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Updates and outlook on NIX in Modular TERRA

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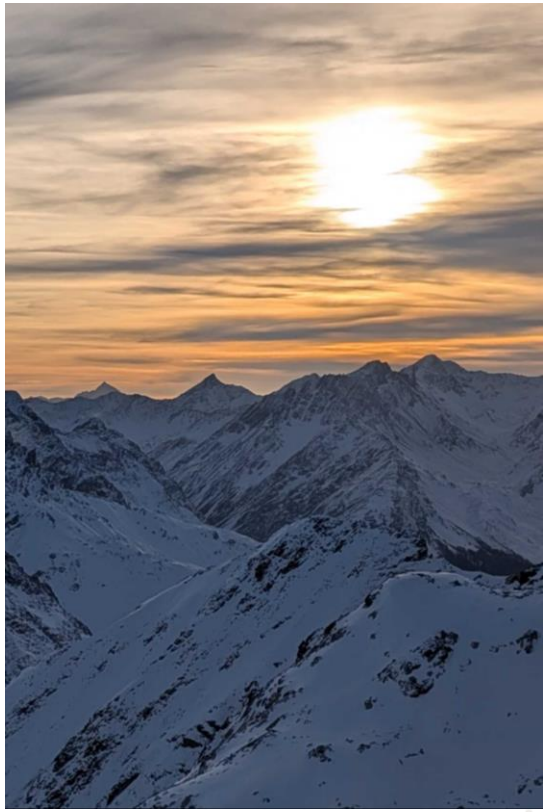
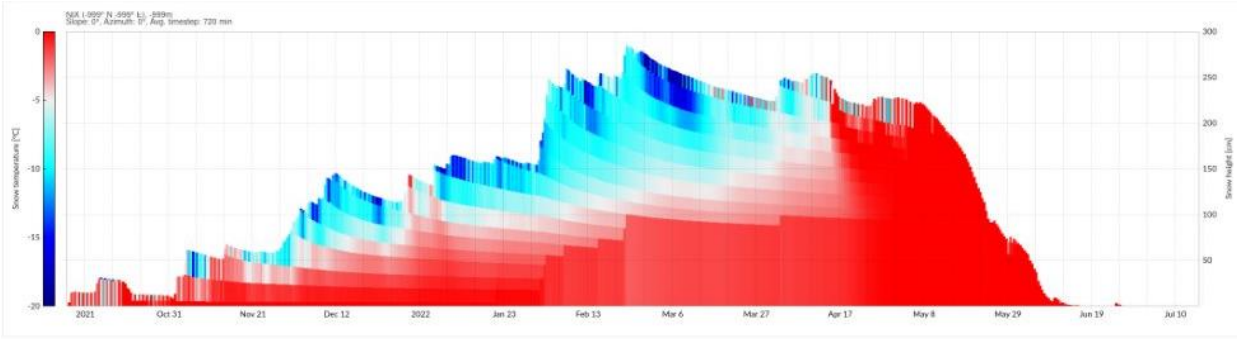
Background

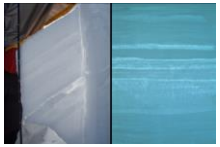
- Concerted effort from MeteoSwiss and the Swiss WSL Institute for Snow and Avalanche Research SLF (Nander Wever) and DWD (Sascha Bellaire) to make NIX broadly available
- The refactoring of TERRA ("Modular TERRA") made integration in TERRA feasible
- **End of 2024, we decided to integrate NIX inside Modular TERRA, and to integrate NIX inside JSBACH**



NIX

- Multi-layer, physics-based snow cover model, based on the SLF SNOWPACK model
- From Essery et al. (2012): "There is no clear link between model complexity and performance, **but the most consistent results come from configurations that have prognostic representations of snow density and albedo and that take some account of storage and refreezing of liquid water within the snow.**"



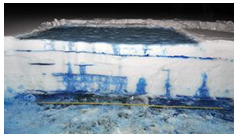


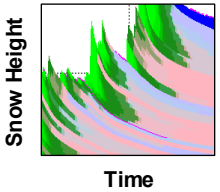
Layering (create/aggregate/split)

Heat Equation (implicit) $\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}; \quad 0 \le x \le L; \quad t > 0$

