45e Colloque annuel du CEN 2025

13 February 2025

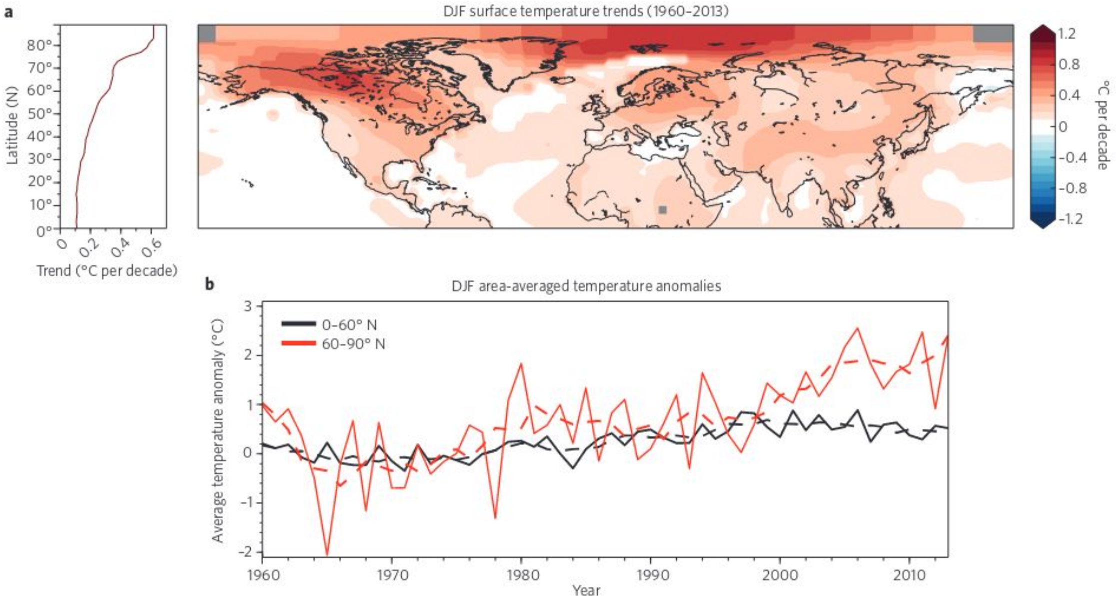
Improving the CLASSIC Snow Model to Better Simulate Arctic Snowpacks

Mickaël Lalande

Postdoc at UQTR / RIVE / GLACIOLAB

ESA CCI Fellowship (SnowC²) — 01/10/2023 to 30/09/2025 (2 years)

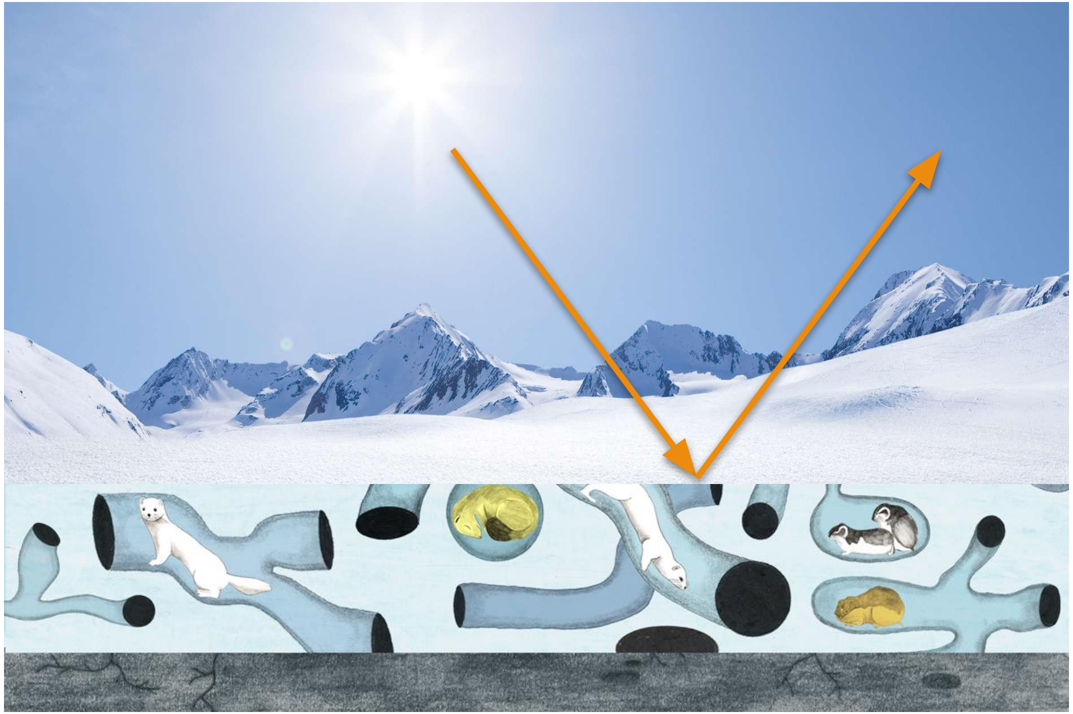
supervised by Christophe Kinnard and Alexandre Roy



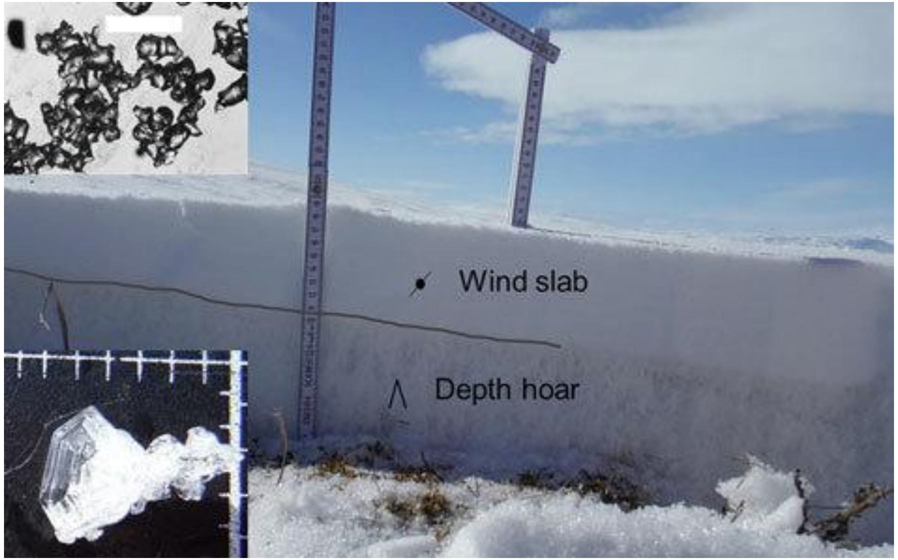
Cohen et al., (2014)

- 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



Current snow models cannot simulate Arctic snowpacks!



Domine et al., (2019)

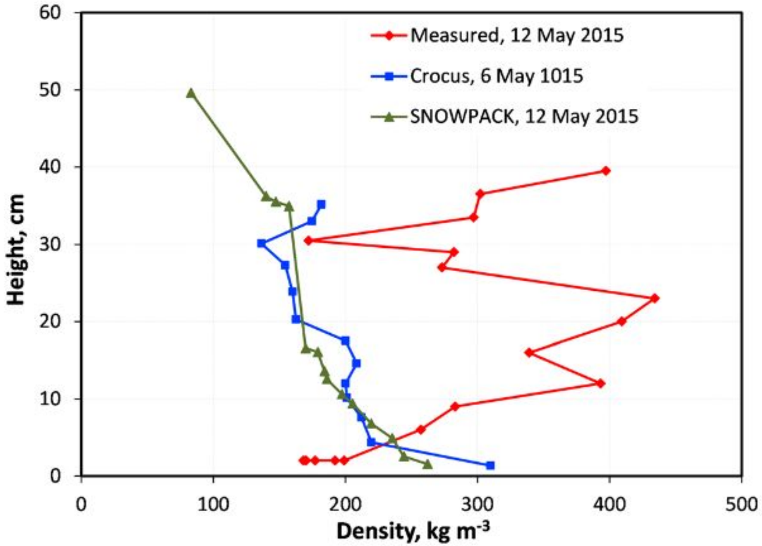


Figure 3. Comparison of measured snow density profiles at Bylot Island in May 2015 with those simulated using the detailed snow models Crocus and SNOWPACK. Crocus runs of 6 May are shown because Crocus simulates melting on 7 May, and this extra process makes comparisons irrelevant on 12 May.

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

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

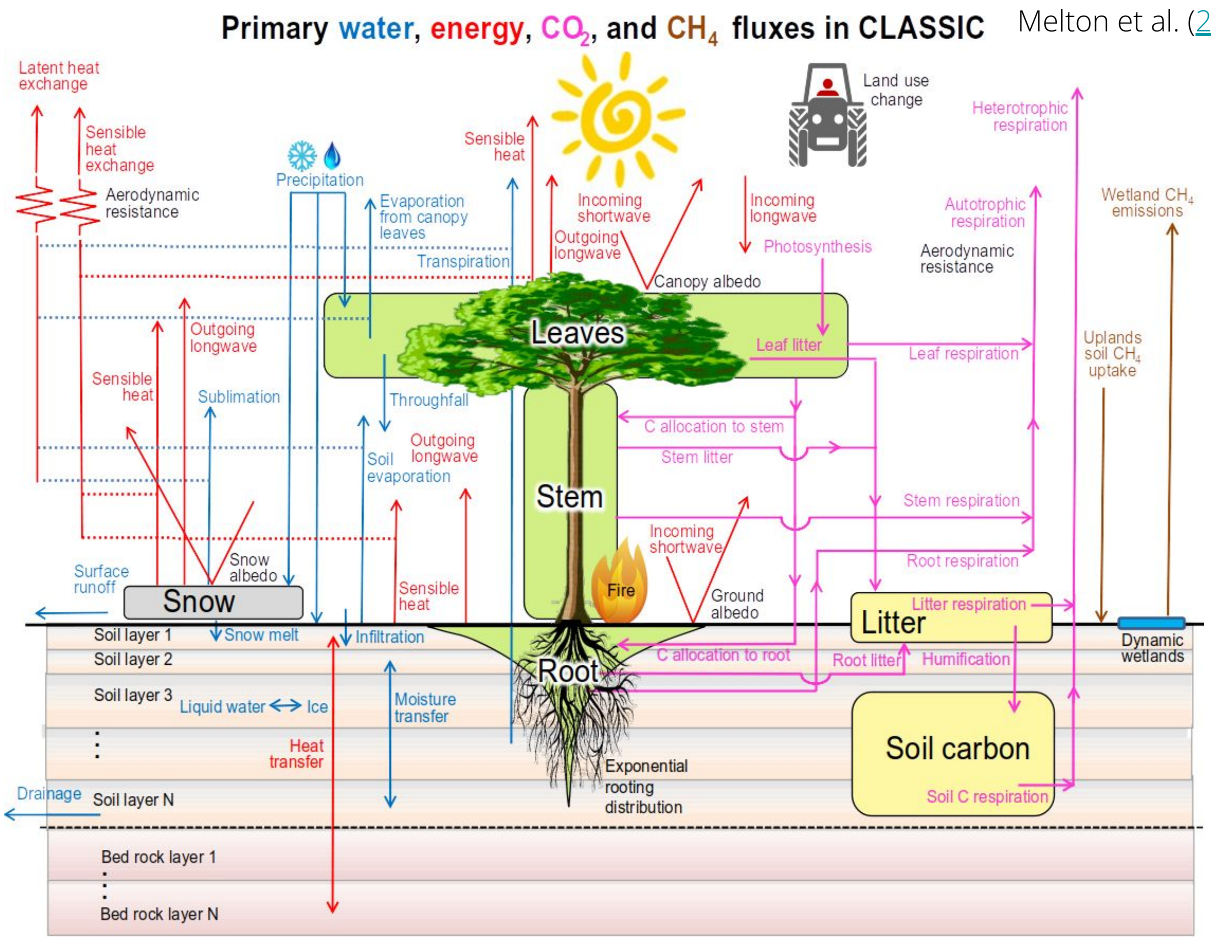
Practical solution

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...

