulted from temperatures slightly warmer than today (c.f. Hill et al., 2007; Pollard & DeConto, 2009). The extent to which East Antarctic Ice Sheet (EAIS) outlet glaciers changed during such ice-sheet reconfiguration(s) is central to this uncertainty (Sugden 1996; Hall et al., 1997; Sugden & Denton 2004), and remains keenly debated, with evidence from the Dry Valleys region suggesting minor Pliocene ice advances (Marchant et al. 1993), whereas temperate glacier deposits of presumed but disputed Pliocene age (McKay 2008) adjacent to the Beardmore and Shackleton Glaciers at >80ºS, may indicate conditions substantially warmer than present (Mercer 1972, Hambrey et al. 2003).

In an attempt to address the problems detailed above, we will attempt to develop an understanding of the mechanistic links between upper atmosphere insolation changes and ice sheet reorganisation at high spatial resolution. Past, present and future behaviour of the EAIS can be interpreted from assessment of major EAIS outlet glacier perturbations as manifest in geometric and dynamic changes of both the glaciers themselves (e.g. Bockheim et al., 1989; Denton et al., 1989a, b) and the Ross Ice Shelf (RIS) into which they feed (Hulbe & Fahnestock 2004, 2007). In connecting the EAIS with the marine component of the West Antarctic Ice Sheet (WAIS), TAM glaciers are ideally situated for understanding ice sheet interaction at the local and regional scale. Furthermore, these glaciers contribute significantly to the RIS, the presence of which may maintain through buttressing the stability of much of the WAIS (especially Siple Coast ice streams – c.f. Hulbe & Fahnestock 2004, 2007). The East Antarctic Ice Sheet (EAIS) margin along the Trans-Antarctic Mountains (TAM) has also been identified as the westernmost limit recent decadal warming (Steig et al., 2009), and continuing warming or change in ocean properties may ultimately result in ice shelf instability migrating southward from the Antarctic Peninsula to the Ross Ice Shelf. Despite the apparent significance of TAM glaciers, however, the dynamics of most remain poorly known, thus a baseline of 'normal' operation is lacking.

OBJECTIVES

Our aims are threefold (Fig. 1):

- To better characterise glacier dynamics at the transition from glacier to ice shelf (grounding line) by undertaking field investigations on the Beardmore Glacier (Trans-Antarctic Mountains) using a variety of geophysical techniques.

- To use these data, together with remotely-sensed (satellite) data, to appropriately constrain high-resolution numerical ice sheet models of the Beardmore Glacier and put this into context of present-day dynamics of TAM glaciers flowing into the RIS.

- To gauge the sensitivity of TAM glaciers to forcing perturbations, and use the geological record from ANDRILL core sites to establish the nature of glaciological and climate variability in the during key episodes of the recent geological past, including the warmest Pliocene and Pleistocene super interglacials.

PROPOSED RESEARCH:

