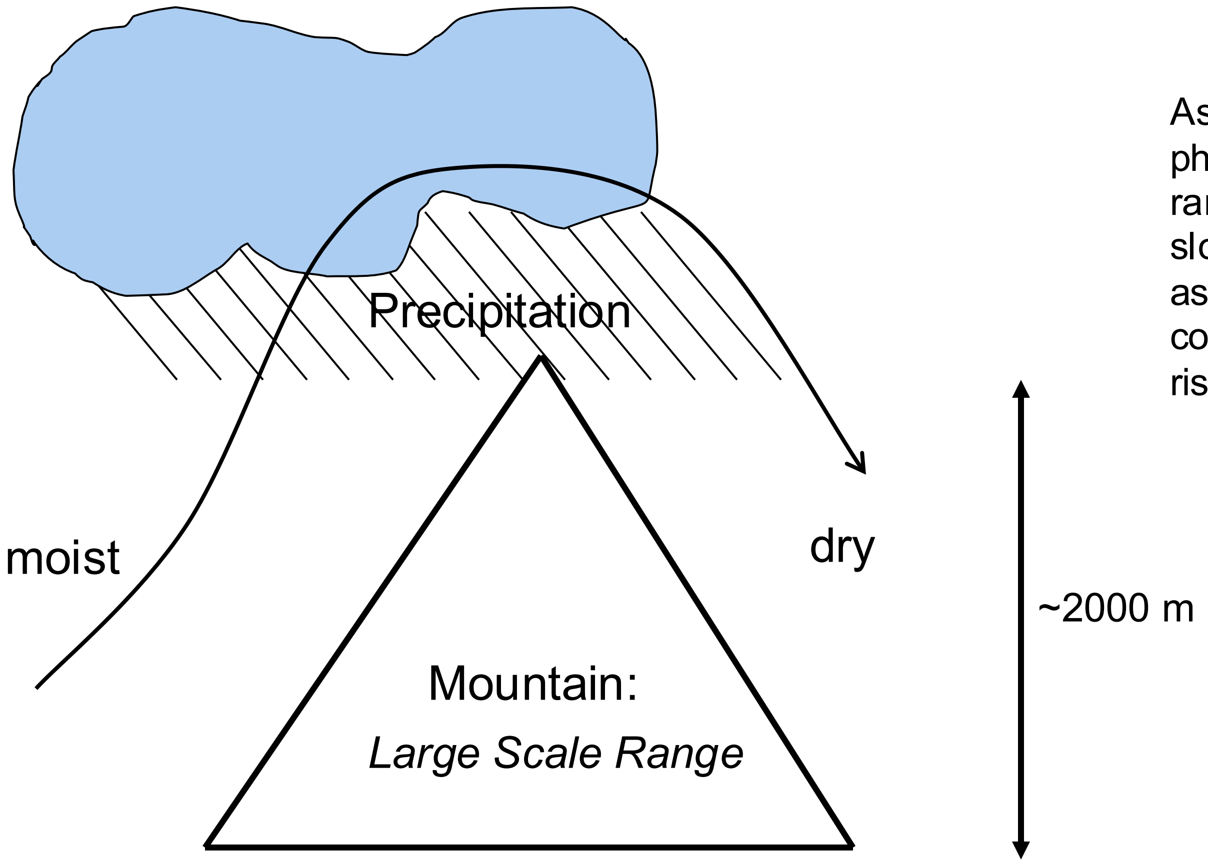
Snow Spatial Variability Accumulation and Transport Part II

Outline

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

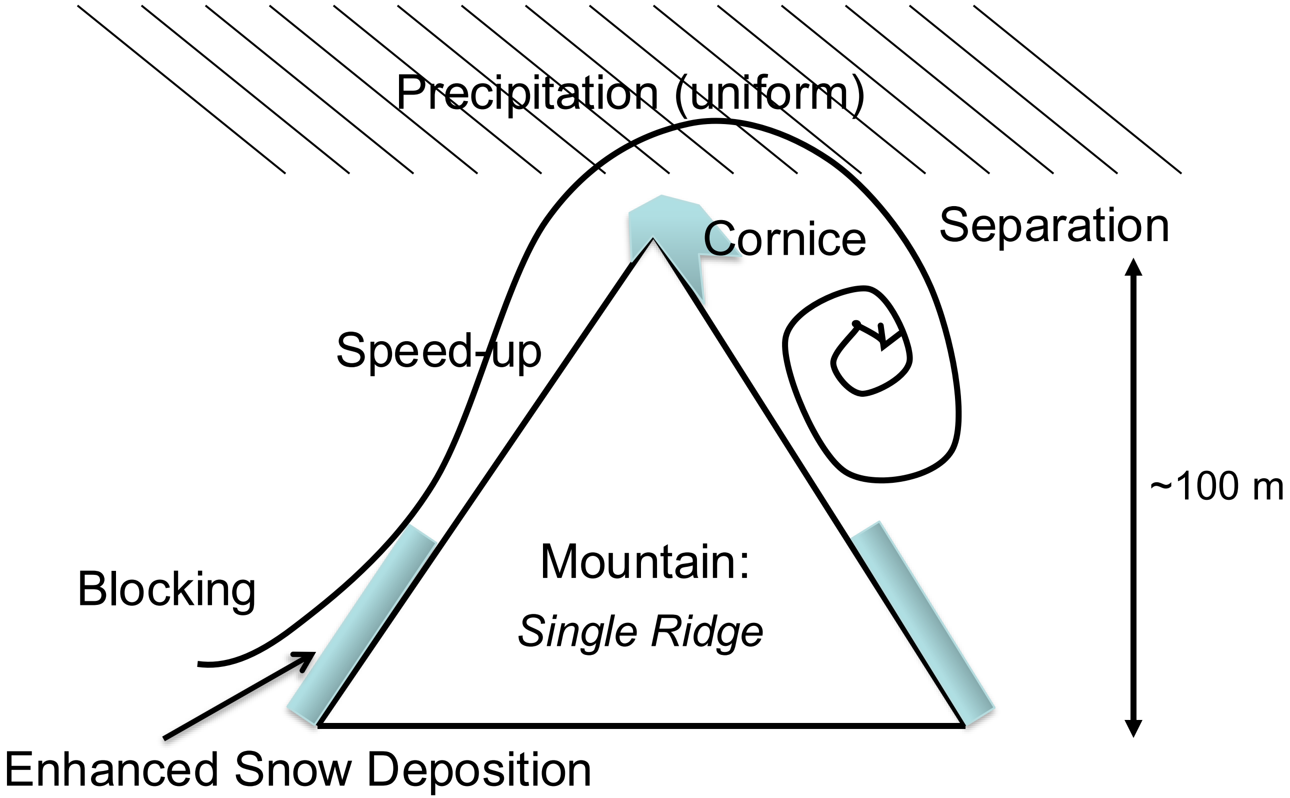
Suspension

Precipitation and Mountains



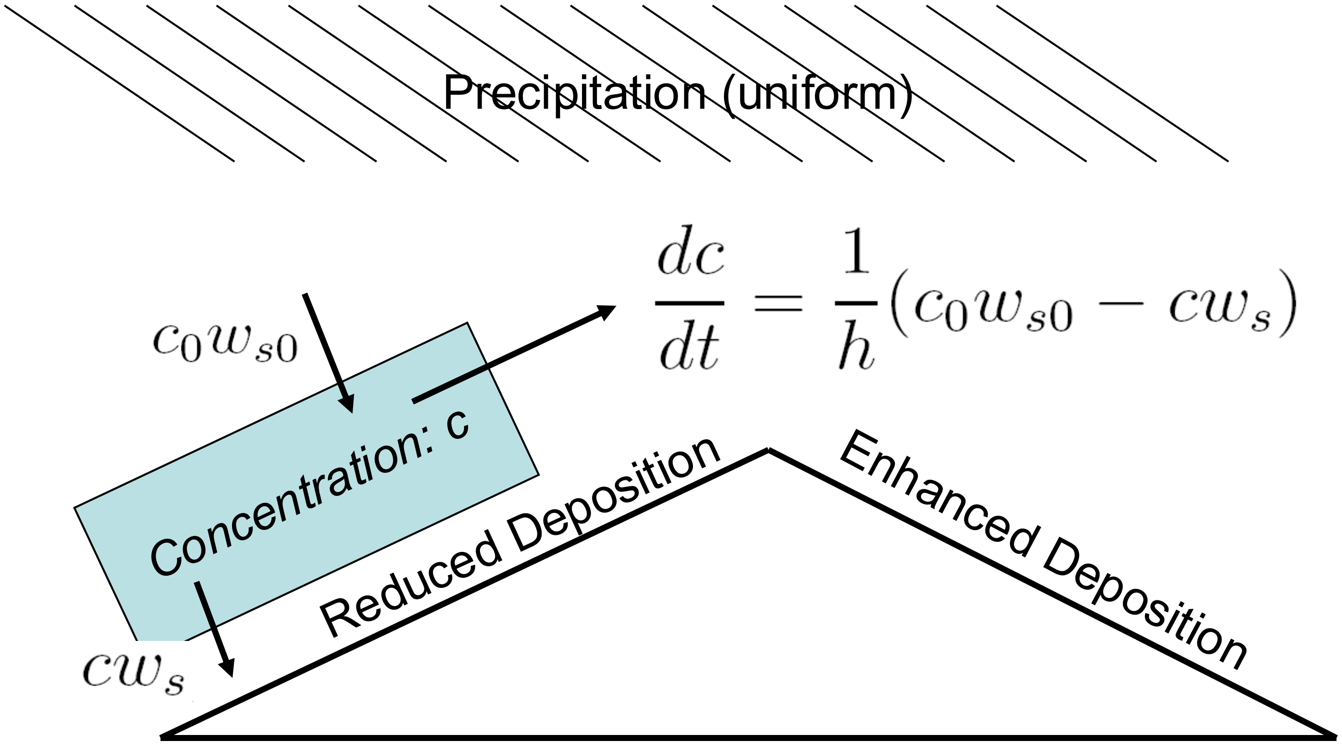
As learned in the atmospheric physics class, on the mountain range scale, the windward slopes get more precipitation as convection and condensation is triggered by rising air masses.

