



A multi-layer snow cover scheme for numerical weather and climate models

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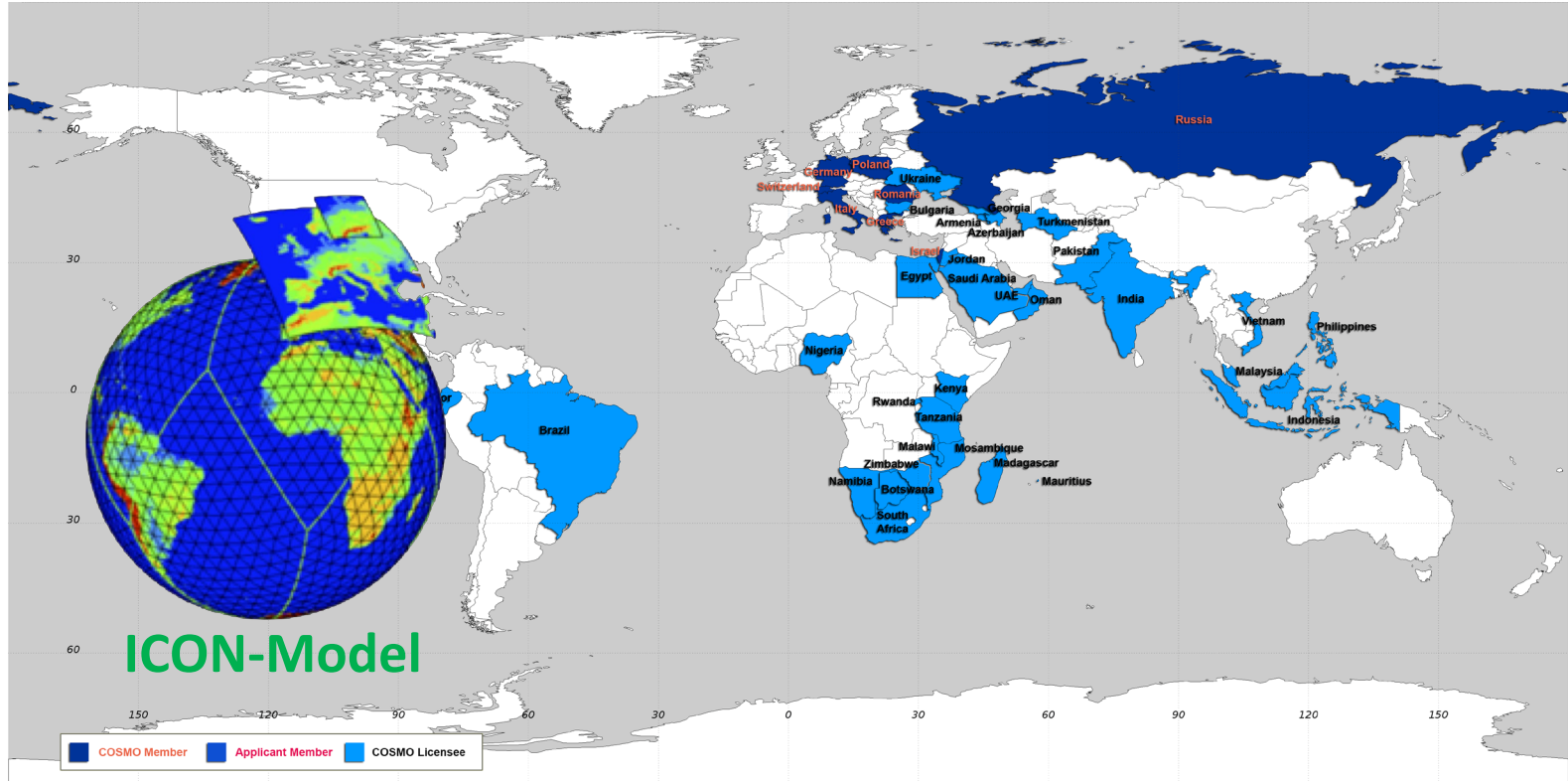
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²CRYOS, School of Architecture, Civil and Environmental Engineering, EPFL, Lausanne, Switzerland

³MeteoSwiss, Zurich, Switzerland

Zurich, 08.08.2019

COSMO (Global usage) & ICON_{Global, LAM, LES}



COSMO & ICON used in climate mode

Single layer snow cover scheme – COSMO

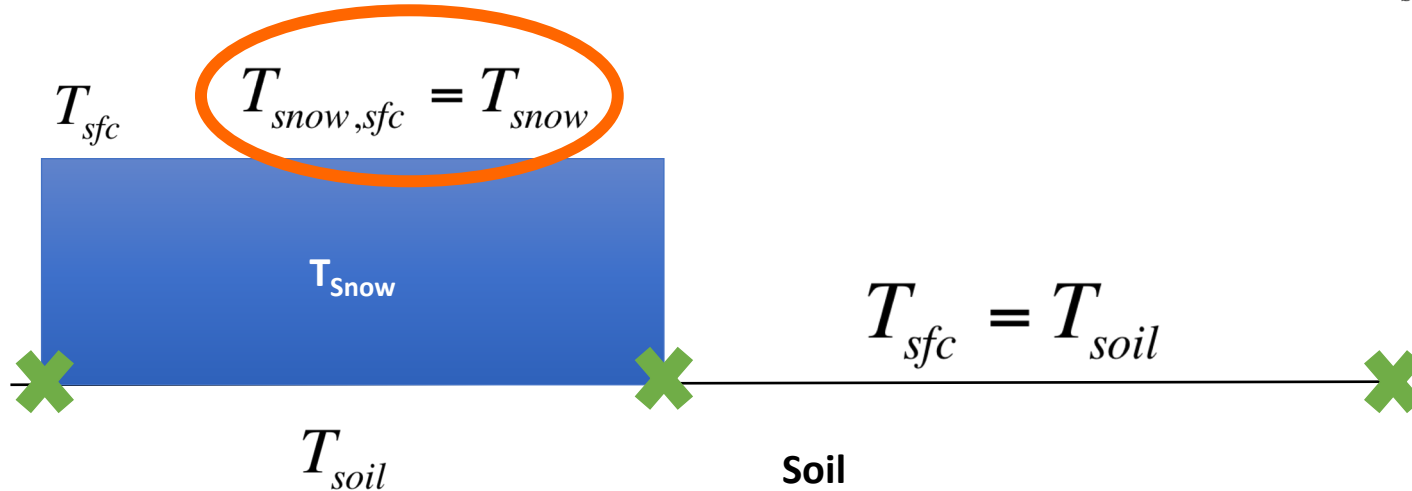
$$\frac{\partial T_{snow}}{\partial t} = \frac{1}{(\rho c \Delta z)_{snow}} (Q_F - Q_G + Q_M)$$

Atmospheric Forcing:

$$Q_F = Q_S^* + Q_L^* + Q_{HE} + Q_{SE}$$

Ground heat Flux:

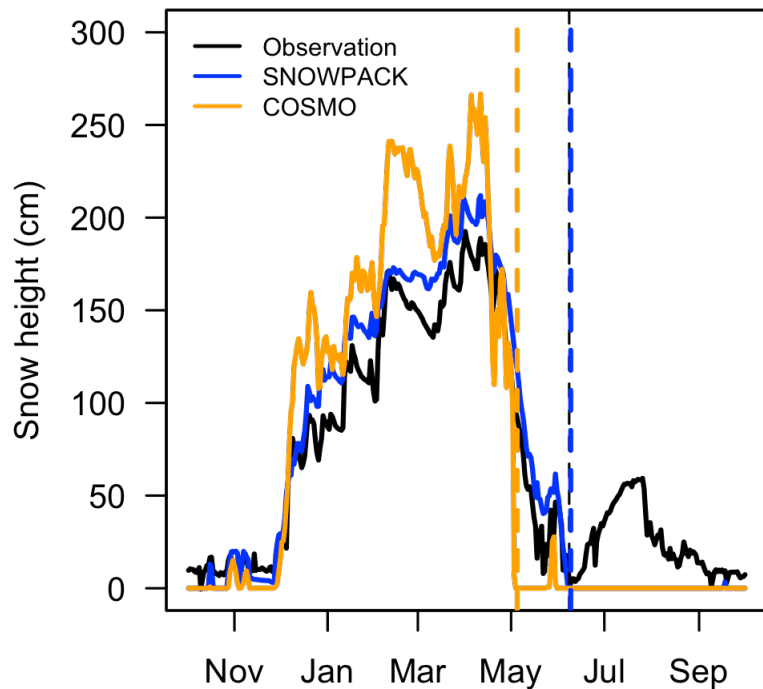
$$Q_G = \lambda_{snow} \frac{T_{snow,sfc} - T_{soil}}{z_{snow}}$$



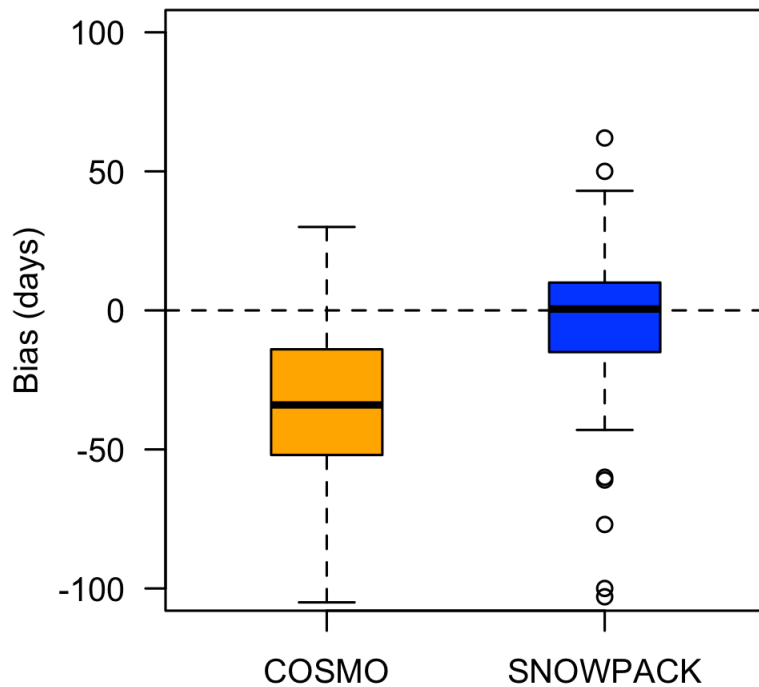
$$\lambda_{snow} = \lambda_{ice} \left(\frac{\rho_s}{\rho_w} \right)^{1.88}$$

COSMO-2 validation (Snow depth)

Weissfluhjoch



IMIS



Single layer snow cover scheme – SnowMIP project

Annals of Glaciology 38 2004
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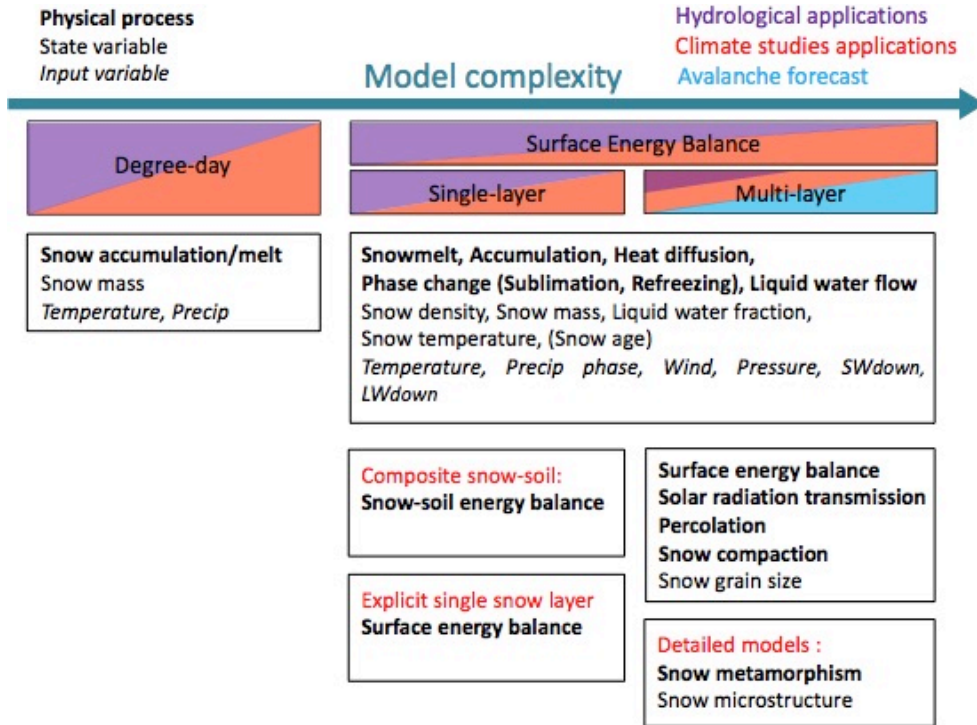
Validation of the energy budget of an alpine snowpack simulated by several snow models (SnowMIP project)

PIERRE ETCHEVERS,¹ ERIC MARTIN,¹ ROSS BROWN,² CHARLES FIERZ,³ YVES LEJEUNE,¹
ERIC BAZILE,⁴ AARON BOONE,⁴ YONG-JIU DAI,⁵ RICHARD ESSERY,⁶ ALBERTO FERNANDEZ,⁷

From Conclusions:

simulated amount of melting that is too small. Finally, the model complexity appears to have a strong impact on the net longwave radiation simulation. Indeed, snow surface temperature is the result of a complex equilibrium in the snowpack, and the models which explicitly simulate internal snow processes simulate the snow surface temperature best. In contrast, model complexity has relatively little

Snow cover schemes – Model complexity

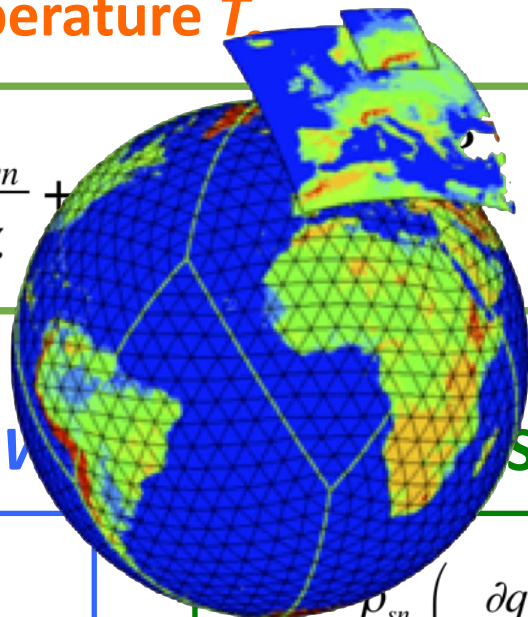


- ‘Good’ models must include ...
- multiple layers,
- new snow density,
- albedo parameterization (SEB),
- heat conduction/equation,
- phase changes,
- water transport.
- compaction/settlement.

