

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

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Rome, 10.09.2019

Proposed COSMO Priority Task (PT) Project – SAINT

COSMO Priority Task: Snow cover Atmosphere INTeractions (SAINT)

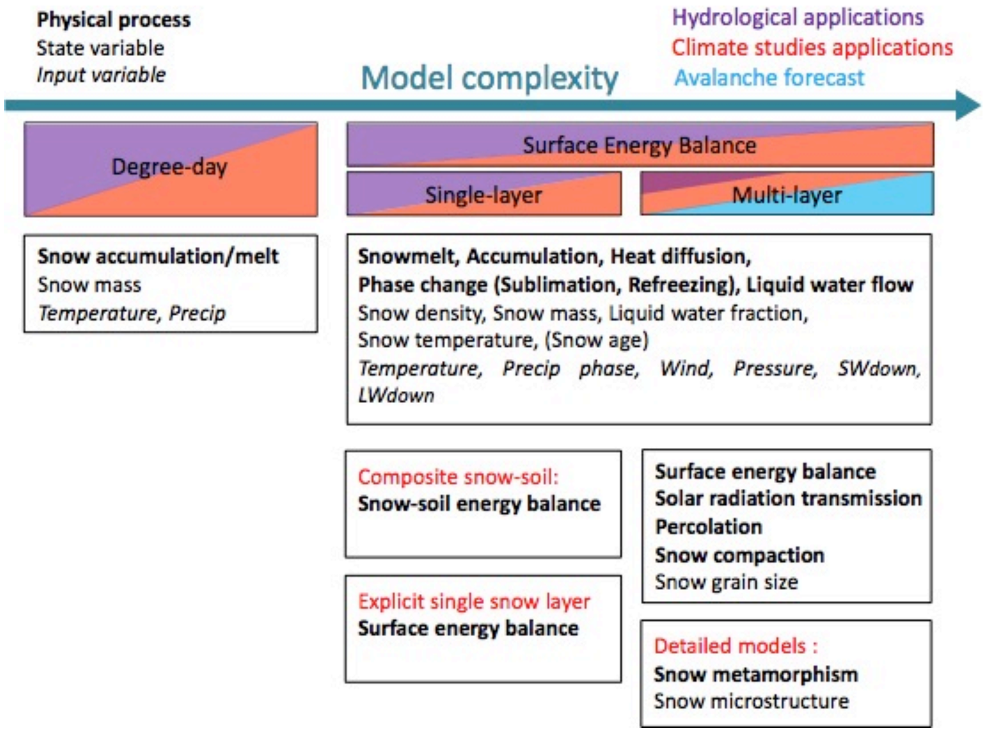
Version 1.0, 13.10.2017

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

Main goal

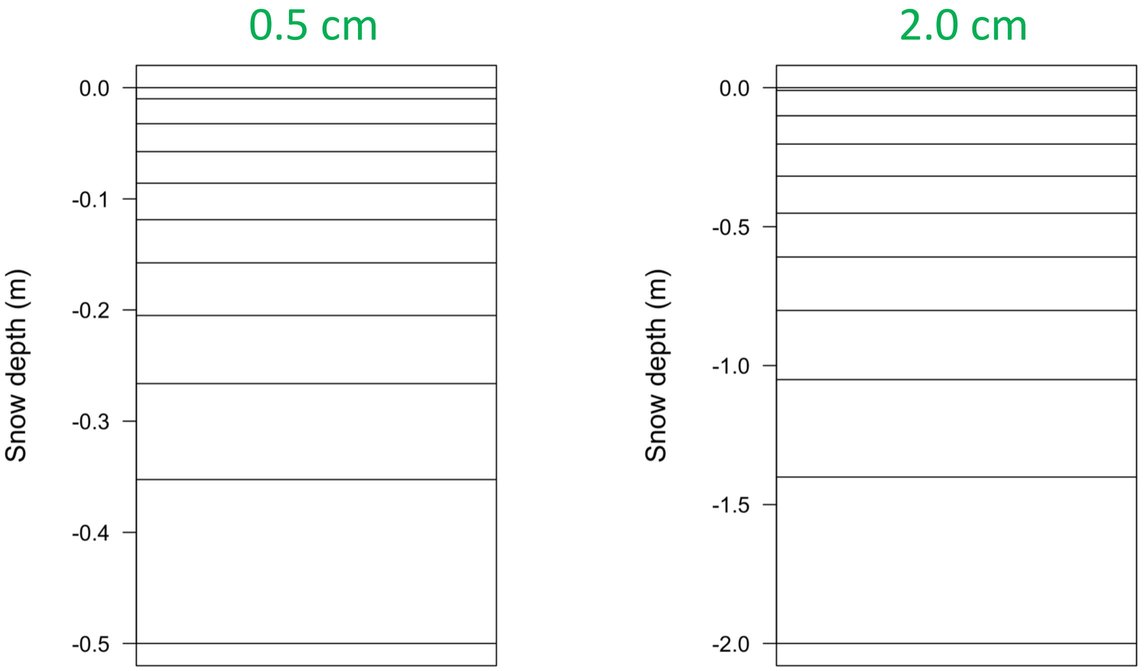
Improving the current multi-layer snow cover scheme

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.

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



General Structure:

- **Maximum 10 (default) snow layers.**
- **Fixed first layer thickness 0.01 m.**
- **Logarithmic increase of layer thickness with depth.**

Limitations:

- **No layer smaller than 0.01 m after re-meshing.**
- **Special treatment for snow depth < 0.05 m, i.e. single layer snow cover scheme.**

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:

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

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

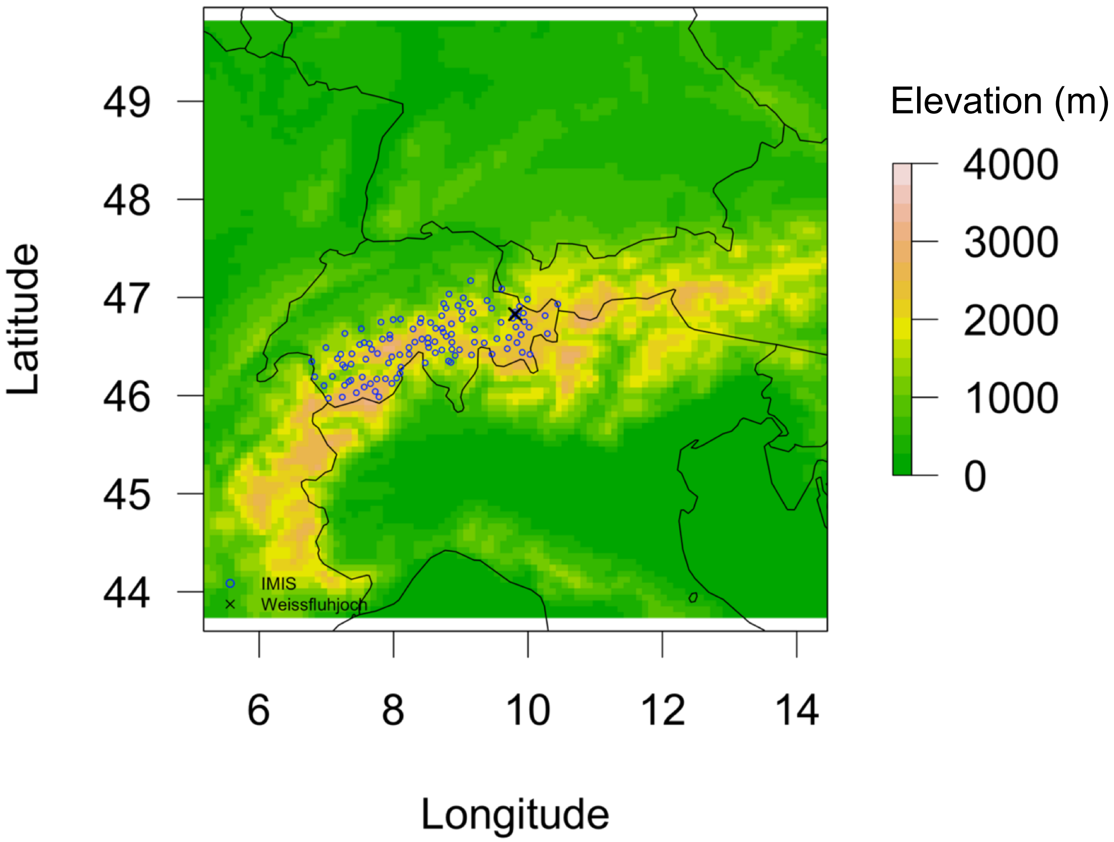
$$\rho_s c_p = \rho_i c_i \theta_i + \rho_w c_w \theta_w + \rho_a c_a \theta_a$$

T_S: Temperature of Snow (K)

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

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

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 …
- … hourly forecast/hindcast days up to month.

