

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

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

[1]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

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

[3]MeteoSwiss, Zurich, Switzerland

Rome, 11.09.2019

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

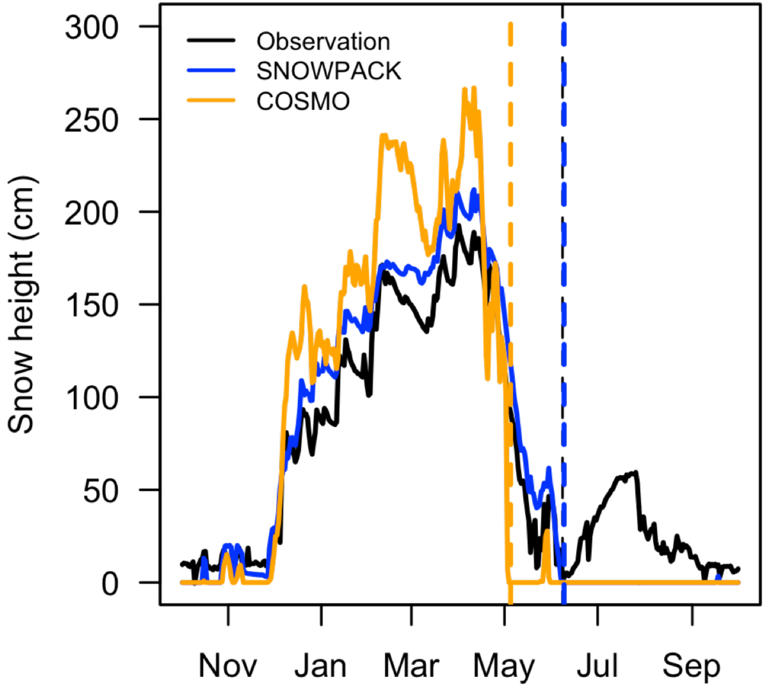
Task Leader: Sascha Bellaire (WSL Institute for Snow and Avalanche Research SLF)

Main goal

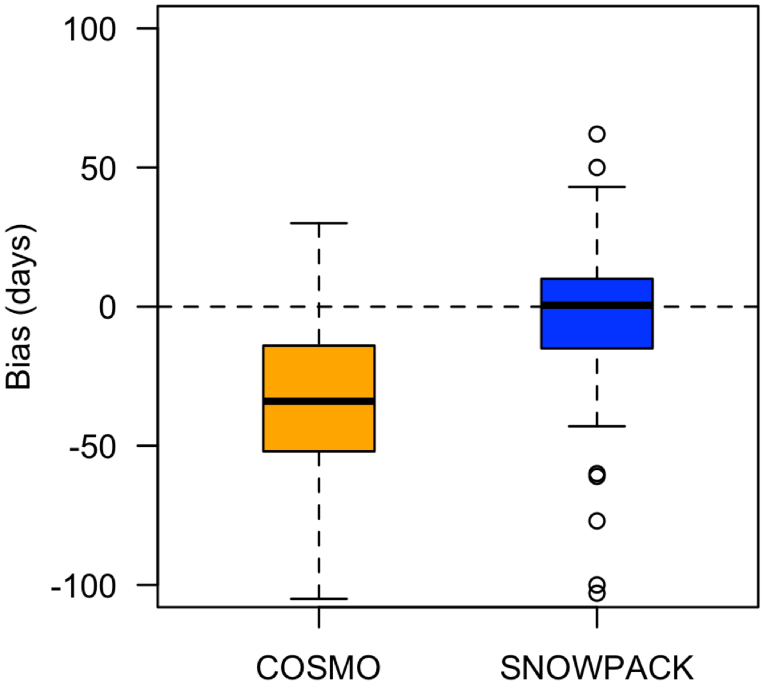
Improving the current multi-layer snow cover scheme

COSMO-2 validation (Snow depth)

Weissfluhjoch

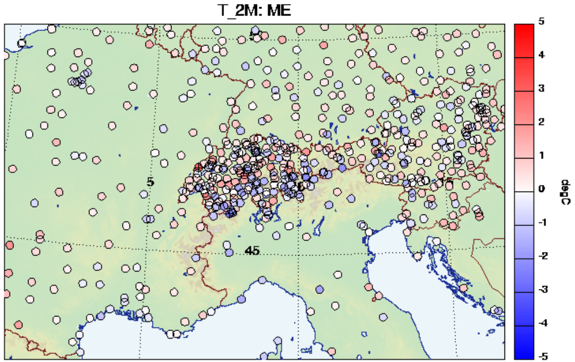


IMIS



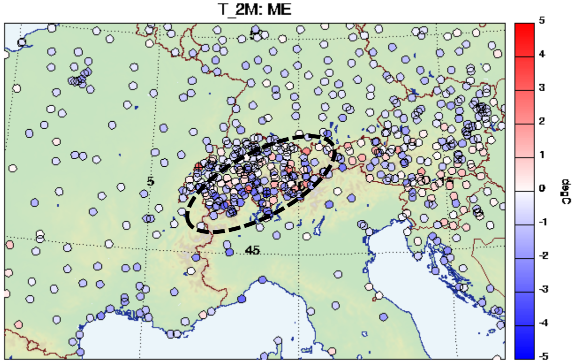
Verification – COSMO$_{MASTER}$ vs. Observation (2018-2019)

SON



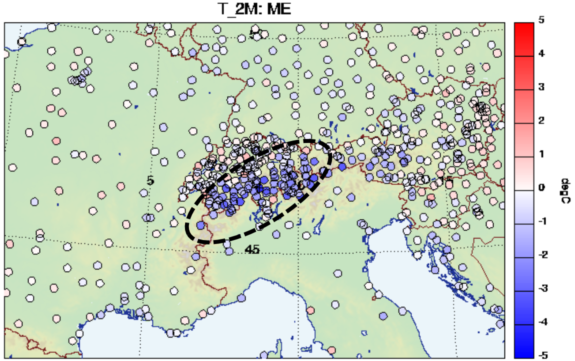
C-E-100@alps 2018-09-01 15:00 to 2018-12-01 0:00 15-24
+Min: -2.485 degC at station 16052 +Max: 2.998 degC at station 06617

DJF



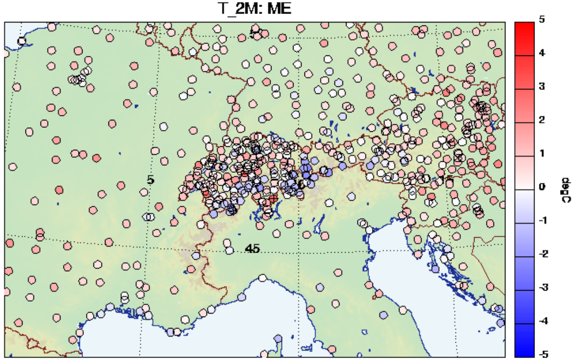
C-E-100@alps 2018-12-01 15:00 to 2019-03-01 12:00 15-24
+Min: -3.604 degC at station 06754 +Max: 2.788 degC at station 06617

MAM



C-E-100@alps 2019-03-01 15:00 to 2019-06-01 12:00 15-24
+Min: -3.890 degC at station 06753 +Max: 1.497 degC at station 06712

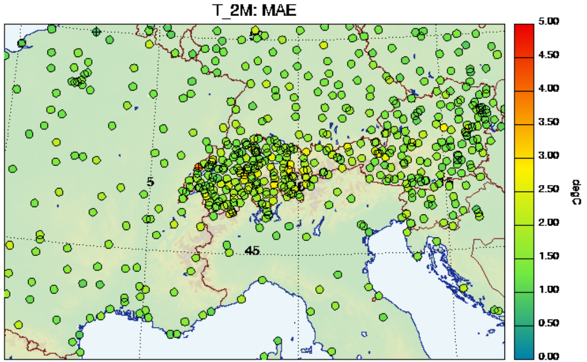
JJA



C-E-100@alps 2019-06-01 15:00 to 2019-08-15 12:00 15-24
+Min: -2.299 degC at station 06747 +Max: 2.915 degC at station 06758

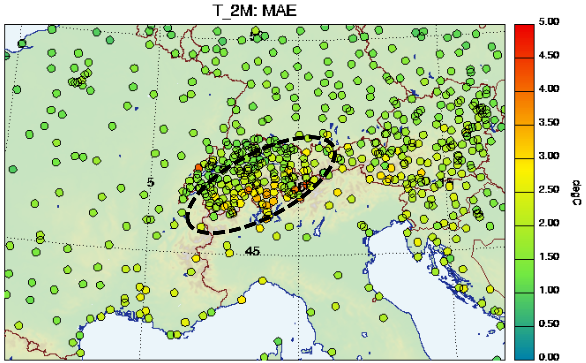
Verification – $COSMO_{MASTER}$ vs. Observation (2018-2019)