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

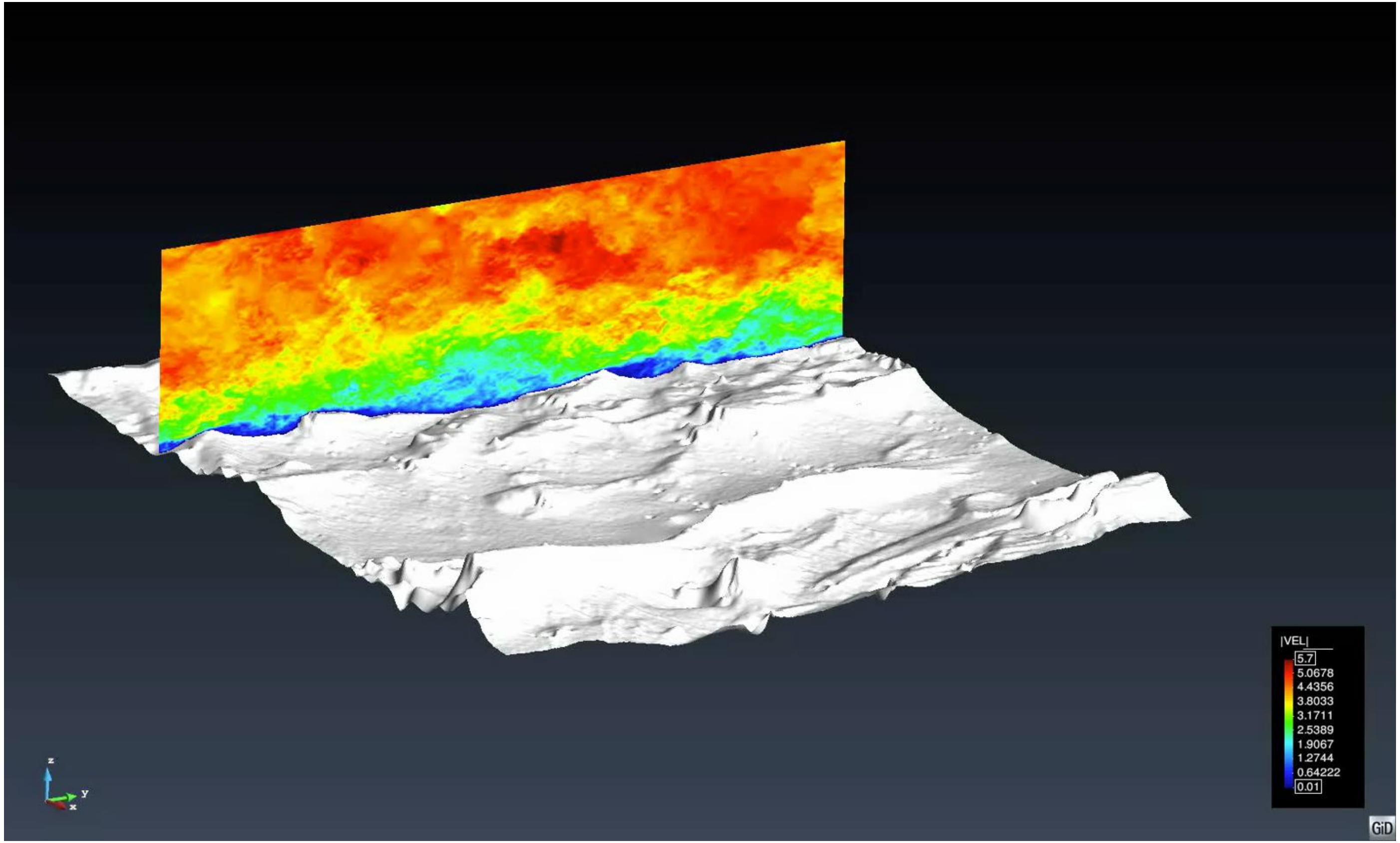


$$\frac{dc}{dt} = \frac{1}{h}(c_0 w_{s0} - c w_s)$$

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.

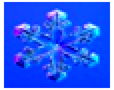
c: concentration
h: height of parcel
w_s: vertical velocity (settling)

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.



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

u, x: fluid velocity, position

U, X: particle velocity, position

Δ: drag

π: pressure

f: force

τ: shear stress

t_p: particle relaxation time

SGS: subgrid scale

Stokes Number:

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

Inertia over flow advection

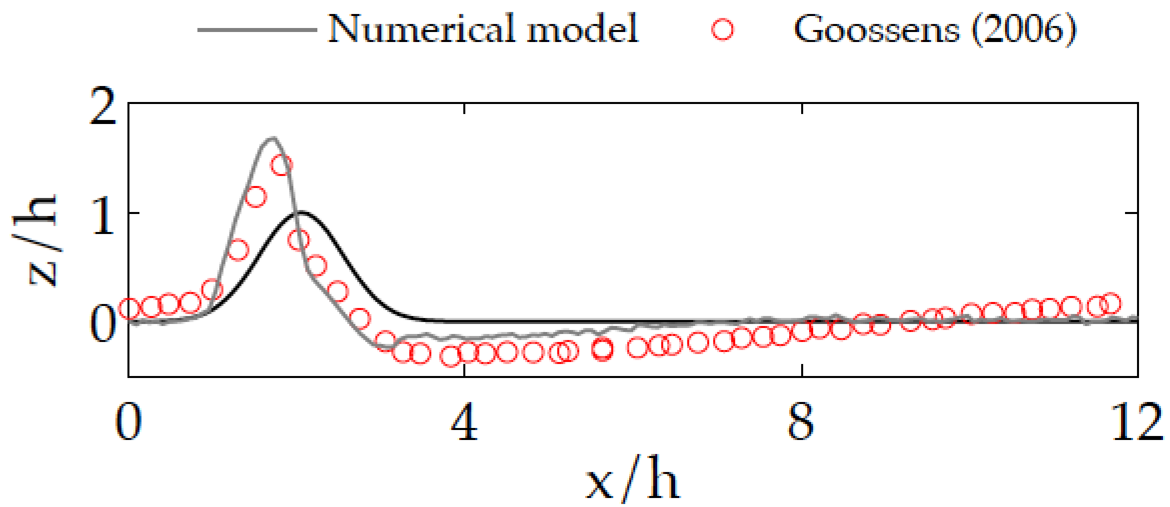
Froude Number:

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

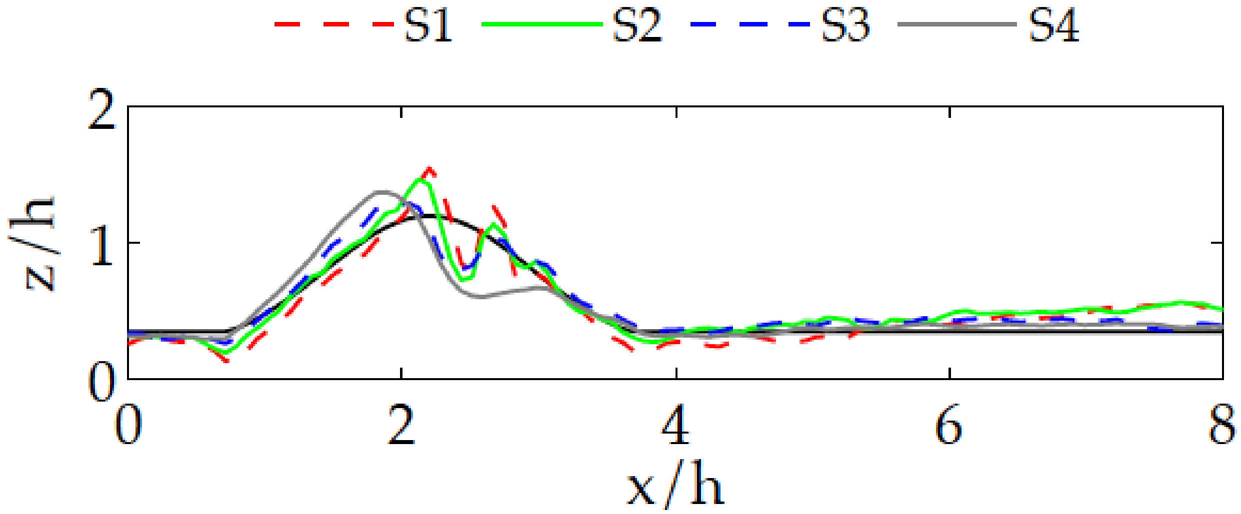
Inertia over gravity

Comola et al., JGR Atmospheres, 2019

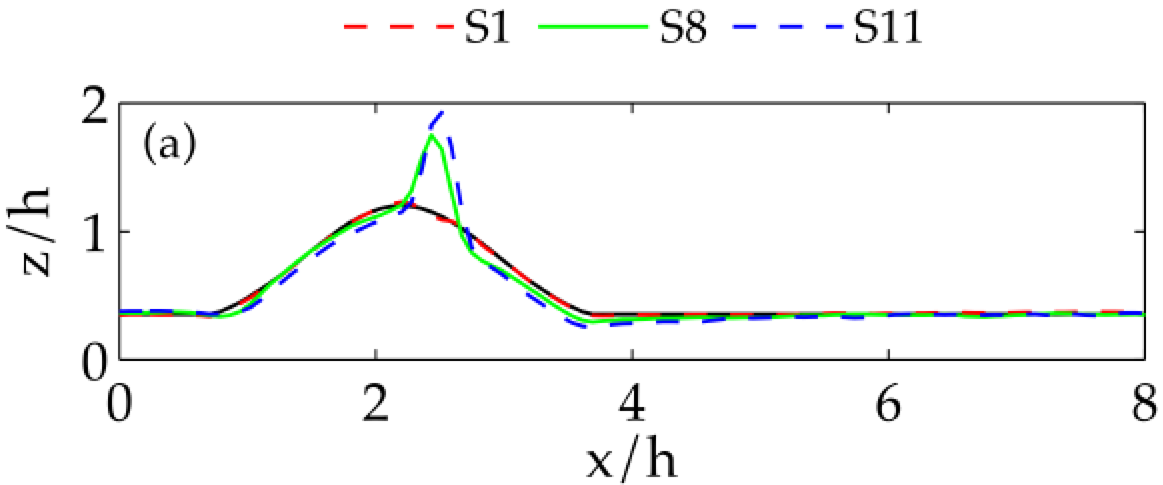
LES – LSM (Lagrangian Stochastic Model) Validation



Wind tunnel comparison shows good model performance (for sand)

