IGE seminar

16 May 2025

Improving the CLASSIC Snow Model to Better Simulate Arctic Snowpacks

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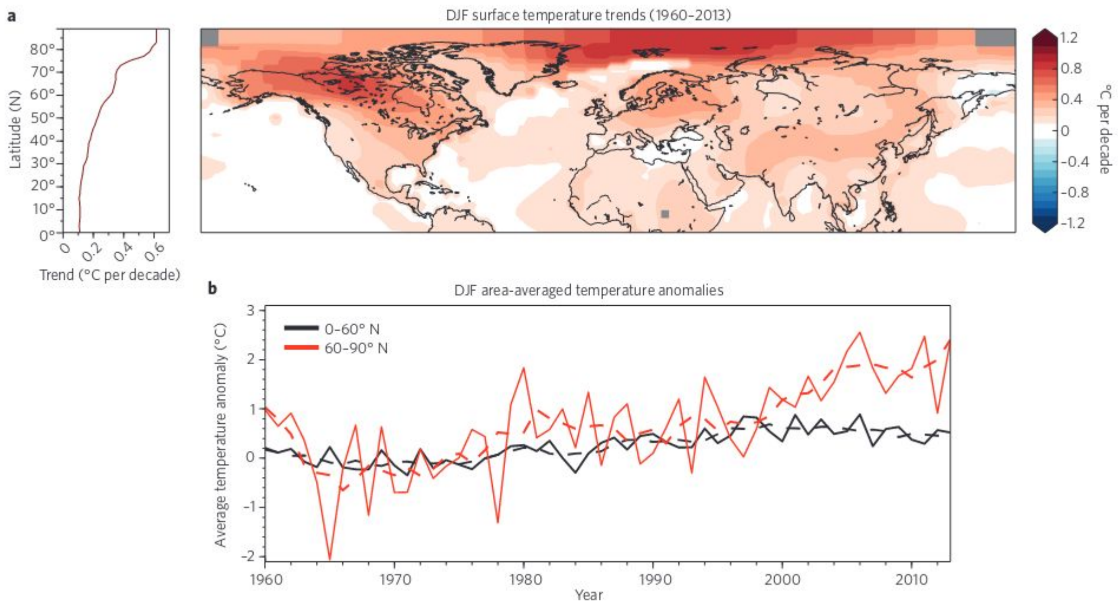
ESA CCI Fellowship — 01/10/2023 to 30/09/2025 (2 years)

supervised by Christophe Kinnard and Alexandre Roy

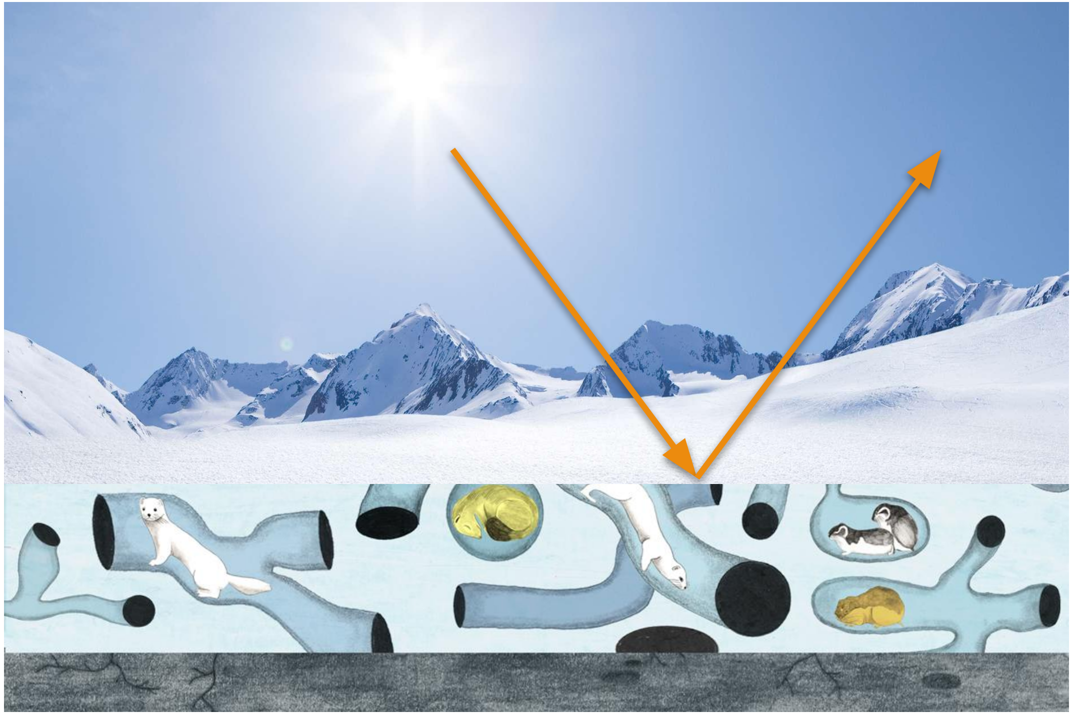
Context: Arctic Amplification



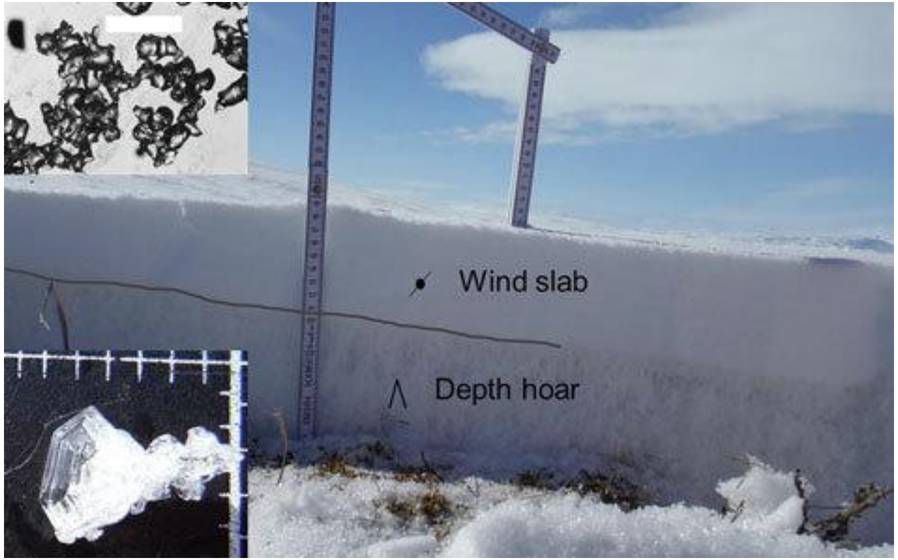
Cohen et al., (2014)

- 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)

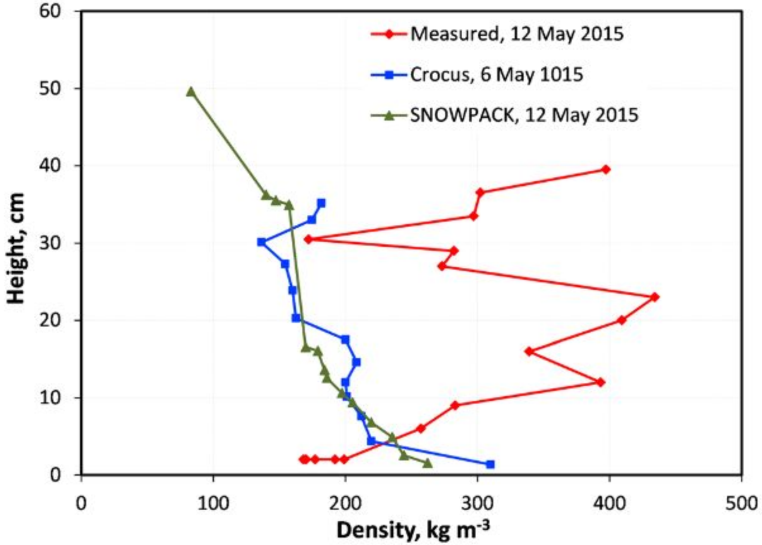


Figure 3. Comparison of measured snow density profiles at Bylot Island in May 2015 with those simulated using the detailed snow models Crocus and SNOWPACK. Crocus runs of 6 May are shown because Crocus simulates melting on 7 May, and this extra process makes comparisons irrelevant on 12 May.

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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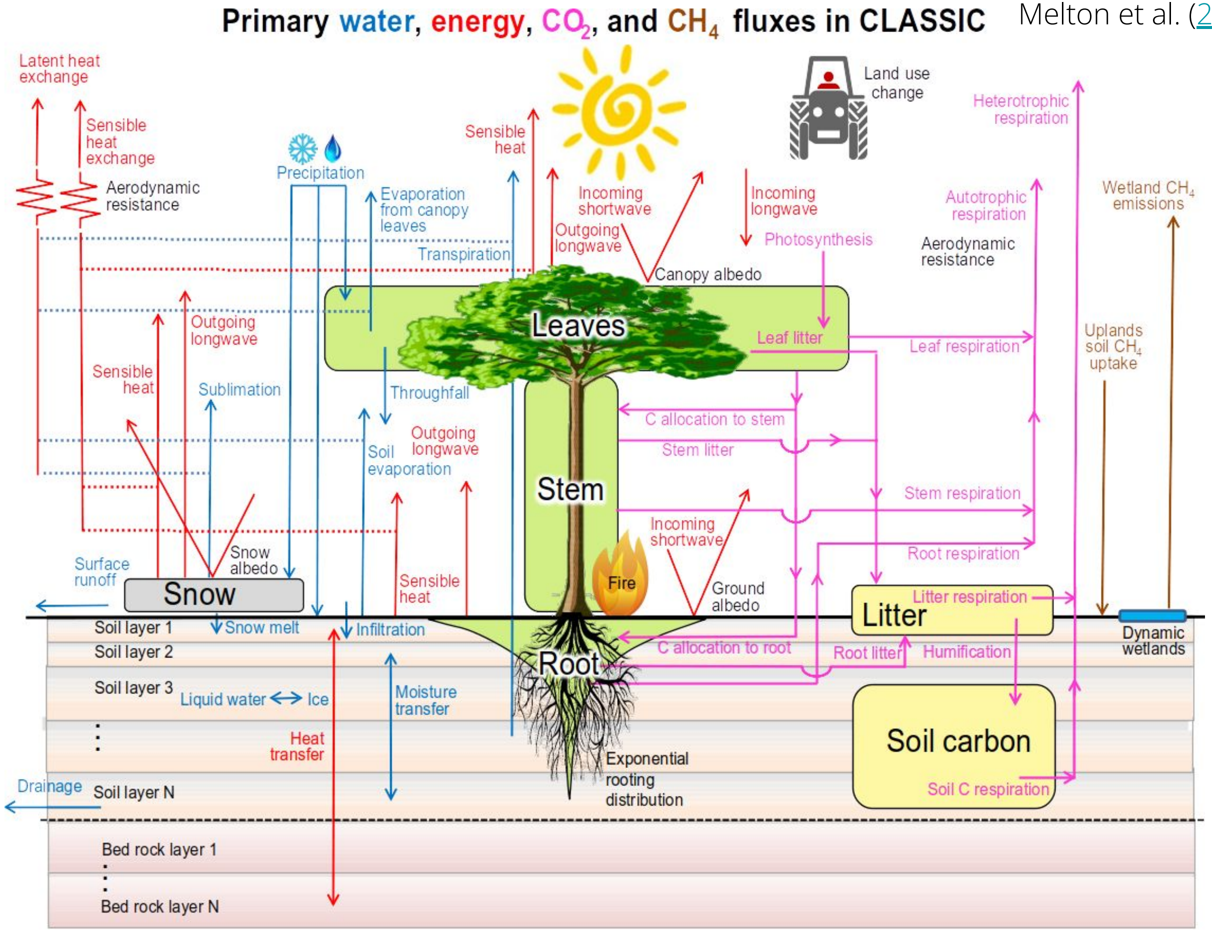
Practical solution

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…

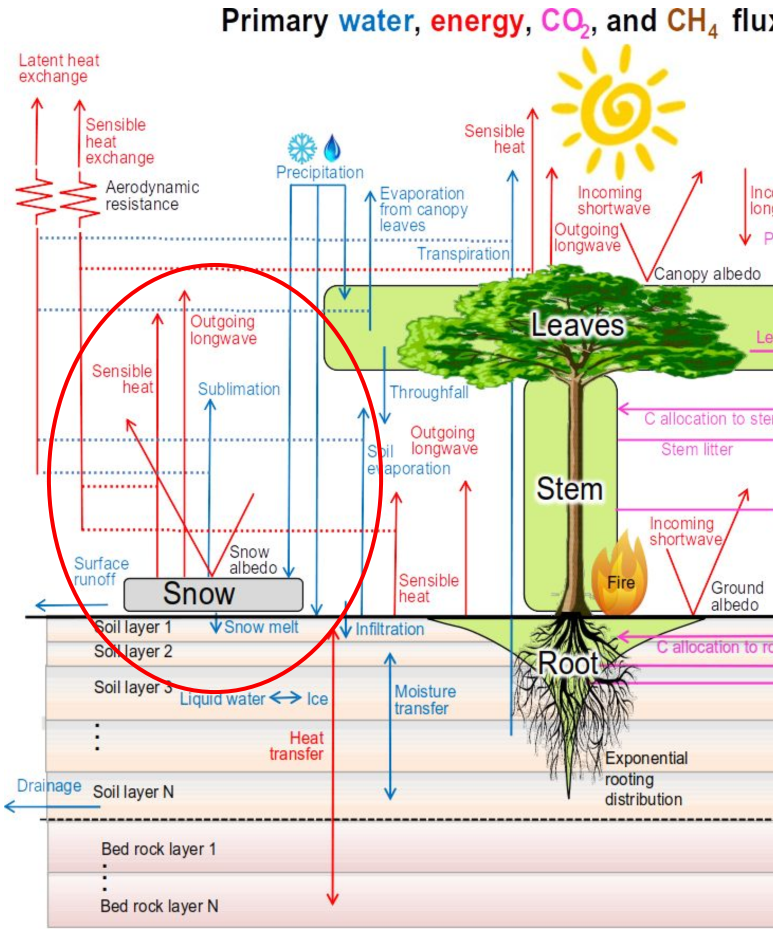
CLASSIC LSM: description



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.
  - CTEM: photosynthesis, carbon cycle, etc.
- → used operationally within the Canadian Earth System Model (CanESM; Swart et al., 2019) for climate change impact assessment (CMIP6, SnowMIP, Global Carbon Project, etc.)

CLASSIC land surface model (LSM): description

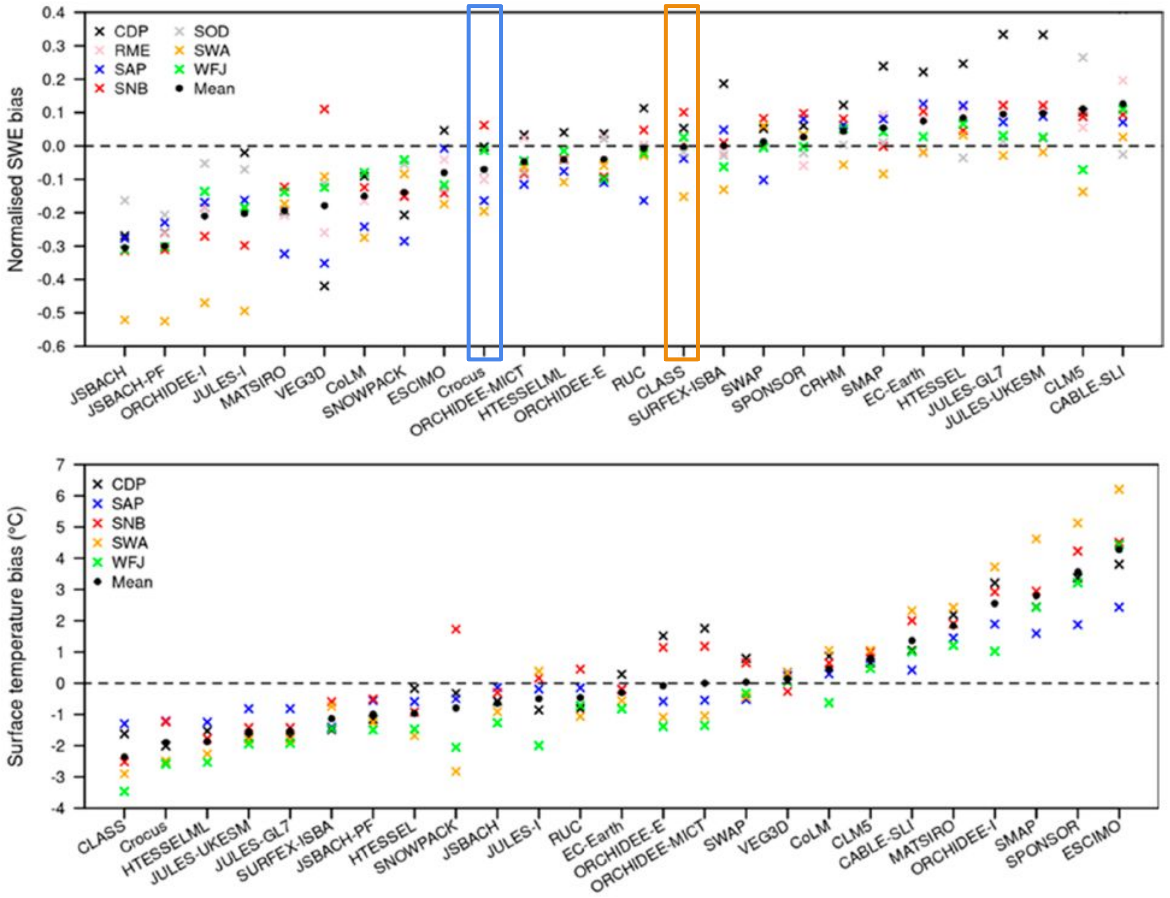


Snow model description (Bartlett et al., 2006; Brown et al., 2006; Langlois et al., 2014; Verseghy et al., 2017 - version 2.7 → 3.6.1):

- 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)
- Percolation and refreezing taken into account
- Interception of snowfall by vegetation is explicitly modeled (Bartlett et al., 2006)

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.)

