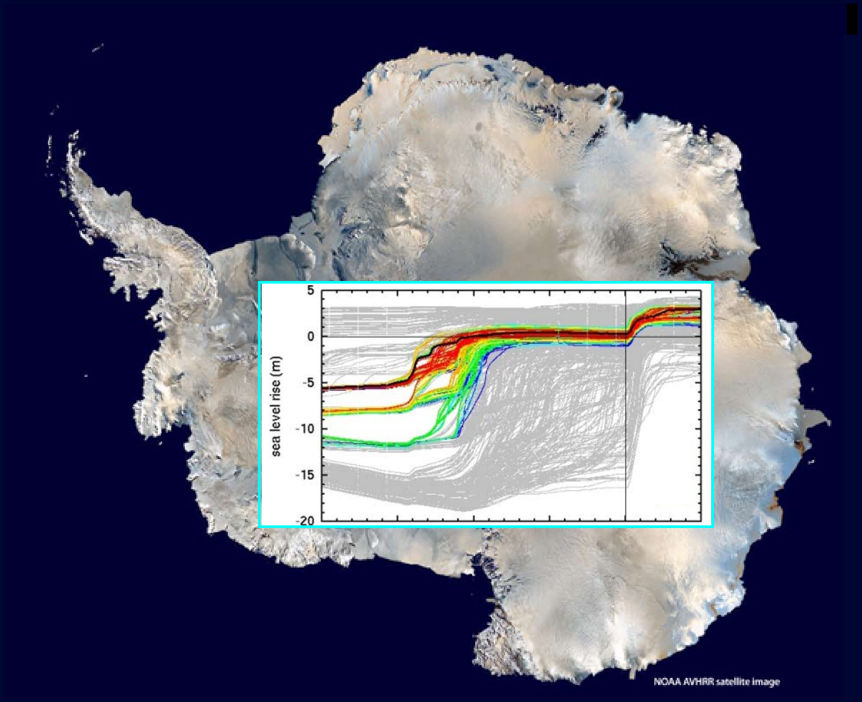
Modeling past and future variations of the Antarctic Ice Sheet



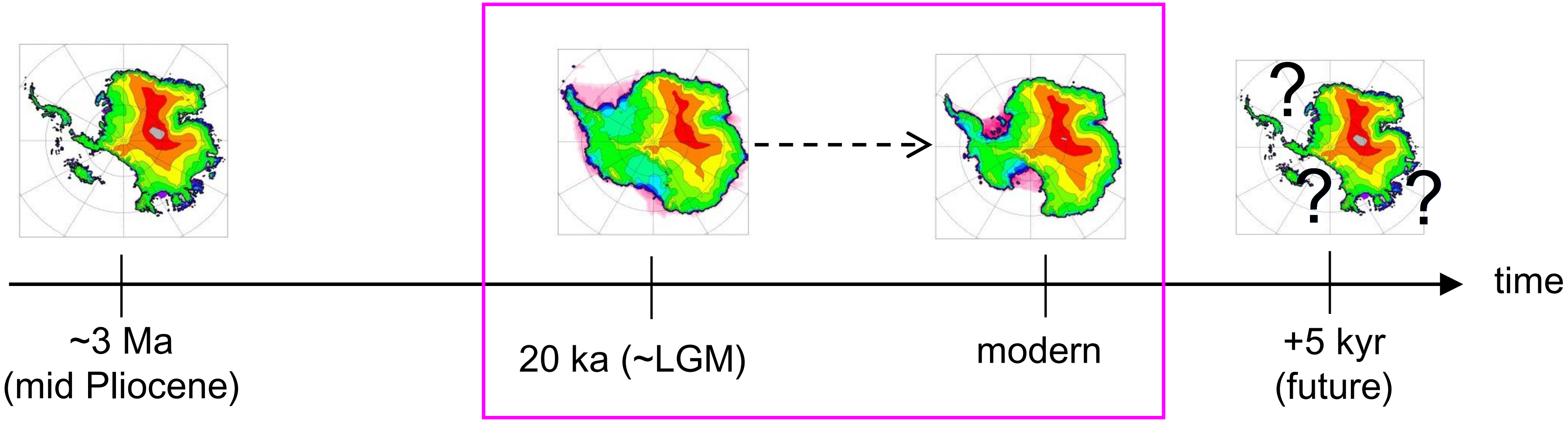
NOAA AVHRR satellite image

David Pollard[1] and Robert DeConto[2]

[1]Pennsylvania State Univ. [2]Univ. of Massachusetts

NCAR CESM/LIWG meeting, June 22, 2016

Outline



(1) Calibration vs. last 20,000 years with Large Ensembles

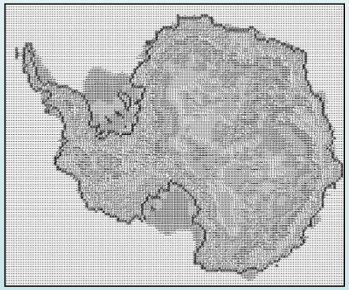
(2) Add drastic warm-climate mechanisms to capture Pliocene sea-level rise

(3) Apply to future 5000 years, for RCP 2.6 to 8.5 scenarios

Introduction: Steps in Large-Ensemble modeling

Run model from 30 kyr BP to present → Repeat for 625 runs, systematically varying model parameters → Aggregate score for each run vs. modern and geologic data → Statistical LE analysis

- Probability densities of model parameter values
- Envelopes of future ice retreat and sea-level rise

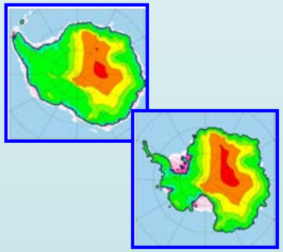


Ice sheet model:

(Pollard et al., 2012)

- 20 km grid.
- SSA+SIA dynamics, grounding line flux (Schoof, 2007).
- Atmospheric forcing: uniform shifts.of modern climatology
- Oceanic forcing: Liu et al., Science, 2009, CSM 22 kyrs.

× 625



Aggregate score:

$$S = (S_1\ S_2\ S_3\ S_4\ S_5\ S_6\ S_7\ )^{1/7}$$

S_1. Modern area of grounded ice

S_2. Modern grounded-ice thickness

S_3. Past 1-D grounding-line distance along PIG, Ross, Ronne centerlines

S_4. Past 2-D grounding line positions

S_5. Past Relative Sea Level records

S_6. Past elevation-age data

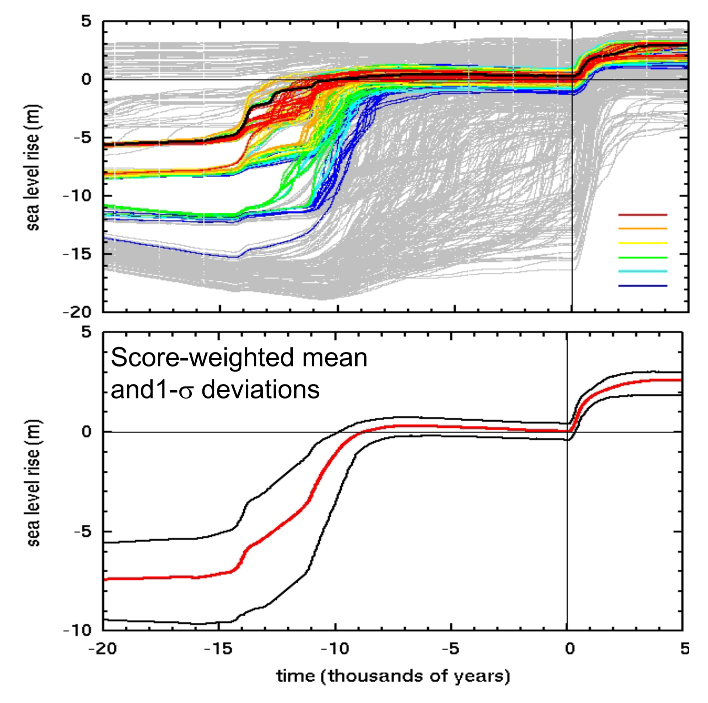
S_7. Modern uplift rates

Reconstructions of grounding lines by RAISED Consortium (QSR, 2014)

Data compilations by Briggs and Tarasov (2013), Whitehouse et al. (2012).

Equivalent sea-level envelopes

Showing all 625 runs (grey: score S = zero)



Pollard et al., GMD, 2016.

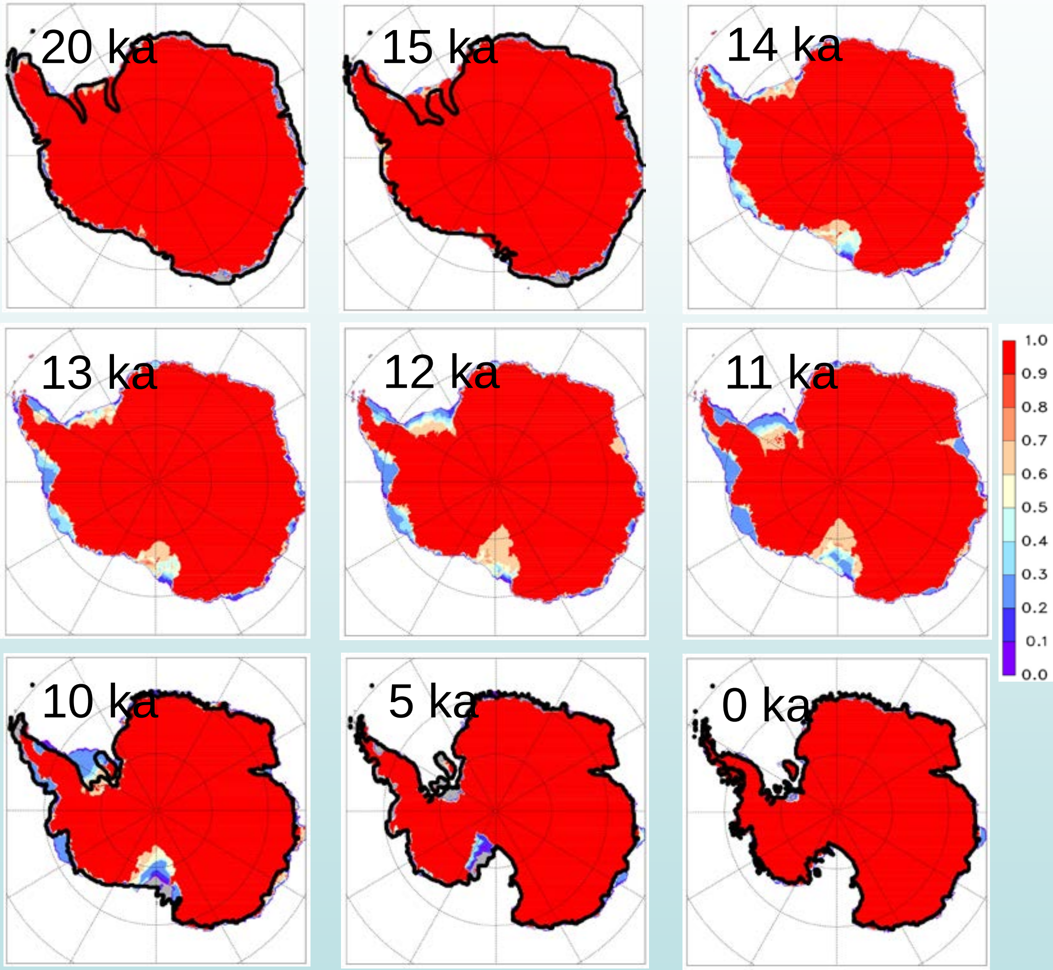
Other recent Antarctic ~LE modeling:

- Whitehouse et al., 2012a,b.
- Briggs and Tarasov, 2013-14.
- Golledge et al., 2014.
- Maris et al., 2014.

