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

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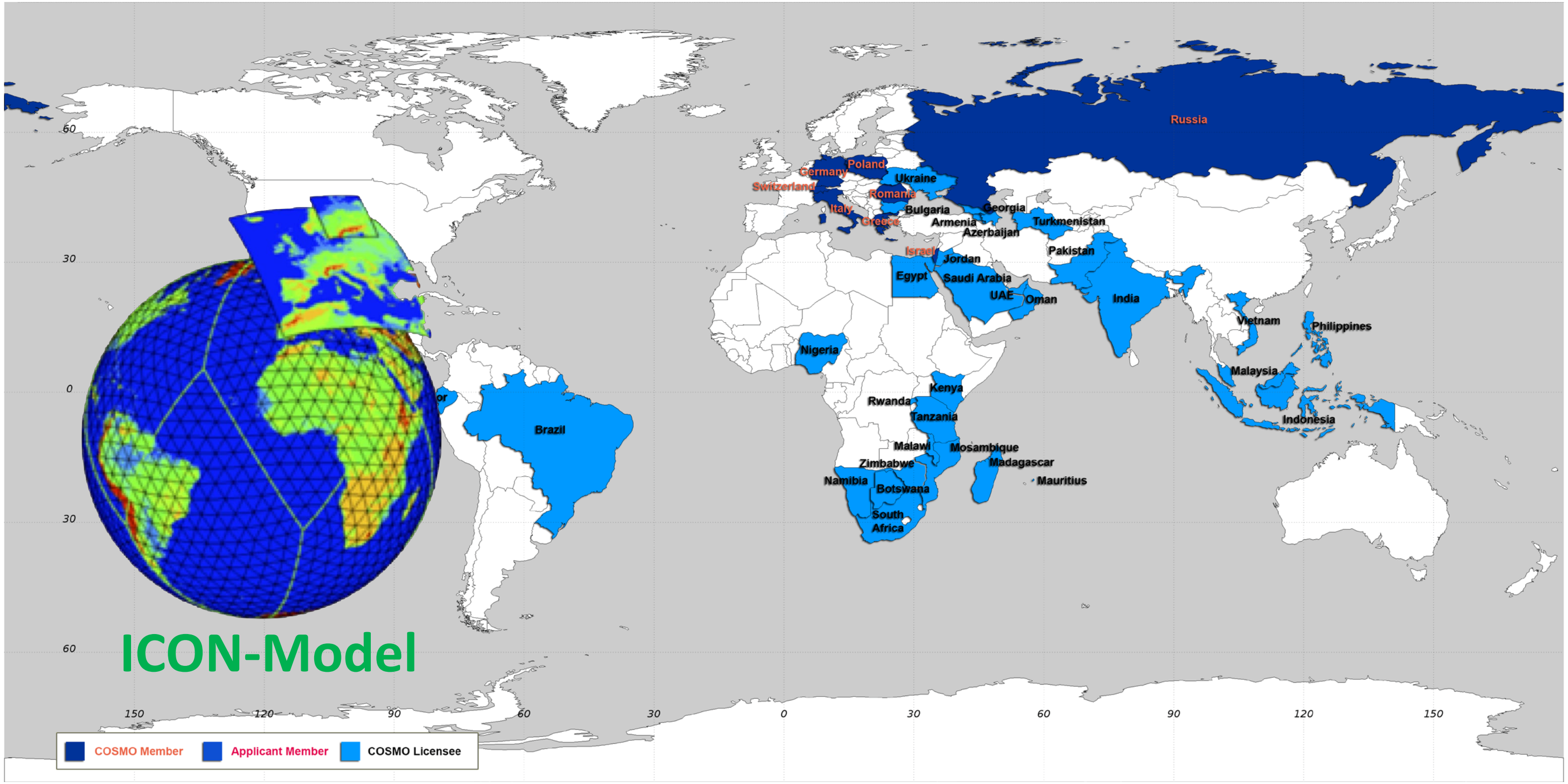
Zurich, 08.08.2019

COSMO (Global usage) & ICON$_{\text{Global, LAM, LES}}$



COSMO & ICON used in climate mode

Single layer snow cover scheme – COSMO

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

Atmospheric Forcing:

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

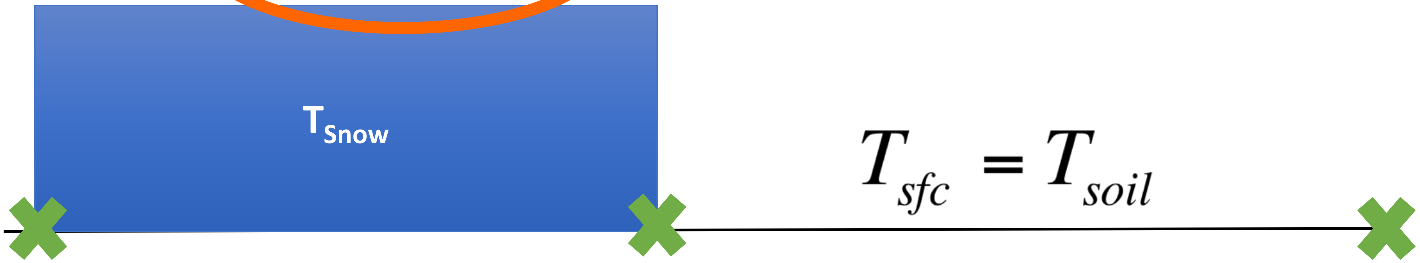
Ground heat Flux:

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

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

T_{sfc}

$$T_{snow,sfc} = T_{snow}$$



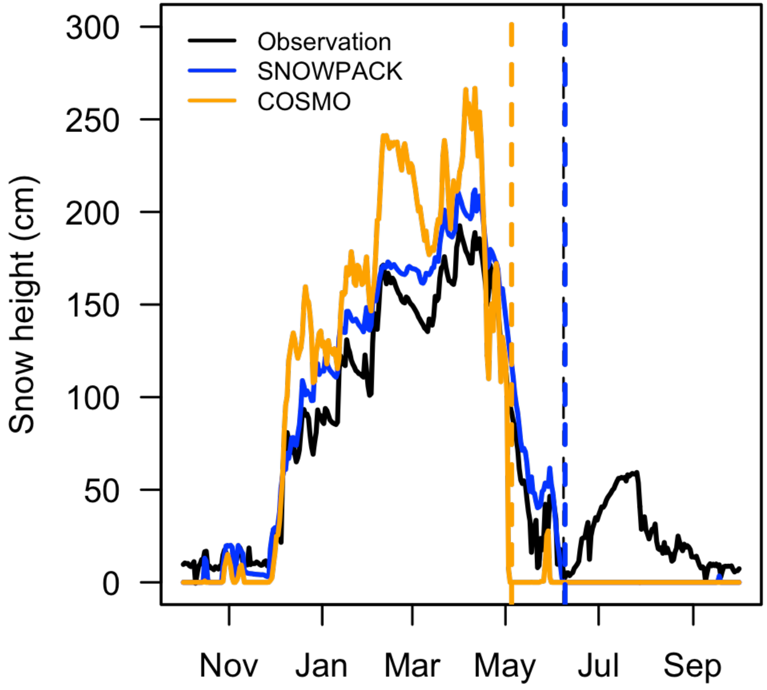
$$T_{sfc} = T_{soil}$$

T_{soil}

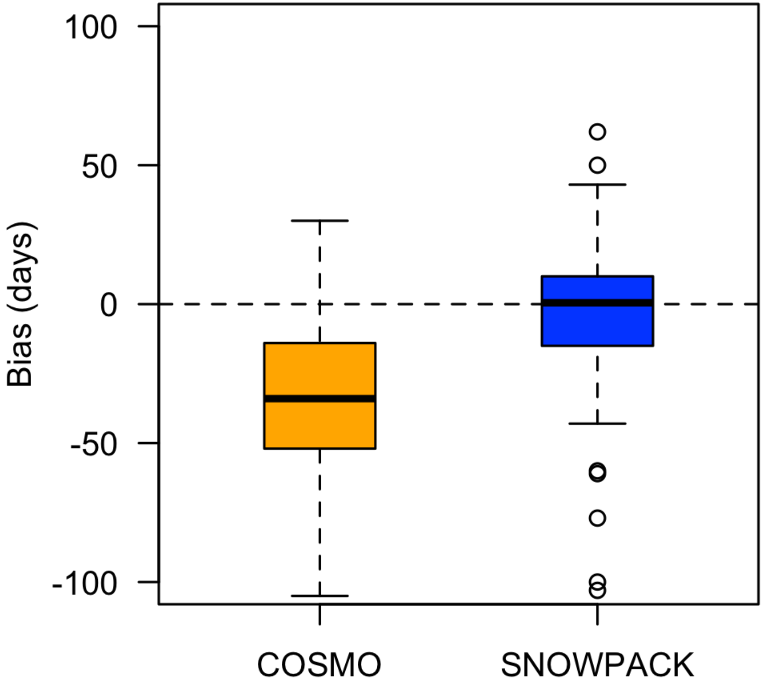
Soil

COSMO-2 validation (Snow depth)

Weissfluhjoch



IMIS



Single layer snow cover scheme – SnowMIP project

Annals of Glaciology 38 2004

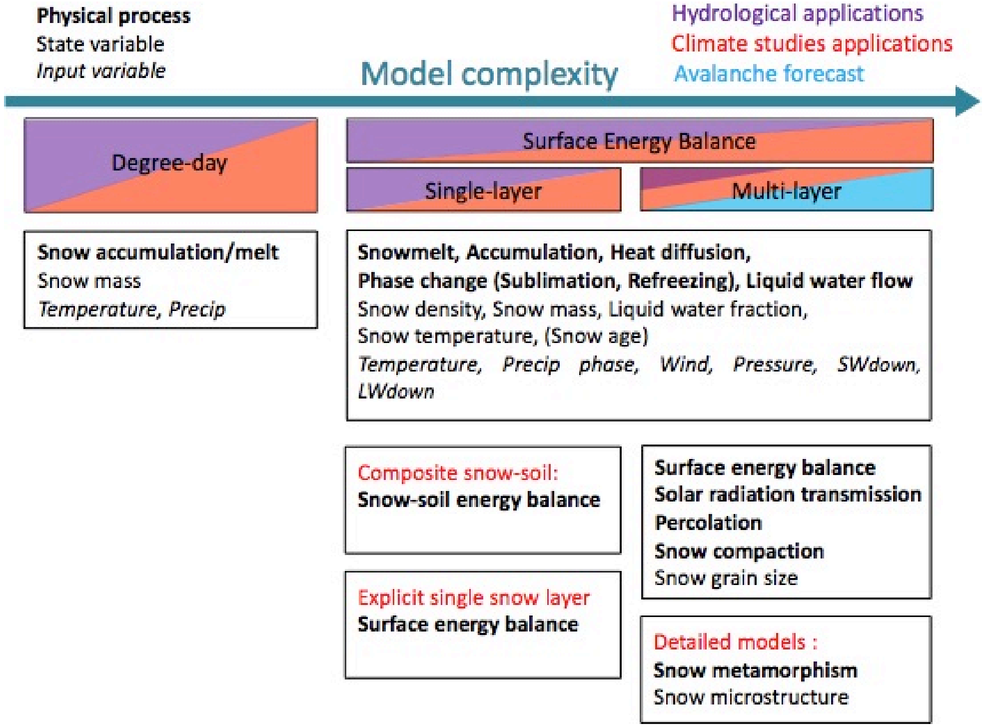
Validation of the energy budget of an alpine snowpack simulated by several snow models (SnowMIP project)

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.**

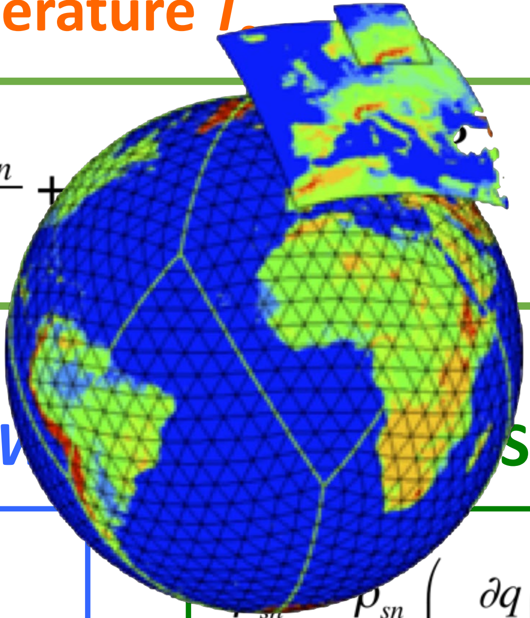
Multi-layer snow cover scheme – COSMO

Snow Temperature $T_{}$

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

Liquid Water W_{liq}

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



Total Water (SWE) W

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

Snow density ρ_{sn}

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

Proposed COSMO Priority Task (PT) Project – SAINT

CONSORTIUM FOR SMALL SCALE MODELING
COSMO

COSMO Priority Task: Snow cover Atmosphere INTeractions (SAINT)

