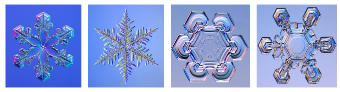

Written exam, 27.01.2023, 09:15 – 11:15, CM 1 4, (120min); total: 60 Points

Instructions / Information: (same as on Moodle, posted and announced on 04.01.2023).

Open book exam - permitted resources and tools: course slides, personal notes, exercises and solutions, pocket calculator. Personal laptop **exclusively** for browsing the slides. The use of smartphones is not authorized (please bring a **pocket calculator**). Any type of communication and exchange (e.g., phone, SMS, chat, email, etc.) is NOT allowed and considered as cheating. Any suspicion requires further investigation (see "Internal directive concerning examinations at EPFL" LEX 2.6.1, Article 6).

Each question has its point value (in red, "**XP**") and indicative time for answering (in blue, "**Xmin**"). The small red circles ° in the questions indicate the distribution of points. Please use a black or blue ball-pen for writing. Always give the correct/appropriate units of your results. Document intermediate steps leading to your final answer. In case of questions, give a sign; supervisors will assist. Please write your name on all sheets you return. - **Good luck !**

Hendrik, Johan, Michi, Sonja, Adrien, Yael, Tatjana, Minyang

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Values of variables or constants:

- Density of water at 0°C: 1000 kg m^{-3}
- Specific heat capacity of water at 0°C 4220 J kg^{-1} K^{-1}
- Specific heat capacity of ice at 0°C 2110 J kg^{-1} K^{-1}
- Latent heat of fusion of water 3.34e5 J kg^{-1}

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1. Energy balance, radiation (3P – 5min)

During a dust storm the albedo of a snowpack decreases from 0.85 to 0.55. Compute the relative change in net shortwave radiation (in %). ° What does that mean for the snow pack in terms of temperature and potential melt? °°

Albedo = 0.85 -> net SW = Incoming - outgoing shortwave = 0.15 * incoming
Albedo = 0.55 -> net SW = Incoming - outgoing shortwave = 0.45 * incoming
Percent change: 0.45/0.15*100 = 300% (SWnet increases by a factor of 3!) °
3 times more SW radiation is absorbed, leading to rapid temperature increase to 0°C ° and a melt rate up to a factor 3 larger than without the dust. °

2. Snow properties and microstructure (9P – 15min)

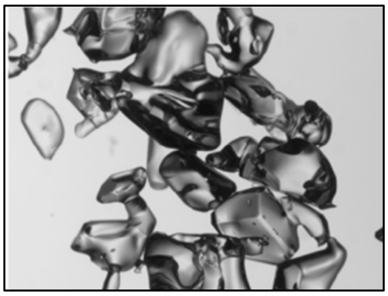
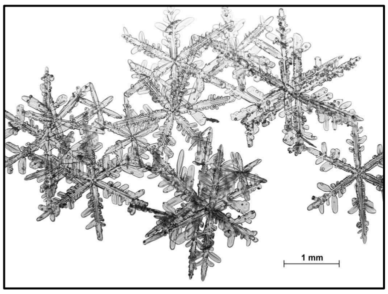
Examine the snow microstructure shown on the pictures below. Photo width corresponds to 6 mm.

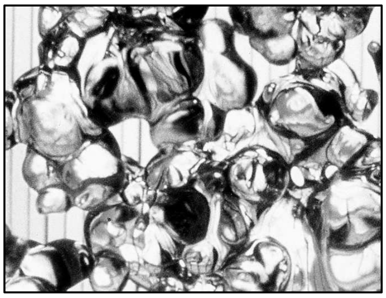
(a) Attribute the correct grain type (see list below) to the ice particles shown in the pictures: °°°
(A) new snow, (B) small rounded grains, (C) large rounded grains, (D) facetted grains, (E) cup crystals, (F) melting grains