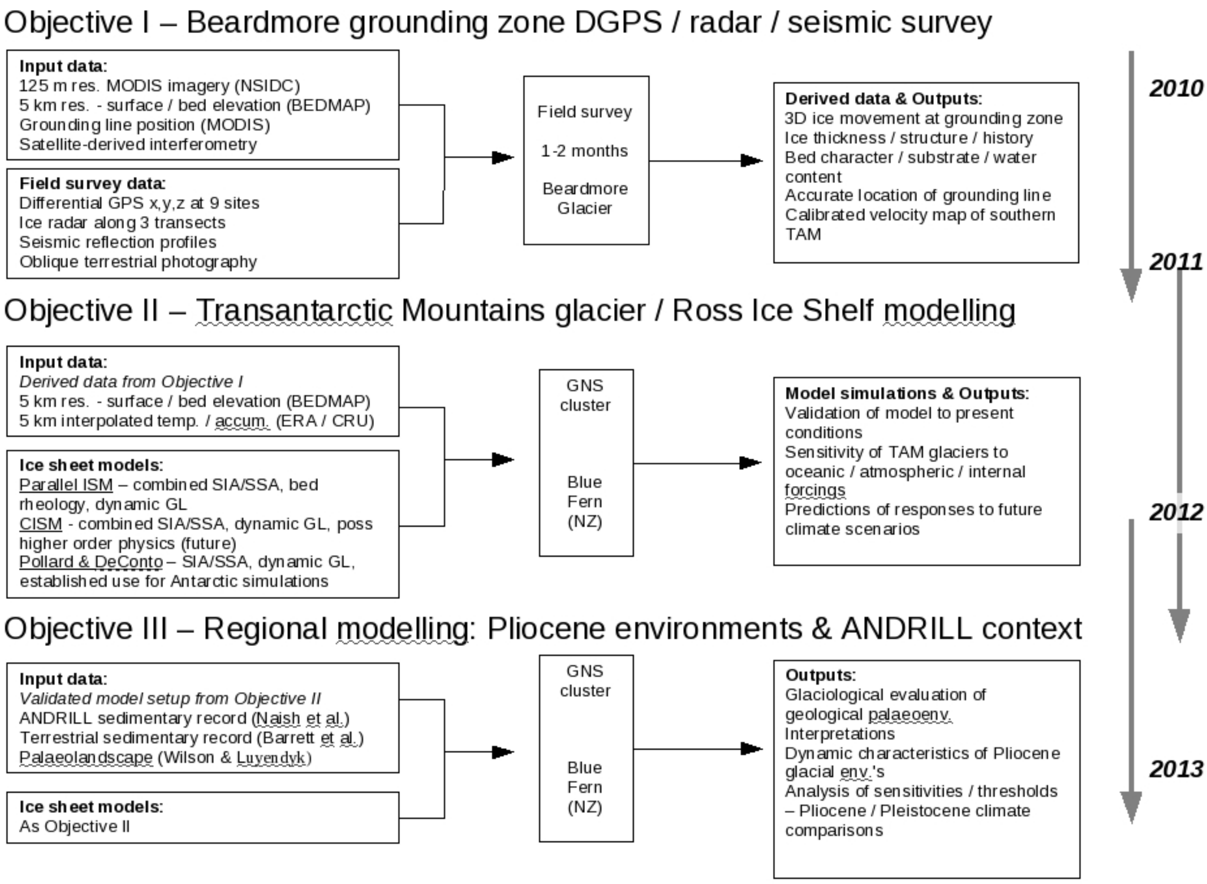

Figure 1: Overview of project objectives and strategy

Objective 1: Establish detailed empirical baseline for grounding-zone dynamics of Beardmore Glacier, Trans-Antarctic Mountains

