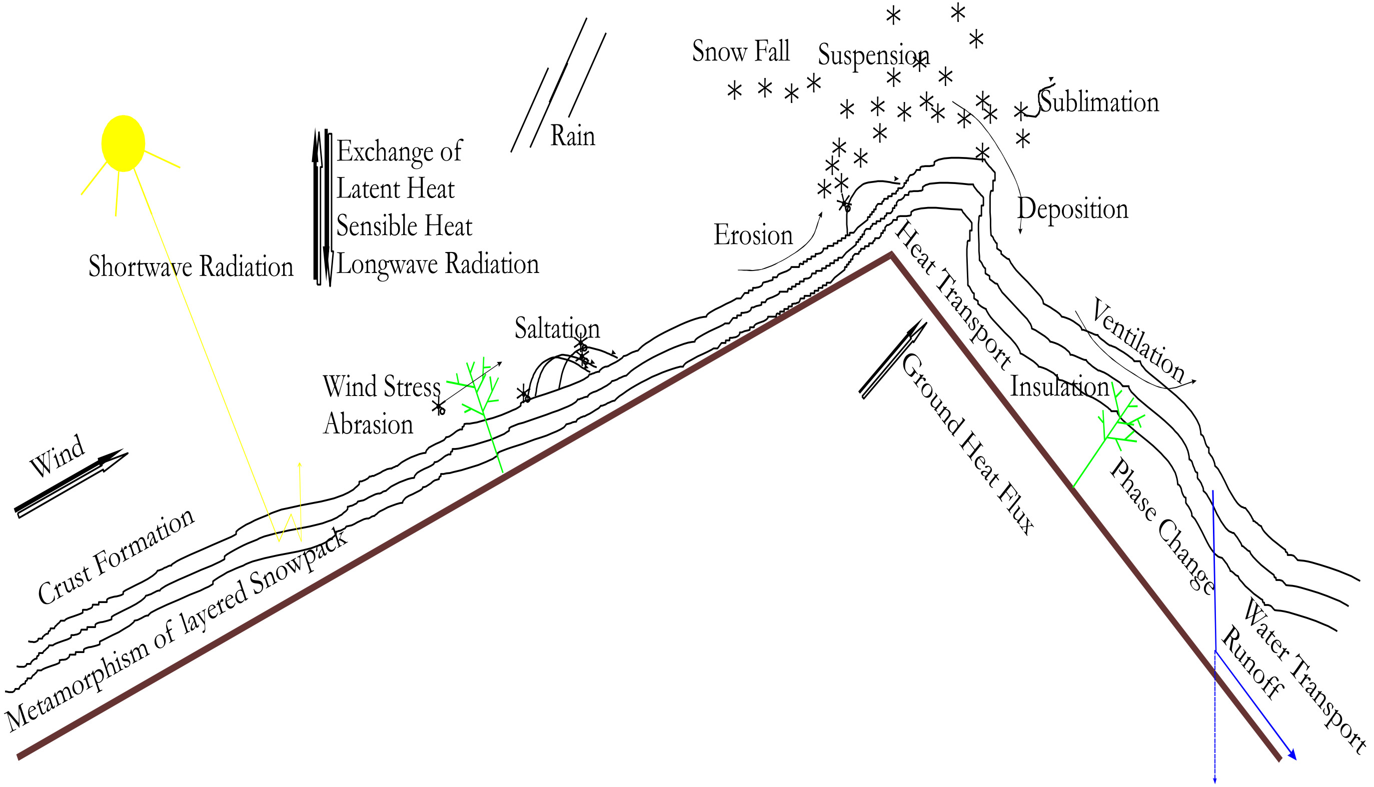
Snow Spatial Variability Accumulation and Transport

Outline

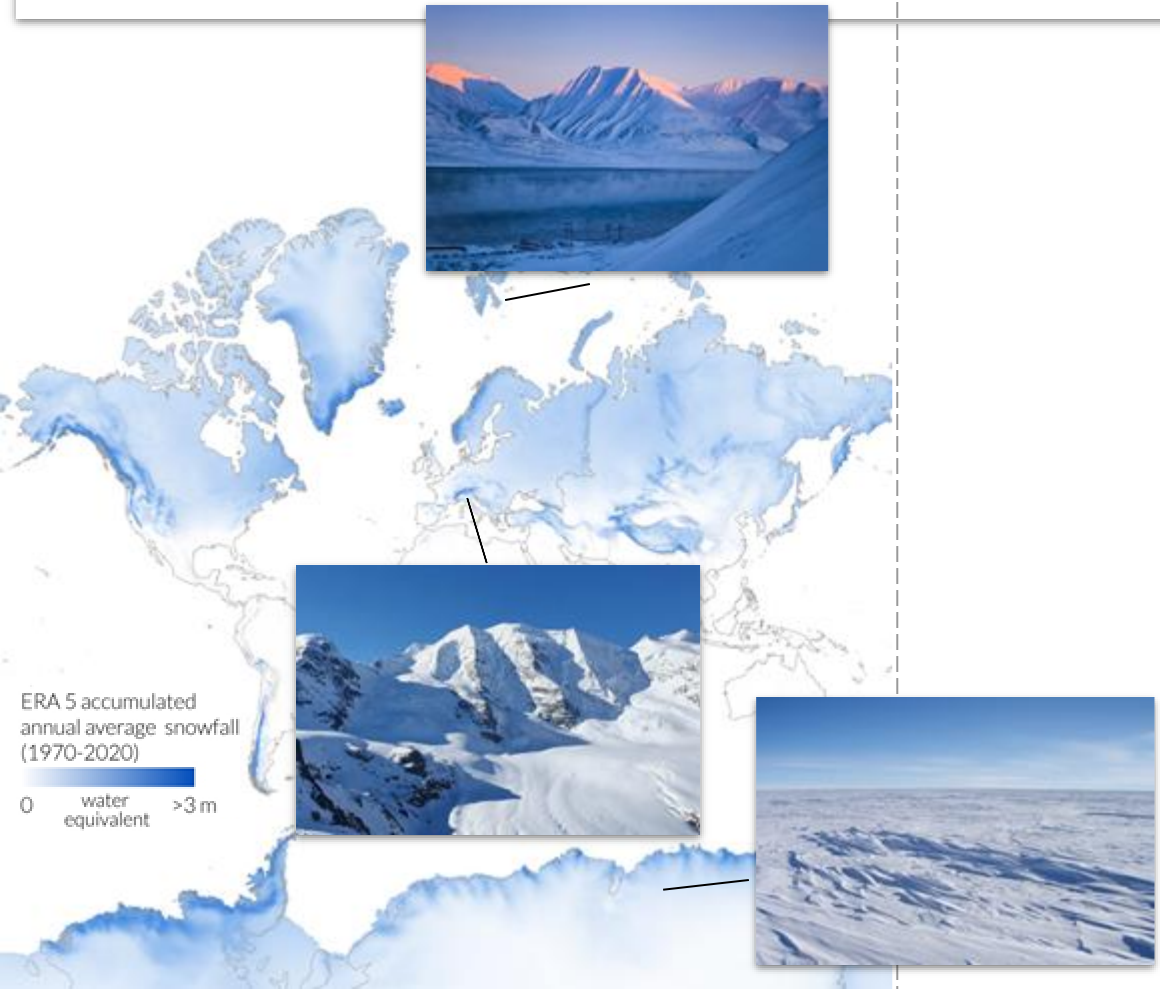
- General Introduction on Snow Spatial Heterogeneity and Transport
- Saltation and a simple SNOWPACK based drift index
- Suspension and Preferential Deposition
- Drifting Snow Sublimation
- Statistical Descriptions and Scaling

Overview – Where are we?

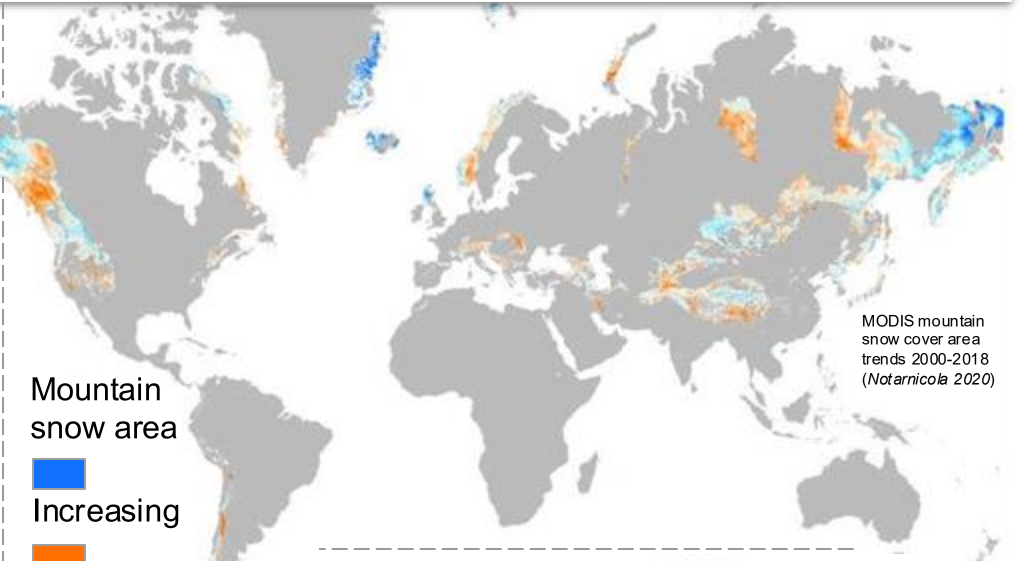
Processes at the Snow - Atmosphere Interface



Massively varying snow amounts …



Massively varying snow amounts … … with contrasting trends

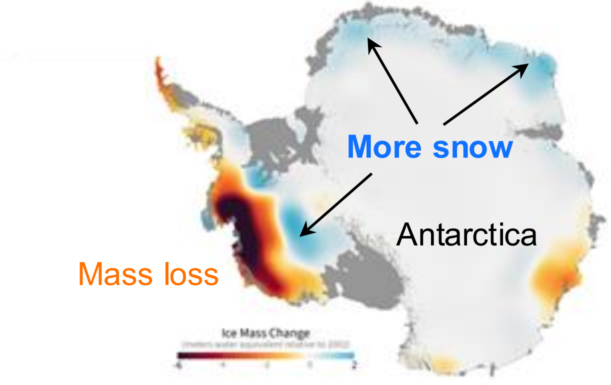


Mountain snow area

🟦 Increasing

🟧 Decreasing

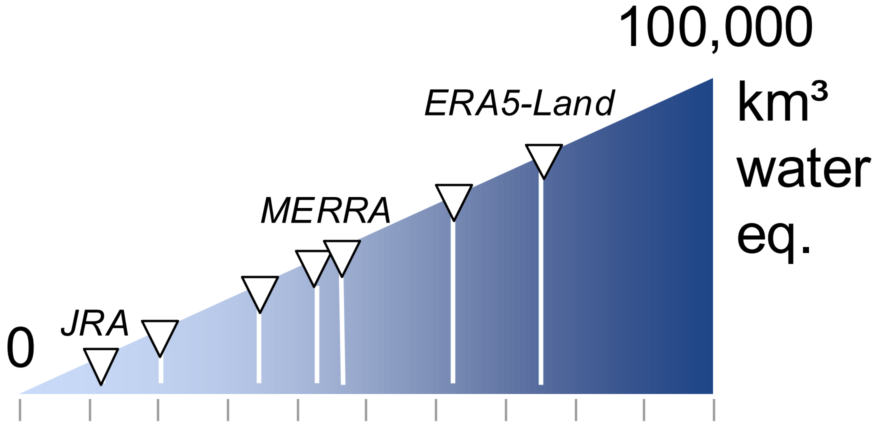
MODIS mountain snow cover area trends 2000-2018 (*Notarnicola 2020*)



2002-2020. GRACE/-FO / NASA /JPL

Global snow estimates

Model/System	Global total average snowfall (km^3 or Gt water/yr)	Northern hemisphere	“Extreme environments”
ERA5-Land	76’000	40’600	NH: 23000 SH: 20000 G: 43000
ERA5	62’000	31’200	
ERA-interim	21’300		
MERRA	43’400		
MERRA-2	47’100	22’000	
JRA-55	11’300		
CloudSat	35’000		



Compiled from Daloz etal. 2020, Cryosphere; Kouki etal. 2023, Cryosphere; Hersbach etal. 2020, Copernicus CCS; Mortimer etal. 2020, Cryosphere

Global snow estimates

"Estimating the spatial distribution of snow water equivalent (SWE) in mountainous terrain is currently the most important unsolved problem in snow hydrology. … the right answer remains elusive… Among all the uses of remote sensing in hydrology, SWE is the one where new innovations would deliver the greatest benefit."
(Dozier etal. 2016)

"The overall performance of the best multiproduct combinations is still at the margins of acceptable uncertainty for scientific and operational requirements; only through combined and integrated improvements in remote sensing, modeling, and observations will real progress in SWE product development be achieved."
(Mortimer etal. 2020)

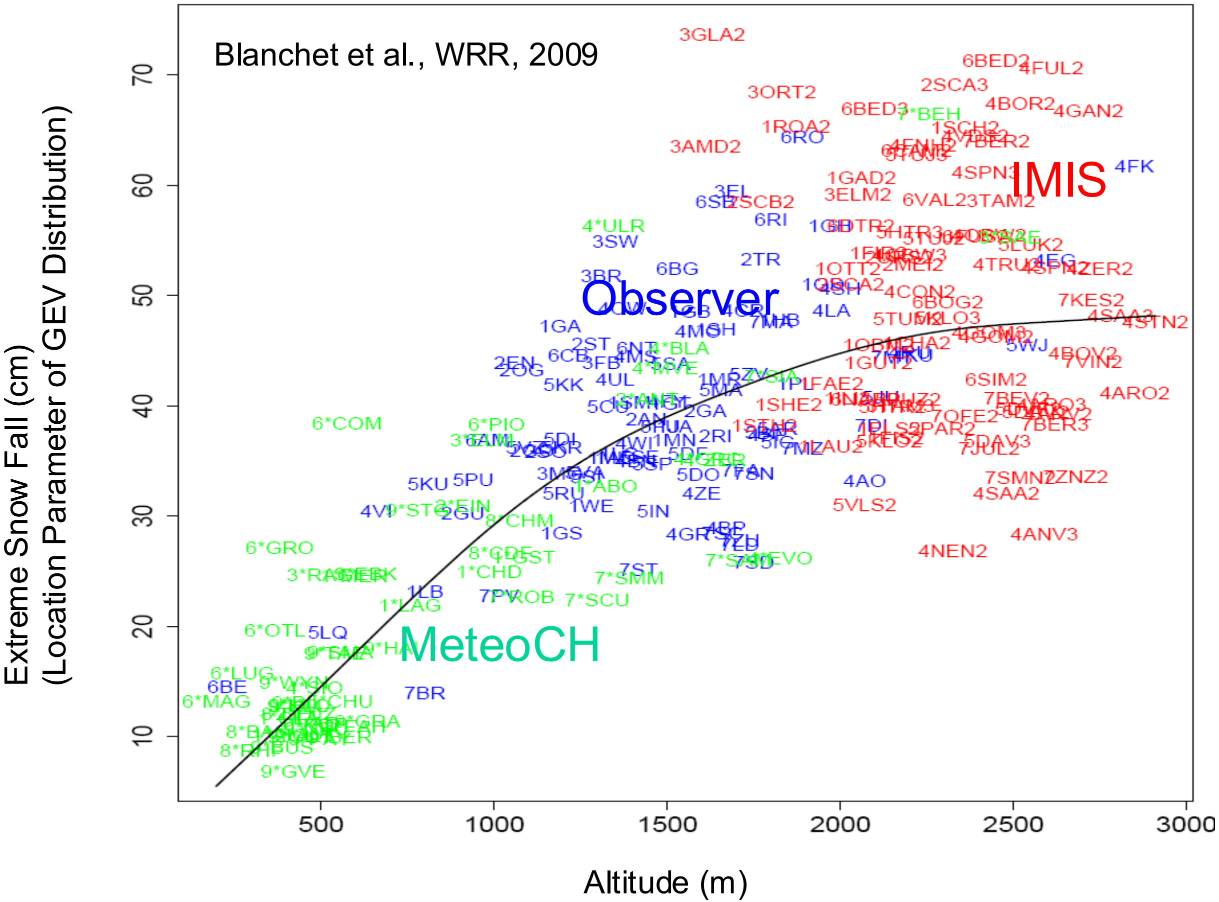
"…could indicate that large-scale forcings may be similar in the five datasets while local orographic enhancements at smaller scales may not be captured"
(Daloz etal. 2020)

"The negative NH SWE trends in ERA5 range from −249 to −236 Gt per decade in spring, which is 2 to 3 times larger than the trends detected by the other datasets (ranging from −124 to −77 Gt per decade)."
(Kouki etal. 2023)

What does it look like?

Formation of Cornices and Dunes

Extreme Snow Falls in Swiss Alps

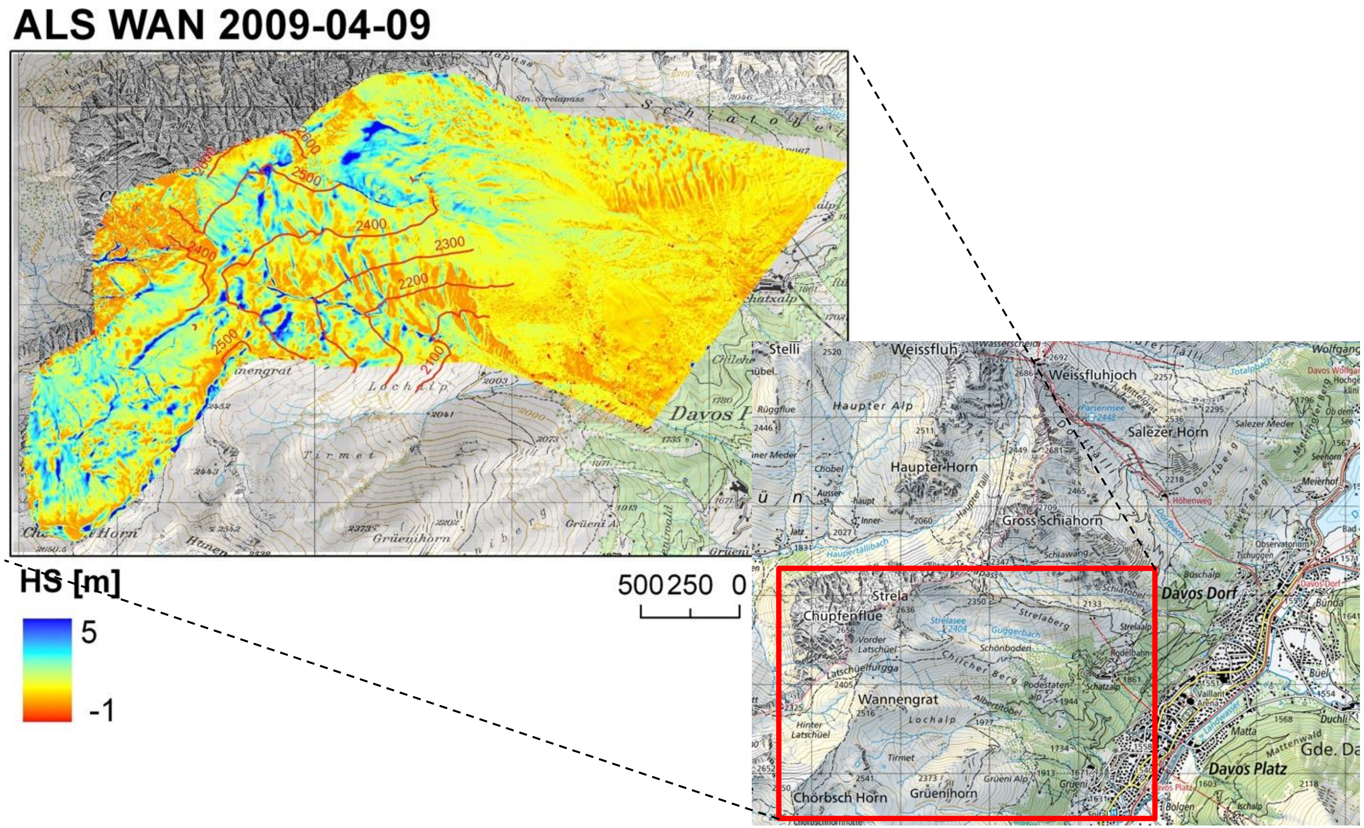


Shown is snowfall data across the Swiss Alps from three different observational networks:

- Snowfall increases with elevation
- Variability increases strongly

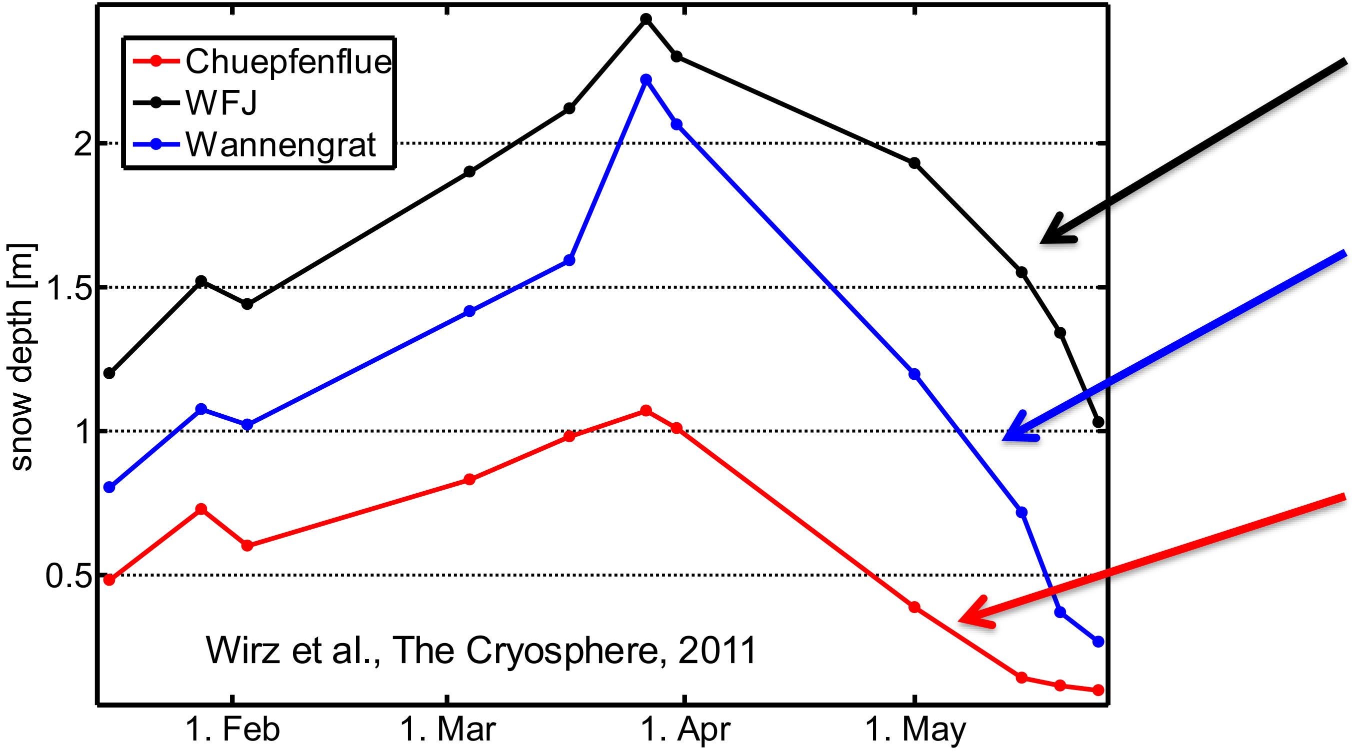
→ Know about (at least) three reasons for this variability at different spatial scales

Peak of Winter snow distribution 2008



Measurement of snow distribution with a laser scanner from a helicopter

Systematic topographical differences



Wirz et al., The Cryosphere, 2011

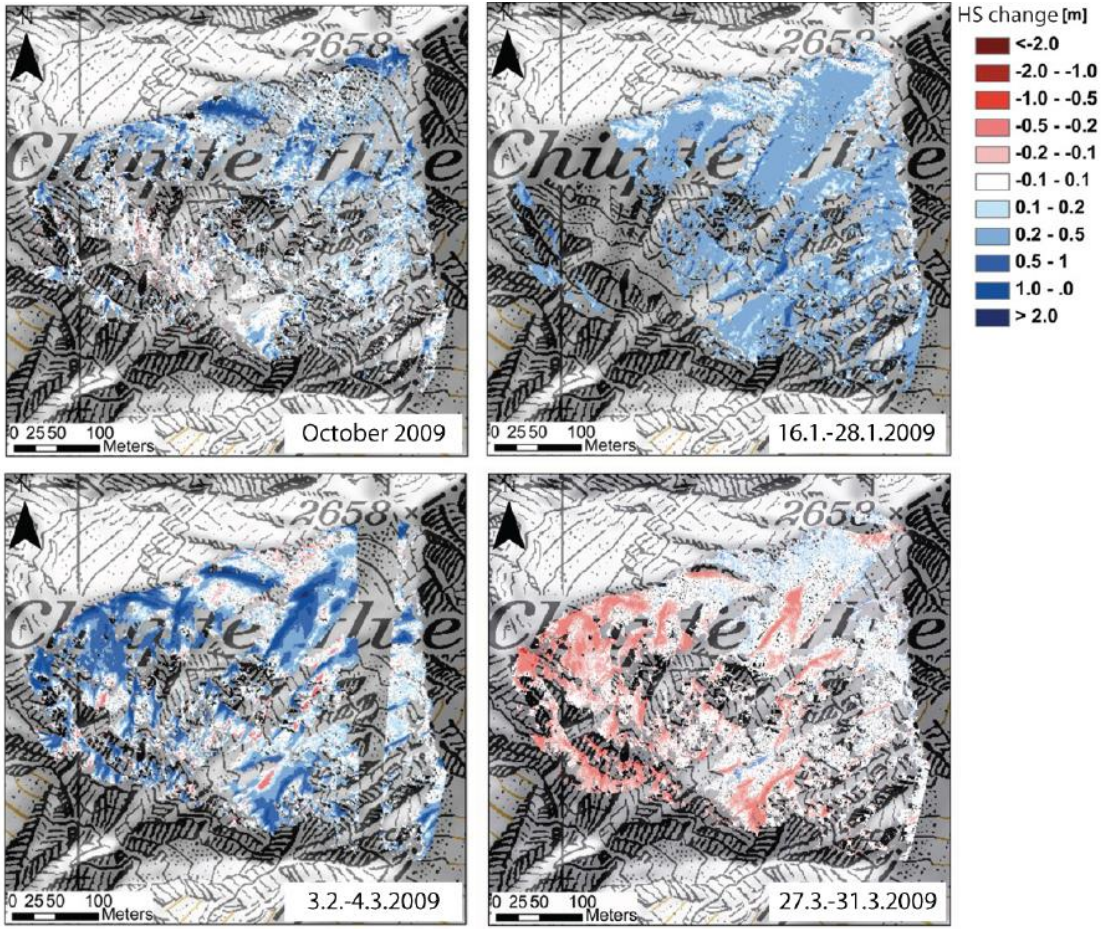
Single Point

Catchment Mean (4 km^2)

Rockwall Mean (1 km^2)

A typical “flat-field” may have more snow than a catchment and much more than in rock walls → Questions on the causes

Snow Depth Change in Rockwall

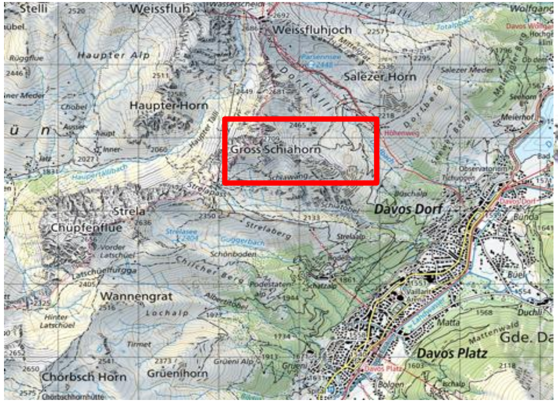


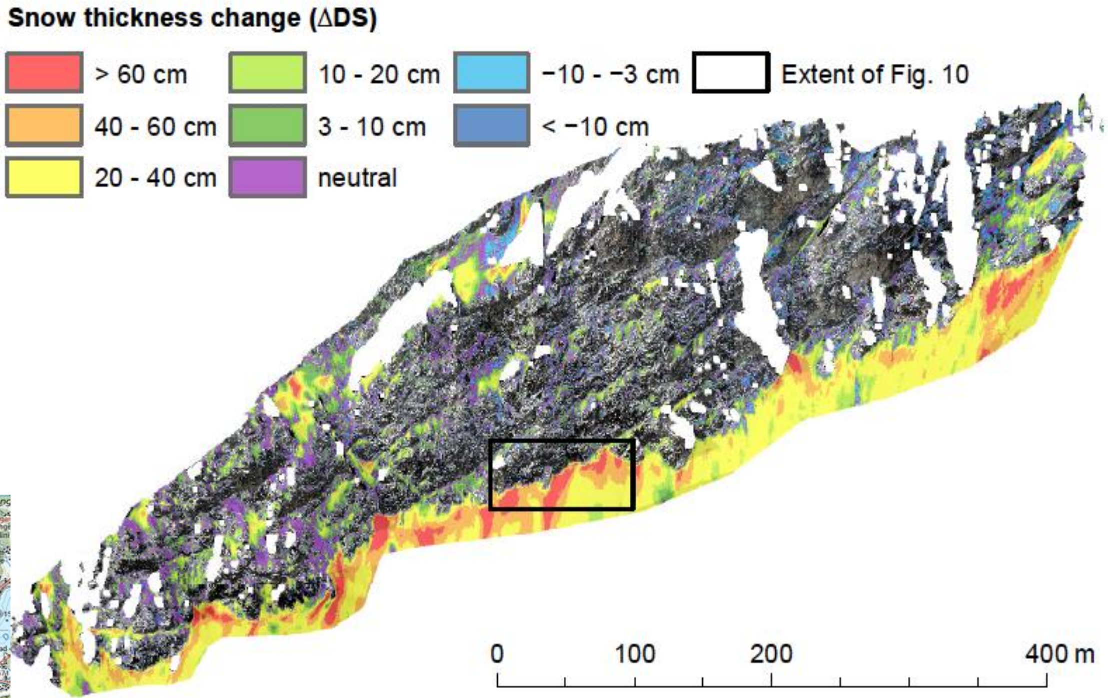
Chüpfenflue above Davos

Consecutive laser scans of snow depth allow to calculate snow depth changes:
wind appears to dominate snow redistribution in this rockwall (steepness: 50) because snow is increasing mostly in terrain depressions and gullies and eroded from ridges.

Slides dominate in steeper rockwall

Schiahorn Rockwall:
here, snow accumulates at the base of the wall mostly by snow sliding off the wall via the action of gravity (not necessarily avalanches)





Sommer et al., ***Frontiers in Cryospheric Sciences****, 2015*

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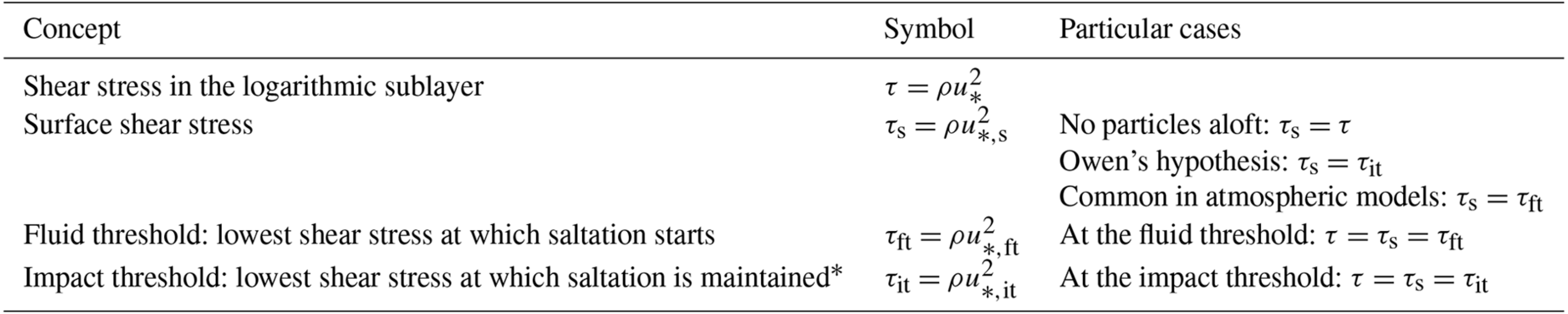
Saltation of Sand in our Wind Tunnel

Grains hop over the surface and follow ballistic trajectories, main forces are from the wind and gravity while in the air, interaction with the sand bed is complex.
→ Question on what can happen when a grain hits the ground and on the difference between sand and snow

What is the driving force behind snow transport?

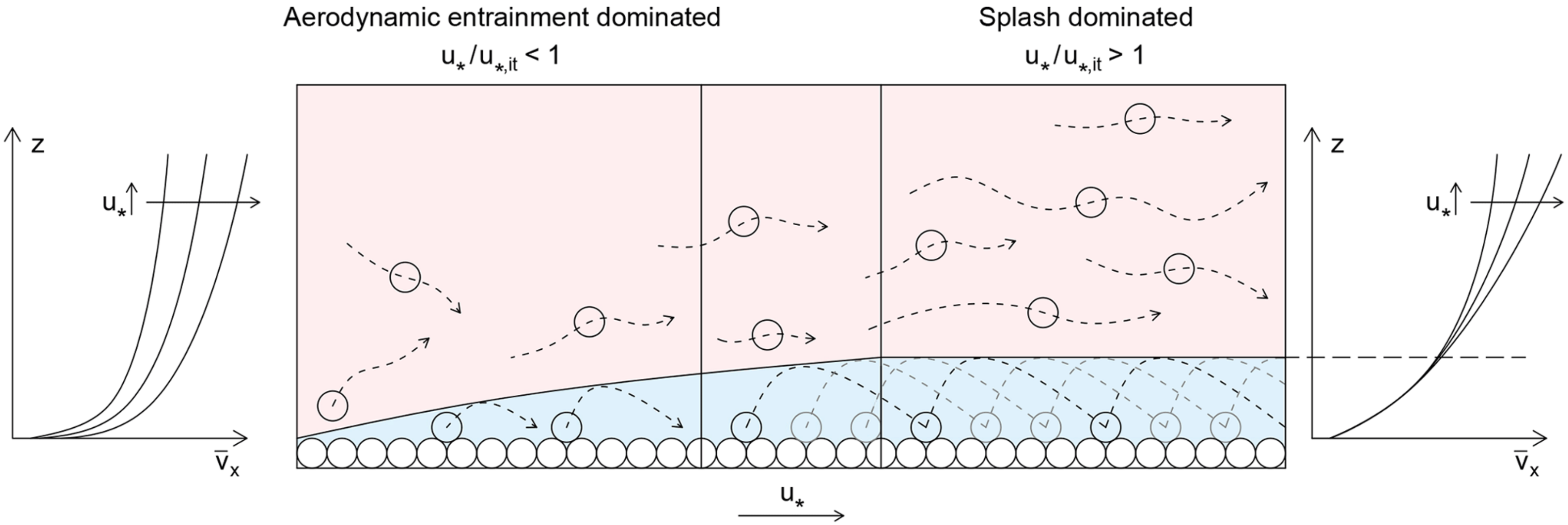


Concept	Symbol	Particular cases
Shear stress in the logarithmic sublayer	$\tau = \rho u_*^2$	
Surface shear stress	$\tau_\mathrm{s} = \rho u_{*,\mathrm{s}}^2$	No particles aloft: $\tau_\mathrm{s} = \tau$ Owen's hypothesis: $\tau_\mathrm{s} = \tau_\mathrm{it}$ Common in atmospheric models: $\tau_\mathrm{s} = \tau_\mathrm{ft}$
Fluid threshold: lowest shear stress at which saltation starts	$\tau_\mathrm{ft} = \rho u_{*,\mathrm{ft}}^2$	At the fluid threshold: $\tau = \tau_\mathrm{s} = \tau_\mathrm{ft}$
Impact threshold: lowest shear stress at which saltation is maintained*	$\tau_\mathrm{it} = \rho u_{*,\mathrm{it}}^2$	At the impact threshold: $\tau = \tau_\mathrm{s} = \tau_\mathrm{it}$

*Brito Melo et al., **The Cryosphere**, 2024*

Of course, the wind, but there is a bit of a mystery behind the onset of saltation. Because once there are grains in the air, then the erosion of additional grains is facilitated through particle impact (splash). While getting it going through drag from the wind alone (aerodynamic entrainment) is quite hard. This is why there are different threshold friction velocities defined in the table above.