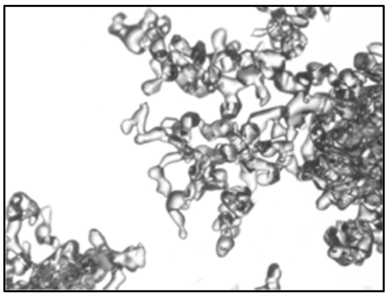
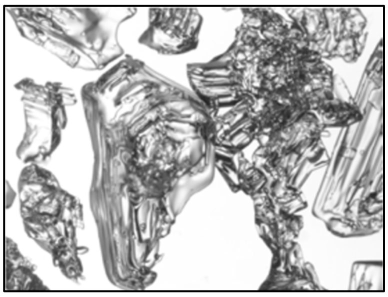
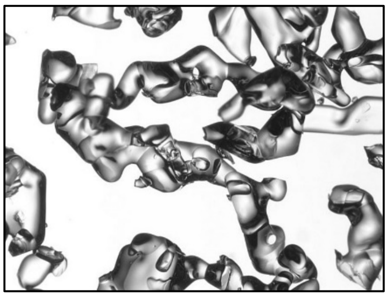
(b) Attribute a corresponding metamorphism process acting just before the picture was taken. °°°

(c) Mention whether the metamorphism in (b) leads to mechanical strengthening or weakening of the snow pack structure. °°°

Suggestion: a table may be a convenient way to answer Question 2, (a) – (c).

(1) 
(2) 

(3) 

(4) 
(5) 
(6) 

Sample ID	(a)	(b)	(c)
(1)	D: solid facetted grains, FG, [☐]	KM	weaker
(2)	A: stellar fresh snow (precipitation particles), PP, [+]	EM	stronger
(3)	F: clustered rounded melting grains, MF, [○]	WM	weaker
(4)	B: small rounded grains, RG, [●]	EM	stronger
(5)	E: hollow cup crystals, depth hoar, DH, [^]	KM	weaker
(6)	C: large rounded grains, RG, [●]	EM	stronger

3. Energy balance, rain on snow (16P – 35min)

A 50cm snowpack of uniform density (360 kg m^{-3}) has an isothermal temperature profile of -2°C. A rain event adds 2mm of 3°C warm water on the snow. Assume that the water percolates uniformly into the snow with a horizontal front descending everywhere at the same speed.

(a) Explain qualitatively what happens to the water and the snowpack once they are in contact. °°°°
(b) Will the rain event in this scenario trigger liquid water output at the base of the snowpack? °°°°
(c) How deep into the snowpack would the water percolate in this case? °°
(d) Why is this scenario only theoretical and which process/es would you expect in reality? °°°
(e) With climate change, we will see more rain-on-snow (ROS) events. Explain briefly what a ROS event means for snow melt dynamics, especially when the snow temperature is very close to the melting point. °°°

(a) Energy (sensible & latent heat) will be exchanged between the two phases until equilibrium is reached. ° The rain will cool down to 0°C transferring this energy to the snow. ° Liquid water will freeze in the sub-freezing snowpack, releasing latent heat. ° This process continues until all water is frozen or until the entire cold content (CC) of the snowpack is 'consumed' or 'neutralized'. °

(b) Compute the sensible heat of the rain with respect to 0°C reference:
rho_w*cp_w*dT*dz = 1000 kg m^{-3} * 4220 J kg^{-1} K^{-1} * 3K * 0.002m = 25'320 J m^{-2} °

Compute the latent heat released if all rain (2 kg m^{-2}) freezes in the snowpack:
2 kg m^{-2} * 334'000 J kg^{-1} = 668'000 J m^{-2} °
Total heat introduced by the re-freezing rain (RE): 693'320 J m^{-2}
Cold content (CC) of the snowpack:
rho_s*cp_i*dT*dz = 360 kg m^{-3} * 2110 J kg^{-1} K^{-1} * 2K * 0.5m = 759'600 Jm^{-2} °
CC > RE, therefore NO liquid water output. °

(c) RE = rho_s*cp_i*dT*dz, where dT = 2C. °°
Solving for dz results in 0.456m
Alternative: RE/CC = 0.913, and thus 0.5m * 0.913 = 0.456m
Here it is assumed that the water percolates slow enough that local thermodynamic processes (heat transfer and phase change) can happen until completion. In reality, the wet snow would also settle and compact and snow depth would be less than the original 50cm.