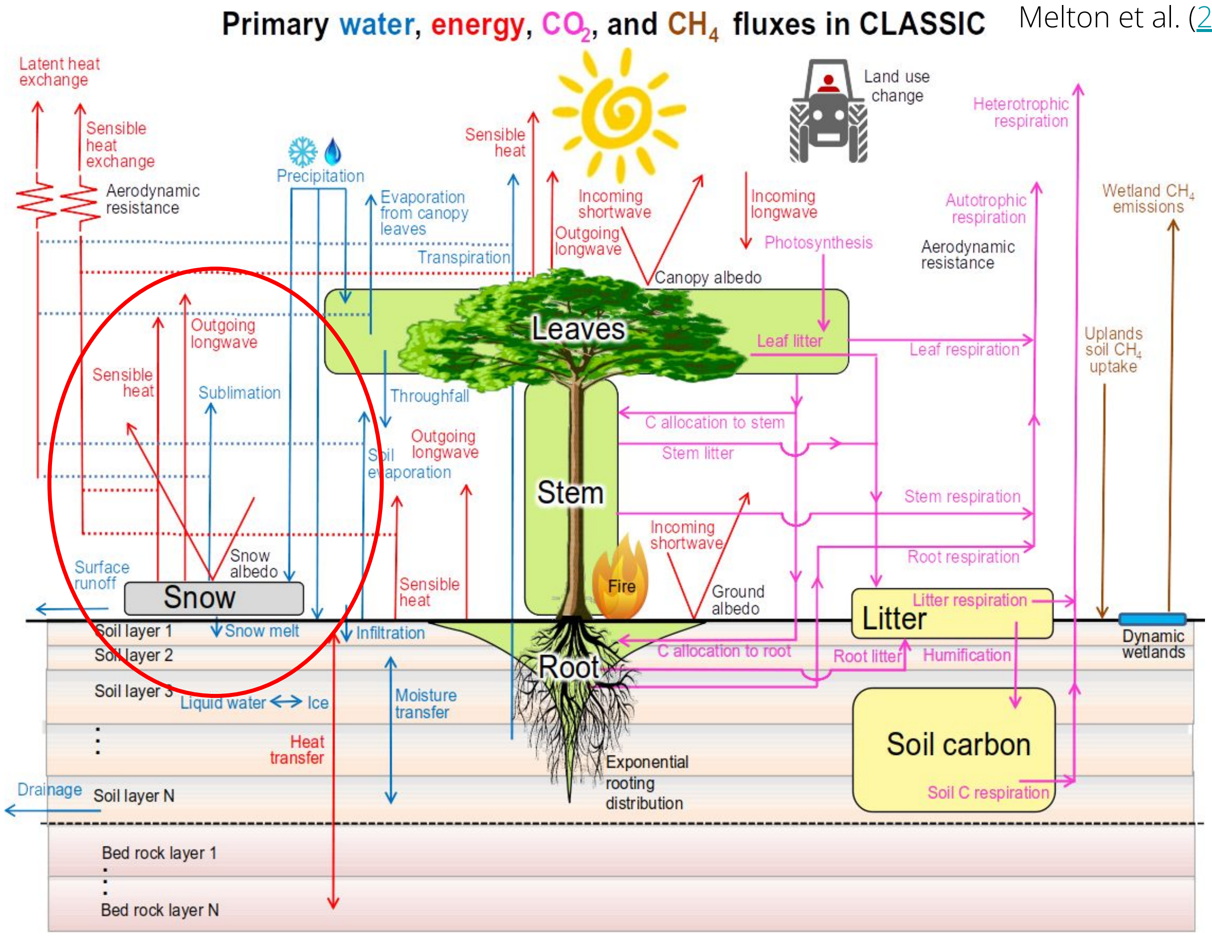
CLASSIC land surface model (LSM): description



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

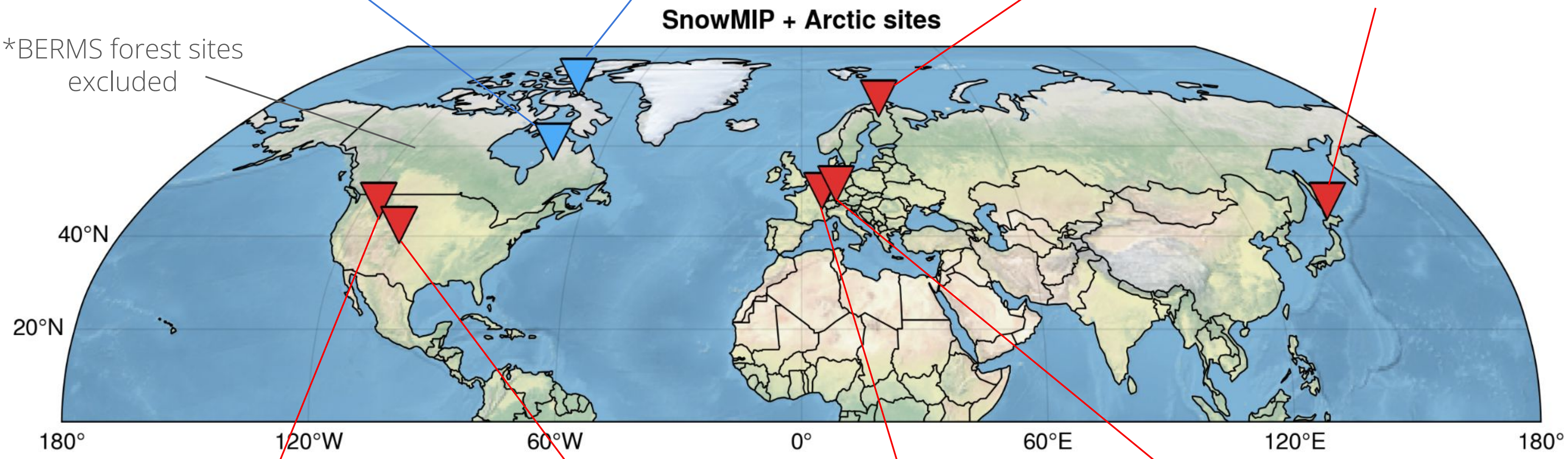


Melton et al. (2020), Fig. 1

- 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.)

Methods

Methods: 1D simulations at SnowMIP and Arctic sites



Bylot Island (25 m), Canada

Umiujaq TUNDRA (132 m), Canada

*BERMS forest sites excluded

Sodankylä (179 m), Finland

Sapporo (15 m), Japan

Reynolds Mountain East (2060 m), USA

Col de Porte (1325 m), France

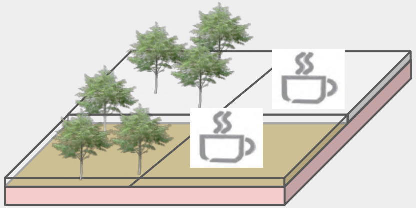
Senator Beck (3714 m) / Swamp Angel (3371 m), USA

Weissfluhjoch (2540 m), Switzerland

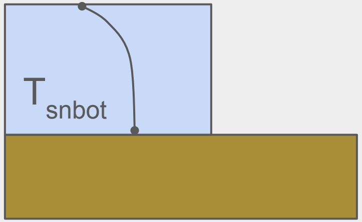
Snow model improvements

Physics improvements

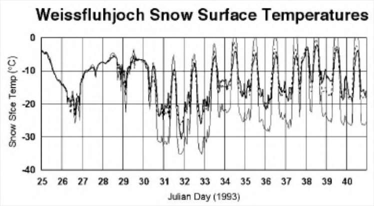
#1 Soil conductivity under snow (bug)



#2 Bottom snow temperature



#3 Windless exchange coefficient



Source: Brown et al., (2006)

Arctic adaptions

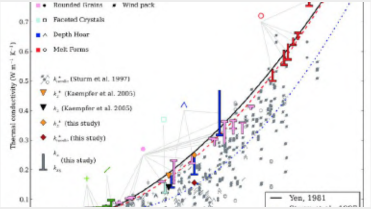
#4 Blowing snow sublimation losses

Credit: Les Anderson/ Unsplash

#5 Increasing snow compaction

Credit: Sawtooth Avalanche Center

#6 Snow thermal conductivity

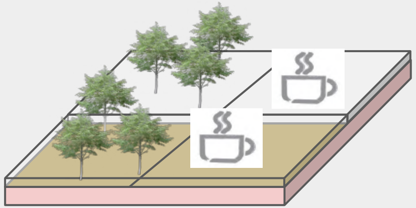


Source: Calonne et al. (2011)

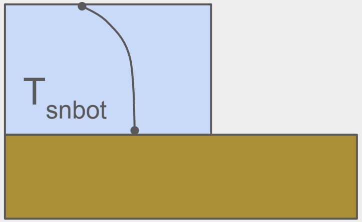
Snow model improvements

Physics improvements

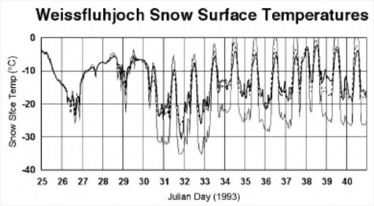
#1 Soil conductivity under snow (bug)



#2 Bottom snow temperature



#3 Windless exchange coefficient



Source: Brown et al., (2006)

