ESA CCI SnowC2 Mid-Term Review meeting

3 October 2024

Snow cover heterogeneity and its impact on the Climate and Carbon cycle of Arctic regions

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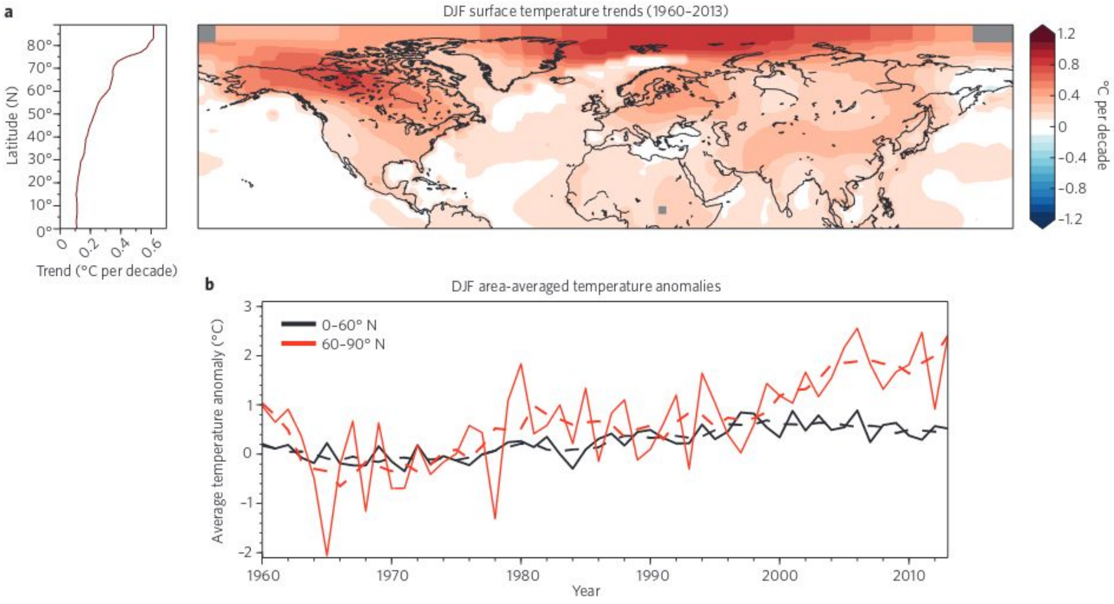
ESA CCI Fellowship — 01/10/2023 to 30/09/2025 (2 years)

supervised by Christophe Kinnard and Alexandre Roy

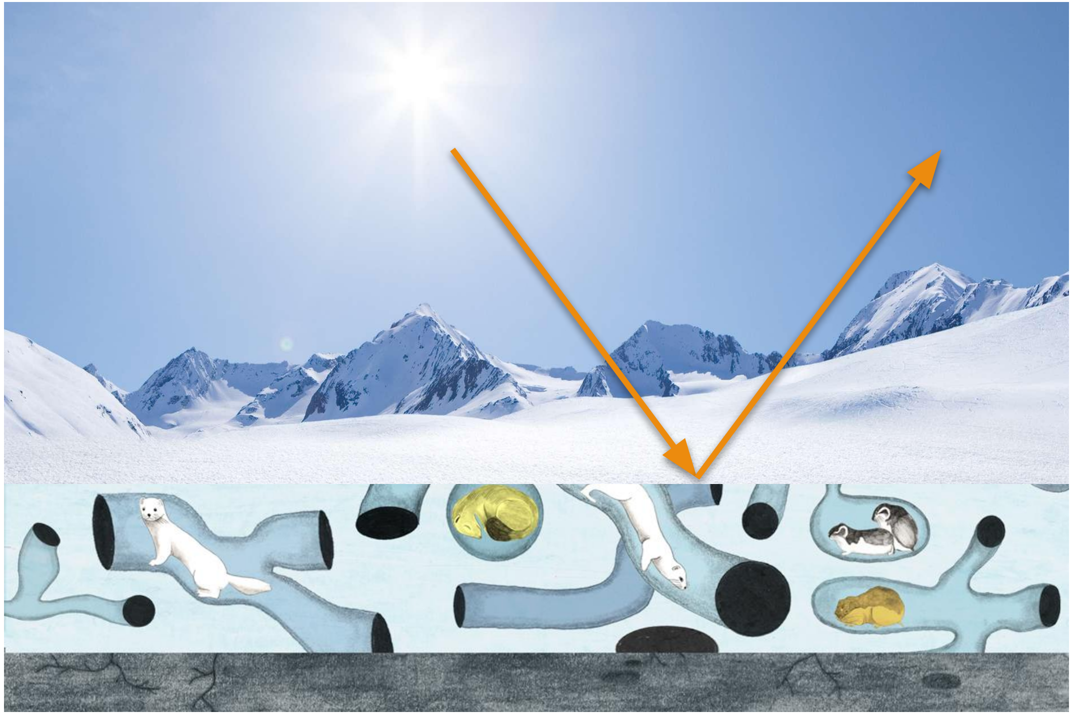
Context: Arctic Amplification



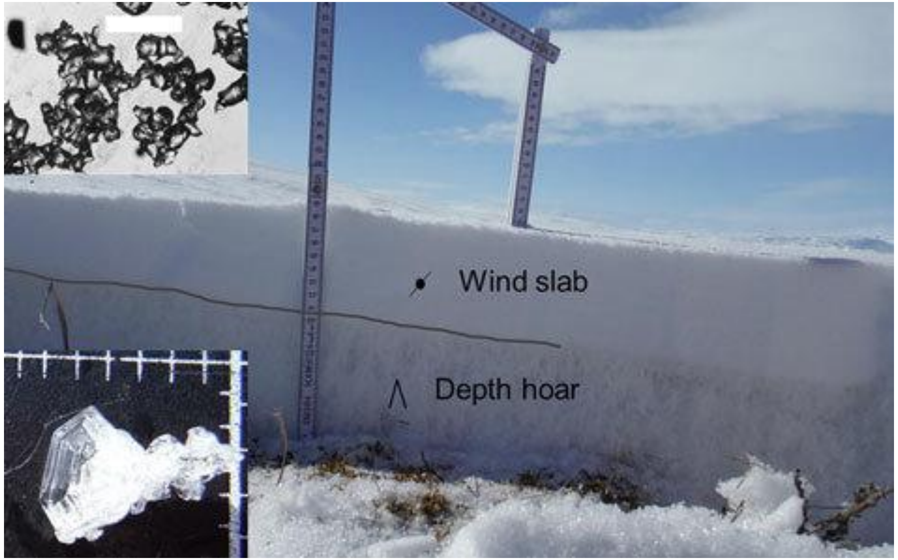
Cohen et al., (2014)

- The Arctic has warmed 2 to 3 times faster than the global average (e.g., Cohen et al., 2014); nearly four times faster than the globe since 1979 (Rantanen et al., 2022)
- ⇒ melting of Arctic sea ice and spring snow cover
- Impacts on ecosystems and human activities such as transportation, resource extraction, water supply, use of land and infrastructure among others.
- 1.035 Pg-C (>66° N, 3m soil) - By 2100, 55 to 232 Pg C-CO2-e could be emitted via permafrost degradation (Schuur et al., 2022)

Snow: essential component of the climate system



Arctic snowpack



Domine et al., (2019)

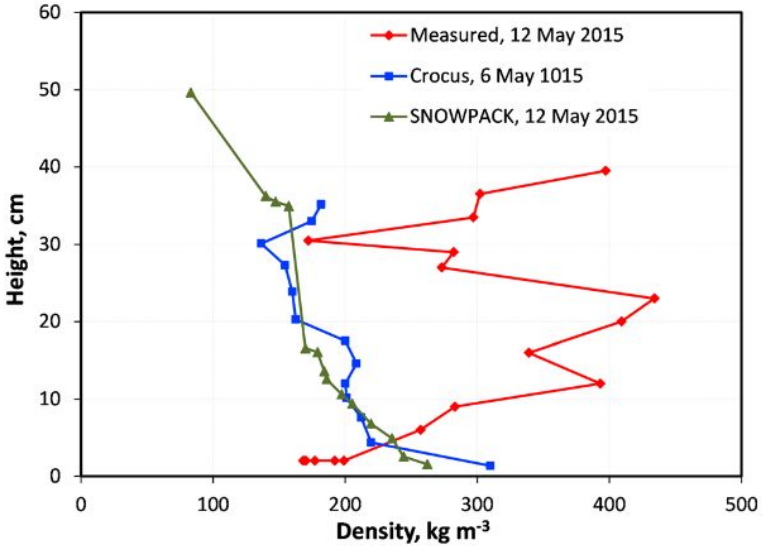


Figure 3. Comparison of measured snow density profiles at Bylot Island in May 2015 with those simulated using the detailed snow models Crocus and SNOWPACK. Crocus runs of 6 May are shown because Crocus simulates melting on 7 May, and this extra process makes comparisons irrelevant on 12 May.

Domine et al., (2018)

Arctic snowpack: solution?

Physical solution

Implement the water vapor fluxes explicitly in the snowpack (→ snow mass redistribution):

- IVORI project (Marie Dumont, ERC ~2M €)
- Jafari et al., (2020): The Impact of Diffusive Water Vapor Transport on Snow Profiles in Deep and Shallow Snow Covers and on Sea Ice
- Simson et al. (2021): Elements of future snowpack modeling – Part 2: A modular and extendable Eulerian–Lagrangian numerical scheme for coupled transport, phase changes and settling processes

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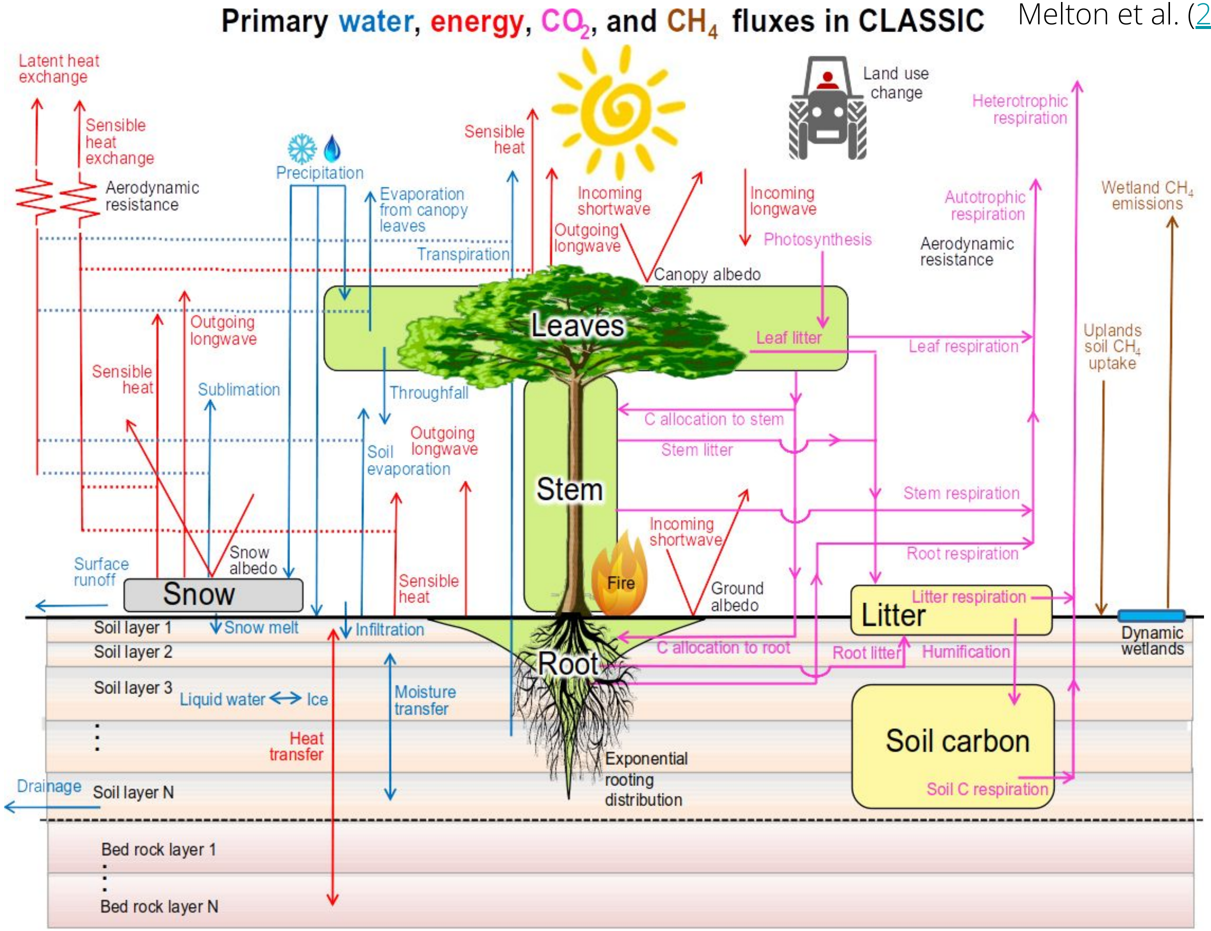
Practical solution

Increase the compaction due to the wind + reduce the density of the lower layers, e.g.:

- Royer et al. (2021): Improved Simulation of Arctic Circumpolar Land Area Snow Properties and Soil Temperatures
- Lackner et al., (2022): Snow properties at the forest–tundra ecotone: predominance of water vapor fluxes even in deep, moderately cold snowpacks

Challenge: never applied worldwide and often site specific...

CLASSIC LSM: description



Melton et al. (2020), Fig. 1

- CLASSIC v1.0 LSM: Canadian Land Surface Scheme Including Biogeochemical Cycles (Melton et al., 2020)
- → couples CLASS 3.6.2 (Verseghy et al., 2017) and CTEM 2.0 (Melton & Arora, 2016)
  - CLASS: physics (energy/water fluxes), etc.
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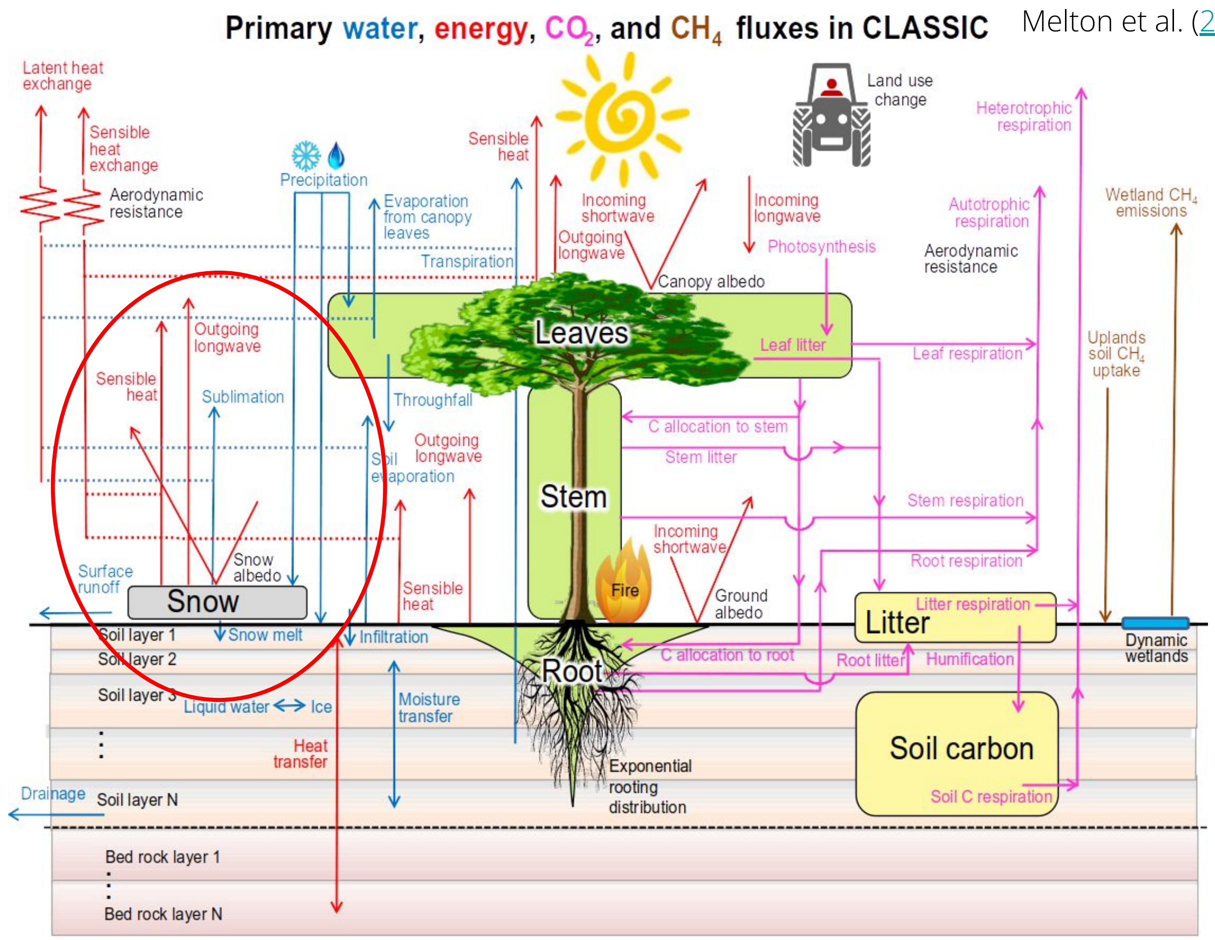

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Objectives of the project

1. Adapt CLASSIC snow model to Arctic conditions (1D simulations)

Model development and assessments

New Arctic simulations

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Credit: Sawtooth Avalanche Center

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2. Test new snow cover fraction parameterizations + Arctic snow in spatial simulations
   → use of ESA CCI data (snow, land type, etc.) to calibrate and asses these new developments

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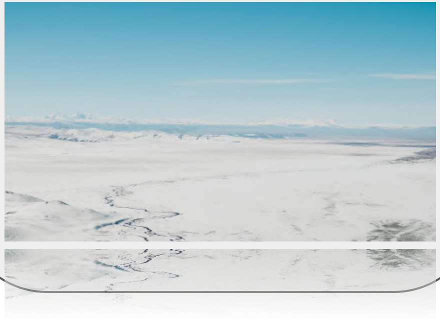

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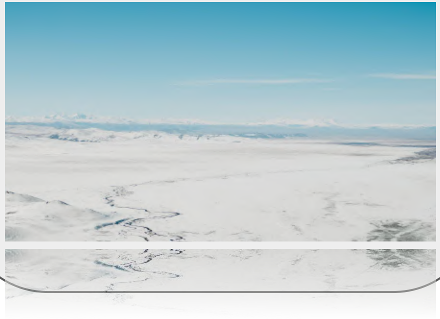


Presentation Outline

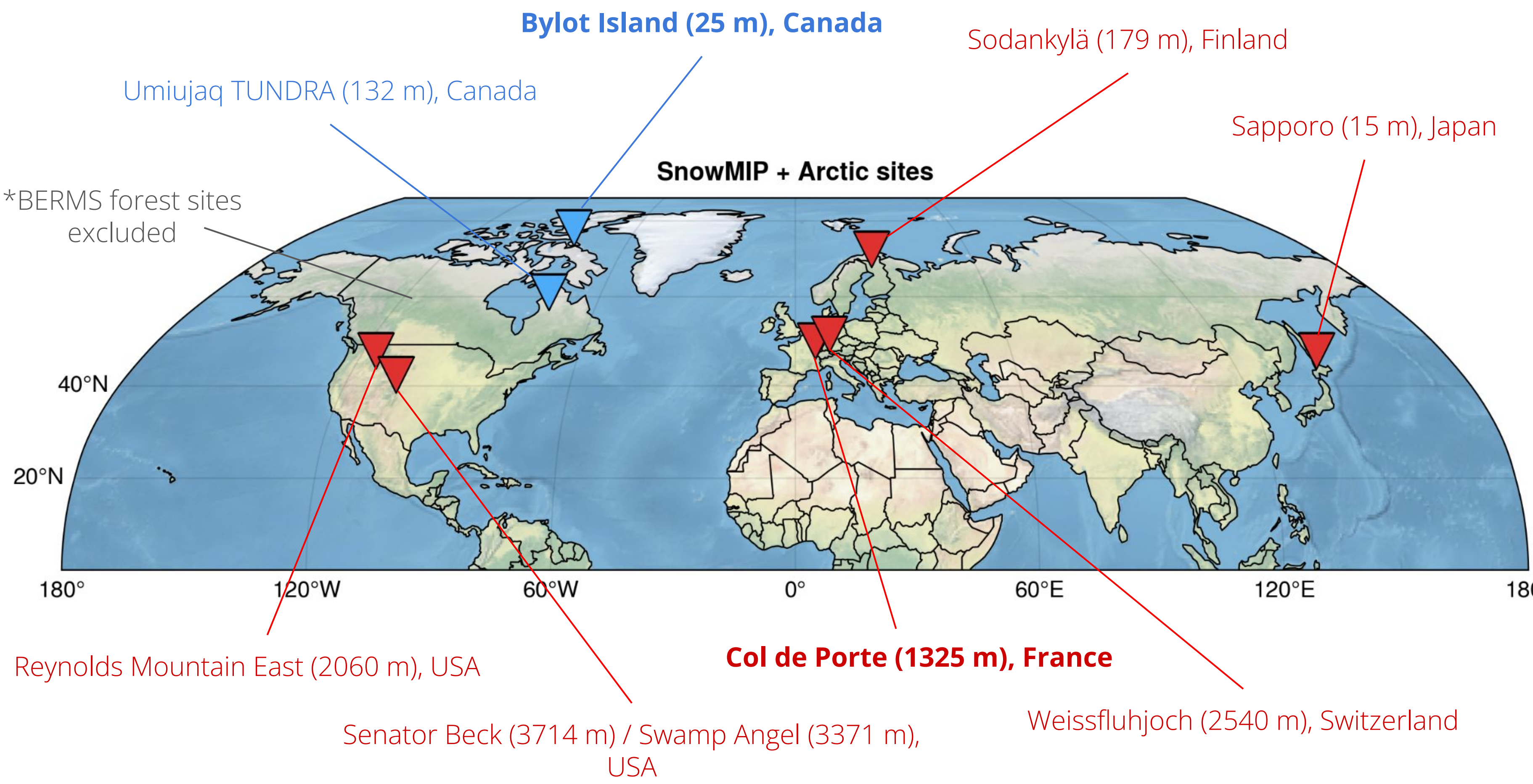
Adapt CLASSIC snow model to Arctic conditions (1D simulations)

1. Methods
   - 1.1. SnowMIP and Arctic sites
   - 1.2. CLASSIC snow model description
   - 1.3. Model and simulations set-up
2. Physics improvements
   - 2.1. Soil conductivity under snow (bug)
   - 2.2. Bottom snow temperature (TSNB)
   - 2.3. Windless exchange coefficient (EZERO)
3. Arctic adaptation
   - 3.1. Blowing snow sublimation losses
   - 3.2. Wind effect on snow compaction
   - 3.3. Snow conductivity

Part #1

Methods

Methods: SnowMIP and Arctic sites



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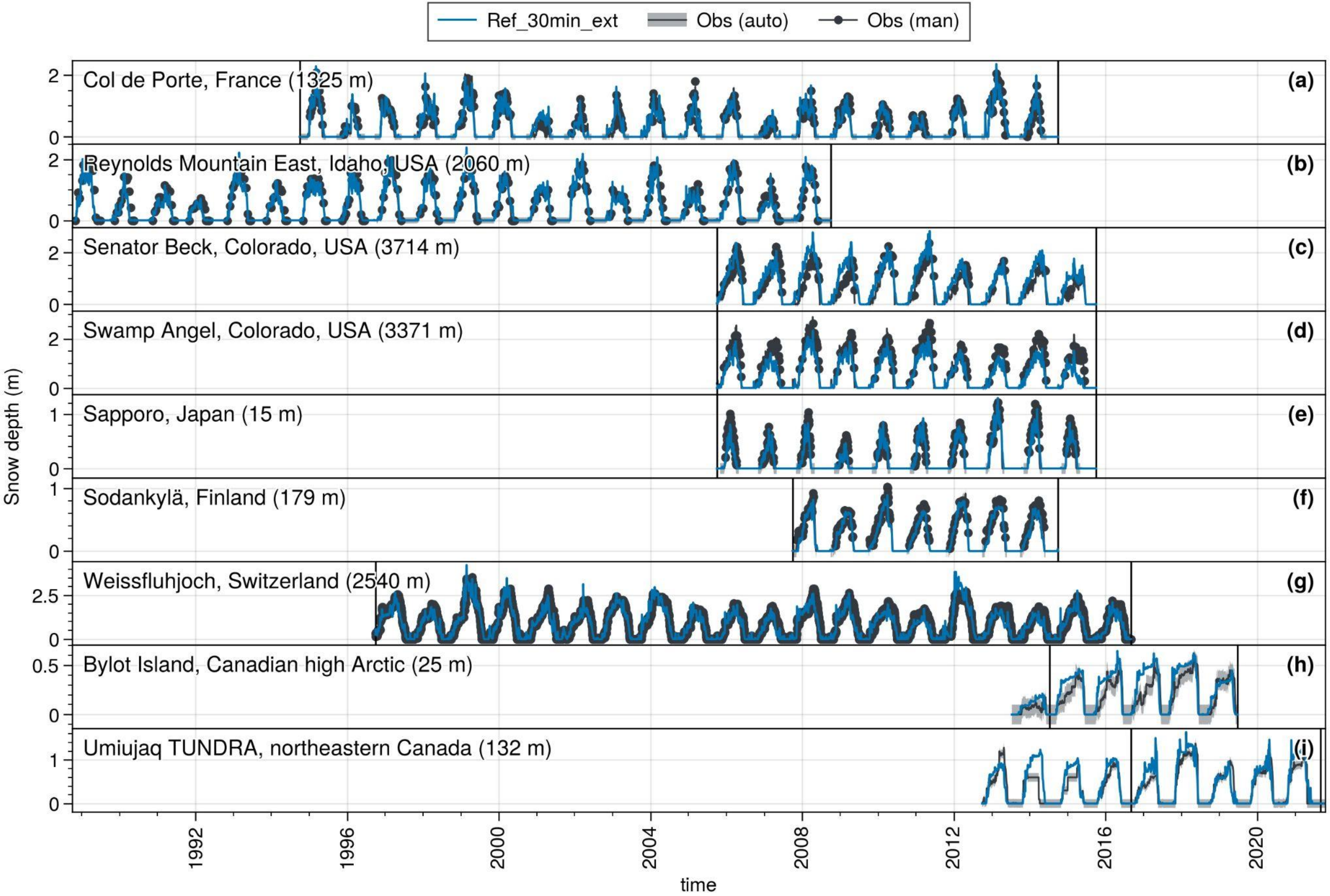
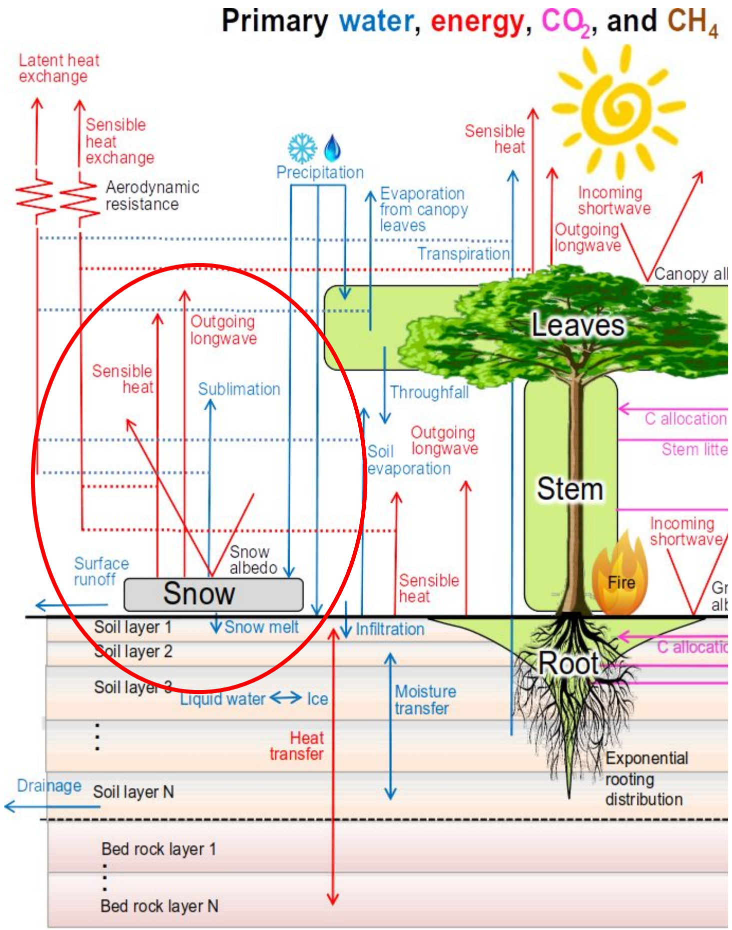


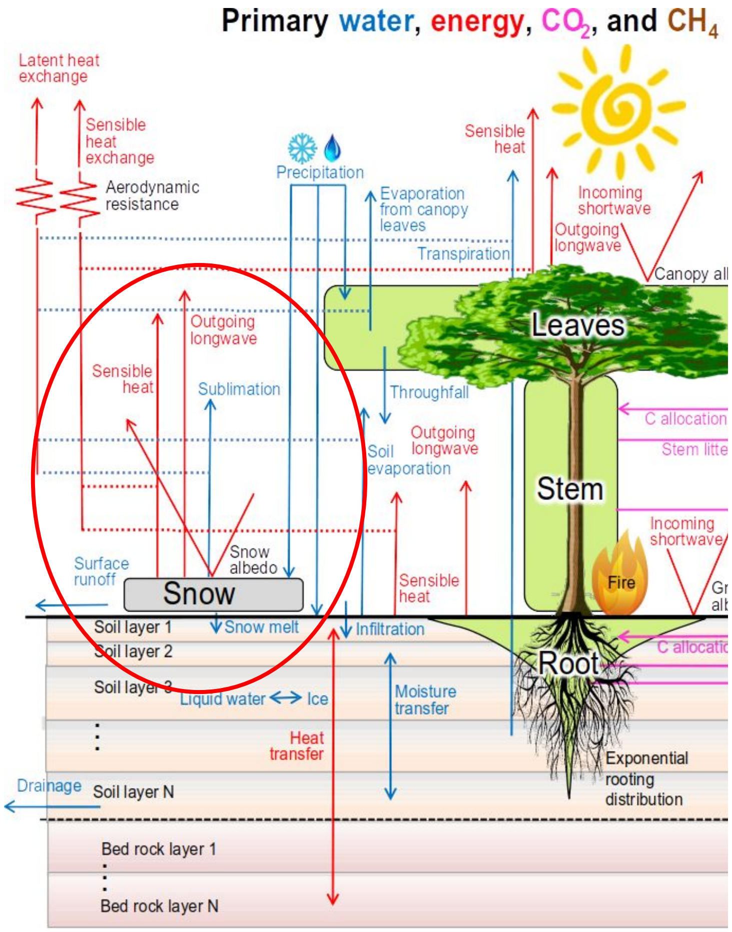
Methods: CLASSIC snow model



Snow model description (Bartlett et al., 2006; Brown et al., 2006; Langlois et al., 2014; Verseghy et al., 2017 - version 2.7 → 3.6.1):

- Separate energy and water balances for the vegetation canopy, snow, and soil
- Single-layer snow model
- Quadratic temperature profile within the snowpack
- Snow albedo decreases and the snow density increases exponentially with time
- Fresh snow density is determined as a function of the air temperature (Pomeroy & Gray, 1995)
- The snow thermal conductivity is derived from the snow density (Sturm et al., 1997)

Methods: CLASSIC snow model



- Melting of the snow layer can occur either from above or from below (percolation and refreezing taken into account) + water retention taken into account
- Interception of snowfall by vegetation is explicitly modeled (Bartlett et al., 2006)
- SCF = 100 % if SD > 10 cm then linear decrease

A few recent CLASSIC noticeable developments:

- Extension of the number of soil layers from 3 to 20 up to 61 m depth (Melton et al., 2019)
- Inclusion of shrubs in the plant functional types (PFTs; Meyer et al., 2021)

Note: A preliminary parameterization of the effect of black carbon on the snow albedo has recently been developed in CLASS (when coupled with CanAM5) – not ready to be used in this study.

