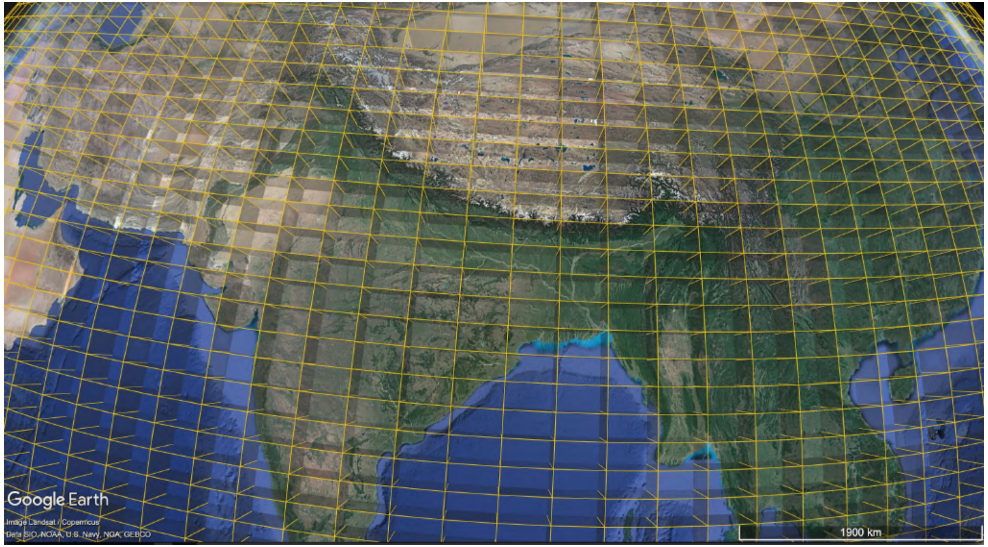
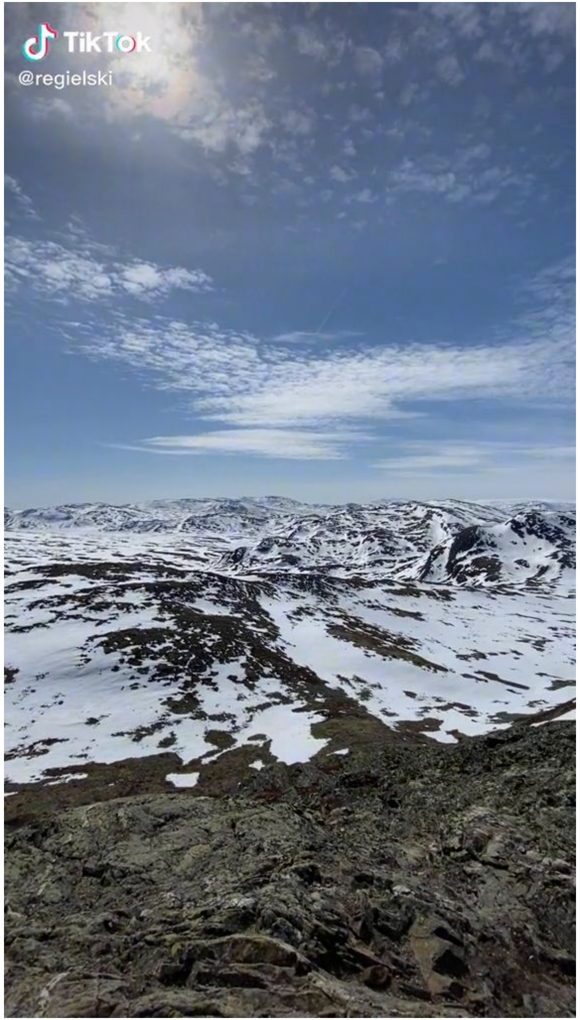
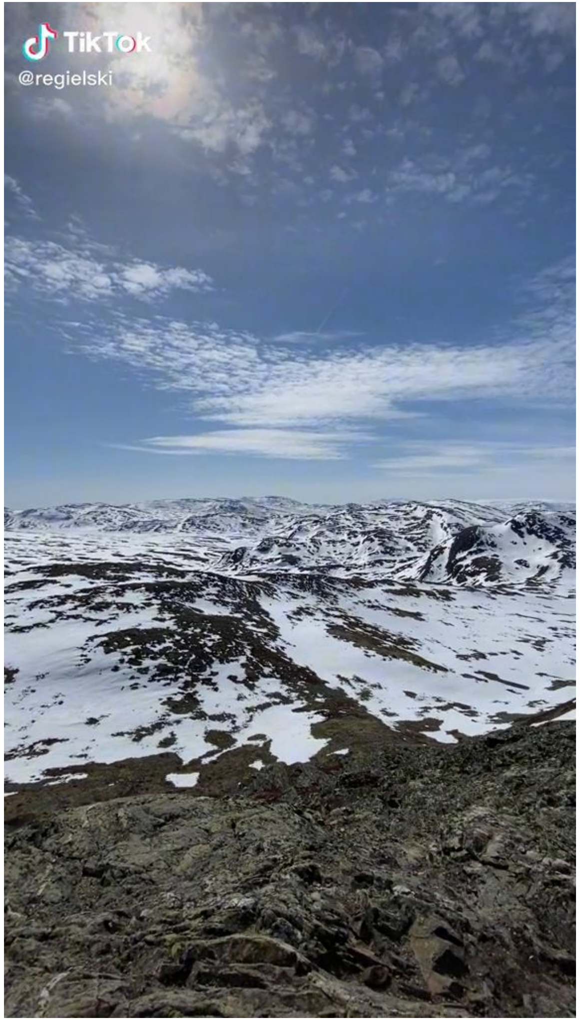
Adaptation of a snow cover scheme for complex topography areas:
regional calibration over High Mountain Asia and application in global models



