ICE – CLIMATE INTERACTIONS

MARTIN SHARP – UNIVERSITY OF ALBERTA
CANDAC Summer School, July 2012
What do we Mean by Land Ice?

- Ice grounded on land (even if below sea level)
- Distinguished by scale and relationship to bedrock topography
- Mountain Glaciers, Ice Caps, Ice Sheets
- Mountain glaciers occupy topographic depressions; ice caps and ice sheets subsume underlying bedrock topography
Antarctic Ice Sheet

RAMP Mosaic of Antarctica

Devon Ice Cap  Dowdeswell et al.; CJES 2004
Dynamic Complexity of Ice Sheets and Ice Caps

Source: E. Rignot, 2012

Ice Streams and Outlet Glaciers

Dowdeswell et al.; CJES 2004
Mountain Glaciers

Franz Josef Glacier, New Zealand

Exit Glacier, Alaska

Some Added Issues........
• Avalanching
• Debris Cover
• Multiple reflected radiation
• LW emission from valley walls
Some Reach the Ocean

Aiakhik Glacier, Alaska
Land Ice in the Climate System

• Atmosphere, Ocean, Cryosphere, Biosphere, Solid Earth
• Interactions with other system components
  – Surface mass exchange (snowfall, evaporation, melt/runoff)
  – Energy/heat exchange: (surface: radiative, turbulent, conductive fluxes; base: geothermal, meltwater)
  – Ice/albedo feedback
  – (Evolving) Topography and atmospheric circulation: (surface temperature and precipitation)
  – Interactions with oceans (flotation, calving, subaqueous melt/freezing, tides, sea level, freshwater input)
  – Isostasy (crustal loading/unloading)
  – Erosion, sediment transport and deposition (bed modification (height, roughness, hydraulic transmissivity))
How Does Land Ice Respond to External Forcing?

- **Changes in climatic balance** (snowfall-melt/runoff)
- **Changes in internal balance** (freezing of percolating meltwater in cold snow/firn)
- **Changes in frontal balance** (iceberg calving/subaqueous melt)
- **Changes in ice temperature** (esp. important near PMP – affect ice viscosity, bed friction, meltwater abundance)
- **Changes in dynamics** (linked to changes in hydrology, bed temperature, bed stability)
- **These can all be inter-linked**
What Makes Glaciers Change Their Geometry?
CONTINUITY EQUATION

- Basis for understanding how ice masses respond to external forcing and changes in internal properties
  
  \[
  \frac{\Delta H}{\Delta t} = \frac{\Delta Q}{\Delta x} + B_c + B_f
  \]

- Units = \( m \, s^{-1} = m^2 \, s^{-1} \, m^{-1} + m \, s^{-1} + m \, s^{-1} \)

- \( H = \) ice thickness, \( t = \) time, \( Q = \) ice flux =\(((U_s + U_d)H)\); \( x = \) distance; \( B_c = \) climatic balance, \( U_s = \) sliding velocity, \( U_d = \) mean deformation velocity, \( B_f = \) frontal balance
CONTINUITY EQUATION

\[ \frac{\delta H}{\delta t} = \frac{\delta Q}{\delta x} + B_c + B_f \]

Geometric Change can be initiated by changes in \( B_c \), \( B_f \), or flow velocity.
Climatic Balance ($B_c$)

- $B_c = \text{Annual Inputs} - \text{Annual outputs (melt/runoff)}$
- Glacier splits into 2 zones
- Accumulation Zone: $B_c > 0$
- Ablation Zone: $B_c < 0$
- Equilibrium Line: $B_c = 0$

Source: Glaciers On-Line
www.swisseduc.ch/glaciers/
Importance of Climatic Mass Balance

• Connects ice mass to the atmosphere
• Role in glacier contributions to sea level change
• Major term in continuity equation for ice thickness - driver for change
• Defined as (accumulation – runoff)
• Runoff = (melt – internal accumulation)
Glacier Meteorology

Unique properties of a glacier

- High surface albedo
- Upper limit to surface temperature
- Melt provides a sink of energy for overlying air on warm days

Taylor Valley, Antarctica
Distinctive circulation associated with a glacier

Figure 1. The basic structure of atmospheric circulation in a glacierised mountain region.

Source: W. Greuell)
Balloon Profiles over Pasterzegletscher (Austria)

Energy exchanges between atmosphere and glacier take place within this boundary layer. Development of boundary layer needs to be taken into account in modelling interactions between climate forcing and climatic balance

(W. Greuell)
Key Issues

• How do magnitude and spatial pattern of climatic balance change over time as climate varies?

