Principles of snow melt

GEO4430 snow hydrology
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How does snow melt?

• We need energy to melt snow/ice.

\[ E = m_s \cdot L_f \]

\[ \ldots = \rho_w h_{we} \cdot L_f \]

\[ h_{we} = \frac{E}{\rho_w L_f} \]

\( E \) – energy (J)
\( m_s \) – mass (kg) of snow
\( h_{we} \) – height of snow (m w.e.)
\( \rho_w \) – density (kg m\(^{-3}\)) of water
\( L_f \) – latent heat of fusion = 333400 J kg\(^{-1}\)

• Energy flux onto a unit surface:

\[ Q \text{ (Wm}^2) = \frac{E}{t} \text{ (s)} \]

Amount of energy per unit time

Where does the energy come from?

Energy balance

\[ 0 = Q_R + Q_H + Q_L + Q_G + Q_P + Q_M \]

\[ Q_R = S \downarrow - S \uparrow + L \downarrow - L \uparrow \]
Radiation

- Black body radiation (Stefan-Boltzmann law)
  \[ Q = \sigma T^4 \]
  \[ \sigma = 5.6703 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \]

Real world:
Gray body radiation
\[ Q = \varepsilon \sigma T^4 \]
\( \varepsilon \) – emissivity [0, 1]

Electromagnetic radiation

Wien’s law:
\[ \lambda_{\text{max}} = \frac{2.89 \times 10^3}{T} \text{ m K} \]

Electromagnetic spectrum
Radiation

GLOBAL RADIATION

- S: 0.15-5 µm
- Direct / diffuse component

DEM of 25m resolution

Engabreen

POTENTIAL DIRECT SOLAR RADIATION

MEASURED GLOBAL RADIATION

Longwave radiation

- 4-120 µm
- Emitted by atmosphere (water vapour, CO₂, ozone)
- Function of air temperature and humidity (cloudiness)

\[ L \uparrow=\varepsilon\sigma T^4 \]

Max = 316 Wm²

L acts day & night
Cloud effect:

Why are values positive in polar regions???

Turbulent heat fluxes

**Sensible heat flux**
- Function of temperature gradient
- Function of wind speed

**Latent heat flux**
- Function of vapour pressure gradient
- Function of wind speed

Fluxes also affected by
- Surface roughness
- Atmospheric stability

reflexion

shortwave reflectance = albedo

<table>
<thead>
<tr>
<th>Surface</th>
<th>Reflectance (shortwave)</th>
</tr>
</thead>
<tbody>
<tr>
<td>new snow</td>
<td>0.75 – 0.95</td>
</tr>
<tr>
<td>old snow</td>
<td>0.4 – 0.7</td>
</tr>
<tr>
<td>glacier ice</td>
<td>0.3 – 0.45</td>
</tr>
<tr>
<td>soil, dark</td>
<td>0.1</td>
</tr>
<tr>
<td>grass</td>
<td>0.2</td>
</tr>
<tr>
<td>rain forest</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Longwave reflectance of snow: < 0.1
reflectance = 1 - emissivity
snow is dark on IR image!
snow emits a lot L↑

Turbulent exchange

Momentum (T)

Heat (H)

Water vapor (E)

\[ \rho \, u \, K_u \, \frac{\partial u}{\partial z} \]

\[ \rho \, C_p \, K_T \, \frac{\partial T}{\partial z} \]

\[ \rho \, L_e \, K_h \, \frac{\partial u}{\partial z} \]

\[ \rho \, L_e \, K_w \, \frac{\partial v}{\partial z} \]

\[ \rho \, L_e \, K_h \, \frac{\partial u}{\partial z} \]

\[ \rho \, L_e \, K_w \, \frac{\partial v}{\partial z} \]

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\[ \rho \, L_e \, K_w \, \frac{\partial v}{\partial z} \]
Melt physics

- To melt 1 kg of snow/ice requires 334,000 J kg\(^{-1}\)
  Latent heat of fusion
- To sublimate 1 kg of snow requires 2,600,000 J kg\(^{-1}\)
  Latent heat of sublimation (8x \(L_f\) !!!)
- To warm 1 kg of snow 1 K requires 2009 J kg\(^{-1}\) K\(^{-1}\);
  ice: 2097 J kg\(^{-1}\) K\(^{-1}\)

**Specific heat capacity**

Refreezing of 1 g water → warms 160 g snow by 1 K

Dry conditions:
Sublimation of snow occurs
\[ L_s = 8L_f \rightarrow 8x \text{ less ablation than under wet conditions} \]

Removing cold content

**melt-water**

\[ T_m = 0 °C \]

**snow**

\[ V_s = 1 \text{ m}^3 \]
\[ T_s = -1 °C \]

Condition for melt: snow must be at melting temperature, otherwise refreezing will occur.

Cold content = energy needed to bring the snow / ice to 0 °C.

