Effect of Ocean Warming on West Antarctic Ice Streams and Ice Shelves

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Ice Sheet Mass Balance/WAIS Dynamics

-<u>Mass Balance</u> = (Ice/Snow Accumulation) – (Surface melting, ice outflux, etc.)

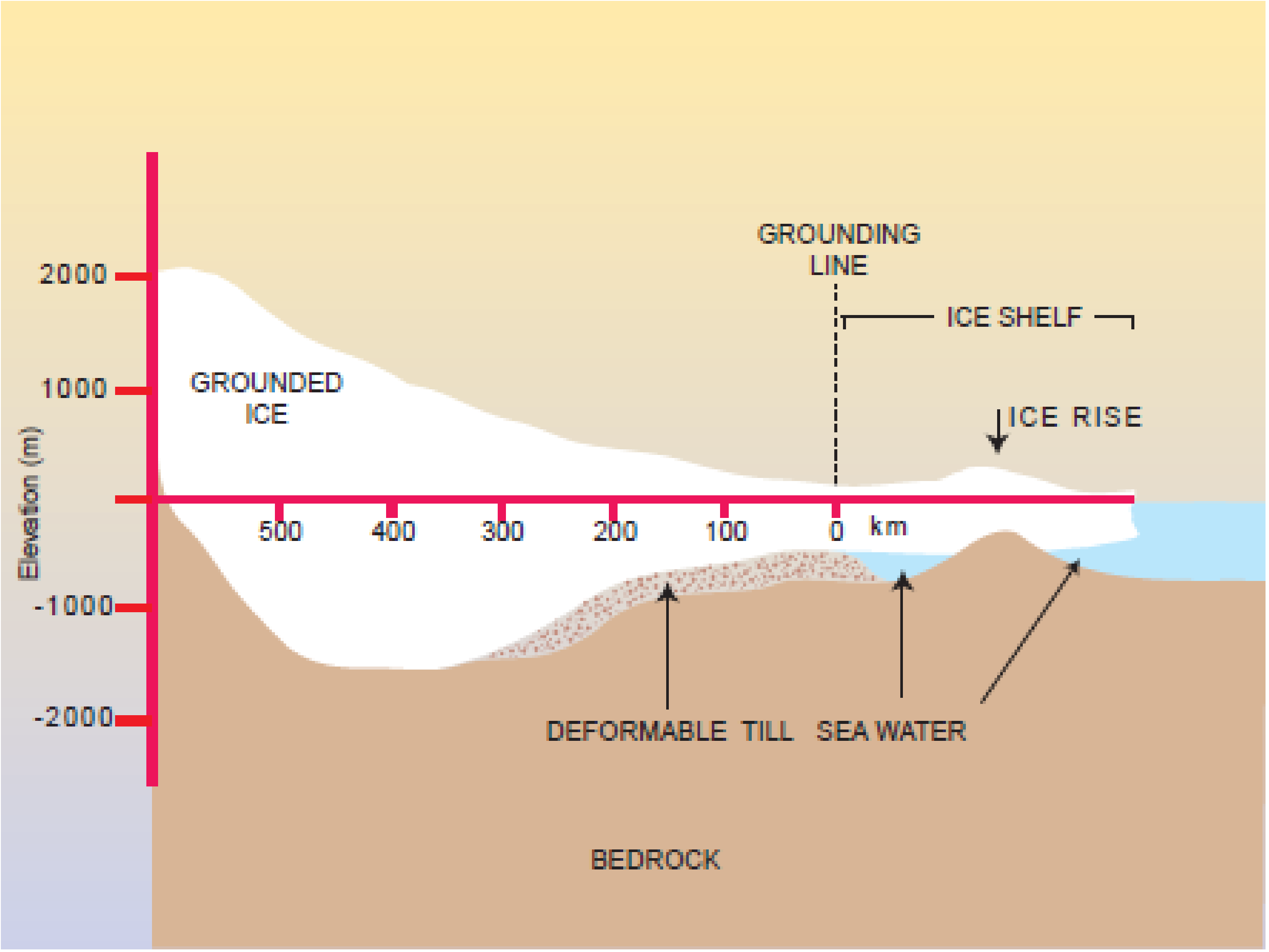
- -1) Greenland – -50 to -100 Gt/yr
- -2) Antarctica - +50 to -200 Gt/yr
  - -Positive mass balance (growth) for East Antarctica, mass loss for West Antarctica
  - -West Antarctic Ice Sheet (WAIS) has potential for collapse