SON



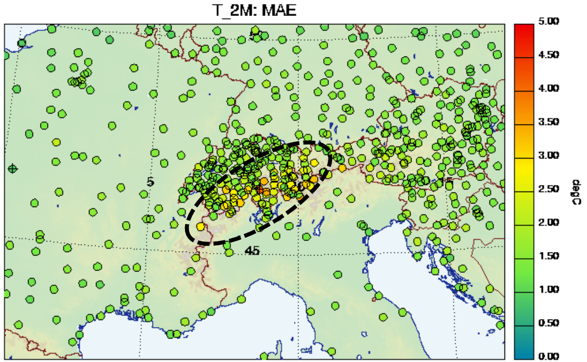
C-E-100@alps 2018-09-01 15:00 to 2018-12-01 0:00 15-24
+Min: 0.8410 degC at station 07059 +Max: 3.809 degC at station 06617

DJF



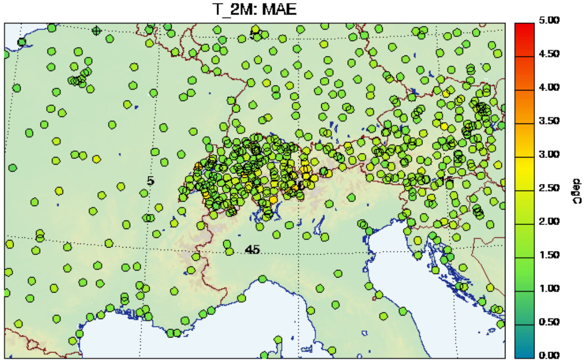
C-E-100@alps 2018-12-01 15:00 to 2019-03-01 12:00 15-24
+Min: 0.8018 degC at station 07027 +Max: 4.286 degC at station 06778

MAM



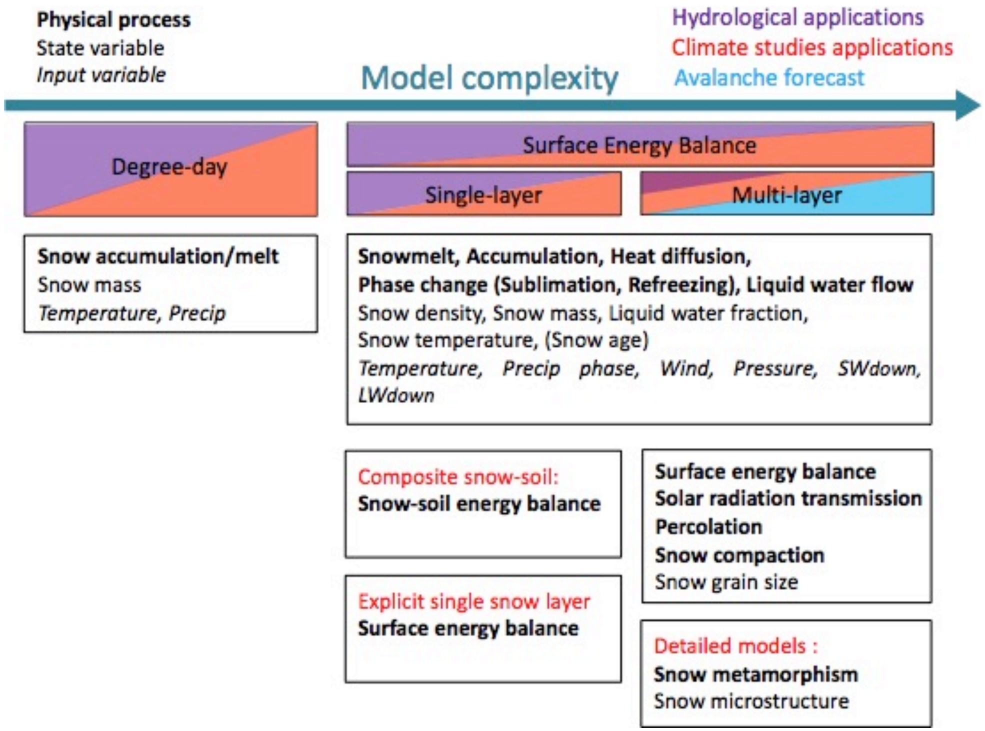
C-E-100@alps 2019-03-01 15:00 to 2019-06-01 12:00 15-24
+Min: 0.8928 degC at station 07335 +Max: 4.060 degC at station 06753

JJA



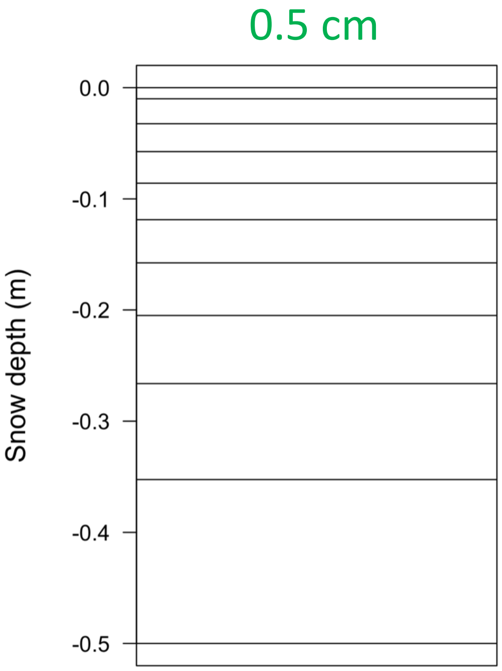
C-E-100@alps 2019-06-01 15:00 to 2019-08-15 12:00 15-24
+Min: 0.9948 degC at station 07059 +Max: 3.139 degC at station 06617

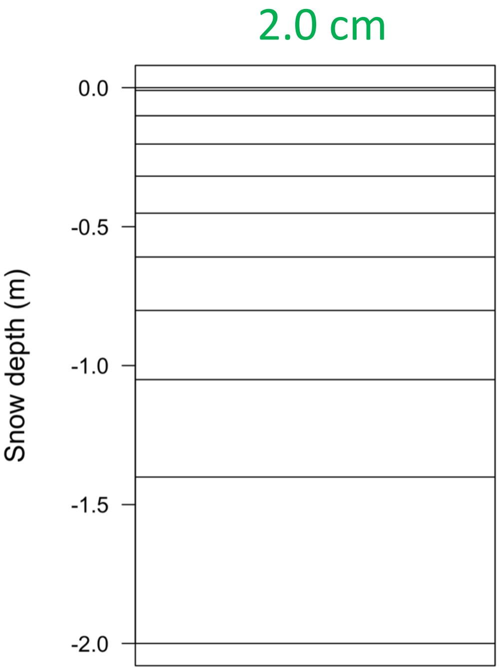
Snow cover schemes – Model complexity



- ‘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:

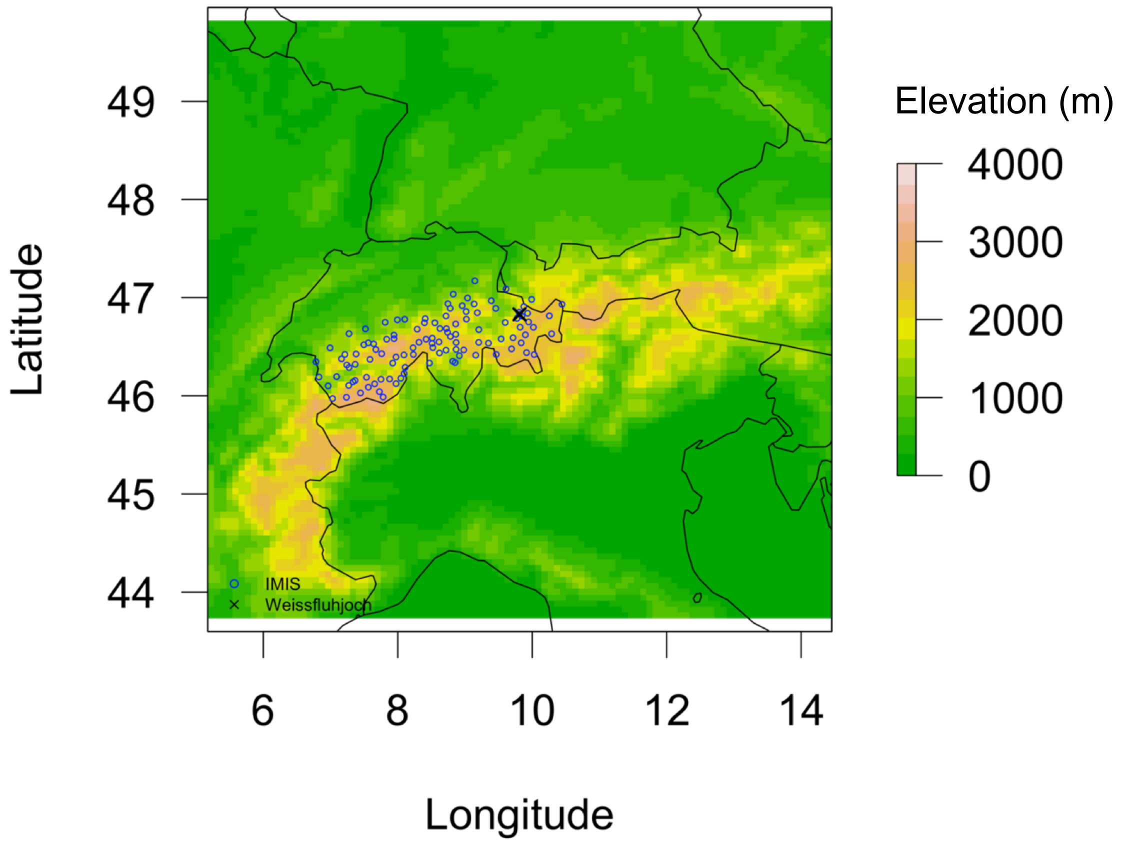
$$\rho_s c_p \frac{\partial T_s}{\partial t} - \frac{\partial}{\partial z}\left(k_{eff} \frac{\partial T_s}{\partial z}\right) = [Q_{pc}] + [Q_{mm}] + Q_{sw} \;;$$