Arctic adaptions

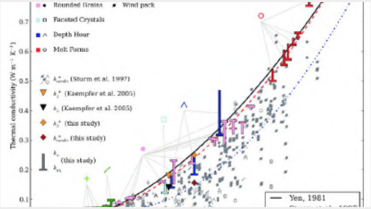
#4 Blowing snow sublimation losses

Credit: Les Anderson/ Unsplash

#5 Increasing snow compaction

Credit: Sawtooth Avalanche Center

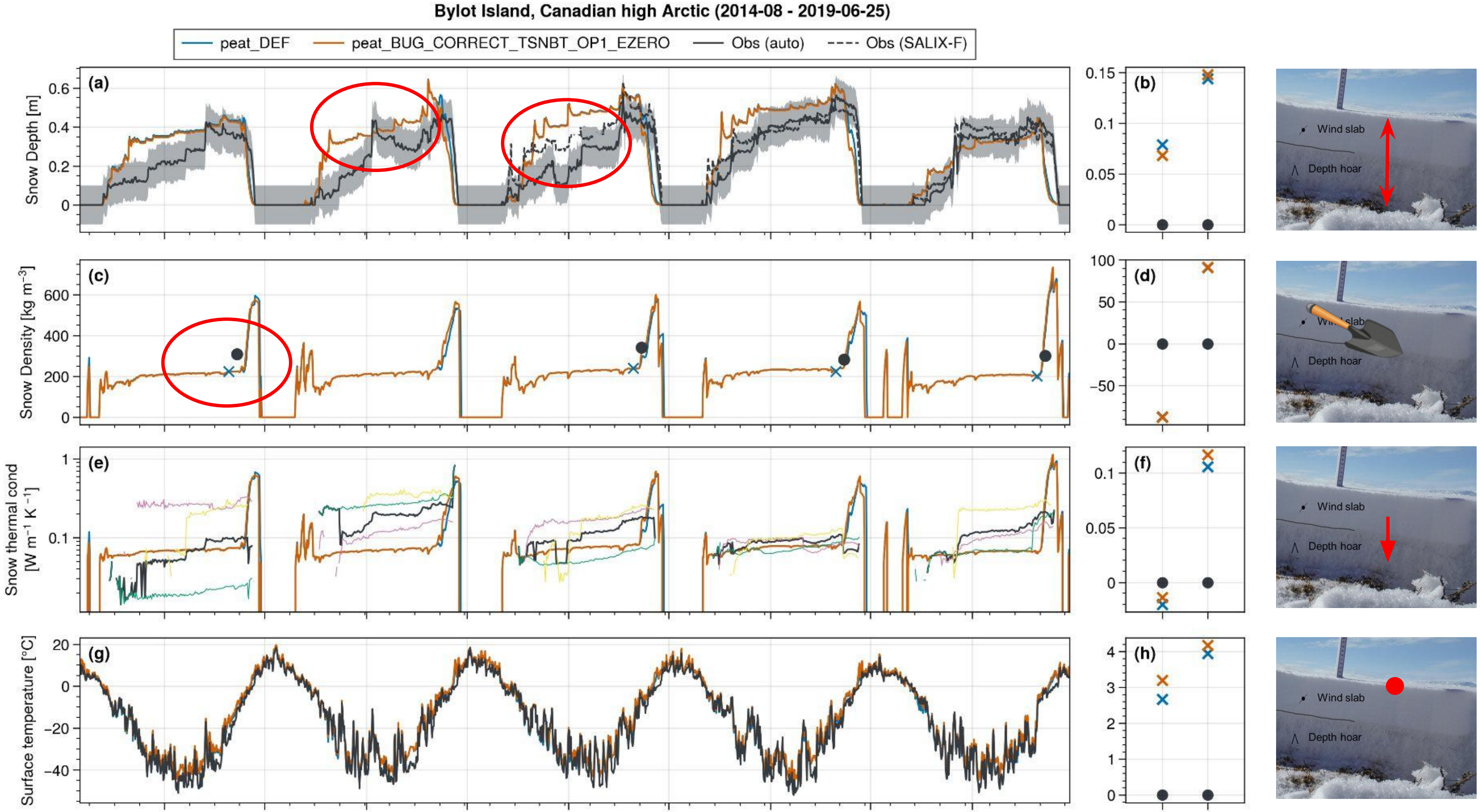
#6 Snow thermal conductivity



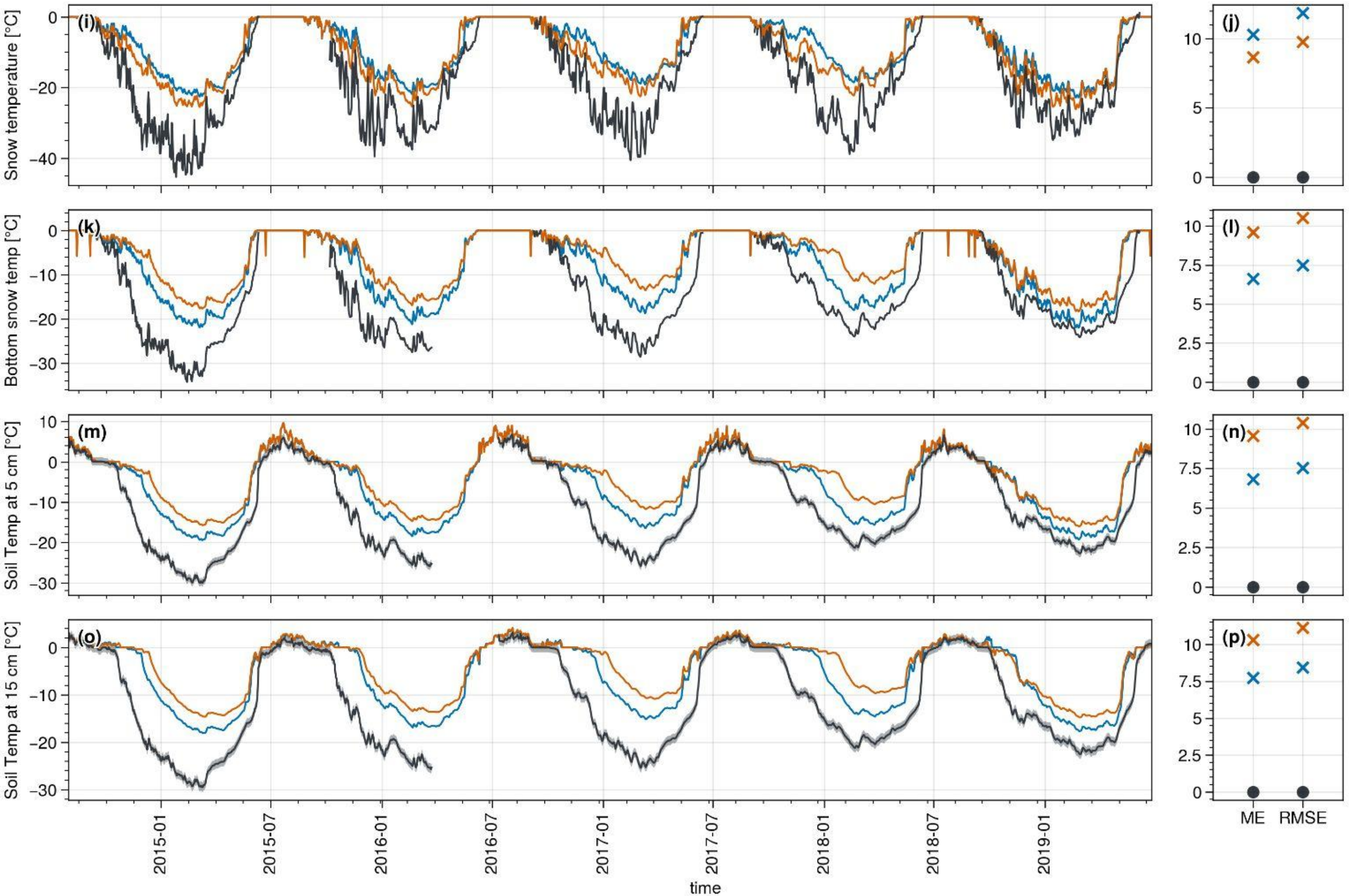
Source: Calonne et al. (2011)

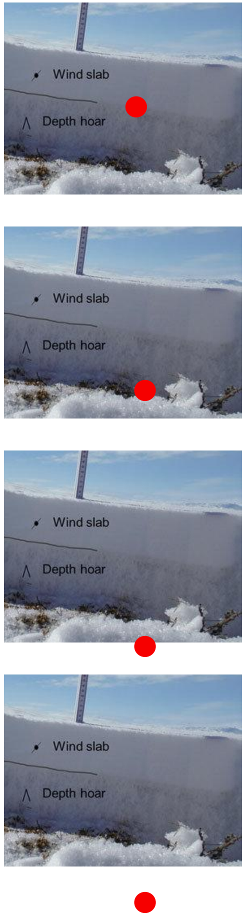
Results

Example: Bylot biases



Example: Bylot biases





Snow compaction scheme

Wind effect on snow compaction: max snow density

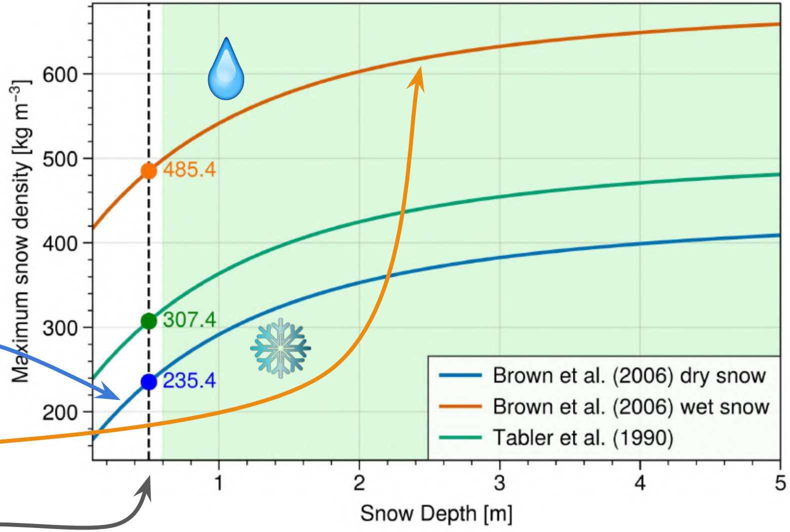
The snow density increase towards a ρ_{max} value in an exponential way as:

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

with

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

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



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).

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.)

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.

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

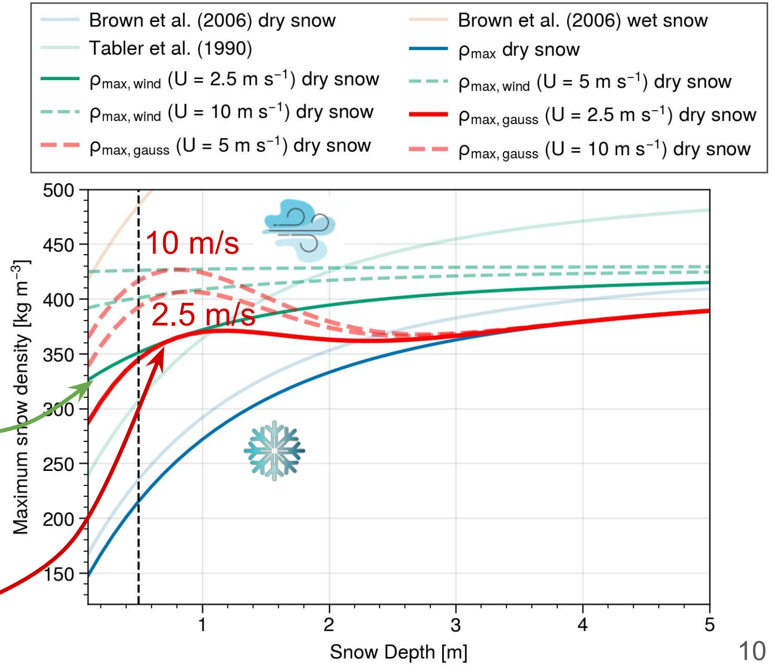
$$\rho_{\max}(d_s) = 430 - \frac{204.7}{d_s} \cdot \left(1 - \exp\left(-\frac{d_s}{0.673}\right)\right)$$

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

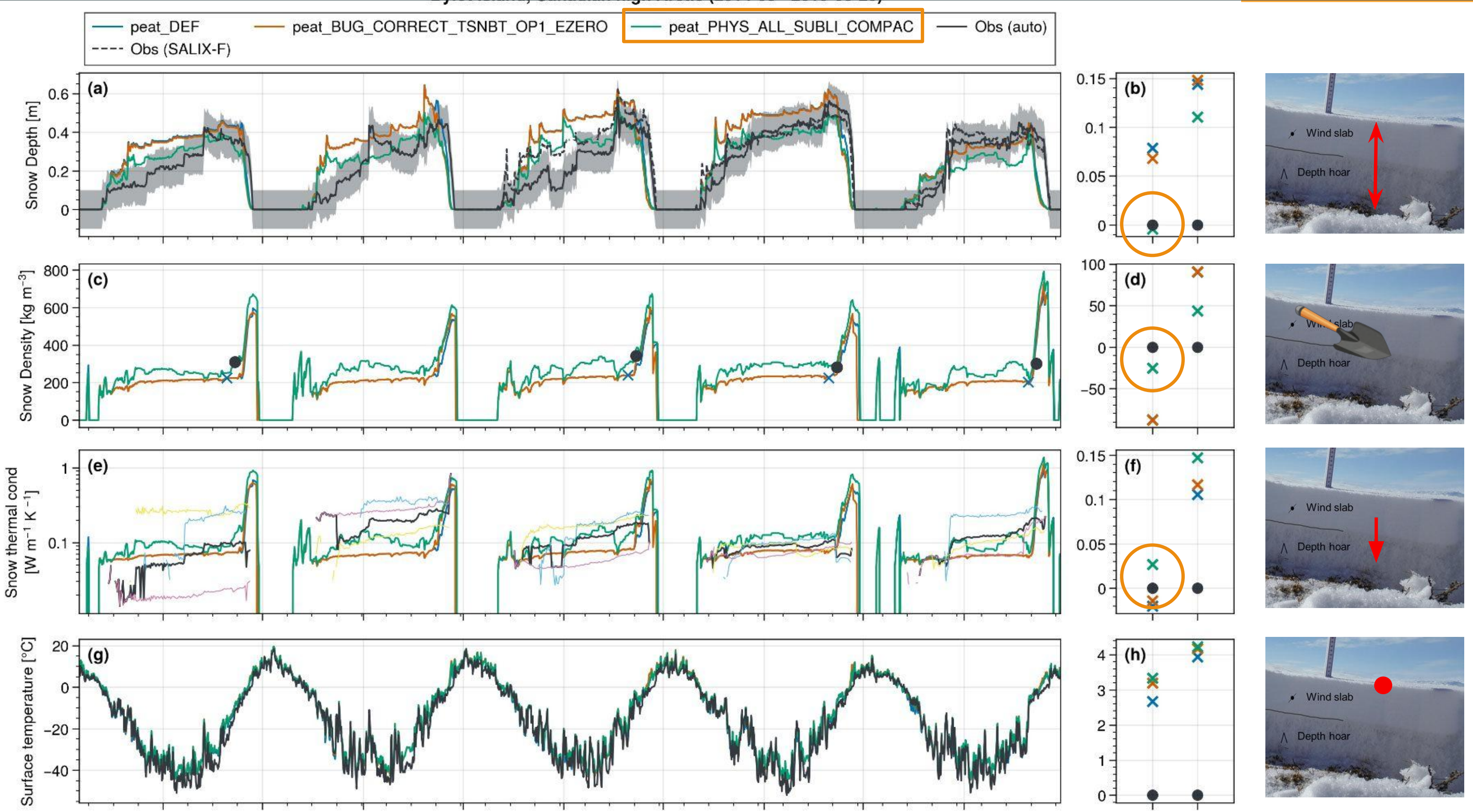
$$\rho_{\max,\ \mathrm{wind}}(d_s) = 430 - \frac{204.7}{d_s} \cdot \left(1 - \exp\left(-\frac{d_s}{0.673}\right)\right) \cdot \exp\left(-\frac{U}{U_0}\right)$$

Final Function with Gaussian Peak:

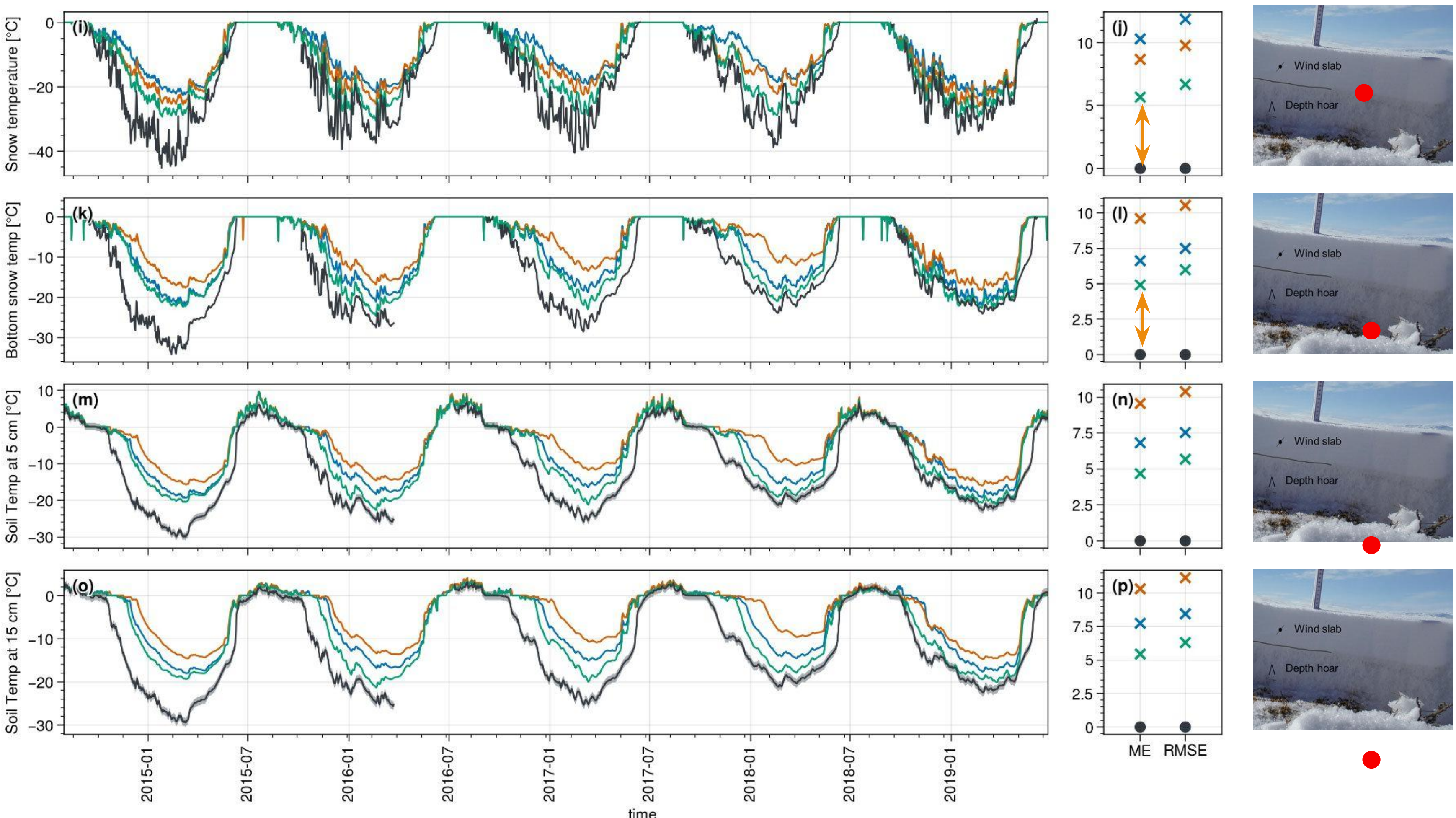
$$f(d_s) = \rho_{\max}(d_s) + (\rho_{\max,\ \mathrm{wind}}(d_s) - \rho_{\max}(d_s)) \cdot \exp\left(-\frac{(d_s - d_0)^2}{2\sigma^2}\right)$$



Example: Bylot example

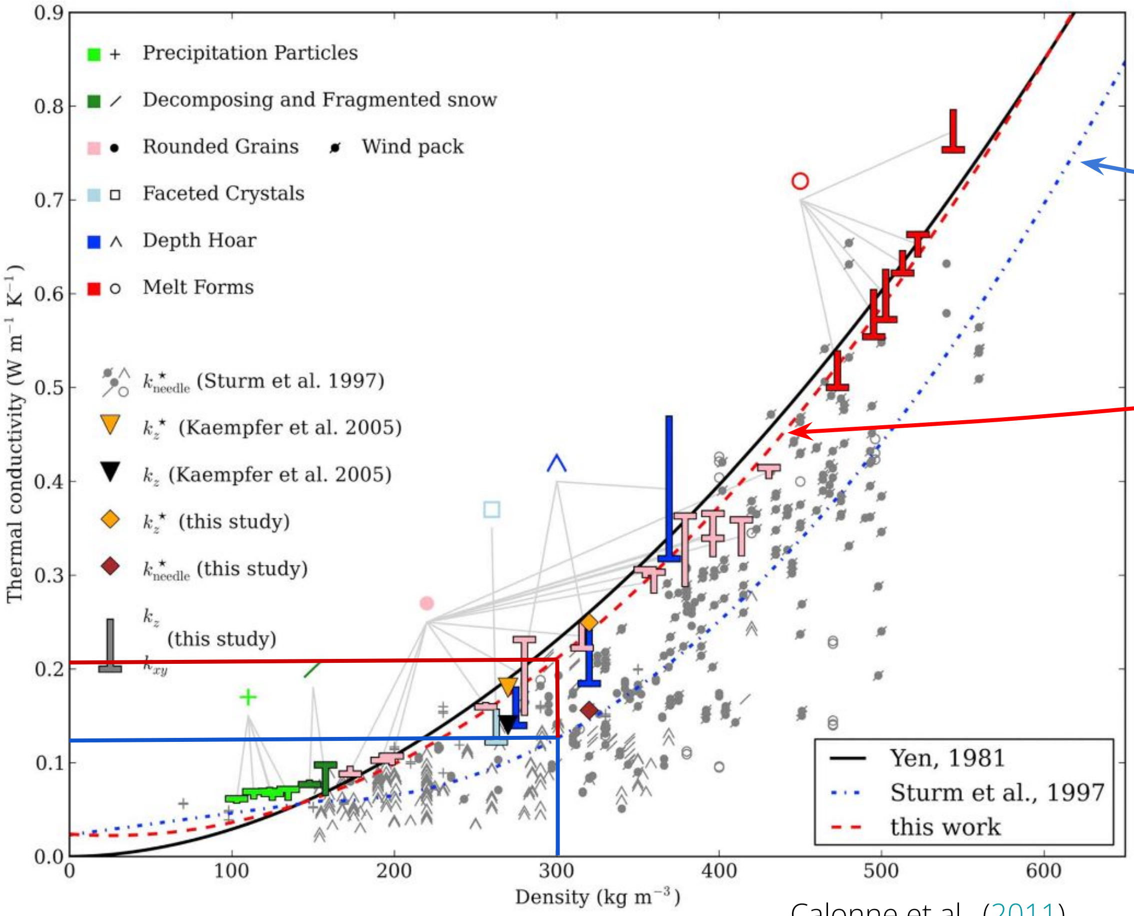


Example: Bylot example



Snow thermal conductivity

Arctic adaptation: Snow conductivity



Calonne et al., (2011)

CLASS snow conductivity (k_{eff}):

→ Sturm et al. (1997)

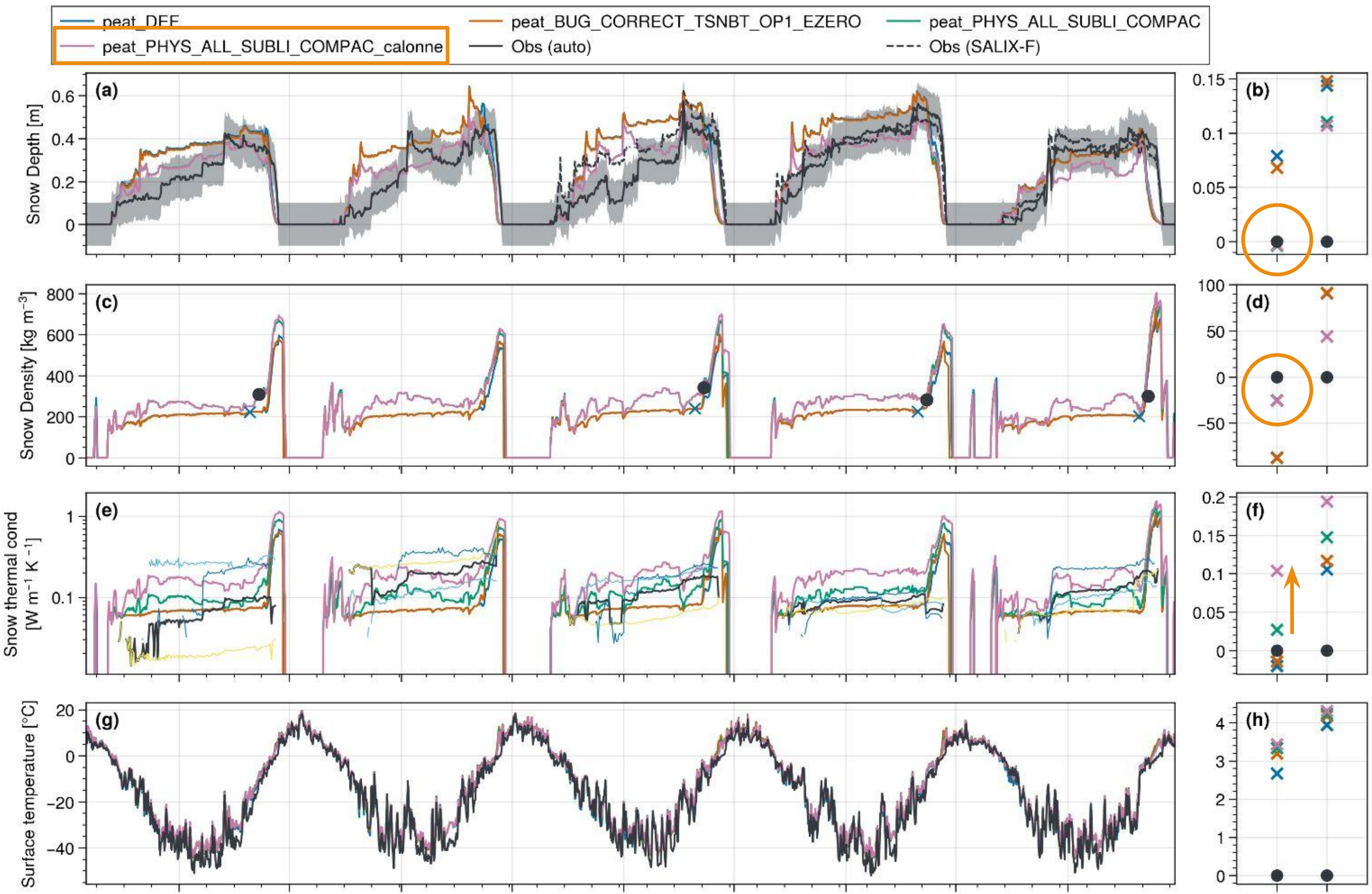
$$k_{\text{eff}} = 0.138 - 1.01\rho + 3.233\rho^2 \qquad \{0.156 \leq \rho \leq 0.6\}$$

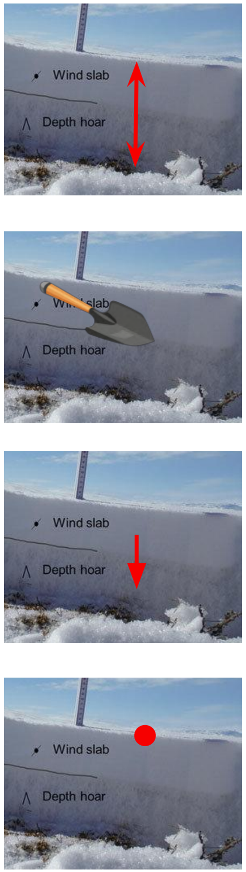
$$k_{\text{eff}} = 0.023 + 0.234\rho \qquad \{\rho < 0.156\}$$

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].*"

