Linking changing snow cover properties to altered avalanche flow regimes and effects on run-out distances at Bird Hill, south-central Alaska

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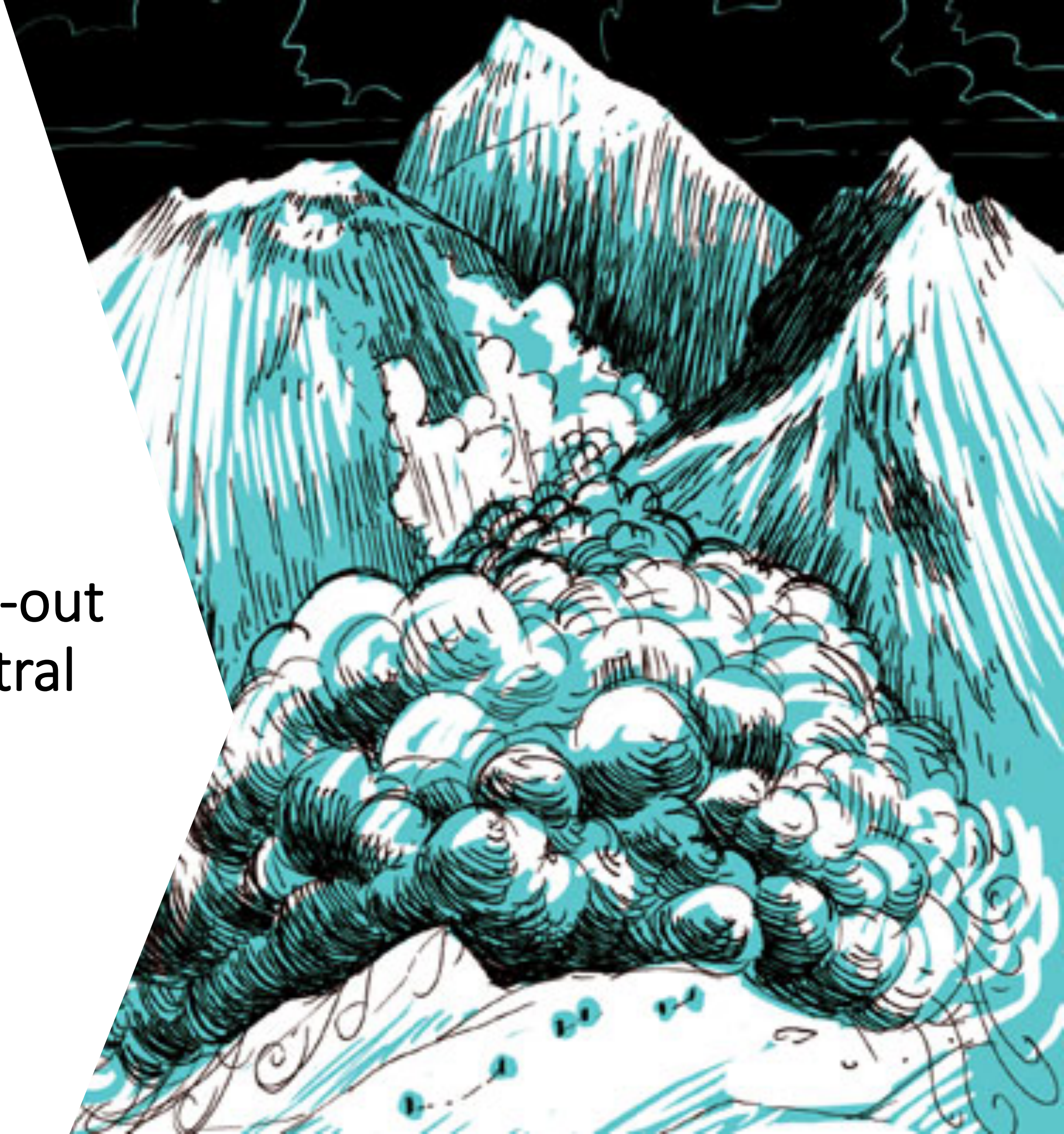


» How far will the avalanche go?

(Left) Fracture in Kern, April 2015 (Photo: Wikstrom Jones)
(Middle) Long run-out in Kern, April 2015, despite bare ground (Photo: Wikstrom Jones),
(Right) Road clearance at Bird Hill (Photo: ADOT&PF)

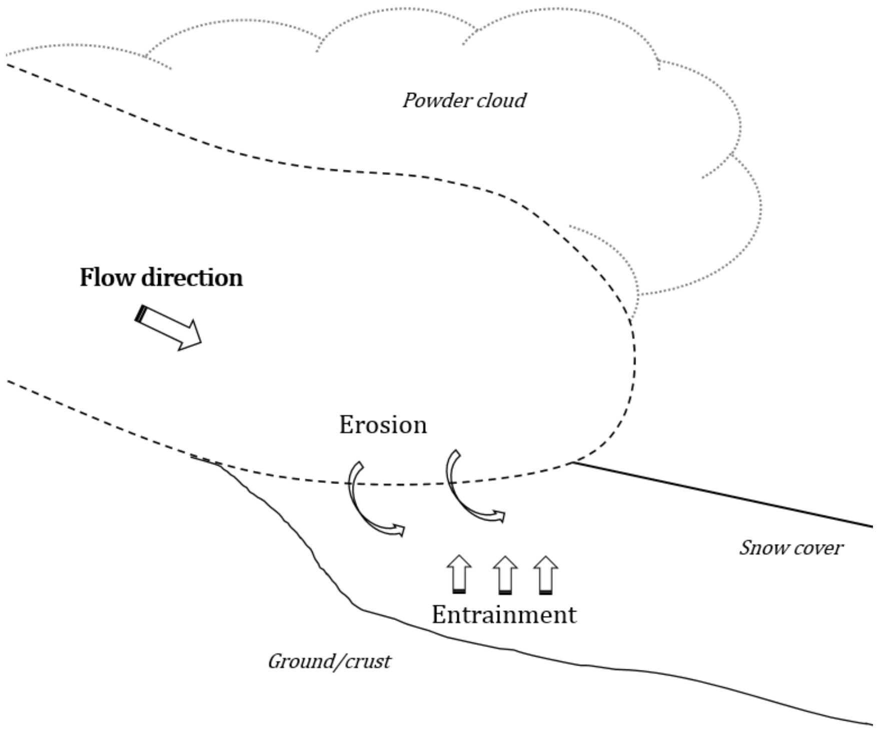
Bird Hill,
south-central Alaska

Photo: Wikstrom Jones

(Top) Road clearance
(Middle) Train hit by avalanche
(Bottom) 1979 wet avalanche cycle
(Photos: ADOT&PF)

Snow entrainment

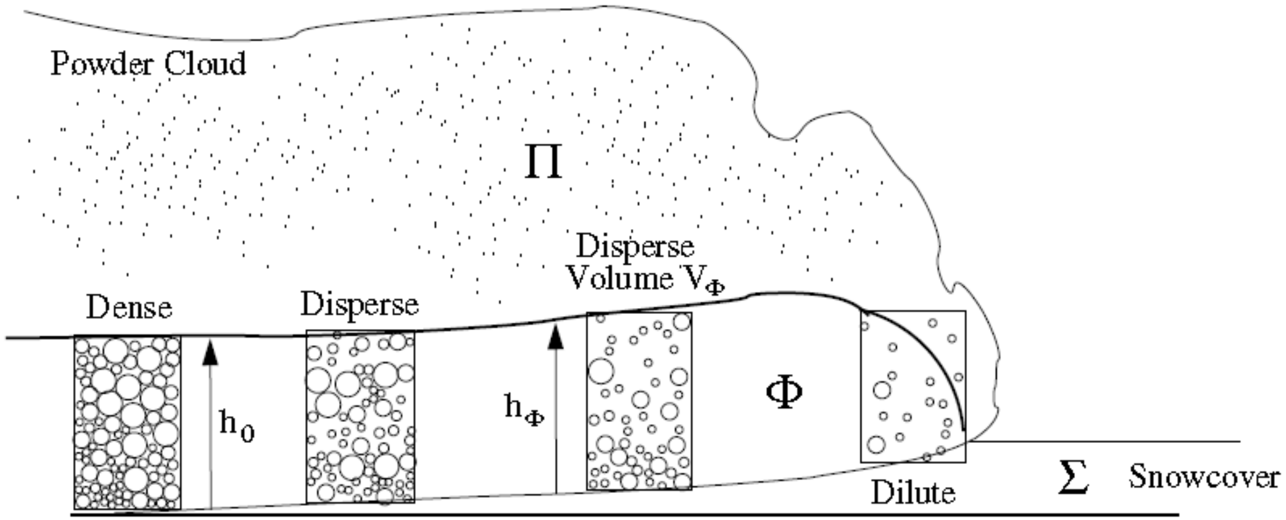
- Quantitatively measured as growth index
- Frontal, step and basal entrainment
- Counteracts development of shear gradients in the avalanche tail that slows down the avalanche
- Temperature of entrained snow defines mechanical properties of avalanche through flow regimes