Phase Changes

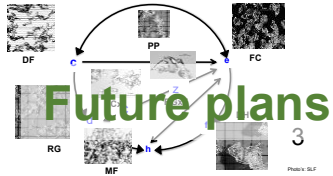
Water transport





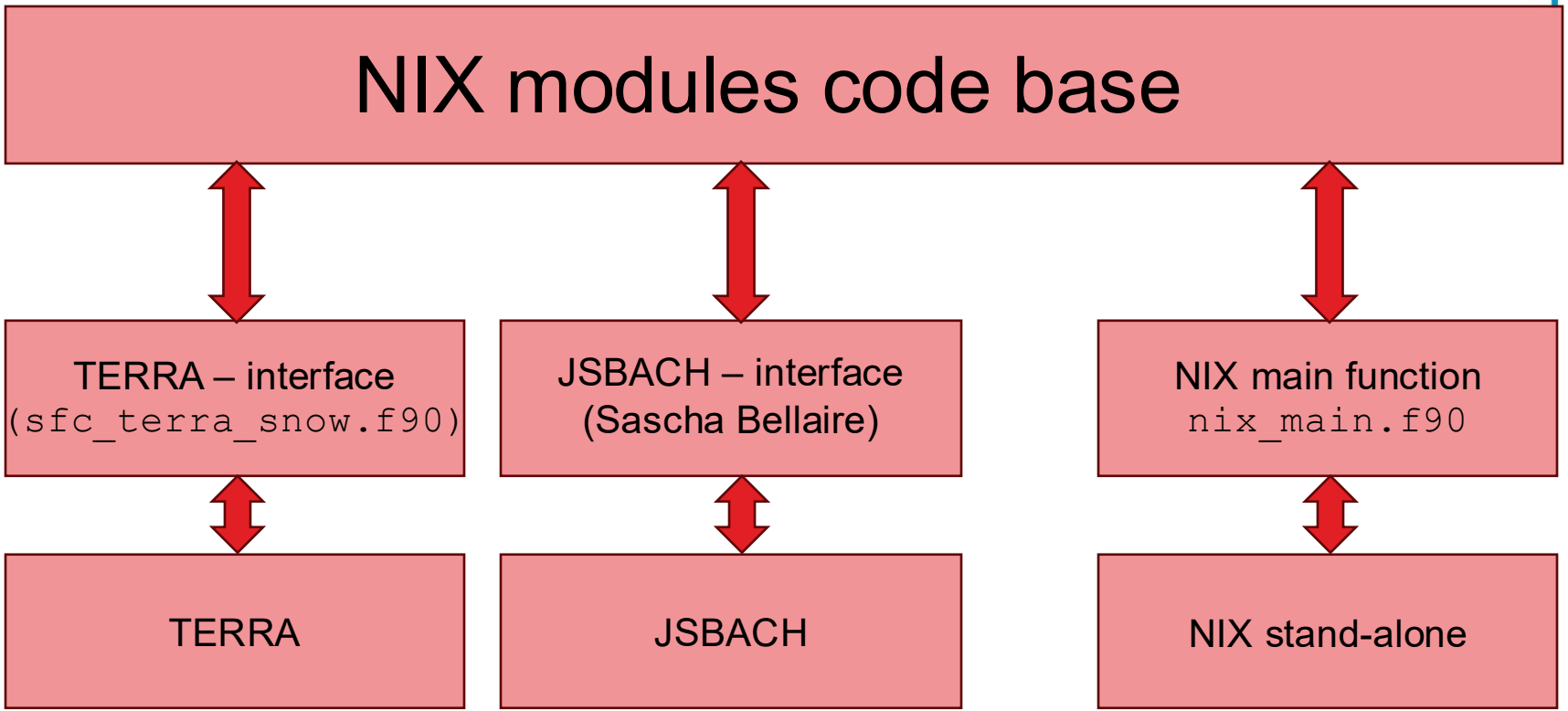
Settling

Snow microstructure



Future plans

Long-term vision for NIX



Development status for NIX in TERRA

1. Improved data structure to pass NIX state around inside TERRA: simplifies code and easier maintenance, like when adding a new snow parameter
2. NIX is fully optional, and can be activated/deactivated on a per-tile basis, for example excluding high latitudes, sea ice and glaciers easily (note: only possible between single-layer snow model and NIX, not the multi-layer model)
3. NIX is fully coupled with the heat and mass balance in TERRA
4. NIX can start "cold" (from bulk fields), "warm" (from NIX state fields), and also adapt to snow analysis fields
5. GPU port runs (basic validation done, but not yet fully validated against CPU)
6. Buildbots for the `icon-nwp-nix-dev` branch mostly green
7. First seasonal test run

NIX-TERRA coupling (1/2)

1. TERRA: General preparations (calculating precipitation rates, heat conductivities, turbulent exchange coefficients, etc.)
2. NIX: Preparations (checking state)
3. TERRA: Water infiltration and percolation in soil
4. NIX: Adding snowfall and updating layer ages
5. NIX: Solving heat equation
    - Calculate snow-soil heat flux
    - Solve heat equation with an implicit finite elements scheme (from SNOWPACK)
    - Calculate phase change
    - Update snow-soil heat flux for TERRA
6. TERRA: solving heat equation in soil

NIX-TERRA coupling (2/2)

1. TERRA: Evaporation from soil and soil freezing/thawing
2. NIX: Water transport --> snowpack runoff added to first layer, or added to runoff
3. NIX: stratigraphy updates:
   - Settling / compaction
   - Layer merging / removal
4. NIX: Update TERRA variables with the NIX state:
   - H_SNOW (snow height)
   - W_SNOW (snow water equivalent)
   - RHO_SNOW (snow density, averaged over all layers)
   - T_SNOW (snow surface temperature)
   - Etc ...

NIX-TERRA interface (`sfc_terra_snow.f90`)

```
PUBLIC :: snow_single_prepare
PUBLIC :: snow_single_soil_forcing
PUBLIC :: snow_single_melt
PUBLIC :: snow_single_calc_temperature
PUBLIC :: snow_single_update_new_state

PUBLIC :: snow_multi_prepare
PUBLIC :: snow_multi_handle_snowfall
PUBLIC :: snow_multi_soil_forcing
PUBLIC :: snow_multi_calc_heat_conduction
PUBLIC :: snow_multi_melt
PUBLIC :: snow_multi_update_new_state

PUBLIC :: snow_nix_prepare
PUBLIC :: snow_nix_handle_snowfall
PUBLIC :: snow_nix_energy_balance
PUBLIC :: snow_nix_mass_balance
PUBLIC :: snow_nix_update_new_state
```

Interface functions for single-layer snow scheme

Interface functions for NIX

Example: energy balance

```
SUBROUTINE snow_nix_energy_balance ( ivstart, ivend, nvec, ke_soil, ke_snow, dt, nix_state_t, ... )

  ! Calculate the latent and sensible heat
  CALL calculate_turbulent_fluxes( ... )

  ! Calculate soil flux

  ! Copy back turbulent fluxes
  shfl_snow(i)                    = nix_state_t%shflx_sn_t(i)
  lhfl_snow(i)                    = nix_state_t%lhflx_sn_t(i)
  hfl_snow_soil(i)                = ...
  ...

  ! Calculate radiative fluxes
  CALL calculate_radiative_fluxes( ... )

  ! Calculate temperature profile
  CALL heat_equation_implicit( ... )

  ! Calculate phase changes
  CALL phase_change( ... )

  ! Update layering
  CALL update_nix_state( ... )

  ! Update h_snow
  h_snow = sum(nix_state_t%dzm_sn_t)
END SUBROUTINE snow_nix_energy_balance
```