In the given example, refreezing of 2.5 l melt-water is needed to compensate for the cold content of the snow pack (snow density, \(\rho_s = 400 \text{ kg m}^{-3}\)).
Cold content

\[ Q_{cc} = C_i \rho_s h_s (T_s - T_m) \]

- \( Q_{cc} \): cold content
- \( C_i \): density of snow
- \( h_s \): snow height
- \( T_s \): specific heat of ice
- \( T_m \): melting temperature of ice in K or °C

Energy partitioning

<table>
<thead>
<tr>
<th>Component</th>
<th>60-69</th>
<th>70-71</th>
<th>72-73</th>
<th>74-75</th>
<th>76-77</th>
<th>78-79</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net shortwave radiation, ( K )</td>
<td>-8111</td>
<td>4999</td>
<td>4904</td>
<td>4053</td>
<td>3709</td>
<td>3400</td>
<td>4088</td>
</tr>
<tr>
<td>Net longwave radiation, ( L )</td>
<td>-3137</td>
<td>-2891</td>
<td>-2856</td>
<td>-2902</td>
<td>-3491</td>
<td>-3026</td>
<td>-3040</td>
</tr>
<tr>
<td>Net radiation, ( K + L )</td>
<td>-1148</td>
<td>-7890</td>
<td>-7860</td>
<td>-7908</td>
<td>-6035</td>
<td>-5036</td>
<td>-7066</td>
</tr>
<tr>
<td>Solar radiation, ( S )</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>Net solar radiation, ( S - K )</td>
<td>-733</td>
<td>1287</td>
<td>750</td>
<td>907</td>
<td>629</td>
<td>710</td>
<td>768</td>
</tr>
<tr>
<td>Net net radiation, ( S - (K + L))</td>
<td>-1049</td>
<td>-796</td>
<td>-1316</td>
<td>-1046</td>
<td>-775</td>
<td>-86</td>
<td>-944</td>
</tr>
<tr>
<td>Surface exchange, latent, ( E )</td>
<td>-286</td>
<td>-418</td>
<td>-680</td>
<td>-784</td>
<td>-346</td>
<td>-400</td>
<td>-604</td>
</tr>
<tr>
<td>Surface exchange, sensible, ( LE)</td>
<td>2925</td>
<td>1489</td>
<td>2669</td>
<td>2427</td>
<td>1875</td>
<td>1765</td>
<td>2324</td>
</tr>
<tr>
<td>Net load input</td>
<td>-476</td>
<td>509</td>
<td>733</td>
<td>577</td>
<td>408</td>
<td>364</td>
<td>449</td>
</tr>
</tbody>
</table>

Precipitation...

- Heat Adveected by Rain on Snow (\( Q_p \))
  - First Case
  - Rainfall on a melting snow pack, where the rain does not freeze
    - \( Q_p = 4.2T_pP \) (kJ/m²·d)
      - where \( T_p \) is the temperature of the rain (°C)
      - and \( P \) is the depth of the rain (mm/day)
    - If \( T_p = 2°C \) and \( P = 2 \) mm, then \( Q_p = 16.8 \) kJ/m²·d or 0.19 W/m²
      - Very small compared to 800 W/m² (incident Solar Radiation)

\[ A = C_i \rho_s P (T_p - T_m) \]

- \( A \) is the advected energy, usually rain on snow, in m³·s⁻¹·day⁻¹
- \( C_i \) specific heat of liquid water
- \( \rho_s \) density of liquid water
- \( T_p \) average snow temperature in K or °C
- \( T_m \) temperature of the rain
- \( P \) is the precipitation amount in mm·day⁻¹

Energy Flux Partitioning

500 mb Synoptic Weather Patterns, Spring, 1994
Energy Flux Partitioning

Summary

• Ice and snow melt are determined by the energy balance → Do not necessarily melt at air temperature ≥ 0°C
• Snow/ice surface temperature must be raised to 0°C before melting can occur (2 steps: warming, melting)
• Fixed maximum surface temperature (0°C) → under melting conditions: constant \( L \) = 316 Wm\(^{-2}\), surface vapour pressure = 611 Pa
• Often net radiation dominant source of energy
• Sublimation reduces energy available for melt

Energy partitioning (%)

<table>
<thead>
<tr>
<th>Glacier</th>
<th>( Q_R )</th>
<th>( Q_H )</th>
<th>( Q_L )</th>
<th>( Q_G )</th>
<th>( Q_M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aletschgletscher, Switzerland</td>
<td>92</td>
<td>8</td>
<td>-6</td>
<td>0</td>
<td>-94</td>
</tr>
<tr>
<td>Hintereisferner, Austria</td>
<td>90</td>
<td>10</td>
<td>-2</td>
<td>0</td>
<td>-98</td>
</tr>
<tr>
<td>Peytoglacier, Canada</td>
<td>44</td>
<td>48</td>
<td>8</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>Storglaciären, Sweden</td>
<td>66</td>
<td>30</td>
<td>5</td>
<td>-3</td>
<td>-97</td>
</tr>
</tbody>
</table>

Austfonna 2005

Radiation components \((S_\downarrow, S_\uparrow, L, L'\))

Temperature

Humidity

Wind speed & direction
surface lowering (melt)
snow/ice temperature
alternative use: limbo championship...☺

Meteo data