(d) Due to the heterogeneity of most snowpacks, a uniformly advancing liquid wetting front is unrealistic, water rather percolates following preferential flow paths in addition to matrix flow ° and will thus reach the snowpack base earlier than in the scenario. ° Even more so as the maximum liquid water holding capacity of the snow has not to be reached everywhere in the snowpack (which would retain some of the melt water, i.e., ripening phase of the snowpack). ° Sensible heat exchange is limited due to a finite thermal conductivity °, and water percolates faster (gravitation) than freezing process can hold it back. ° Preferential flow may be intercepted by less permeable layers leading to lateral extension and ponding and subsequent formation of ice lenses. ° (max. 3P)

(e) The cold content of the snow will be very small ° and the energy input via sensible and especially latent heat from rain (if some water freezes) will rapidly bring the snowpack to 0°C ° and efficiently melt it with the excess energy. ° Most relevant for low and mid elevations, where the snow season will be shorter as a consequence. ROS accelerates melt dynamics and the snow melt adds to the runoff from the rain event and increases the risk of (flash) floods.

4. Renewable Energy and Snow (15P – 30min)

Consider a vertically installed bi-facial (active on front- and backside) photovoltaic (PV) panel on a flat infinitely extending surface located at 47°N, e.g., in Davos (Switzerland). The panel surfaces are facing South and North, respectively.
On the 21st of December at local noon (highest sun elevation), the sky is clear (no clouds). At this moment, the sun elevation is about 20° and the global solar radiation measured by a horizontally leveled pyranometer equals 350 W m^{-2} (see Figure 1). 30% of the measured irradiation is due to diffuse light. (Diffuse light is typically uniform in all directions everywhere in the atmosphere under clear sky conditions.) The rest is direct (beam) irradiation.

(a) Assuming no reflection at the Earth's surface (albedo = 0), calculate the global (total) solar irradiation to the surfaces of the panel (both sides). °°°°°
(b) Assuming the ground is covered in snow (high albedo) and that snow forward scattering reflects 30% of the incident beam directly to the solar panel's surface (i.e., the surface acts like a mirror for the fraction of forward scattered radiation), calculate the portion of irradiation exclusively due to the presence of snow on ground. °°°
(c) Taking the irradiation on the south face of the panel in situation (a) as 100%, express the relative total irradiance both on the south and north face of the panel for situation (b). °°°
(d) Finally, for each situation, give reasons why the assumption made may under- or overestimate the irradiation on the solar panel. °°°°

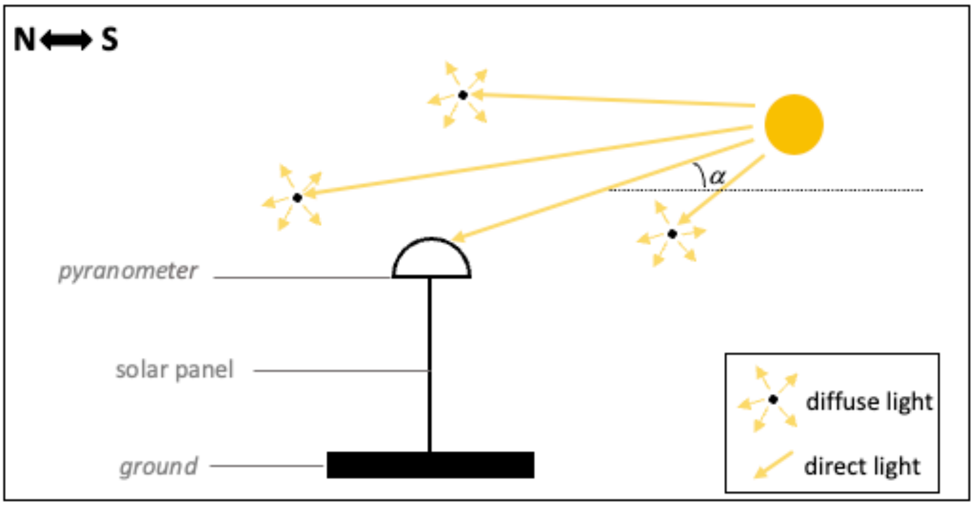


Figure 1: *Scheme of radiation measurement with the pyranometer. α is the sun elevation angle. NB: For direct beam radiation, the pyranometer measures the component normal to the sensor plane (cosine law).*