Saltation: Physical Principles



Forces on grains:

- Drag Force

- Gravity

(Lift Force, Magnus Force, Added Mass Force, Pressure Gradient, Electrostatic Forces, Basset History Term)

Processes:

- Aerodynamic Entrainment
- Rebound, Splash

Saltation Mass Flux Approximations

- Original Bagnold: $Q \sim (u - u_{th})^3$

Mass Flux (kg m^{-1} s^{-1})

Threshold Wind Speed (m s^{-1})

- Empirical (Sorenson): $Q = 0.0014\rho_a u_*(u_* - u_{*th})(u_* + 7.6u_{*th} + 205)$

Friction Velocity (m s^{-1}): square root of average surface shear

- Threshold Wind Speed (Schmidt):

$$u_{*th} = \sqrt{\frac{A\rho_i g r_g (SP + 1) + B\sigma N_3 \frac{r_b^2}{r_g^2}}{\rho_a}}$$

A,*B*: Coefficients, $\rho_{i,a}$: ice, air density, *g*: gravity, $r_{g,b}$: grain, bond radius,
SP: Sphericity, σ: ice strength N_3: coordination number

Saltation

U(z): Fluid velocity (m s^{-1})
U_r: Relative velocity (m s^{-1})
d: Particle diameter (m)
C_d: Drag coefficient ()

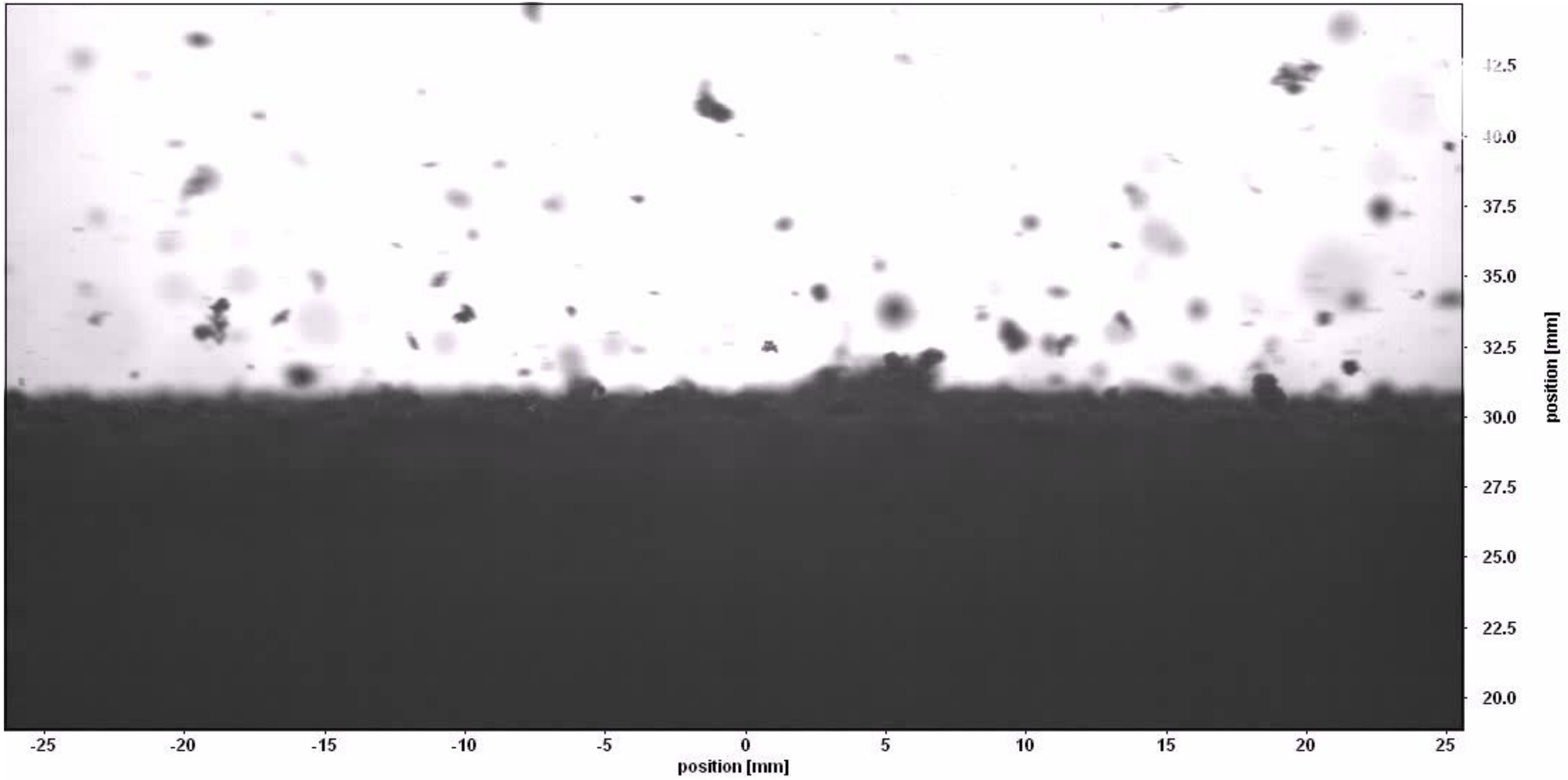
Saltation:

- Ballistic Trajectories (Initial Velocity is important)
- Velocity change described by fluid drag and gravity

$$\frac{\partial^2 x}{\partial t^2} = -0.75 \frac{\rho_a}{\rho_p} \frac{U_r}{d} C_d \left(\frac{\partial x}{\partial t} - U(z) \right)$$

$$\frac{\partial^2 z}{\partial t^2} = -0.75 \frac{\rho_a}{\rho_p} \frac{U_r}{d} C_d \frac{\partial z}{\partial t} - g.$$

Wind Tunnel Saltation of Snow



Drift Index for Avalanche Warning

Based on the ability to model the snow at a local station and some first knowledge on snow transport, we want to develop a drift index, which shows semi-quantitatively the intensity of drifting and blowing snow in some mountain environment.

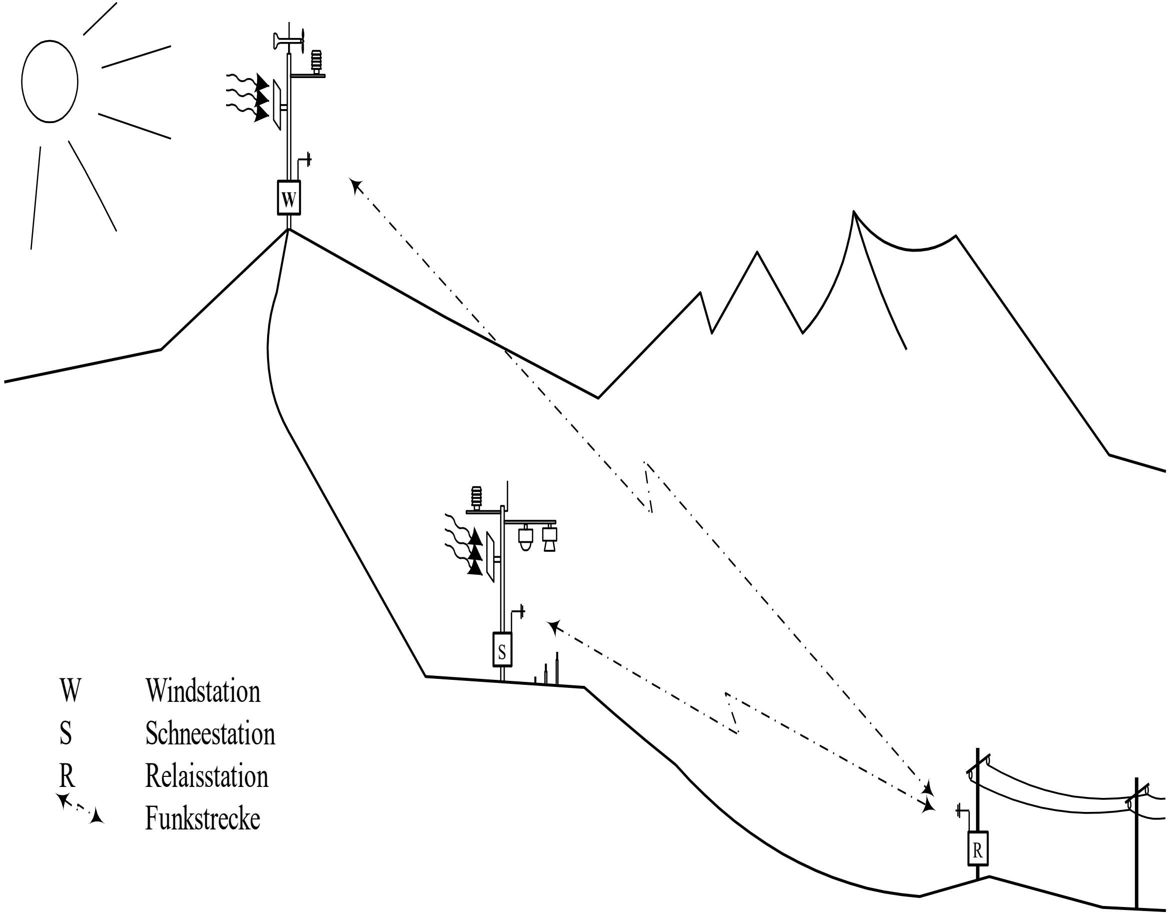
We want:

- A local to regional assessment of drifting snow (lee slope loading) based on Automatic Weather Station (AWS) input – should be representative !!

We don’t want:

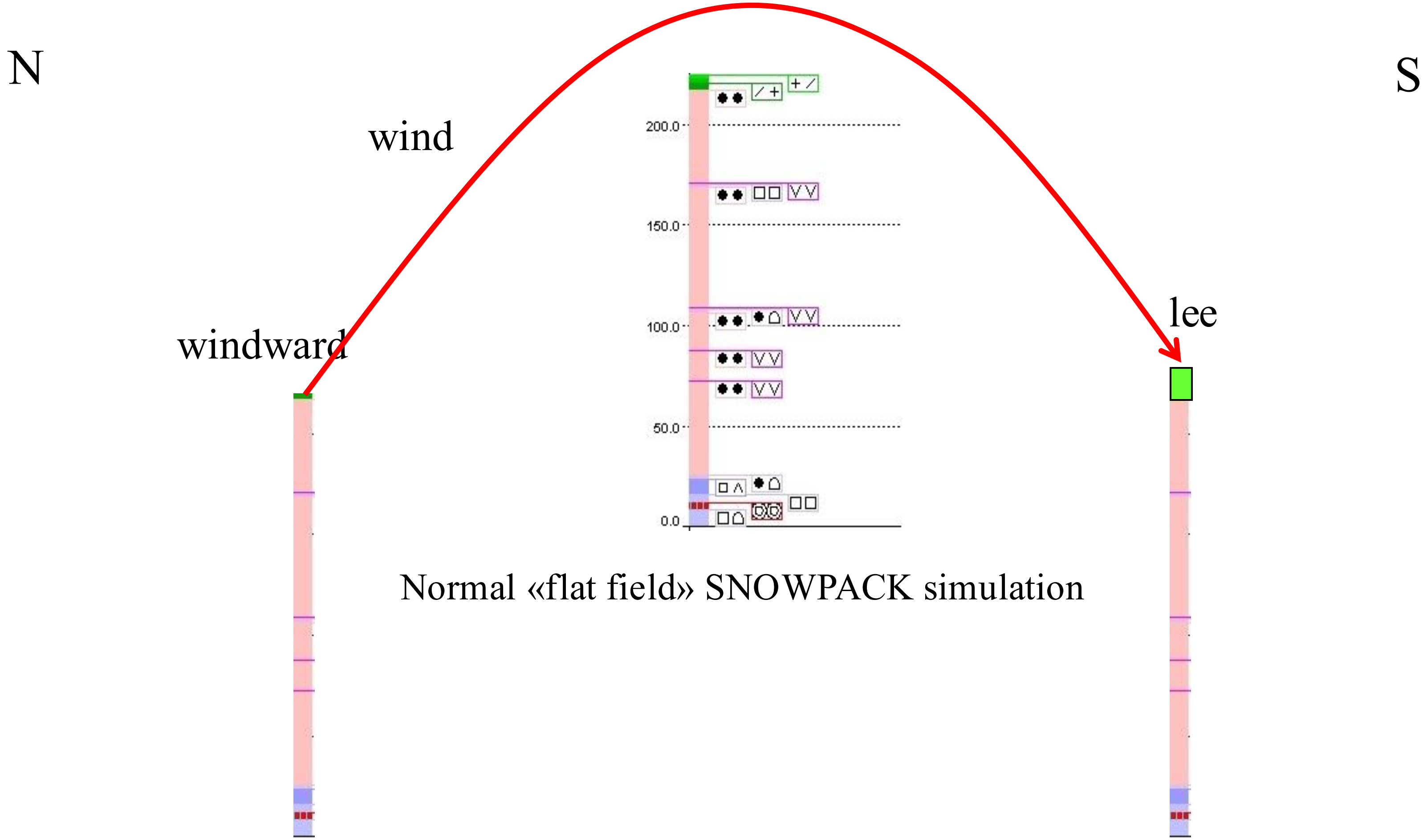
- A single point info (measurement) of snow drift mass flux
- Erosion or deposition at a single point (the AWS location)
- A simple u^3 calculation of snowdrift
- ....

Concept of an IMIS AWS



An IMIS station consists of two (or three) connected locations, a wind station on an exposed place and a snow station at a place where snow accumulates “representatively”. The snow station measures snow depth (and liquid precipitation), temperature, humidity, reflected shortwave radiation, outgoing longwave radiation and surface temperature.

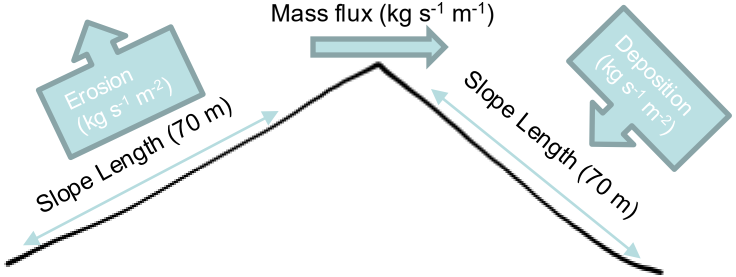
Virtual Slope Simulations



Normal «flat field» SNOWPACK simulation

Drift Index for Avalanche Warning: wind_trans24

- Calculate a mass flux based on threshold wind speed (friction velocity) of the eroding slope
- Arbitrarily apply the mass flux divergence over a typical slope length (70 m).



- Consider maximum amount of snow that can be eroded (e.g. until a crust re-surfaces
- Determine erosion and deposition fluxes (mm water equivalent) and move mass from windward to lee
- Sum erosion/deposition amounts (mm) for 24 h → wind_trans24

Contingency Table

	Drift observed	No Drift observed
Drift in SNP	15 %	10 %
No Drift in SNP	25 %	50 %

Lehning and Fierz, CRST, 2008

The SNOWPACK drift index can be compared against observations of drift either by observers (yes/no) or by instruments which measure transport of snow particles (see following slides).

- The contingency table shows a typical performance
- It has been found useful by avalanche warning services despite its certainly limited accuracy

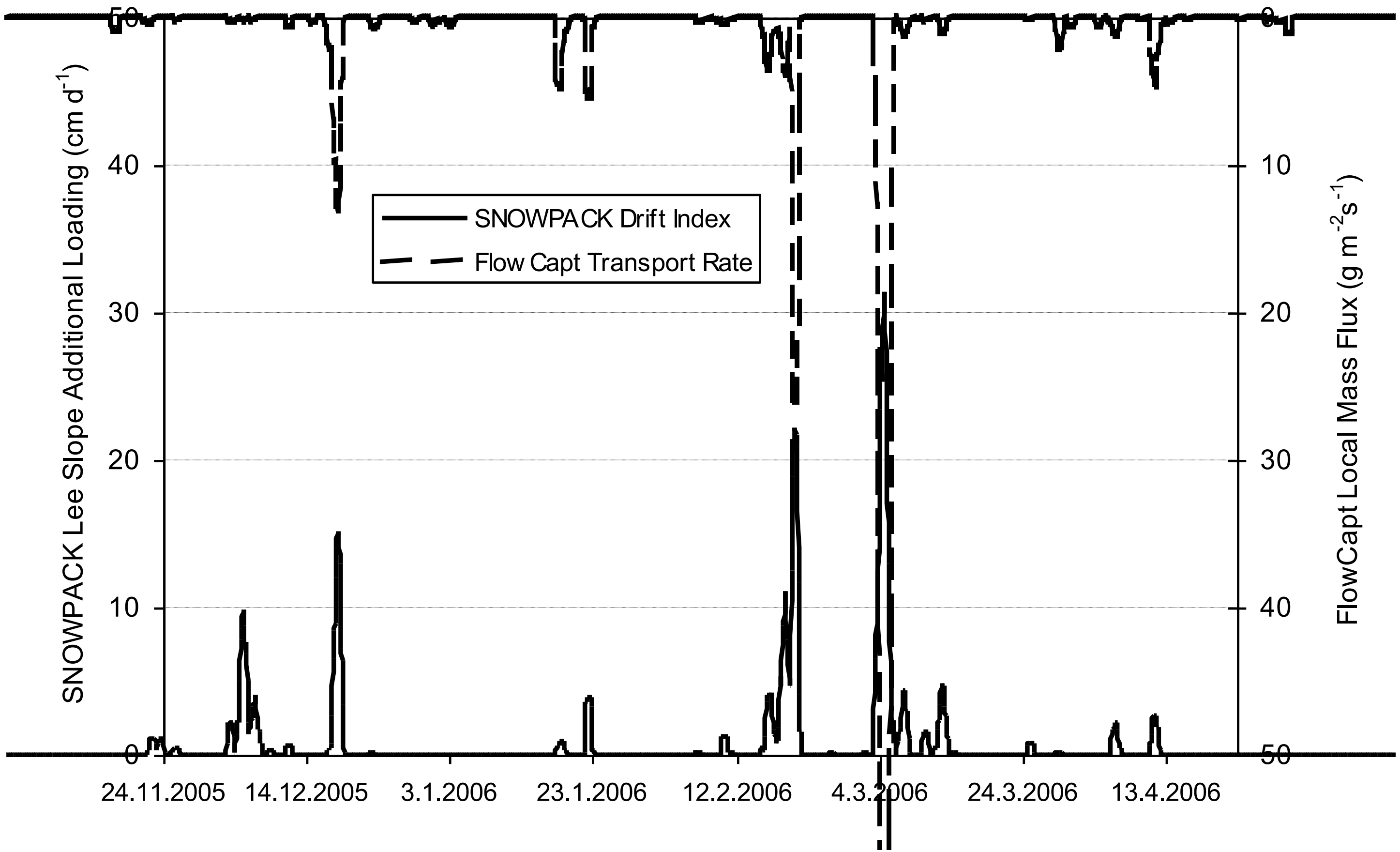
→ Difficult to work from observations only

Comparison to FlowCapt

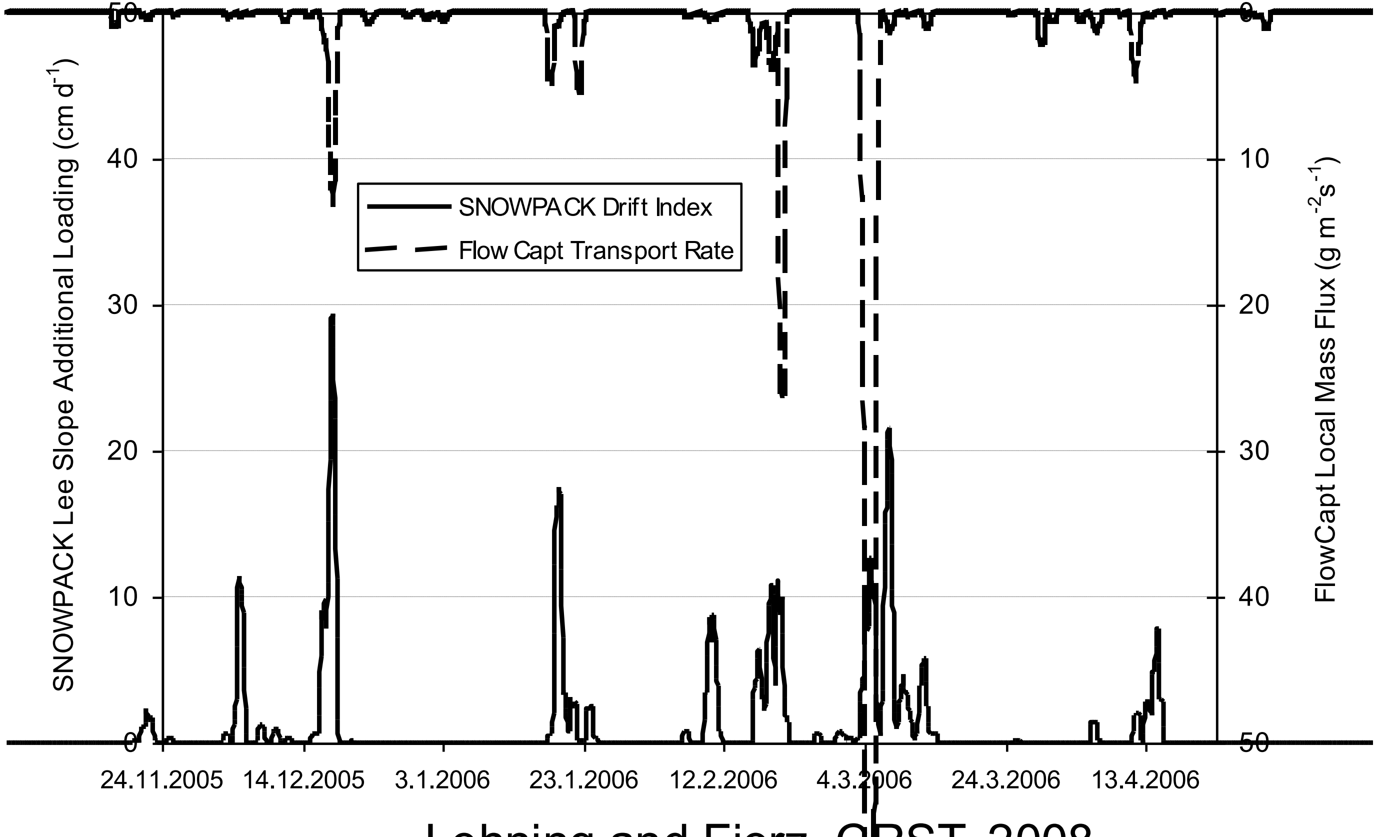
FlowCapt is a tube with a microphone inside; the sound of impacting (snow) particles onto the tube is analyzed spectrally to calculate a particle flux; also wind generates sound in the tube – with the spectral analysis the instrument can distinguish wind from particle noise;

