Written exam, 29.01.2024, 09:15 – 11:15, CE 1 106, (120 min); total: 60 Points

Instructions / Rules / Information:

Open book exam - permitted resources and tools: course slides, personal notes, exercises and solutions, pocket calculator. Personal laptop **exclusively** for browsing the slides, your notes, and any other course material of this class. The use of smartphones is not authorized. Any type of communication and exchange (e.g., phone, SMS, chat, email, etc.) is NOT allowed and considered as cheating. Rules are enforced according to the 'Internal directive concerning examinations at EPFL', LEX 2.6.1, Article 6.
Each question has a point value (indicated in red, "**XP**") and an indicative time for answering (given 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. Provide the correct/appropriate units of your results where applicable. Document intermediate steps leading to your final answer. In case of questions, give a sign; exam supervisors will assist.

→ Please answer Questions 1-3, Questions 4-5, and Question 6, respectively, on separate pages.
→ Please write your name on all sheets you return.

Good luck ! *Hendrik, Michi, Grégoire, Yael, Daniela, Elizaveta*

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Values of variables or constants:

- Specific heat capacity of ice at 0°C — 2.11e3 J kg^{-1} K^{-1}
- Latent heat of fusion of ice/water — 3.34e5 J kg^{-1}
- Extinction coefficient of fresh and old snow — 20; 10 m^{-1}

1. Energy balance, radiation (9 P – 18 min)

A 20 cm deep fresh alpine snow cover has an albedo of 0.75, and SW = 400 Wm^{-2} is the incoming shortwave radiation at this location at a given time.

(a) Compute the energy flux of transmitted solar radiation at the base of the snowpack, expressing it as a faction of the net SW radiation. °°°

(b) If the snowpack of (a) was composed of old, consolidated snow, how would the repartitioning of the net SW radiation change with respect to SW radiation absorption within the snow and at the soil surface? °°°

(c) A few days later, a Sahara sandstorm transports dust and deposits it on the snow cover of (b) changing its albedo to 0.6. What are the implications for the amount of radiation reaching the (soil or rock) surface below the snow pack? °°°

(a) SWnet = R_0 = (1 - albedo)*SW = 100 Wm^{-2} °
SW(z) = R_0*exp(-kz); k=20m^{-1}, z=0.2m, ° SW(0.2) = R_0*0.018 (1.8%); 1.8 Wm^{-2} (or 1.8/400 = 0.46%) °

(b) While old snow has a lower albedo than fresh snow, we only consider here the extinction coefficient for old snow which is smaller than that for fresh snow °, meaning that a smaller fraction of R_0 would be absorbed within the snowpack ° and a larger fraction by the ground. °
SW(z) = R_0*exp(-kz); k=10m^{-1}, z=0.2m, ° SW(0.2) = R_0*0.135 (13.5%); 13.5 Wm^{-2} (or 13.5/400 = 3.4%) °

(c) R_0 will be significantly larger than in (a), meaning that part of it is absorbed at the surface due to the dust potentially leading to surface melt, and more radiation is reaching the ground ° where it is absorbed, leading to more local warming and potentially basal melt of the snow pack. °
SW(z) = R_0*exp(-kz); k=10m^{-1}, z=0.2m, SW(0.2) = R_0*0.135 (13.5%);
with R_0 = 400(1-0.6) = 160 Wm^{-2} → 21.7 Wm^{-2} (or 21.7/400 = 5.4%) °

2. Energy balance, snow melt (6 P – 12 min)

The snowpack of Question (1a) has a mean density of 126 kg m^{-3}, and a linear temperature profile. The temperature at the surface is -9°C and -1°C at the base. Compute (a) the snowpack cold content, °° (b) the amount of energy required to melt it °°, and (c) the time this would take for a constant net energy input of 100 W m^{-2} present during 8 hours per day °° (express your result in days, hours, minutes, seconds).

