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

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Abstract

The Intergovernmental Panel on Climate Change (IPCC) has deemed the Western Antarctic Ice Sheet (WAIS) as *very likely* to have contributed to sea level rice over the past two decades, estimating a loss of 44 ±13 Gt/yr. Focus has shifted to the behavior and dynamics of the WAIS ice streams since ~90 % of the outward ice flux flows through the ice streams. The behavior and movement of the ice streams is directly coupled with the condition of the ice shelves they flow onto. Recent satellite radar altimetry observations have shown that the three main ice shelves in the Amundsen Sea have simultaneously decreased in elevation, pointing to warming oceans as the common cause. Warming oceans have increased basal melting at the bottom of the ice shelves, causing them to thin. Models have shown that the increased basal melting can produce perturbations at the grounding line that will cause upstream ice to thin at distances ~200 km from the grounding line. This additional coupling of the ice stream to inland ice has signified a potentially dangerous instability of the WAIS that could cause it to eventually enter a rapid "collapse" phase where it would contribute 60-120 cm of sea level rise for 5-7 centuries. In terms of anthropogenic forcing, increased precipitation accompanying rising global temperatures may have decreased the salinity of the surrounding oceans, decoupling the warm ocean surface with the colder deep waters. The result is the possible warming of the surface and subsurface waters, leading to the basal melting of the ice shelves. So far, computer models have not been able to fully implement all of the dynamic forces involved with the flow of the ice streams, so the stability issue of the WAIS is not fully resolved. Nevertheless, the combination of observations of ice shelf thinning and model predictions of inland thinning demand that more attention should be spent to modeling ice streams and monitoring ocean conditions.

Introduction

With the advent of global warming, the behavior and response of the cryosphere to the increasing global temperature has become an issue of great interest. Of particular importance is the contribution of the melting ice sheets at Greenland and Antarctica to global sea level rise. The IPCC (Intergovernmental Panel on Climate Change) 2007 report states that those ice sheets "very likely" have been causing a rise of sea level over the time span of 1993 to 2003. Quantitatively, the IPCC estimates a mass balance of -50 to -100 Gt/yr for Greenland and +50 to -200 Gt/yr for the entire Antarctic Ice Sheet for the years 1993 to 2003 (IPCC, 2007). This report will focus on the current mass balance and dynamics of the West Antarctic Ice Sheet (WAIS) since there is a general consensus that it poses the most immediate threat to sea level rise due to its potential instability (Oppenheimer, 1998). It has been calculated that if the entire ice sheet were to melt, the global mean sea level would rise by approximately 4-6 meters, which would prove to be devastating to coastal areas, cities, and habitats (Oppenheimer, 1998). Even though such a complete release of ice is very unlikely, the potential danger posed by the ice sheet in conjunction with rising global temperatures has drawn an increased amount of interest. There are roughly two questions of main concern on the WAIS: 1) What are the forcing functions causing melting and are they a result of human actions, and 2) What are the dynamics and response of the ice sheet to the forcing functions and how will the subsequent response affect sea level rise. This report will evaluate several current theories and models as well as examine the current known facts about the behavior of the WAIS.

General Mass Balance of WAIS

Overall, the mass balance of an ice sheet is a balance between the amount of snow accumulation (positive mass balance) versus surface melting, runoff, ice discharge, etc. (negative mass balance). To measure these quantities, a wide variety of measurement methods have been developed. *In situ* measurements are direct measurements of quantities such as ice velocity, surface characteristics, ice sheet depth, et. al. (IPCC, 2007). These measurements are generally fairly accurate yet cannot efficiently cover wide areas of the ice sheet. Remote sensing methods are used to measure mass balance over the entire ice sheet and can be performed by airborne/satellite altimetry, Interferometric Synthetic Aperture Radar (InSAR), gravity field measurements, and other methods. With these methods, the drawback is a higher degree of uncertainty and bias between the measured quantities and the actual quantities. Nevertheless, both *in situ* and remote sensing measurements have yielded very useful information about ice sheet mass balances. Figure 1 displays the cross-section of an ice sheet with its different components. The terminology in the picture will be used throughout the report.