Glacier – ice-shelf connectivity across the grounding zone remains a key uncertainty in process glaciology (Mayer & Huybrechts, 1999; Walker et al., 2008) and ice-sheet modelling (e.g. Nowicki & Wingham 2008). Reducing this uncertainty is essential for model-based assessments of grounding-line position, stability, migration, and mass-flux (Vieli and Payne, 2005; van der Veen et al., 2007). The analytical solution for ice flux at the grounding line for rapidly-sliding grounded ice (Schoof, 2007) is increasingly used in ice sheet models (e.g. Pollard and Deconto 2009) although it does not account for the case where there is significant shearing in the grounded ice (Nowicki and Wingham, 2007, 2008), as is expected in TAM glaciers. We intend to undertake fieldwork to locate the present grounding-line of the Beardmore Glacier, and to obtain information on the flow structure and internal ice deformation in the grounding zone (Fig. 2). Using differential GPS (DGPS) arrays along flow-parallel transects spanning this zone we will record real-time [x,y,z] displacements of the ice surface for comparison with historic records (e.g. Swithinbank 1963: Beardmore velocity c. 365 m a^{-1}), as well as the identification of short-term variability. Data-logging over an optimal field survey period of one - two months will enable the complete lunar (tidal) signal to be resolved, as well as diurnal variations. Skidoo-mounted ice-penetrating radar surveys along each transect line will be carried out during the field period in order to establish ice thickness and any evidence of internal (flow) deformation (Corr et al., 2002). Additionally this will characterise the nature of the basal contact and will allow direct linkage between dynamics interpreted from DGPS measurements and glaciology (grounded-ice – shelf transition effects). Seismic survey will also be necessary in order to accurately image the glacier bed and lower reflectors, from which we can infer variation in substrate rheology, in particular the extent / thickness of dilatant till and presence/absence of a stabilising sediment wedge (e.g. Blankenship et al., 1986; Anandakrishnan et al. 2007d). DGPS data will be used to calibrate repeat oblique terrestrial imagery of the grounding zone taken from Mt. Hope and Mt. Kiffin (Fig. 2) and, by enabling photogrammetric analysis, will allow high-resolution velocity interpretations to be derived for the grounding zone area. The ground-based information will be completed with information from satellite repeat pass imagery (Rignot et al, 2008) to obtain surface velocity fields, as well as ICESat (since 2003) and CryoSat-2 (launch December 2009) data for surface elevation and changes thereof. Estimates on snow accumulation in the catchment area will be obtained from passive microwave sensors. Satellite data analysis will be used to assess the dynamics and mass balance of other TAM outletglaciers discharging ice into the RIS.

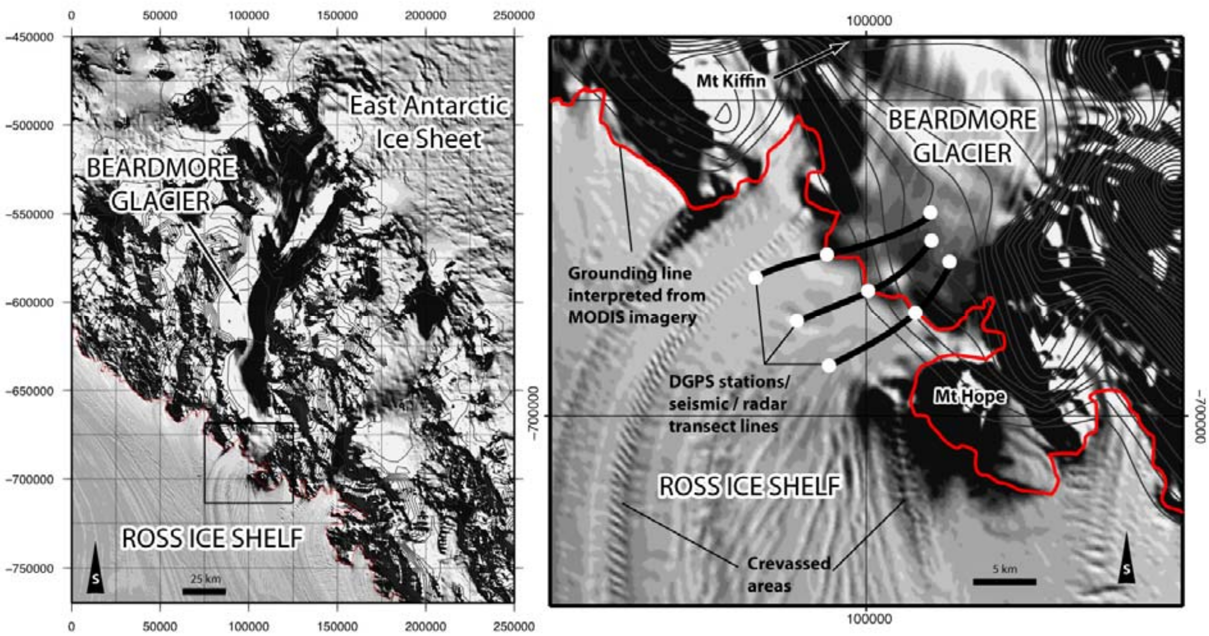

Figure 2: MODIS imagery illustrating location of the Beardmore Glacier in context of East Antarctic Ice Sheet and Ross Ice Shelf, with indicated survey locations. Red line indicates likely position of grounding line inferred from MODIS-derived glacier surface contrasts. Coordinates are km from pole in Polar Stereographic projection.