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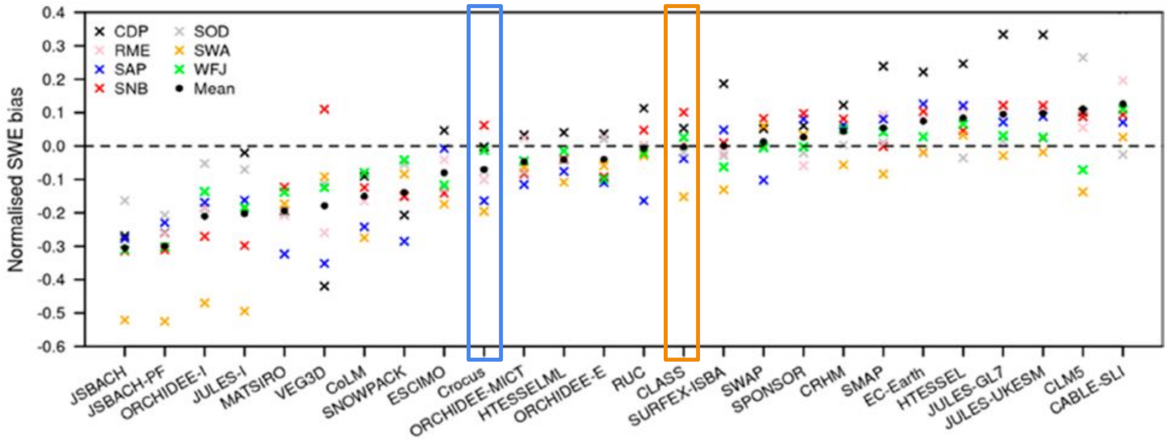
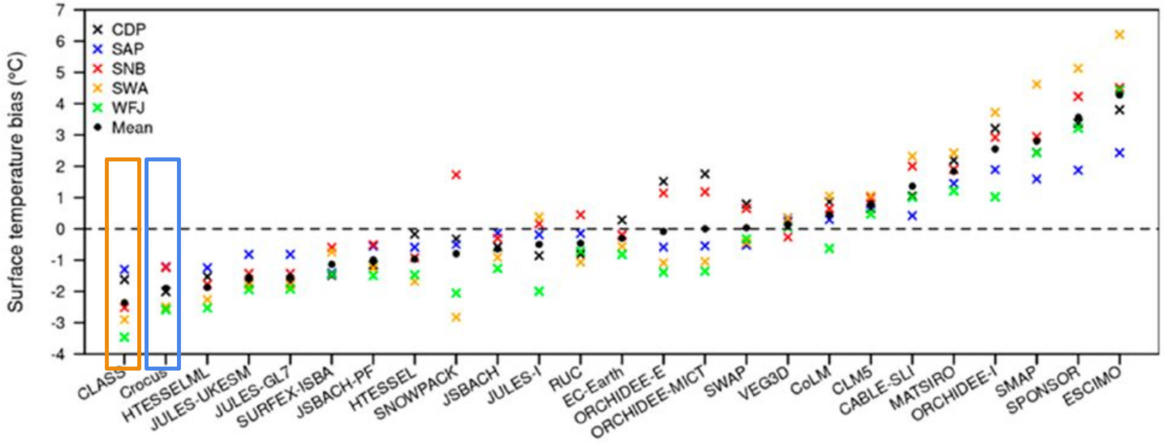




CLASS → one of the best performing model in the last SnowMIP experiments! (SWE, SD, albedo, soil temperatures, etc.)

But performs quite bad for the surface temperature...

Main objectives / questions

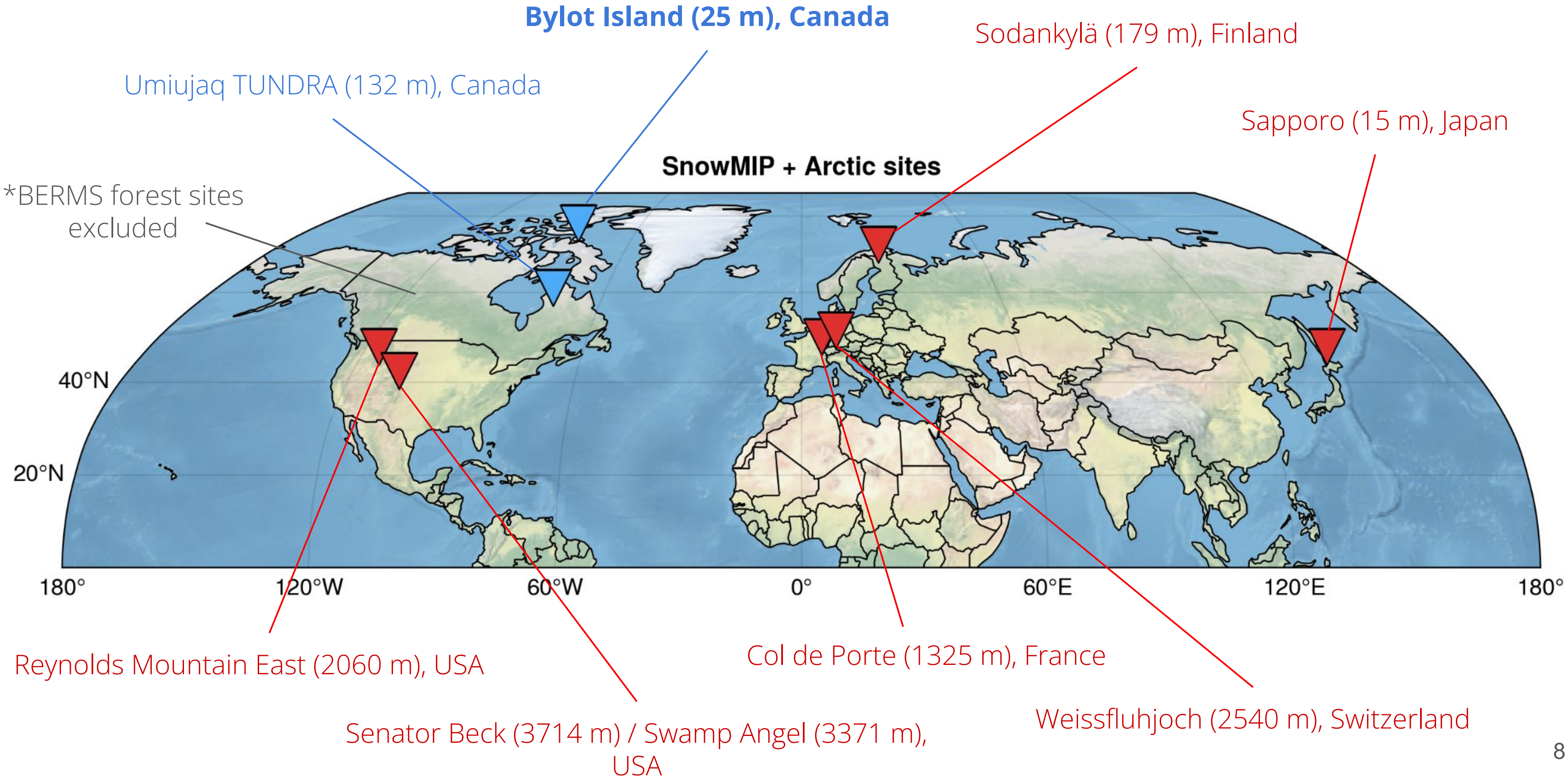
- Can a single-layer snow model reproduce the bulk Arctic snow characteristic?

- Can Arctic snowpack adaptations be implemented without deteriorating model performance elsewhere (e.g., mid-latitude Alpine snowpacks)?

- How do those adaptations impact the soil temperatures and carbon fluxes?

Methods

Methods: 1D simulations at SnowMIP and Arctic sites



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)

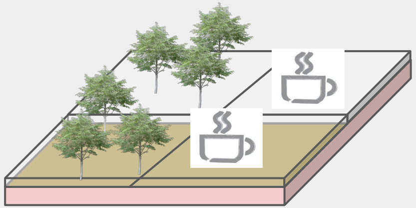
Spin-up:

- 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

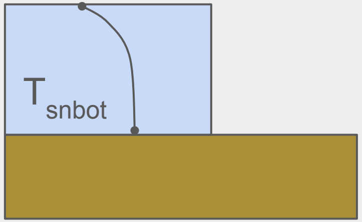
Snow model improvements

Physics improvements

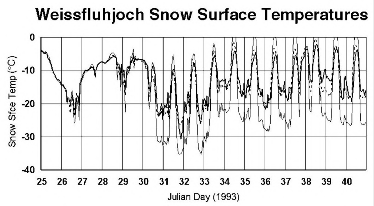
#1 Soil conductivity under snow (bug)



#2 Bottom snow temperature



#3 Windless exchange coefficient



Source: Brown et al., (2006)

Arctic adaptions

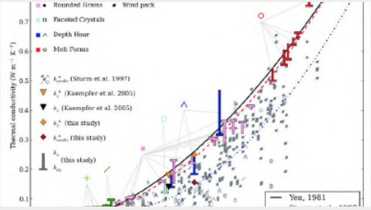
#4 Blowing snow sublimation losses

Credit: Les Anderson/ Unsplash

#5 Snow compaction scheme

Credit: Sawtooth Avalanche Center

#6 Snow thermal conductivity



Source: Calonne et al. (2011)

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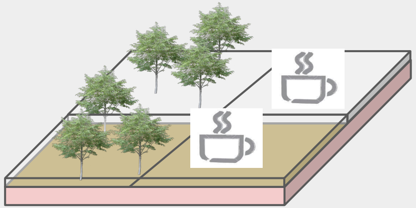

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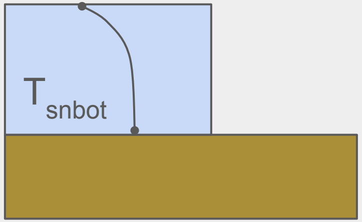

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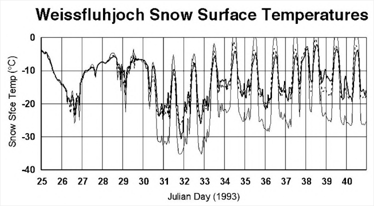

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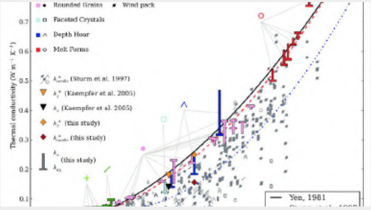

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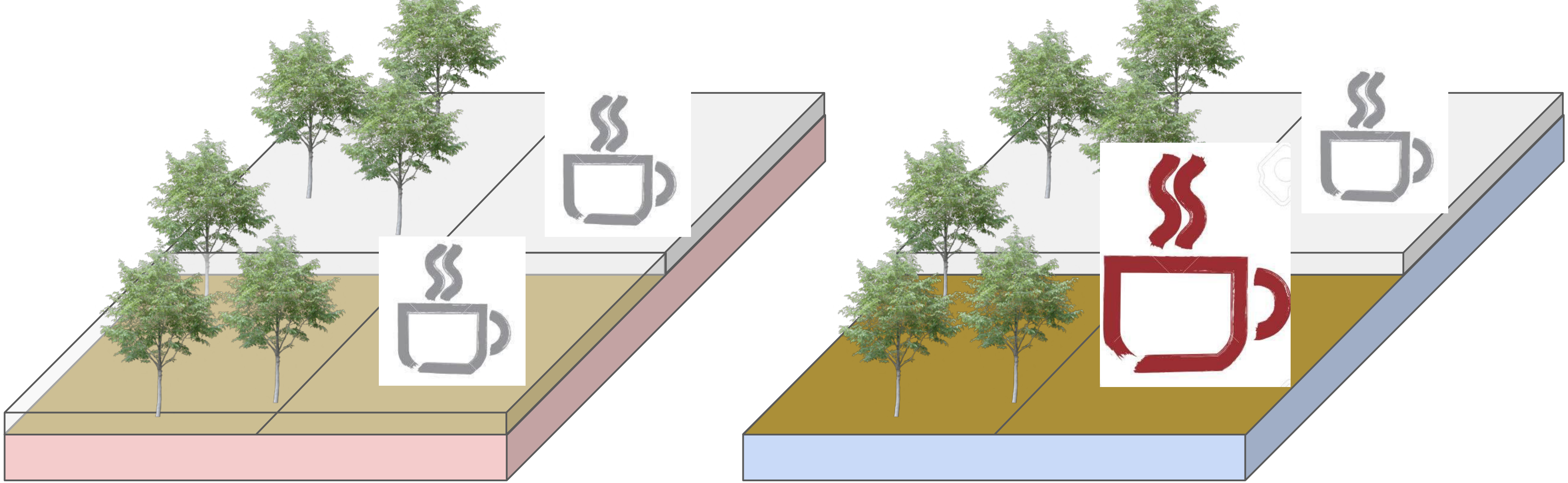
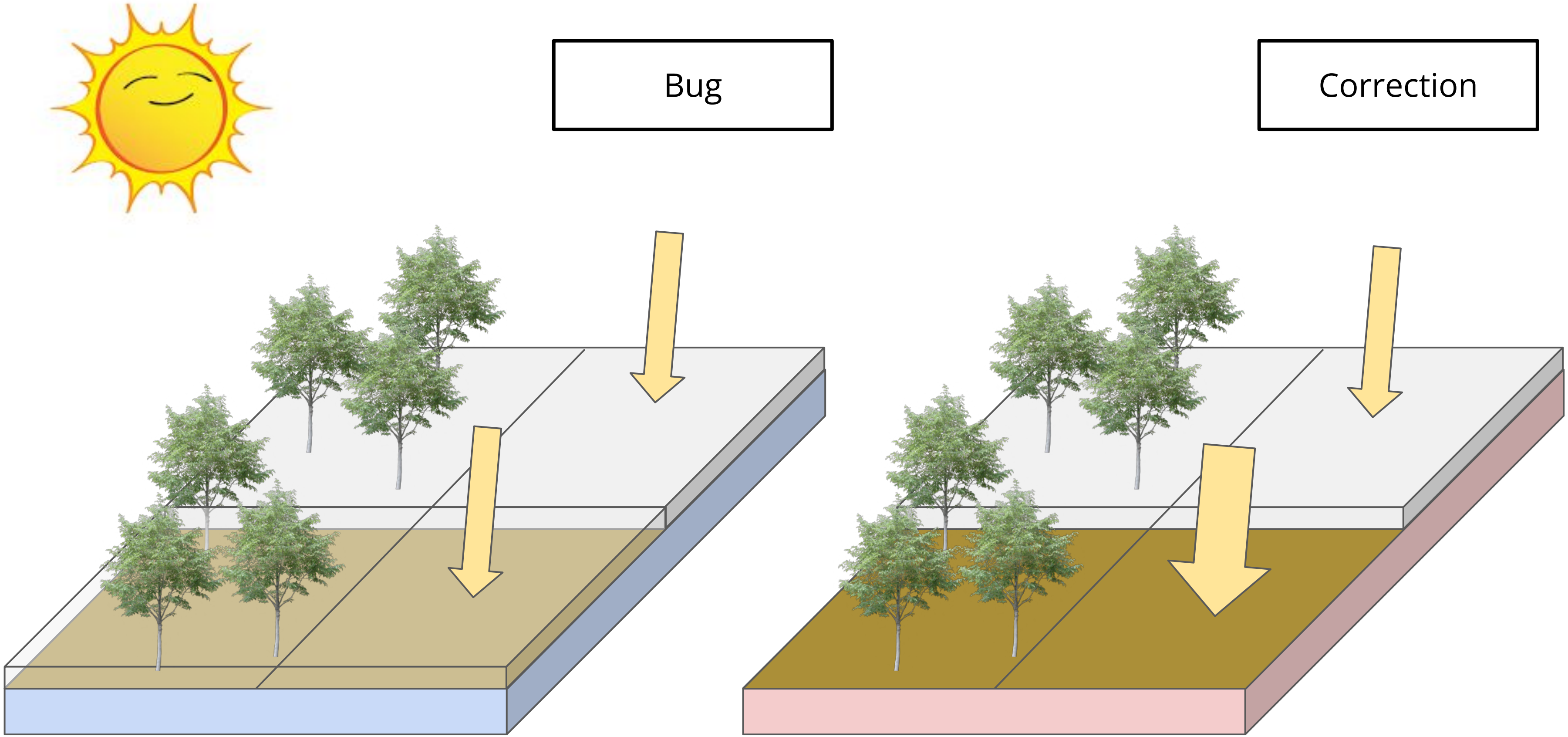
Physics improvements

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

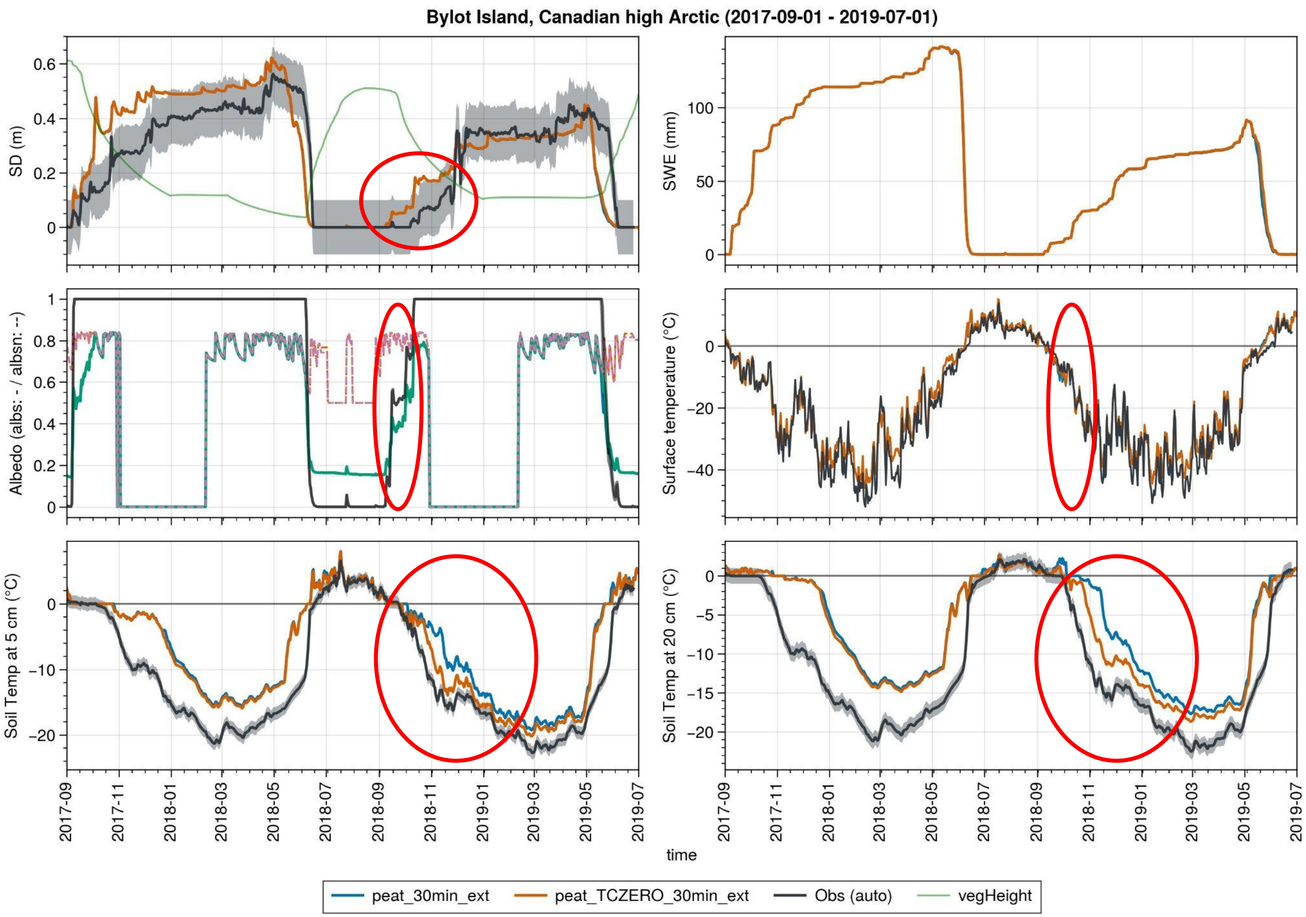
$\lambda_{1,top}$ over snow-free areas (bug): **autumn**