- A value for wind speed is given
- Vertically integrated particle flux is given for a tube segment (ca. 50 cm)
- Accuracy is limited, especially when partially buried by snow

Comparison using „Wind Local“

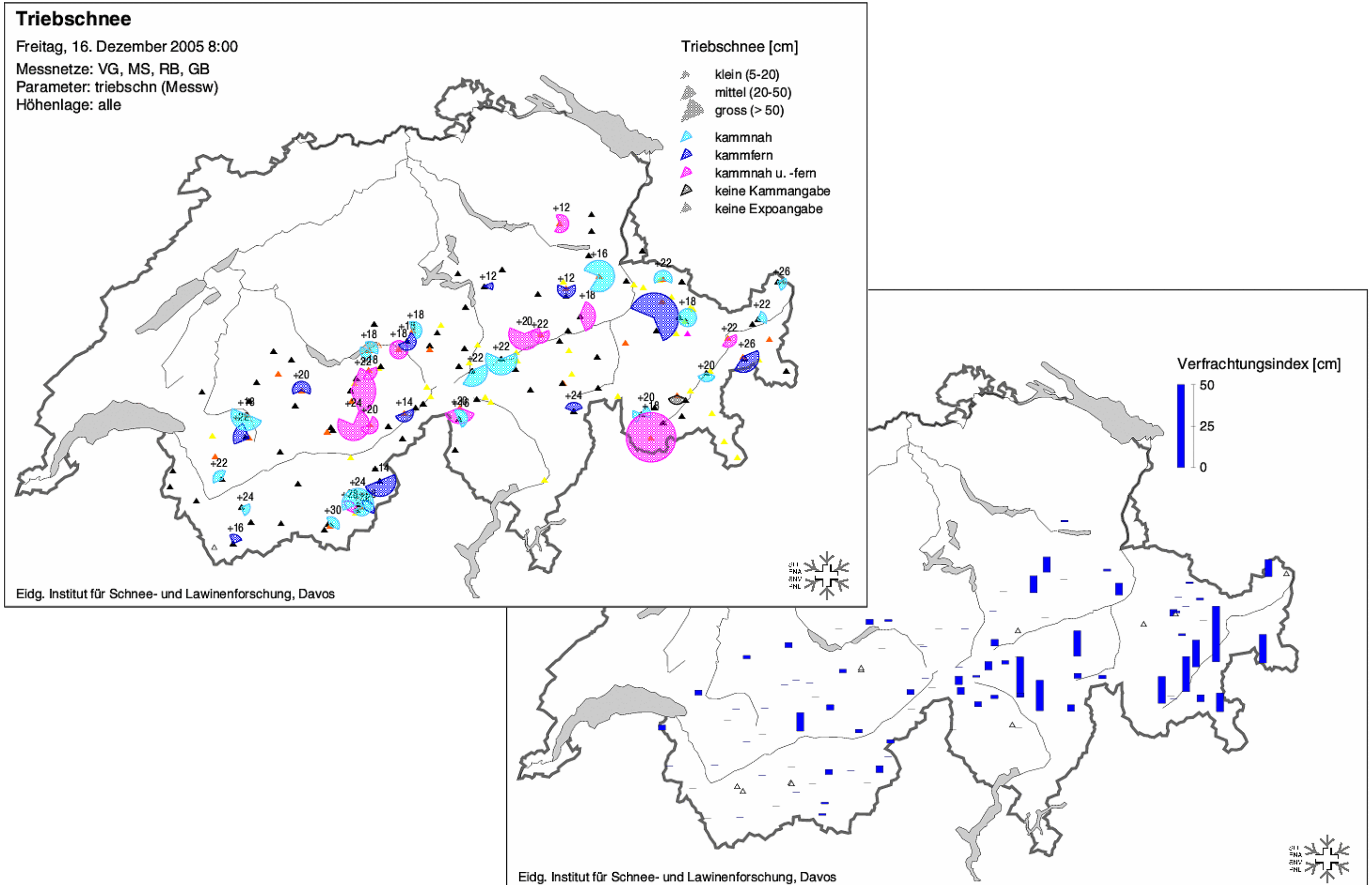


Comparison using „Wind Summit“

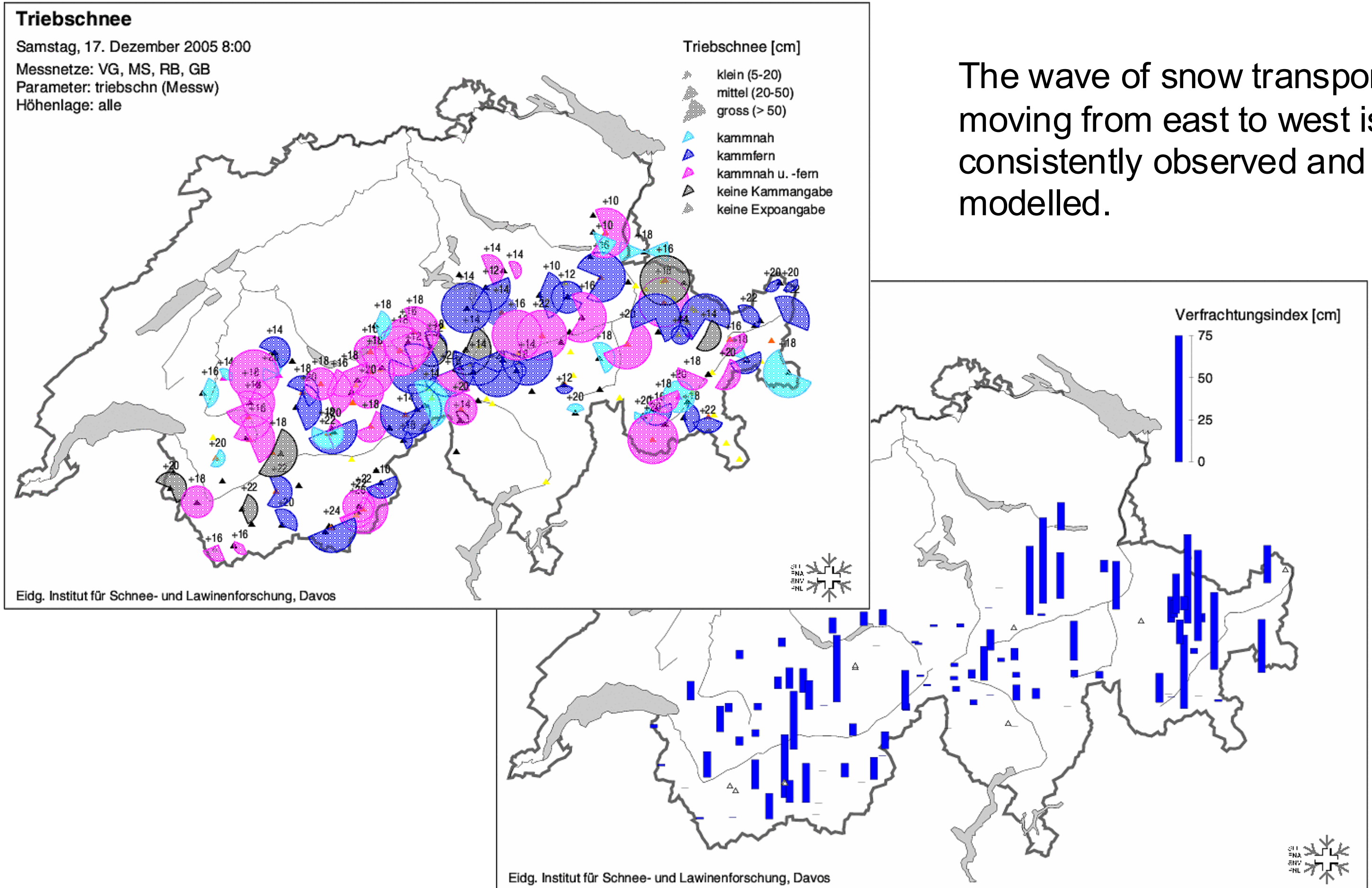


Lehning and Fierz, CRST, 2008

Mountain Range Pattern Comparison



One day later



The wave of snow transport moving from east to west is consistently observed and modelled.

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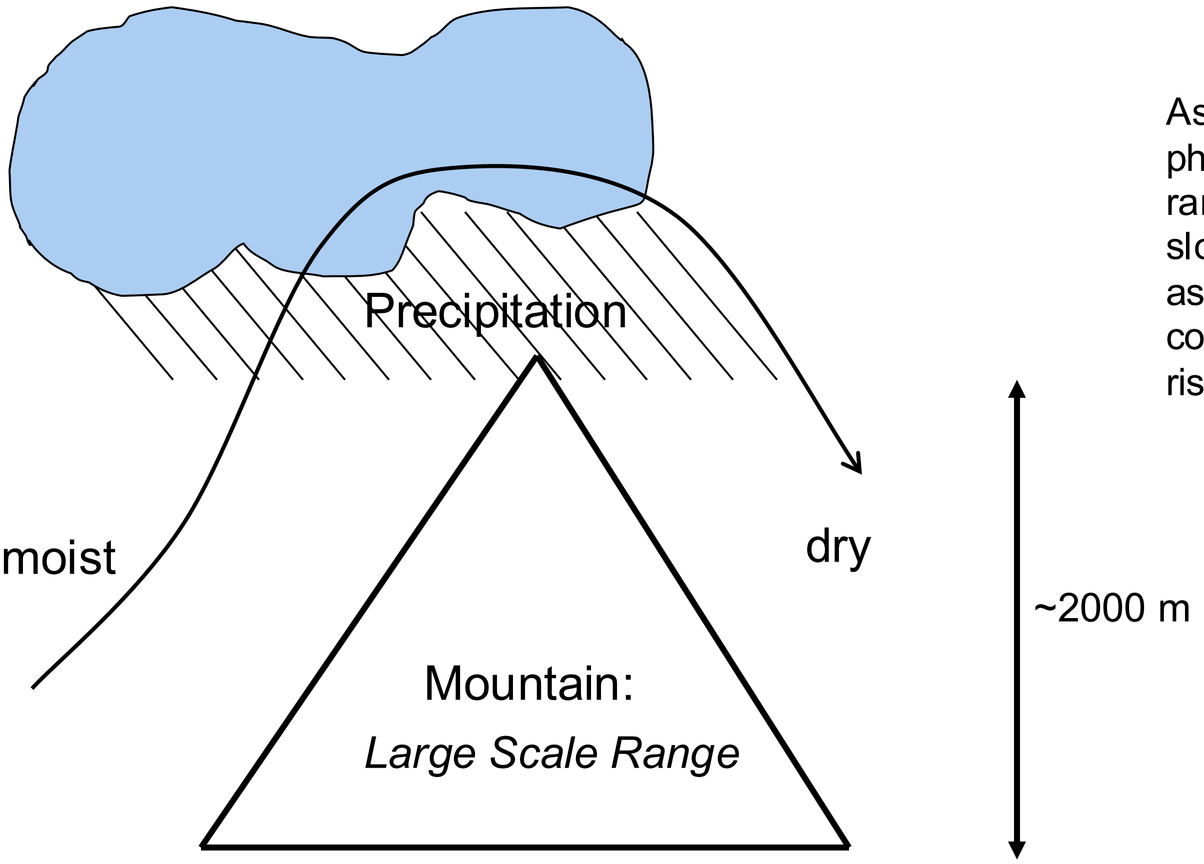
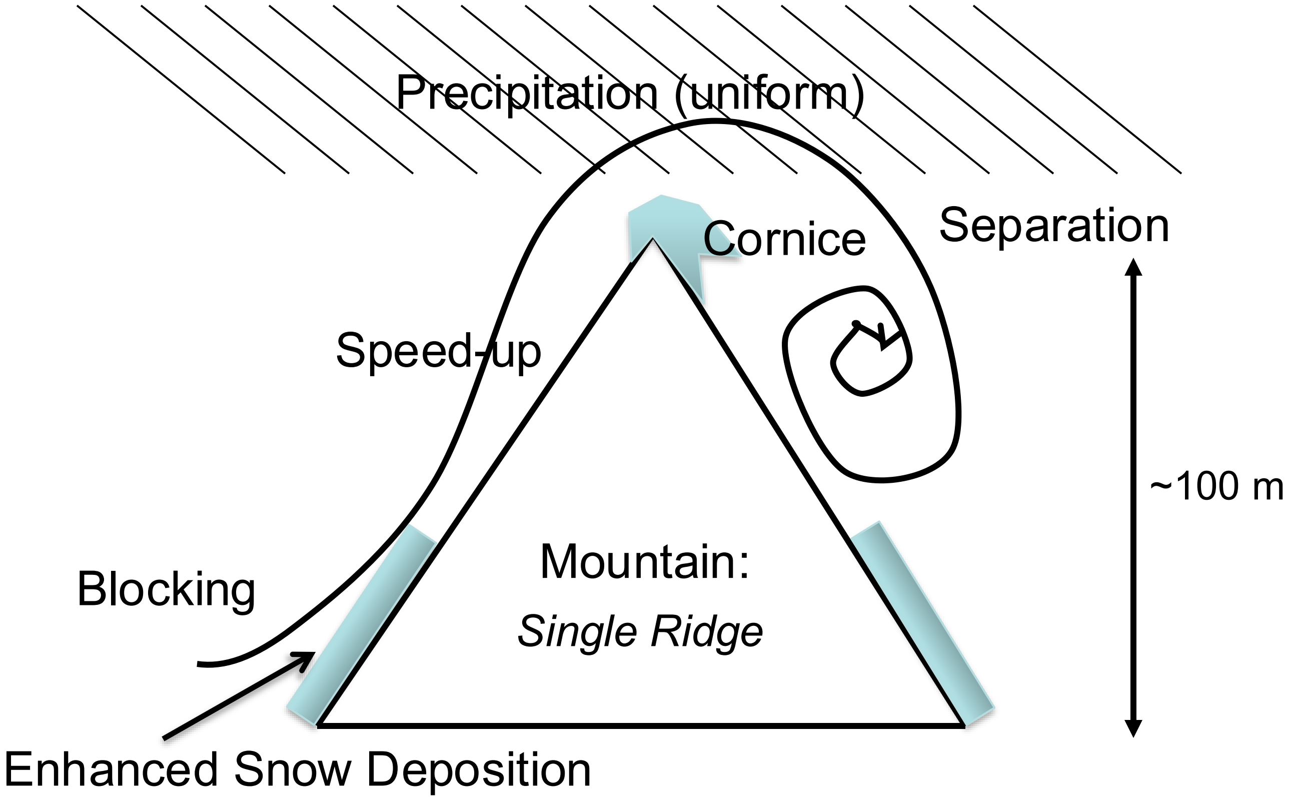
Suspension

Precipitation and Mountains



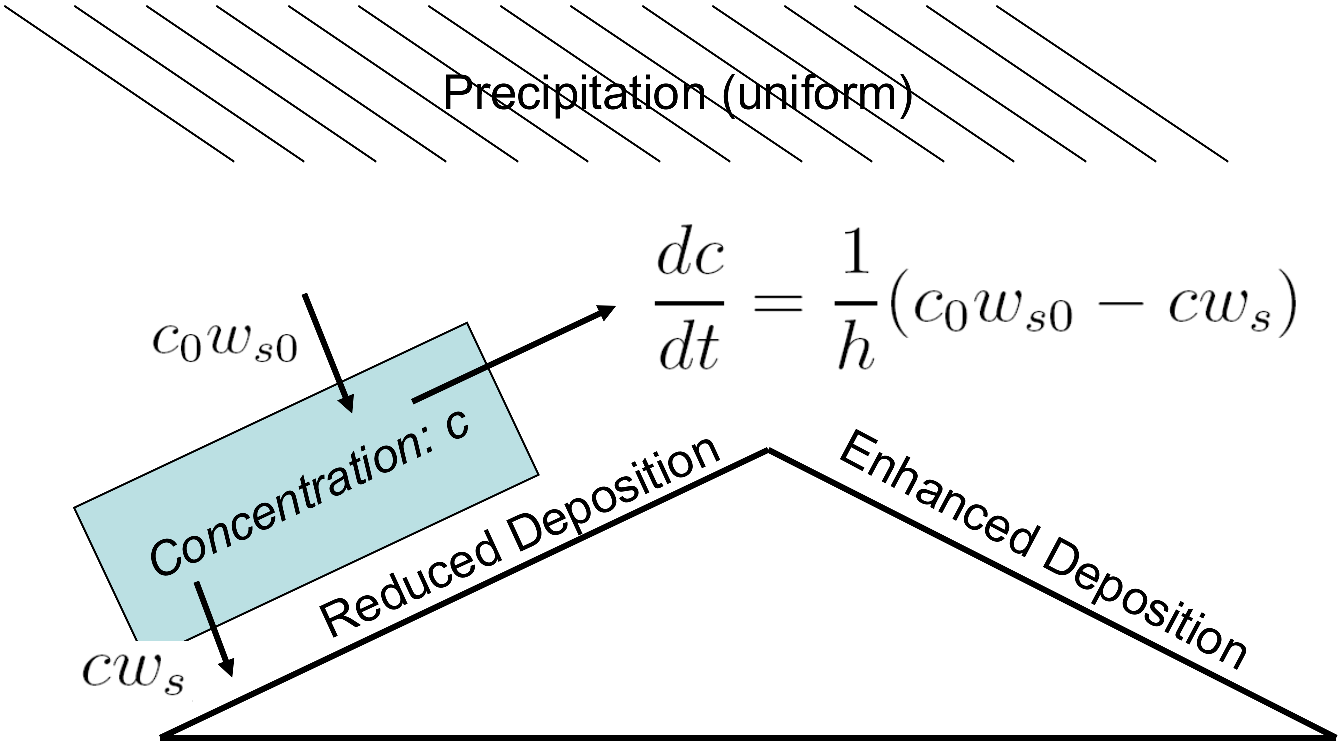
As learned in the atmospheric physics class, on the mountain range scale, the windward slopes get more precipitation as convection and condensation is triggered by rising air masses.

Preferential Deposition



At smaller scale, i.e. a single hill, a ridge or the mountain top, particles interact with complex flow structures such as blocking (windward – foot of the hill), speed-up (windward – ridge top), or a recirculation eddy as a result of flow separation (lee slope). Enhanced snow deposition is shown by the colored areas.