Probability density maps

Probability of grounded ice (0 to 1)

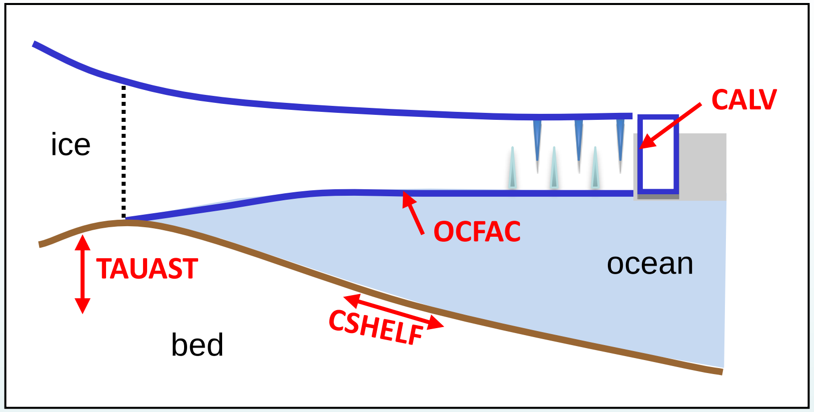
= Σ(S_i with grounded ice at x,y,t) / Σ(S_i, i =1 to 625)

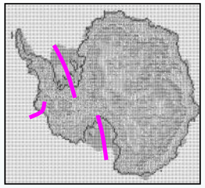


Black lines: grounding line reconstructions,
RAISED Consortium, QSR, 2014

4 model parameters calibrated

Large Ensemble, 5 values for each of 4 parameters (625 runs)





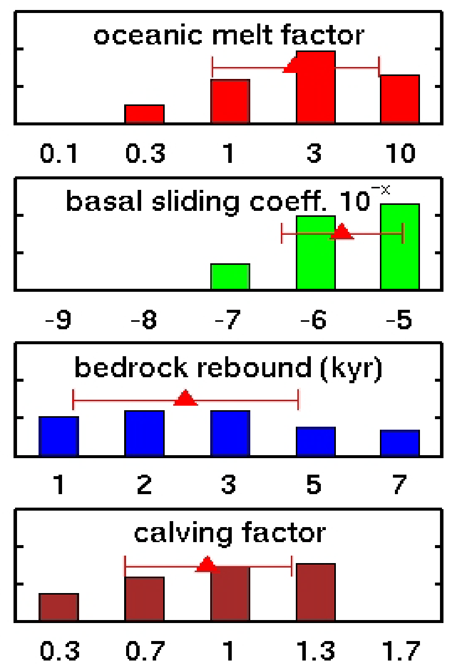
OCFAC:

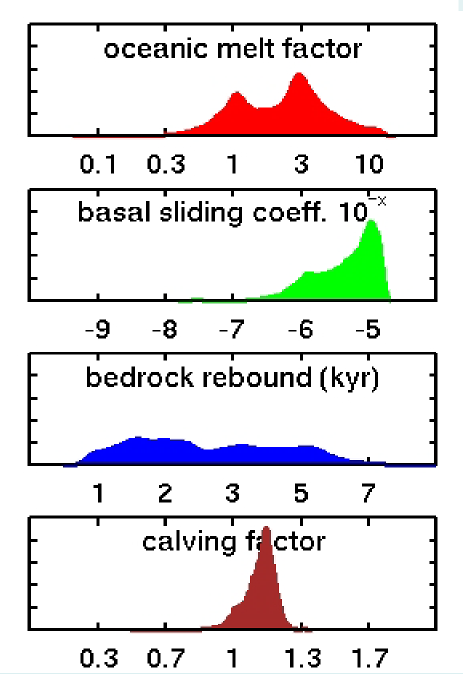
CSHELF:

TAUAST:

CALV:

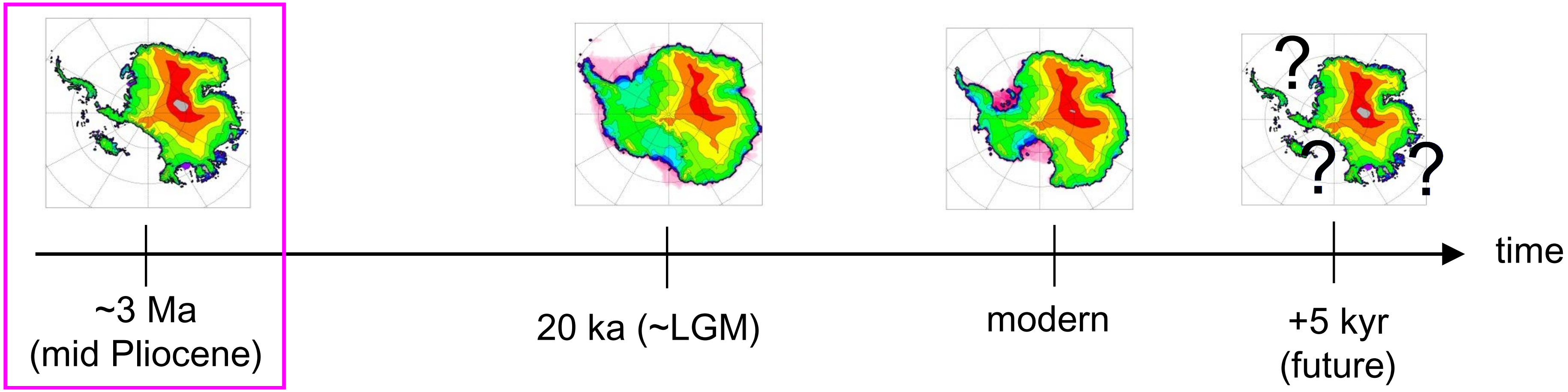
Pollard et al., GMD, 2016. Simple score-averaging.





Chang et al., J. Amer. Stat. Assoc., 2016. State-of-the-art Bayesian approach: emulation, likelihood functions, MCMC.

Outline



(1) Calibration vs. last 20,000 years with Large Ensembles

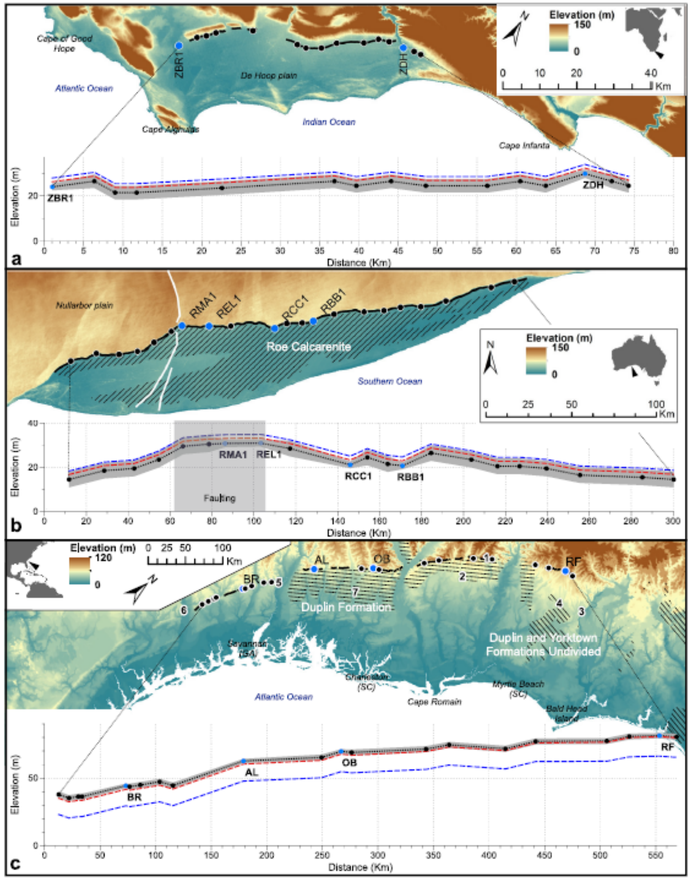
(2) Add drastic warm-climate mechanisms to capture Pliocene sea-level rise

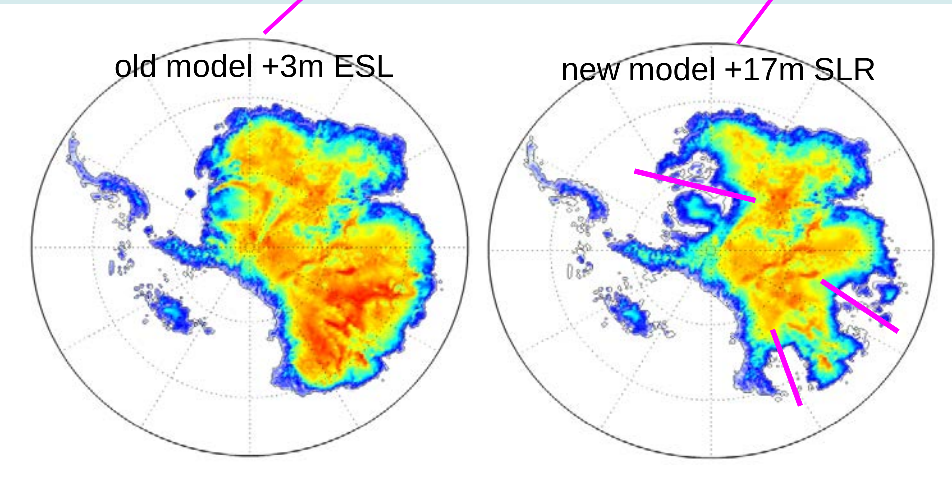
(3) Apply to future 5000 years, for RCP 2.6 to 8.5 scenarios

Adding hydrofracture & cliff failure, to produce large Pliocene sea-level rise

- Geologic evidence of Pliocene, Miocene episodes up to ~20m SLR
  - *May be less, due to GIA and dynamic topography effects (later)*
- Earlier models simulate *Marine Ice Sheet Instability* only in West Antarctica during warm climates, < ~5 m equiv. sea-level rise
- 2 drastic retreat mechanisms added to this model
  - produces mid-Pliocene retreat in East Antarctic basins, +17 m SLR

Rovere et al., EPSL, 2014: mid-Pliocene shore-line elevations > ~20 m. But note uncertainty due to GIA and tectonic uplift (Austermann et al., Geol., 2015)




old model +3m ESL

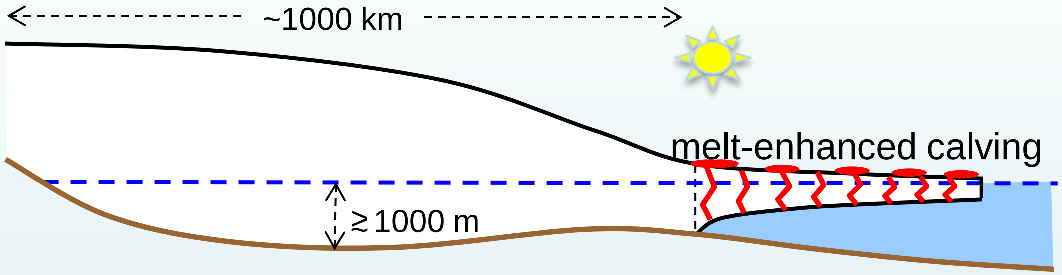
new model +17m SLR

Adding hydrofracture & cliff failure, to produce large Pliocene sea-level rise

Two mechanisms to produce drastic EAIS basin retreat in warm Pliocene climates:

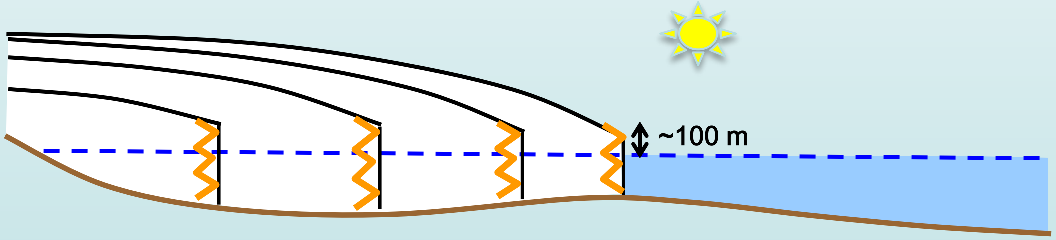
(1) Surface melt and hydrofracture, (2) Large tidewater cliff failure

(1) Hydro-fracture

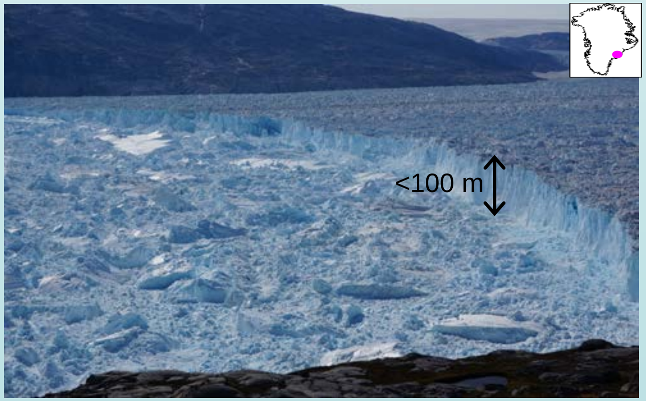


Larsen B breakup, 2002
(Scambos et al. 2003)