-WAIS is classified as a marine ice sheet, i.e. part of it is grounded on land below sea level and the other part floats on the oceans as ice shelves

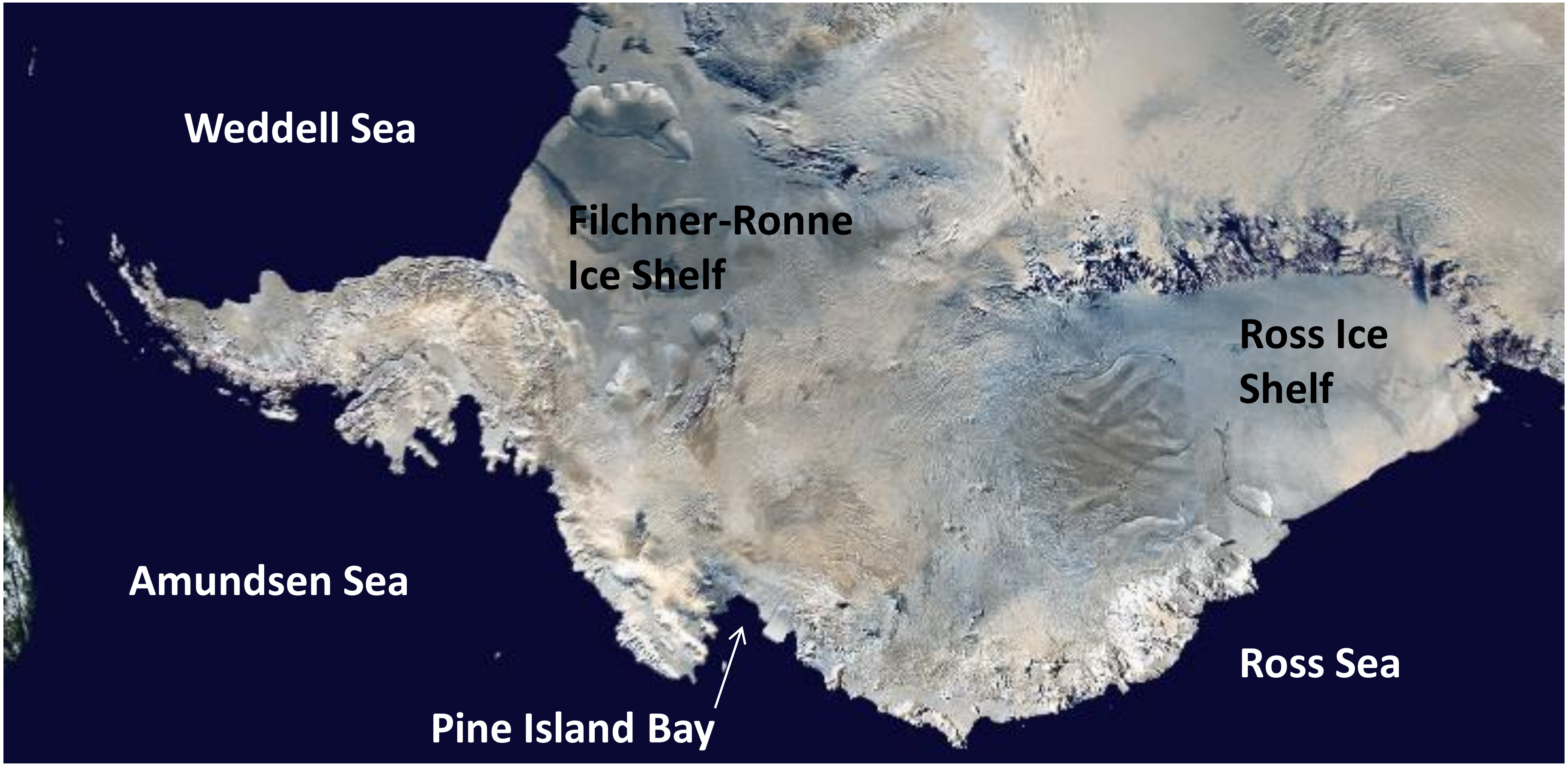
- -Dynamics of ice behavior at grounding line (junction of grounded ice with ice shelf) signifies potential instability.
- -Over 90% of ice loss flows through only 10 ice streams