Multi-layer snow cover scheme – COSMO

Snow Temperature T_{sn}

$$\rho_{sn} \frac{\partial T_{sn}}{\partial t} = \frac{\partial}{\partial z} \lambda_{sn} \frac{\partial T_{sn}}{\partial z} +$$



Liquid Water W_{liq}

$$\frac{\partial W_{liq}}{\partial t} = M - F - \frac{\partial q}{\partial z}$$

Total Water (SWE) W_{tot}

$$\frac{\partial W_{tot}}{\partial t} = - \frac{\partial q}{\partial z}$$

Snow density ρ_{sn}

$$\frac{\partial \rho_{sn}}{\partial t} = \frac{\rho_{sn}}{W_{tot}} \left(- \frac{\partial q}{\partial z} \left(1 - \frac{\rho_{sn}}{\rho_w} \right) + \rho_{sn} \frac{\rho_w - \rho_i}{\rho_w \rho_i} (M - F) \right) + \sigma(t)$$

Proposed COSMO Priority Task (PT) Project – SAINT



COSMO Priority Task: Snow cover Atmosphere INTeractions (SAINT)

Version 1.0, 13.10.2017

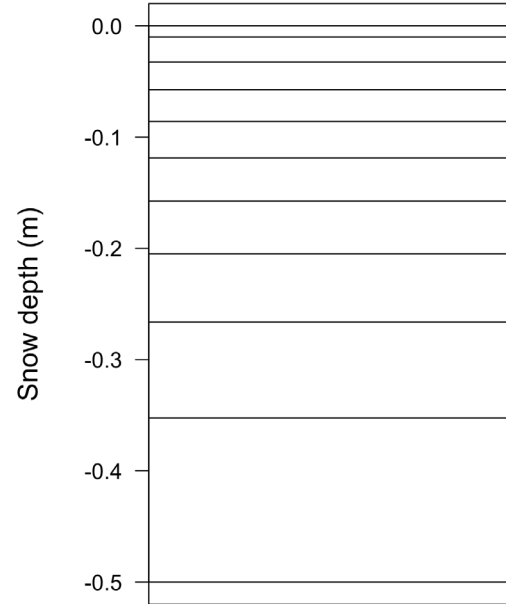
Task Leader: Sascha Bellaire (WSL Institute for Snow and Avalanche Research SLF)

Main goal

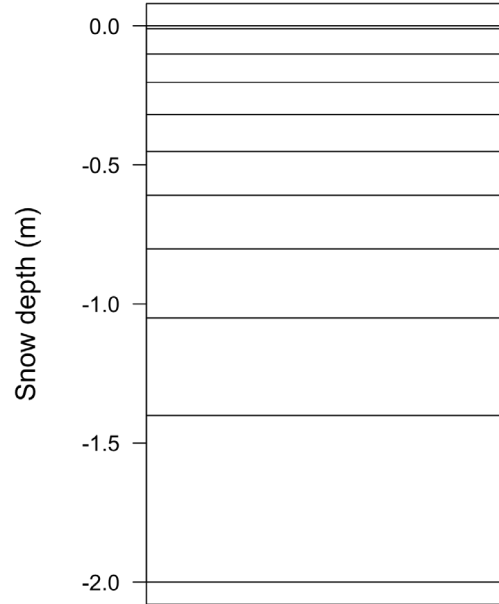
Improving the current multi-layer snow cover scheme

The Scheme: Multi-layer snow cover scheme (MLS; Layering)

0.5 cm



2.0 cm



General Structure:

- Maximum 10 snow layers
- fixed first layer thickness 0.01 m
- Logarithmic increase of layer thickness with depth

Limitations:

- No layer smaller than 0.01 m
- Special treatment for snow depth < 0.01 m

Snow cover Modelling – Volumetric fractions

Formulation in SNOWPACK:

$$\theta_i + \theta_w + \theta_a = 1$$

$$\rho_s = \rho_i \theta_i + \rho_w \theta_w + \rho_a \theta_a$$

θ : Volumetric Fraction (-)

ρ : Density (kg m^{-3}) s, i, w, a, v : subscripts for Snow, Ice, Water, Air, Vapor

Bulk Temperature Equation:

$$\rho_s c_p \frac{\partial T_s}{\partial t} - \frac{\partial}{\partial z} (k_{\text{eff}} \frac{\partial T_s}{\partial z}) = [Q_{pc}] + [Q_{mm}] + Q_{sw};$$

$$[Q] = \text{Wm}^{-3} \text{ Volumetric Heat Source}$$

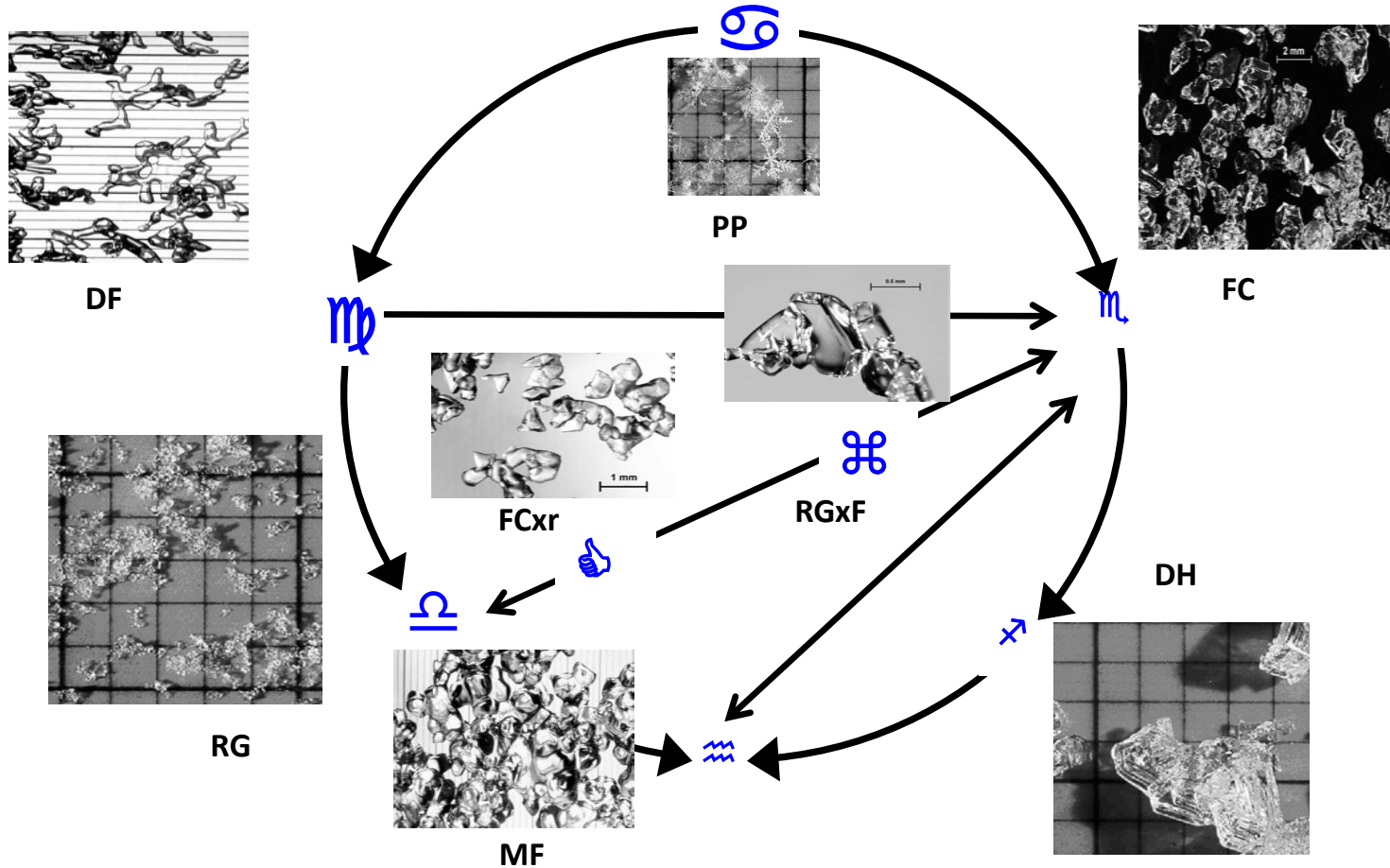
$$\rho_s c_p = \rho_i c_i \theta_i + \rho_w c_w \theta_w + \rho_a c_a \theta_a$$

T_s : Temperature of Snow (K)

c_p : Heat Capacity ($\text{J kg}^{-1} \text{K}^{-1}$)

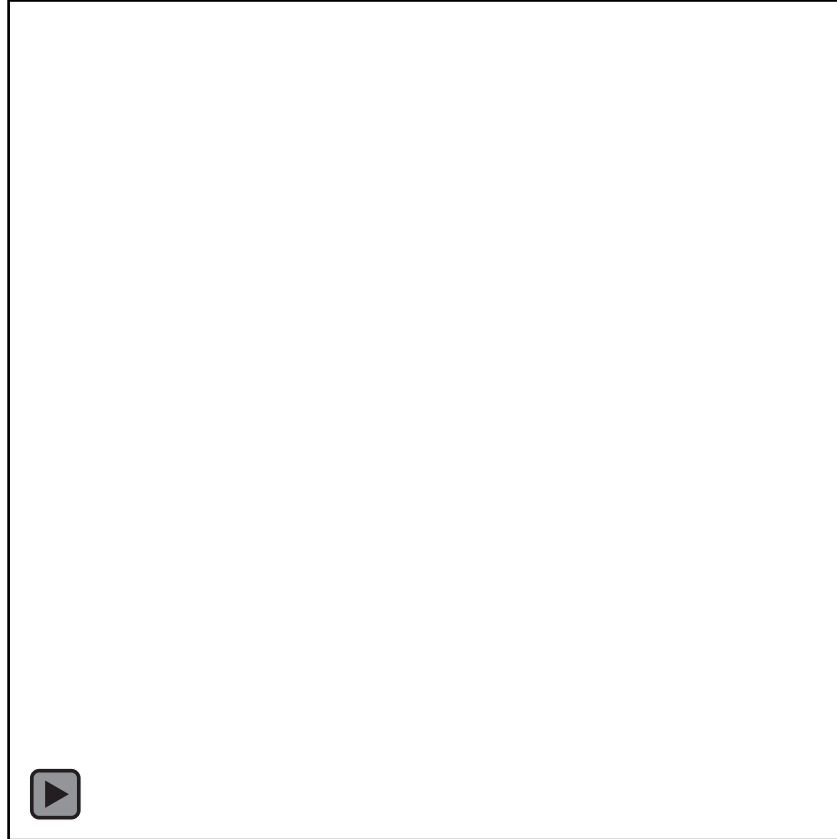
k_{eff} : Effective Thermal Conductivity ($\text{W m}^{-1} \text{K}^{-1}$)

Snow Metamorphism: Grain Types



Snow Metamorphism: Faceting (CT images)

cold



warm

Movie: SLF

Heat Equation – Implementation

1D heat equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}; \quad 0 \leq x \leq L; \quad t \geq 0$$

- Solve the one-dimensional heat equation.
- Setup a tridiagonal matrix for set of linear equations for each layer.
- Solved using the Thomas-Algorithm

```
! Setup tridiagonal matrix for set of linear equations for each layer ...
! ... TOP LAYER
dz_low = zm_sn(top_sn)
! ... TOP LAYER
a(top_sn) = 0.0_dp
b(top_sn) = 1 + (1 - cn) * alpha(top_sn) * hcon_sn_now(top_sn)/dz_low - alpha(top_sn)*dlw_u_sn
c(top_sn) = - (1 - cn) * alpha(top_sn) * hcon_sn_now(top_sn)/dz_low
d(top_sn) = t_sn(top_sn) + alpha(top_sn) * (for_sn - lw_u_sn*t_sn(top_sn) + cn*hdif_sn(top_sn))

! ... INNER LAYERS
DO i = top_sn+1, bot-1, 1
  dz_up = zm_sn(i) - zm_sn(i-1)
  dz_low = zm_sn(i+1) - zm_sn(i)
  a(i) = - (1 - cn) * alpha(i) * hcon_sn_now(i-1)/dz_up
  b(i) = 1 + (1 - cn) * alpha(i) * (hcon_sn_now(i) /dz_low + hcon_sn_now(i-1)/dz_up)
  c(i) = - (1 - cn) * alpha(i) * hcon_sn_now(i) /dz_low
  d(i) = t_sn(i) + cn*alpha(i) * (hdif_sn(i) - hdif_sn(i-1))
ENDDO

! ... BOTTOM LAYER
dz_up = zm_sn(bot) - zm_sn(bot-1)
a(bot) = - (1 - cn) * alpha(bot) * hcon_sn_now(bot-1)/dz_up
b(bot) = 1 + (1 - cn) * alpha(bot) * hcon_sn_now(bot-1)/dz_up
c(bot) = 0.0_dp
d(bot) = t_sn(bot) - cn*alpha(bot-1) + alpha(bot)*hdif_sn(bot)

! Solve the system - Thomas Algorithm
! NOTE: The following can be put in a subroutine
DO i = 1, bot, 1
  e(i) = t_sn(i)
ENDDO

beta = b(top_sn)
! Forward substitution
DO j = 1, bot, 1
  IF(j == 1) THEN
    e(j) = d(j) / beta
  ELSE
    gama(j) = c(j-1) / beta
    beta = b(j) - a(j) * gama(j)
    e(j) = (d(j) - a(j) * e(j-1)) / beta
  ENDIF
END DO ! end of j

! Backward substitution
DO j = bot-1, 1, -1
  e(j) = e(j) - gama(j+1) * e(j+1)
ENDDO
```

Top layer

for_sn = forcing = SEB

Snow cover scheme (MLS) – Implementation

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150 USE sfc_snow
151 USE snow_utilities
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New snow model called in TERRA ...