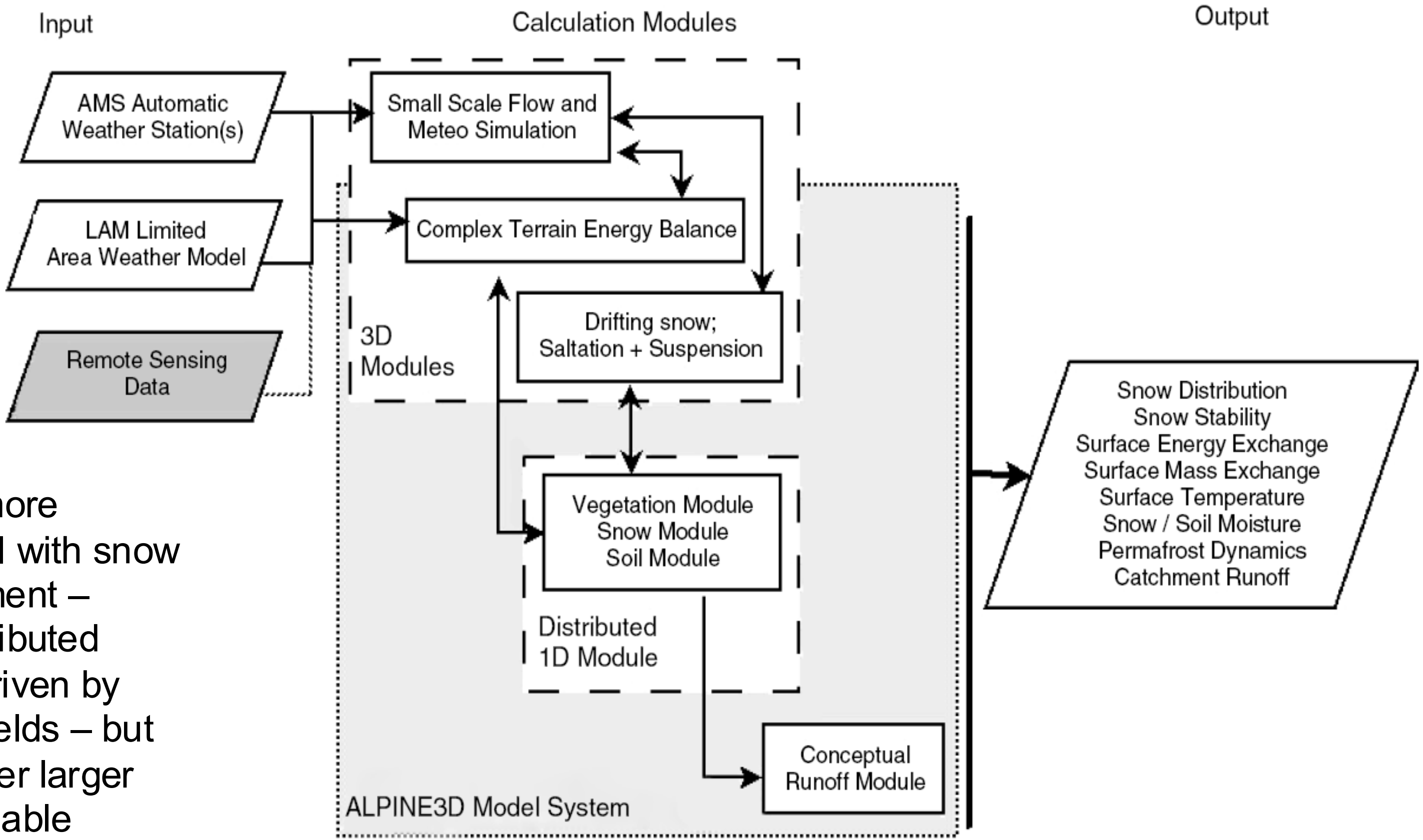


Snow distribution over Gaussian hill for increasing Stokes numbers: when inertia is dominating as for S4 (for heavy particles, e.g. sand or ice pellets), the windward side gets preferential deposition up to the hilltop and the lee is in the “rain shadow”. For snow, inertia is often small compared to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



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

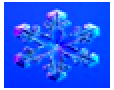


Alpine3D is a more complete model with snow cover development – basically a distributed SNOWPACK driven by external wind fields – but can be used over larger areas at reasonable computational cost.

Lehning et al., WRR, 2008

Formulation of Suspension in A3D



Stationary Diffusion Equation for Snow Particles:

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

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

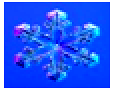
K: Diffusion coefficient (m^2 s^{-1})

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



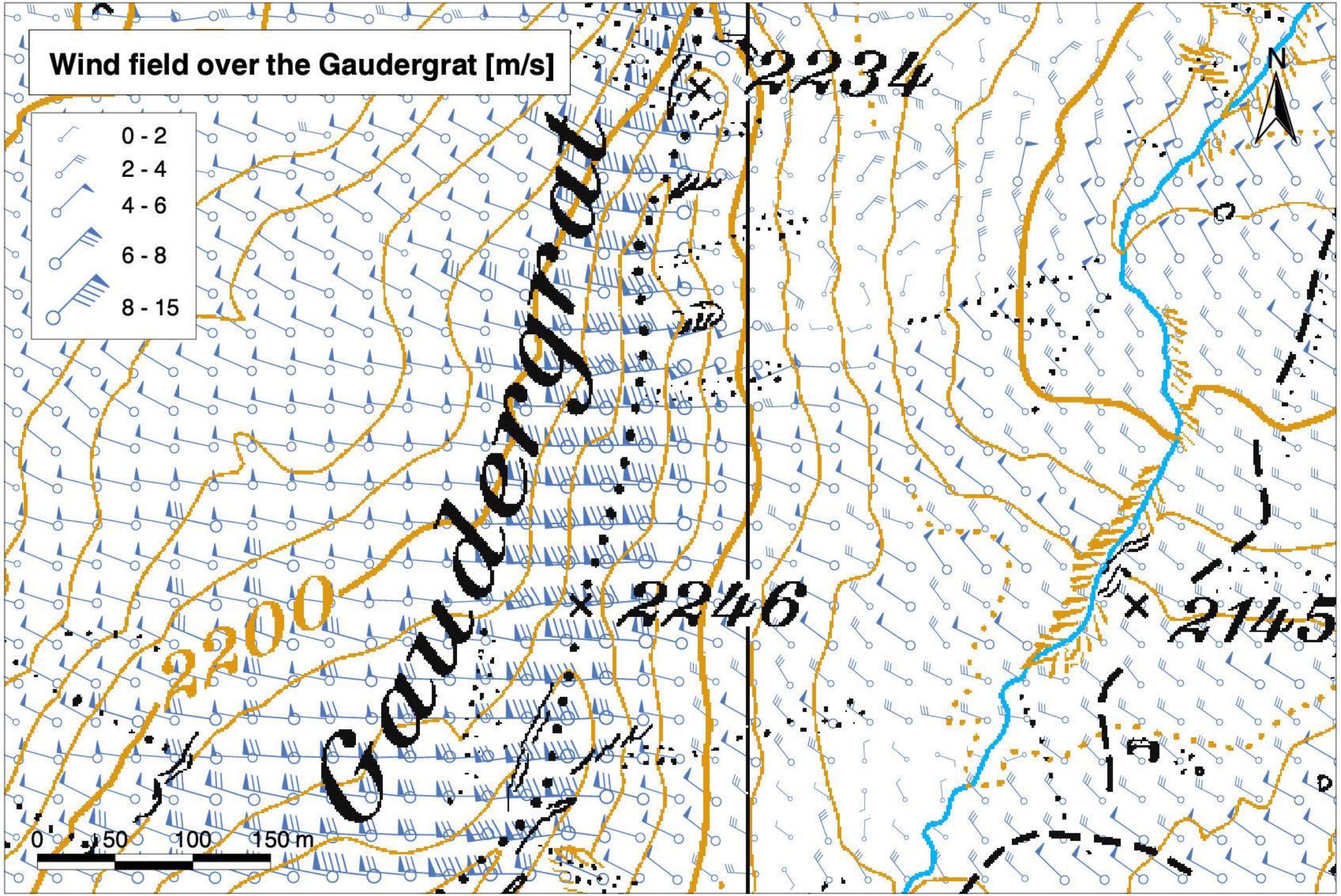
<u>Classical:</u>

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

<u>Alpine3D:</u>

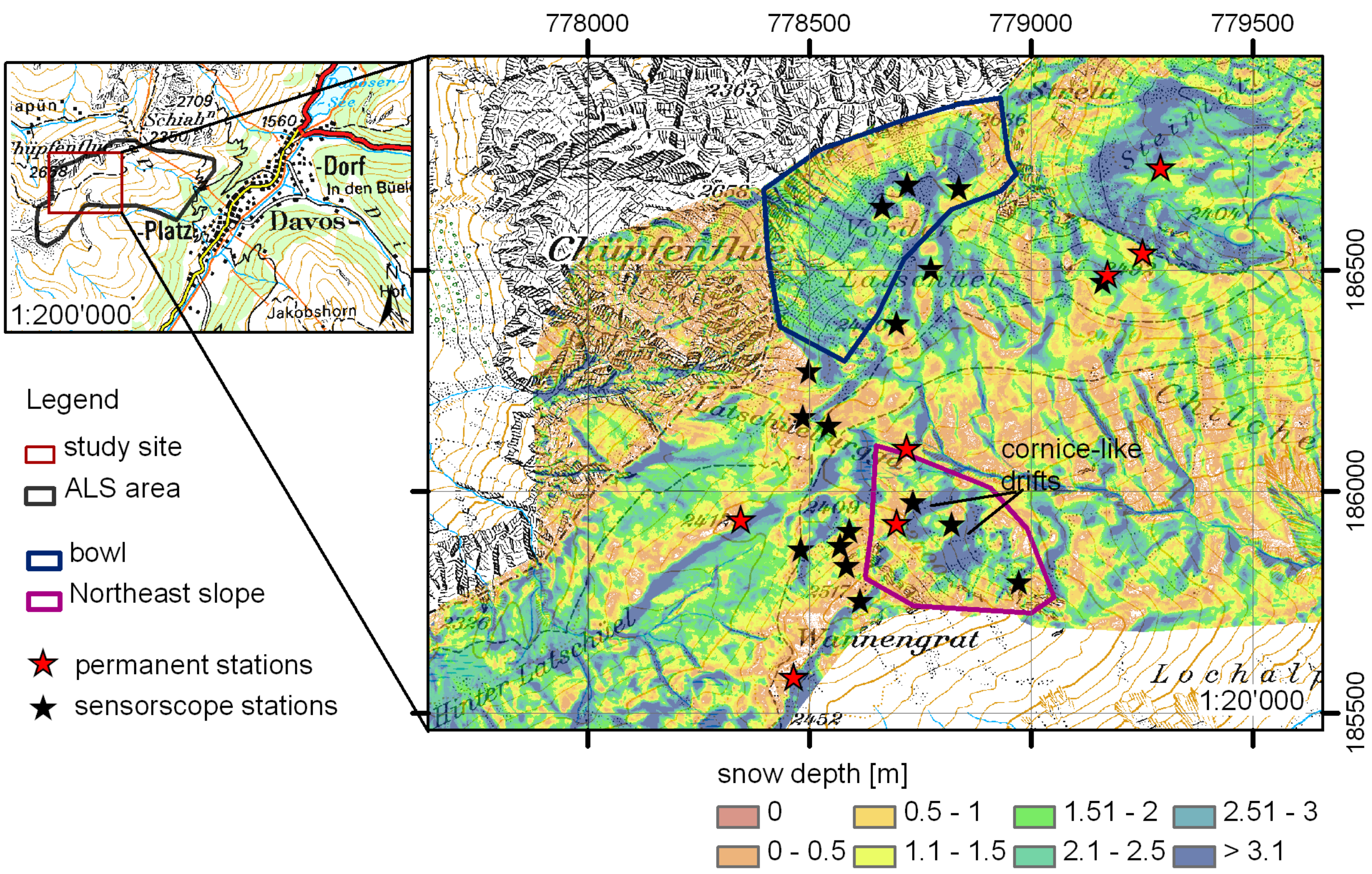
- Precipitation
- Wind and Terrain
- Settling Velocity as function of Flow
- Spatially Varying Concentration
- Deposition/Erosion
- SnowCover

