Tidally induced increases in melting of Amundsen Sea ice shelves

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[1] Tidal effects on the circulation under the ice shelves and ice shelf melting in the Amundsen Sea were investigated using a numerical model, through comparison of simulations with and without tides. In the Amundsen Sea, tidal impacts were dependant on the location of the ice shelf front with respect to the $M_2$ effective critical latitude. The critical latitude is the latitude where the tidal frequency equals the inertial frequency. The effective critical latitude is where the tidal frequency equals the inertial frequency adjusted by relative vorticity, such as that associated with a wind-driven gyre. For ice shelves located equatorward of the $M_2$ effective critical latitude, tides increased both mixing in front of and under the ice shelf and flow into the ice shelf cavities by as much as 50%, despite weak tides compared with the mean flows. Tides also increased melting for these ice shelves by 1–3.5 m yr$^{-1}$, a 50% increase for Dotson Ice Shelf and 25% for Pine Island Ice Shelf. These enhancements were not a result of tidal residual flows, but instead originated from resonant effects, increases in the baroclinity of the velocities, and higher mixing, all of which are associated with critical latitude effects on internal tides. For ice shelves located poleward of the effective critical latitude, tides very slightly retarded flow into the cavity and slightly reduced melting.


1. Introduction

[2] Recently, ice shelves in the Amundsen Sea have experienced the most rapid melting in the Antarctic [Rignot et al., 2008]. This melting is driven by the ocean and occurs at the base of the ice shelf with the most rapid melting near the grounding line [Bindschadler, 2006]. The flow of “warm” water into the ice shelf cavity and the circulation within it are primarily density-driven and highly influenced by topographic controls and the hydrography [Jenkins et al., 2010; Schodlok et al., 2012]. Tides are also believed to increase melting through enhancing both mixing and the flow of warm water under the ice shelf.

[3] Since measurements of ice shelf melting are exceedingly difficult and expensive to obtain, models have been used to investigate the role of density-driven flows and tides in under ice shelf circulation and ice shelf melting. Simulations have shown that the flow into and under the ice shelf is predominantly determined by the topography both of the sea floor and the ice shelf, which act as controls on the flow, particularly on the warmer water entering the ice shelf cavity. A recent example is Pine Island Ice Shelf (Figure 1c), where a combination of the ice shelf and a bottom ridge restricted the flow of “warm” water entering the ice shelf cavity [Jenkins et al., 2010]. When the ice shelf eroded, the gap between the ice shelf and the sea floor widened, enabling more “warm” water to pass over the ridge into the cavity beyond, thus increasing the basal ice shelf melting in the cavity beyond the ridge [Jenkins et al., 2010].

[4] Several investigators have found that tides play a significant role. Makinson et al. [2011] determined that tides significantly increased mixing and the circulation under the Ronne-Filchner ice shelf in the Weddell Sea and doubled ice shelf melting. Further west in the Weddell Sea, tides generated mean currents up to 5 cm s$^{-1}$ that equaled or exceeded the mean density-driven flow, doubled ice shelf melting, and modified its distribution [Mueller et al., 2012]. And in the Amery Sea, tidal currents enhanced the melting and freezing rates with large fluctuations in heat content associated with the spring-neap cycle [Galton-Fenzi et al., 2012]. The goal of this project is to quantify tidal effects on the melting of ice shelves and circulation and mixing in the ice shelf cavities in the Amundsen Seas, recognizing that topography is the predominant controlling factor for these processes.

2. Modeling

[5] To investigate tidal effects on ice shelf melting, the flows beneath three ice shelves in the Amundsen Sea were simulated: Getz, Dotson, and Pine Island (full domains shown in Figure 1). The simulations were performed both
with and without tides to identify the role of tides in the circulation and heat fluxes both in and out of the ice shelf cavities and into the ice shelves. The Regional Ocean Modeling System (ROMS) [Shchepetkin and McWilliams, 2004] was used for these simulations with modifications to the tidal forcing as done previously [Robertson, 2006] and the Holland-Jenkins [1999] ocean-ice sheet thermodynamics as adapted by Jenkins et al. [2001]. For the simulations, the bathymetry and ice shelf drafts were taken from the RTOPO data set [Timmermann et al., 2010] with a model grid resolution of 2 km and temperature and salinity from CTD data collected during various research voyages, including NBP0702, NBP0901, available from the National Oceanographic Data Center (NODC) website (http://www.nodc.noaa.gov/General/getdata.htm). Although some smoothing is necessary over steep topography since ROMS is a sigma-coordinate model, it was kept to a minimum. No attempt was made to include tidally induced wetting/drying, since the total tidal range in this region barely reaches 1 m and the uncertainty in the topography of the ice shelf and the sea bottom near the grounding line is 10–100 m. Changes were not made for the ice shelf thickness as the simulations were only for 30 days, not long enough for ice shelf changes to reach the uncertainty.

