Neogene perspectives on the stability of the West Antarctic Ice Sheet

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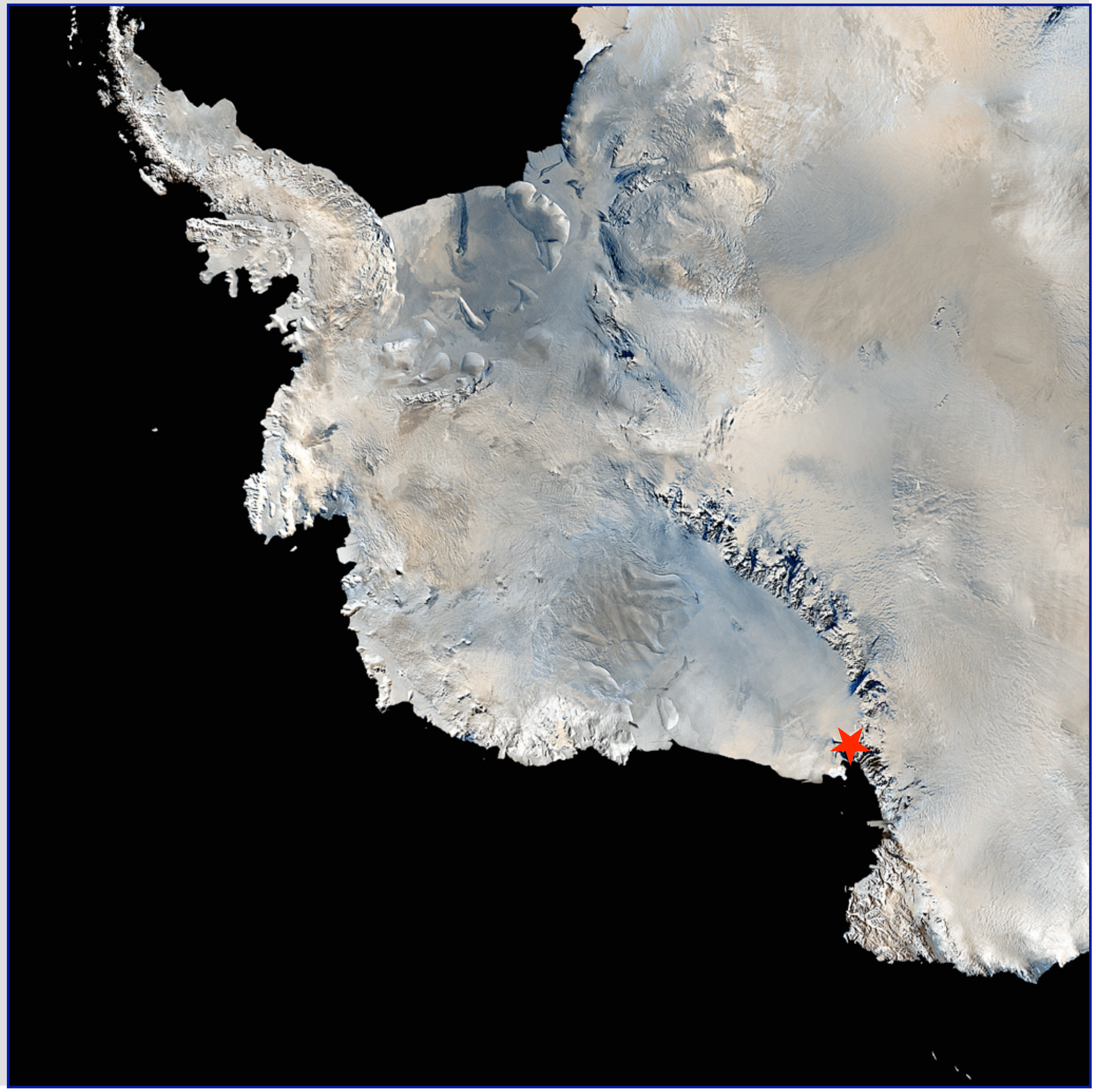
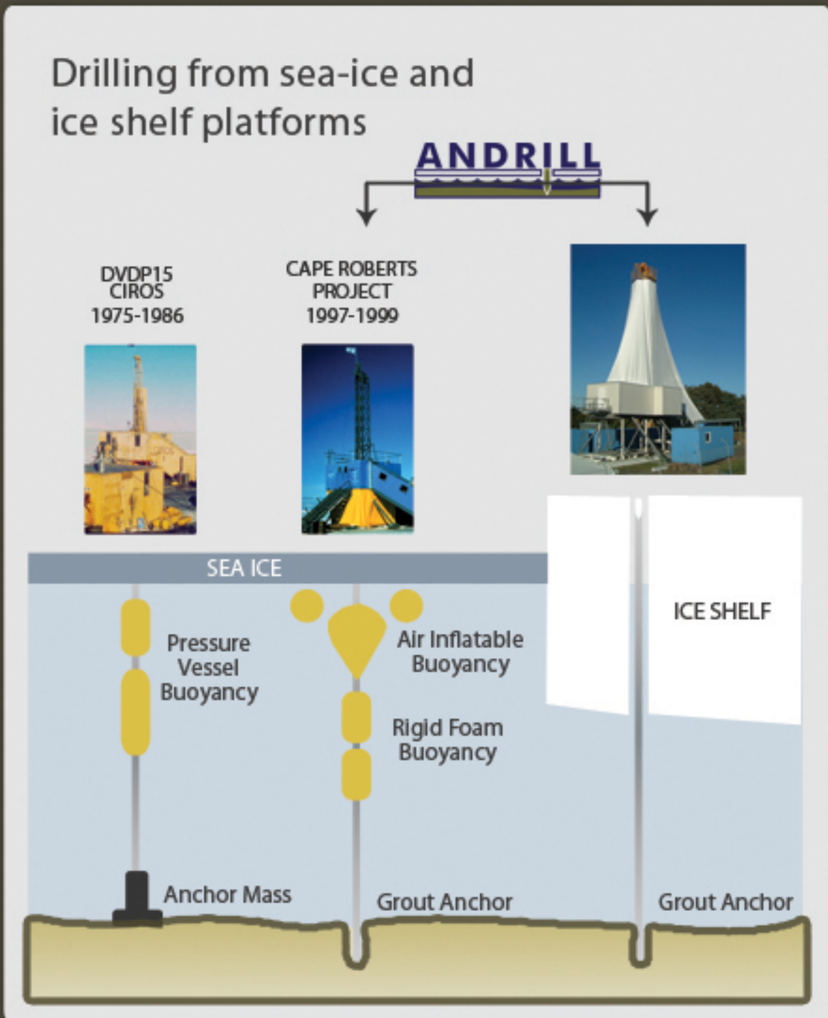
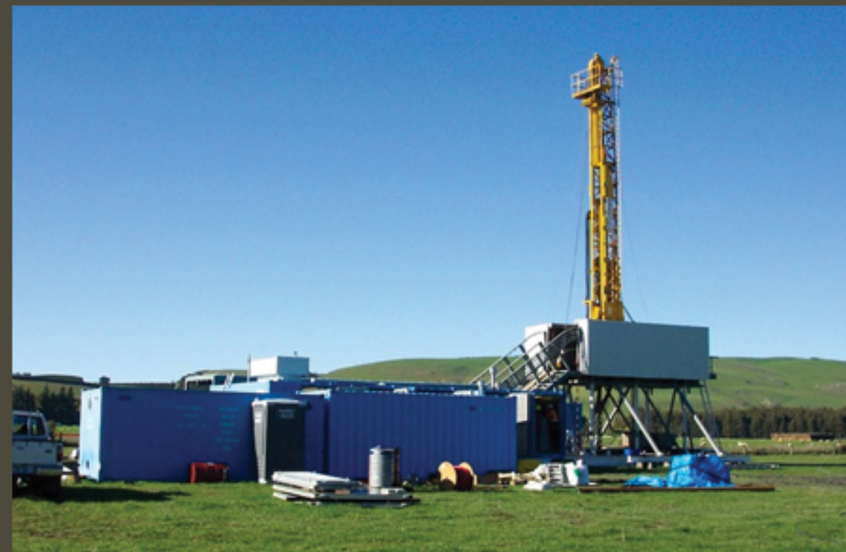
ANtarctic DRILLing

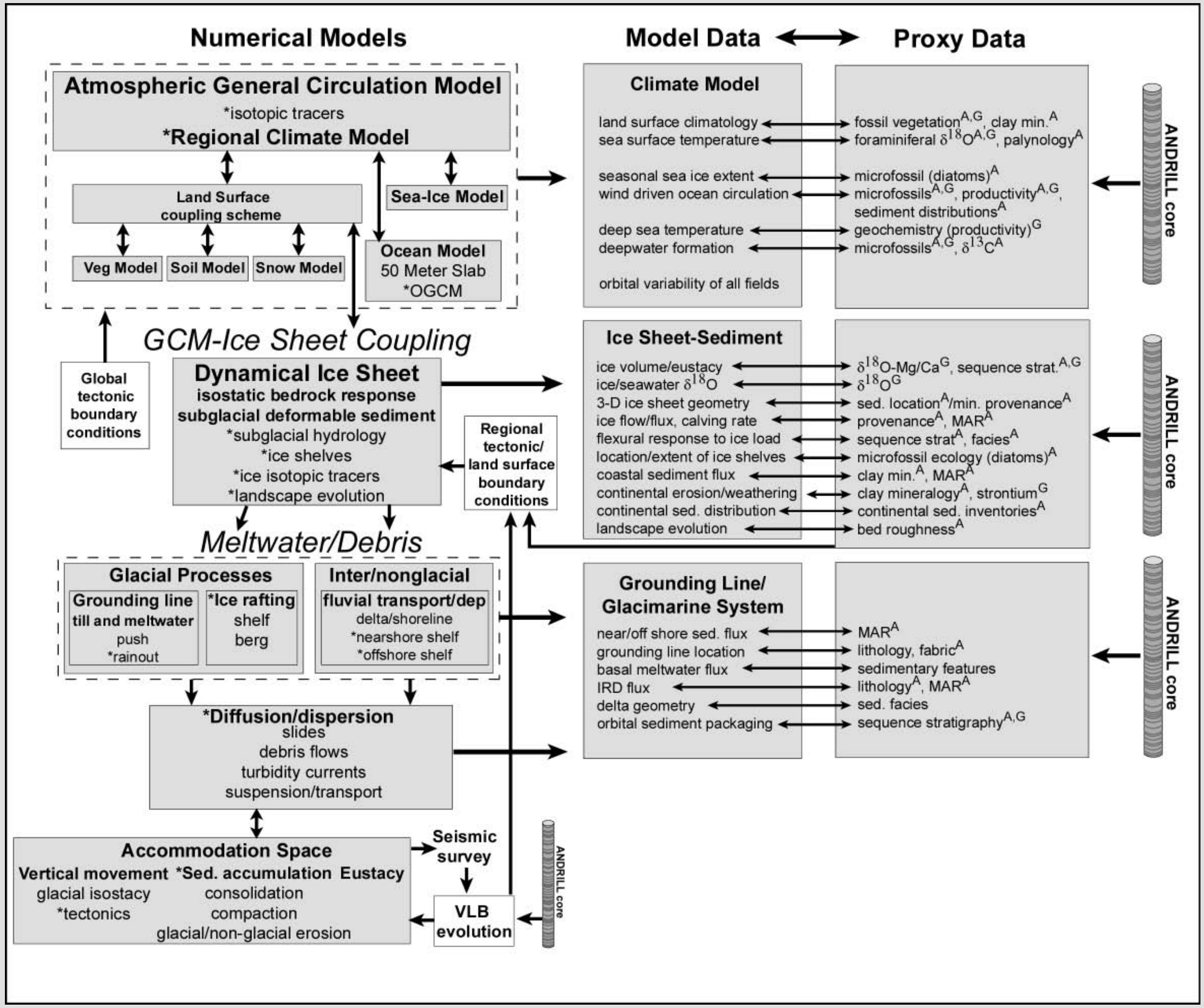


DRILLING TECHNOLOGY





ANDRILL modeling and data comparisons



Outline

- Background
  - EAIS vs. WAIS
  - Grounding-line instability, ice shelf buttressing

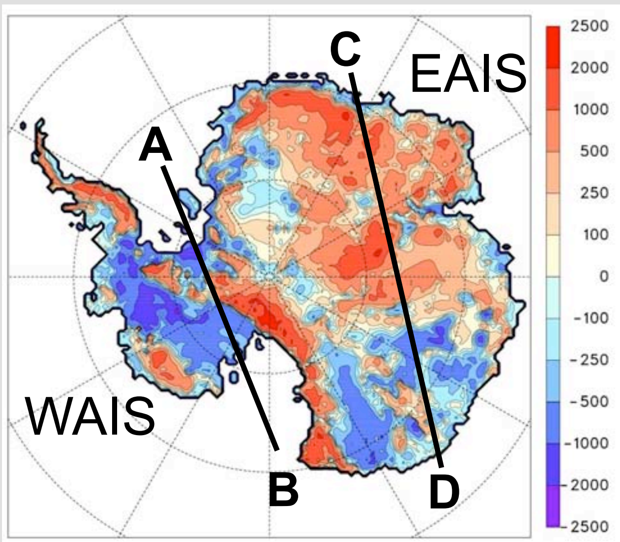
- Ice sheet model applied to last 5 million years
  - Model features
  - Comparisons with new ANDRILL record

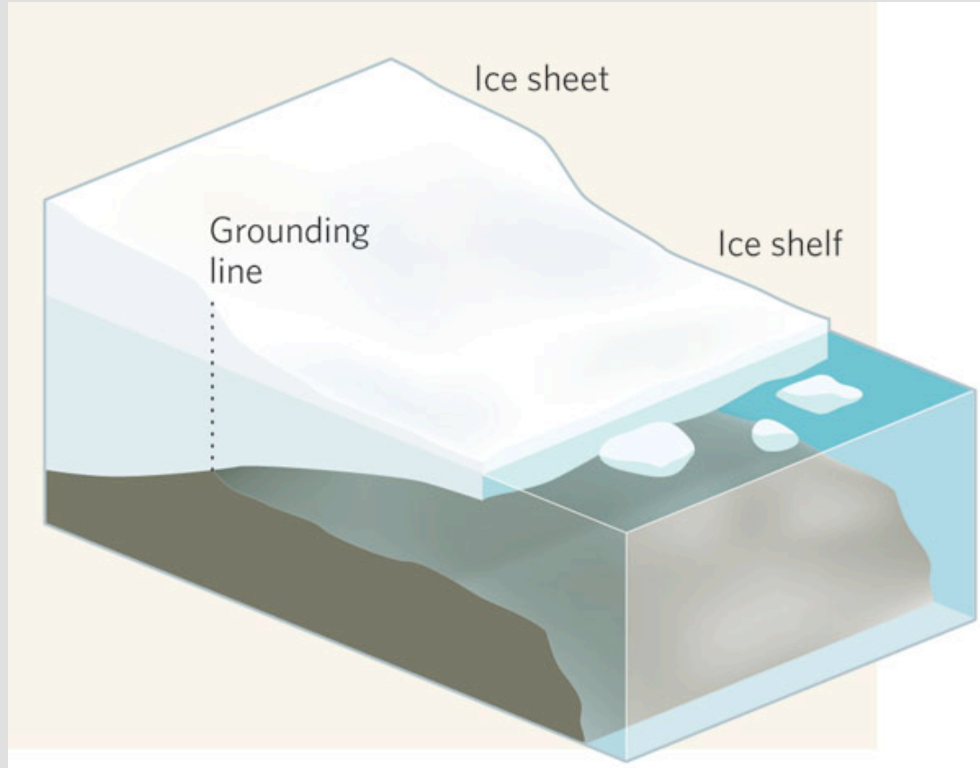
- EAIS vs. WAIS hysteresis and Pleistocene sea level records
  - New GCM and nested GCM-RCM simulations

- Same ice model run into future
  - With prescribed increases in sub-ice-shelf oceanic melting
  - Explore envelopes of WAIS retreat