Calculated topographical flow features

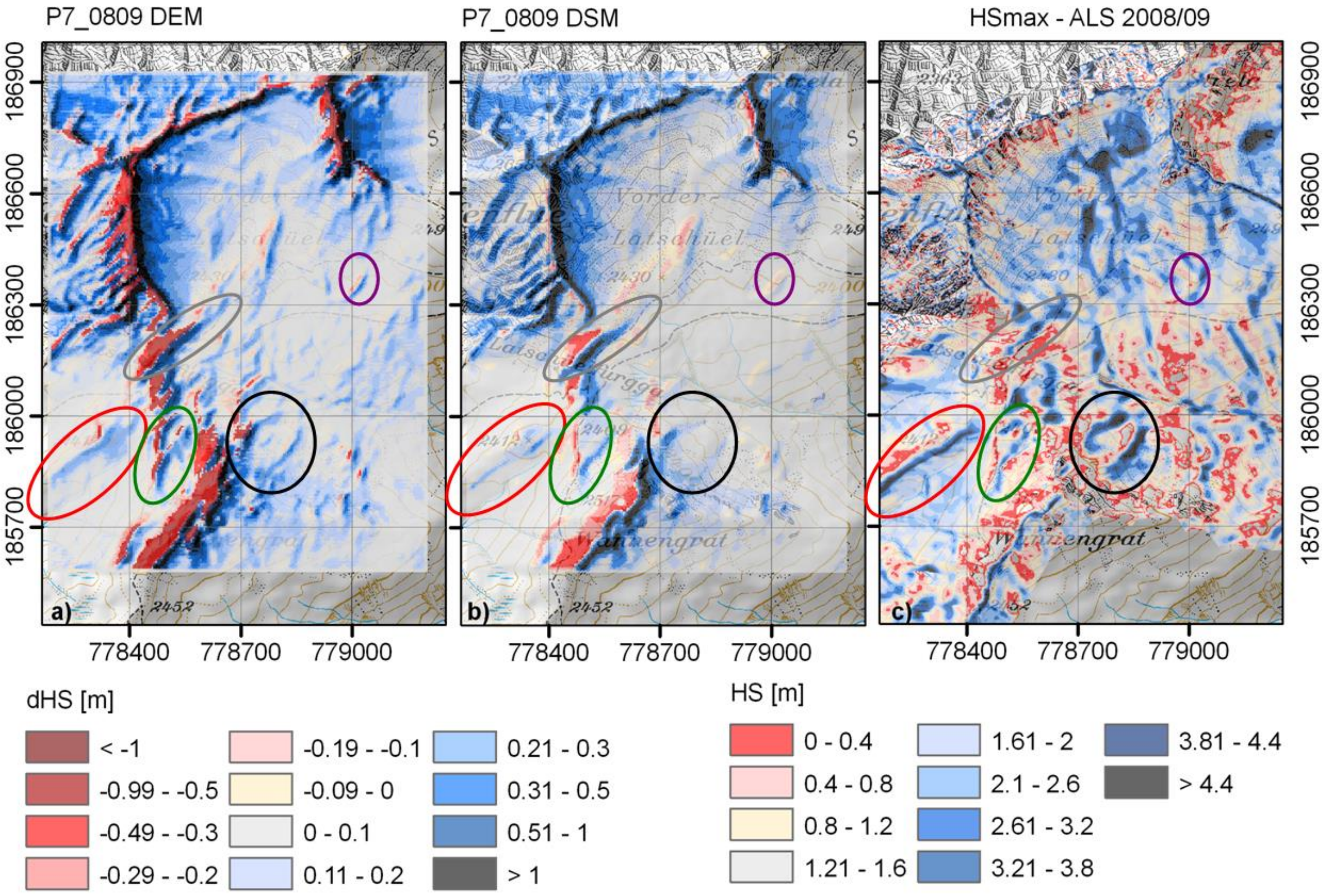


Raderschall et al., WRR, 2008

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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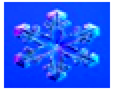
- Statistical Descriptions and Scaling

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

$$\frac{\partial}{\partial \vec{x}}\left(K_c \frac{\partial c}{\partial \vec{x}}\right) + \vec{u}_p \cdot \frac{\partial c}{\partial \vec{x}} = -S$$

$$\frac{\partial}{\partial \vec{x}}\left(K_q \frac{\partial q}{\partial \vec{x}}\right) + \vec{u} \cdot \frac{\partial q}{\partial \vec{x}} = \frac{S}{\rho_{air}}$$

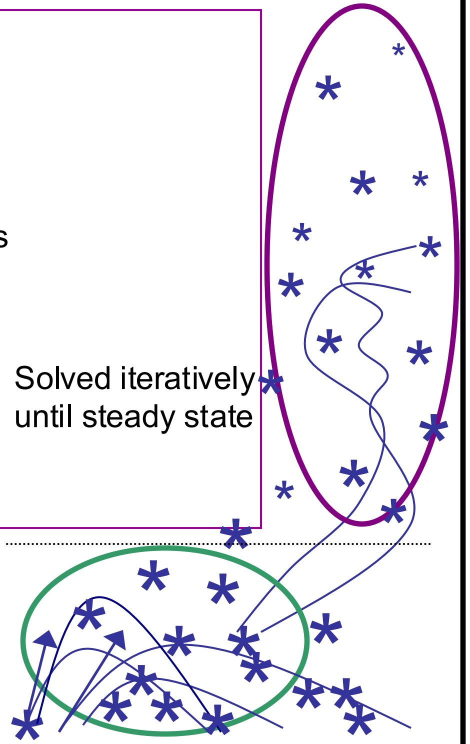
$$\frac{\partial}{\partial \vec{x}}\left(K_\theta \frac{\partial \theta}{\partial \vec{x}}\right) + \vec{u} \cdot \frac{\partial \theta}{\partial \vec{x}} = -\frac{1}{\rho_{air} \cdot C_P}(L_v S)$$

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

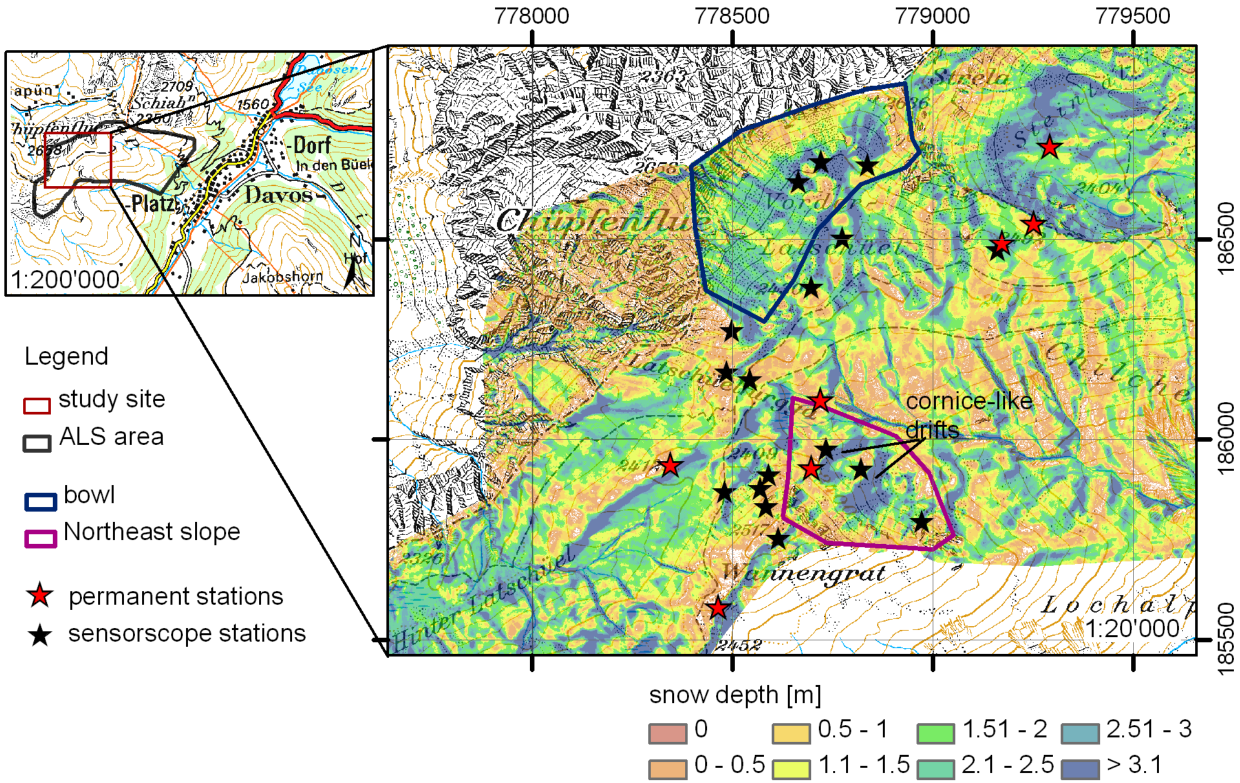


Sublimation can be described by the same advection – diffusion equation as transport of particles. Equations for humidity and temperatures are added and a coupled set of PDEs results.

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

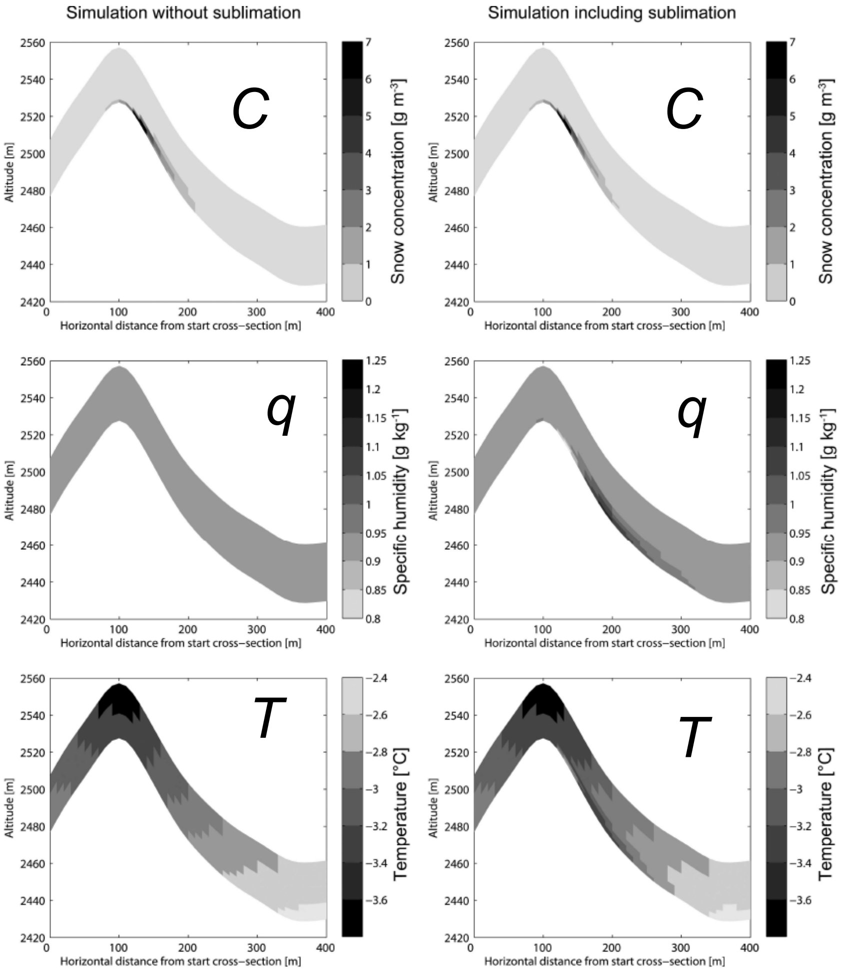


Results: The effect of sublimation

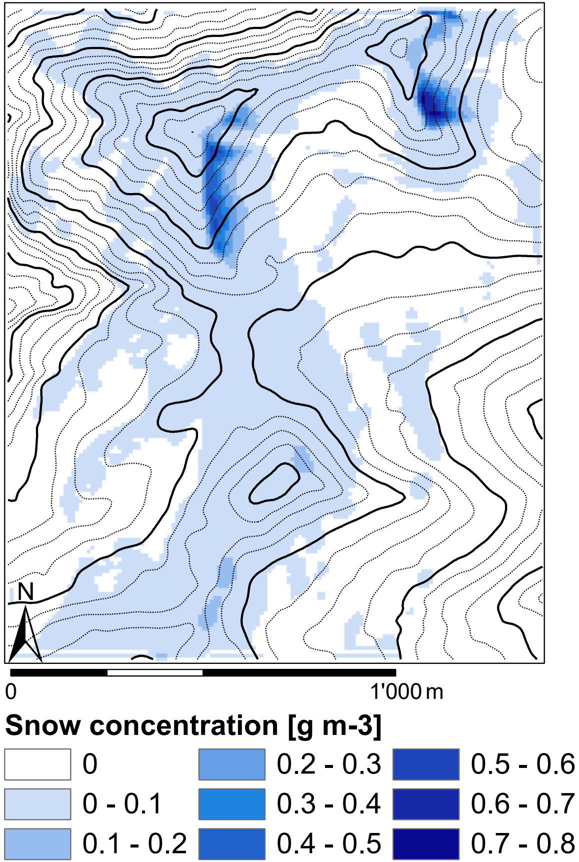
Wannengrat Cross-Section:

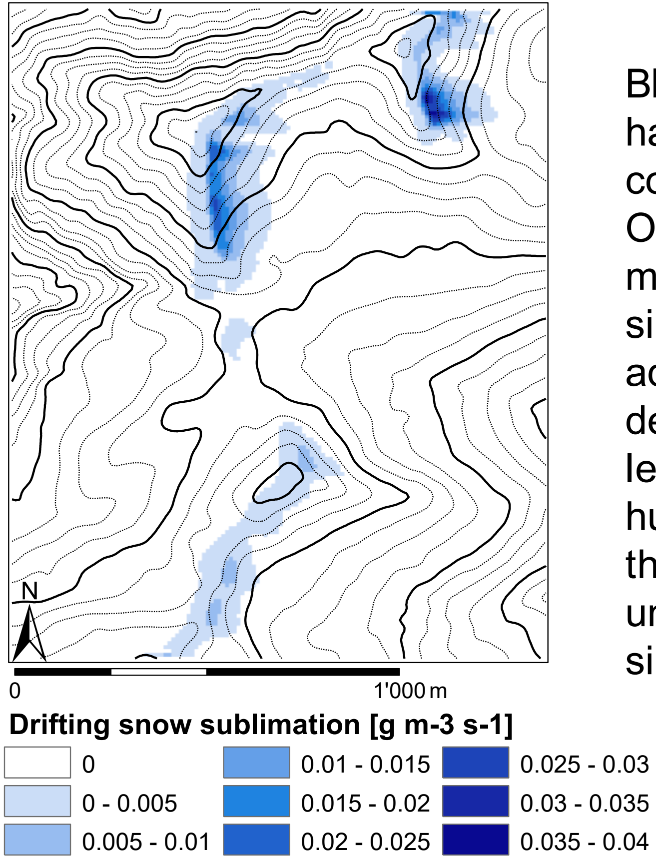
Effect on

- Concentration
- Moisture
- Temperature



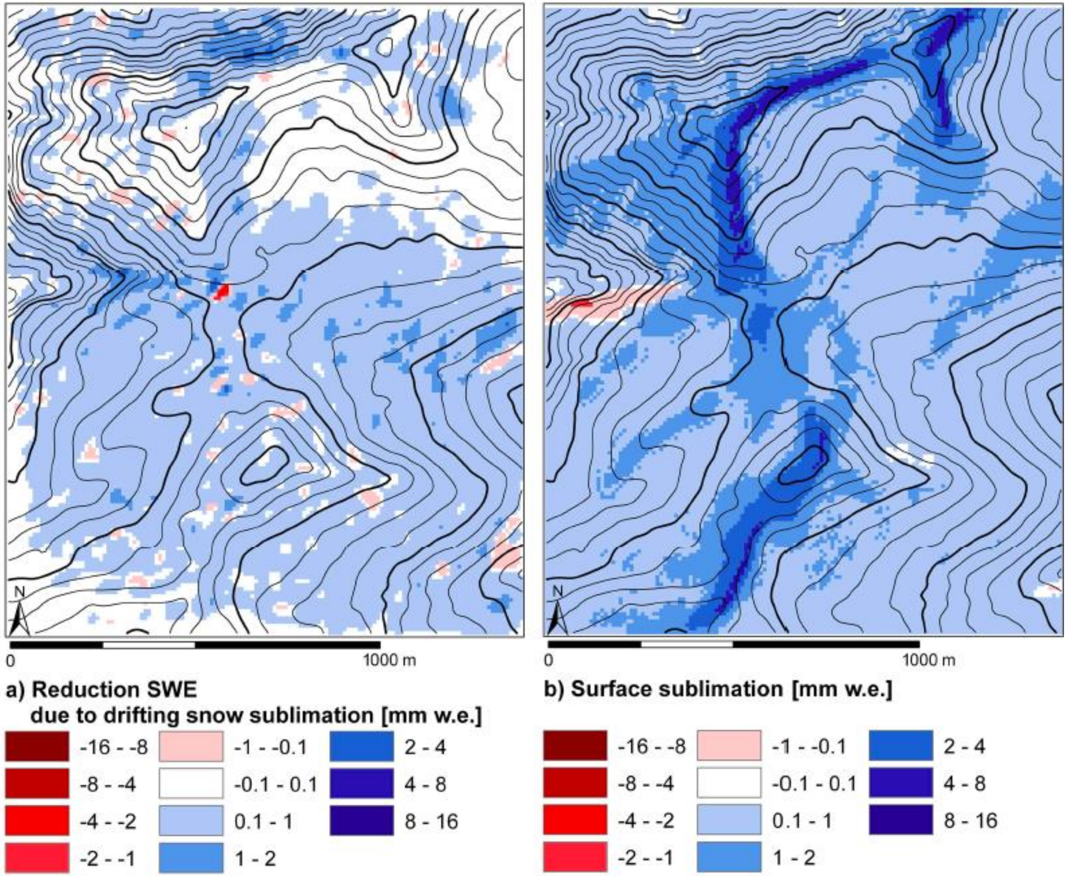
Results: The spatial distribution





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.

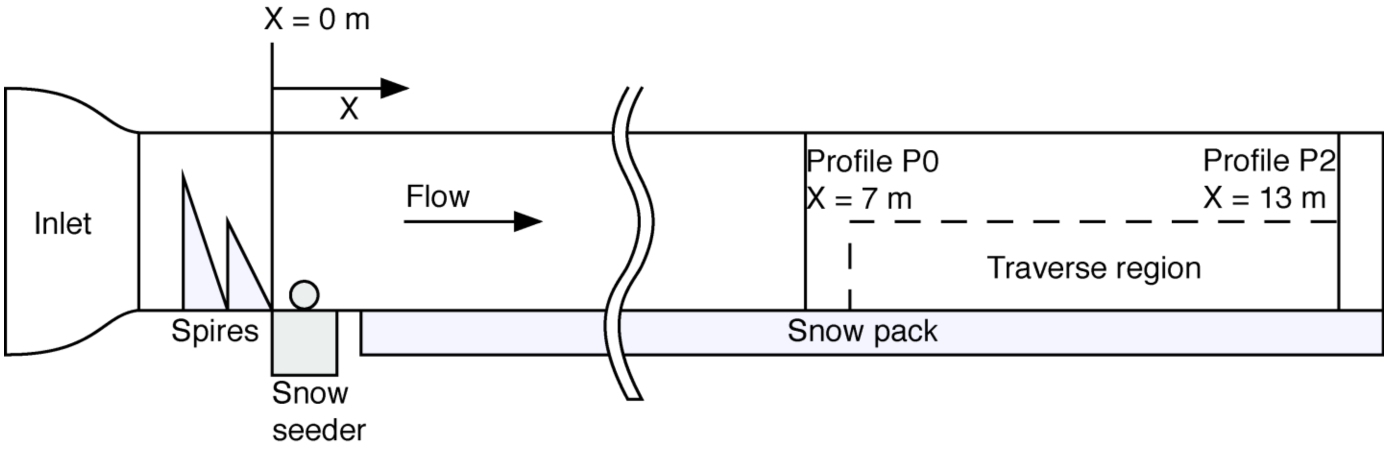
Results: Comparison to surface sublimation



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

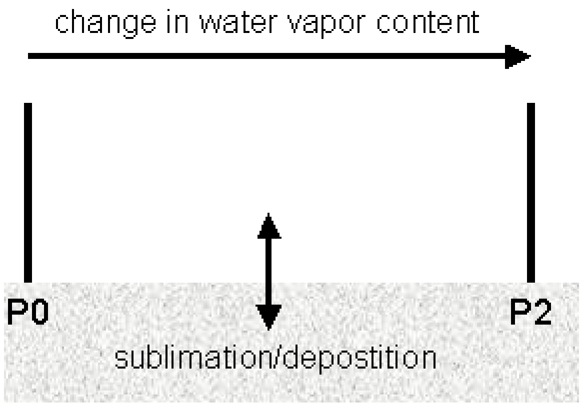


As models are uncertain, we could try to measure the effect in a wind tunnel with blowing snow. Need to have accurate measurements of moisture changes and not too many side effects;
→ can you think of potential experimental complications?