• Important factors:
  – Atmospheric moisture content, atmospheric circulation, precipitation distribution
  – Circulation feedbacks from evolving ice sheet geometry and extent
  – Internal accumulation feedbacks
  – Surface energy balance and air temperature
  – Albedo feedback
AIR FLOW AND PRECIPITATION OVER GREENLAND

Strong interaction between topography, air flow and accumulation

Fig. 2. Annual total precipitation in mm for Greenland. Dots on glaciers are locations of cores and pits. Solid circles are meteorological stations.

Fig. 3. Monthly resultant wind stream lines at 850 hPa (mbar) for January.

Source: A. Ohmura and N. Reeh; J. Glaciology 1991
Impact of LGM Ice Sheet Growth on N. Hemisphere Circulation

Example of LGM ice sheets (Source: Wright and Kutzbach, QSR 1984)
INTERNAL ACCUMULATION FEEDBACKS

- Internal accumulation important balance term in cold glaciers, where *summer melt occurs but much of it may refreeze when it percolates into cold snow and firn*
- Ice formed may have to be melted at least one more time before runoff can occur, so effectively adds to accumulation
- IA changes as climate changes – can increase or decrease
- **Contrast Canadian Arctic with northern Alaska**
ENERGY FLUXES BETWEEN ATMOSPHERE AND GLACIER

\[ Q_0 = S\downarrow (1 - \alpha) + (L\downarrow - L\uparrow) + Q_H + Q_L + Q_R \]

- \( S\downarrow \): short-wave incoming radiative flux
- \( \alpha \): albedo of the surface
- \( L\downarrow \): long-wave incoming radiative flux
- \( L\uparrow \): long-wave outgoing radiative flux
- \( Q_H \): turbulent flux of sensible heat
- \( Q_L \): turbulent flux of latent heat
- \( Q_R \): heat flux supplied by rain.

How Much Energy is Exchanged? In Which Direction?
GLACIER SURFACE ENERGY BALANCE

\[ Q_0 = L_f \frac{dm}{dt} + M_i c_{pi} \frac{dT_i}{dt} \] [Wm\(^{-2}\)]

Energy exchange with atmosphere melting / freezing heating / cooling of the ice or snow

- \( Q_0 \) energy flux atmosphere to glacier
- \( L_f \) latent heat of fusion (0.334 \( \times \) \( 10^{-6} \) J kg\(^{-1}\))
- \( m \) amount of melt water
- \( M_i \) mass of the ice
- \( c_{pi} \) specific heat capacity of ice (2009 J kg\(^{-1}\) K\(^{-1}\))
- \( T_i \) ice temperature

How is Available Energy Utilised?
Annual Cycle in Surface Energy Balance
Which fluxes matter?

Analysis of the surface energy balance for the year 2000. The turbulent exchange coefficient has been found by matching the observed and calculated ablation (see next sheet).

Energy fluxes towards the surface are positive. All values shown are daily mean values. The sensible heat flux is always positive, also in winter (this does not apply to 30-min values, however). The latent heat flux is generally small.

Best estimates of the annual mean fluxes are (in W m$^{-2}$):
- Solar net: 67
- Longwave net: -36
- Sensible heat: 36
- Latent heat: 6
- Used for melting: -76
- Imbalance: -3
Figure 10. A one-year record of daily mean global radiation from the Morteratsch AWS. The dashed line is an attempt to estimate the clear-sky global radiation.

Clouds Affect Radiation Receipts

Radiation tends to increase with elevation

Lower in maritime settings

W. Greuell
Fraction of radiation absorbed by surface depends on albedo ($f(\text{surface type})$)

### TABLE 4.1. Albedos (per cent) of snow and ice surfaces

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Range</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry snow</td>
<td>80–97</td>
<td>84</td>
</tr>
<tr>
<td>Melting snow</td>
<td>66–88</td>
<td>74</td>
</tr>
<tr>
<td>Firn</td>
<td>43–69</td>
<td>53</td>
</tr>
<tr>
<td>Clean ice</td>
<td>34–51</td>
<td>40</td>
</tr>
<tr>
<td>Slightly dirty ice</td>
<td>26–33</td>
<td>29</td>
</tr>
<tr>
<td>Dirty ice</td>
<td>15–25</td>
<td>21</td>
</tr>
<tr>
<td>Debris-covered ice</td>
<td>10–15</td>
<td>12</td>
</tr>
</tbody>
</table>

Strong feedback as surface evolves during melt season
DIRTY ICE - PASTERZEGLETSCHER

MELTING SNOW

$\alpha \approx 0.7$

$\alpha \approx 0.2$
Albedo Variations on Morteratschgletscher linked to Snow Depth/Age/Wetness

An example of the relation between snow depth and daily albedo. The daily albedo is defined as the ratio of the daily total of reflected solar radiation to the daily total of incoming solar radiation. A typical value for the snow albedo is 0.75, for the ice albedo 0.35.

