International Summer School in Glaciology
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GEOGRAPHY OF GLACIERS 1

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OUTLINE

• Why do we need a geography of glaciers?
• Where are the glaciers?
• What are the glaciers doing?
• What does a geography of glaciers look like?
2. Glacier mass balance and global sea level

The relationship between glaciers, climate and sea level can be illustrated by the general equation:

$$\text{SLR} = -\left(\frac{1}{A_0}\right) \sum_{r=1}^{R} S_r b_r \quad (1)$$

where SLR is the global average sea level rise (m a$^{-1}$) due to melting of glaciers and ice caps and $b_r$ is the glacier mass balance (m a$^{-1}$) in the $r$th region with a glacier area of $S_r$ (km$^2$). $R$ is the total number of glaci-erized regions in the world and $A_0$ is the total area of the oceans (km$^2$). The minus sign in (1) is necessary because a decrease in mass balance corresponds to an increase in sealevel rise. The sensitivity of SLR to temperature change is given by

$$\frac{\Delta \text{SLR}}{\Delta T_G} = -\left(\frac{1}{A_0}\right) \sum_{r=1}^{R} S_r \left(\frac{\Delta b_r}{\Delta T_r}\right) \left(\frac{\Delta T_r}{\Delta T_G}\right) \quad (2)$$

where $\Delta \text{SLR}/\Delta T_G$ is the sensitivity of SLR (m a$^{-1}$ K$^{-1}$) to change in global temperature $T_G$. $\Delta b_r/\Delta T_r$ is the sensitivity of glacier mass balance (m a$^{-1}$ K$^{-1}$) in the $r$th region to temperature changes $\Delta T_r$ in the region. $\Delta T_r/\Delta T_G$ is the sensitivity of regional temperature to changes in global temperature $\Delta T_G$. The regional tem-

CONSIDER

GLACIER EFFECT

ON GLOBAL SLR

- Global SLR is sum of contributions from different regions
- Need to define regions and assess $S_r b_r$ and $\Delta b_r/\Delta T_r$ in each region
Sensitivity Study
Braithwaite and Raper (2002)

Table 1
Global sea level sensitivity for five different scenarios of mass balance sensitivity applied to all mountain glaciers and ice caps, excluding Greenland and Antarctic.

<table>
<thead>
<tr>
<th>MB Sensitivity (m a⁻¹ deg⁻¹)</th>
<th>Global glacier area, Sea level sensitivity (mm a⁻¹ deg⁻¹)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0.52 x 10⁶ km²</td>
</tr>
<tr>
<td>Very low</td>
<td>-0.2</td>
</tr>
<tr>
<td>Low</td>
<td>-0.4</td>
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<tr>
<td>Medium</td>
<td>-0.6</td>
</tr>
<tr>
<td>High</td>
<td>-0.8</td>
</tr>
<tr>
<td>Very high</td>
<td>-1.0</td>
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</tbody>
</table>

Calculations made for two different estimates of global glacier area. The higher value (0.68 x 10⁶ km²) from Dyrugierov and Meier (1997) may be more correct but only about 0.52 x 10⁶ km² are presently localised within 1° of latitude and longitude.

- Could be even higher in regions like New Zealand!
- Realistic global figure?
GEOGRAPHY OF GLACIERS

• Mass balance sensitivity is not constant!

• A “geography of glaciers” would show the variations in $S_r$, mass balance $b_r$, and mass balance sensitivity $\Delta b_r/\Delta T_r$ across the world.