Snow cover scheme (MLS) – Implementation

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

MODULE sfc_terra

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

```

!SB <
USE sfc_snow
USE snow_utilities
!SB >

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

New snow model called in TERRA

Private ICON branch merged with COSMO

… consists of 2 (or 3) main subroutines + utili~~ty~~ **routines …**

INTENT INOUT (?)

CALL snow_forcing(…)

- snow specific atmospheric forcing

CALL snow_on_soil(…)

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

CALL inte… ow(…)

- preparation … ed input (# layers, la… 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: <
!****************************************************************************************************

```

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

```fortran
! ----------------------------------------------------------------
! 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

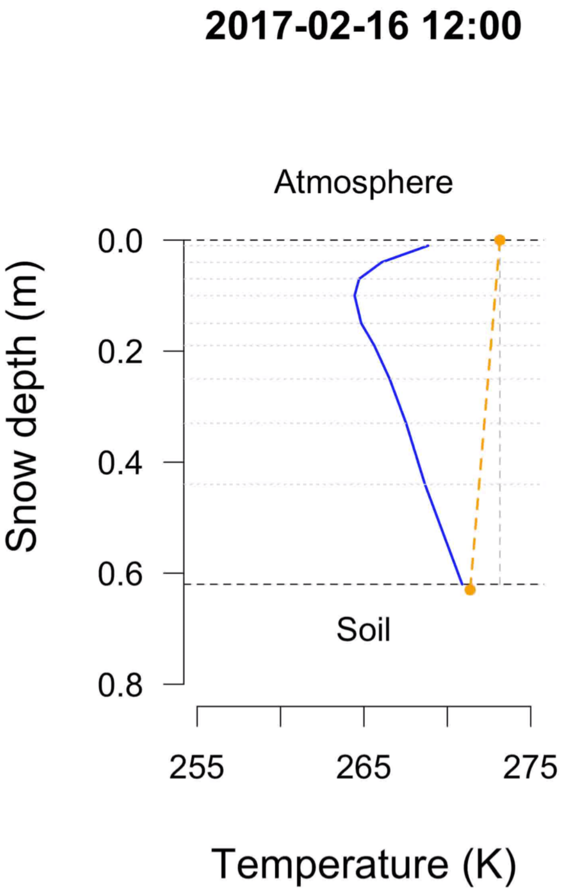
     e(j) = e(j) - gama(j+1) * e(j+1)

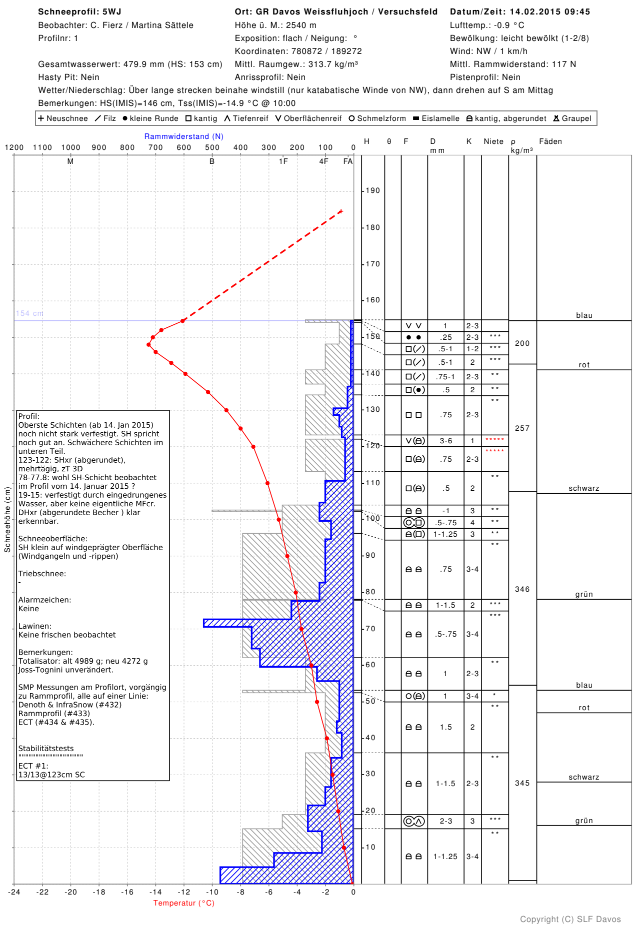
   ENDDO
```

Top layer

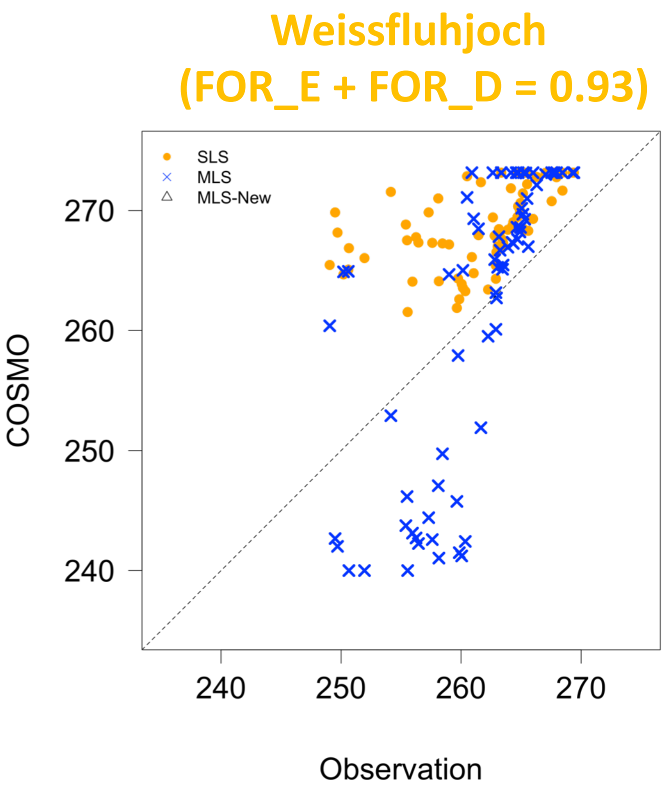
for_sn = forcing = SEB

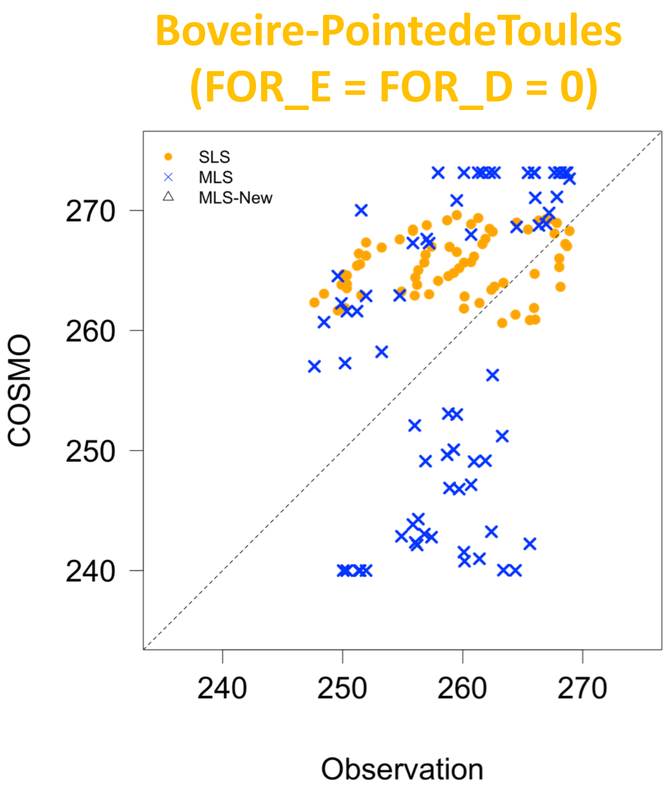
Heat Equation – Snow temperature profile