Methods: Model and simulations set-up

Forcing:

- For each site: incoming shortwave and longwave radiation, air temperature, precipitation rate (total and solid), air pressure, specific humidity, and wind speed
  - → linearly interpolated to the model time step (30 minutes; see issue with 1h)
  - → quality-controlled data, including correction for wind-induced solid precipitation undercatch

Initialization and boundary conditions:

- Soil properties (sand, clay, and organic matter), soil permeable depth, soil color index (SoilGrids250m), CLASS and CTEM PFTs, greenhouse gas concentration, etc.
  (note: no moss and lichen, so a peat layer was added to the first soil layer (10 cm) in certain cases, e.g., at Bylot)

Spin-up:

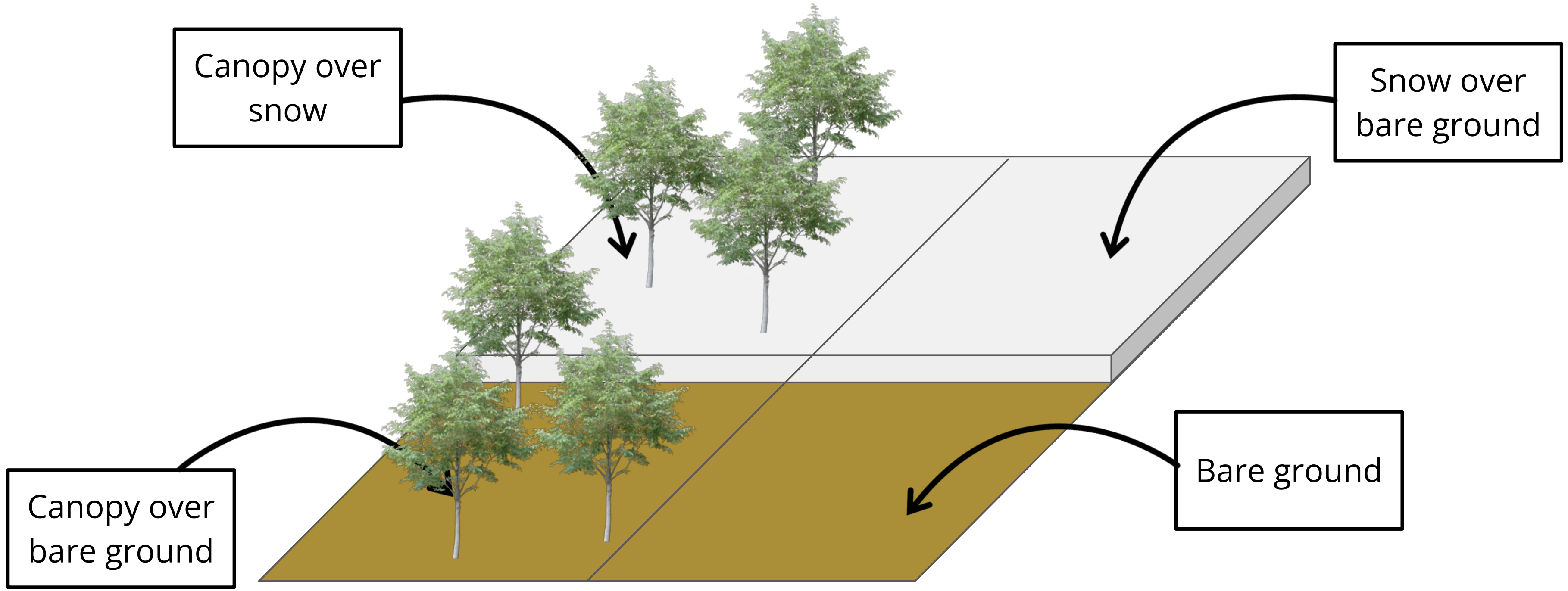
- First spin-up 100 to 300 years (with spinfast = 10) until reaching carbon balance (looping over the full forcing files period)
- Final spin-up same duration (spinfast = 1)
- CO2 concentration fixed to the first year forcing file value

Part #2

Physics improvements

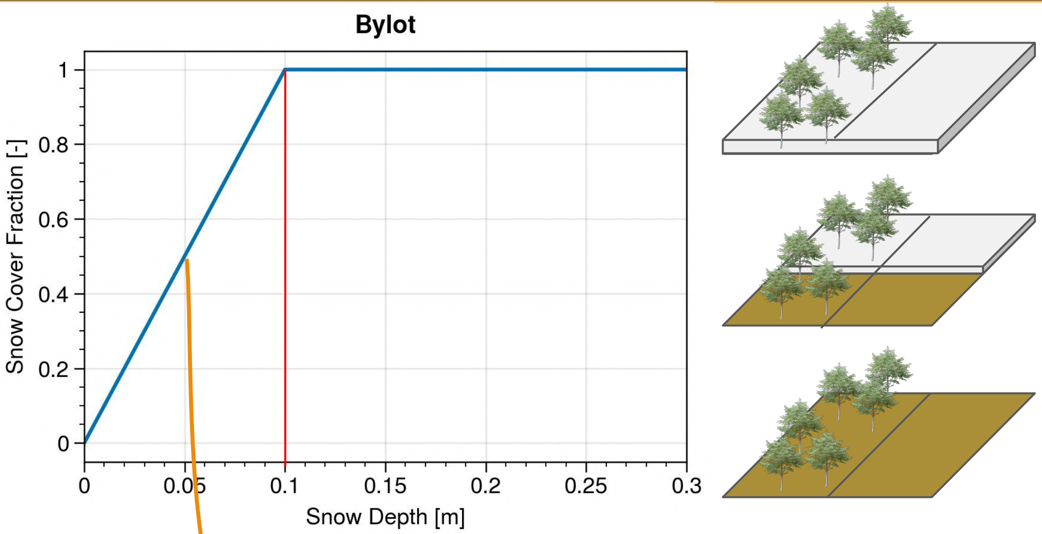
- → Soil conductivity under snow (bug)
- → Bottom snow temperature (TSNB)
- → Windless exchange coefficient (EZERO)

Context: CLASSIC subgrid areas

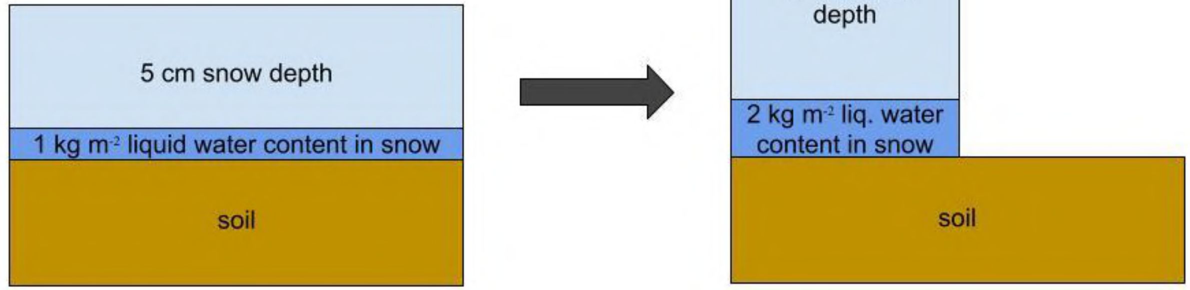


→ Evolve dynamically (depending on vegetation height, snow depth, etc.)

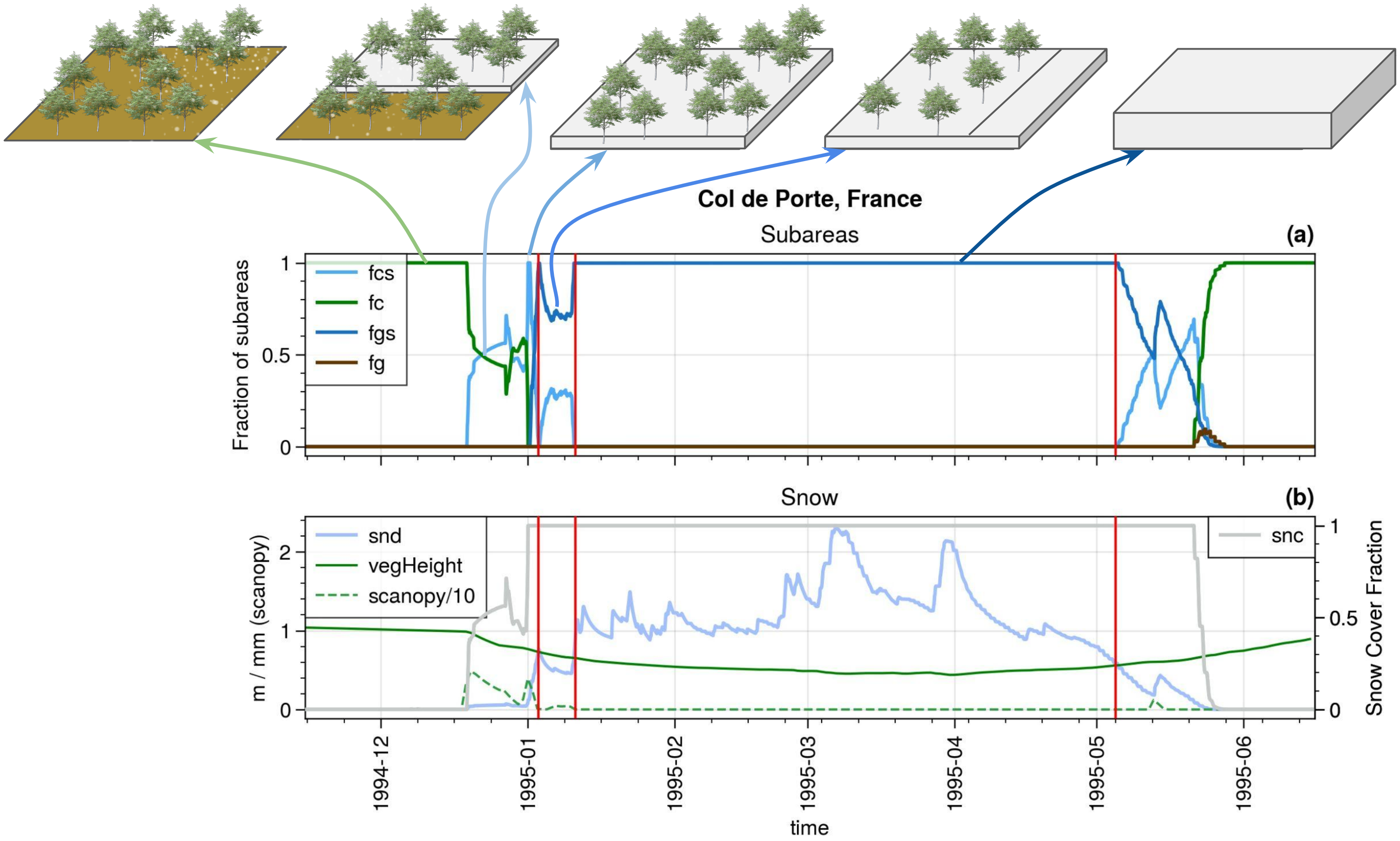
Context: CLASSIC snow cover fraction



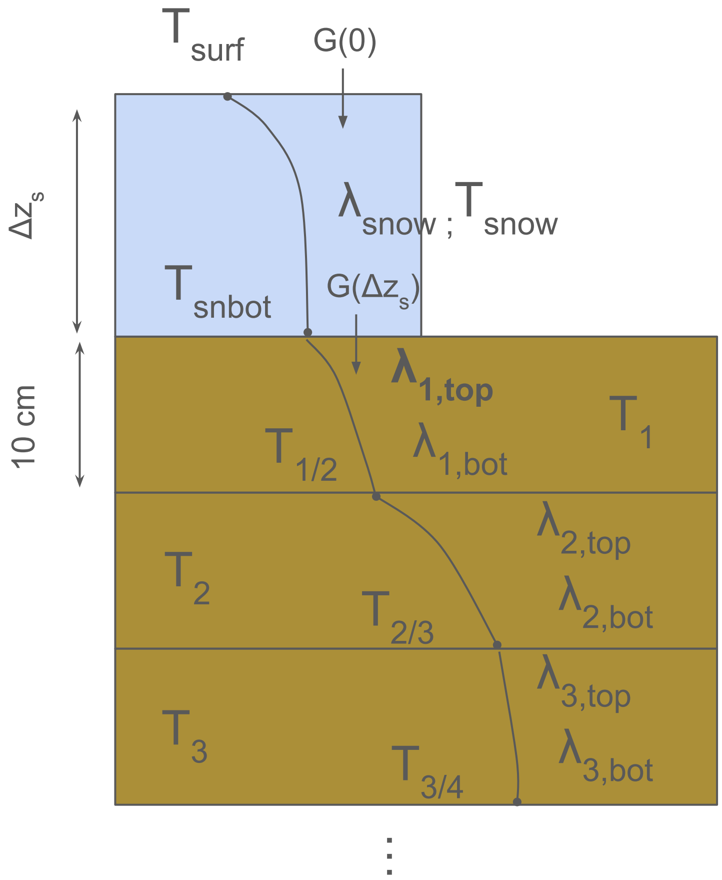
/!\ Min snow depth: 10 cm
(for model stability) /!\



Context: dynamic subareas evolution



Context: CLASSIC snow model physics (radiation)



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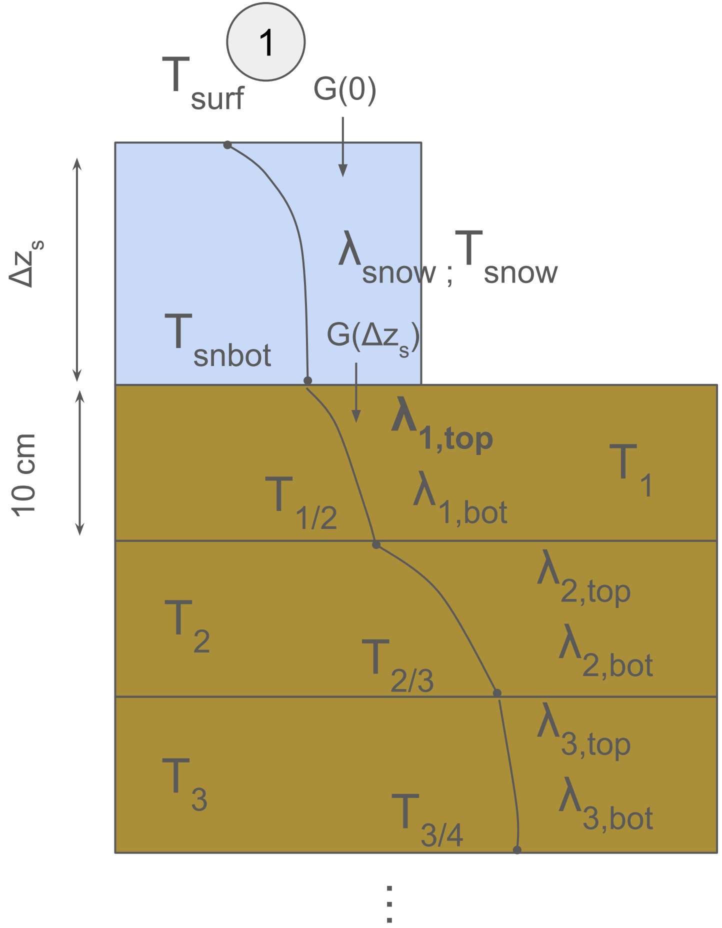

1. Surface energy budget: $K_* + L_* - Q_H - Q_E - G(0) = 0$

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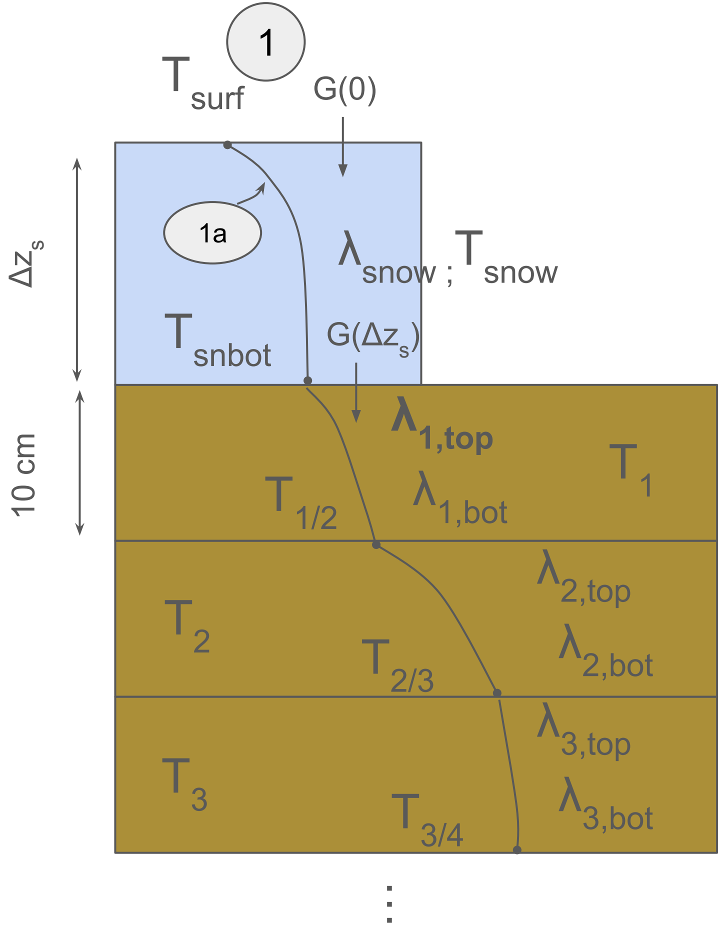

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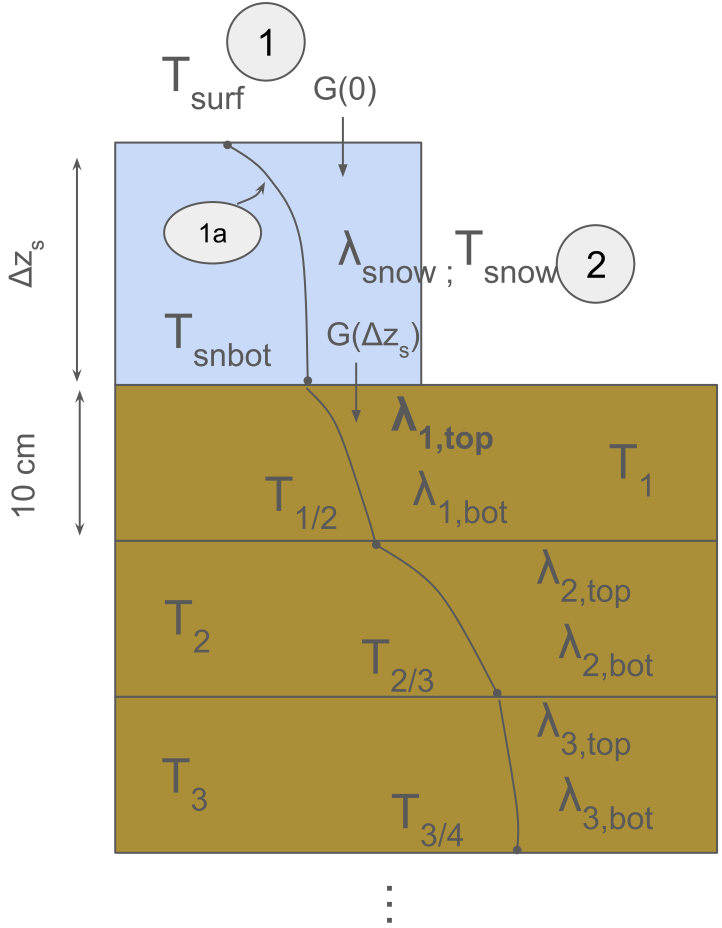

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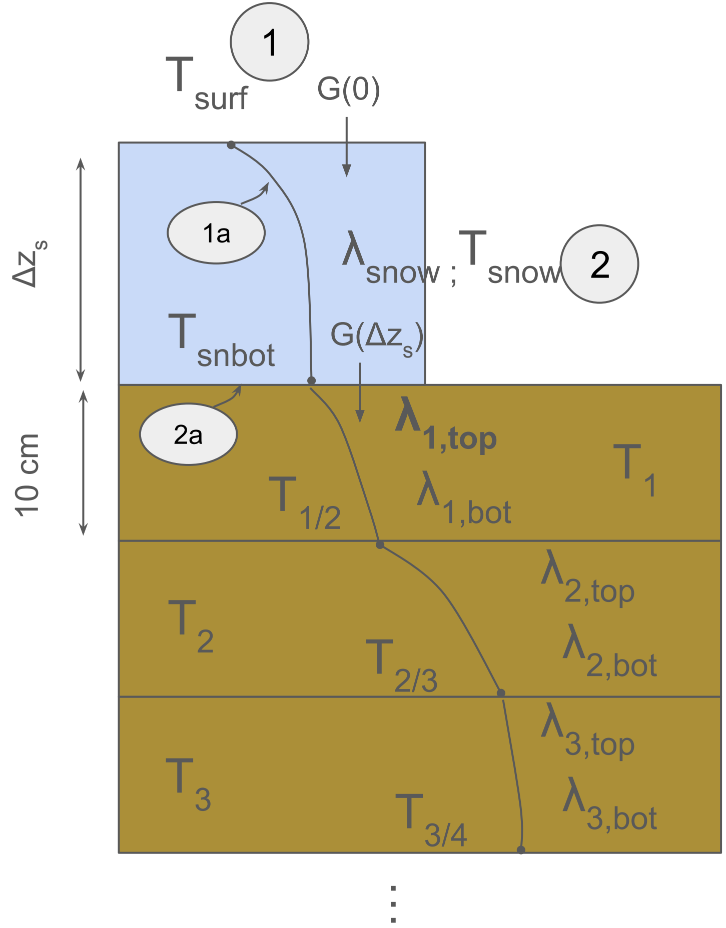

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```
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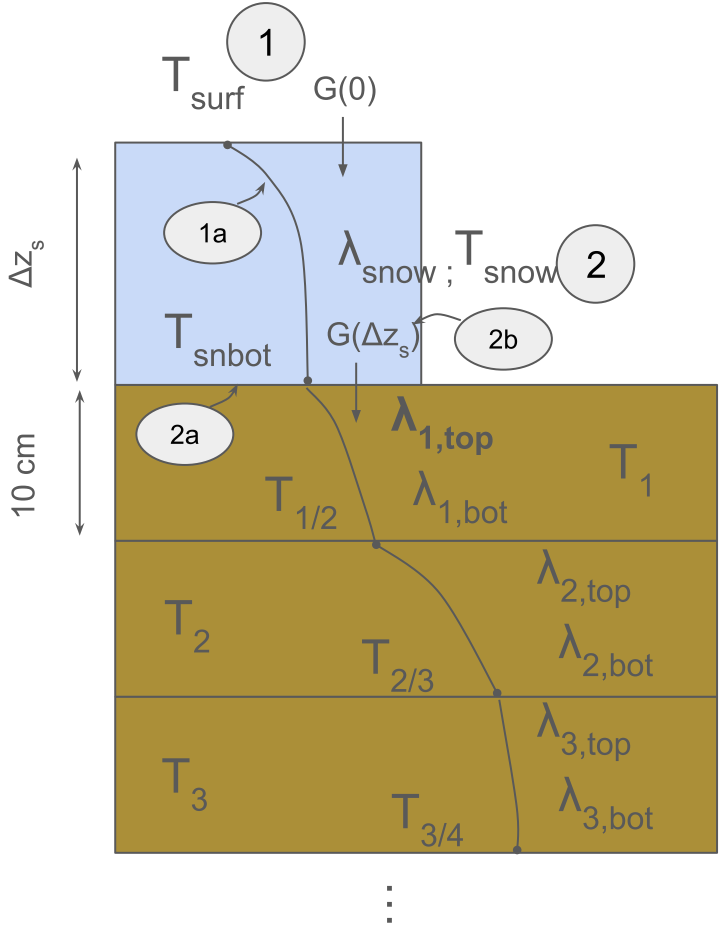

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Note: In the computation of $G(\Delta z_s)$, $\lambda_{1,top}$ is considered as a harmonic average of the snow thermal conductivity and the one of the first soil layer.