... consists of 2 (or 3) subroutines called ...

CALL snow_forcing(...)

- snow specific atmospheric forcing

CALL snow_on_soil(...)

- layering/new snow
- 'heat conduction'
- phase changes
- water transport
- settling
- re-meshing
- ...

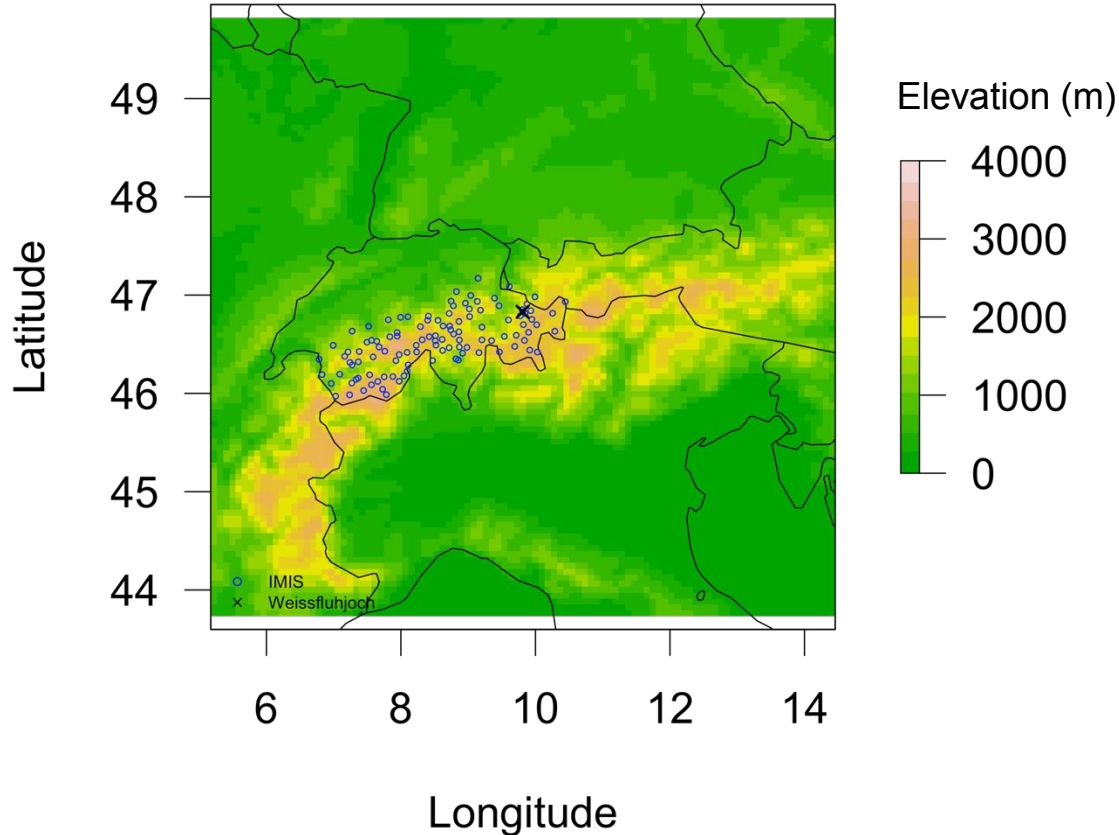
CALL interface_snow(...)

- preparation of required input (# layers, layering, heat conductivity etc.) for solving heat equation in TERRA

... before solving the heat equation in TERRA

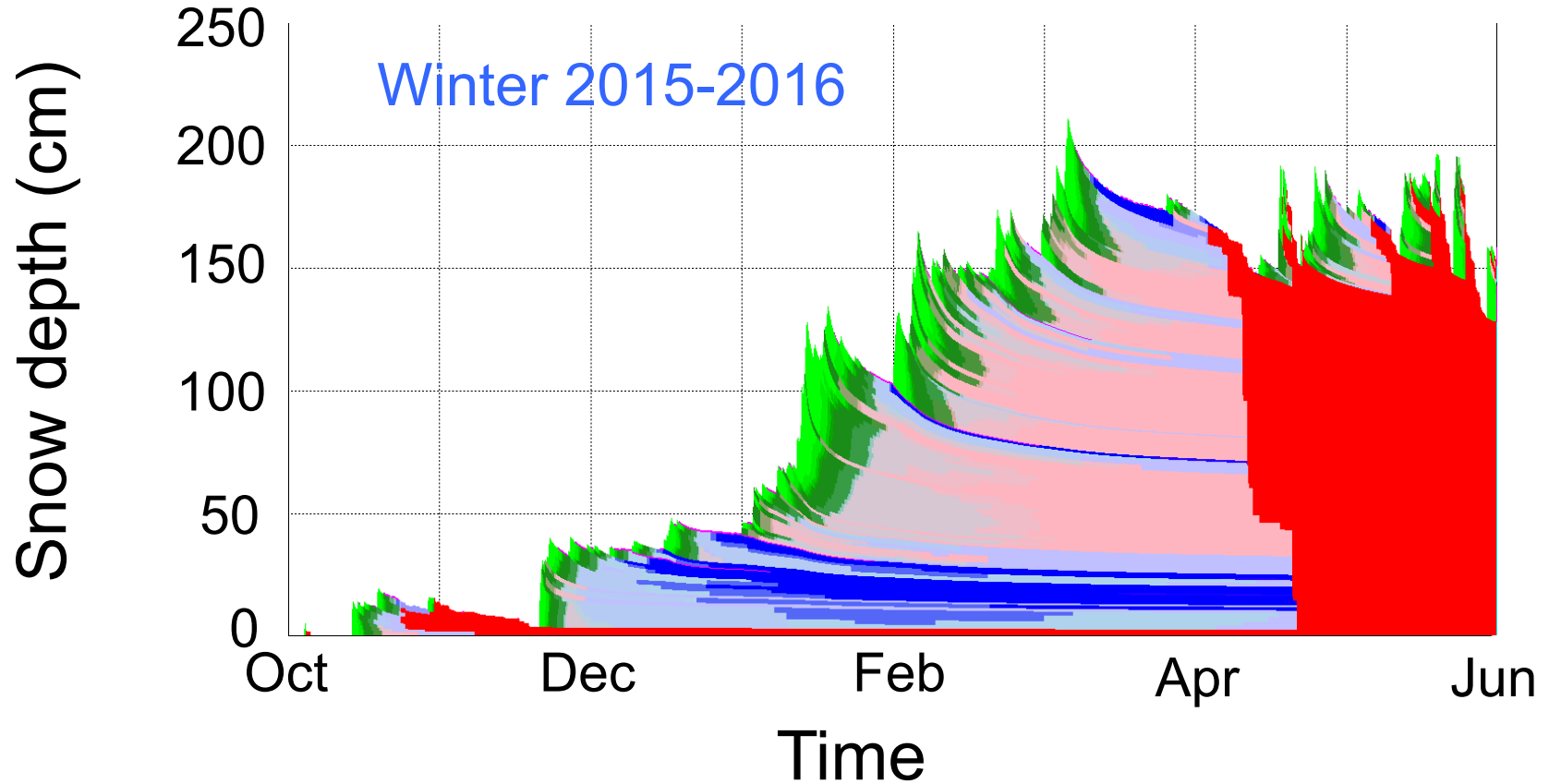
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5646
5647     END DO
5648     END DO           ! soil layers
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5650 !MR: 05.05.2017 and later: heat-budget for inner soil layers substituted by a slightly different notation: >
5651 !-----
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5653 !*****
5654 !MR: 05.05.2017: modified heat-budget for boundary soil layers including a single-layer snow-cover: <
5655 !*****
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```

The Method: Validation (COSMO-7)

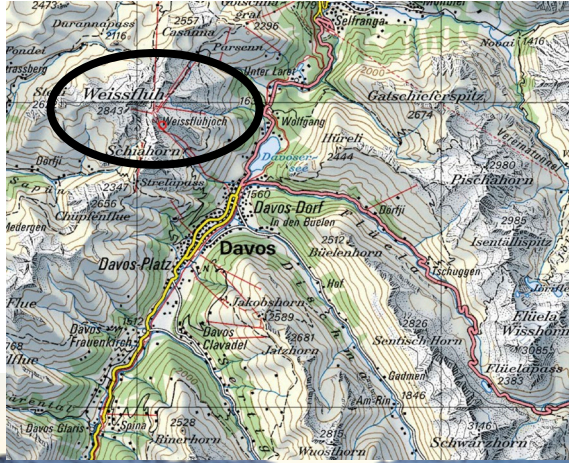


- ... ~ 700 km x 700 km domain centered around Davos ...
- ... covering most of the Alpine ridge ...
- ... computationally inexpensive ...
- .. boundary conditions from COSMO-7 analysis ...
- ... 72-hour forecast/hindcast

Surface Temperature – Benchmarking (SNOWPACK vs. MLS)



Heat Equation – Benchmarking (Observations)

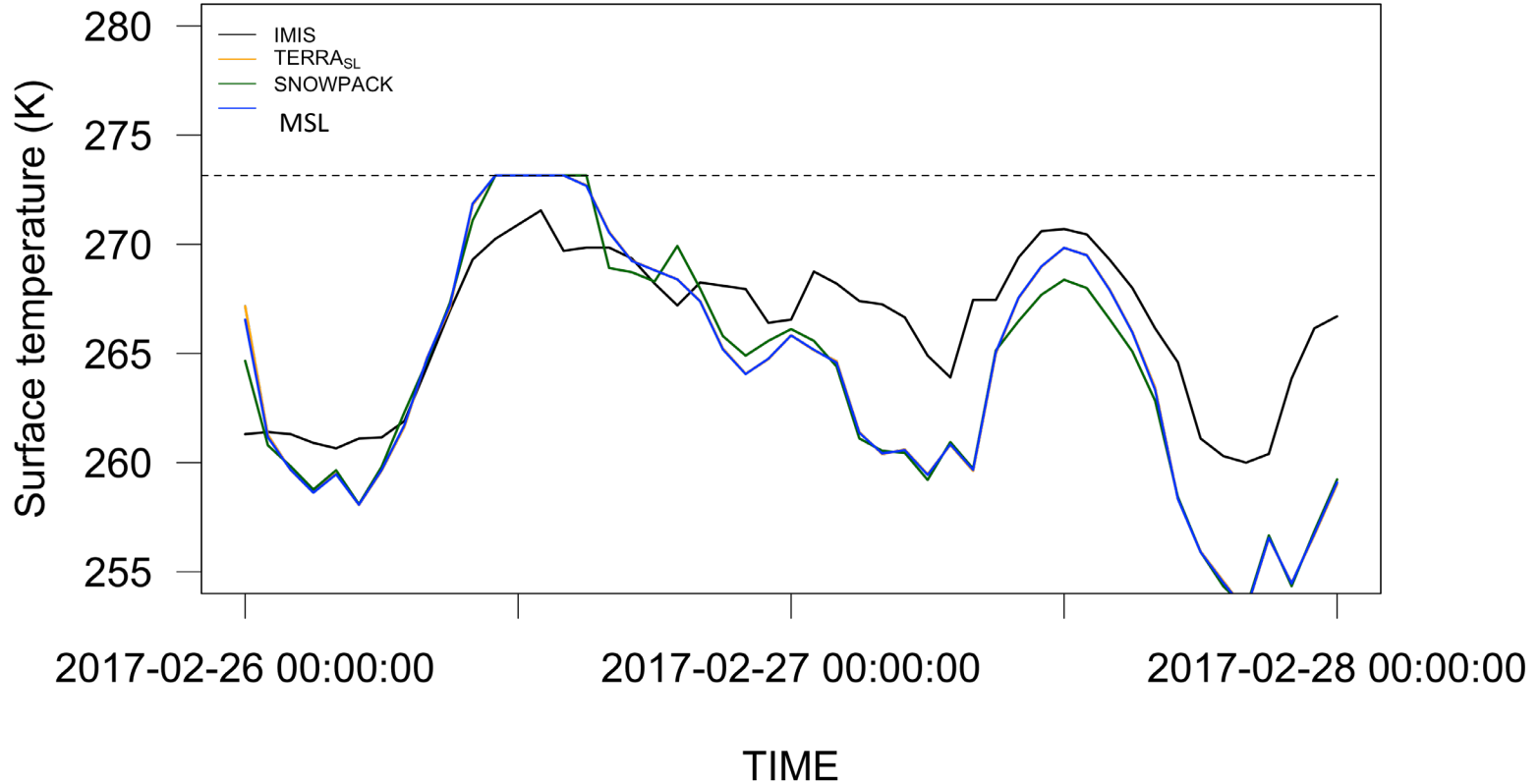


Experimental Site Weissfluhjoch, Davos, Switzerland



Heat Equation – Benchmarking (SNOWPACK vs. MLS)