Results – Forcing (Surface Temperature)

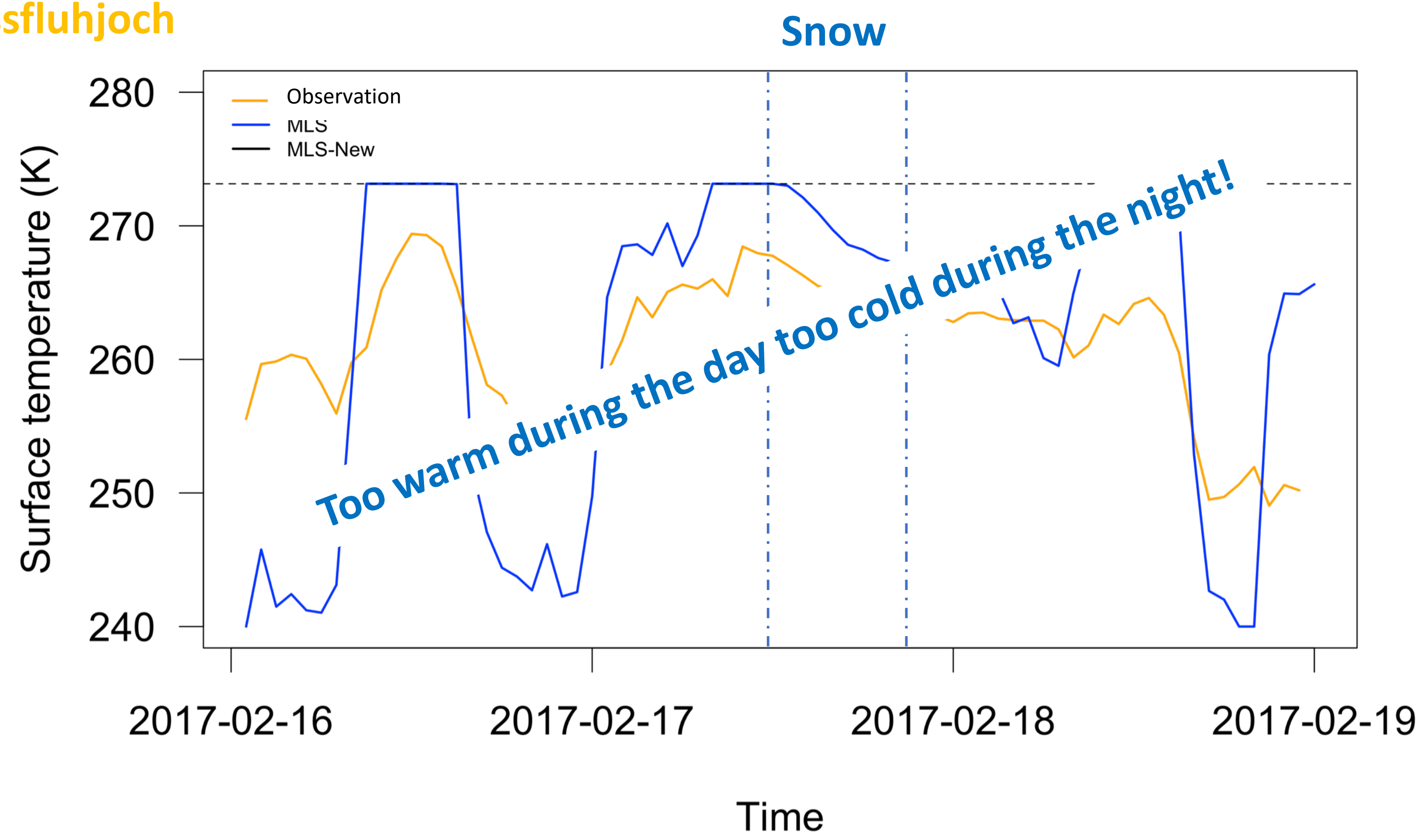




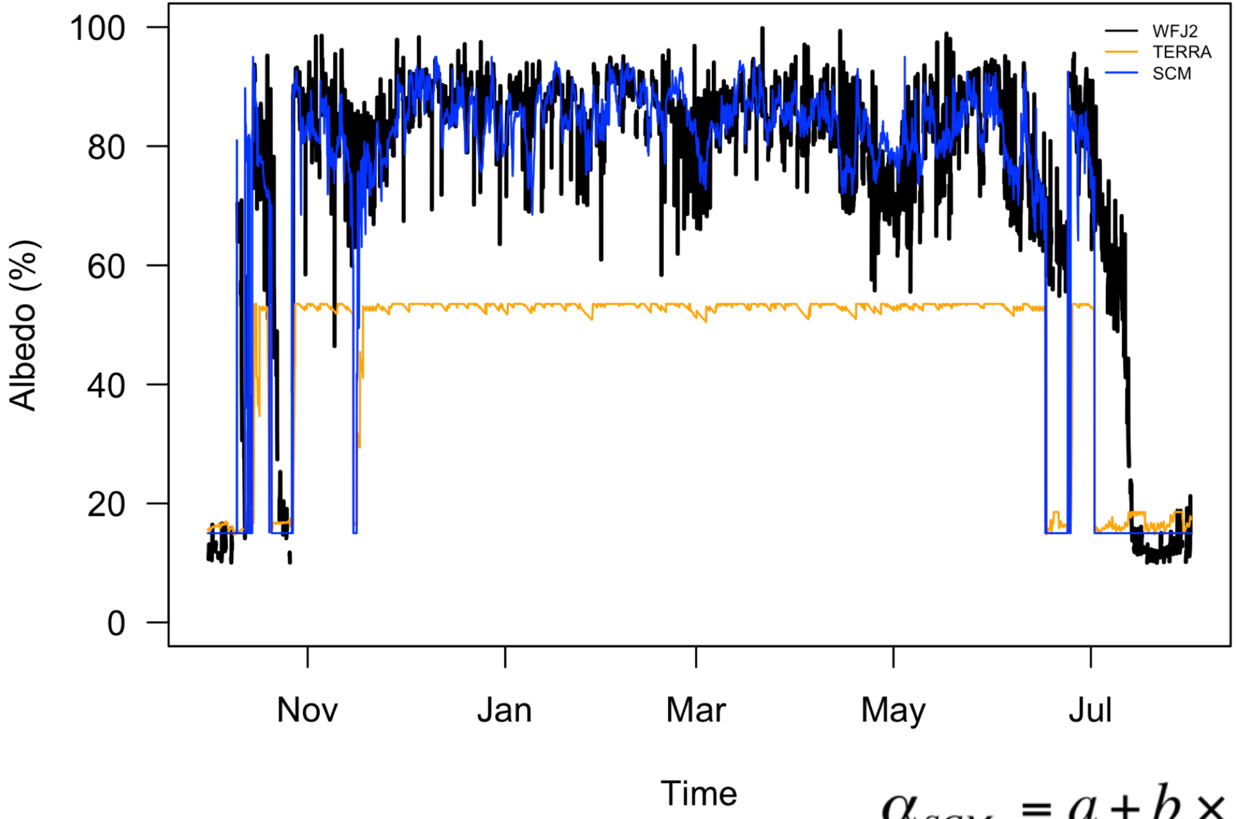
● = **Single layer snow cover scheme (SLS)**   **X = Multi-layer snow cover scheme (MLS)**