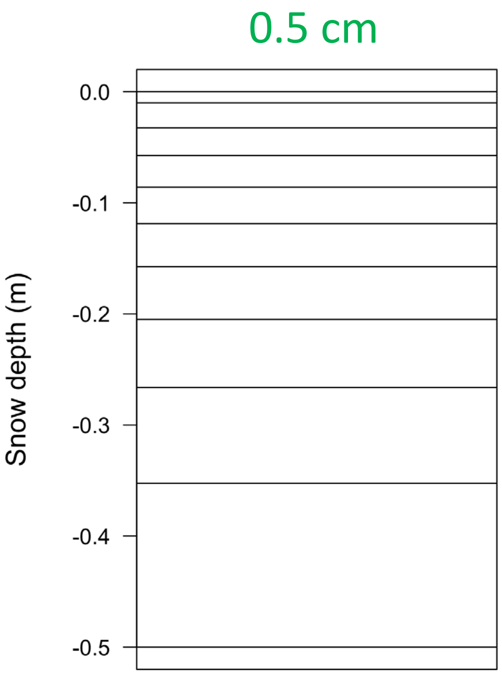
Version 1.0, 13.10.2017

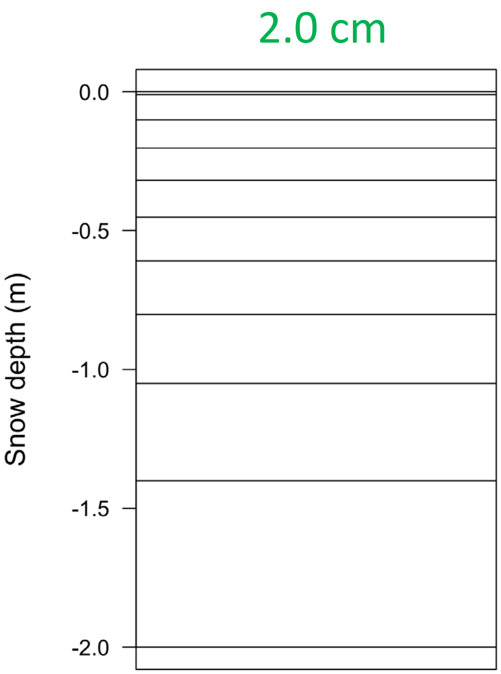
Task Leader: Sascha Bellaire (WSL Institute for Snow and Avalanche Research SLF)

Main goal

Improving the current multi-layer snow cover scheme

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





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:

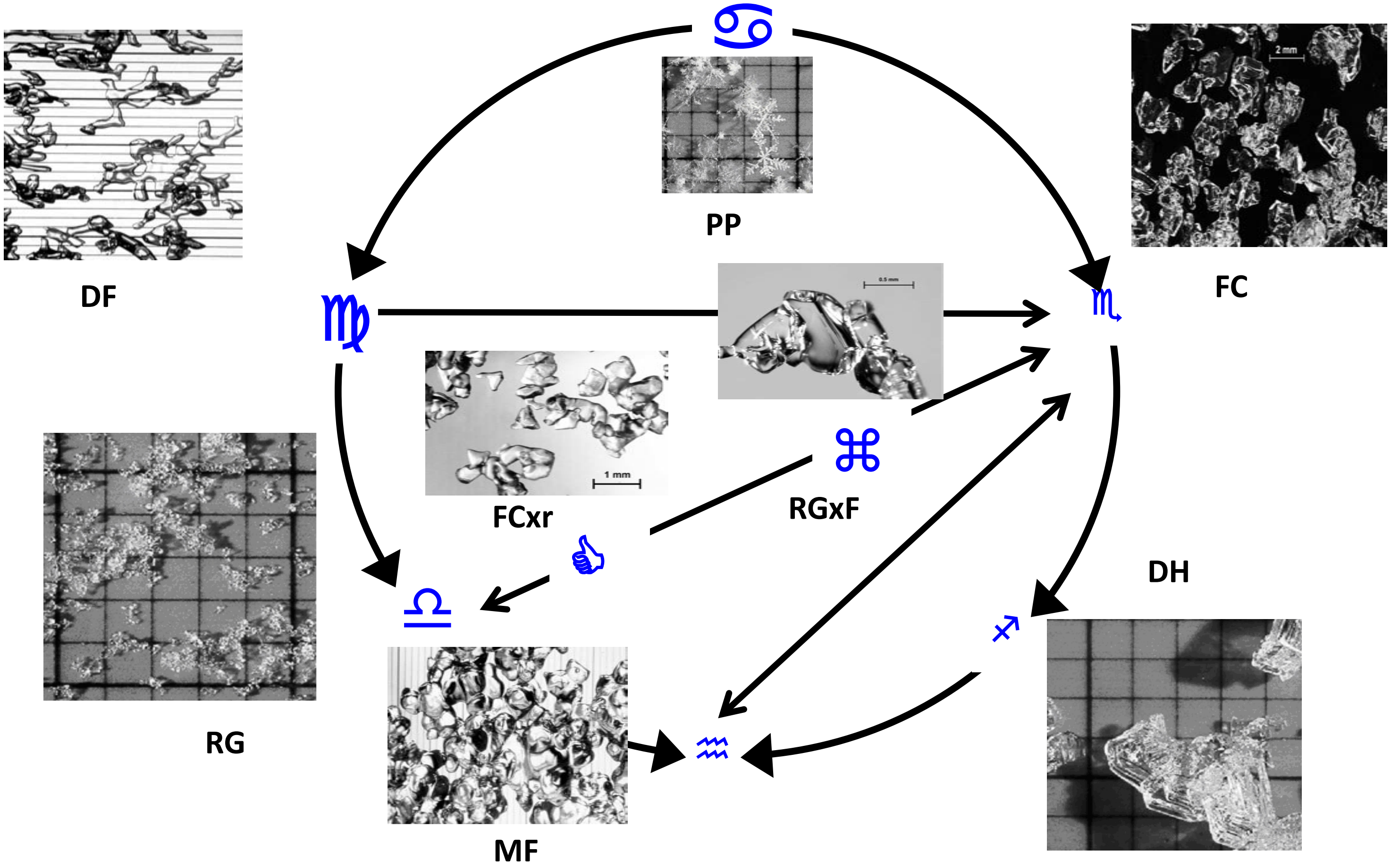
$$\rho_s c_p \frac{\partial T_s}{\partial t} - \frac{\partial}{\partial z}\left(k_{eff}\frac{\partial T_s}{\partial z}\right) = [Q_{pc}] + [Q_{mm}] + Q_{sw} ;$$

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

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

T_S: Temperature of Snow (K)
c_p : Heat Capacity (J kg^{-1} K^{-1})
k_{eff}: Effective Thermal Conductivity (W m^{-1} K^{-1})

Snow Metamorphism: Grain Types



Photo's: SLF

Snow Metamorphism: Faceting (CT images)

cold

warm

Movie: SLF

Heat Equation – Implementation

1D heat equation:

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

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

Top layer

for_sn = forcing = SEB

```
! ------------------------------------------------------------
! Setup tridiagonal matrix for set of linear equations for each layer ...
! ------------------------------------------------------------

 ! ... TOP LAYER
 dz_low = zm_sn(top_sn+1)

 a(top_sn) = 0.0_wp
 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 - dlw_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_wp

 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
```

Snow cover scheme (MLS) – Implementation

```
!!=========================

MODULE sfc_terra

!===================
```

```

!SB <
USE sfc_snow
USE snow_utilities
!SB >

!-------------------------------------------

```

New snow model called in TERRA …

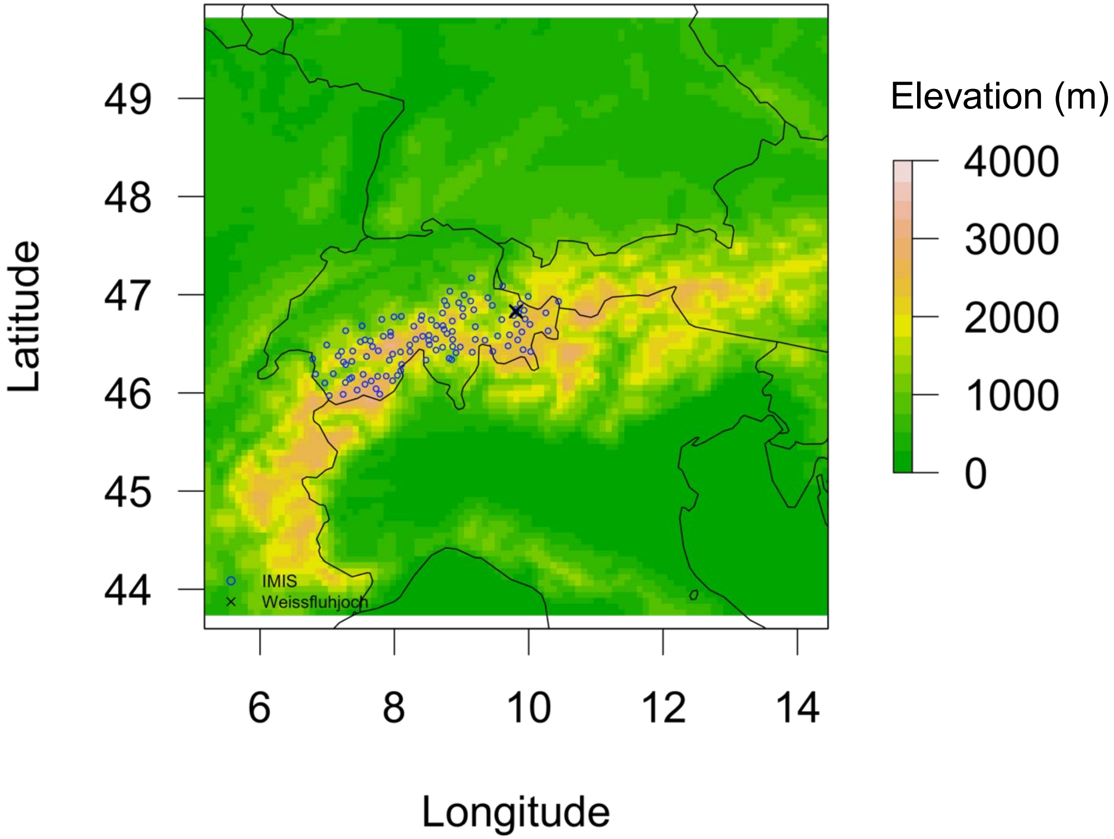
… consists of 2 (or 3) subroutines called …

CALL snow_forcing(…)	CALL snow_on_soil(…)	CALL interface_snow(…)
● snow specific atmospheric forcing	● layering/new snow ● ’heat conduction’ ● phase changes ● water transport ● settling ● re-meshing ○ …	● preparation of required input (# layers, layering, heat conductivity etc.) for solving heat equation in TERRA

… before solving the heat equation in TERRA

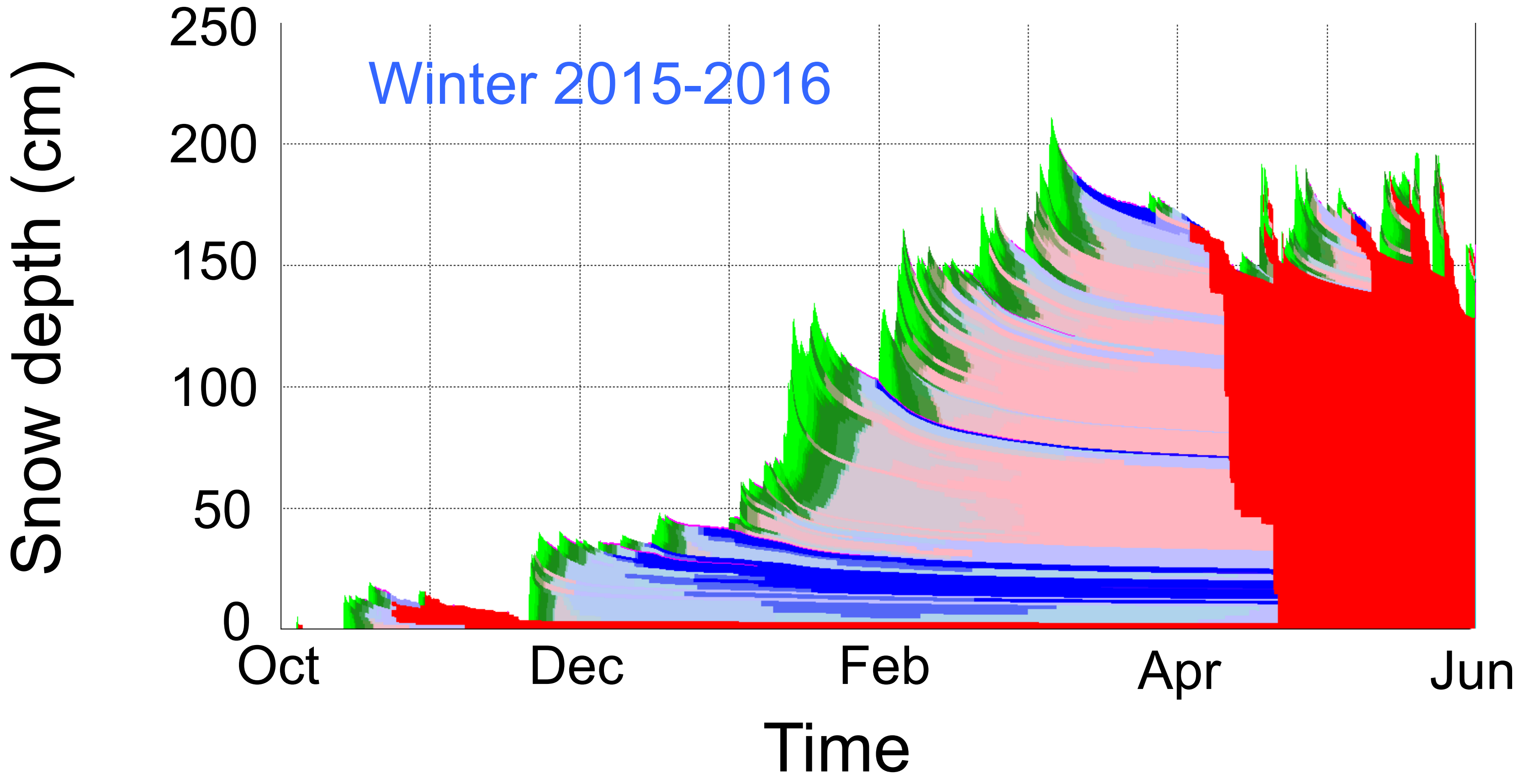
```

    END DO
  END DO         ! soil layers

!MR: 05.05.2017 and later: heat-budget for inner soil layers substituted by a slightly different notation: >
!-----------------------------------------------------------------------------------------------------------

!**********************************************************************************************************
!MR: 05.05.2017: modified heat-budget for boundary soil layers including a single-layer snow-cover: <
!**********************************************************************************************************