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

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

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 …
- … houtly forecast/hindcast

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 + utility routines …

INTENT INOUT (?)

CALL snow_forcing(…)	CALL snow_on_soil(…)	CALL inte…ow(…)
• snow specific atmospheric forcing	• layering/new snow • ’heat conduction’ • phase changes • water transport • settling • re-meshing ○ …	• preparation … ed input (# layers, … 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:

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

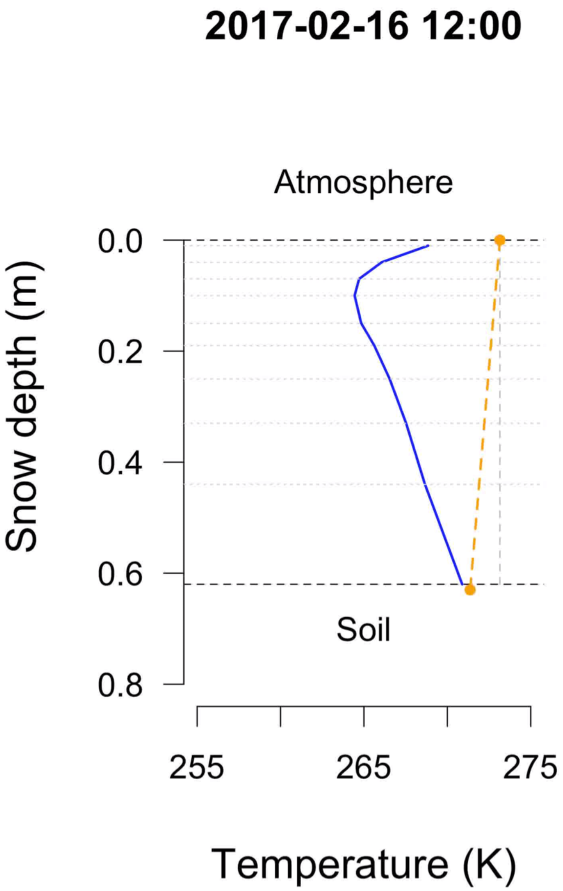
- Solve the one-dimensional heat equation.
- Setup a tridiagonal matrix for set of linear equations for each layer.
- Solved using the Thomas-Algorithm