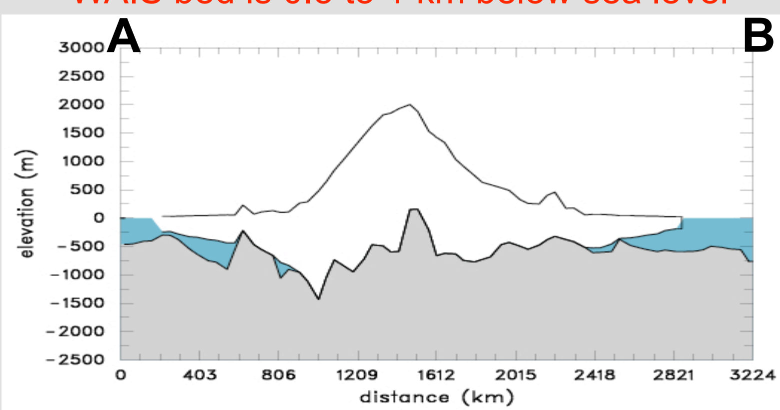
East versus West Antarctic ice sheets

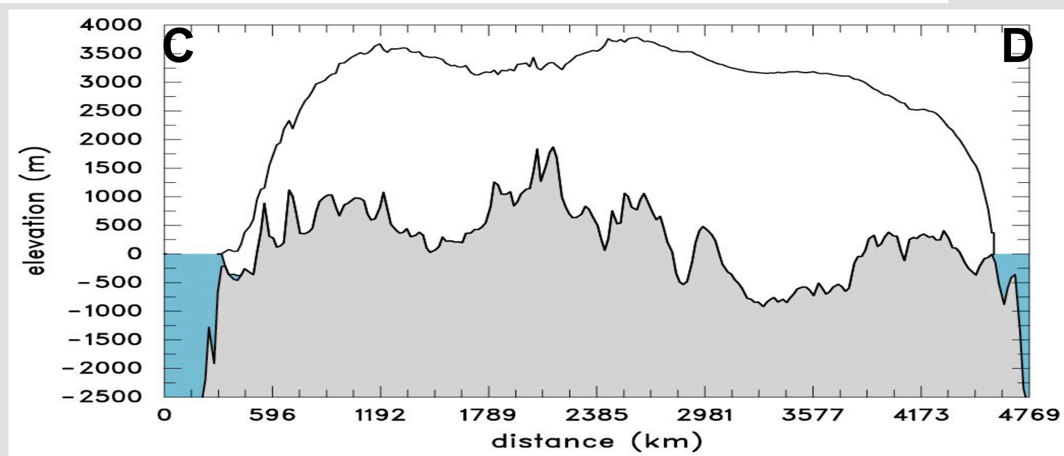
Bedrock Elevations (BEDMAP)



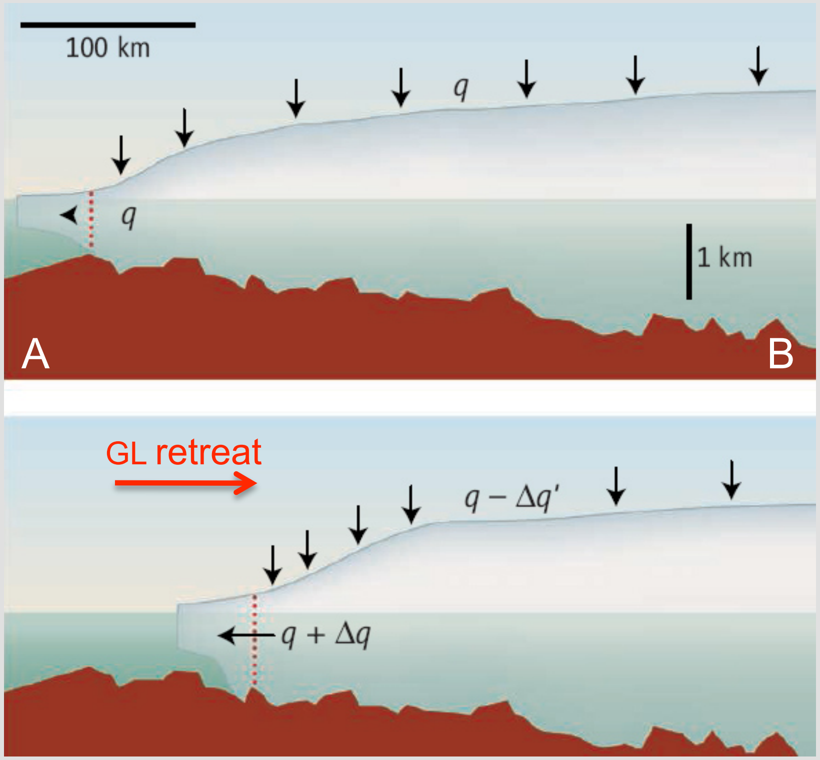


WAIS bed is 0.5 to 1 km below sea level



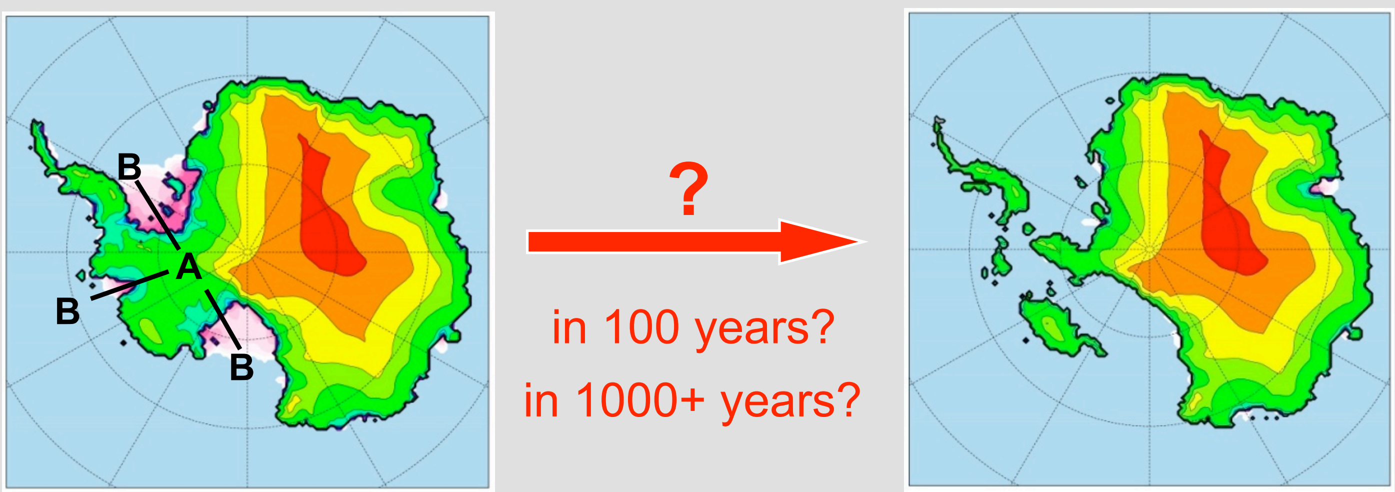


Grounding-Line Retreat Instability



- Ice velocities across the grounding line increase strongly with g.l. depth.
- So, if the bed deepens upstream from the grounding line…
- then possibility of runaway retreat !

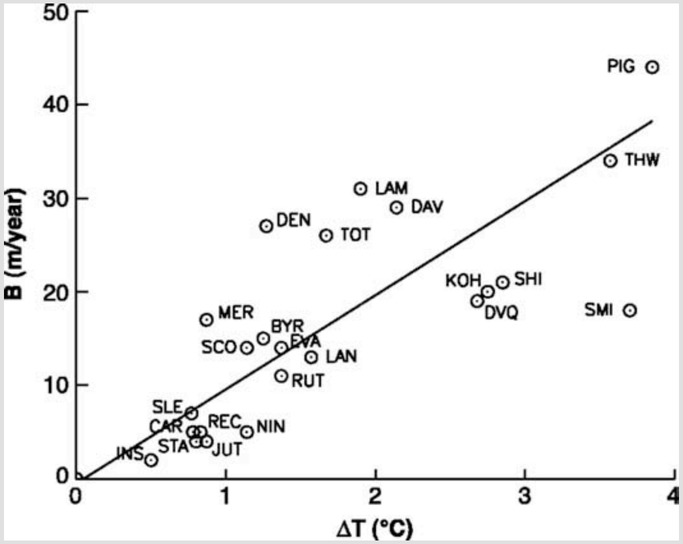
Weertman (1976, Nature); Mercer (1978, Nature); Schoof (2007, JGR)



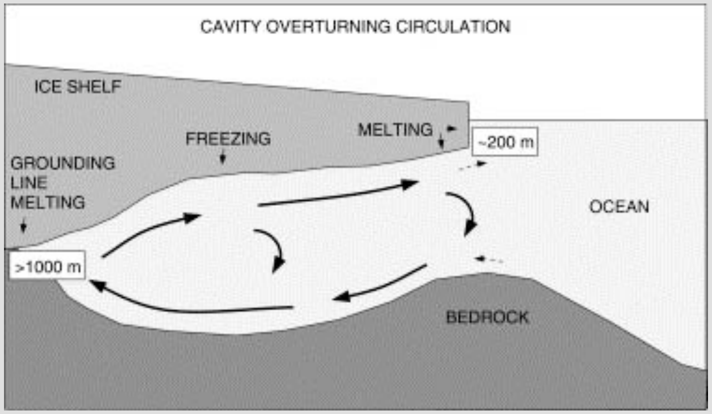
Ice shelf-sheet response to ocean warming

Basal ice melt under shelf, at grounding line, and grounded ice parameterized according to GCM results and based on observed melt rates (e.g., Rignot, et al., 2002, Shepherd et al., 2004)

ΔT:melt rate = 1ºC:10 myr^{-1}

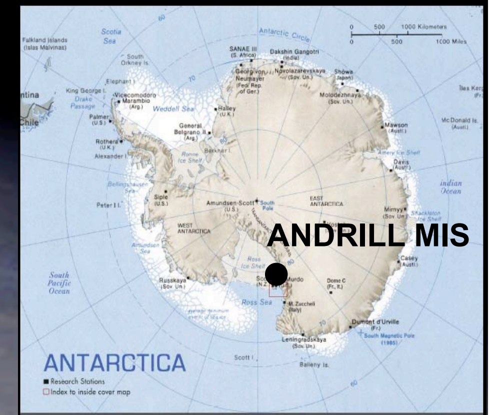


Rignot and Jacobs, 2002; Shepherd et al., 2004

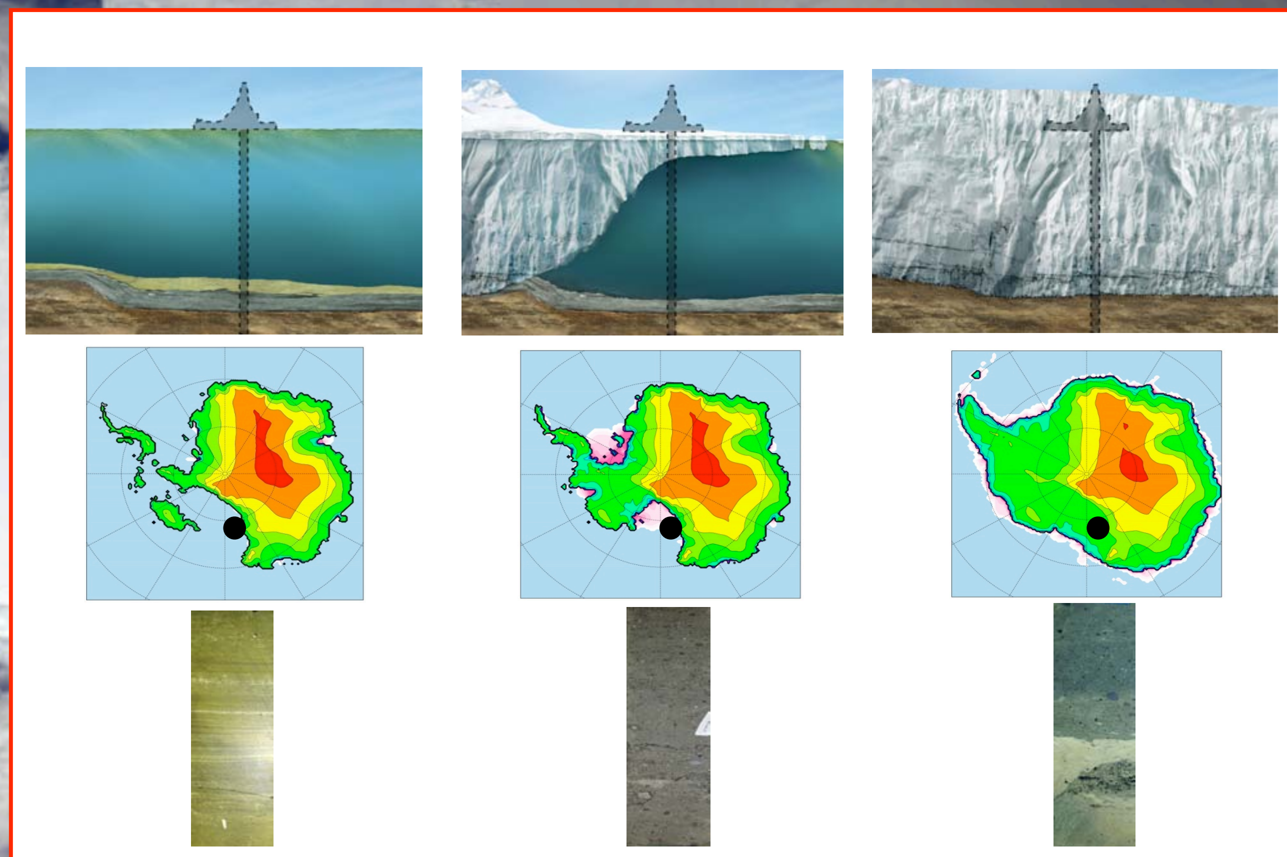


Beckman and Goose, 2003; Holland et al., 2008

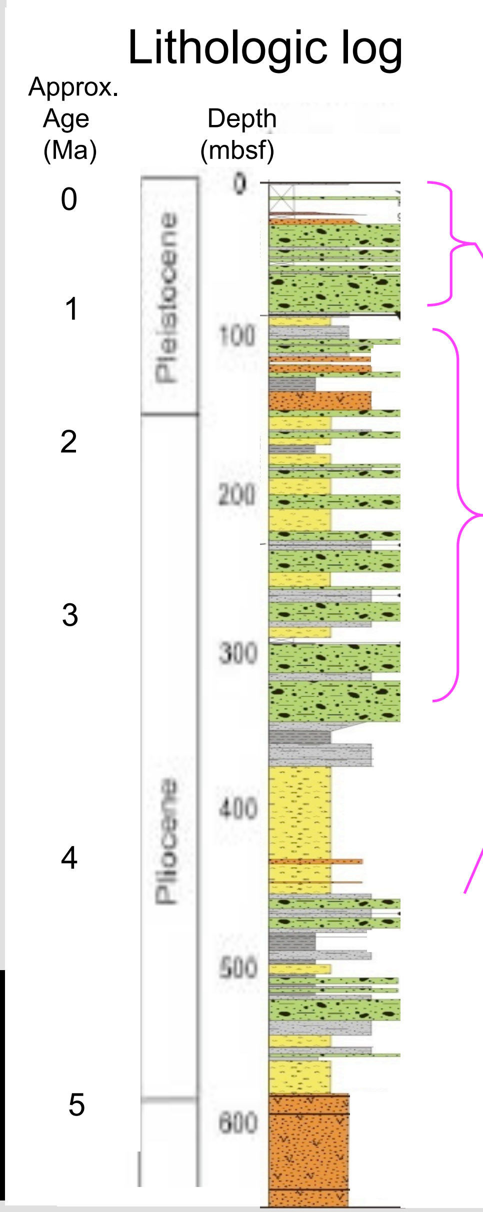
Past WAIS behavior?



