Of rocks and ice: The glacier-rock glacier cycle

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Estimates of Sea Ice Thickness Distribution Using Observations and Theory

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The thickness distribution of sea ice is determined by a balance of thermal and mechanical processes. Observations were made over an area where the ice thickness was between 1 and 3 m. The measurements were made by using a combination of satellite data and in situ observations. The data were analyzed using a computational model that incorporates both the thermal and mechanical processes. The model was able to reproduce the observed distribution well, indicating that the model is capable of predicting the thickness distribution accurately.

Introduction

The thickness of sea ice varies widely across regions and seasons. Understanding the distribution of ice thickness is crucial for modeling the dynamics of the ice system, predicting changes in polar ice, and assessing the impact of climate change on the Arctic. This study aims to estimate the thickness distribution of sea ice using observational data and a theoretical framework.

When the concept of the sea ice thickness distribution was introduced in 1973 (Thorndike et al., 1973), it was a new idea to understand the distribution of ice thickness. Since then, many observations of ice thickness have been made, leading to a better understanding of the thermal and mechanical processes that determine the thickness distribution.

Let $h$ denote ice thickness, and $p(h)$ be the proportion of ice in the thickness range $h$ to $h + dh$. Let $f(h)$ be the (log) growth rate of sea ice, and $v$ the horizontal velocity vector. Then the evolution of the thickness distribution is governed by

$$\frac{\partial p}{\partial t} + \nabla \cdot (v p) = \frac{\partial}{\partial h} (\frac{f(h)}{h} p(h)).$$

This equation describes how the thickness distribution changes over time due to the growth and movement of the ice. The growth rate $f(h)$ and the horizontal velocity $v$ are functions of the ice thickness and are determined by the physical processes acting on the ice.

Results

The model was able to reproduce the observed thickness distribution well. The results indicate that the thickness distribution is controlled by both thermal and mechanical processes. The thermal processes, such as freezing and melting, are responsible for the formation of new ice, while the mechanical processes, such as ice deformation and bending, determine the thickness of the existing ice.

Conclusion

The study demonstrates the importance of understanding the thickness distribution of sea ice for predicting changes in the polar regions. The model provides a useful tool for studying the dynamics of the ice system and assessing the impact of climate change on the Arctic.
Lyell and Maclure glaciers, Yosemite NP
A. Glacier

B. Debris-covered glacier

C. Rock glacier

ELA

supraglacial transport

englacial path

rockfall

avalanche
South Cascade Glacier, Washington
Basic architecture of a glacier

Accumulation zone
Equilibrium line
Ablation zone
Conservation of ice volume in a column

\[ \frac{\partial H}{\partial t} = b - \frac{\partial Q}{\partial x} \]
Approach to steady state for a simple pure ice case
British Columbia Coast Range
The dirty snout of Kennicott Glacier
Key elements of the debris-covered glacier
How does the presence of debris reduce sub-debris ice melt?

Dependence of melt rate on debris thickness is well described by a hyperbolic (1/h) function.

Why? It is to 1st order a conduction problem.
The rocky umbrella

\[ \dot{m} = \frac{Q}{(\rho \cdot L)} \]

\[ Q_z \]

\[ Q_{z+dz} \]

\[ T \]

\[ 0^\circ C \]

\[ \text{time} \]

shortwave

longwave
Effects of debris cover include glacier extension

Leif Anderson
Bottom line: debris-covered glaciers can be way longer than their debris-free cousins
The rock glacier end-member
Sourdough rock glacier, Alaska
Note the strong asymmetry
Mt Sopris, Colorado

Accumulation area

Mt Sopris camera
Installed 10/7/2016
at blue dot by Brett Oliver
They are cruising into the trees!
InSAR Displacement Map, zoomed over the rock glacier, scaled from displacements over 46 days to annual rate in cm/year. The fastest movement is up to ~1 m/year. The toe is also moving. Slow movements are marked in red. Courtesy of Lin Liu.
Mass balance pattern on a rock glacier

- wind scour
- wind deposition and cornising
- avalanching
- avalanche cone
- rock fall

modern ELA above peaks

- snowfall
- wind deposition
- net accumulation

net loss

mass balance, b

- fate of snow
  - avalanche deposit
  - net
  - direct snow

- fate of rock
  - subsurface
  - direct to surface
Some debris outruns avalanche
Vertical speed structure in a rock glacier

$t = 500$ years
Response to slight climate warming of 1°C
Rock glaciers are survivors
Sinusoidal climate: debris-covered to rock-glacier cycling
Rock glacier
Debris-covered glacier

A
Terminus position (km)

Time (years)

B
$T_{\text{wmax}}$ (m/yr)

$T$ (°C)

Time (years)
Stripes from Space: medial moraines

Rhone Glacier, Wrangell-St Elias National Park, Alaska
Barnard Glacier, Alaska
Medial moraine
The Medial Moraine

**What the glacier provides:**
- debris-rich septum
- motion down-valley

**What the climate provides:**
- a pattern of down-valley
- Increasing melt rates

**The pieces of the problem**
- ablation rate altered
- slope generated
- debris moves downslope
The topple-walk mechanism

propensity for downslope motion

$D (1 + \beta \tan(\alpha))$
Emergence of medial moraines below the ELA
Medial moraine collision leads to complete debris cover
Summary

• A model that includes both ice and rock dynamics can explain the continuum of glacier types

• Debris-covered glaciers can be significantly longer than debris-free counterparts

• Rock glaciers require both an avalanche source of snow and a headwall source of rock

• In complex terrain debris cover is dominated by medial moraines and their collisions
A model in which glacier is pure ice with only a thin rocky cap succeeds

Surface speeds expected on measured slopes for a range of possible thicknesses
Assuming pure ice, deformation only

\[
A = 7.5 \times 10^{-17} \text{ Pa}^{-3} \text{ yr}^{-1}
\]
Mars
Martian glacial features

By Jim Secosky modified NASA image
Glacial signature in alpine landscapes
Our own Longs Peak
Our own Longs Peak

moraine
Asymmetry of divides - Mt Evans
Moving on to longer time scales: How has climate changed over the last couple million years?
Melt less, snow more -> lower ELA
Ice transfer: How does ice move?

Deformation plus sliding
Front Range, Colorado
Displacement history
From GPS monuments

Sliding speed

Bench glacier, Alaska

Photo: Neil Humphrey
InSAR also shows slow movement
~30 Ma granite
Blobs embedded in sedimentary rock

West Elks
Central Colorado

Image Landsat / Copernicus
Note the strong asymmetry
The importance of edges: they migrate...

Conservation of debris requires:
\[ e_{\text{cliff}} H = U h \]
\[ e_{\text{cliff}} = U (h/H) \]

If \( U = 1 \text{ m/yr}, h = 1 \text{ m}, H = 300 \text{ m} \)

\[ e_{\text{cliff}} = 3.3 \text{ mm/yr} \gg e_{\text{top}} = 0.01-0.03 \text{ mm/yr} \]