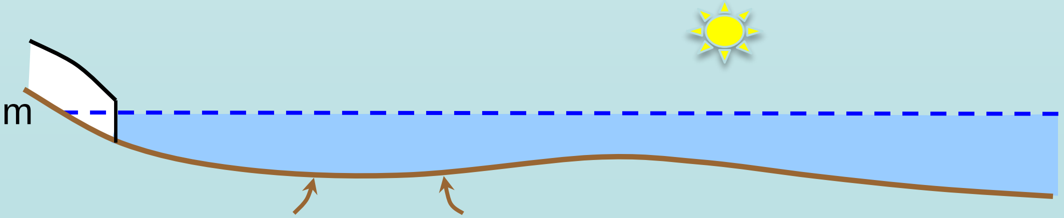
(2) Cliff failure



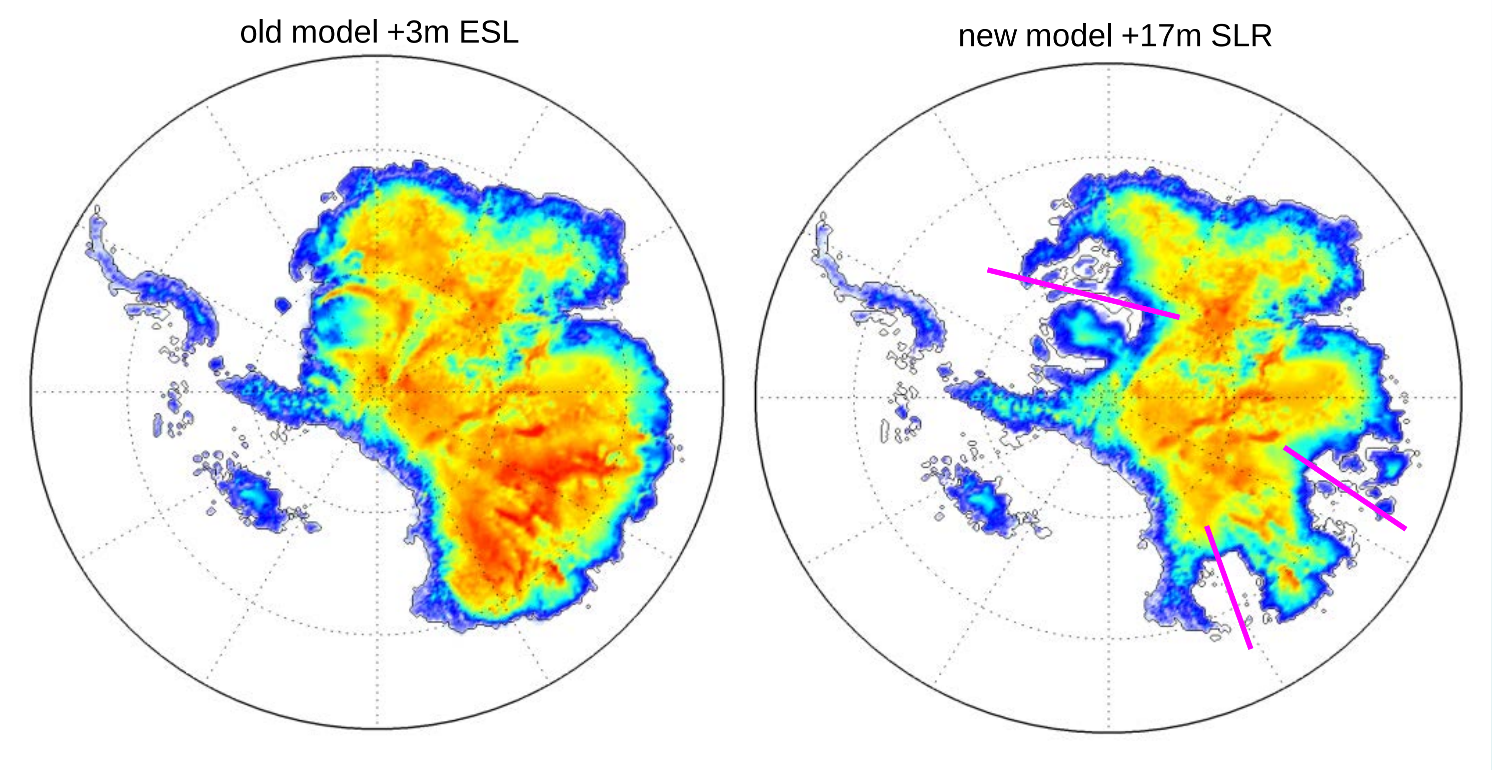
Terminus of Helheim Glacier, E. Greenland.
Cliff height above waterline is nearly ~ 100m.
Photo: Knut Christianson, U. Washington.



(3) Maximum retreat

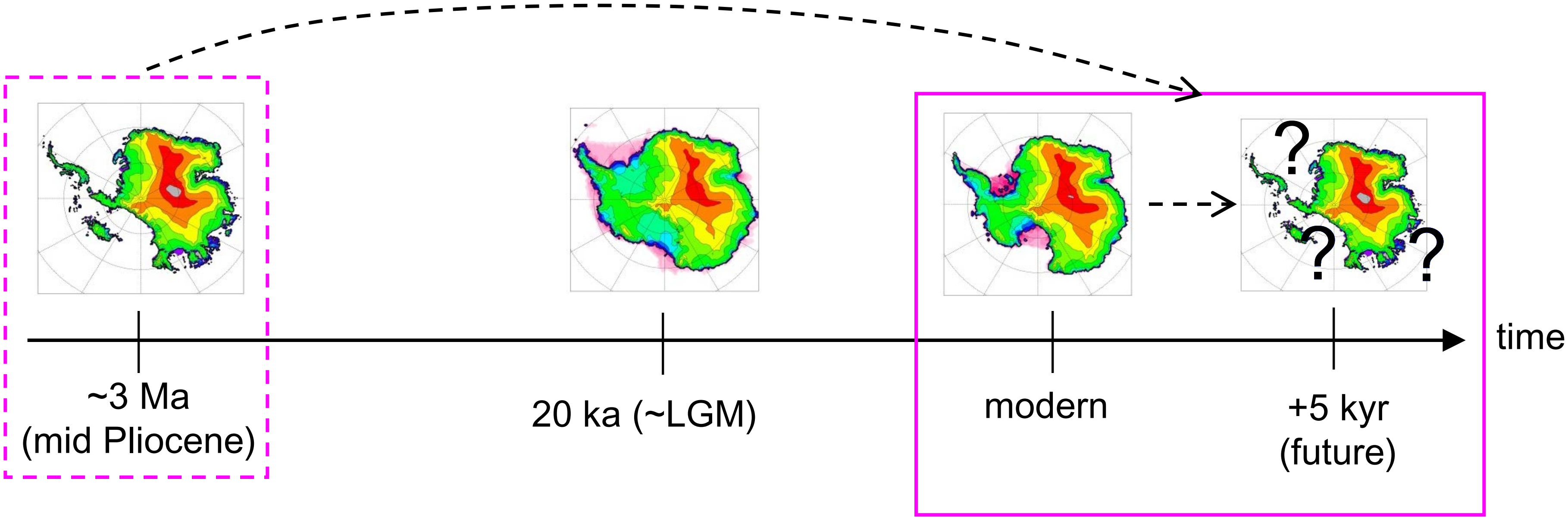


Adding hydrofracture & cliff failure, to produce large Pliocene sea-level rise



Pollard et al., EPSL, 2015

Outline



~3 Ma
(mid Pliocene)

20 ka (~LGM)

modern

+5 kyr
(future)

time

(1) Calibration vs. last 20,000 years with Large Ensembles

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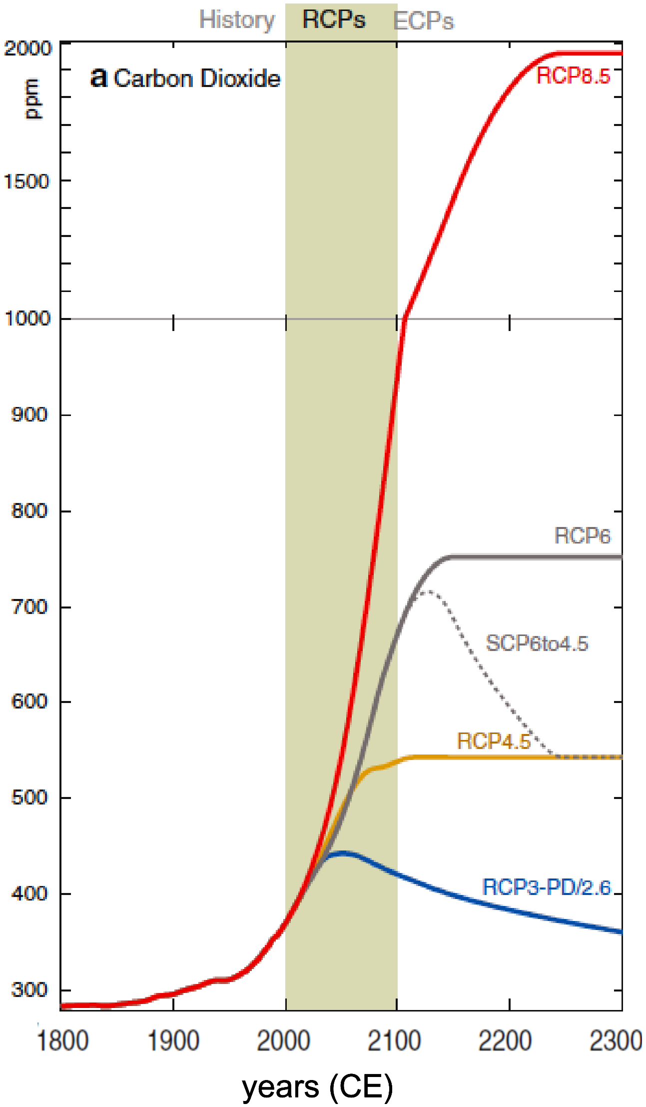
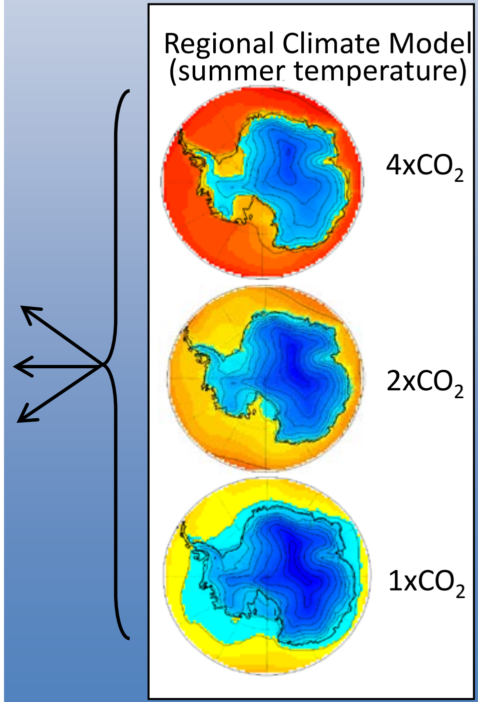
Future extensions: Large Ensembles for RCP 2.6, 4.5, and 8.5 scenarios

Future CO_2 (Meinhausen et al., 2011)



Extend runs into future, +5000 years

- using atmos.+ocean models following RCP scenarios
- adding hydrofracturing, ice-cliff failure
- scoring includes Pliocene SLR target



Atmospheric forcing:

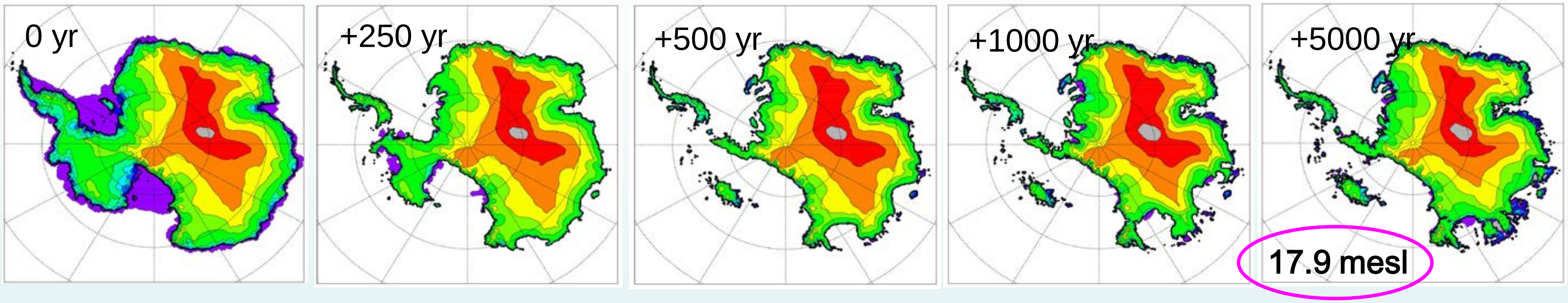
from RegCM3 regional climate model, snapshots for 1x,2x,4x,8x PAL CO2

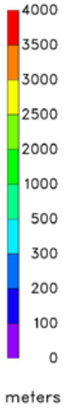
Oceanic forcing:

from NCAR CCSM4 future transient runs for RCP 2.6, 4.5, 8.5

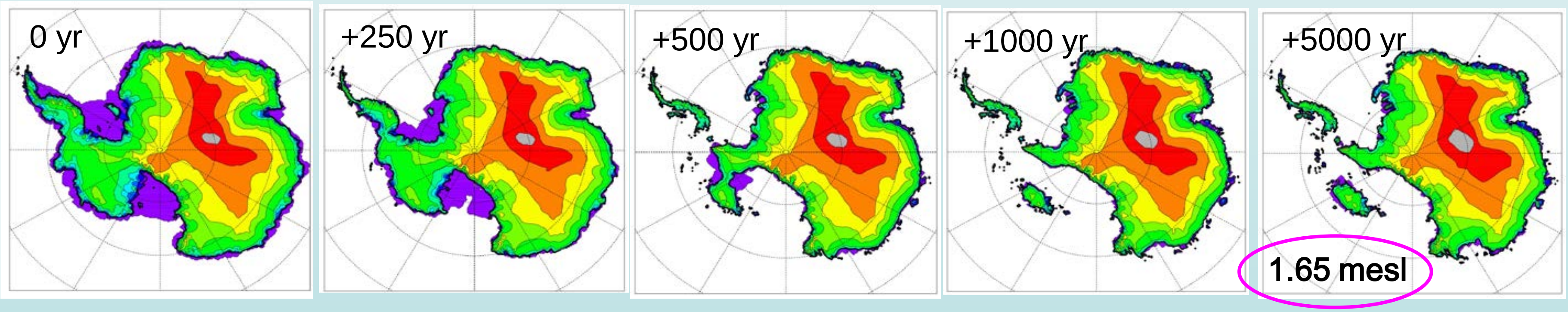
Future: Snapshots, modern to +5000 yr, RCP8.5, with and without mechanisms