- ANDRILL(2006-2007) platform on McMurdo Ice Shelf
- Recovered ~1200 m of sediment core, ~14 Ma to present
- Best proximal record of ice sheet variations through last few million years



ANDRILL MIS Core, upper 600 m (~0-5 Ma)



Yellow = open ocean (diatomite)

Green = grounded ice (diamictite)

Grey = proximal GL (mud/silt/sand)

Orange = volcanic

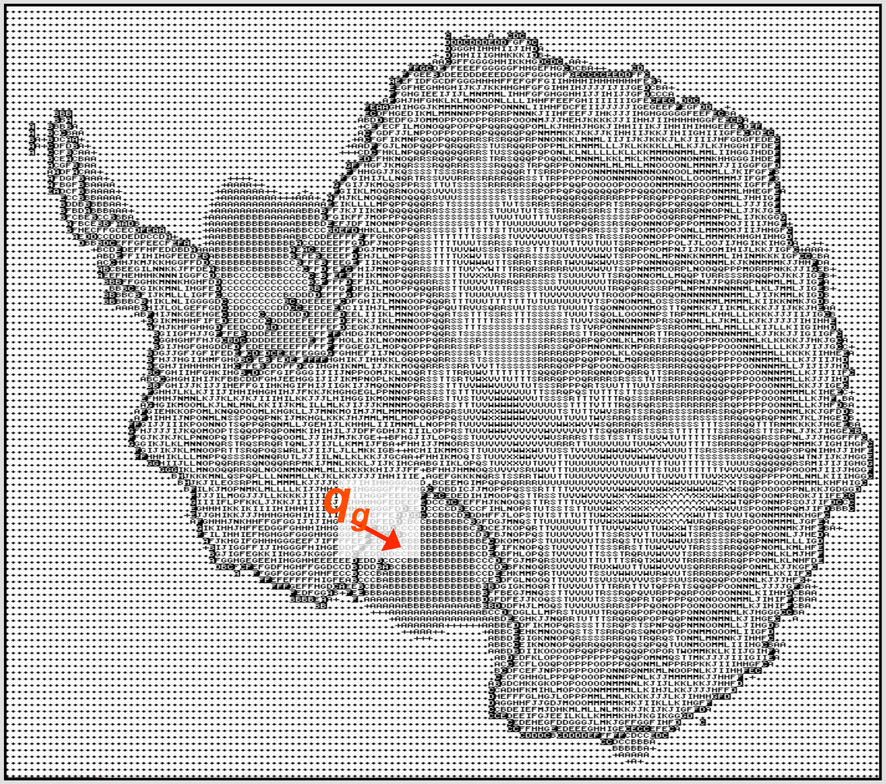
Main Results

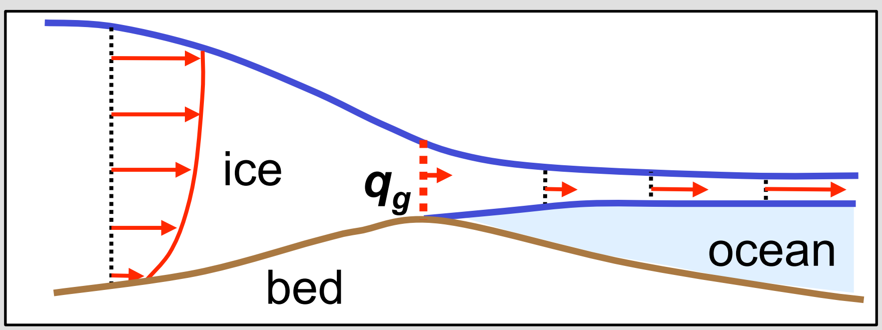
- WAIS has been *dynamic,* advancing and retreating on ~40 kyr obliquity cycles
- Long-term trends:
  - Modern glacials, 1 to 0 Ma
  - Cooling transition, 3 to 1.5 Ma
  - Warmest in early Pliocene, extended interglacials, 5 to 3.5 Ma

Naish et al., Nature., 2009

New features in 3-D Ice Sheet Model

See Pollard and DeConto, 2007; 2009





Predicts ice thickness, temperature, bedrock elevation. 40-20 km grid size. Follows standard model lineage…

PLUS:

1) Heuristic combination of the 2 scaled equations for shearing (grounded interior) and stretching (floating/stream) ice flow

2) Nested grids (allowing high resolution (5-10 km) over “sensitive” regions

3) C. Schoof’s (2007, JGR) parameterization of flux across grounding lines (q_g). Allows realistic grounding-line migration and ice-shelf buttressing

$$\boxed{q_g = u_g h_g = A\, h_g^{\left(\frac{m+n+3}{m+1}\right)}}$$

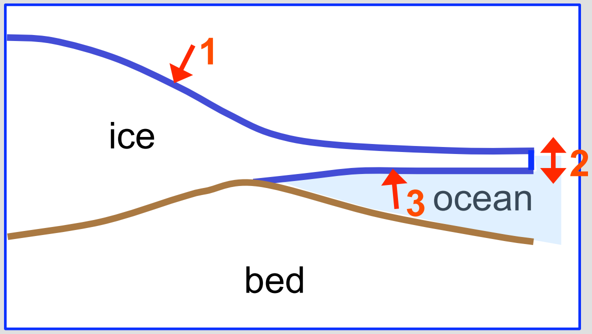
h_g = thickness, u_g = velocity, q_g = flux

4) Past variations of parameterized forcing
   - sea level
   - surface mass balance and temperature
   - sub-ice-shelf oceanic melt rate

   are assumed proportional to benthic $\delta^{18}O$

Climate forcing needed for last 5 million years

- Three forcing fields must be provided to drive the ice sheet-shelf model:
  1. Surface mass balance
  2. Sea level
  3. Sub-ice-shelf oceanic melt



- Use empirical parameterizations for modern (1-3), and past (1-2)

- Past variations of sub-ice oceanic melting (3) are assumed to be controlled by far-field changes*, proportional to deep-sea-core benthic $\delta^{18}O$ record.

M_p (protected inner shelf), M_e (exposed shelf), M_d (deep ocean)
Modern [.1, 5, 5]; Max glacial [0, 0, 2]; Max interglacial [2, 10, 10]

Modern

$$T = T_m + 34.46 - .00914\, h_s - .68775|\phi| + .1\,\Delta q_a + 10\Delta s/125$$

$$P = 1.5\;\; 2^{(T-T_m)/10}$$

$$M = (1-z_d)\left[(1-z_e)M_p + z_e\, M_e\right] + z_d\, M_d$$

$$z_d = \max\left[\,0, \min\left[1, (h_b - 1400)/200\,\right]\right]$$

$$z_e = \max\left[\,0, \min\left[1, (A-80)/30\,\right]\right]\; e^{-D/100}$$

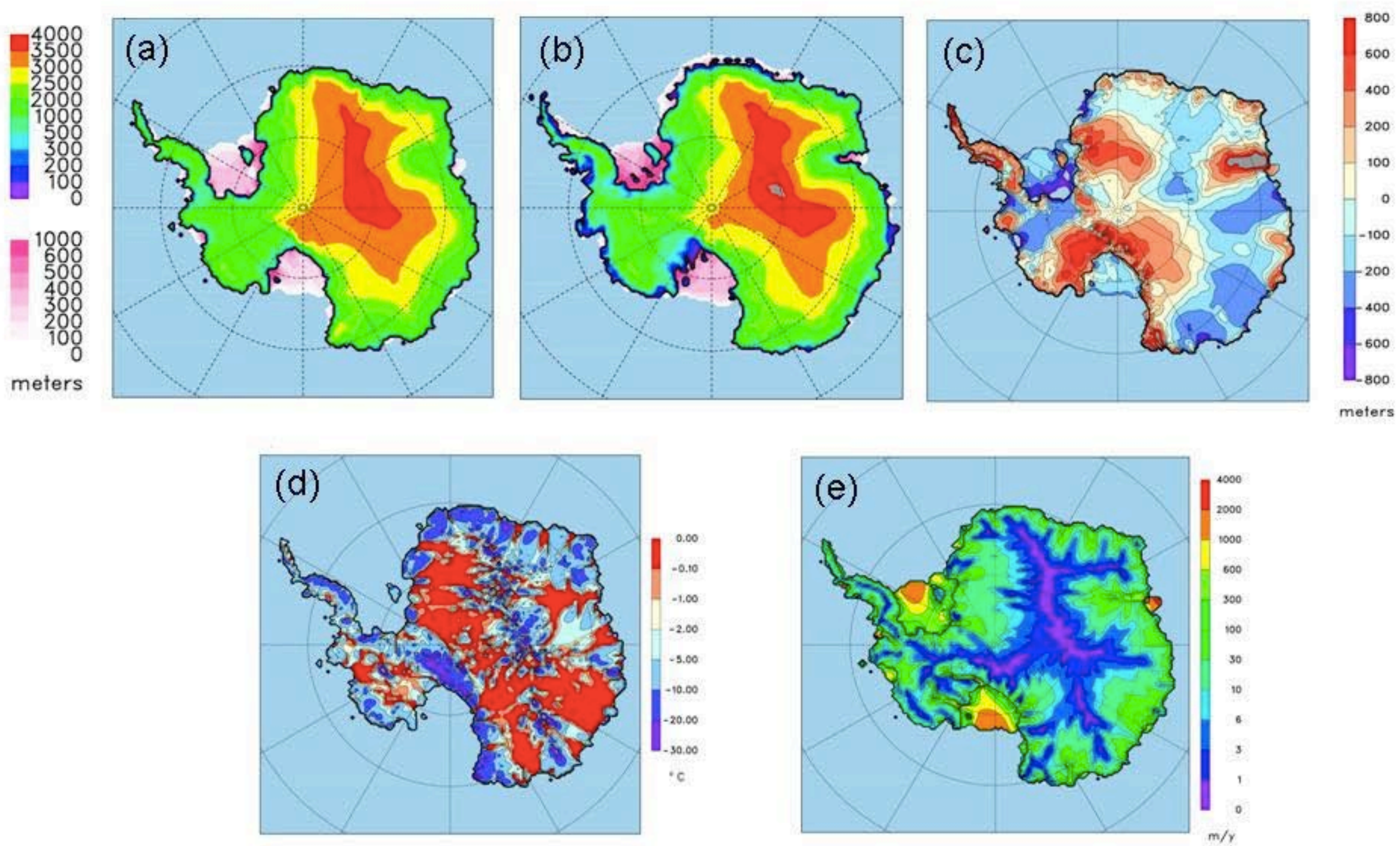
Past

$$w_g = \max\left[\,0,\; \min\left[\,2,\; 1+\Delta s/85 + \max\left(0, \Delta q_j/40\right)\,\right]\right]$$

$$\left[M_p, M_e, M_d\right] = (1-w_g)\left[0,0,2\right] + w_g\left[.1,5,5\right]$$

$$\left[M_p, M_e, M_d\right] = (2-w_g)\left[.1,5,5\right] + (w_g - 1)\left[2,10,10\right]$$

Model Simulation (present day):

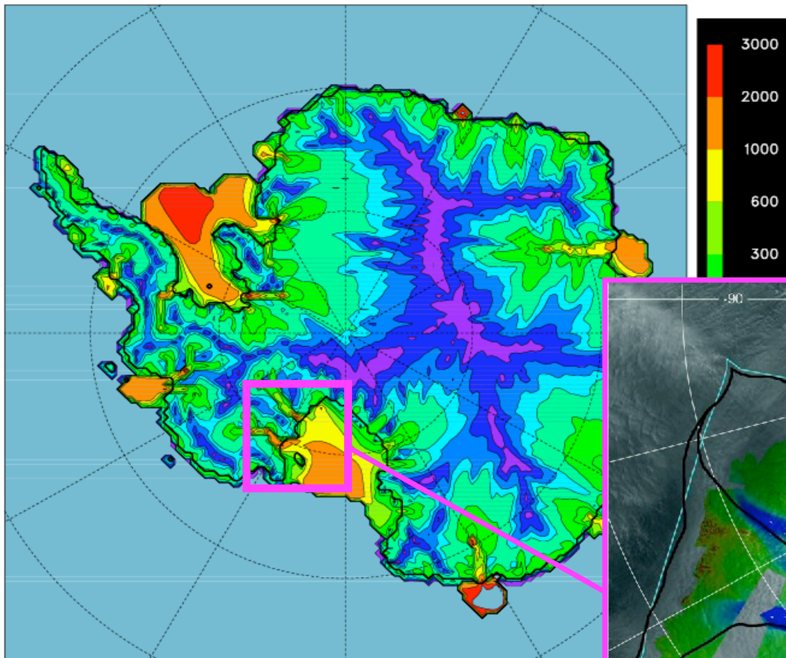


Pollard and DeConto, 2007; 2009

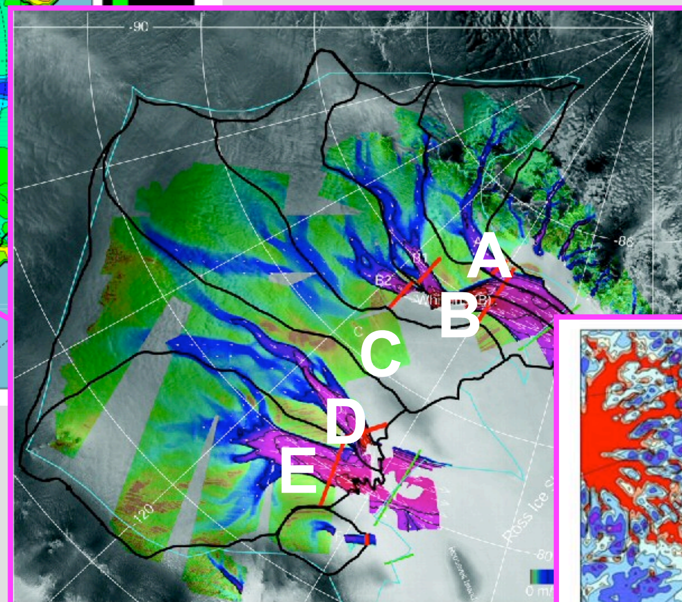
Supplementary Figure S5

Model resolves WAIS ice stream networks

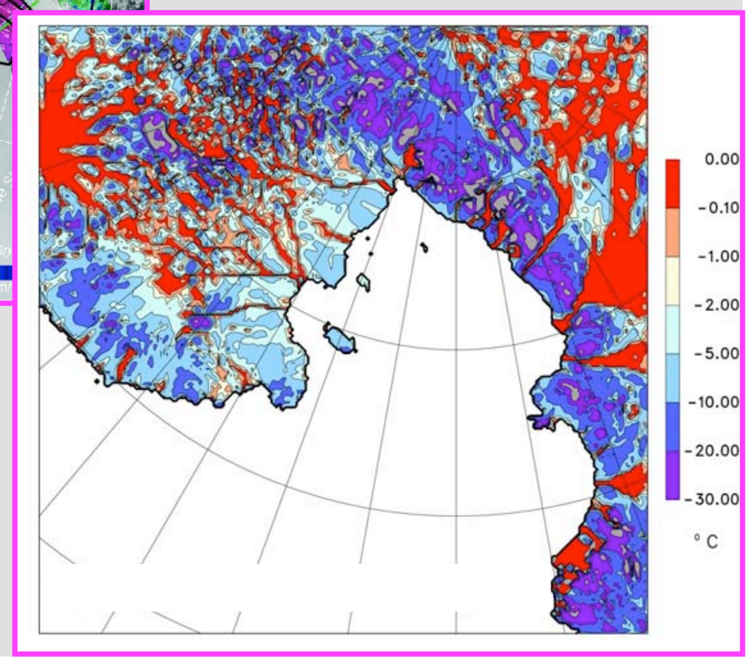
Model surface ice speeds (m/y), 40 km grid

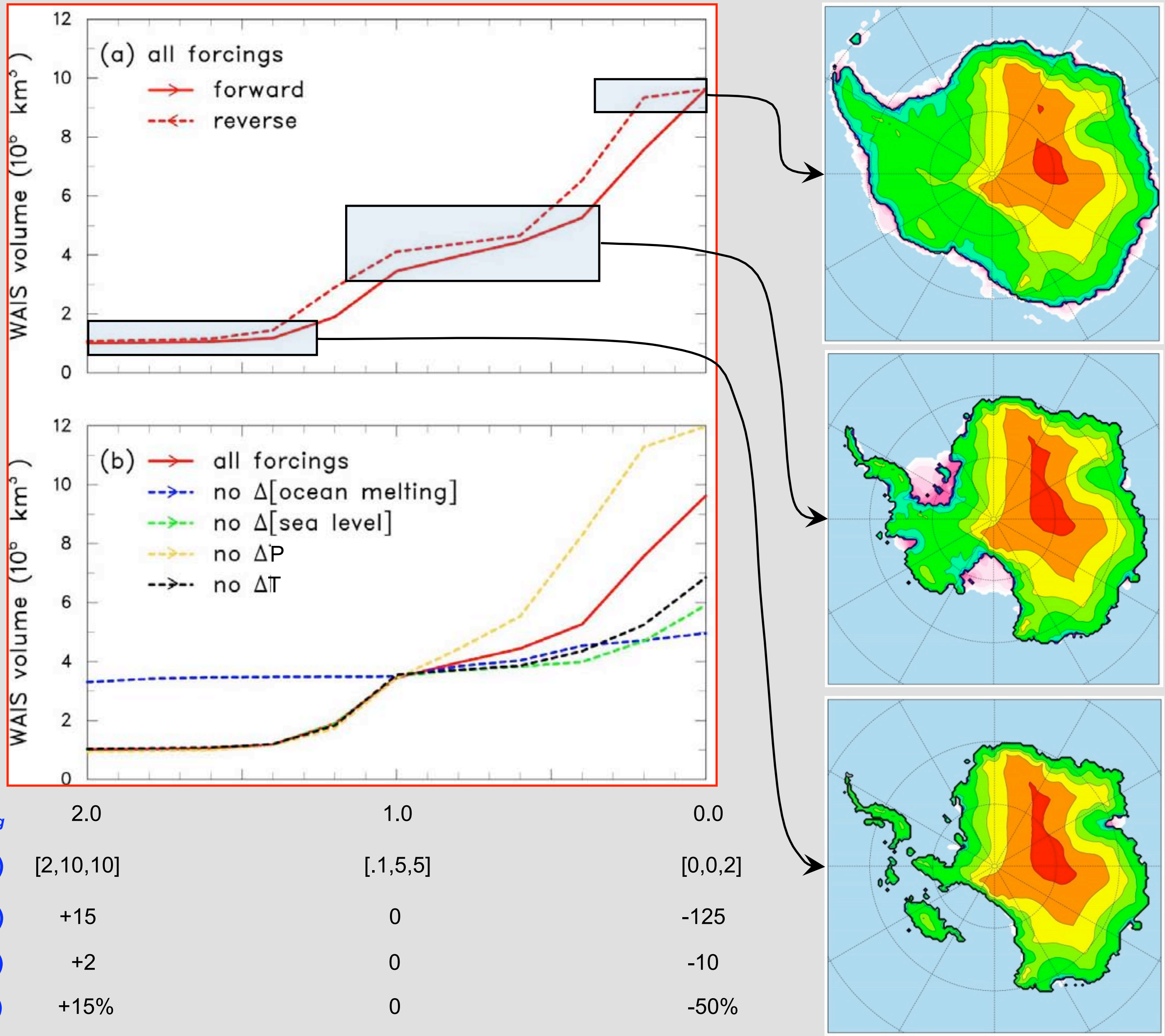


Observed speeds (I. Joughin, U. Washington, in C. Raymond, Science, 2002)