-Total collapse of WAIS would lead to sea level rise of 4-6 meters

Marine Ice Sheet Cross-Section



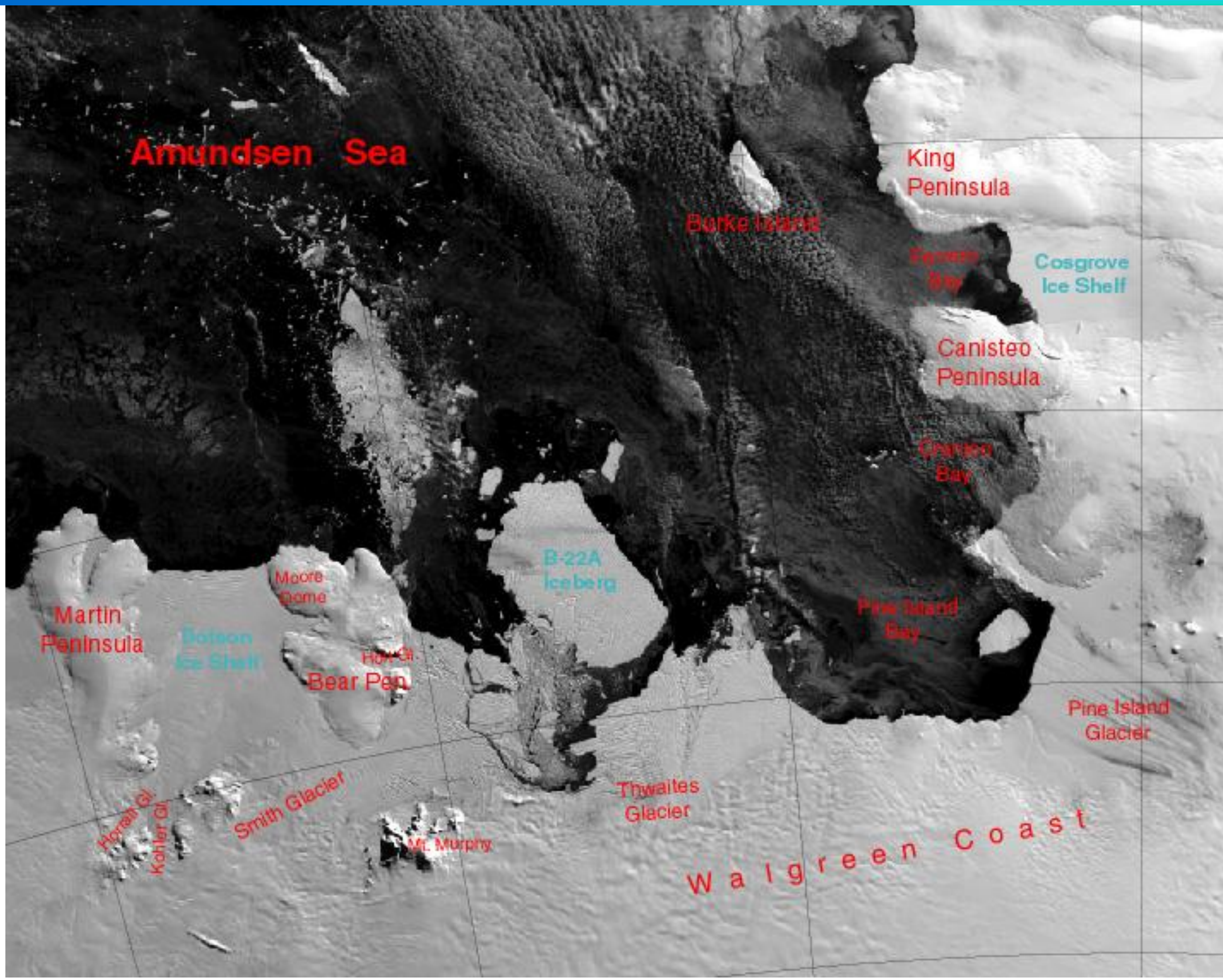
Oppenheimer, 1998



http://en.wikipedia.org/wiki/Antarctica

- ~50% of WAIS ice discharge flows onto Ross Ice Shelf through 5 ice streams
- ~40% flows into Amundsen Sea region through Pine Island Glacier (PIG) and Thwaites Glacier ice streams
    - PIG ice stream is the largest and primary ice stream of entire WAIS.