```

The Method: Validation (COSMO-7)

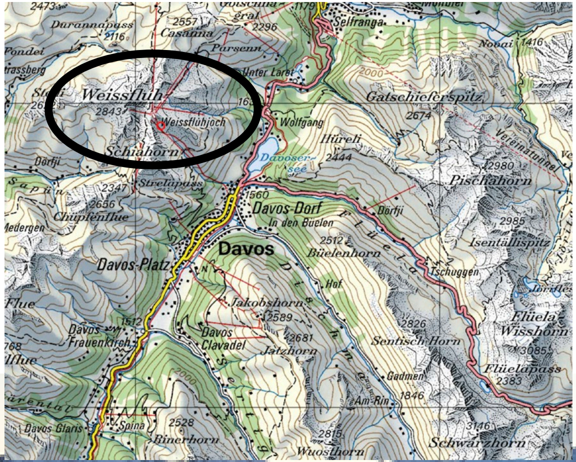


- … ~ 700 km x 700 km domain centered around Davos …
- … covering most of the Alpine ridge …
- … computationally inexpensive …
- .. boundary conditions from COSMO-7 analysis …
- … 72-hour forecast/hindcast

Surface Temperature – Benchmarking (SNOWPACK vs. MLS)



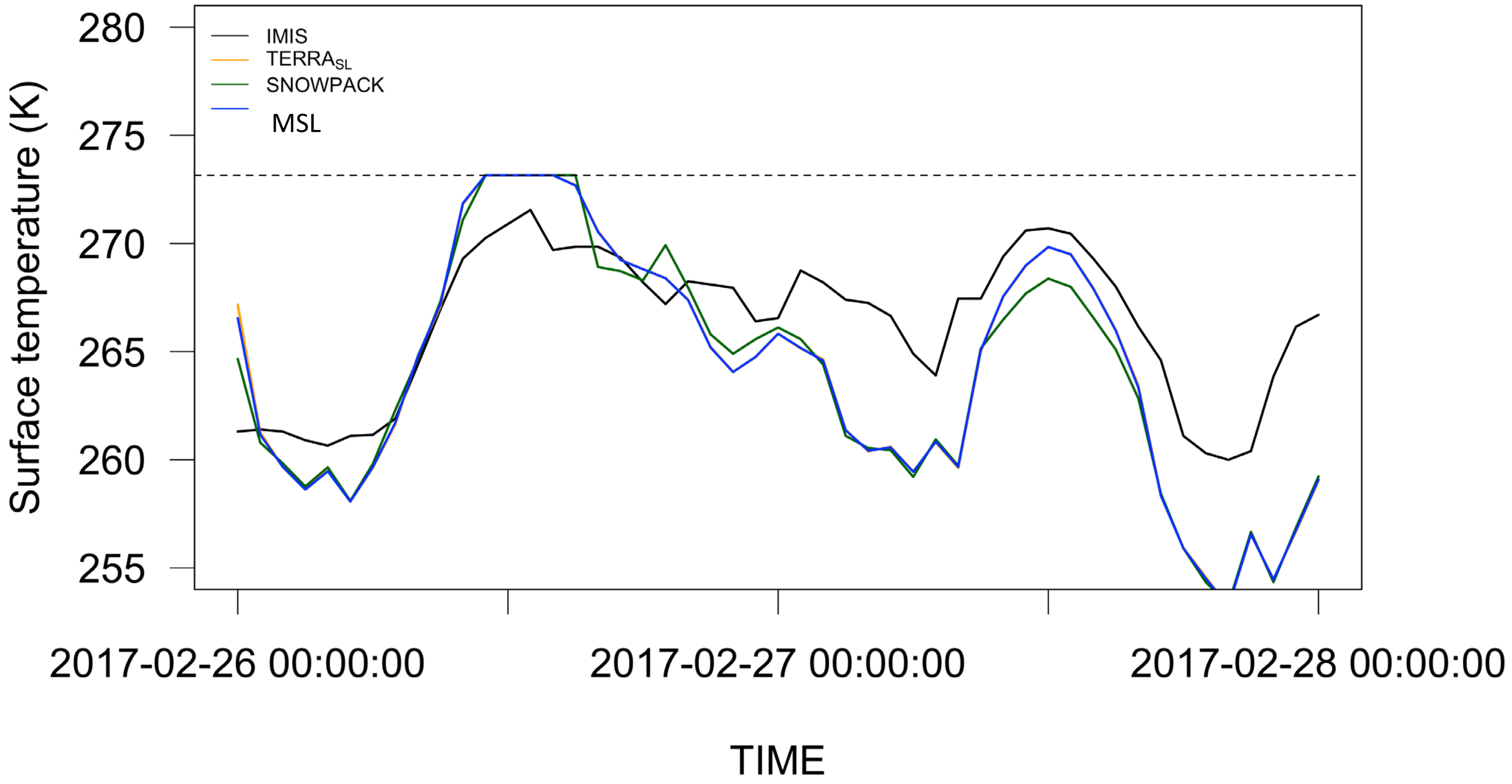
Heat Equation – Benchmarking (Observations)



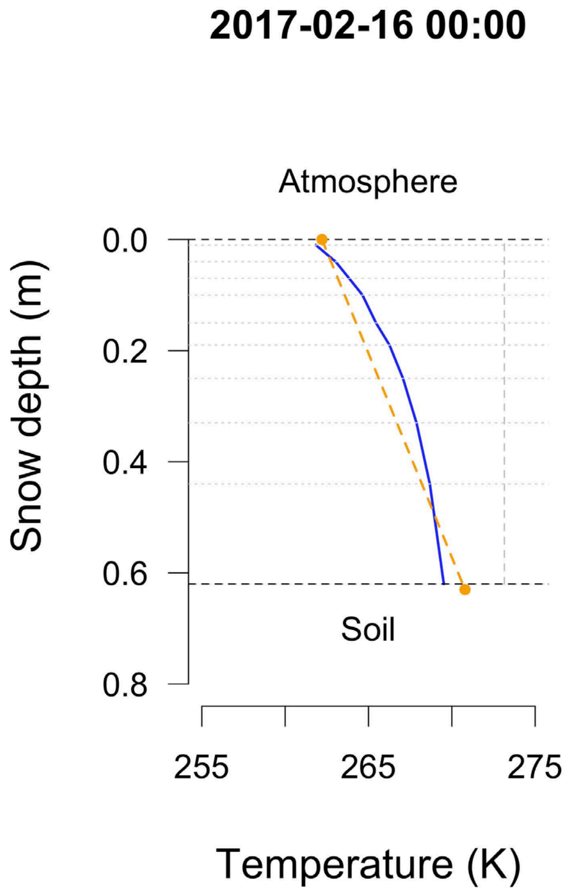
Experimental Site Weissfluhjoch, Davos, Switzerland

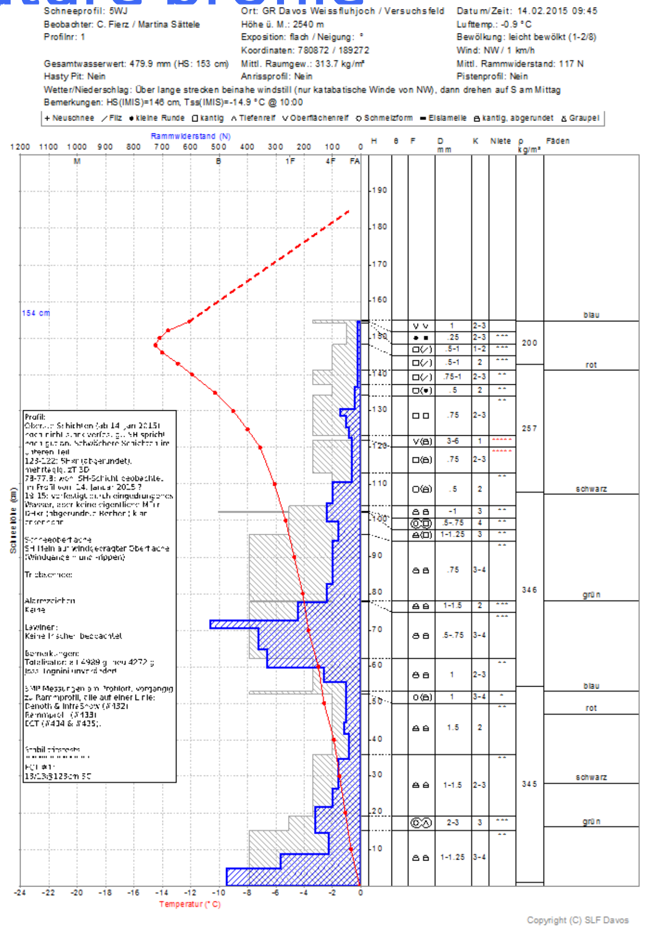
Heat Equation – Benchmarking (SNOWPACK vs. MLS)

Weissfluhjoch



Heat Equation – Snow temperature profile

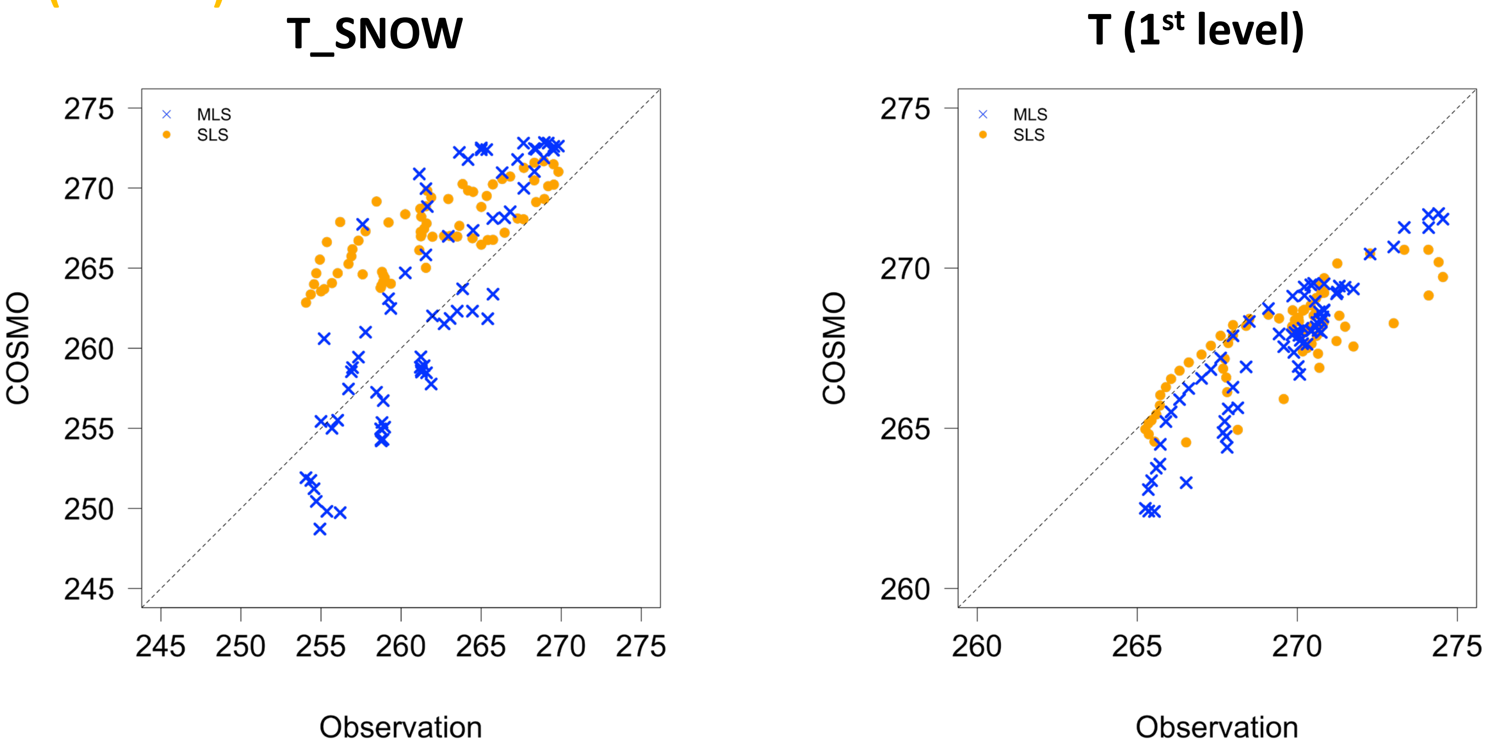




Intercantonal Measurement and Information System (IMIS)