(a) The presence of diffuse light only means that the front and back side of the panel receive the same amount of radiation, 30% of 350 W m^{-2}, i.e., 105 W m^{-2}. ° From direct beam radiation we have 245 W m^{-2} / sin(α) * cos(α) = 673 W m^{-2} °°°, i.e., 673+105 = 778 W m^{-2} on the south face of the panel. °
(b) We get 673 W m^{-2} * 0.3 = 202 W m^{-2}. ° Important to note that after reflection, perfect forward scattering hits the panel at the same angle as the direct beam, thus no need for further calculations. °°
(c) 778 = 100% °, South with reflection: 778+202 = 980 = 126% °, North only diffuse: 105/778 = 13.5% °
(d) Even without snow, albedo will not be > 0 ° and some surface reflection will happen such that the panel gets some direct radiation from it. ° With snow, the diffuse radiation will also increase and lead to higher yield. ° Additional terrain or cloud effects may in- or decrease actual radiation received. °

5. SNOWPACK, Erosion and Slopes (17P – 35min)

A SNOWPACK simulation (with snow transport from windward to lee slopes as presented in the lecture) for the high-alpine station "Gessi" close to the town of Livigno (IT) of the current 2022/23 winter season gives the results shown in Figure 2. Slope inclination and orientation are indicated on the Figure. Note the different scale of snow depth on the y-axis in both panels.

(a) Which are the two dominant processes explaining the differences between the north-facing and south-facing slope? ° Indicate the time periods during which these drivers were dominating the snow cover development. °° In particular, explain differences in snow depth and the disappearance of snow in October.° Describe at least two additional prominent events/processes or features of the snow pack. °°
(b) Based on the simulations shown in Figure 2, can you tell the direction of strong winds present in October and early November, and then later in early December? °°
(c) Which slope would you pick to ski on? Give a justification for your choice. °°
(d) For the north-facing slope, consider the weak layer identified by SNOWPACK based on the SK38.
   (i) Is this weak layer persistent or non-persistent? °°
   For this weak layer, the associated slab has a thickness of H=54 cm and a mean density of ρ=200 kg m^{-3}.
   (ii) Use the SK38 value calculated by SNOWPACK to back-calculate the shear strength of the weak layer and comment on its value (take a skier line load R=500 N m^{-1}, and $\alpha_{max} = 54.34°$). °°°
   (iii) Use the strength–density relationship provided by Jamieson and Johnston (2001) to give the density of the weak layer. °°