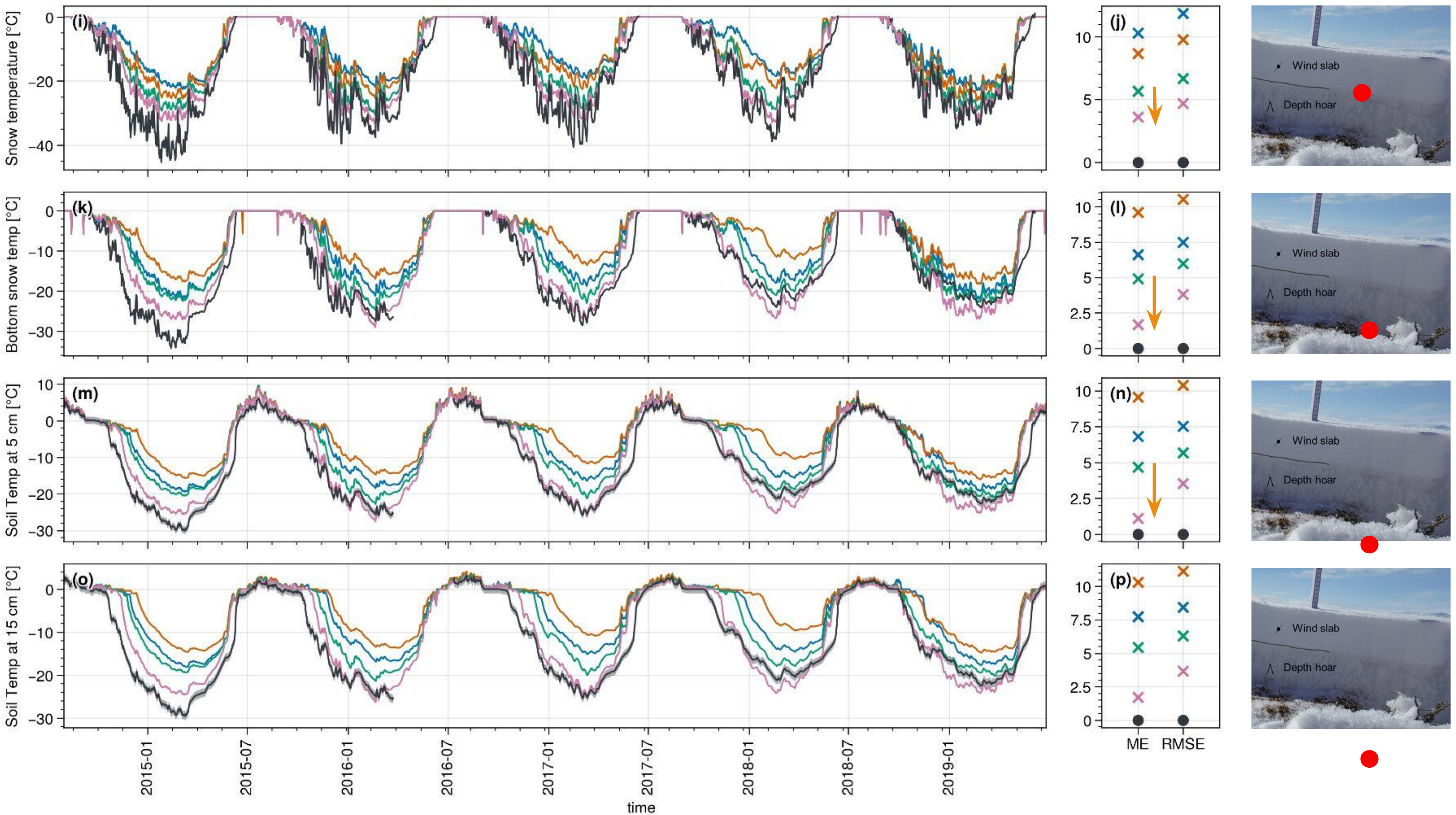
$$k_{\text{eff}} = 2.5 \times 10^{-6}\rho^2 - 1.23 \times 10^{-4}\rho + 0.024$$