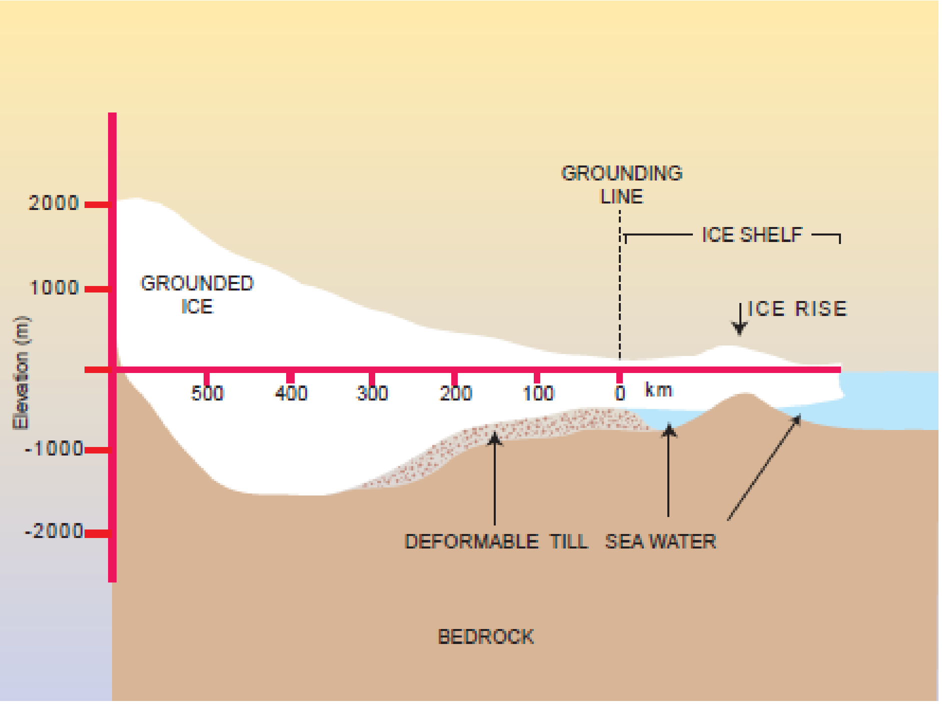

Figure 1. Cross-section of an Ice Sheet. (Oppenheimer, 1998)

The IPCC 2007 report estimates a mass growth for East Antarctica of 20 ± 21 Gt/yr and a mass loss for West Antarctica of 44 ±13 Gt/yr with the balance of the Antarctic Peninsula not assessed (IPCC, 2007). These figures were obtained as an average of the estimates obtained through different measurement methods. Most figures tend to agree upon a growth in East Antarctica and shrinkage in West Antarctica. Unlike the Greenland ice sheet, the IPCC estimates that surface melting plays a fairly small role in the overall mass balance of Antarctica, so more effort has been placed on studying the movement of the ice streams and melting of the glaciers and ice shelves (IPCC, 2007). WAIS is classified as a marine ice sheet, meaning that part of the ice sheet is grounded on land below sea level, where the grounded part is then joined with the floating ice shelves at the grounding line. Contrarily, Greenland is mostly grounded above sea level and less effected by ablation due to moderate warming (Oppenheimer, 1998). This fundamental difference is one of the leading reasons why it is believed that the WAIS is potentially unstable and poses the most immediate threat.

Overall WAIS Dynamics

While the mass balance provides a good overall picture of what is happening at the WAIS, the dynamics of the ice sheet’s movement, melting, and discharge processes lie at the core of understanding the true response of the ice sheet to rising global temperatures. As previously stated, the effect of surface melting on the mass balance is assumed negligible. Oppenheimer points to the net flux of ice at the grounding line as the main culprit for affecting the mass budget and the global sea level (Oppenheimer, 1998). With this in mind, attention is then turned to the ice streams, which provide the main route for ice discharge of the ice sheet. Payne, et. al. state that over 90% of the mass lost from the ice sheet flows through approximately only 10 ice streams (Payne, 2004). Figure 2 shows the general geography of Antarctica.