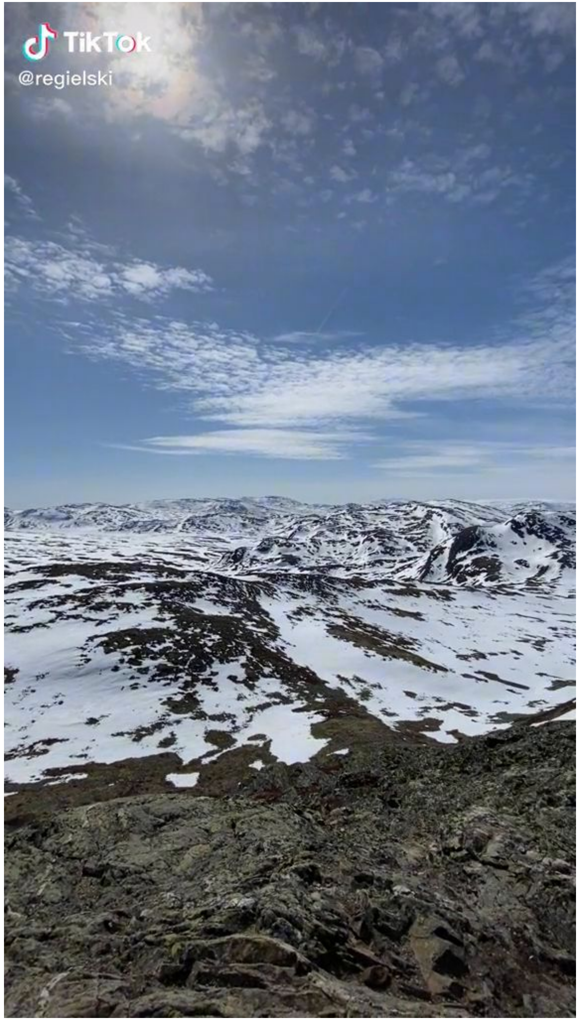
Mickaël Lalande[1], Martin Ménégoz[1], Gerhard Krinner[1], Catherine Ottlé[2]
[1] Univ. Grenoble Alpes, CNRS, IRD, G-INP, IGE, 38000 Grenoble, France
[2] LSCE-IPSL (CNRS-CEA-UVSQ), Université Paris-Saclay, Gif-sur-Yvette, France