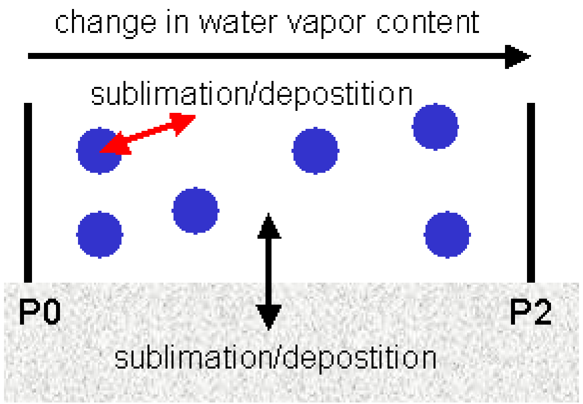
Wever et al., WRR, 2009

Moisture Mass Balance

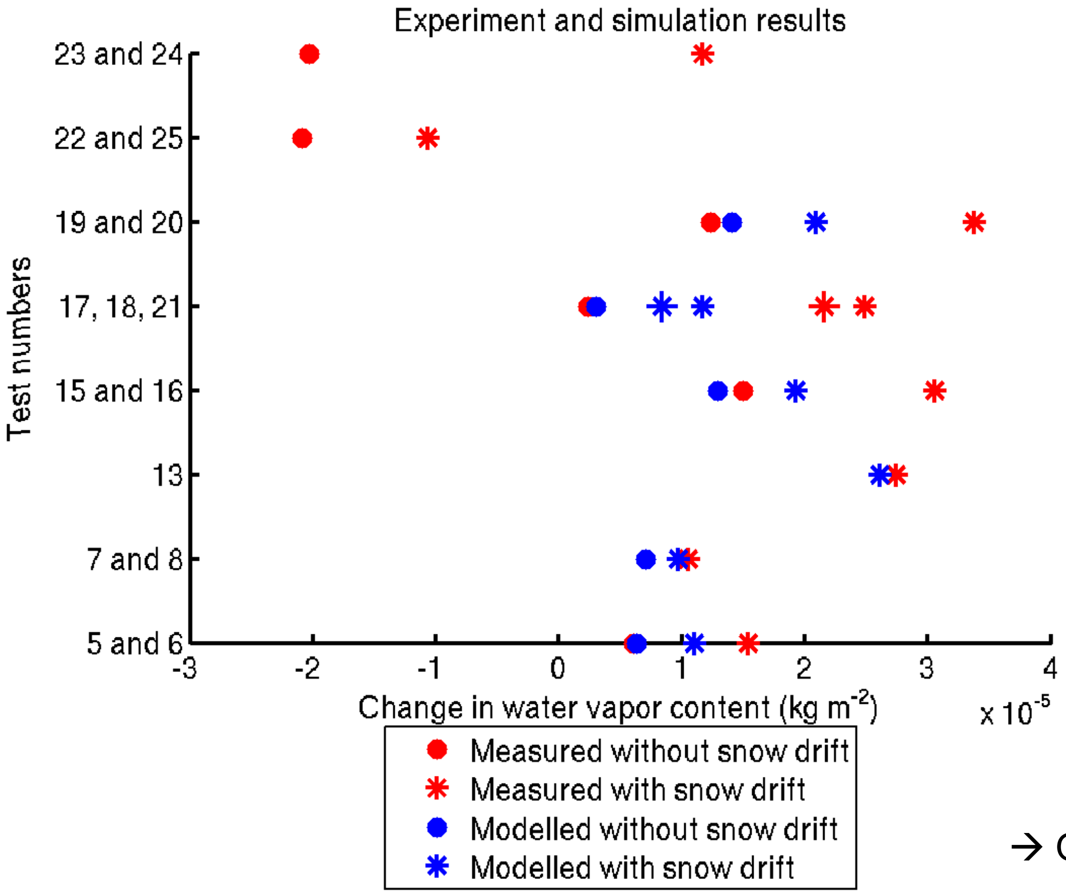
without drift



with drift



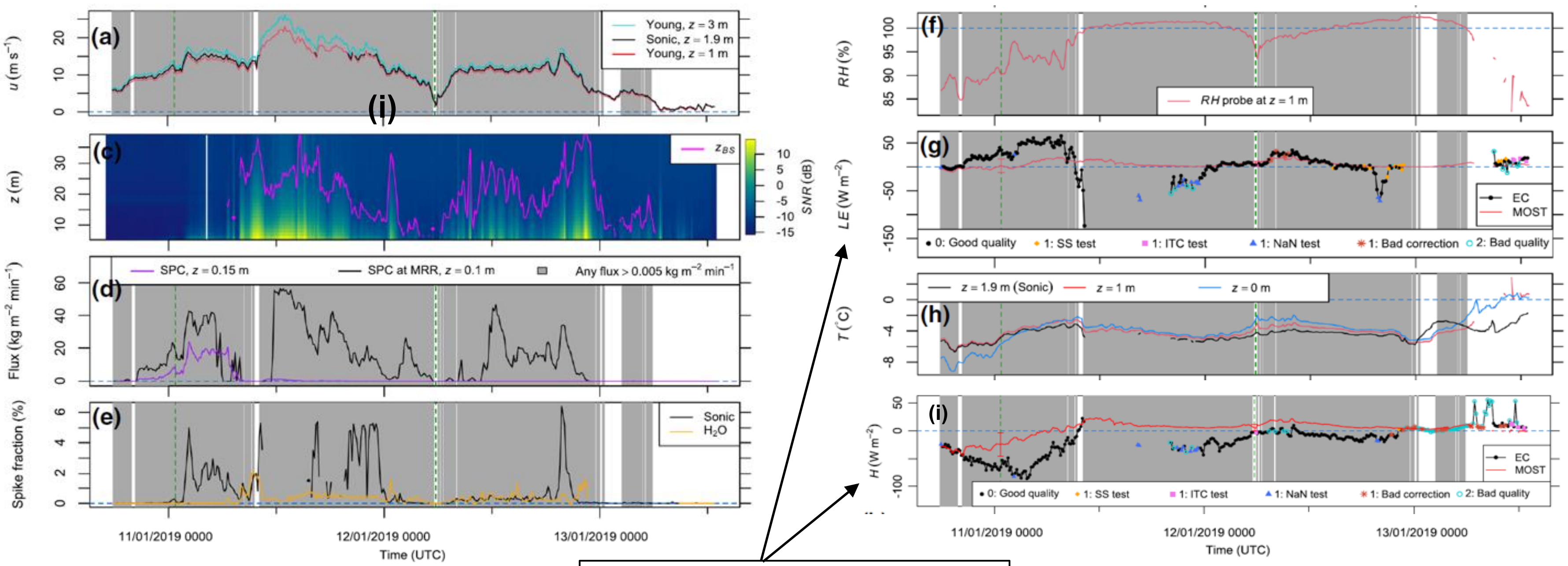
Clear effect on total mass balance



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



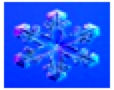
Below a height of 2 m.
How much happens above?

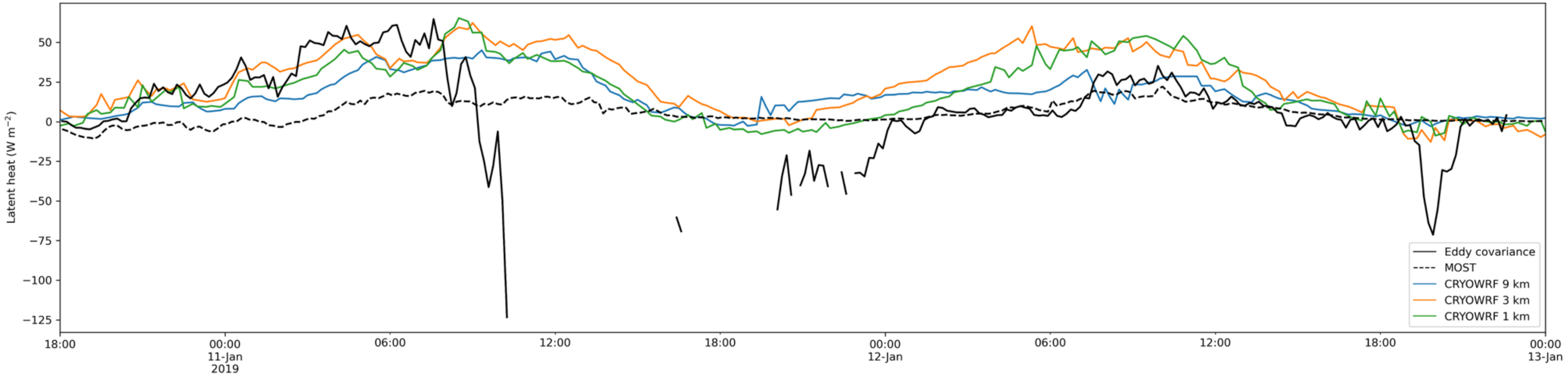
Sigmund et al. BLM, 2021

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



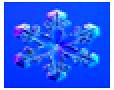





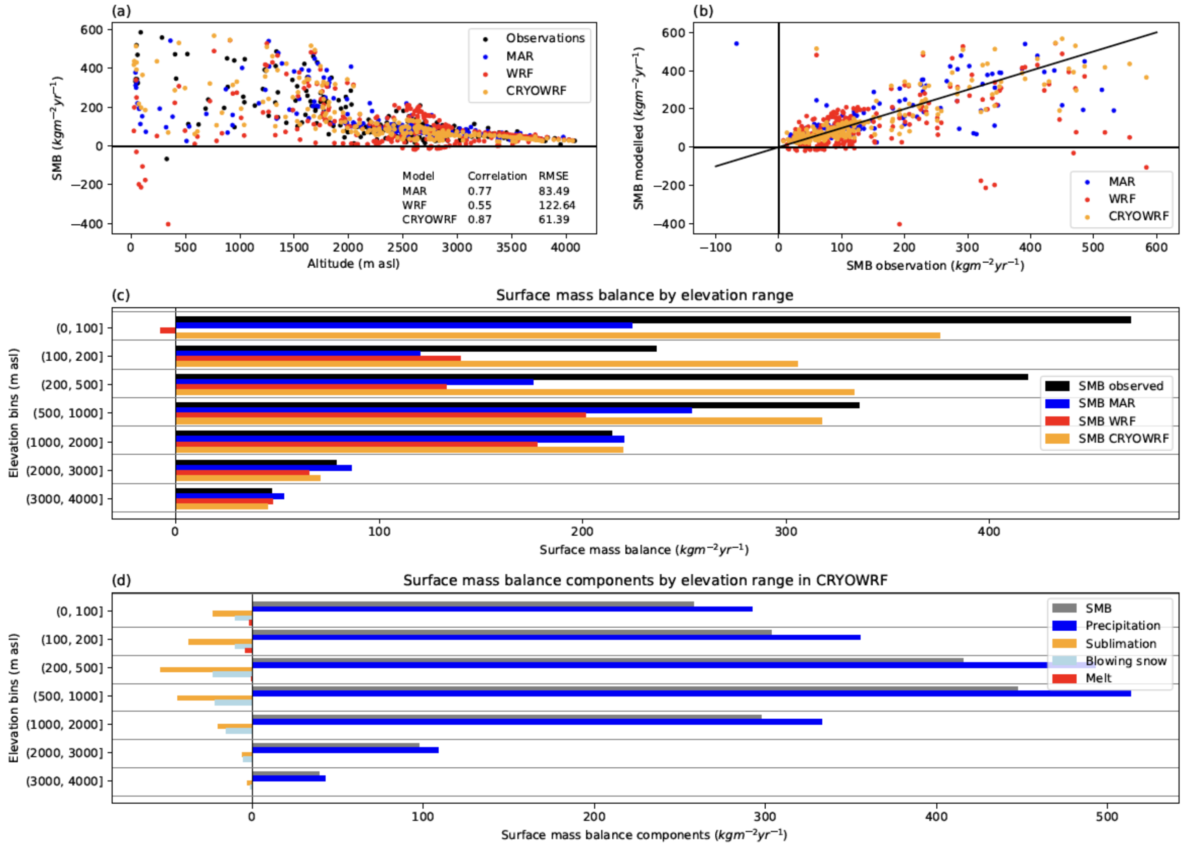
When representing the drifting and blowing snow cloud in a numerical model, you can see similar dynamics as measured. However it needs not only the correct physical representation but also enough resolution, which is a problem for meteorological or climatological modelling because of the high computational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