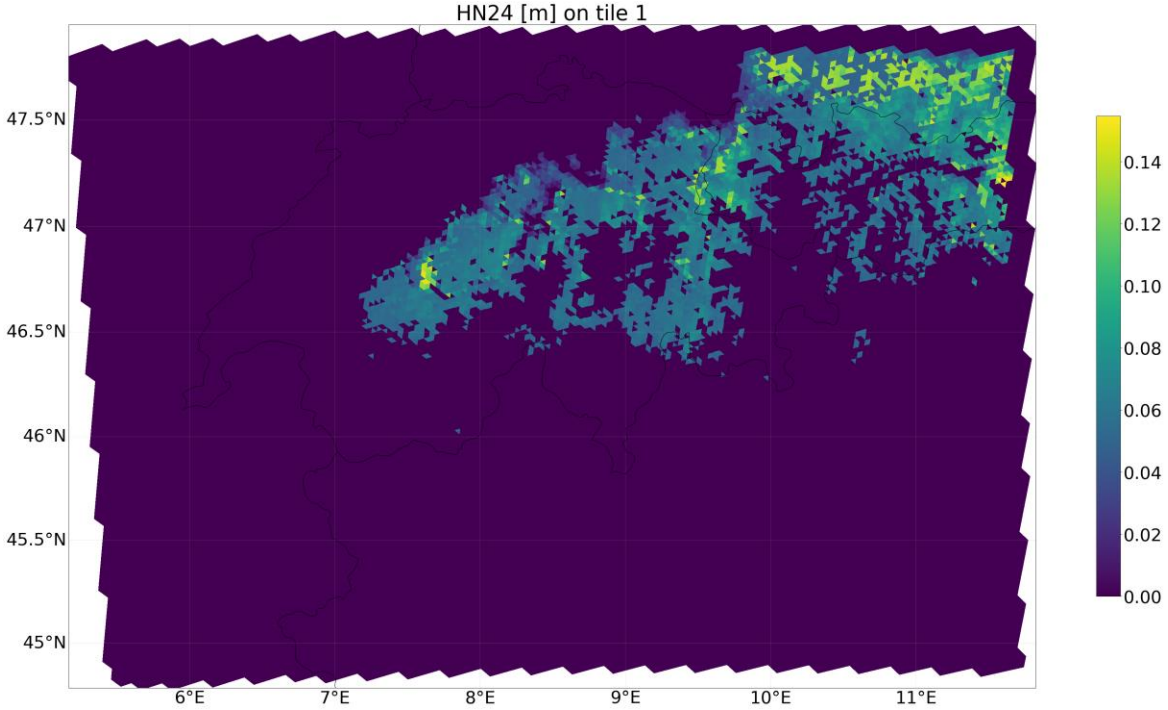
Function calls to NIX modules and functions

Connect NIX state to TERRA internal variables

Snow analysis: 6 cases

1. No snow in NIX and no snow in snow analysis (< minimum new snow layer):
   - do nothing
2. More than 40cm of snow in NIX and snow analysis:
   - do nothing
3. No snow in snow analysis, but snow in NIX:
   - remove all snow
4. No snow in NIX, but snow in snow analysis:
   - build snow cover:
   - air temperature < freezing: cold snow, air temperature > freezing: warm snow
     - Cold snow: density = 100 kg/m^3, albedo: 0.85
     - Warm snow: density = 250 kg/m^3, albedo: 0.7
5. Snow depth in NIX < snow depth in snow analysis
   - determine optimal layer spacing
   - remap layers from old to new grid spacing
6. Snow depth in NIX > snow depth in snow analysis:
   - Scale all layers

Snow accumulation 24h (HN24)



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How much snow accumulates over 24 hours?

- Including melt
- Including compaction

NIX keeps age per layer to determine HN24, controlled using namelist options:

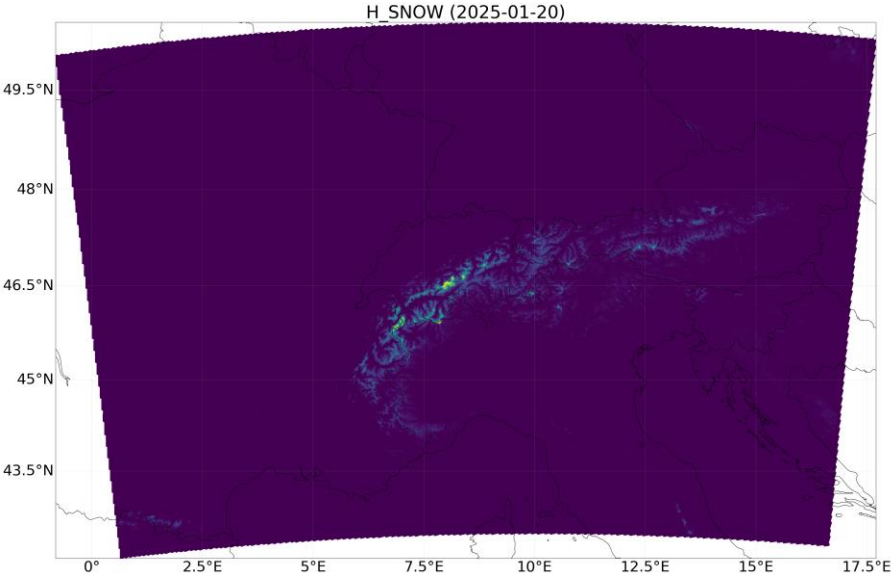
```
new_snow_period    = 24
new_snow_subperiod = 6
```

Current testing

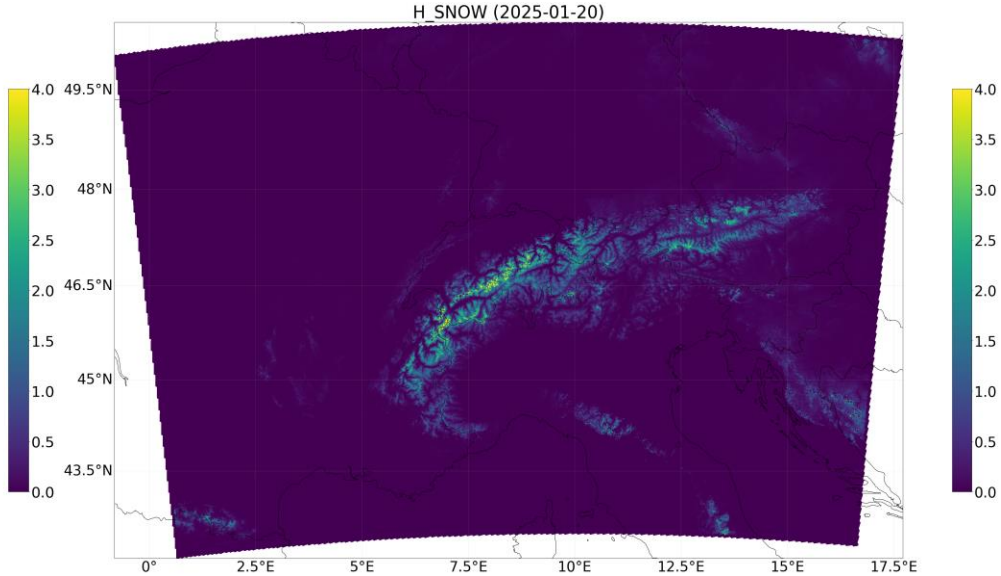
- Starting two weeks ago: testing NIX in REA-L setup
  - CH-1 domain
  - No KENDA
  - Snow analysis (although, doesn't work as intended)
  - Latent heat nudging
  - Note: radiation fluxes not consistent between NIX and TERRA
- Numerous new little bug fixes and improvements
- Simulation for period 2024-10-01 to 2025-02-09
- Some numerical instabilities in the heat equation appear for very thing snow covers (~2 cm)
- No quantitative validation yet
- Results are very preliminary!