Objective 2: Sensitivity analysis of Trans-Antarctic Mountain glacier systems to dominant forcings

The stability / presence of buttressing ice shelves has long been suggested as an essential control on the dynamics of tributary glaciers (Weertman 1974; Mercer 1978), perhaps with some observational support (e.g. De Angelis & Skvarca 2003; Scambos et al., 2004). Ice shelf sensitivity to changes in sea level and ocean warming (leading to sub-shelf melting), as well as atmospheric warming, affects grounding-line stability (Rignot & Jacobs, 2002; Walker et al., 2008, Scambos et al., 2000, 2009), which may in turn affect flow in grounded catchment areas. Surface mass balance of grounded portions may be negatively affected by atmospheric warming, or may benefit from possible precipitation increases. Complex feedbacks between individual forcings mean that it is difficult to predict their relative importance from present observations. To understand and quantify forcing sensitivities with respect to environmental changes forecast for the future, we will develop a high-resolution numerical ice sheet model simulation of the RIS / TAM region (Fig. 3). The model will be constrained by empirical data gathered remotely and from field survey during Objective 1, and supplemented with publicly available datasets wherever possible. Essential in this model will be i) the ability to closely simulate growth and behaviour of large ice shelves, ii) sufficiently well-resolved physics to allow free migration of the grounding-line, and iii) a robust mechanism with which shelf flow and grounded ice flux are coupled. Additionally, the model will need to be computable at 1 – 5 km resolution over a domain space of 0.25 – 5 M km^2 for time-dependent experiments of a multi-millennial scale. Parallel-processing and grid computation capability are necessary, for which we will employ the GNS cluster and the Blue Fern supercomputer at University of Canterbury as appropriate. Numerical models best able to deal with the complexities of an Antarctic ice sheet / shelf domain include the Parallel Ice Sheet Model (PISM) (Bueler & Brown, 2009; Bueler et al., 2009), the Community Ice Sheet Model (CISM – a development of 'GLIMMER'), and the model of Pollard and DeConto (2009). Each has the capability to simulate shelf flow and accommodate a dynamic grounding-line, using an analytical mass flux solution (Schoof 2006). PISM has the advantage of being specifically designed for parallel-processing, whereas CISM will in the near future incorporate higher-order physics that better simulates stress transfer across the grounding zone and areas of localised fast-flow. The Pollard and DeConto model has previously been used successfully to model Antarctic ice sheet dynamics and sediment flux (DeConto & Pollard, 2003; Pollard & DeConto 2003, 2009) and could be adapted for higher-resolution simulations.