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 (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:

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

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

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

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

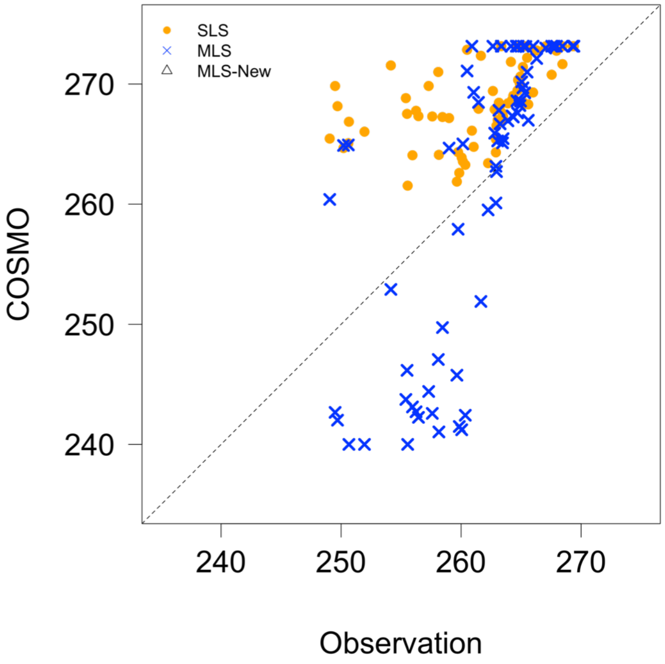
$$B = \Delta T / \bar{T}$$

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

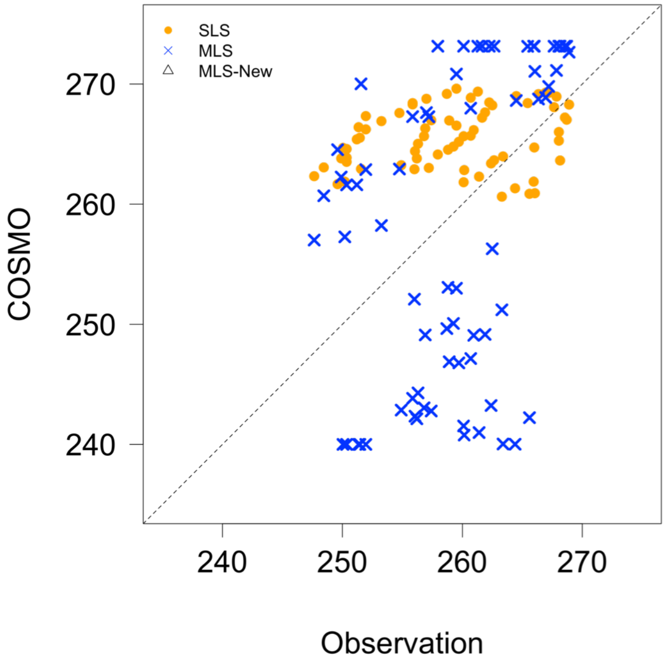
test site	a_1	b_1	test site	a_2	b_2
WFJ07 (3 m)	3.227	0.0043	WFJ07 (3 m)	−982.90	−0.0005
WFJ07 (5 m)	−4.441	0.0025	WFJ07 (5 m)	−642.51	0.0009
WFJ11	−30.74	0.0008	WFJ11	−1135.4	−0.0015
PM07 NWW	−191.93	0.0008	PM07 NWW	−751.73	−0.0005
PM07 SEE	−29.55	0.0090	PM07 SEE	−692.74	−0.0123
GR00 (1 m)	−145.41	−0.0914	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 (Surface Temperature)

Weissfluhjoch
(FOR_E + FOR_D = 0.93)



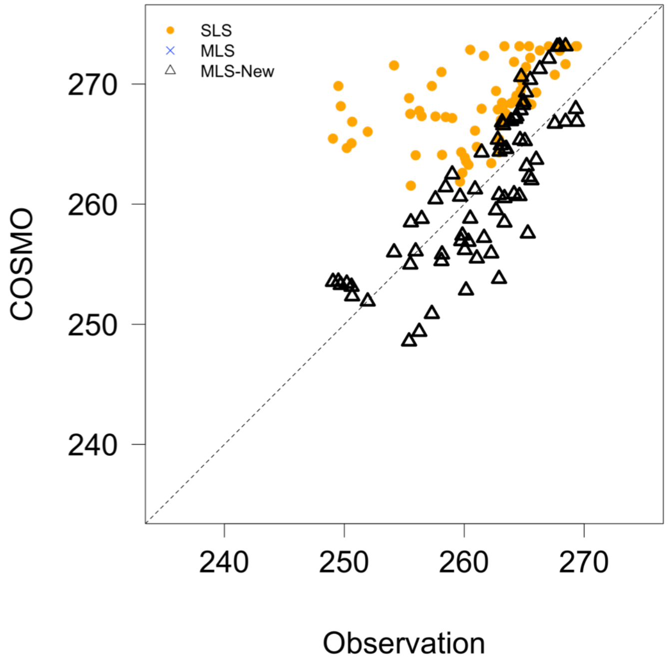
Boveire-PointedeToules
(FOR_E = FOR_D = 0)



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

Heat Equation – Initial Results

Weissfluhjoch (FOR_E + FOR_D = 0.93)



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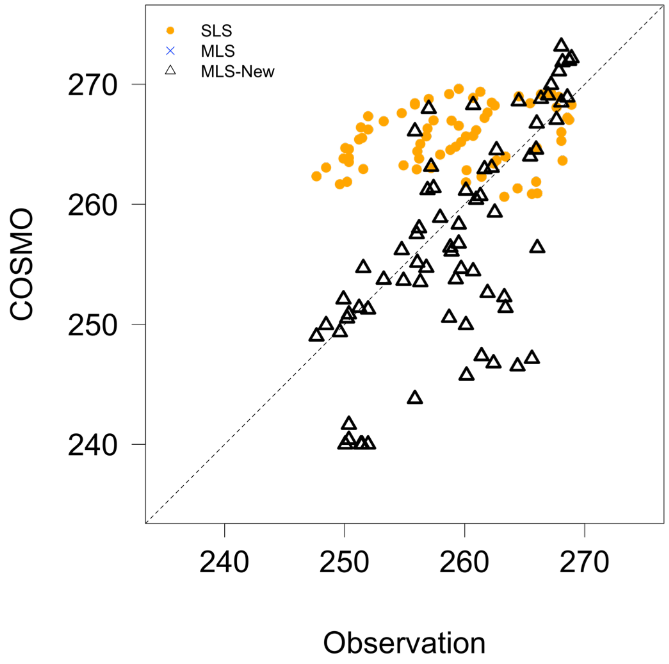

△ = Multi-layer snow cover scheme (MLS) with new flux parameterizations

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

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    END DO
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!-----------------------------------------------------------------------------------------------------------