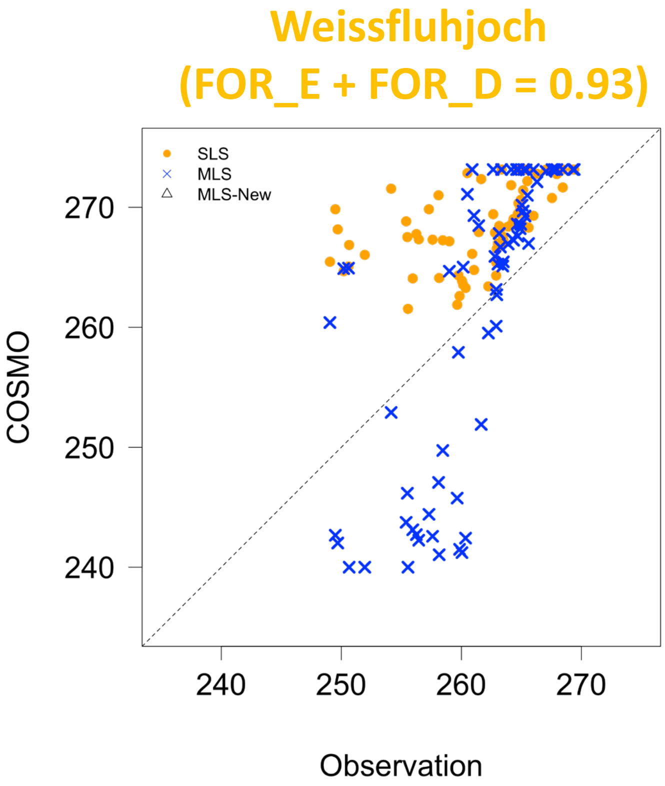
Results – Forcing (Surface Temperature)

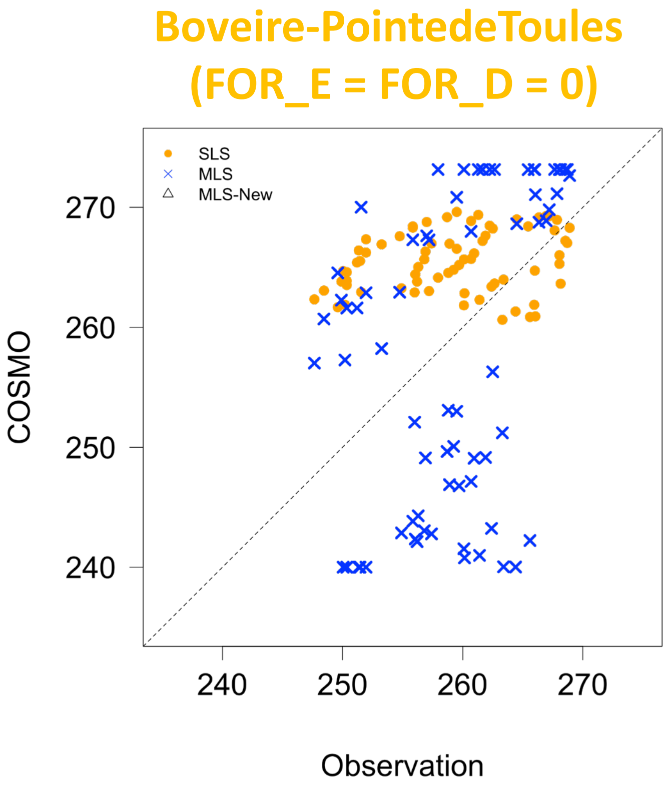
All IMIS (N = 112)



● = Single layer snow cover scheme (SLS)   X = Multi-layer snow cover scheme (MLS)

Results – Forcing (Surface Temperature)

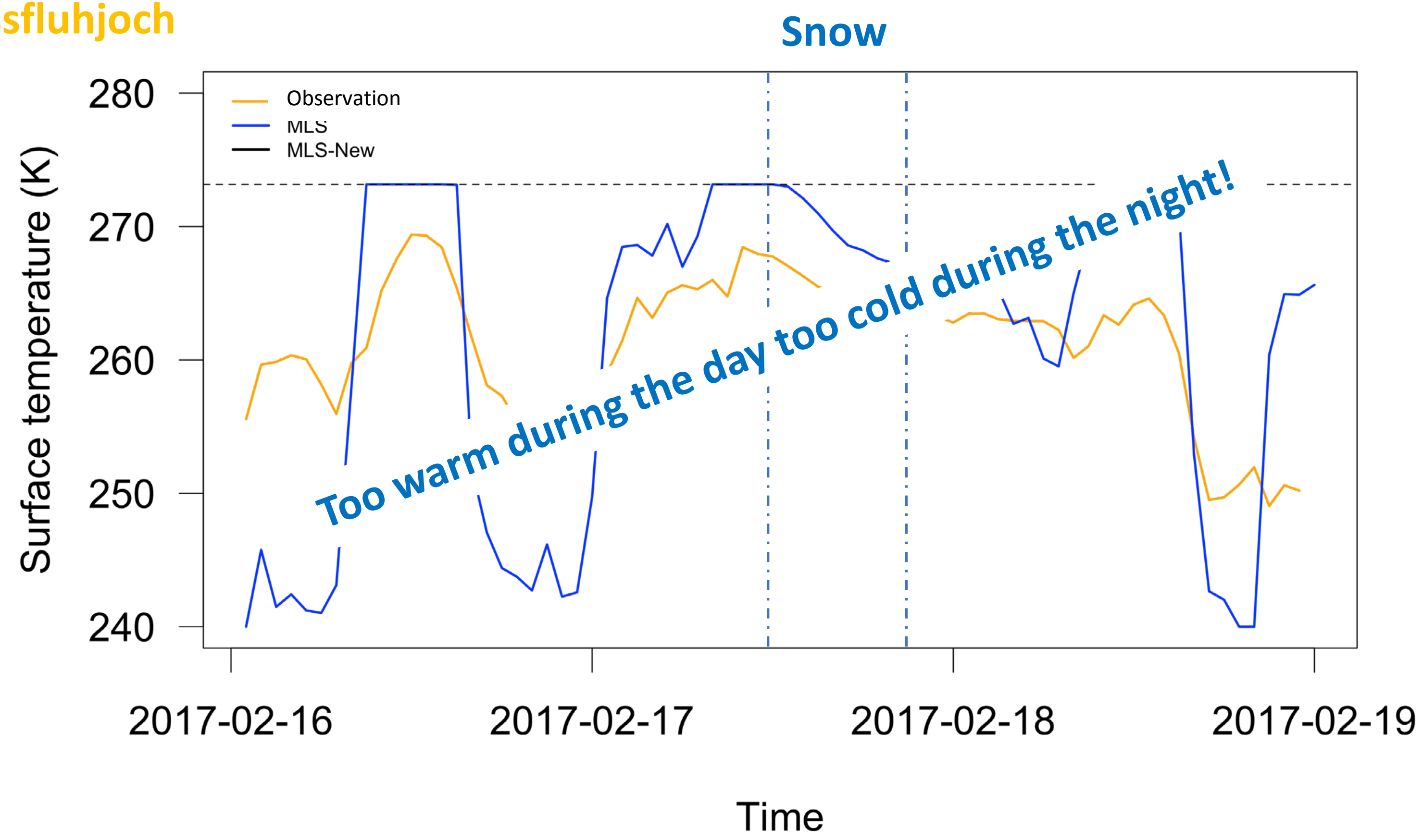




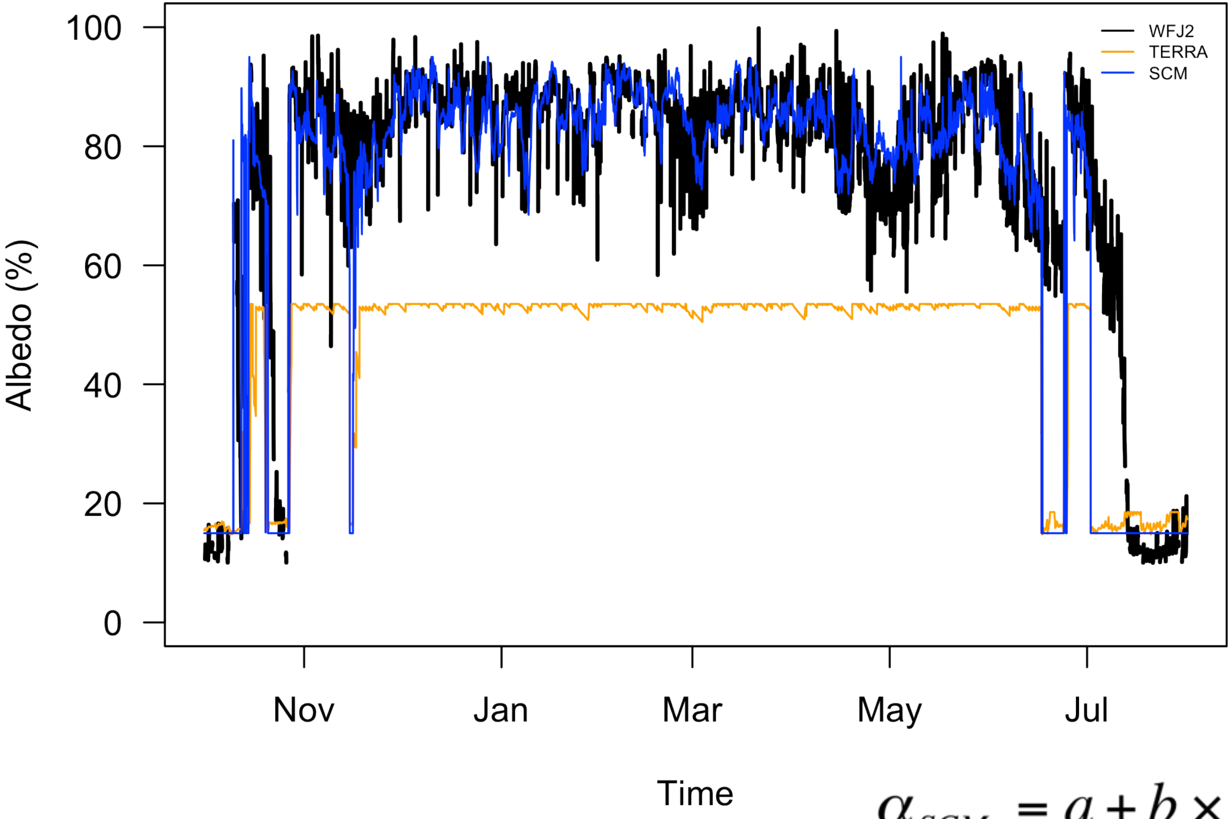
● = Single layer snow cover scheme (SLS) **X** = Multi-layer snow cover scheme (MLS)

Results – Forcing (Surface Temperature)

Weissfluhjoch



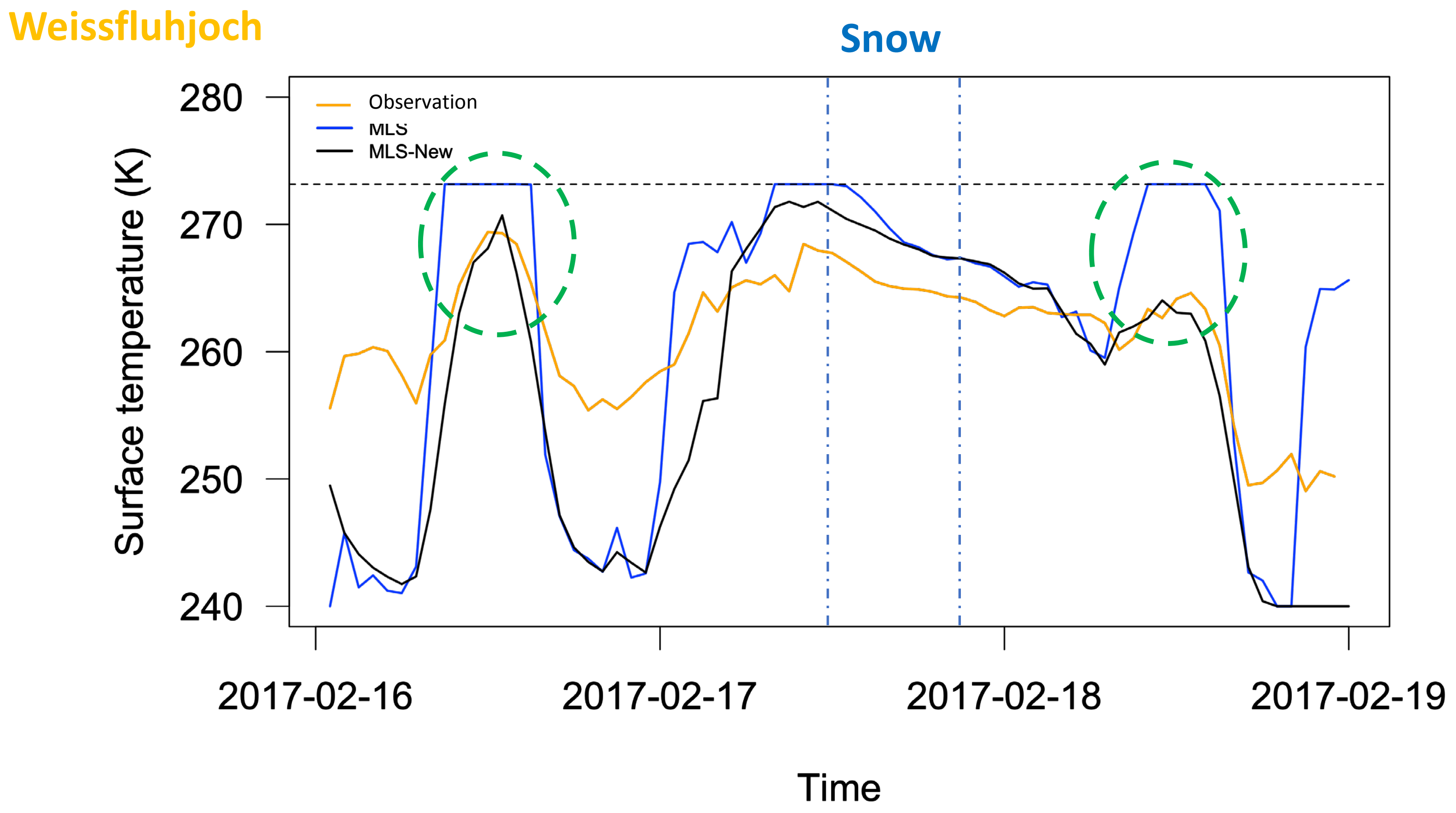
Results – Forcing (Albedo)