(a) CC = rho*cp*dT*dz = 126*2110*(-9 + -1)/2*0.2 = 265'860 J m^{-2} °°
(b) LH = rho*dz*Lf = 126*0.2*334'000 = 8'416'800 J m^{-2} °°
(c) Time = (CC+LH) /100 = 86'826.6 s = 1.005 d (non-stop) = 24h 7m 7s, or here in the example with only 8h energy input per 24h: 3 days 7 min, 7 sec °°

3. Climate change and Snow (10 P – 20 min)

Consider Figure 1 (see separate page) recently published by the BBC on the occasion of the globally warmest year since the beginning of temperature records. Comparing the two years 1976 and 2023, which differences of the global snow cover do you infer for these years? Reply, considering (a) seasonality and timing,°°° (b) precipitation,°° (c) geography and climate,°° and (d) interaction with other cryospheric components.°°°

(a) Seasonality and timing:
1. The snow cover duration is reduced, resulting in a shorter snow season. °
2. The figure does not tell when, i.e. during which season the anomalies occur. However, the most critical time (highest sensitivity) is when the air temperature is around 0°C, determining whether snowfall or rain occurs, or melting or not, and, when positive (Celsius), any further air temperature increase leads to accelerated melting. °°

(b) Precipitation:
1. A warmer atmosphere can carry more moisture (Clausius-Clapeyron-Eqn.) which may locally lead to more precipitation. °
2. But, the fraction of solid precipitation is decreasing. °

(c) Geography and climate:
1. The SCA (or SCE) is reduced, limited to high altitudes and high latitudes. °
2. Enhanced and intensified temperature-albedo effect, directly feeding back on the local snow cover and climate. Areas with conditions of point (a2) are most sensitive. °

(d) Cryosphere interaction:
1. The presence or absence of a snow cover has direct impact on collocated permafrost, sea ice, and glaciers via albedo, thermal insulation, and mass balance. °°
2. The hydrological cycle (hydrograph) is affected, (timing and amplitude), cf. also a) – c). °

4. Snow Transport, Turbulent Fluxes and Isotopes (20 P – 40 min)

Figure 2 (see separate page), which has been shown in class during the snow transport and isotopes lectures, presents measurements taken during a snowstorm in Antarctica.

(a) Name the quantities measured in panels (a), (c) and (d) and provide one or two key words for the measurement principle, for example for relative humidity (f) it would be capacitance changes or for temperature (h) it would be speed of sound or metal expansion respectively. °°°

(b) Explain how the data shown by the two different curves in each of the panels (g) and (i) are calculated. First, name the calculated quantity; second, mention the measurements needed for its calculation and at which temporal resolution; and third, briefly explain how the fluxes in question are calculated. You may give the equations if considered helpful. °°°°°°

(c) Explain why during situations of drifting and blowing snow the Monin-Obukhov Similarity Theory (MOST) may underestimate the turbulent sensible and latent heat fluxes. °°°°

(d) From the data shown in Figure 2, identify two of the most intense blowing snow events and approximately say when they occurred. While during most drifting and blowing snow conditions LE is positive, there are also periods with negative latent heat flux when the latter is computed with the Eddy Covariance (EC) method. What does this mean and how do you explain it? °°°

(e) Why do negative latent heat flux values help explaining isotopic fractionation (oxygen and hydrogen stable water isotopes) in drifting and blowing snow? °°°°

(a) Panel (a): wind speed – calibrated propellor (rpm), and speed of sound °
Panel (c): radar reflectivity and height of blowing snow layer – radar (EM waves) °
Panel (d): snow transport rate – optical (laser light absorption) °

(b) Panel (g): latent heat flux = exchange coefficient * wind speed * difference in vapor pressure (wind, humidity, temperature each at two heights for MOST); latent heat flux = correlation between vertical velocity and humidity fluctuations (high frequency measurements of vertical wind speed and humidity for eddy covariance, EC). °°°
Panel (i) sensible heat flux = exchange coefficient * wind speed * difference in temperature (wind, temperature each at two heights for MOST); sensible heat flux = correlation between vertical velocity and (virtual) temperature fluctuations (high frequency measurements of vertical wind speed and temperature for eddy covariance, EC). °°°