H_SNOW: snow depth (m)

REA-L: TERRA-snow



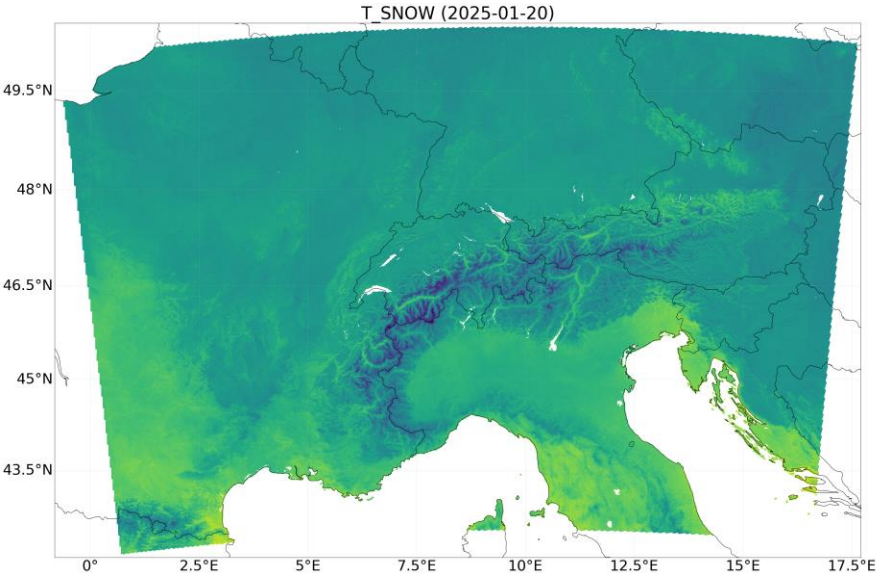
REA-L: NIX



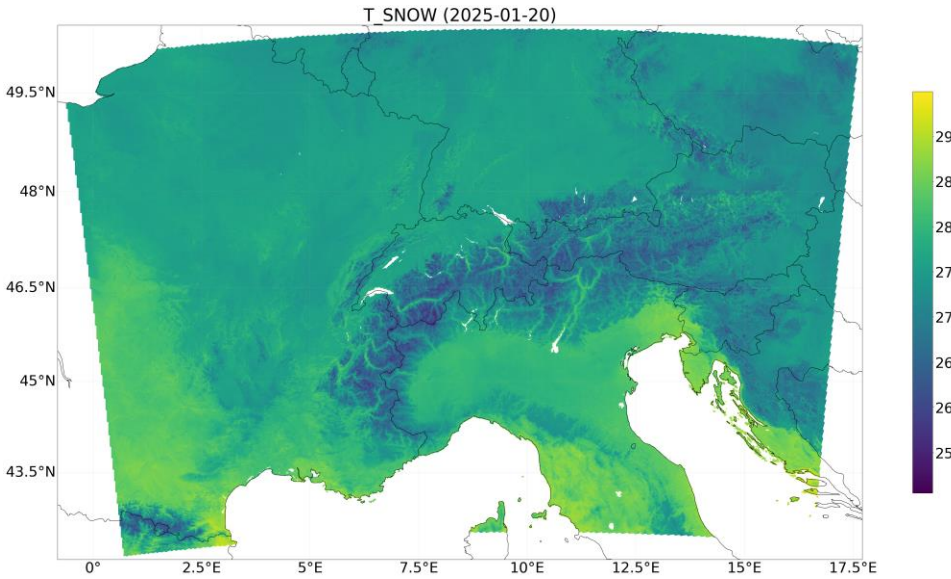
--> More snow in NIX than in TERRA-snow, see later

T_SNOW: snow surface temperature (K)