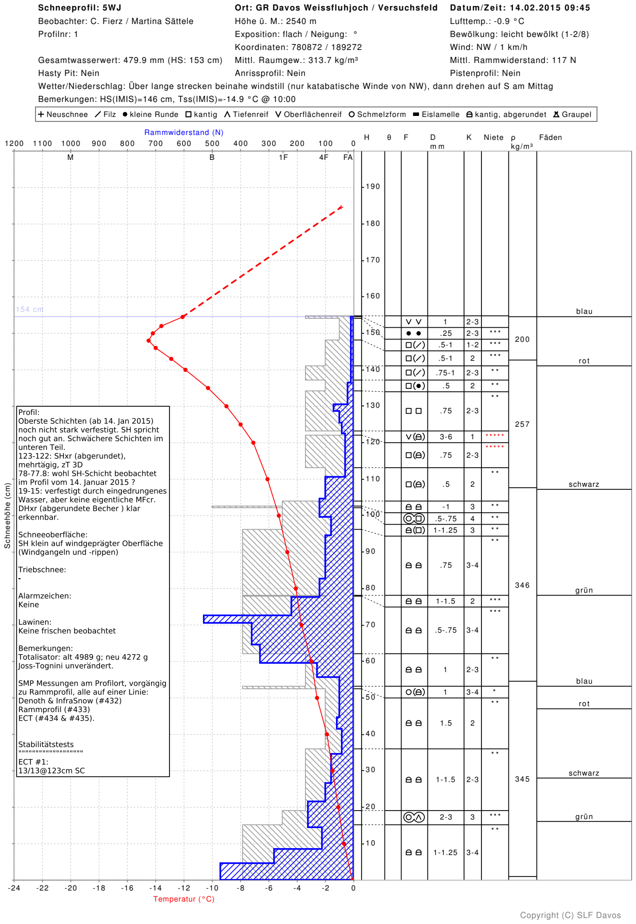
```fortran
! ------------------------------------------------------------
! Setup tridiagonal matrix for set of linear equations for each layer ...
! ------------------------------------------------------------

! ... 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

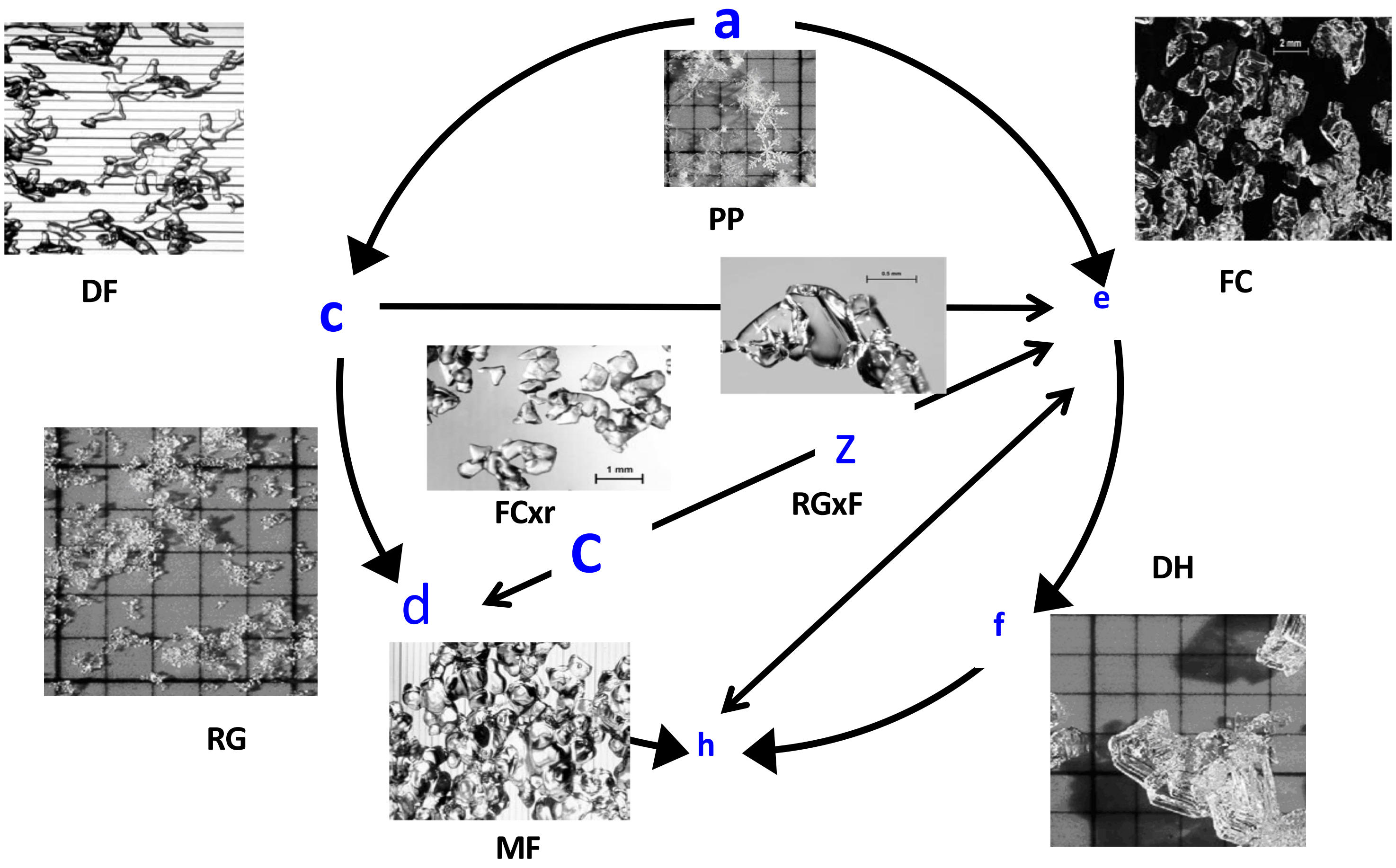
for_sn = forcing = SEB

Heat Equation – Snow temperature profile





Snow Metamorphism: Grain Types

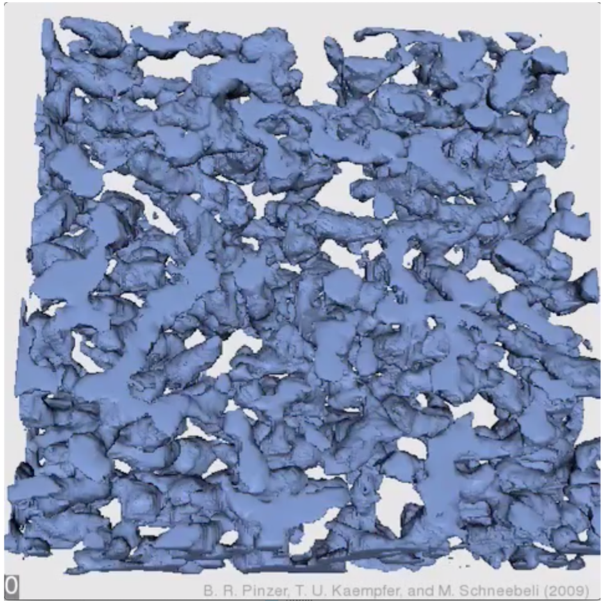


Photo’s: SLF

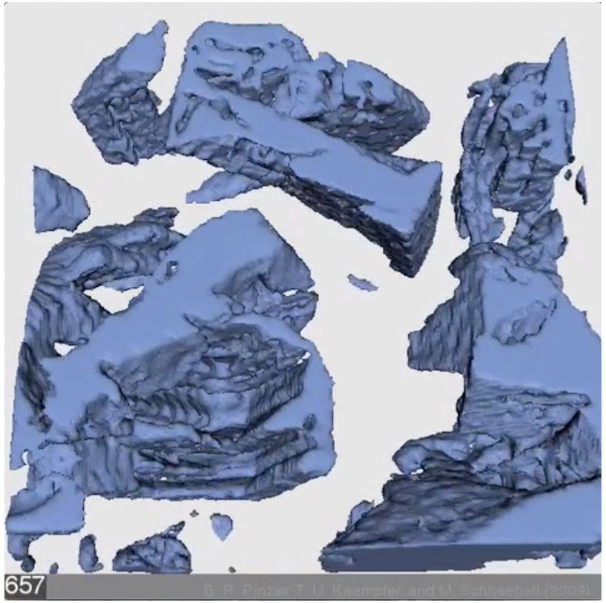
Snow Metamorphism: Different types, different properties

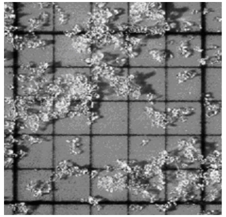