P_{rate} = Precipitation rate
T_{SFC} = Snow surface temperature
T_{10m} = Air Temperature 10 m

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

Results – Forcing (Albedo)



Results – Forcing (Transfer Coefficients)

Boundary-Layer Meteorology
October 2017, Volume 165, Issue 1, pp 161–180 | Cite as

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

Authors Authors and affiliations

Sebastian Schlögl, Michael Lehning, Kouichi Nishimura, Hendrik Huwald, Nicolas J. Cullen, Rebecca Mott

Sensible heat flux:

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

Transfer Coefficient:

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

where $k = 0.4$ is the von Kármán constant, $\zeta = (-k\, z_{\mathrm{ref}}\, g T_*) / (\theta_s u_*^2)$ is the modelled stability parameter (stability parameter henceforth), $u_* = k\bar{U}(\ln(z_{\mathrm{ref}}/z_{0M}) - \psi_m)^{-1}$ is the modelled friction velocity, $T_* = k(\theta_s - \theta_{z_{\mathrm{ref}}})(\ln(z_{\mathrm{ref}}/z_{0M}) - \psi_s)^{-1}$ 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

Stability Corrections:

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

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

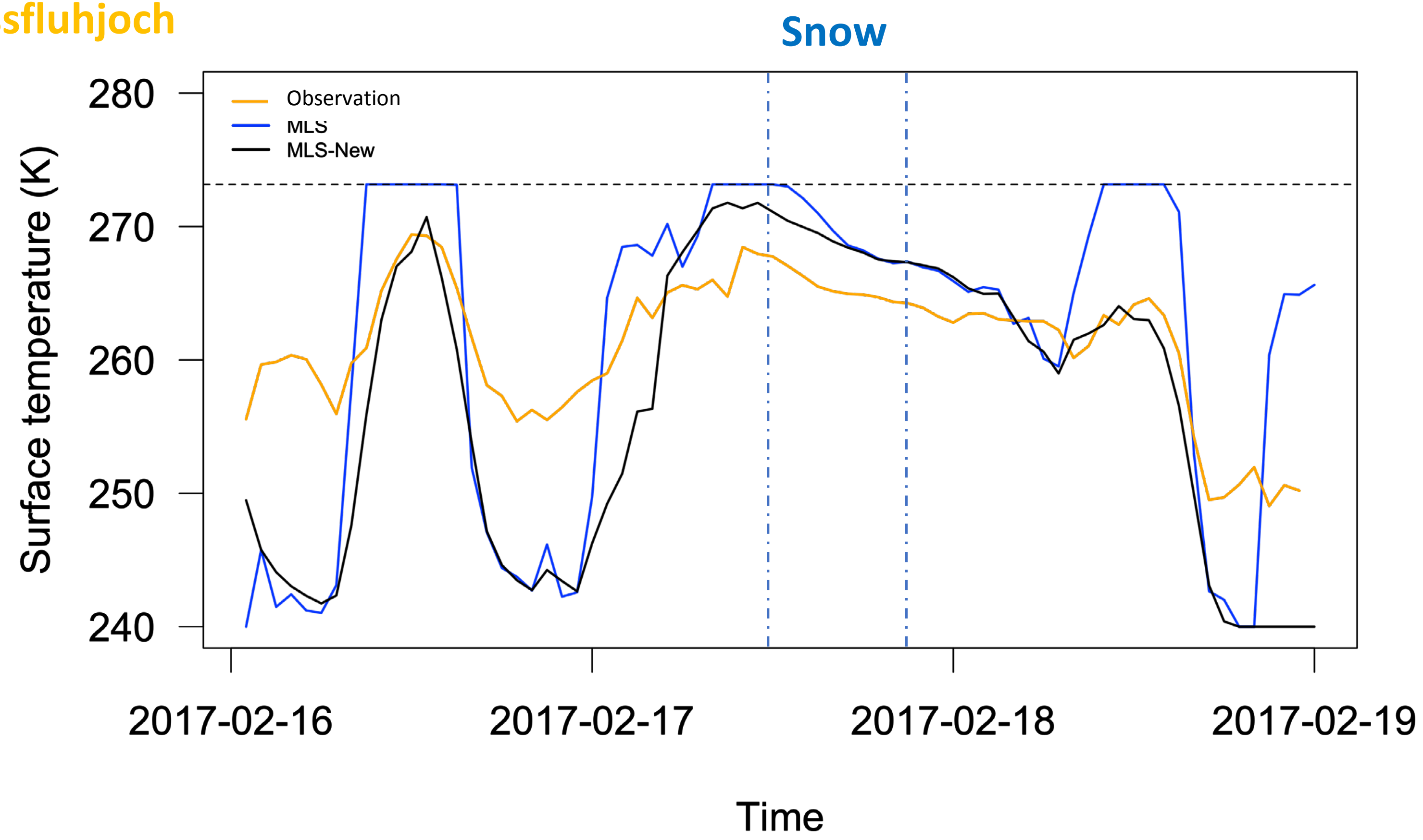
$$B = \Delta T / \bar{T}$$

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

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

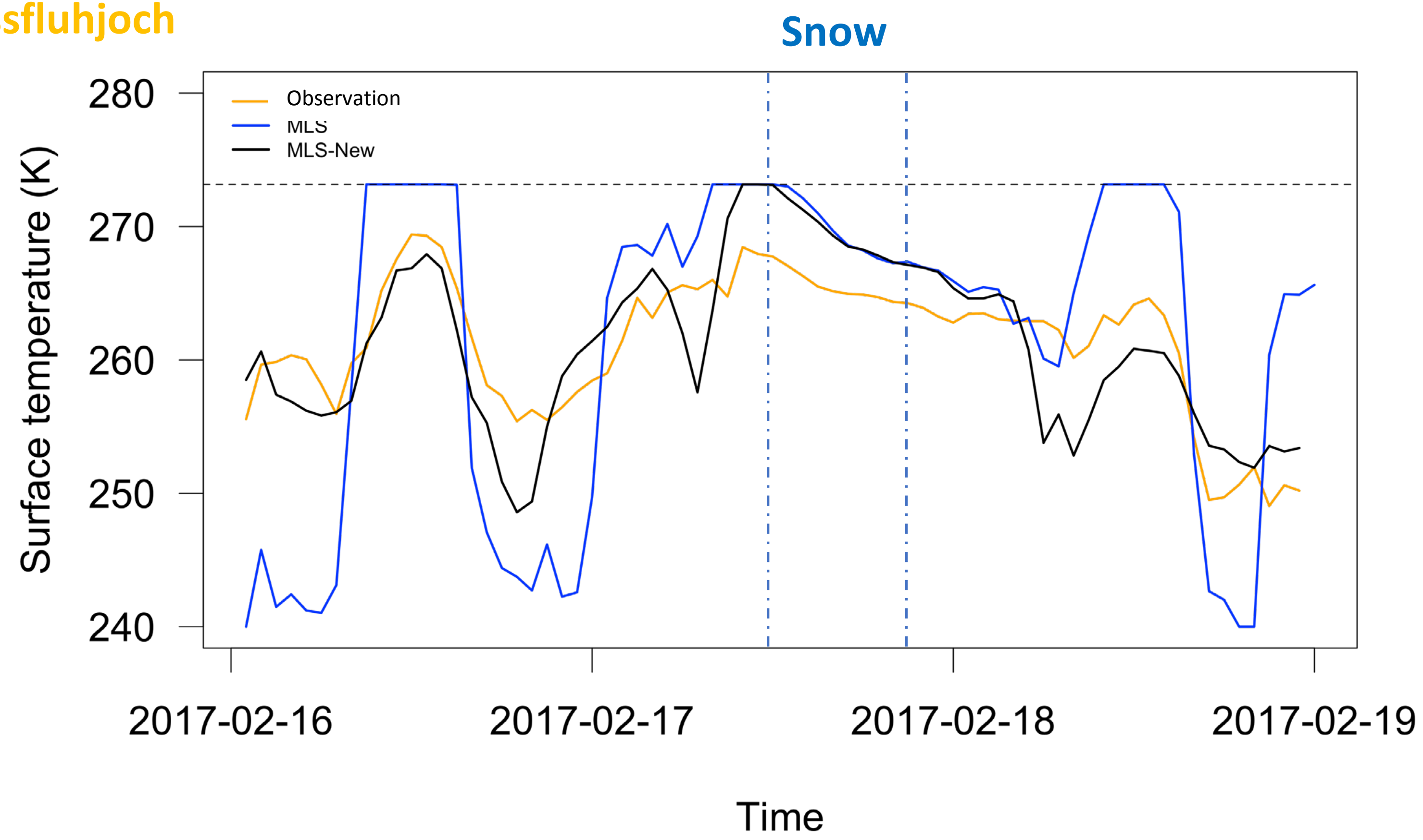
Results – Forcing (Transfer Coefficients)

Weissfluhjoch

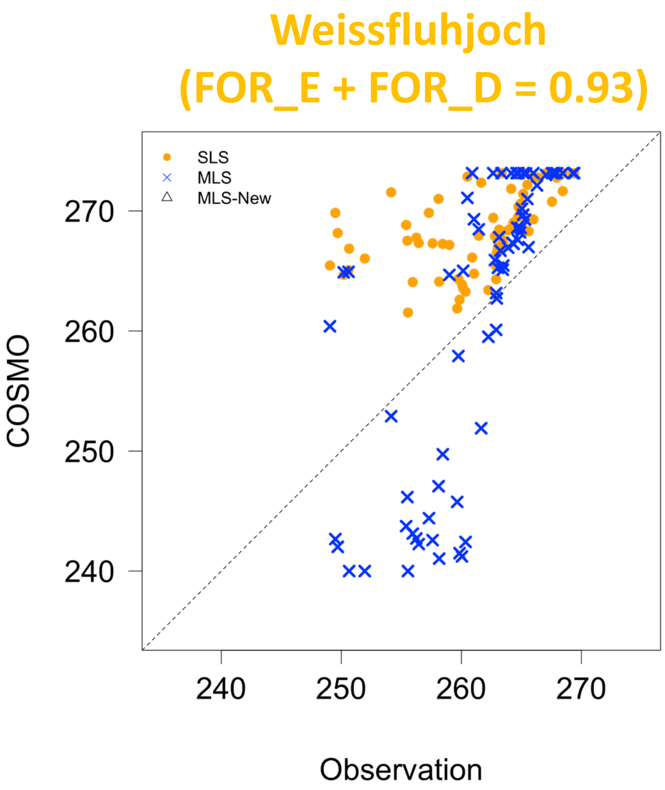


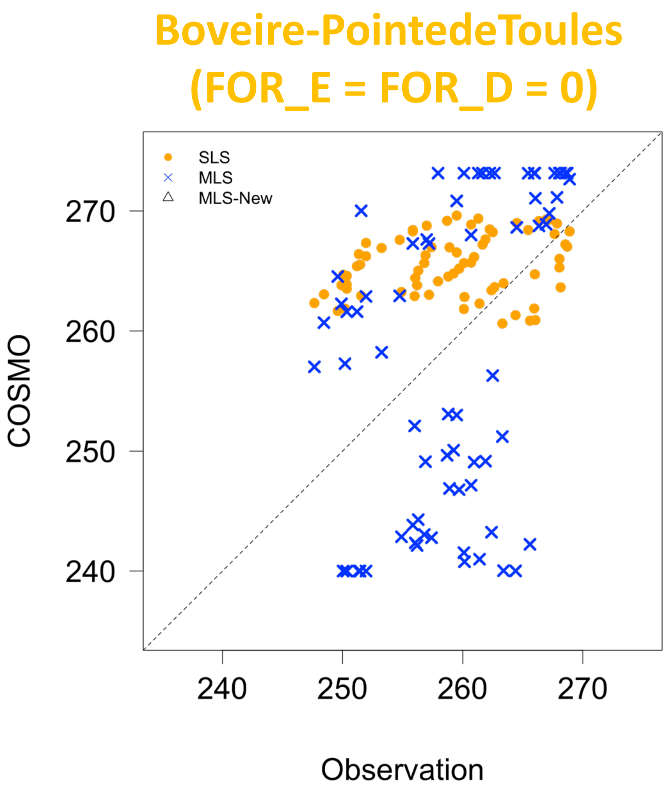
Results – Forcing (Transfer Coefficients)