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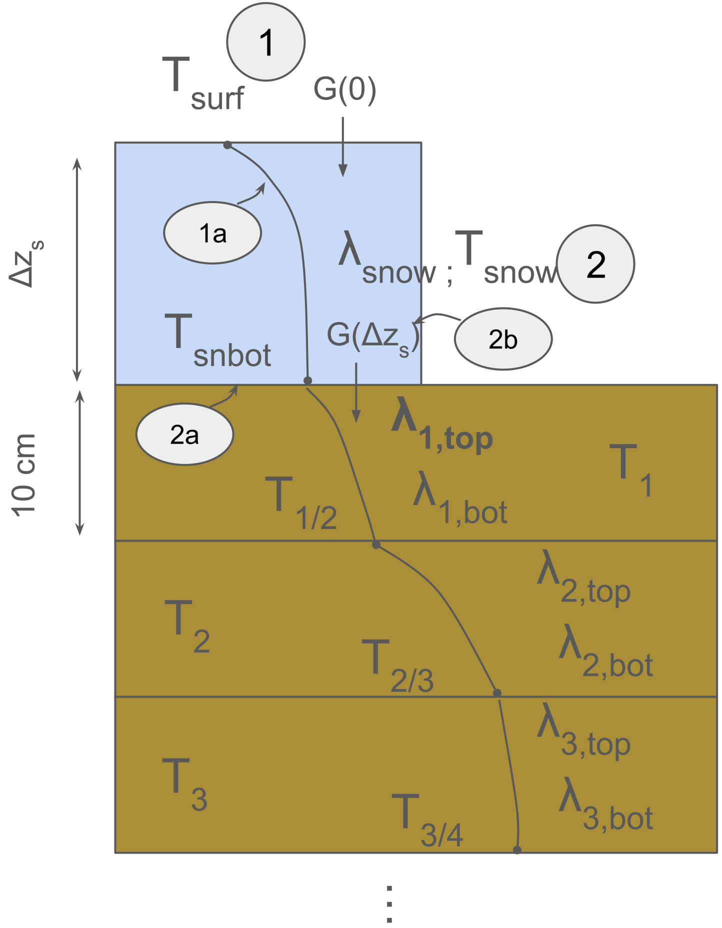

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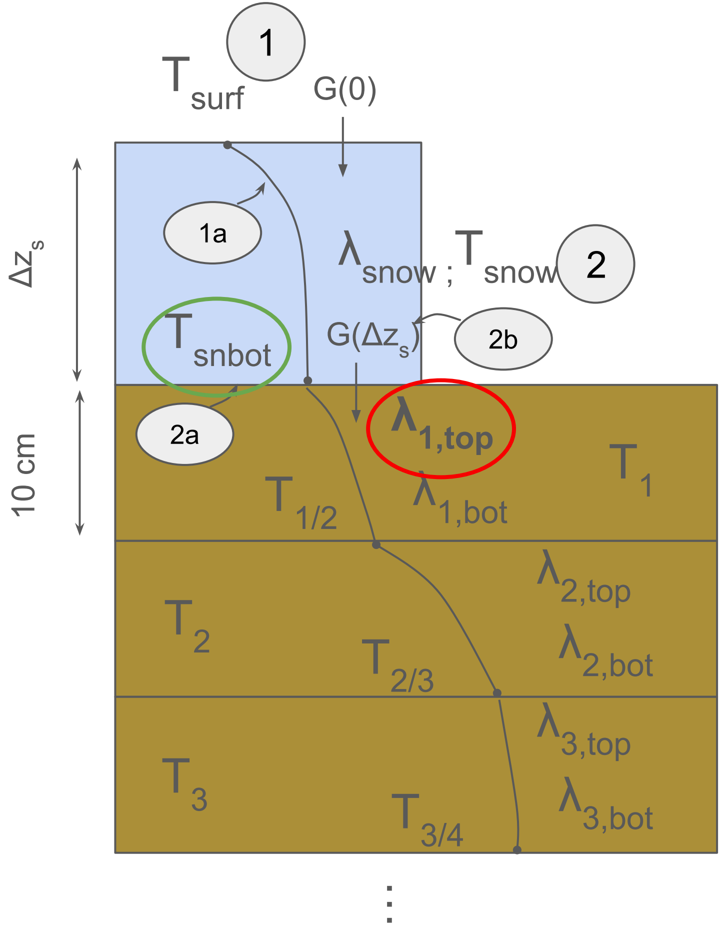

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Part #2

Physics improvements

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  - → Bottom snow temperature (TSNB)
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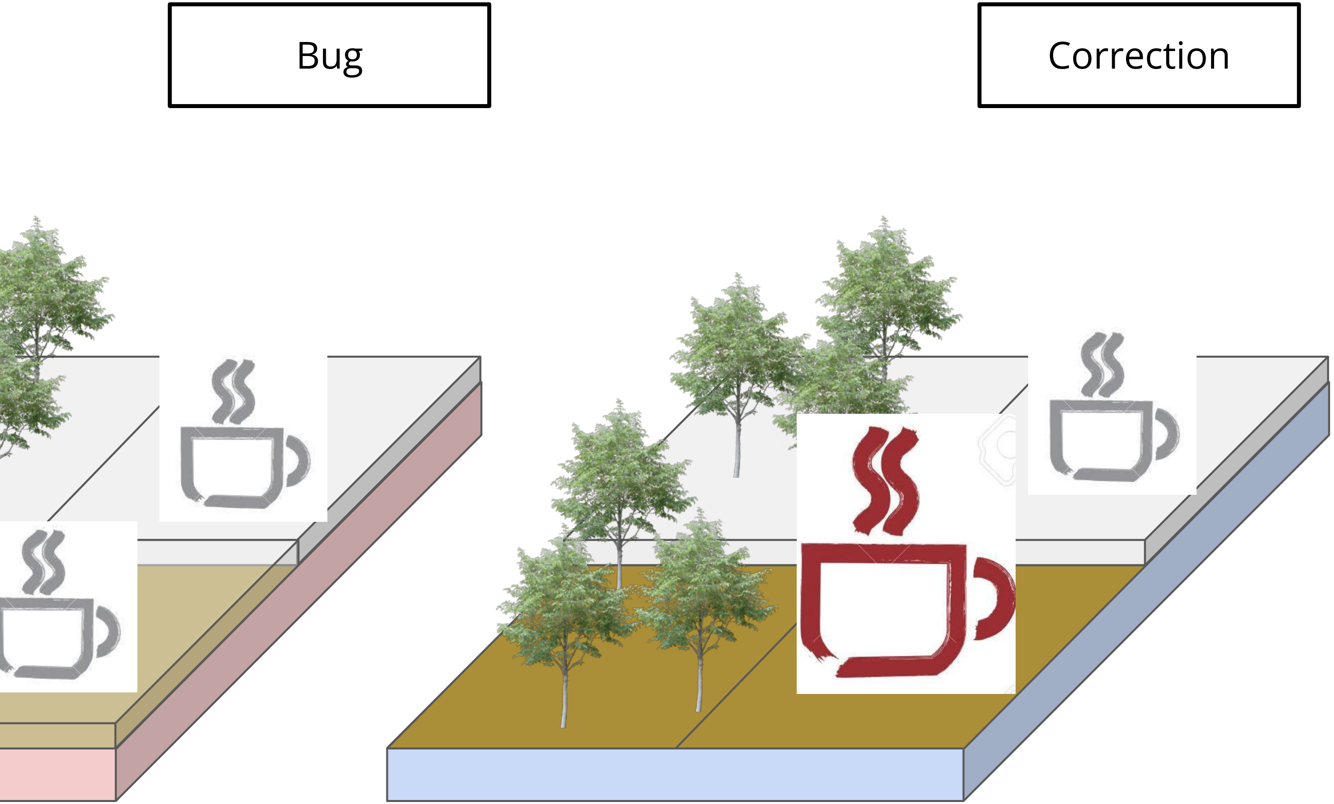
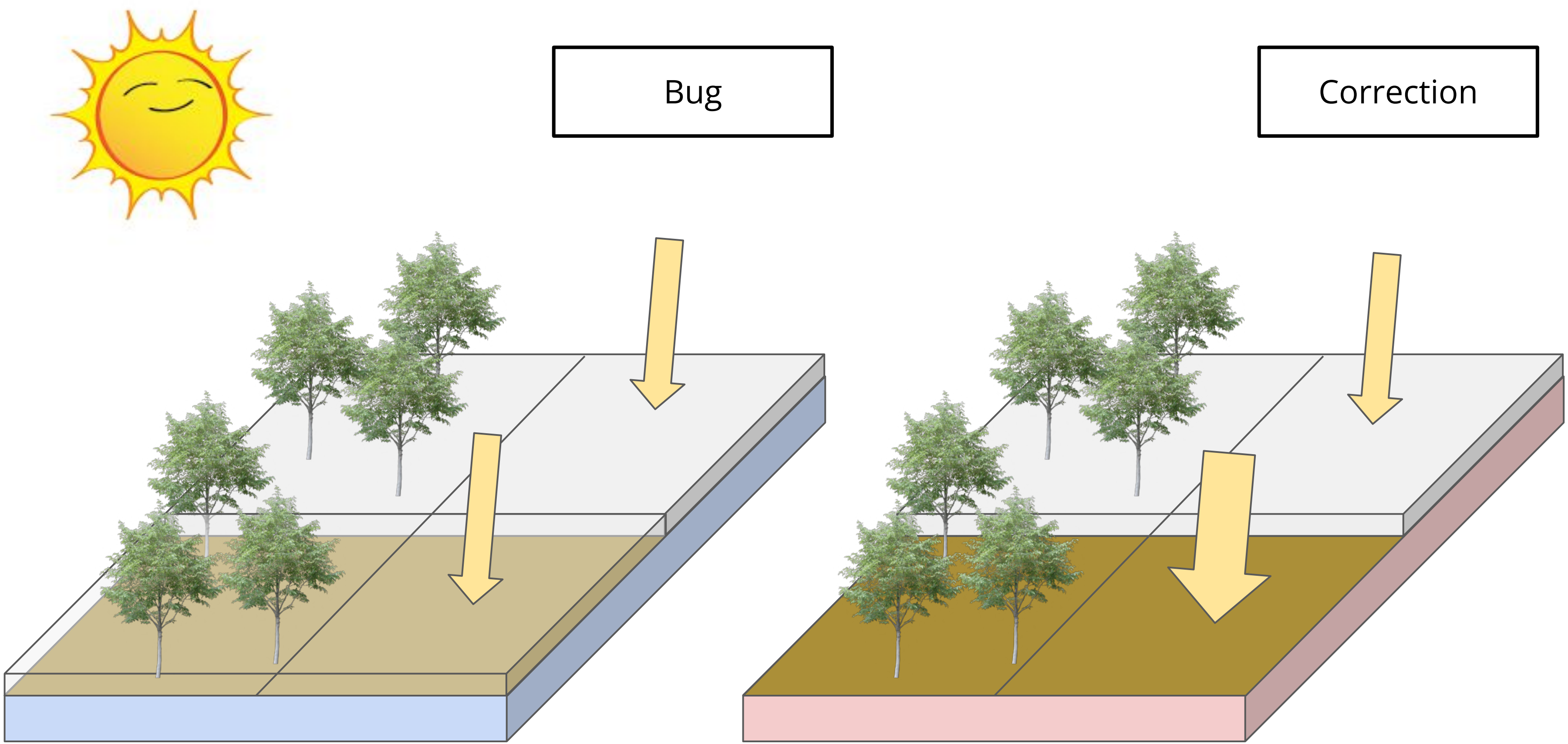
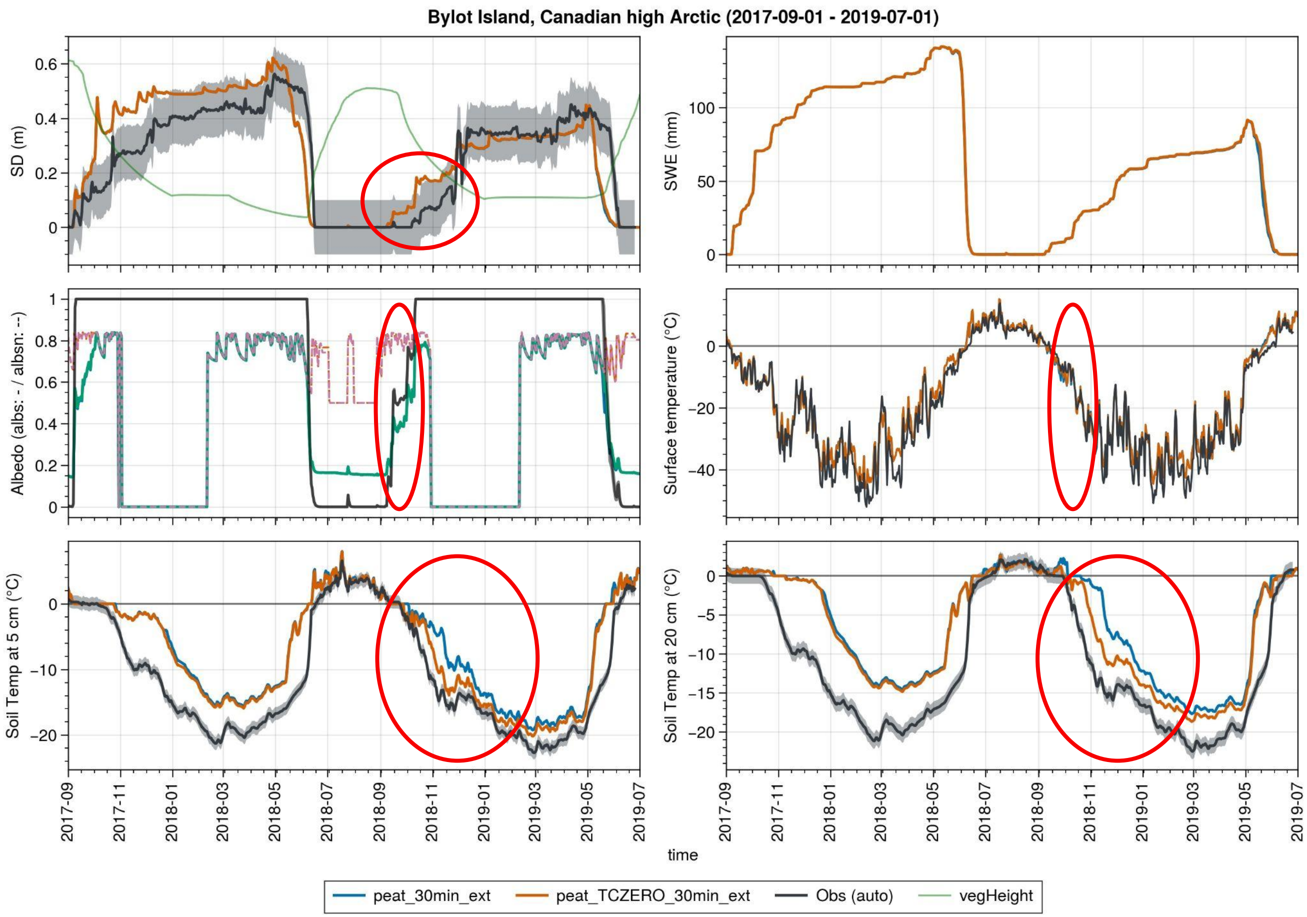
$\lambda_{1,top}$ over snow-free areas (bug): **autumn**



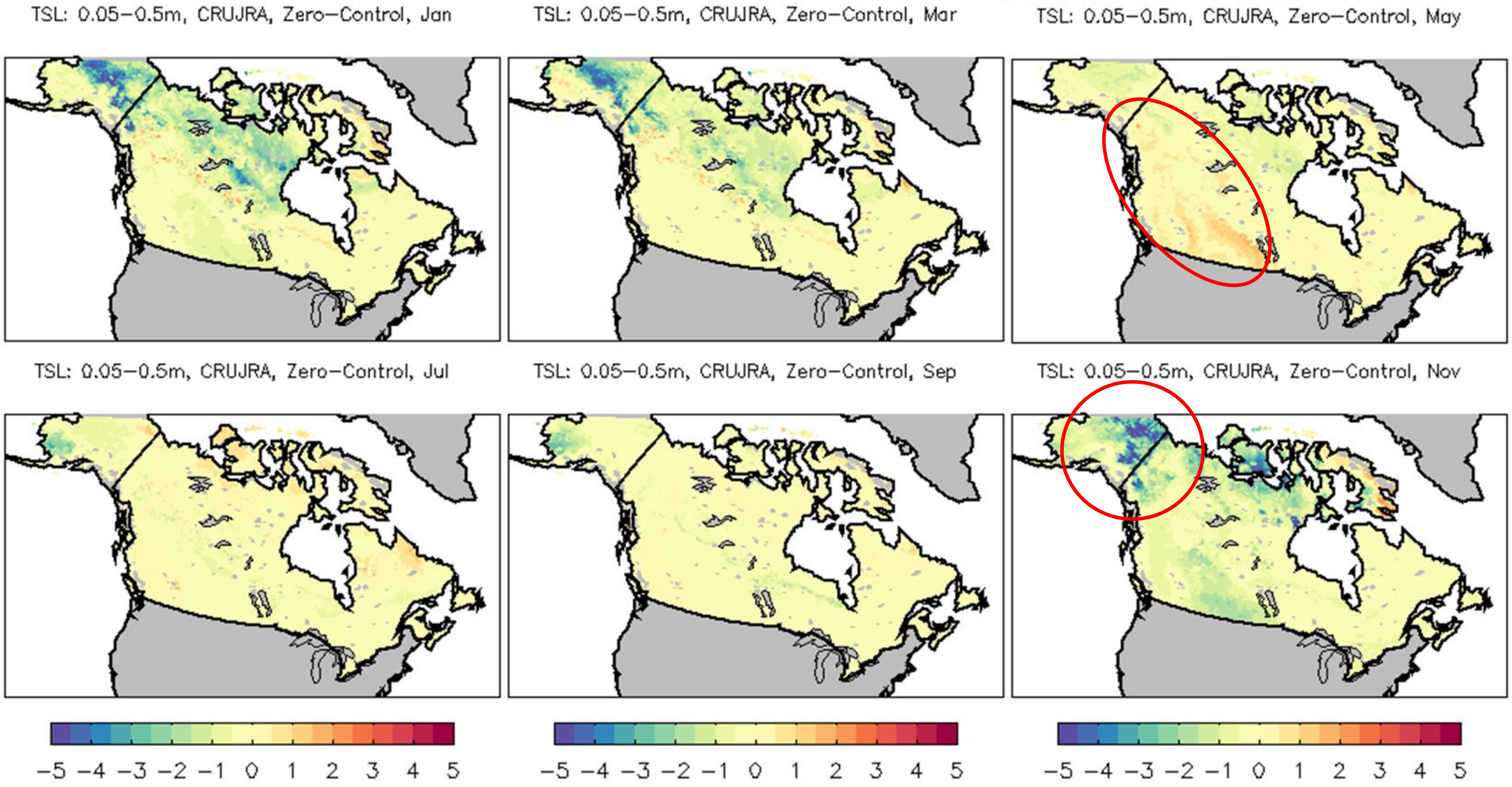
$\lambda_{1,top}$ over snow-free areas (bug): **spring**



Impacts: site simulations (Mickaël)



Impacts: spatial simulations (Libo)



More details: https://gitlab.com/cccma/classic/-/issues/119

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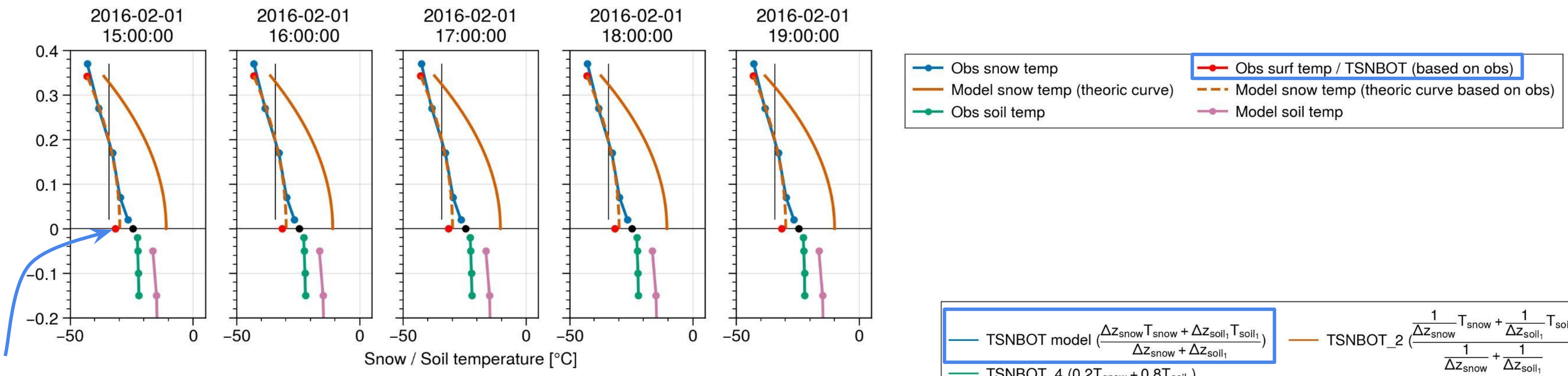
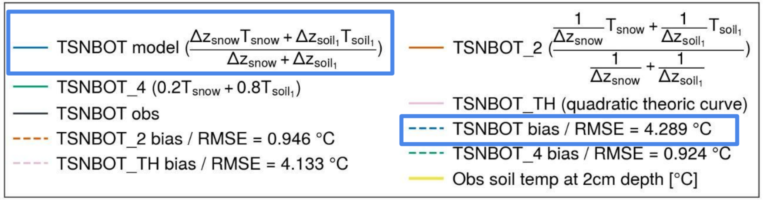
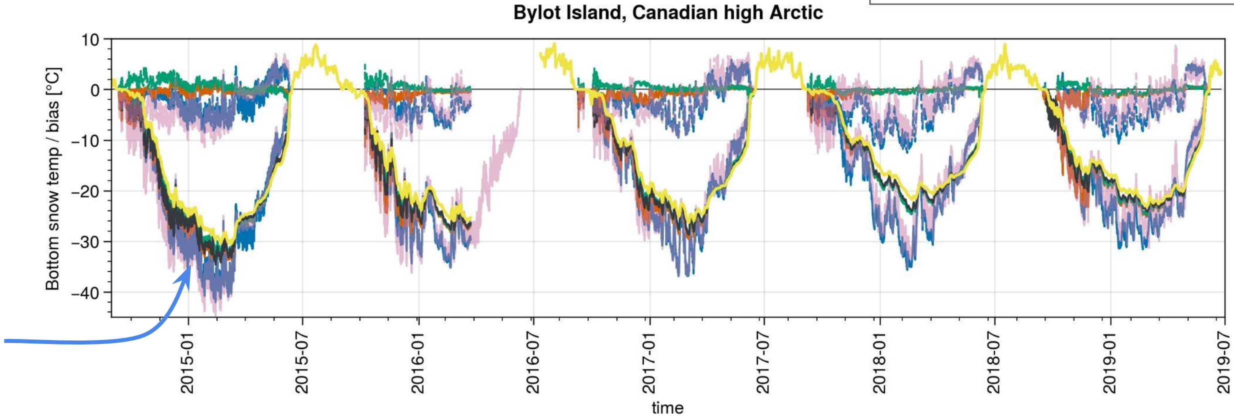


G(Δz_s) overestimated → soil too cool / snowpack too warm





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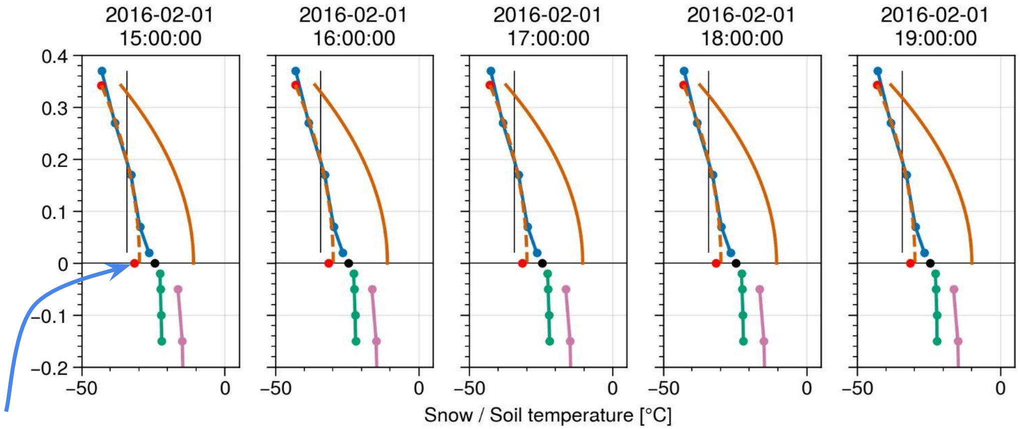

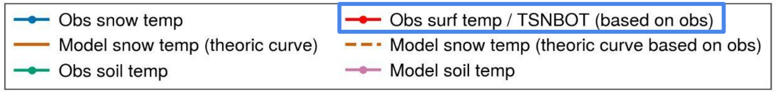

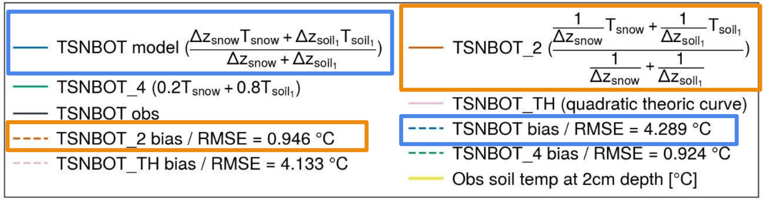

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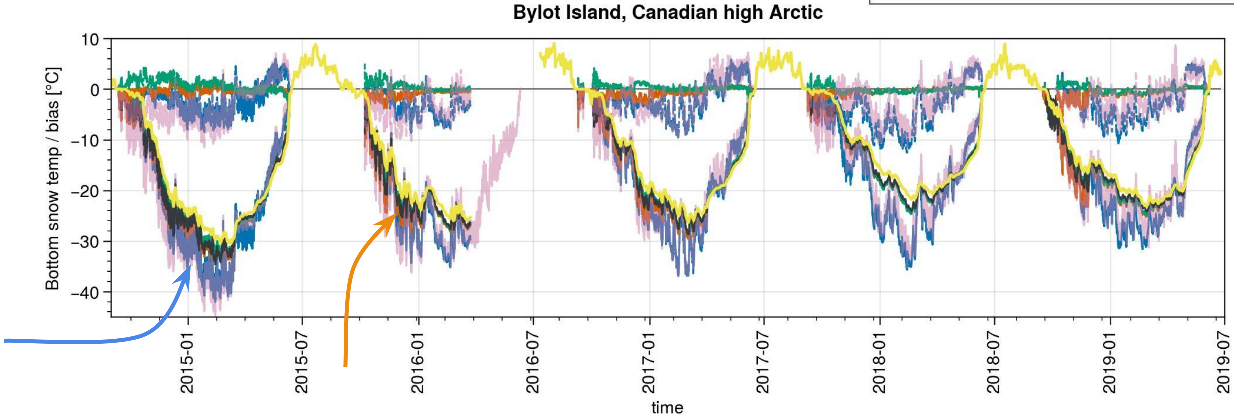

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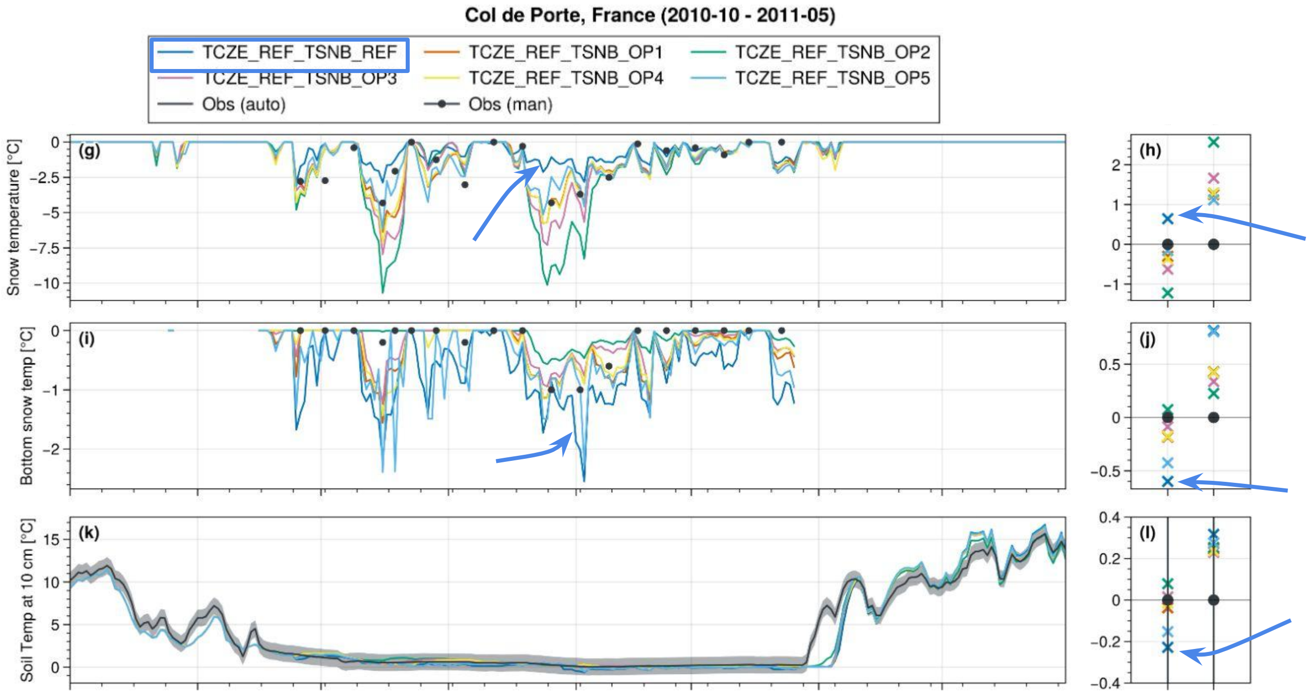

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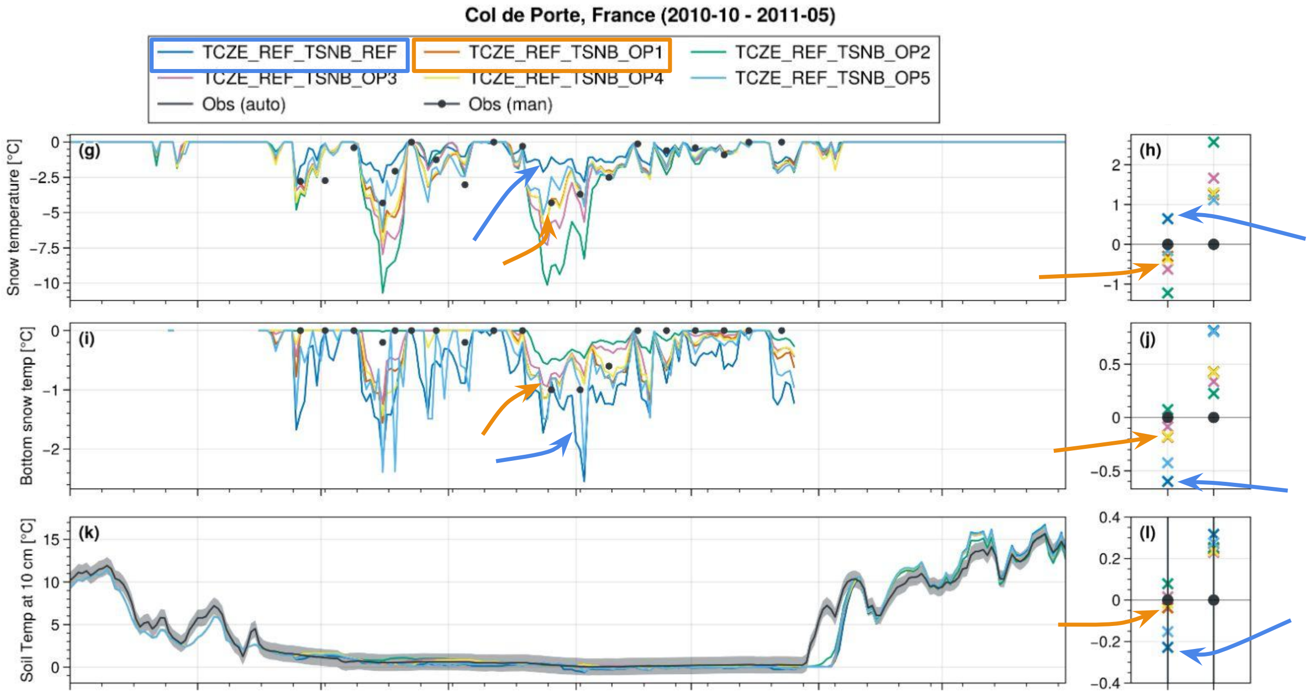