A simulation was run using the observational data as initial and boundary conditions and without wind or tidal forcing, until the kinetic energy had stabilized. The stabilized temperature, salinity, elevation, and velocity fields from this run were then used as the initial conditions for the tidal and nontidal simulations in this study. Transects along the front of the ice shelves (Figure 2 with transect locations given in Figure 1) showed basically a two-layer structure with colder, fresher water over warmer, saltier modified Circumpolar Deep Water (CDW) (salinities not shown). Typically, the transition between these two layers occurred at a depth of 400–500 m. Wind forcing was set at zero, with the exception of one case, where observed wind velocities from NPB0901 were used as discussed later. Tidal forcing was implemented at the boundaries by forcing elevation changes with time. This elevation was a combination of four tidal constituents, M2, S2, K1, and O1, with the coefficients taken from TPXO7.1 [Egbert and Erofeeva, 2002]. Simulations were run for 45 days, saving the last 30 days for analysis. In prior simulations, an initialization period of 15 days has proved sufficient for the tidal elevations and velocities to develop [Robertson, 2005a, 2005b]. Inspection of the surface heat fluxes into the ice shelf indicated that they had reached a nominal value around 15 days even at the back of the ice shelf (not shown). Superimposed on these nominal values were fluctuations of 100–200 W m², which appear to be associated with the passage of eddies. Tidal residual velocities were essentially negligible, as discussed later, so there is no need for a long simulation time for them to develop.

Figure 1. The domains used for the simulations for the (a) Getz, (b) Dotson, and (c) Pine Island ice shelves. Depth contours are shown for 50, 100, 200, 400, and 800 m, and labeled for 100, 400, and 800 m. The thick gray line indicates the location of ice shelf front.
Shelf and the mean flow followed the same basic pattern, in
be noted that there are several channels under the Getz Ice
sheet cavities, mean flow was stronger at depth. It should
on the southern side (negative values
on the northern side (positive values
3b). For the Pine Island ice shelf cavity, mean flow entered
3. Results
Figure 2. Potential temperature along the front of the (a)
Getz, (b) Dotson, and (c) Pine Island ice shelves, looking
out of the ice shelf cavities (North for Getz and Dotson and
West for Pine Island). Note the entire front of Pine Island
Ice Shelf is not shown, due to the eastern portion being
shallow and of less impact.