Weissfluhjoch



Results – Forcing (Surface Temperature)

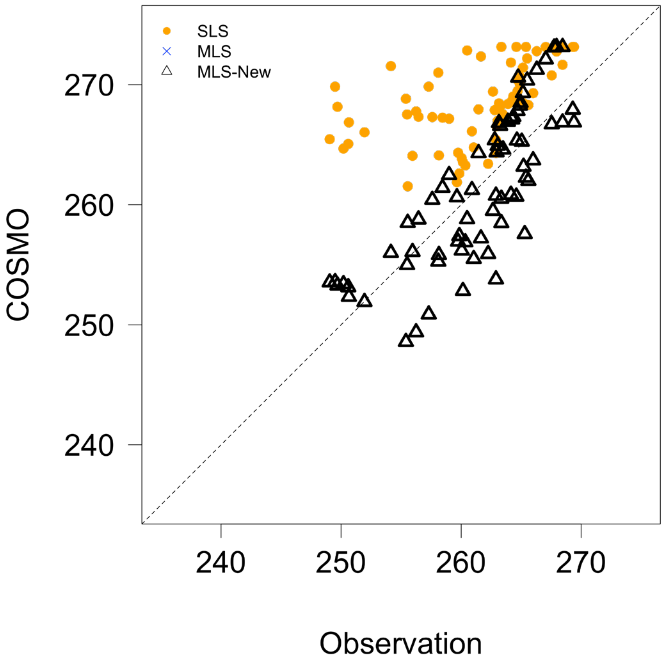




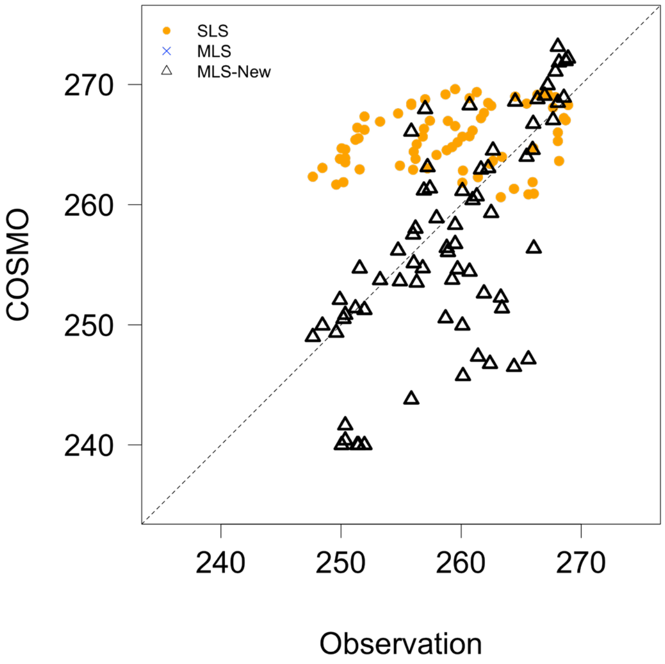
● = Single layer snow cover scheme (SLS)   X = Multi-layer snow cover scheme (MLS)

Heat Equation – Initial Results

Weissfluhjoch
(FOR_E + FOR_D = 0.93)



Boveire-PointedeToules
(FOR_E = FOR_D = 0)



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

Snow cover scheme (MLS) – Implementation

```
!!========================

MODULE sfc_terra

!==================
```

```
!SB <
USE sfc_snow
USE snow_utilities
!SB >

!-------------------------------------------
```

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
- …

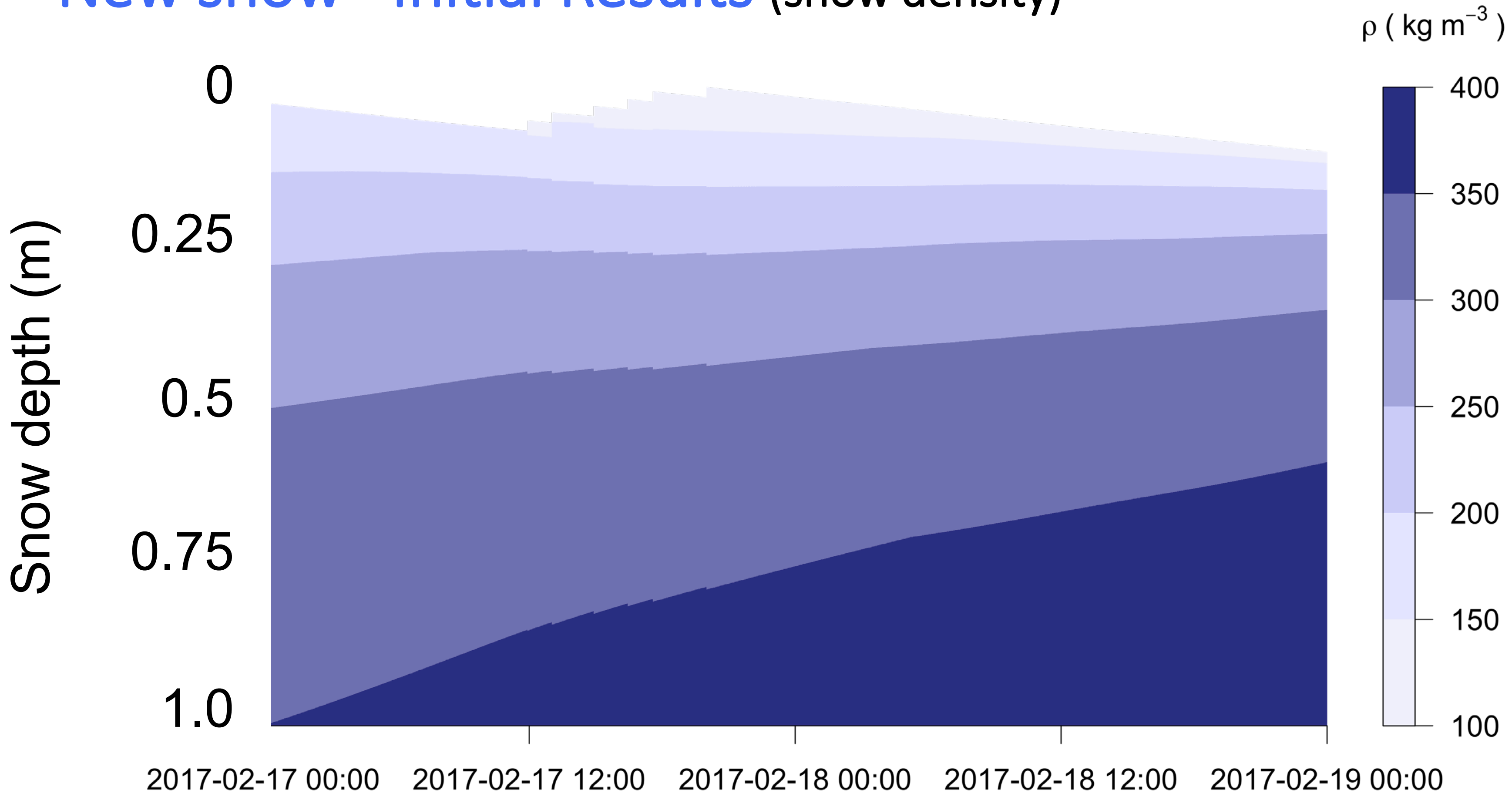
CALL interface_snow(…)

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

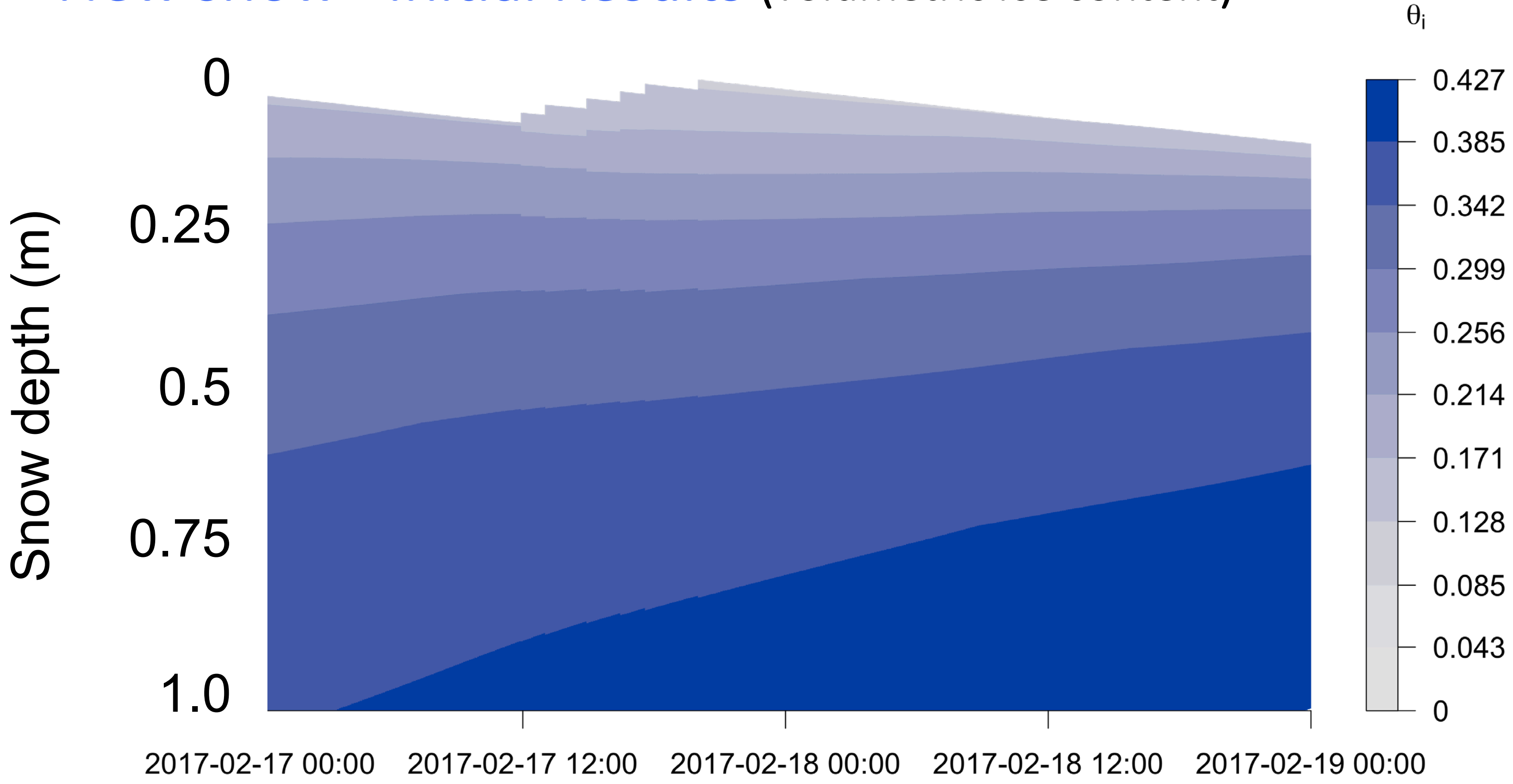
… before solving the heat equation in TERRA

```
    END DO
  END DO        ! soil layers

!MR: 05.05.2017 and later: heat-budget for inner soil layers substituted by a slightly different notation: >
!------------------------------------------------------------------------------------------

!*******************************************************************************************
!MR: 05.05.2017: modified heat-budget for boundary soil layers including a single-layer snow-cover: <
!*******************************************************************************************
```

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.