Example: Bylot example

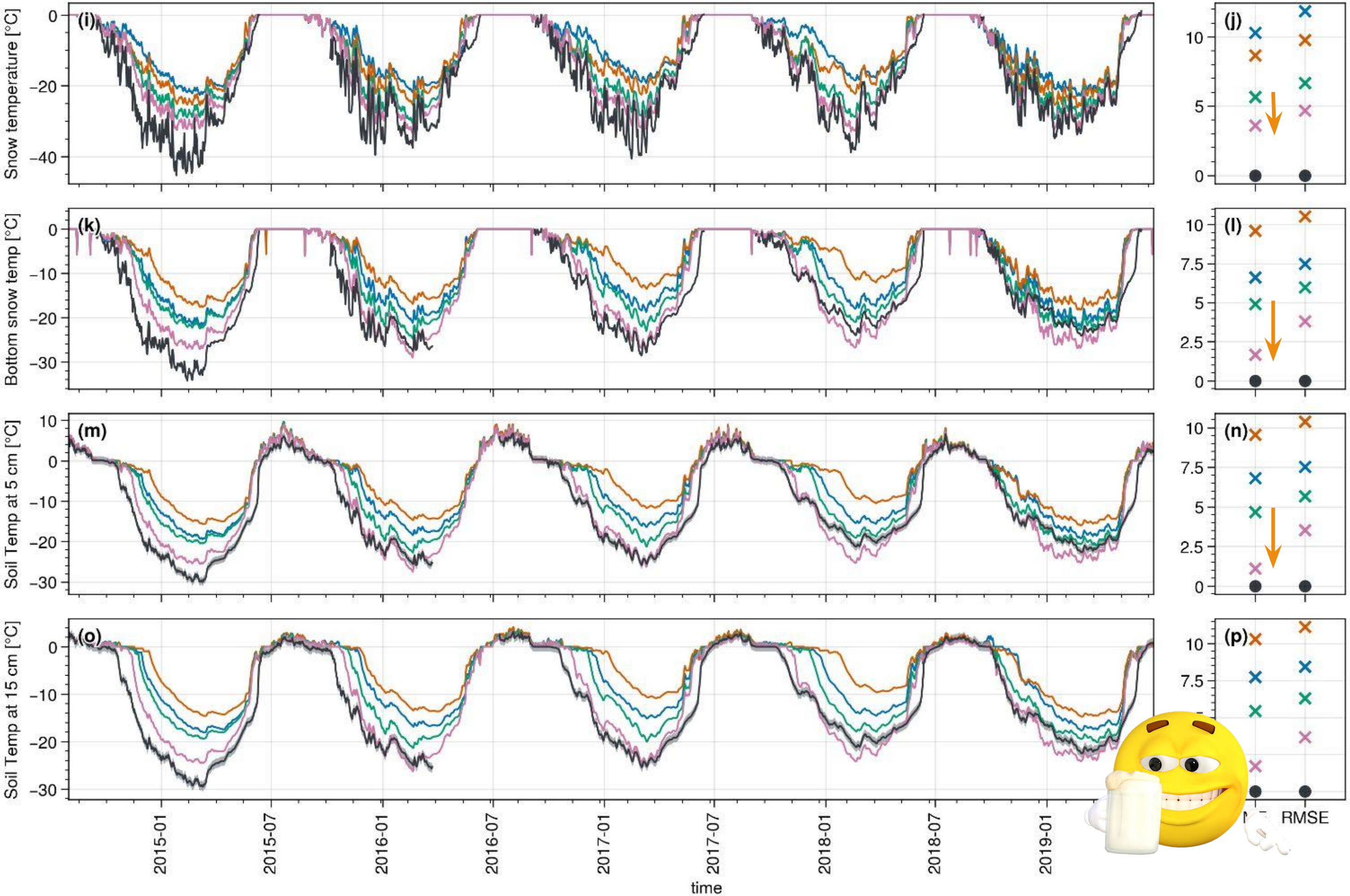


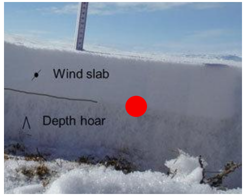


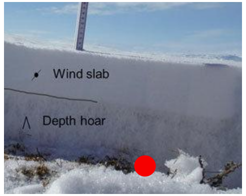
Example: Bylot example

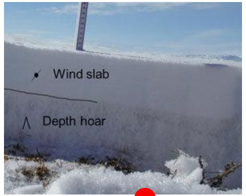


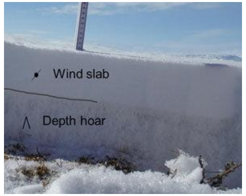
Example: Bylot example





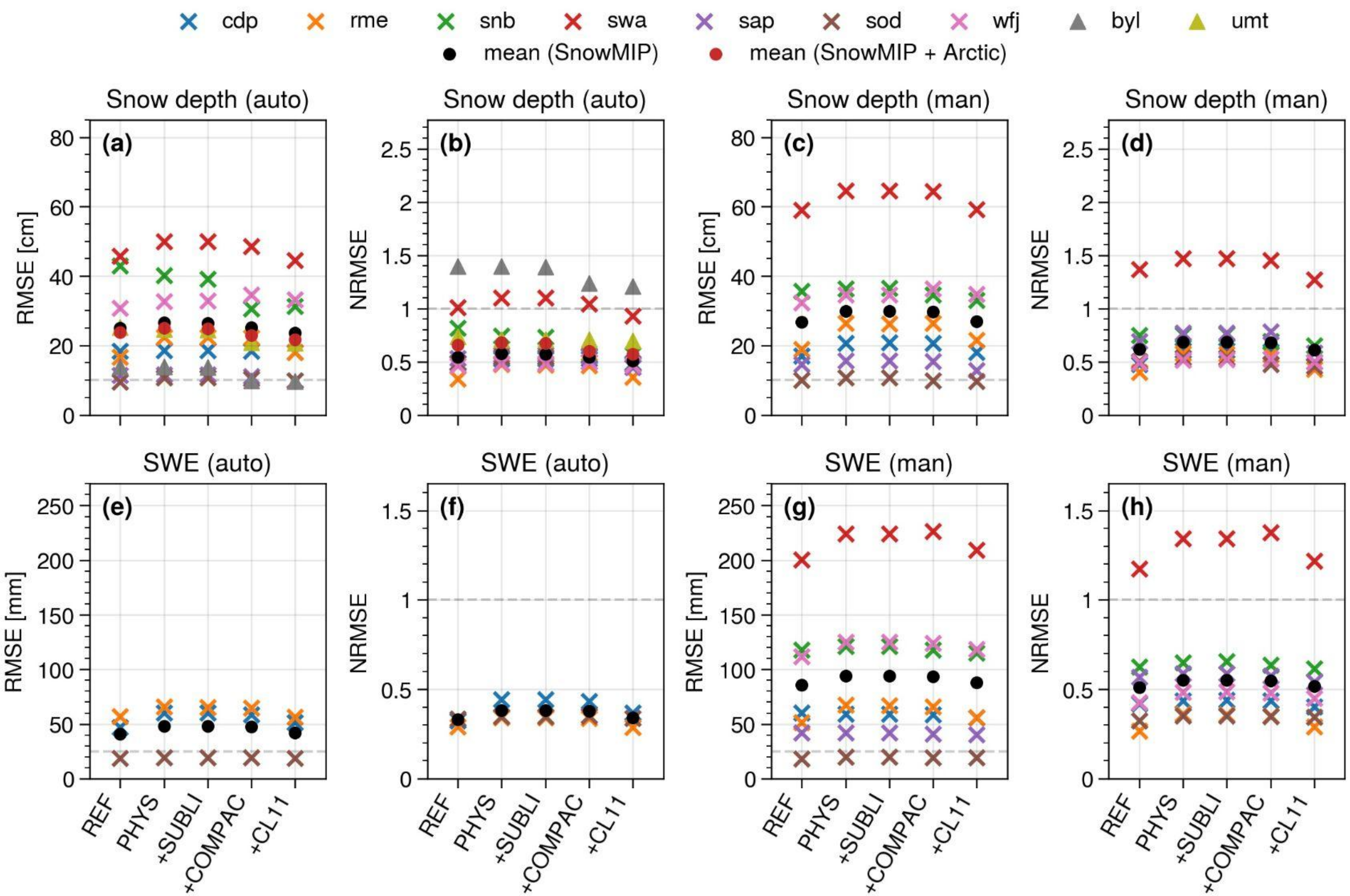




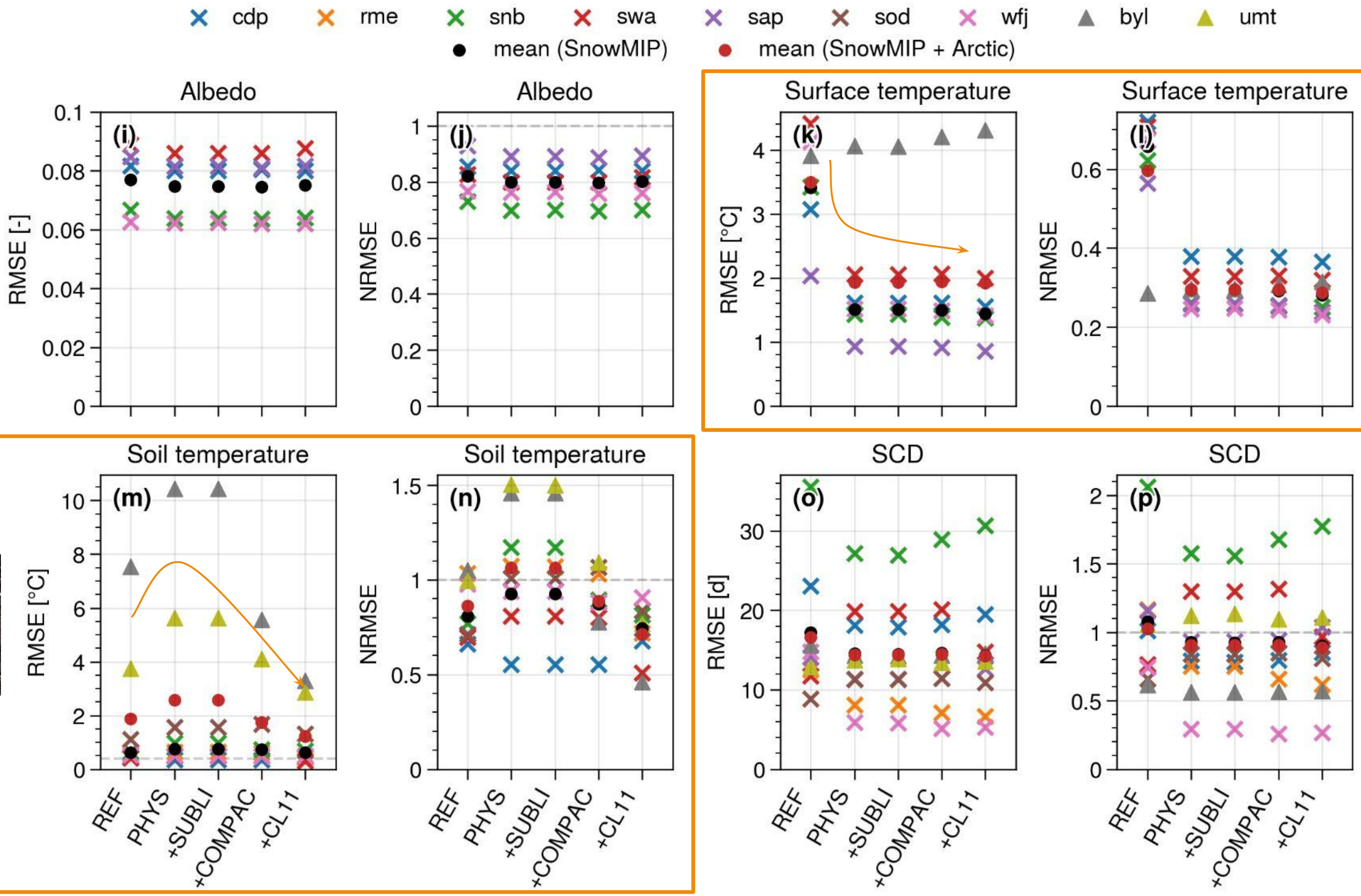


Overall results

Overall results at all sites: RMSE



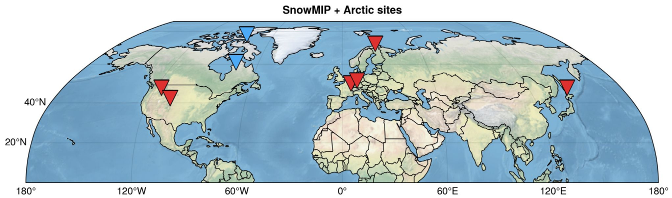
Overall results at all sites: RMSE

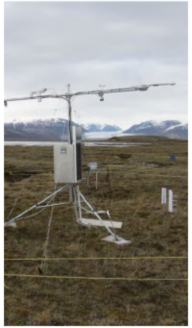


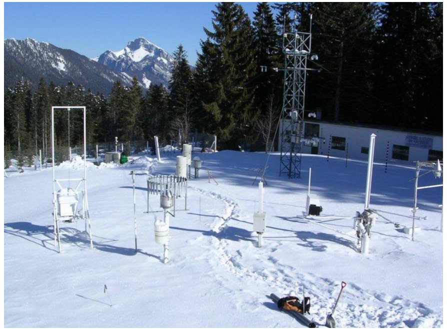
Conclusion

Take home message

- First time to adapt a snow model to the Arctic and SnowMIP sites!
- Only a few Arctic sites → need more snow Arctic obs sites! (with all forcing: SW, LW, rain/snow, RH, wind, etc.)
- Still a lot of uncertainties related to vegetation, soil properties, snow drifts, precip, etc.
- Simulate better soil temperature → winter carbon fluxes
- More snow obs will be needed (thermal conductivities, density time series for dry/wet snow, etc.) + more constraints on the snow cover fraction around a site (camera)
- Future studies over the whole Arctic with spatial simulation + new SCF parameterizations







Mickaël Lalande

SOCIAL NETWORKS

- @LalandeMickael
- @mickaellalande
- @mickaellalande
- mickaellalande.github.io

Email: Mickael.Lalande@uqtr.ca

Bibliography

References

Bartlett, P. A., MacKay, M. D., & Verseghy, D. L. (2006). Modified snow algorithms in the Canadian land surface scheme : Model runs and sensitivity analysis at three boreal forest stands. Atmosphere-Ocean, 44(3), 207‑222. https://doi.org/10.3137/ao.440301

Brown, R., Bartlett, P., MacKay, M., & Verseghy, D. (2006). Evaluation of snow cover in CLASS for SnowMIP. Atmosphere-Ocean, 44(3), 223‑238. https://doi.org/10.3137/ao.440302

Calonne, N., Flin, F., Morin, S., Lesaffre, B., du Roscoat, S. R., & Geindreau, C. (2011). Numerical and experimental investigations of the effective thermal conductivity of snow. Geophysical Research Letters, 38(23). https://doi.org/10.1029/2011GL049234

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., & Jones, J. (2014). Recent Arctic amplification and extreme mid-latitude weather. Nature Geoscience, 7(9), 627‑637. https://doi.org/10.1038/ngeo2234

Domine, F., Belke-Brea, M., Sarrazin, D., Arnaud, L., Barrere, M., & Poirier, M. (2018). Soil moisture, wind speed and depth hoar formation in the Arctic snowpack. Journal of Glaciology, 64(248), 990‑1002. https://doi.org/10.1017/jog.2018.89

Domine, F., Picard, G., Morin, S., Barrere, M., Madore, J.-B., & Langlois, A. (2019). Major Issues in Simulating Some Arctic Snowpack Properties Using Current Detailed Snow Physics Models : Consequences for the Thermal Regime and Water Budget of Permafrost. Journal of Advances in Modeling Earth Systems, 11(1), 34‑44. https://doi.org/10.1029/2018MS001445

Domine, F., Lackner, G., Sarrazin, D., Poirier, M., & Belke-Brea, M. (2021). Meteorological, snow and soil data (2013–2019) from a herb tundra permafrost site at Bylot Island, Canadian high Arctic, for driving and testing snow and land surface models. Earth System Science Data, 13(9), 4331‑4348. https://doi.org/10.5194/essd-13-4331-2021

Jafari, M., Gouttevin, I., Couttet, M., Wever, N., Michel, A., Sharma, V., Rossmann, L., Maass, N., Nicolaus, M., & Lehning, M. (2020). The Impact of Diffusive Water Vapor Transport on Snow Profiles in Deep and Shallow Snow Covers and on Sea Ice. Frontiers in Earth Science, 8. https://www.frontiersin.org/articles/10.3389/feart.2020.00249

References

Keenan, E., Wever, N., Dattler, M., Lenaerts, J. T. M., Medley, B., Kuipers Munneke, P., & Reijmer, C. (2021). Physics-based SNOWPACK model improves representation of near-surface Antarctic snow and firn density. The Cryosphere, 15(2), 1065‑1085. https://doi.org/10.5194/tc-15-1065-2021

Lackner, G., Domine, F., Nadeau, D. F., Lafaysse, M., & Dumont, M. (2022). Snow properties at the forest–tundra ecotone : Predominance of water vapor fluxes even in deep, moderately cold snowpacks. The Cryosphere, 16(8), 3357‑3373. https://doi.org/10.5194/tc-16-3357-2022

Langlois, A., Bergeron, J., Brown, R., Royer, A., Harvey, R., Roy, A., Wang, L., & Thériault, N. (2014). Evaluation of CLASS 2.7 and 3.5 Simulations of Snow Properties from the Canadian Regional Climate Model (CRCM4) over Québec, Canada*. Journal of Hydrometeorology, 15(4), 1325‑1343. https://doi.org/10.1175/JHM-D-13-055.1

Liston, G. E., Haehnel, R. B., Sturm, M., Hiemstra, C. A., Berezovskaya, S., & Tabler, R. D. (2007). Simulating complex snow distributions in windy environments using SnowTran-3D. Journal of Glaciology, 53(181), 241‑256. https://doi.org/10.3189/172756507782202865

Melton, J. R., & Arora, V. K. (2016). Competition between plant functional types in the Canadian Terrestrial Ecosystem Model (CTEM) v. 2.0. Geoscientific Model Development, 9(1), 323‑361. https://doi.org/10.5194/gmd-9-323-2016

Melton, J. R., Verseghy, D. L., Sospedra-Alfonso, R., & Gruber, S. (2019). Improving permafrost physics in the coupled Canadian Land Surface Scheme (v.3.6.2) and Canadian Terrestrial Ecosystem Model (v.2.1) (CLASS-CTEM). Geoscientific Model Development, 12(10), 4443‑4467. https://doi.org/10.5194/gmd-12-4443-2019

Melton, J. R., Arora, V. K., Wisernig-Cojoc, E., Seiler, C., Fortier, M., Chan, E., & Teckentrup, L. (2020). CLASSIC v1.0 : The open-source community successor to the Canadian Land Surface Scheme (CLASS) and the Canadian Terrestrial Ecosystem Model (CTEM) – Part 1 : Model framework and site-level performance. Geoscientific Model Development, 13(6), 2825‑2850. https://doi.org/10.5194/gmd-13-2825-2020

Menard, C. B., Essery, R., Krinner, G., Arduini, G., Bartlett, P., Boone, A., Brutel-Vuilmet, C., Burke, E., Cuntz, M., Dai, Y., Decharme, B., Dutra, E., Fang, X., Fierz, C., Gusev, Y., Hagemann, S., Haverd, V., Kim, H., Lafaysse, M., … Yuan, H. (2021). Scientific and Human Errors in a Snow Model Intercomparison. Bulletin of the American Meteorological Society, 102(1), E61‑E79. https://doi.org/10.1175/BAMS-D-19-0329.1

References

Meyer, G., Humphreys, E. R., Melton, J. R., Cannon, A. J., & Lafleur, P. M. (2021). Simulating shrubs and their energy and carbon dioxide fluxes in Canada's Low Arctic with the Canadian Land Surface Scheme Including Biogeochemical Cycles (CLASSIC). Biogeosciences, 18(11), 3263-3283. https://doi.org/10.5194/bg-18-3263-2021

Pomeroy, J., & Gray, D. (1995). Snowcover : Accumulation, Relocation, and Management. In Bulletin of the International Society of Soil Science (Vol. 7). https://research-groups.usask.ca/hydrology/documents/reports/pomeroy-j.w.-and-gray-d.m._snowcover-accumulation,-relocation-and-management_book_1995.pdf

Rantanen, M., Karpechko, A. Yu., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, 3(1), 168. https://doi.org/10.1038/s43247-022-00498-3

Royer, A., Picard, G., Vargel, C., Langlois, A., Gouttevin, I., & Dumont, M. (2021). Improved Simulation of Arctic Circumpolar Land Area Snow Properties and Soil Temperatures. Frontiers in Earth Science, 9(June), 1-19. https://doi.org/10.3389/feart.2021.685140

Royer, A., Domine, F., Roy, A., Langlois, A., Marchand, N., & Davesne, G. (2021a). New northern snowpack classification linked to vegetation cover on a latitudinal mega-transect across northeastern Canada. Écoscience, 28(3-4), 225-242. https://doi.org/10.1080/11956860.2021.1898775

Schuur, E. A. G., Abbott, B. W., Commane, R., Ernakovich, J., Euskirchen, E., Hugelius, G., Grosse, G., Jones, M., Koven, C., Leshyk, V., Lawrence, D., Loranty, M. M., Mauritz, M., Olefeldt, D., Natali, S., Rodenhizer, H., Salmon, V., Schädel, C., Strauss, J., … Turetsky, M. (2022). Permafrost and Climate Change : Carbon Cycle Feedbacks From the Warming Arctic. Annual Review of Environment and Resources, 47(1), 343-371. https://doi.org/10.1146/annurev-environ-012220-011847

Simson, A., Löwe, H., & Kowalski, J. (2021). Elements of future snowpack modeling – Part 2 : A modular and extendable Eulerian–Lagrangian numerical scheme for coupled transport, phase changes and settling processes. The Cryosphere, 15(12), 5423-5445. https://doi.org/10.5194/tc-15-5423-2021

Sturm, M., Holmgren, J., König, M., & Morris, K. (1997). The thermal conductivity of seasonal snow. Journal of Glaciology, 43(143), 26-41. https://doi.org/10.3189/S0022143000002781