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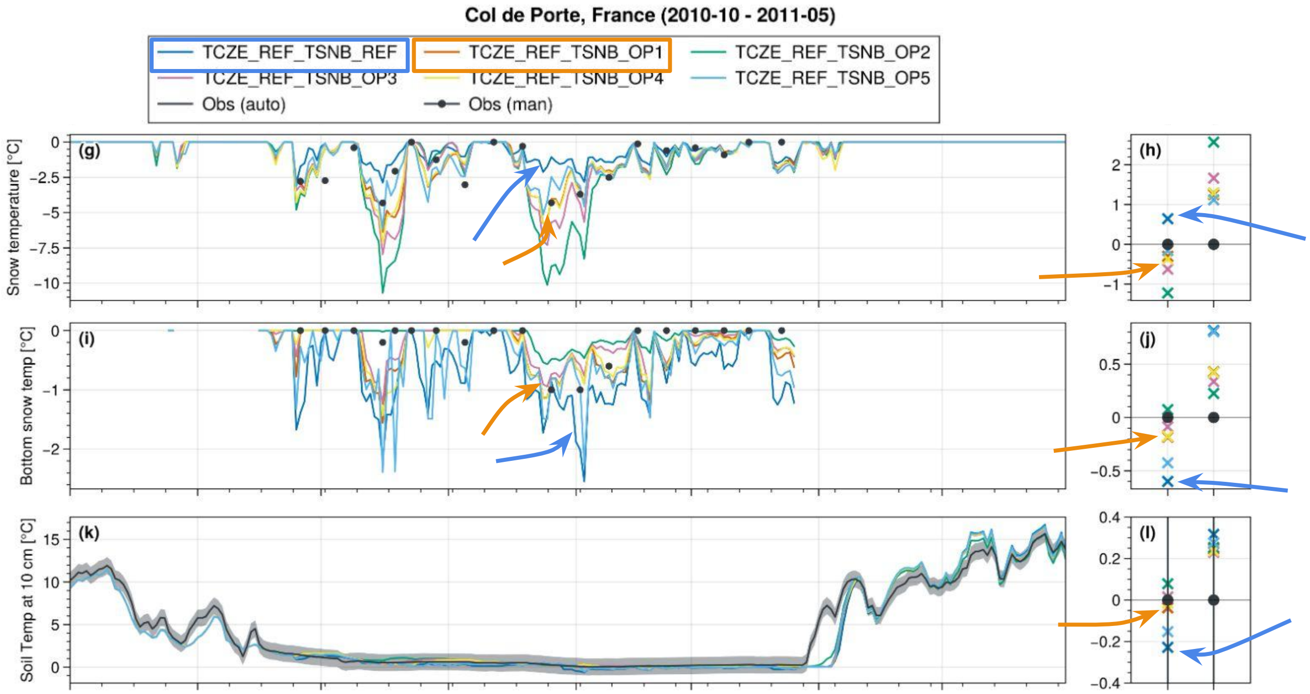

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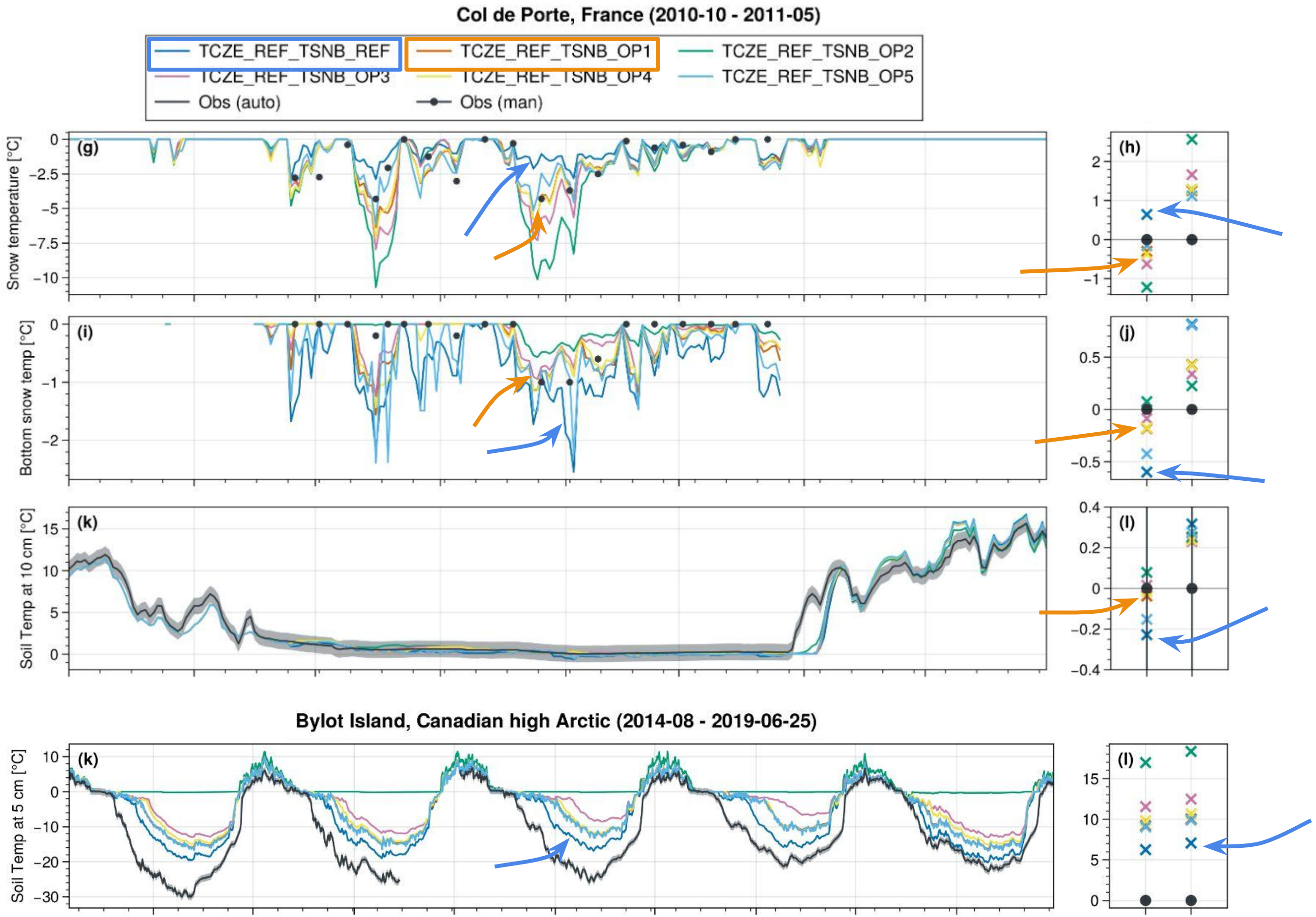

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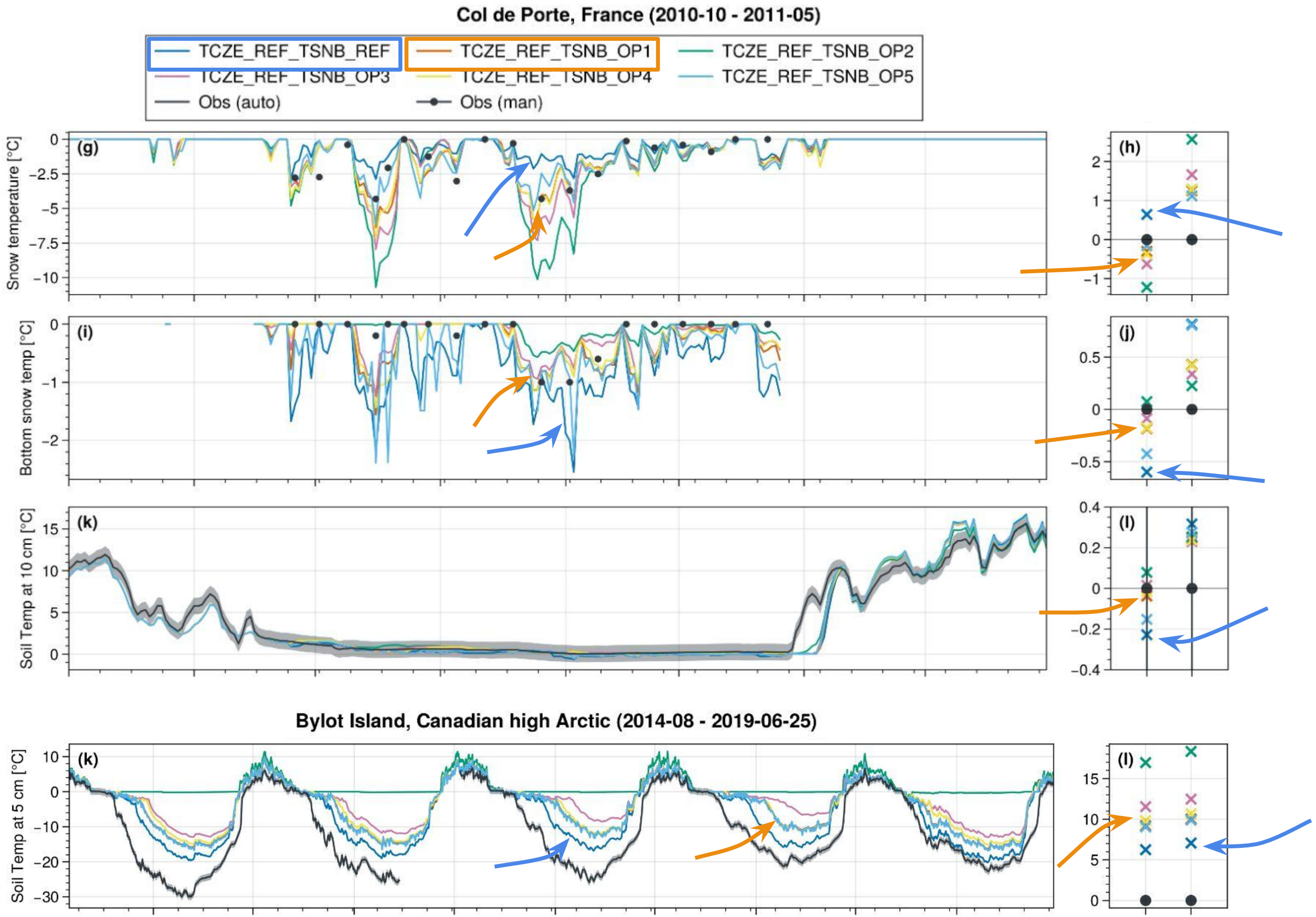
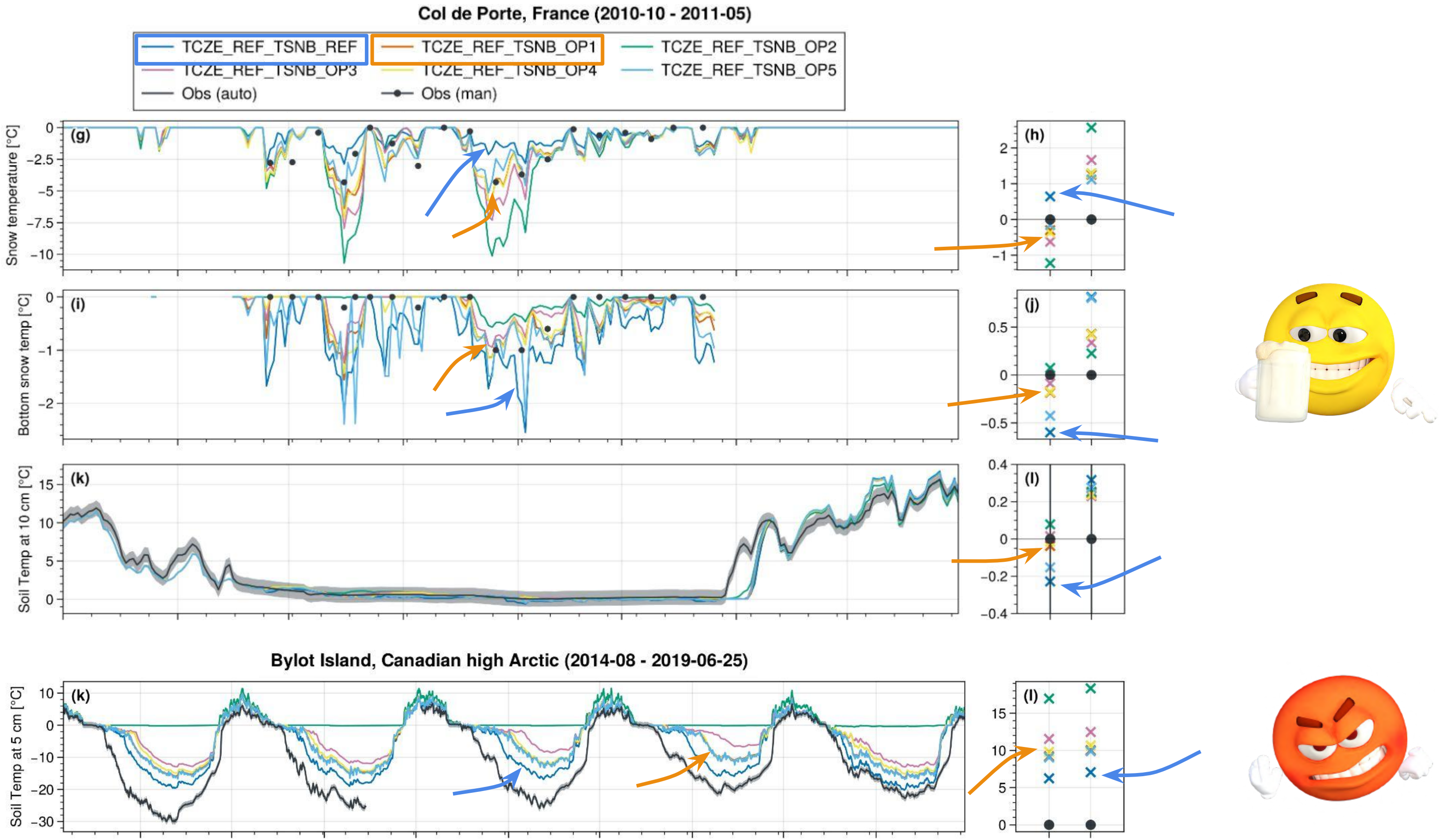


Bottom snow temperature (TSNB)

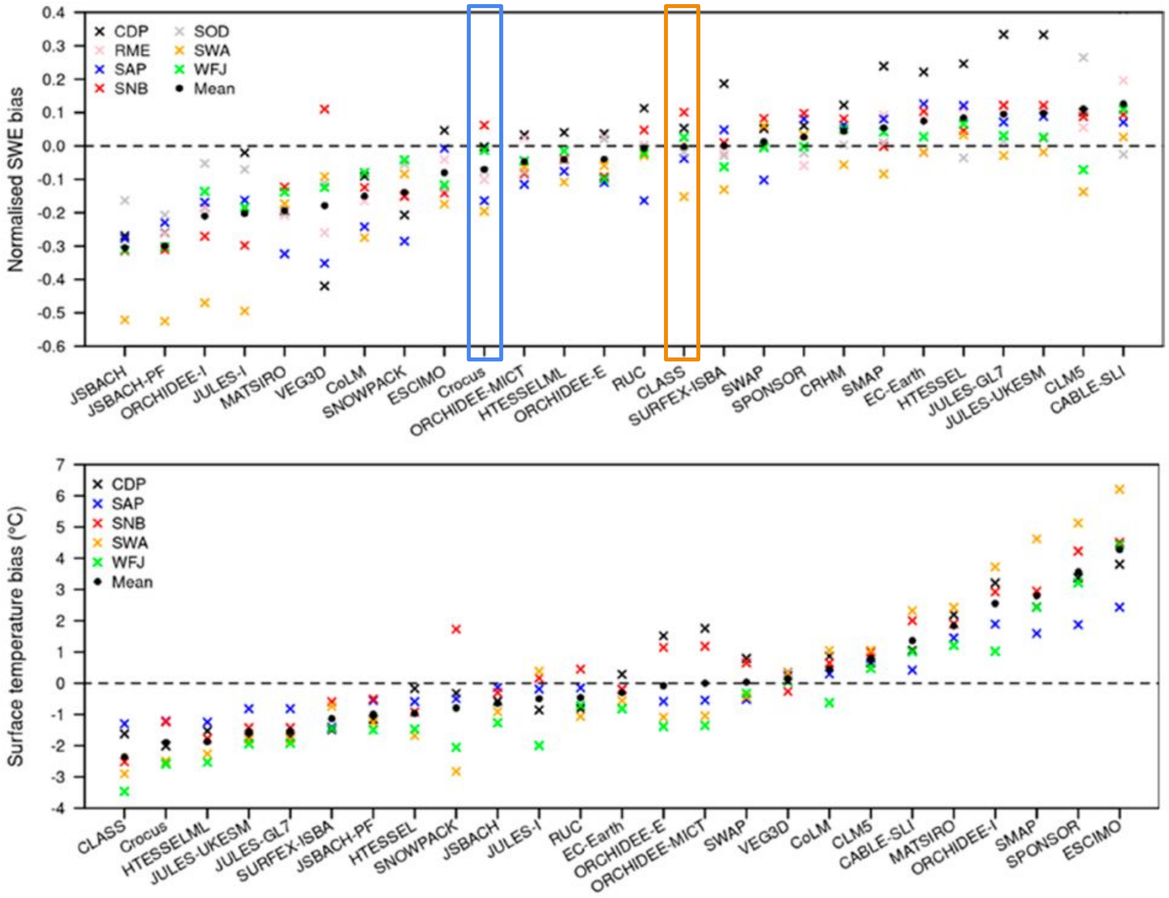


Part #2

Physics improvements

- → Soil conductivity under snow (bug)
- → Bottom snow temperature (TSNB)
- → **Windless exchange coefficient (EZERO)**

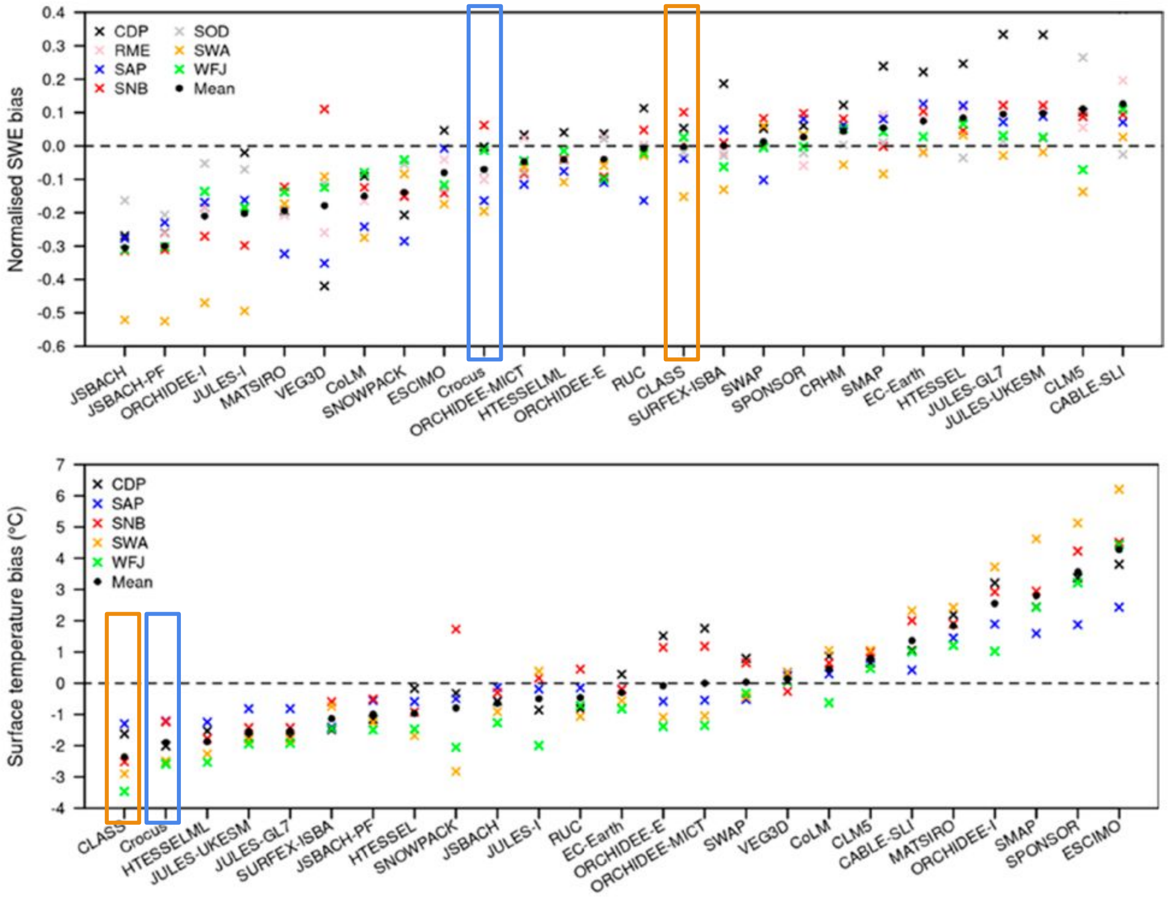
Menard et al., (2021)



CLASS → one of the best performing model in the last SnowMIP experiments! (SWE, SD, albedo, soil temperatures, etc.)

Context: surface temperature bias

Menard et al., (2021)

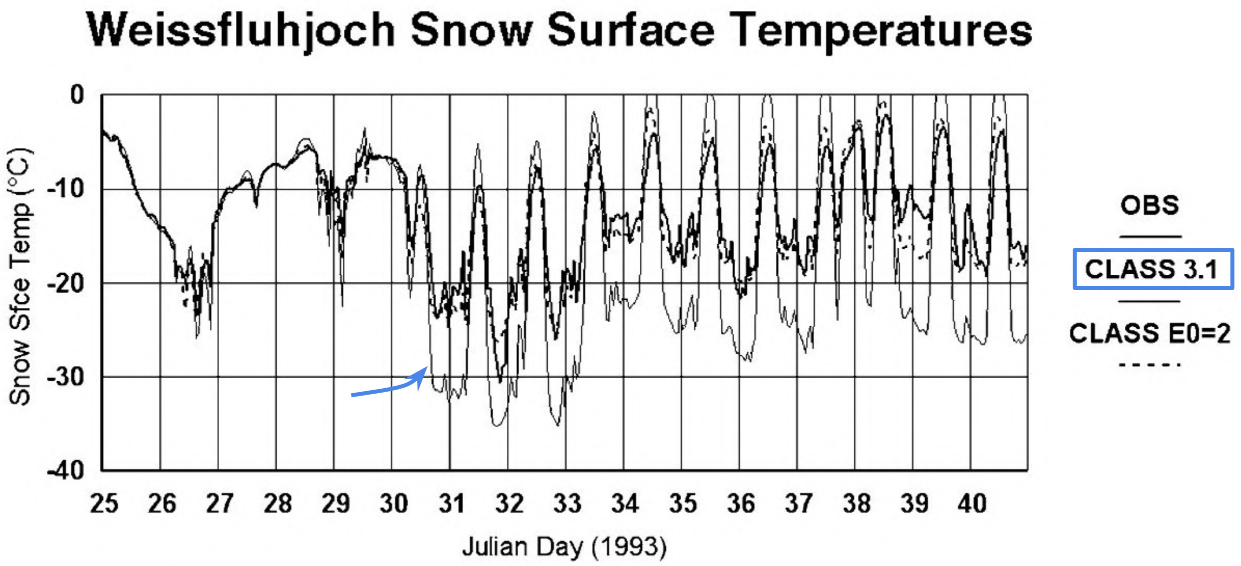


CLASS → one of the best performing model in the last SnowMIP experiments! (SWE, SD, albedo, soil temperatures, etc.)

But performs quite bad for the surface temperature...

Windless transfer coefficient

Monin-Obukhov similarity theory → unable to explain turbulent energy exchanges over snow and ice surfaces under stable atmospheric conditions (turbulence does not shut down completely and is characterized by intermittent bursts). (Brown et al., 2006)



Brown et al., (2006)

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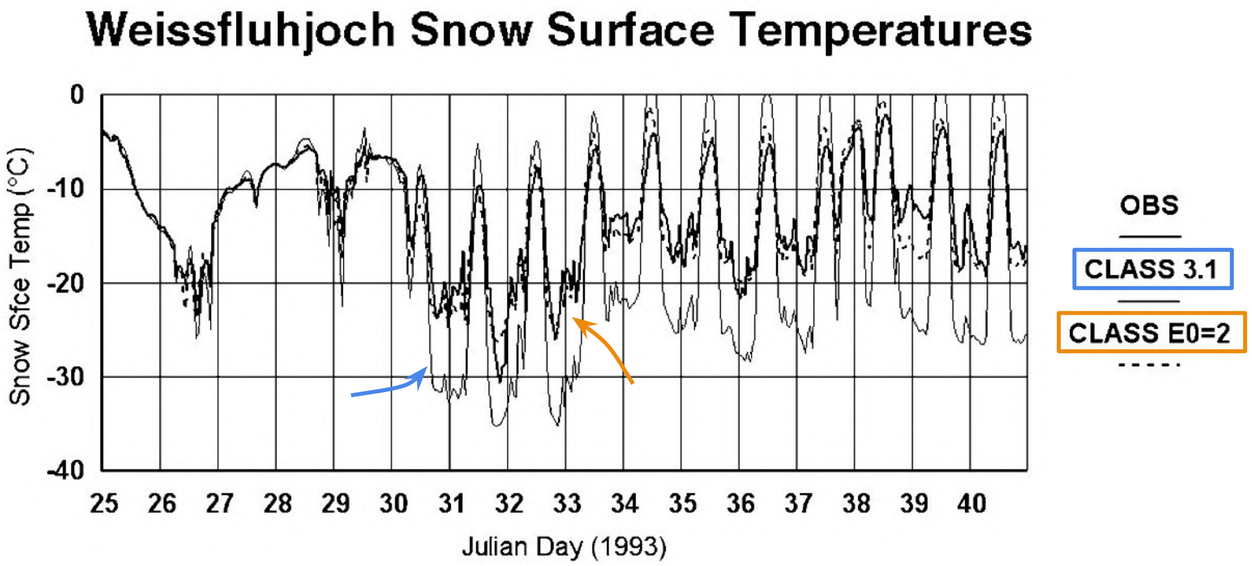


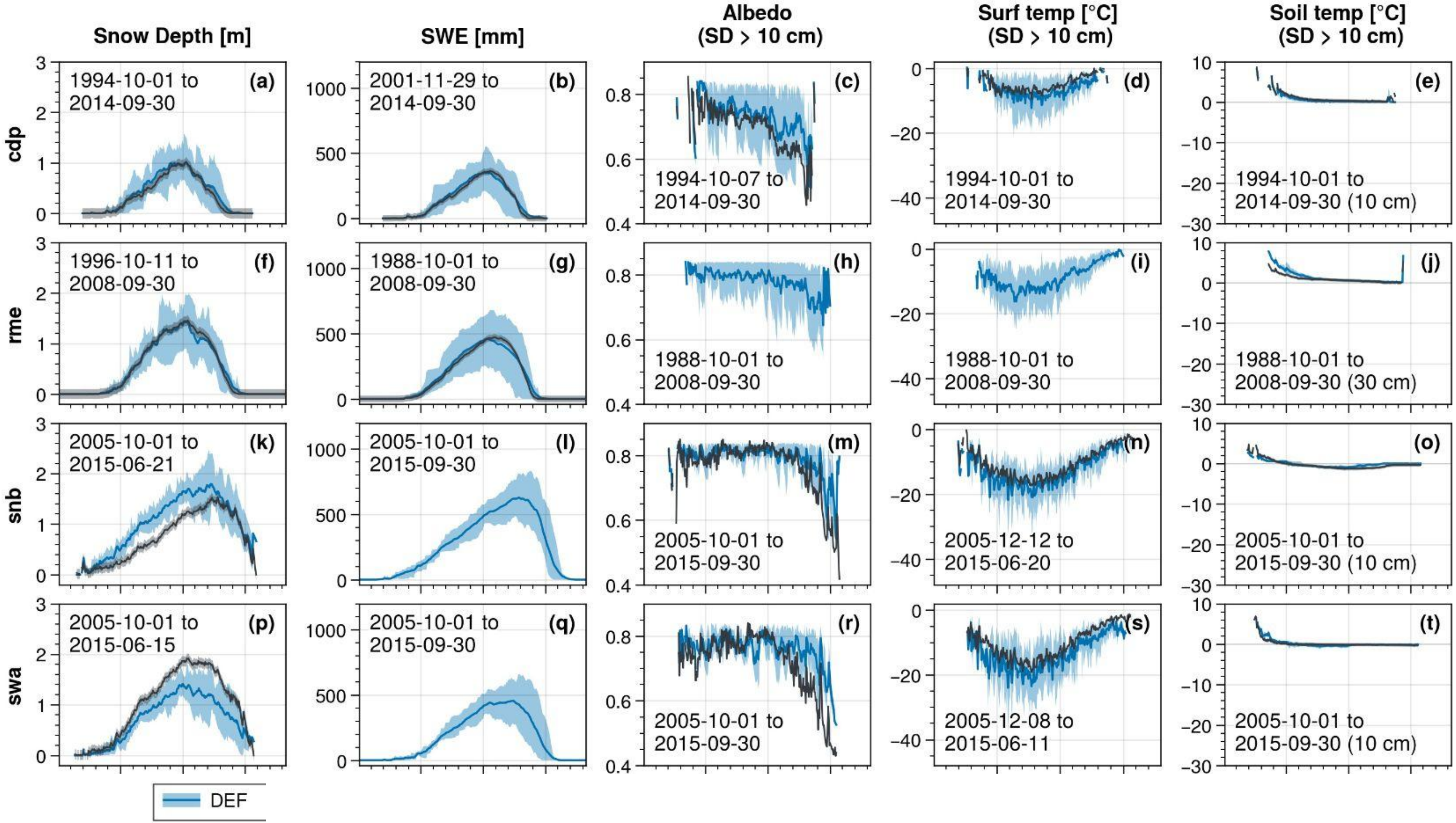
Brown et al., (2006)