!**********************************************************************************************************
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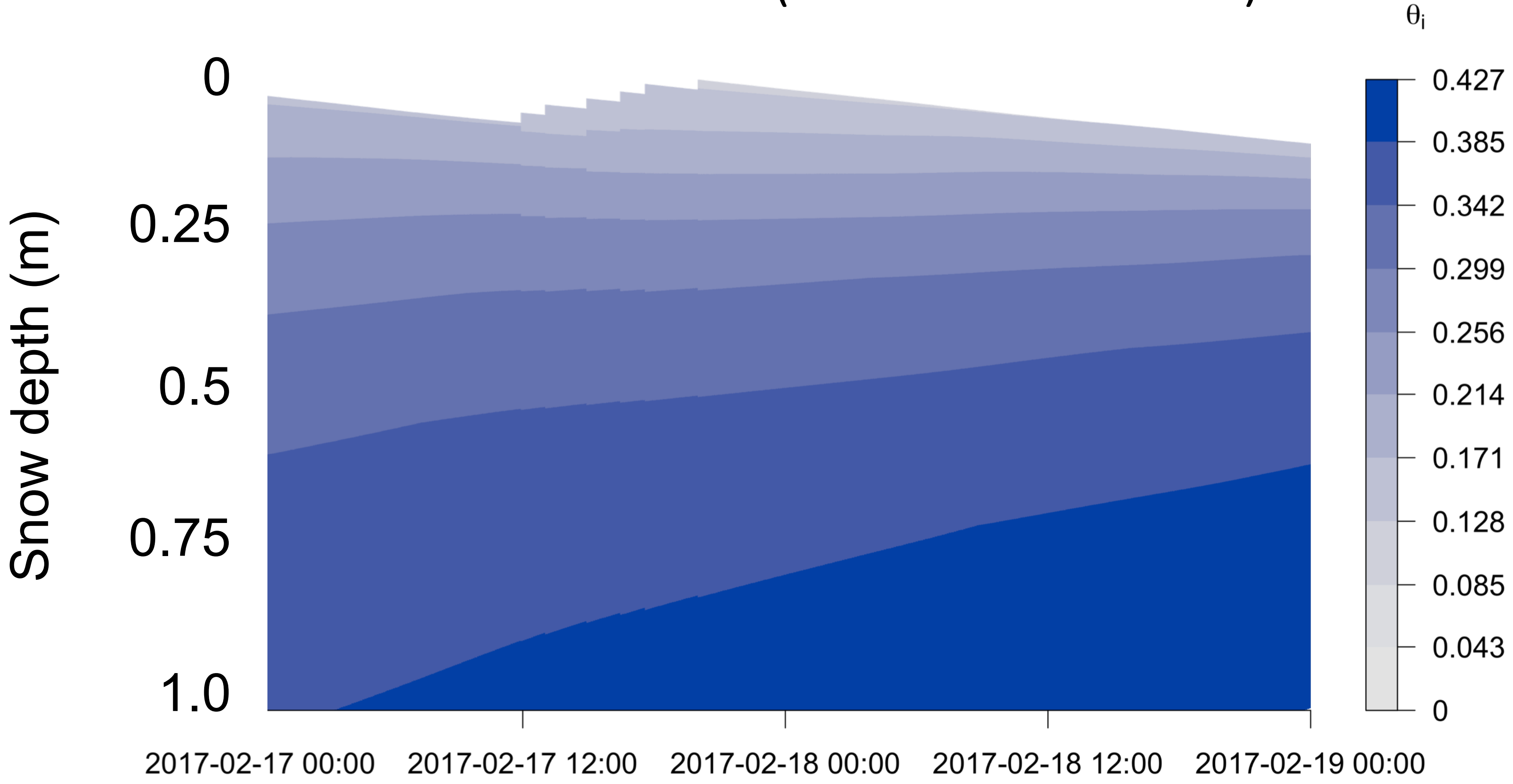
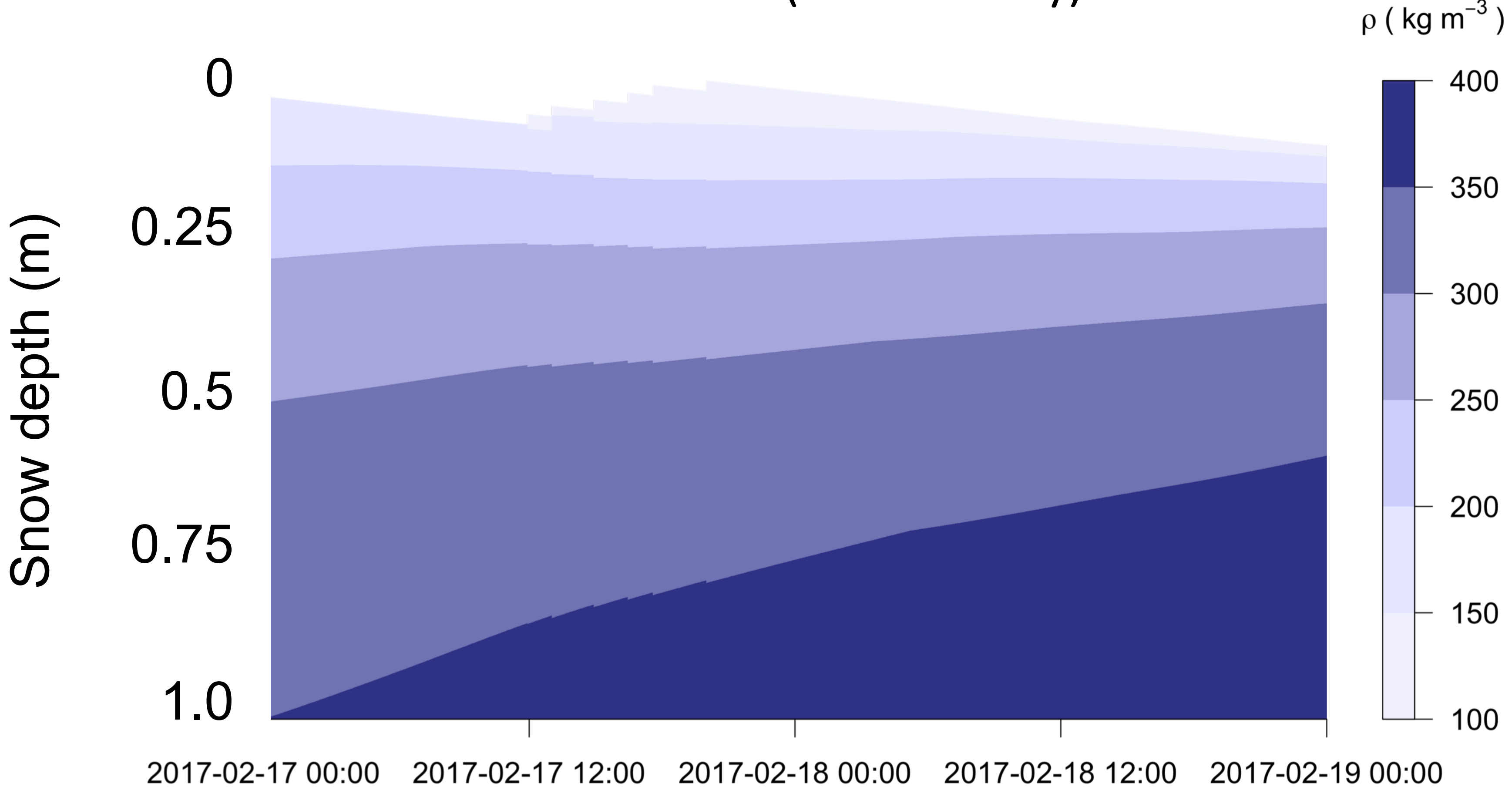
!**********************************************************************************************************

```

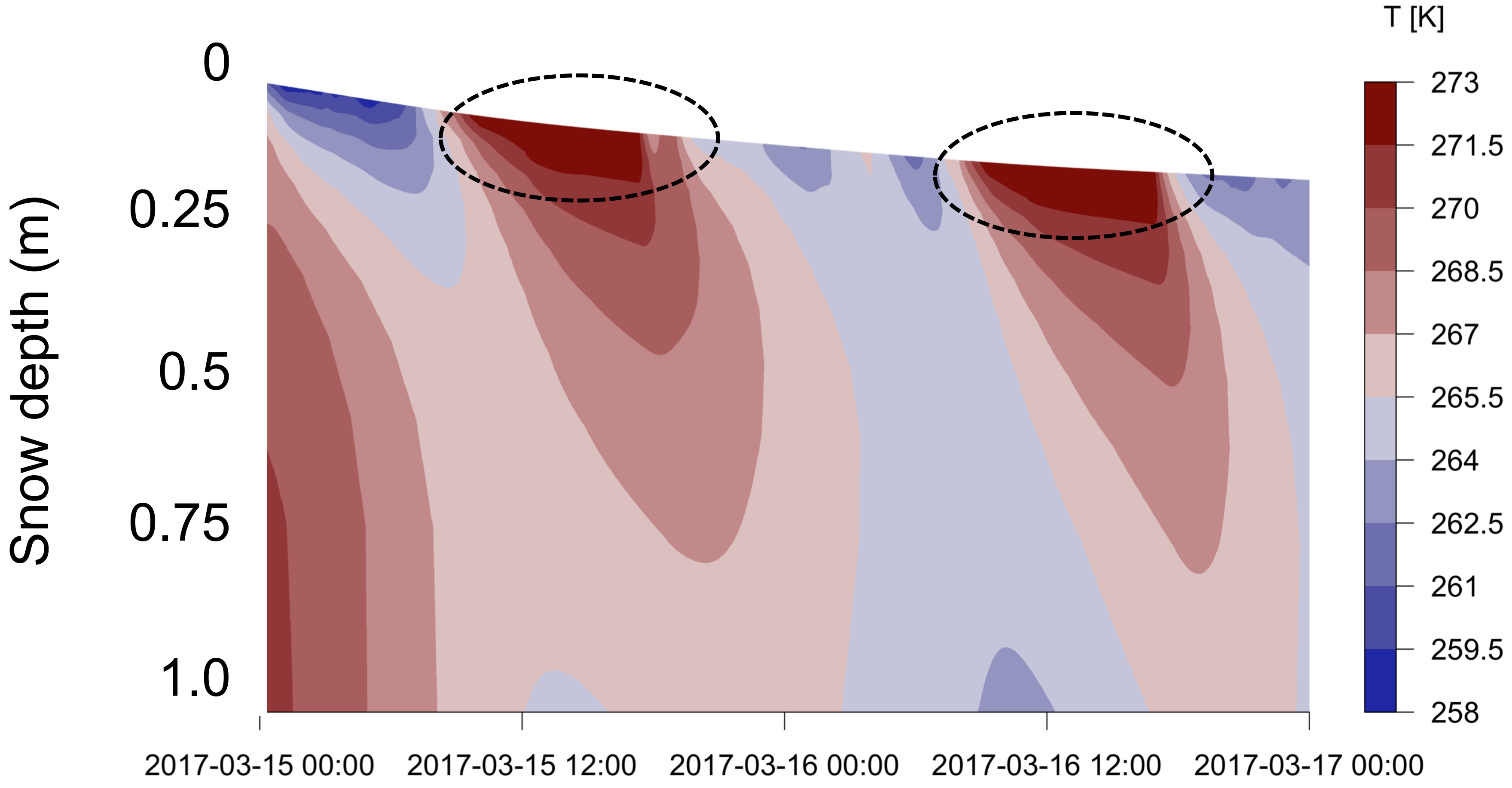
New snow– Initial Results (volumetric ice content)



New snow– Initial Results (snow density)



Phase Changes – Initial Results (Snow temperature)



Snow cover modelling: SNOWPACK (Phase Changes)

Treatment in SNOWPACK:

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

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

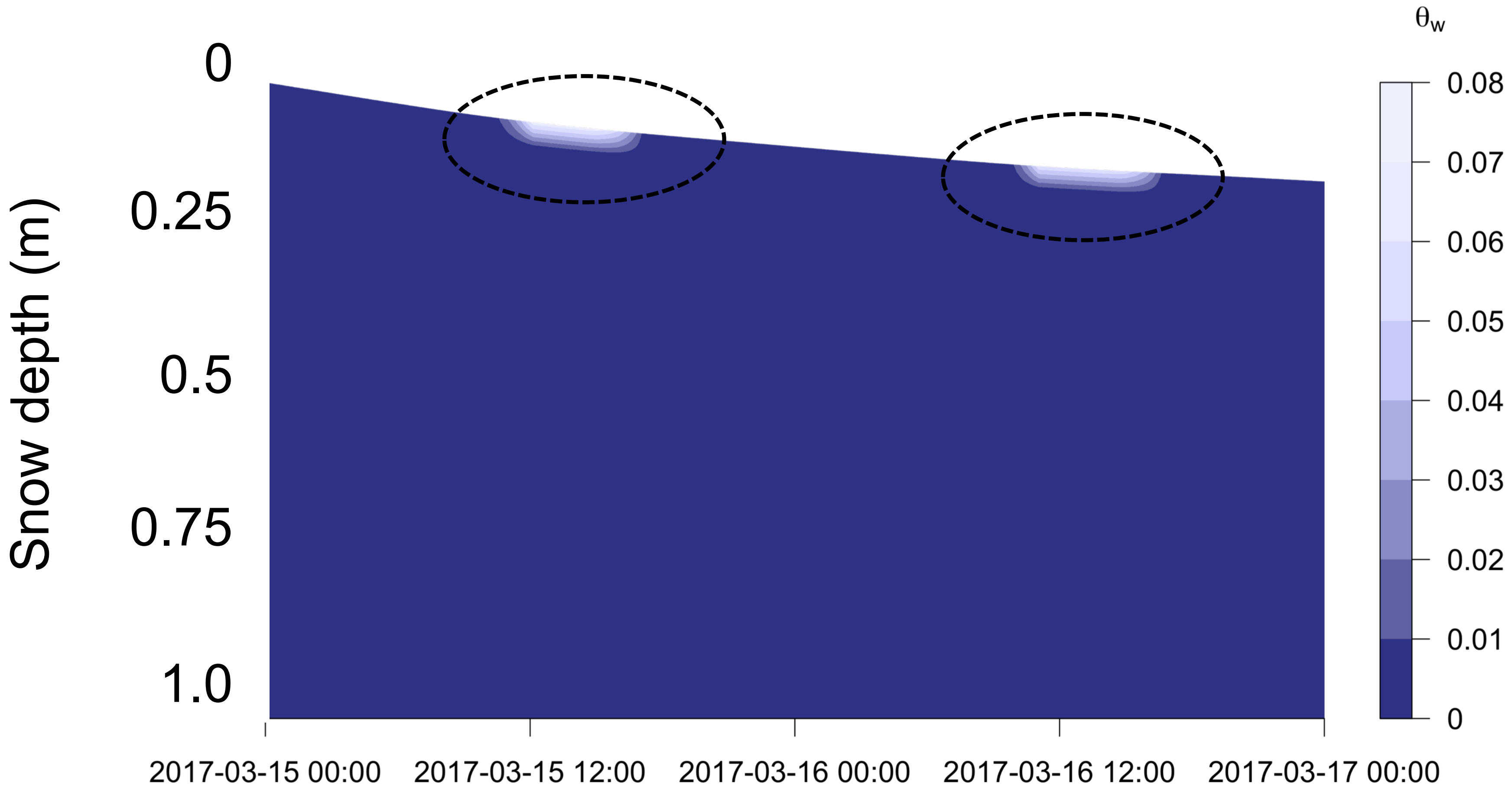
$$\Delta\theta_w = \frac{c_s \theta_i \rho_i \Delta T}{L_f \rho_w}$$

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

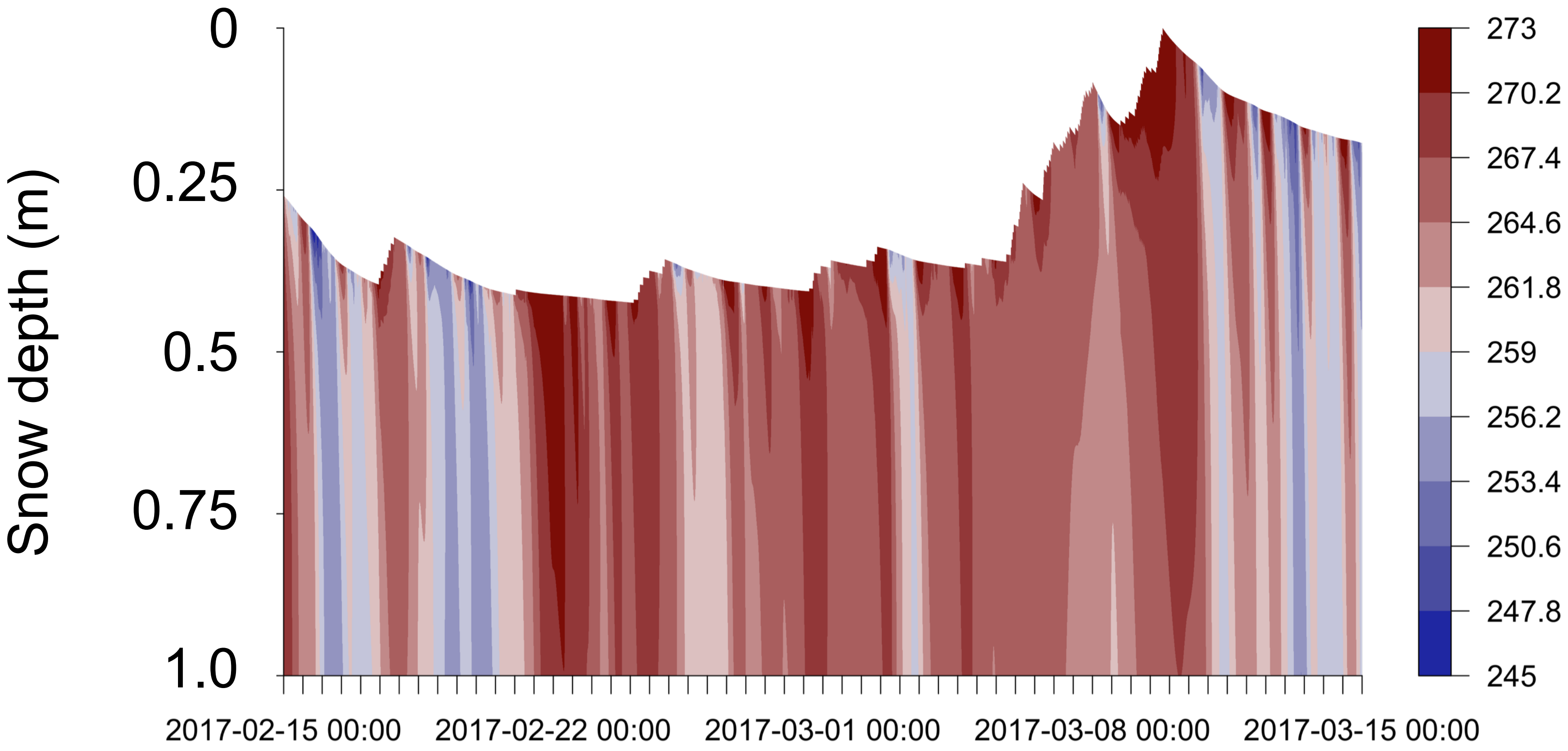
$$Q_{pc} = \Delta\theta_i \rho_i L_f$$

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

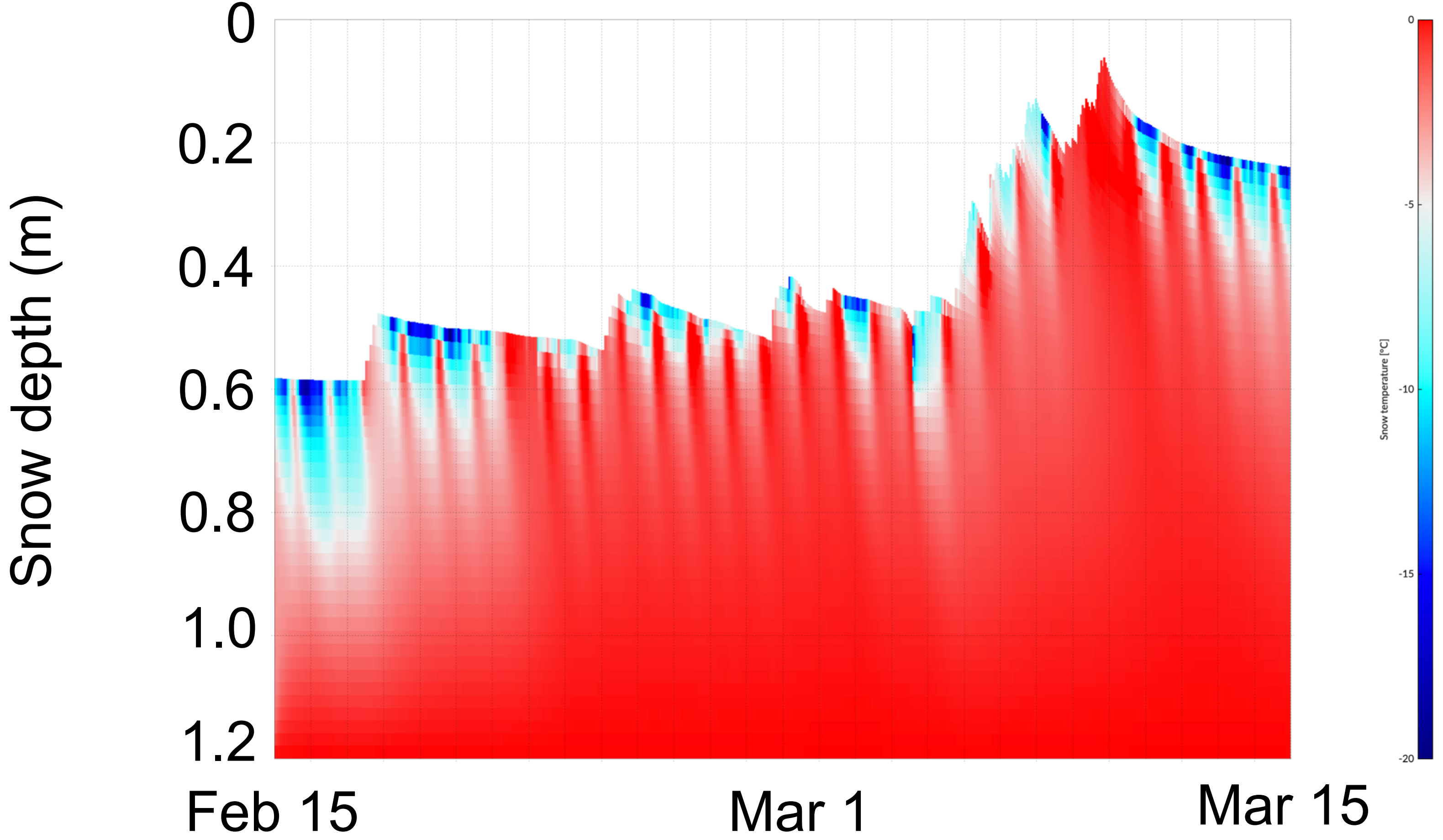
Phase Changes – Initial Results (Water content)



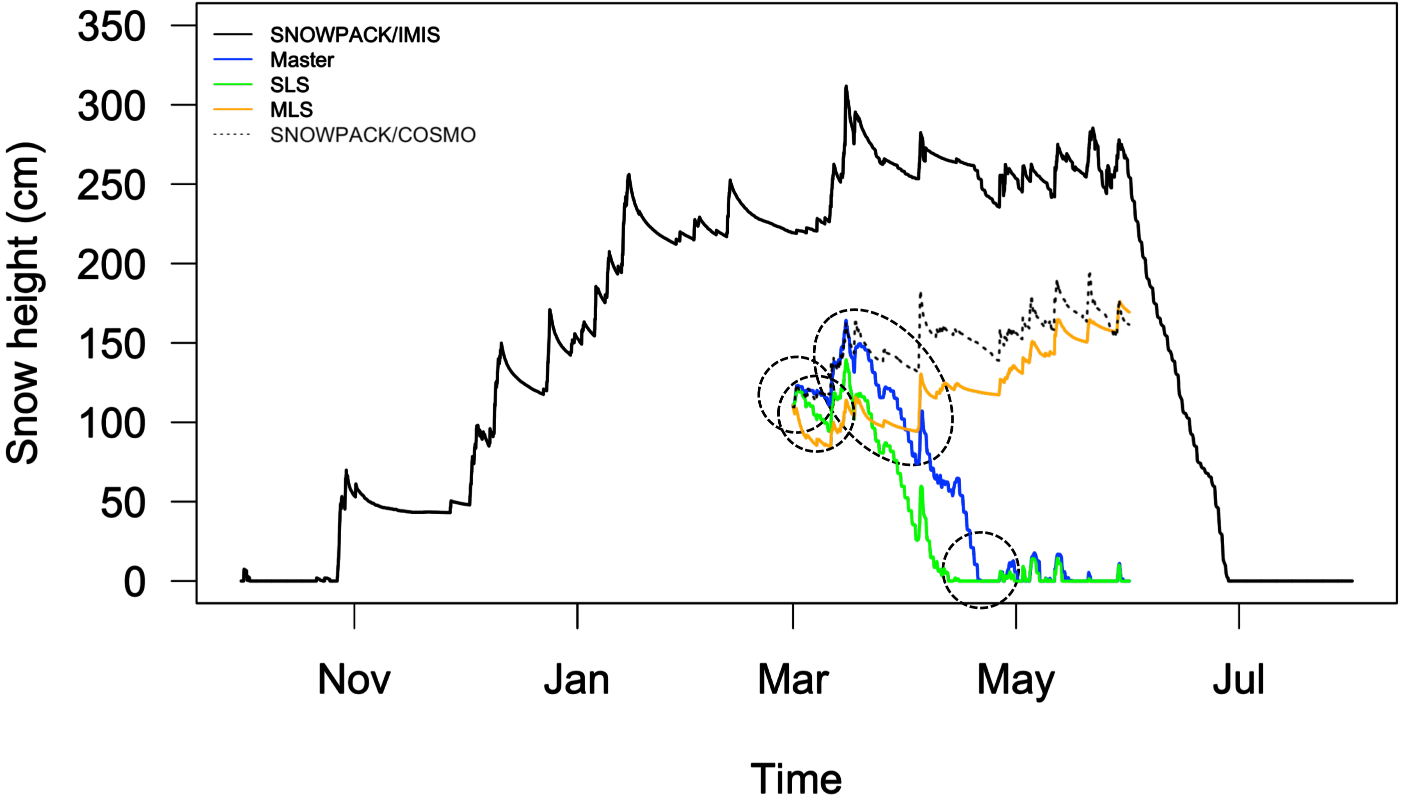
Verification – ‘long-term’ testing (1 month)