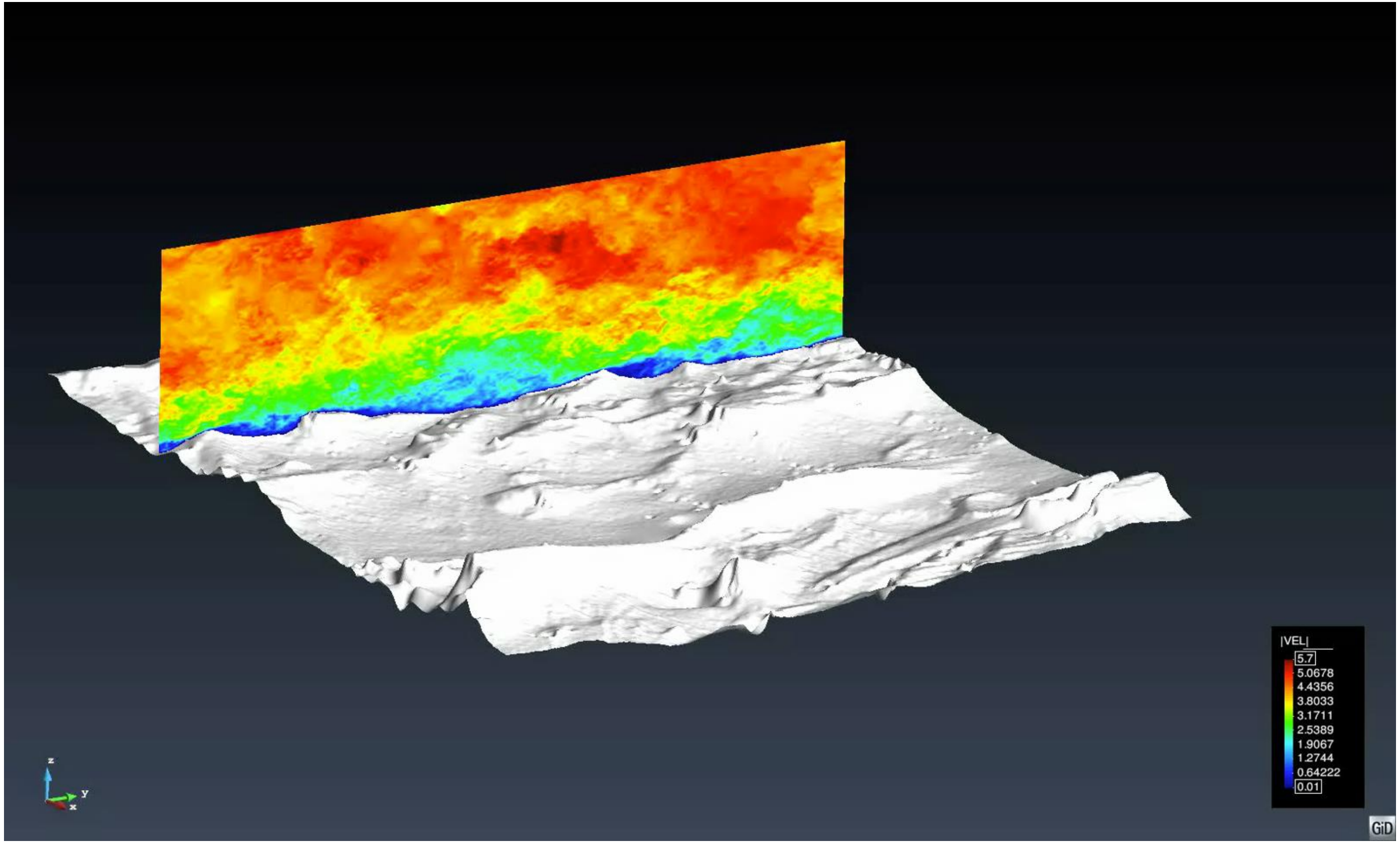
Preferential Deposition II



$$\frac{dc}{dt} = \frac{1}{h}(c_0 w_{s0} - c w_s)$$

As in the speed-up region the deposition is reduced, some extra mass may accumulate in an air parcel crossing the ridge. The concentration change can be described by a simple differential equation.

LES Simulations of Coupled Flow – Particle Motion



LES (Large Eddy Simulation) numerical models, which solve the Navier-Stokes equations and part of the turbulent motions (larger scales), are an appropriate tool to investigate flow structures and fluid – particle interactions.

LES Simulations of Coupled Flow – Particle Motion

Navier-Stokes (Flow):

Constant pressure forcing

Particle forces on flow

$$\frac{\partial \hat{\tilde{u}}_i}{\partial \hat{t}} + \hat{\tilde{u}}_j \left(\frac{\partial \hat{\tilde{u}}_i}{\partial \hat{x}_j} - \frac{\partial \hat{\tilde{u}}_j}{\partial \hat{x}_i} \right) = - \frac{\partial \hat{\tilde{\pi}}}{\partial \hat{x}_i} - \frac{\partial \hat{\tau}_{ij}^{SGS}}{\partial \hat{x}_j} - \hat{\Pi}_1 + \hat{\tilde{f}}_i^{\Gamma_s} - \frac{\rho_p}{\rho \mathrm{St}} \sum_{n=1}^{N_p} \Delta_{\hat{u}}^n \delta \left(\hat{\mathbf{x}} - \hat{\mathbf{X}}_p^n \right).$$

Fluid velocity rate of change + advection

Filtered, modified pressure

Body Force

Particle Dynamics:

$$\frac{\mathrm{d}\hat{U}_{p,i}}{\mathrm{d}\hat{t}} = \frac{\Delta_{\hat{u}}}{\mathrm{St}} - \frac{1}{\mathrm{Fr}^2} \delta_{i3}$$

Drag

Gravity

Stokes Number:

$$\mathrm{St} = \frac{t_p U}{L}$$

Inertia over flow advection

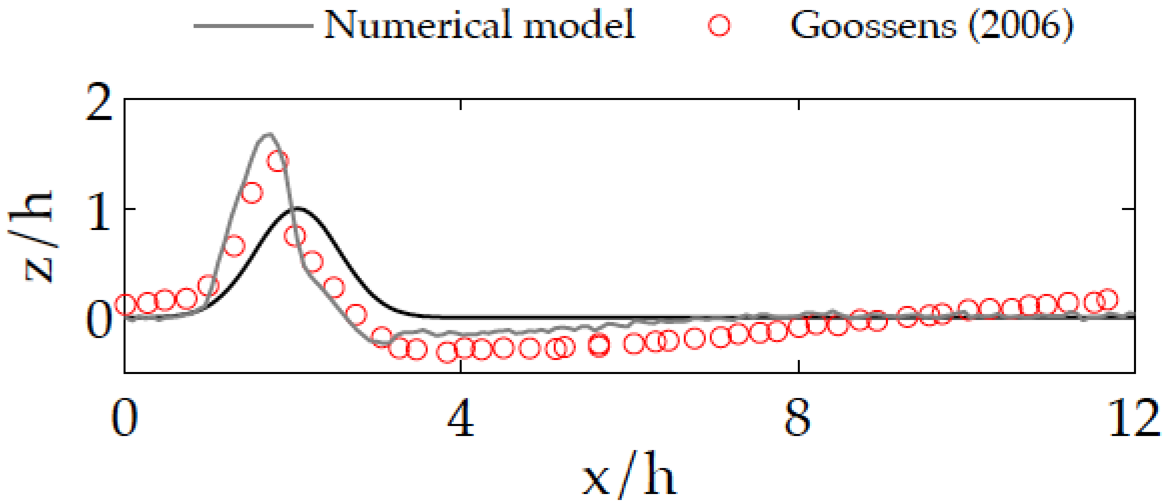
Froude Number:

$$\mathrm{Fr} = \frac{U}{\sqrt{gL}}$$

Inertia over gravity

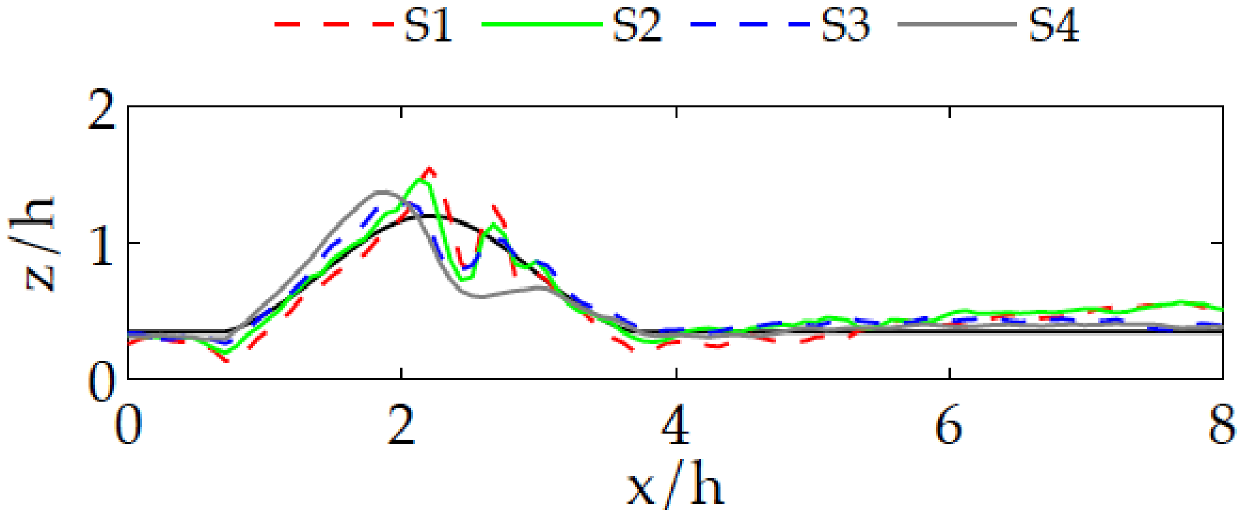
Comola et al., JGR Atmospheres, 2019

LES – LSM (Lagrangian Stochastic Model) Validation



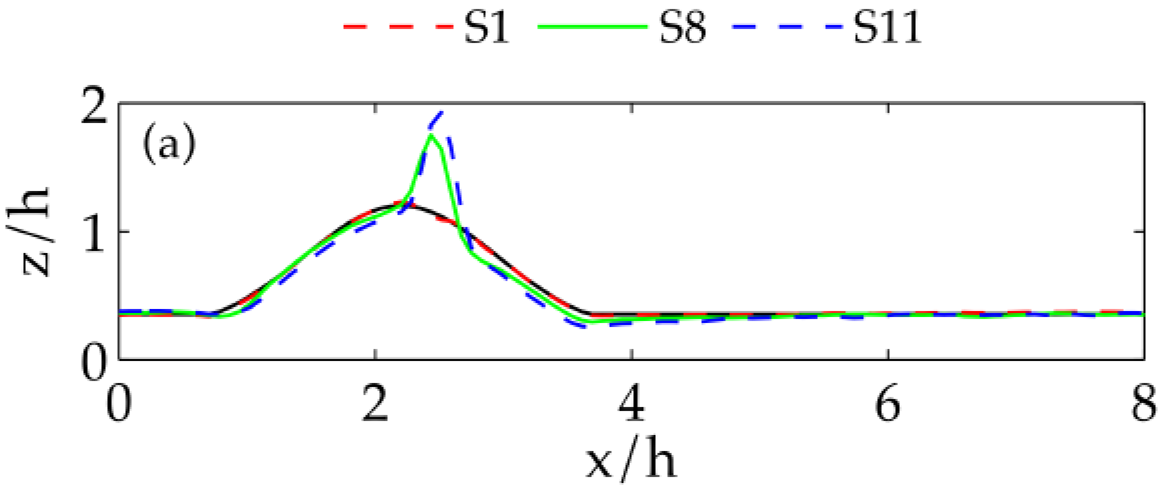
Wind tunnel comparison shows good model performance (for sand)

LES – LSM (Lagrangian Stochastic Model) Hill Deposition



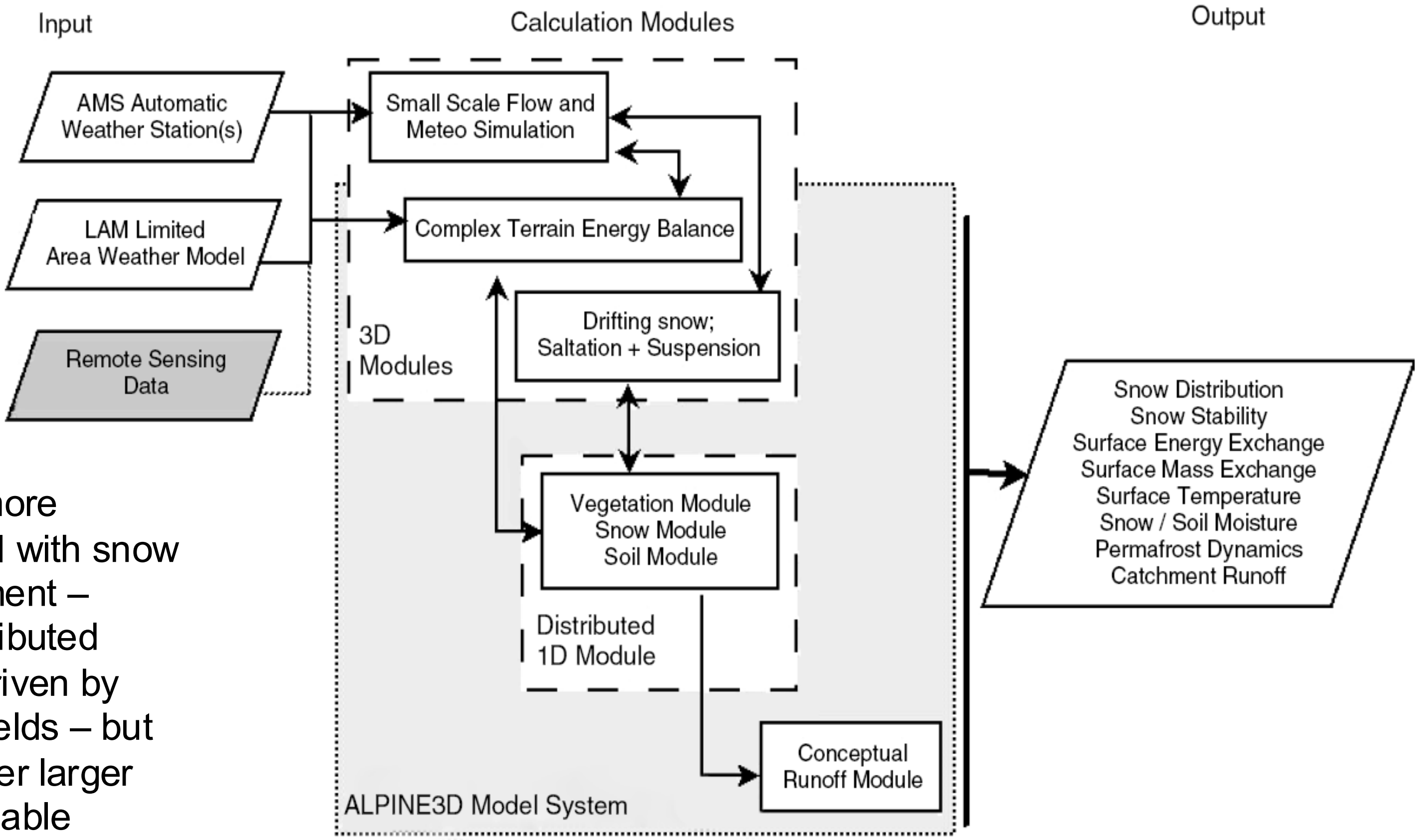
Snow distribution over Gaussian hill for increasing Stokes numbers: when inertia is dominating as for S4 (for heavy particles, e.g. sand or ice pellets), the windward side gets preferential deposition up to the hilltop and the lee is in the “rain shadow”. For snow, inertia is often small compared to propensity to follow the flow (advection) and more complicated patterns such as a cornice evolve.

LES – LSM (Lagrangian Stochastic Model) Hill Deposition



Snow distribution over Gaussian hill for dendritic crystals (S8: very small Stokes) and inertialess particles (S11) → Question on lee slope loading?

Modelling Snow Deposition in Alpine3D



Alpine3D is a more complete model with snow cover development – basically a distributed SNOWPACK driven by external wind fields – but can be used over larger areas at reasonable computational cost.

Lehning et al., WRR, 2008

Formulation of Suspension in A3D

Stationary Diffusion Equation for Snow Particles:

$$\nabla \cdot \Big(K(\mathbf{x})\, \nabla c(\mathbf{x}) \Big) - \mathbf{u}(\mathbf{x}) \cdot \nabla c(\mathbf{x}) = 0$$

$$\mathbf{u} = (u, v, w - w_s)$$

K: Diffusion coefficient (m^2 s^{-1})

Lower Boundary Condition (Robin Type):

$$-\mathbf{n}(\mathbf{x}) \cdot K(\mathbf{x}) \nabla c(\mathrm{x}) = \frac{K^{\perp}(\mathbf{x})}{h_{\mathrm{ref}}} \Big[c(\mathbf{x}) - (c_{\mathrm{salt}}(\mathbf{x}) + c_{\mathrm{prec}}) \Big]$$

A new paradigm of snow accumulation

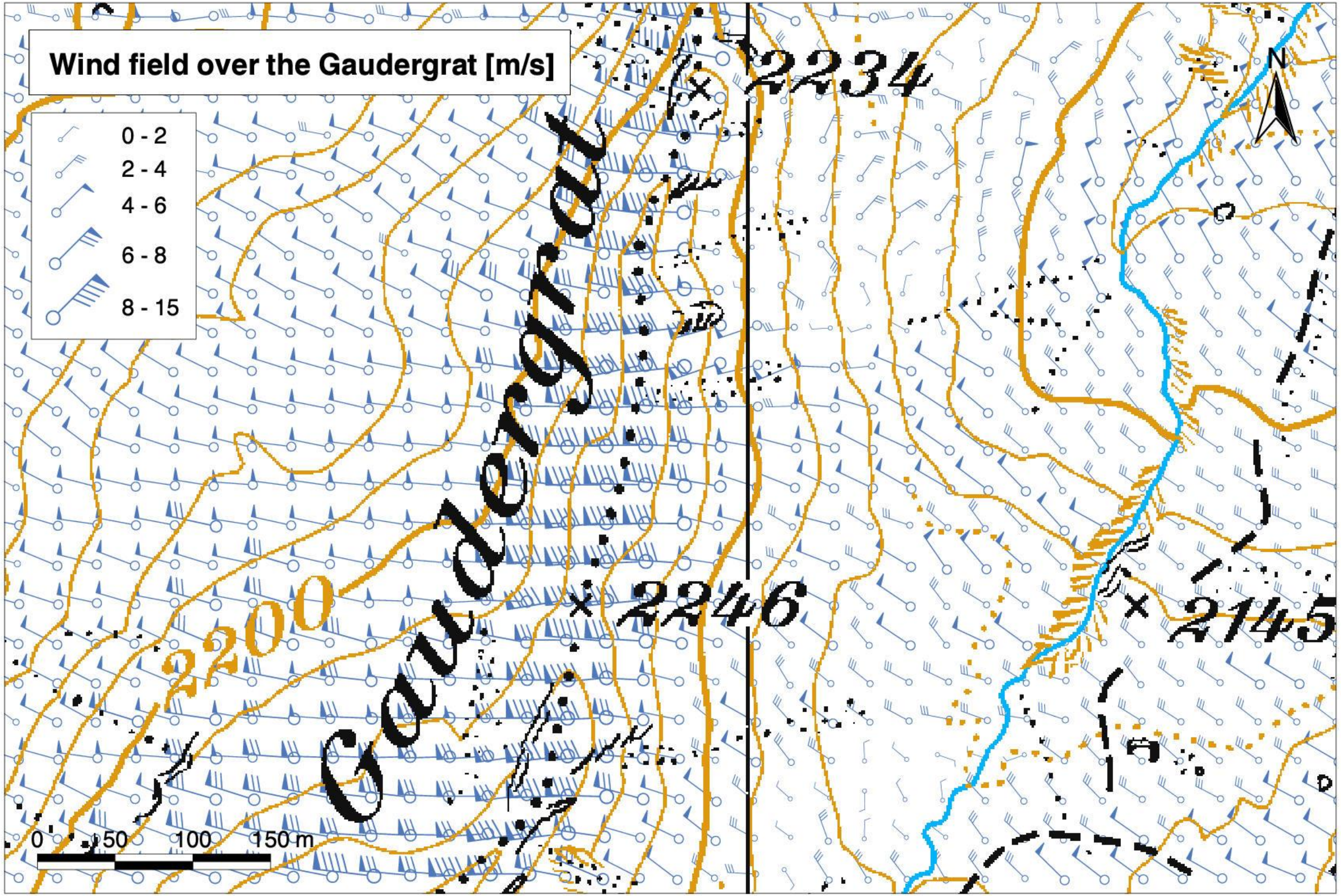
Classical:

- Saltation (*leads to*)
- Suspension
- Mass Flux Divergence

Alpine3D:

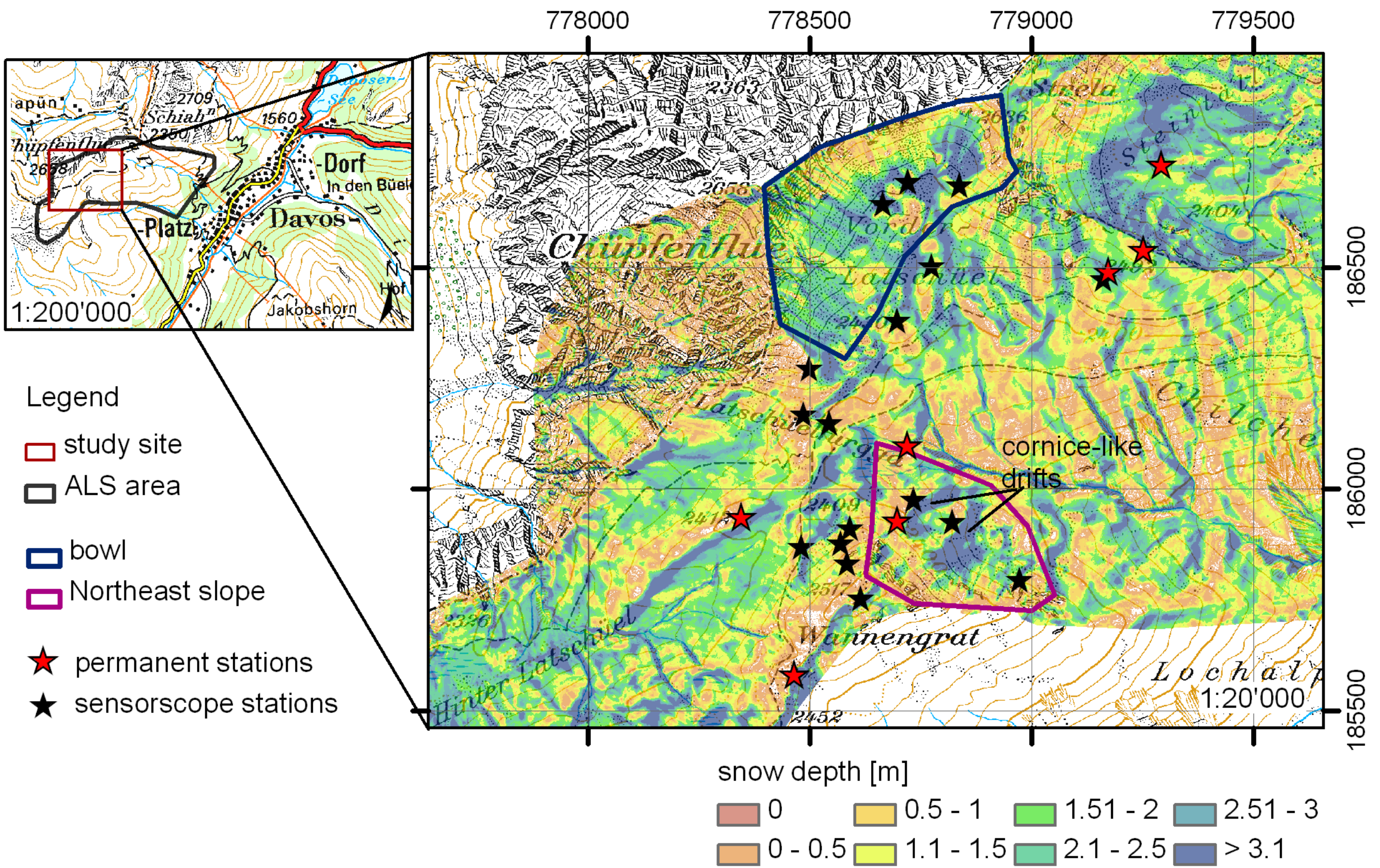
- Precipitation
- Wind and Terrain
- Settling Velocity as function of Flow
- Spatially Varying Concentration
- Deposition/Erosion
- SnowCover

Calculated topographical flow features

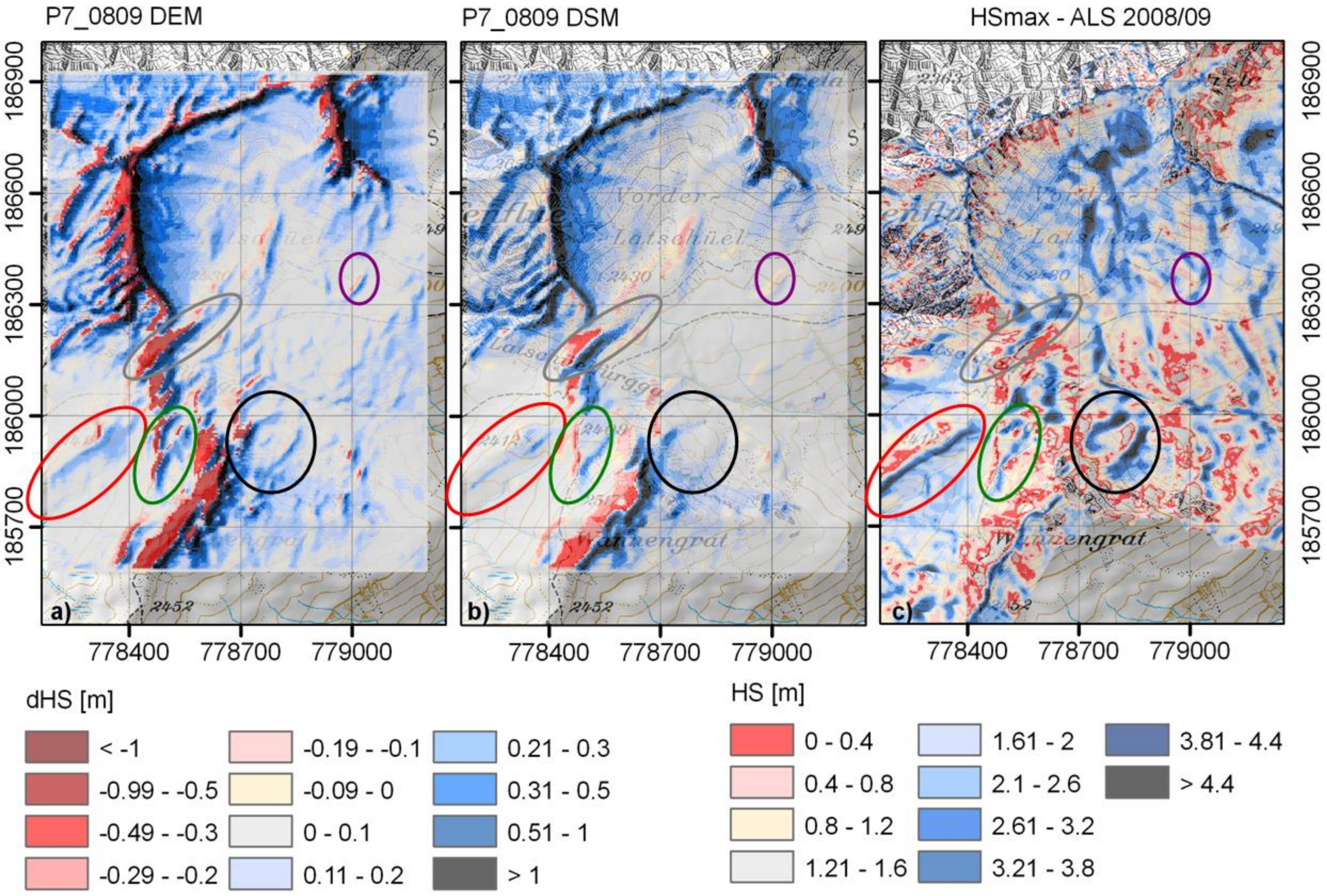


Raderschall et al., WRR, 2008

Wannengrat field results



Simulation and measurements at Wannengrat



The panel on the right shows the measured snow distribution, the two on the left Alpine3D simulations with the no-snow topography (left) or the smoothed snow topography (middle). Cornice formation is overestimated but many features are captured by the model.

Mott et al., The Cryosphere, 2010

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Motivation – Why would we care?

- Model predictions for Arctic and Tundra drift sublimation loss range from 10 to 50% of total precipitation

- “Arid” mountains lose a lot of water but how much ?

- In Antarctica, blowing snow sublimation is important and probably a significant fraction of total precipitation (some research finds 85% locally) but estimates on sublimation over the whole continent vary over a factor of **4**!

- Feed-back (boundary layer saturation) poorly understood

Sublimation Model

Suspension

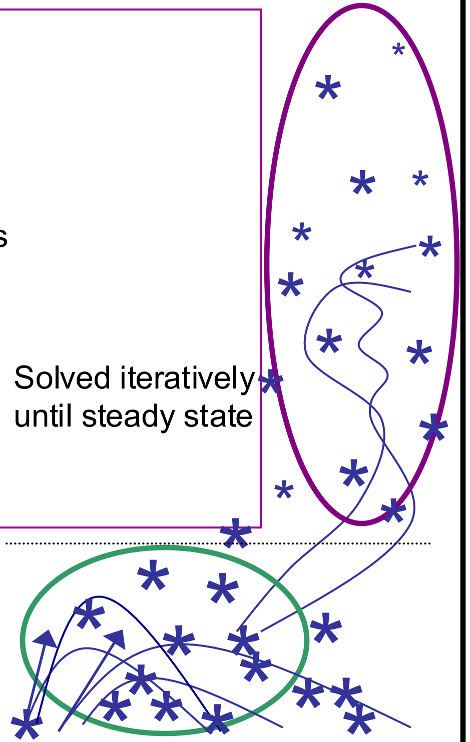
- Regard snow/air mixture as continuous fluid
- Snow from saltation and snow fall
- Solve steady state advection-diffusion equation
  - Sublimation as sink/source in conservation equations

$$\left.\begin{aligned}
&\frac{\partial}{\partial \vec{x}}\left(K_c \frac{\partial c}{\partial \vec{x}}\right) + \vec{u}_p \cdot \frac{\partial c}{\partial \vec{x}} = -S \\
&\frac{\partial}{\partial \vec{x}}\left(K_q \frac{\partial q}{\partial \vec{x}}\right) + \vec{u} \cdot \frac{\partial q}{\partial \vec{x}} = \frac{S}{\rho_{air}} \\
&\frac{\partial}{\partial \vec{x}}\left(K_\theta \frac{\partial \theta}{\partial \vec{x}}\right) + \vec{u} \cdot \frac{\partial \theta}{\partial \vec{x}} = -\frac{1}{\rho_{air} \cdot C_P}(L_v S)
\end{aligned}\right\}$$

Solved iteratively until steady state

Saltation

- Starts when shear stress exceeds threshold
- Threshold varies with surface snow properties
- Equilibrium state



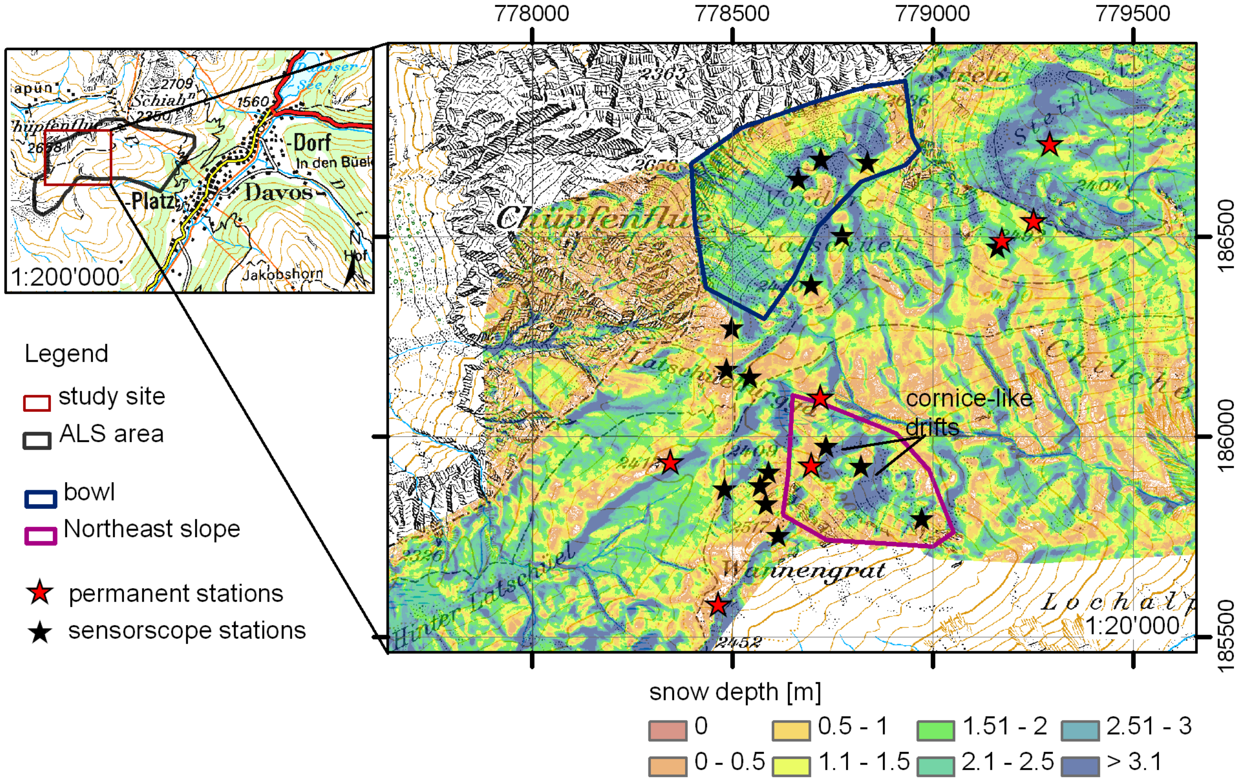
SNOWPACK Stratigraphy and energy balance snow cover

Sublimation can be described by the same advection – diffusion equation as transport of particles. Equations for humidity and temperatures are added and a coupled set of PDEs results.

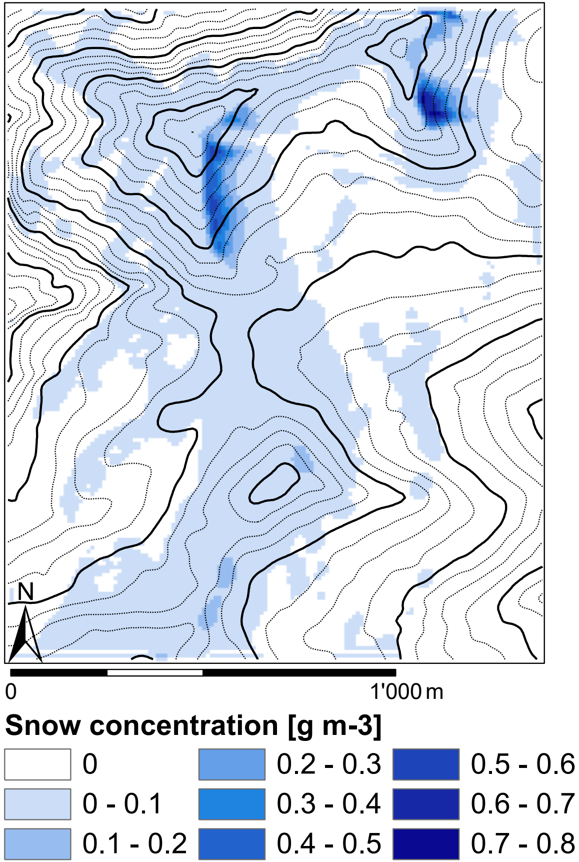
c: concentration (kg m^{-3}), *S*: source term (kg m^{-3} s^{-1}), K_x: Diffusion coefficient (m^2 s^{-1}), *q*: moisture mixing ratio (), *θ*: potential temperature (K)

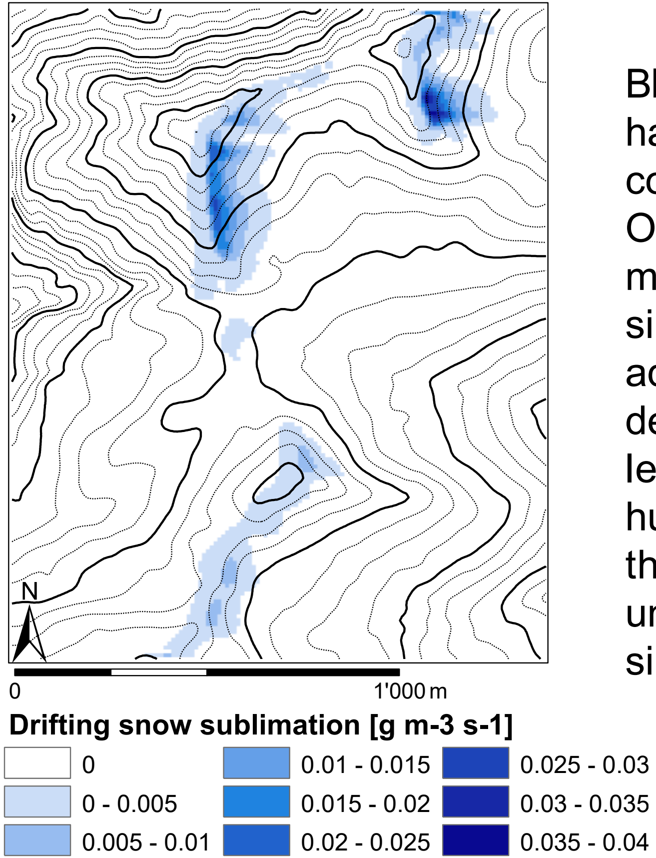
Groot Zwaaftink et al., JGR, 2011

Wannengrat field results



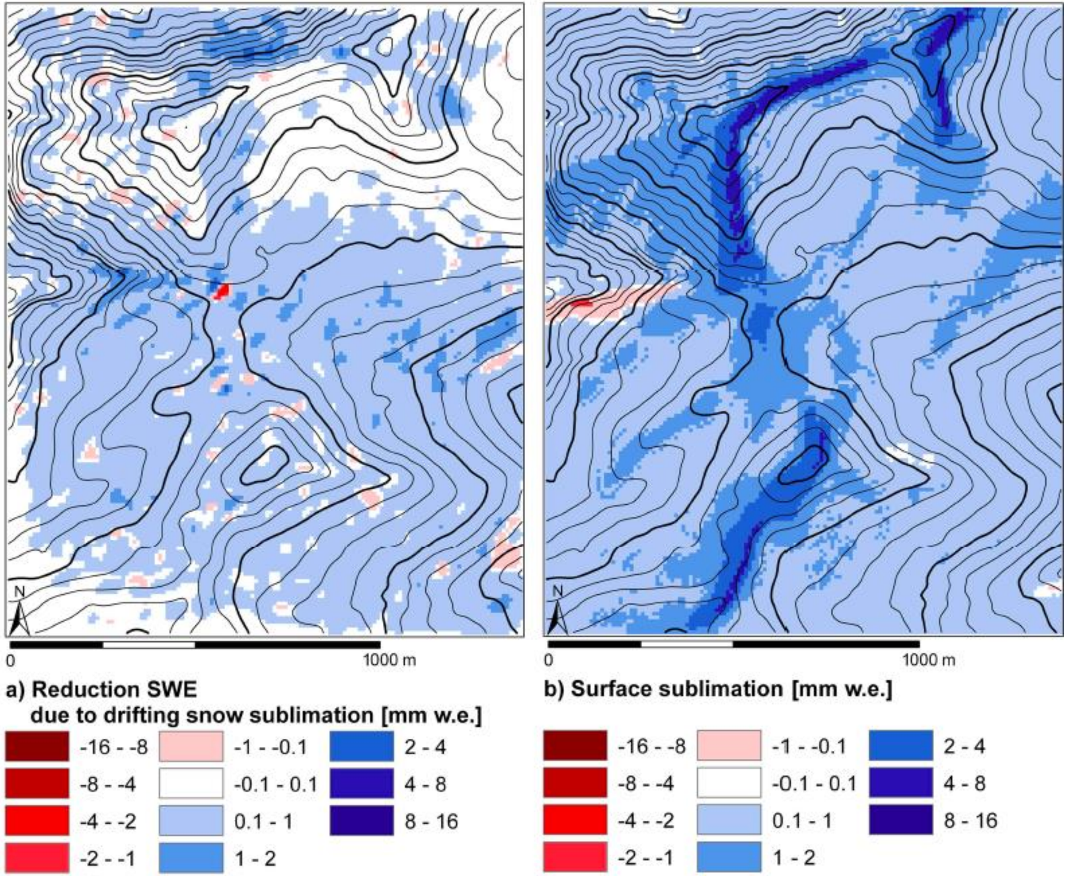
Results: The spatial distribution





Blowing snow sublimation has the same patterns as concentration in the flow; Only a few percent of the mass sublimates in these simulations. Note that both adiabatic warming of descending air masses in lee slopes as well as humidity transport out of the domain may be underestimated in these simulations.