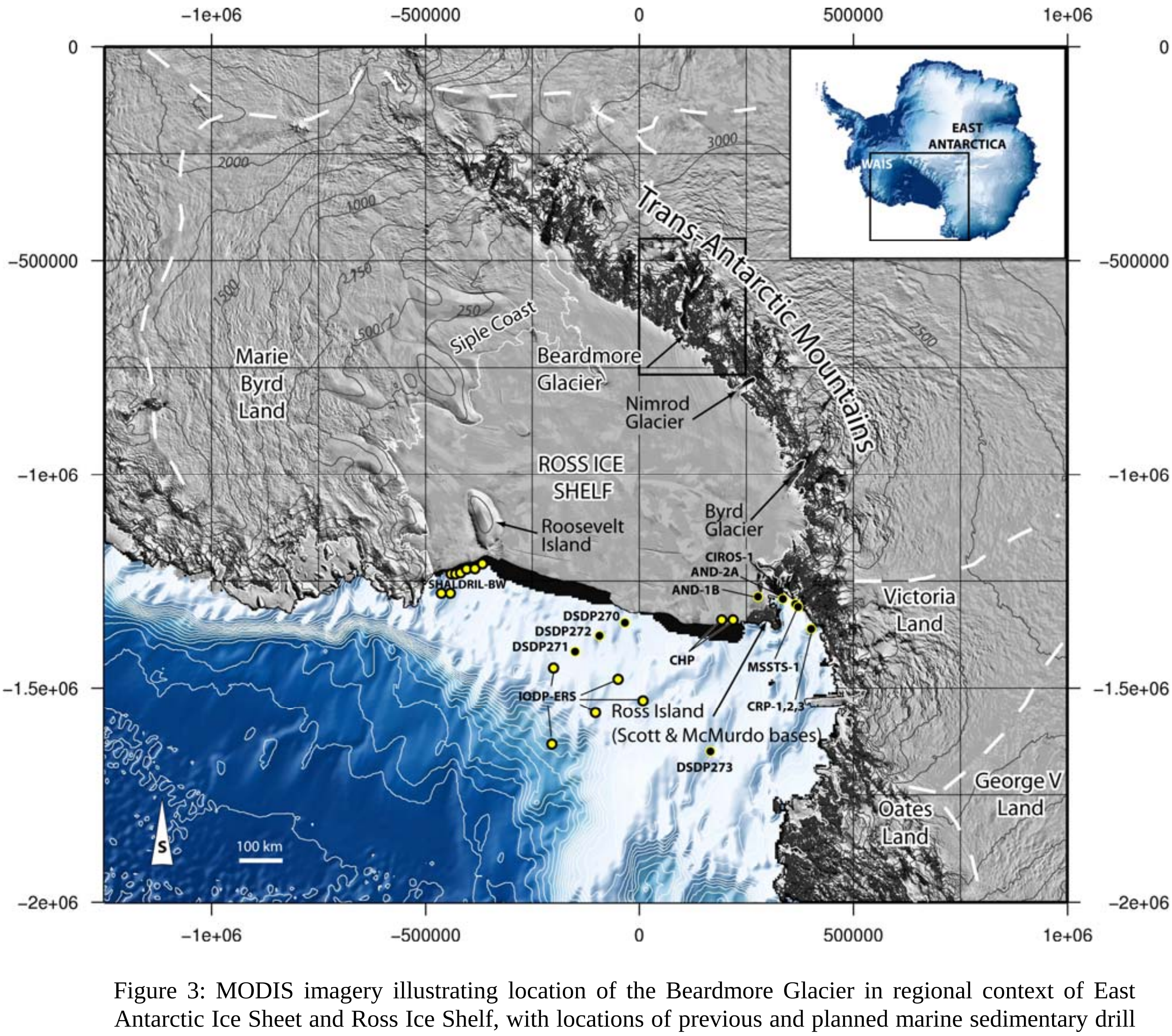

Figure 3: MODIS imagery illustrating location of the Beardmore Glacier in regional context of East Antarctic Ice Sheet and Ross Ice Shelf, with locations of previous and planned marine sedimentary drill sites. Bathymetry from BEDMAP (Lythe & Vaughan, 2000) [http://antarctica.ac.uk/bedmap]. Coordinates are km from pole in Polar Stereographic projection.

Initial model set-up and testing will involve simulations run to steady-state (equilibrium) conditions, and the tuning of forcing parameters to achieve dynamical characteristics consistent with those determined from empirical data gathered under Objective 1. From this starting point we will quantify the magnitudes and styles of glacier change likely to occur under a range of geologically recent and projected future environmental scenarios. This will be achieved through a series of experiments designed to isolate the influence of each principal forcing factor. Our analysis will focus particularly on grounding-line behaviour and associated dynamic / mass balance changes in inland accumulation areas. Of key interest is the sensitivity of the system to changing oceanic properties through their influence on ice shelf mass balance, and the implications this may have for TAM glaciers.