Note that small amounts of snow in summer lead to high albedos for a couple of days.

FEEDBACK: ALBEDO ↔ SNOW AND ICE MELT

1) Faster metamorphism of snow
2) Ice appears earlier
3) More meltwater on top of ice
4) More water between snow grains

Lower albedo

More net short-wave radiation

More melt
DIRECT IMPACT OF TEMPERATURE INCREASE ON MELT

- Higher air temperature
- Turbulent fluxes
- Incoming long-wave radiation
- More melt
SENSITIVITY INCREASES DUE TO ALBEDO FEEDBACK

Higher air temperature

1) Faster metamorphosis of snow

Turbulent fluxes
Incoming long-wave radiation

Lower albedo

More net short-wave radiation

More melt

2) Ice appears earlier
3) More meltwater on top of ice
4) More water between snow grains
At the ice sheet scale, there is also a significant albedo feedback on the climate. This will change as ice sheets grow and decay.
Controls on Frontal Ablation

• May be controlled by ice flux to terminus or changes at terminus
• Changes in subaqueous melt rate/terminus undercutting (link to water temperature)
• Terminus thinning and flotation
• Tidal forcing – variable flotation (Maybe amplified by tidal damming of meltwater outflow)
• Changes in restraint by sea ice/iceberg melange
• Effect of bed height and ice thickness variations on tendency to float as ice retreats
The Role of Ice Dynamics

Source: Glaciers On-Line
www.swisseduc.ch/glaciers/
ICE TEMPERATURE

• Critical influence on glacier flow and meltwater drainage

• Ice can exist at temperatures at (warm) or below (cold) the pressure melting point (PMP)

• Glaciers can be:
  – **Cold** – all ice at $T < \text{PMP}$
  – **Temperate** – all ice at $T = \text{PMP}$
  – **Polythermal** – mix of ice at $T = \text{and} \ T < \text{PMP}$ (here warm ice usually near bed and in interior of glacier)
Key Internal Processes: Glacier Flow

Ice deformation (always occurs – faster in warmer ice)

Basal sliding (needs bed at PMP)

Bed deformation (needs bed at PMP plus unconsolidated substrate)
Meltwater Drainage

• **Water at glacier bed** facilitates sliding and can weaken subglacial sediment, allowing bed to deform

• **Nature of subglacial drainage system** (channelised/distributed – low/high water pressure) is critical – and can change over melt season or abruptly due to instabilities

• **Feedback on glacier flow** – can mediate flow response to external forcing via changes in basal friction or sediment yield strength/viscosity *(Hydrological Transitions)*

• **Important linkages** between climate, ice temperature, water flux, drainage system properties, and ice flow
Key Internal Processes: Meltwater Drainage

Source: AM Gurnell and MJ Clark. 1987 Glaciofluvial sediment transfer: an Alpine perspective

Source: Glaciers On-Line www.swisseduc.ch/glaciers/
Linking Temperature, Flow and Meltwater Drainage

• **Cold Glaciers**: Slow Flow by ice deformation; Meltwater runoff over the glacier surface

• **Temperate Glaciers**: Flow by ice deformation, sliding and/or bed deformation; Surface, englacial and subglacial meltwater drainage

• **Polythermal Glaciers**: Flow mechanism and drainage routing may vary with location in glacier. Thermal damming possible.

• **Thermal transitions** can cause sudden changes in hydrology and flow of glaciers (potential non-linear response to climate forcing)
Ice Sheet Flow Regimes

- divide, sheet, stream, shelf
- Flow regime transitions: in space and time
- Flow instabilities: divide migration, surging, piracy
- Can change geometry – feedback to climate
So..........

• Direct climate forcing/mass balance response
• Internal dynamics – temperature/hydrology/flow
• Feedbacks – albedo, topography, circulation
• They all matter