REA-L: TERRA-snow



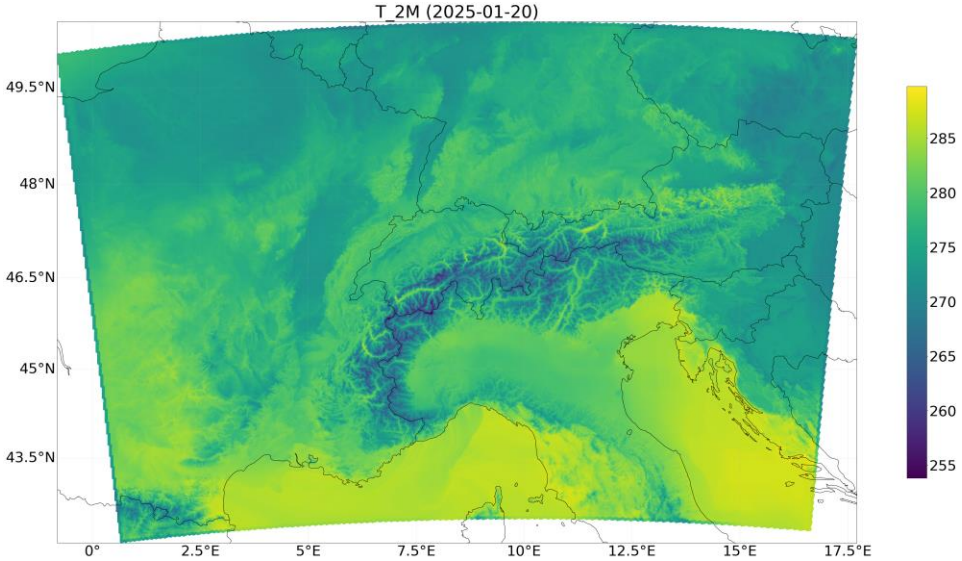
REA-L: NIX



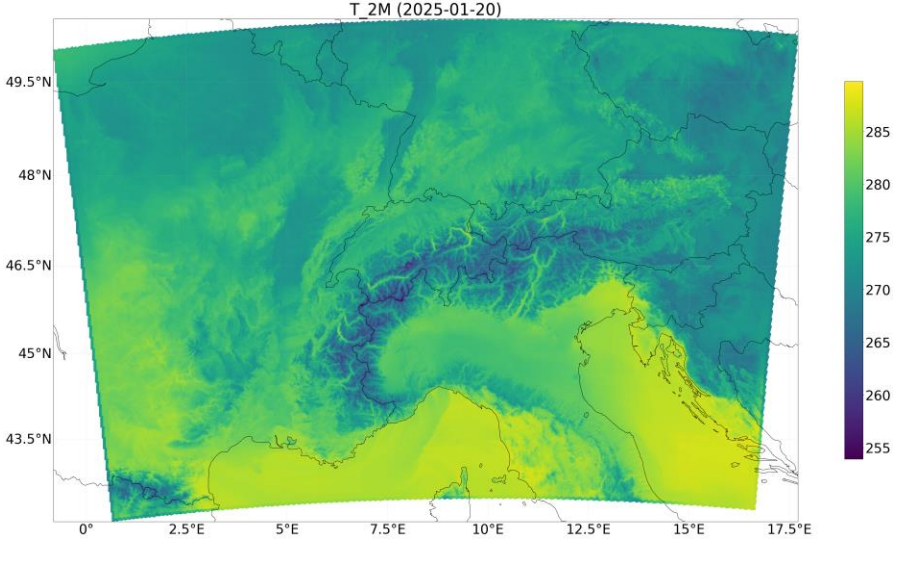
- Snow depth discrepancy also visible here
- Less variability in NIX than in TERRA-snow

T_2M: 2m air temperature (K)

REA-L: TERRA-snow



REA-L: NIX

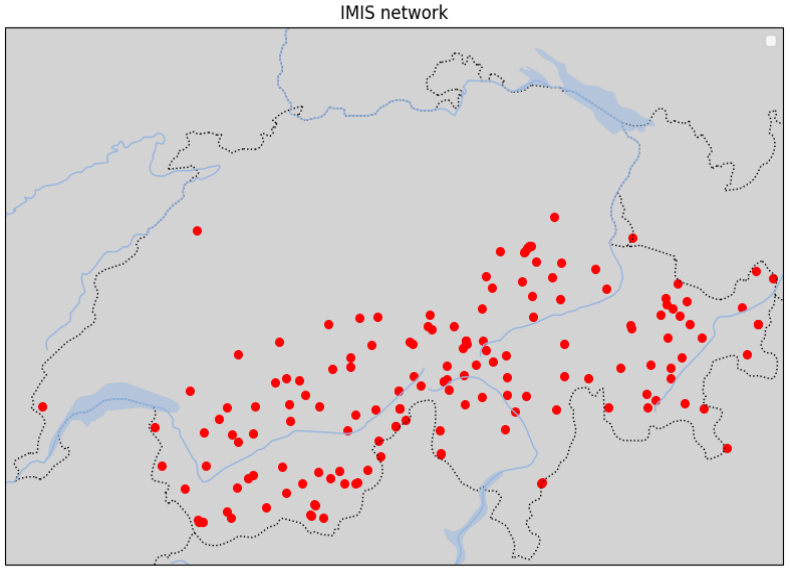


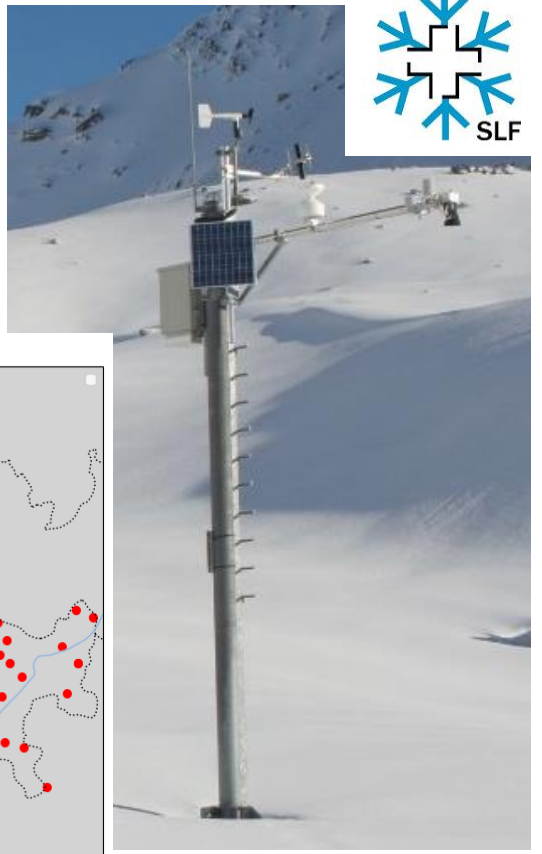
--> Generally, very similar

--> Indicates that the fully coupled energy balance behaves stable

IMIS station network

- Snow stations in Switzerland
- Between 2000-2500m a.s.l.
- In addition to standard parameters:
  - Snow height
  - Snow surface temperature
  - Internal snow temperatures at fixed heights
- Note: T/RH sensor not ventilated