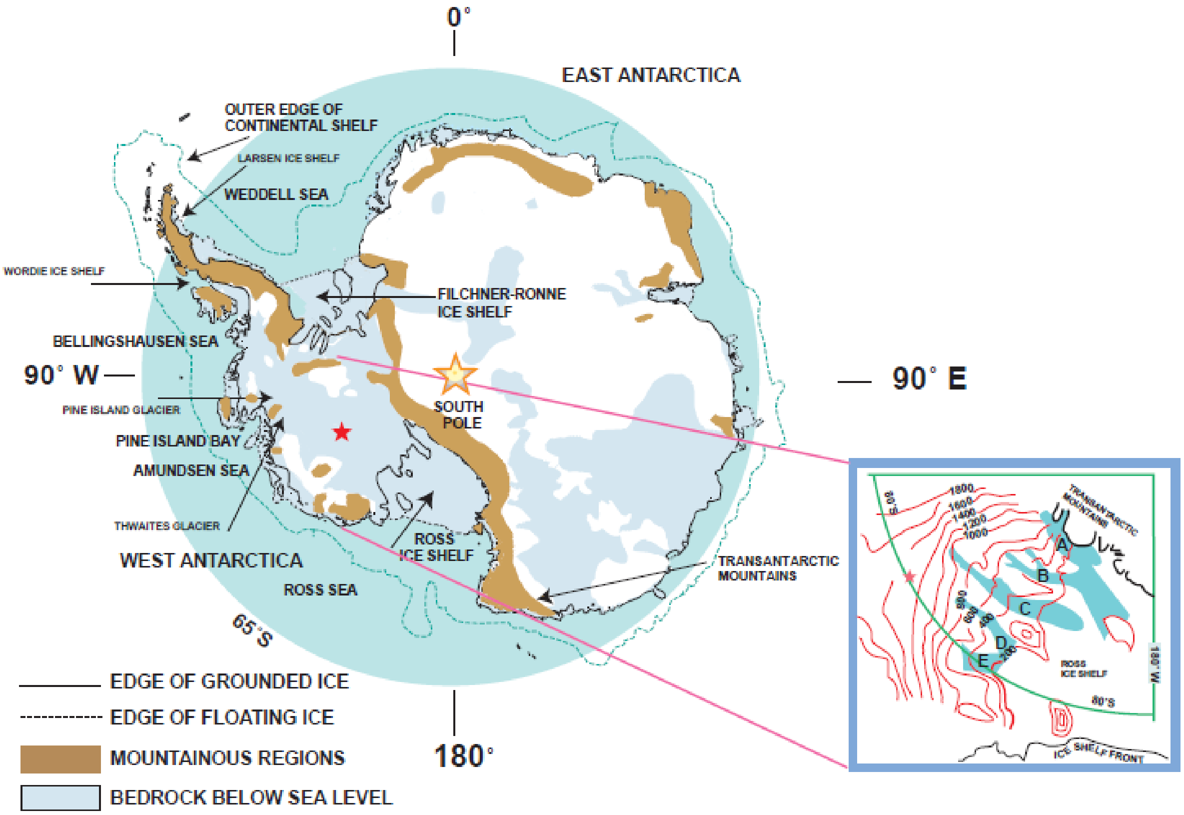

Figure 2. Antarctica Geography (Oppenheimer 1998).

Approximately half of the ice discharges onto the Ross Ice Shelf through five ice streams with an average velocity of ~0.5 km/yr (Oppenheimer, 1998). In general, the entire ice sheet moves and deforms due to its own weight (gravitational forcing) and through basal sliding, which is sliding of the ice sheet due to lubrication of its base through ice melting. The deformation is approximately proportional to the cube of the forcing stress (i.e, gravitational stress, latitudinal stress, et. al.) (IPCC, 2007). Ice streams arise when ice flow is channeled between slower-moving ice walls and is enhanced when there is greater gravitational stress on the ice (possibly due to increased slope characteristics) or increased basal melting (IPCC, 2007). Ice shelves themselves lose mass through iceberg calving and basal melting from the ocean underneath

(IPCC, 2007). In general, ice sheet velocity changes slowly in response to surface temperature change, but ice stream velocity and outlet glaciers can exhibit rapid responses to changing basal conditions or ice shelf characteristics (IPCC, 2007). Oppenheimer states that two of the ice streams that flow onto the Ross Ice Shelf lie atop "unconsolidated saturated sediment" or deformable till rather than bedrock, allowing for more lubricated flow (Oppenheimer, 1998). The destinations of the other half of the outward ice flux are the Filchner-Ronne Ice shelf in the Weddell Sea and the Amundsen Sea (AS) through the Pine Island Glacier (PIG) and Thwaites Glacier ice streams. The latter destination (AS) accounts for roughly 40% of the ice discharge and is one of the main focal points of this report because the PIG ice stream is the largest and primary ice stream of the entire WAIS (Payne, 2004). The response of the Amundsen Sea ice streams to rising temperatures plays a key role in determining the stability of the WAIS.

Amundsen Sea Ice Streams: Forcing and Ocean Warming

Shepherd, et. al state that the grounded AS sector of the WAIS loses about 51 ± 9 km^3 of volume per year (Shepherd, 2004). A key observation signifying this mass loss is the retreat of the grounding line of PIG, which between 1992 and 1996 retreated at a rate of 1.2 ± 0.3 km/yr with an ice thinning rate of 3.5 ± 0.9 m/yr (Payne, 2004). Furthermore, the flow of PIG is believed to have accelerated between 1994 to 2000 (Payne, 2004). Shepherd, et. al. hypothesize that a flow disturbance near the grounding line is responsible for removing a total of 17 ± 2 km^3/yr from all of the three main AS ice streams (PIG, Thwaites, and Smith glacier) (Shepherd, 2004). Furthermore, Shepherd, et. al. used satellite radar altimeter measurements to determine the change in surface elevation of all the corresponding AS ice shelves, which is shown in Table 1.Now, the discussion turns toward possible causes for high melt rates of the AS ice streams.

