Modeling ice lens and firn aquifer: formation, timescales, and evolution

Old name: *Modelling the Juneau Icefield with M&H's Firn Aquifer Model*

Motivation

Where the surface melts or rain falls in percolation and accumulation zones, water can either refreeze or else remain liquid in isothermal firn aquifers. This work investigates the formation of ice lenses and firn aquifers, together and separately. In many locations these occur together -- in Greenland, Antarctica, and the Juneau Icefield, cores have been drilled into aquifers that reveal the coexistance of liquid water and refrozen ice. Ice lenses can exist absent of aquifers when there is enough cold content in the glaciers. The right conditions (enough cold and enough meltwater) may also produce impermeable ice slabs, which decrease available storage space for refrozen or liquid meltwater in the firn column.

Main working questions

1. What aquifer structures/configurations does the existing (Juneau) data support?
2. Can the Meyer/Hewitt Model produce a stacked firn aquifer?
    - Secondary question: can it produce big ice slabs?
        - yes
        - where do they form and why do they form?
            - when does an ice lens become an ice slab?
3. What kinds of aquifer configurations have been found on glaciers/ice sheets?
4. What are the control parameters under which ice lenses form?
    1. permeability
    2. porosity of falling snow
    3. amount of rain/meltwater
    4. initial conditions
    5. phase space exploration / regime diagram
    6. then, what are present day realistic conditions and how are these areas predicted to change under future climate scenarios?
5. When do ice lenses form in conjunction with firn aquifers?

6. What are the timescales of the formation of these processes? HOw are they impacted by climate & seasonality?

Progress as of May 2021

Code Updates

The code has been updated twice from the original code on github/published with the paper.

model_march2020/old code/Simplified_RunCode_20201020.m

The code that I first tried to modify, `model_march2020/old code/Simplified_RunCode_20201020.m` was based on `OriginalSupplementCode/RunCode.m` .

Modifications

I added various functions to easily vary environmental inputs or initial conditions:

- theta evolution so that surface Qbar could be
  - seasonal
  - constant
- accumulation
  - seasonal
  - constant
- initial states for phi
  - exponential
  - constant with a gaussian (to approximate an ice lens)
  - exponential with a gaussian, uniform
  - uniform phi with a step change for an ice lens
  - exponential with a step change for an ice lens)

Successes

- firn aquifers could form
- ice lenses could be initialized w/ phi0

Issues

- Firn aquifers could form but would not saturate upwards.

Notes

- `old code/RunCode_20201020` doesn't currently run; not trying to fix it

model_march2020/RunCode_UPDATE

Modifications

- Colin added in an option to use saturated fluxes on either side of the cell that is actually saturated

```
I = S_nm1>=1;
if I(I)
    [qp,qm,pressure] = FullySaturatedWaterPressure...
    if 0
    ...

    elseif 1
        Ip = or([I(2:N); I(N)],I);
        Im = or([I(1); I(1:(N-1))],I);
        % Total Water
        FpWS(Ip)=qp(Ip);
        FmWS(Im)=qm(Im);
        % Enthalpy
        FpS(Ip)=Stefan*qp(Ip);
        FmS(Im)=Stefan*qm(Im);
    end

    ...

end
```

expanding `or([I(2:N); I(N)],I);` →

- `I` = [0 0 1 1 1 0 0]
- `Ip = [I(2:N); I(N)]` = [0 1 1 1 0 0 0]
- `Im = [I(1); I(1:(N-1))]` = [0 0 0 1 1 1 0]

Successes

- aquifer fills now

Issues

- breaks when we try to form an ice lens e.g. by initializing `theta0` as a tanh function

**Notes

- unfortunately not all code was copied over from dave's computer, so some of the work on this is missing (but exists on there)
-

model_may2020/RunCode_updateSatFlux.m

Modifications

The notes are sketched in the hobonichi notebook pgs 67-71.

- In essence, when choosing which fluxes to use (saturated or unsaturated), there was one flux boundary that wasn't being set (below the first saturated cell)
- slocations needed to be transposed, otherwise was an array and i did not really iterate. THIS DID NOT BREAK THE CODE BUT IT IS AN ISSUE.