References

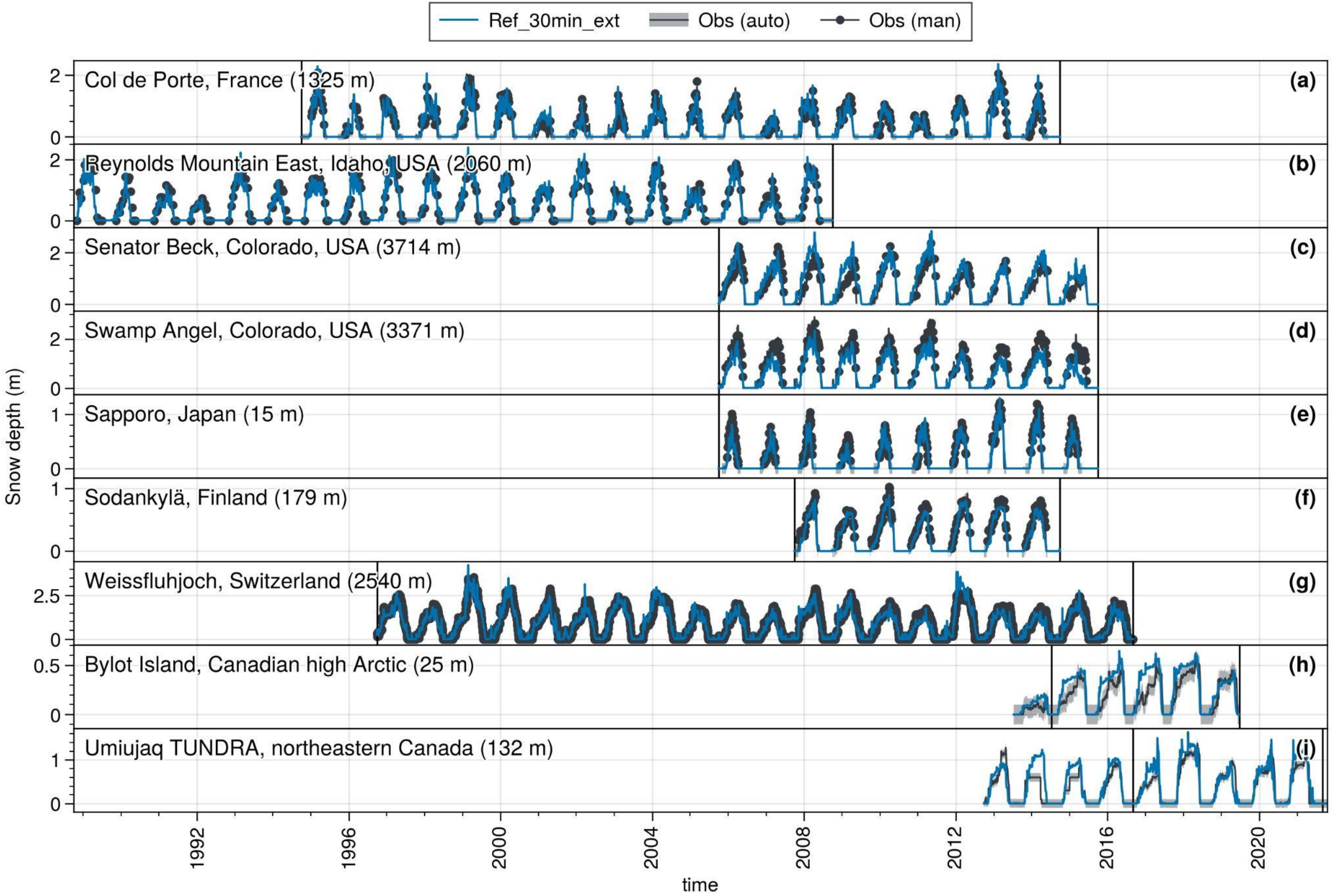
Swart, N. C., Cole, J. N. S., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., Anstey, J., Arora, V., Christian, J. R., Hanna, S., Jiao, Y., Lee, W. G., Majaess, F., Saenko, O. A., Seiler, C., Seinen, C., Shao, A., Sigmond, M., Solheim, L., … Winter, B. (2019). The Canadian Earth System Model version 5 (CanESM5.0.3). Geoscientific Model Development, 12(11), 4823-4873. https://doi.org/10.5194/gmd-12-4823-2019

Verseghy, D., Brown, R., & Wang, L. (2017). Evaluation of CLASS Snow Simulation over Eastern Canada. Journal of Hydrometeorology, 18(5), 1205-1225. https://doi.org/10.1175/JHM-D-16-0153.1

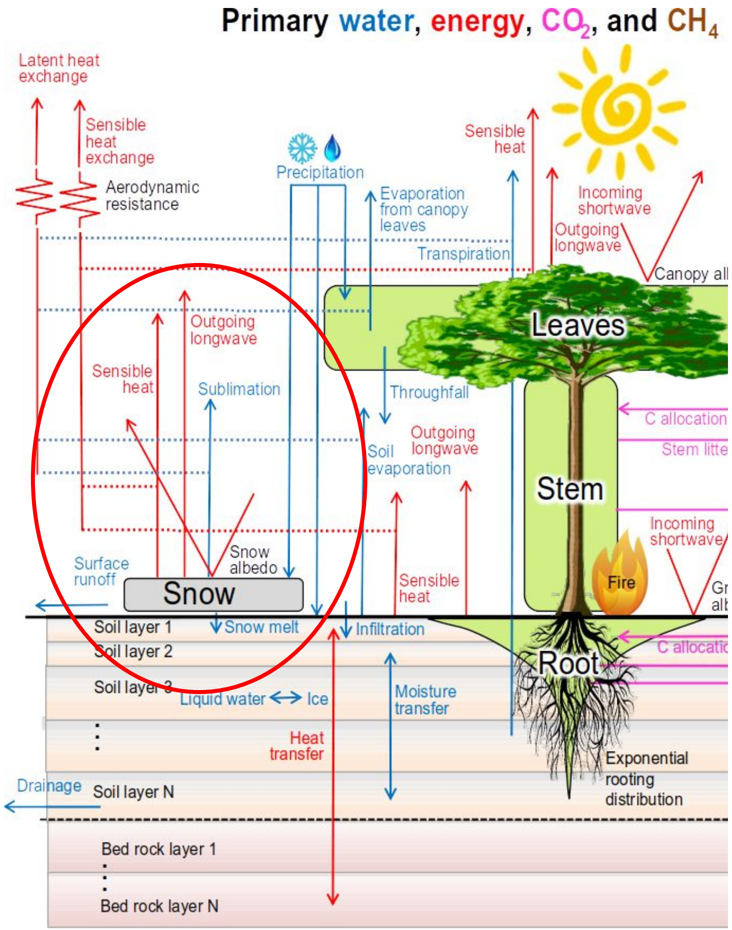
Walter, B., Weigel, H., Wahl, S., & Löwe, H. (2024). Wind tunnel experiments to quantify the effect of aeolian snow transport on the surface snow microstructure. The Cryosphere, 18(8), 3633-3652. https://doi.org/10.5194/tc-18-3633-2024

Supplementary materials

Methods: SnowMIP and Arctic sites



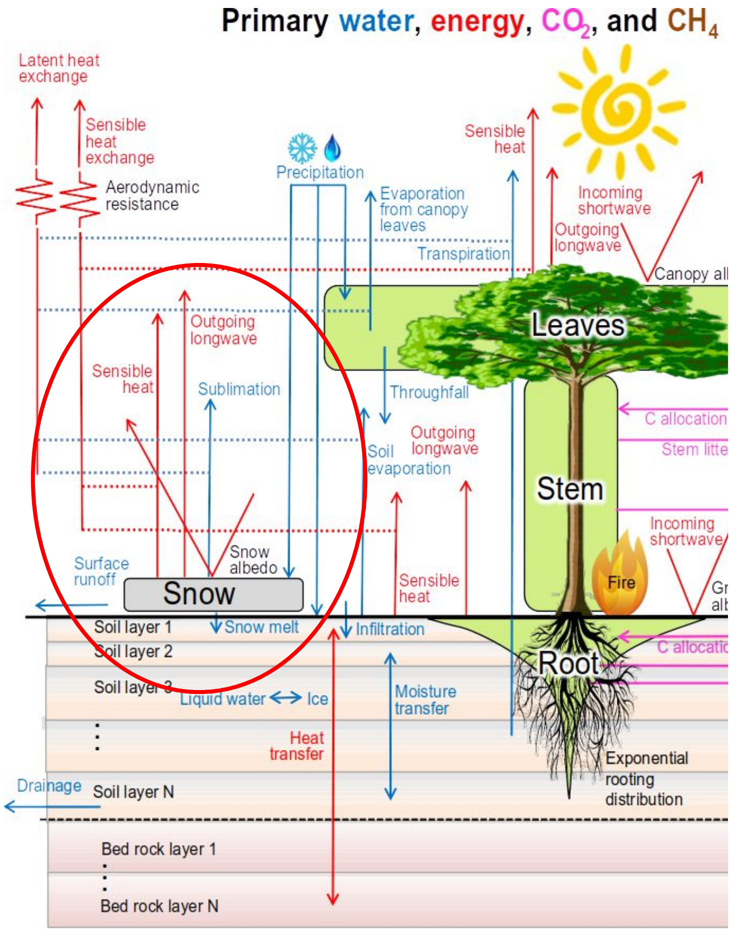
Methods: CLASSIC snow model



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

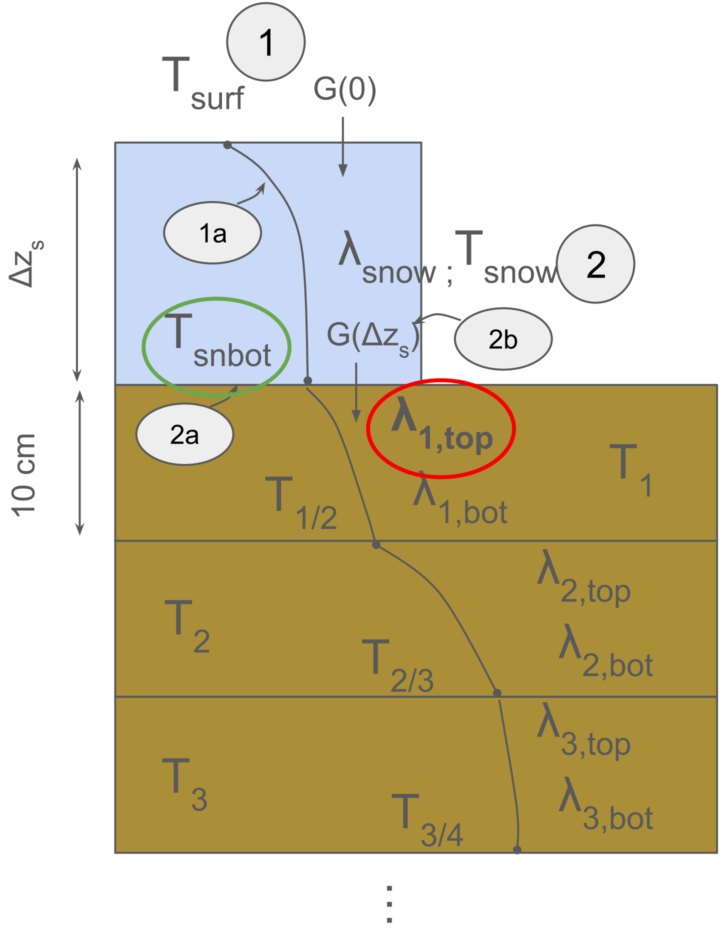
Initialization and boundary conditions:

- 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

Context: CLASSIC snow model physics (radiation)



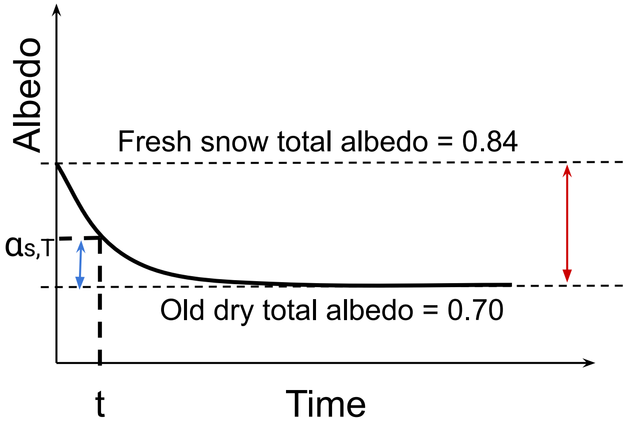
1. Surface energy budget: $K_*+L_*-Q_H-Q_E-G(0) = 0$
   a. G(0) derived from the hypothesized quadratic temperature profile (depend only on T(0) + λ_{snow})
   b. + hypothesis: $G(\Delta z_s)=0$ → T_{surf}
2. Computation of the snow temperature:
   a. Estimate bottom snow temperature
      TSNBOT(I)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

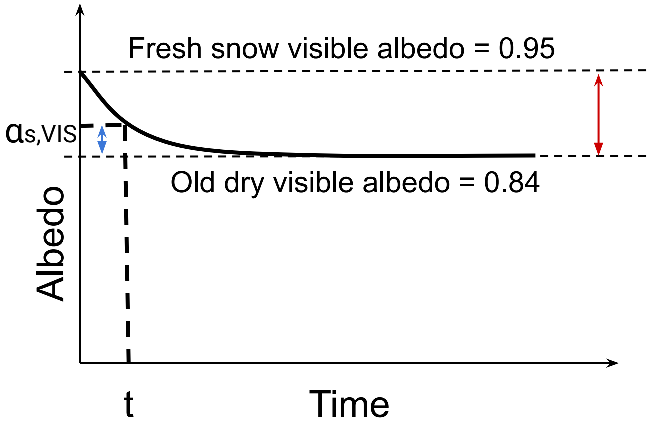
Note: In the computation of $G(\Delta z_s)$, $\lambda_{1,top}$ is considered as a harmonic average of the snow thermal conductivity and the one of the first soil layer.