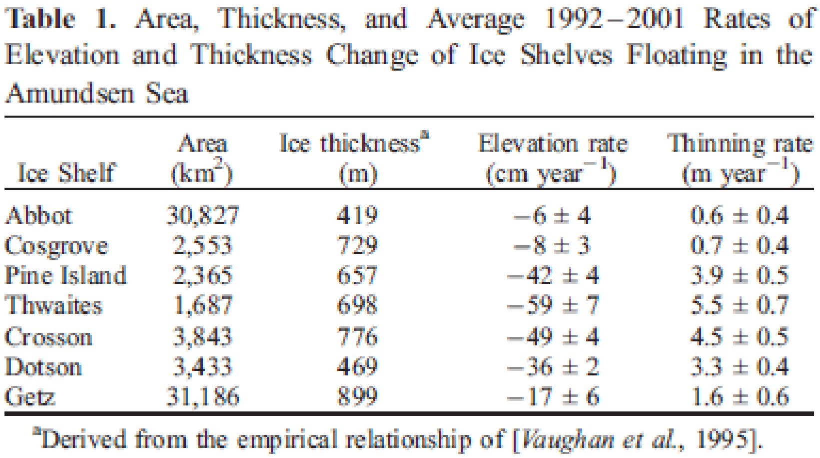

Table 1. Area, Thickness, and Average 1992–2001 Rates of Elevation and Thickness Change of Ice Shelves Floating in the Amundsen Sea

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].

For PIG, Shepherd, et. al. state that computer simulations have been able to reproduce the accelerated flow by incorporating reductions in inland basal shear stress and lateral stress from ice thinning and grounding line retreat (Shepherd, 2004). However, such success has not been found for the other two AS ice streams, and since all three have thinned correspondingly, it is deducted that external disturbances are responsible for the thinning (Shepherd, 2004). Payne, et. al. confirm this by determining that the high rate of ice thinning rules out small snowfall variability, pointing to external factors as being the main forcing parameter (Payne, 2004). Shepherd, et. al propose the external disturbance to be the unsteady ocean warming, a process already known to cause basal melting in ice shelves (Shepherd, 2004).

To understand this proposal, we must examine all the forces at work on an ice shelf. Shepherd, et. al list the elevation dependencies for ice floating in hydrostatic equilibrium with no vertical shear: a) sea level height, b) ocean density, c) ice shelf density, d) mass/snow accumulation, e) ice/snow density fluctuations, and f) basal melting (Shepherd, 2004). By examining each of the individual terms and their uncertainties and comparing them to the observed elevation difference, it was concluded that the main dependencies were either glacier influx or basal melting (Shepherd, 2004). Therefore, the possibilities are that the influx of ice onto the ice shelves had somehow decreased or basal melting had increased. Shepherd, et. al reasoned that a decrease in ice influx could not have occurred since it has been observed that grounded ice upstream had thinned at a uniform rate. The response to a thinning of upstream ice would result in a thickening of the ice shelf, not the observed thinning (Shepherd, 2004). Therefore, it was reasoned that basal melting had increased, pointing to warming oceans as the main cause. Fig. 3 is a plot of estimated net melt rate at the ice shelf base vs. ocean temperature measured at the base.

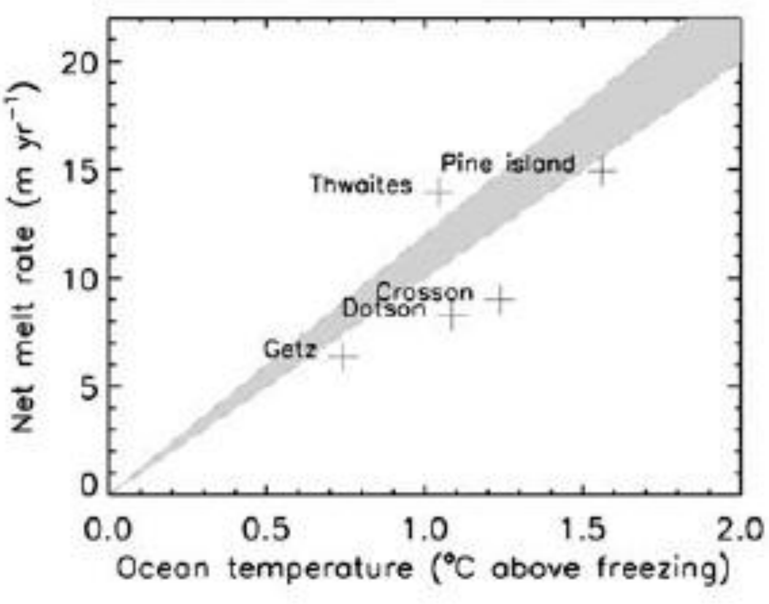

Figure 3. Net Melt Rate vs. Ocean Temperature. (Shepherd, 2004)