- 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

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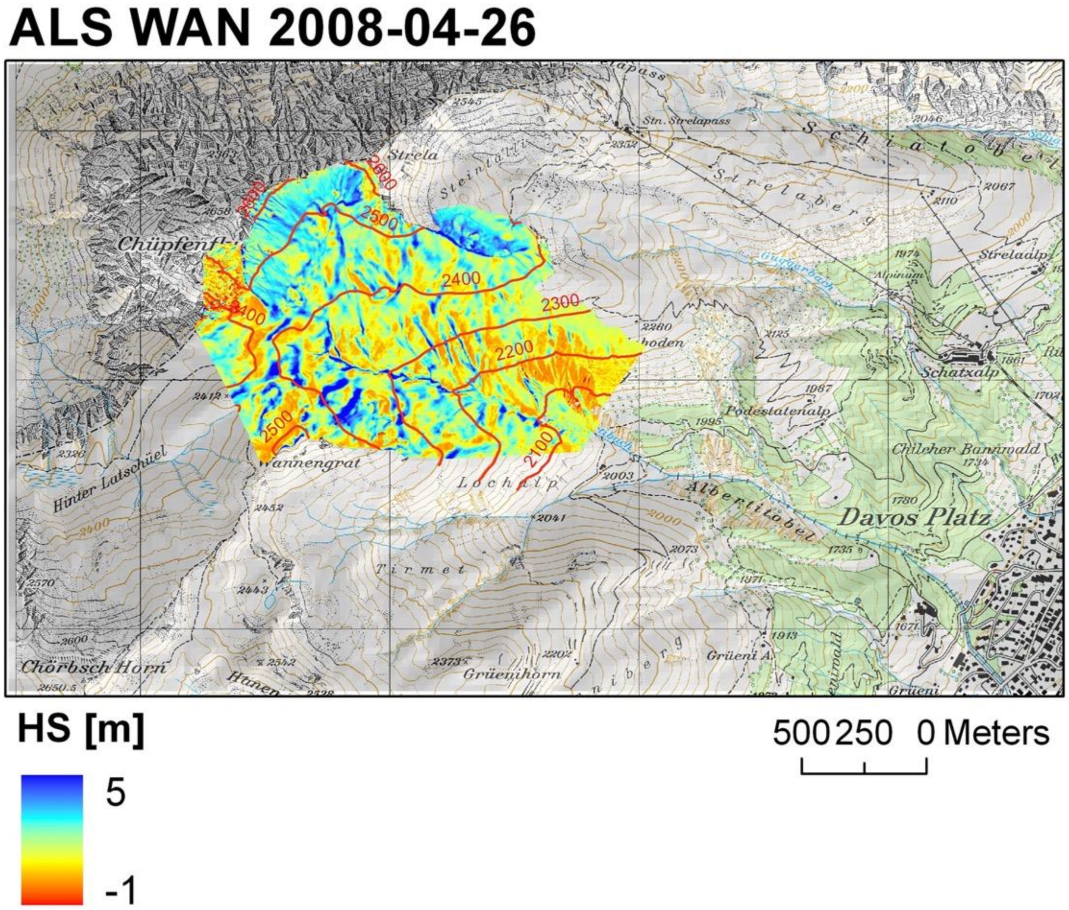
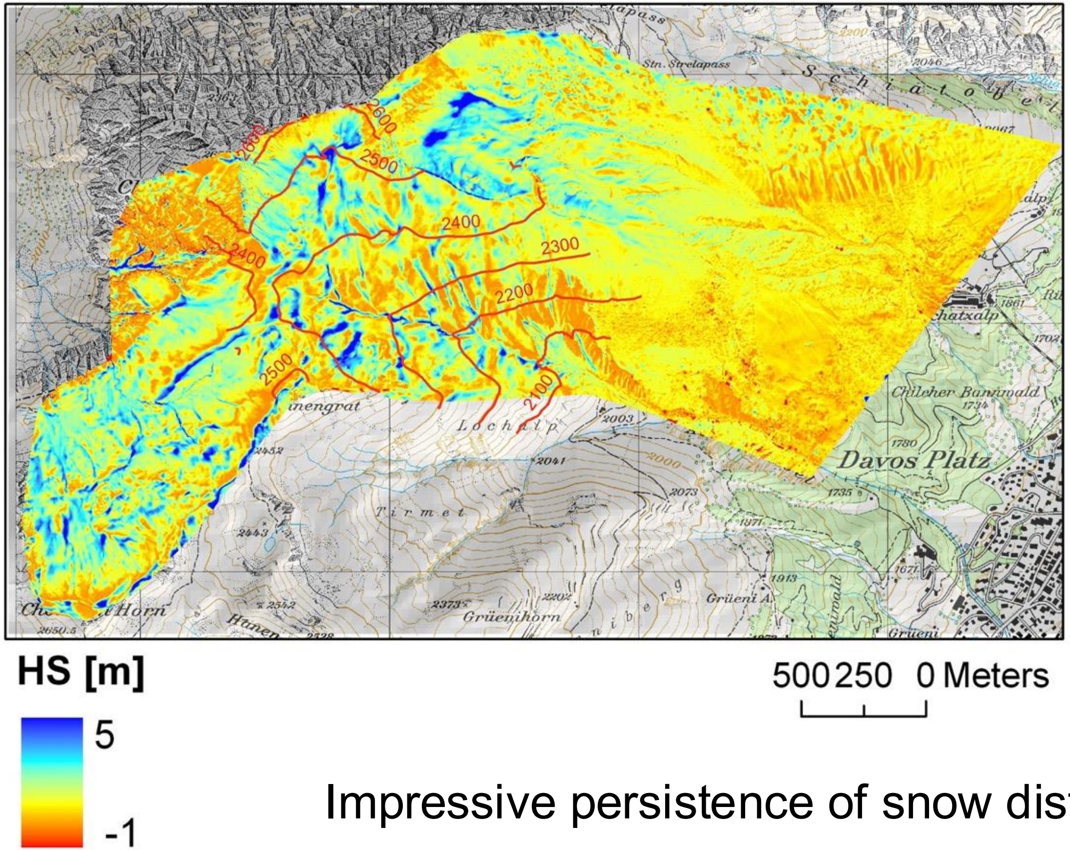
Peak of Winter snow distribution 2008