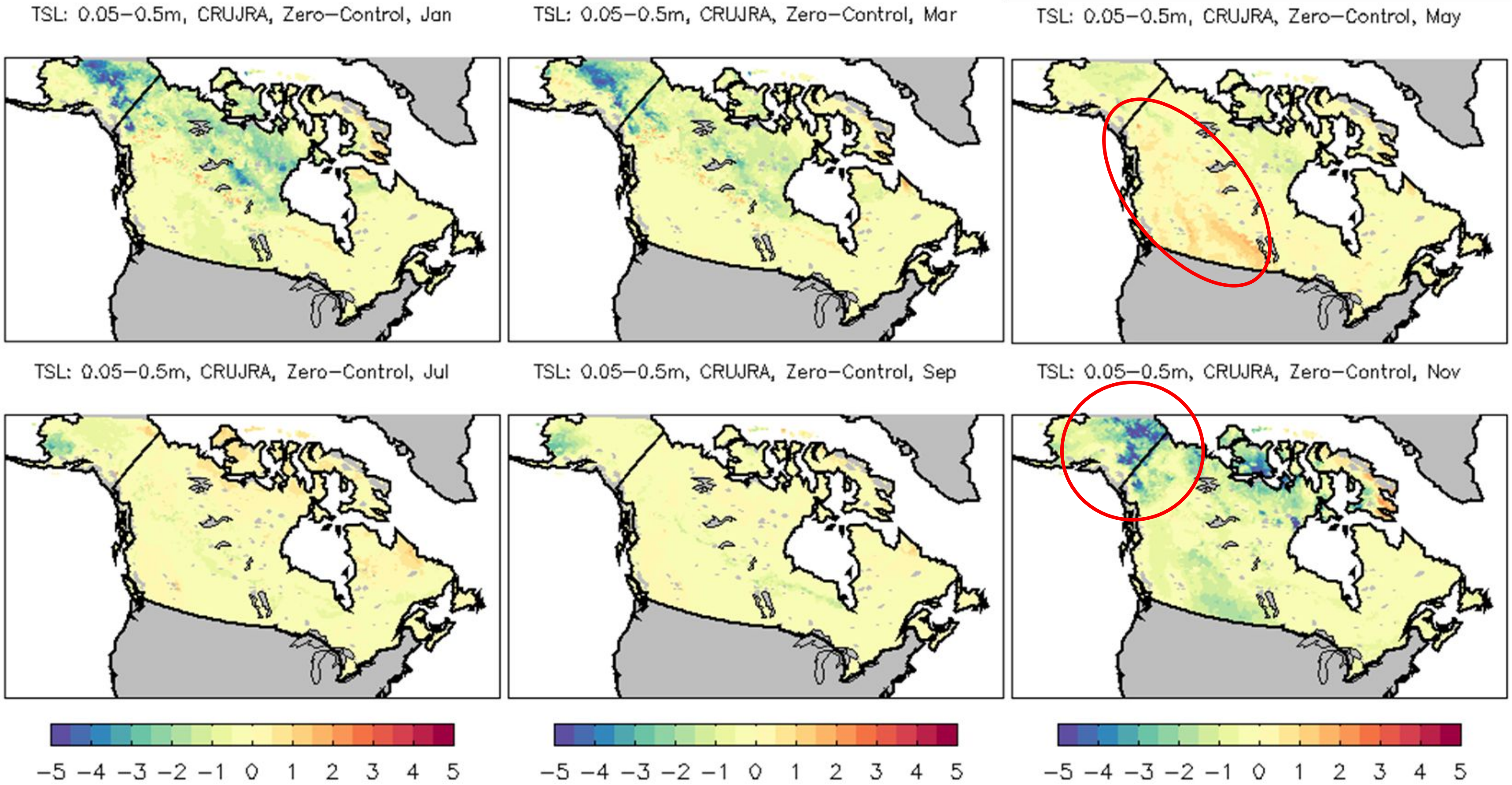
$\lambda_{1,top}$ over snow-free areas (bug): **spring**



Impacts: site simulations (Mickaël)



Impacts: spatial simulations (Libo)



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

Physics improvements

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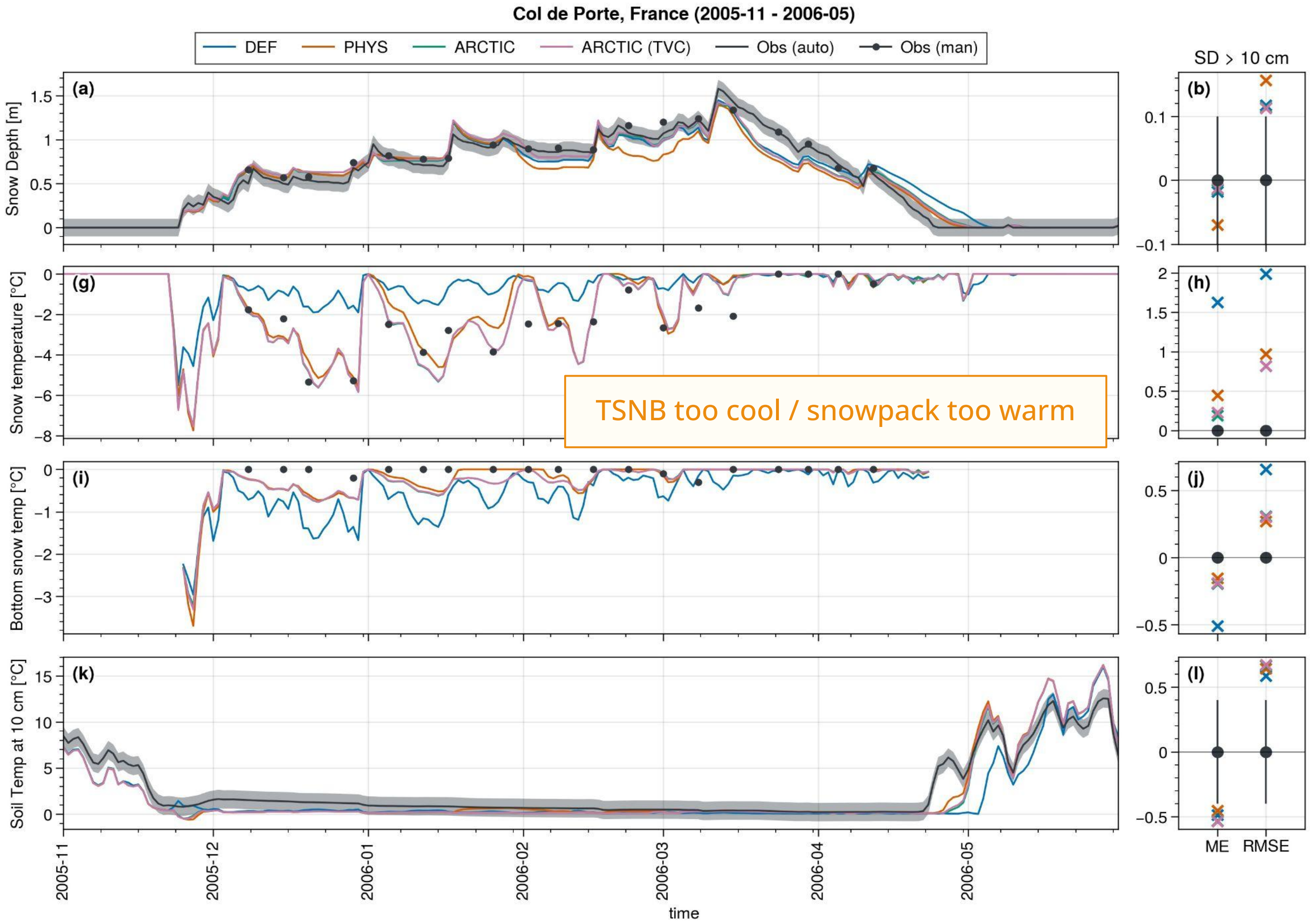
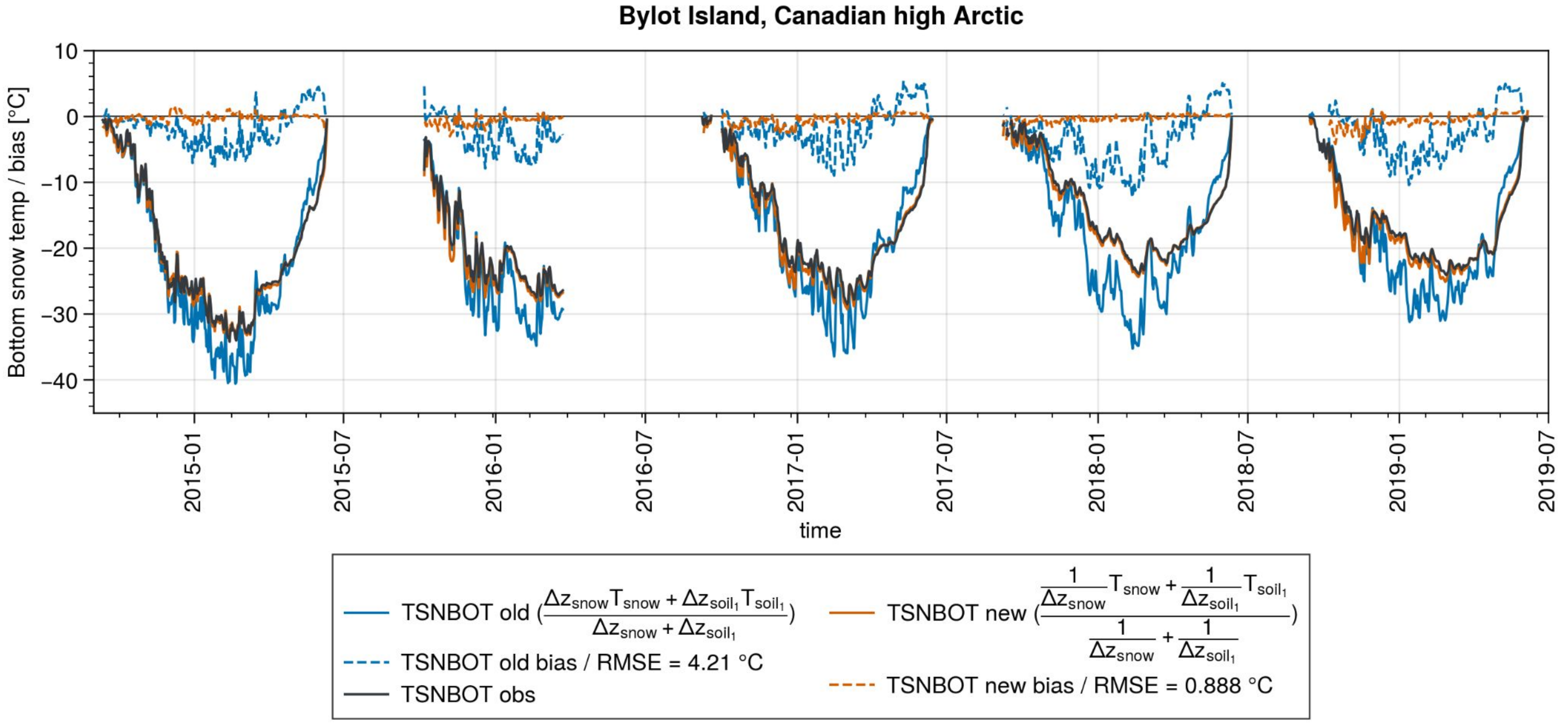
Bottom snow temperature (TSNB)



Bottom snow temperature (TSNB)



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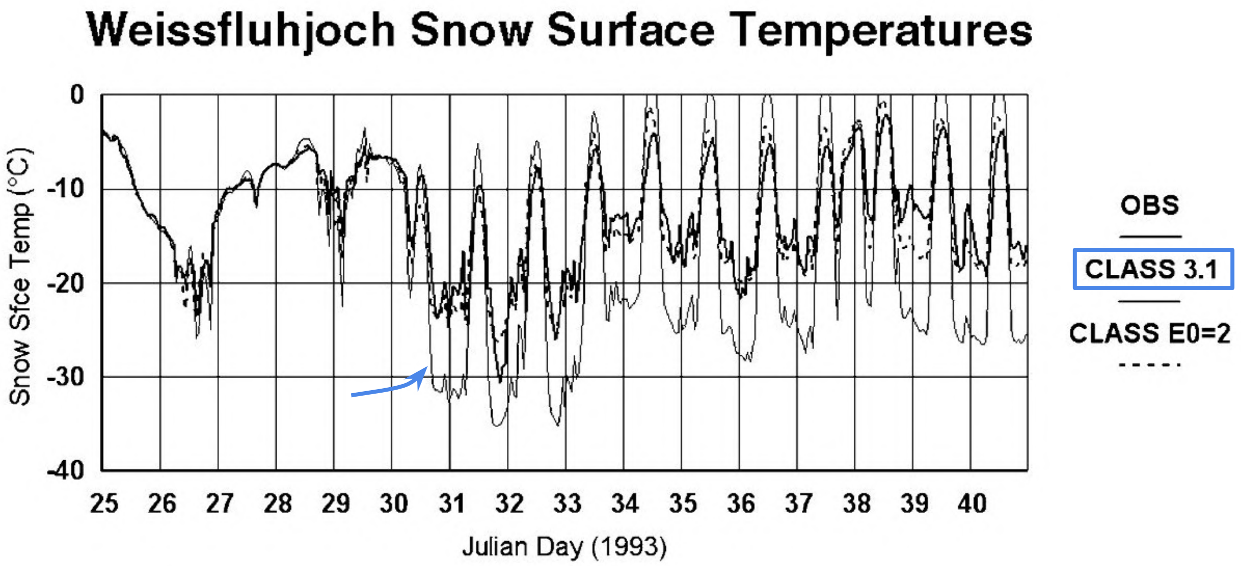
Windless transfer coefficient

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)



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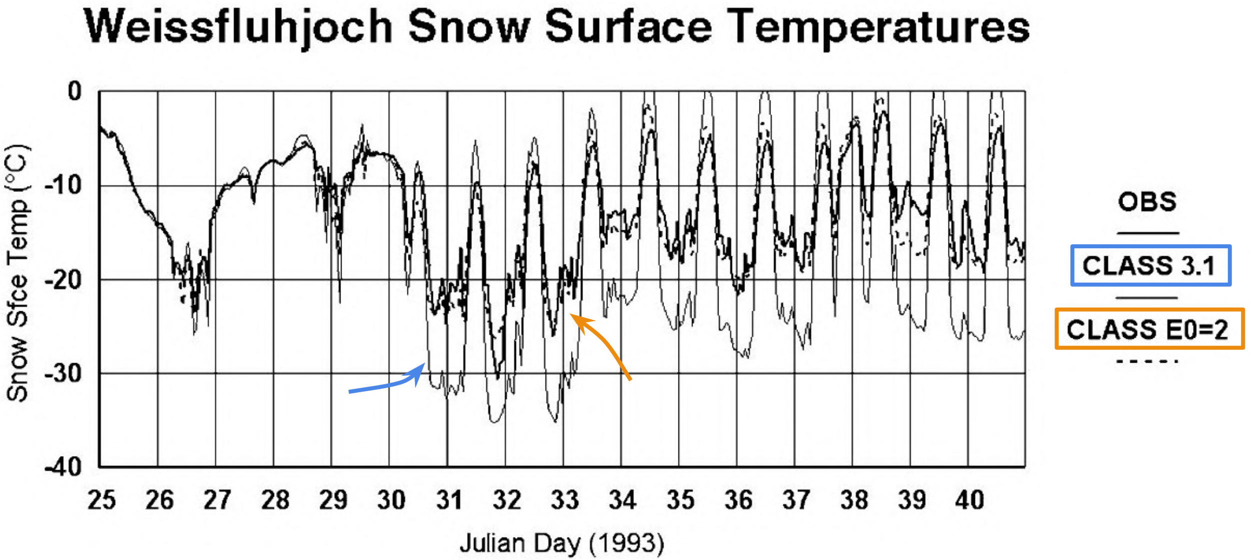


Brown et al., (2006)