Weissfluhjoch



Heat Equation – Snow temperature profile

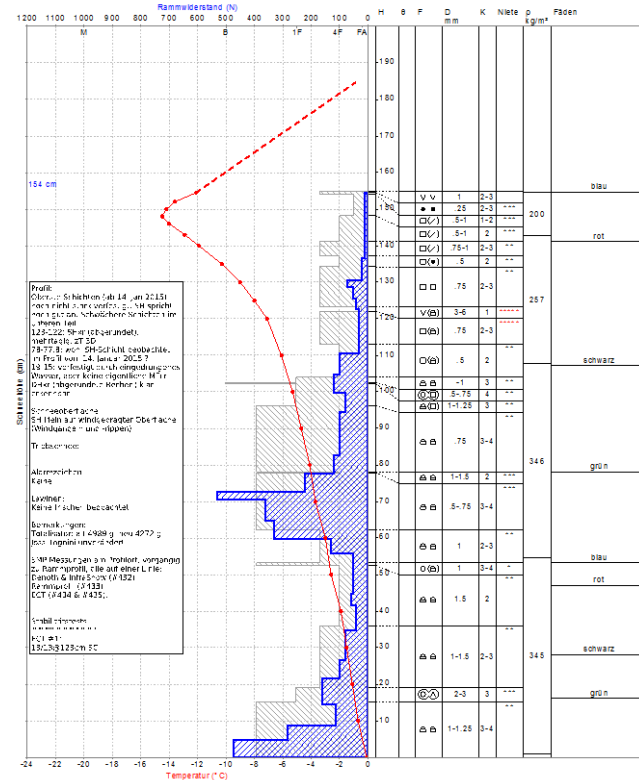
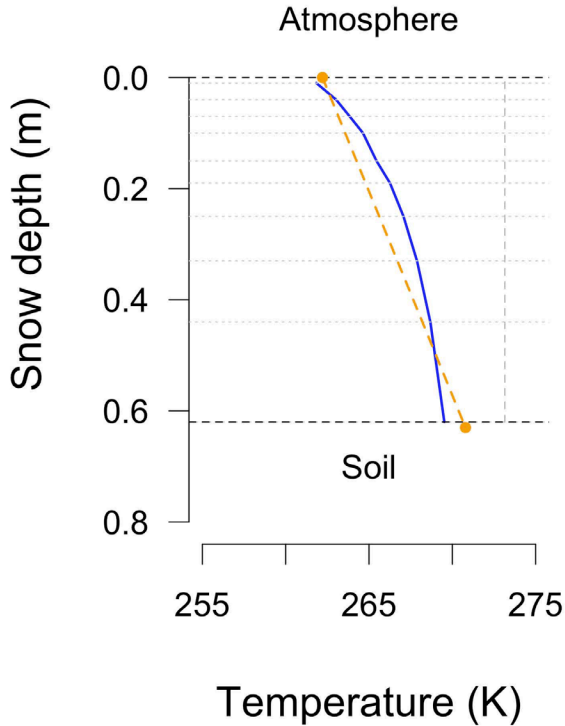
2017-02-16 00:00

Schneeprofil: SWJ
 Beobachter: C. Fierz / Martina Sättele
 Profilnr.: 1
 Gesamtwasserwert: 479.9 mm (HS: 153 cm)
 Hasty Pfl: Nein
 Wetter/Niederschlag: Ober lange strecken beinahe windstill (nur karabatische Winde von NW), dann drehen auf S am Mittag
 Bemerkungen: HS (MIS)=148 cm, Tsst (MIS)=-14.9 °C @ 10.00

Ort: GR Davos Weissfluhjoch / Versuchsfeld
 Höhe ü. M.: 2540 m
 Exposition: fach / Neigung: *
 Koordinaten: 780872 / 189272
 Mett. Raumgew.: 313.7 kg/m³
 Anisprofil: Nein

Datum/Zeit: 14.02.2016 09:45
 Lufttemp: -0.9 °C
 Bewölkung: leicht bewölkt (1-2/8)
 Wind: NW / 1 km/h
 Mitt. Rammwiderstand: 117 N
 Pistanprofil: Nein

➤ Neusnee / Flz • kleine Runce □ kantig ▲ Tiefener V Oberflächener ○ Schneizform ■ Eisamele ◊ kantig, abgerundet ∆ Graupel



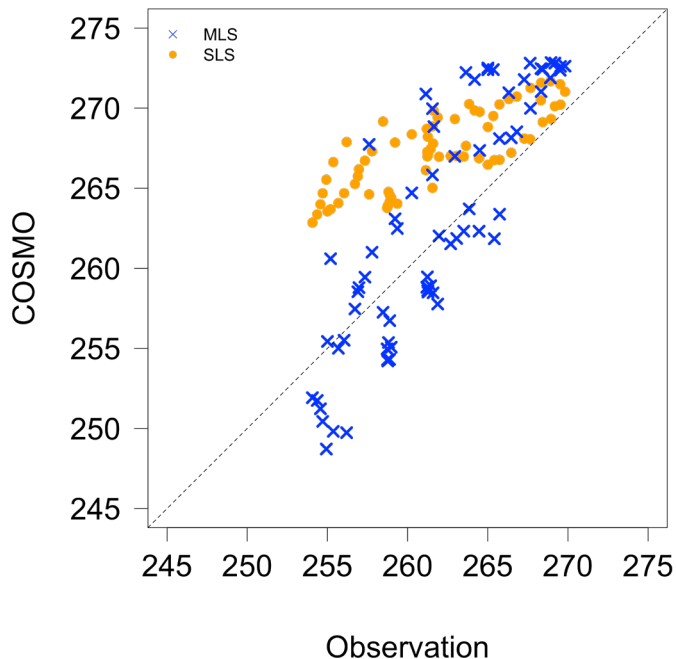
Intercantonal Measurement and Information System (IMIS)



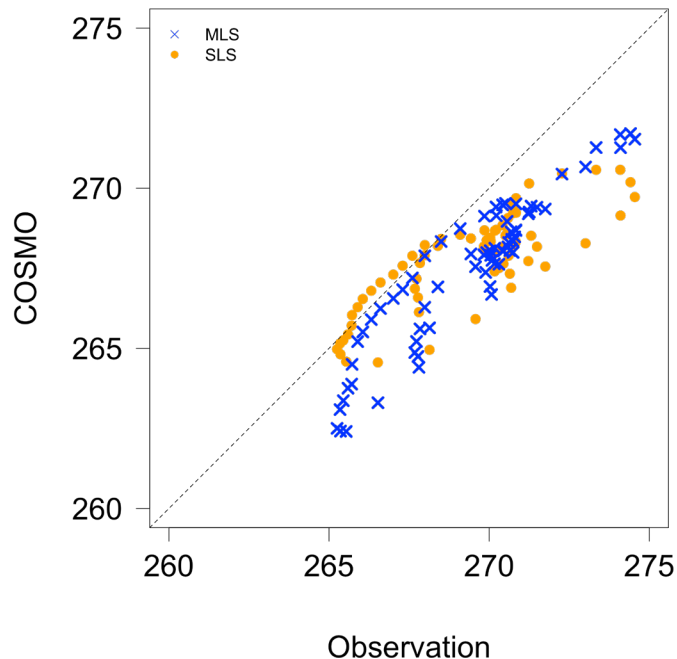
Results – Forcing (surface Temperature)

All IMIS (N = 112)

T_SNOW



T (1st level)

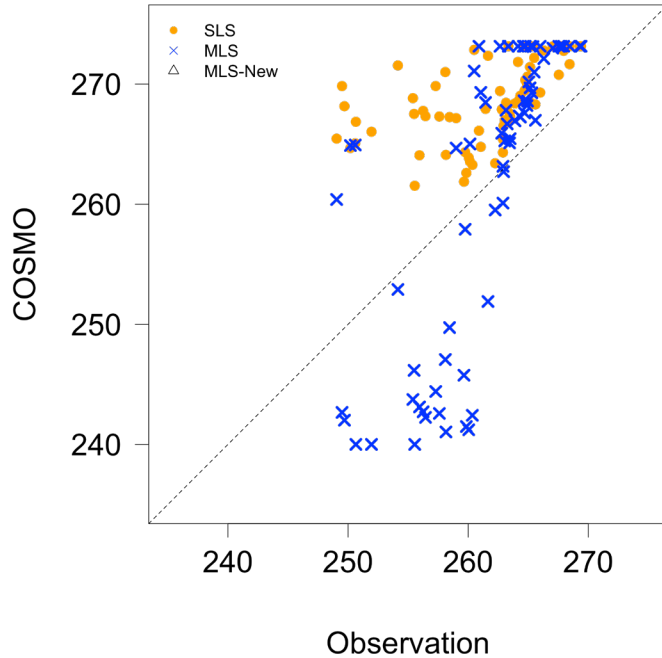


● = Single layer snow cover scheme (SLS)

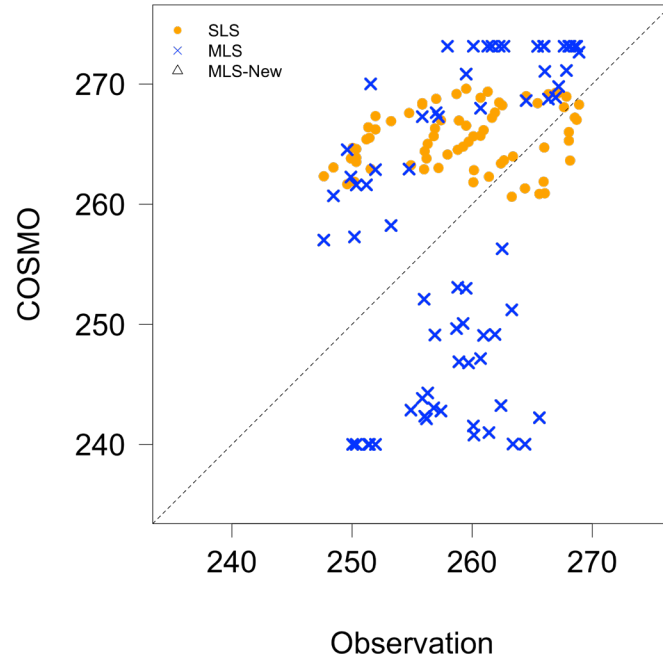
X = Multi-layer snow cover scheme (MLS)

Results – Forcing (Surface Temperature)

Weissfluhjoch
(FOR_E + FOR_D = 0.93)



Boveire-PointedeToules
(FOR_E = FOR_D = 0)



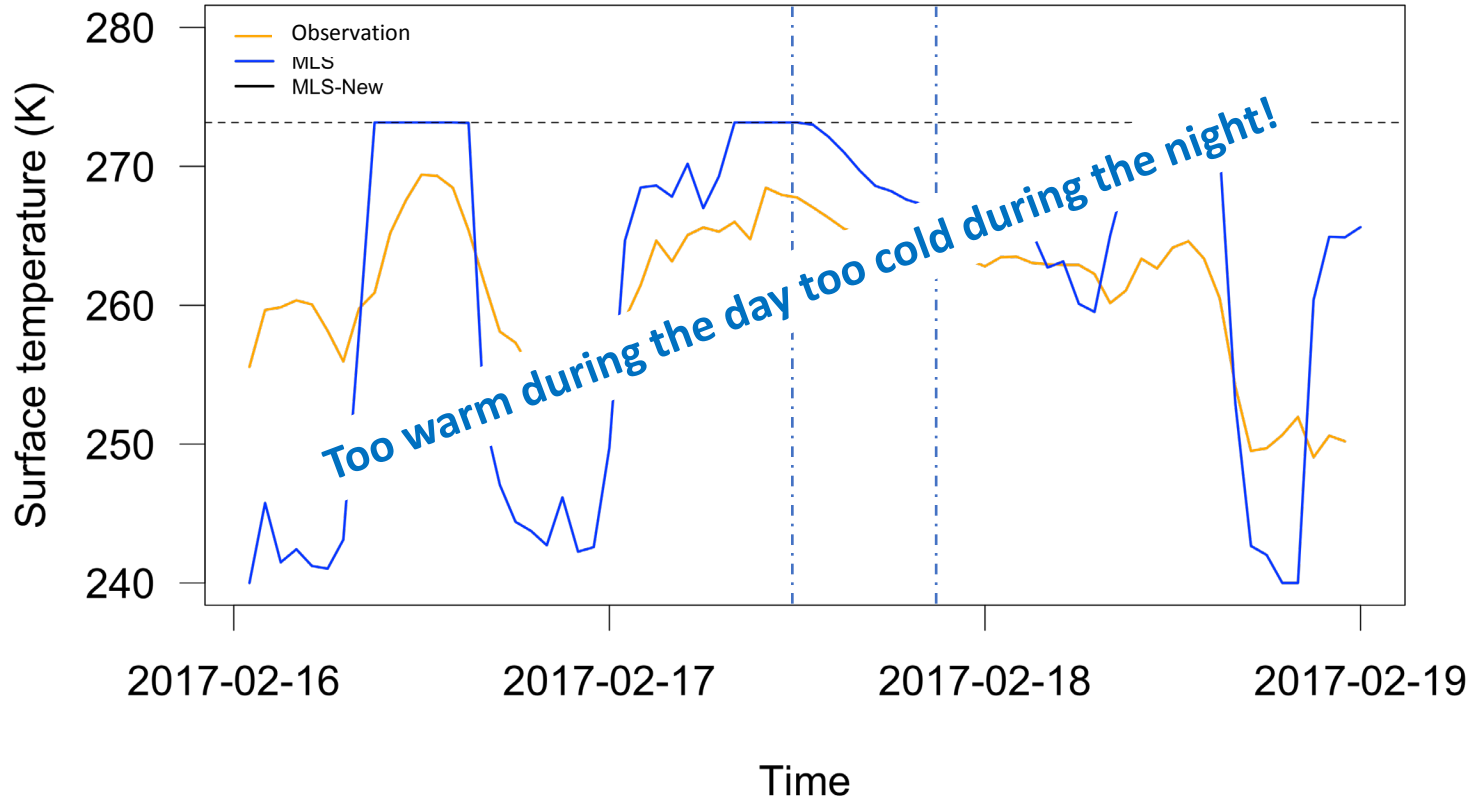
● = Single layer snow cover scheme (SLS)

X = Multi-layer snow cover scheme (MLS)