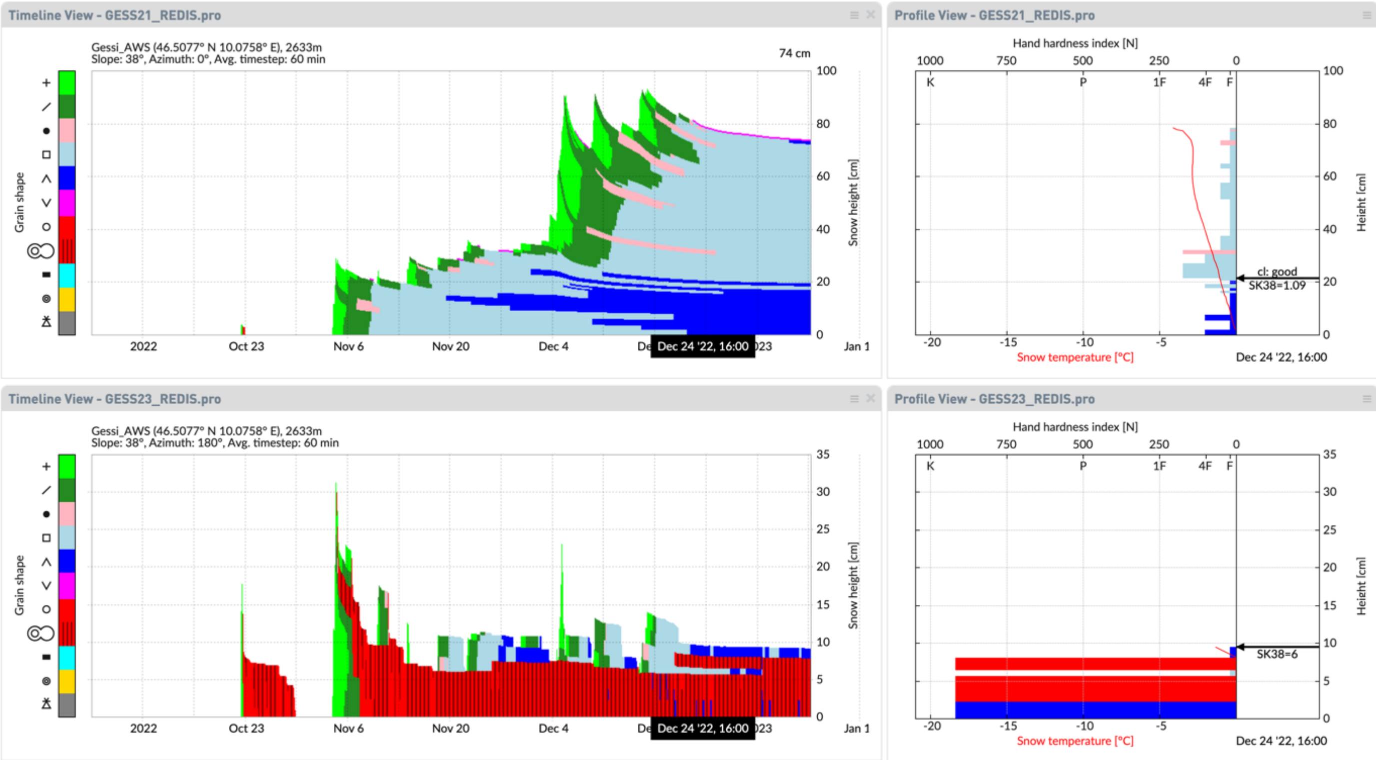


Figure 2: *SNOWPACK simulation result for a virtual North (upper panel) and South (lower panel) slope driven my meteorological measurements close to the town of Livigno (IT).*

(a) The two dominant processes are snow erosion and re-deposition and the different energy (radiation) energy balances. ° On the South slope, snow gets accumulated in October but then melts. ° On the North slope, snow gets eroded in October. ° The heavy snow fall in the beginning of December then gets eroded from the South slope and re-deposited on the North slope. ° During warm and sunny weather in November, the South slope loses snow due to melt and sublimation and forms a crust. ° The crust is then the lower boundary of subsequent erosion. °

(b) In October strong winds from North ° and in December strong winds from South. °

(c) North slope for better powder and no hard crust, however, this slope has a well-developed weak layer and given the small snow depth it might be dangerous to ski there depending on slope angle. °°

(d) The weak layer is made of faceted crystals, a persistent type of weak layer, ° and is very close to the base of the snowpack which consists of depth hoar. ° Calculation of the weak layer shear strength:

  a. $SK38 = \frac{\tau_p}{\tau + \Delta\tau}$

  b. $\rightarrow\ \tau_p = SK38 \times (\tau + \Delta\tau) = SK38 \times \left(\rho g D \sin\psi + \frac{2R}{\pi D} \sin^2\alpha_{max} \sin(\alpha_{max} + \psi) \cos\alpha_{max}\right)$ °°°

  c. with $D = H \cos\psi$ it gives $\tau_p = 874$ Pa. Using the relationship of Jamesion and Johnston (2001), we get a density of the weak layer $\rho_{wl} = 216$ kg/m^3. °°

For exam development only (1P = 2min)

Repartitioning – weights according to lecturing:

ML	4	31%	22P	45min
HH	5	38%	26P	50min
JG	2	15%	12P	25min
AM	1	8%	0P	0min
SW	1	8%	0P	0min
All	13	100%	60P	120min