IMC2022 | Innsbruck — 13/09/2022


TikTok
@regielski


TikTok
@regielski


TikTok
@regielski


TikTok
@regielski

TikTok
@regielski

TikTok
@regielski

Snow cover over mountainous areas in global climate models

IPSL-CM6A

HOW DO WE COMPUTE THE

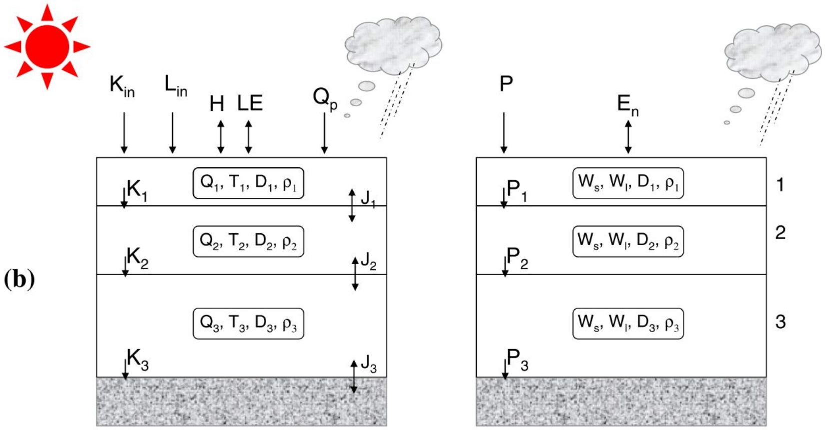
SNOW COVER FRACTION (SCF)

IN GLOBAL CLIMATE MODELS?

&

HOW DOES THE SCF EVOLVES

OVER MOUNTAINOUS AREAS?



K_{in} (short wave radiation), **L_{in}** (longwave radiation), **H** (sensible heat flux), **LE**(latent heat flux), **J** (conduction heat flux), **Q** (snow layer heat content), **Q_p**(advective heat from rain and snow), **W** (snow layer SWE), **W_l** (snow layer liquid water content), **D** (snow layer depth), **ρ** (snow layer density) , **P** (precipitation), **E_n** (evaporation)

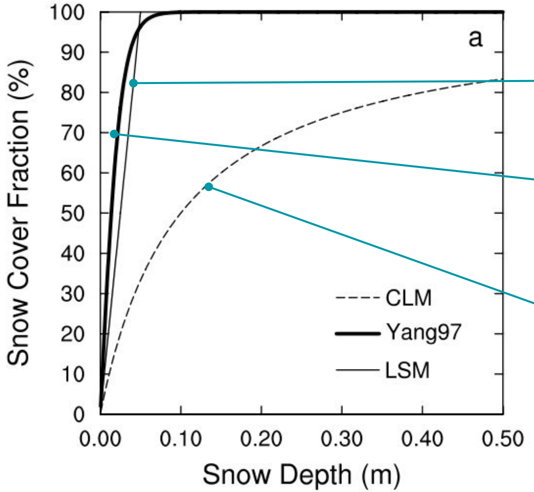
snow scheme in the ORCHIDEE land surface model (Wang et al., 2013)

Snow Depth

Snow Water Equivalent

Snow Density

Snow cover parameterizations



$f_{sno} = \min(1, h_{sno}/0.05)$

$f_{sno} = \tanh\left(\frac{h_{sno}}{2.5 z_{0,g}}\right)$

$f_{sno} = h_{sno} / \left(10 z_{0,g} + h_{sno}\right)$

Figure 1. (a) SCF (or f_{sno}) computed from equation (2) (used in the default CLM and BATS), equation (3) of *Yang et al.* [1997], and a formulation used in the NCAR LSM1.0, $f_{sno} = \min(1, h_{sno}/0.05)$, where h_{sno} is snow depth (m) and (b) SCF as a function of ground surface roughness, snow depth, and snow density computed from equation (4) with new snow density $\rho_{new} = 100$ kg m^{-3} and $m = 1.6$. The thick line (i.e., $\rho_{sno} = 100$ kg m^{-3}) is equivalent to equation (3).

Niu and Yang (2007)

Snow Cover parameterization: Niu and Yang (2007) - NY07

$$f_{sno} = \tanh\left(\frac{h_{sno}}{2.5 z_{0g} (\rho_{sno}/\rho_{new})^m}\right)$$