Solution → windless transfer coefficient (E_0) in the sensible heat flux:

$$Q_H = \left(\rho_{air} c_P C_H U + E_0\right)\left(T_s - \theta_a\right)$$

E_0 = 2 W m^{-2} K^{-1} if $T_s < \theta_a$
(and 0 W m^{-2} K^{-1} otherwise)

Physics improvements: synthesis



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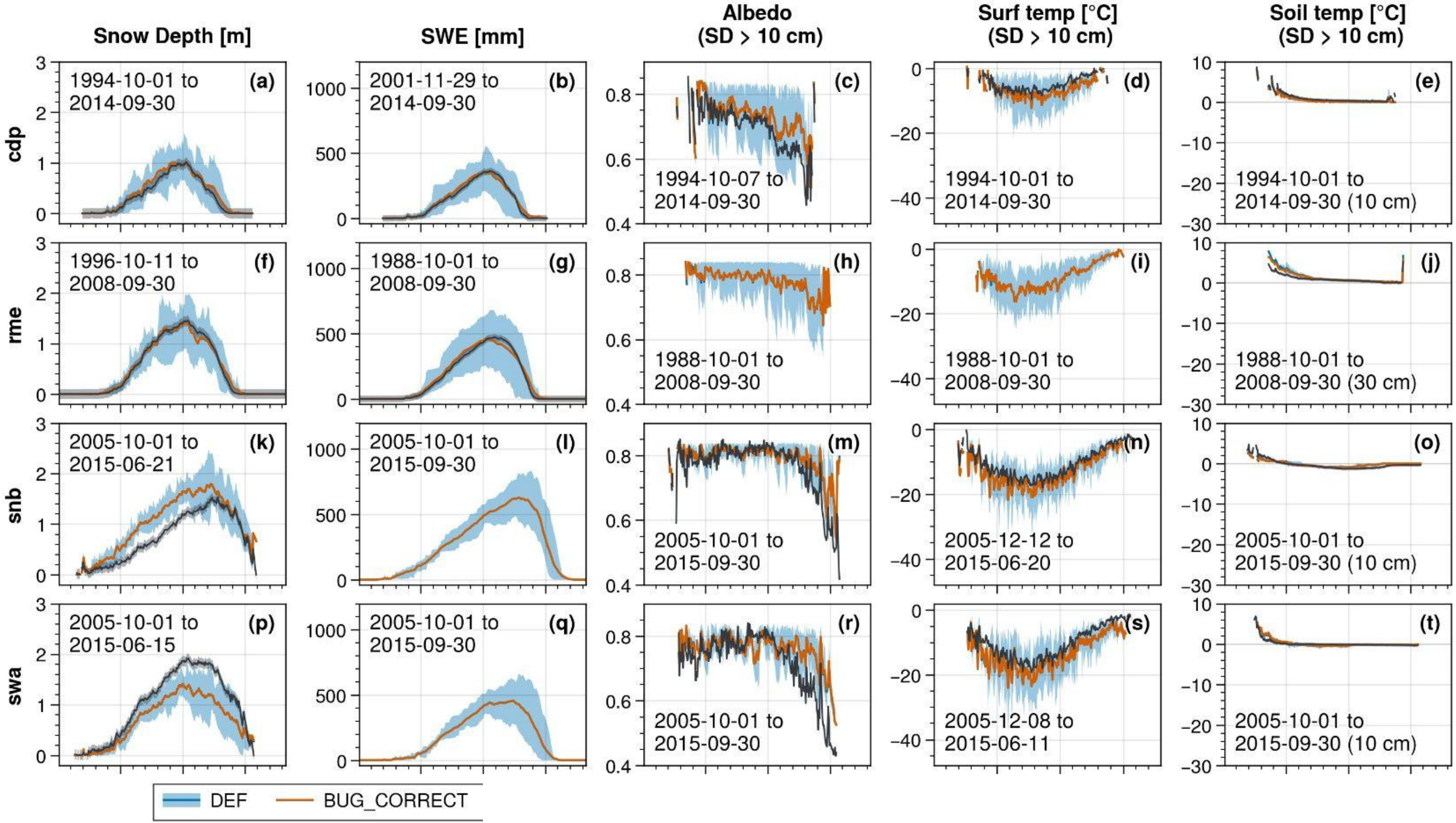

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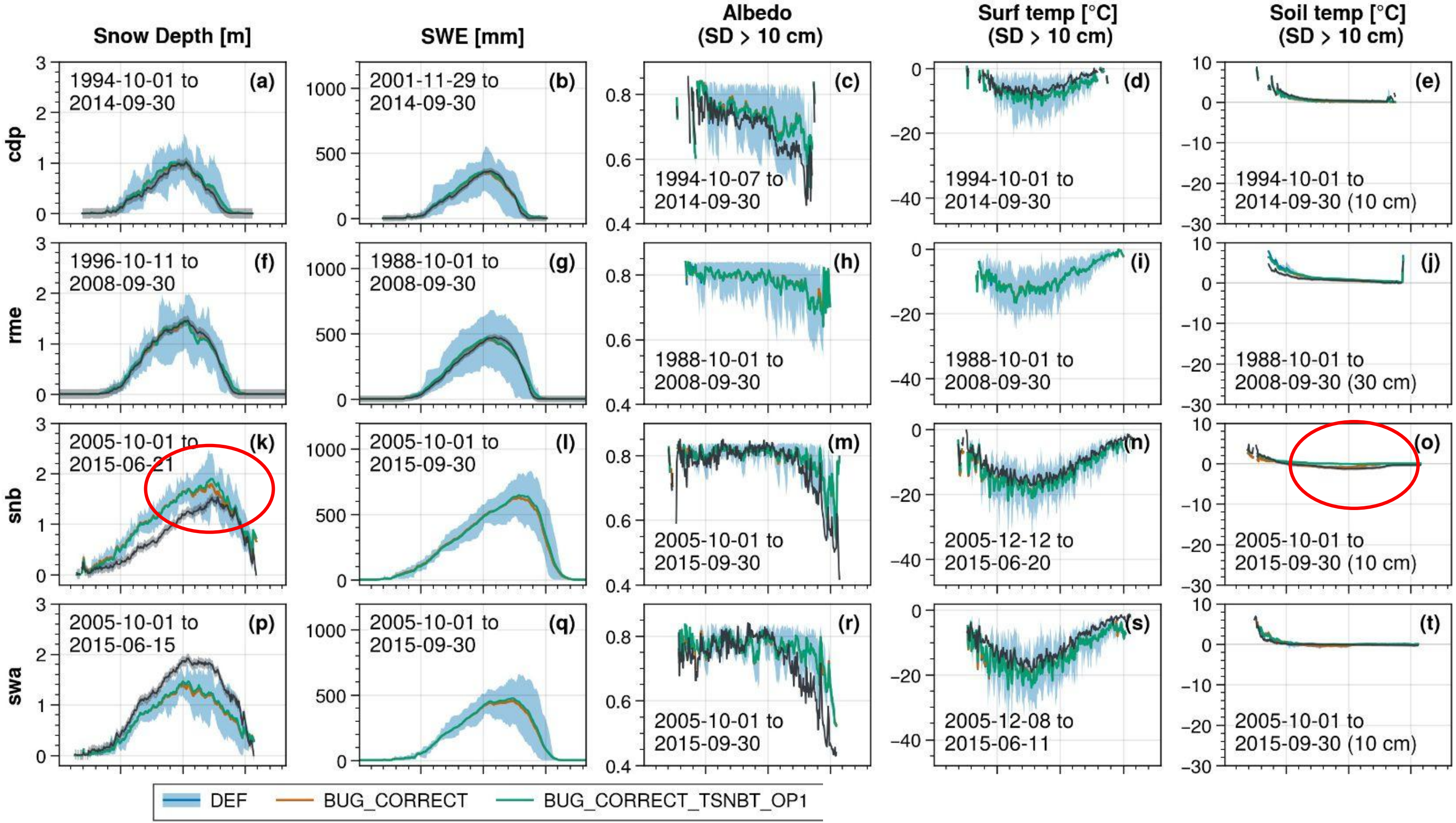

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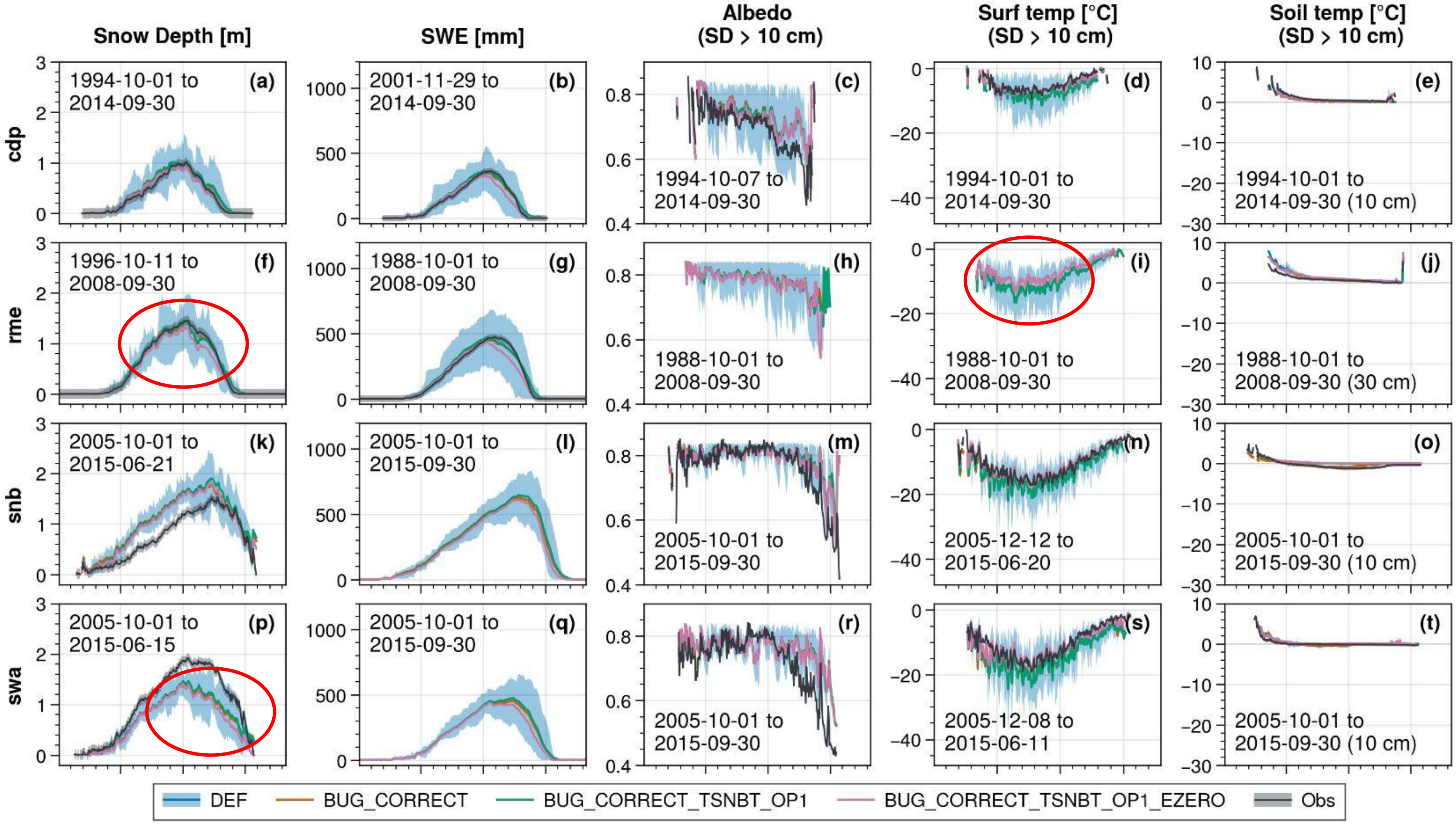

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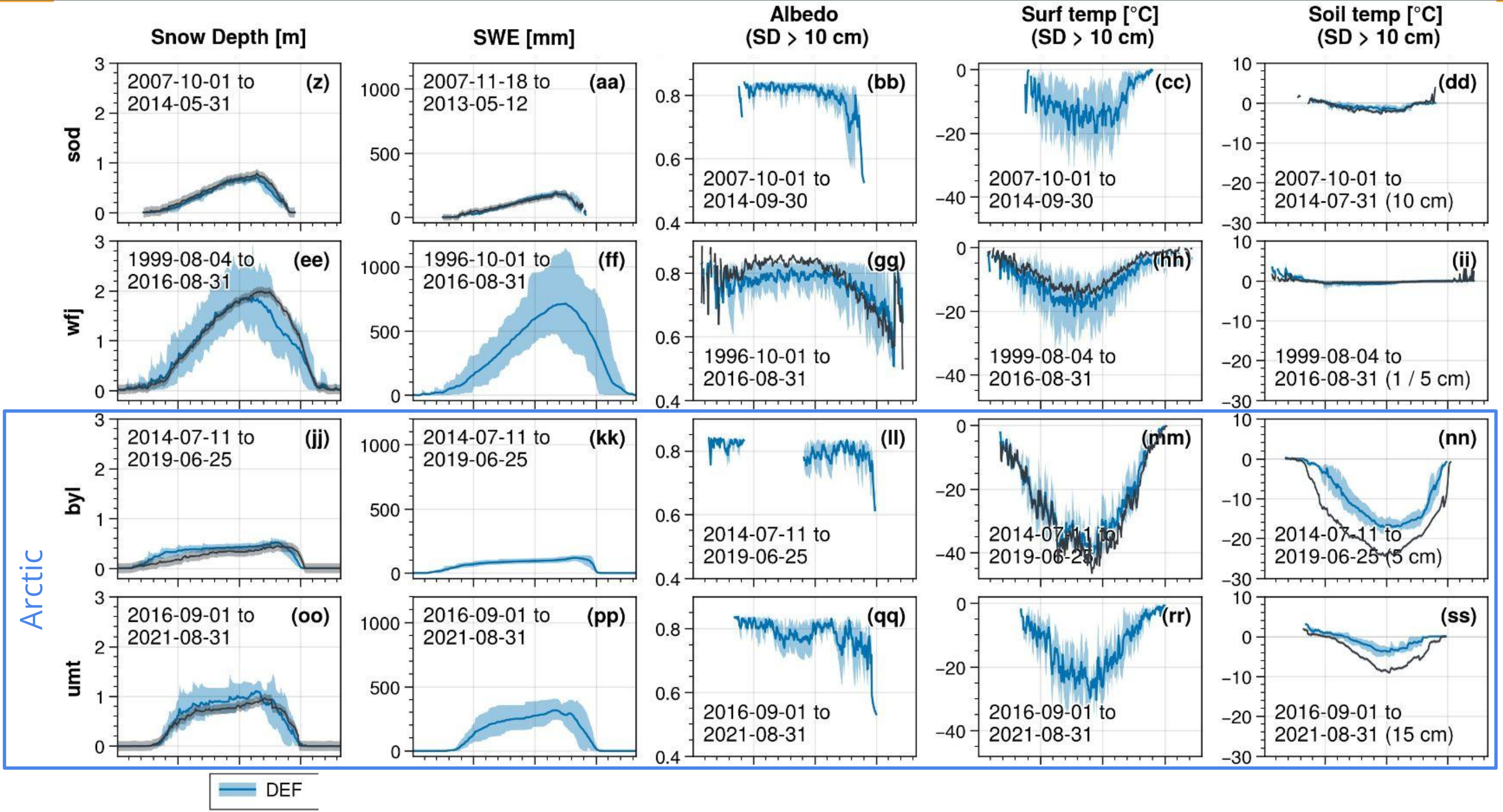

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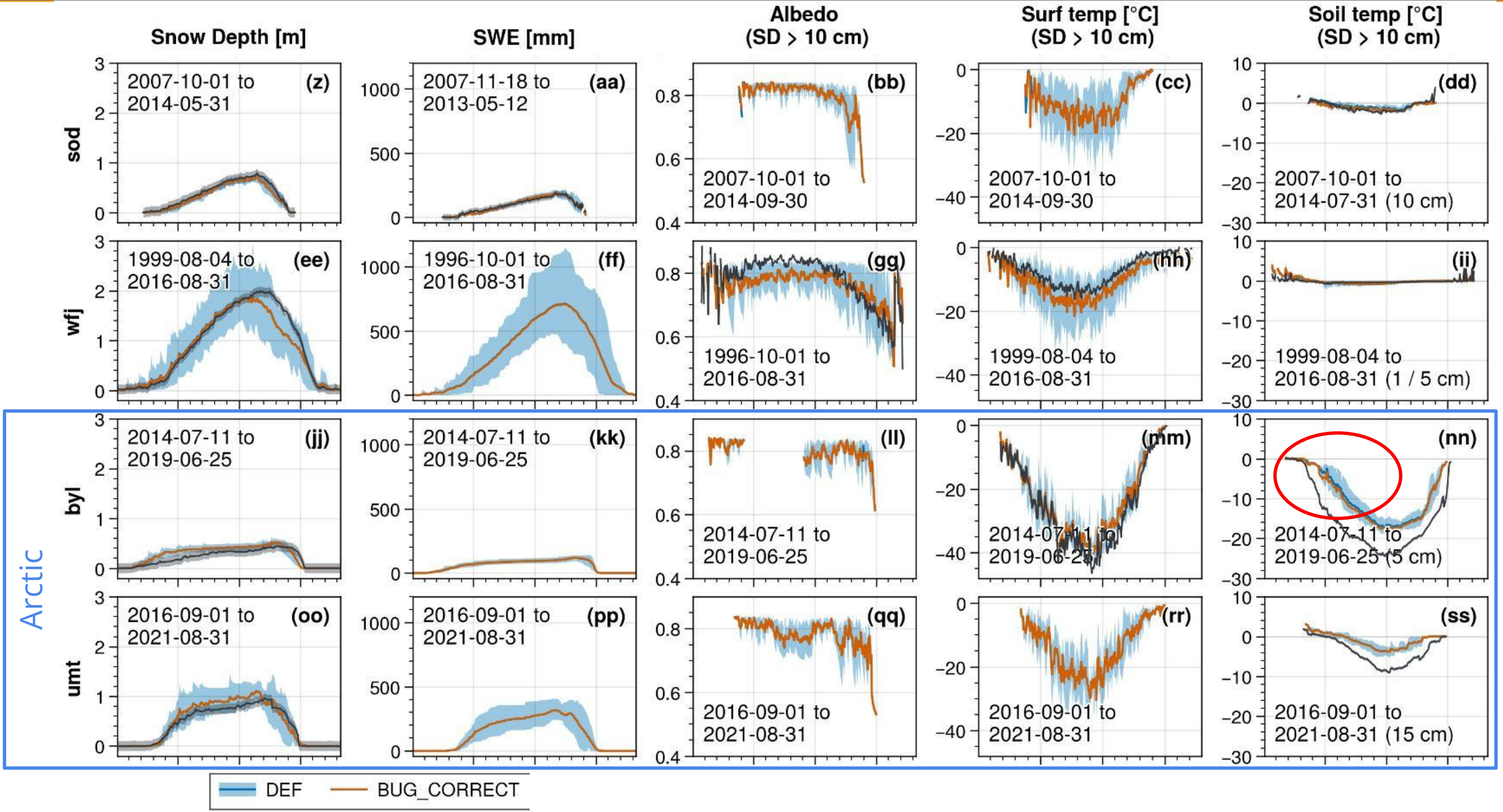

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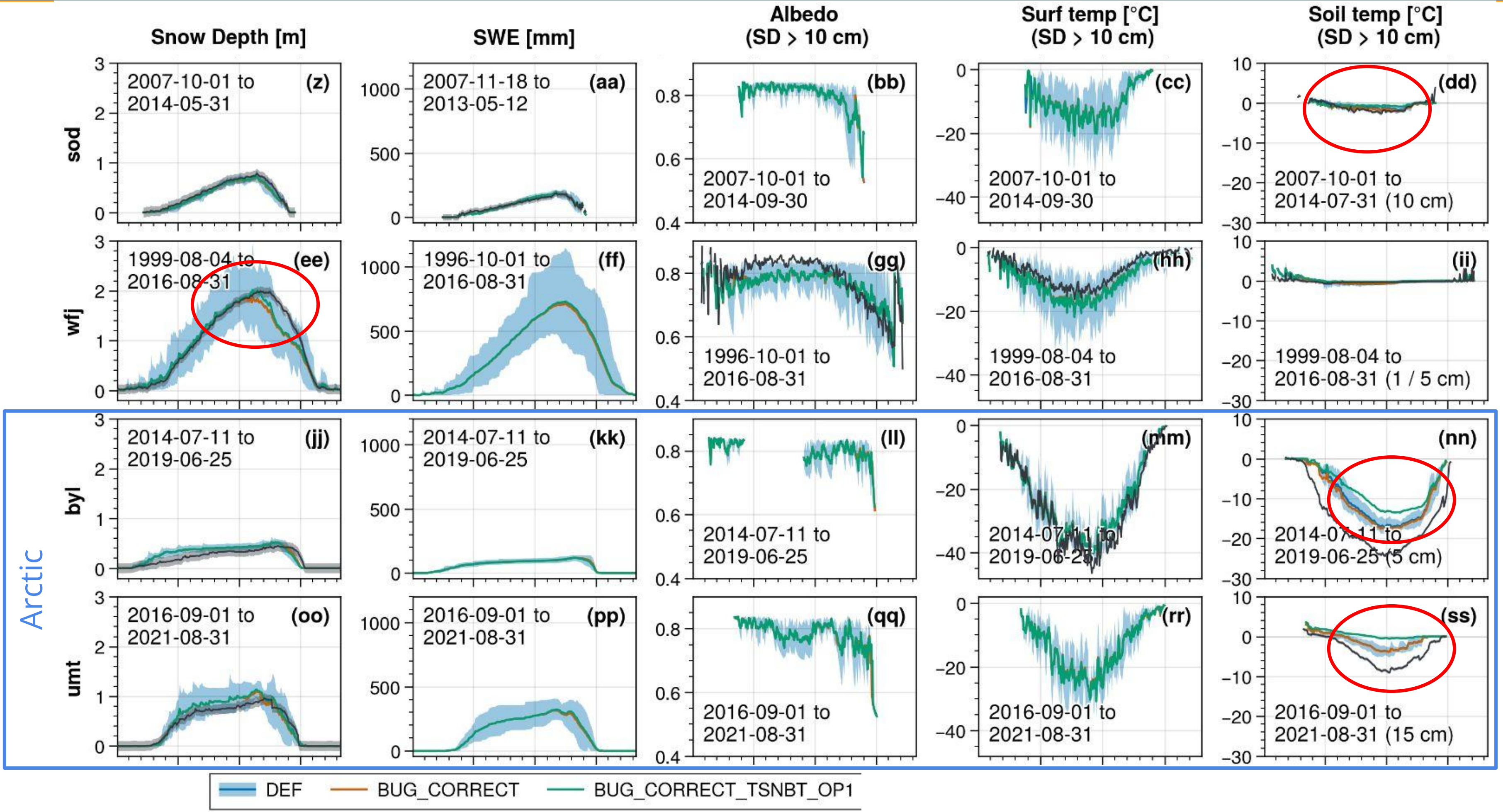
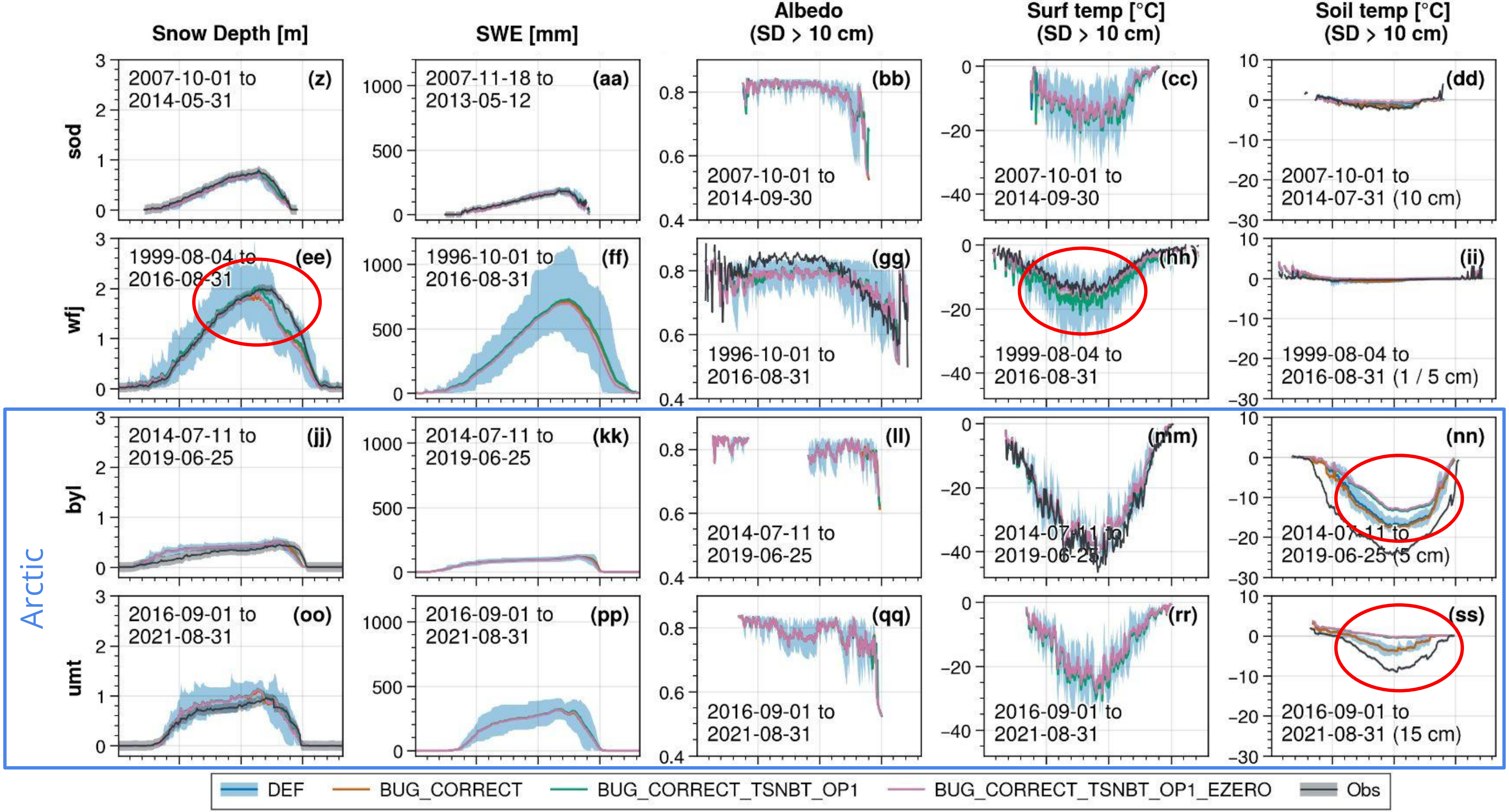