3. Results
[7] The general pattern showed that mean flow entered
the Dotson and eastern Getz ice shelf cavities on the eastern
drop (positive values (red) = inflow) and exited on the western
side (negative values (blue) = outflow) (Figures 3a and
3b). For the Pine Island ice shelf cavity, mean flow entered
on the northern side (positive values = inflow) and exited
on the southern side (negative values = outflow). For all ice
shelf cavities, mean flow was stronger at depth. It should
be noted that there are several channels under the Getz Ice
Shelf and the mean flow followed the same basic pattern, in
on the east or north and out on the west or south.
[8] Velocities normal to the ice shelf front are averaged
for 30 days (Figure 3). Biases develop in time averages
horizontal gradients in the magnitude of the tidal ellipse
velocities in a similar manner as Stokes’ drift results from
vertical gradients in wave orbital velocities.) Baroclinic
tidal velocities are larger than barotropic tidal velocities
and are dominated by the semidiurnal tides. In summary,
the density-driven flow of the subice cavity is stronger than
the barotropic tidal velocities, by a factor of 5–10 and the
baroclinic tidal velocities by a factor of 2–3.
[9] The strongest ice shelf melting occurred near the
grounding line and near the ice shelf front for the Dotson,
Pine Island, and eastern Getz ice shelves (Figure 4). Higher
melting occurred in the eastern channels of the Getz Ice
Shelf cavity than the westernmost, which is consistent with
the lower temperatures measured coming out of the west-
ernmost channel and a reduced melting rate due to cooler
modified CDW in this portion of the Amundsen Sea. The highest melt rates occurred near the grounding line in the
cavity below Pine Island Ice Shelf (Figure 4c). The melt
rate pattern is in agreement with observations that the high-
est melting occurs within 20 km of the grounding line and
melt rates are a factor of 10 times higher near the ground-
ing line than in other portions of the ice shelf cavity
Jacobs et al., 2011.
[10] The spatial mean melt rates over 30 days calculated
here for Pine Island Ice Shelf range from 16.9 to 20.2 m
yr⁻¹, dependent on the forcing, tides, and wind. These melt
rates are slightly lower than the observational 1992–1996
melt rate of 24 ± 4 m yr⁻¹ estimated by Rignot [1998] and
higher than those, 10–12 m yr⁻¹ estimated from observa-
tions by Jacobs et al. [1996]. Part of the difference in
observational estimates is that the melt rate for Pine Island
Glacier seems to be a moving target. Jacobs et al. [2012]
remarked that the melt rate for Pine Island Ice Shelf
changed with time increasing by 50% from 1994 to 2009
Jacobs et al., 2011]. This increase in melt rate is attributed
to the development of a gap between the ice shelf and the
ridge, allowing warm water to enter a back cavity [Jenkins,
2011].
[11] The melt rates determined here for all three Amund-
sen Sea ice shelves are less than those estimated by Schod-
llok et al. [2012], roughly by a factor of 1.7–2.9 (Table 1).
The highest estimate of melting for Pine Island Ice Shelf
here, 20.2 m yr⁻¹, is lower, roughly 70% that of Schodlok
et al. [2012], 28.3 m yr⁻¹. The difference between these
melt rates and Schodlok et al.’s is believed to originate
from several factors. First, different models were used. Sec-
don, Schodlok et al. used wind forcing but no tides, and
here there is tidal forcing and localized wind forcing only
in one case. Last, but definitely not least, different topogra-
phies were used in the two simulations. Schodlok et al.
[2012] found melt rates for the same region determined
the averaging time period not being an exact multiple of
the tidal cycles is estimated to be < 0.2 cm s⁻¹, which is
small compared with the mean flows present, 10–30 cm
s⁻¹. Barotropic tidal velocities in this region are small, par-
ticularly for Pine Island Bay, with tidal velocities < 1.5 cm
s⁻¹, and are dominated by the diurnal tides. The averaged
density-driven flows here are stronger by a factor of 5–10
than the barotropic tidal velocities. Residual mean veloc-
ities generated by tidal flow are smaller than the tidal
velocities, generally by at least an order of magnitude.
(Tidal residual velocities are mean flows which result from
horizontal gradients in the magnitude of the tidal ellipse
velocities in a similar manner as Stokes’ drift results from
vertical gradients in wave orbital velocities.) Baroclinic
tidal velocities are larger than barotropic tidal velocities
and are dominated by the semidiurnal tides. In summary,
the density-driven flow of the subice cavity is stronger than
the barotropic tidal velocities, by a factor of 5–10 and the
baroclinic tidal velocities by a factor of 2–3.
with different topographies varied by 10 m yr$^{-1}$. For Getz Ice Shelf, the two simulations defined the regions differently, with the simulation here having $\sim$2.5 times more area. The additional area included in this simulation covers the western basins, where the melt rates are much lower, which contributes to the much lower melt rate here. However, since the goal of this study is to examine the role of tides in the melt rate, the relative melt rate is of more importance than the absolute rate.

[12] Despite the weak tides in this region, tides in the simulation altered the mean inflow and outflow of the density-driven circulation, increasing it for the Getz and Dotson ice shelves (Figure 3). Enhancement of the velocities was stronger deeper in the water column. The general pattern of mean inflow on the eastern (or northern) side and mean outflow on the western (or southern) side remained; however, tides strengthened the inflow and outflow under Getz and Dotson ice shelves. In Dotson, they strengthened some velocities deeper than 400 m by more than 10 cm s$^{-1}$ and inflow by 50% (Table 1) with the strongest flows occurring near the sea floor, bottom intensified (Figures 3b and 3e). The inflow and velocities under the Getz ice shelf were slightly stronger, with increases up to 5 cm s$^{-1}$ (Table 1 and Figures 3a and 3d). However for Pine Island Ice Shelf, tides did not increase the inflow or velocities in the cavity (Figures 3c and 3f); on the contrary, they slightly retarded them. Flow retardation results from higher friction due to the addition of the tidal velocities, without a significant increase in the mean flow due to tidal residual velocities or strong internal tides. Tidal retardation has been observed previously in a tidal simulation for the Weddell Sea, where tides retarded the mean flow by 30% [Robertson et al., 1998]. The flow retardation under Pine Island Ice Shelf is small, essentially negligible. The differences in the mean inflows and outflows often exceeded both the barotropic and baroclinic tidal velocities. Thus, the tidally driven changes in mean flow were not a direct result of the tides, but include density-driven flows resulting from changes in the amount of heat entering the cavity due to the tides, different mixing environments and other nonlinear effects.