Snow Density

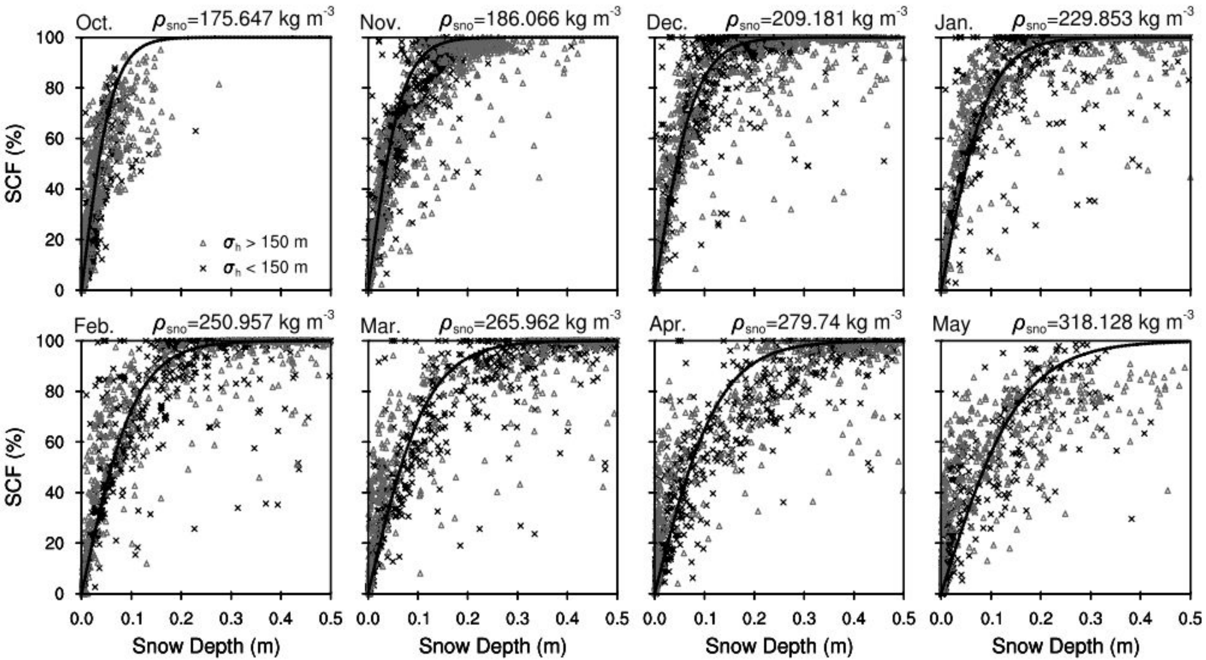


Figure 2. Relationship between AVHRR SCF (%) and CMC snow depth (m) in 1° × 1° grid cells of major NA river basins including the Mackenzie, Yukon, Churchill, Fraser, St. Lawrence, Columbia, Colorado, and Mississippi from October to May. The darker crosses stand for 1° × 1° grid cells where the standard deviation of topography $\sigma_h < 150$ m, and the lighter triangles stand for 1° × 1° grid cells where $\sigma_h > 150$ m. The fitted lines are computed from equation (4) ($m = 1.6$) with the mean snow densities shown above each frame.

Snow Cover parameterization: Niu and Yang (2007) - NY07

$$f_{sno} = \tanh\left(\frac{h_{sno}}{2.5 z_{0g} (\rho_{sno}/\rho_{new})^m}\right)$$