Physics improvements: synthesis



Part #3

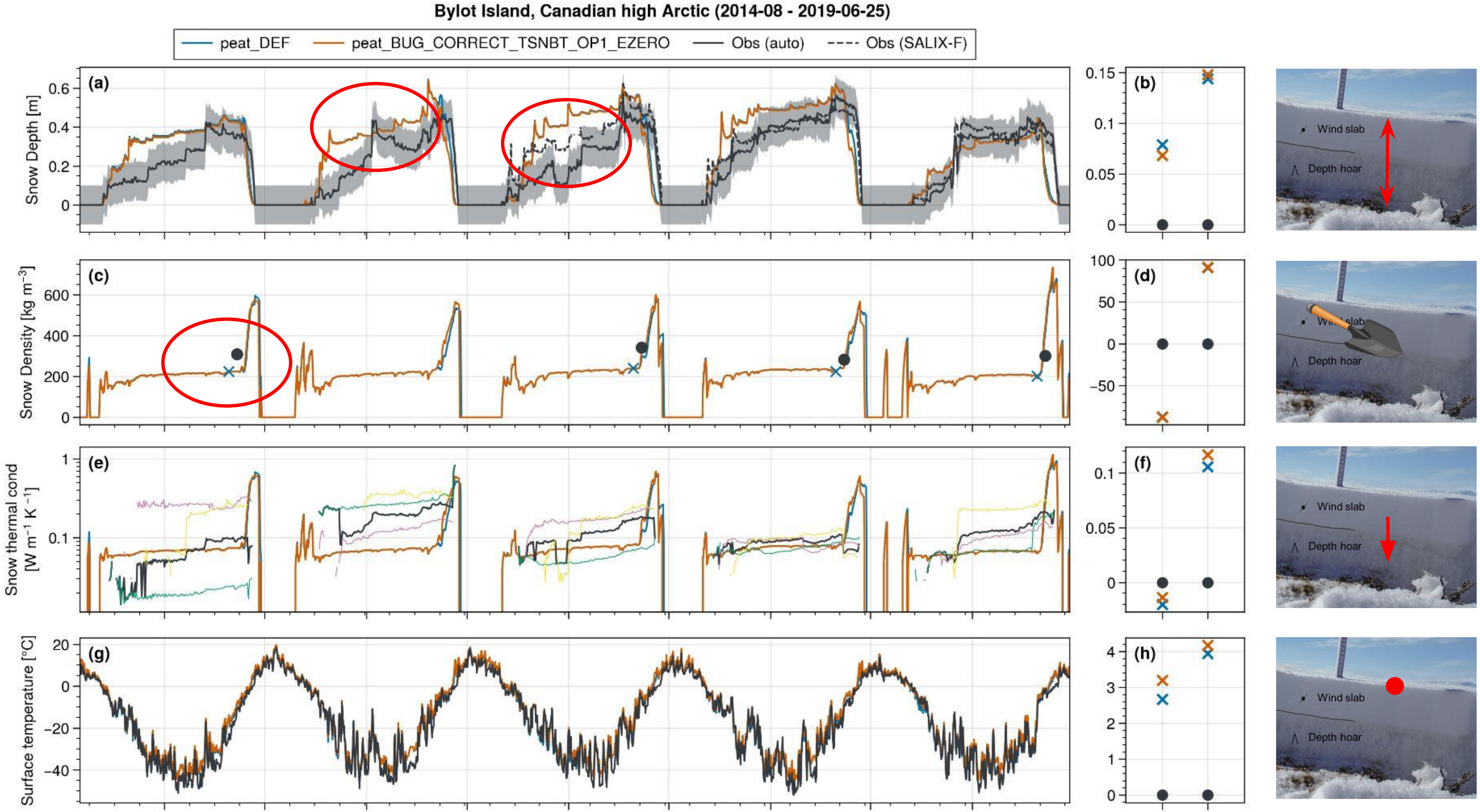
Arctic adaptation

→ Blowing snow sublimation losses

→ Wind effect on snow compaction

→ Snow conductivity

Example: Bylot biases



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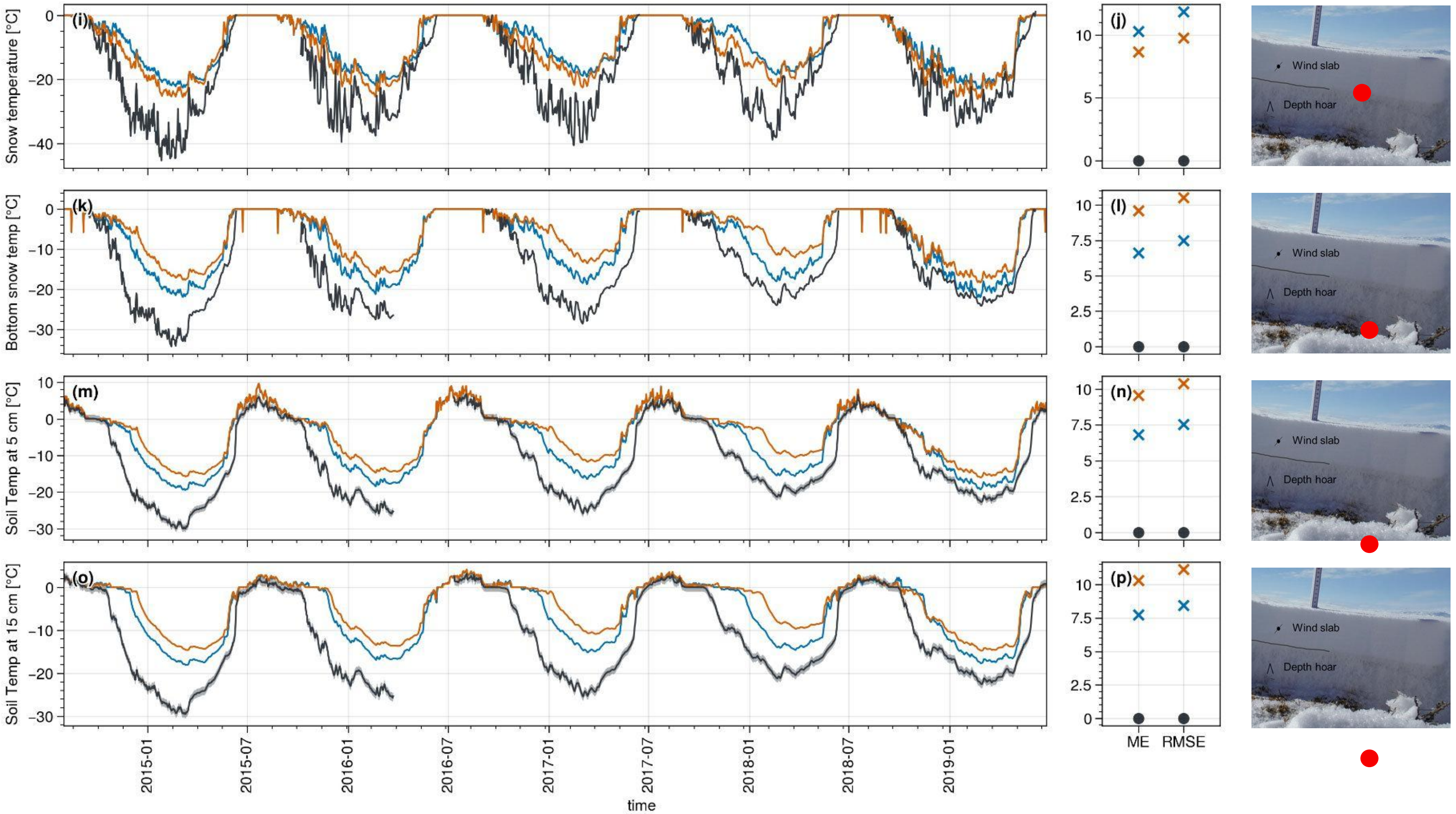


Arctic improvement insights

Current state of the model in the Arctic:

1. Snow depth overestimation (compaction, snow erosion/sublimation by wind, etc.?)

Possible solutions

#1 Blowing snow sublimation losses

Credit: Les Anderson/ Unsplash

Arctic improvement insights

Current state of the model in the Arctic:

1. Snow depth overestimation (compaction, snow erosion/sublimation by wind, etc.?)
2. Snow density underestimated (fresh snow density, compaction, etc.? → k too low?)

Possible solutions

#1 Blowing snow sublimation losses

Credit: Les Anderson/ Unsplash

#2 Increasing compaction (fresh snow density, compaction rate, etc.)

Credit: Sawtooth Avalanche Center

Arctic improvement insights

Current state of the model in the Arctic:

1. Snow depth overestimation (compaction, snow erosion/sublimation by wind, etc.?)
2. Snow density underestimated (fresh snow density, compaction, etc.? → k too low?)
3. Soil temperatures overestimated (previous biases + thermal conduction issues?)

Possible solutions

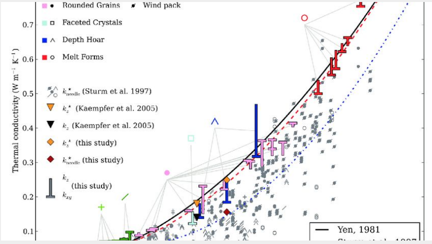
#1 Blowing snow sublimation losses

Credit: Les Anderson/ Unsplash

#2 Increasing compaction (fresh snow density, compaction rate, etc.)

Credit: Sawtooth Avalanche Center

#3 Snow thermal conductivity



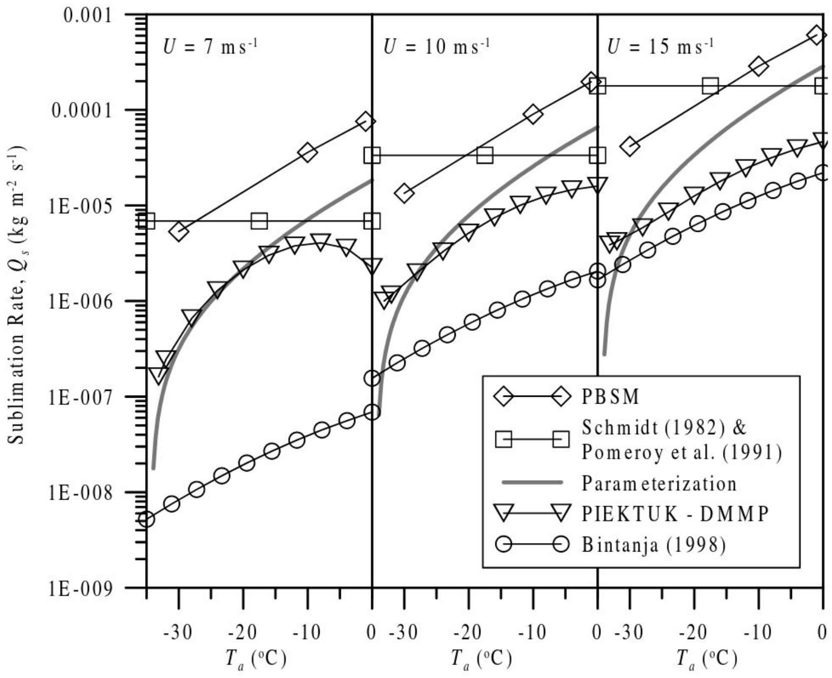
Source: Calonne et al. (2011)

Part #3

Arctic adaptation

- → **Blowing snow sublimation losses**
- → Wind effect on snow compaction
- → Snow conductivity

Arctic adaptation: Blowing snow sublimation losses



E.g. Gordon et al. (2006) → fit over multiple previous blowing snow sublimation losses parameterizations.

Total sublimation rate, Q_s (kg m^{-2} s^{-1}):

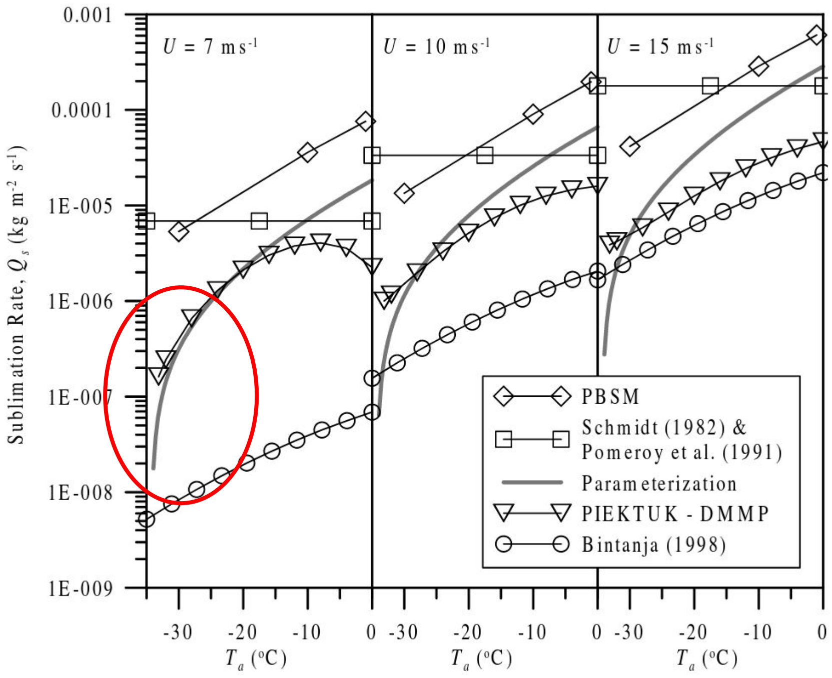
$$Q_s = A\left(\frac{T_o}{T_a}\right)^{\gamma} U_t \rho_a q_{si}(1 - Rh_i)(U / U_t)^B, \text{ for } U > U_t$$

and

$$U_t = U_{t*} + 0.0033(T_a - 245.88)^2$$

with U_{t*} = 6.98 m s^{-1} is the minimum threshold velocity.

Arctic adaptation: Blowing snow sublimation losses



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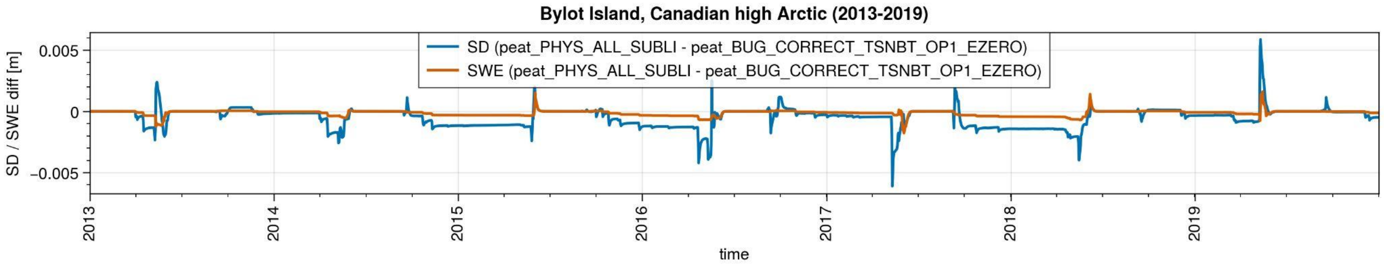
and

$$U_t = U_{t*} + 0.0033(T_a - 245.88)^2$$

with U_{t*} = 6.98 m s^{-1} is the minimum threshold velocity.

Can decrease the snow depth of about ~10 cm at a few sites, but very low impact at SnowMIP and Arctic sites.



Part #3

Arctic adaptation

- → Blowing snow sublimation losses
- → **Wind effect on snow compaction**
- → Snow conductivity

Arctic adaptation: Wind effect on snow compaction

Different mechanisms:

1. Snowflakes completely decomposed for wind velocities > 5 m s^{-1} (e.g., Walter et al., 2024)

Falling snow

#1 Fresh snow density

Reuters: Jason Murawski Jr/Instagram

Arctic adaptation: Wind effect on snow compaction

Different mechanisms:

1. Snowflakes completely decomposed for wind velocities > 5 m s^{-1} (e.g., Walter et al., 2024)
2. Surface snow densities up to 250–400 kg m^{-3} for strongly wind-affected surface snow in Arctic and Antarctic regions (e.g., Domine et al., 2021).

Falling snow

Snow compaction

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Reuters: Jason Murawski Jr/Instagram

#2 Increasing maximum snow density

Expedia: Parc national de Jasper

Arctic adaptation: Wind effect on snow compaction

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3. Densification rates up to 2 orders of magnitude higher (e.g., Liston et al., 2007)

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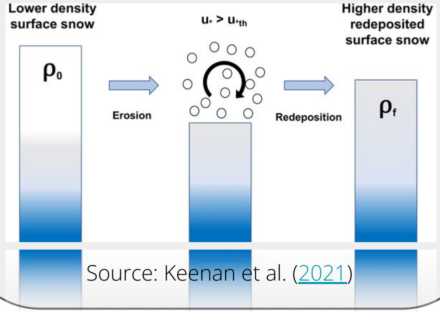

Source: Keenan et al. (2021)

Arctic adaptation: Wind effect on snow compaction

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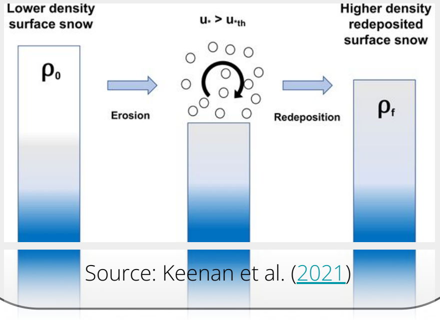

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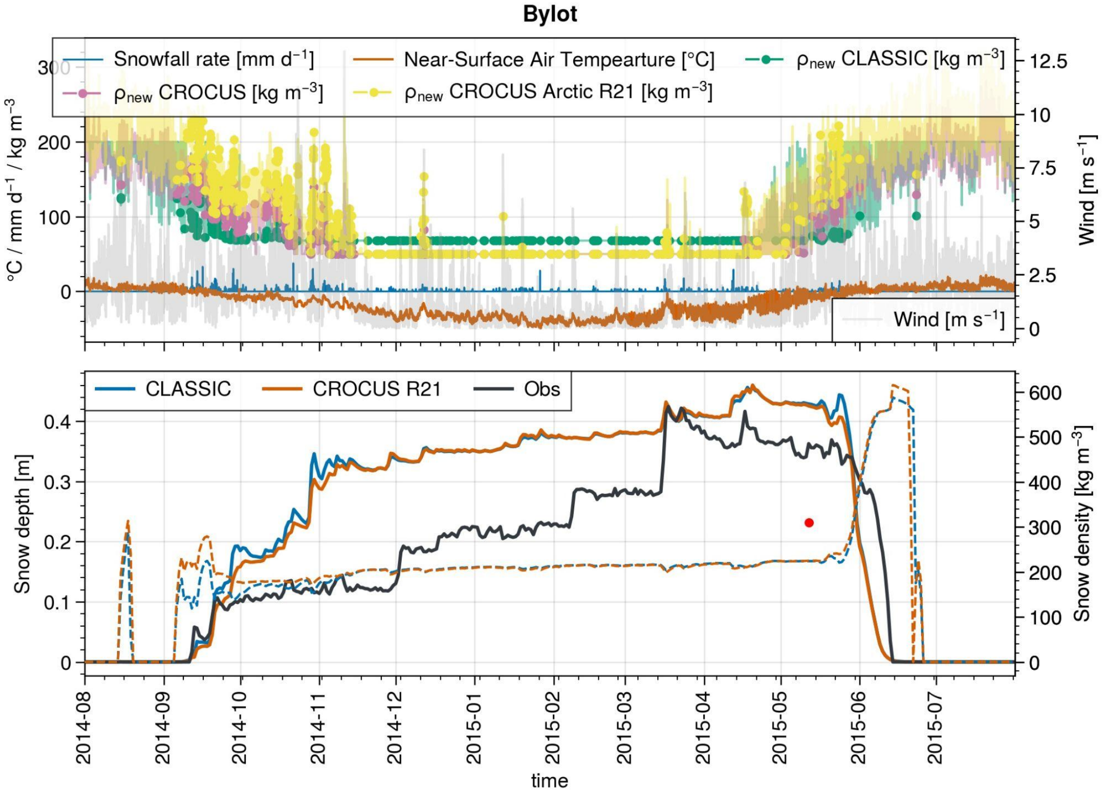
Wind effect on snow compaction: fresh snow density

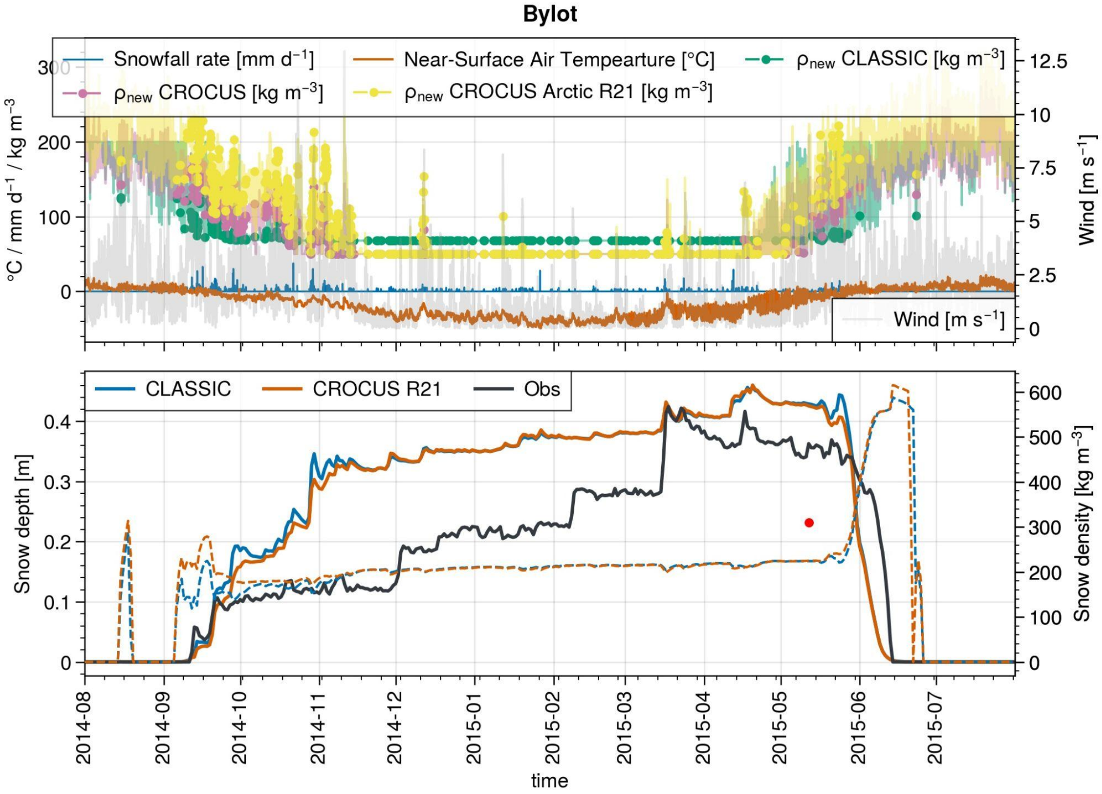


Fresh snow density in CLASSIC:

$$\rho_{sfall} = 67.92 + 51.25\exp(T_{air}/2.59) \quad T_{air} \leq 0°C \qquad (1)$$

$$\rho_{sfall} = \min(200,\ 119.17 + 20.0\ T_{air}) \quad T_{air} > 0°C. \qquad (2)$$

Wind effect on snow compaction: fresh snow density



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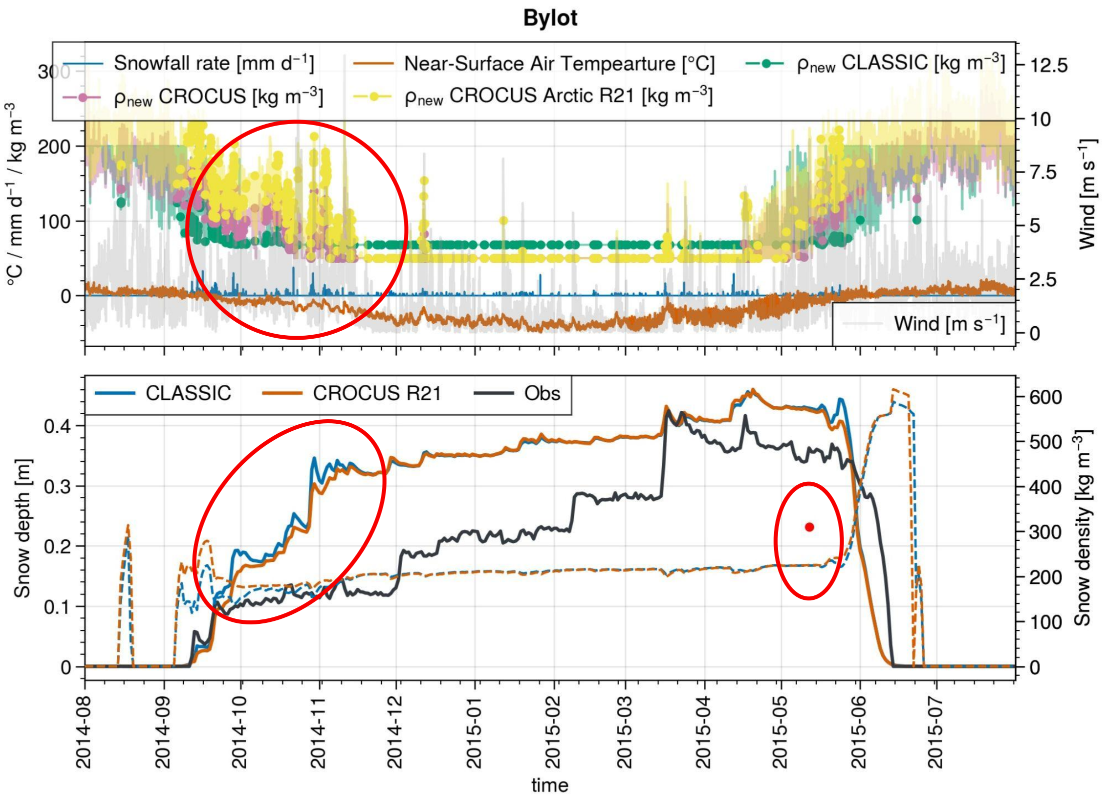
Fresh snow density in CROCUS:

$$\rho_{new} = \max\left(50, a_\rho + b_\rho\left(T_a - T_{fus}\right) + c_\rho U^{\frac{1}{2}}\right)$$

with a = 109 kg m^{-3}, b = 6 kg m^{-3} K^{-1}, and c = 26 kg m$^{-7/2}$ s$^{1/2}$ → Arctic R21 c x 2 (Royer et al., 2021)

Wind effect on snow compaction: fresh snow density



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Slight effect at the snow onset and melting but negligible effect on the snow depth and snow density over most of the snow season + deterioration at other SnowMIP sites (not shown).

→ Snow density underestimated of about 50 to 100 kg m^{-3}

Wind effect on snow compaction: max snow density

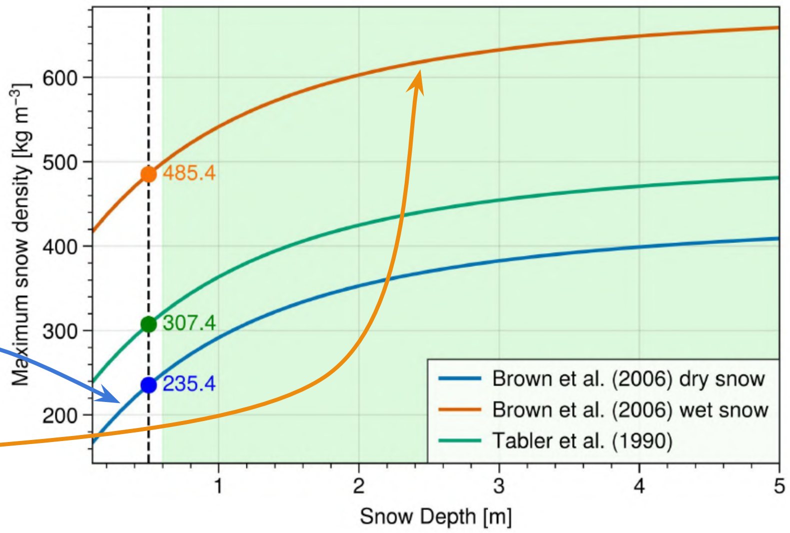
The snow density increase towards a ρ_{max} value in an exponential way as:

$$\rho_s(t+1) = \left[\rho_s(t) - \rho_{s,max}\right] e^{-\frac{0.01\Delta t}{3600}} + \rho_{s,max}$$

with

$$\rho_{max} = 450 - (20470/d_s)(1.0 - \exp(-d_s/67.3)) \quad T_{snow} < 0°C \qquad (4)$$

$$\rho_{max} = 700 - (20470/d_s)(1.0 - \exp(-d_s/67.3)) \quad T_{snow} = 0°C \qquad (5)$$



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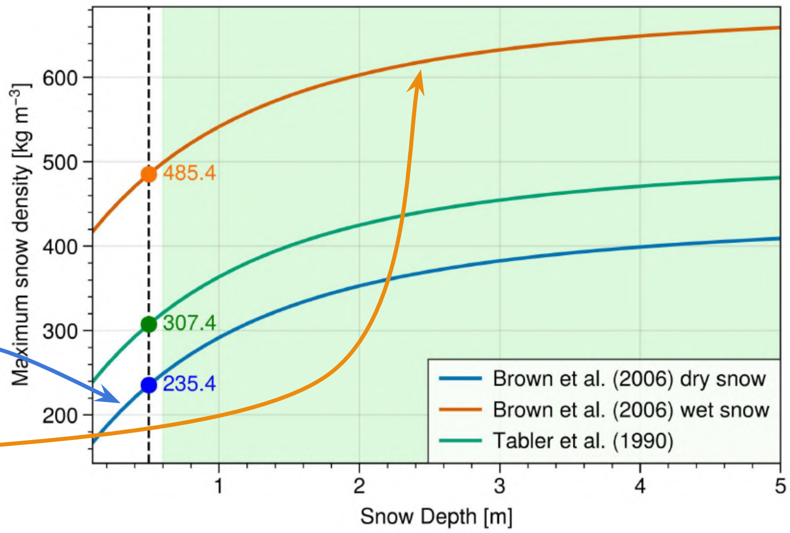

Problem: for typical Arctic snowpack (~50 cm) ρ_{max} limited to about 200 to 250 kg m^{-3} while they usually range from 250 to 400 kg m^{-3} under strongly wind condition for dry snow (e.g., Domine et al., 2021; Royer et al., 2021a).