Nested model, 10 km grid, basal temperatures





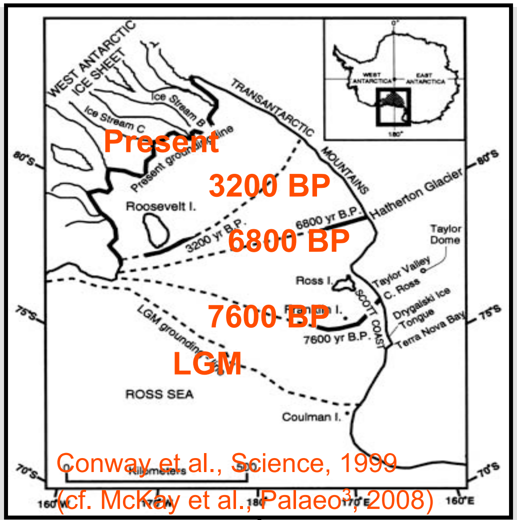
index w_g	2.0	1.0	0.0
ocean melting (m y^{-1})	[2,10,10]	[.1,5,5]	[0,0,2]
Δ [sea level] (m)	+15	0	-125
ΔT (^{o}C)	+2	0	-10
ΔP (%)	+15%	0	-50%
	Extreme Interglacial forcing	**Modern Interglacial forcing**	**Full Glacial forcing**

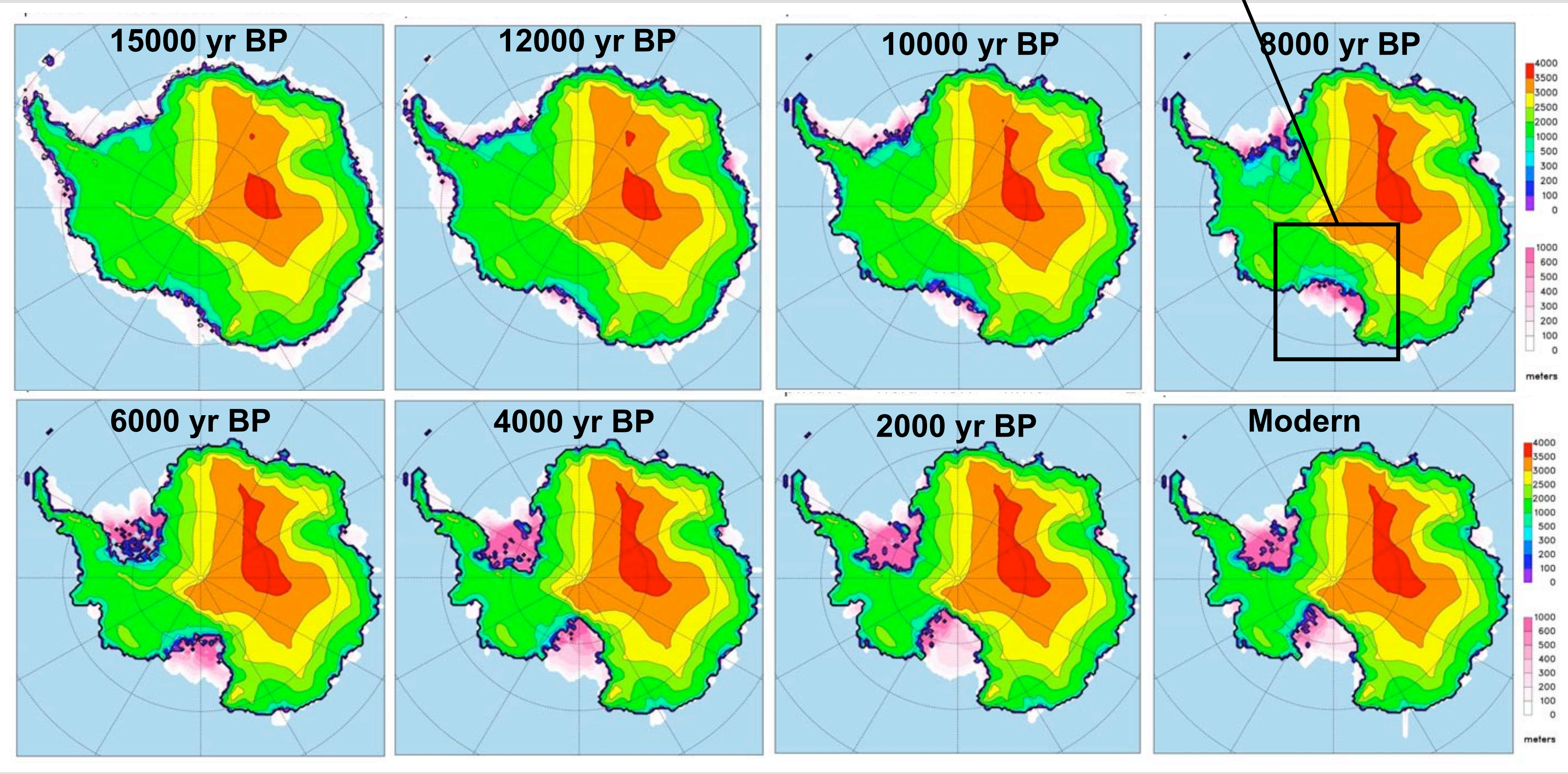
Pollard and DeConto, 2009

Grounding line retreat in Ross Embayment ~15 to 0 ka

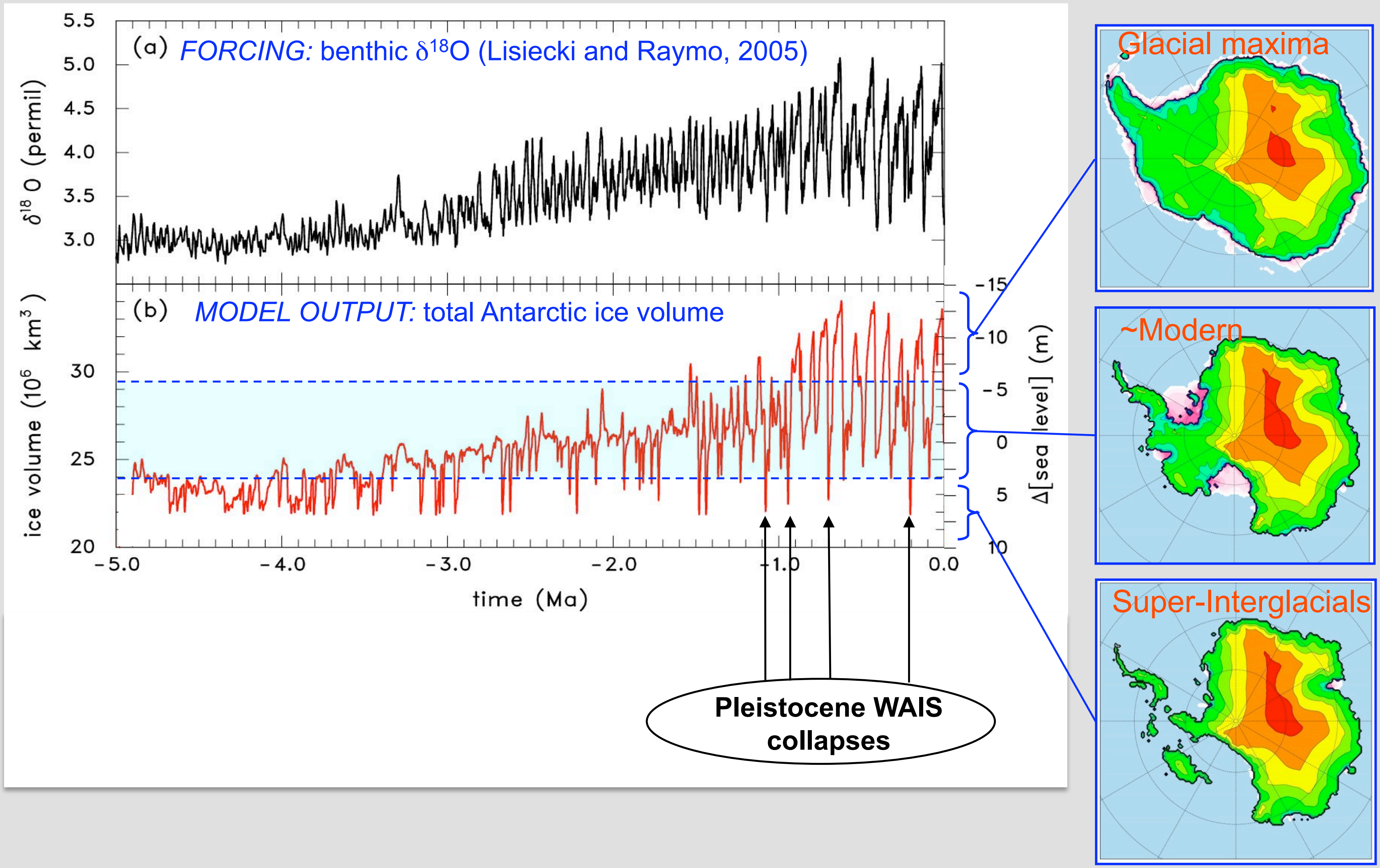
- Good opportunity for model validation
- Need sub-grid ice-shelf pinning for best result

(Previous 3-D models: Budd et al., 1998; Ritz et al., 2001; Huybrechts, 2002; Philippon et al., 2006)

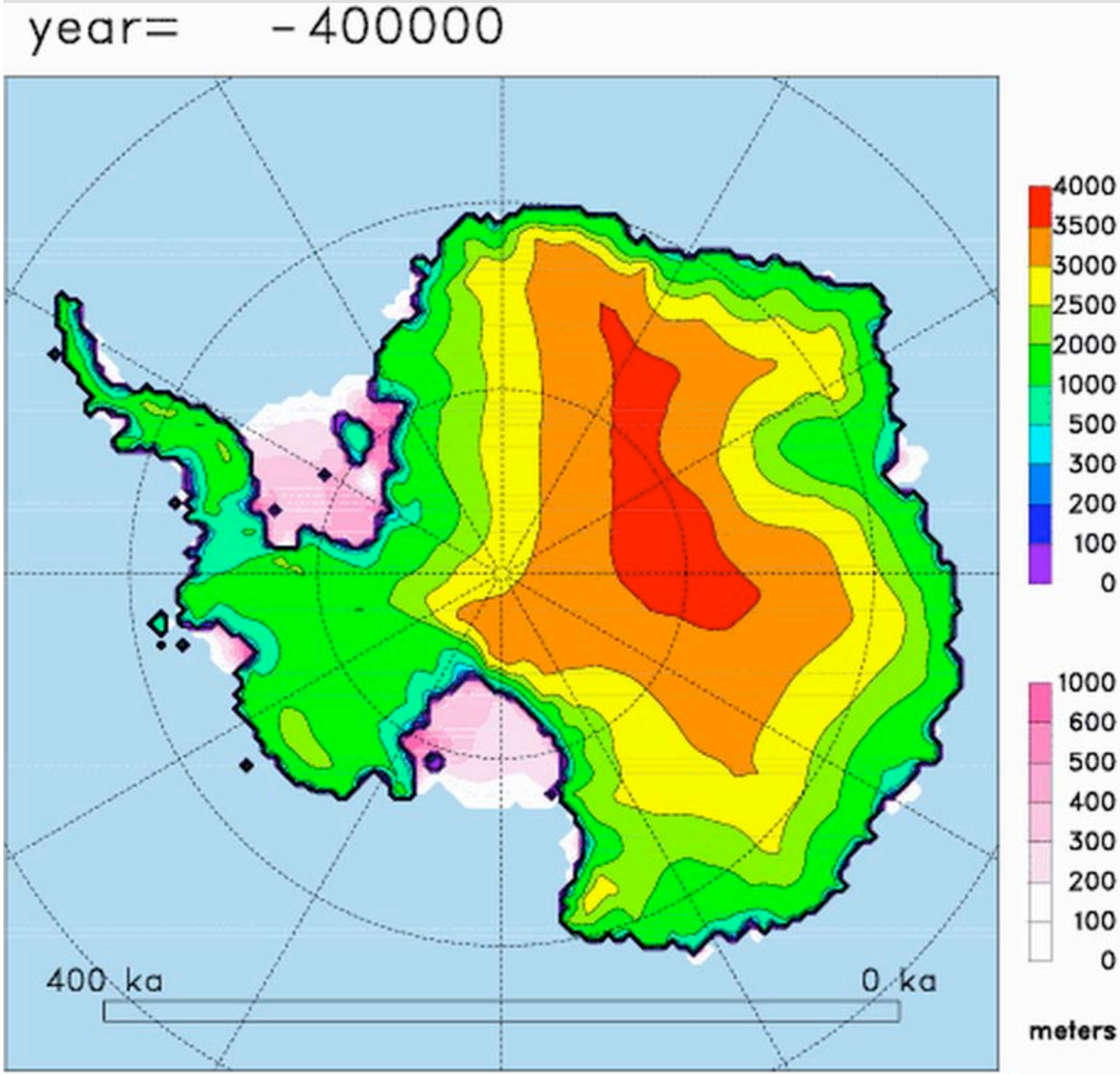


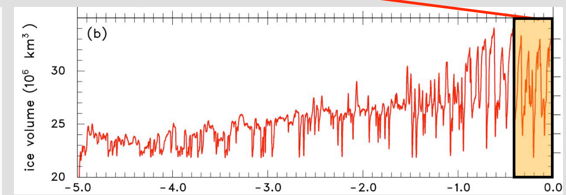


Simulated AIS volume, last 5 million years



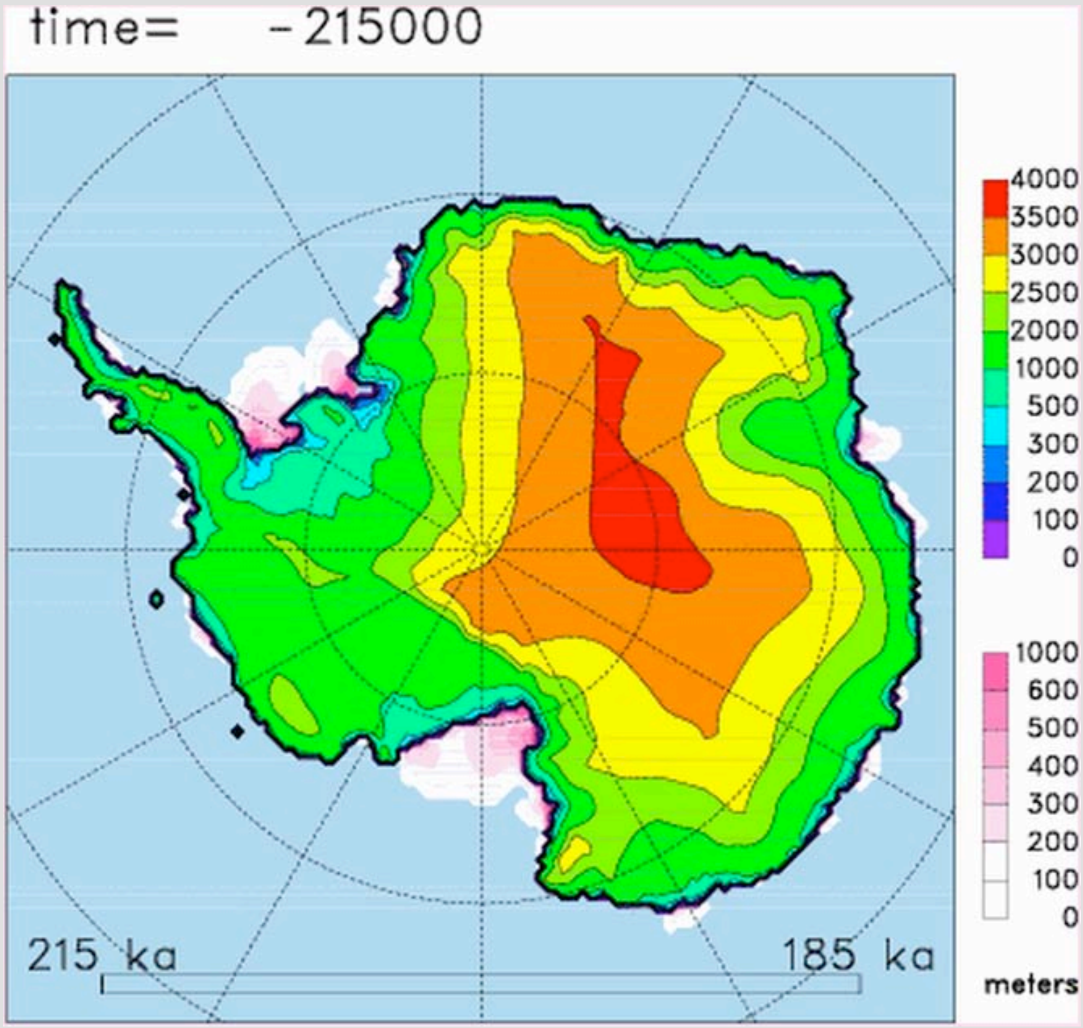
Ice elevation (thickness where floating, last 400 kyrs



