Modelling ice shelf basal melt with Glimmer-CISM coupled to a meltwater plume model

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Contents

Channelized basal melt on Petermann Glacier in NW Greenland. (Rignot & Steffen GRL 2008)

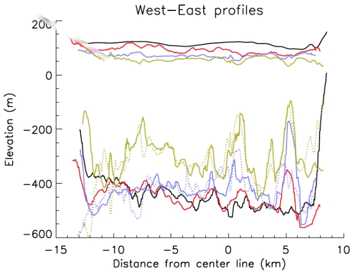


Figure: Ice upper and lower surfaces

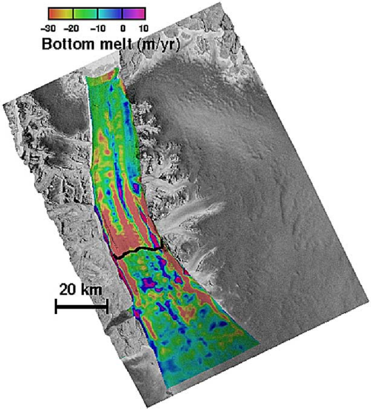


Figure: Basal melt rate

Science Goals

- How do ice shelf melt water channels form?
- Are their wavelengths determined by bedrock or ocean interaction?
- What are they sensitive to?

Contents

Coupled system: Ice-shelf, Melt Water Plume, Ocean Cavity

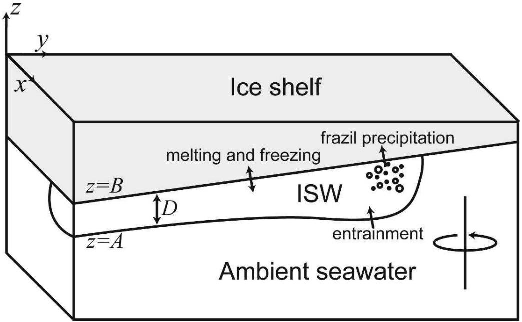
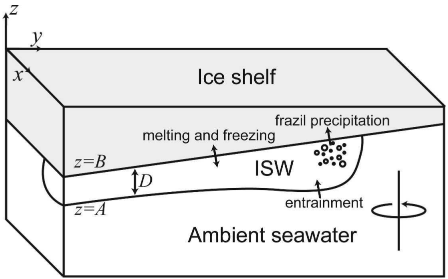


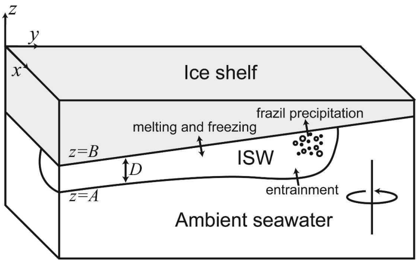
Figure: From P.R. Holland and Feltham (JPO 2006)

Ice model



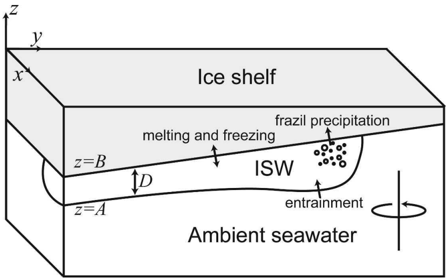
- $\nabla \cdot \sigma = \rho g$
- Glen's law rheology
- 3D advection of temperature, vertical diffusion, strain heating
- incompressible
- imposed accumulation

Plume model



- $\vec{u}$, T, S equations z-integrated from A to B
- incompressible
- D sources: $\dot{e}$, $\dot{m}$
- DU sources: $\nabla\rho$, ∇A, wall drag
- DT sources: $\dot{m}T_B + \dot{e}T_A$, turbulent transfer
- DS sources: $\dot{e}S_A$

Coupling Variables



- Mass exchange: $\dot{m}$
- Geometric: $A = -H\frac{\rho_i}{\rho_o} - D$
- Heat conduction (future)

Entrainment

$$\dot{e} = \frac{c_l^2}{Sc_T}\sqrt{(U^2 + V^2)\left(1 + \frac{Ri}{Sc_T}\right)} + \dot{e}_{\text{source}}$$

where

$$Ri = \frac{g' D}{U^2 + V^2}$$

and

$\dot{e}_{\text{source}}$ enforces a minimum thickness of the plume

Typical $\Delta t_{\text{ice}} = 0.5y$.
Typical $\Delta t_{\text{plume}} = 60.0s$.

Coupling pseudo-code (shelf_driver.F90)

- initialize models
- run plume to steady-state w.r.t. initial ice
- for each ice timestep:
  - run ice timestep
  - subcycle plume to steady-state or end of Δt_{ice}

Contents

Plume only - running to steady-state

- 10km x 10km , 25 days
- 100 by 100 grid, $\Delta t = 60.0s$
- 20 m minimum thickness
- 100m channel amplitude
- Uniform ambient ocean $-1^{\circ}C$ and $34.5 psu$
- with and without rotation