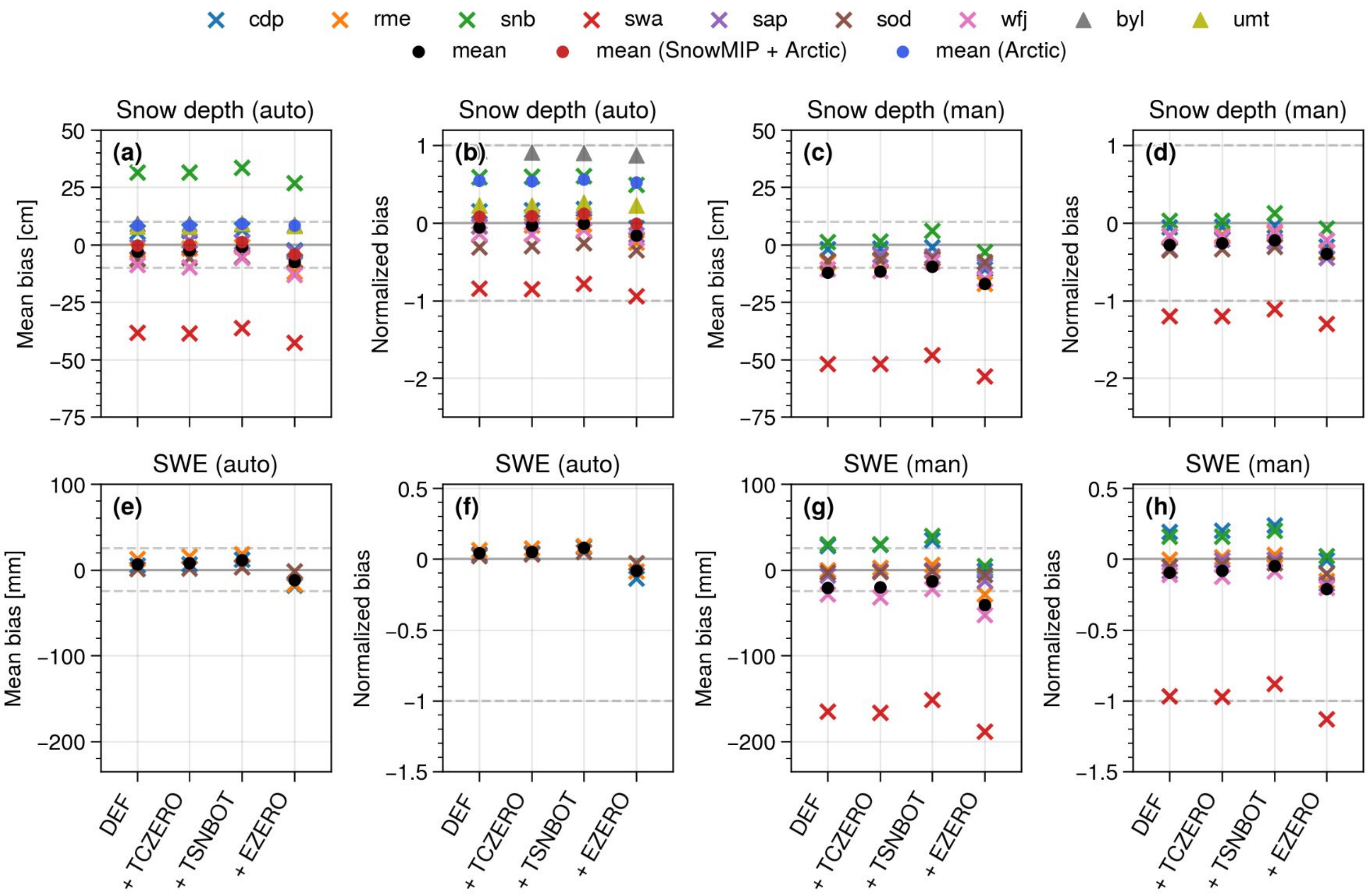
Solution → windless transfer coefficient (E_0) in the sensible heat flux:

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

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

Results

Physics improvements: synthesis



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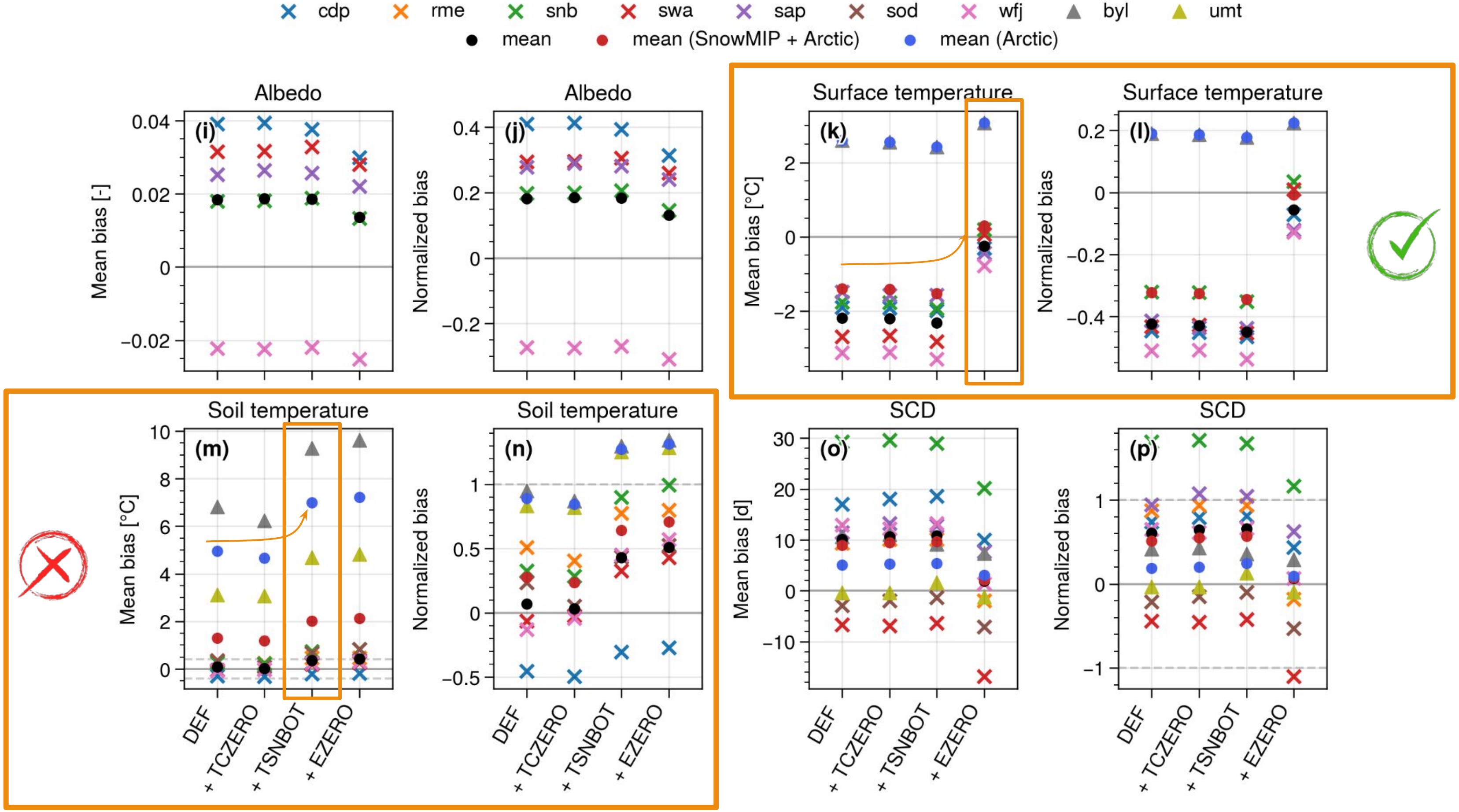
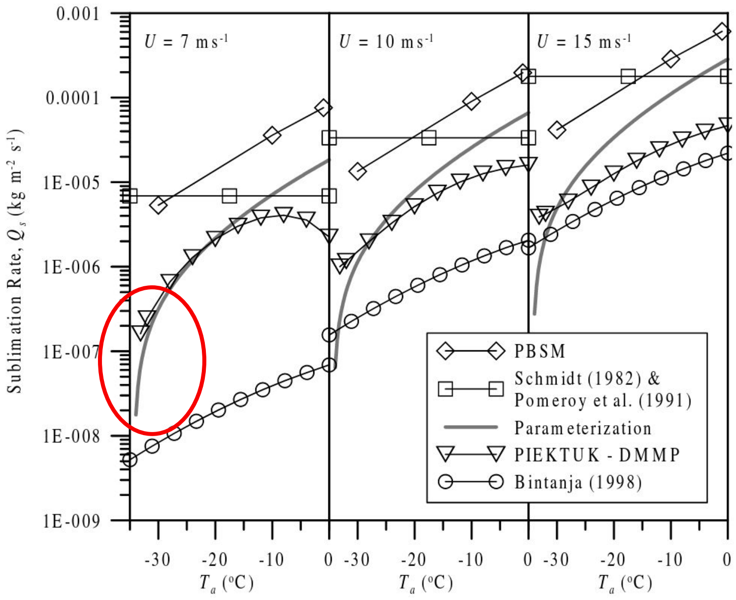


Arctic adaptation

- **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}):

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

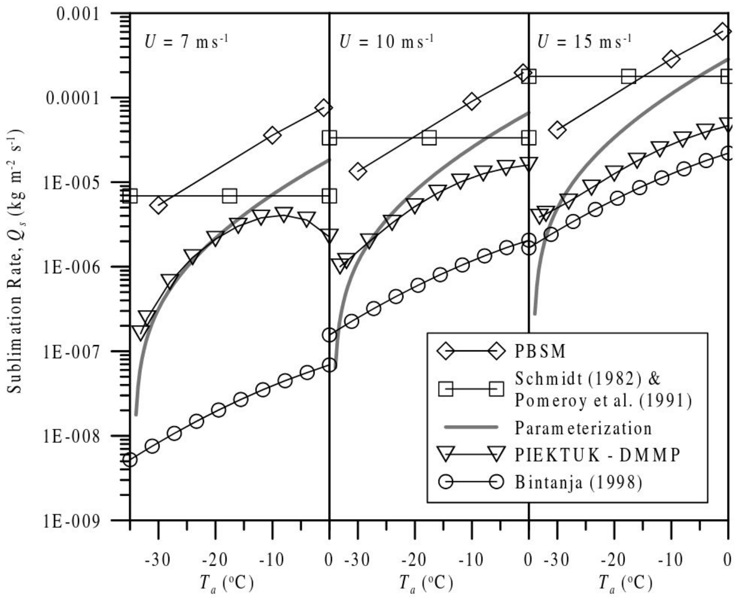
and

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

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

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

Arctic adaptation: Blowing snow sublimation losses



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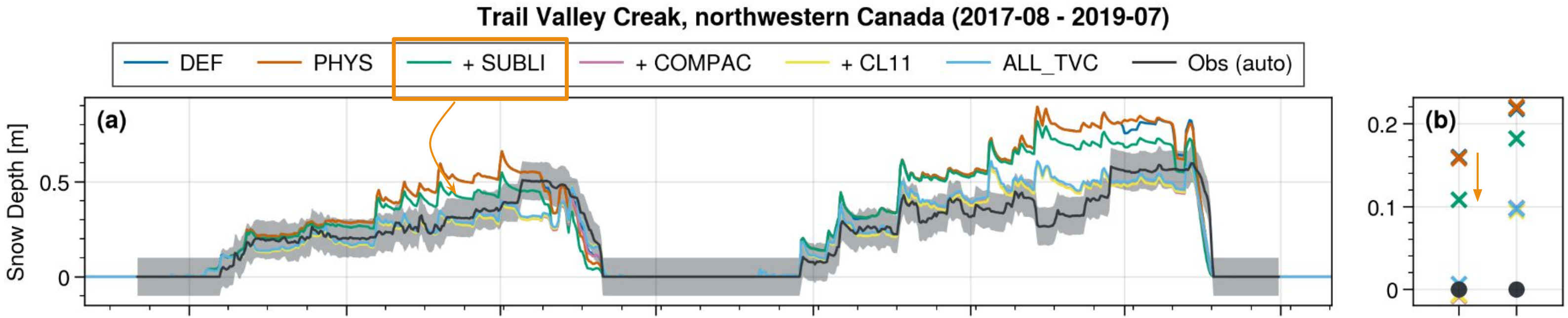

Arctic adaptation

→ 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

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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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#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)

Falling snow

Snow compaction

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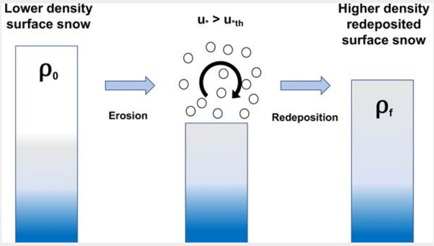
#3 Increasing compaction rate



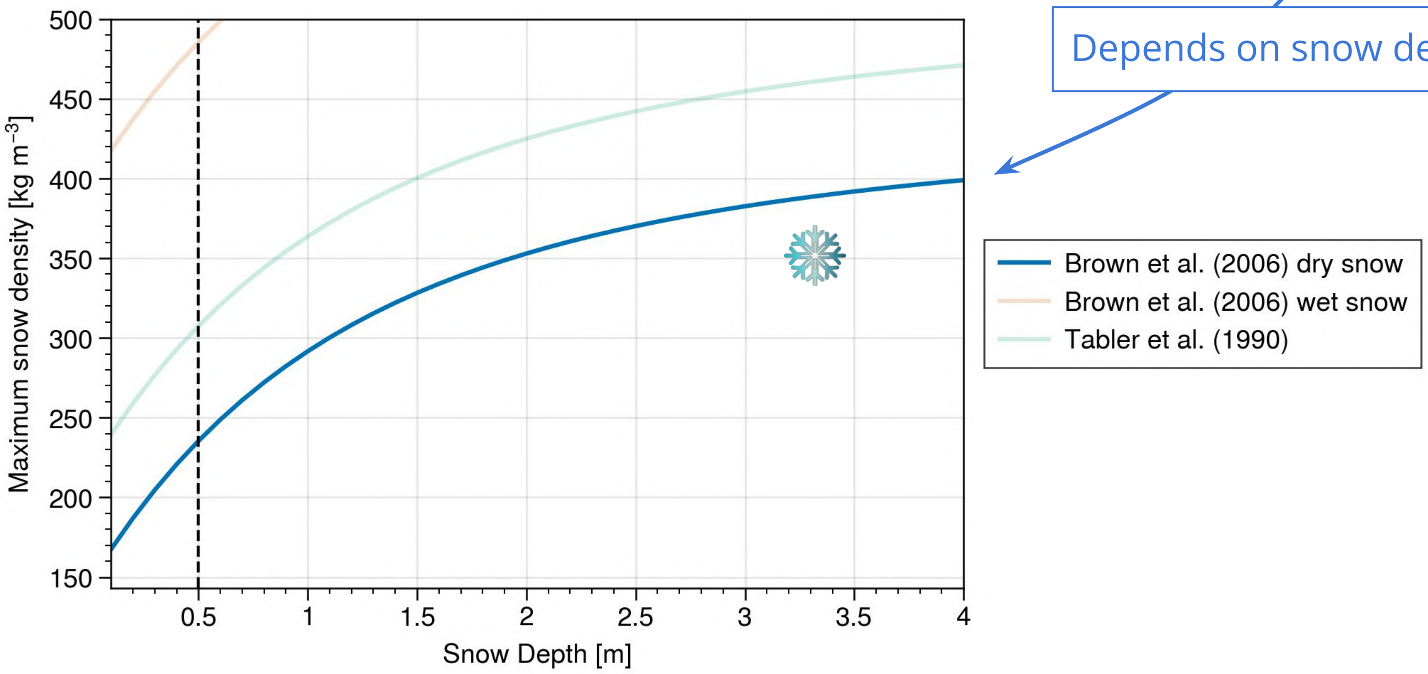
Source: Keenan et al. (2021)

Snow compaction in CLASSIC

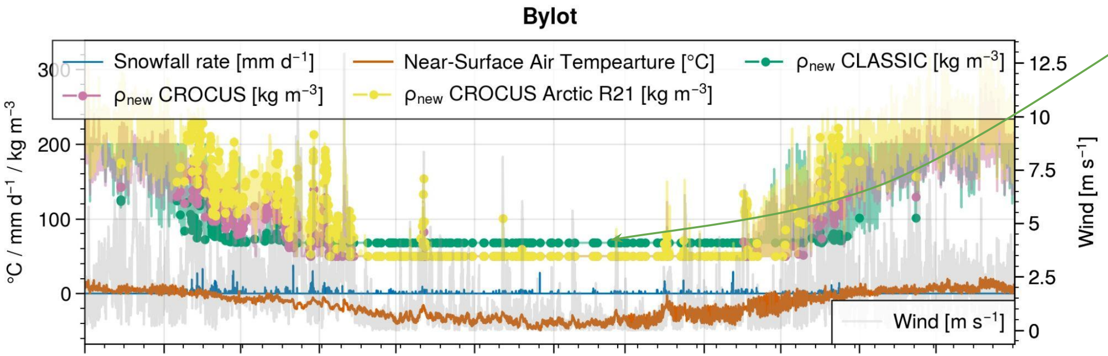
The snow density increase towards a ρ_{max} value as:

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

Depends on snow depth



Wind effect on snow compaction: fresh snow density



Fresh snow density in CLASSIC:

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

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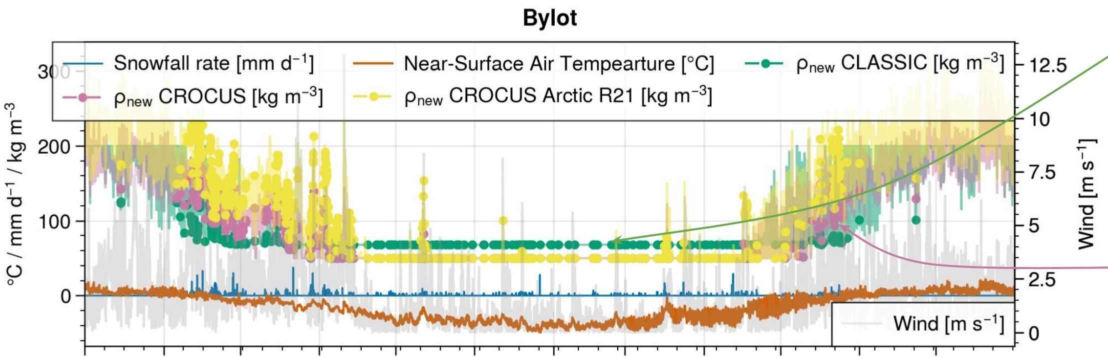

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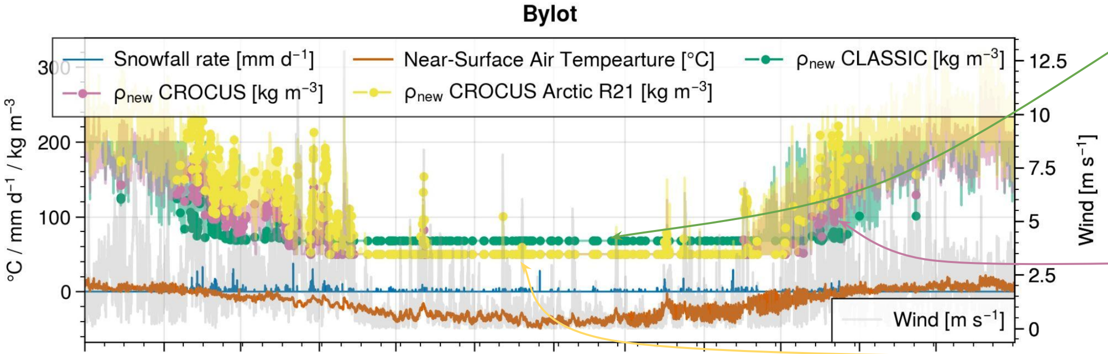
Fresh snow density in CROCUS:

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

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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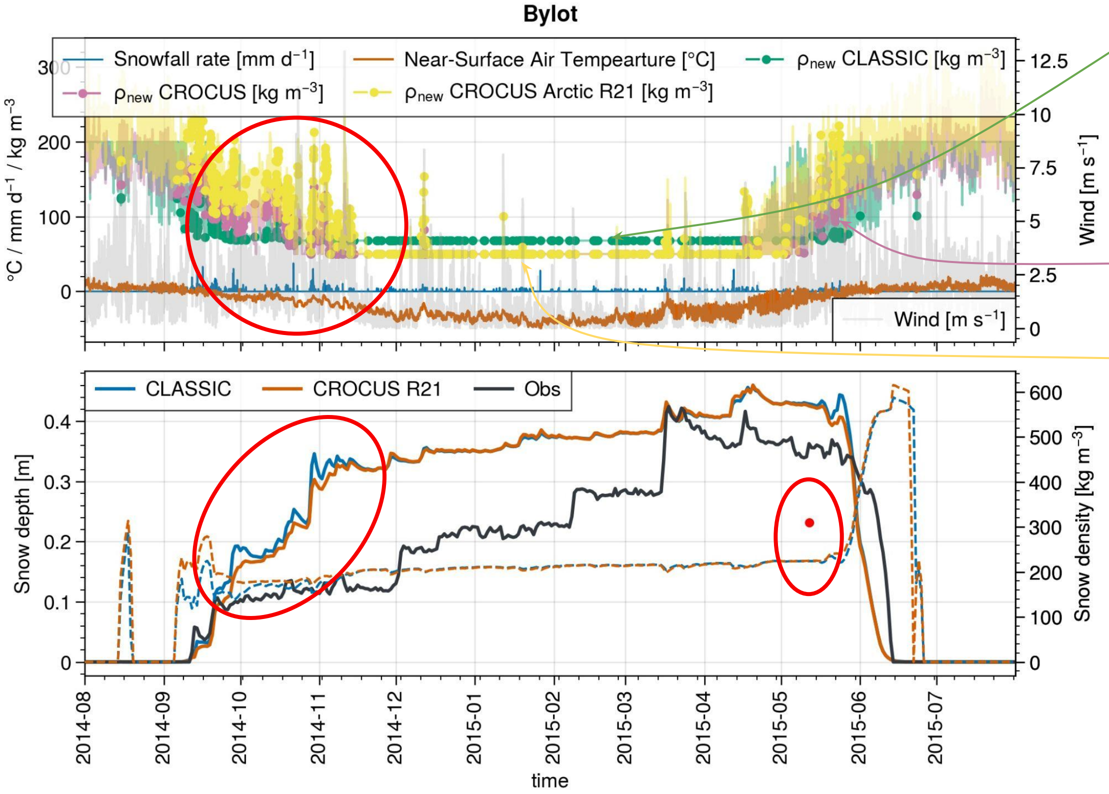

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Slight effect at the snow onset and melting but negligible effect on the snow depth and snow density over most of the snow season + deterioration at other SnowMIP sites (not shown).

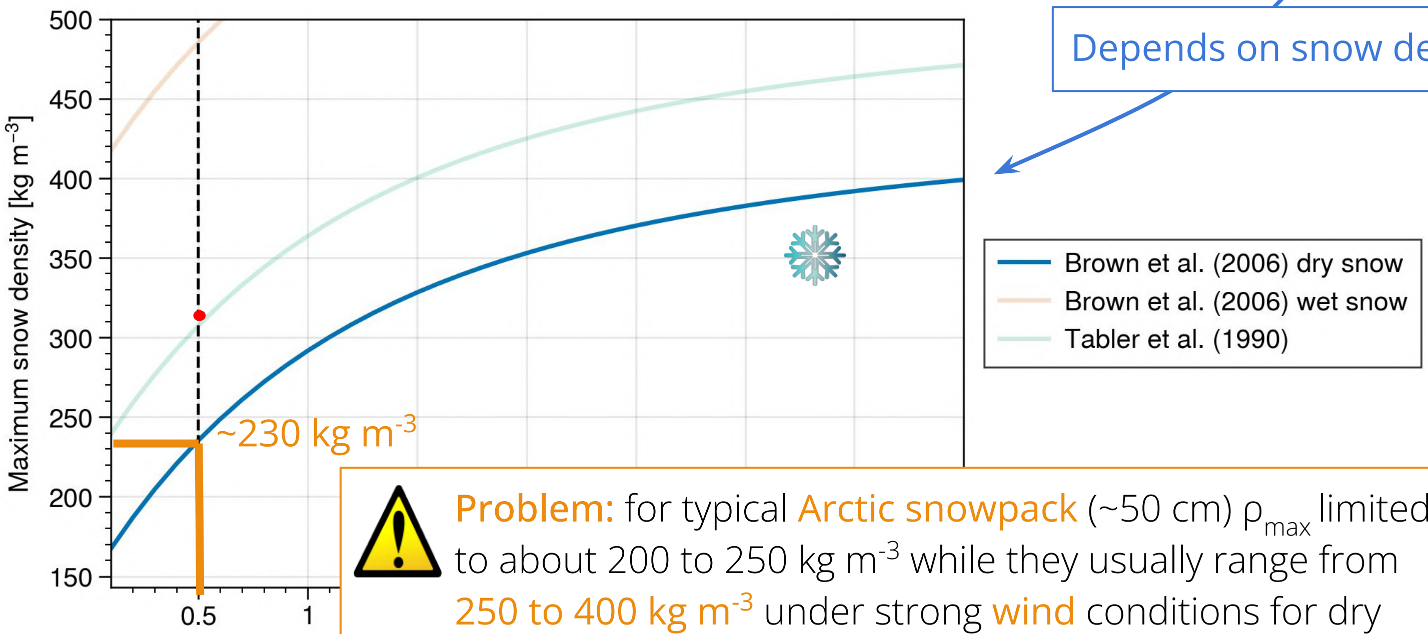
→ Snow density underestimated of about 50 to 100 kg m^{-3}

Wind effect on snow compaction: max snow density

The snow density increase towards a ρ_{max} value as:

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

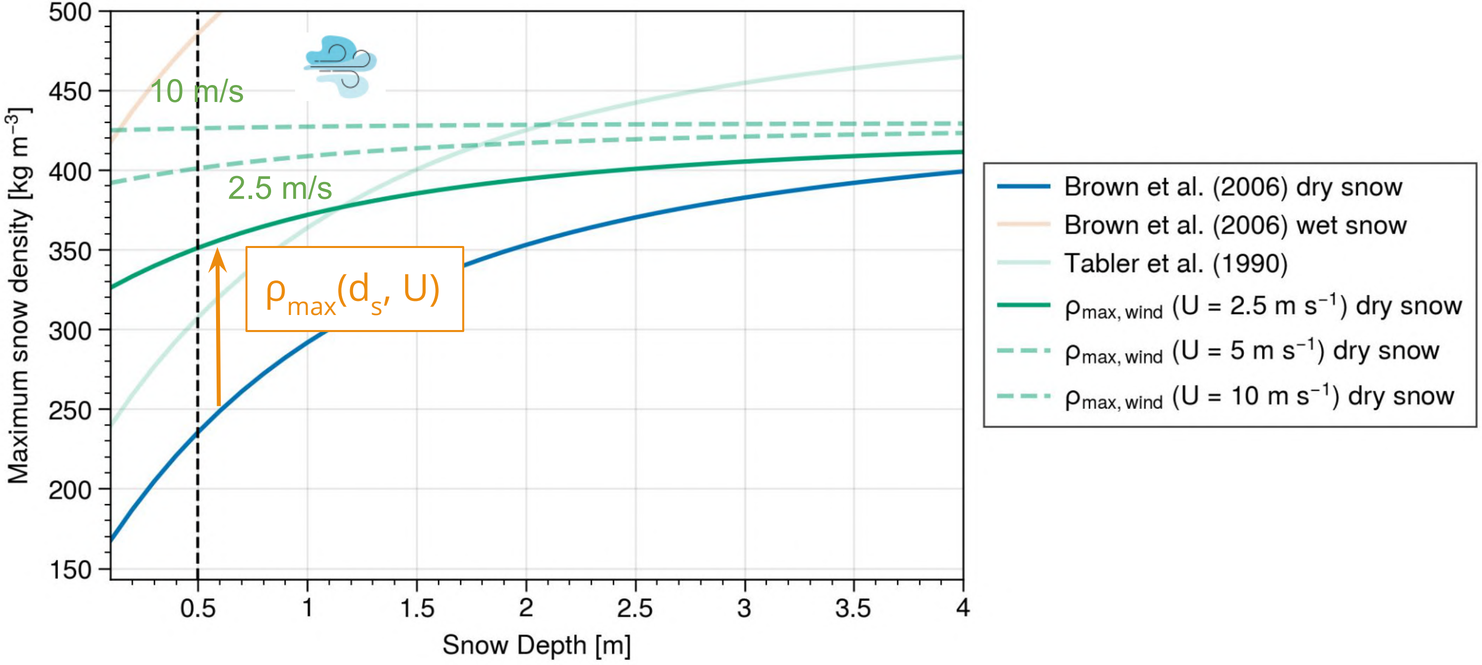
Depends on snow depth



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 strong wind conditions for dry snow (e.g., Domine et al., 2021; Royer et al., 2021a).

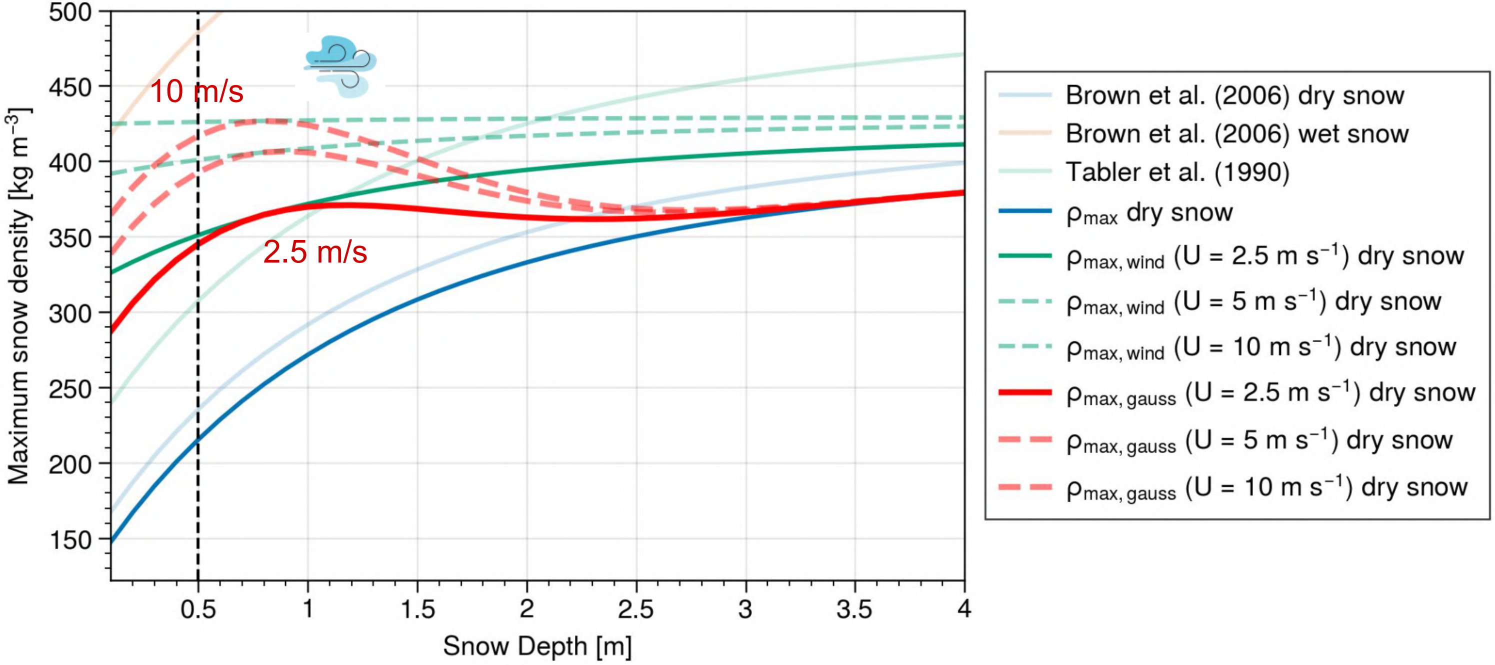
Wind effect on snow compaction: max snow density

The snow density increase towards a ρ_{max} value as: $\rho_s(t+1) = \left[\rho_s(t) - \rho_{s,max}\right] e^{-\frac{0.01\Delta t}{3600}} + \rho_{s,max}$



Wind effect on snow compaction: max snow density

The snow density increase towards a ρ_{max} value as: $$\rho_s(t+1) = \left[\rho_s(t) - \rho_{s,max}\right] e^{-\frac{0.01\Delta t}{3600}} + \rho_{s,max}$$



Snow compaction summary

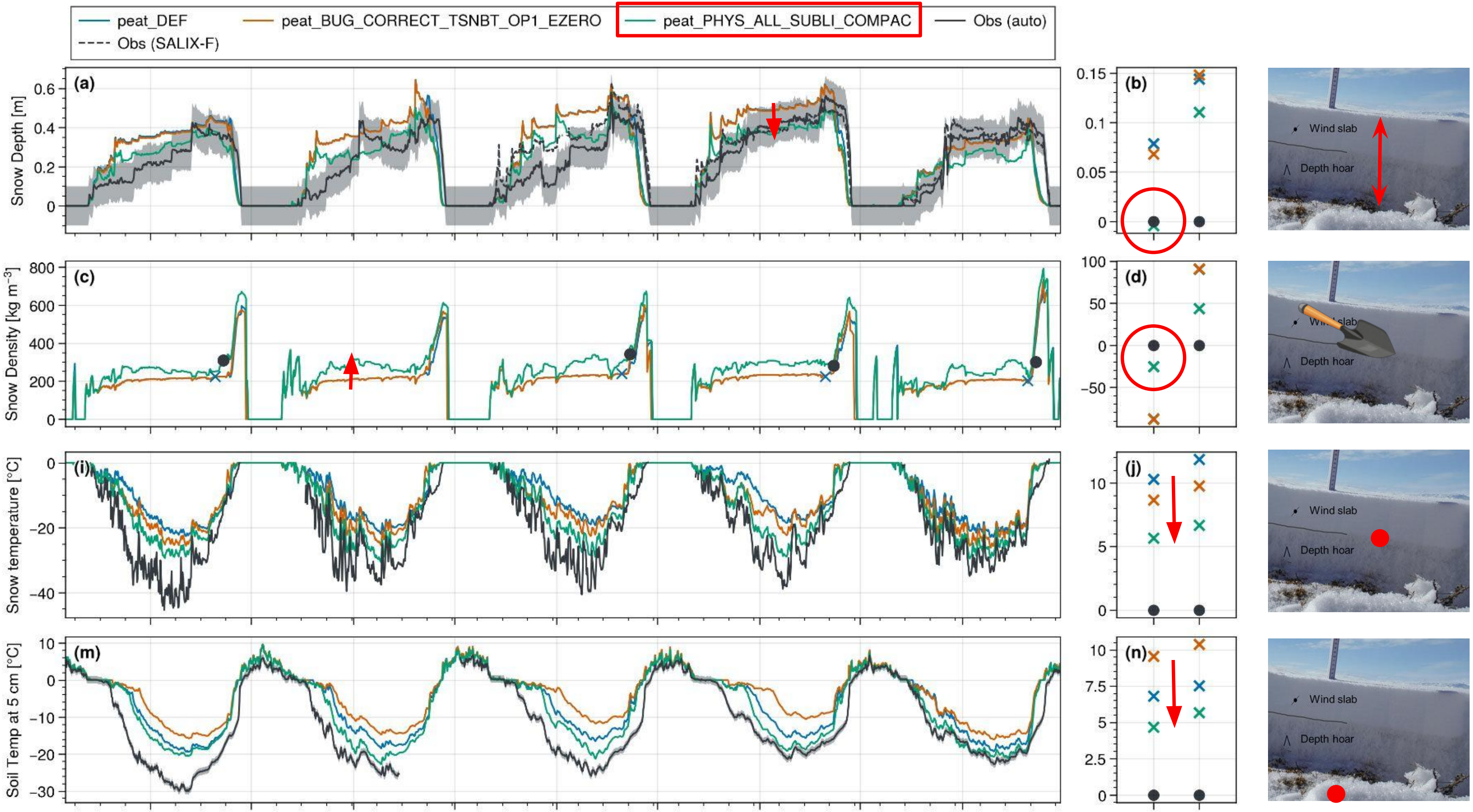
- Bulk effect of depth hoar + wind slab seems to increase the bulk snow density compared to the actual CLASSIC snow compaction scheme

- Increased bulk snow density taken into account through the maximum snow density **only**

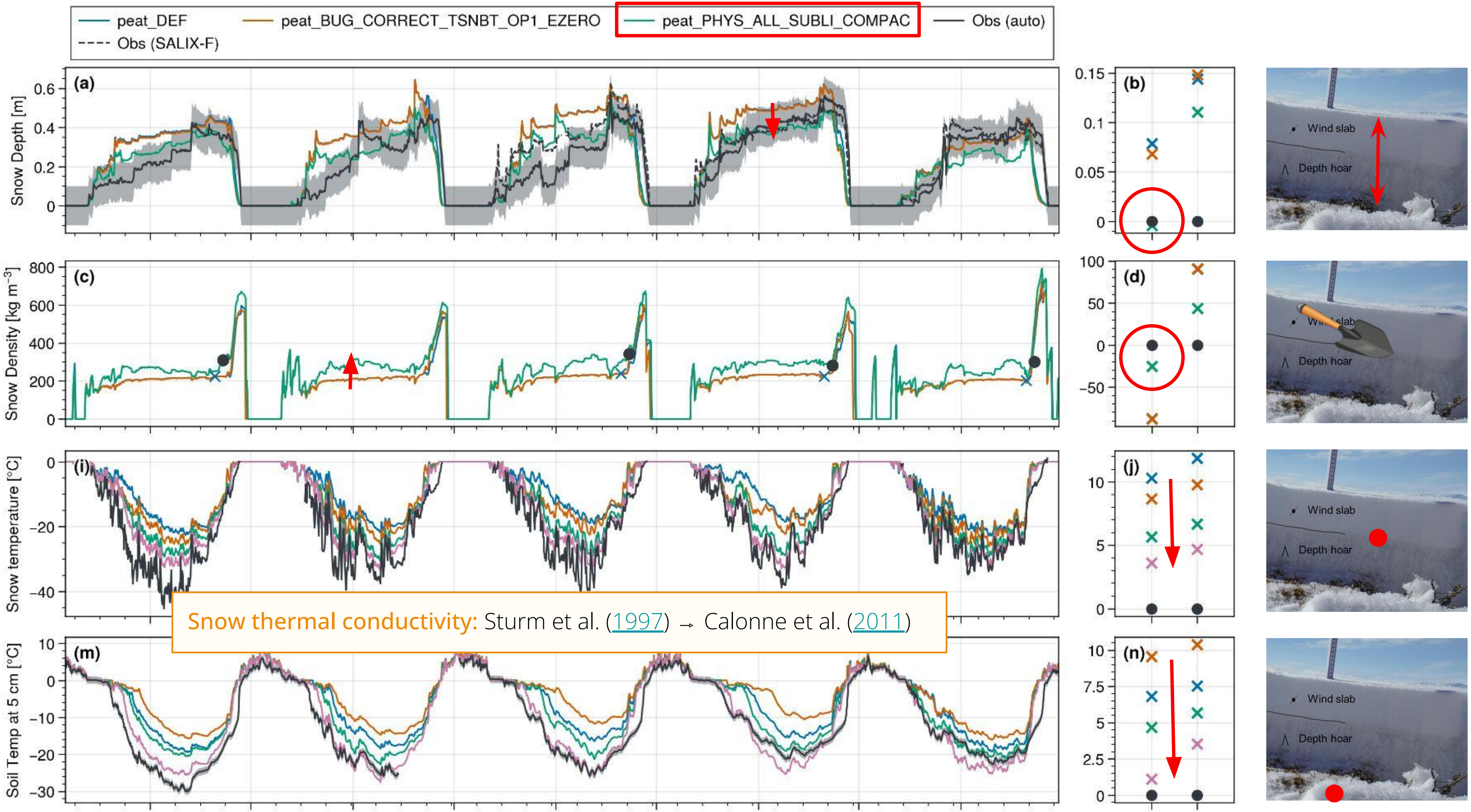
- Ideally we should better constrain and combine the fresh snow density, compaction rate, and max snow density in the future