Successes

- Can form ice lenses e.g. by initializing theta0 with a gaussian cold spike
- Aquifers can saturate upwards and downwards

Issues

- ice lenses do not thicken
  - cold doesn't seem to penetrate through ice lenses (at least not when there is still R coming, haven't tried stopping R)

Notes

How to run

`Ice-lens-and-aquifer-modelling/code/MH-Model/model_may2020/`

`RunCode_updateSatFlux`

var	description
T	simulation time
phi0	sets surface porosity
metersperyear	sets AccumulationRate, which sets AbarFun
Qbar	sets nondimensinoalized surface energy flux; if EbarFun is 0, does nothing

var	description
type	sets type of compaction, currently no compaction occurs
Rbar	fixed surface water flux (aka rain)

Physical parameters

The physical parameters & the non-dimensionalization of this model are described in Appendix B

We nondimensionalize the lengths by $\ell = Q_0 t_0/(\rho \mathcal{L})$ and time by the annual period t_0. We write $T = T_\mathrm{m} + \Delta T \theta$ and choose the temperature scale as $\Delta T = Q_0/h$. Enthalpy is scaled with $\rho_\mathrm{i} c_\mathrm{i} \Delta T$, ice velocity with ℓ/t_0, water velocity with $(\rho_\mathrm{w} g k_0)/\mu$, and water pressure with $\rho_\mathrm{w} g \ell$. We define the parameters

$$\mathcal{U} = \frac{\rho g k_0 t_0}{\ell \mu}, \ \mathcal{S} = \frac{\mathcal{L}}{c_p \Delta T}, \ Pe = \frac{\rho c_p \ell^2}{K t_0}, \ B = \frac{\rho g d_p \ell}{\gamma}, \qquad \text{(B1)}$$

where $\mathcal{U}$ is the scale for the water percolation relative to ice motion, $\mathcal{S}$ is the Stefan number, Pe is the Péclet number, and B is the Bond number. Typical parameter values are shown in Table 1. Both $\mathcal{U}$ and $\mathcal{B}$ are large; this indicates that the water percolates relatively quickly and that the percolation is mainly driven by gravity rather than capillary pressure gradients. Both of these could be seen as justification for tipping-bucket-type models.

Mesh

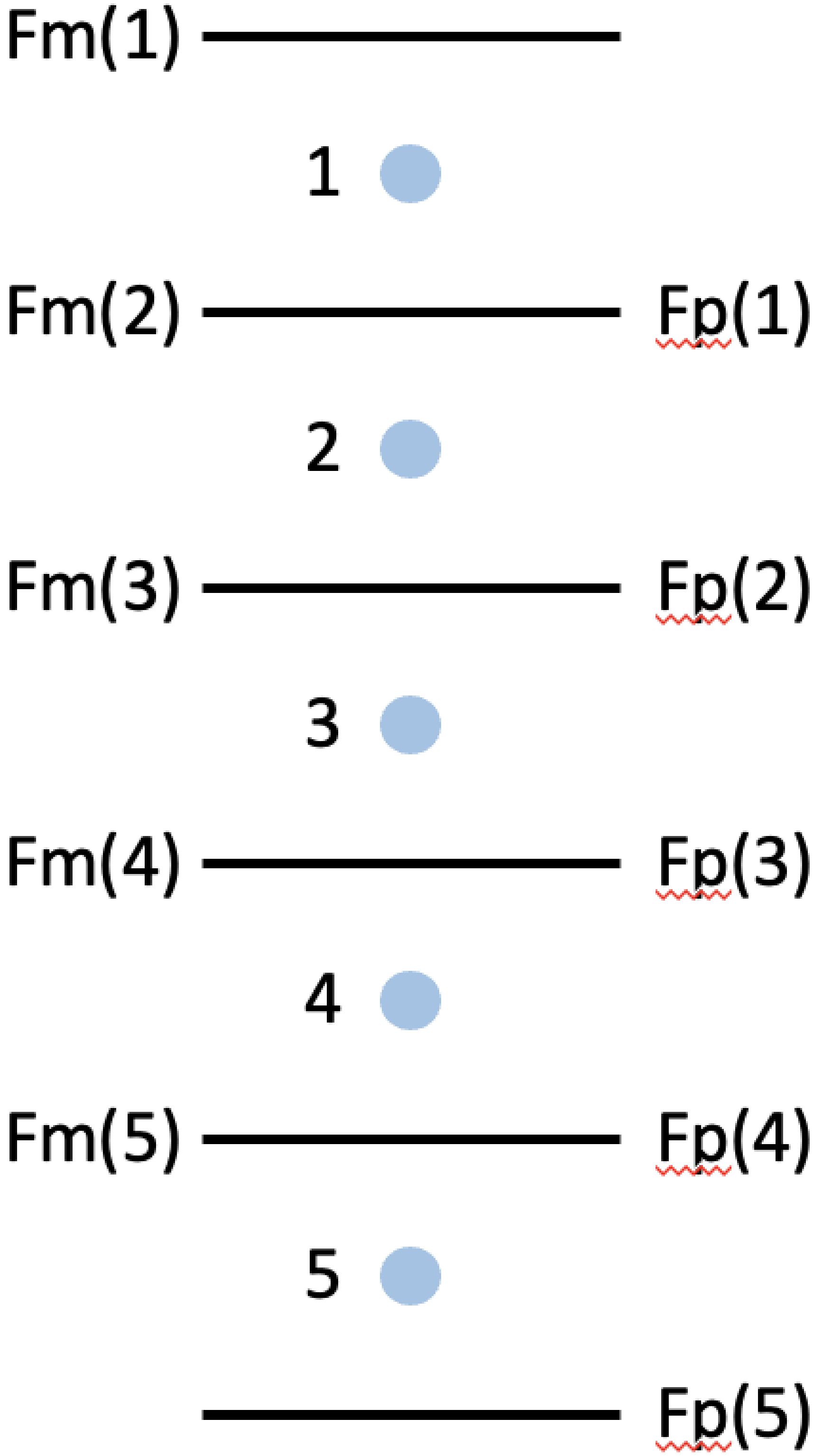
- `N` sets the number of cells
- `xcelledges` describes the edges (where fluxes, etc are calculated)
- `xgrid` describes the centers (where vars like phi, enthalpy, etc are calculated)