The above plot shows a fairly good correlation between melting and ocean temperatures. On average, the ocean temperature is approximately 0.5 °C above freezing (Shepherd, 2004). The PIG ice stream displays the highest melt rate at about 15 m/yr with the Thwaites slightly lower. A good indicator that this process is what is truly going on is the measured freshening of the Ross Sea of ~46 Gt/yr, a result that could sufficiently be explained by the melting of the ice shelves in the Amundsen Sea (Shepherd, 2004). To further understand the dynamics of the warming ocean on the ice shelves, Payne, et. al. have created models predicting changes in the PIG ice stream.

<u>Modeling of Ice Stream Thinning Due to Ocean Warming</u>

To begin, the response of ice stream flow is dependent on changes in the balance of two key forces, gravitational driving stress and total resistance due to lateral drag, basal drag, and longitudinal stress gradients (Payne, 2004). As mentioned before, models incorporating reductions in inland basal shear stress and lateral stress from ice thinning and grounding line retreat have been able to explain PIG thinning but not the other AS ice streams. Furthermore, satellite imagery shows minimal change in lateral extent of the PIG ice stream (Payne, 2004). Another important observation is that the flow variability of PIG occurs on decadal timescales, so the possibility that the ice stream is thinning due to past forcing is unlikely (Payne, 2004). Thus, increased basal melting of the PIG ice shelf was concluded as the primary suspect for the changes in basal drag or longitudinal stress gradients. As a basis for their model, Payne, et. al. also make use of an observation mentioned previously, mainly that grounded ice upstream of the ice shelf has thinned (Shepherd, 2004). Therefore, evaluation of their model depended on whether or not increased oceanic warming can create a perturbation near the grounding line that will result in thinning rates ~200 km upstream of the grounding line (Payne, 2004). The model essentially solves the three-dimensional stress balance equations approximated to first order with key model parameters calibrated using observed ice-surface velocities and known ice-shelf boundary conditions (Payne, 2004). The response of the model to perturbations is separated into an immediate, instantaneous response and a delayed response. The instantaneous response uses the full three-dimensional stress model whereas the delayed response uses a vertically-integrated version (Payne, 2004).

Before a perturbation (potentially oceanic warming) is applied to the model, Payne, et. al first compute a "calibrated" model with normal conditions and no perturbations to simulate the default flow regimes. The result for an ice stream is shown in the top two graphs of Fig. 4.

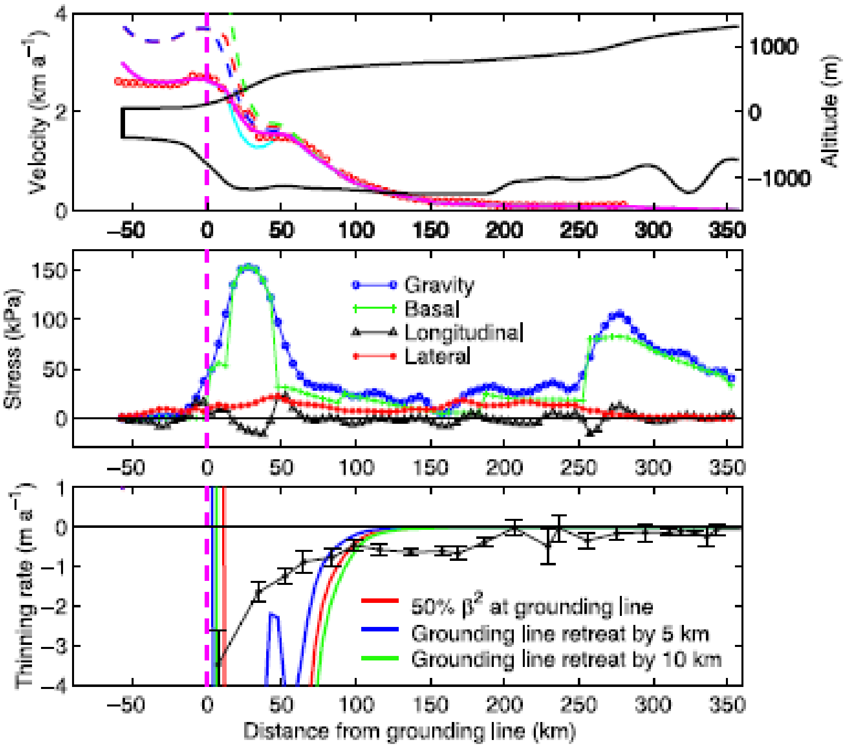

Figure 4. Results from Stress Balance Model. (Payne, 2004).