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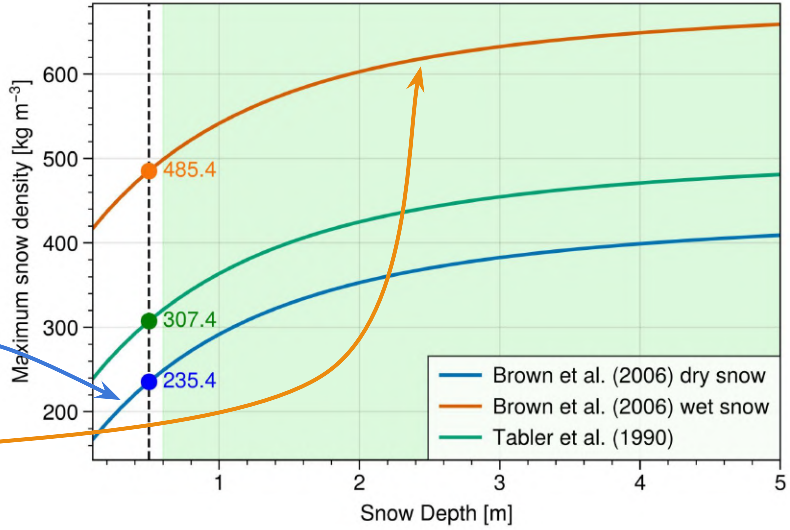

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2 possible solutions:

1. Increasing the compaction rate (τ) → but not effective if ρ_{max} is already reached...
2. Increasing ρ_{max} (+ include a wind dependency)

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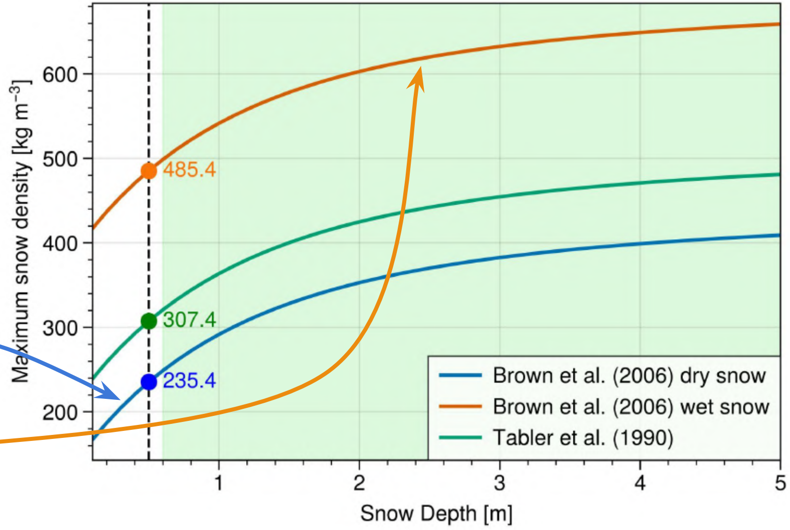

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2 possible solutions:

1. Increasing the compaction rate (τ) → but not effective if ρ_{max} is already reached...
2. **Increasing ρ_{max} (include a dependence to wind)**

Wind effect on snow compaction: max snow density

Objective: increase the bulk snow density under strong wind condition for dry snowpacks.

Conditions: don’t impact too much (1) thick snowpacks (gravitational/metamorphism compaction predominant), (2) very thin snowpacks (depth hoar, vegetation, etc.)

Wind effect on snow compaction: max snow density

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Solution: (1) apply an exp term to the dry ρ_{max} to increase the density for thin snowpacks.

Maximum Snow Density Without Wind ($\rho_{\max}(d_s)$):

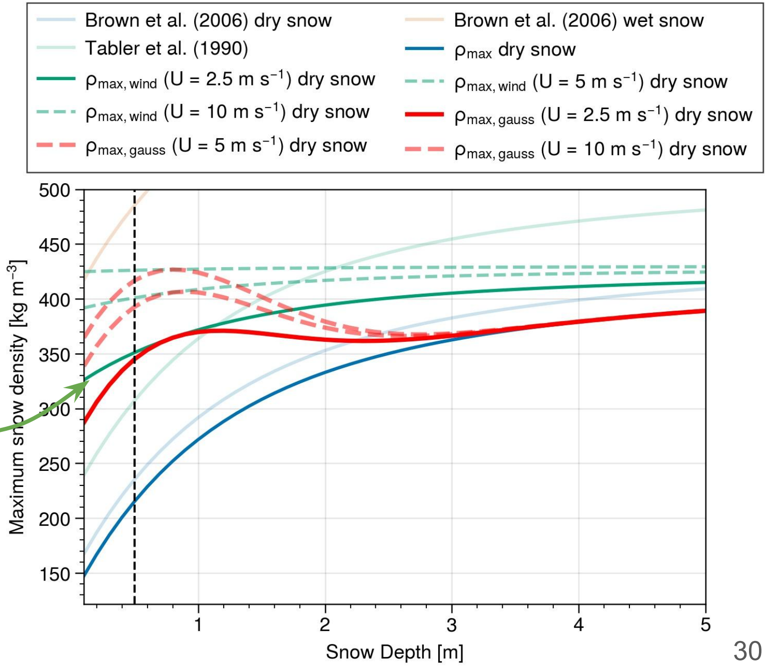
$$\rho_{\max}(d_s) = 430 - \frac{204.7}{d_s} \cdot \left(1 - \exp\left(-\frac{d_s}{0.673}\right)\right)$$

Maximum Snow Density With Wind ($\rho_{\max,\text{ wind}}(d_s)$):

$$\rho_{\max,\text{ wind}}(d_s) = 430 - \frac{204.7}{d_s} \cdot \left(1 - \exp\left(-\frac{d_s}{0.673}\right)\right) \cdot \exp\left(-\frac{U}{U_0}\right)$$

Final Function with Gaussian Peak:

$$f(d_s) = \rho_{\max}(d_s) + (\rho_{\max,\text{ wind}}(d_s) - \rho_{\max}(d_s)) \cdot \exp\left(-\frac{(d_s - d_0)^2}{2\sigma^2}\right)$$



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Solution: (1) apply an exp term to the dry ρ_{max} to increase the density for thin snowpacks. (2) Apply a Gaussian term to make it peak around d_0. (3) not applied under a wind threshold and if vegetation is not entirely buried by snow.

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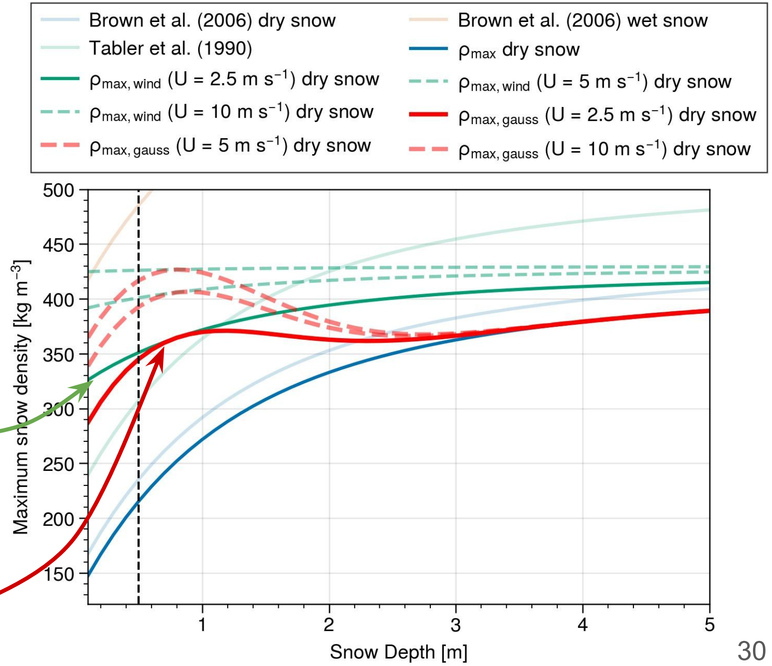
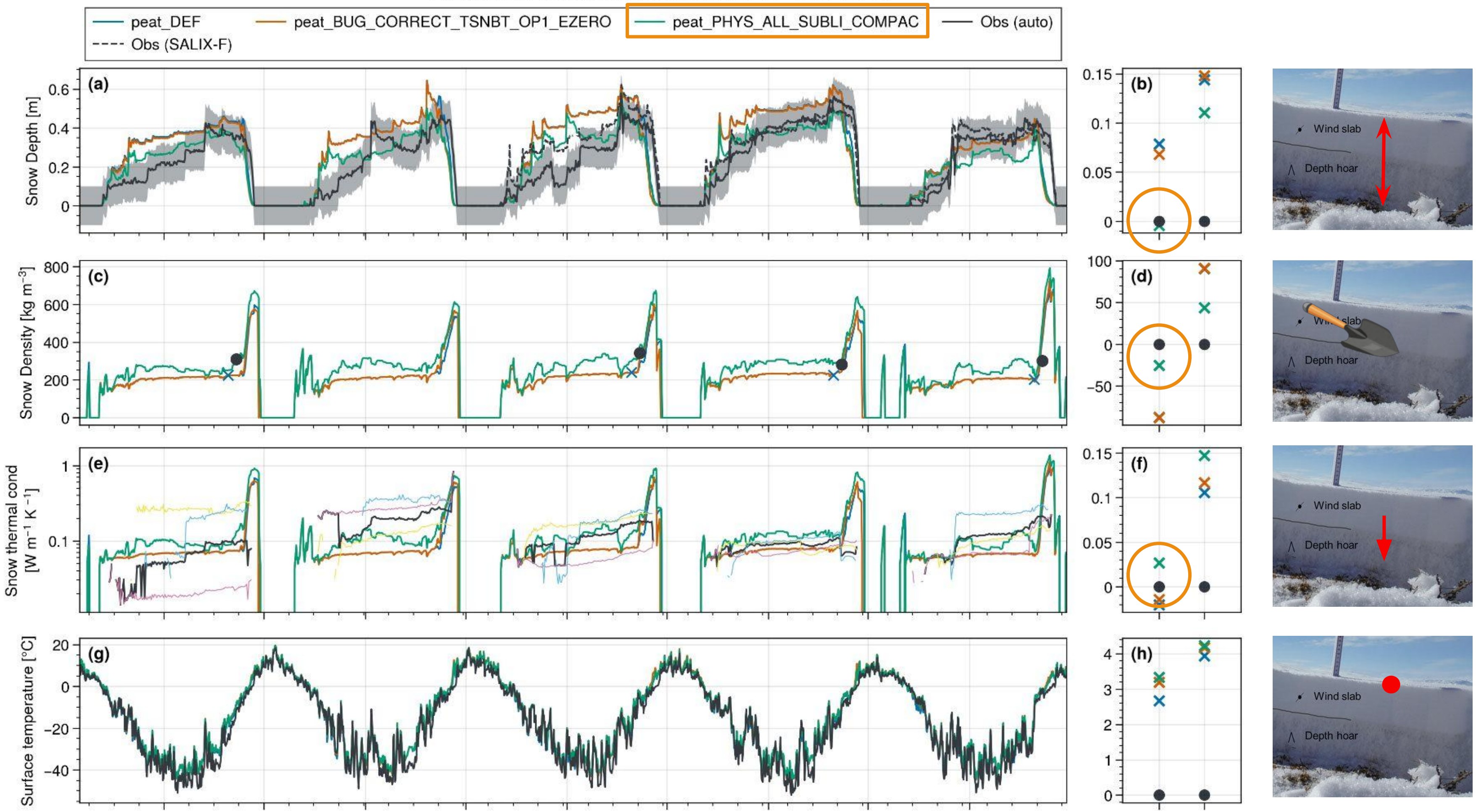


Example: Bylot example



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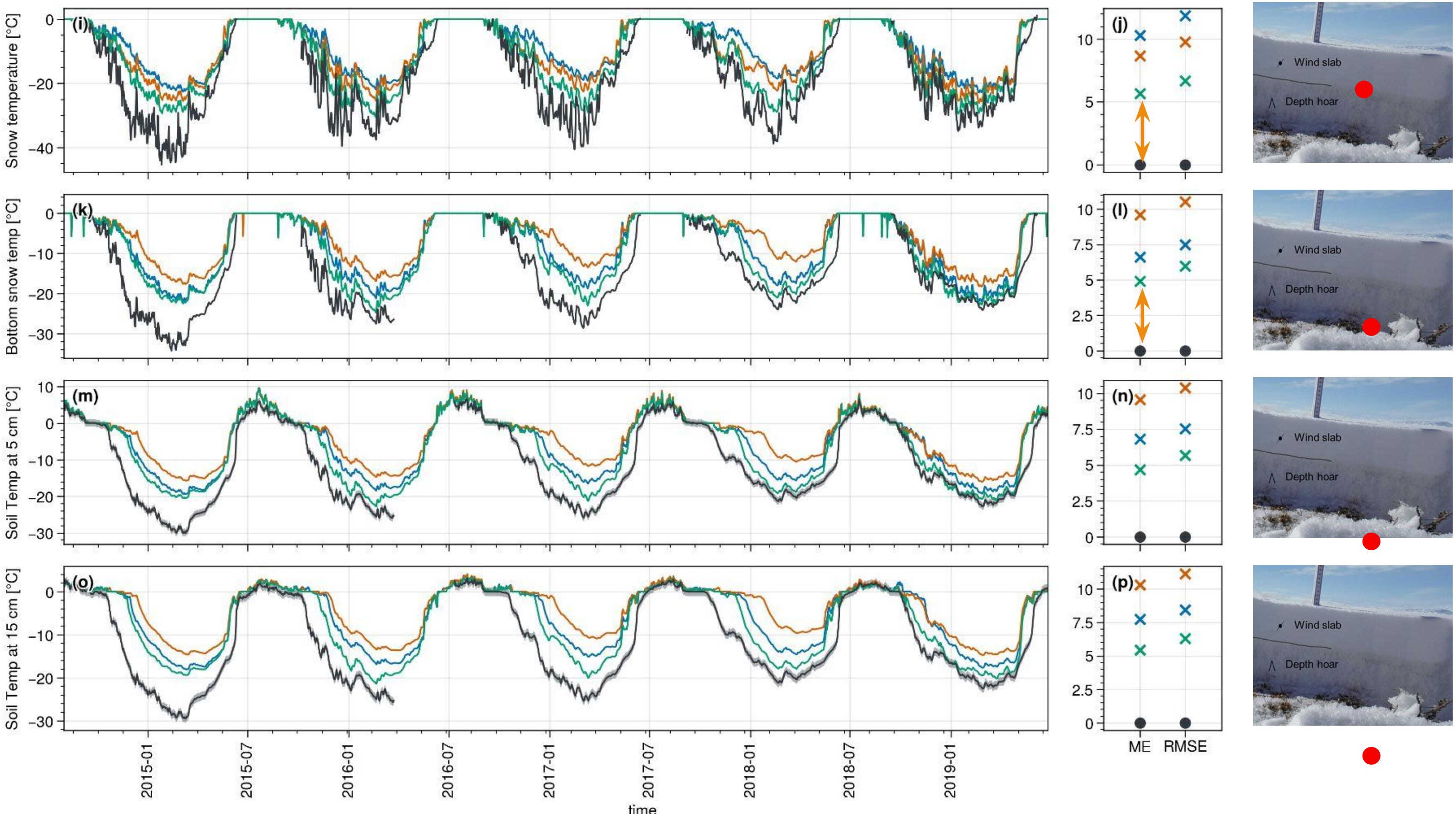
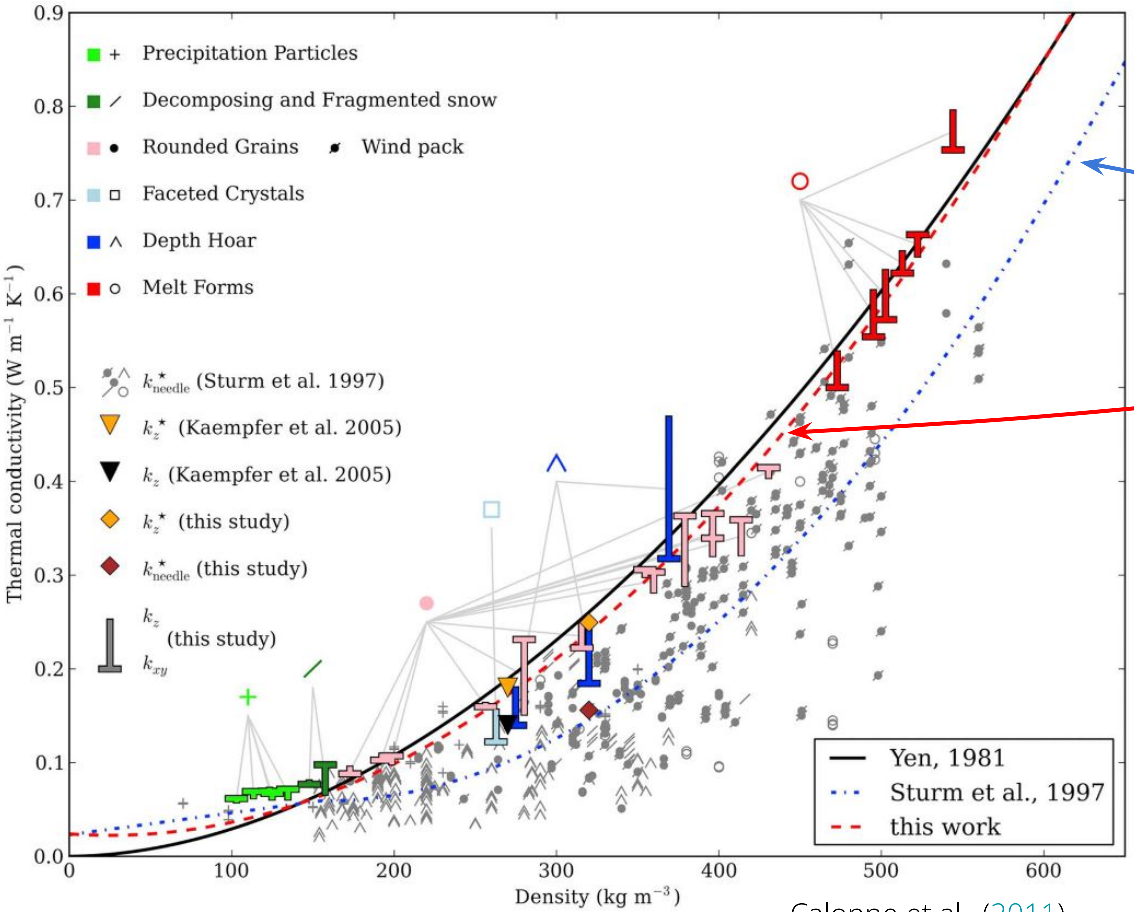


Part #3

Arctic adaptation

- → Blowing snow sublimation losses
- → Wind effect on snow compaction
- → **Snow conductivity**

Arctic adaptation: Snow conductivity



Calonne et al., (2011)

CLASS snow conductivity (k_{eff}):

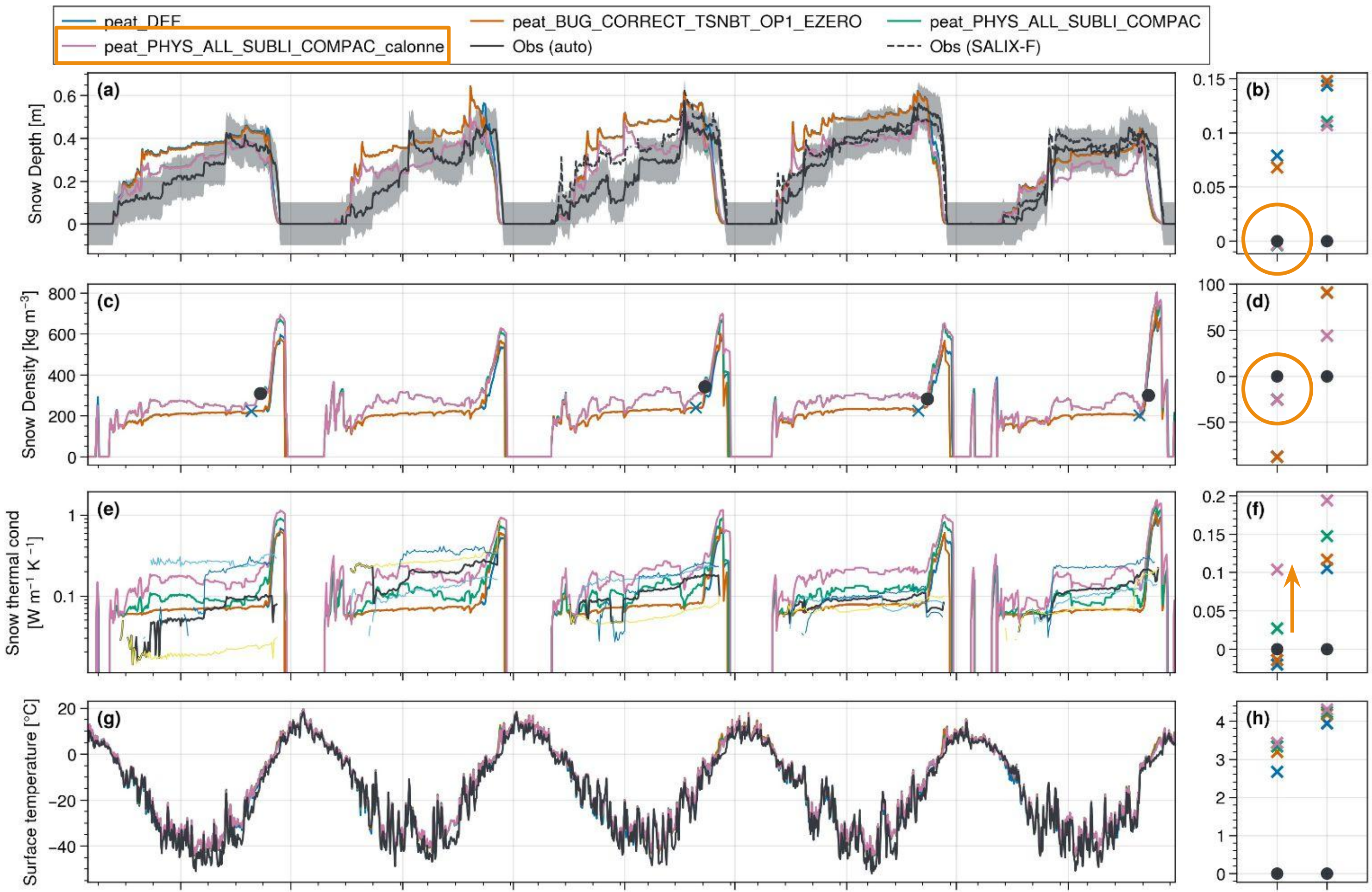
→ Sturm et al. (1997)

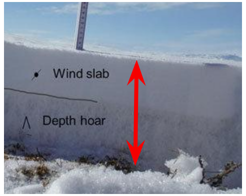
$$k_{eff} = 0.138 - 1.01\rho + 3.233\rho^2 \quad \{0.156 \leq \rho \leq 0.6\}$$
$$k_{eff} = 0.023 + 0.234\rho \quad \{\rho < 0.156\}$$

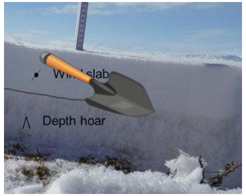
Calonne et al., (2011): *"Our study, carried out on 30 snow samples spanning the full range of seasonal snow type, reveals that the effective thermal conductivity of snow is strongly correlated with snow density, and follows closely the regression curve proposed by Yen [1981]."*

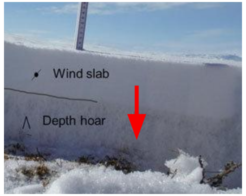
$$k_{eff} = 2.5 \times 10^{-6}\rho^2 - 1.23 \times 10^{-4}\rho + 0.024$$

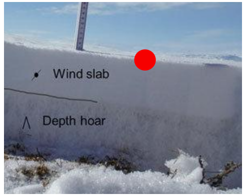
Example: Bylot example











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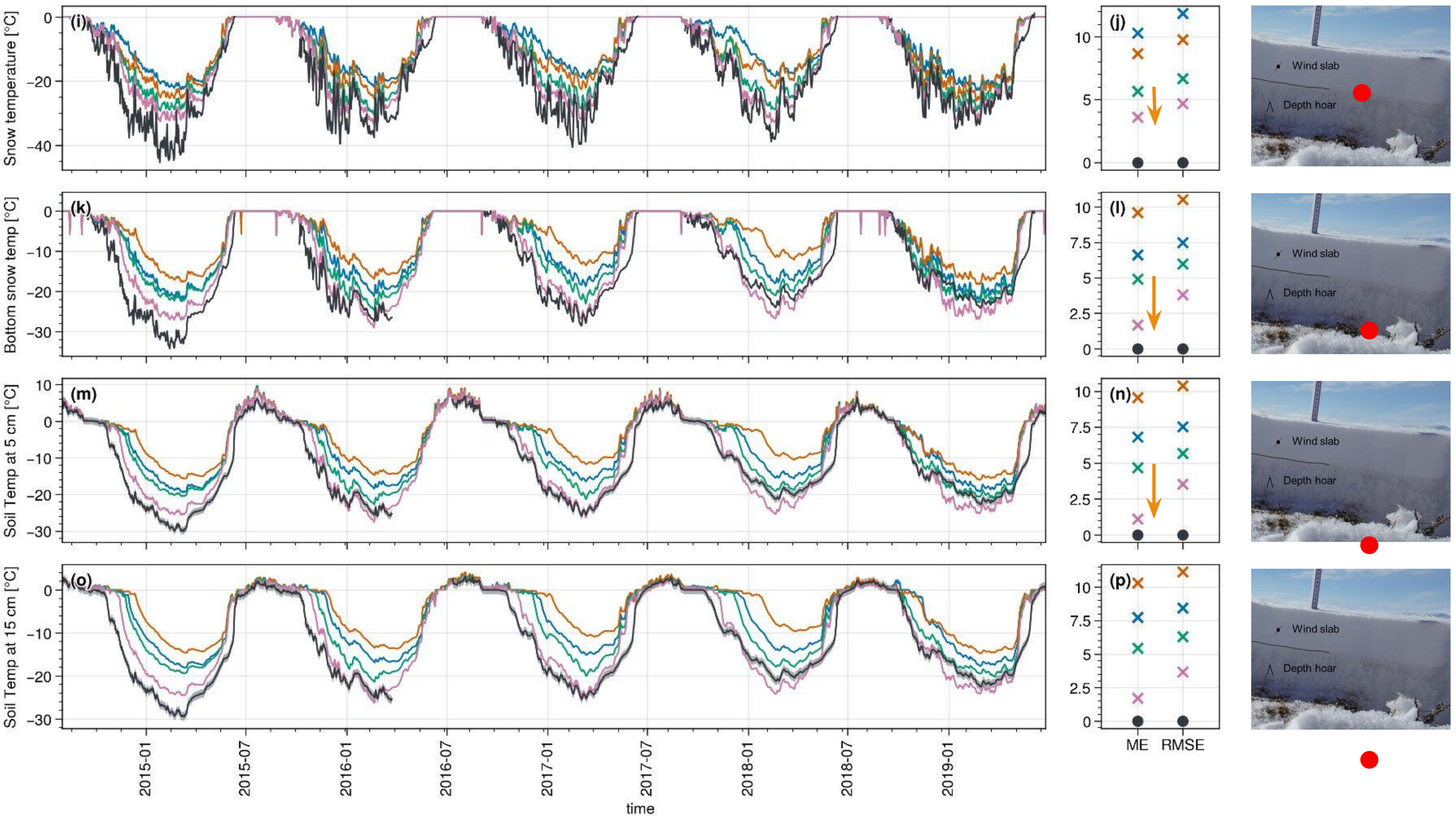
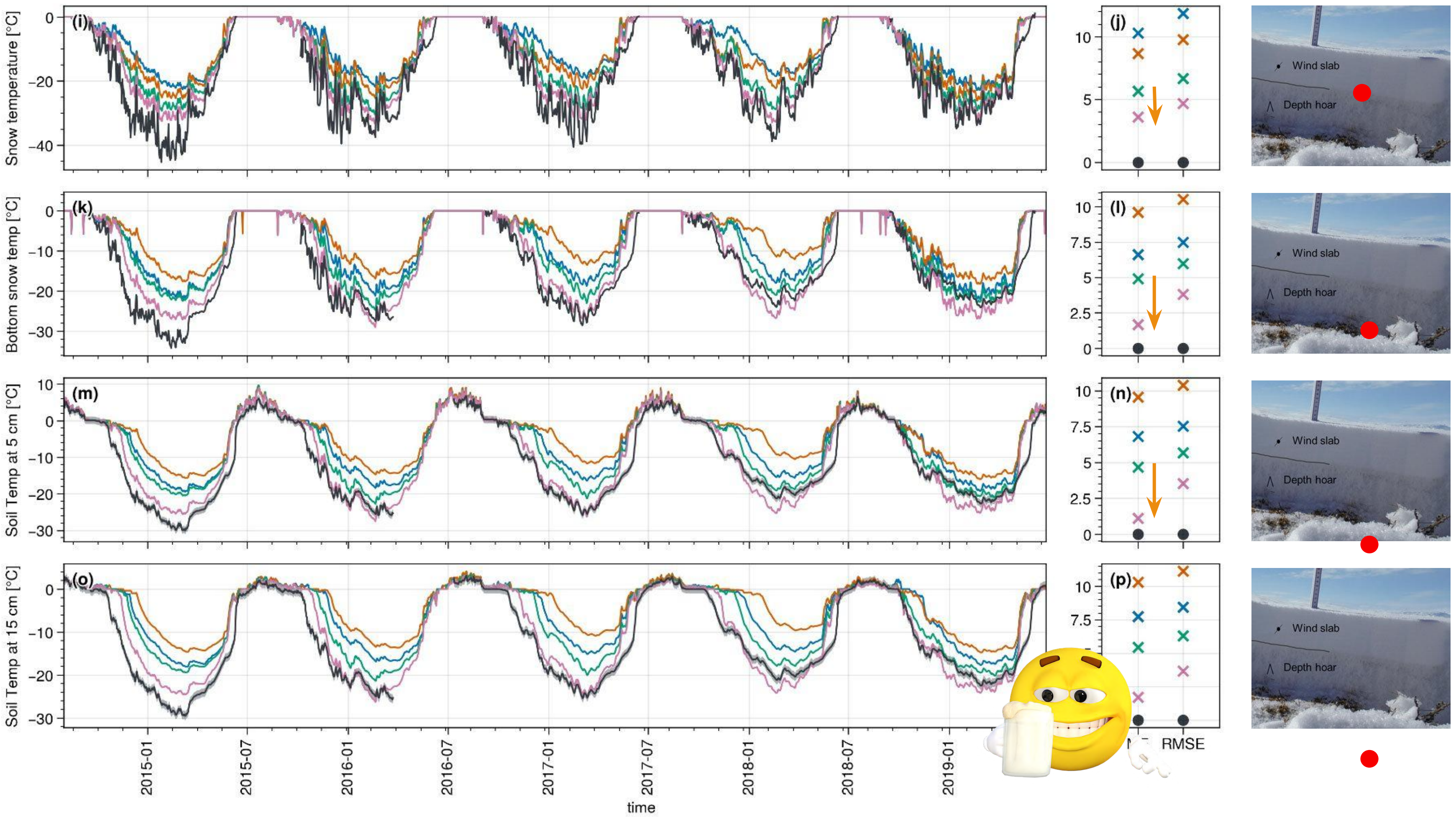
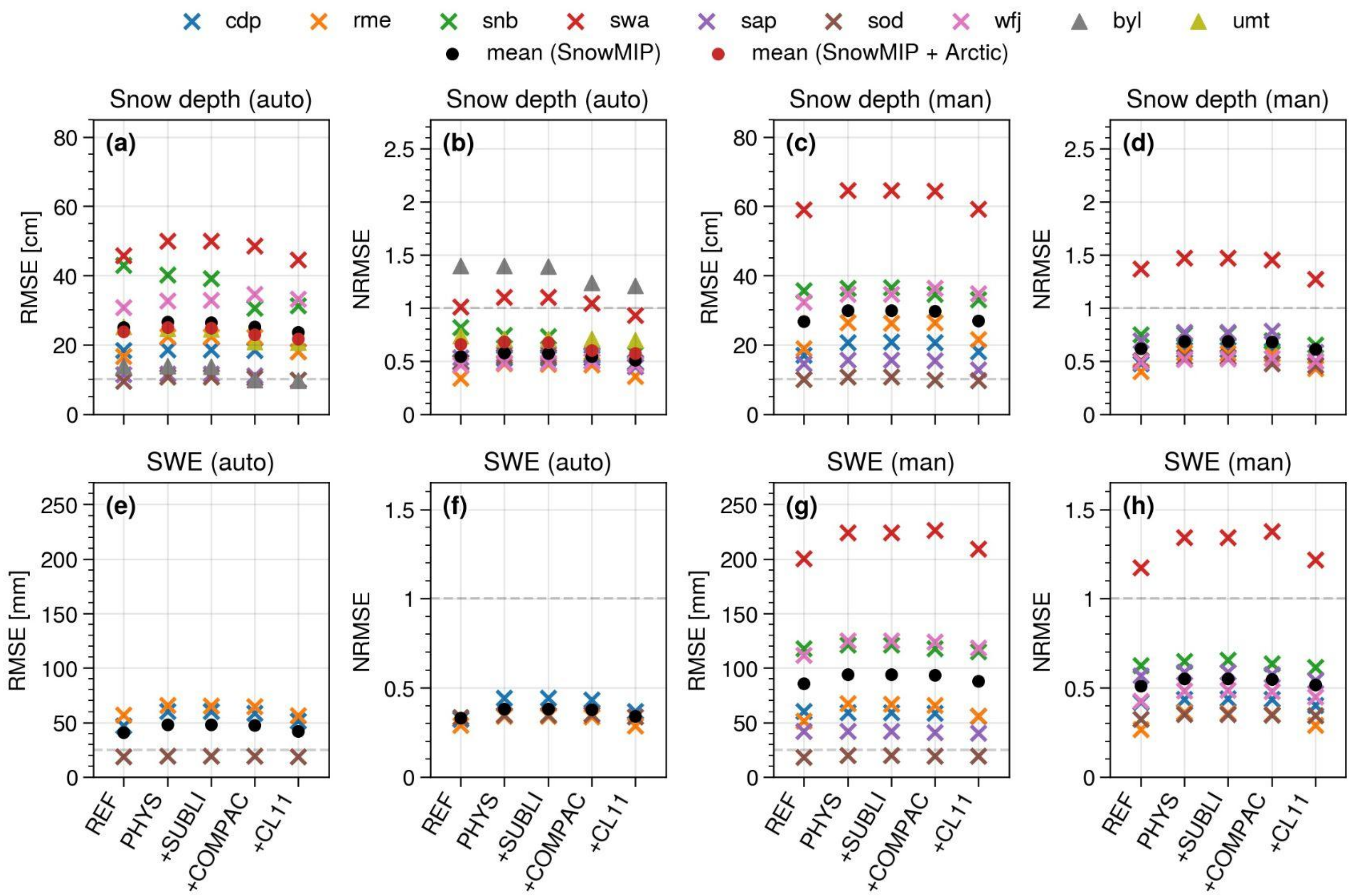