(Right) Cold, dry snow slab released. The avalanche entrained warm moist snow in the transition and runout zones, leading to the formation of a heavy wet snow avalanche (Vera Valero et al., 2015)

Avalanche flow regimes

» Fluidization



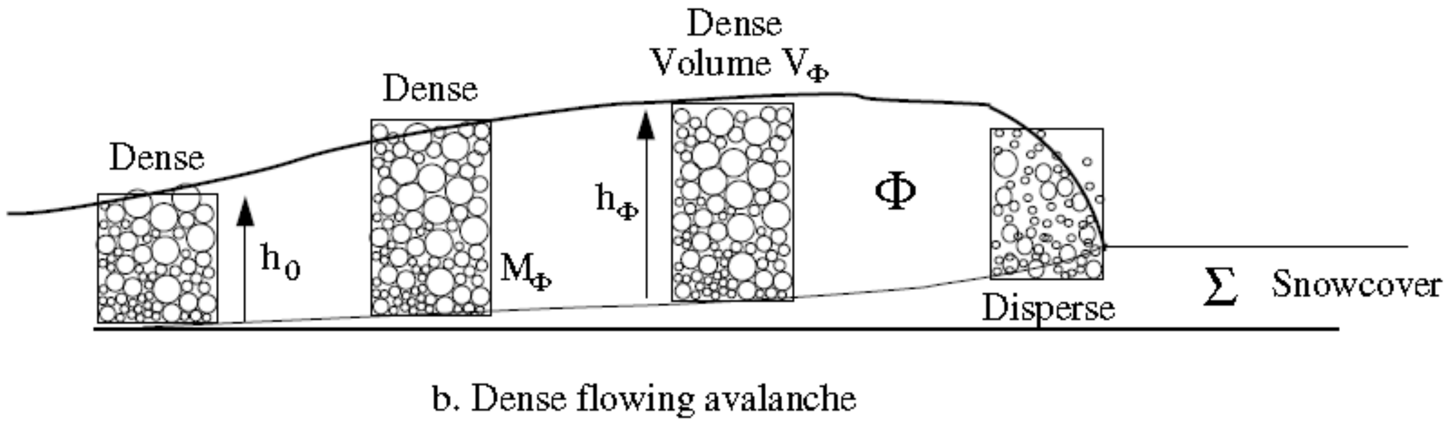
a. Mixed flowing avalanche

Buser and Bartelt, 2014

Photo: AKDOT&PF

Avalanche flow regimes

» Lubrication

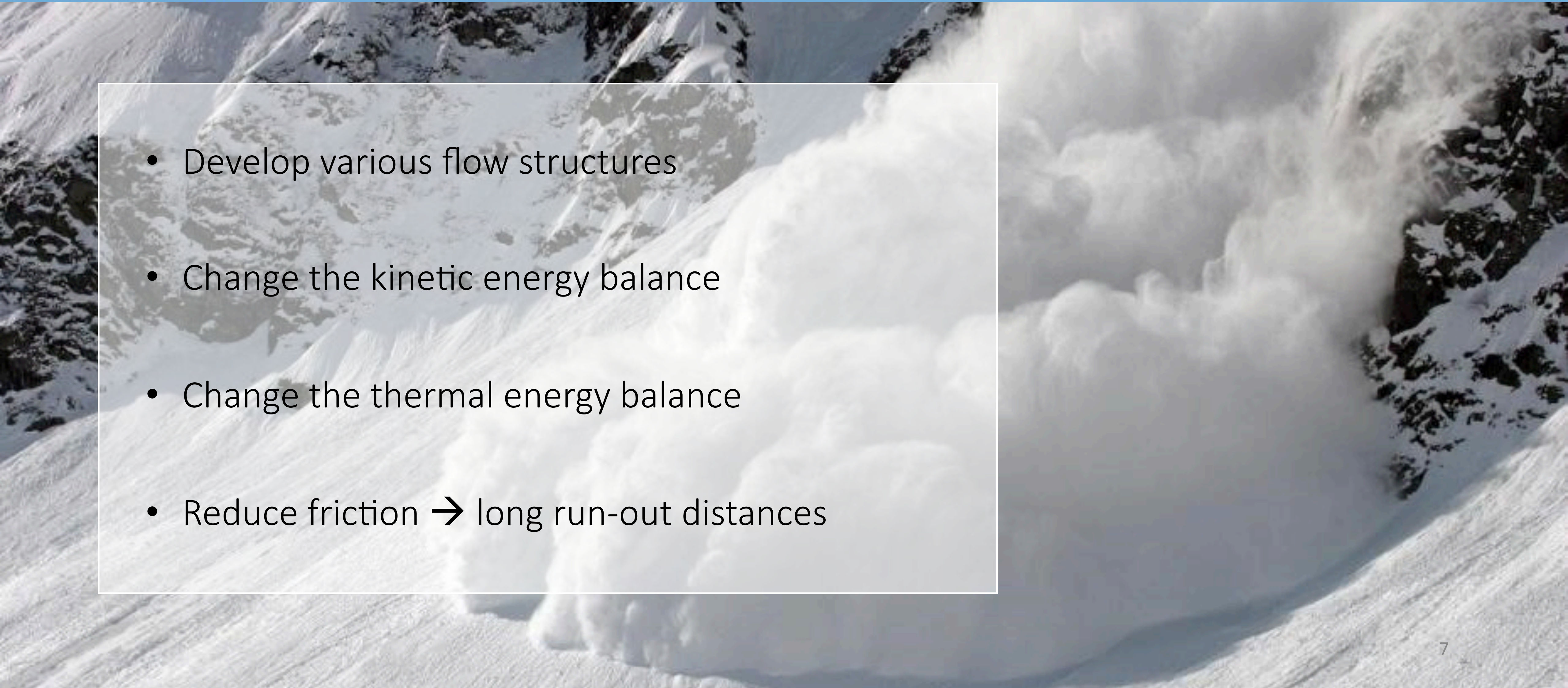


Bartelt and Buser, 2014

Photo: AKDOT

Avalanche flow regimes

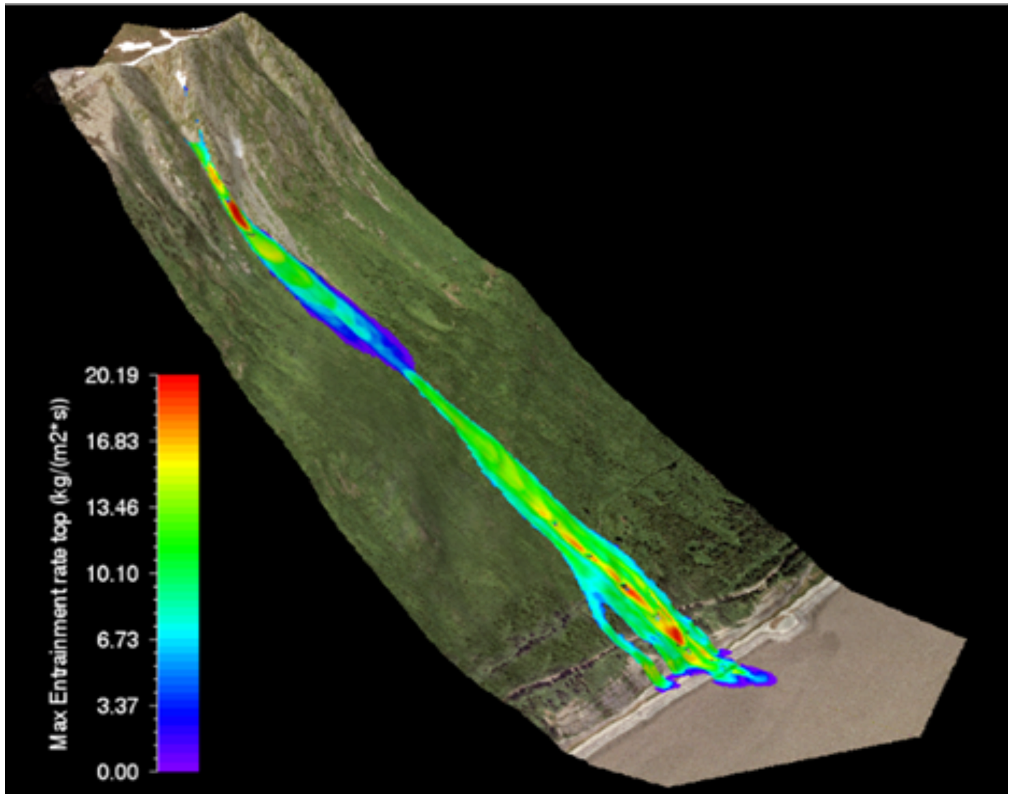
» Why do they matter?



- Develop various flow structures
- Change the kinetic energy balance
- Change the thermal energy balance
- Reduce friction → long run-out distances

Modeling avalanche flow in 3D

P#934 Whiskey during wet avalanche cycle in 1979. (Photo: AKDOT)



Wet avalanche simulation #934 Whiskey, Bird Hill

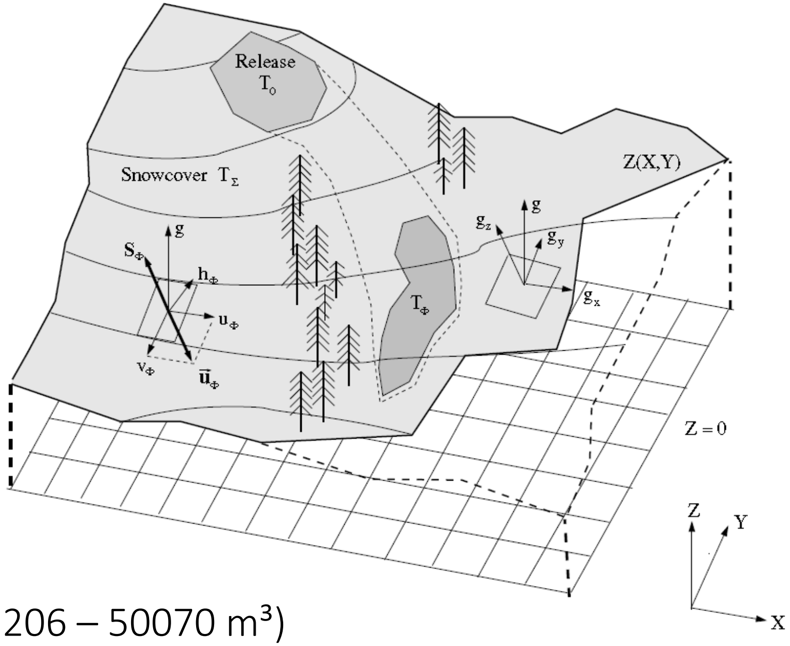
RAMMS
rapid mass movements simulation

Experimental simulations

1. Terrain

» One path - #934 Whiskey
Drop height ~ 1000 m

» DEM with 5 m resolution



2. Release

» 3 fracture depths