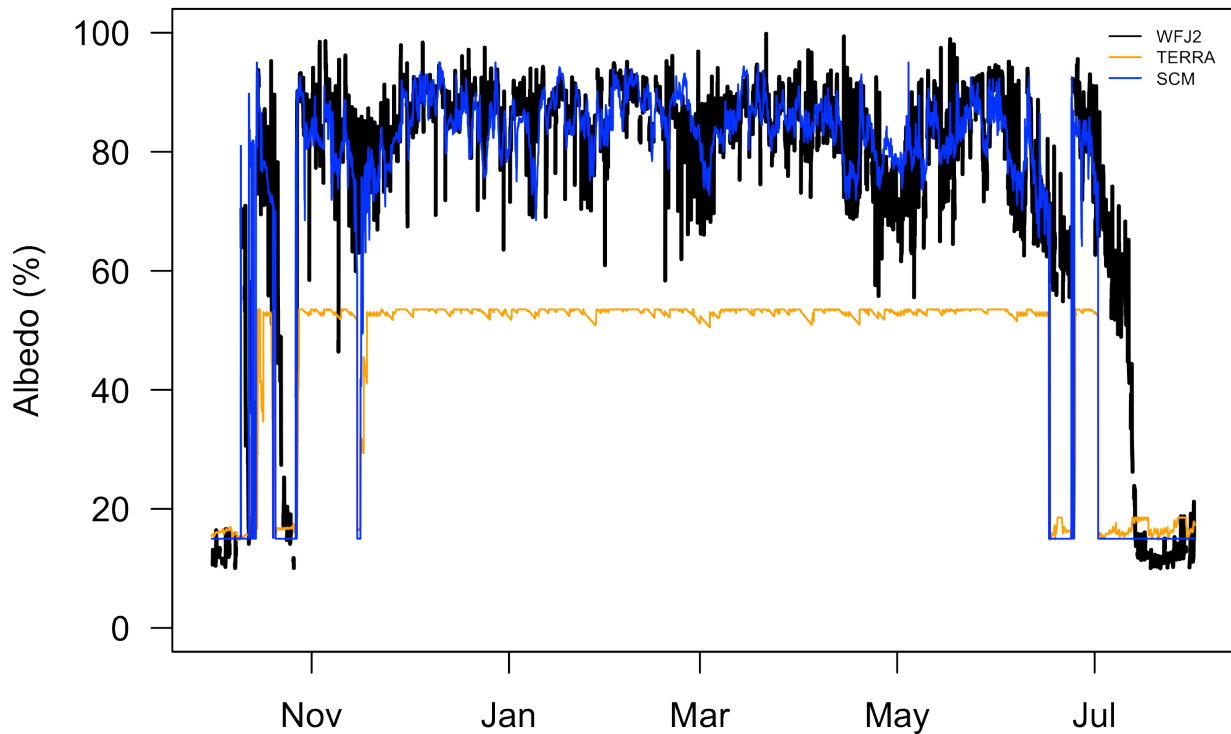
Results – Forcing (Surface Temperature)

Weissfluhjoch

Snow



Results – Forcing (Albedo)



P_{rate} = Precipitation rate

T_{SFC} = Snow surface temperature

T_{10m} = Air Temperature 10 m

Time

$$\alpha_{SCM} = a + b \times P_{rate} + c \times T_{SFC} - d \times T_{10m}$$

Results – Forcing (Transfer Coefficients)

Boundary-Layer Meteorology

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How do Stability Corrections Perform in the Stable Boundary Layer Over Snow?

Authors [Authors and affiliations](#)

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Sensible heat flux:

$$H = \rho c_p C_H \bar{U} \Delta\theta,$$

Stability Corrections:

$$\psi_m (T, T_{sn}, \bar{U}) = a_1 B + b_1 S,$$

$$\psi_s (T, T_{sn}, \bar{U}) = a_2 B + b_2 S,$$

$$B = \Delta T / \bar{T}$$

$$S = z_{\text{ref}} g / \bar{U}^2$$

Transfer Coefficient:

$$C_H = \frac{k^2}{\left[\ln \left(\frac{z_{\text{ref}}}{z_{0M}} \right) - \psi_m(\zeta) \right] \left[\ln \left(\frac{z_{\text{ref}}}{z_{0M}} \right) - \psi_s(\zeta) \right]},$$

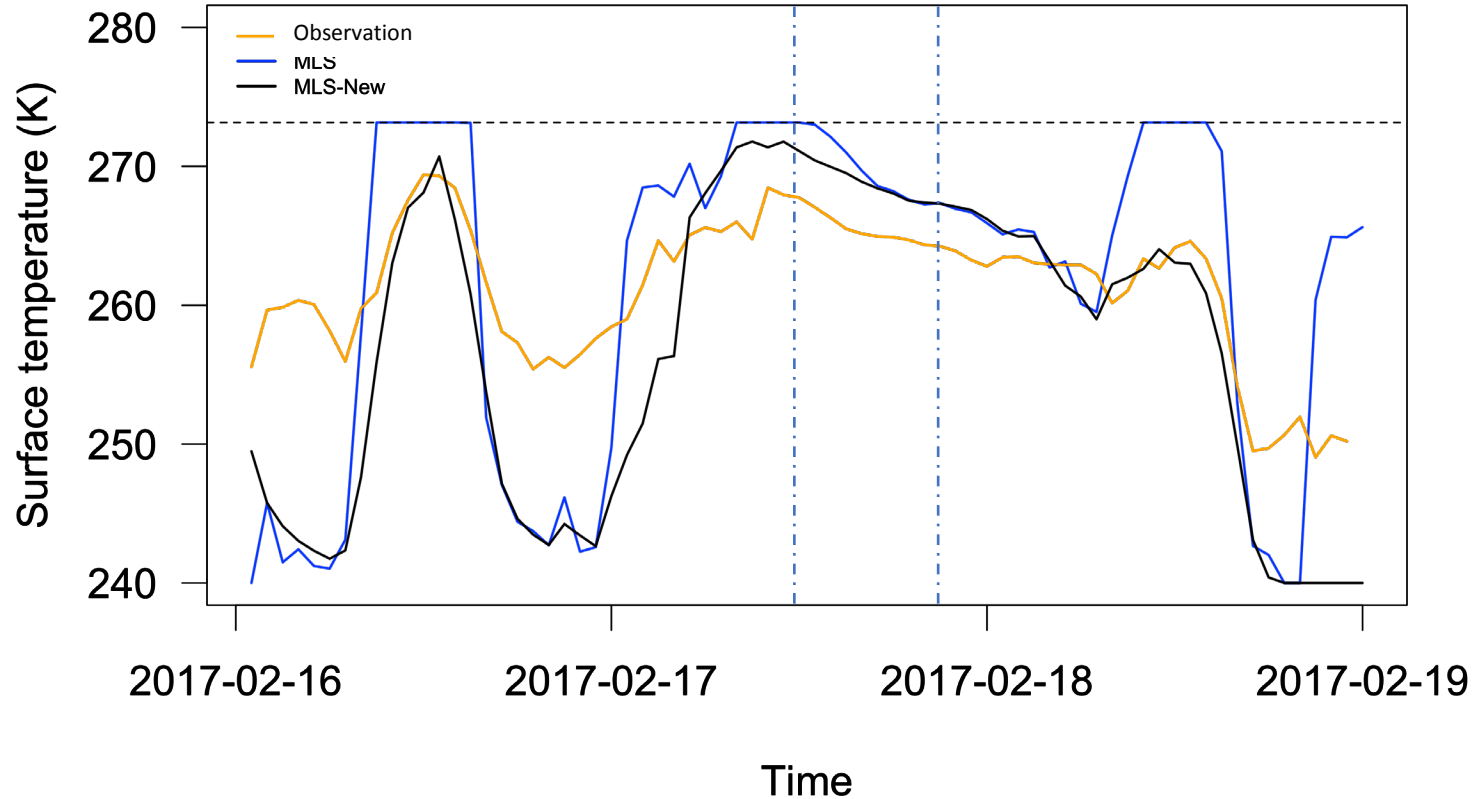
where $k = 0.4$ is the von Kármán constant, $\zeta = (-k z_{\text{ref}} g T_*) / (\theta_s u_*^2)$ is the modelled stability parameter (stability parameter henceforth), $u_* = k \bar{U} (\ln(z_{\text{ref}}/z_{0M}) - \psi_m)^{-1}$ is the modelled friction velocity, $T_* = k (\theta_s - \theta_{z_{\text{ref}}}) (\ln(z_{\text{ref}}/z_{0M}) - \psi_s)^{-1}$ is the modelled temperature scale, z_{0M} is the aerodynamic roughness length and ψ_m and ψ_s are the stability corrections for momentum and scalars. In our analysis, we used the simple approach that the roughness

test site	a_1	b_1	test site	a_2	b_2
WFJ07 (3 m)	3.227	0.0043	WFJ07 (3 m)	-982.90	-0.0005
WFJ07 (5 m)	-4.441	0.0025	WFJ07 (5 m)	-642.51	0.0009
WFJ11	-30.74	0.0008	WFJ11	-1135.4	-0.0015
PM07 NWW	-191.93	0.0008	PM07 NWW	-751.73	-0.0005
PM07 SEE	-29.55	0.0090	PM07 SEE	-692.74	-0.0123
GR00 (1 m)	-145.41	-0.0914	GR00 (1 m)	-378.92	-2.0489
GR00 (2 m)	-179.56	-0.0369	GR00 (2 m)	-243.93	-0.7448
Universal	-65.35	0.0017	Universal	-813.21	-0.0014

Results – Forcing (Transfer Coefficients)

Weissfluhjoch

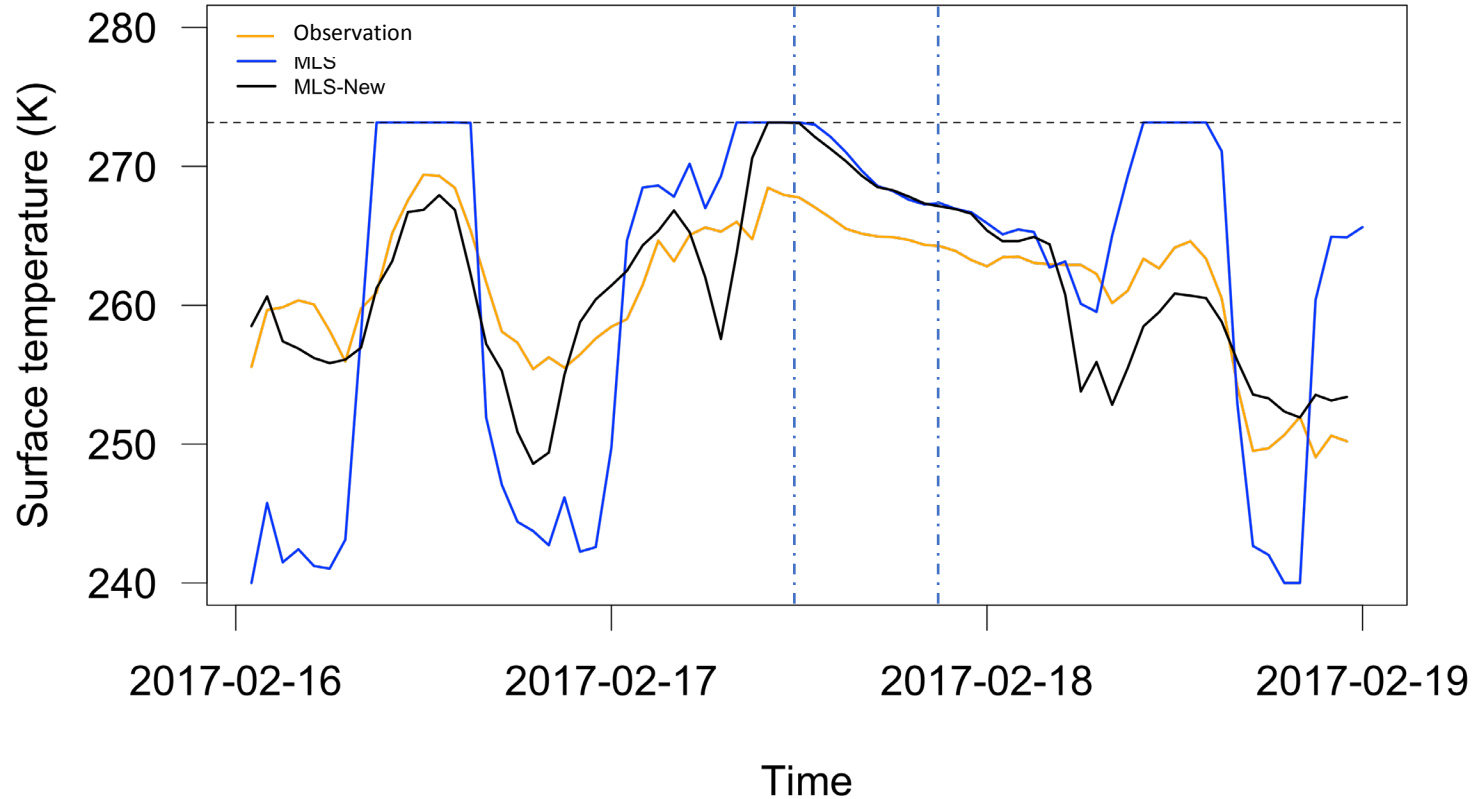
Snow



Results – Forcing (Transfer Coefficients)

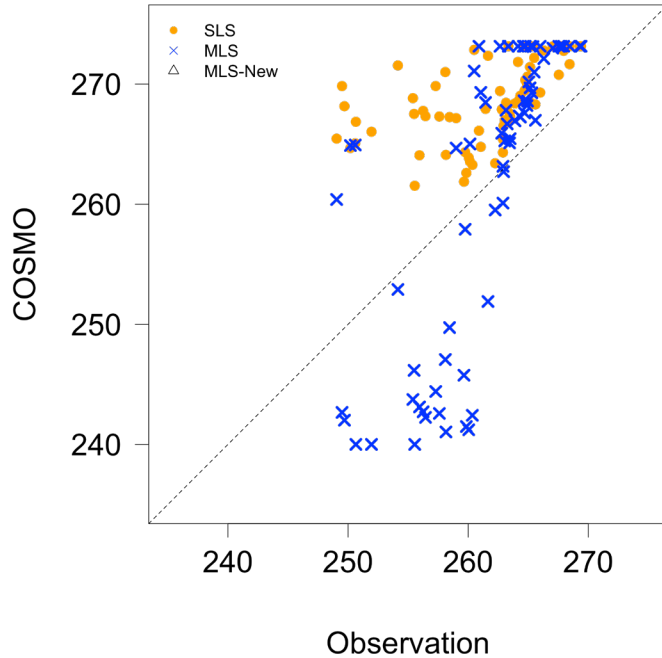
Weissfluhjoch

Snow

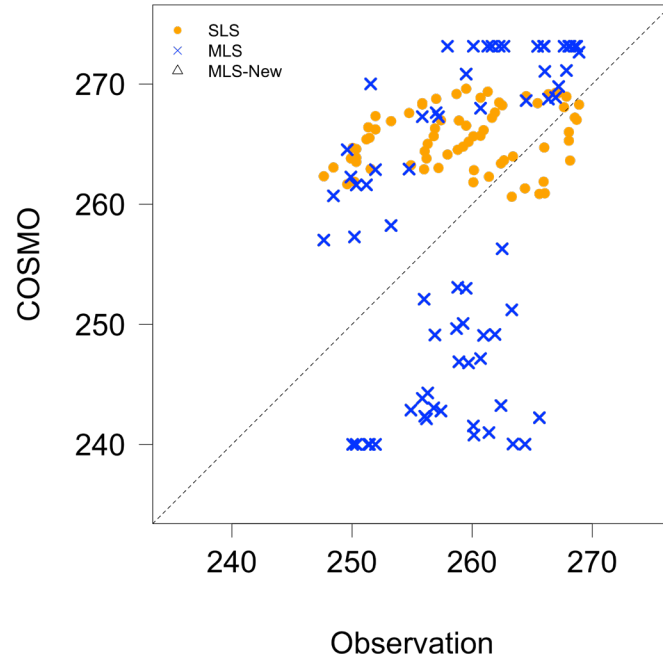


Results – Forcing (Surface Temperature)