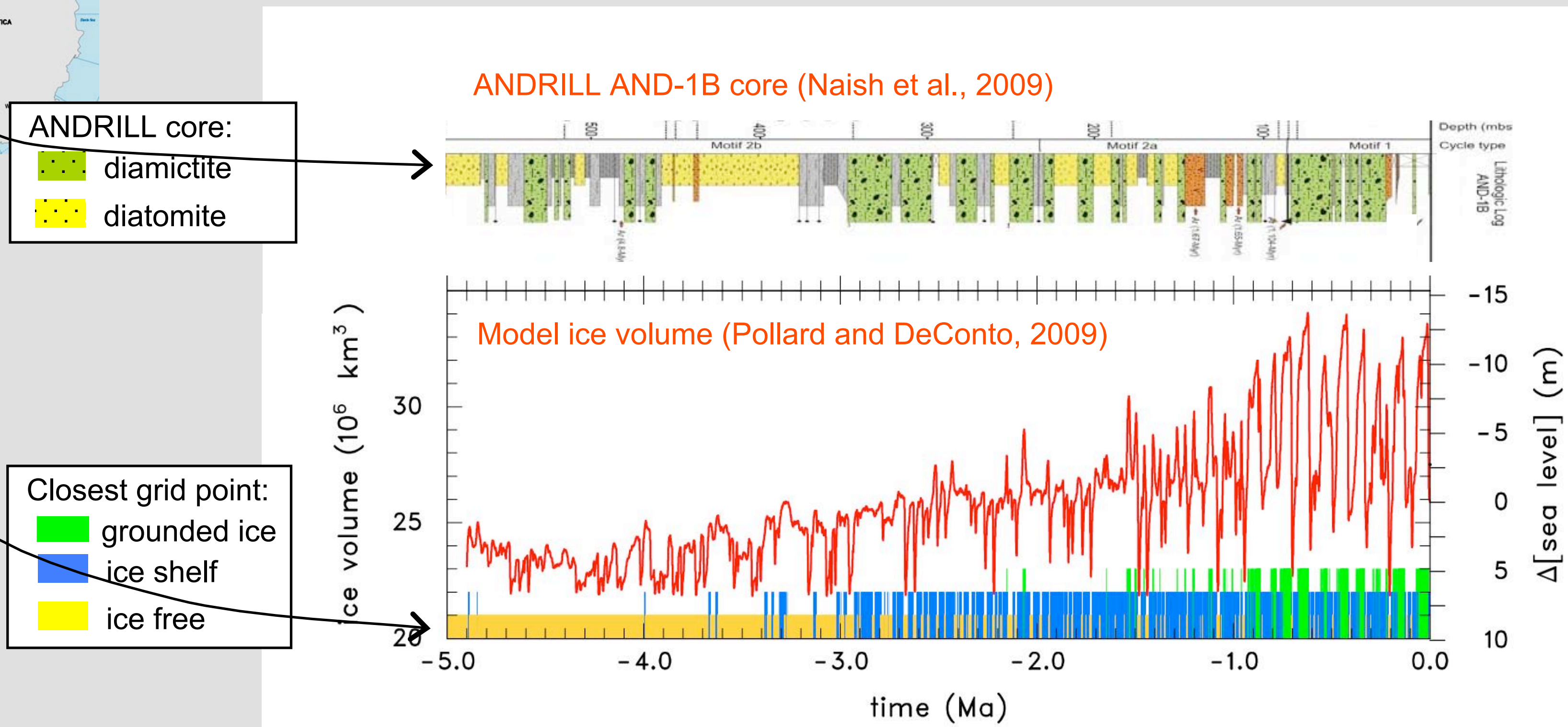


- EAIS is ~stable, WAIS varies
- WAIS retreats are short-lived, sudden
- WAIS sectors vary in unison, “one-dimensionally”

215 to 185 ka


time= -215000
4000
3500
3000
2500
2000
1000
500
300
200
100
0
1000
600
500
400
300
200
100
0
215 ka
185 ka
meters

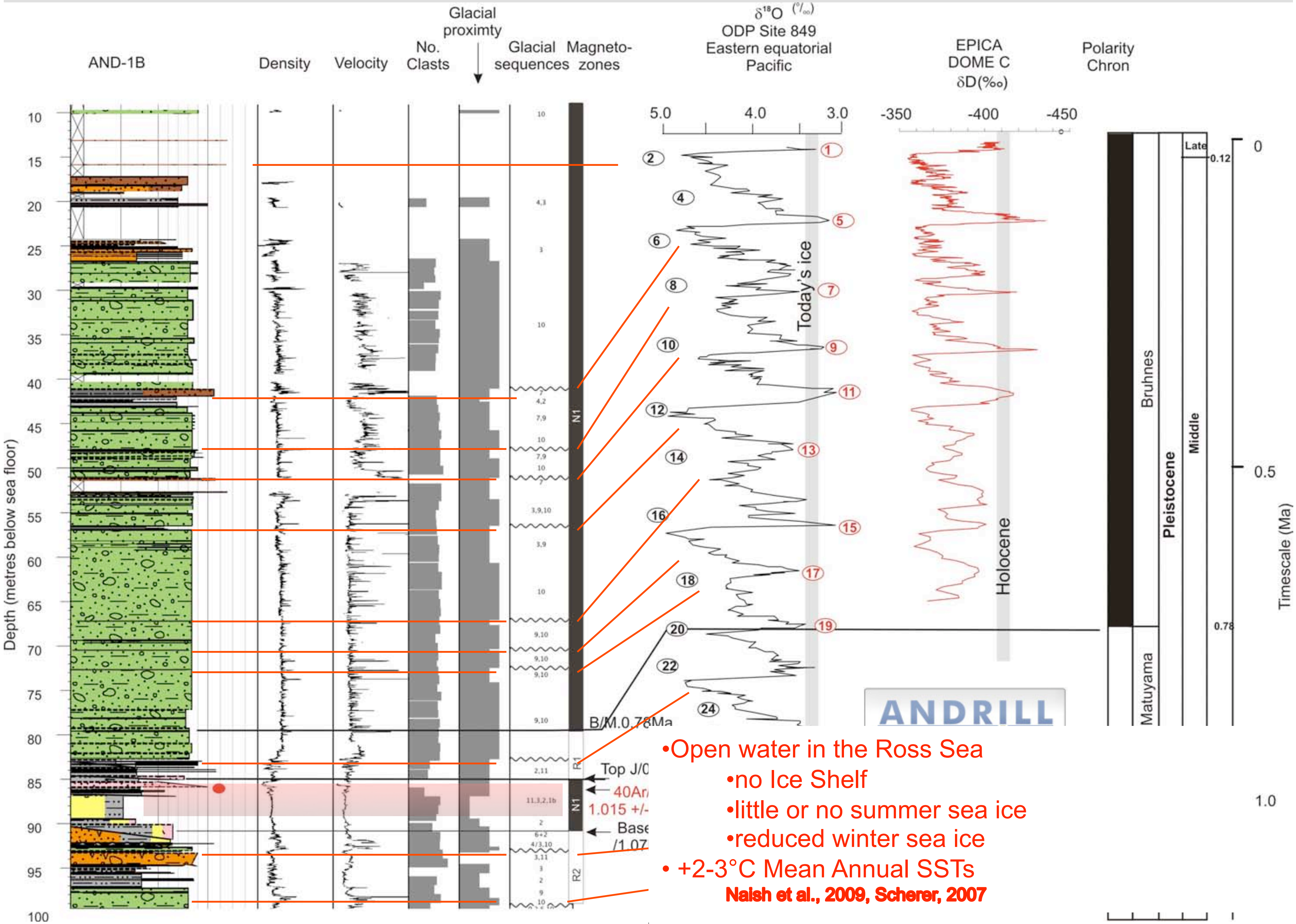
ANDRILL-model comparisons



Closest model grid point and ANDRILL core agree:

- ~5 to 3 Ma: Long periods with open ocean
- ~3 to 1 Ma: Cooling trend
- ~1 to 0 Ma: Current glacial cycles incl. LGM, MIS 31

Pleistocene (1.2-0 Ma), glacial-interglacial variability



•Open water in the Ross Sea

•no Ice Shelf

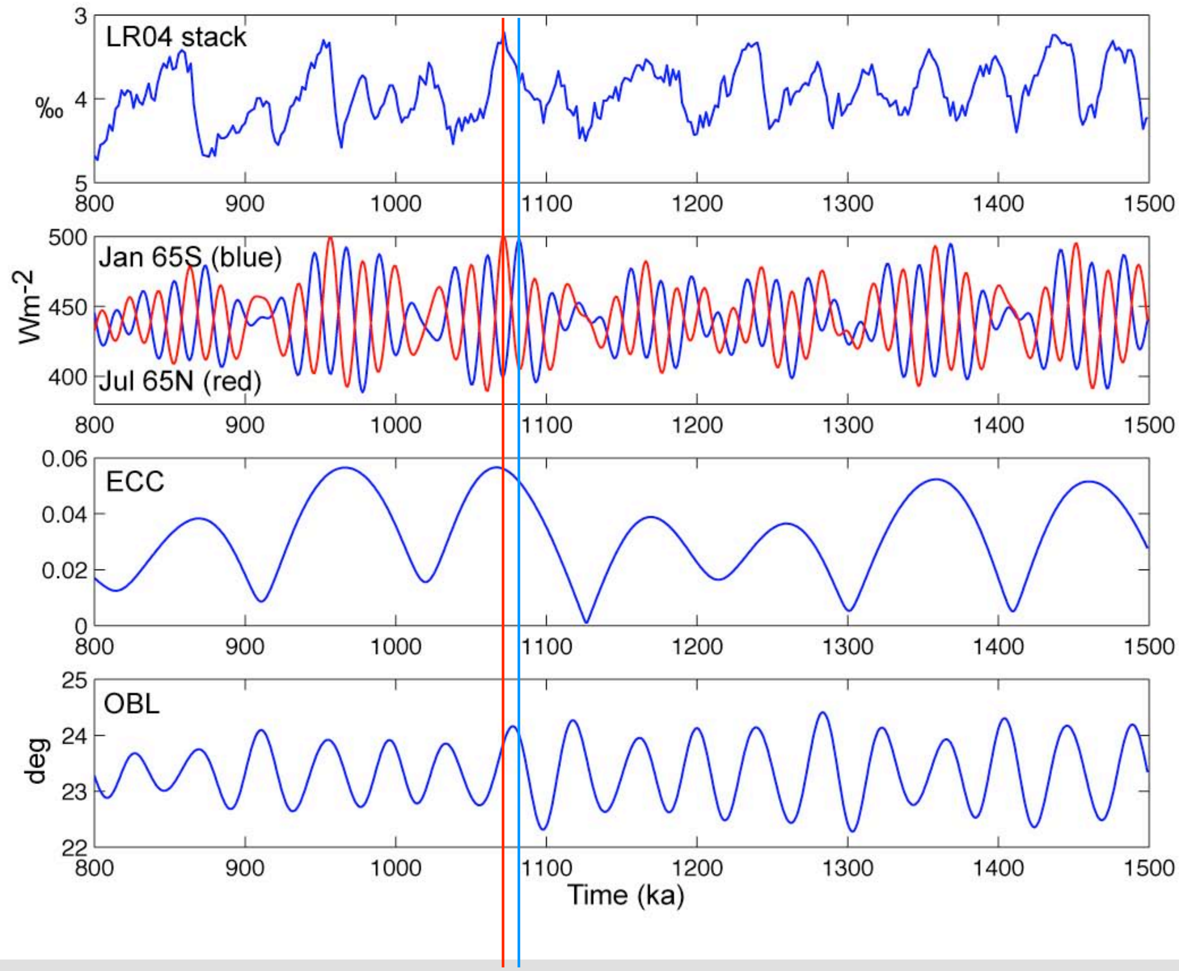
•little or no summer sea ice

•reduced winter sea ice

• +2-3°C Mean Annual SSTs

Naish et al., 2009, Scherer, 2007

MIS 31 orbital parameters



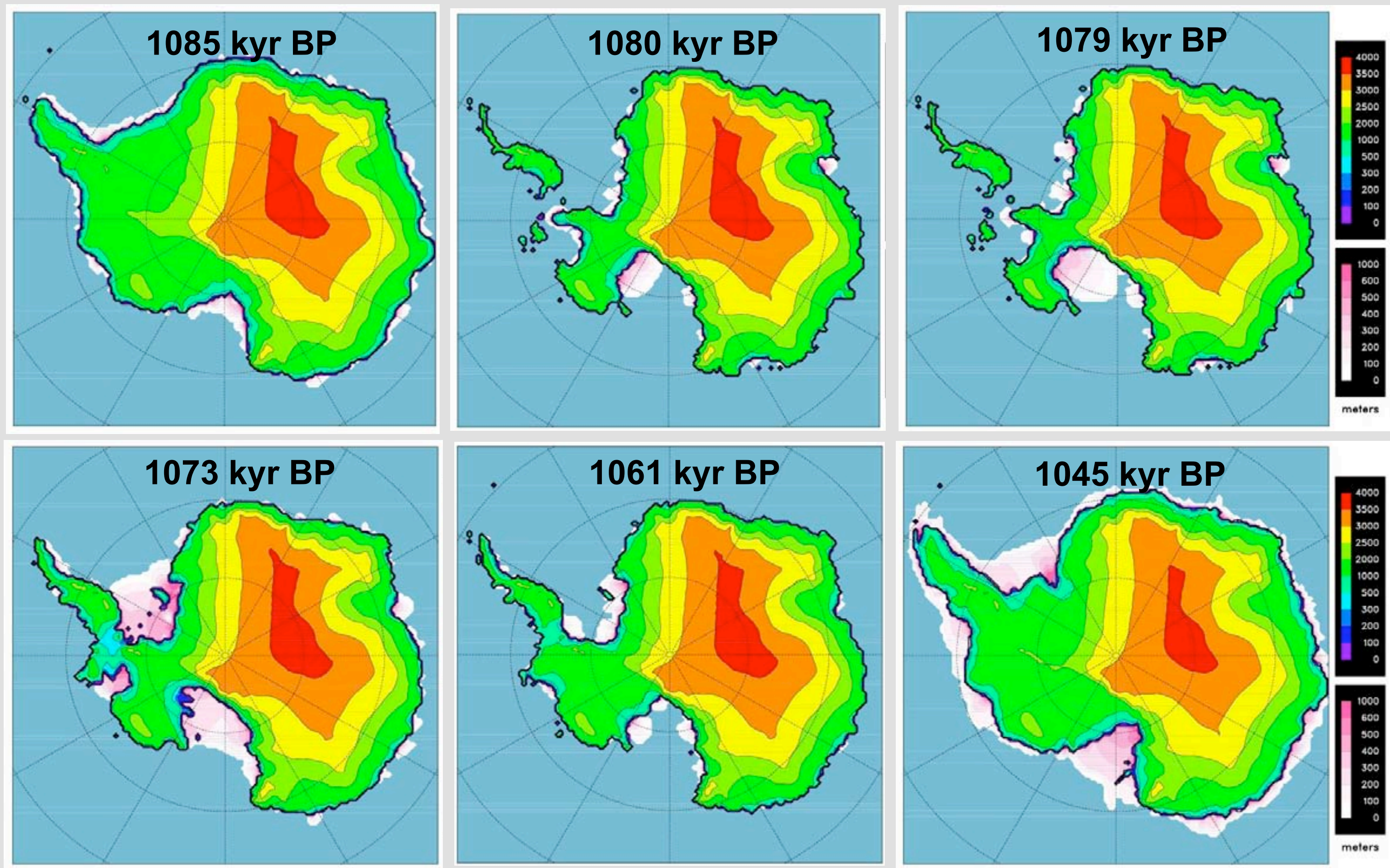
Lisiecki and Raymo, 2005; Laskar, 2004

MIS-31 Simulation

Snapshots through "MIS -31":