CT-images

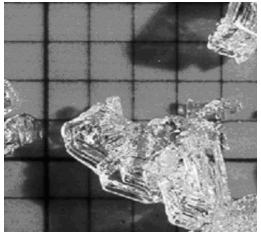
Rounded Grains



Depth Hoar



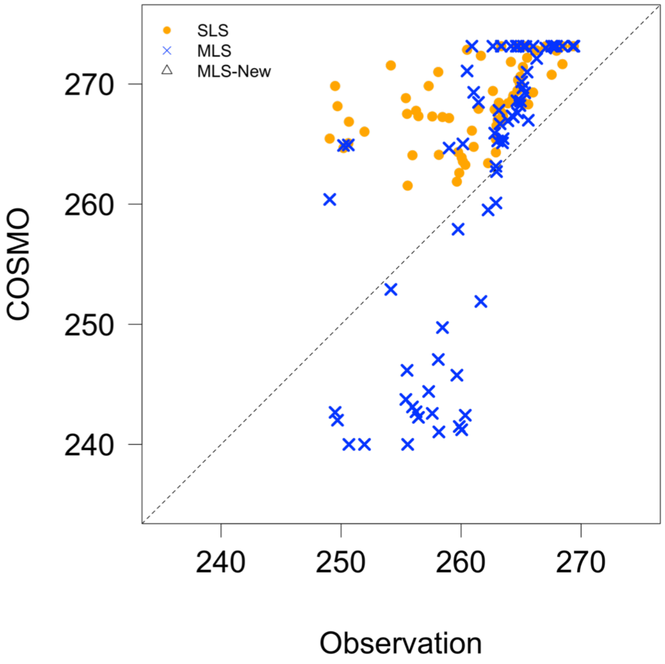




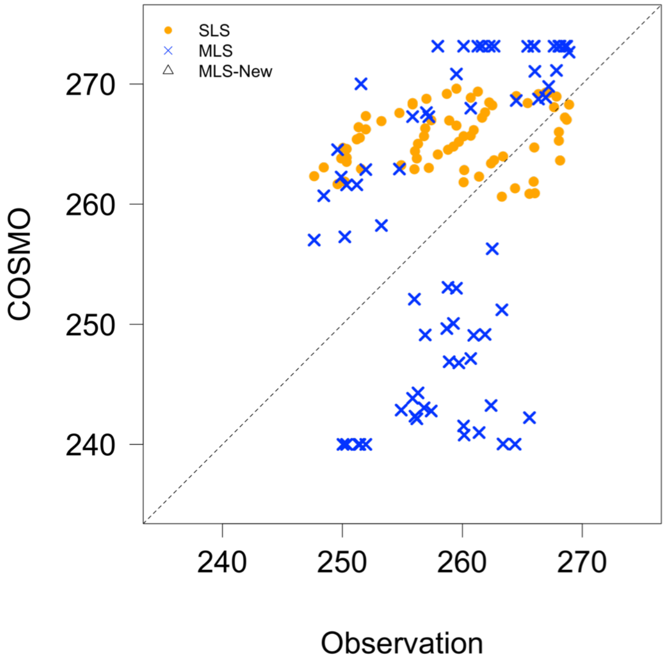
Crystal screen (2 mm raster)

Results – Forcing (Surface Temperature)

Weissfluhjoch
(FOR_E + FOR_D = 0.93)



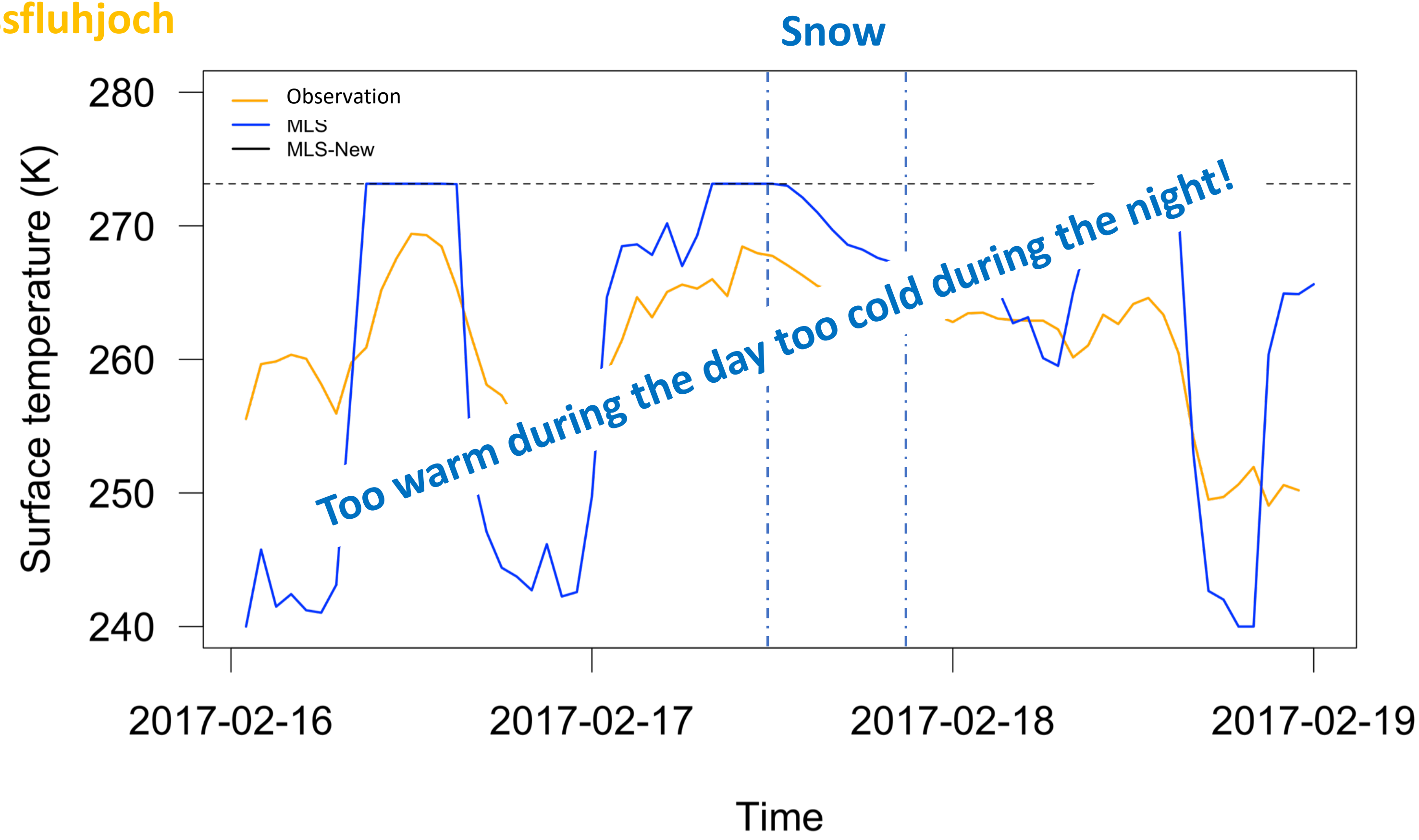
Boveire-PointedeToules
(FOR_E = FOR_D = 0)



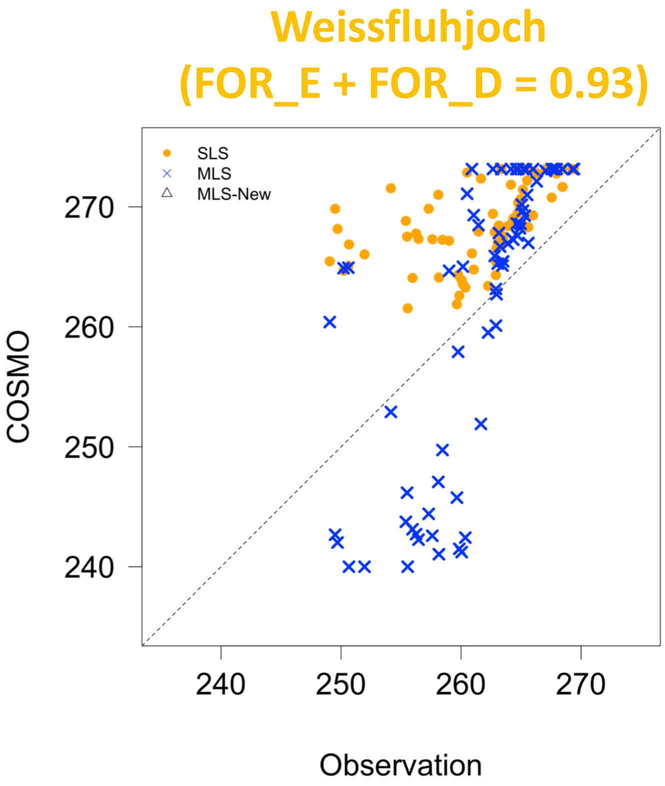
● = **Single layer snow cover scheme (SLS)**   **X = Multi-layer snow cover scheme (MLS)**

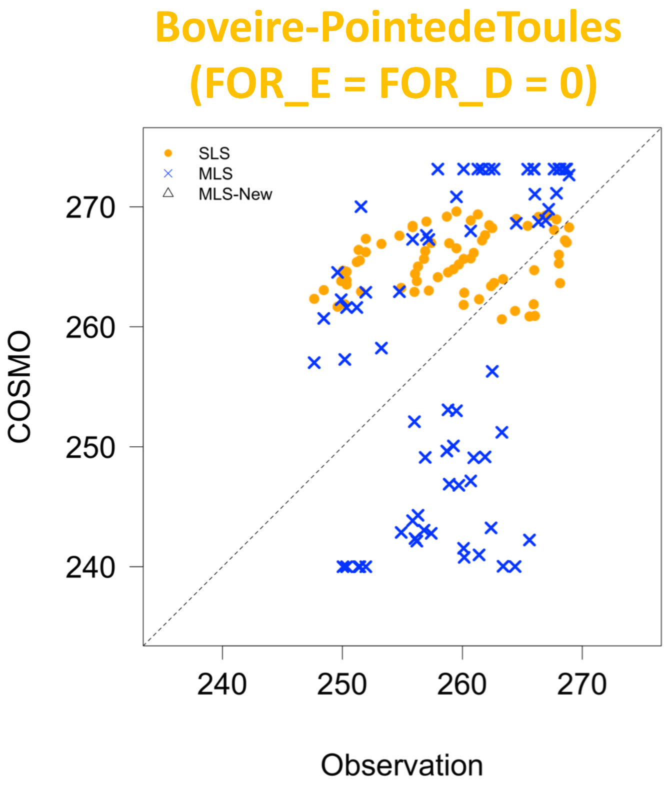
Results – Forcing (Surface Temperature)

Weissfluhjoch



Results – Forcing (Surface Temperature)