Amundsen Sea Close-up



http://nsidc.org/data/iceshelves_images/pine.html

Amundsen Sea Ice Loss and Ice Shelf Elevations

-Grounded AS sector of WAIS loses 51 ± 9 km^3 of ice per year

- -Grounding line of PIG retreated at a rate of 1.2 ± 0.3 km/yr
- -PIG thinning at a rate of 3.5 ± 0.9 m/yr

-All of the AS ice shelves have experienced simultaneous thinning and decreased elevations; suggests common forcing

Table 1. Area, Thickness, and Average 1992–2001 Rates of Elevation and Thickness Change of Ice Shelves Floating in the Amundsen Sea

Ice Shelf	Area (km^2)	Ice thickness[a] (m)	Elevation rate (cm $year^{-1}$)	Thinning rate (m $year^{-1}$)
Abbot	30,827	419	−6 ± 4	0.6 ± 0.4
Cosgrove	2,553	729	−8 ± 3	0.7 ± 0.4
Pine Island	2,365	657	−42 ± 4	3.9 ± 0.5
Thwaites	1,687	698	−59 ± 7	5.5 ± 0.7
Crosson	3,843	776	−49 ± 4	4.5 ± 0.5
Dotson	3,433	469	−36 ± 2	3.3 ± 0.4
Getz	31,186	899	−17 ± 6	1.6 ± 0.6

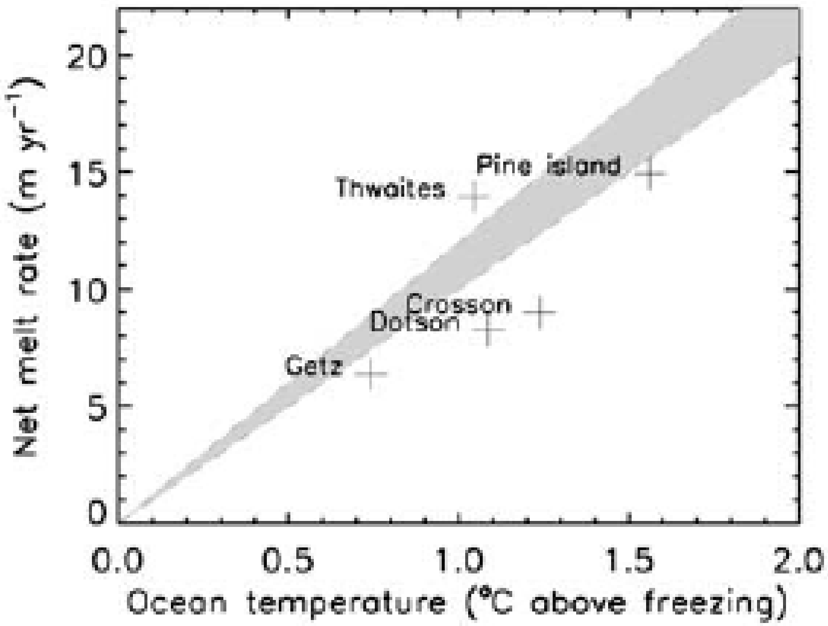
[a]Derived from the empirical relationship of [*Vaughan et al.*, 1995].

Shepherd, 2004

Possible causes for AS ice shelf and ice stream thinning

-Computer simulations show that internal factors (i.e., reduction in inland basal shear stress and lateral stress, inland flow disturbances, et. al.) are not able to reproduce simultaneous thinning
-Snowfall variability too miniscule to explain high rates of thinning
- Must look at <u>external</u> disturbances