• Start by explaining time and space variations in glacier areas $S_r$, mass balance $b_r$ and mass balance sensitivity $\Delta b_r/\Delta T_r$. 
CONDITIONS FOR FORMING GLACIERS

• Need topography on which the glacier can lie
• Need high topography and low temperature to form an accumulation area at high altitude
• Need a path down which the glacier can flow to lower altitude
• Need high temperature at low elevation to melt all the ice flow from higher elevations

Note that “high” and “low” are relative. Note we are only talking about glaciers with melt
GLOBAL DISTRIBUTION OF GLACIERS
(20 km² per 1 degree latitude/longitude)

- Where are they?
- Why are they there?
- Why are they not in other places
GLOBAL TOPOGRAPHY
(5 min topography)

- Generally found in high mountains
- “High” is relative
- Glaciers are lower in Arctic and higher in temperate and tropical areas
GLACIERS AND TOPOGRAPHY IN THE ALPS

- Topography from 5 min global topography
- 5,000 glaciers from World Glacier Inventory
IMPORTANCE OF TOPOGRAPHY

- Geography of glaciers must explain how some glaciers can exist at hundreds of metres above sea level while other glaciers can only exist at thousands of metres above sea level.

- If your topography is not high enough, you can’t have a glacier!

We had glaciers at low altitude in the UK in the Younger Dryas but our mountains are not high enough to maintain an ELA under present climate.
It has location and duration
Point location on global scale

Latitude & longitude
Area & length
Altitude range
All functions of time
IMPORTANCE OF ELA - 1

- ELA is equilibrium line altitude
- Mass balance = zero at ELA, i.e. ablation = accumulation
- Ablation < accumulation above ELA
- Ablation > accumulation below ELA
- ELA is somehow at the “middle of the glacier”
- ELA is key to glacier geography
- Related concepts are snow line and glaciation level/limit
DISCOVERY OF SNOW LINE

P. Bourguer (1698-1758)  
“discovered” snow line in tropical South America

Ability to see snow above you while you are in high temperature leads to concept of “temperature lapse” rate

Note: we are not suggesting that giraffes live in South America
The glaciation level in southern Alaska. *Geografiska Annaler* 63A, 3-4, 251-260)

Glaciation level is a rough proxy for ELA.

Glaciation level rises from coast to the interior.
The glaciation level in southern Alaska. *Geografiska Annaler* 63A, 3-4, 251-260)

Winter precipitation falls from coast to the interior.

Sorry about the units!
TEMPERATURE AT GLACIATION LEVEL
(Østrem et al. 1981)

The glaciation level in southern Alaska. *Geografiska Annaler* 63A, 3-4, 251-260)

- Summer temperature at the glaciation level falls from coast to interior.
- Sounds counter-intuitive as temperature rises when we go inland. But glaciation level rises
MARITIME/CONTINENTAL EFFECTS

• The air in the interior of a continent is generally warmer and drier in summer than air over the ocean at the same latitude and altitude.

• Precipitation is generally higher over oceans than over continents at the same latitude and altitude.

• Relative dryness of continental climate means that glaciers have to be higher to exist in colder temperatures with lower precipitation.
DUAL NATURE OF ELA

As a variable (annual ELA)
from year to year
Measure as part of a mass balance programme

As a parameter
n. (math.). Quantity constant in case considered, but varying in different cases (OED)
IT HAS ALL BEEN DONE BEFORE

This is from L. F. Kaemtz (1801-1867) who is quoting Alexander von Humboldt.

The height of the snow-line being a function of the quantity that falls in winter and of the heat of the summers, it is clear that, in equal latitudes, it must be higher in the interior of continents, where less snow falls, and where the summers are warmer, than on the coasts. Thus it is 650

09/08/2012 Geography of glaciers June 2012 20
IT HAS ALL BEEN DONE BEFORE

This was published in 1854 by A. Schlaginweit (1829-1857) and H. Schlaginweit (1826-1882)

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<td>10</td>
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Uebersicht der Verbreitung und...
Dyurgerov and Meier (2005) is also a valuable source of unpublished data from earlier years.

If you measure glacier mass balance, send it to WGMS. If you need data, can get it from WGMS.
• WGI includes mid- to late-20th Century glacier states but is incomplete
• GLIMS will cover whole globe in its early 21st Century state

Rich countries (China and Russia) have completed their parts of WGI
Poor countries (Canada and USA) have not