RCP8.5, *WITH hydrofrac. and cliff failure (CALVLIQ=100, CLIFFVMAX=3):*





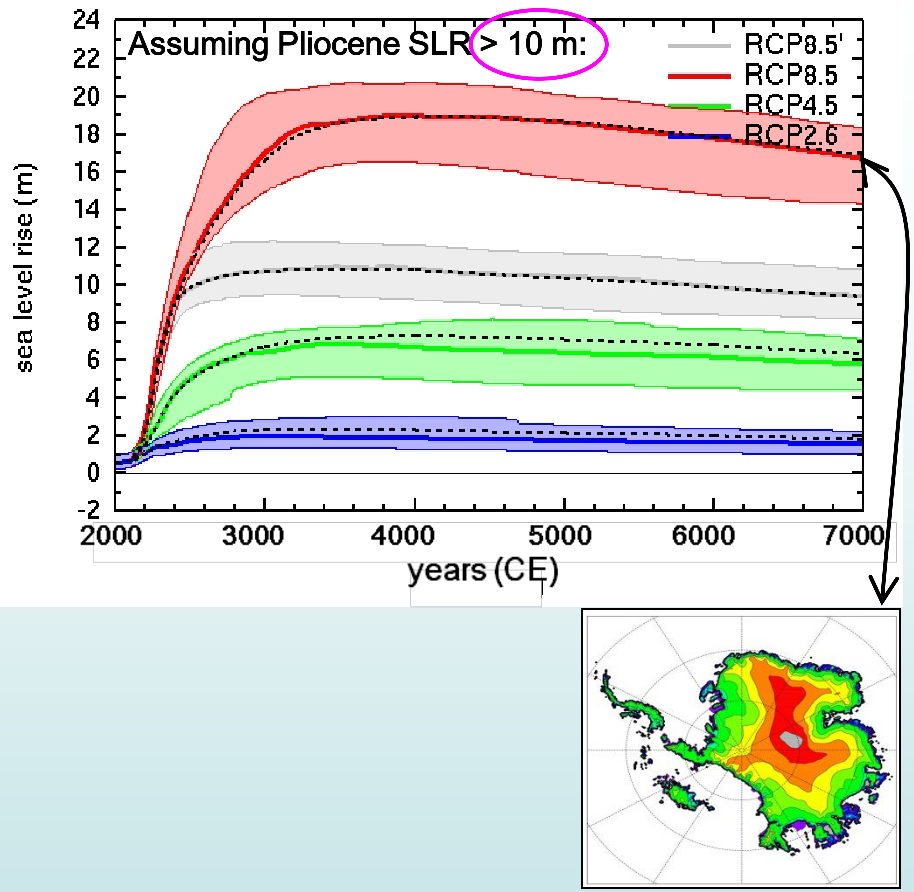
RCP8.5, *NO hydrofrac. or cliff failure (CALVLIQ=0, CLIFFVMAX=0):*

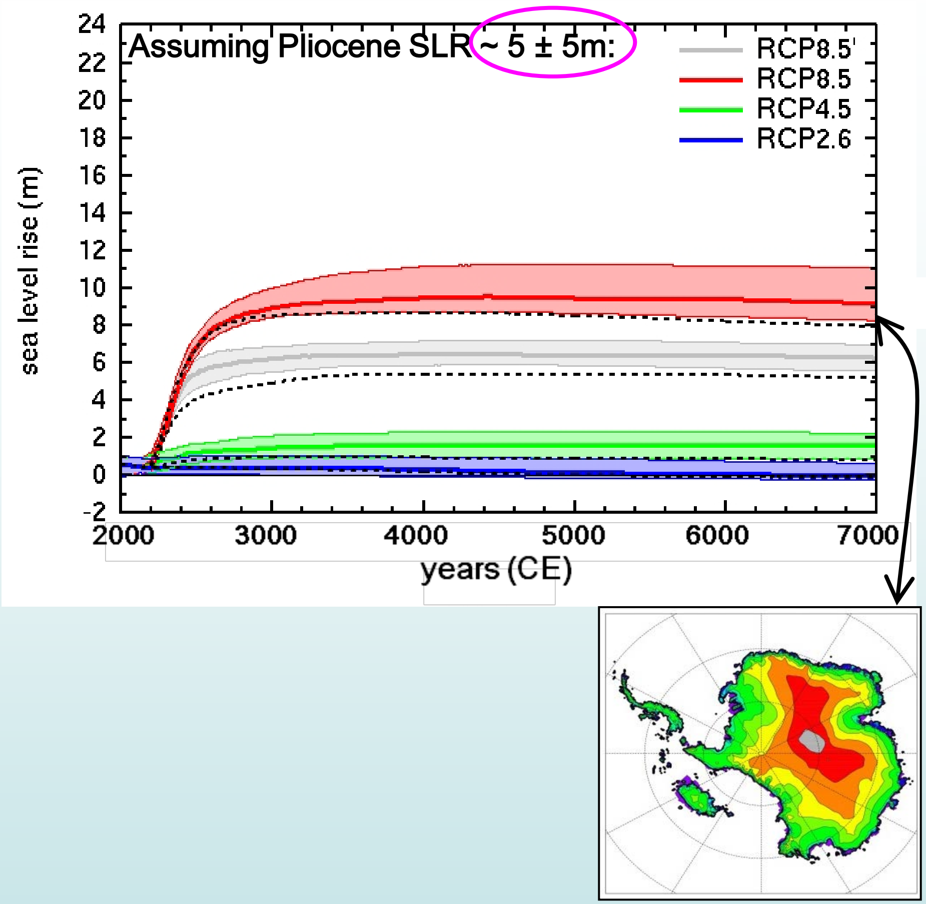


Also:

- Cornford et al., 2015
- Winkelmann et al., 2015
- Golledge et al., 2015
- Feldmann and Levermann, 2015
- Ritz et al., 2015

Future sea-level rise envelopes for RCP 2.6, 4.5 and 8.5





- Actual Pliocene sea-level rise is uncertain, due to possible dynamic topography and GIA effects (Raymo and Mitrovica, 2012; Rovere et al., 2014; Austermann et al., 2015)
- But need to calibrate non-analog processes (here, hydrofracturing, ice-cliff failure) with deep-time data
- PLIOMAX project (www.pliomax.org)

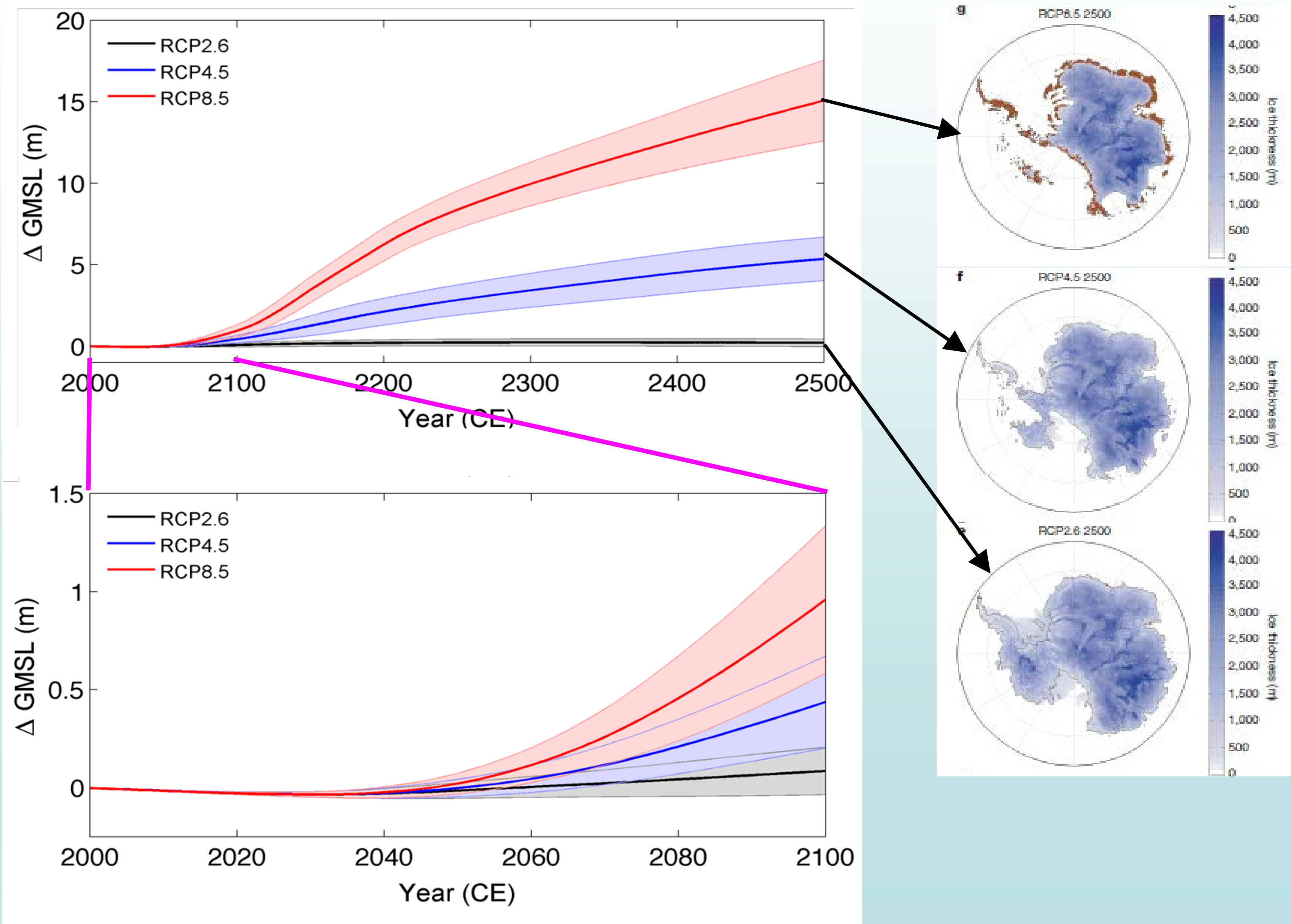
Future: A different large ensemble, with LIG and Pliocene sieves

Binary scoring with pass/fail targets:

(1) Pliocene ~3 Ma sea level: +10 to 20 m

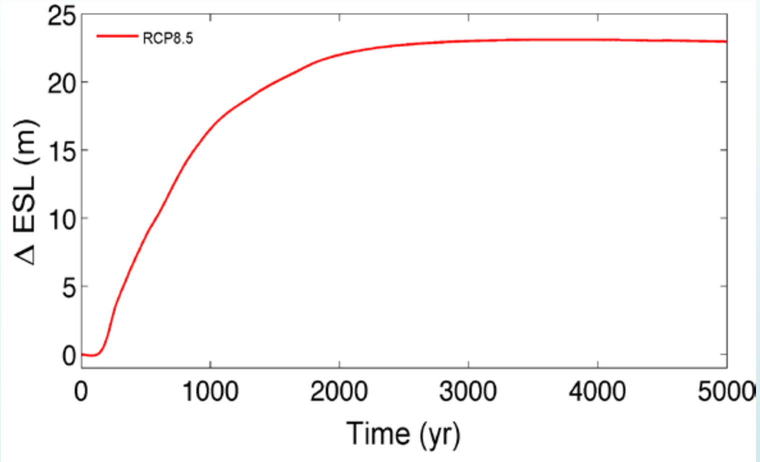
(2) Last Interglacial ~125 ka sea level: +3.5 to 7.5 m