Ice elevations (grounded, m) and ice thicknesses (floating, m)

Note drastic retreat of West Antarctic ice ~1080 kyr BP



Pollard and DeConto, 2009; DeConto et al., submitted

1.078 Ma +7m S.L. contribution from Antarctica

A +20 m middle Pleistocene sea-level highstand (Bermuda and the Bahamas) due to partial collapse of Antarctic ice

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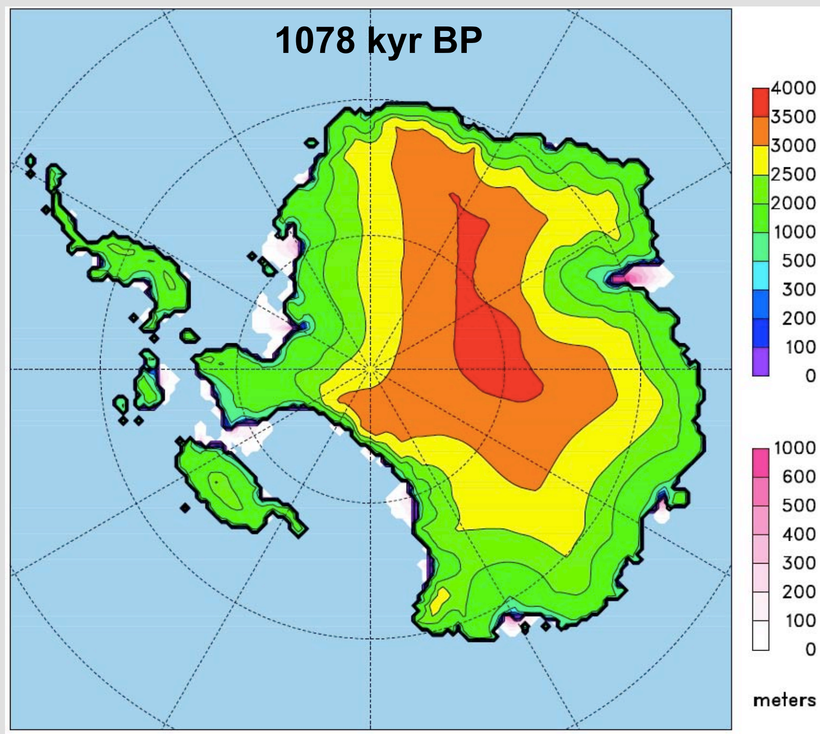
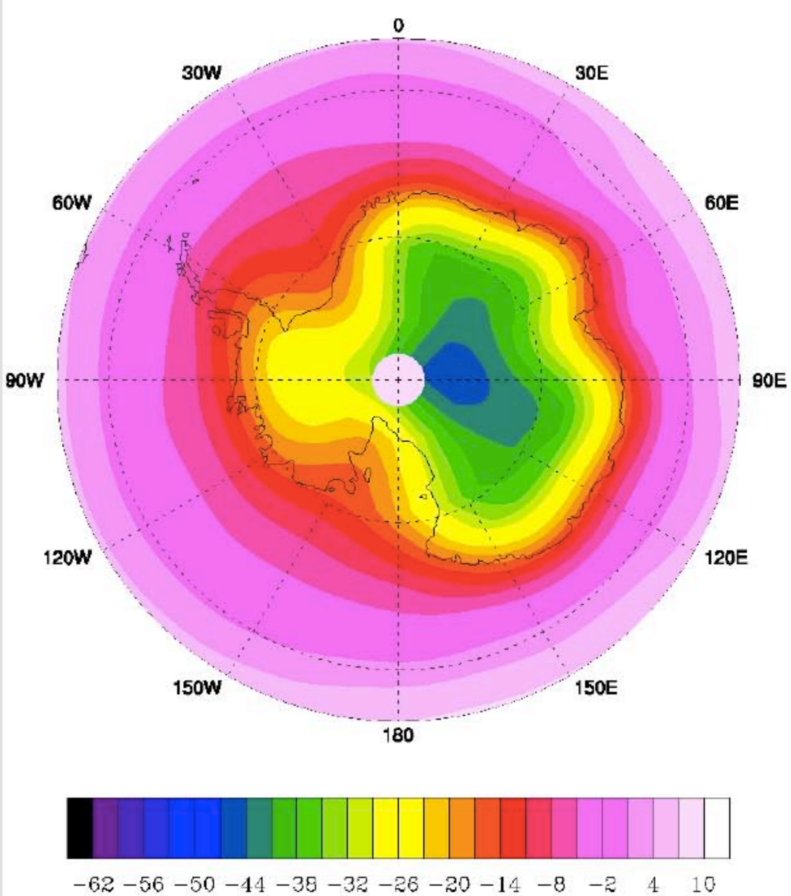
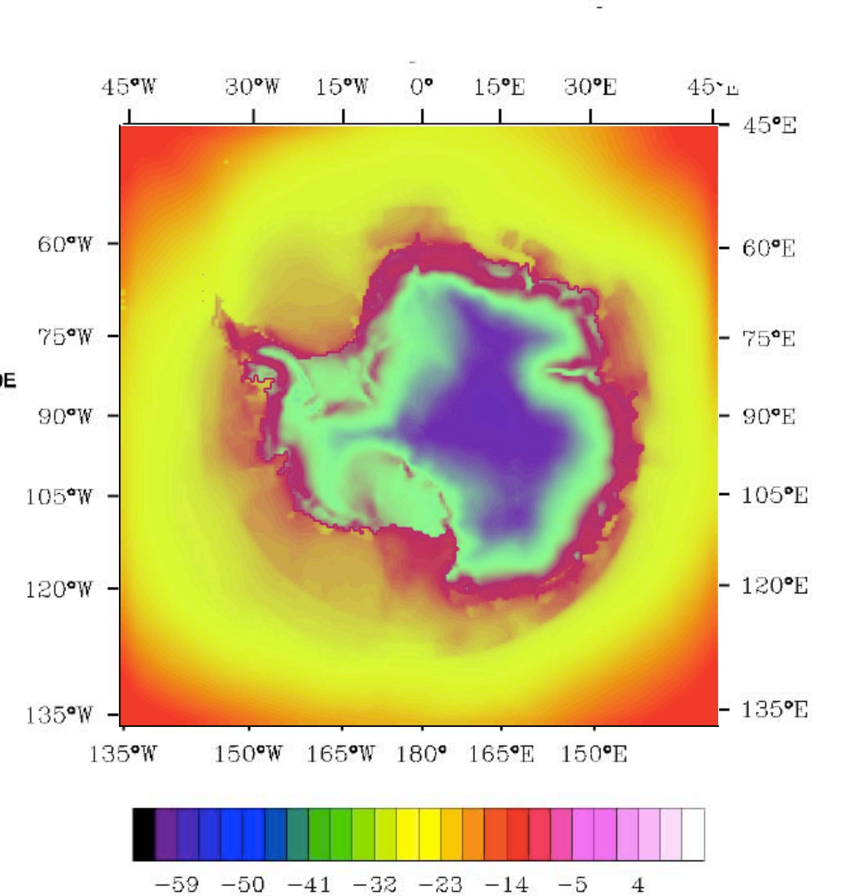


Regional Climate Model (RegCM3, 80km)

GCM

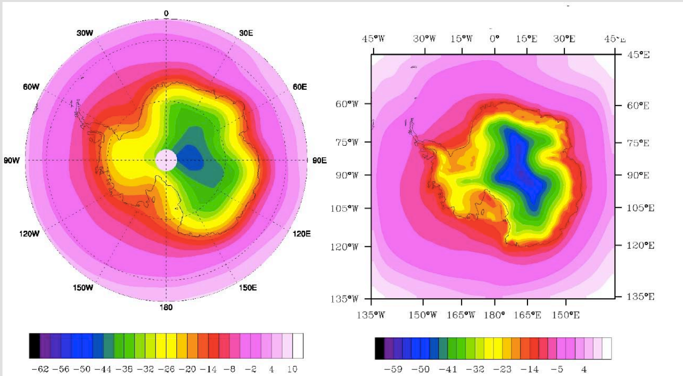


RCM



Nested GCM-RCM simulations

- RegCM3 hydrostatic RCM adapted to Antarctica
- 80 or 40 km polar stereographic grid centered over S. Pole
- Driven by GCM climatologies
  - Exponential relaxation at GCM-RCM boundaries
  - Holtslag PBL scheme
  - Grell convection scheme
  - Adjustments to diagnostic fields over the ice sheet provide improved modern simulations



Nested GCM-RCM 80 km model results

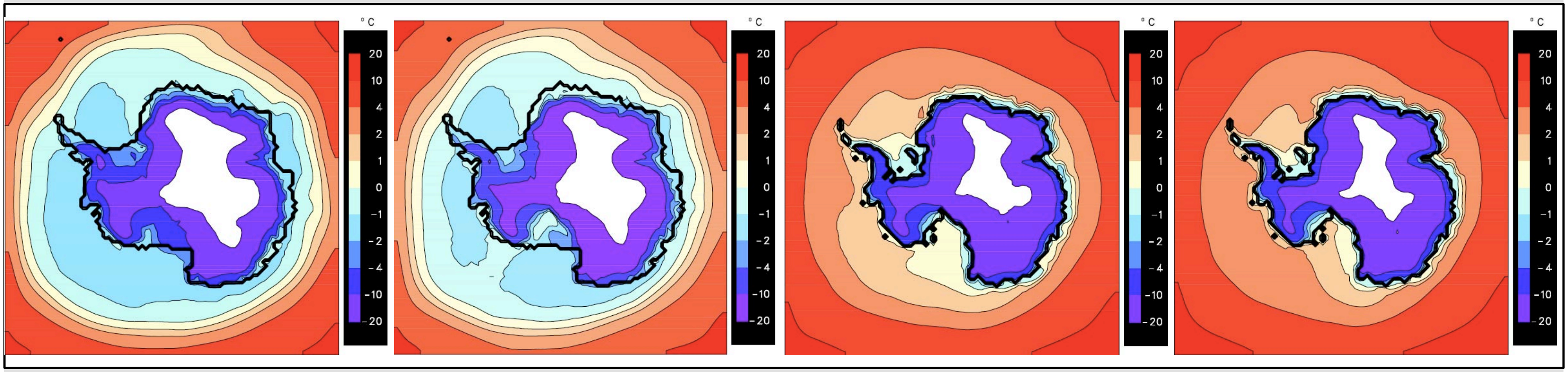
January surface (2m) air temperatures

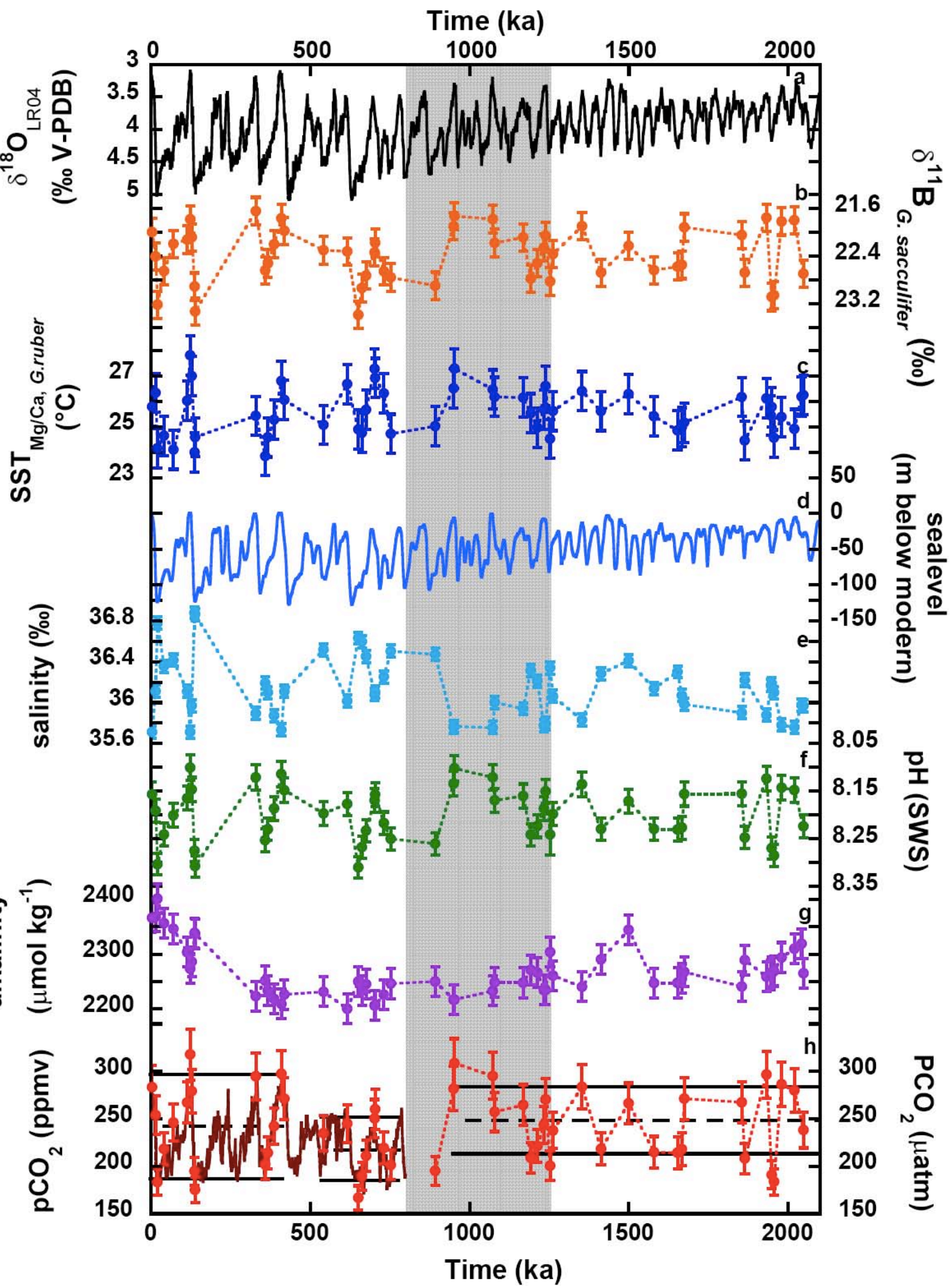
Preindustrial control

MIS 31 orbit (1.082 Ma)

MIS 31 orbit, no shelves
Increased Q_{ice} (70 Wm^{-2})

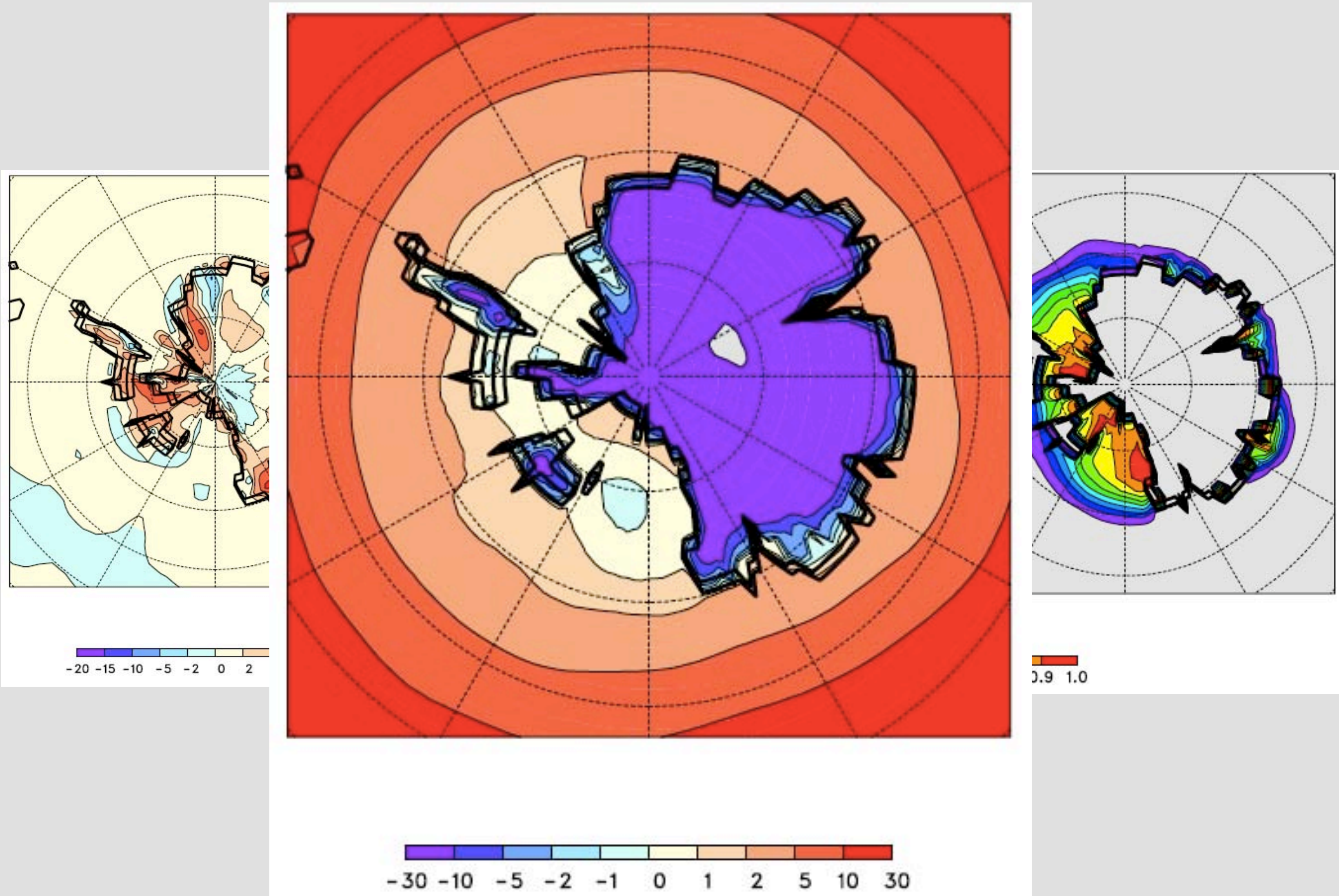
MIS 31 orbit, no shelves
Increased Q_{ice}, 400 ppm CO_2





Bärbel Hönisch et al., 2009

MIS-31 orbit, 400 ppmv CO_2, no WAIS



The Future?