(c) Sublimation happens for grains that are transported in the air, which increases heat and mass transfer processes as compared to when transfer is only at the surface. Snow grains are also increasing the apparent roughness as they are accelerated by the flow. Thus, you increase both the available surface for exchange and the efficiency of the exchange. °°°°

(d) Midday of January 11 and evening of January 12. During these events, EC measures negative humidity fluxes, which suggests deposition of vapor either at the surface and/or on grains suspended in the air. This would mean supersaturated conditions in parts of the snow transport cloud. °°°

(e) Fractionation should not happen / should not be strong during sublimation since sublimation must necessarily remove "layers" of molecules from the surface of grains. But if deposition (inverse sublimation) and sublimation happen continuously and at the same time in different areas of the blowing snow cloud then fractionation can be much stronger as smaller particles may disappear completely while heavier molecules are deposited preferentially on existing (larger) grains and at the surface. °°°°

5. SNOWPACK and avalanche danger (5 P – 10 min)

A SNOWPACK simulation for the station "Les Collines" above Champéry, VS, in most Western Switzerland is shown in Figure 3 (see separate page). With the information that the most active avalanche period of that winter was in December, please answer the following questions.

(a) Which event on which date contributed most to the de-stabilization of the snow cover? °°

(b) Based on the simulations shown in Figure 3, which type of avalanche do you expect? °

(c) What would be the most likely release depth of an avalanche (and why) if it were to start at the elevation of the station "Les Collines" and how would this change if it were to start at much higher elevation (which actually was the case for many avalanches during this period). °°

(a) After heavy snowfalls in early December, the rain event on December 12/13 led to warming of the snow cover and complete moistening to the ground. °°

(b) Wet snow avalanche. °

(c) Depending on the timing of the release, the avalanche could have release depths between 60 cm (minimum snow depth during the rain event) and about 1 m (snow depth with new snow following the rain). If a release would happen at higher elevation, complete wetting may not have happened, and release depths could only concern the new snow. °°

6. Snow mechanics and avalanches (10 P – 20 min) [*please answer this question on a separate sheet*]

(a) Recall three different avalanche types. °
(b) One of the three types of (a) is responsible for more than 90% of the fatalities. Recall the three necessary ingredients for releasing this avalanche type. °°
(c) Recall and explain the process steps required for releasing avalanche type in (b). °°°
(d) Back-calculate the weak layer shear strength τ_p from the Natural Stability Index of 1.3 and the following properties: °°°

$\rho_{slab} = 290\ kg \cdot m^{-3}$	Rounded grain slab density.
$H_{slab} = 52\ cm$	Slab height.
$g = 9.8\ m \cdot s^{-2}$	Gravitational force equivalent.
$\psi = 43°$	Slope angle.

(e) Is this value in line with experimental data? Please give your opinion and discuss this result. °

(a) Slab avalanches
Glide-snow or gliding avalanches
Loose-snow avalanches °

(b) The ingredients necessary to release a slab avalanche are: °°
- A layered snowpack: with a weak layer buried beneath a dense and cohesive snow slab.
- A trigger: which can be natural, such as snowfall, or artificial, like a bomb or a skier.
- A steep slope: steeper than the snow friction angle, generally around 30 degrees.

(c) Failure Initiation: This is the initial stage where the avalanche begins. It involves the formation of an initial crack within the weak layer. °
Crack Propagation: Following failure initiation, the crack propagates through the weak layer. If the crack length exceeds the critical crack length, it leads to self-propagation within the weak layer. This self-propagation is a result of the structural collapse of the weak layer, inducing deformation (bending) in the slab. The bending of the slab causes stress concentration and an increase in shear stress at the edge of the crack. °
Slab Sliding: In this final stage, the slab fractures (in tension), leading to the sliding of the fractured slab down the steep slope. This sliding motion is the end of the preceding processes, resulting in an avalanche.°