Weissfluhjoch
(FOR_E + FOR_D = 0.93)



Boveire-PointedeToules
(FOR_E = FOR_D = 0)

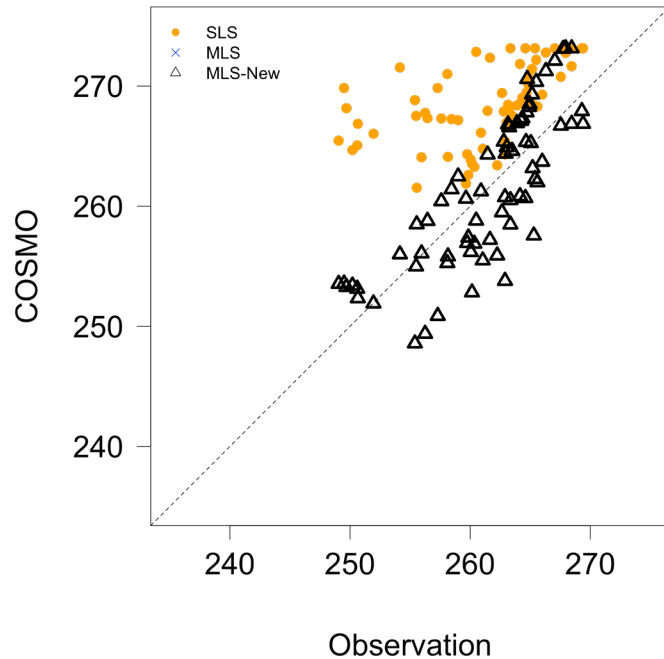


● = Single layer snow cover scheme (SLS)

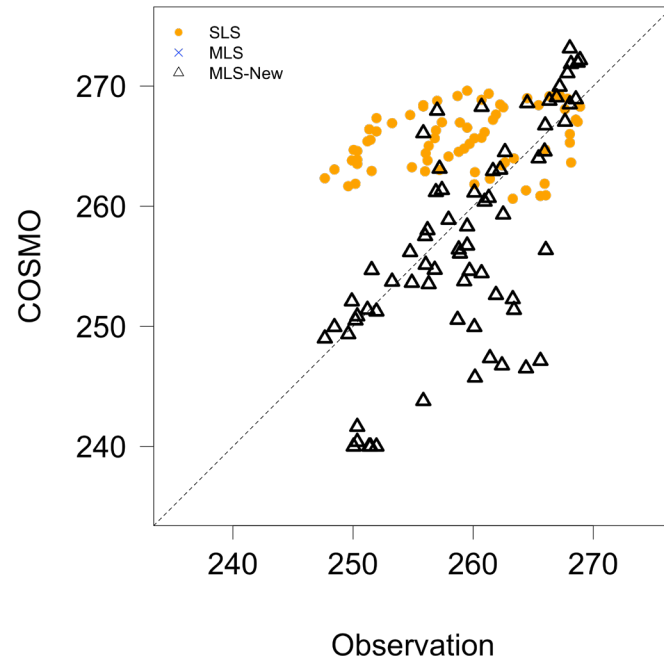
× = Multi-layer snow cover scheme (MLS)

Heat Equation – Initial Results

Weissfluhjoch
(FOR_E + FOR_D = 0.93)



Boveire-PointedeToules
(FOR_E = FOR_D = 0)



△ = Multi-layer snow cover scheme (MLS) with new flux parameterizations

Snow cover scheme (MLS) – Implementation

```
39 !!=====
40
41 MODULE sfc_terra
42
43 !!=====
44
148
149 !SB <
150 USE sfc_snow
151 USE snow_utilities
152 !SB >
153
154 !-----
155
---
```

New snow model called in TERRA ...

... consists of 2 (or 3) subroutines called ...

CALL snow_forcing(...)

- snow specific atmospheric forcing

CALL snow_on_soil(...)

- layering/new snow
- 'heat conduction'
- phase changes
- water transport
- settling
- re-meshing
- ...

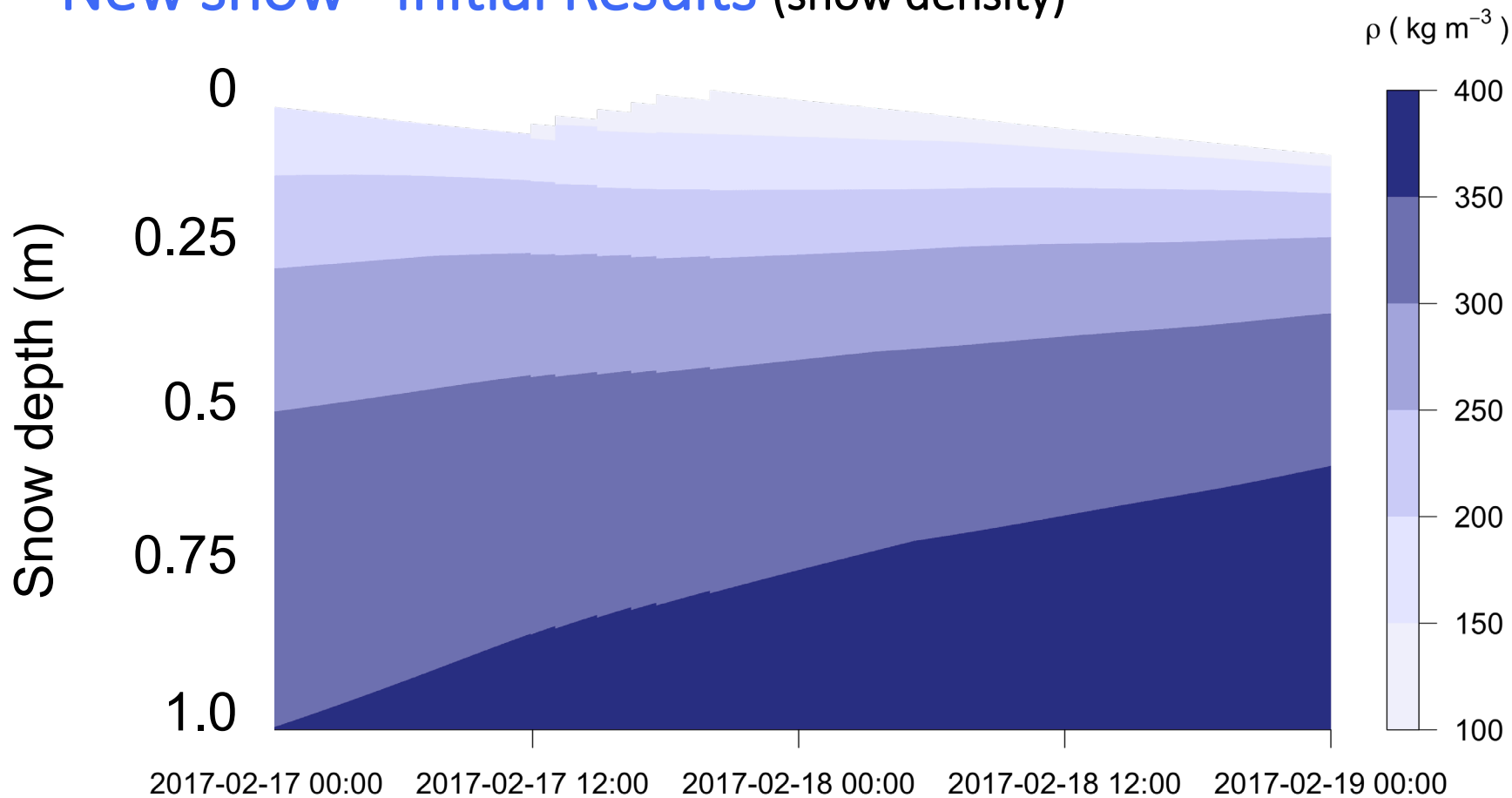
CALL interface_snow(...)

- preparation of required input (# layers, layering, heat conductivity etc.) for solving heat equation in TERRA

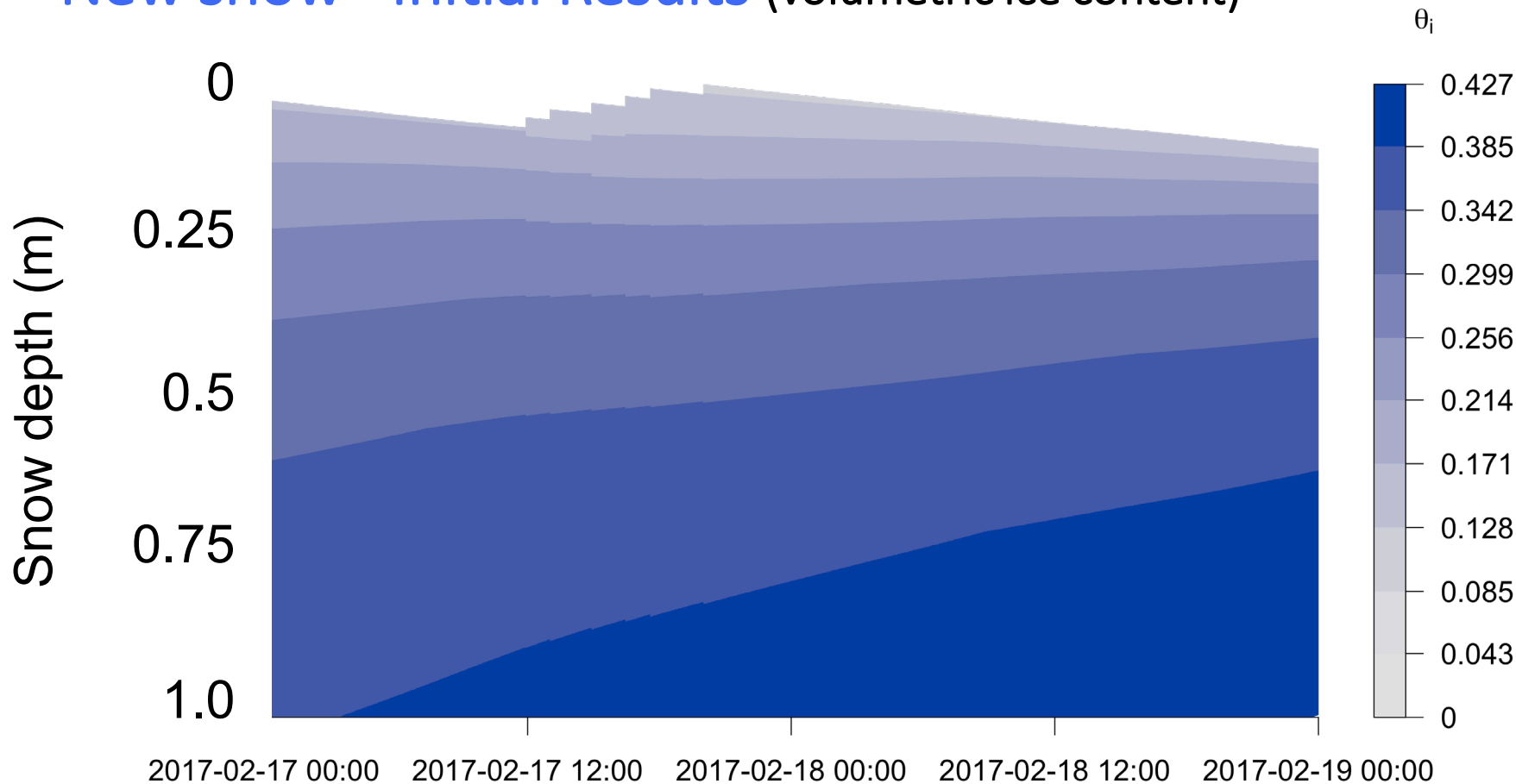
... before solving the heat equation in TERRA

```
5646
5647     END DO
5648     END DO           ! soil layers
5649
5650 !MR: 05.05.2017 and later: heat-budget for inner soil layers substituted by a slightly different notation: >
5651 !-----
5652
5653 !*****
5654 !MR: 05.05.2017: modified heat-budget for boundary soil layers including a single-layer snow-cover: <
5655 !*****
5656
```

New snow— Initial Results (snow density)



New snow— Initial Results (volumetric ice content)



Snow cover modelling: SNOWPACK (Phase Changes)

Treatment in SNOWPACK:

- Calculate „Hypothetical“ Temperature
- Determine mass & energy associated with phase change.