Results: Comparison to surface sublimation



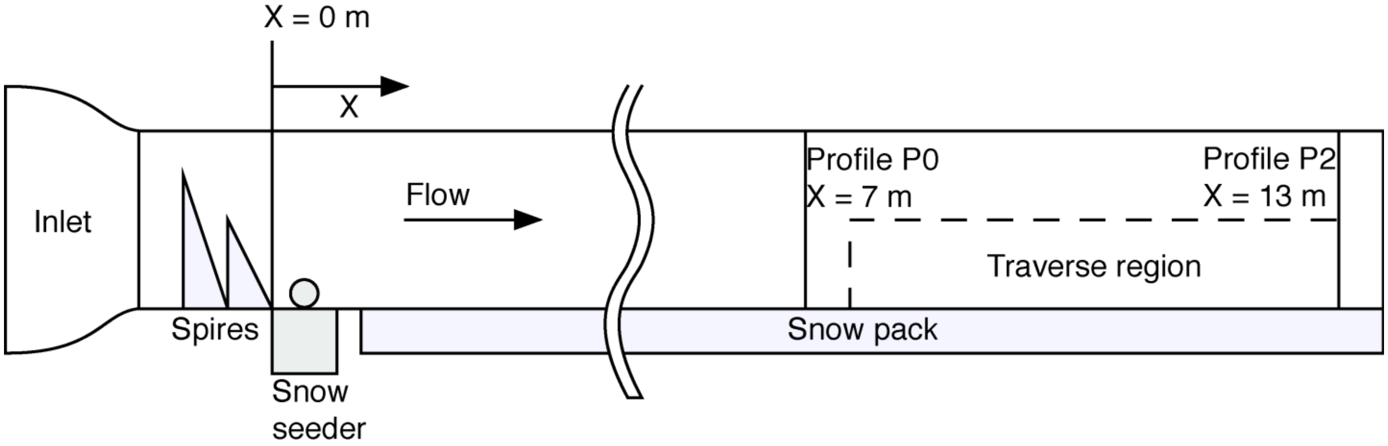
a) Reduction SWE due to drifting snow sublimation [mm w.e.]

b) Surface sublimation [mm w.e.]

Blowing snow sublimation in the same range as surface sublimation over the season; Values need to be compared to total precipitation over one season, which is in the order of 1000 mm.

Groot Zwaaftink et al., JGR, 2011

Measurement of effect in windtunnel

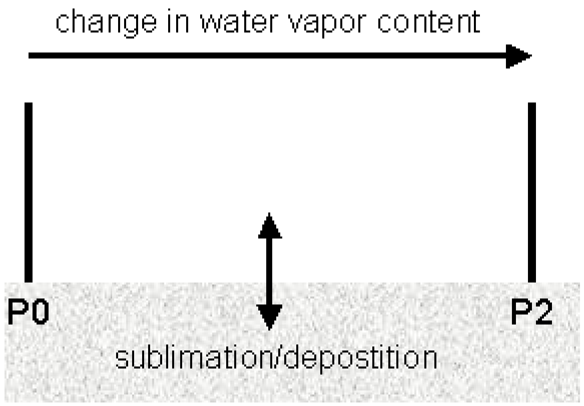


As models are uncertain, we could try to measure the effect in a wind tunnel with blowing snow. Need to have accurate measurements of moisture changes and not too many side effects;
→ can you think of potential experimental complications?

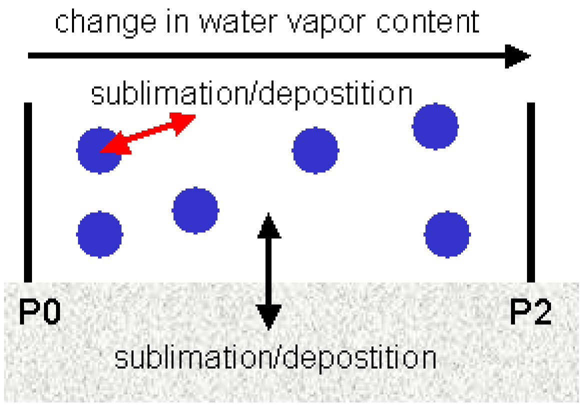
Wever et al., WRR, 2009

Moisture Mass Balance

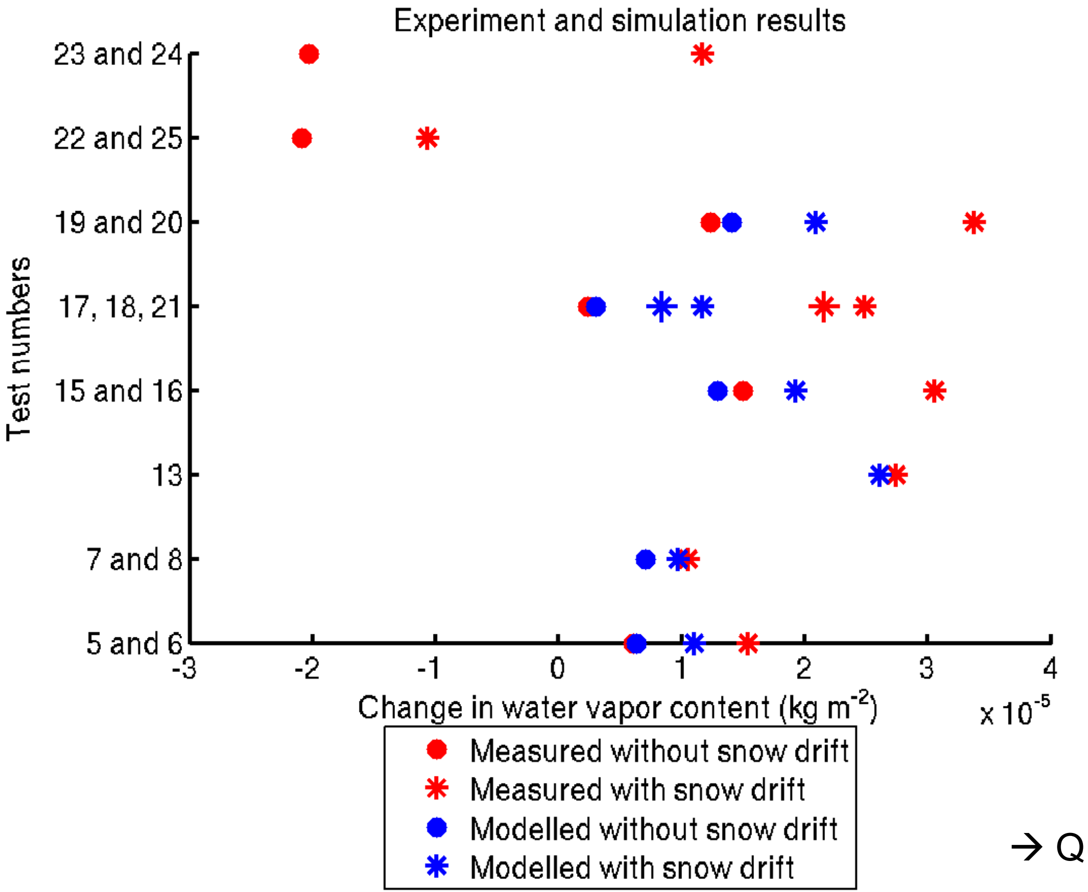
without drift



with drift



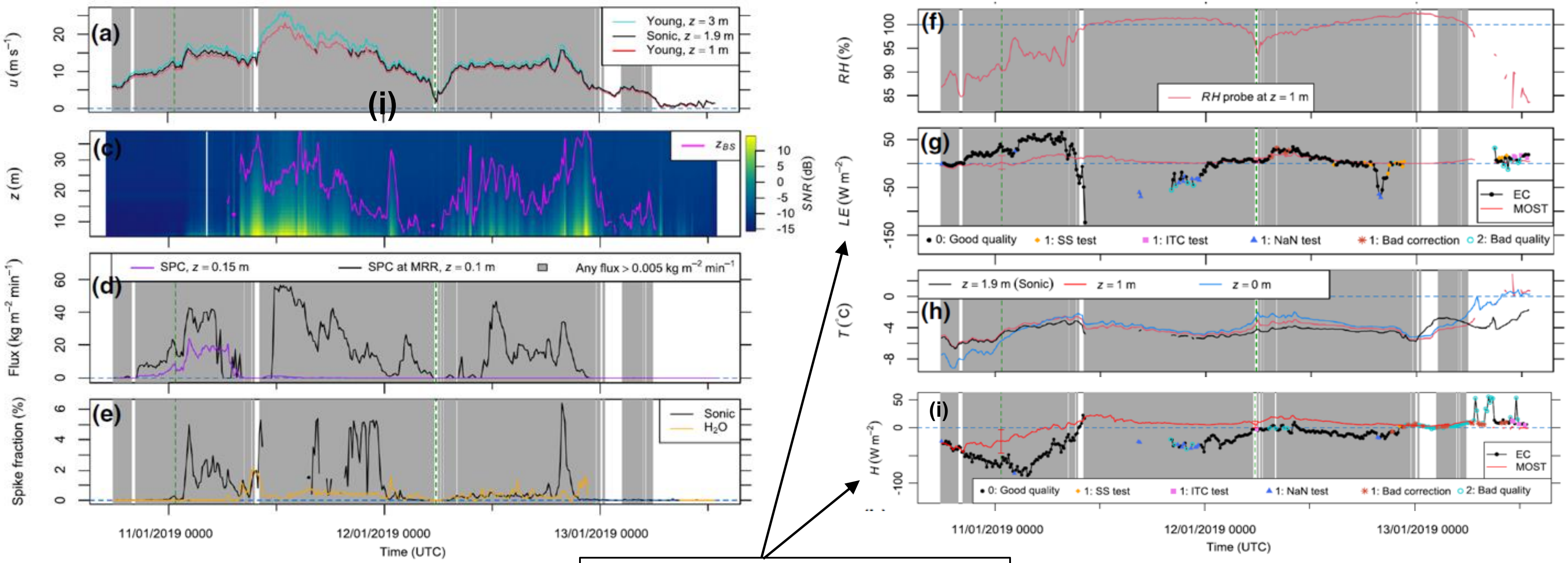
Clear effect on total mass balance



Despite the large scatter in measured data, an effect is clearly visible. Model results are more consistent but suggest a smaller magnitude of the effect.

→ Question on Sunshine and Sublimation

Measurements from a storm in Antarctica

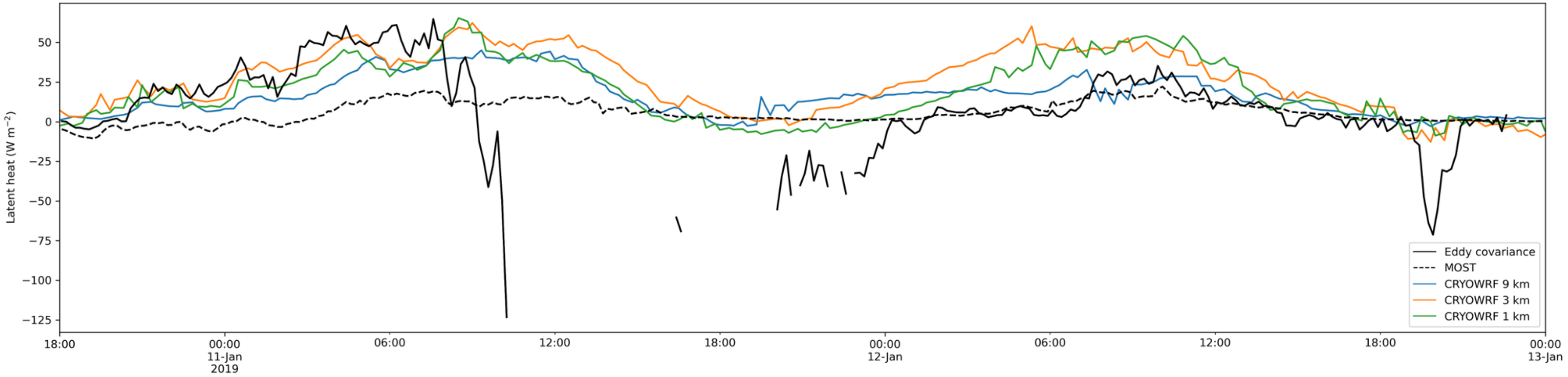


Below a height of 2 m.
How much happens above?

Sigmund et al. BLM, 2021

Panel shows wind speed (*u*), height of the blowing snow cloud (*z*, measured by a radar) flux of drifting and blowing snow, [spike fraction], relative humidity (*RH*), vertical latent heat flux (LE), temperature (T) and sensible heat flux (H). During snow transport, the latent heat flux may change sign, which indicates deposition of vapour onto the snow grains. This may only be at that height though. Fluxes are in general larger than predicted by surface exchange models (MOST, Prandtl).

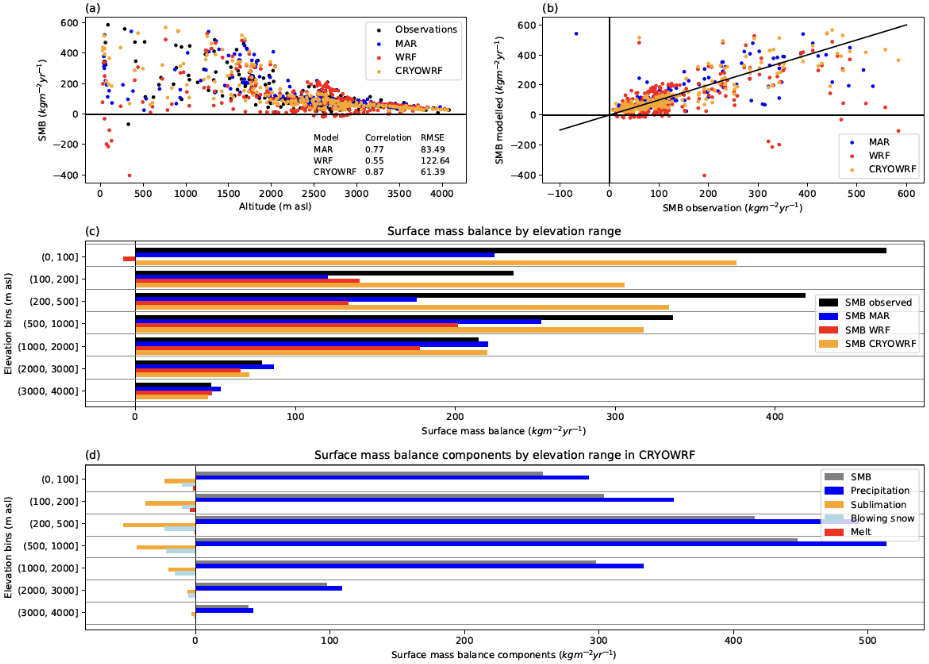
Results: High resolution modelling with snow transport physically represented in the CRYOWRF model



When representing the drifting and blowing snow cloud in a numerical model, you can see similar dynamics as measured. However it needs not only the correct physical representation but also enough resolution, which is a problem for meteorological or climatological modelling because of the high computational demand. The need for parameterization remains, therefore.

CRYOWRF: Coupling between the meteorogical model WRF and SNOWPACK with a blowing snow scheme that has advanced physics.

CRYOWRF – Results Antarctica – coarse resolution



Model	Correlation	RMSE
MAR	0.77	83.49
WRF	0.55	122.64
CRYOWRF	0.87	61.39

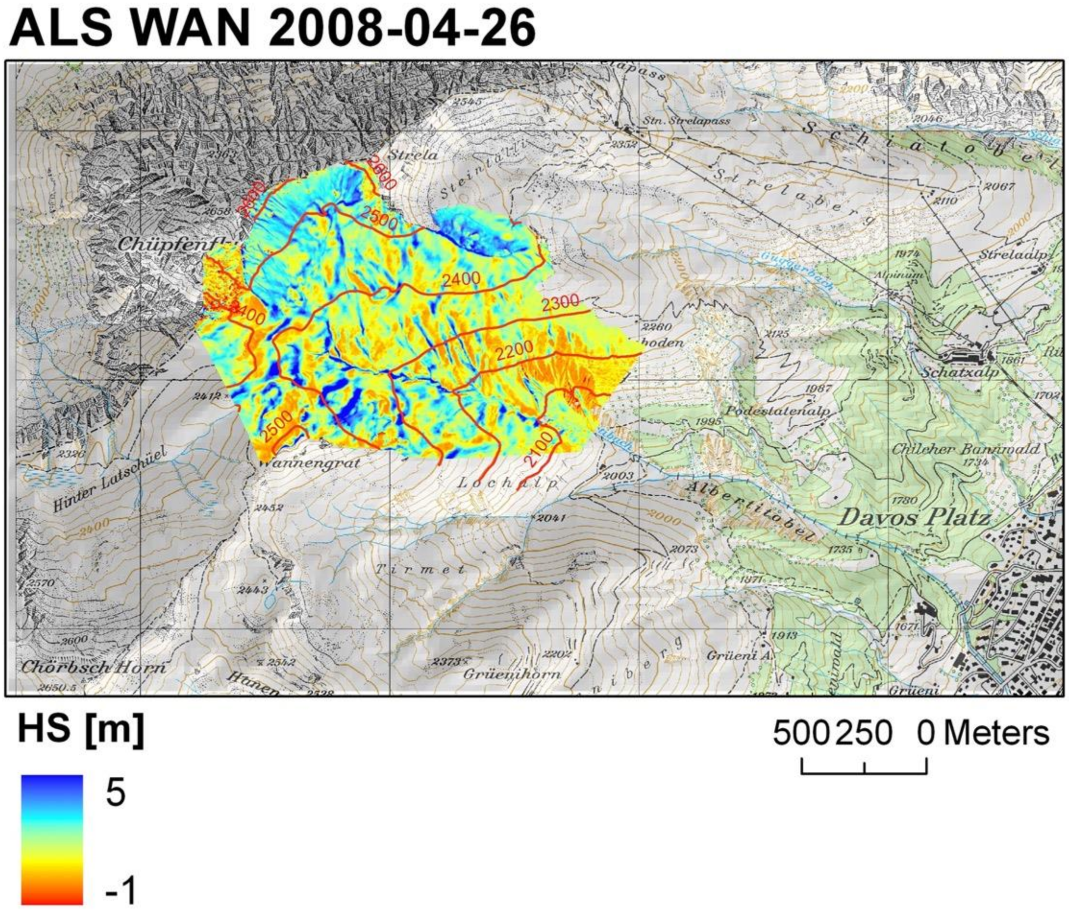
- At a rough resolution of 27 km, CRYOWRF improves surface mass balance
- It has more (surface and blowing snow) sublimation than MAR or RACMO (other, simpler models)
- More in line with Palm (TC, 2017) than with van Wessem (TC, 2018)