2 m (release volume 35206 – 50070 m³)
1 m (release volume 17603 – 25035 m³)
0.5 m (release volumes of 8801 – 12518 m³)

» 3 released snow temperatures paired with density
-5°C (250 kg/m³)
-3°C (300 kg/m³)
0°C (500 kg/m³)

3. Entrained snow cover

» Two entrainment zones

Above 500 m a s l
Snow cover depth 1 m, 0.5 m, 0.25 m
Snow cover temperature -5°C, -3°C, -1°C, 0°C

Below 500 m a s l
Snow cover depth 1 m, 0.5 m, 0.25 m or bare ground
Snow cover temperature -5°, -3°, -1°, 0°

Bare ground = higher friction values

Avalanche output

» **Run-out distance** – normalized as percentage to Beta point distance

Classification
Class 1 (beyond Beta point)
Class 2 (shorter, upslope from Beta point)

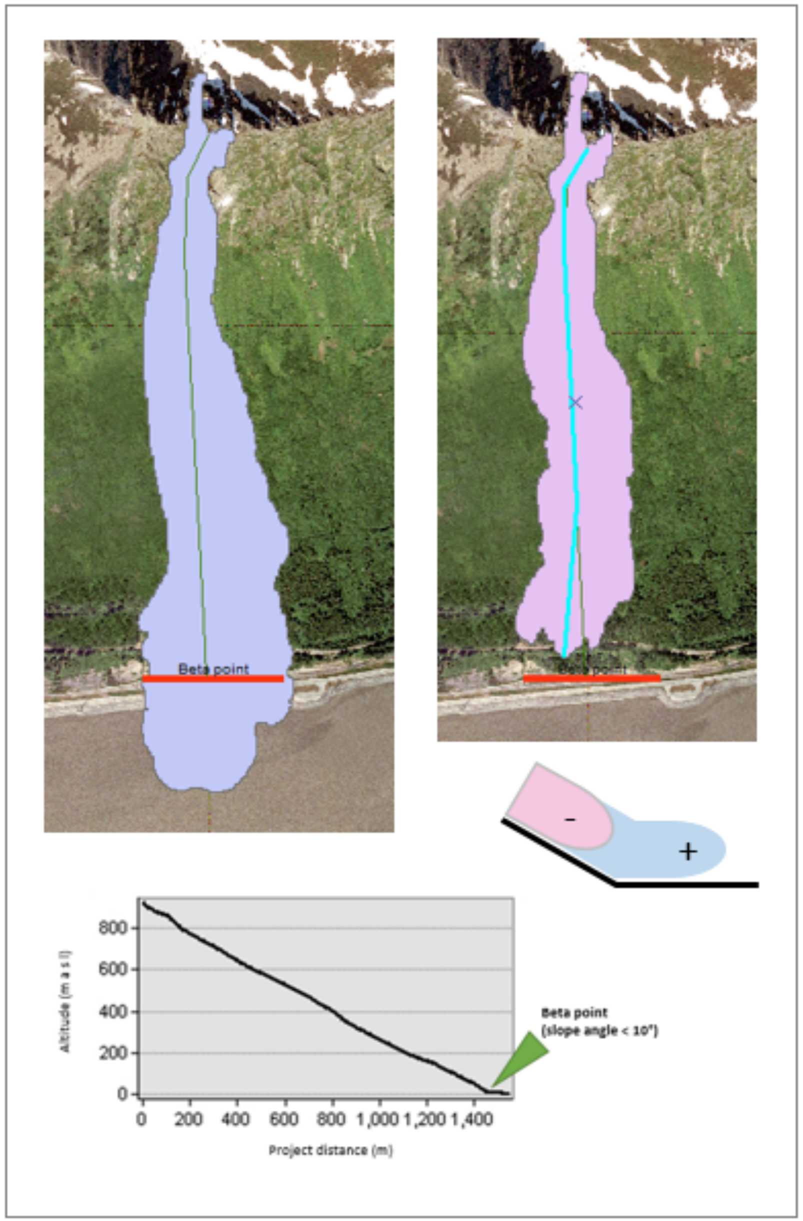
» Velocities

» Flow heights

» Avalanche temperature

» Random kinetic energy production rates

» Meltwater production



Calculation of run-out distance as percentage of Beta point distance in ArcMAP

Preliminary results

» Summary

- ***Initial release conditions determined how changes in snow cover depth and temperature influence the run-out distance.***