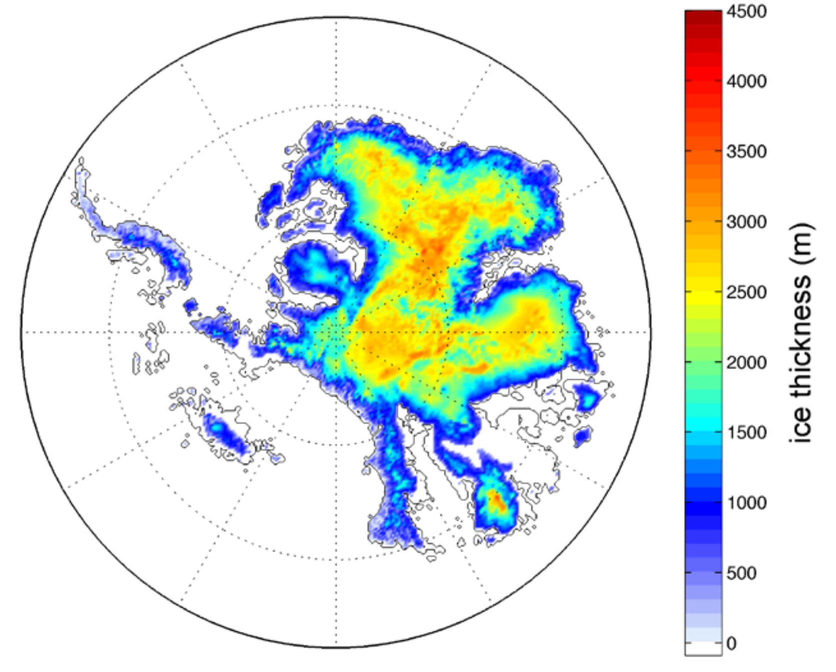
DeConto and Pollard, 2016



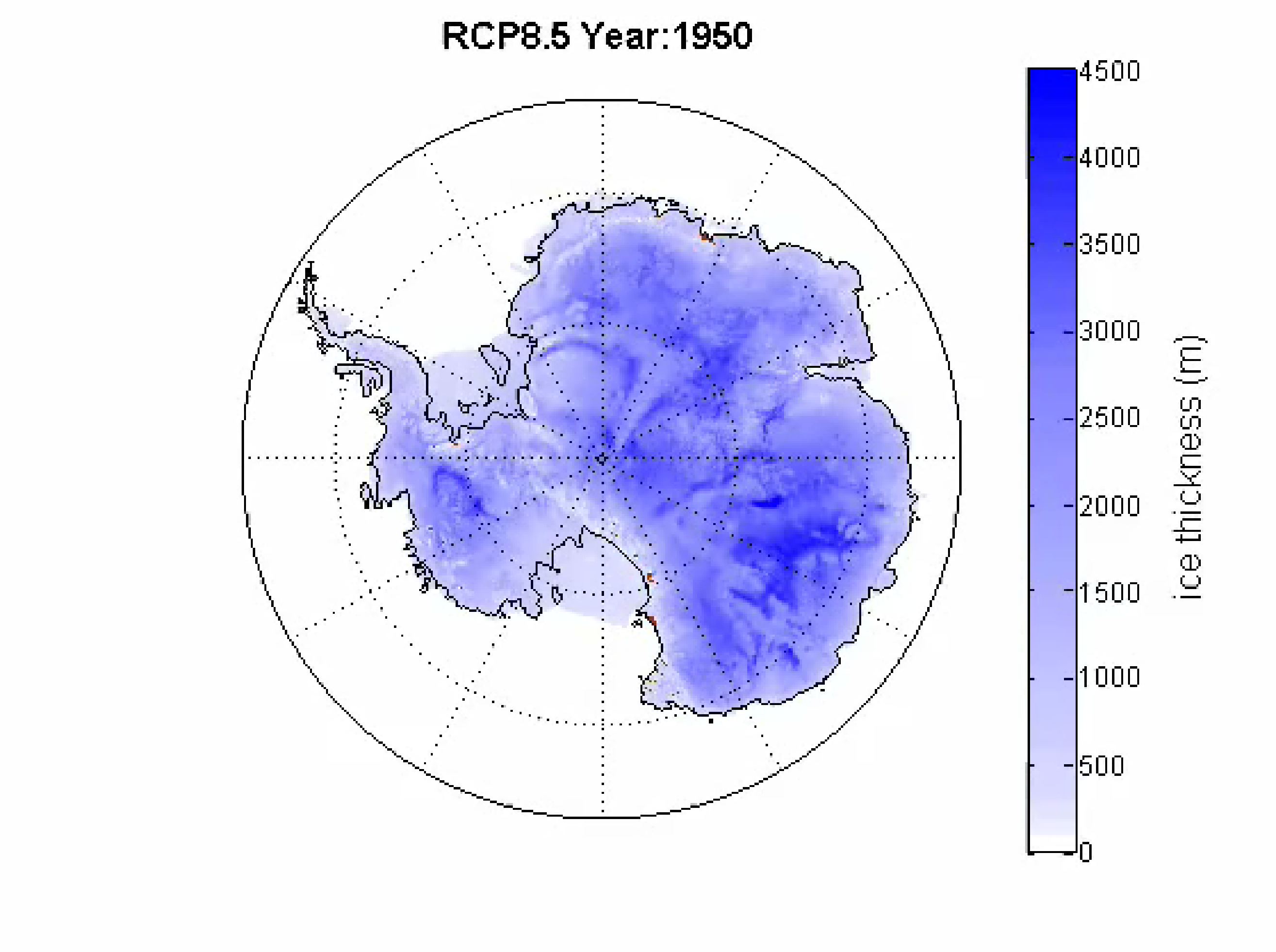
Future: If peak RCP8.5 (CO_2 ~2000 ppm) is maintained for 5000 years…

cf. Winkelmann et al., Science Adv., 2015

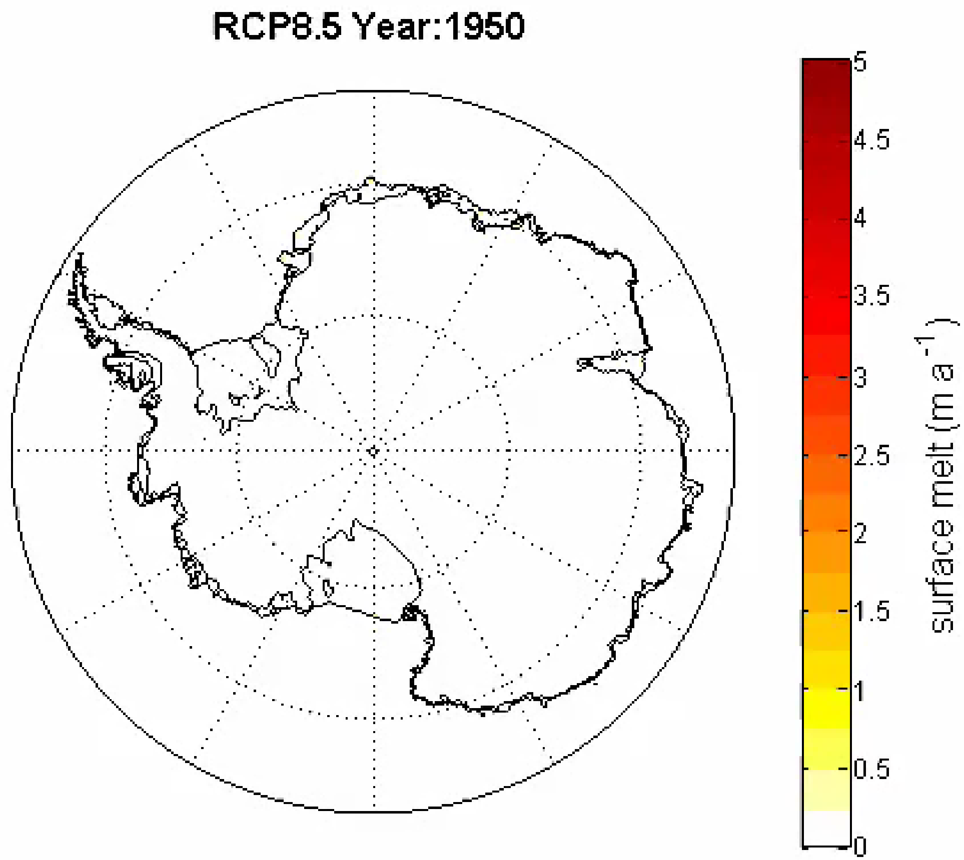




Ice thickness, 1950 to 2500, RCP8.5 (avi)



Surface melt, 1950 to 2500, RCP8.5 (avi)



Ice speed, 1950 to 2500, RCP8.5 (mov)

Summary

Large Ensembles

Calibration vs. last 20,000 years

Pliocene sea level targets

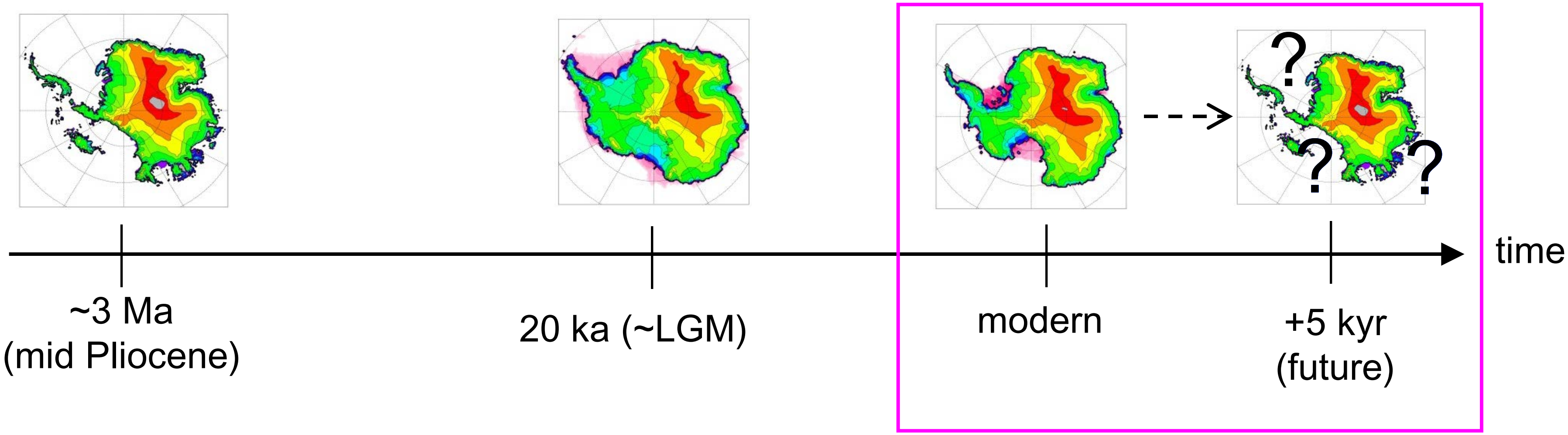
Drastic retreat mechanisms

LIG sea level target

RCP scenarios climate forcing

- Future atmospheric melting, hydrofracturing will be important at Antarctic margins
- Drastic future sea-level rise with RCP 8.5 (> ~10 m by 2500 CE)
- Future results depend on actual mid-Pliocene sea-level rise (~5 m, or 15 m?)
- Need to calibrate non-analog processes with deep-time data – PLIOMAX project

Outline



(1) Calibration vs. last 20,000 years with Large Ensembles

(2) Add drastic warm-climate mechanisms to capture Pliocene sea-level rise

(3) Apply to future 5000 years, for RCP 2.6 to 8.5 scenarios

(4) Simple bedrock replaced by global Earth-GIA-sea level model

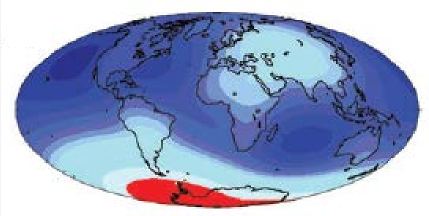
Coupled ice sheet – Earth models

in collaboration with N. Gomez (McGill) and J. Mitrovica (Harvard)

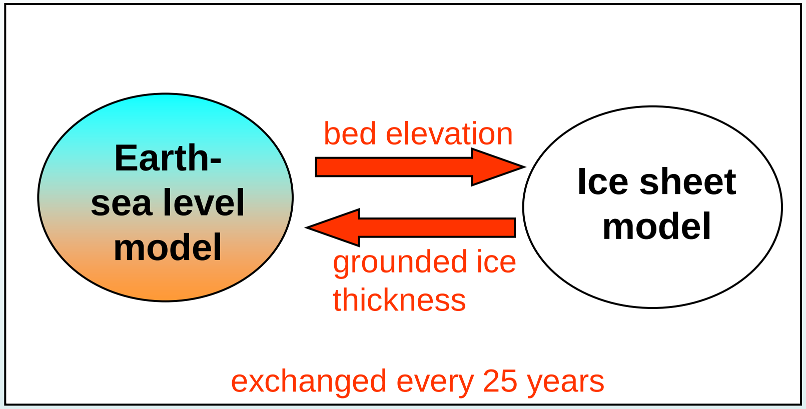
Earth-sea level model

(Kendall et al., 2005; Gomez et al., 2010)

- Pseudo-spectral solution method (degree 512, ~40 km)
- Viscoelastic profile vs. depth, spherically symmetric
- Includes Earth rotational perturbations



Sea level fingerprint of WAIS collapse (Mitrovica et al., 2009)



Earth-sea level model

bed elevation

grounded ice thickness

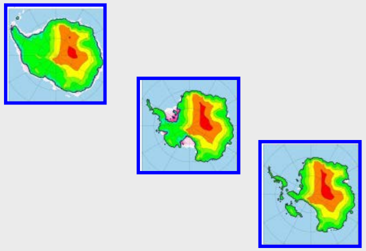
Ice sheet model

exchanged every 25 years

3-D ice sheet model

(Pollard and DeConto, 2012):

- 10 to 40 km grid resolutions
- Hybrid combination of sheet and shelf flow equations, parameterized grounding-line flux



Gomez et al., 2012, 2013, 2015

Other coupled models (full Earth, interactive sea level):
deBoer et al., 2014
Konrad et al., 2015

Sea level variations simulated with global Earth model

Sea level change relative to global average rise, for:

Clark et al.,
Science, 2002

A) S. Laurentide melting:

B) W. Antarctic melting:

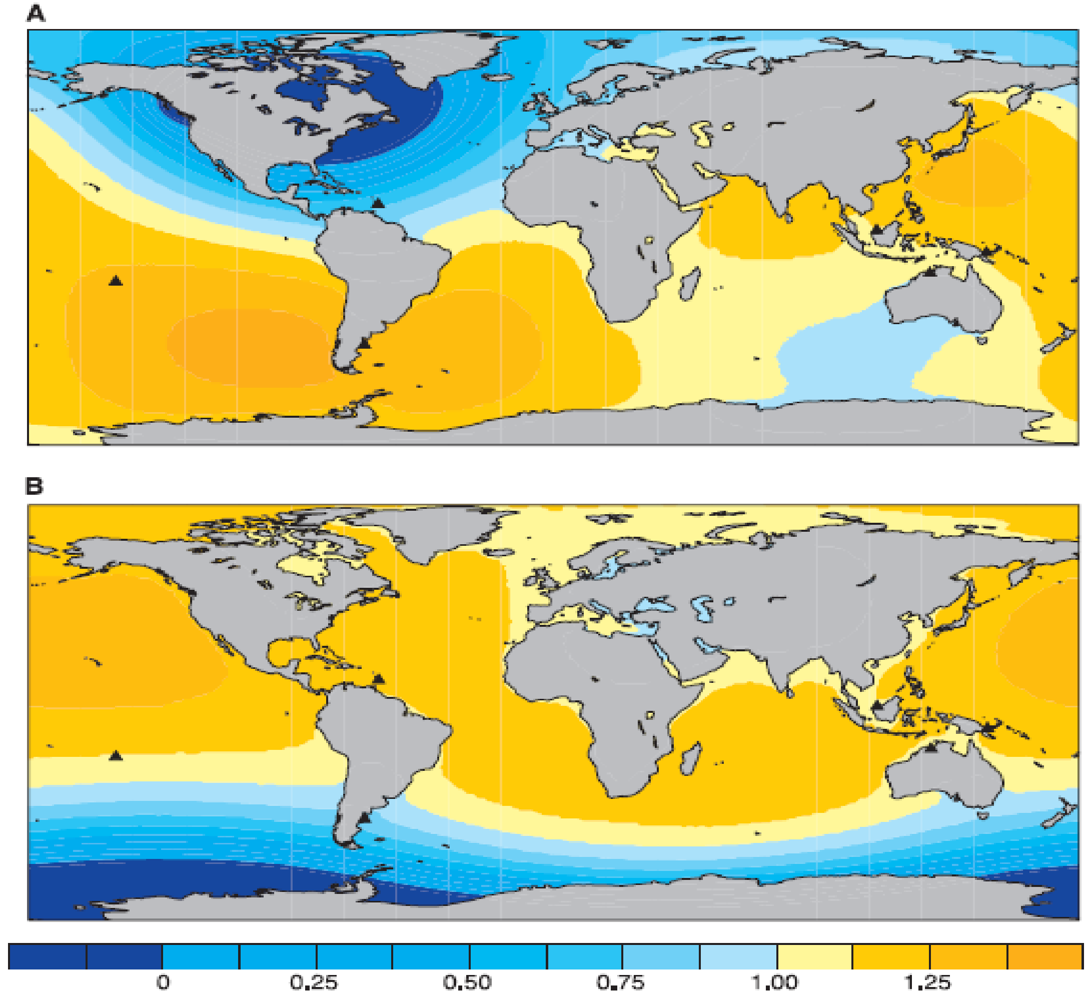
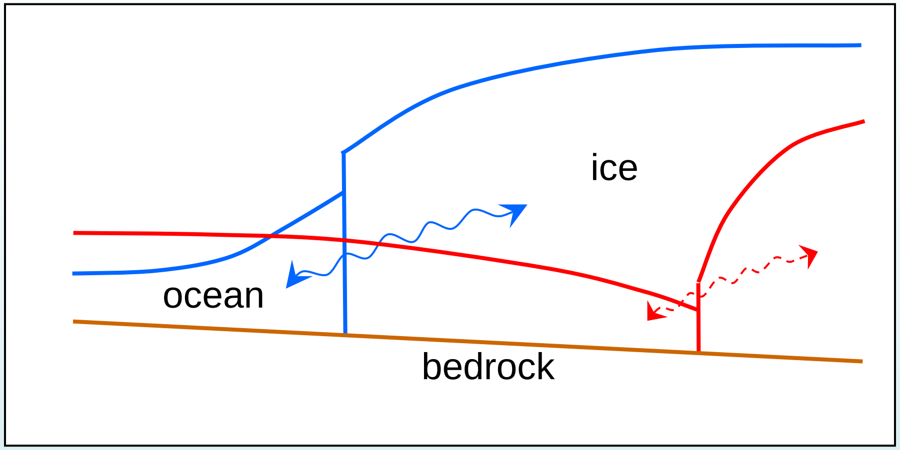