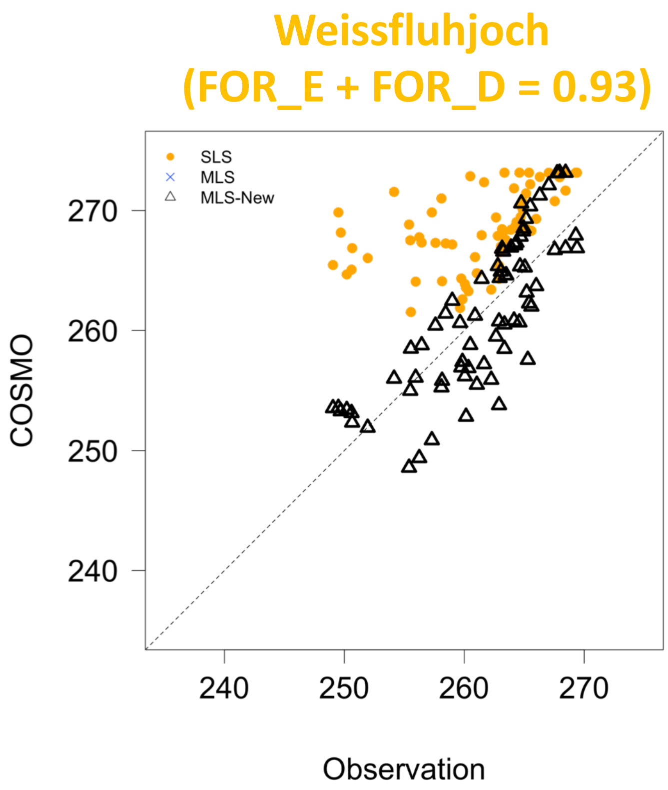


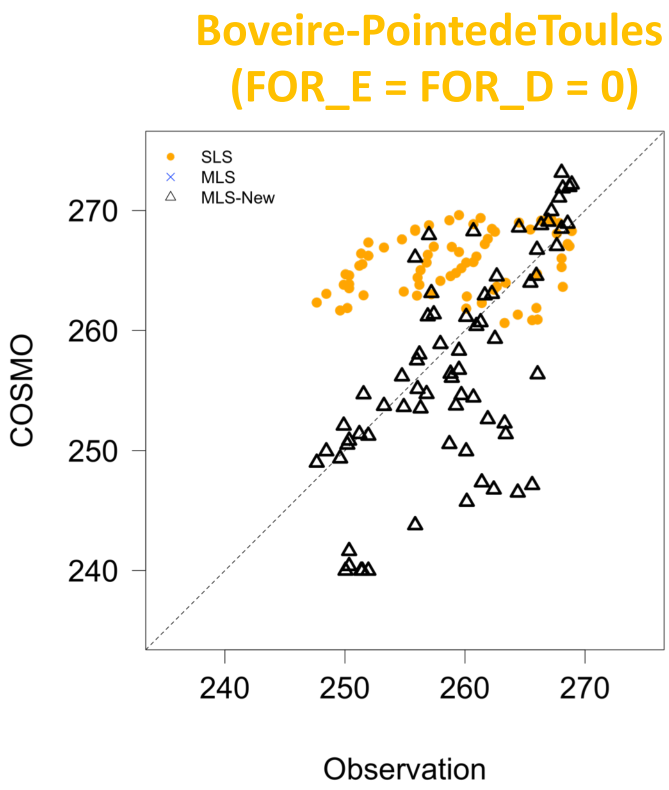


● = Single layer snow cover scheme (SLS)

X = Multi-layer snow cover scheme (MLS)

Heat Equation – Initial Results





△ = 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) main subroutines + utility routines …

CALL snow_forcing(…)

- snow specific atmospheric forcing

CALL snow_on_soil(…)

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

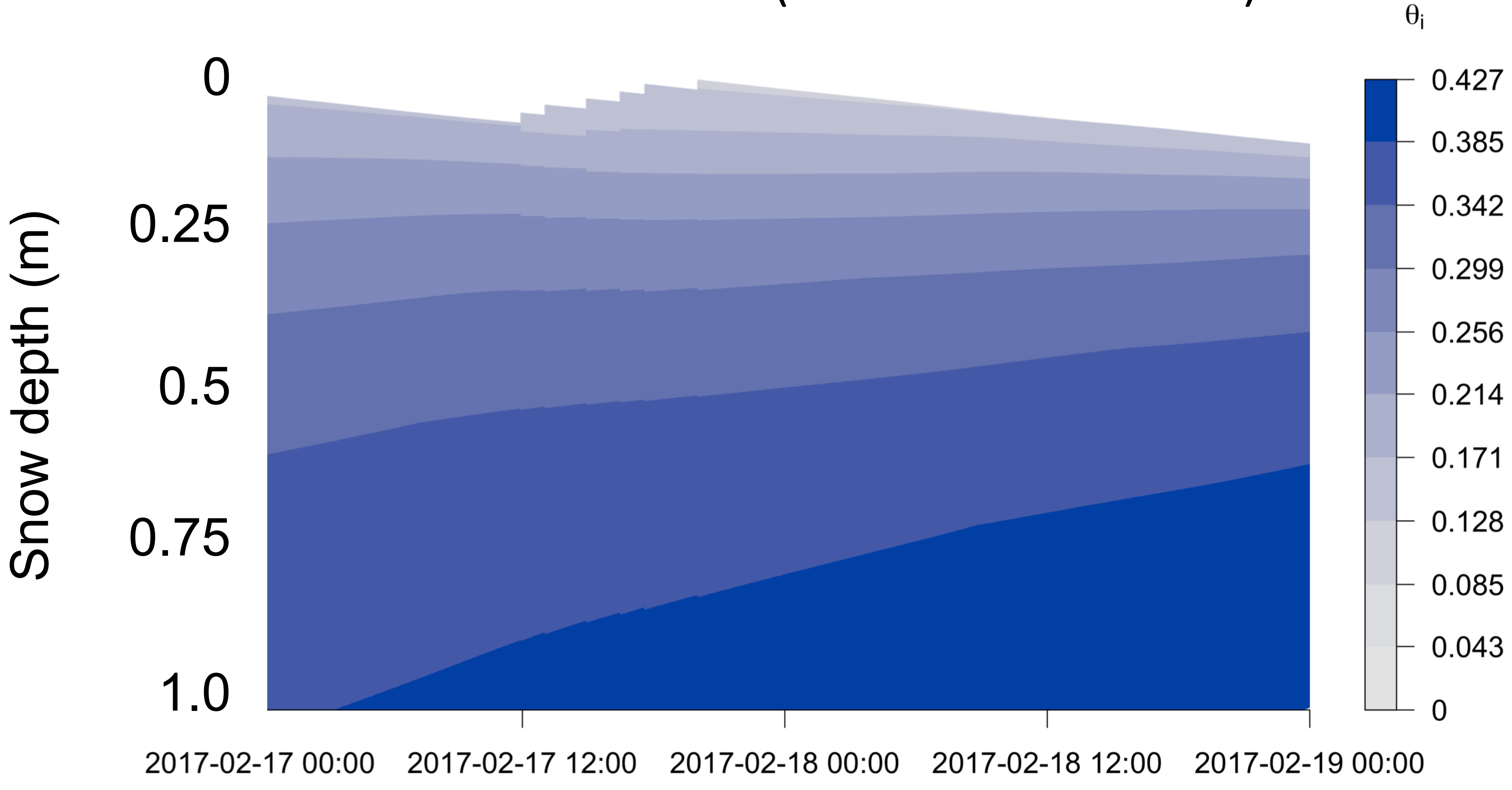
CALL interface_snow(…)

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

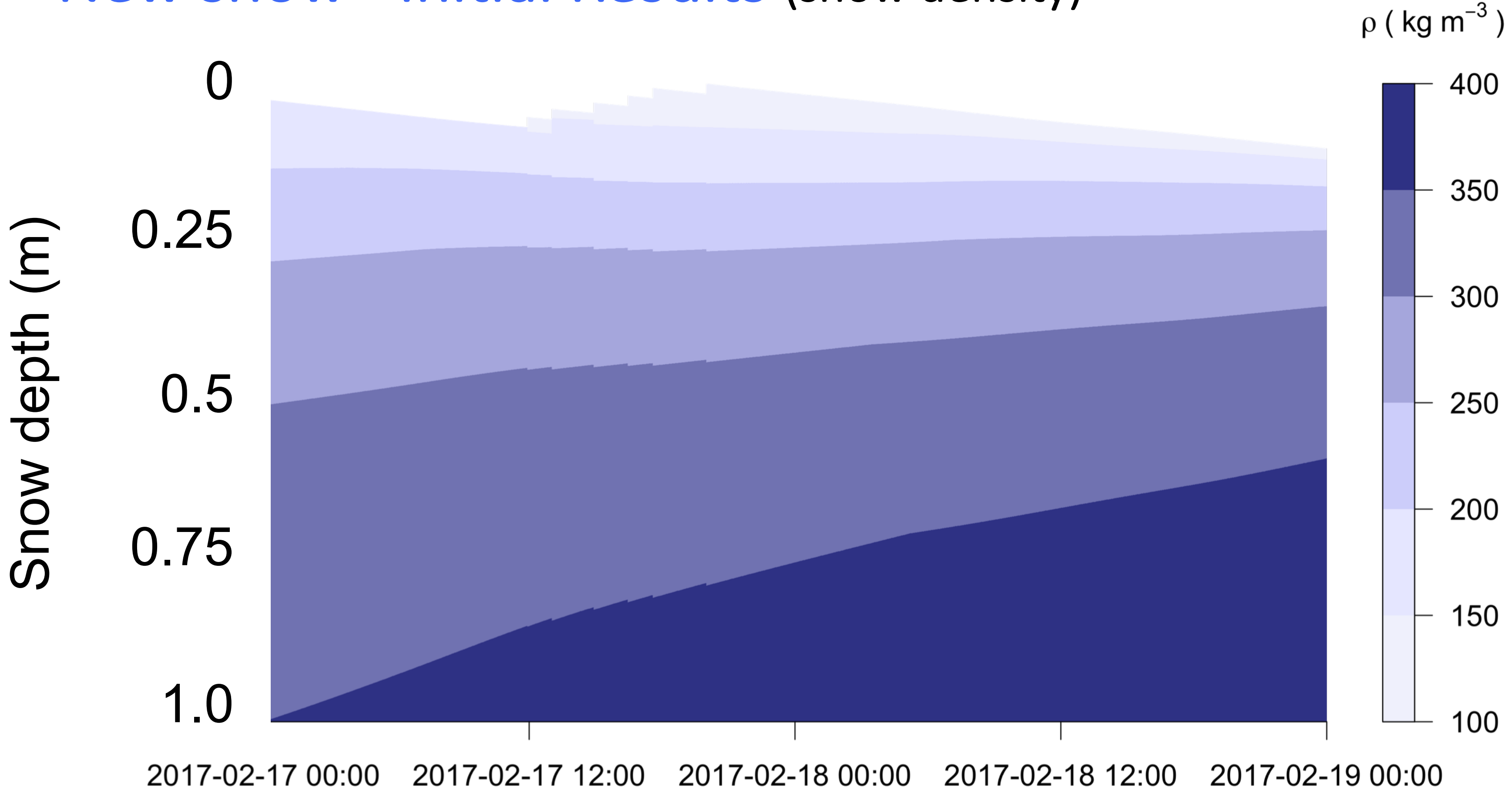
… before solving the heat equation in TERRA