Large release volumes (2 m fracture; 35206 - 50070 m^3) generated Class 1 avalanches independent of changes in snow cover conditions

For medium sized releases (1 m fracture, 17603 - 25035 m^3), all releases became Class 1 avalanches ***besides***

- Release temperature -5°C or -3°C and bare ground below 500 m a s l
- Release temperature -3°C and snow cover temperature -3°C above and below 500 m a s l

Preliminary results

» Summary

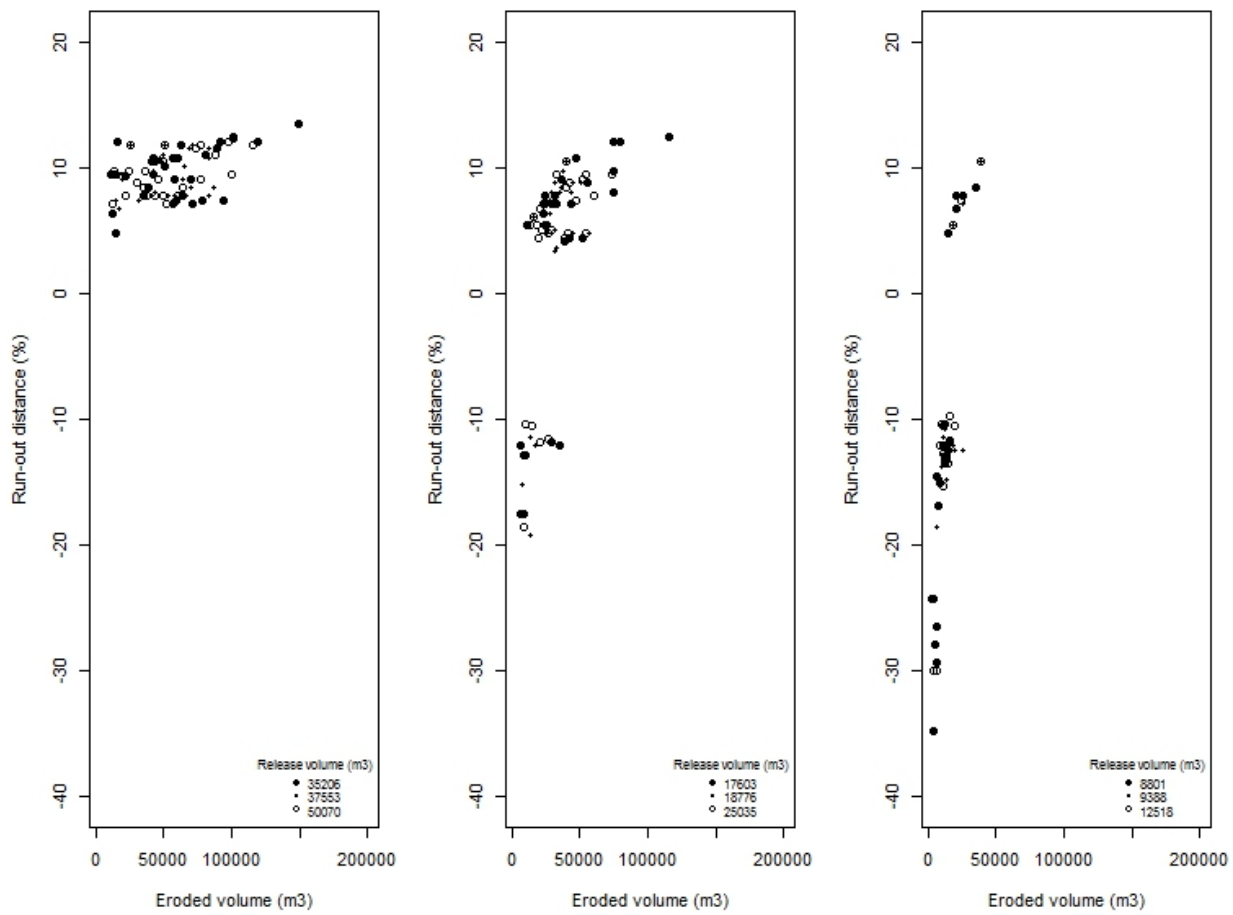
For smallest releases (8801 - 12035 m^3), all releases became Class 2 avalanches ***besides***

- 0°C releases with continuous snow entrainment above and below 500 m a s l
- -5°C releases which entrained -1°C snow or warmer above 500 m a s l and 0°C below 500 m a s l
- -3°C releases which entrained 0°C snow of at least 0.5 m depth above 500 m a s l and 0°C of 0.25 m below 500 m a s l

Preliminary results

» Total eroded snow volume controlling run-out distance

… especially for the smallest release volumes!