In the top graph of ice velocity vs. distance from grounding line, the calibrated model result is shown in pink with interferometry observations shown as red dots (blue is modeled basal velocity). By comparing the top graph with the second graph of stress vs. distance from grounding line, it can be observed that there are three distinct zones in the ice stream (Payne, 2004). The region from -50 km to 0 km is the ice shelf where all stresses are of equal magnitude. The second main region extends to about 60 km from the grounding line and is characterized by a large increase in gravitational driving stress and basal drag which are nearly balanced. The final region is called the "trunk" and extends upstream for the rest of the ice stream (Payne, 2004). Now that the default configuration was established, three different perturbations were applied to the three-dimensional model to predict the instantaneous thinning rates upstream from the grounding line, and the result is shown in the bottom graph of Fig. 4. The main perturbation of concern is the reduction of basal drag in the ice plain, symbolized by the black line with error bars. It can be seen that the region that is predicted to thin the most is the second region where higher gravitational driving stress and basal drag exist. However, the instantaneous response predicts little to no thinning in the trunk of the ice stream near 200 km, which does not agree with the observed thinning of the upstream ice. Therefore, Payne, et. al turned to the delayed response to help explain the disagreement.

Payne, et. al describe the delayed response as the resulting thickness of PIG in response to velocity perturbations which in turn affect the stress field (Payne, 2004). The bottom graph of Fig. 5 displays the predicted cumulative thinning after a variable number of years. From the plot, it can be seen that after one year, the initial perturbation propagated for only 50 km upstream. However, after only a decade (dashed line between 1-year line and 20-year line), the perturbation propagated over 150 km upstream, which brings the result closer to the goal of thinning ~200 km upstream. This result shows that a decrease in the basal drag coefficient can cause thinning in relatively short timescales (Payne, 2004). Payne, et. al. explain that the propagation of the perturbation can be quantified as the sum of “source, kinematic-wave and diffusive responses” with equivalent response times of ~130 and ~20 years (Payne, 2004). The top graph of Fig. 5 shows the cross-section of the ice stream after 20 years, marking a thinning in the ice stream accompanied by a thickening in the ice shelf, a process mentioned earlier.

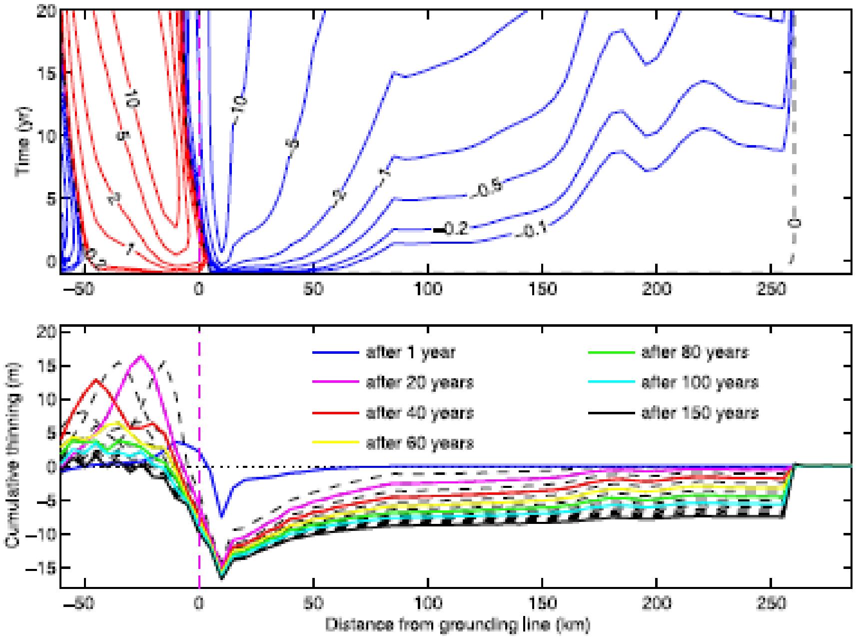

Figure 5. Delayed Response of Basal Drag Perturbation. (Payne, 2004)

Overall, the numerical results show that an instantaneous perturbation in basal drag near the ice shelf and grounding line can lead to significant thinning far upstream in the ice stream. However, in reality, positive feedback mechanisms have the potential to apply a continuous decrease in basal drag to increase basal melting (presumably by oceanic warming) which in turn can cause even further thinning of the ice stream (Payne, 2004). This effect will inevitably affect the stability of the ice sheet.

Stability of the WAIS

As previously mentioned and further described by the numerical models of Payne, et. al., large velocity changes can occur on ice streams on fairly rapid timescales. The main question now is whether or not the ice stream is a sign of the instability of the ice sheet or a natural, stable process that only serves to link the grounded ice to the ice shelf (Oppenheimer, 1998). Oppenheimer approaches this question by focusing on the extent of basal lubrication.