Objective 3: Glaciological reconstruction of Pliocene environment of the Ross Sea region

Transitions from an extensive, grounded, WAIS in the Ross Sea extending to the continental shelf, to intermediate configurations similar to present, to a collapsed state characterised by disparate ice masses grounded above sea level occurred rapidly (millennial-scale) during the recent geological past (last 5 Ma – Pliocene-Pleistocene period) (Naish et al., 2009; Pollard & DeConto, 2009). Currently, nested 10 km-resolution domains within a continental ice-sheet model (Pollard & DeConto, 2009) reveal the major flow trajectories of shelf ice in the Ross Sea basin and modelled oscillations in glacier extent correlate well with strata recovered in the eastern Ross Sea at AND-1B (Naish et al., 2009). However, a key question remains over the relative stability of the *East* Antarctic Ice Sheet during the interpreted warm-period collapses of the WAIS (see Sugden 1996 for discussion). Using our ice sheet model(s) (Objective 2), validated against modern empirical data (Objective 1), we will address the issue of EAIS stability by simulating the TAM / Ross Sea sector of the EAIS / WAIS divide under conditions likely to have characterised the Pliocene environment. Locally reconstructed sea surface temperatures (Gavin Dunbar in prep) and sediment provenance studies from ANDRILL 1B (McKay 2009) will be used as additional model constraints as appropriate. Particularly we will quantify both the mass balance and dynamic responses of TAM outlet glaciers, and their impact on EAIS accumulation centres. Using topography adjusted for post-Pliocene erosion (Wilson & Luyendyk 2009), our model will assess relative differences in response of the two ice sheets, and thus make inferences concerning their relative sensitivities to, for example, high CO_2 or warm ocean scenarios.

REFERENCES

Anandakrishnan, S., G. A. Catania, R. B. Alley, and H. J. Horgan (2007), Discovery of Till Deposition at the Grounding Line of Whillans Ice Stream, *Science*, *315*(5820), 1835-1838, doi:10.1126/science.1138393.

Barrett, P. 2009. ACE volume summary of Ross Sea drilling. I don’t have the reference available here but it is readily available in Wellington.

Blankenship, D.D., Bentley, C.R., Rooney, S.T. And Alley, R.B. 1986. Seismic measurements reveal a saturated porous layer beneath an active Antarctic ice stream. Nature, 322, 54-57

Bockheim, J.G., Wilson, S.C., Denton, G.H., Andersen, B.G. and Stuiver, M. 1989. Late Quaternary ice-surface fluctuations of Hatherton Glacier, Transantarctic Mountains. Quaternary Research, 31, 229-254

Bueler, E., and 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.

Bueler, E., Khroulev, C., Brown, J., and Shemonski, N. 2009. PISM, A Parallel Ice Sheet Model: User's Manual. www.pism-docs.org

Corr, H. F. J., A. Jenkins, K. W. Nicholls, and C. S. M. Doake. 2002. Precise measurement of changes in ice-shelf thickness by phase-sensitive radar to determine basal melt rates. *Geophys. Res. Lett.*, 29(8), 1232, doi:10.1029/2001GL014618.

DeAngelis, H. and Skvarca, P. 2003. Glacier surge after ice shelf collapse. Science, 299, 1560-1562

DeConto, R. M. and Pollard, D., 2003, Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO2, Nature, v. 421, p. 245-249.

Denton, G.H., Bockheim, J.G., Wilson, S.C., Leide, J.E., and Andersen, B.G. 1989. Late Quaternary ice-surface fluctuations of Beardmore Glacier, Transantarctic Mountains. Quaternary Research, 31, 183-209

Denton, G.H., Bockheim, J.G., Wilson, S.C., and Stuiver, M. 1989. Late Wisconsin and early Holocene glacial history, inner Ross Embayment, Antarctica. Quaternary Research, 31, 151-182

Hall, B. L., Denton, G. H., Lux, D. R. and Schlüchter, C. 1997. Pliocene paleoenvironment and Antarctic ice sheet behaviour: evidence from Wright Valley. The Journal of Geology, 105, 285-294

Hambrey, M., Webb, P., Harwood, P., Krissek, L. 2003. Neogene glacial record from the Sirius Group of the Shackleton Glacier region, central Transantarctic Mountains, Antarctica. GSA Bulletin 115, 994-1015.