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

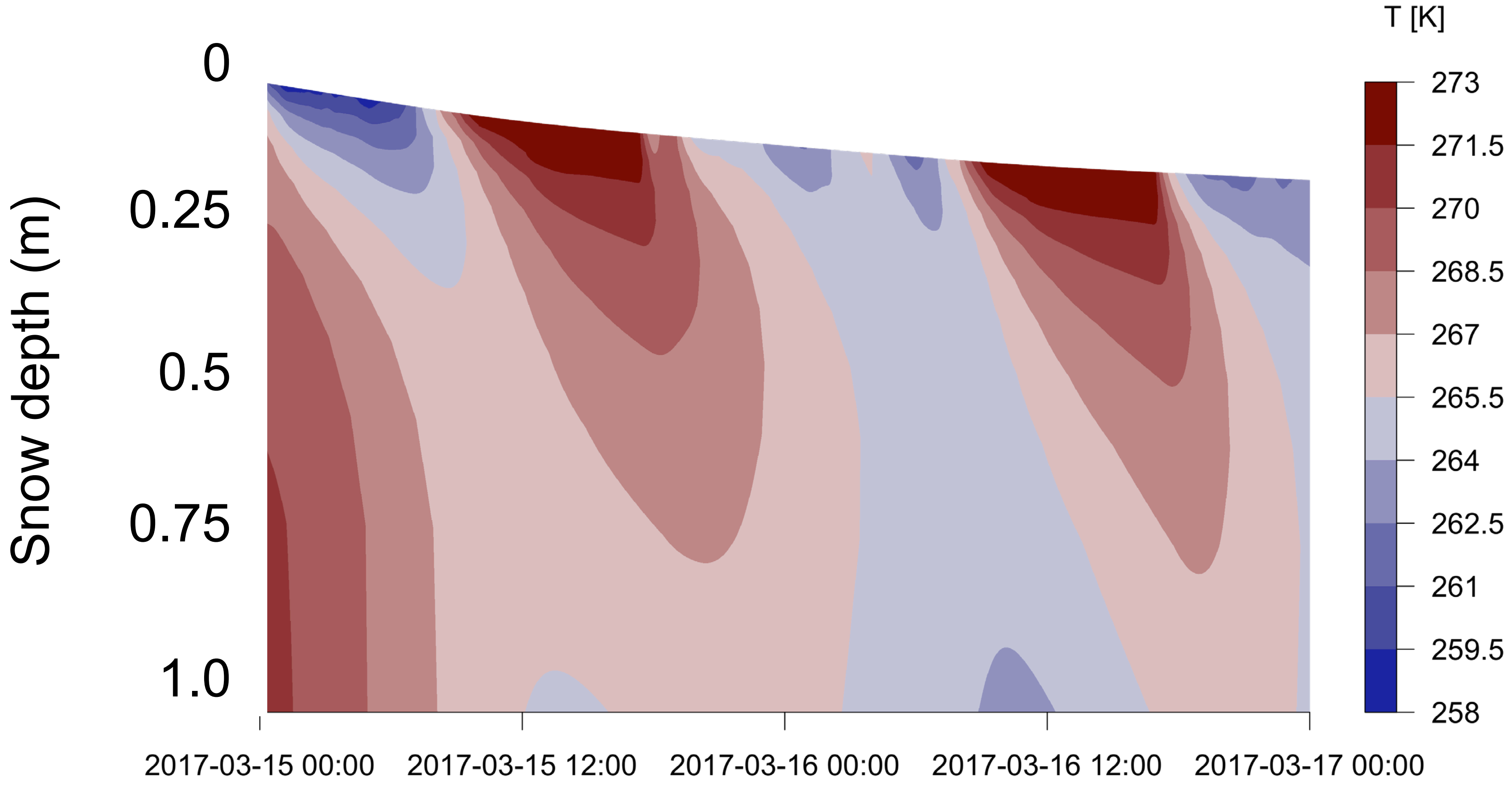
$$\Delta\theta_w = \frac{c_s \theta_i \rho_i \Delta T}{L_f \rho_w}$$

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

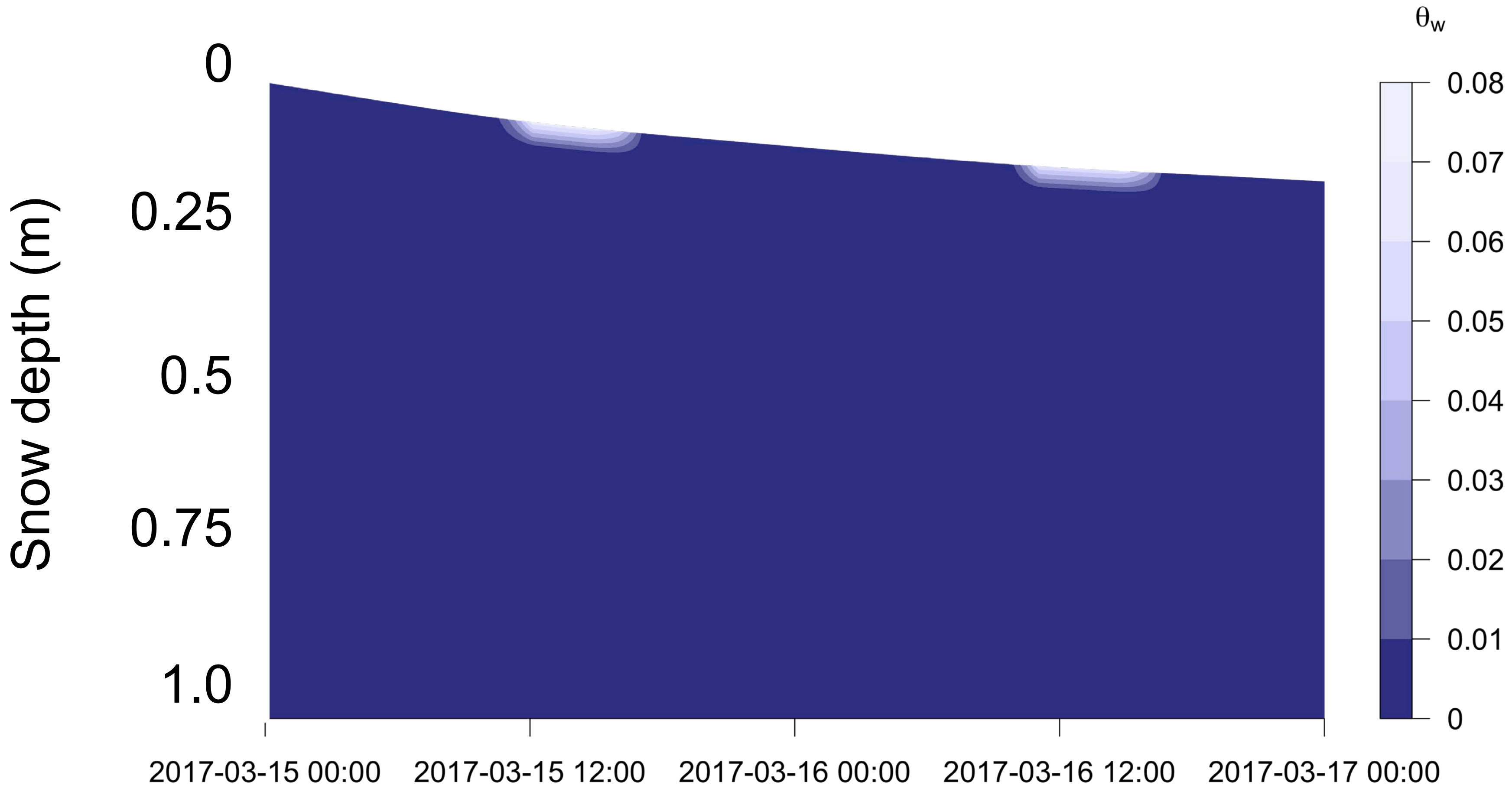
$$Q_{pc} = \Delta\theta_i \rho_i L_f$$

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

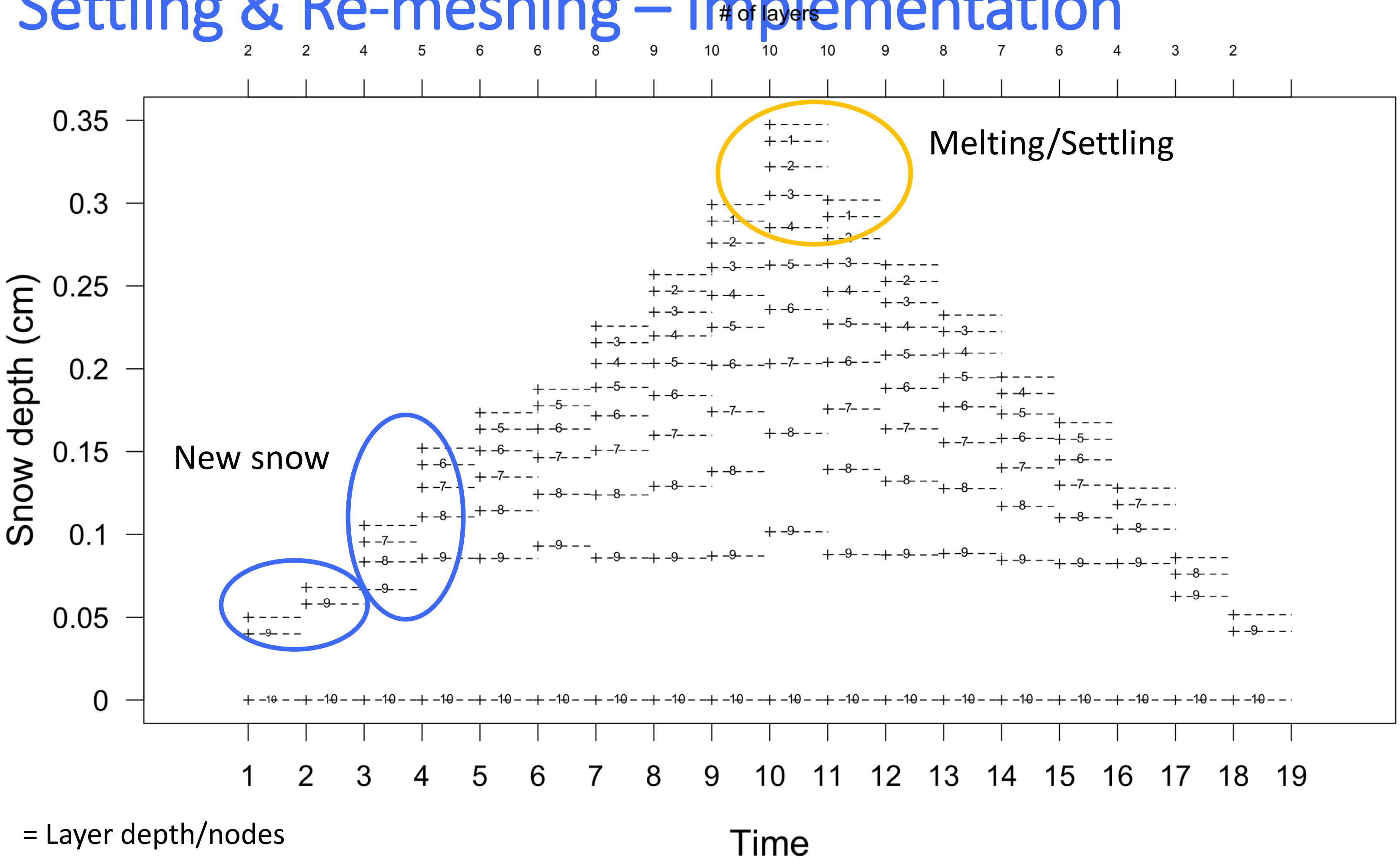
Phase Changes – Initial Results (Snow temperature)



Phase Changes – Initial Results (Water content)