Functions

- `AbarFun = @(tau)AccumulationRate` $\longrightarrow$ constant accumulation rate; for seasonal, use sin (high in winter, low in summer) or other relevant function
- `EbarFun = @(tau)0.0*(Qbar-cos(2*pi*tau))` $\longrightarrow$ if zero, gives us constant temperate conditions; remove zero if you want seasonality

Initial Values
`S0` $\longrightarrow$ saturation (usually set to zero)
`theta0` = 0 (temperate), but can set theta0 to gaussian or tanh function to add cold into pack & freeze water (e.g. to create ice lens/slab)
`phi` = set initial porosity to gaussian or exponential or uniform
`W` $\longrightarrow$ total water depends on amt of ice ($1-\phi$) and initial liquid water content ($\phi * S0$)
`H` $\longrightarrow$ Enthalpy depends on total water, temperature, and saturated pore space
- note, if theta0 is always 0 (e.g. temperate), only change in enthalpy is due to presence of liquid water

choice of flux at xcelledge
see this powerpoint for visualization and changes to this section



1. unsaturated fluxes are calculated everywhere

2. if S >=1 anywhere(`I = S\_nm1>=1;`), then saturated fluxes are calculated everywhere
3. then `if` statements set edge fluxes as choice between unsaturated and saturated
    1. always chooses saturated in current experiments
    2. first if statement sets fluxes at upper and lower boundaries of first saturated cell
    3. the second two `if` statements set the fluxes at the base of saturated cells (when neighboring is saturated or unsaturated, respectively)
4. running the `elseif 0` option always chooses saturated cells, but code also acts like cells on either side of indexed saturated cells are saturated. so this is different than the option above, which acknowledges where saturation & unsaturation exist
5. within saturation if statement, H, & W are recalculated; just after, theta, phi, S, H, and W are recalculated

`Simplified_RunCode_updateSatFlux`

all the same physics as RunCode_updateSatFlux, but with built in options about initialization of accumulation, temperature, and density, as well as seasonality options

```
thetaOpt = {'constant', 'seasonal'}; %(temperature seasonality)
thetaIOpt = {'uniiso', 'tanh', 'gausiso'}; %uniiso = uniform &
isothermal; tanh and gausiso both can be customized below
accOpt = {'constant','seasonal'}; %(snow acc. seasonality)
phiOpt = {'exponential', 'gausuni', 'gausexp', 'ice lens uni', 'ice
lens exp'}; % porosity initialization
```

To do

Upon return

- [ ] relate `dt` and `dx` explicitly through CFL condition
- [ ] `% compute fully saturated water pressure` flux choice (e.g. in if statements after `i=slocations`) always chooses saturated option -- is this physical/expected? is there any reason to allow for the choice? are there cases where the unsaturated flux is chosen?
- [ ] look for any differences between H and W recalculated during saturation, and H, W recalculated after saturation `if` statement
- [ ] phase space exploration -- under what Q, a, and theta (and rain) do ice lenses form? ice slabs? aquifers? ice lenses and aquifers?

- [ ] given future scenarios of environmental conditions on antarctic ice shelves, how and where can we expect ice lenses, slabs, and aquifers to form and change?