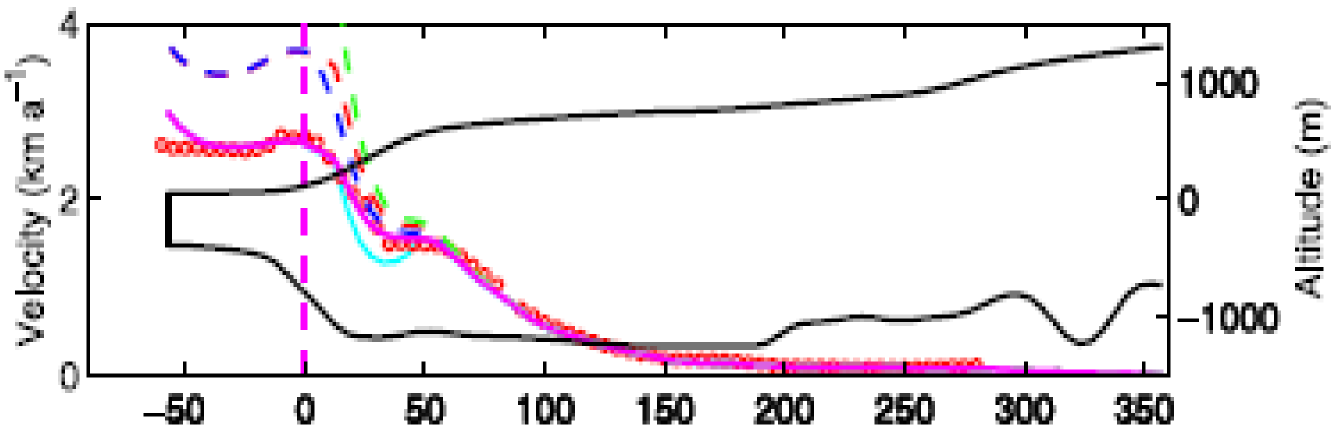
-Shepherd, et. al. hypothesize that basal melting is the key ice shelf elevation dependency
-Propose ocean warming to be the external disturbance (see plot)
-Possible proof: measured freshening of Ross Sea of ~ 46 Gt/yr
-Payne, et. al. have created models to predict ice stream behavior due to such an external disturbance



Net melt rate vs. Ocean temperature.
Shepherd, 2004

Ice Stream Modeling: Default Calibrated Ice Stream

Payne, 2004



Velocity vs. Distance from Grounding line

-Payne, et. al. use a three-dimensional stress balance model to predict thinning of ice streams.

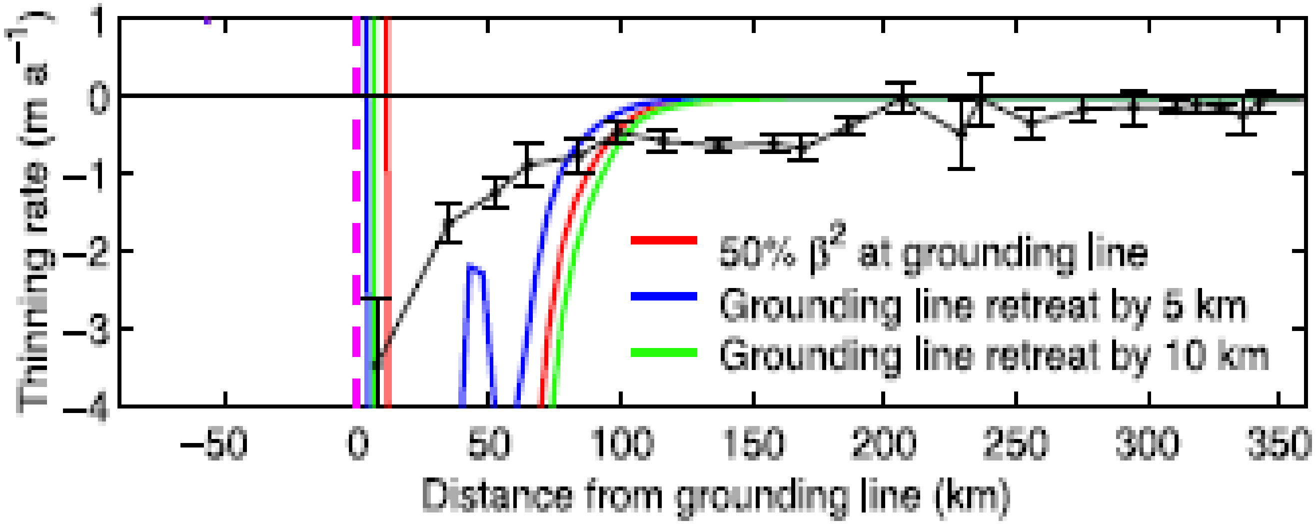
-The above plot displays the default calibrated ice stream velocities (with no perturbations) with the grounding line at 0 km

-Calibration was performed using interferometry observations of ice velocities and known ice shelf boundary conditions