Results

Example: Bylot example

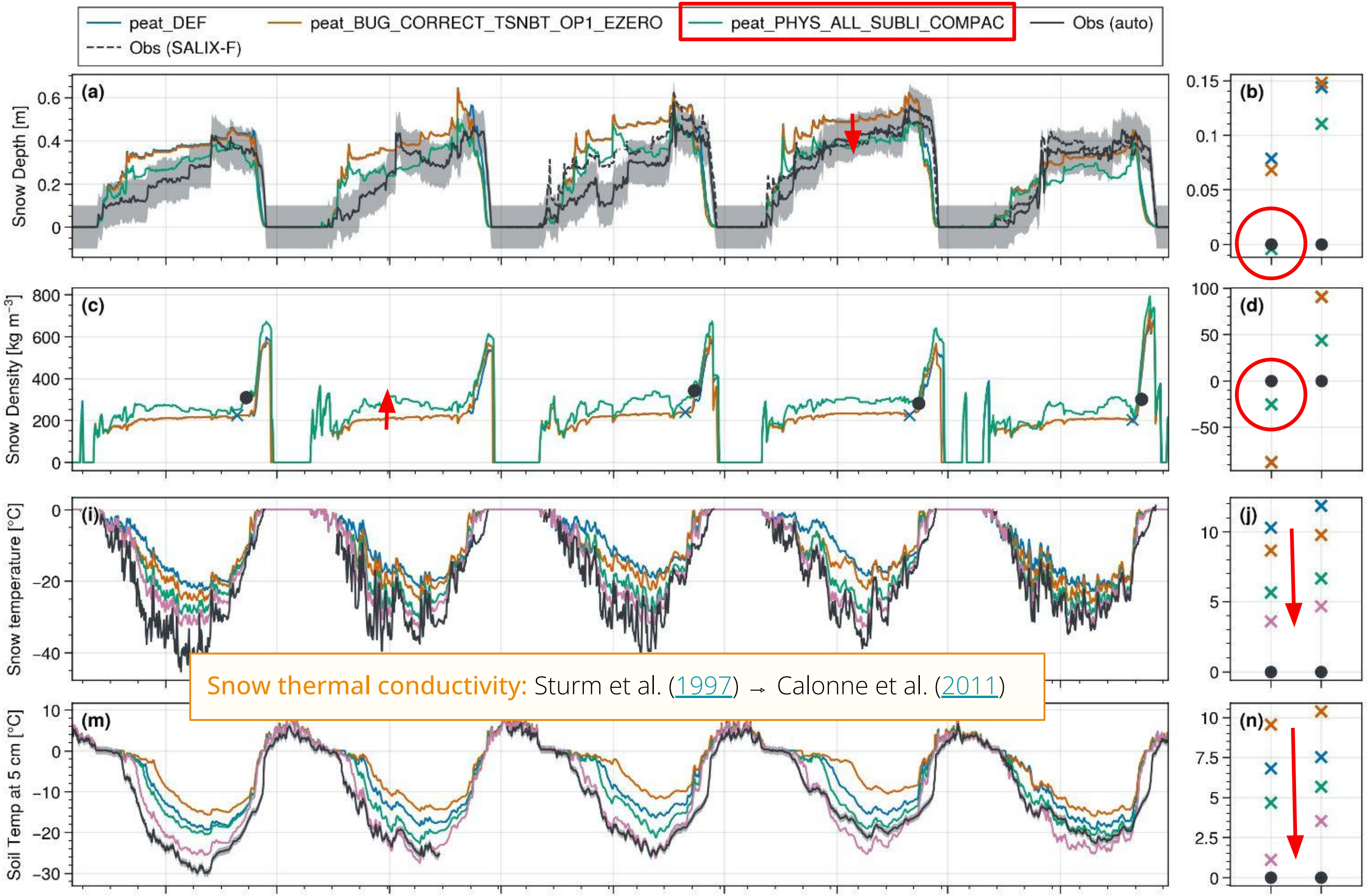


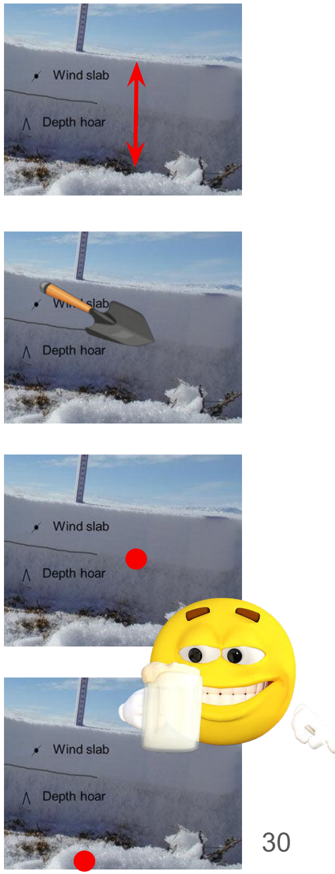
Example: Bylot example



Snow thermal conductivity: Sturm et al. (1997) → Calonne et al. (2011)

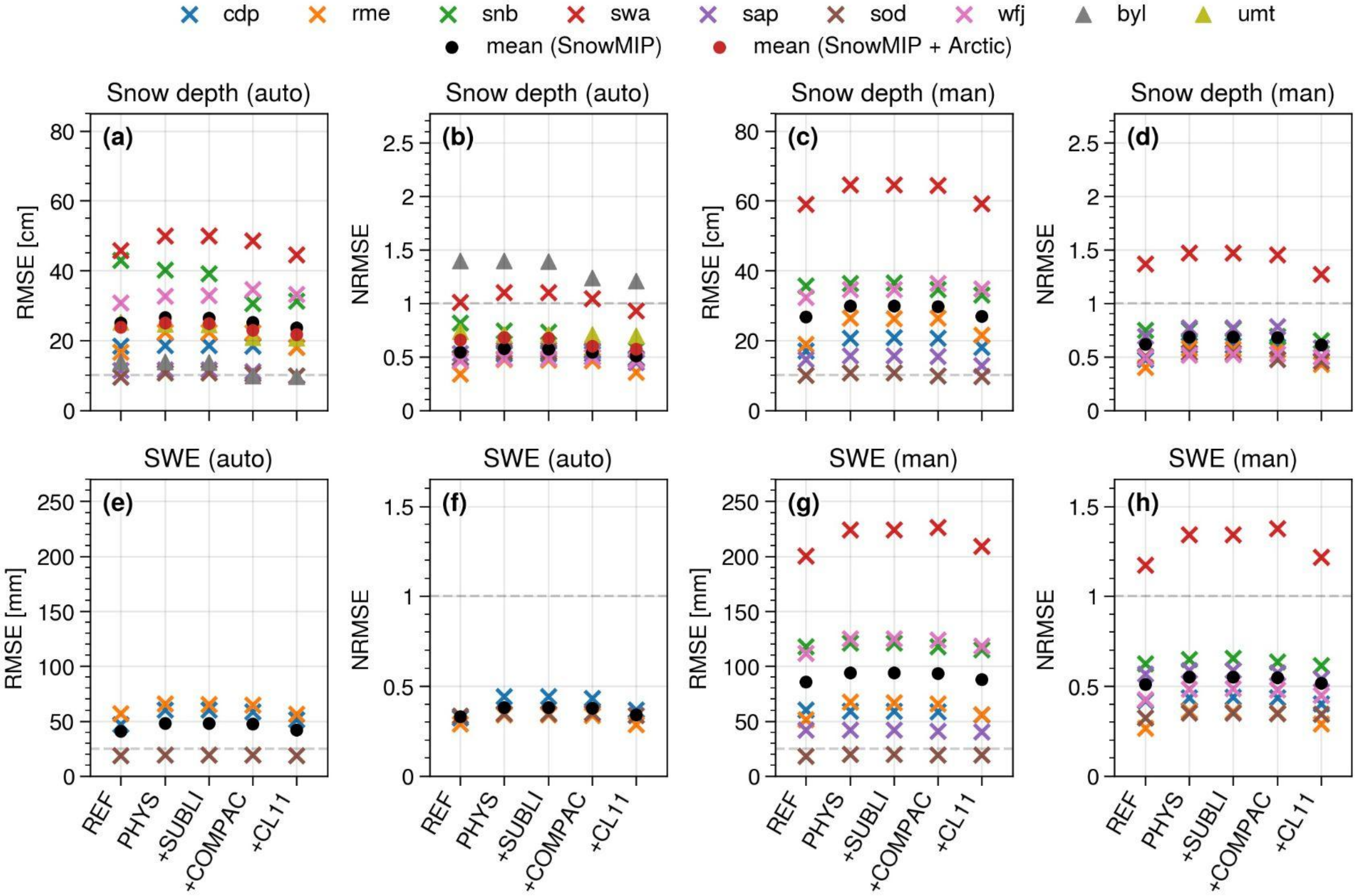
Example: Bylot example



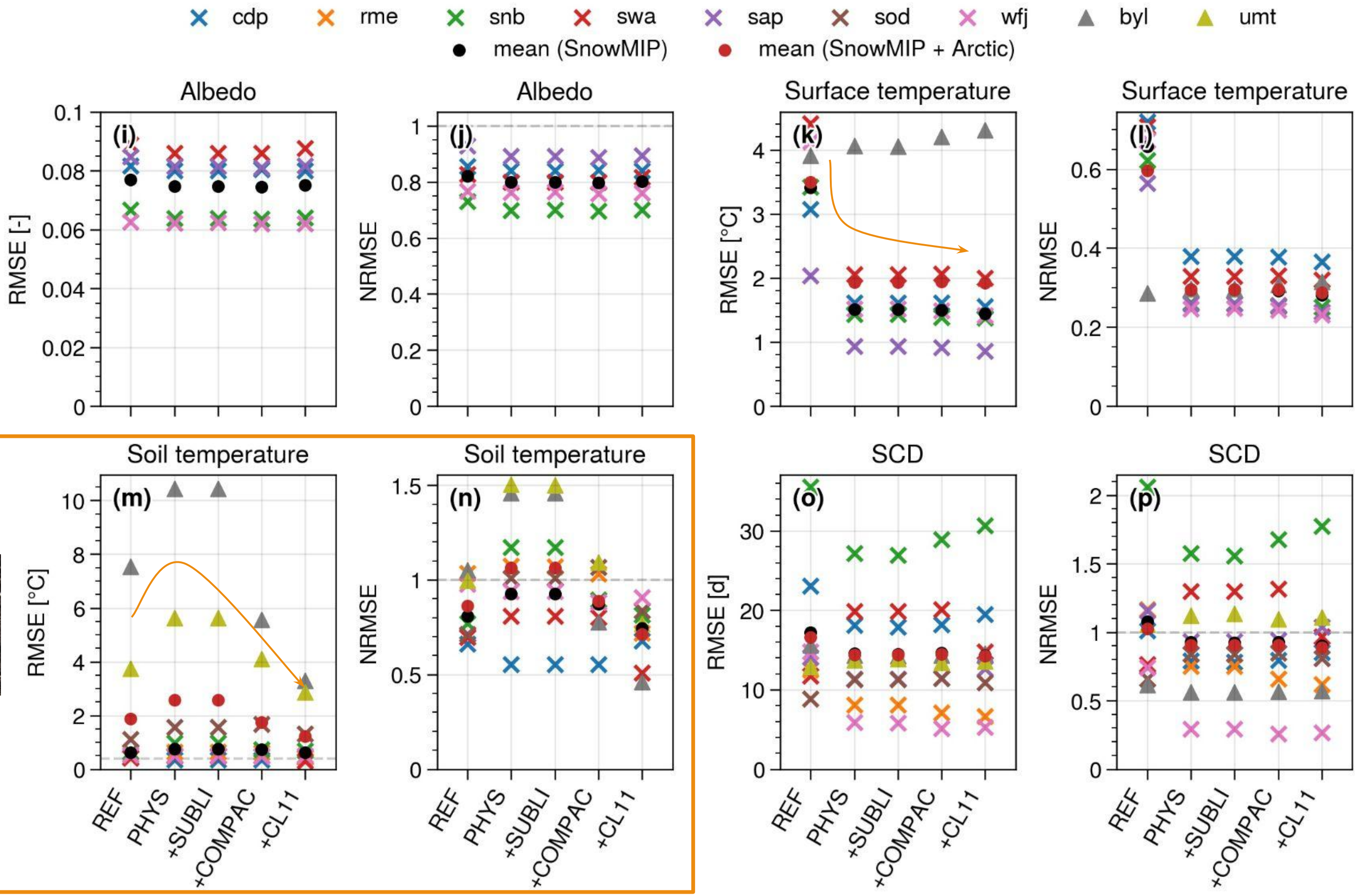


Snow thermal conductivity: Sturm et al. (1997) → Calonne et al. (2011)

Overall results at all sites: RMSE



Overall results at all sites: RMSE



Discussion and Conclusion

Discussion

Vegetation

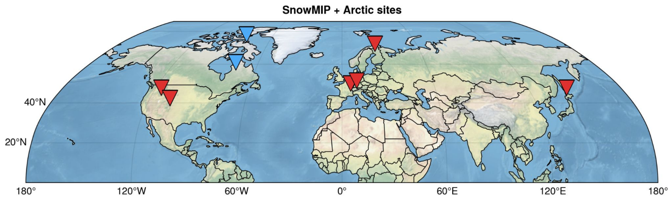
- Vegetation height (no small Arctic grass → issues about albedo, etc.)
- Vegetation bending not taken into account (exploit cameras?)
- Shrub's thermal bridge → can reduce the soil temp. by up to 4°C during cold spells (Domine et al., 2023)
- Moss/lichen not taken into account (use peat layer as a band-aid solution)
- Snow/soil interface thermal conductivity? (mix of bent vegetation, dead leaves, etc.)

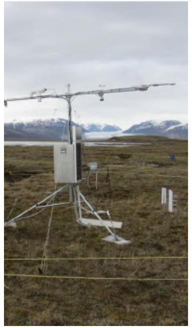
Snow

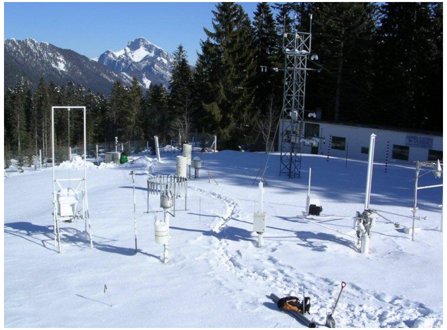
- Depth hoar not directly taken into account so possible limitation of our method
- SCF uncertainty (+ does it need to be activated or not for point scale simulation?)
- Single layer snowpack and the quadratic thermal profile within the snowpack might still be a limitation in certain case (warming/melting too fast?)
- We should better constrain and combine the fresh snow density, compaction rate, and ρ_{max}
- Light-absorbing particles not taken into account → revise compaction scheme

Take home message

- Improved simulated snowpack in CLASSIC at both SnowMIP and Arctic sites!
- Snow depth biases reduced from 11.1 to 0.2 cm at the Arctic sites.
- Improved simulated snow density and temperature.
- Reduces the RMSE of the simulated soil temperatures from 5.2 °C to 3.1 °C on average at all Arctic sites.
- Simulate better soil temperature → winter carbon fluxes.
- Still uncertainties related to vegetation, soil properties, snow drifts, precip, etc. + need more snow Arctic obs sites!
- Future studies over the whole Arctic with spatial simulation + new SCF parameterizations.