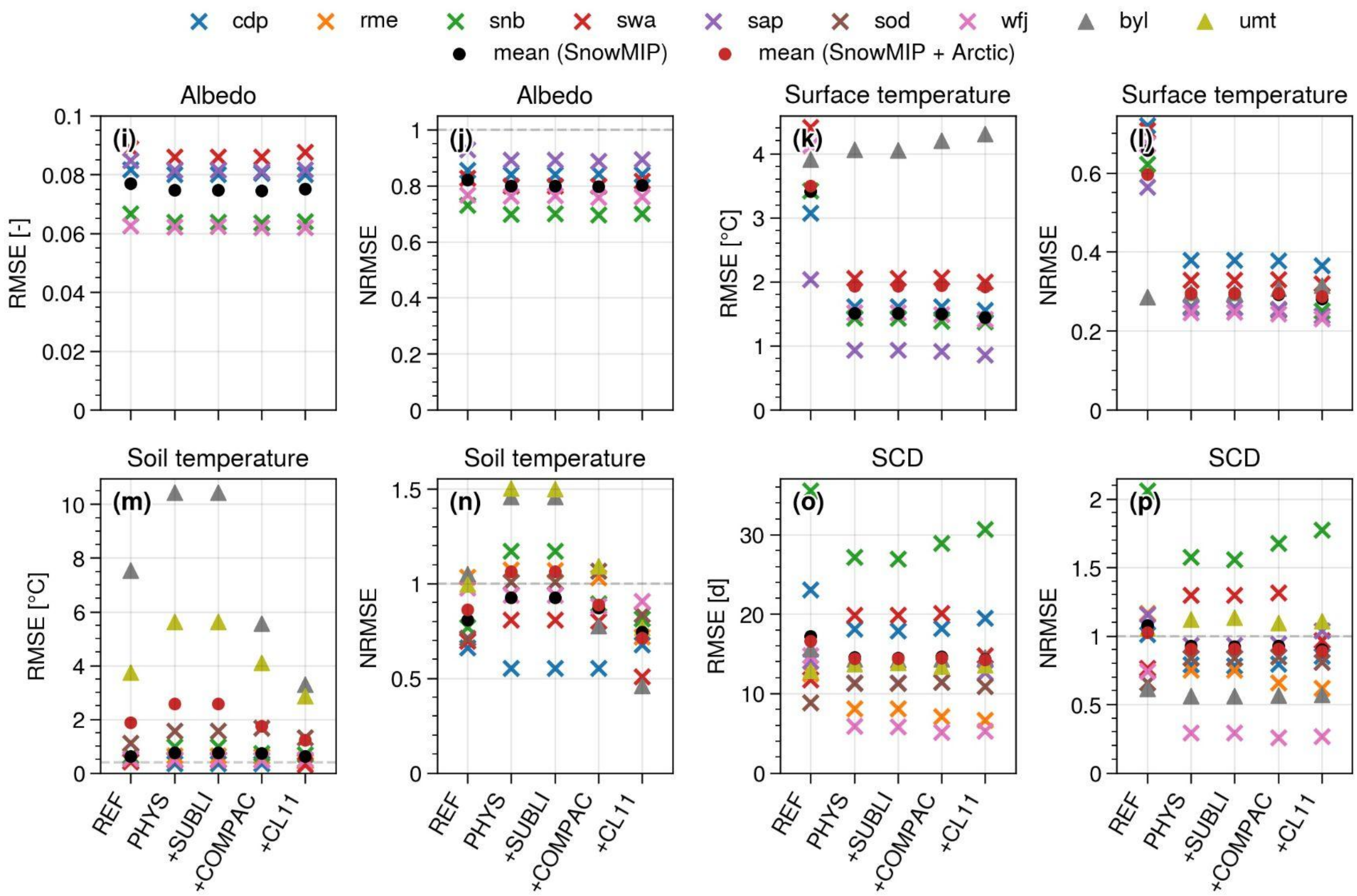
Example: Bylot example



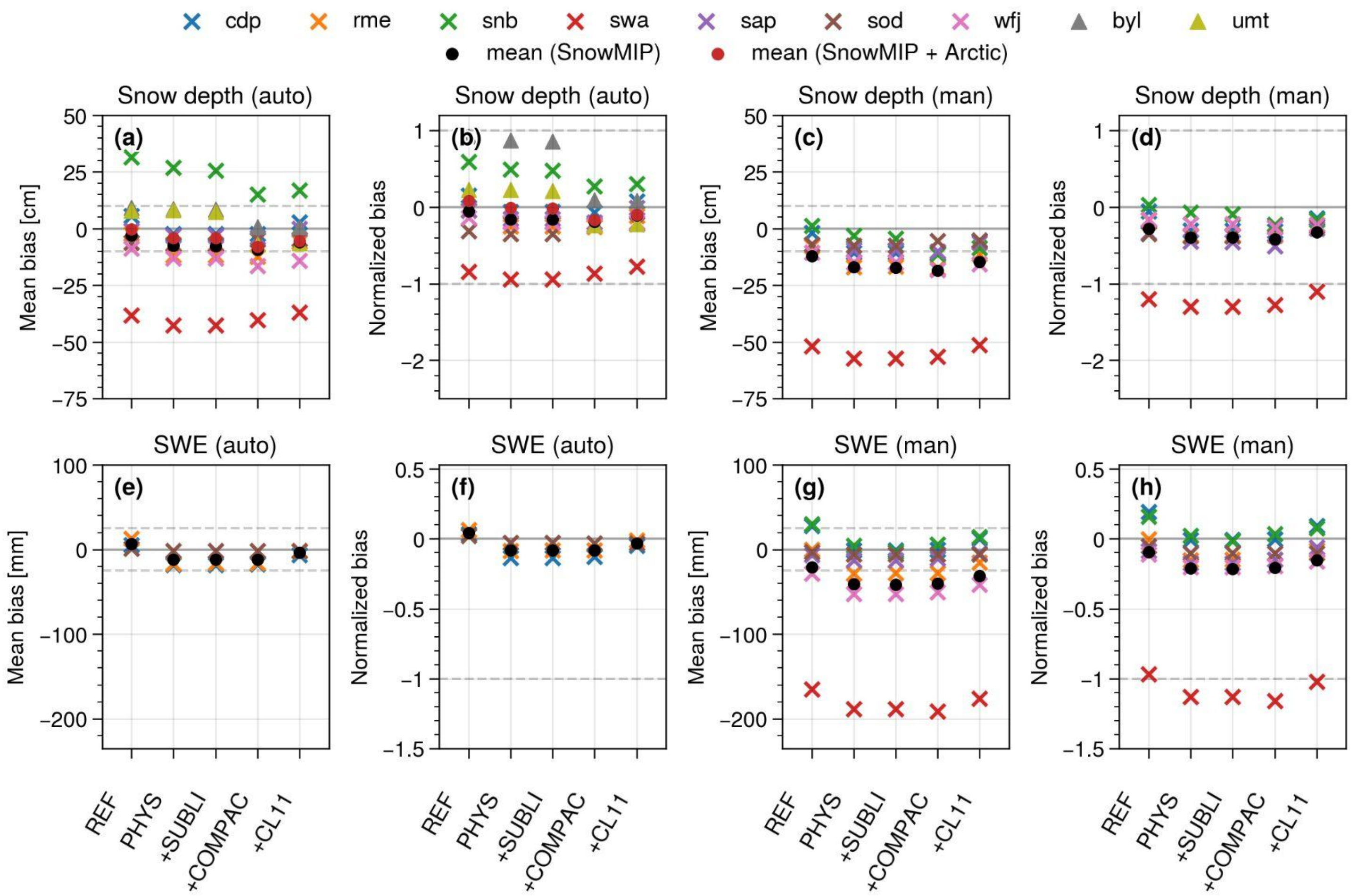
Overall results at all sites: RMSE



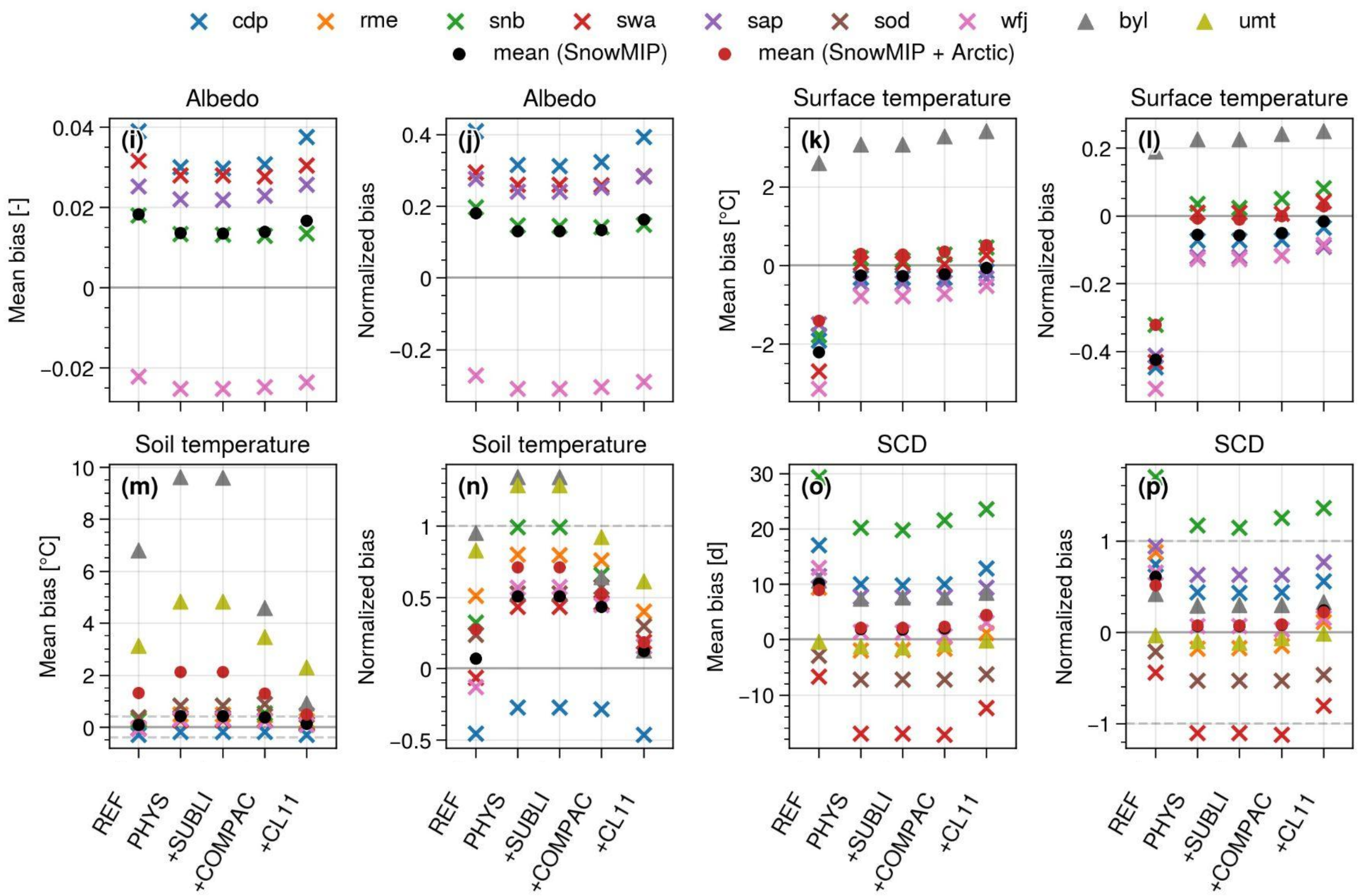
Overall results at all sites: RMSE



Overall results at all sites: MB



Overall results at all sites: MB



Discussion and Conclusion

Discussion

Vegetation

- Vegetation height (no small Arctic grass so too high → issues about albedo, etc.)
- Shrub's thermal bridge (e.g., at Umiujac?)
- Vegetation bending not taken into account (exploit cameras?)
- Moss/lichen not taken into account (the peat layer is only a band-aid solution)
- Snow/soil interface thermal conductivity? (mix of bent vegetation, dead leaves, etc.)

Snow

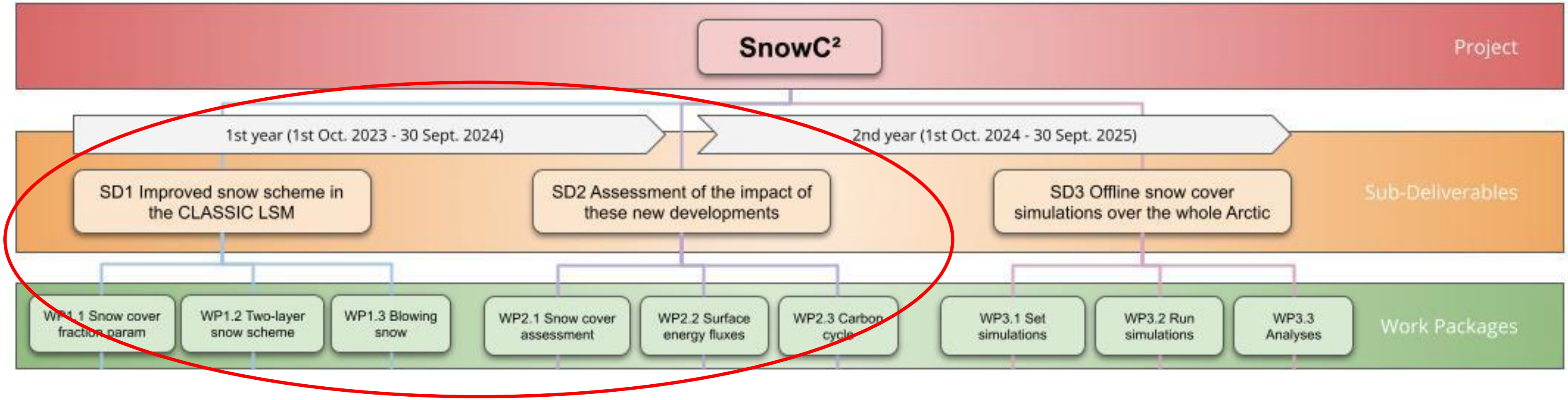
- Depth hoar not directly taken into account so possible limitation of our method
- SCF uncertainty (+ does it need to be activated or not for point scale simulation?)
- Single layer snowpack and the quadratic thermal profile within the snowpack might still be a limitation in certain case (warming/melting too fast?)
- Including the wind in the fresh snow density + recalibrating the compaction equation?
- Rough solution that may be refined in the future (and/or get more physical)

Take home message

- First time to calibrate it over the whole Arctic and SnowMIP sites!
- See how it performs at other sites (like TVC, etc.), our metrics might be not representative of the whole climate zones (Arctic underrepresented → we could have given more weight to the Arctic sites)
- Future studies over the whole Arctic + with trying new SCF parameterizations
- Impact over the winter carbon respiration.
- We successfully simulated the soil temperature, better snow depth, density, thermal conductivity, etc. + improved the physics of CLASSIC (better repartition of the temperature between the snowpack and bottom snow temperature + bug solved over snow free areas for the topsoil thermal conductivity)
- More physical solution will be needed for the future (water vapor fluxes within the snowpack) but at the scale of a global climate model solution presented in this work might still work as “easy” and performant compromise parameterization
- More observations will be needed (thermal conductivities, density time series for dry/wet snow, etc.) + more constraints on the SCF around a site (camera)
- Big uncertainty about drifting snow in the Arctic

Work Package breakdown: Snow cover heterogeneity and its impact on the Climate and Carbon cycle of Arctic regions

ESA CCI Fellowship - Mickaël Lalande - supervised by Christophe Kinnard at UQTR / RIVES (Canada)



Work Package breakdown: Snow cover heterogeneity and its impact on the Climate and Carbon cycle of Arctic regions

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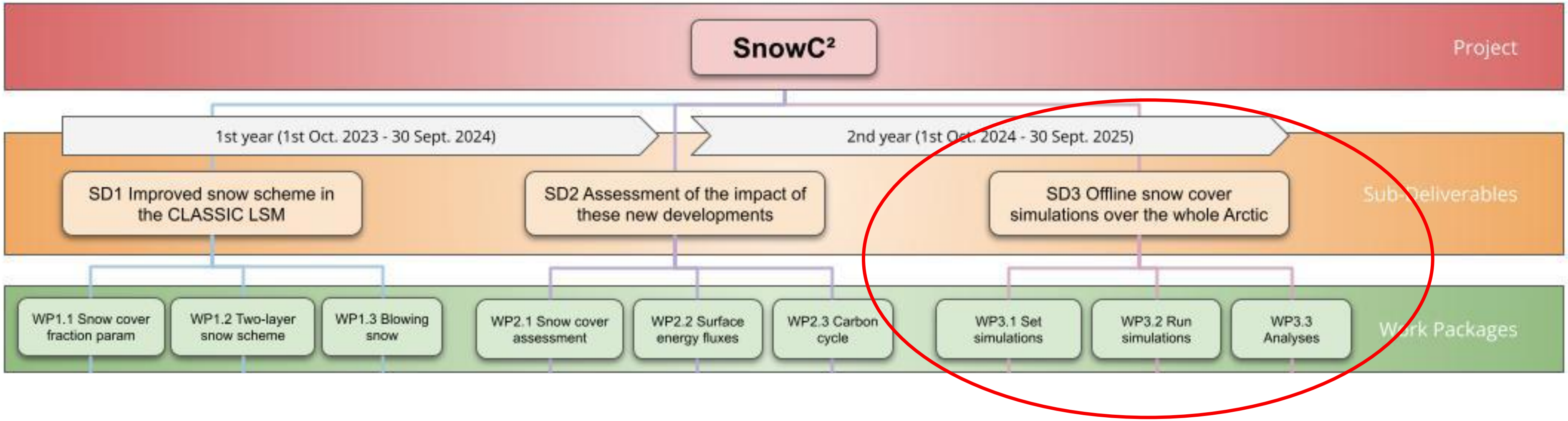

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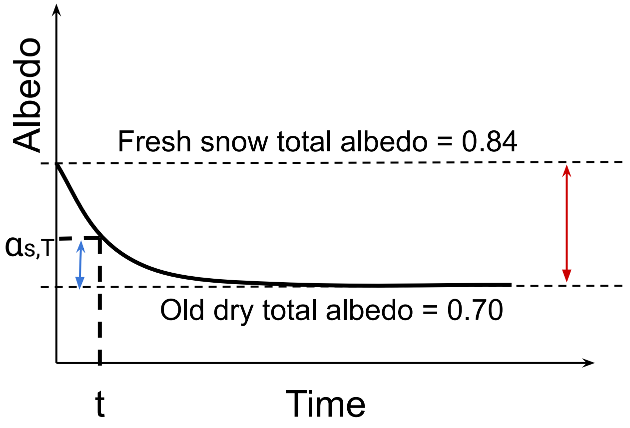
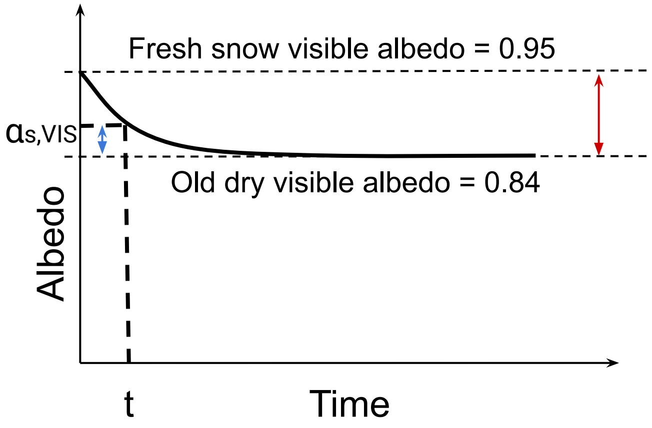
Supplementary materials

Methods: CLASSIC snow model (albedo)

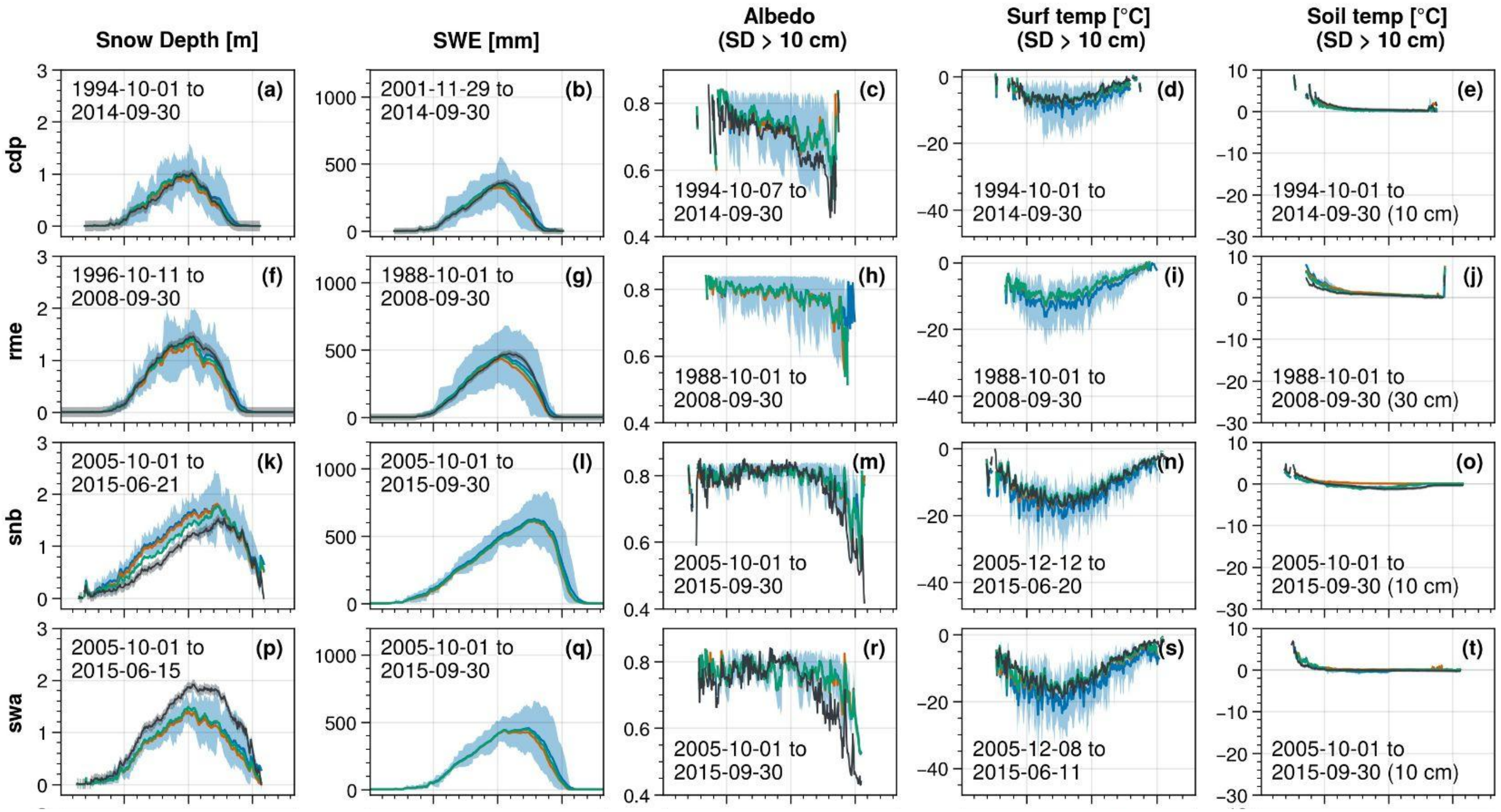
$$\alpha_s(t+1) = \left[\alpha_s(t) - \alpha_{s,old}\right] e^{-\frac{0.01\Delta t}{3600}} + \alpha_{s,old}$$

	Total albedo	Visible albedo	Near-IR albedo
Fresh snow	0.84	0.95	0.73
Old dry snow	0.70	0.84	0.56
Melting snow	0.50	0.62	0.38





Physics + Arctic improvements: synthesis



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