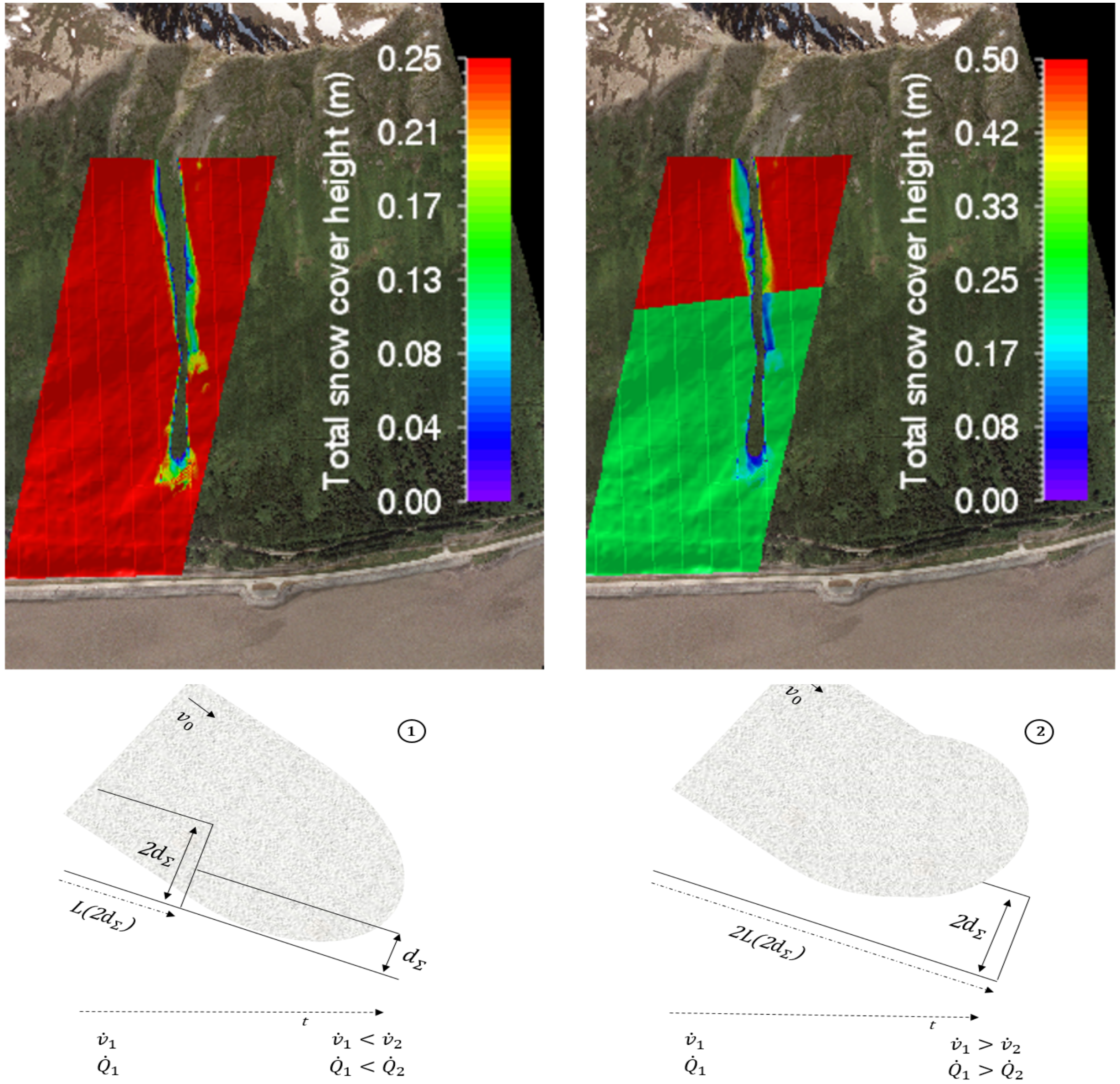
2 m 1 m 0.5 m

Results

» Snow cover depth

Snow cover depth 0.25 m
> 500 m a s l

Snow cover depth 0.5 m
> 500 m a s l



Shown: Release depth 0.5 m (release volume 8801m³.
Release temp. -5°C, -3°C above and -1°C below 500 m a s l

- Potential erosion depth ≠ actual erosion depth
- Snow entrainment rate - function of density ratio between snow layer and avalanche, and the velocity
- Length of the entrainment zone is critical