Fig 1. Normalized (dimensionless) sea-level change associated with melting from (A) the southern one-third of the Laurentide Ice Sheet and (B) West Antarctica, as they existed at the onset of the mwp-IA event. The predictions, which are described in detail in the text, assume that melting is proportional to ice height in this region relative to present-day values, as given by the ICE-3G deglaciation model (*21*). The predictions are normalized by the eustatic sea-level change; the color scale refers to fractions of this change. The small triangles denote the locations of six far-field sites considered in Table 1: (from left to right) Tahiti, Argentine Shelf, Barbados, Sunda Shelf, Bonaparte Gulf, and Huon Peninsula.

Ocean-ice self gravity: negative feedback

Ocean-ice gravitational effect: reduces Marine Ice Sheet Instability



Gomez et al., 2012, 2013, 2015

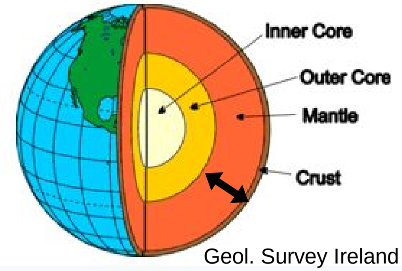
Nearby ocean depth is affected by gravitational attraction of ice mass.

Negative feedback during MISI retreat:

smaller interior ice mass
→ lower ocean
→ less water depth at grounding line
→ less ice thickness at grounding line (assumed to stay at flotation)
→ less ice flux across grounding line (Schoof, 2007)
→ less interior ice drawdown

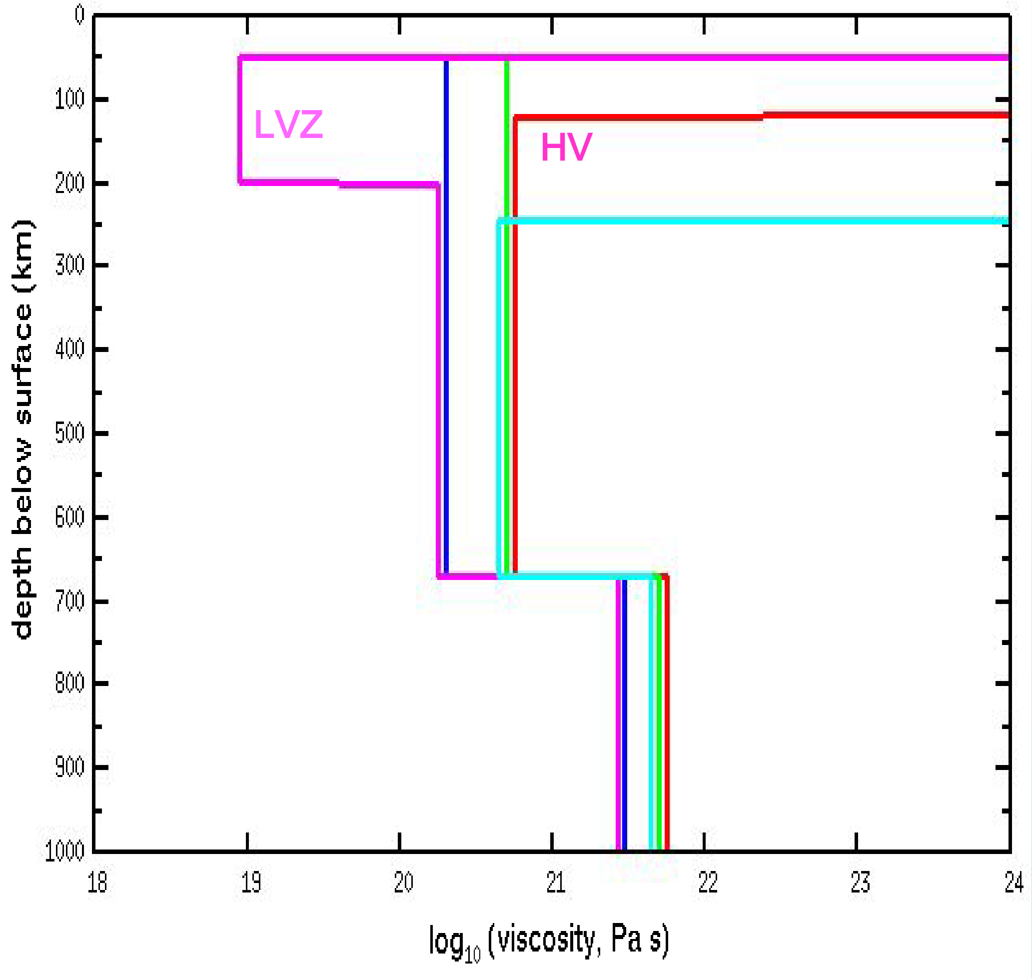
Viscoelastic profiles # 1 to 5

- Specify a range of viscosity profiles through lithosphere & mantle
- No lateral heterogeneity (for now)
- Elastic properties vs. depth as in PREM (Dziewonski and Anderson, 1981)



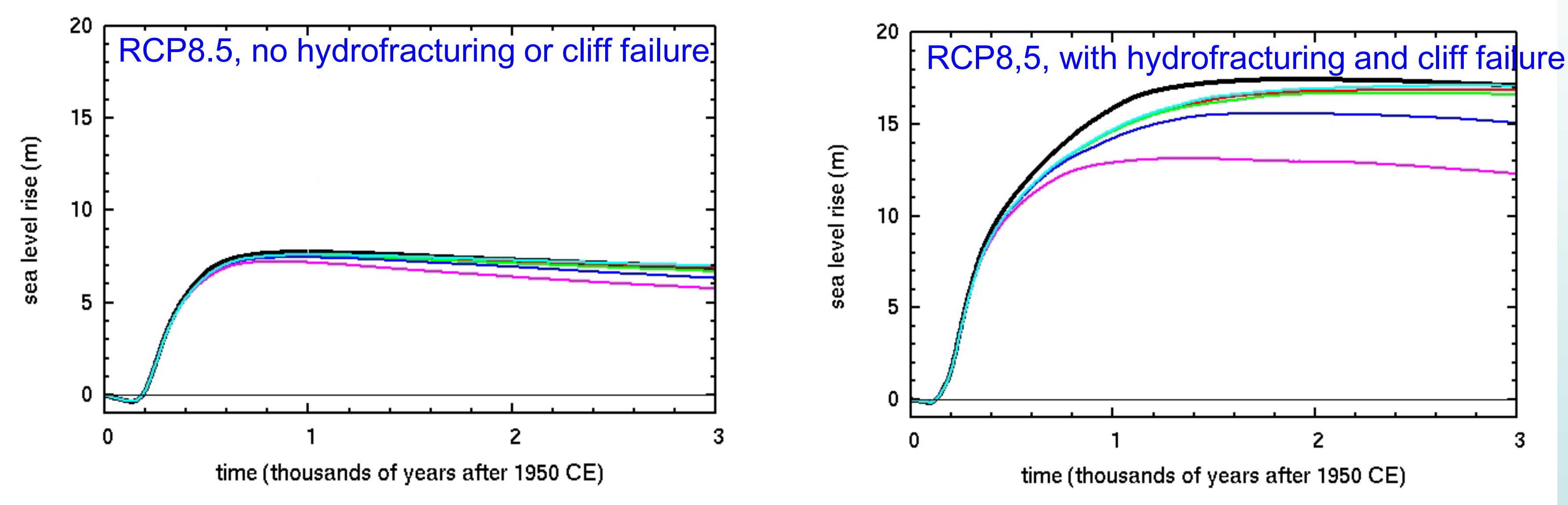
Geol. Survey Ireland

- (1) **HV** (high viscosity, ≈ previous global-based models)
- (2) **50 HV** (thinner lithosphere)
- (3) **50-p2-3** (variation on 50 HV)
- (4) **LVZ** (very low viscosity zone, ≈ W. Antarctica)
- (5) **ThLi** (very thick lithosphere)



Future 3000 years, with viscosity profiles 1-5 and ELRA

(1) HV (high viscosity, ≈ previous global-based models)
(2) 50 HV
(3) 50-p2-3
(4) LVZ (very low viscosity zone, thin lith., ≈ W. Antarc.)
(5) ThLi
(6) simple ELRA bed (τ =3000 yr)



- Earth models produce less sea-level rise than simple ELRA model
  - due to full Earth physics, and self-gravitation negative feedback.
- LVZ profile produces more reduction in SLR
  - due to faster and more localized rebound, less grounding-line retreat.

Similar results in:
Gomez et al. (Nat. Comm., 2015)
Konrad et al. (EPSL, 2015)

Future snapshots at +3000 yr (~5000 CE), HV vs. LVZ

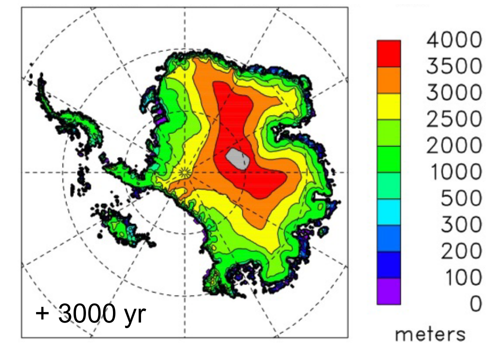
RCP 8.5, with hydrofracturing and cliff failure

- LVZ rebound is faster, more localized than HV
- So LVZ has shallower beds, less grounding-line retreat, thicker marginal ice, less equiv. sea level rise

Similar results in Gomez et al. (Nat. Comm., 2015)

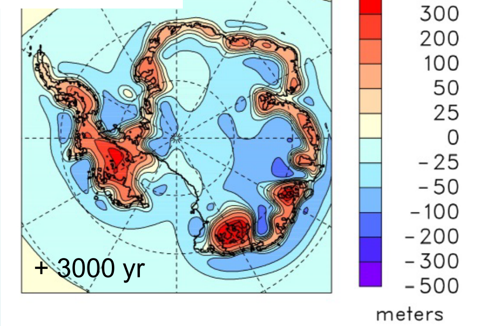
ice elevation

LVZ



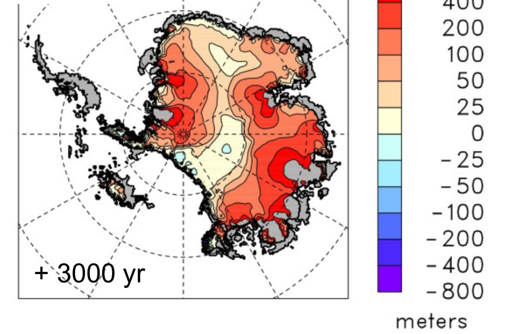
Δ(bed elevation)

LVZ - HV



Δ(ice thickness)