[13] The ice shelf melting responded similarly to the tides, as did the circulation. Tides had a significant impact.
on melt rates for Dotson and Getz Ice Shelf cavities, but not for Pine Island (Table 1). Under Dotson and Getz Ice Shelves where inflow and outflow increased, melting also increased by 2.2 and 3.4 m yr\(^{-1}\), respectively. The smaller melting increase under Getz reflects the lower melt rates in the western basins (Figure 4a). Under Pine Island Ice Shelf, tides decreased melting by a small amount, 0.5 m yr\(^{-1}\).

The different behaviors of these ice shelves appear linked to the critical latitude for the M2 tide. The critical latitude is the latitude where the tidal frequency equals the inertial frequency. For the M2 tidal constituent, critical latitude is 74°28’S or 74.46° S. Poleward of critical latitude, several relevant processes occur. The most important are that internal tides do not propagate freely, but are trapped, and that the horizontal velocities in the water column become more uniform with depth. Near critical latitude, internal wave activity and mixing increase, resonant effects with the inertial frequency come into play, and the boundary layer thickens until it encompasses the entire water column at critical latitude [Furevik and Foldvik, 1996]. This thickened boundary layer imparts vertical shears in the horizontal velocities to more of the water column. And vertical shears in the horizontal velocities can lead to mixing if the destabilizing effect of the shear overrides the stratification. The stratification in this region is very weak, < 4 cph, even at the interface between the fresher water and the modified CDW; consequently, little shear is required to induce mixing. The general depth dependence of the flow follows a

Table 1. Melt Rates and Inflows for the Getz, Dotson, and Pine Island Ice Shelves Both Without and With Tides and the Ice Shelf Areas\(^a\)

<table>
<thead>
<tr>
<th>Ice Shelf</th>
<th>Melt Rate Without Tides (m yr(^{-1}))</th>
<th>Melt Rate With Tides (m yr(^{-1}))</th>
<th>Ice Shelf Area (km(^2))</th>
<th>Inflow Without Tides (Sv)</th>
<th>Inflow With Tides (Sv)</th>
<th>Melt Rate, Schodlok et al. [2012] (m yr(^{-1}))</th>
<th>Area, Schodlok et al. [2012]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Getz</td>
<td>7.9</td>
<td>9.1</td>
<td>20,128</td>
<td>0.64</td>
<td>0.66</td>
<td>23.0</td>
<td>8207</td>
</tr>
<tr>
<td>Dotson</td>
<td>6.5</td>
<td>9.9</td>
<td>3224</td>
<td>0.13</td>
<td>0.21</td>
<td>18.2</td>
<td>3000</td>
</tr>
<tr>
<td>Pine Island</td>
<td>16.9</td>
<td>16.4</td>
<td>4956</td>
<td>0.09</td>
<td>0.08</td>
<td>28.3</td>
<td>4573</td>
</tr>
<tr>
<td>Pine Island shifted 1°N</td>
<td>15.9</td>
<td>18.6</td>
<td>4956</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pine Island with wind-driven gyre</td>
<td>20.2</td>
<td>4956</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Melt rates for two additional cases for the Pine Island Ice Shelf are given with the domain shifted 1°N and with a wind-driven gyre. Also, melt rates and the area for the ice shelf from Schodlok et al.’s [2012] ice bridge simulation are shown for comparison.

Figure 4. Ice shelf melt rates for the (a) Getz, (b) Dotson, and (c) Pine Island ice shelves.
boundary layer response with the bottom of the ice shelf acting as the prominent boundary at the top and the sea floor as another at the bottom.

[15] Inspection of the locations of these ice shelves (Figure 1) shows that the fronts and most of the Getz and Dotson ice shelves fall equatorward of the M2 critical latitude by 0.5–0.75°; however, Pine Island Ice Shelf is poleward (Figure 1). The circulation into Dotson Ice Shelf (Figure 3b) shows a strong depth dependence, but under Pine Island Ice Shelf, the circulation is more uniform with depth and weaker (Figure 3c). Both behaviors are consistent with critical latitude considerations.

[16] To test this hypothesis, a simulation was made for the Pine Island Ice Shelf after shifting the domain north by 1° so that the front of the ice shelf is equatorward of the M2 critical latitude by 0.5–0.75°; however, Pine Island Ice Shelf is poleward (Figure 1). The circulation into Dotson Ice Shelf (Figure 3b) shows a strong depth dependence, but under Pine Island Ice Shelf, the circulation is more uniform with depth and weaker (Figure 3c). Both behaviors are consistent with critical latitude considerations.