Hill, D. J., Haywood, A. M., Hindmarsh, R.C.A. And Valdes, P.J. 2007. Characterising ice sheets during the Pliocene: Evidence from data and models. In Williams, M., Haywood, A.M., Gregory, F.J., Schmidt, D. N. (eds) Deep-time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies. Micropalaeotological Society Special Publication, Geological Society of London, 517-538.

Hulbe, C.L. and M.A. Fahnestock, 2004, West Antarctic ice stream discharge variability: mechanism, controls, and pattern of grounding line retreat, *Journal of Glaciology*, 50, 471-484.

Hulbe, C.L. and M.A. Fahnestock, 2007, Century-scale discharge stagnation and reactivation of the Ross ice streams, West Antarctica, *JGR Earth Surface*, v 112, doi:10.1029/2006JF000603.

Lewis, A.R., D.R. Marchant, A.C. Ashworth, L. Hedenas, S.R. Hemming, J.V. Johnson, M.J. Leng, M.L. Machlus, A.E. Newton, J.I. Raine, J.K. Willenbring, and A.P. Wolfe, 2008, Mid-Miocene cooling and the extinction of tundra in continental Antactica. *Poc Nat Acad Sci*, v. 105, n. 31, p. 10676-10680.

Lythe, M.B., Vaughan, D.G. and the BEDMAP Consortium. 2000. BEDMAP - bed topography of the Antarctic. 1:10,000,000 scale map. BAS (Misc) 9. Cambridge, British Antarctic Survey.

Marchant, David R., Denton, George H. and Swisher, C. C. III, 1993: Miocene-Pliocene-Pleistocene glacial history of Arena Valley, Quartermain Mountains, Antarctica. Geogr. Ann. 75 A (4): 269-302.

Mayer, C. & Huybrechts, P. (1999). Ice-dynamic conditions across the grounding zone, Ekstr misen, East Antarctica. Journal of Glaciology, 45, 384–393.

McKay – PhD thesis? Or maybe in his new GSA paper (I haven't read it).

McKay, R., Barrett, P, Harper, M. and Hannah, M. 2008. Atmospheric transport and concentration deposits in surficial and glacial sediments of the Alan Hills, Transantarctic Mountains. Paleogeography, Palaclimatology, Palaeogeography 260, 168-183.

Mercer, J.H. 1978. West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster. Nature, 271, 321-325

Mercer, J.H., 1972, Some observations of the glacial geology of the Beardmore Glacier area, *in* Adie, R.J., ed., Antarctic geology and geophysics: Oslo, Universitetsforlaget, p. 427–433 (International Union of Geological Sciences, Ser. B, no. 1).

Naish, T.R., Woolfe, K.J., Barrett, P.J., Wilson, G.S., Atkins, C., Bohaty, S.M., Bucker, C., Claps, M., Davey, F., Dunbar, G., Dunn, A., Fielding, C.R., Florindo, F., Hannah M., Harwood, D.M., Watkins, D., Henrys, S., Krisseck, L., Lavelle, M., van der Meer, J. J.P., McIntosh, M.C., Niessen, F., Passchier, S., Powell, R., Roberts, A.P., Sagnotti, L., Scherer, R.P., Strong, C.P., Talarico, F., Verosub, K. L., Villa, G., Webb, P-N., Wonik, T., 2001. Orbitally induced oscillations in the East Antarctic ice sheet at the Oligocene/Miocene boundary. Nature, 413, 719-723