$$\Delta T = T_s - T_{melt}$$

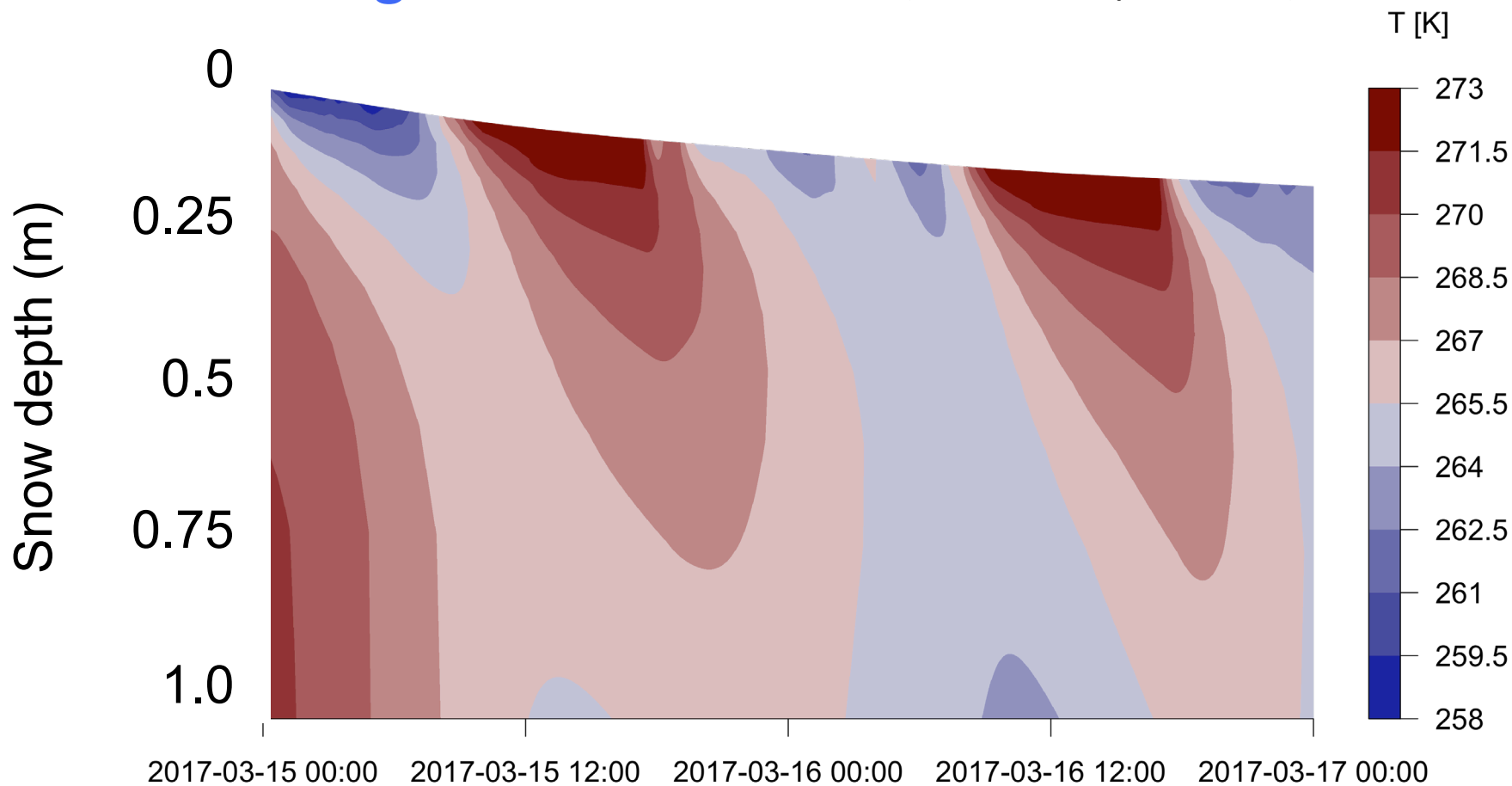
$$\Delta \theta_w = \frac{c_s \theta_i \rho_i \Delta T}{L_f \rho_w}$$

$$\Delta \theta_i = \frac{\rho_w \Delta \theta_w}{\rho_i}$$

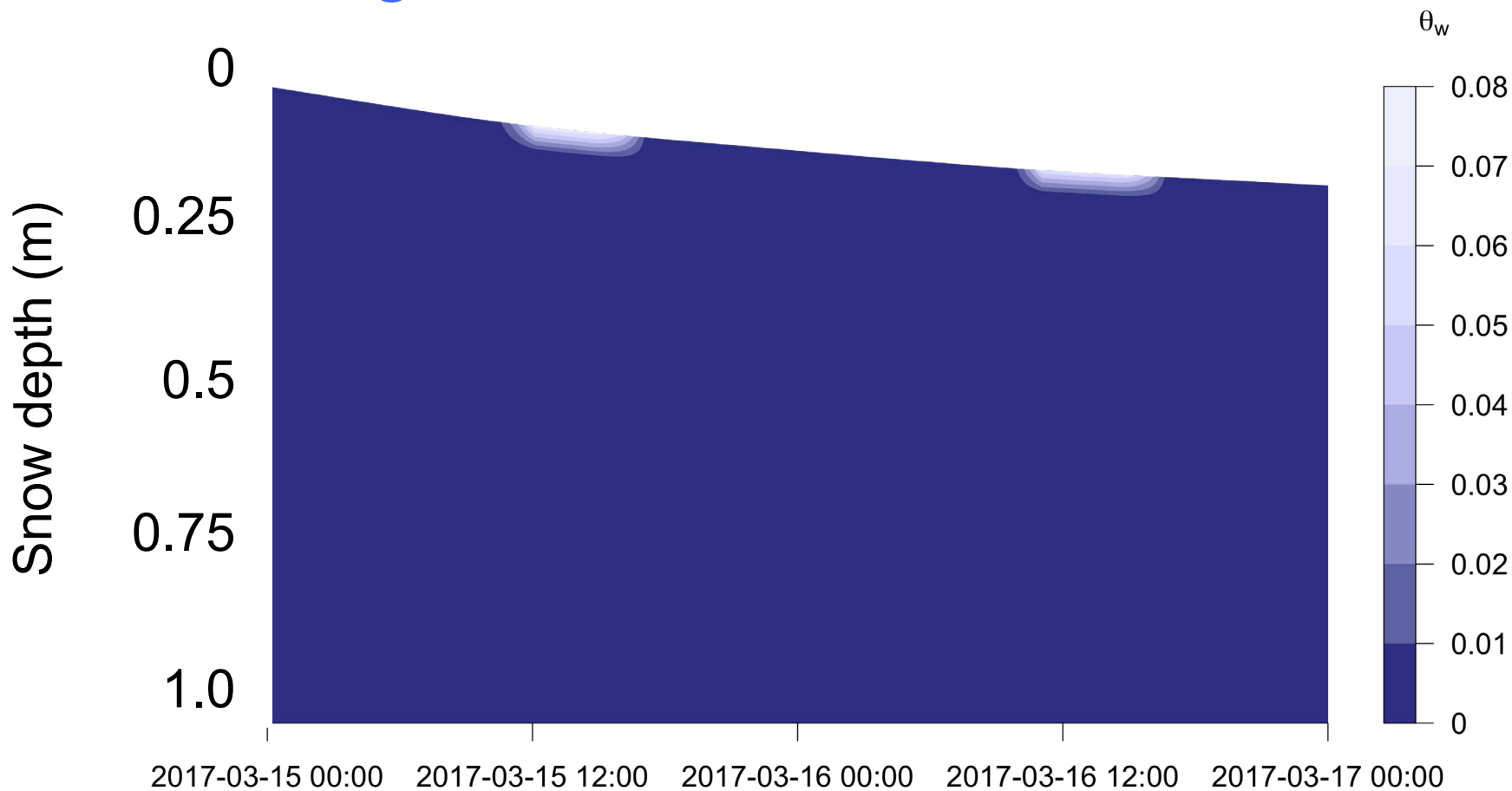
$$Q_{pc} = \Delta \theta_i \rho_i L_f$$

$$L_f = 334 \frac{J}{kg}$$

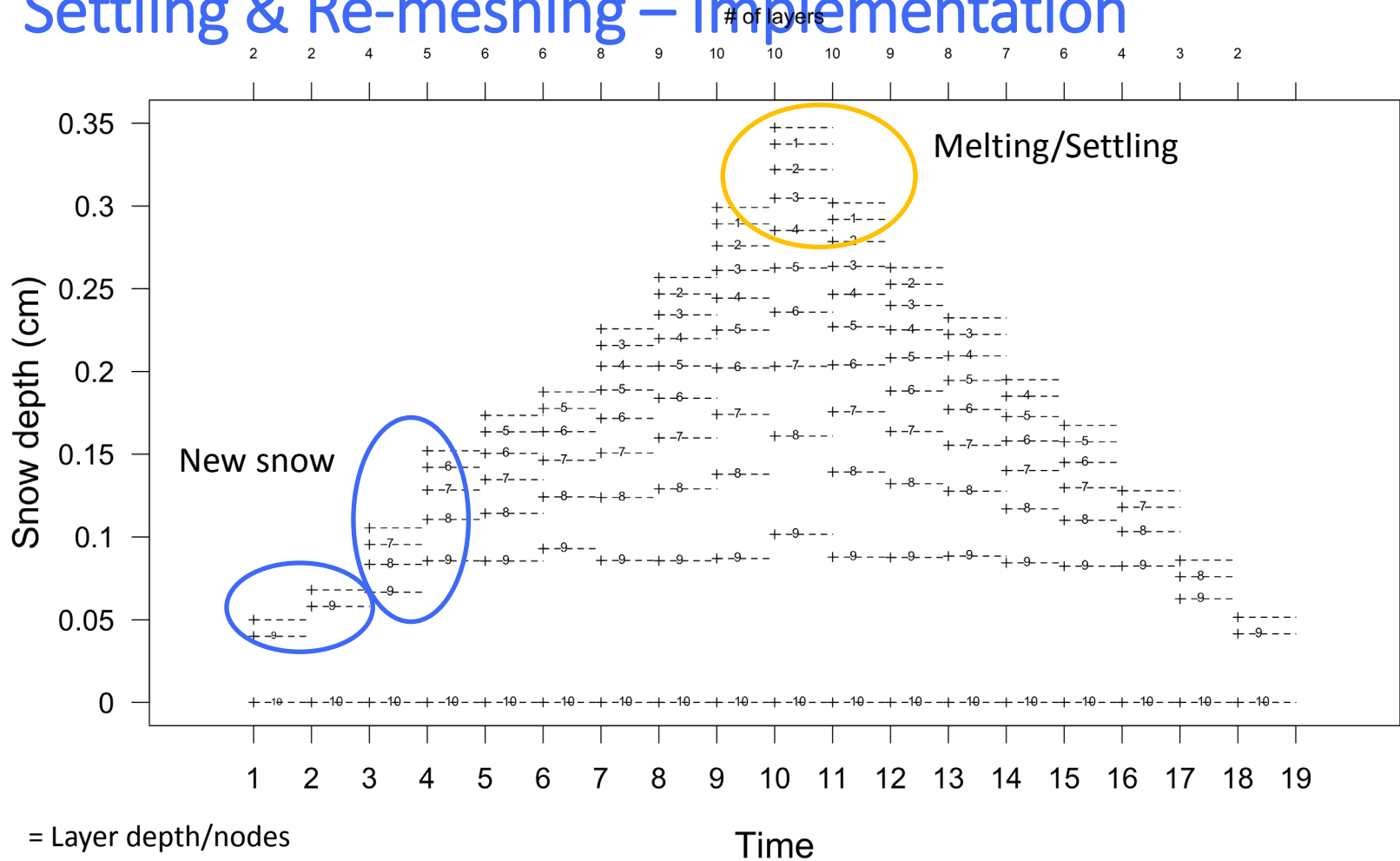
Phase Changes – Initial Results (Snow temperature)



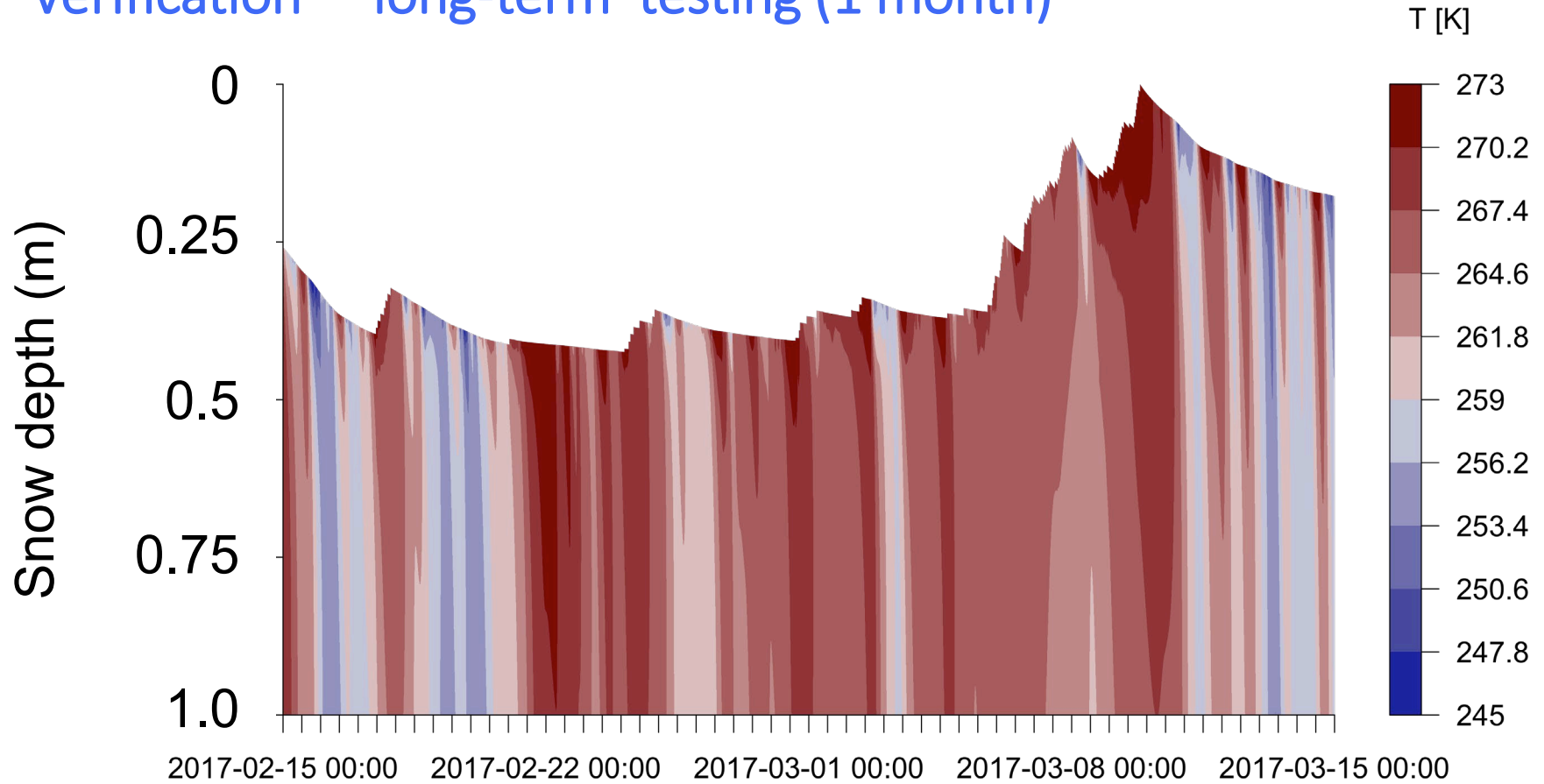
Phase Changes – Initial Results (Water content)