Results

» Flow regimes

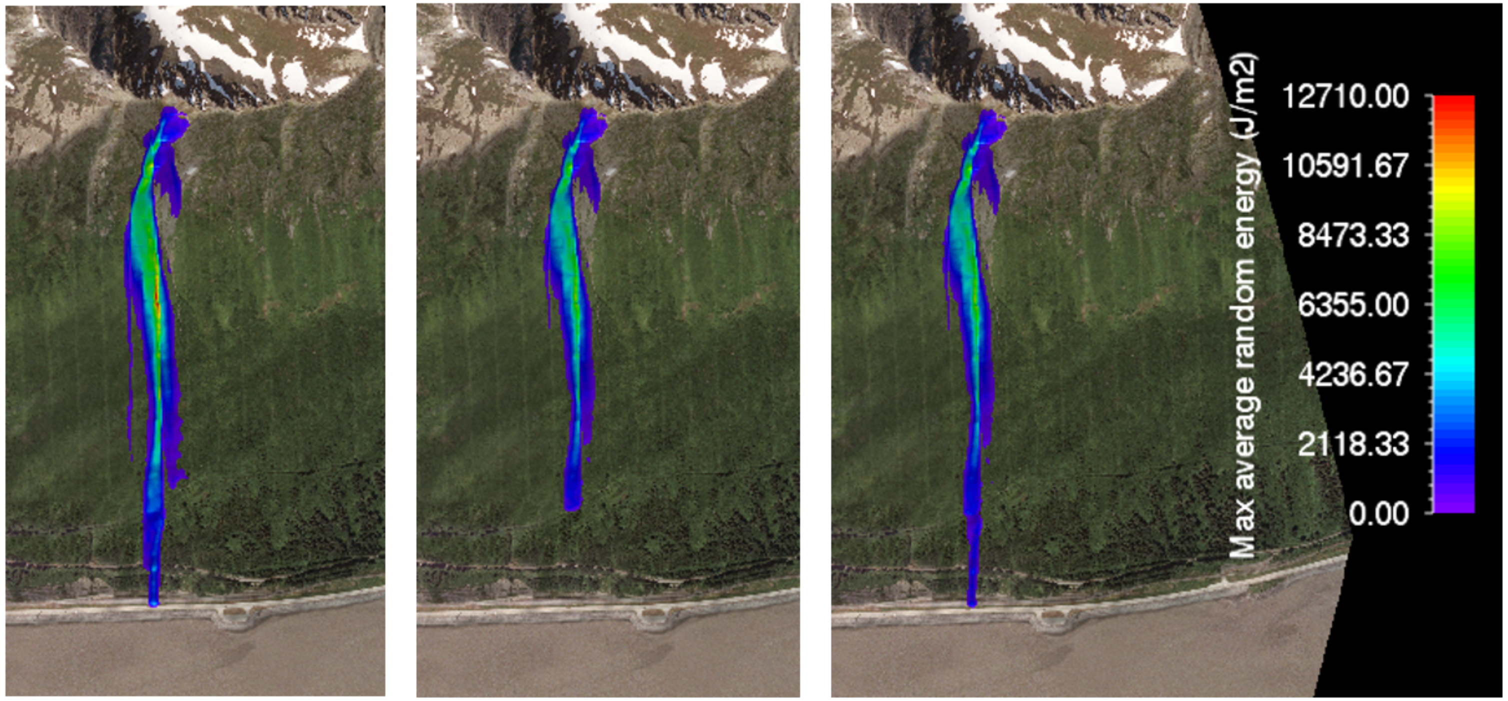
Fluidized regime

Lubricated regime

Release temp. -5°C
-5°C > 500 m a s l
-3°C < 500 m a s l

Release temp. -3°C
-3°C > 500 m a s l
-3°C < 500 m a s l

Release temp. -3°C
-3°C > 500 m a s l
-1°C < 500 m a s l



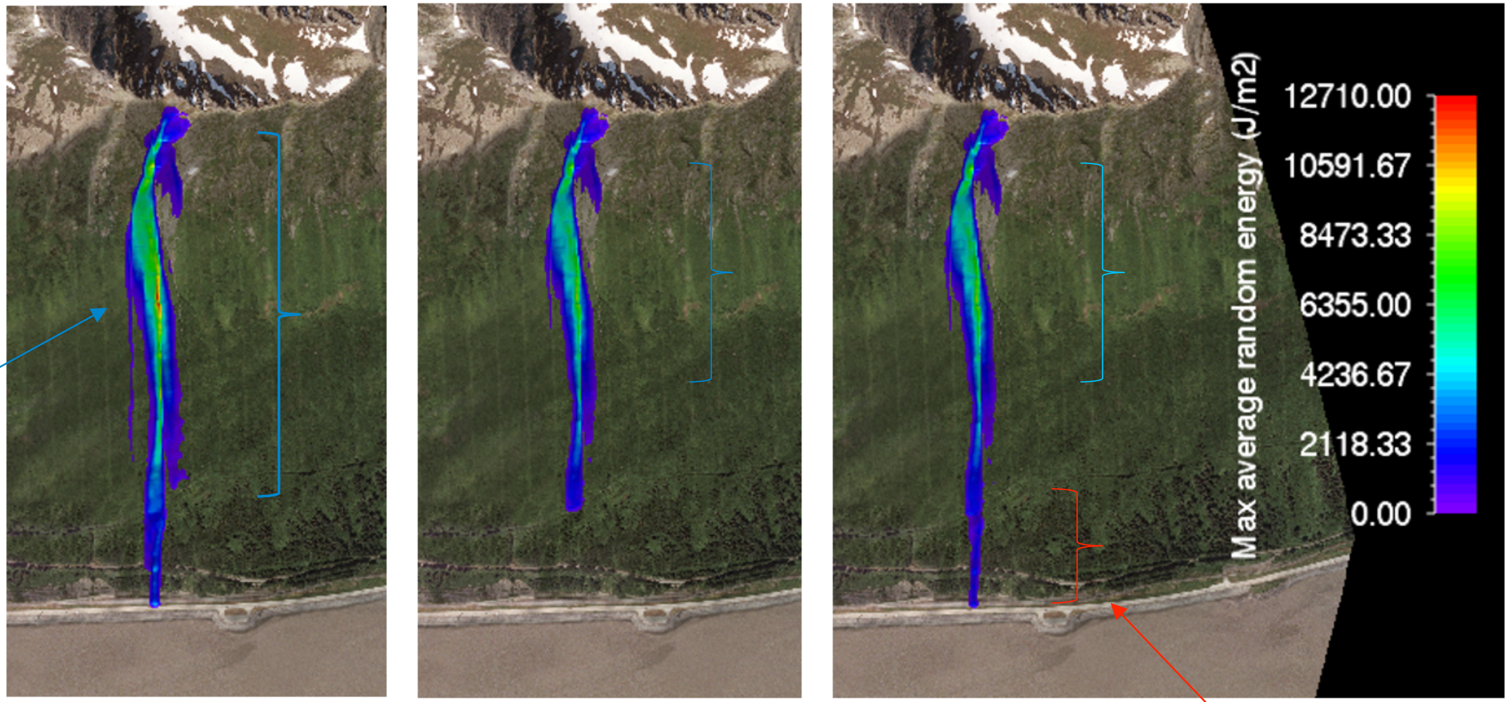
Results

» Development of flow regimes and varying run-out distances

Fluidized regime

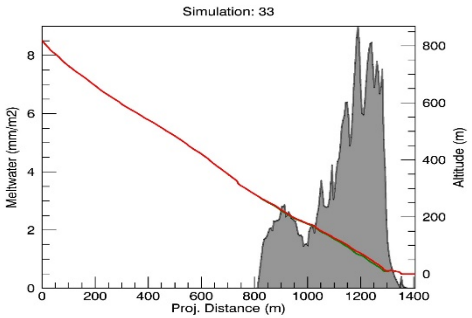
Lubricated regime

Release temp. -5°C	Release temp. -3°C	Release temp. -3°C
-5°C > 500 m a s l	-3°C > 500 m a s l	-3°C > 500 m a s l
-3°C < 500 m a s l	-3°C < 500 m a s l	-1°C < 500 m a s l



High production rates of random kinetic energy (=high magnitude of fluidization)

Meltwater production



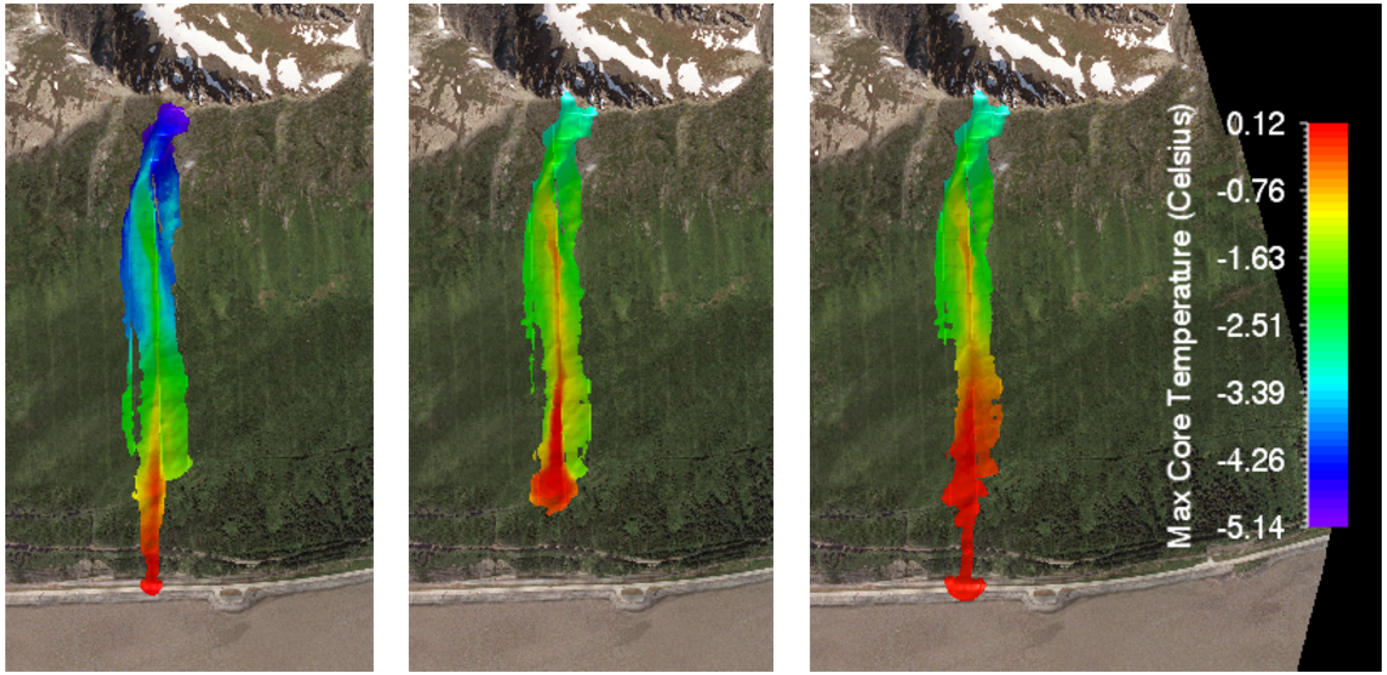
Results

» Avalanche temperature and “dampening”

Release temp. -5°C
-5°C > 500 m a s l
-3°C < 500 m a s l

Release temp. -3°C
-3°C > 500 m a s l
-3°C < 500 m a s l

Release temp. -3°C
-3°C > 500 m a s l
-1°C < 500 m a s l



» Numerical models in avalanche run-out distance assessments

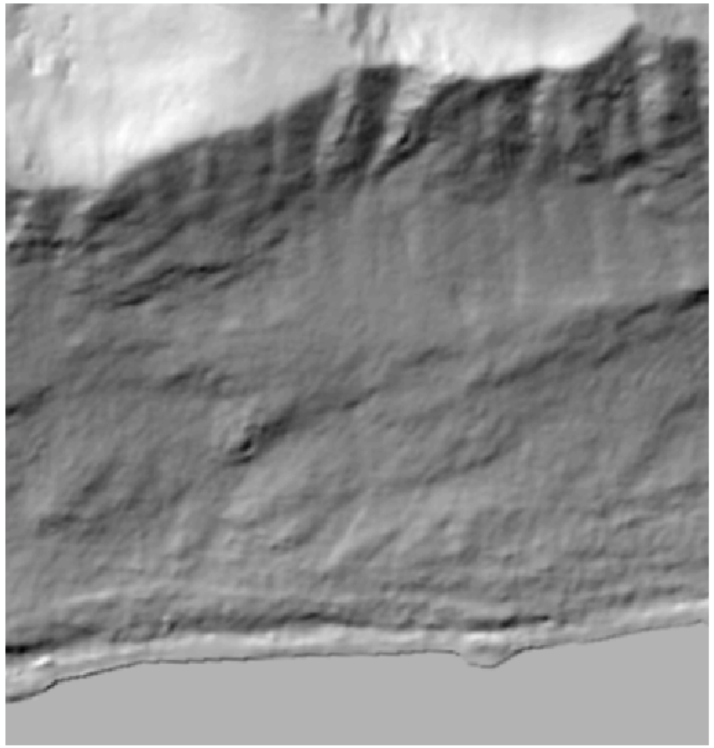
- Provide information for greater understanding of avalanche flow behavior
  - Test a wide range of avalanche scenarios