-Note three main regions of ice stream based on velocity

Instantaneous Response to Decreased Basal Drag

Payne, 2004



Instantaneous thinning rates vs. distance from grounding line

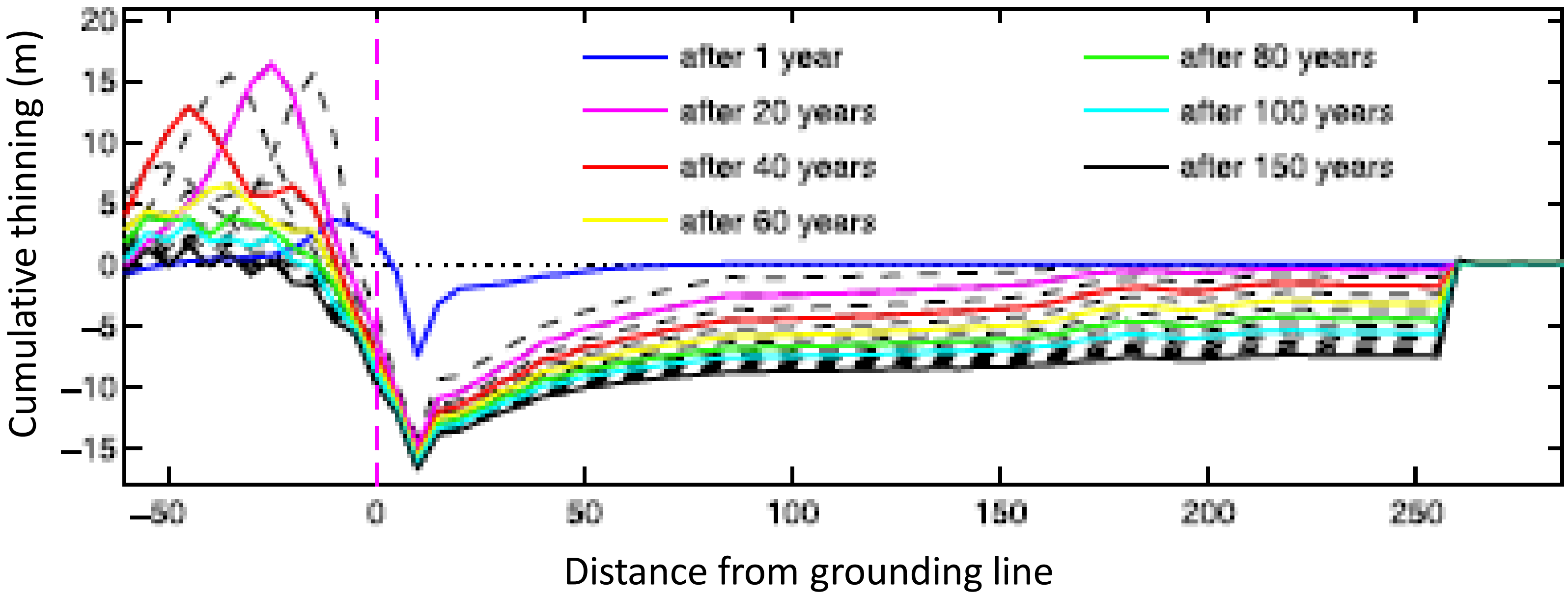
-To simulate basal melting of oceans, Payne, et. al. applied a reduction of basal drag near grounding line and predicted instantaneous response of thinning rates (solid red line).

-However, prediction does not agree with observations farther upstream (black line with error bars).

-Must look at <u>delayed</u> response.

Delayed Response to Decreased Basal Drag

Payne, 2004



-After 1 year, the thinning has propagated ~50 km upstream of grounding line.
-After only 10 years (dashed line between 1 year and 20 year lines), the thinning has propagated > 150 km upstream.
-Therefore, thinning of ice streams can occur fairly rapidly
-Continuous decrease in basal drag can increase predicted thinning

WAIS Stability Issues

-Large ice stream velocity fluctuations and inland thinning rates suggest potential WAIS instability

-Some models predict downward sloping bedrock can lead to runaway ice stream flow due to ice shelf melting or disintegrating → Unstable

-Does not incorporate role of non-bedrock sediment, i.e. deformable till, in movement of ice streams

-Model by MacAyeal incorporates deformable till to show oscillatory response in ice sheet growth and discharge to climate change and global sea levels → Potential Stability

-None of the models fully incorporate all factors such as role of basal melting of the ice shelves, sub-ice topography, basal layer thermodynamics, et. al.