[17] Thus, the role of tides in ice shelf melting appears to be linked to the position of the ice shelf with respect to the M2 critical latitude. If the front of the ice shelf and most of the ice shelf is equatorward of critical latitude then the addition of tides will increase the circulation and the melting. If the ice shelf is poleward of the M2 critical latitude, tides will slightly retard the circulation and melting. Furthermore, this role is not dependent on the residual tidal velocities, but rather on the increased baroclinicity of the water column, enhanced mixing, and resonant effects, and it can be significant even in weak tidal regions.

4. Discussion

[18] Conceptually, the critical latitude is taken as the exact latitude based on the planetary vorticity. However, observations indicate that the dynamics are really controlled by an effective critical latitude, based on total vorticity, both planetary and relative. The relative vorticity of a swirling mean flow can shift the critical latitude by several degrees [Kunze and Toole, 1997] and this shift can be either equatorward/poleward depending on the sign of the relative vorticity.

[19] Observations of the circulation in Pine Island Bay showed the existence of a gyre [Figure 13 in Tortell et al., 2012]. The relative vorticity of this gyre is sufficient to shift the critical latitude ~1.0°S with the result that Pine...
Island Ice Shelf is effectively north of critical latitude and would experience an increase in circulation and melting due to tides. To test this, a simulation was performed with the Pine Island Ice Shelf at its real location with the wind conditions experienced during NBP0901 and a resultant wind-driven surface gyre. The resulting circulation into the ice shelf cavity is very similar to the shifted domain (Figure 5c compared with Figure 5b). Likewise, the melt rate with the wind-driven gyre is higher (Table 1). Thus, the wind-driven gyre effectively shifts the critical latitude southward by 1°, although it is noted that differences exist between the wind-driven and shifted simulations.

[20] A wind-driven gyre in Pine Island Bay was observed during summer 2009. Since this region can be ice covered much of the time, it is quite possible that the wind will not generate a gyre throughout most of the year. However, Schodlok et al. [2012] observed frequent formation of a gyre in front of the Pine Island Ice Shelf in their wind-driven simulations and Mankoff et al. [2012] notes that in observations, two modes have been present in Pine Island Bay over the last 25 years. One mode exhibits a single large polynya and more open water, and the other mode presents persistent, small polynyas and more sea ice cover. The small polynyas were also observed by Bindschadler et al. [2011] at three locations in front of the ice shelf. Both of these modes, especially the former, increase the potential for the effective critical latitude to be shifted poleward of the ice shelf front and for tides to promote flow under the ice shelf and ice shelf melting here.

[21] The critical latitude also affects the boundary layer thickness and mixing, with both the boundary layer thickness and mixing increasing near critical latitude. Taking diffusivities of temperature as determined by the model using the Mellor-Yamada 2.5 level turbulence closure scheme as indicative of mixing, mixing increased in the ice shelf cavity and in front of the ice shelf in Pine Island Bay both for the shifted domain (not shown) and for the wind-driven gyre (Figures 5d and 5e). With the wind-driven gyre, a beam of high diffusivity, typical for internal wave mixing, emanates from the top of the ridge in the ice shelf cavity, indicating higher mixing there (Figure 5e).

[22] Tides have been shown to play a significant role in ice shelf melting and circulation under the ice shelf in strong tidal regimes, such as the Ross and Weddell Seas, through the mechanisms of tidal rectification and mixing [Makinson, et al., 2011; Mueller et al., 2012]. Now, tides have been shown to play a significant role even in weak tidal regimes when they are subject to critical latitude effects, through the mechanisms of baroclinicity, mixing, and resonance. Several ice shelves along the Antarctic Peninsula are likely to respond to tides in a similar way as the Getz and Dotson ice shelves, including George VI Ice Shelf. And the Brunt and Riiser-Larsen ice shelves in the Weddell Sea are near enough to the M2 critical latitude to be affected by tides. In the Arctic, the M2 critical latitude passes through Greenland and tidal effects potentially could influence melting in the northern tide water glaciers there. Although the major control of the circulation under an ice shelf is the topography, tides play a lesser but significant role when certain conditions with respect to the critical latitude are met, even in regions of weak tidal velocities. Tidal effects on the heat flux to the ice shelf in these areas near critical latitude are a result of a more baroclinic water column due to internal tides, resonant effects, increased mixing, and nonlinear effects on the density-driven circulation, rather than tidal residual velocities. These effects can increase ice shelf melt rates by up to 3.5 m yr⁻¹, effectively increasing it by 25% for Pine Island Ice Shelf and 50% Dotson Ice Shelf.

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