May 2021

- [x] ~~update so that dt and dx are related by their cfl condition~~
- [x] ~~retransfer code (`model_march2020` , previously called `model`) from dave's laptop~~

Feb 1-5

- 20210202-Tue: run systematically varying Q + A

Jan 25-29

Jan 18-22

- [ ] transfer and clean up MH paper onto Obsidian

Jan 4-8

- [x] ~~create file structure for project~~
- [x] ~~create initial literature review for project~~
- [ ] create to do for MH code
- [x] ~~transfer notes on MH paper from Notion to Obsidian~~
- [x] ~~develop timeline for project~~

Notes on data

Juneau Icefield

Weather

- [description of data](/Users/elizabeth/Documents/home_research/projects/JIRP Firn Aquifer/data/readme_data.md)
- as of 2/2/2021

> *From README_WeatherData_JIF.pdf*
> **Reference:** Baker, E. H., McGee, S., Campbell, S. W., Pierce, J. L., McNeil, C. J., 2019, Weather Station Data on the Juneau Icefield (ver. 1.0, June 2019): U.S. Geological Survey data release, https://doi.org/10.5066/P90RCN51.
> **Units:** Celsius (temperature), incremental - mm (precipitation, mulitply

> by site specific factor), cumulative - m, W m^2 (radiation)
> **CRS:** WGS 84
> **Data of Interest:** C26 is closest; Precip and Temp; Lvl1 and Lvl2 data are both fine for this analysis

Mass balance

- [description of data](/Users/elizabeth/Documents/home_research/projects/JIRP Firn Aquifer/data/readme_data.md)
- as of 2/2/2021

> *From JIF_GlacierWide_README*
> Direct field measurements of point glaciological data are combined with weather and geodetic data to estimate the seasonal and annual mass balance at each glacier in both a conventional and reference surface format (Cogley and others, 2011). The basic analysis framework (O'Neel, 2019, in prep; McNeil et. al, 2019) is the same at each glacier to enable cross-comparison between output time series. However, in this data release for Taku and Lemon Creek glaciers temperature lapse rates are optimized using on-icefield weather data. This changes the degree day factor in the melt model, giving small post-geodetic calibration differences on the order of 2-3 cm. Details are described in McNeil (2019). Vocabulary used follows Cogley and others (2011) Glossary of Glacier Mass Balance.
> **Reference:** O'Neel and Others (2019)
> **CRS:** UTM Zone 8N (EPSG 26908) ref to WGS84
> **Units:** m.w.e.
> **Data of interest:** (from JuneauICefield_UTM8N.csv)
>
> - MG6 (some yearly data 1962-2019 in Input_Taku_Glaciological_Data) and TSQG1 (none in Input_Taku_Glaciological_Data); other close datapoints include MG2 and LLG1
> - Input_Taku_Glaciological_Data (MG6)
> - Input_Taku_Daily_Weather (from airport, elev 5m, [58.3566, -134.5640])

> **Related files**
>
> - **JuneauIcefieldDivide QGIS:** JuneauIcefield_UTM8N_massbalance

Notes on code

Links to relevant daily notes

- 20210513_Thu - notes from Jonny and Colin about cold conduction through ice lenses
- 20210507_Fri - updated code for saturation physics, making ice lenses
- 20210419_Mon - questions about fluxes and math; notes were written out but not stored in obsidian
- 20210422_Thu - thoughts on structure for iteration, need update with regeneration of S from new H and S below saturation physics
- 20210312_Fri - figures of intial attempts to a) fill an aquifer given an ice lens, b) seasonal accumulation effects, and c) generate an ice lens
- 20210224-Wed - initializing φ
- 20210222-Mon - meeting with Jonny and Colin on possibly directions for this work -- e.g. idealized conditions, ice lenses, stacked aquifers, method of lines
- 20210218-Thu - trying to input juneau icefield conditions (we eventually nixed this; not important right now to recreate specific regional conditions)
- 20210107-Thu - brief notes with discussion from jonny about simplifying model conditions, e.g. force model (no changes) with: flat weather; seasonal weather; stochastic variability at various timescales; climate trend (e.g. steadily increasing)
- MH code description in @meyerContinuumModelMeltwater2017 > ^c629cb

Literature

1. Meyer CR and Hewitt IJ (2017) A continuum model for meltwater flow through compacting snow. *The Cryosphere* **11**(6), 2799–2813 (doi:10.5194/tc-11-2799-2017) @meyerContinuumModelMeltwater2017
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10. Miller O, Solomon DK, Miège C, Koenig L, Forster R, Schmerr N, Ligtenberg SRM and Montgomery L (2018) Direct Evidence of Meltwater Flow Within a Firn Aquifer in Southeast Greenland. *Geophysical Research Letters* **45**(1), 207–215 (doi:10.1002/2017GL075707)
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