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



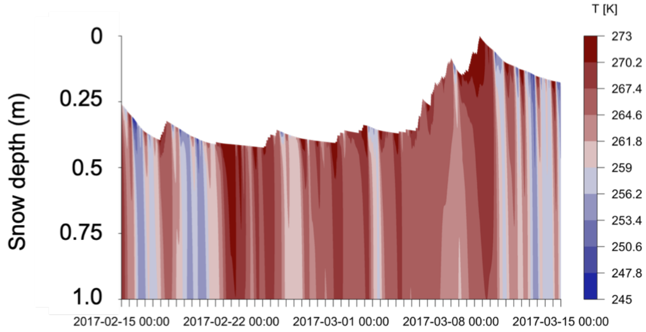
Verification – ‘long-term’ testing (3+ month)



Summary: Priority Task (PT) project - SAINT

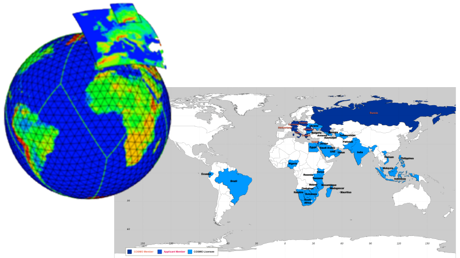
- PT SAINT: Joined project of MeteoSwiss and SLF
- Start: July 2017 ; **Ends June 2020; Possible extension to December 2021**
- Goal: New 'operational' multi-layer snow cover scheme for NWP models COSMO and ICON.
- **'Limited' SNOWPACK version:**
    - Max. 10 Layers
    - 'Heat conduction'
    - Phase 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

- Port Version 1 to GPU.
- Further testing/standard verification. Validation of snow cover scheme (coupled with TERRA)
- Further adaptations of the scheme (e.g. absorption of solar energy, sublimation/evaporation, rain on snow …).
- First runs with ICON (global, LAM) 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!!!** Interest of various research groups from e.g. ETH/KIT (climate studies, isotope modeling, snow drift, aerosol deposition etc.)





Thanks!
Questions and/or comments?

Sascha Bellaire[1], Michael Lehning[1,2] & Jean-Marie Bettems[3]