Methods: CLASSIC snow model (albedo)

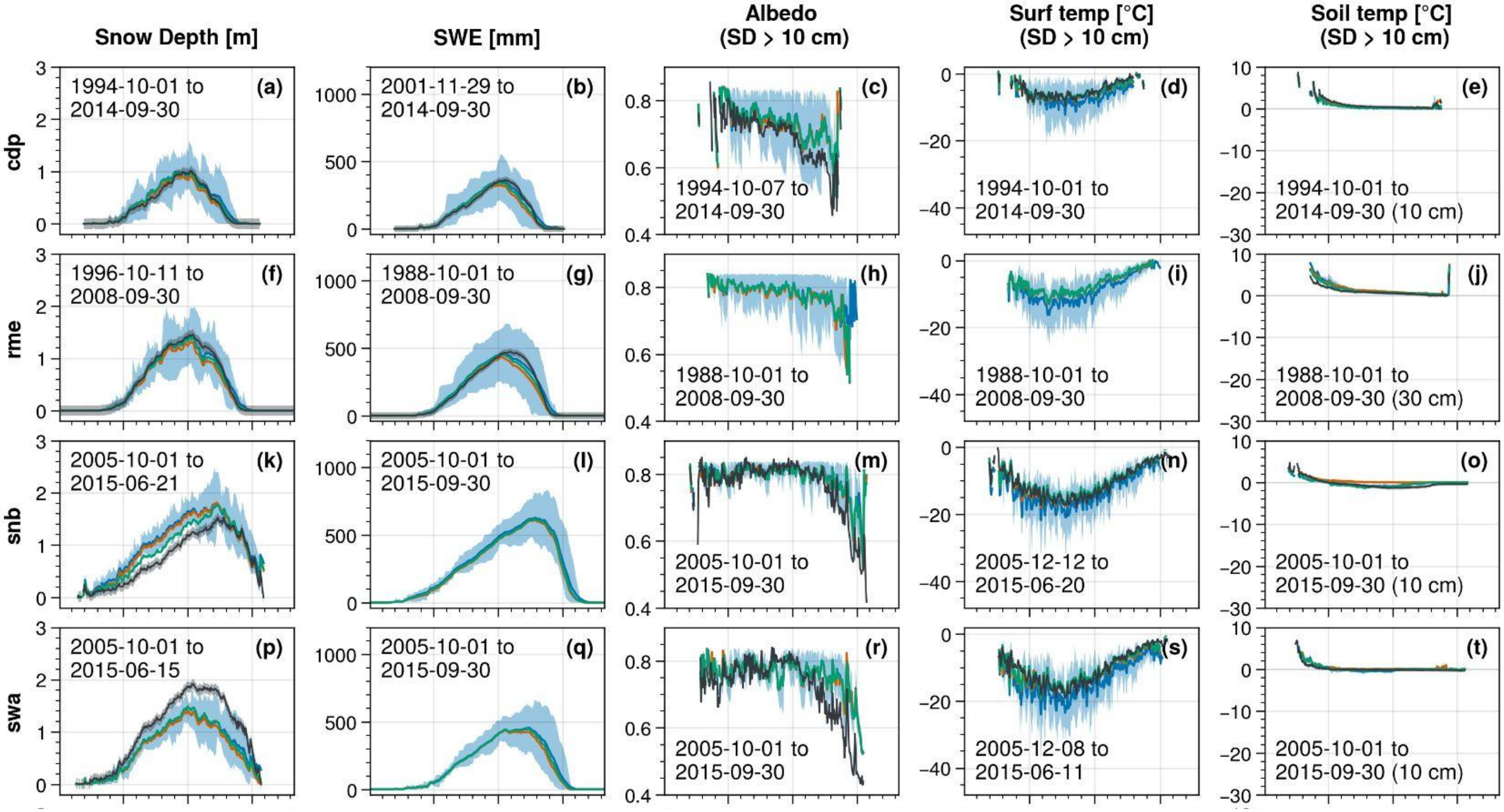
$$\alpha_s(t+1) = \left[\alpha_s(t) - \alpha_{s,old}\right] e^{-\frac{0.01\Delta t}{3600}} + \alpha_{s,old}$$

	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

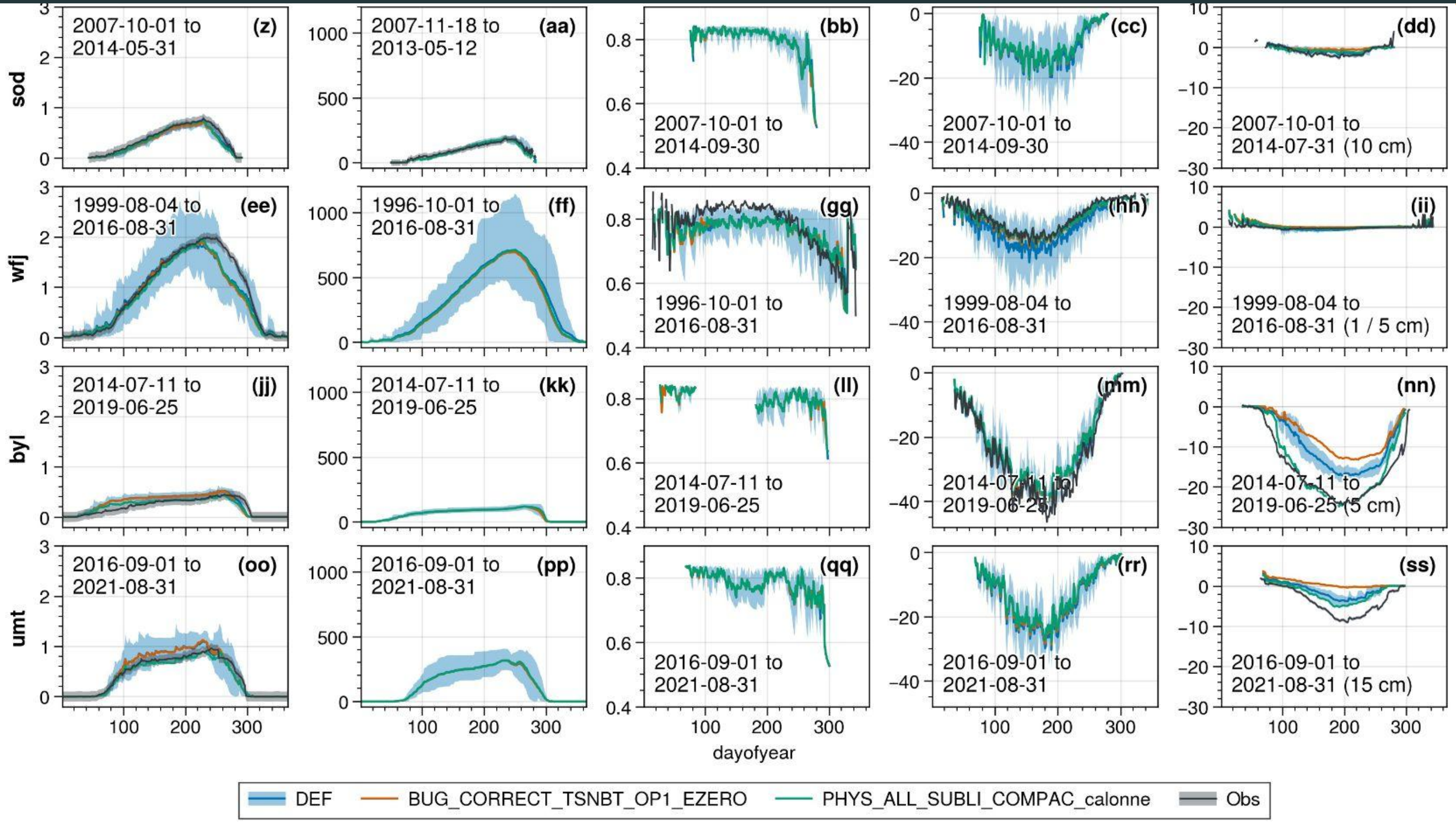




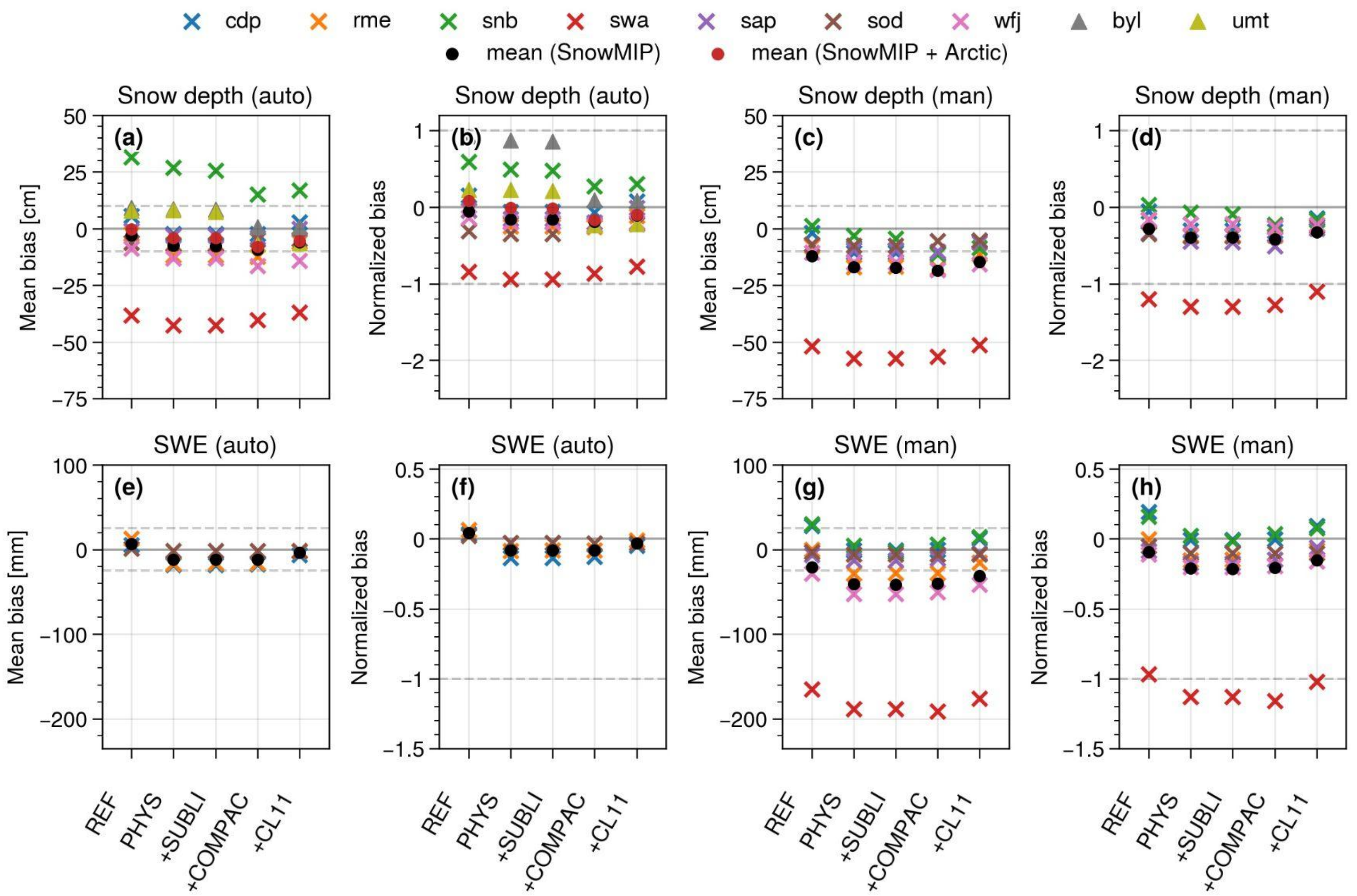
Physics + Arctic improvements: synthesis



Physics + Arctic improvements: synthesis



Overall results at all sites: MB



Overall results at all sites: MB