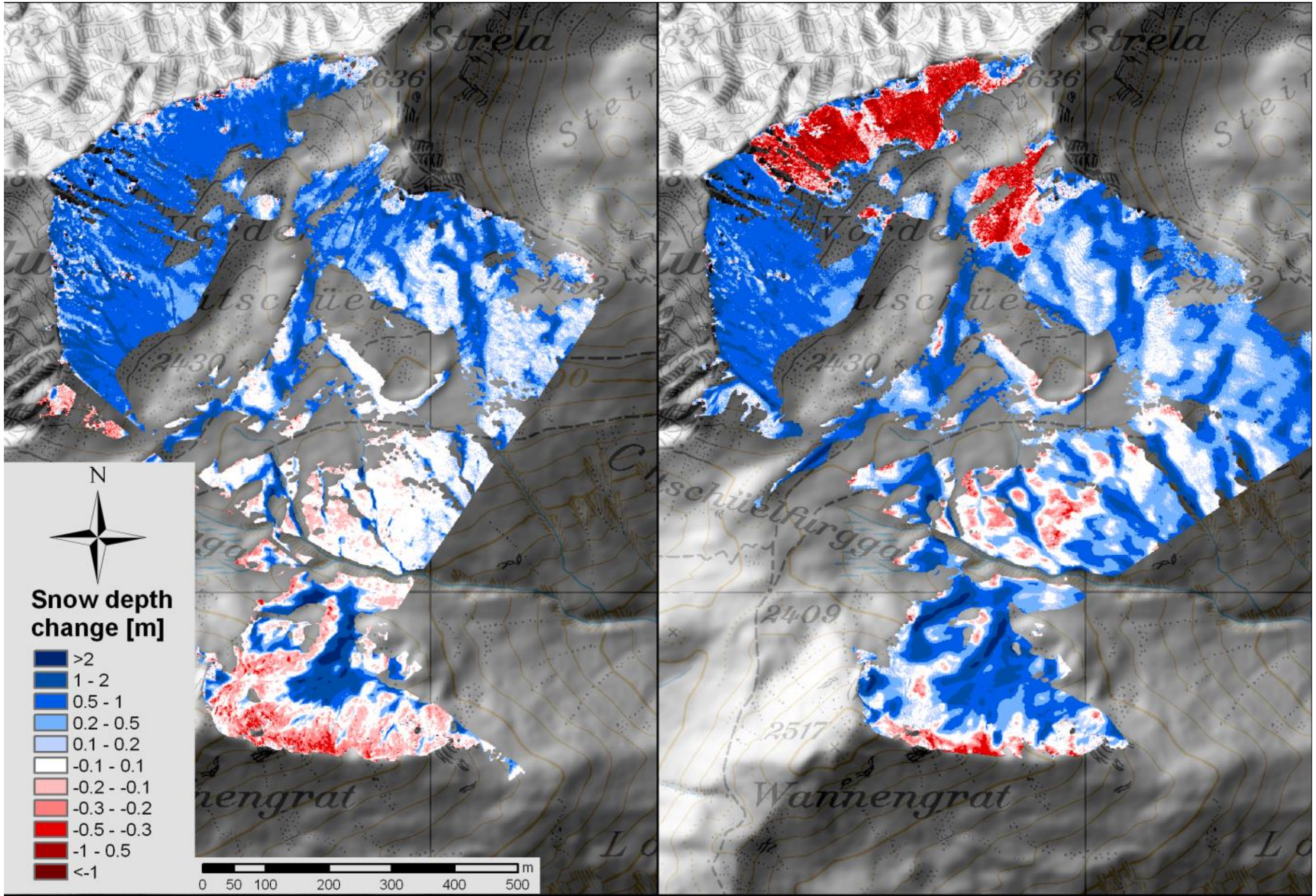
Peak of Winter snow distribution 2008

ALS WAN 2009-04-09

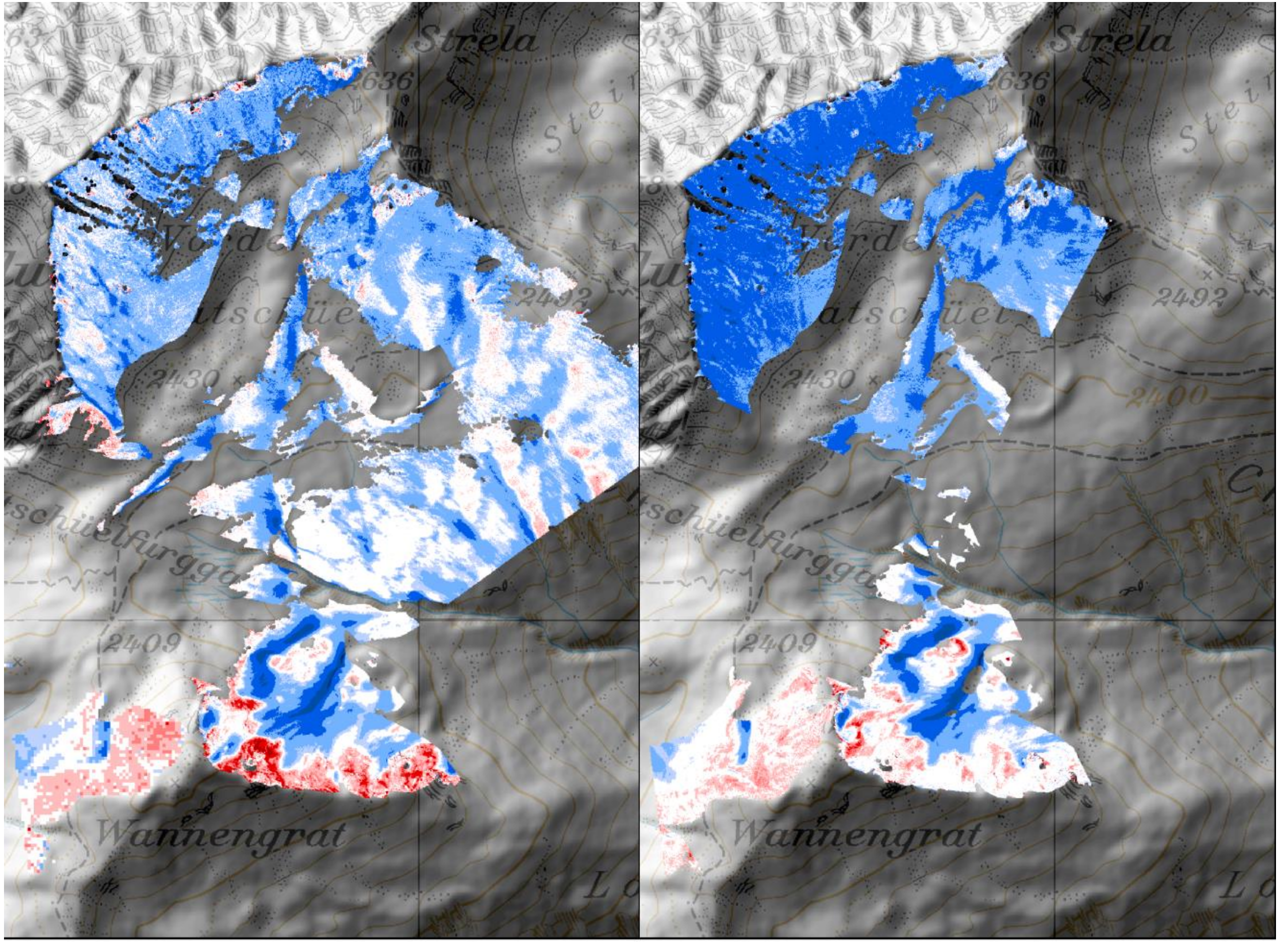


Impressive persistence of snow distribution pattern

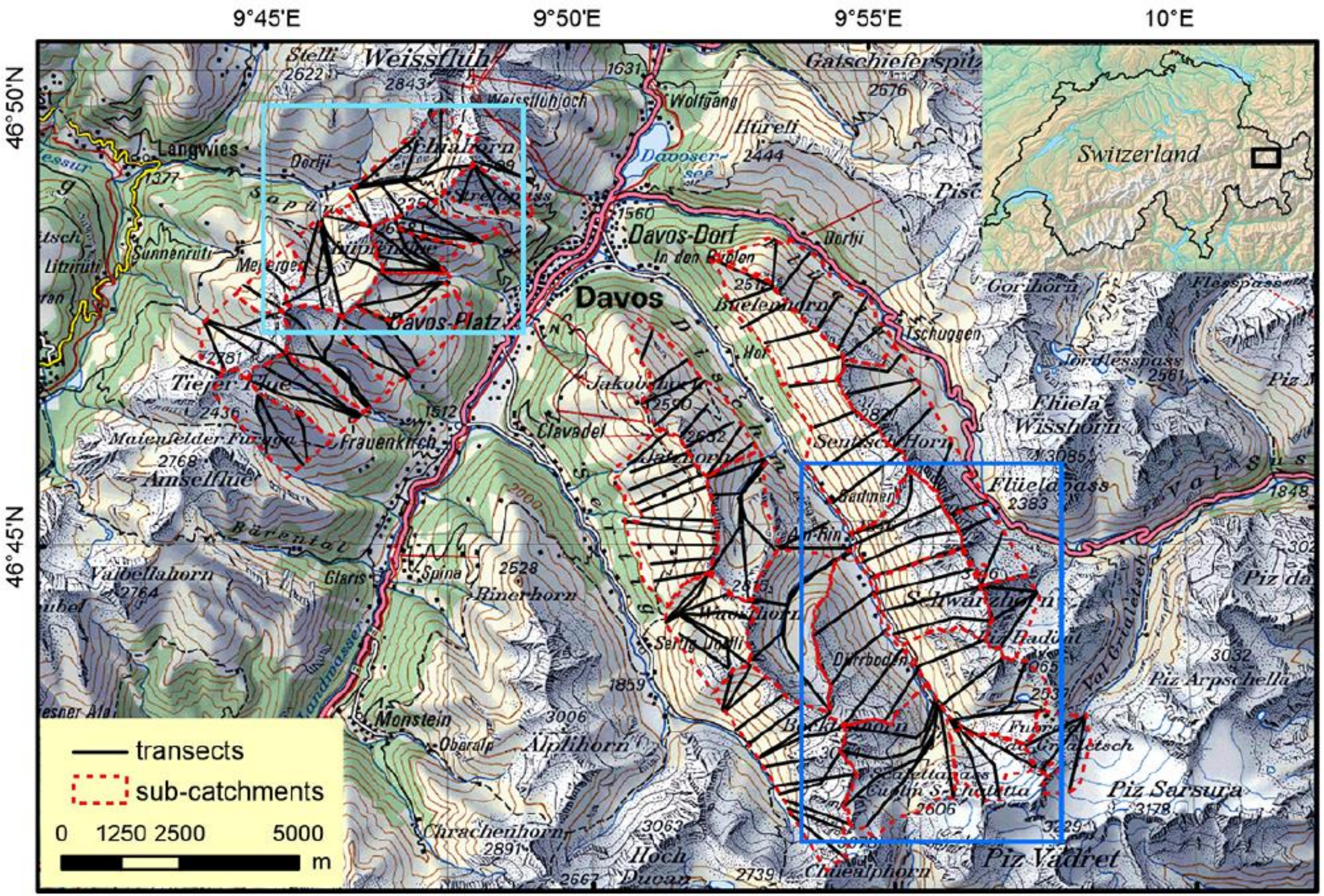
Intra-annual SWE development



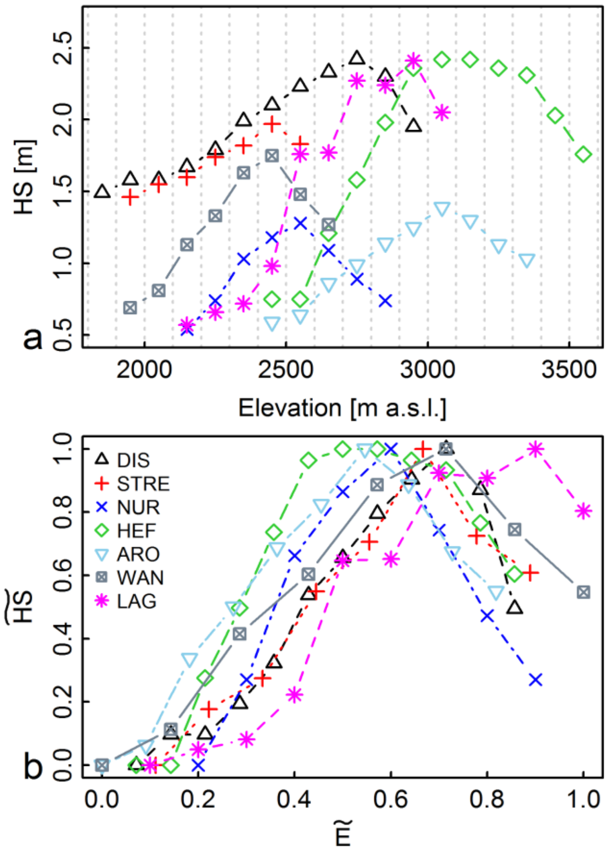
Intra-annual SWE development



Example of Transects in Davos



Elevation Gradient of Snow Depth



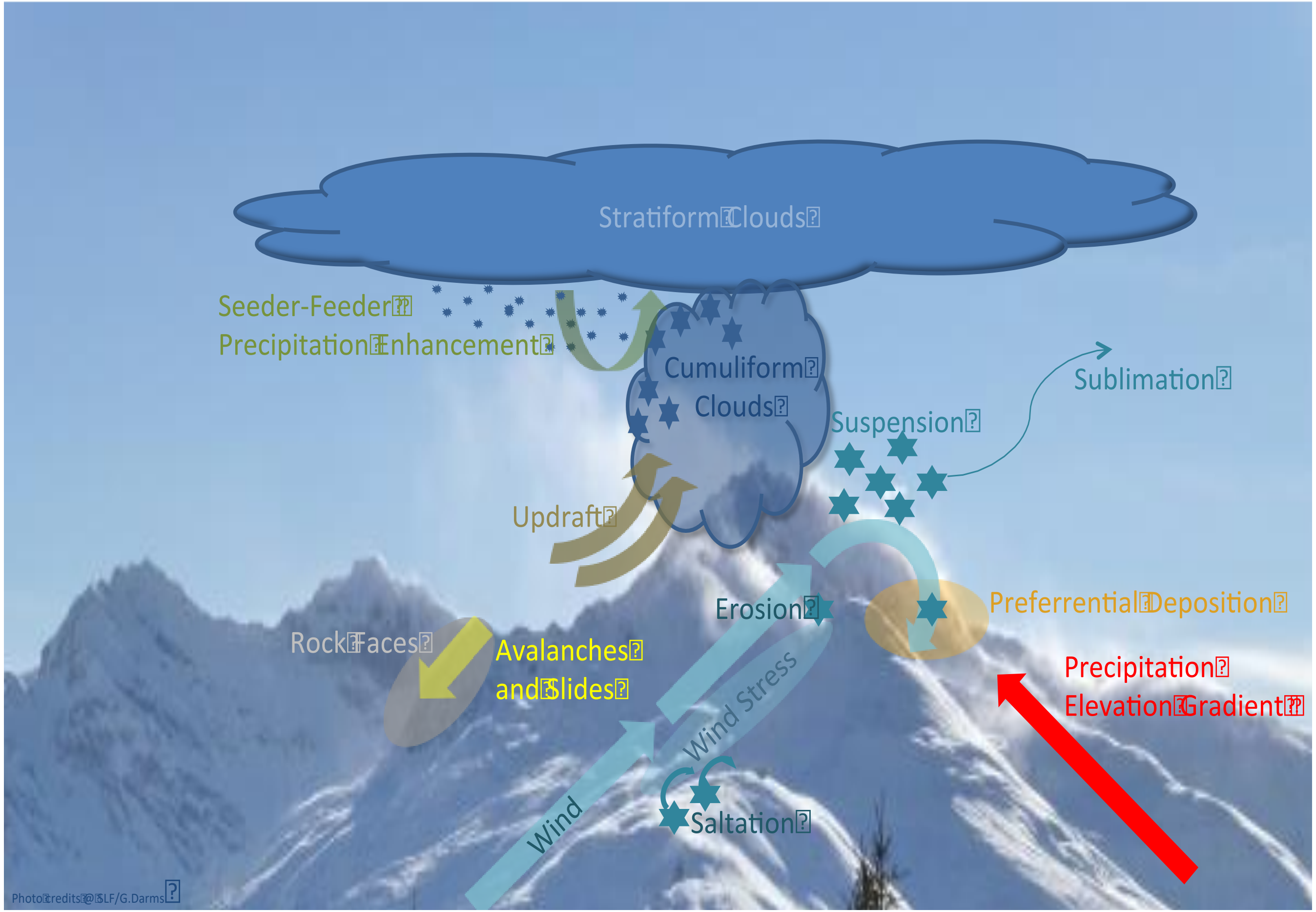
Given are mean snow depth in 100 m elevation bands for all catchments; catchments have area extensions between 3 and 78 km^2.

Scaled axes according to:

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

Grünewald et al., Hydrological Processes, 2014

Summary of Processes



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!