Gerber et al., JGR, 2022

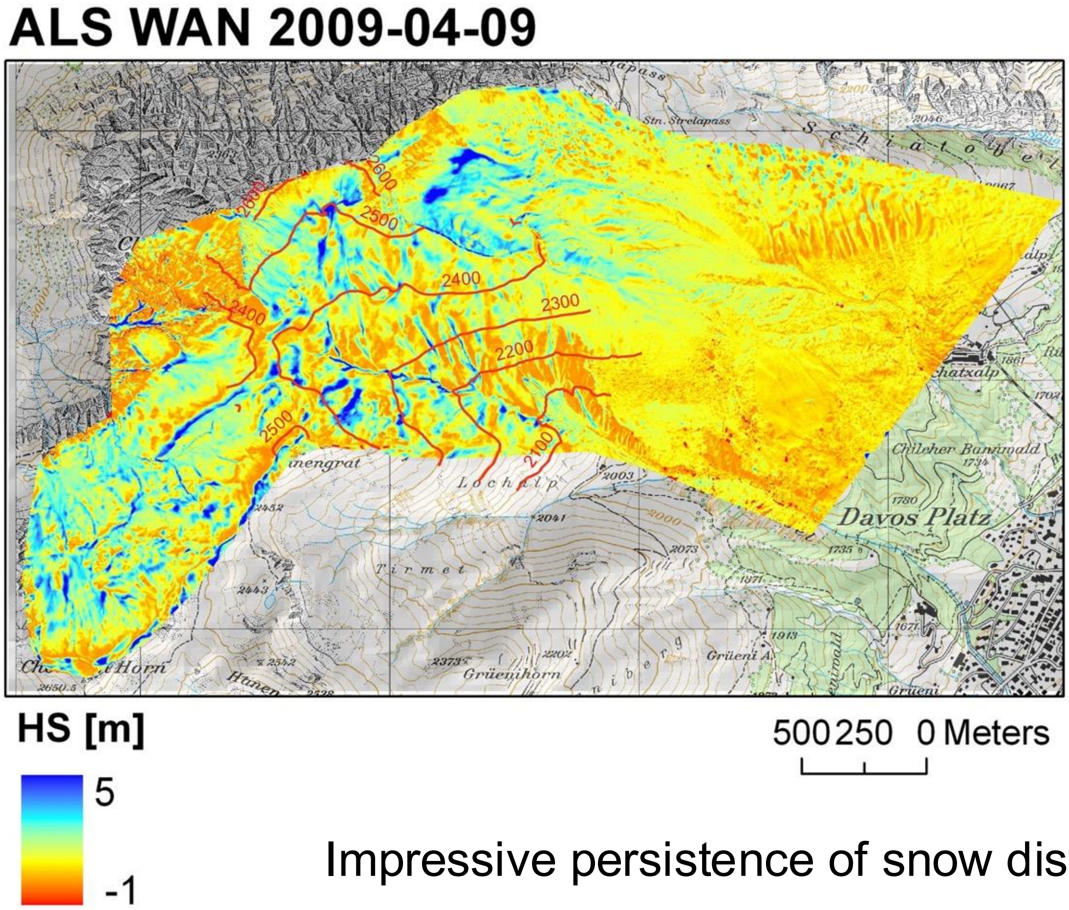
Outline

- General Introduction on Spatial Heterogeneity and Transport
- Saltation
- Suspension and Preferential Deposition
- Drifting Snow Sublimation
- Statistical Descriptions and Scaling

Peak of Winter snow distribution 2008

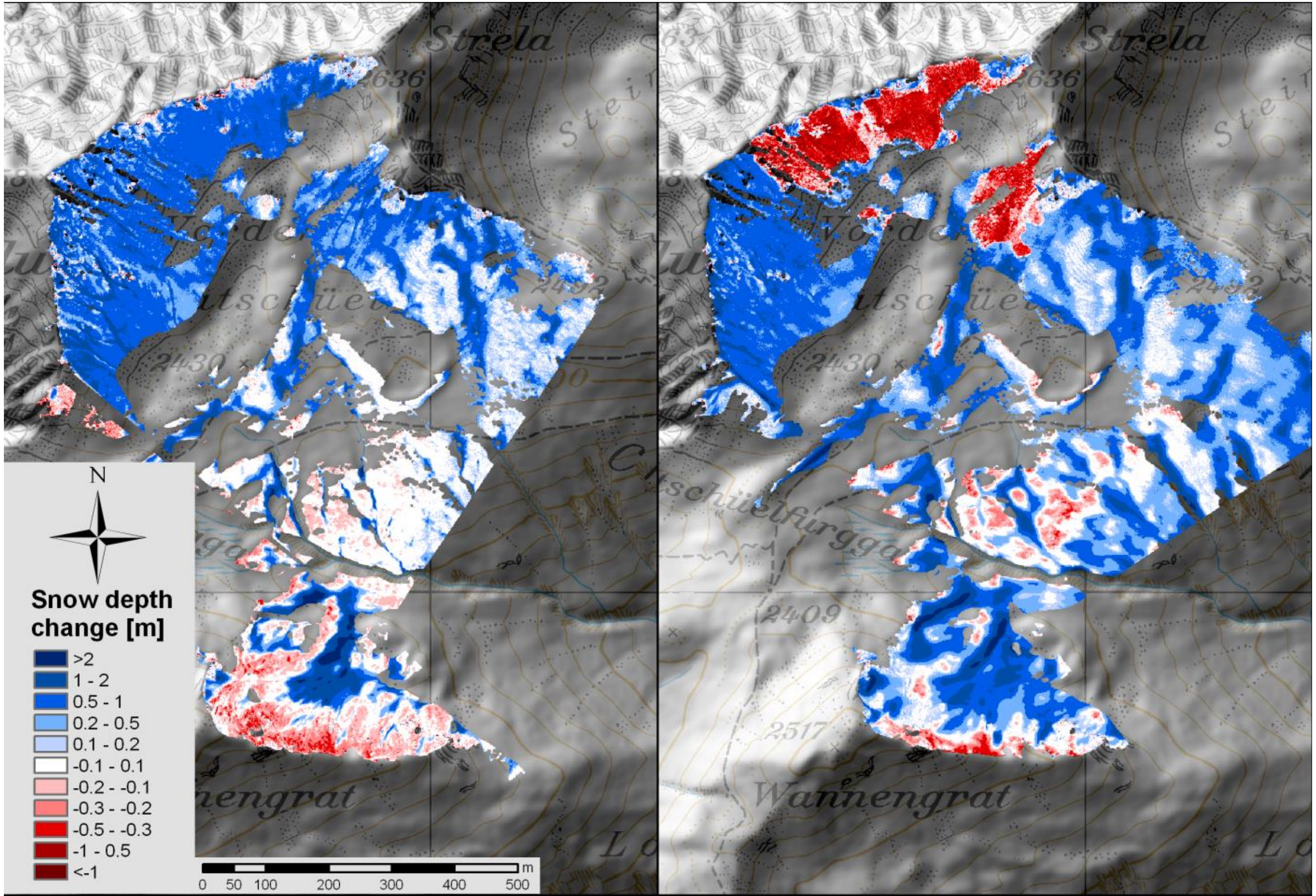

ALS WAN 2008-04-26

Peak of Winter snow distribution 2008

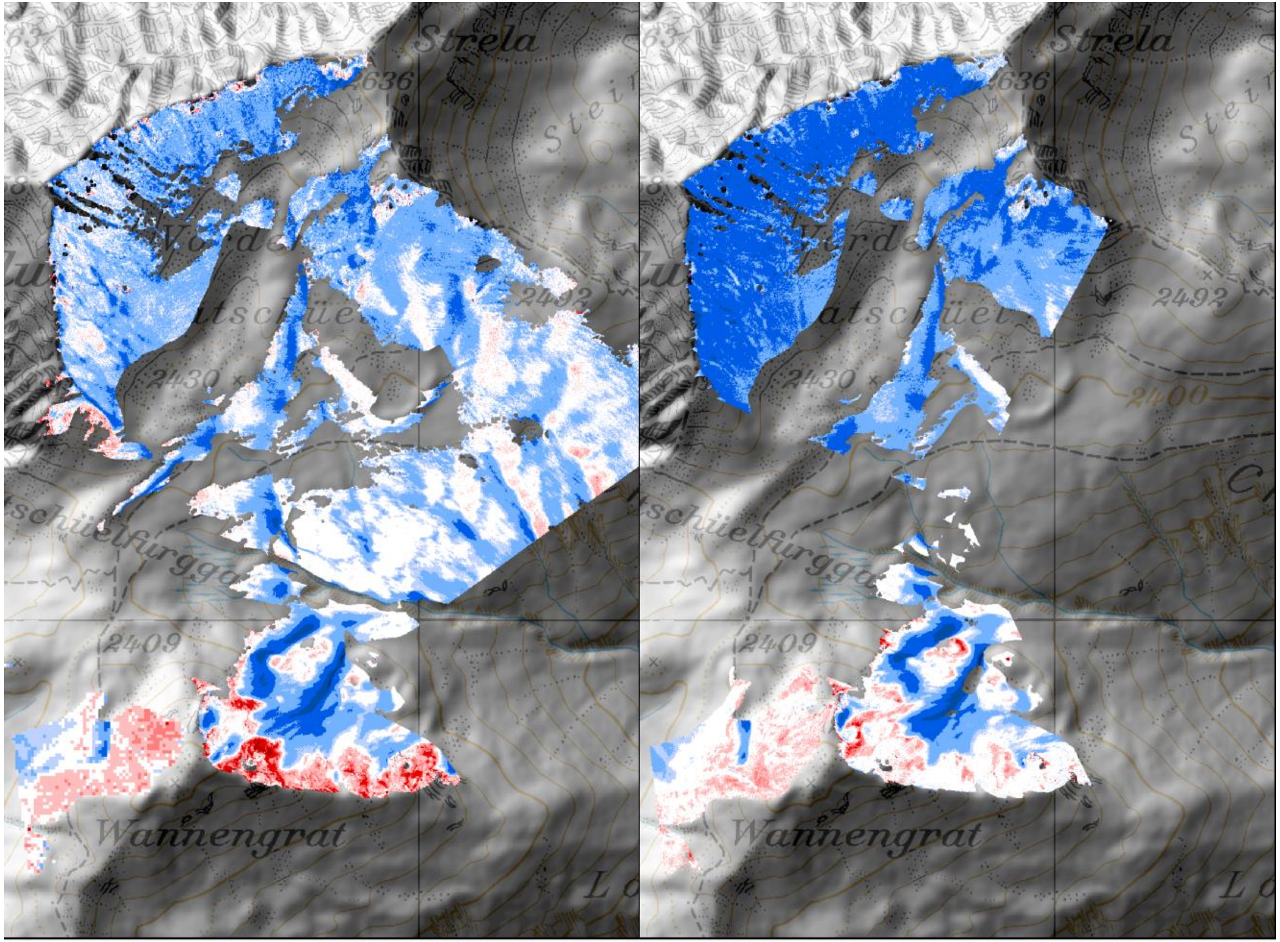


Impressive persistence of snow distribution pattern

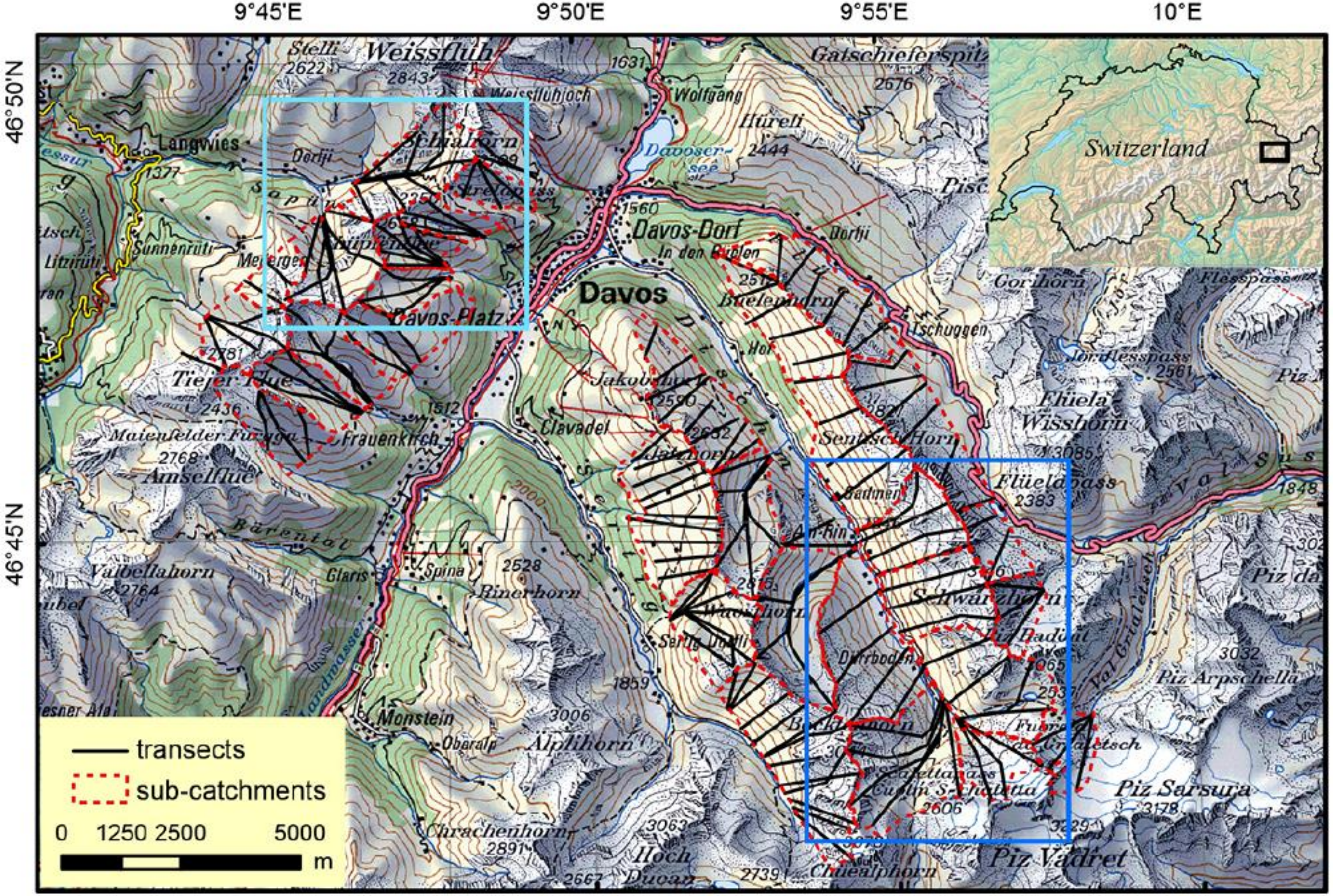
Intra-annual SWE development



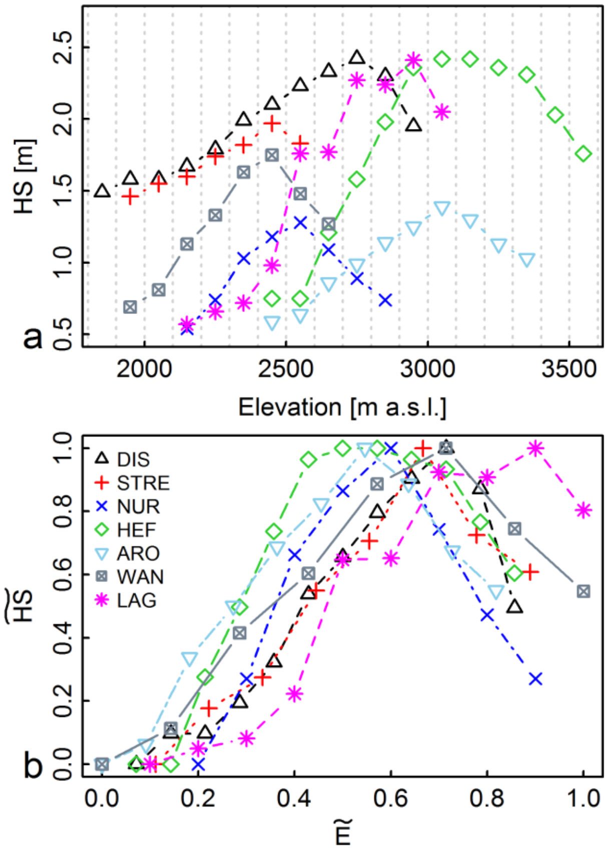
Intra-annual SWE development



Example of Transects in Davos



Elevation Gradient of Snow Depth



Given are mean snow depth in 100 m elevation bands for all catchments; catchments have area extensions between 3 and 78 km^2.

Scaled axes according to:

$$\tilde{X} = \frac{X - \min(X)}{\max(X) - \min(X)}$$

Grünewald et al., Hydrological Processes, 2014

Summary of Processes

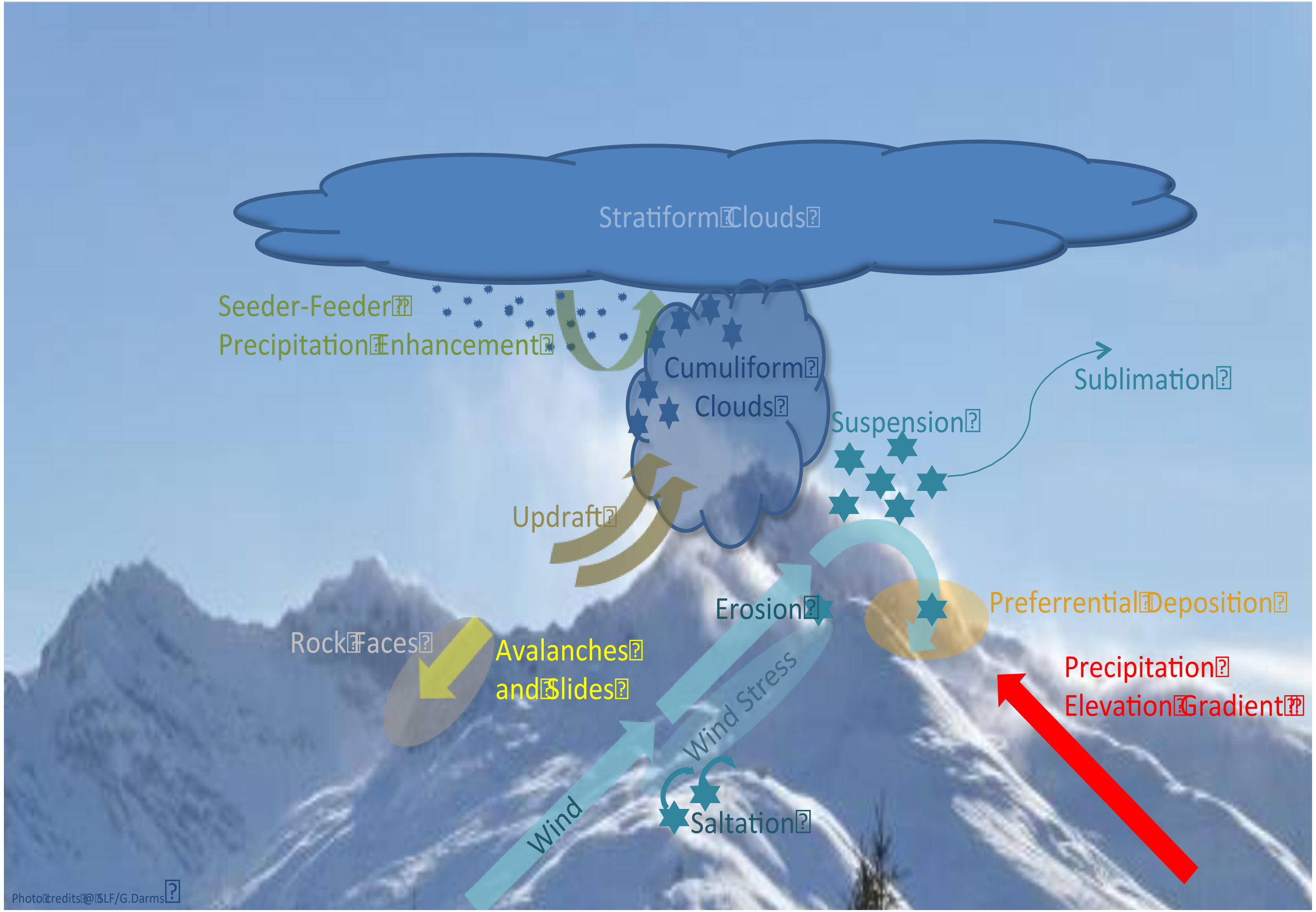


Photo credits @ SLF/G.Darms

Models, Morals, etc.

- Combination of physical model descriptions and measurements!

- Many more secrets on snow need to be investigated!

- All models are wrong but some are useful!