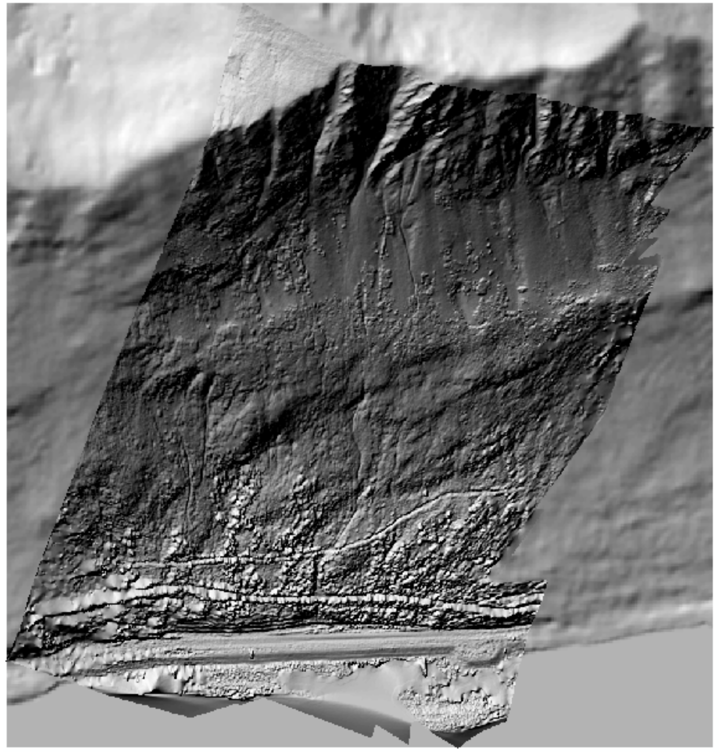
- Provides relatively low cost investigation of:
  - Risk factors
  - Effectiveness of hazard mitigation strategies
  - Sensitivity to initial snow cover conditions

Up-next

» Re-simulations

IFSAR DEM with 5 m resolution → "Home made" DEM with 2 m resolution





- Higher resolution DEM – more realistic flow in bare ground terrain
- New RAMMS version with temperature-dependent Beta (=decay rate of RKE) to better illustrate "dampening"

» Thank you!

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Timothy Glasset – ADOT&PF
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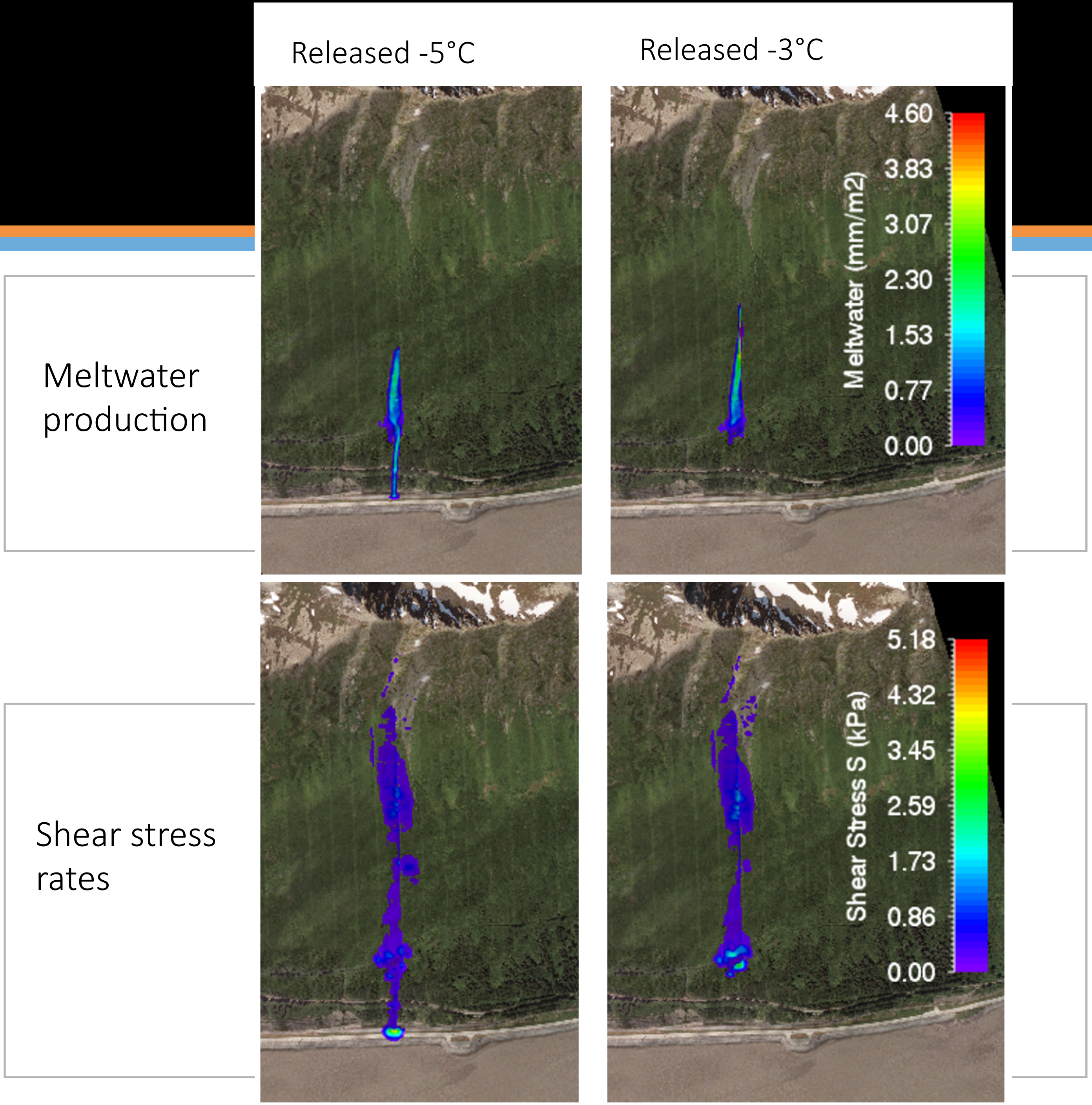
Henry Munther
Alpine Air
Beaded Stream
Alex Jones – field assistant
Lauren Rocco – field assistant

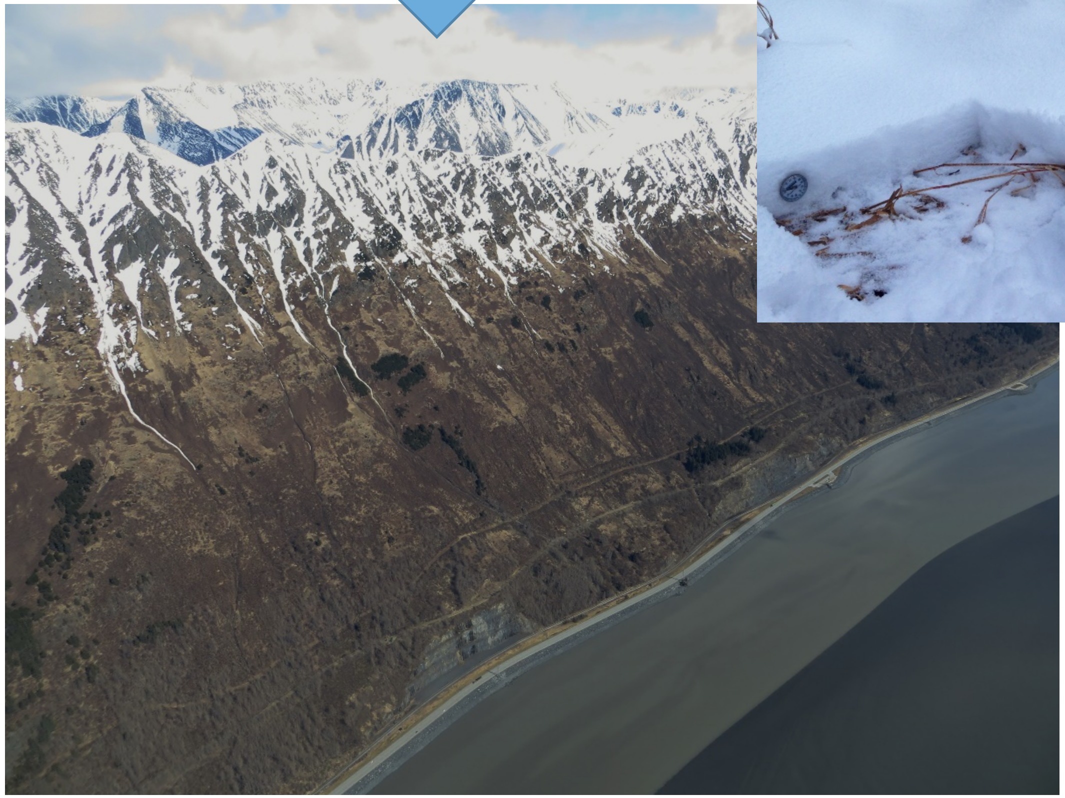
Results

» Friction

- “Dampening” – onset of high shear stress rates due to increased basal or internal friction
- ”Dampened” flow behavior exhibited by -3°C releases that entrained -3°C snow – *too warm to fluidize, too cold to reach melting point*