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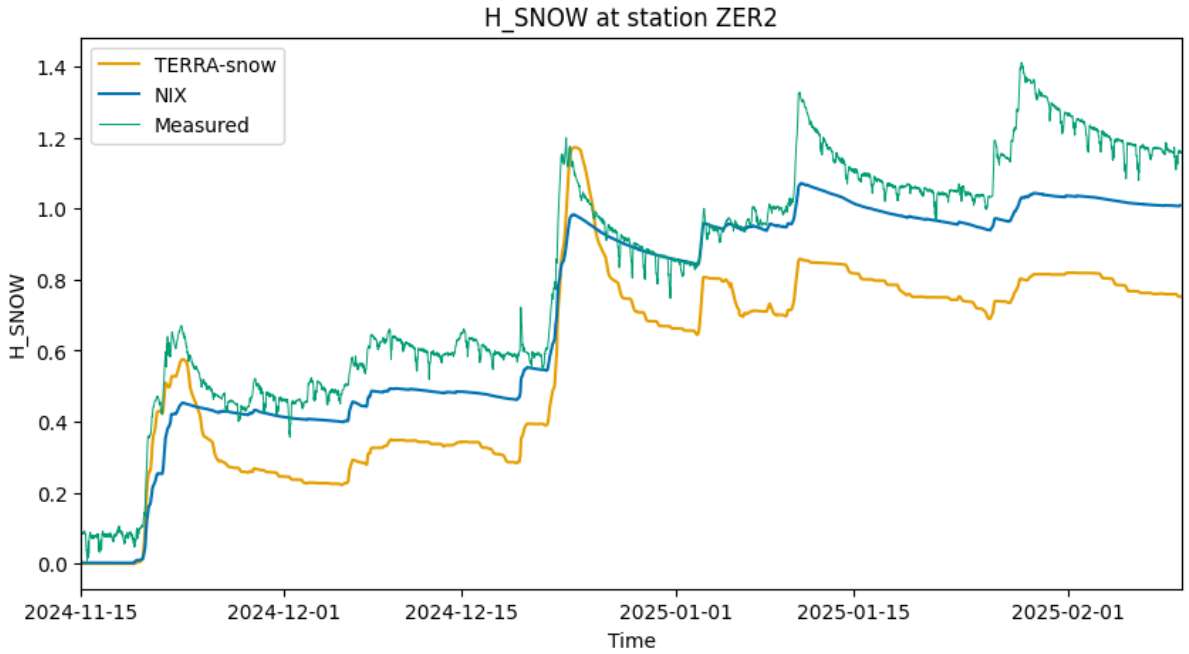
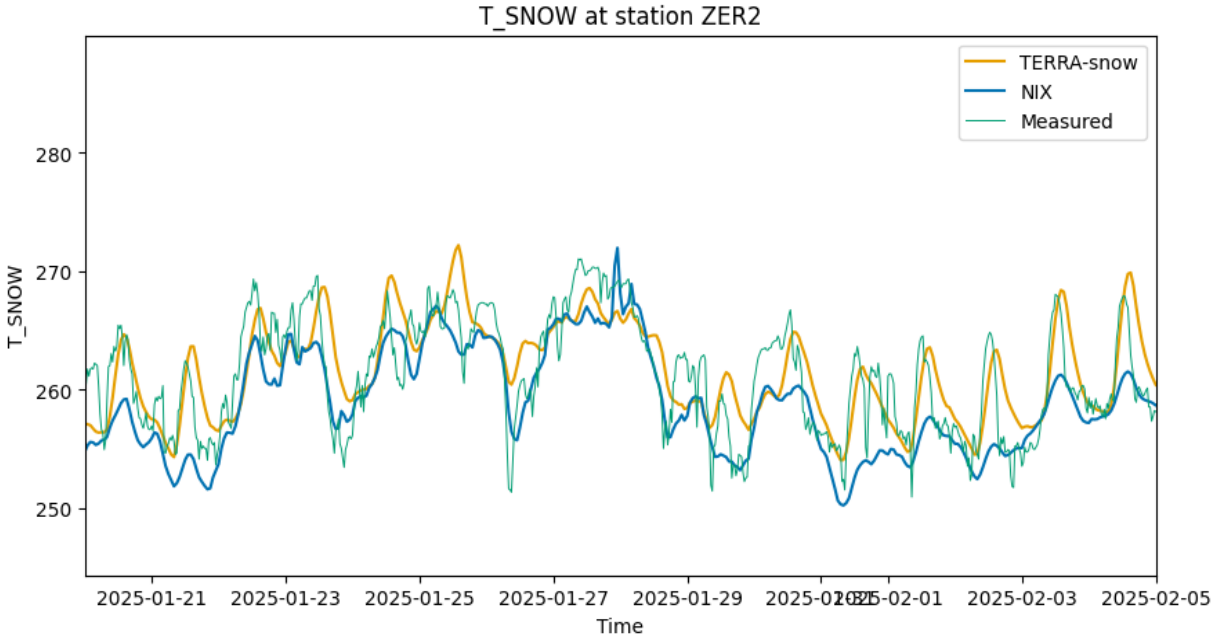
ZER2 snow height



Snow height generally well reproduced, but

- Overestimated new snow density / underestimated settling

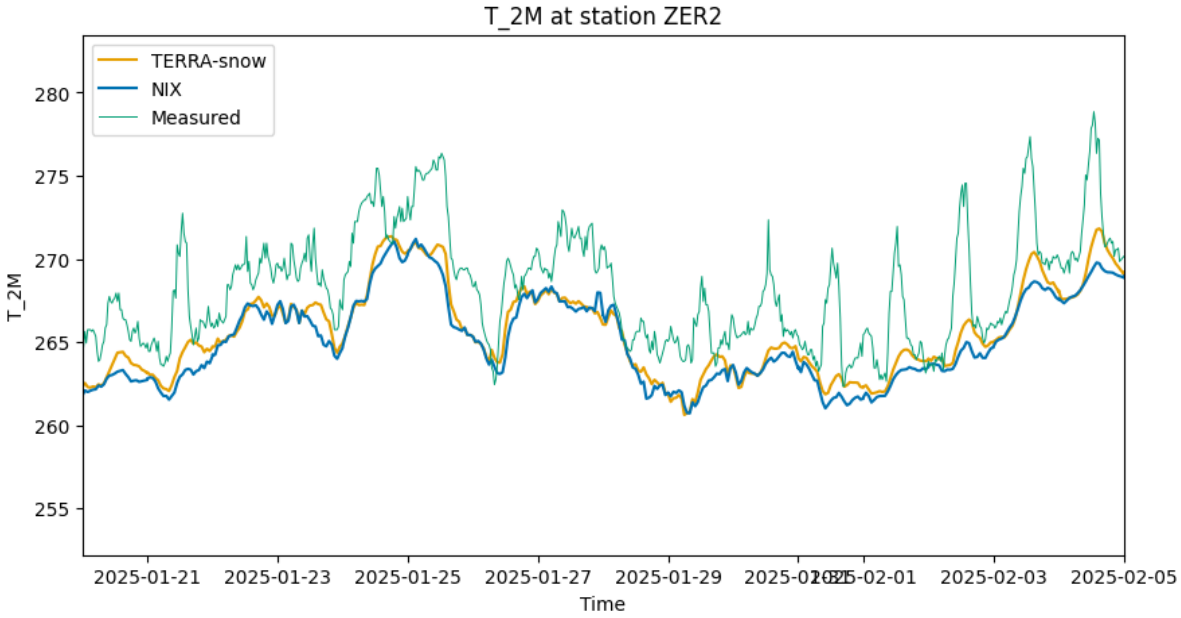
ZER2: Snow surface temperature



Snow temperature follows general trends quite well, but:

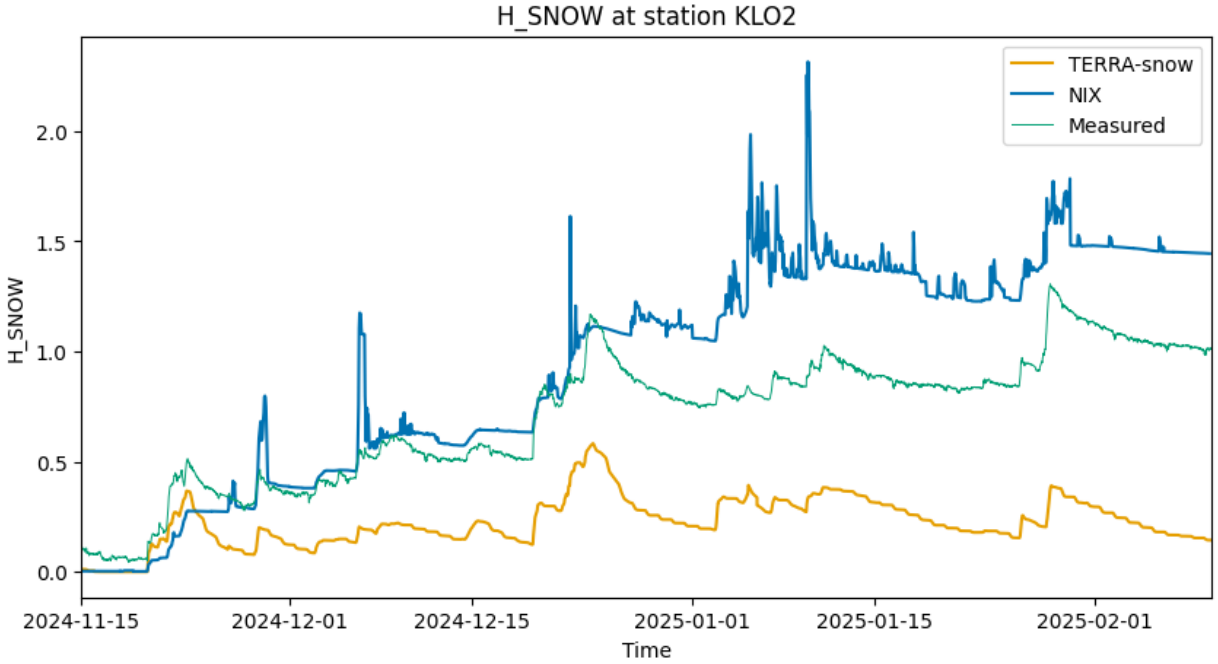
- NIX shows some reduced amplitude
- Both seems to underestimate nightly minimums