Anthropogenic Forcing on WAIS: Air Temperatures

-It has been proved that global mean air temperature rise can best be explained by a combination of natural and anthropogenic forcing.

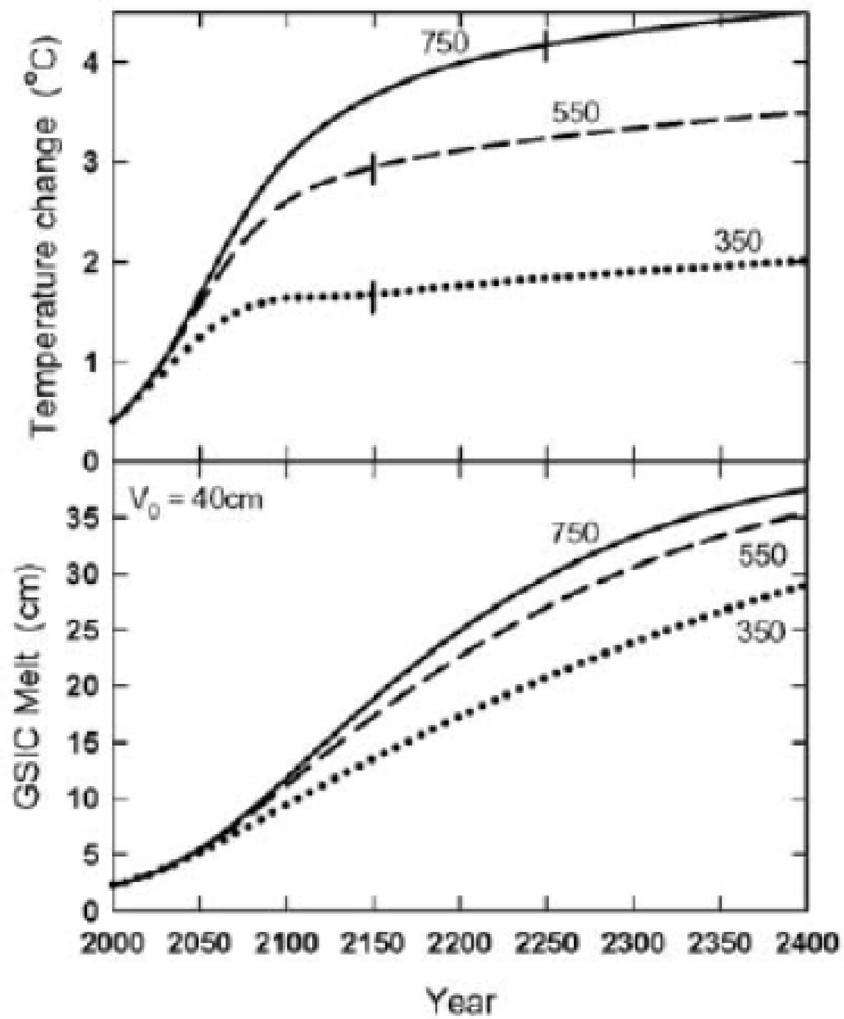
-What about direct effect of air temperature on ice stream thinning?

-Wigley and Raper derive a modification for the IPCC TAR formula for Glacier and Small Ice Cap Melt (GSIC):

$$g_s(t) = g_s(1990)\exp(-0.8\beta_0 t / V_0) + V_0\{1 - \exp(-0.8\beta_0 t / V_0)\}$$

-With an input of three different CO2 concentrations, Wigley and Raper predict large temperature changes but nearly uniform melt rates.

-Low melting sensitivity to greenhouse gases



Wigley and Raper, 2005

Anthropogenic Forcing on WAIS: Ocean Temperatures

-Therefore, temperature rise due to increased CO_2 levels has minimal direct effect on WAIS ice stream and ice shelf thinning (recall minimization of surface melting to ice outflux)

-However, increased temperatures result in increased precipitation and snowfall, leading to a freshening of nearby ocean waters

- -Decreased salinity would decouple the convective exchange between the warm surface waters and colder deep waters
- -Result in warmer surface waters

