High Resolution Simulation of Dissolving Ice-shelves in Sea Water

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Motivation

- Satellite radar measurements (Rignot et al. 2008) from 1992 to 2006 show Antarctic ice mass loss increased by 75% in 10 years.

- Melting is strong along the west Antarctic coastline: the Amundsen and the Bellingshausen Seas, Pine Island Bay and Antarctic Peninsula (Figure 1).

- The total mass loss from Antarctica (or from icesheets) from 2002 to 2009 was 190±77 Gt (Chen et al. 2009).

- Antarctic ice-shelves melt by turbulent transport of heat and salt to the ice face, increased melting due to warmer and salty water from the surrounding Southern Ocean (Payne et al. 2004, Rignot et al. 2008).

- Background salinity gradient influences the melting

- Data are limited due to lack of observations. Rely on numerical simulations based on parameterizations. No boundary resolving simulations reported.

Fig. 1 (a) Ice-loss from large Antarctic basins in Gt/year (Rignot et al. 2008). Relative size of circles indicates mass loss (red) or gain (blue). Ice velocities are also shown in colour. (b) Salinity field (in psu) in the ocean cavity beneath the ice shelf at PIG (marked) of the Pine Island Glacier (Jenkins et al. 2010).
Problem set up: Interface condition

Interface equation:
\[ T_i = (S_i, P_i) \]

Conservation of Heat:
\[ Q_i^H - Q_w^H = Q_{\text{latent}}^H \]

Conservation of Salt:
\[ Q_i^S - Q_w^S = Q_{\text{brine}}^S \]
Governing equations and DNS/LES method

\[ \nabla \cdot \mathbf{u} = 0 \]

\[ \frac{D\mathbf{u}}{Dt} = -\nabla p^* + \nu \nabla^2 \mathbf{u} - \frac{\rho^*}{\rho_0} g \mathbf{k} \]

\[ \frac{DT}{Dt} = \kappa_T \nabla^2 T \]

\[ \frac{DS}{Dt} = \kappa_S \nabla^2 S \]

\[ Gr = \frac{g (r_i - rw) H^3}{r_w^2} \]

\[ \Pr = \frac{T}{\nu} \]

\[ Sc = \frac{S}{\nu} \]

\[ St = \frac{g_s L_w}{w_c (T_w - T_i)} \]

- NS is solved using staggered grid, clustered in b.l.
- Low Storage third-order Runge-Kutta-Wray method for time stepping
- Derivatives in spanwise direction: pseudo-spectral method
- Derivatives in vertical and streamwise direction: second order finite differences
- Subgrid model: dynamic eddy viscosity and diffusivity
Visualization of the flow field next to ice interface (uniform ambient)

\[ T_w = 5^\circ C, S_w = 35\% \text{ psu} \quad H=1m \]
Boundary layer structures (uniform ambient with turbulent bl.)

$T_w = 2.3^\circ C$, $S_w = 35\%$ psu, $H=1m$
Comparison of DNS with experiments
(Josberger & Martin 1981, ANU experimental work)

- DNS remarkably agrees with the previous laboratory experiments by predicting the melting rate and interface conditions
- Melting happens even for surrounding fluid temperature of 0°C, due to depression of freezing point by salinity

Ref. Gayen et al. JFM (2016)
Turbulence structures

- Enhanced tke above the transition.
- \( TKE \) is produced from buoyancy and shear at a comparable rate.
Effect of stratification on the melting boundary layer (Formation of double-diffusive layer with laminar bl)

The formation of double-diffusive convective layers in a linear salt gradient against a melting vertical ice block (Huppert & Turner, 1978, 1980).

H. = 0.3m height of ice, Far field temperature \( T_w \sim 2^\circ \text{C} \), linear salinity gradient
Visualization of the flow field next to ice interface (stratified ambient with turbulent boundary layer)

$H = 3 \text{ m}, \ T_w = 2.5 \ ^\circ\text{C}, \ ds/dz = 0.67 \ \text{psu/m}$
The flow field next to ice interface (stratified ambient)

\[ H = 100 \text{m}, \quad T_w = 2.5 \degree \text{C}, \quad \frac{ds}{dz} = 0.003 \text{ psu/m} \]
Modeling the convection under sloping ice-shelves

\[
\frac{\partial u_\eta}{\partial t} + u_\eta \nabla \tilde{u} = -\frac{1}{\rho_0} \frac{\partial p^*}{\partial \eta} + \nu \nabla^2 u_\eta + \frac{\rho^*}{\rho_0} g \cos \theta
\]

\[
\frac{\partial u_\zeta}{\partial t} + u_\zeta \nabla \tilde{u} = -\frac{1}{\rho_0} \frac{\partial p^*}{\partial \zeta} + \nu \nabla^2 u_\zeta - \frac{\rho^*}{\rho_0} g \sin \theta
\]

Stern, Holland, Jenkins; Exp. Fluids, 2014.
With shallower slopes, the flow becomes weaker and makes a transition from turbulent to laminar regime.
Results and scaling:

- Meltrate is independent of slope length if boundary layer is turbulent.
- Melt rate decreases with decreasing slope angle
  - Laminar case $V \sim (\sin \theta)^{1/4}$
  - Turbulent case $V \sim (\sin \theta)^{2/3}$
Turbulence energetics:

- For shallower angle $TKE$ is produced predominantly from shear production.
Conclusion

• Our model consistent with laboratory experiments. Dissolution velocity is nearly uniform over depth and well predicted by theory for uniform ambient which gives

\[ V \sim (T_w - T_L)^{4/3} \]

• At present Grashof there has comparable contributions from both buoyancy and shear in the convective boundary layer.

• Stratification drops the meltrate

• Double diffusive layers form under stratified environment:
Layer thickness \( \sim \int (dS_w/sz, \rho(T_i), \rho(T_w)) \]

• Angle plays a significant role in melting dynamics