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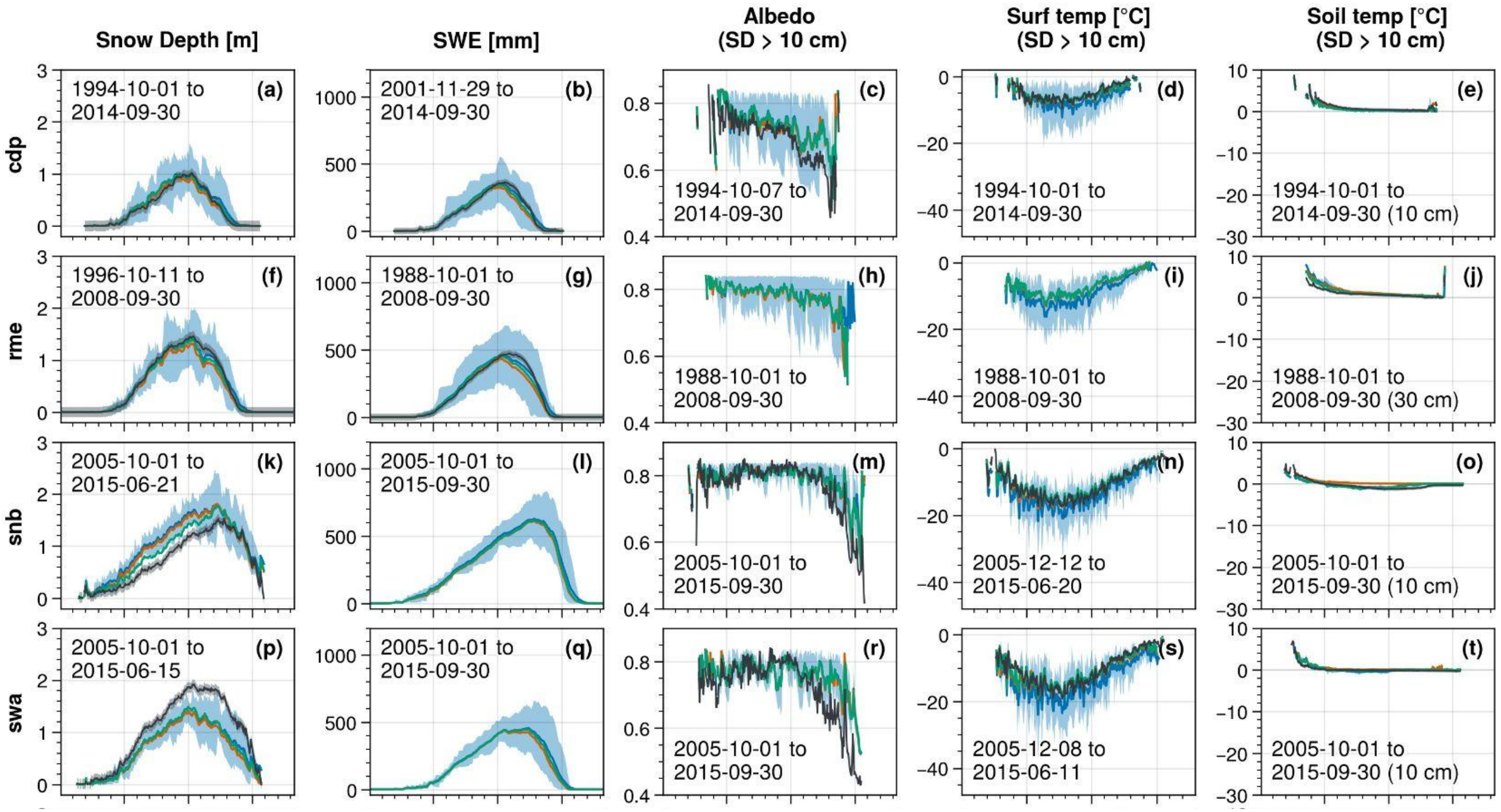
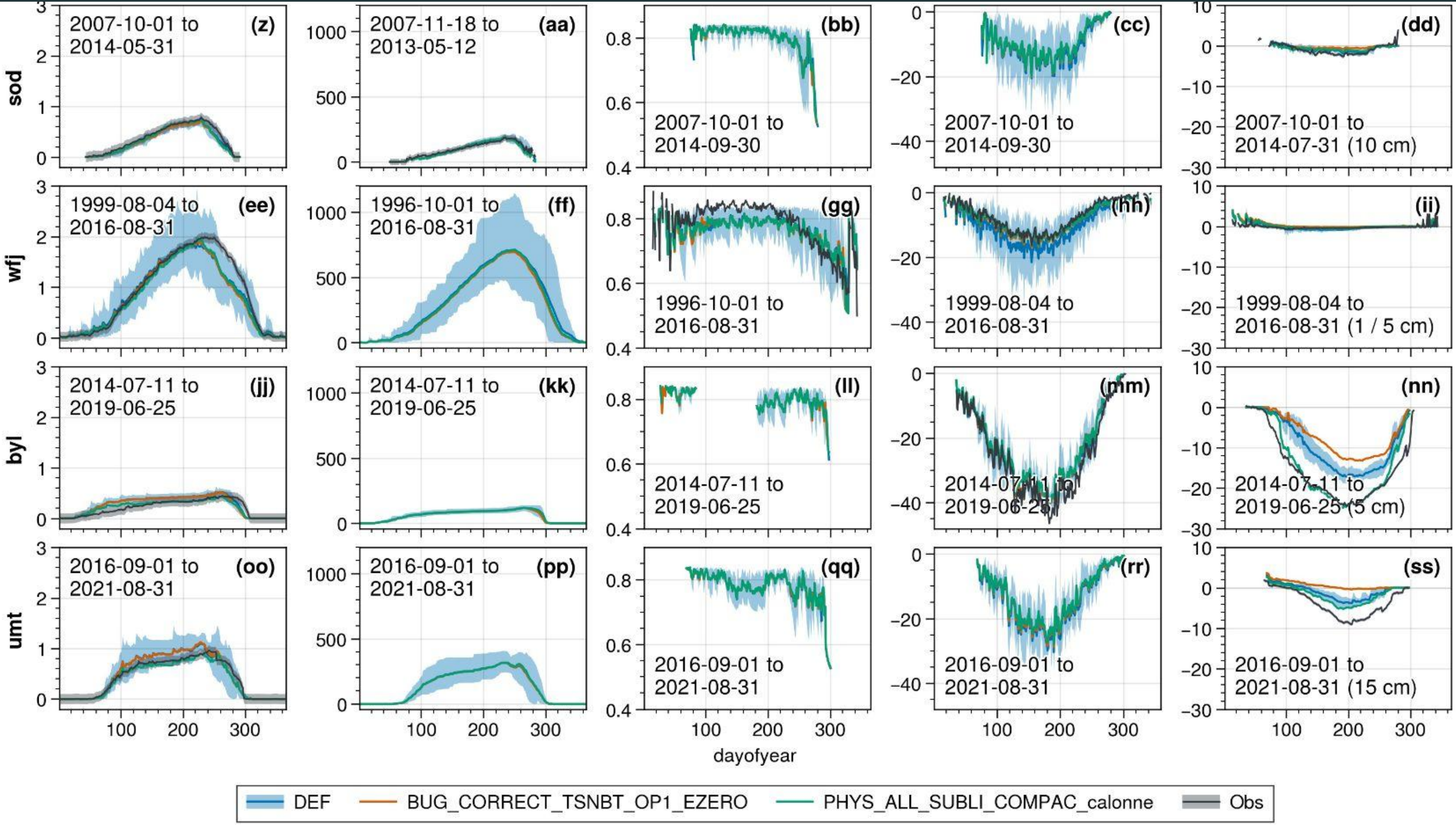
Supplementary materials

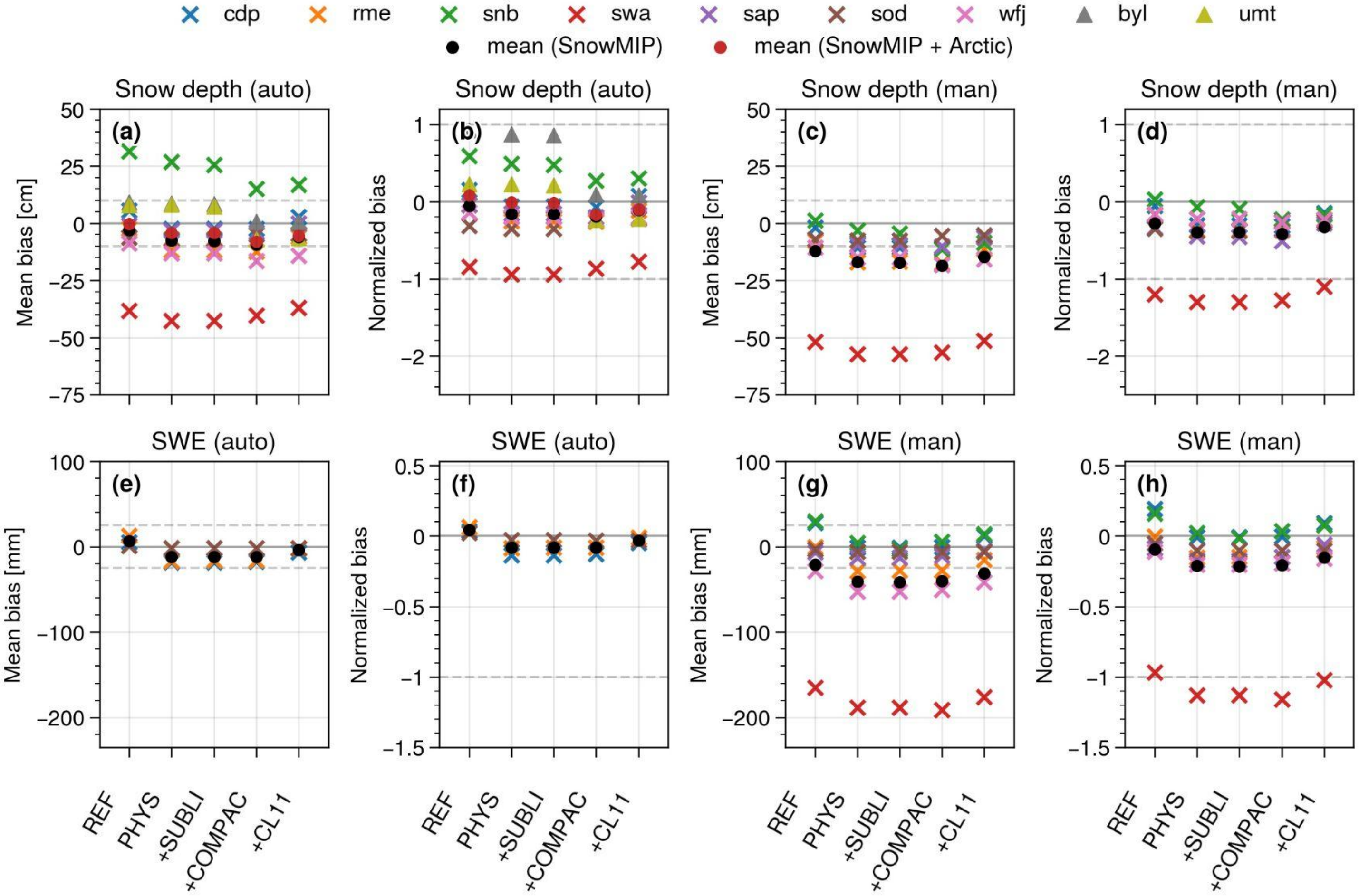
Physics + Arctic improvements: synthesis



Physics + Arctic improvements: synthesis



Overall results at all sites: MB



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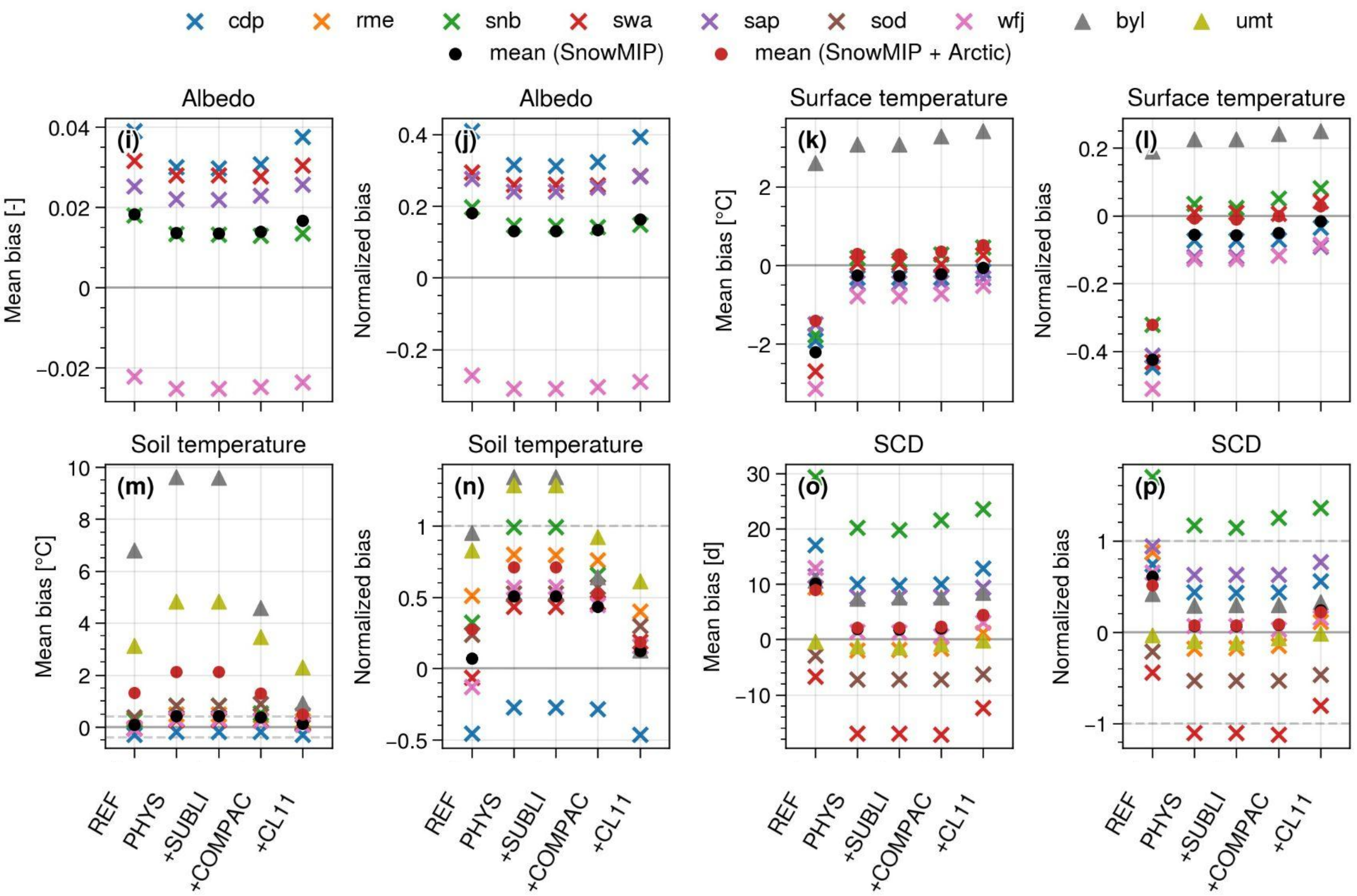
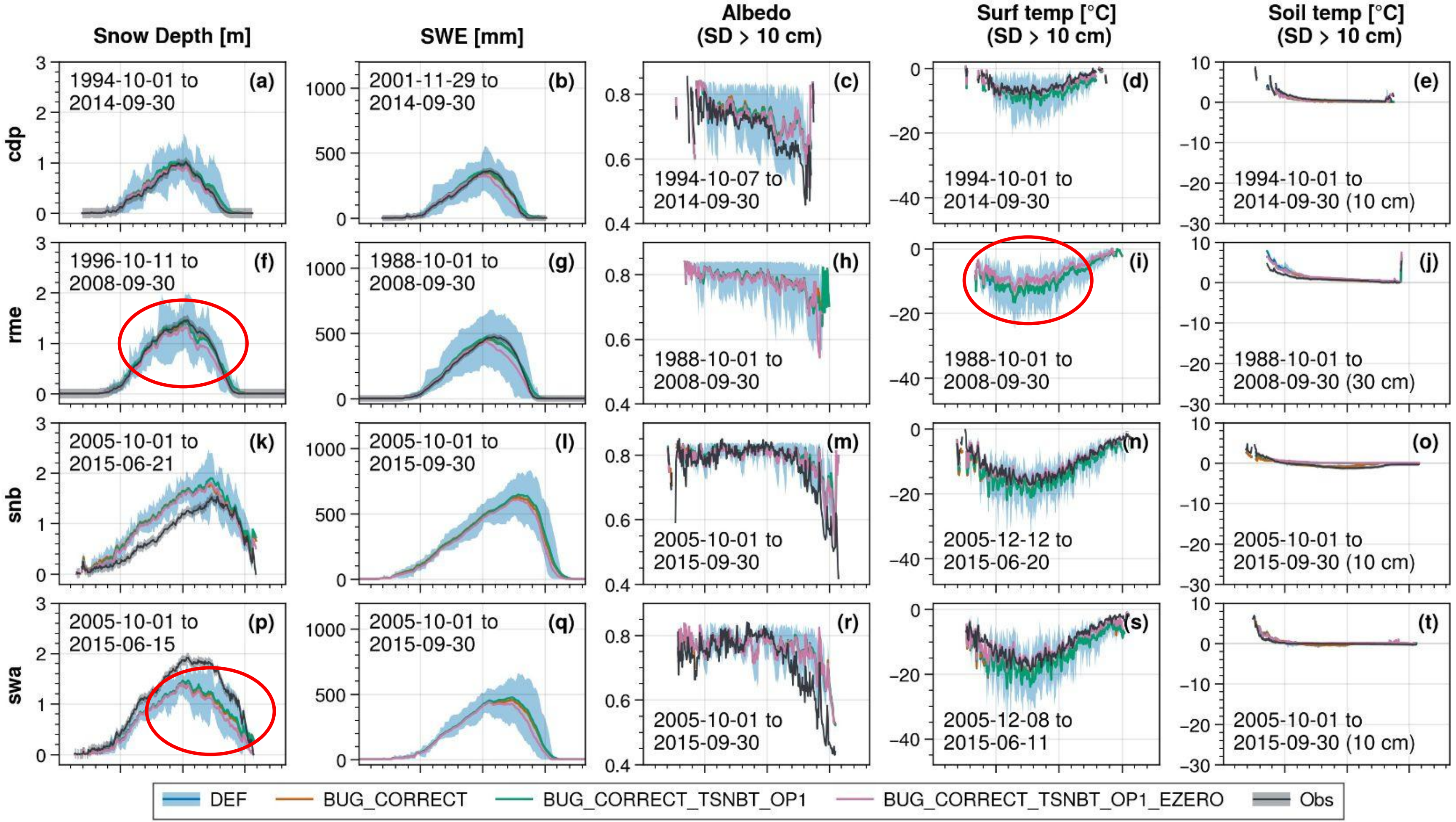
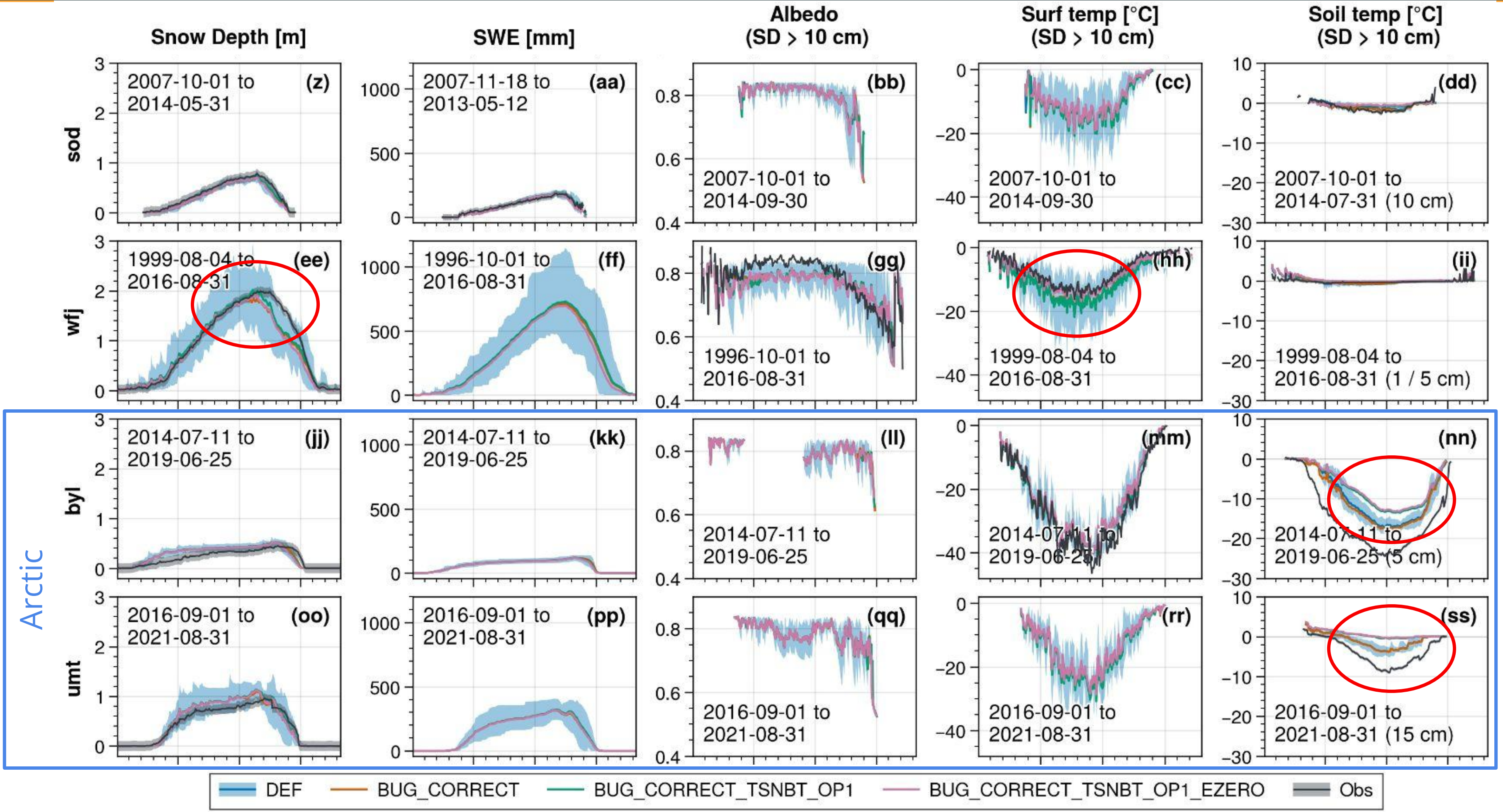