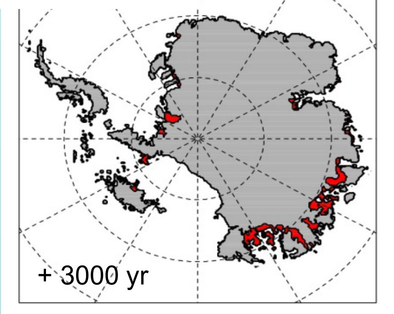
LVZ - HV



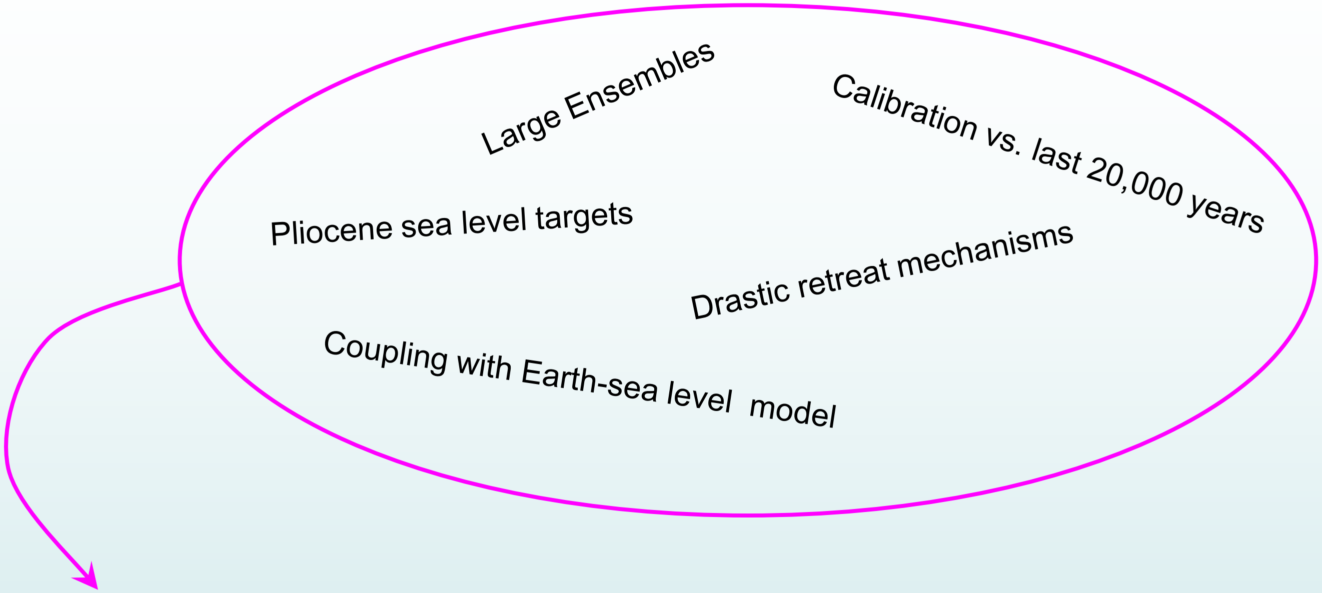
Δ(grounded ice area)

red = LVZ, not HV

blue = HV, not LVZ



Summary



Large Ensembles

Calibration vs. last 20,000 years

Pliocene sea level targets

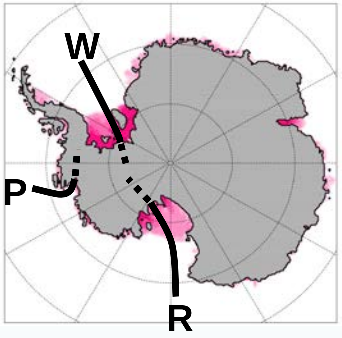
Drastic retreat mechanisms

Coupling with Earth-sea level model

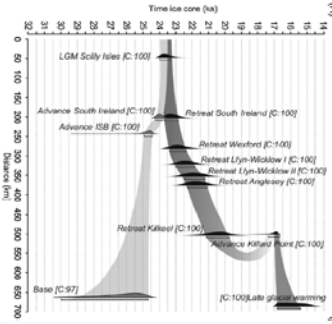
- Drastic future sea-level rise with RCP 8.5 (~10 m by 2500 CE). But…
- Future results depend on actual mid-Pliocene sea-level rise (~5 m, or 15 m?)
- Need to calibrate non-analog processes with deep-time data – PLIOMAX project
- Replacing ELRA with Earth-sea level model reduces future SLR (full Earth, self-gravitation).
- larger SLR reduction with Low-Viscosity-Zone profile (faster, localized rebound).

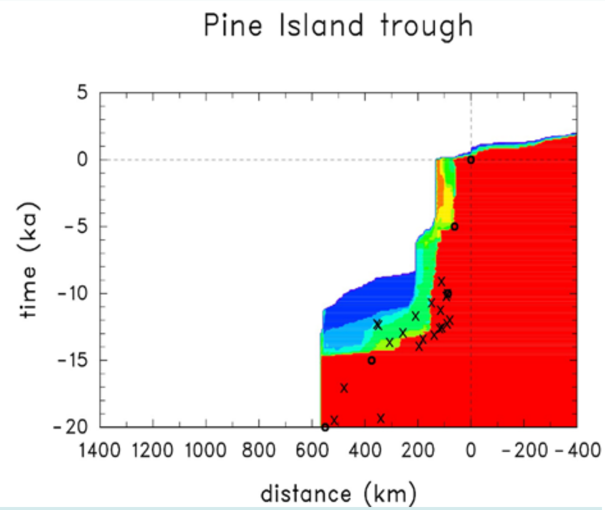
End

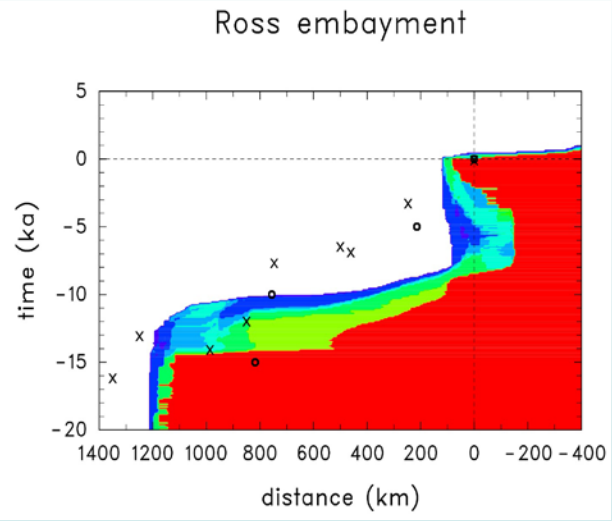
Probability density of grounded ice, centerlines