Naish, T., Powell, R., Levy, R., Wilson, G., Scherer, R., Talarico, F., Krissek, L., Niessen, F., Pompilio, M., Wilson, T., Carter, L., DeConto, R., Huybers, P., McKay, R., Pollard, D., Ross, J., Winter, D., Barrett, P., Browne, G., Cody, R., Cowan, E., Crampton, J., Dunbar, G., Dunbar, N., Florindo, F., Gebhardt, C., Graham, I., Hannah, M., Hansaraj, D., Harwood, D., Helling, D., Henrys, S., Hinnov, L., Kuhn, G., Kyle, P., Läufer, A., Maffioli, P., Magens, D., Mandernack, K., McIntosh, W., Millan, C., Morin, R., Ohneiser, C., Paulsen, T., Persico, D., Raine, I., Reed, J., Riesselman, C., Sagnotti, L., Schmitt, D., Sjunneskog, C., Strong, P., Taviani, M., Vogel, S., Wilch, T., Williams, T., 2009. Obliquity-paced Pliocene West Antarctic ice Sheet oscillations. Nature, 458, 322-328.

Nowicki, S.M.J., & Wingham, D.J. 2008. Numerical solutions to grounding line flux issue: Conditions for a steady ice sheet–ice shelf junction. Earth and Planetary Science Letters, 265, 246-255

Oswald, G.K.A., & Gogineni, S. 2008 Recovery of subglacial water extent from Greenland radar survey data. Journal of Glaciology, 54, 94-106

Pollard, D. and DeConto, R. 2003. Antarctic ice and sediment flux in the Oligocene simulated by a climate-ice sheet-sediment model. Palaeogeography, Palaeoclimatology, Palaeoecology 198, 53-67

Pollard, D. and DeConto, R. 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. Nature, **458**, 329-332

Rignot, E. & Jacobs, S. S. 2002. Rapid bottom melting widespread near Antarctic ice sheet grounding lines. Science, 296, 2020 - 2023

Scambos, T.A., Hulbe, C., Fahnestock, M. and Bohlander, J. 2000. The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. Journal of Glaciology, 46, 516-530

Scambos, T.A., Bohlander, J.A., Shuman, C.A. and Skvarca, P. 2004. Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. Geophysical Research Letters, 31, L18402, doi:10.1029/2004GL020670

Scambos, T.A., Fricker, H.A., Liu, C.-C., Bohlander, J., Fastook, J., Sargent, A., Massom, R. and 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 and Planetary Science Letters, 280, 51-60

Schoof, C. 2006, A variational approach to ice stream flow, J. Fluid Mech., 556, 227 – 251.

Steig,E . J., Schneider, D. P., Rutherford, S. D., Mann, M. E., Comiso J. C., & Shindell D. T. 2009. Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. Nature, 457, 459-463

Sugden, D. E. et al. 1995. Preservation of Miocene glacier ice in East Antarctica. *Nature* **376**, 412-414.

Sugden, D. E. 1996. The East Antarctic Ice Sheet: unstable ice or unstable ideas? Transactions of the Institute of British Geographers, 21, 443-454

Sugden, D. and Denton, G. 2004. Cenozoic landscape evolution of the Convoy Range to Mackay Glacier area, Transantarctic Mountains: Onshore to offshore synthesis. GSA Bulletin, 116, 840-857

Swithinbank, C. W. 1963. Ice movement of valley glaciers flowing into the Ross Ice Shelf, Antarctica. Science, 141, 523-524

van der Veen, C. J. & ISMASS Members 2007. A need for more realistic ice-sheet models. SCAR Report 30. SCAR, Cambridge. 27pp.

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

Walker, R. T., T. K. Dupont, B. R. Parizek, and R. B. Alley. 2008. Effects of basal-melting distribution on the retreat of ice-shelf grounding lines. *Geophys. Res. Lett.*, 35, L17503, doi:10.1029/2008GL034947.

Weertman, J. 1974. Stability of the junction of an ice sheet and an ice shelf. Journal of Glaciology, 35, 68-80

Wilson, D. S., and B. P. Luyendyk 2009. West Antarctic paleotopography estimated at the Eocene-Oligocene climate transition, Geophys. Res. Lett., 36, L16302, doi:10.1029/2009GL039297.