Oppenheimer first presents a result from a model by J. Weertman that demonstrated that downward sloping bedrock (upstream of the ice shelf) can cause a marine ice-sheet to be inherently unstable (Oppenheimer, 1998). Nominally, ice shelves can provide “support” for an ice sheet through buttressing, and if those ice shelves break away due to melting, the grounded ice would thin at an accelerated and runaway rate (Oppenheimer, 1998). Combining this fact with the result from Payne, et. al.’s model results and with the observation that many of the WAIS ice streams display a downward sloping bedrock leads to alarming possibilities. However, Oppenheimer explains that Weertman’s model, and other models simulating the junction of the ice stream and ice shelf, do not incorporate the role of non-bedrock sediment such as deformable till, which would serve to provide basal lubrication for the ice stream (Oppenheimer, 1998). Modeling the basal lubrication of the ice stream itself has proved to be difficult, mainly at the junction of the ice stream with the slow moving ice sheet, and preliminary model results have predicted unreasonable instability parameters (Oppenheimer, 1998).

Oppenheimer then presents another model by D.R. MacAyeal that incorporates both ice-stream dynamics and deformable till into his ice sheet model at the cost of lower resolution. This model actually predicts that an ice sheet forced with periodic changes in climate and global sea level will respond in a similarly oscillatory manner through ice/snow accumulation and ice stream discharge (Oppenheimer, 1998). Therefore, MacAyeal’s model seems to demonstrate a stable ice sheet through the incorporation of the deformable till. Still, MacAyeal’s and none of the aforementioned models directly take into account basal melting and freezing under the ice shelves. Rather, other models have shown that ice sheet velocity can be affected by completely removing the shelves or incorporating a rapid thinning (Oppenheimer, 1998). Oppenheimer concludes that a good overall model should include ice stream dynamics, deformable till, basal layer thermodynamics, and sub-ice topography in order to sufficiently determine the stability of the WAIS (Oppenheimer, 1998). Nevertheless, the results from Payne, et. al.'s model and Shepherd's analysis of oceanic warming do point to a coupling between the thinning ice shelves and the inland ice sheet. The possibility that continuous basal melting of ice shelves can lead to runaway thinning of the inland ice sheet strongly hints at potential WAIS instability, independent of the bedrock/deformable till that the ice stream flows over. Thus, even though the stability question is not fully answered, there is enough evidence to demand more detailed examination of the ice sheet dynamics and ice sheet stability.

Anthropogenic Forcing on Ice Sheet melting

It has been suggested and demonstrated by various models that warming oceans have led and could lead to increased basal melting of ice shelves with subsequent thinning of ice sheets, causing the global mean sea level to rise. The final question now turns to the role of anthropogenic forces and rising global temperatures on those processes. It was previously discussed that surface melting through rising temperatures does not apply an appreciable flux on the mass balance of the WAIS. To examine this fact, we can turn to other research focused on scenarios for the melting of Glaciers and Small Ice Caps (GSICs) which can then be applied to the AS ice streams and WAIS.

Wigley and Raper expand upon the IPCC Third Assessment Report's (TAR) formula for sea level rise from GSIC melt given below:

$$g_u(t) = g_u(1990) + \int_{1990}^{t} \left[\alpha(0.15 + T(t'))\right] dt'$$

$$g_s(t) = g_u(0.934 - 0.01165 g_u)$$

where α is a global mass balance sensitivity, T is a global mean temperature, and g_u and g_s are the raw and corrected sea level rise, respectively. Wigley and Raper modified the equation by including an upper bound on the ice melt based on the initial ice volume and by incorporating an area correction term (based on the area of the ice). The resulting equation is as follows:

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

where β is a newly defined mass balance sensitivity that takes into account the area correction (Wigley and Raper, 2005). Wigley and Raper explain that the new governing equation allows them to run their model on timescales much longer than the TAR model (Wigley and Raper, 2005). Many different scenarios were forced on the model to explain the sensitivity of glacier melt to initial ice volume and climate sensitivities. The result of prime importance to this discussion is the predicted melting based on three different CO_2 concentrations and stabilization scenarios and a given initial ice volume, which is displayed below in Fig. 6.