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

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Discussion – Open points (Agenda)

1) In which version of COSMO are we finally implementing the new snow cover scheme
   a. COSMO-6.0, i.e. official final version?
   b. A local (MCH) development branch? Using latest Matthias developments?
   c. Which version of TERRA will make it into 6.0 - standard TERRA or Matthias re-written version.

2) How do we proceed in terms of ICON?
   a. Which version? NWP vs. research branch?
   b. What is the planning for Matthias (SAT/TERRA) developments?
   c. What is our time frame?
   d. Resources?

3) What else are we missing?
   a. GRIB / NetCDF output
   b. Re-start possibility
   c. Global validation
   d. Data assimilation
   e. Standalone mode
   f. Other communities like CLM and ART (again ICON vs. COSMO)

Discussion – Strategy Proposal

PT SAINT, 07.2017 – 06.2020

S. Bellaire / SLF (PTL)

- **Code basis** will be reviewed during the SAINT parallel session on Tuesday
  - Due to the need of an **implicit coupling**, and after consultation with DWD colleagues (SMC 09.2017), the SAINT code base has been initiated from a **private ConSAT branch of Matthias**, merged into the **COSMO** master
  - An understanding between Matthias and Sacha about the way to **integrate** SAINT in Matthias code has been reached; **interface routine** has been provided by Matthias
  - The **latest** ConSAT developments will again be merged into **COSMO**, the SAINT developments integrated, the code debugged and ported to GPU, and the code systematically tested (with **both** old and new snow model)
  - If successfull, these developments will be put back in the private **ICON** branch of Matthias

Discussion – Strategy Proposal (‘fall back’)

- Use current COSMO (TERRA) version 5.06x.
- Update snow related fluxes (mainly turbulence), surface temperature and snow height calculated by the multi-layer scheme (MLS).
- Solve heat equation for the snow/soil column within the multi-layer scheme and update soil temperatures in TERRA accordingly.

- Pro: Independent (for the moment) of MR’s developments
- Pro: Snow cover will be implicitly coupled to the atmosphere.
- Con: Soil won’t be implicitly coupled.
- Pro: ICON and COSMO using the same TERRA, i.e. implementation ‘should’ be straight forward
- Pro: GPU porting almost done, MLS scheme is missing.