Our past 5 Myr forcing parameterizations (~$\delta^{18}O$) for:

- sea level
- surface mass balance and temperature
- sub-ice-shelf oceanic melt rates

are not applicable to future change ($CO_2 \uparrow$)

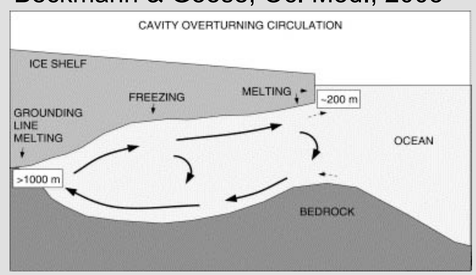
- Here we simply prescribe crude increases in ocean melt rate, and keep other forcings same as present

Sub-ice shelf oceanic melt rates

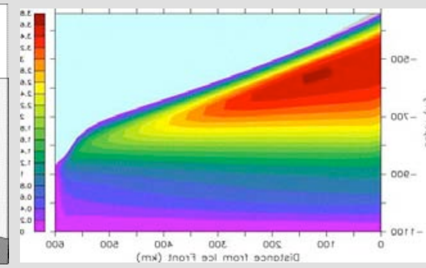
- Sources of sub-ice-shelf water depend on larger-scale circulation

- Will need A/OGCMs and Regional Ocean Models to project future ocean melt rates

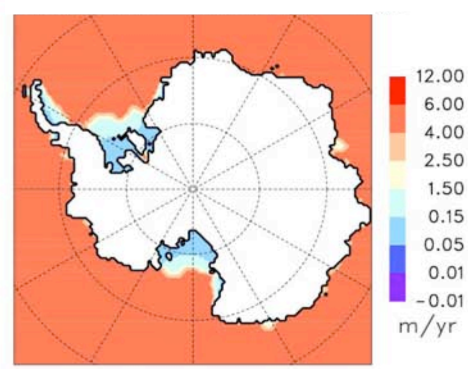
Beckmann & Goose, Oc. Mod., 2003



Walker & Holland, Oc. Mod., 2007



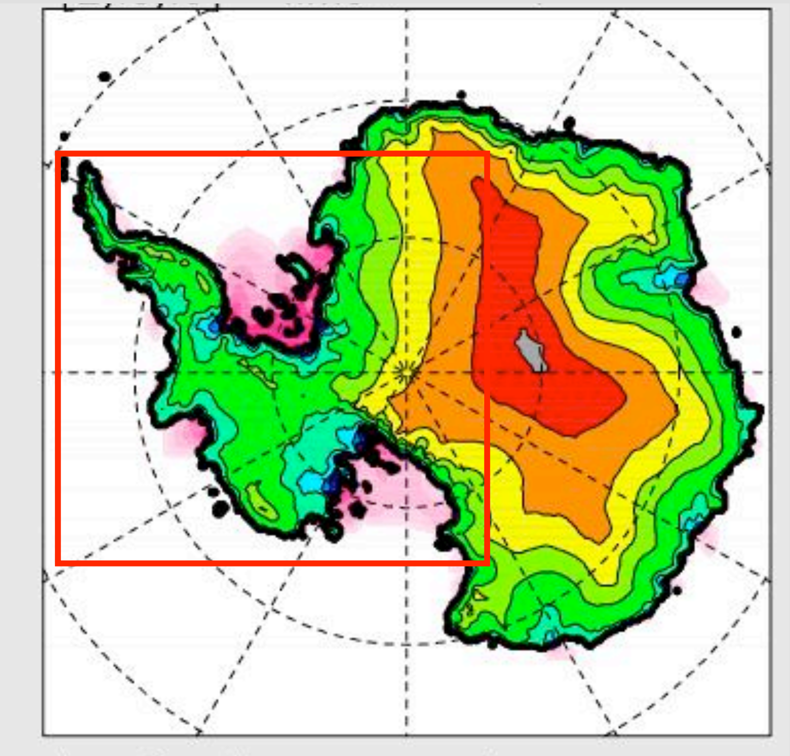
- For now, we simply prescribe sudden increases in ocean melt rates, from modern [.1,5,5] to [2,10,10] m/yr, or to [∞,∞,∞] (no floating ice)



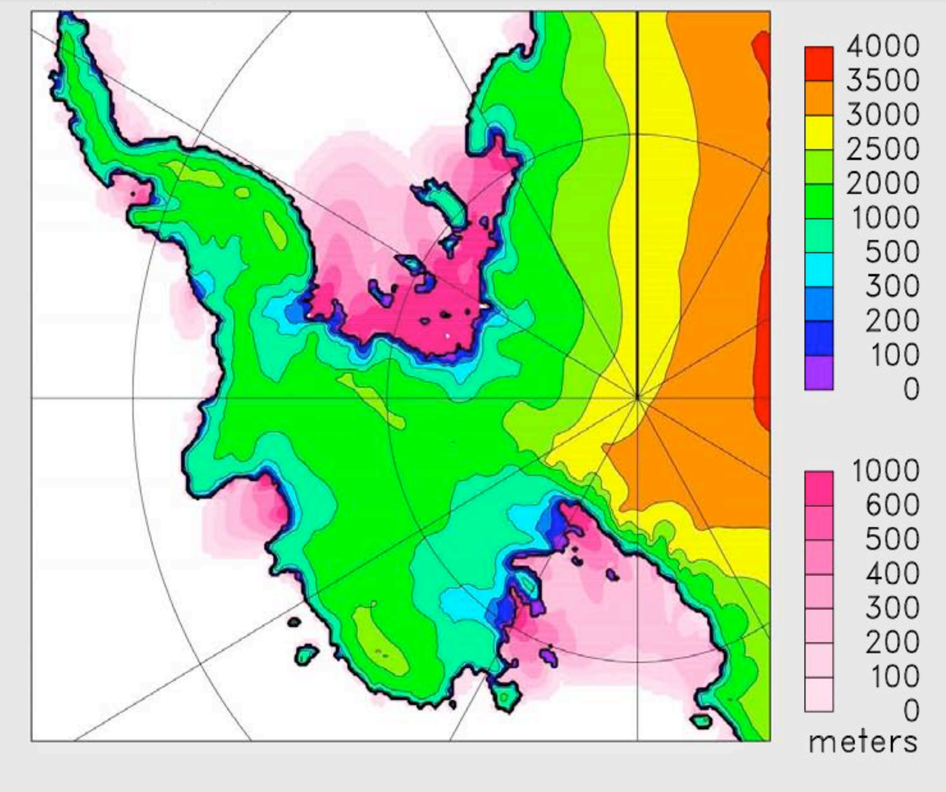
Modern ocean melt rates = [.1,5,5], where
.1 = protected shelf (most important)
5 = exposed shelf
5 = deep ocean areas