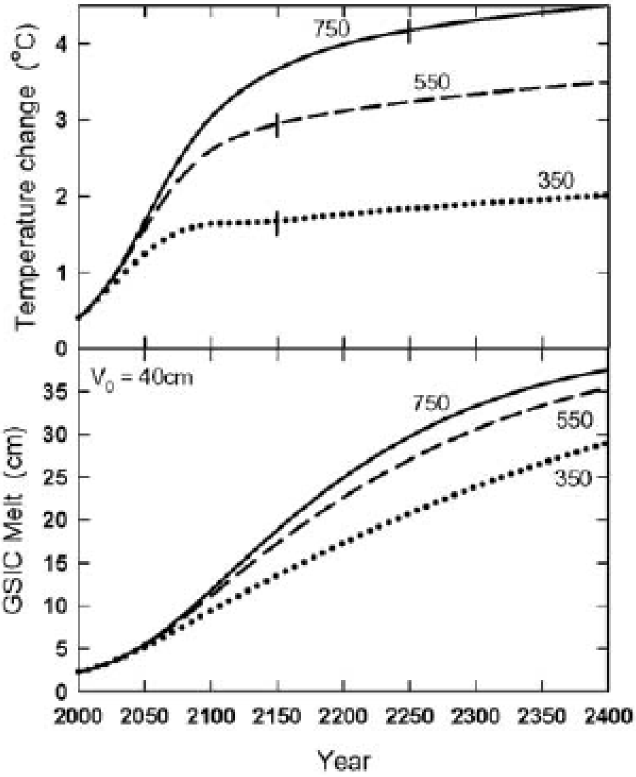

Figure 6. Temperature and GSIC Melt vs. Time Based on CO_2 Concentrations. (Wigley and Raper, 2005)

Wigley and Raper used initial CO_2 concentrations of 350, 550, and 750 ppm and propagated the model to the year 2400. The most important conclusion that can be drawn from the above plot is that while the temperature experiences large changes based on the different CO_2 concentrations, the cumulative melting of the GSICs is still fairly close (Wigley and Raper, 2005). Doubling of the CO_2 concentrations only leads to about 8 cm difference in sea level rise due to GSIC melt after 400 years. Therefore, the direct effect of anthropogenic forces on GSIC melt is predicted to be minimal based on this model.

However, the effect of rising temperatures is not constrained to surface and ice melting and can play an indirect role on the WAIS. In general, increased global temperatures lead to increased precipitation, which would mean increased snow accumulation at the ice sheet and a positive mass balance. On the other hand, Oppenheimer points out that increased precipitation would cause a freshening of the waters, decreasing the salinity of the ocean surface. This salinity decrease would decouple the convective exchange between the surface and cold deep waters, allowing the surface water to increase in temperature (Oppenheimer, 1998). An atmospheric-ocean general circulation model (AOGCM) predicts that even subsurface ocean waters would experience an increase of 0.5-1.5°C by mid-century and 3 °C by 2200 (Oppenheimer, 1998). Such a large increase in water temperatures in the Amundsen Sea could spell disaster for the ice shelves there. Based on these observations and predictions, Oppenheimer believes that the most likely future scenario for WAIS is that the ice streams will remain active and basal melt rates will gradually increase, draining away the Ross Ice Shelf in about 200 years. The negative ice flux due to basal melting will offset the increased ice/snow accumulation for a net contribution to global sea level of 0-19 cm per century (Oppenheimer, 1998). The thinning ice shelf will lead to increased ice stream velocity and outward ice flux, eventually leading to a “collapse” phase where the WAIS will contribute approximately 60-120 cm of sea level rise per century for approximately 5-7 centuries (Oppenheimer, 1998).

Conclusions

We have shown there is a net negative mass balance for West Antarctica where most of the outward ice flux passes through the ice streams and settles onto ice shelves. However, observations have shown a decrease in elevation for the ice shelves which can affect the state of the interior ice. Oceanic warming is the most likely cause for the simultaneous thinning of the three main Amundsen Sea ice shelves and ice streams. Even a modest increase in ocean surface temperatures can increase basal melting of the ice shelves, which in turn can lead to thinning of the ice sheet itself at distances of ~200 km upstream of the grounding line and at time scales of only a few decades. While the stability of the entire WAIS is still not fully realized, observations of ice shelf thinning combined with ice stream model predictions point to a future for WAIS that cannot depend on meticulous decision-making and hand-waving. Fully coupled models for ice stream dynamics and ice sheet stability must be developed as soon as possible. The refinement of atmospheric-ocean general circulation models should provide more insight into how anthropogenic forcings directly affect ocean temperature and ice discharge. These model predictions should then be backed up by direct measurements of ocean temperature, specifically in the Amundsen Sea and probably the Ross Sea as well. Additionally, other ice streams of Antarctica must be studied to determine any other common forcings that could eventually lead to full WAIS melt. The mere possibility of a melt rate of 60-120 cm of sea level rise in only a few hundred years signifies that action must be taken by both the scientific and political community. Such action is most likely dependent on hard observational facts and convincing model results, both of which are non-trivial items.

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.