ZER2: 2m air temperature



2m air temperature between both snow models is very similar

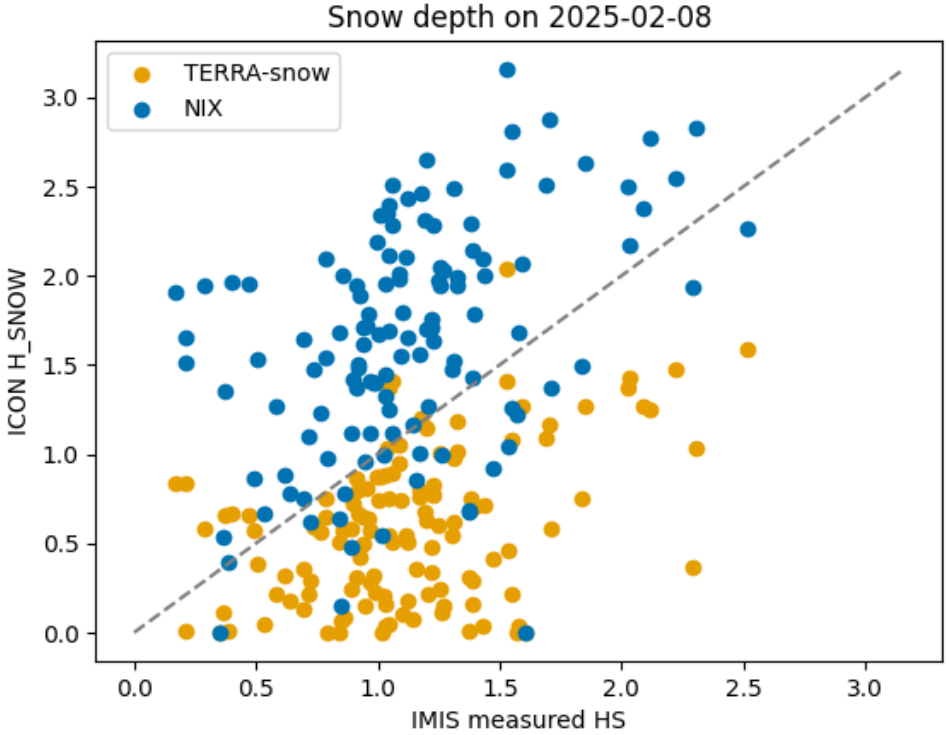
KLO2 snow height



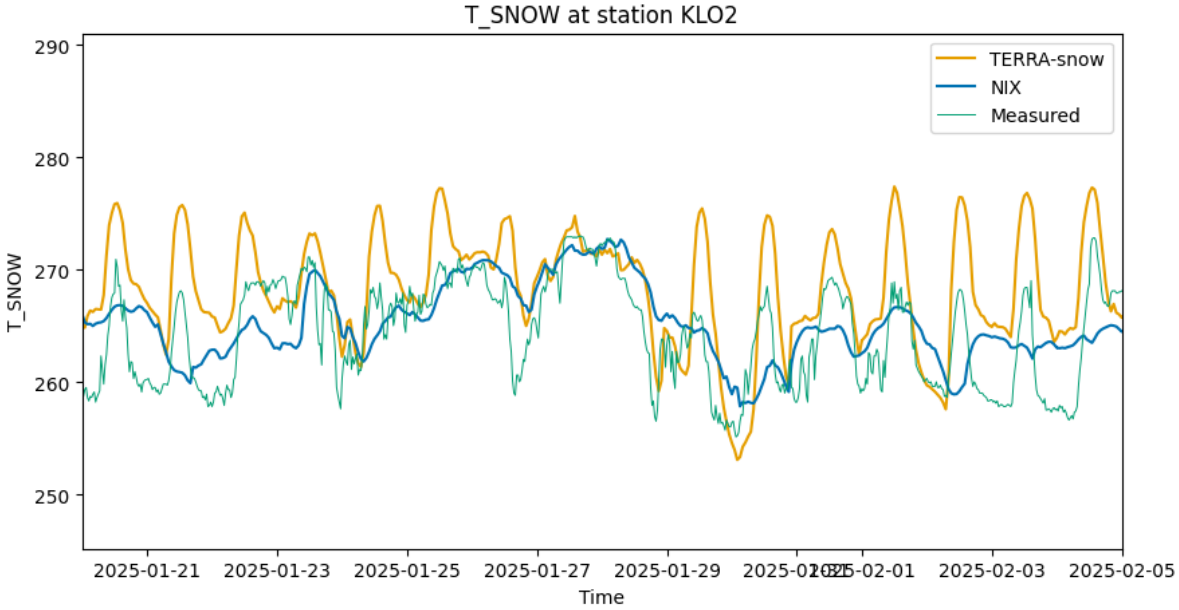
NIX snow depth in closer agreement with measured snow height, compared with TERRA-snow

- Spikes indicate inconsistent snow cover fraction scaling
- Snow analysis issues?

Measured vs modelled snow depth



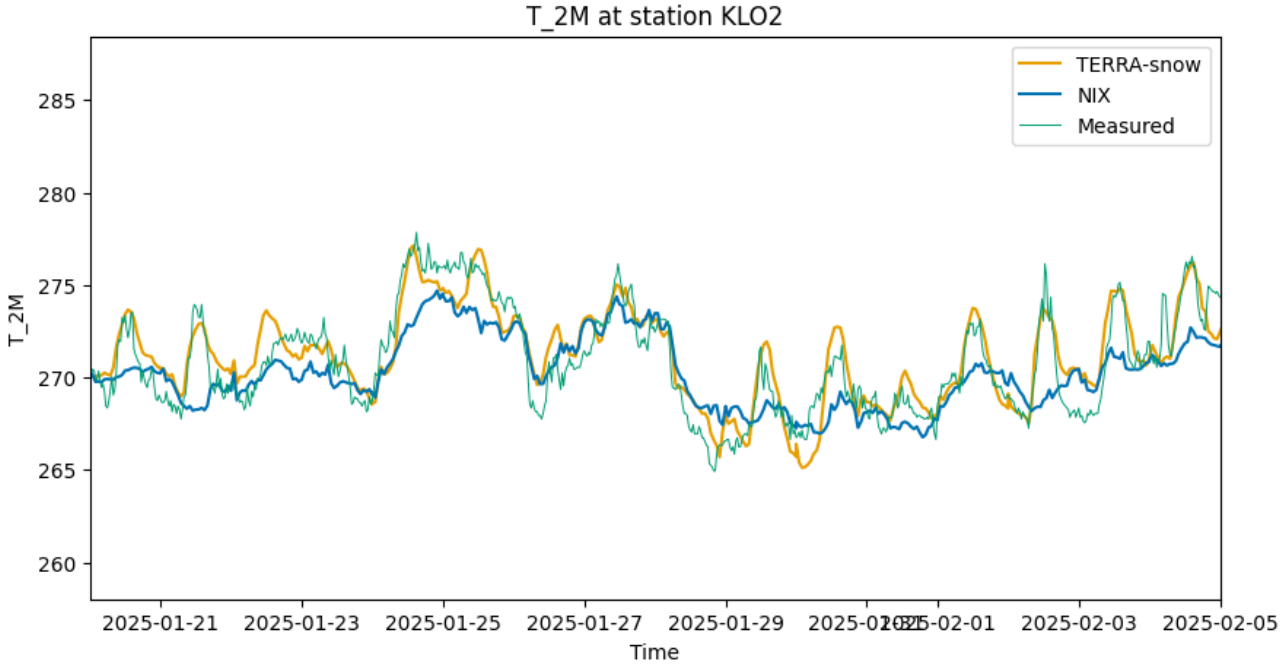
KLO2: Snow surface temperature



Snow surface temperature strongly impacted by snow depth

- TERRA-snow: overestimated amplitude
- NIX: underestimated amplitude

KLO2: 2m air temperature



TERRA-snow reproduces air temperature and its daily cycle really well

- Indicates compensating errors
- Shows importance of snow cover scheme, and its coupling to the boundary layer

Next development steps

- Fixing the heat equation instabilities
- Fixing the remaining tile management issues
- Verifying that snow analysis works as intended
- Fully validating GPU port
- Implementing some remaining code optimizations (removing a few unused fields, some code simplification)
- Some improvements to code documentation (adding/verifying units and signs for all variables etc.)
- Merge with main

Conclusion

1. Integrating NIX inside modular TERRA is an important step for the future of modelling snow in TERRA
2. What works:
   - Able to run for a few months, also on GPU
   - Results of fully coupled heat and energy balance are consistent
   - Snow height well reproduced (note that this also implies good snowfall rates from ICON)
3. What needs work:
   - Occasional bad feedback between turbulent fluxes, soil fluxes and heat equation solver, particularly with shallow snow covers (few cm).
   - Missing some daily cycle dynamics in snow surface temperatures
   - Snow cover fraction scaling
   - Snow analysis
   - Some tuning for new snow density and compaction

Outlook

Short term (2025):

- Merge with main

Long term (2026 and beyond):

- Unified code base between TERRA, JSBACH and NIX stand-alone
- Implementation canopy interactions → strong community interest
- Microstructure (grain size) → geographical independence
- Extension to glaciers, ice sheets and sea ice

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