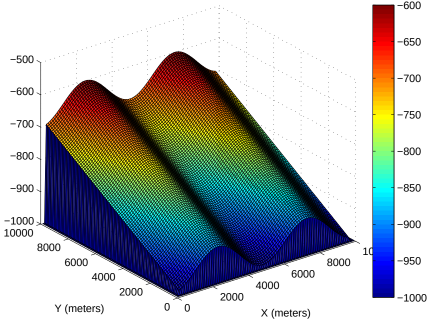
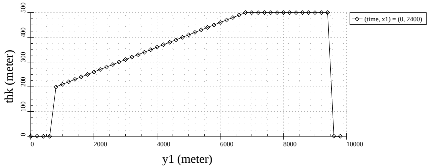


Figure: Ice shelf basal depth

Movie of plume runs to 'steady-state'

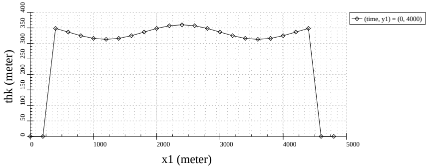
Coupled Ice-Plume run

- 5km x 10km , 50 years
- 25x50 grid, $\Delta t_{\text{ice}} = 0.5$
- no-slip on North,East,West boundaries



ice thickness from coupled confined shelf test

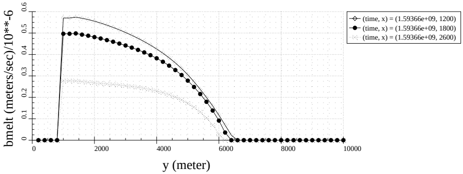
Figure: Initial thickness along flow



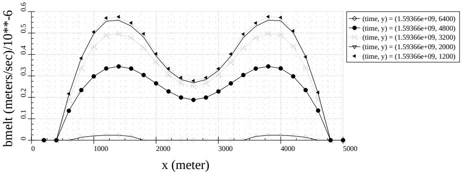
ice thickness from coupled confined shelf test

Figure: initial thickness across flow

Basal melt rate



basal melt rate



basal melt rate

Figure: Along-flow $\dot{m}$ at 50 years

Figure: Across-flow $\dot{m}$ at 50 years

Movie of upper surface

Contents

blue = neglected terms
red = coupling terms
Momentum equation (force balance)

$$\partial_x \sigma_{xx} + \partial_y \sigma_{xy} + \partial_z \sigma_{xz} = 0$$
$$\partial_x \sigma_{yx} + \partial_y \sigma_{yy} + \partial_z \sigma_{yz} = 0$$
$$\partial_x \sigma_{zx} + \partial_y \sigma_{zy} + \partial_z \sigma_{zz} = \rho_{\text{ice}} g$$

Constitutive law

$$\begin{pmatrix} \frac{\partial u}{\partial x} & \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) & \frac{\partial v}{\partial y} & \frac{1}{2}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) \\ \frac{1}{2}\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right) & \frac{1}{2}\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right) & \frac{\partial w}{\partial z} \end{pmatrix} = A(T)\sigma_{\text{eff}}^{n-1} \begin{pmatrix} \sigma'_{xx} & \sigma'_{xy} & \sigma'_{xz} \\ \sigma'_{yx} & \sigma'_{yy} & \sigma'_{yz} \\ \sigma'_{zx} & \sigma'_{zy} & \sigma'_{zz} \end{pmatrix}$$

Mass equation (incompressibility)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Temperature Equation

$$\rho c_p \left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \Phi$$

Thickness equation

$$\frac{\partial H}{\partial t} = -\nabla \cdot \int_B^s \mathbf{u}\, dz + M_s - M_B = -\nabla \cdot (\bar{\mathbf{u}} H) + \dot{a} - \dot{m}$$

$$B = -H\frac{\rho_i}{\rho_o}$$

Momentum Equation

Start with Navier-Stokes x-equation:

$$u_t + \nabla \cdot (uu, uv, uw) - fv = -\frac{1}{\rho}\left(p_x + \partial_i \sigma_{xi}\right)$$

After depth integration:

$$(DU)_t + \nabla \cdot (DUU, DUV) - DfV = \nabla \cdot (K_h D \nabla U) + \frac{gD^2}{2\rho_0}\rho_x + g' DA_x - c_d U|(U, V)|$$

$$D = B(x, y, t) - A(x, y, t)$$

Thickness equation (from incompressibility)

$$D_t + \nabla \cdot (DU, DV) = \dot{m} + \dot{e}$$

Temperature equation

$$\begin{aligned}(DT)_t + \nabla \cdot (DUT, DVT) =& \nabla \cdot (K_h D \nabla T) + \\ & T_A \dot{e} + T_B \dot{m} - \gamma_T |(U, V)|(T - T_B)\end{aligned}$$

Salinity equation

$$\begin{aligned}(DS)_t + \nabla \cdot (DUS, DVS) =& \nabla \cdot (K_h D \nabla S) + \\ & S_A \dot{e} + S_B \dot{m} - \gamma_S |(U, V)|(S - S_B)\end{aligned}$$

Plume thermodynamics

Linearized phase-transition boundary:

$$T_B = aS_B + b - cB$$

Linearized equation of state:

$$\rho = \rho_0(1 + \beta_S(S - S_0) - \beta_T(T - T_0)).$$

Melting is given by the flux balances:

$$\gamma_T|(U,V)|(T - T_B) = \dot{m}\mathcal{L} + \dot{m}c_{\text{ice}}(T_B - T_I)$$
$$\gamma_S|(U,V)|(S - S_B) = \dot{m}S_B$$