(d) τ_p = 1310 Pa. °°°

(e) The Natural Stability Index suggests a fairly stable snowpack. The weak layer strength value seems aligns well with experimental data. To go further into the analysis, the cohesion is computed to be 895 Pa, considering an internal friction angle of 21 degrees. This cohesion value corresponds to a weak layer density ranging between 150 and 300 kg/m^3. This aligns closely with the typical density of weak layers associated with depth or surface hoar. Therefore, the results appear consistent with established experimental data. °

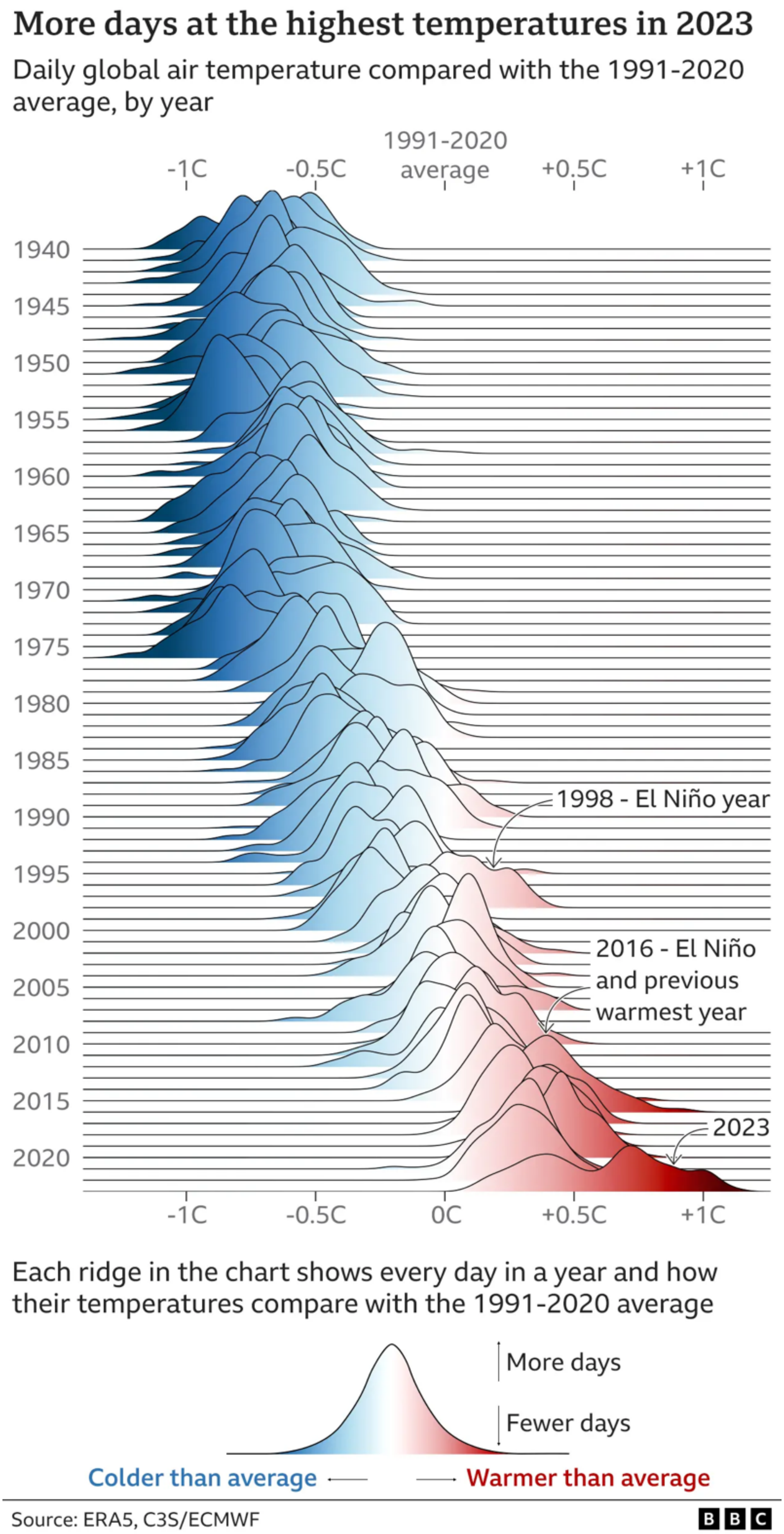

***Figure 1**: Distributions of daily global air temperature anomalies with respect to the 1991-2020 reference period.*

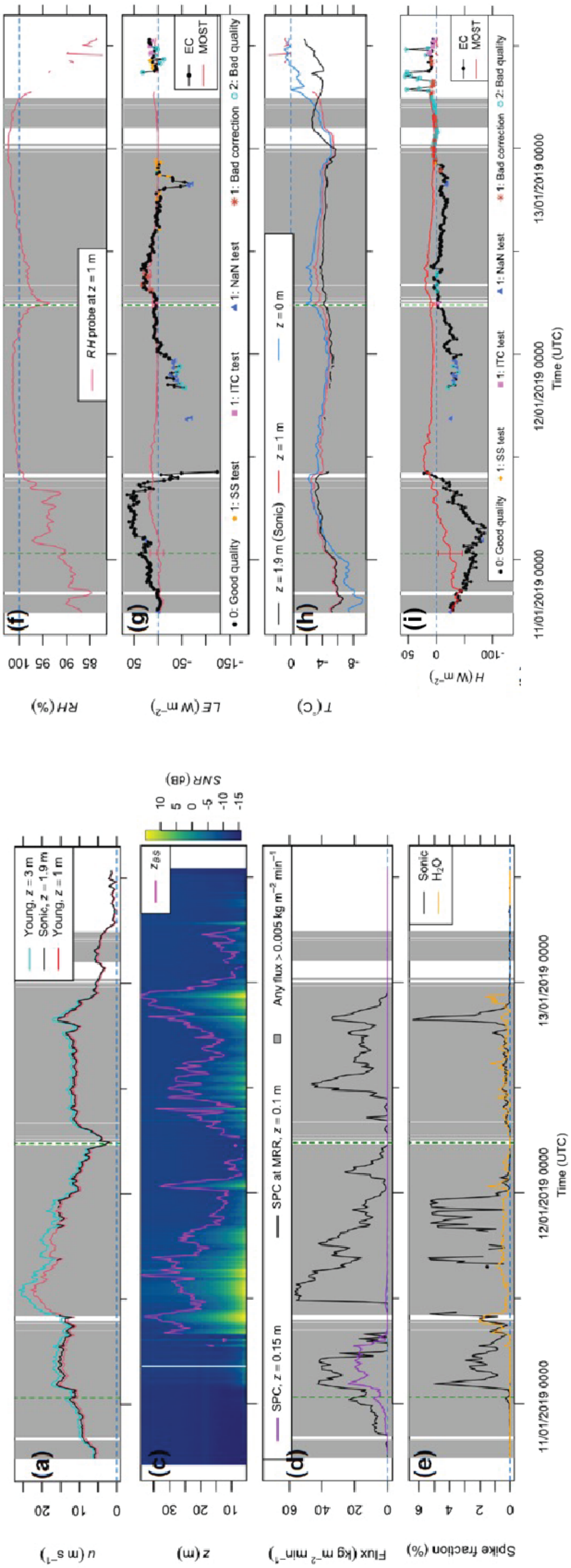