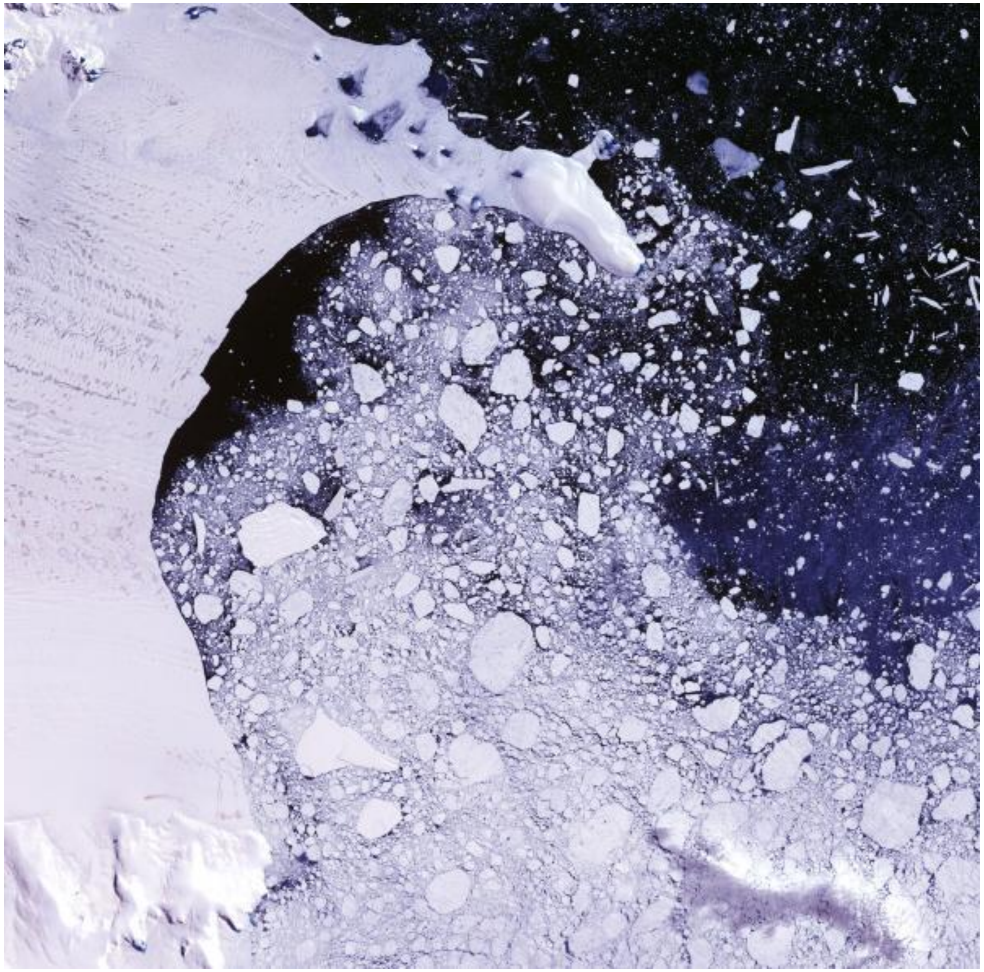
-Atmospheric General Circulation models predict increase of 0.5-1.5 °C in surface and subsurface waters by 2050 and 3 °C by 2200

Possible Future for WAIS

-If basal melting of the ice shelves continues and increases in magnitude, ice streams will continue to remain active and thinning will accelerate.

-Eventually, even the Ross Ice Shelf could drain away in about 200 years, leading to more freshening of the surrounding ocean waters

-Initial sea level of rise of 0-19 cm per century would give way to "collapse" phase where sea levels will rise ~60-120 cm per century



-Larson Ice Shelf collapse in 2002
http://www.sciencedaily.com/releases/2008/02/080210100441.htm

References

Lemke, P., J. Ren, R.B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas and T. Zhang, 2007: Observations: Changes in Snow, Ice and Frozen Ground. In: C*limate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Oppenheimer, M., 1998: Global warming and the stability of the West Antarctic Ice Sheet. *Nature*, **393**, 325-332.

Payne, A., Vieli, A., Shepherd, A., Wingham, D., and Rignot, E., 2004: Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans. *Geophysical Research Letters*, **31**, 1-4.

Shepherd, A., Wingham, D., and Rignot, E., 2004: Warm ocean is eroding West Antarctic Ice Sheet. *Geophysical Research Letters*, **31**, 1-4.

Wigley, T.M.L. and Raper, S.C.B., 2005: Extended scenarios for glacier melt due to anthropogenic forcing. *Geophysical Research Letters*, **32**, 1-5.