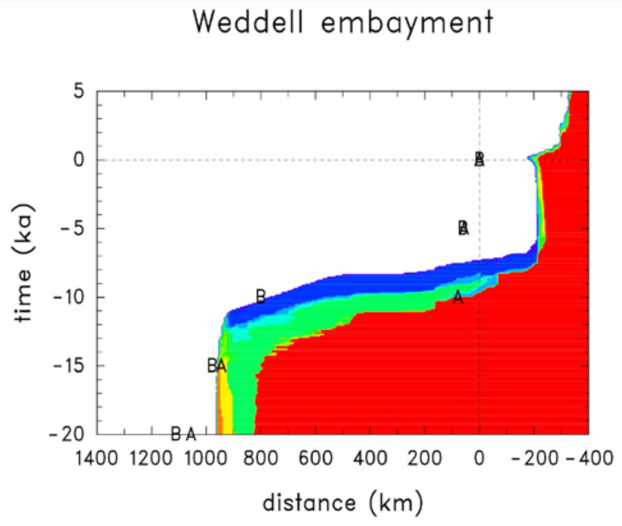


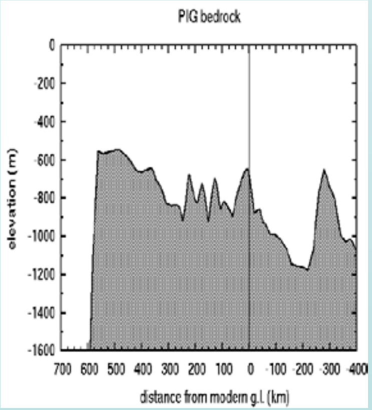
Chiverrell et al.,
J. Quat. Sci., 2013

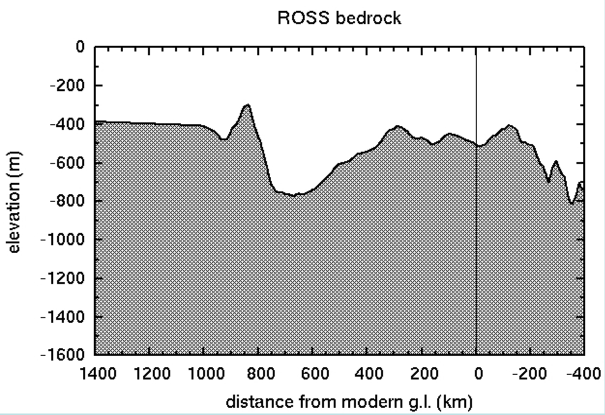


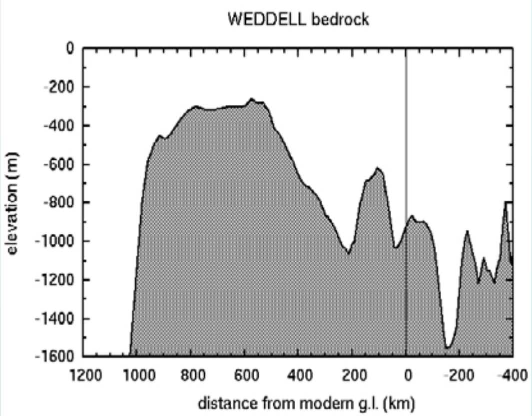


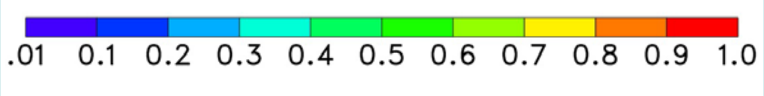




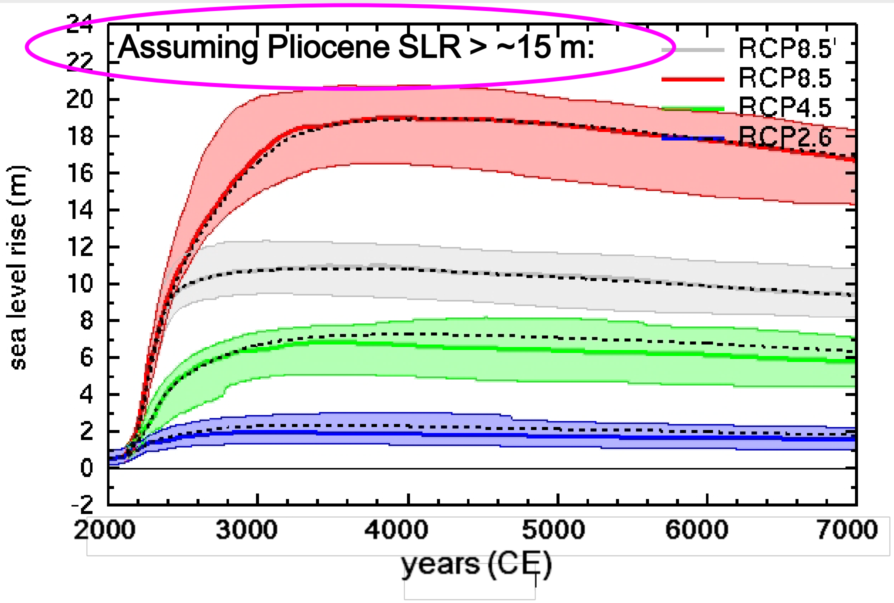


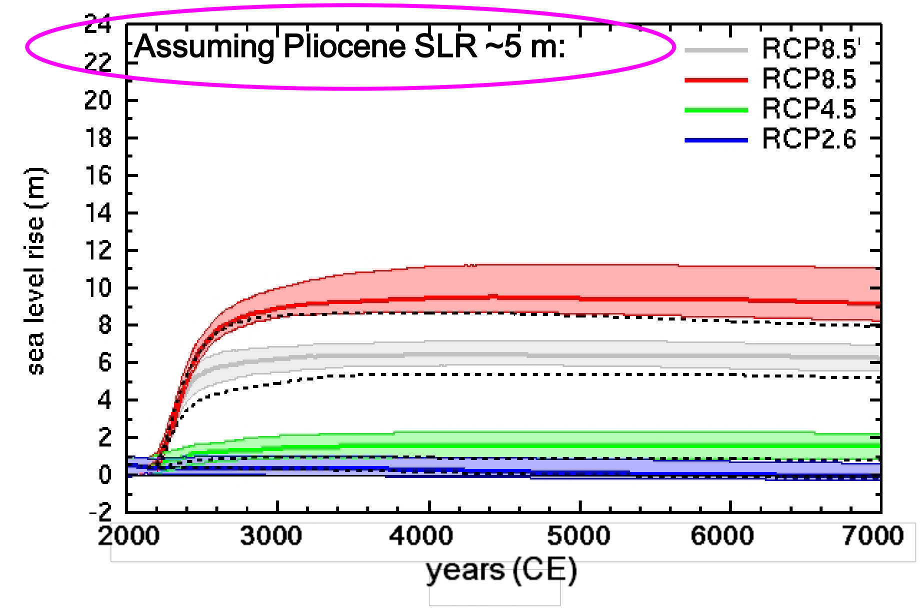




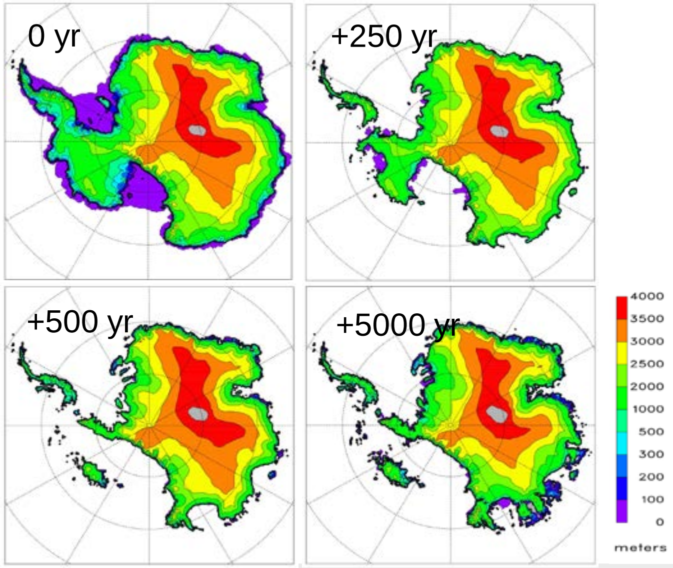


Sea-level-rise envelopes for the various RCPs



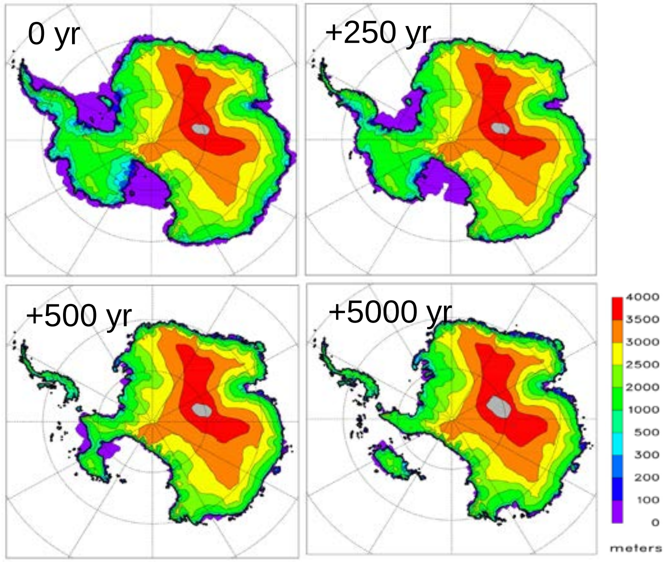


RCP8.5, *VCLIF*=3, *CREVLIQ*=100



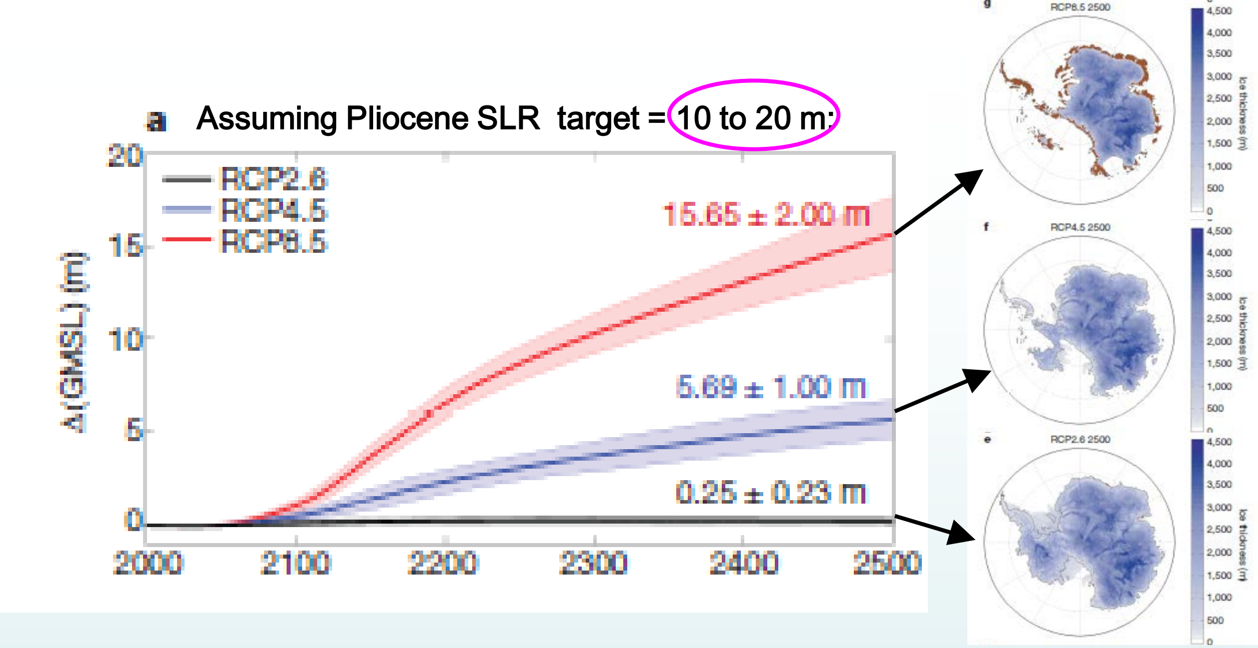
DeConto and Pollard, in review

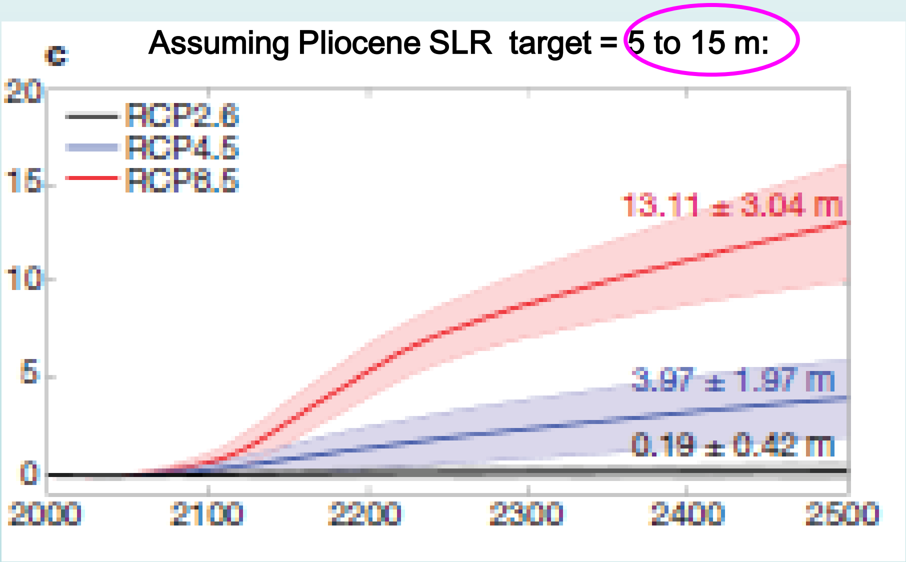
RCP8.5, *VCLIF*=0, *CREVLIQ*=0



Large ensemble, type 2: Pliocene and Last Interglacial sea level targets (pass/fail)

(DeConto and Pollard, Nature, 2016).

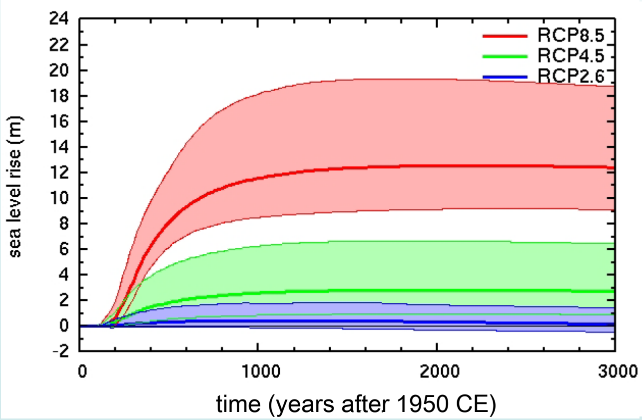

Assuming Pliocene SLR target = 10 to 20 m:


Assuming Pliocene SLR target = 5 to 15 m:

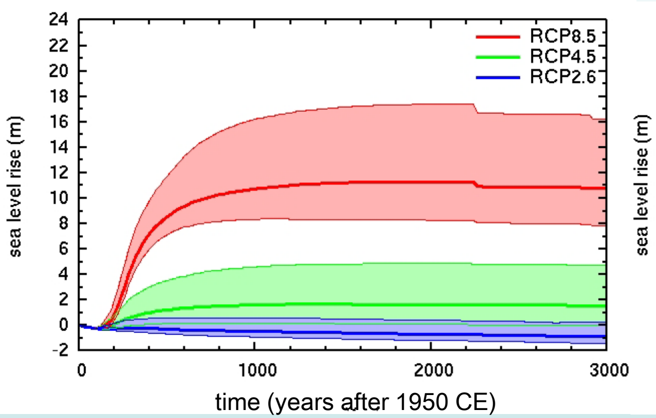
Large Ensembles, future 3000 years, ELRA vs. HV vs. LVZ

Large Ensembles for each RCP, varying hydrofracturing and cliff parameters.

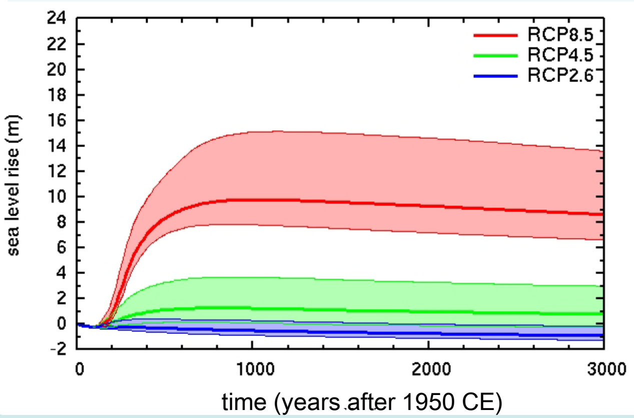
Scoring vs. last deglacial observations (*not* vs. Pliocene SLR).



ELRA bed model



Earth model, profile HV



Earth model, profile LVZ

- Again, Earth profile HV produces less SLR than ELRA (full Earth, self-gravitation)
- Earth profile LVZ produces less SLR than HV (faster, more localized rebound)

Summary

- Simple LE score-weighting is viable, but only for Full Factorial sampling.
- Basal sliding coefficients on continental shelves *ARE* large (slippery).
- LGM ice volumes *WERE* small...ESL contribution was only ~5 to 8 m.
- With RCP8.5, potential for drastic future sea-level rise:
    - Need to calibrate non-analog processes (hydrofracturing, ice-cliff failure) with deep-time data.
    - Future SLR envelopes depend on actual mid-Pliocene sea-level rise.

Limitations:

- Not definitive! Just maps out a procedure to calibrate vs. past, produce future envelopes.
- Only parametric uncertainty is addressed. Should address structural uncertainty, other data-scoring strategies.

Ice thickness, 1950 to 2500, RCP8.5 (mov, rainbow)

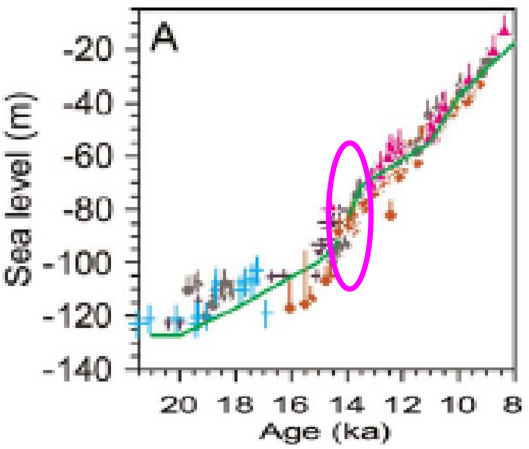
Ice thickness, 1950 to 2500, RCP8.5 (mov)

Surface melt, 1950 to 2500, RCP8.5 (mov)

Meltwater Pulse 1A

- Rapid global mean sea-level rise, ~14-18 m, ~14.6 to ~14.3 ka (Carlson and Clark, 2012; Deschamps et al., 2012)
- Sea-level fingerprinting suggests significant contribution from Antarctica (> ~5 m, Clark et al., 2002; Bassett et al., 2005)

Carlson and Clark, Rev Geophys., 2012



Clark et al., Science, 2002

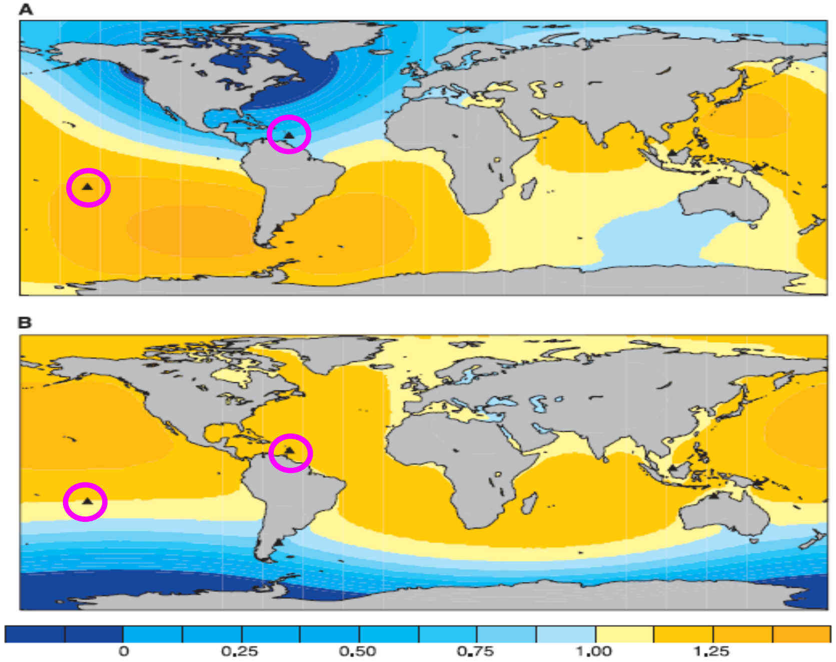


Fig 1. Normalized (dimensionless) sea-level change associated with melting from (**A**) the southern one-third of the Laurentide Ice Sheet and (**B**) West Antarctica, as they existed at the onset of the mwp-IA event. The predictions, which are described in detail in the text, assume that melting is proportional to ice height in this region relative to present-day values, as given by the ICE-3G deglaciation model (*21*). The predictions are normalized by the eustatic sea-level change; the color scale refers to fractions of this change. The small triangles denote the locations of six far-field sites considered in Table 1: (from left to right) Tahiti, Argentine Shelf, Barbados, Sunda Shelf, Bonaparte Gulf, and Huon Peninsula.