***Figure 2**: Measurements from Syowa, Antarctica. [NB: there is no panel (b).]*

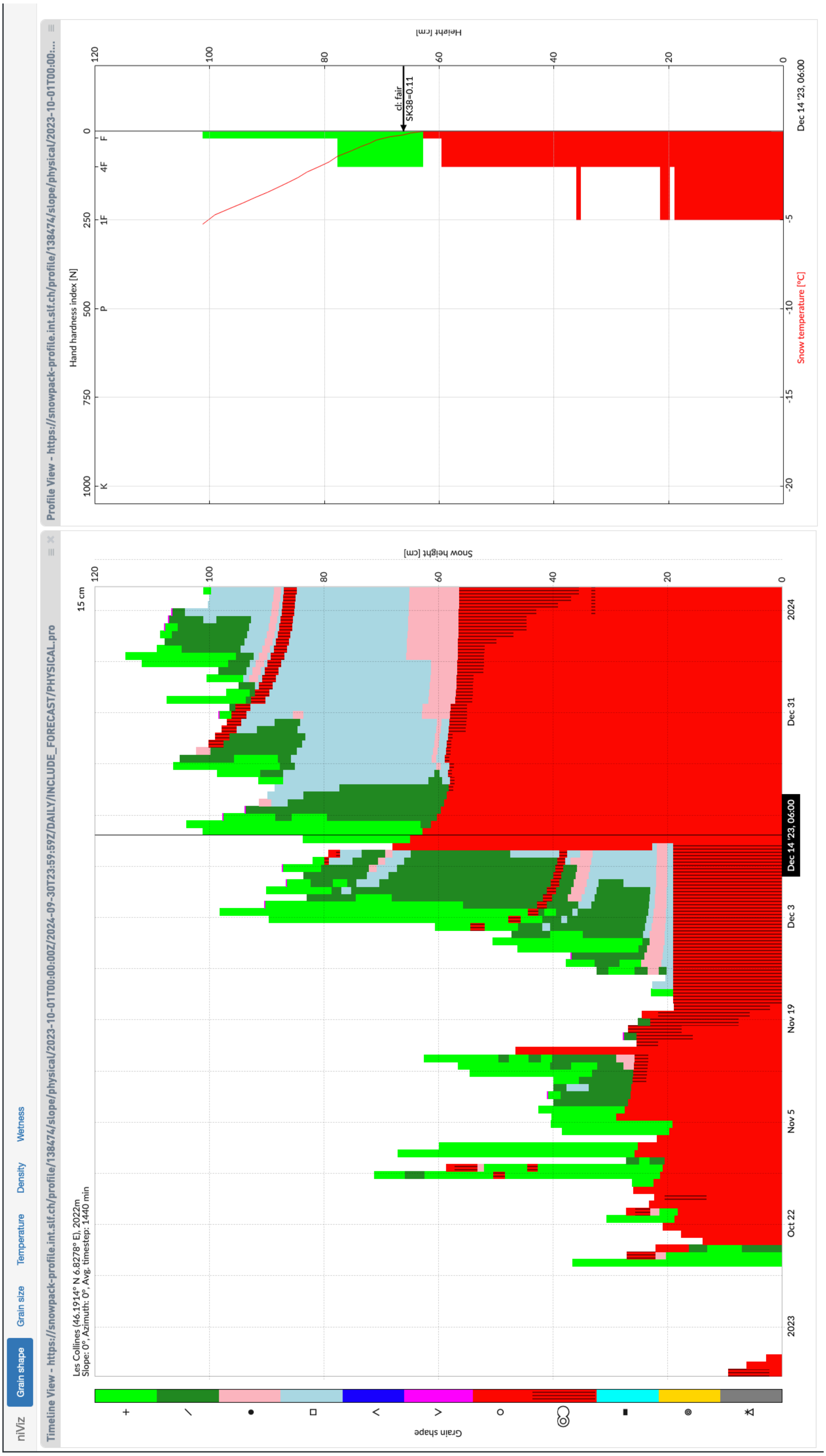

Figure 3*: SNOWPACK snow profile showing grain types for the IMIS station " Les Collines " close to the " Portes du Solei l" ski area.*

For exam development only (1P = 2min)
Repartitioning – weights according to lecturing:

ML	5	42%	25P	50min
HH	5	42%	25P	50min
GB	2	16%	10P	20min
KN	1	0%	0P	0min
YF	1	0%	0P	0min
All	14	100%	60P	120min