Physics improvements: synthesis



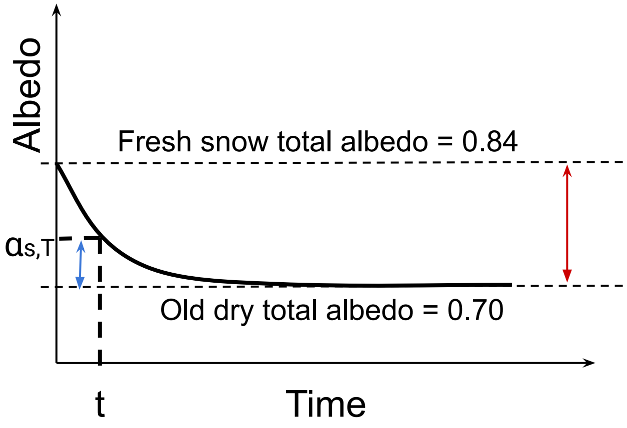
Physics improvements: synthesis

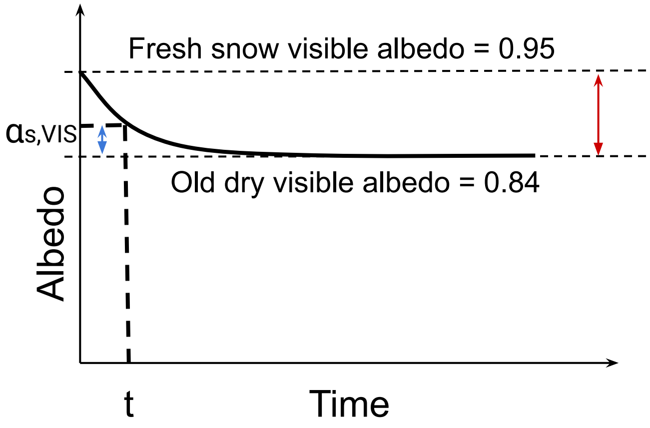


Methods: CLASSIC snow model (albedo)

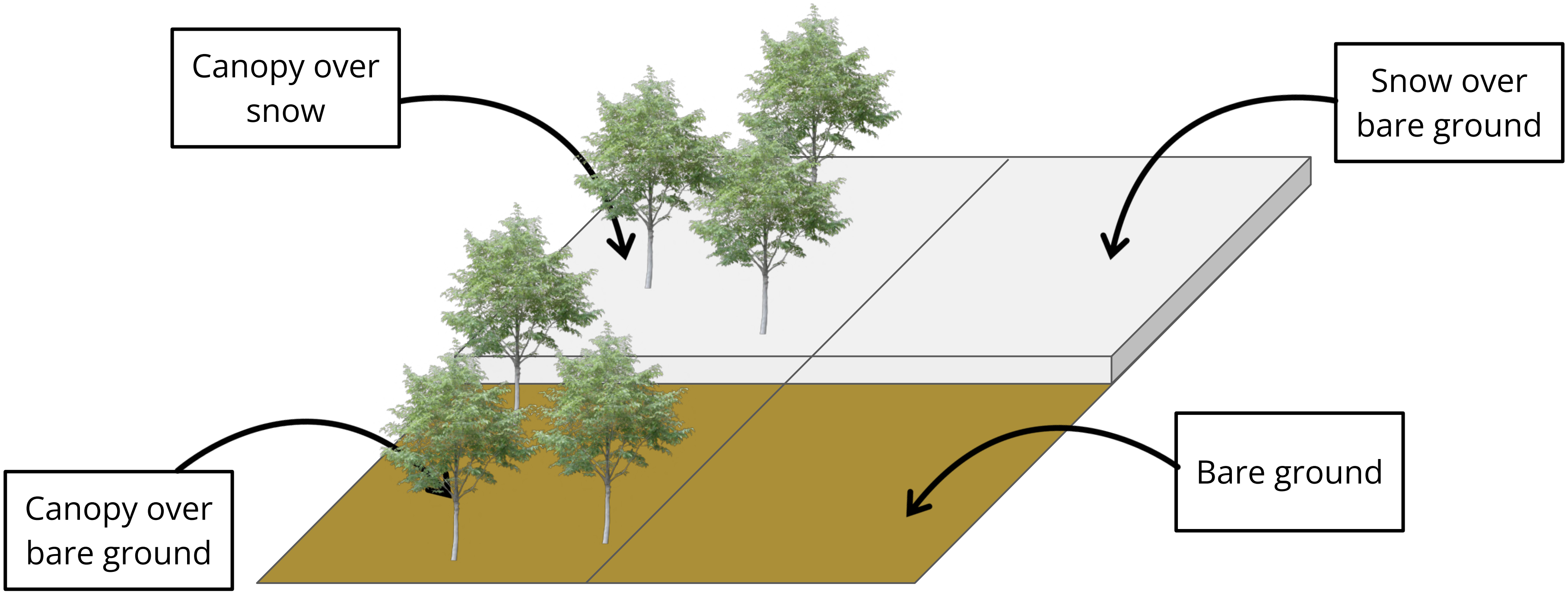
$$\alpha_s(t+1) = \left[\alpha_s(t) - \alpha_{s,old}\right] e^{-\frac{0.01\Delta t}{3600}} + \alpha_{s,old}$$

	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



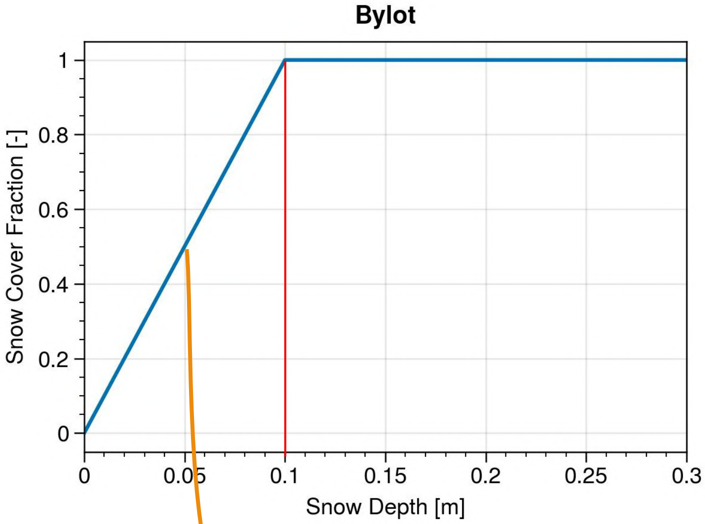


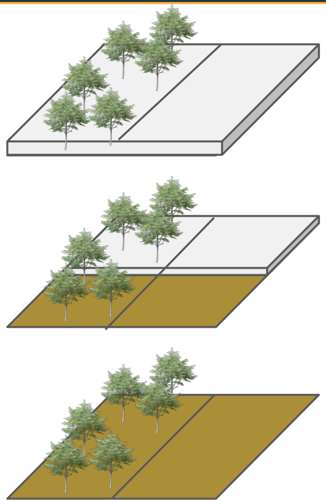
Context: CLASSIC subgrid areas



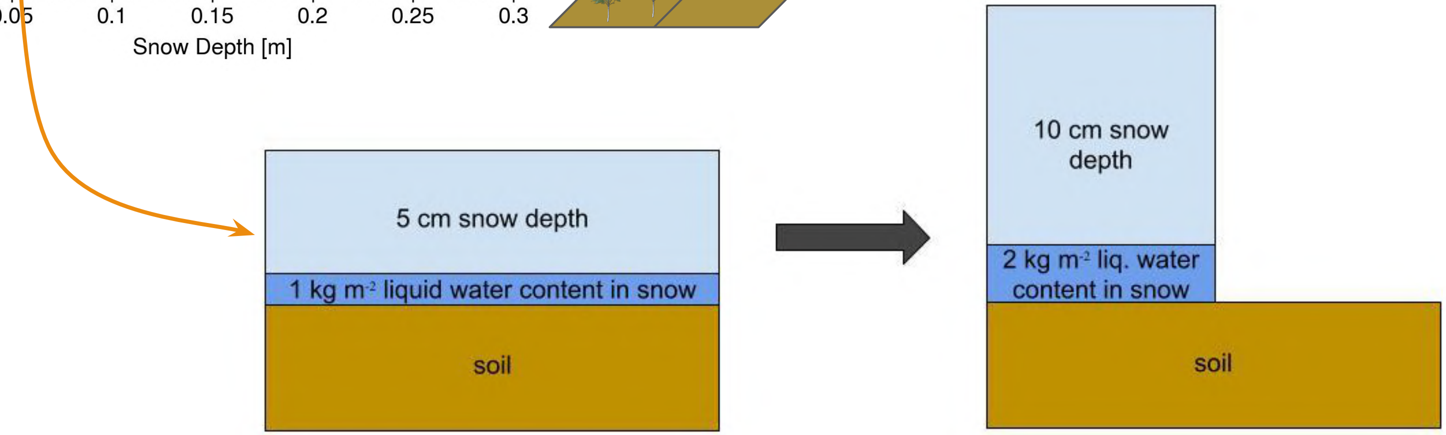
→ Evolve dynamically (depending on vegetation height, snow depth, etc.)

Context: CLASSIC snow cover fraction

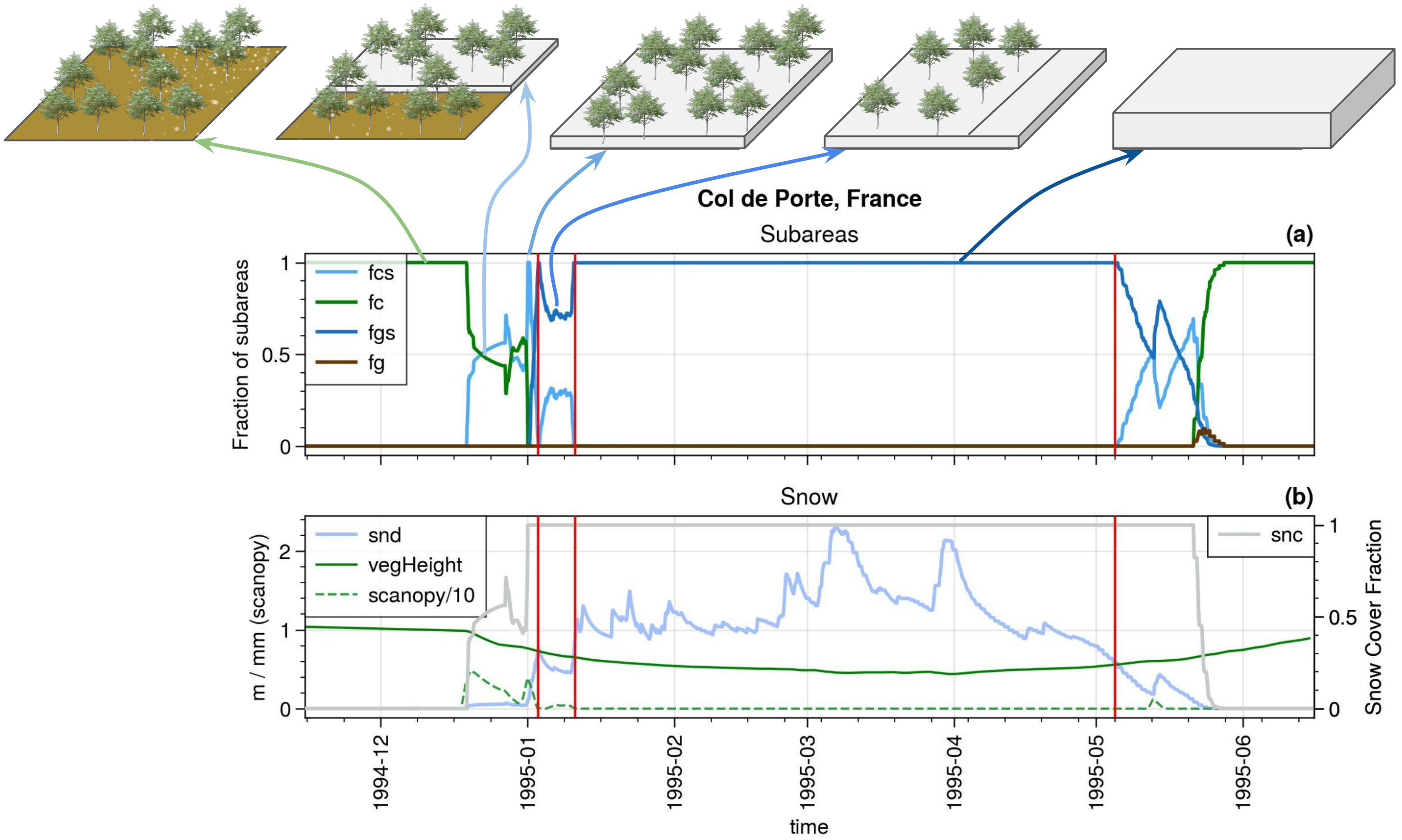




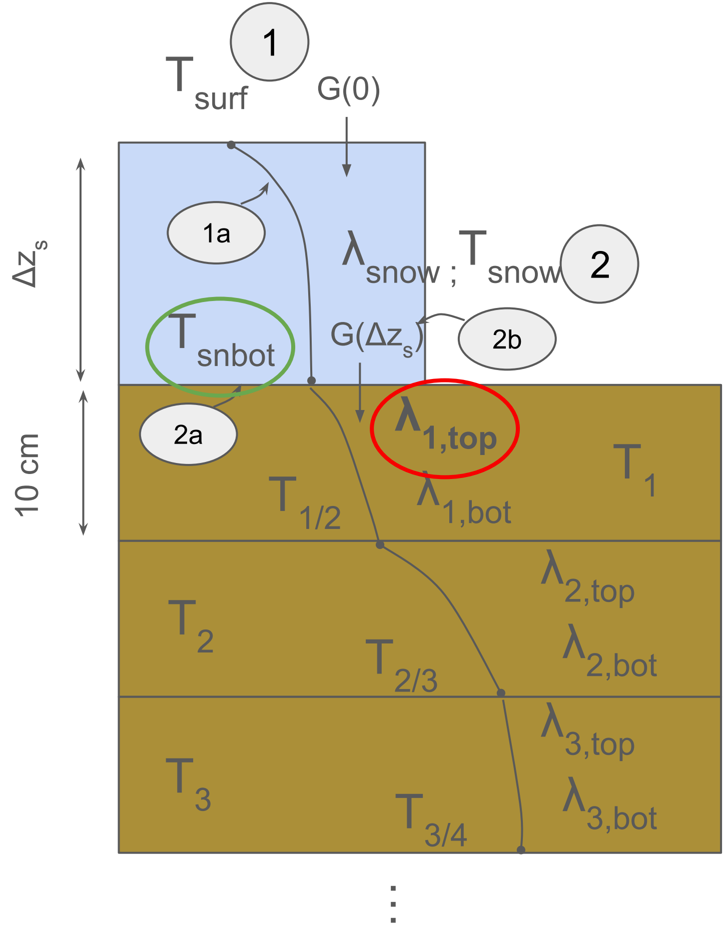
/!\ Min snow depth: 10 cm
(for model stability) /!\



Context: dynamic subareas evolution



Context: CLASSIC snow model physics (radiation)



1. Surface energy budget: $K_*+L_*-Q_H-Q_E-G(0) = 0$
   a. G(0) derived from the hypothesized quadratic temperature profile (depend only on T(0) + λ_{snow})
   b. + hypothesis: $G(\Delta z_s)=0 \rightarrow T_{surf}$
2. Computation of the snow temperature:
   a. Estimate bottom snow temperature
      TSNBOT(I) = (ZSNOW(I) * TSNOW(I) + DELZ(1) * TBAR(I,1)) / (ZSNOW(I) + DELZ(1))
   b. Compute $G(\Delta z_s)$ (same as for G(0))
   c. $\Delta T_s = [G(0) - G(\Delta z_s)]\Delta t/(C_s \Delta z_s)$

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.