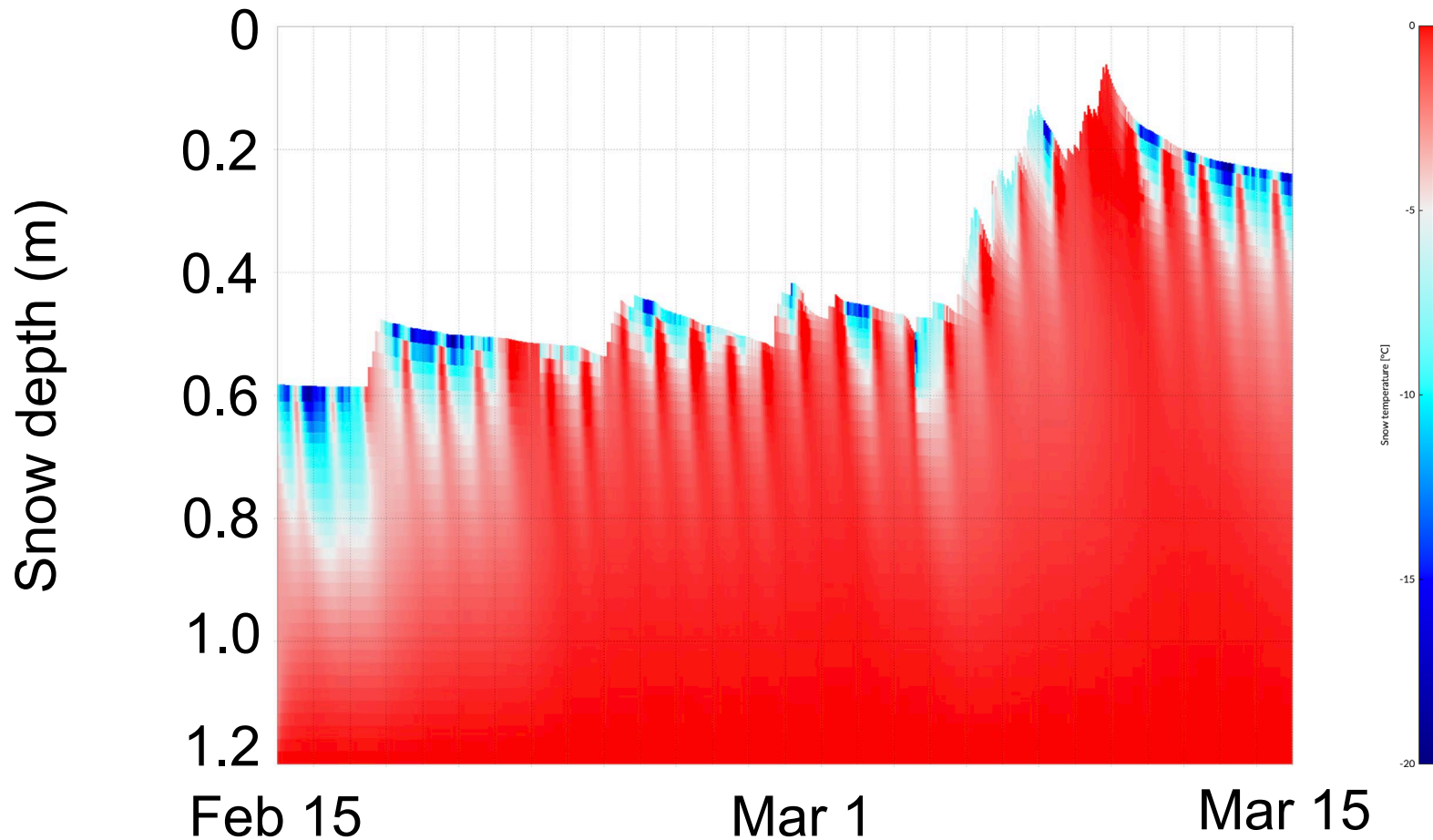
Settling & Re-meshing – Implementation



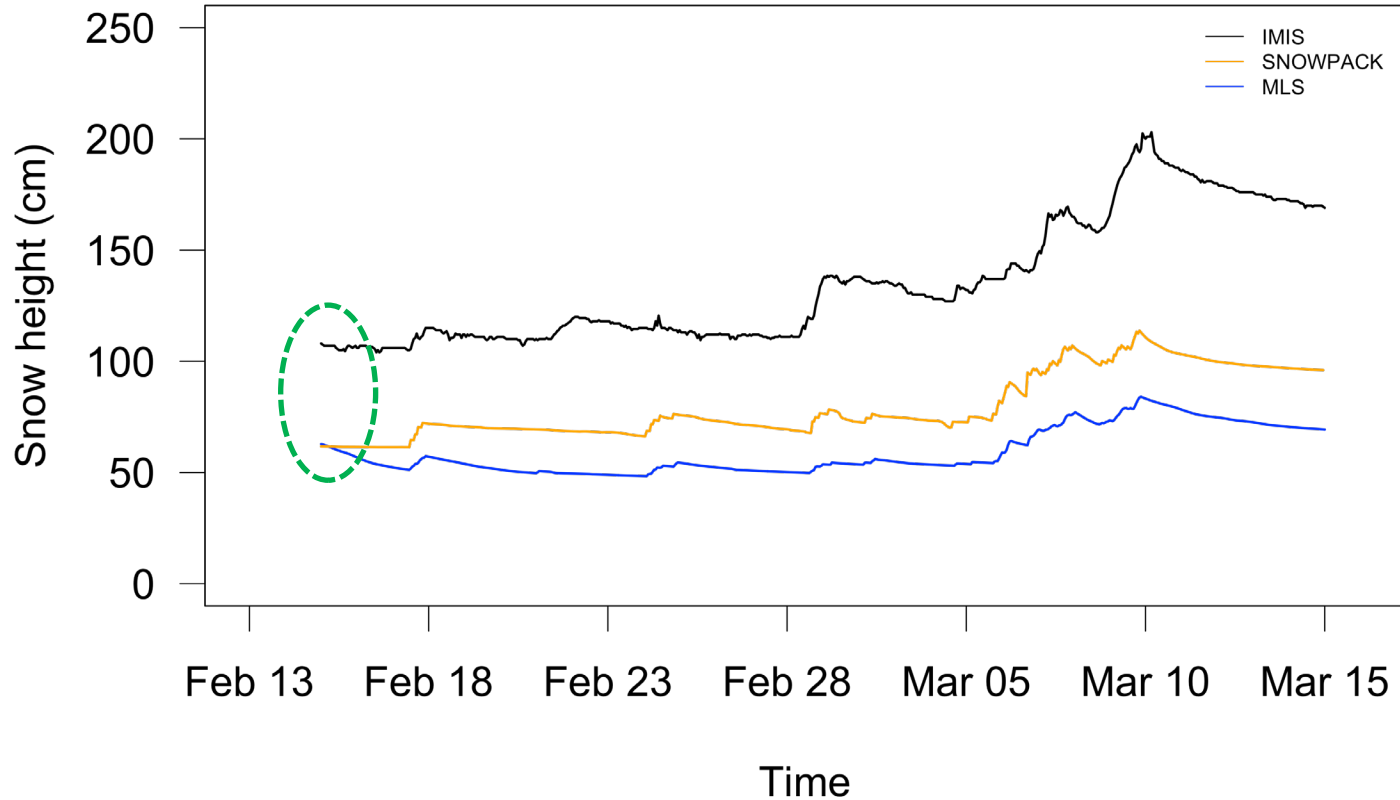
Verification – ‘long-term’ testing (1 month)



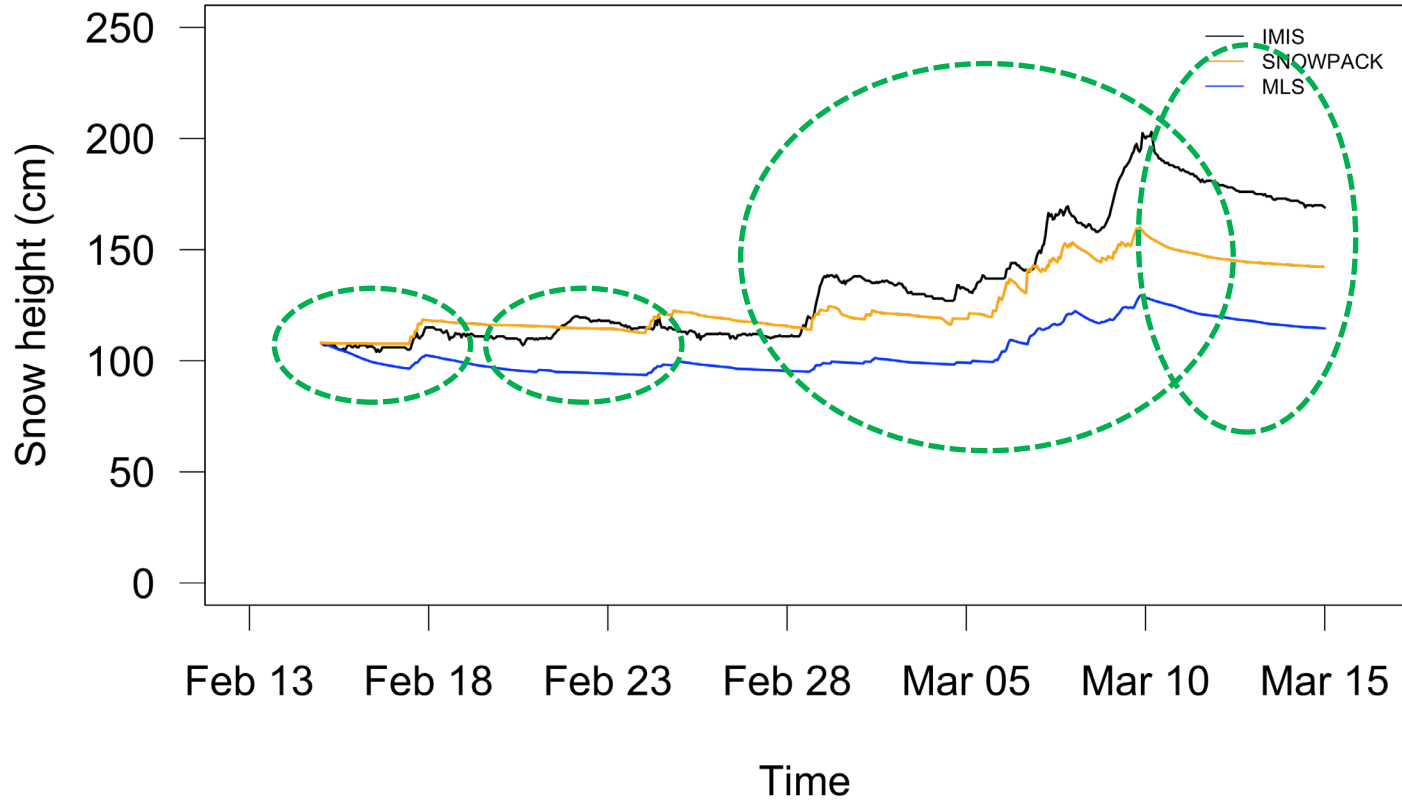
Verification – ‘long-term’ testing (1 month)



Verification – ‘long-term’ testing (1 month)

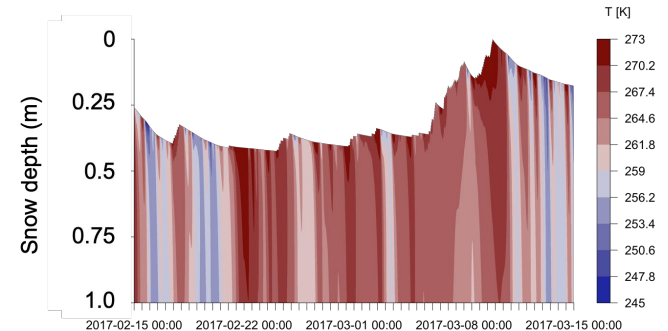


Verification – ‘long-term’ testing (1 month)



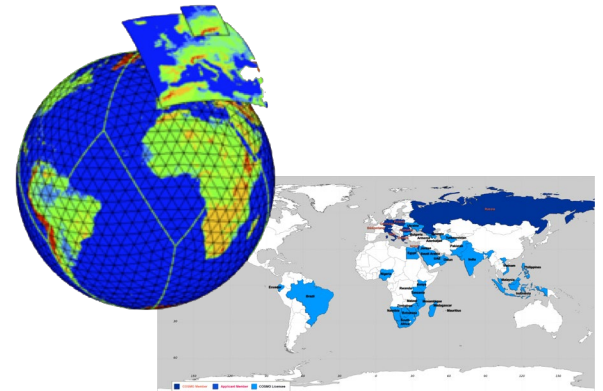
Summary: Priority Task (PT) project - SAINT

- PT SAINT: Joined project of MeteoSwiss and SLF
- Start: July 2017 ; **Ends June 2020**
- Goal: New ‘operational’ multi-layer snow cover scheme for NWP models COSMO and ICON.
- **‘Limited’ SNOWPACK version:**
 - Max. 10 Layers
 - ‘Heat conduction’
 - Phase changes (SNOWPACK)
 - Water transport (SNOWPACK)
 - Settling/Compaction
 - ...
- Promising initial results in terms of snow cover evolution and properties.
- Comparable to SNOWPACK.
- Intensive validation pending, but ...
- ... so far it is numerically stable even on larger domains, i.e. varying snow cover



Outlook & Future work

- Version 1 on GPU 'ready' by mid/end September.
- Further testing/standard verification. Validation of snow cover scheme (fully coupled with TERRA_ML; interface routine)
- Further adaptations of the scheme (e.g. absorption of solar energy, sublimation/evaporation, rain on snow ...).
- First runs with ICON (global, LAM) fall/winter 2019/2020.
- Adaptation of snow analysis and data assimilation.
- Standalone version of the snow cover scheme to be able to force it externally (e.g. INCA, AWS etc.).
- **Science!!!**





Thanks!

Questions and/or comments?

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