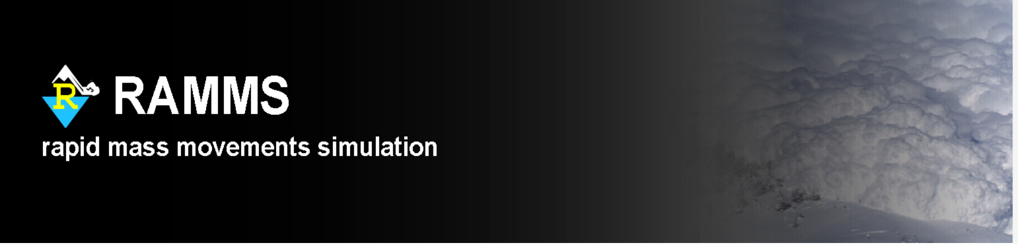


2014-2015 avalanche season



P#934 Whiskey during wet avalanche cycle in 1979. (Photo: AKDOT)

#934 Whiskey, Bird Hill for most of winter 2014-2015



Governing Equations

M_ϕ	Mass per unit area
U	Velocity
Q	Vol. entrainment rate
h_ϕ	Height of avalanche core
g'	Slope perp. acceleration
G	Gravitational force component

S	Frictional resistance
R	Random kinetic energy
N	Normal pressure
α	Energy production rate
β	Energy decay rate
R_0	Activation energy of static snow

Mass balance

1) $$\partial_t M_\phi + \partial_x (M_\phi U_x) + \partial_y (M_\phi U_y) = Q_{\Sigma\to\phi}$$

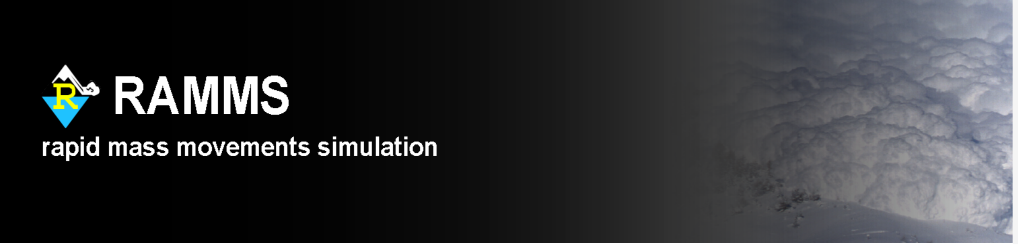
Momentum

2) $$\partial_t (M_\phi U_x) + \partial_y (M_\phi U_x U_y) + \partial_x \left(M_\phi U_x^2 + 1/2\,(M_\phi g' h_\phi)\right) = G_x - S_x - (Q_{\Sigma\to\phi}) U_x$$

3) $$\partial_t (M_\phi U_y) + \partial_x (M_\phi U_x U_y) + \partial_y \left(M_\phi U_y^2 + 1/2\,(M_\phi g' h_\phi)\right) = G_y - S_y - (Q_{\Sigma\to\phi}) U_y$$

Kinetic Energy Exchange

4) $$\partial_t (R h_\phi) + \partial_x (R U_x h_\phi) + \partial_y (R U_y h_\phi) = \alpha(S_\phi \cdot U_\phi) - \beta(R h_\phi)$$



Governing Equations

H	Flow height
U	Velocity
Q	Vol. entrainment rate
Φ	Avalanche core
g	Gravitational acceleration
S	Frictional resistance
G	Gravitational Force
F	Centripetal acceleration

M	Mass per unit area
R	Random kinetic energy
N	Normal pressure
α	Energy production rate
β	Energy decay rate
R_0	Activation energy
C	Cohesion
D	Dispersive pressure

1) $\partial_t H + \partial_x (H U_x) + \partial_y (H U_y) = Q_{\Sigma\to\phi}$ **Mass balance**

Volumetric entrainment rate $Q_{\Sigma\to\phi}$

$$Q_{\Sigma\to\phi}(x,y,t) = \begin{cases} 0 & \text{if } h_i = 0 \\ \frac{\rho_i}{\rho_a} h_i \left(\frac{U}{l}\right) & \text{if } k_i l \geq h_i \frac{\rho_i}{\rho_a} \\ k_i U & \text{if } k_i l < h_i \end{cases}$$

Heat energy influx $E_{\Sigma\to\phi}\, h_\phi$

$$E_{\Sigma\to\phi}\, h_\phi = c_\Sigma\, Q_{\Sigma\to\phi}\, T_\Sigma$$

RAMMS
rapid mass movements simulation

Governing Equations

H	Flow height	M	Mass per unit area
U	Velocity	R	Random kinetic energy
Q	Vol. entrainment rate	N	Normal pressure
Φ	Avalanche core	α	Energy production rate
g	Gravitational acceleration	β	Energy decay rate
S	Frictional resistance	R_0	Activation energy
G	Gravitational Force	C	Cohesion
F	Centripetal acceleration	D	Dispersive pressure

2) $$\partial_t (HU_x) + \partial_y (HU_x U_y) + \partial_x (HU_x^2 + g_z H^2/2) = G_x - S_x - (Q_{\Sigma\to\phi})U_x$$

3) $$\partial_t (HU_y) + \partial_x (HU_x U_y) + \partial_y (HU_y^2 + g_z H^2/2) = G_y - S_y - (Q_{\Sigma\to\phi})U_y$$

Momentum

Gravitational Force Components

$G_x = g_x M_\phi$ and $G_y = g_y M_\phi$

Frictional resistance S_ϕ (Pa)

$S_\phi = u_\phi/\|u_\phi\| \; [\mu(R)[N+F+D]\rho_g g\|u_\phi\|^2/\xi(R)]$

$$\mu(R,T) = \mu_0(T)\exp\left[-\frac{R}{R_0}\right] \qquad \xi(R,T) = \xi_0(T)\exp\left[\frac{R}{R_0}\right]$$

RAMMS
rapid mass movements simulation

Governing Equations

H	Flow height
U	Velocity
Q	Vol. entrainment rate
Φ	Avalanche core
g	Gravitational acceleration
S	Frictional resistance
G	Gravitational Force
F	Centripetal acceleration

M	Mass per unit area
R	Random kinetic energy
N	Normal pressure
α	Energy production rate
β	Energy decay rate
R_0	Activation energy
C	Cohesion
D	Dispersive pressure

Mass balance

1) $$\partial_t H + \partial_x (HU_x) + \partial_y (HU_y) = Q_{\Sigma\to\phi}$$

Momentum

2) $$\partial_t (HU_x) + \partial_y (HU_x U_y) + \partial_x \left(HU_x^2 + g_z H^2/2\right) = G_x - S_x - (Q_{\Sigma\to\phi}) U_x$$

3) $$\partial_t (HU_y) + \partial_x (HU_x U_y) + \partial_y \left(HU_y^2 + g_z H^2/2\right) = G_y - S_y - (Q_{\Sigma\to\phi}) U_y$$

Kinetic Energy Exchange

4) $$\partial_t (HR) + \partial_x (HRU_x) + \partial_y (HRU_y) = \alpha(S\cdot U) - \beta(RH)$$

Production of RKE

Decay of RKE

$$R_0 = mgh + C$$