Model Simulations

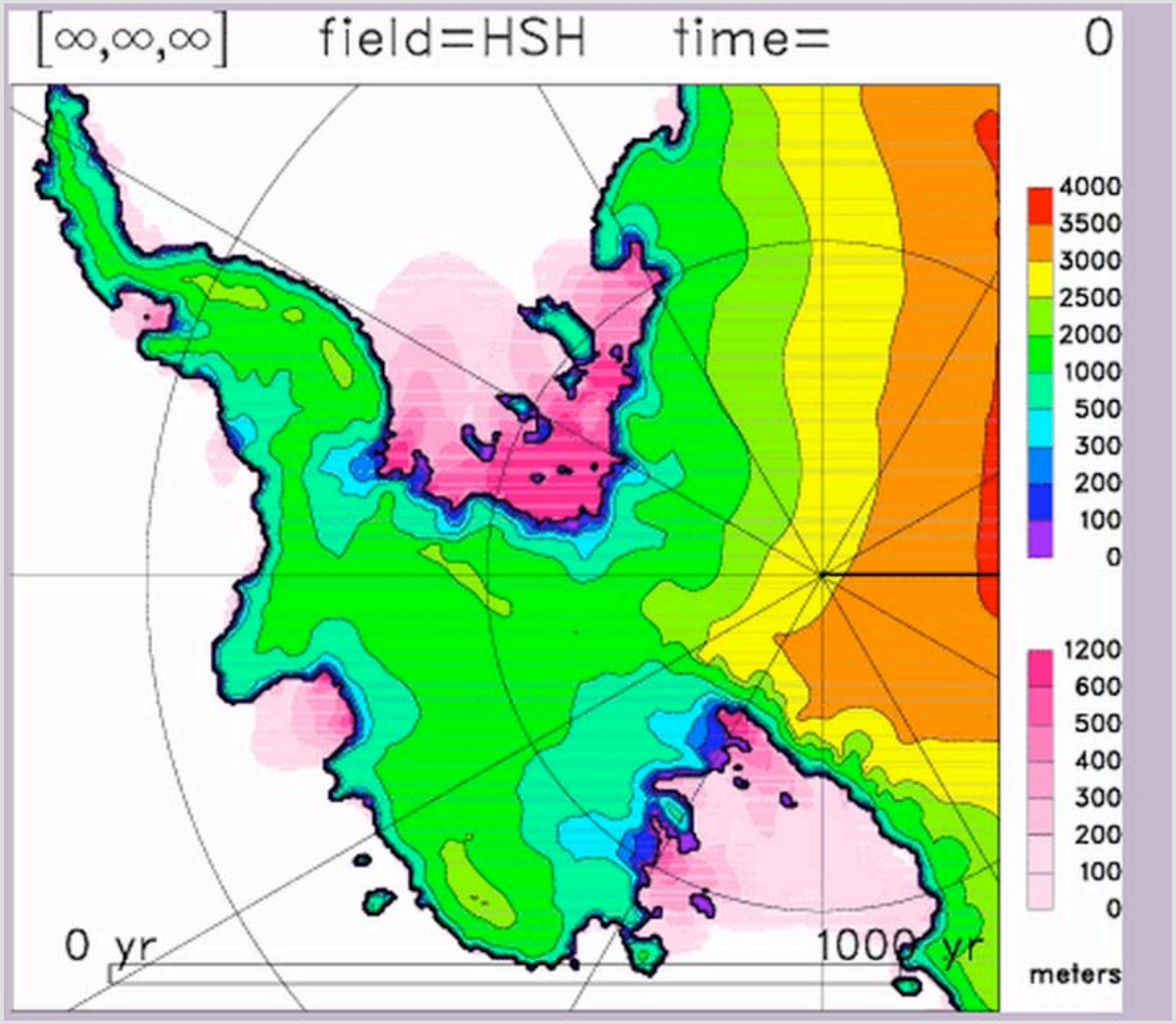
Continental Antarctica, 20 km grid



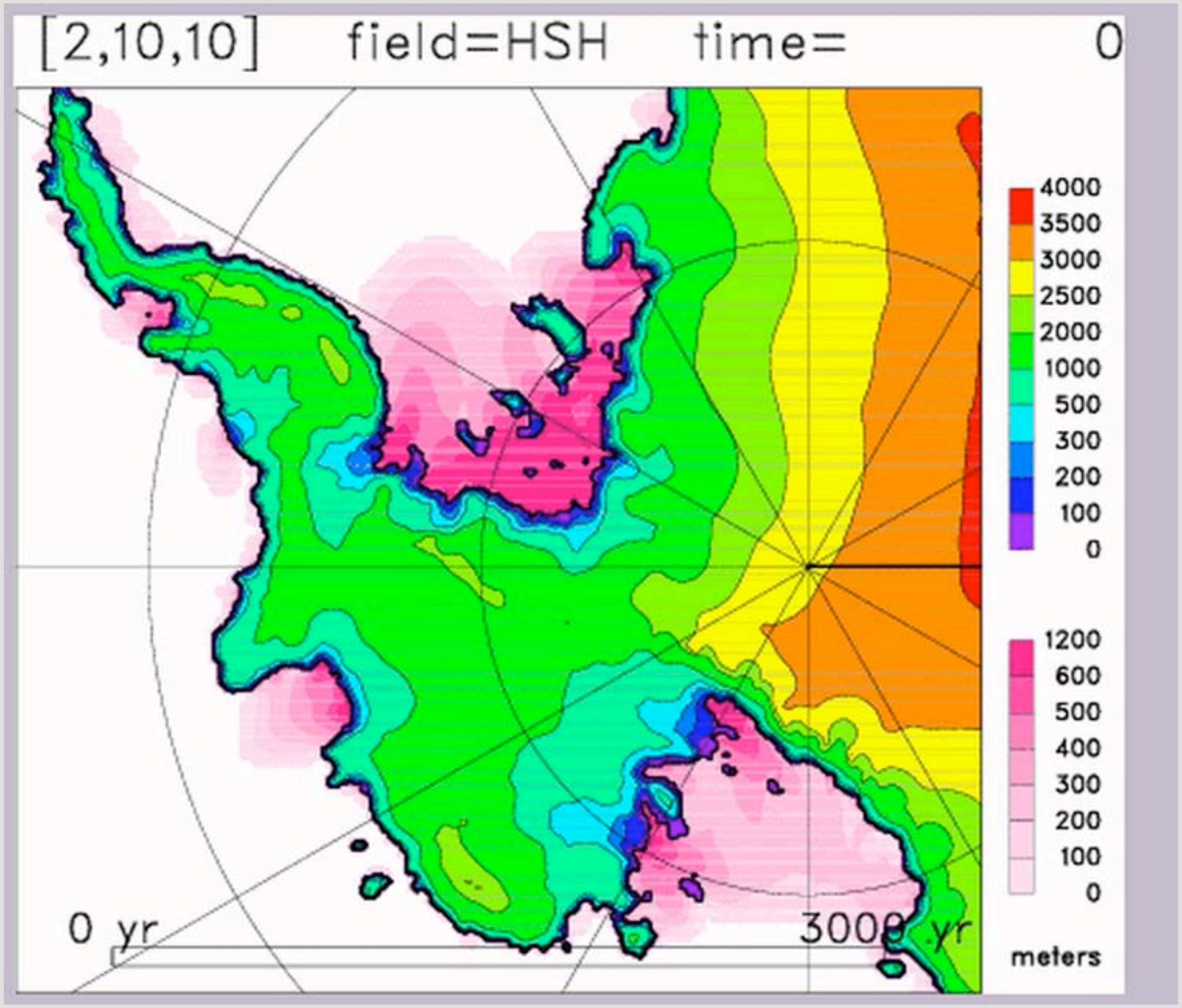
Nested WAIS, 10 km grid



Ocean melt = [∞, ∞, ∞], 0 to +500 years

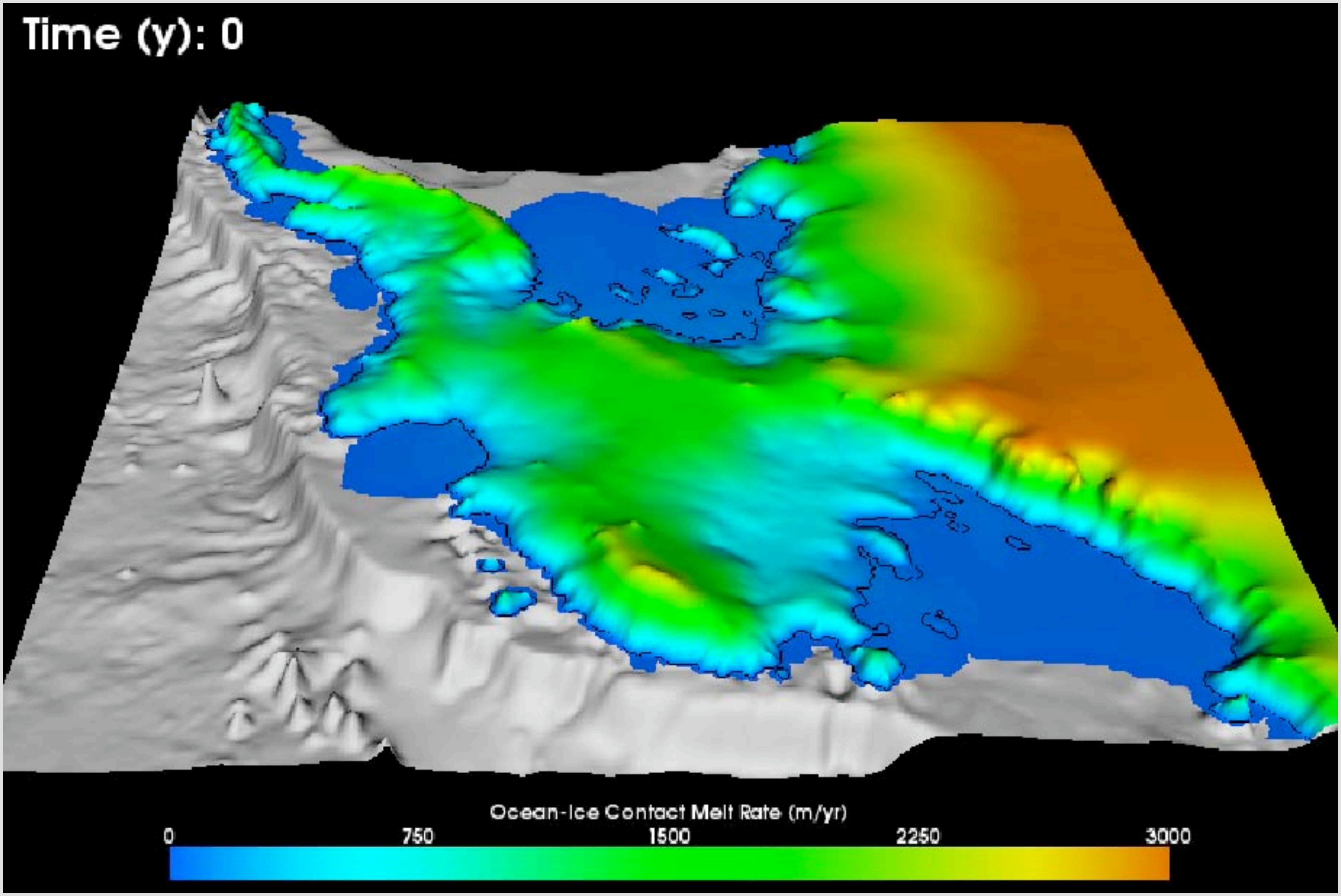


Ocean melt = [2, 10, 10], 0 to +3000 years

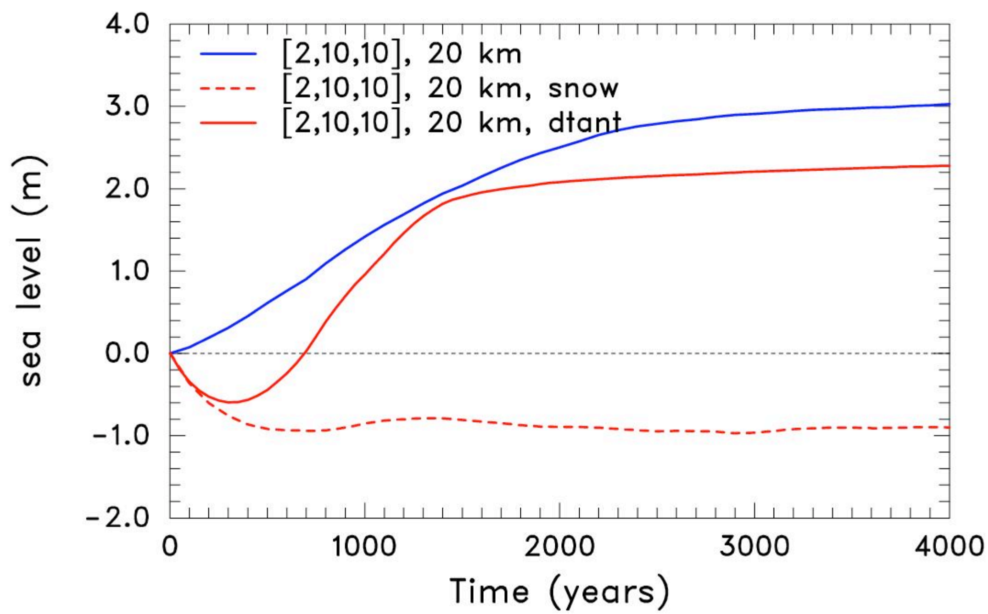


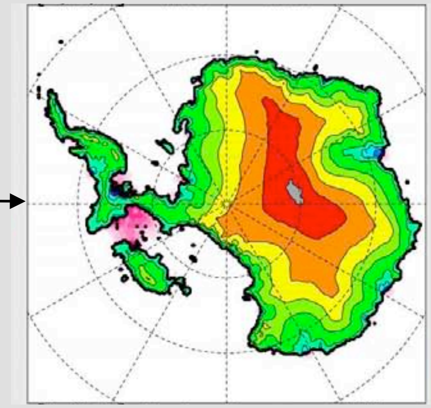
Ocean melt = [2, 10, 10] m yr^{-1} (0-3000 yr)

Animation by Chuck Anderson, EESI, Penn State

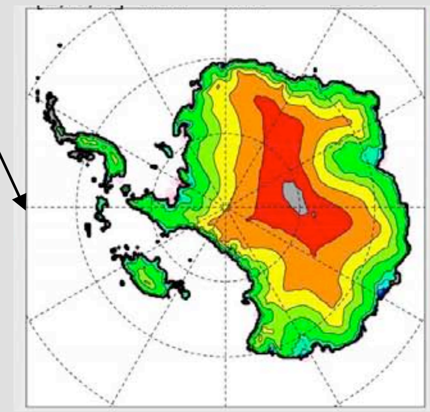


[2, 10, 10] ocean melt + δ(snowfall) + δ(surface melt)

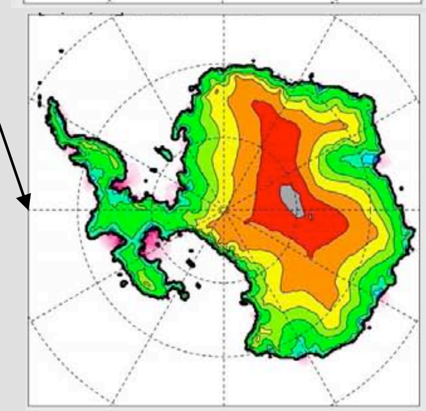




no surface budget change



precip x 2
and
air temps +10^{o}C

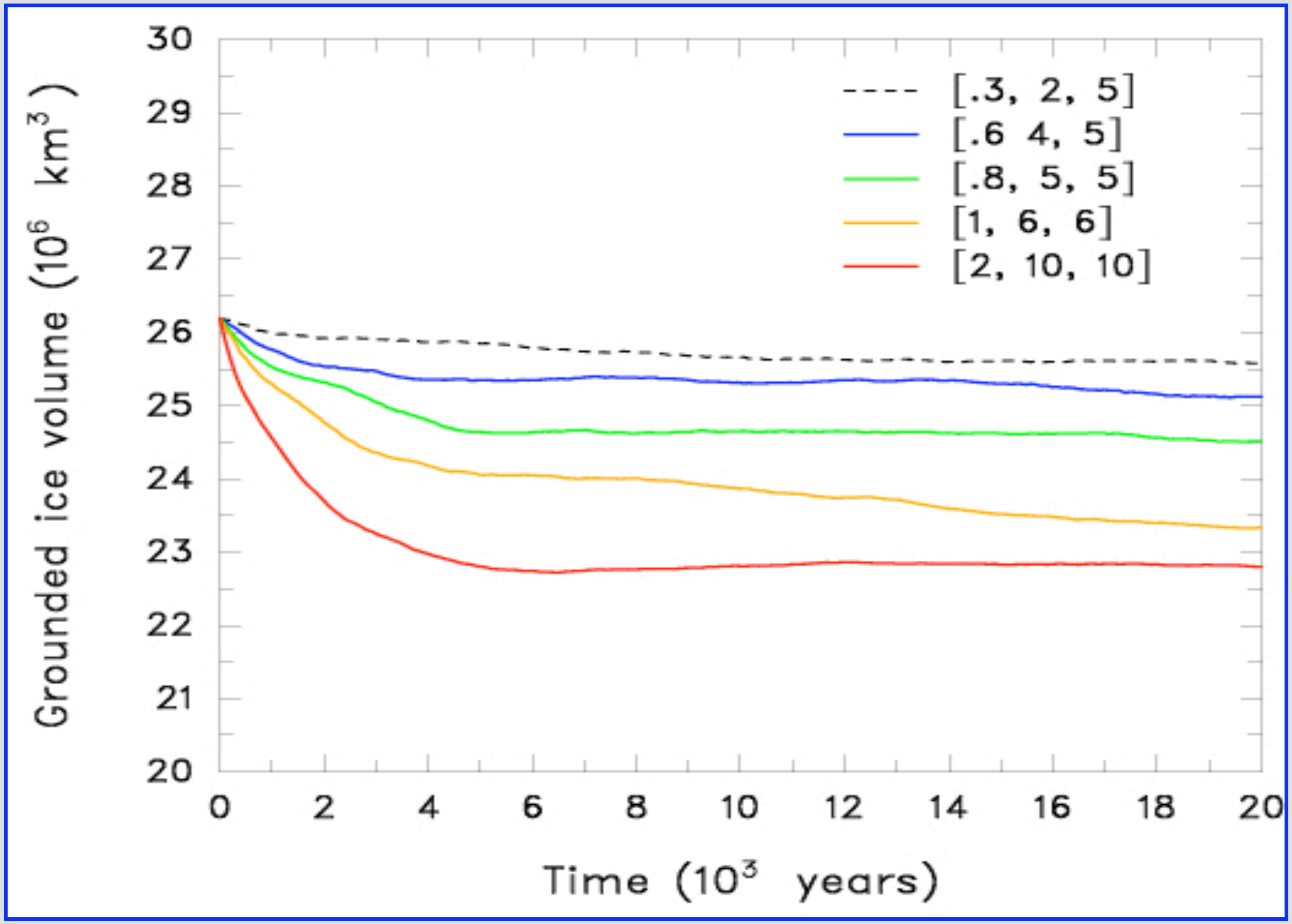


precip x 2

- WAIS ~collapses in all cases…sub-ice ocean melt is dominant
- But, sea level rise is significantly reduced by extra snow accumulation (cf. Huybrechts et al., 1999, 2004)

Applying difference amounts of melt increase

e-folding time is ~1200 years

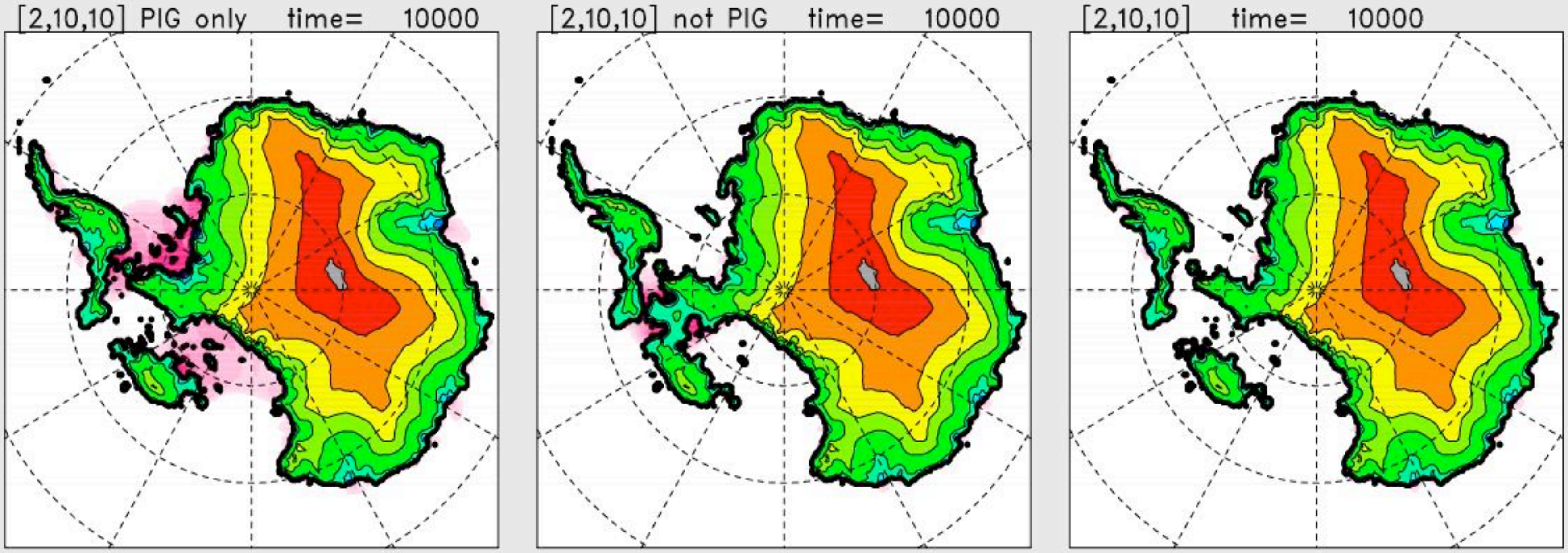


Ocean melt in particular embayments

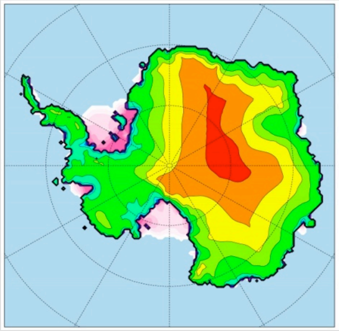
[2,10,10] in PIG-THW sector ***only***

[2,10,10] ***except*** in PIG-THW sector

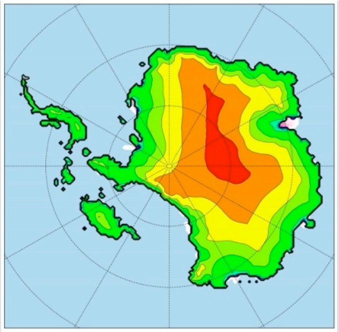
[2,10,10] in ***all*** sectors



- Still get WAIS collapse with Pine Island-Thwaites melt alone, but takes ~2x longer
- PIG-Thwaites alone is more effective than Ross+Weddell alone

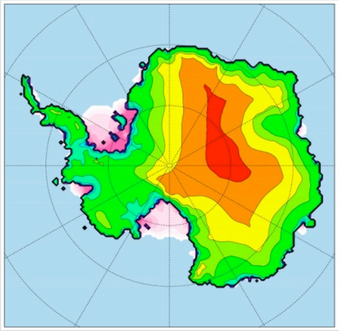


Summary

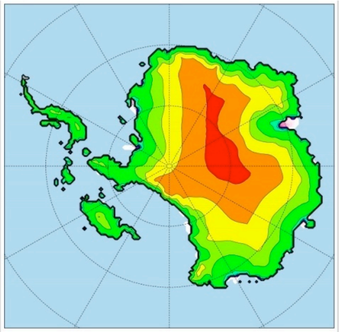


Based on a new ice sheet-shelf model, calibrated to the present <u>and</u> past:

- WAIS is vulnerable
- Time scale of retreat is “fast”, but not decadal-centennial
- Fast response time implies the potential for past Greenland-WAIS anti-phasing (e.g., Raymo)
- Potential total contribution to sea level rise is ~7m
  - MIS-11 +20 m?, Pleistocene +20-40 m?, Surface melt? EAIS hysteresis?
- Sensitivity to sub-ice oceanic melt is important to considerations of sea level “commitment”
- WAIS is most sensitive to increased ocean melt in PIB



Immediate needs…



- Estimates of future sub-ice shelf temperature change (coupling with Regional Ocean Models)
- High resolution future surface climatologies (RCMs)
- More proximal records from around the Antarctic margin
- Better Boundary Conditions (Bathymetry!)

Lack of EAIS melt with warm Pliocene BC's: Implications?

- Pliocene CO_2 was >> 400 ppmv
- Sea level was not +25 m ESL
- Critical physical mechanisms are still missing in ice sheet models (basal hydrology?
- Pliocene tropical forcing (El Padre) affects Antarctic summer temperature
- GCMs/RCMs are way under-sensitive to GHG forcing, especially in polar regions

Warm orbit + ocean heating + 400 ppmv CO_2