```

    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: <
!**********************************************************************************************************

```

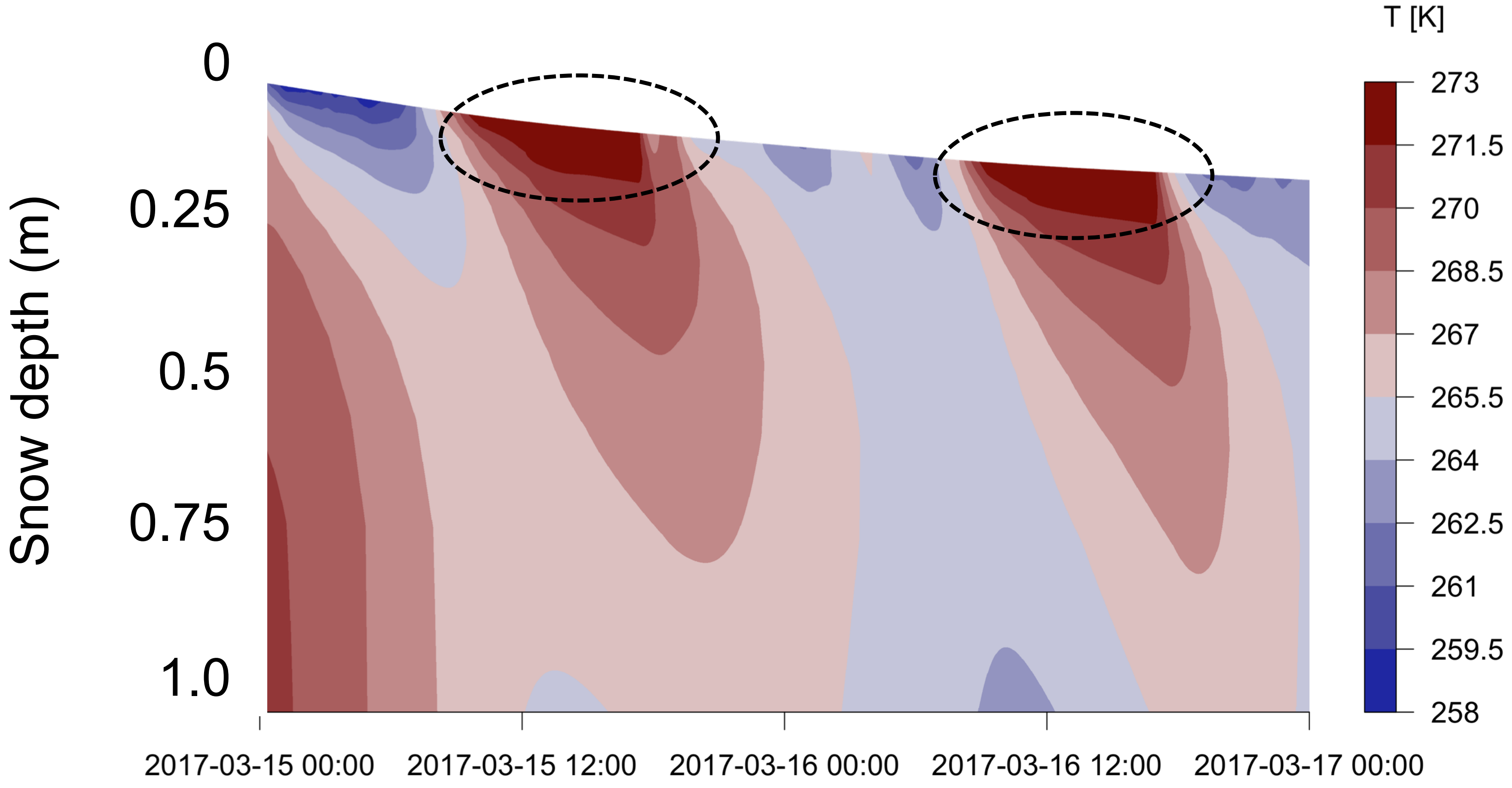
New snow– Initial Results (volumetric ice content)



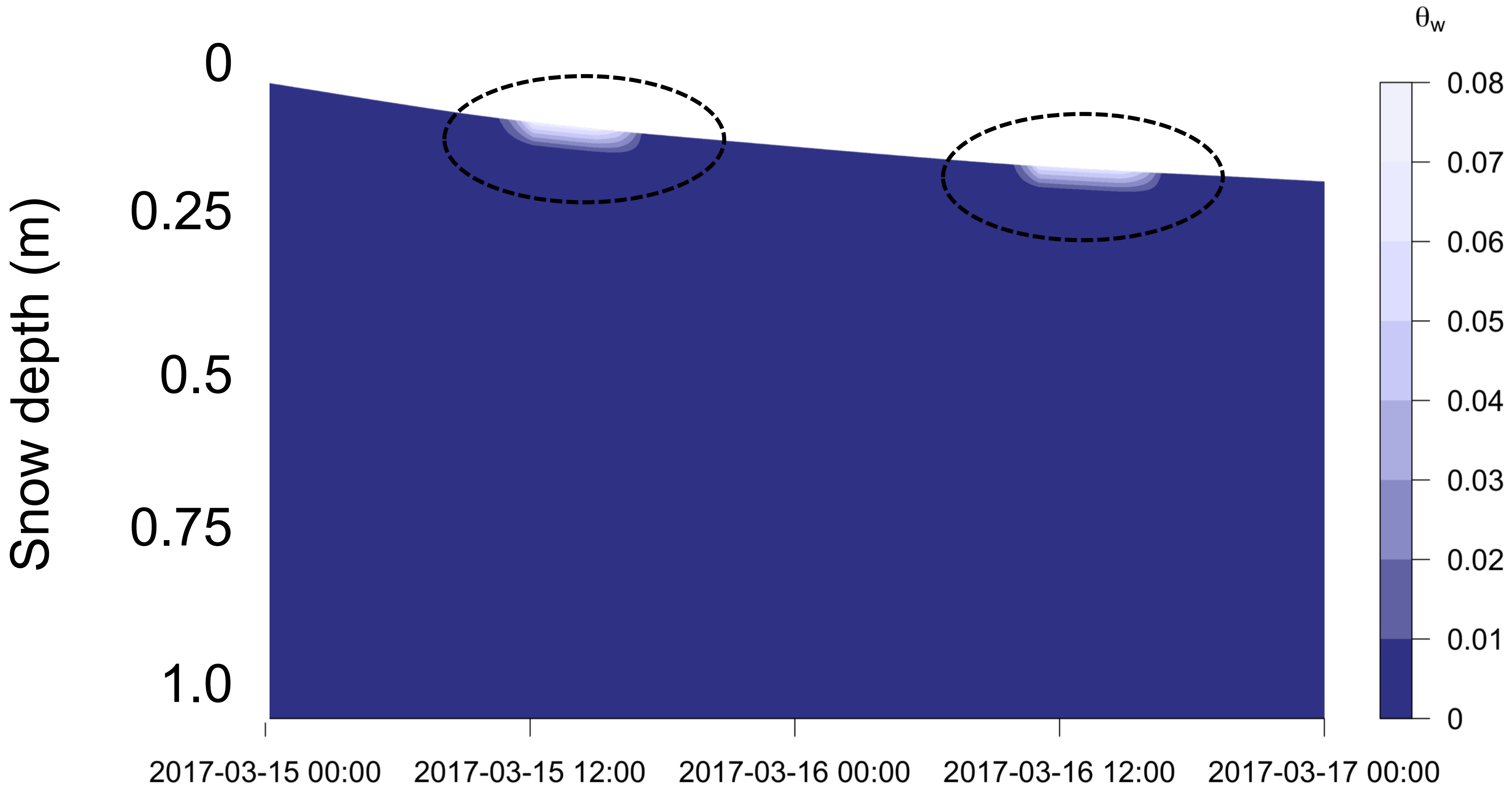
New snow– Initial Results (snow density)



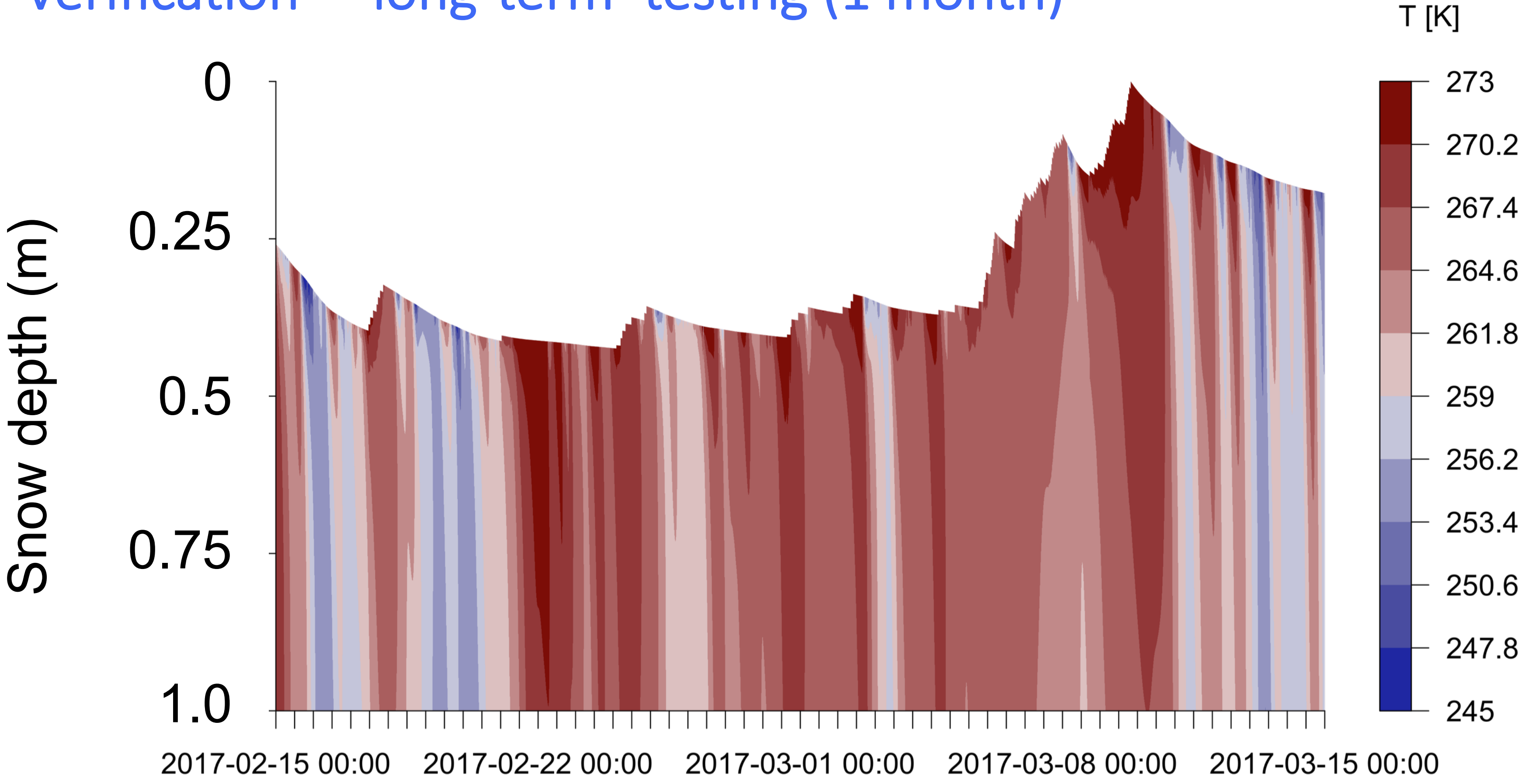
Phase Changes – Initial Results (Snow temperature)



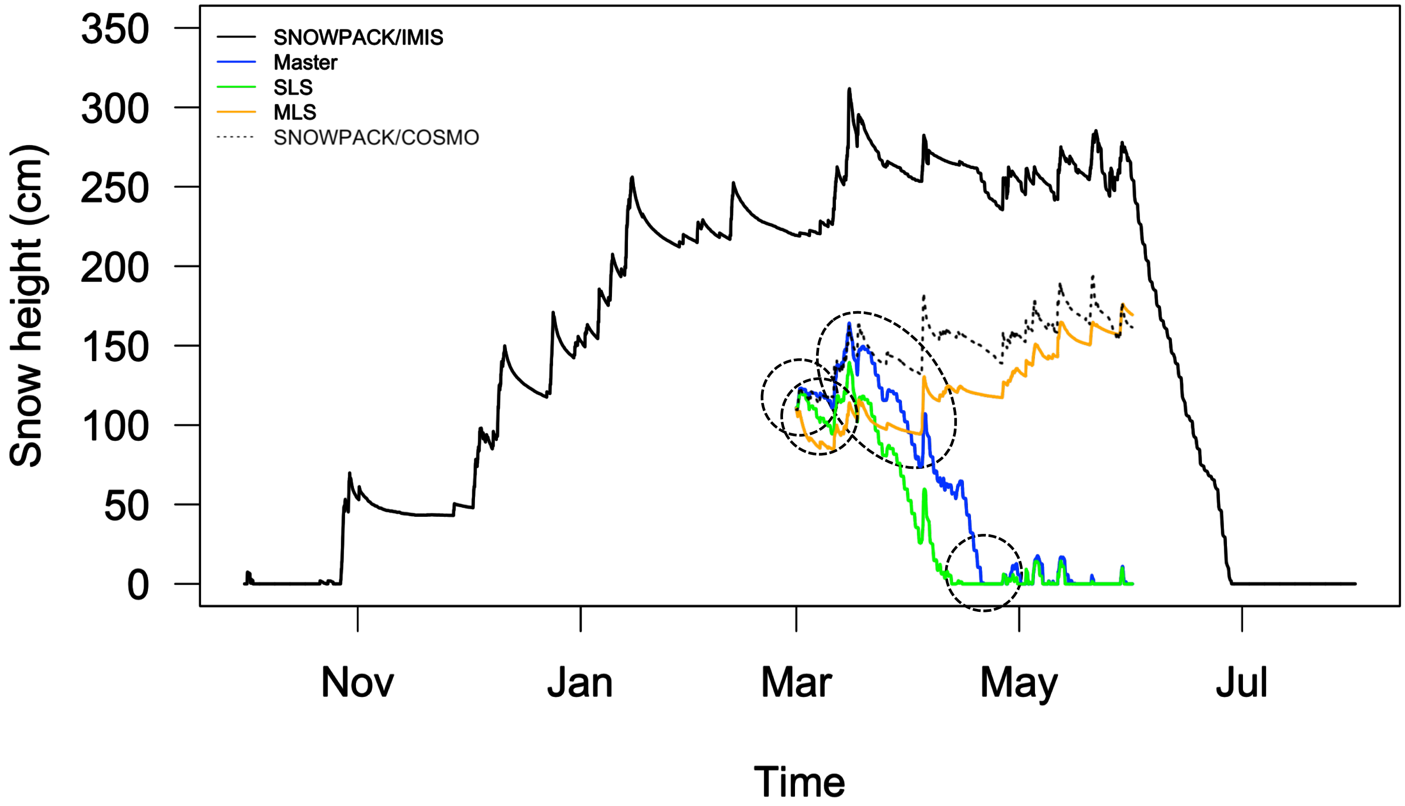
Phase Changes – Initial Results (Water content)



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



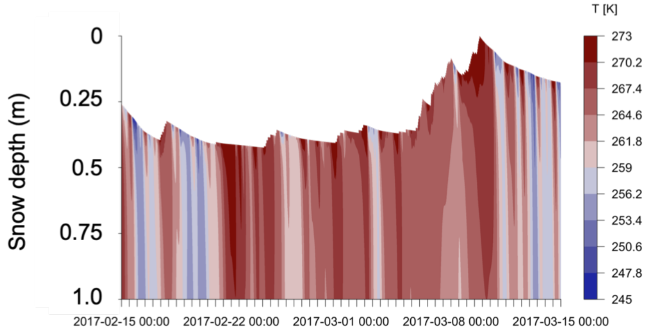
Verification – ‘long-term’ testing (3+ month)



Summary: Priority Task (PT) project - SAINT

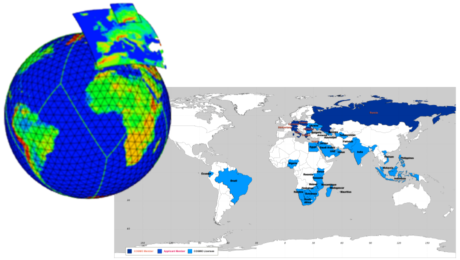
- PT SAINT: Joined project of MeteoSwiss and SLF
- Start: July 2017 ; **Ends June 2020; Possible extension to December 2021**
- Goal: New ‘operational’ multi-layer snow cover scheme for NWP models COSMO and ICON.
- **‘Limited’ SNOWPACK version:**
    - Max. 10 Layers
    - ‘Heat conduction’
    - Phase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

[1]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

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

[3]MeteoSwiss, Zurich, Switzerland

Email: bellaire@slf.ch