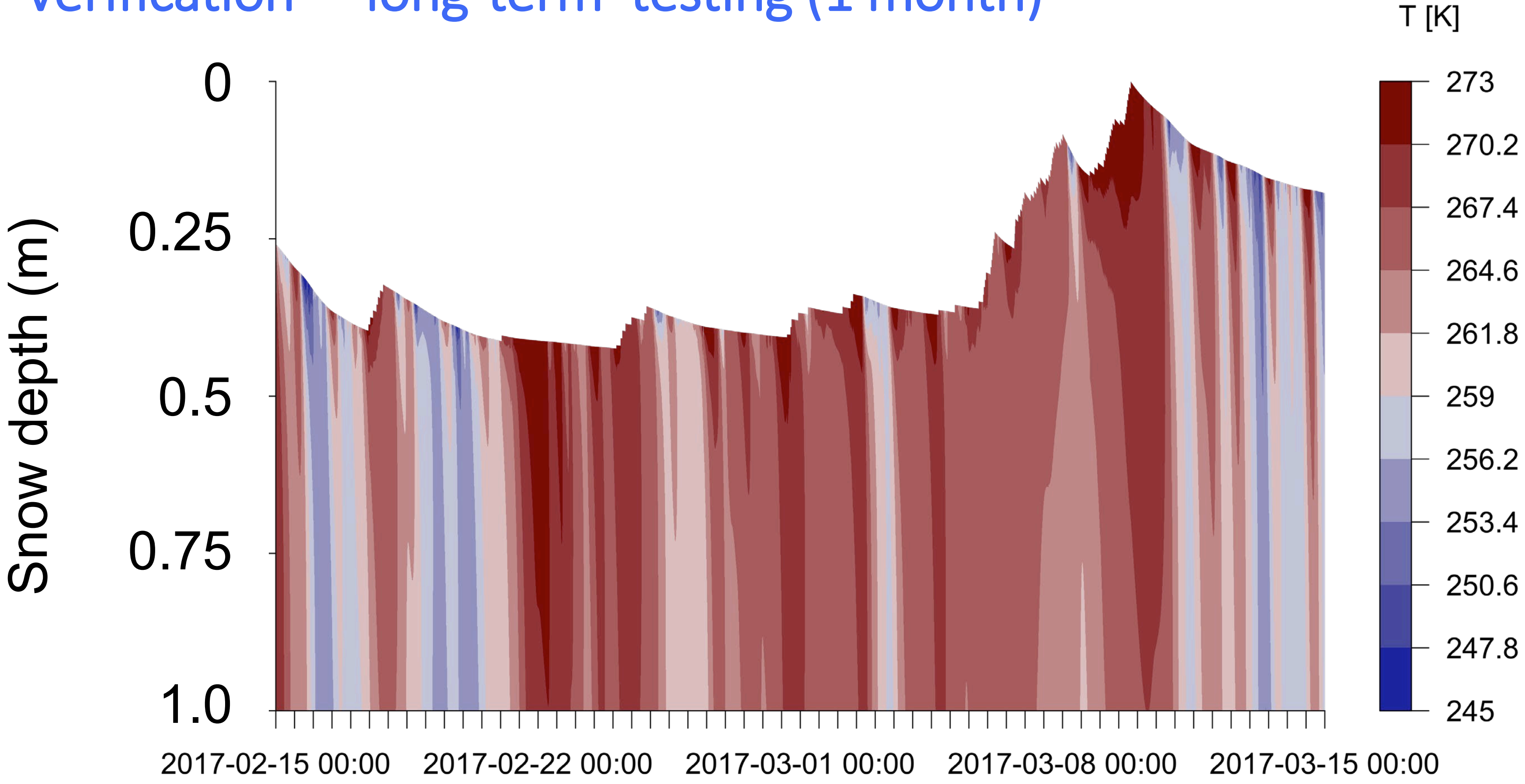


Settling & Re-meshing – Implementation

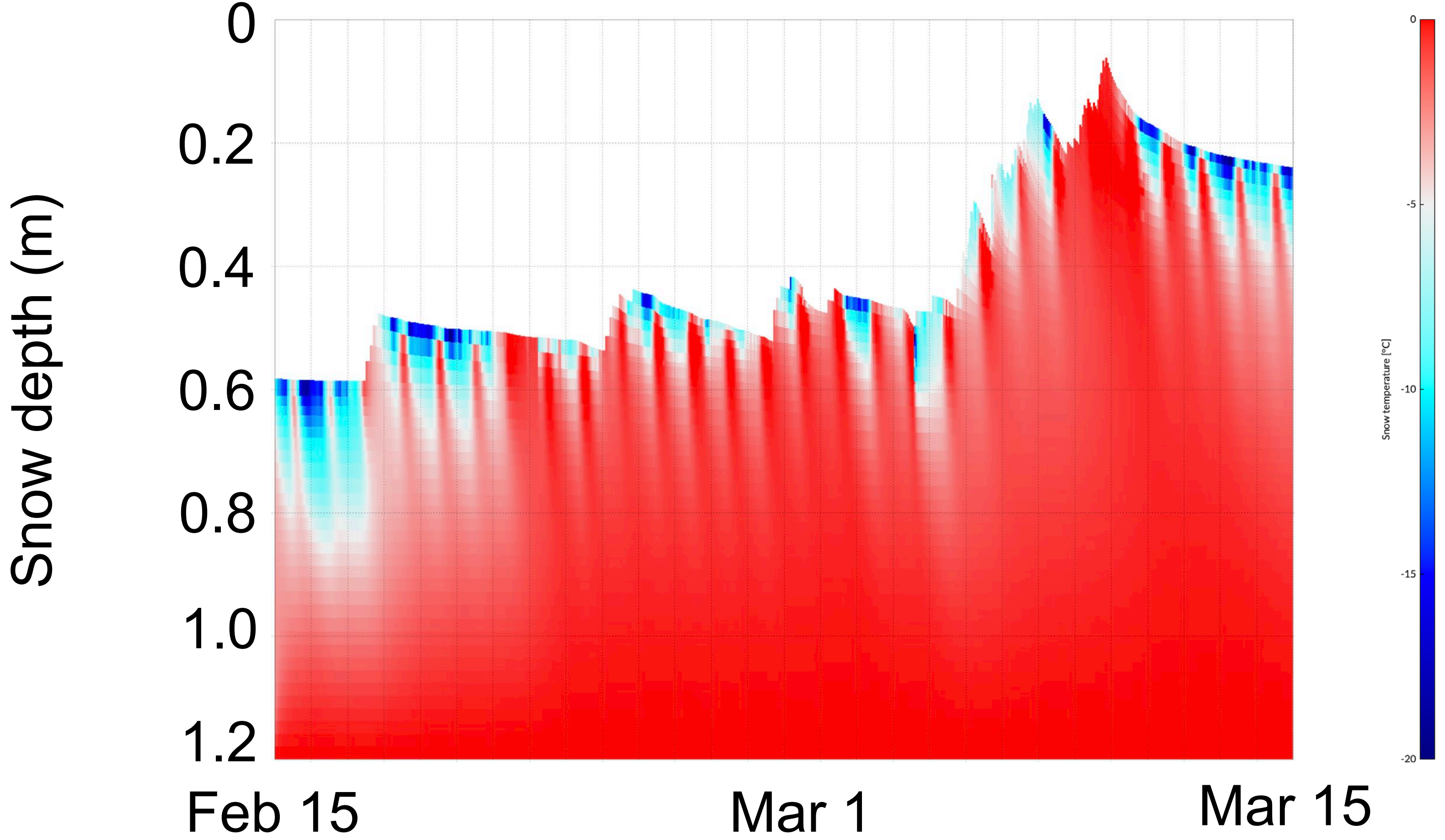


= Layer depth/nodes

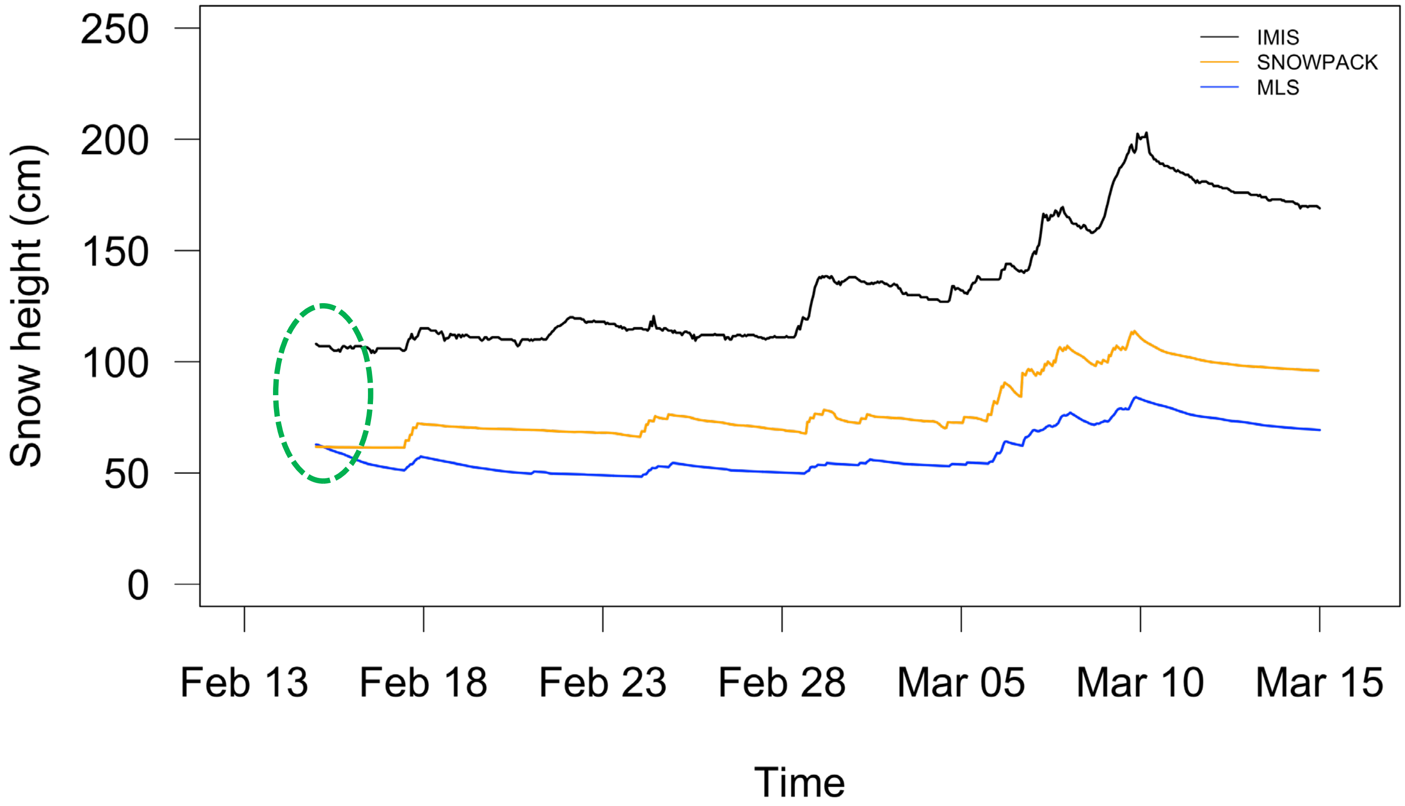
Verification – ‘long-term’ testing (1 month)



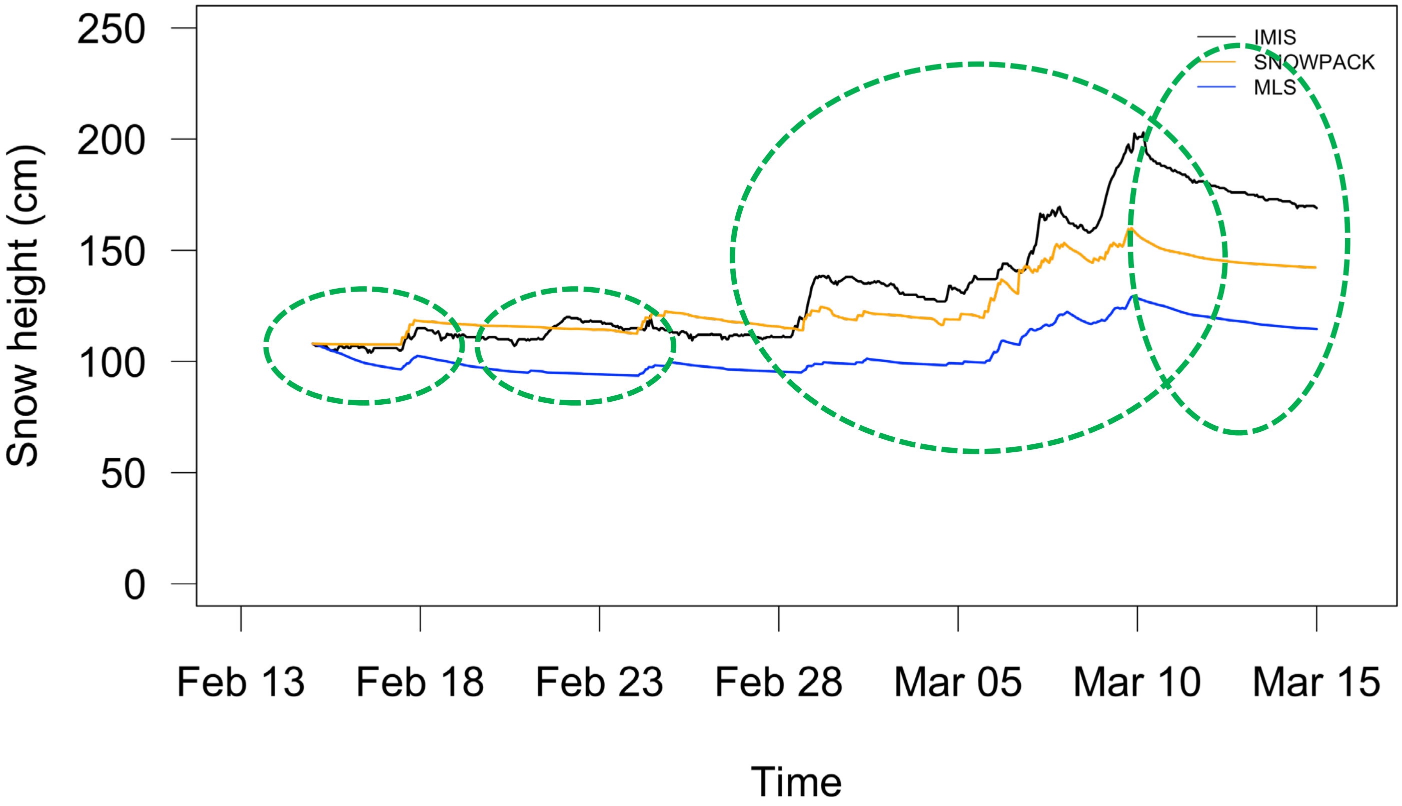
Verification – ‘long-term’ testing (1 month)



Verification – 'long-term' testing (1 month)

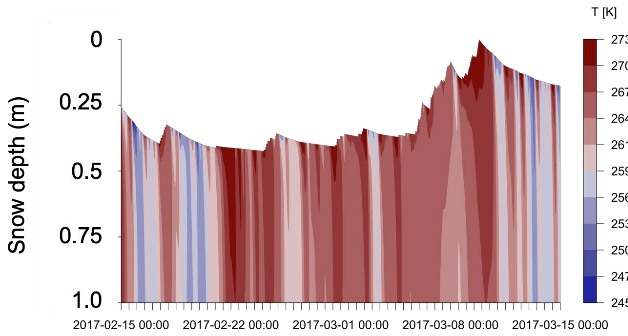


Verification – 'long-term' testing (1 month)



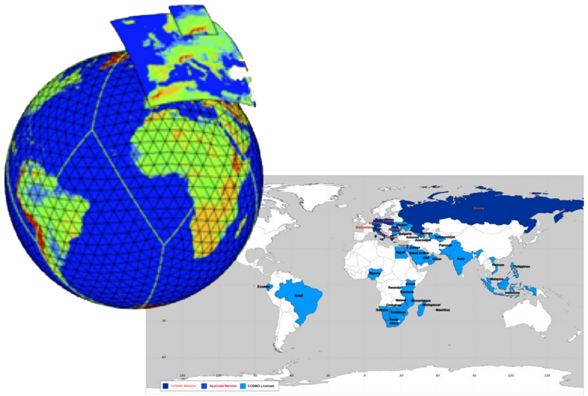
Summary: Priority Task (PT) project - SAINT

- 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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