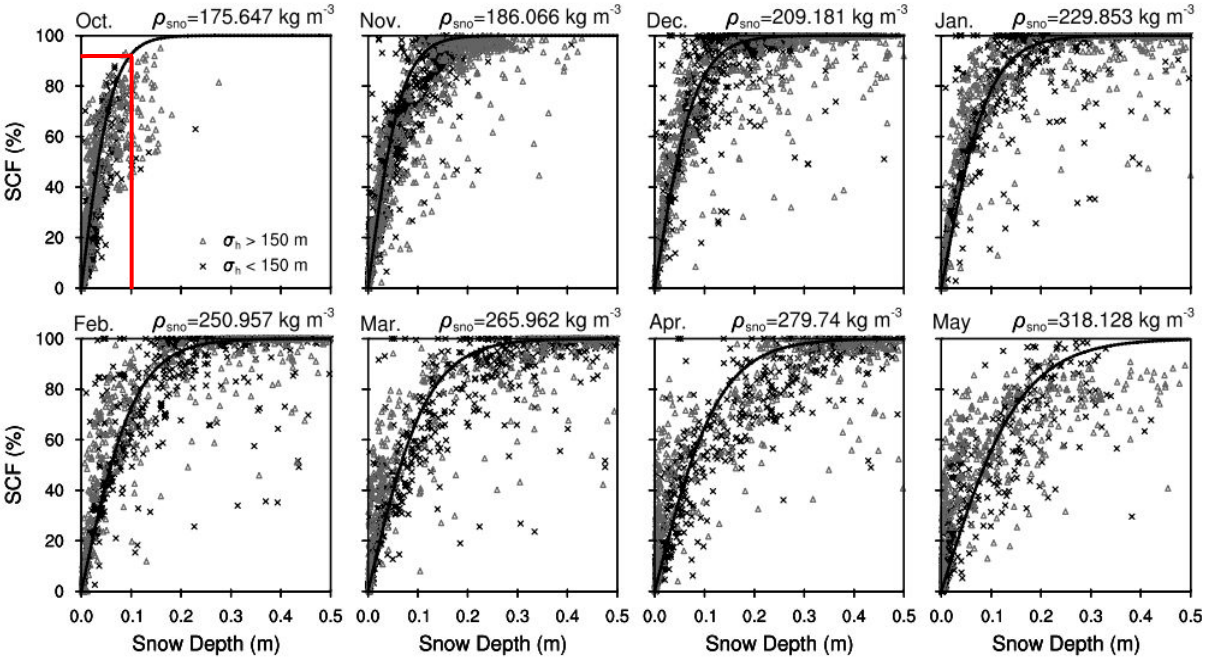


Figure 2. Relationship between AVHRR SCF (%) and CMC snow depth (m) in 1° × 1° grid cells of major NA river basins including the Mackenzie, Yukon, Churchill, Fraser, St. Lawrence, Columbia, Colorado, and Mississippi from October to May. The darker crosses stand for 1° × 1° grid cells where the standard deviation of topography σ_h < 150 m, and the lighter triangles stand for 1° × 1° grid cells where σ_h >150 m. The fitted lines are computed from equation (4) (m = 1.6) with the mean snow densities shown above each frame.

Snow Cover parameterization: Niu and Yang (2007) - NY07

$$f_{sno} = \tanh\left(\frac{h_{sno}}{2.5 z_{0g} (\rho_{sno}/\rho_{new})^{m}}\right)$$

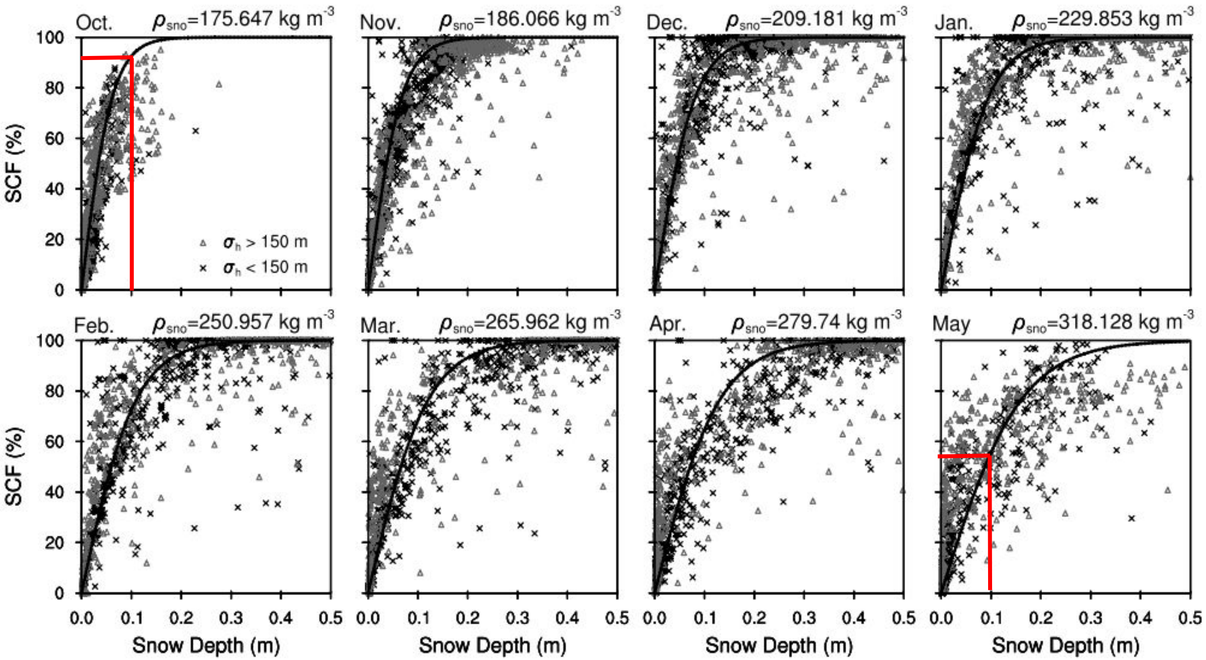
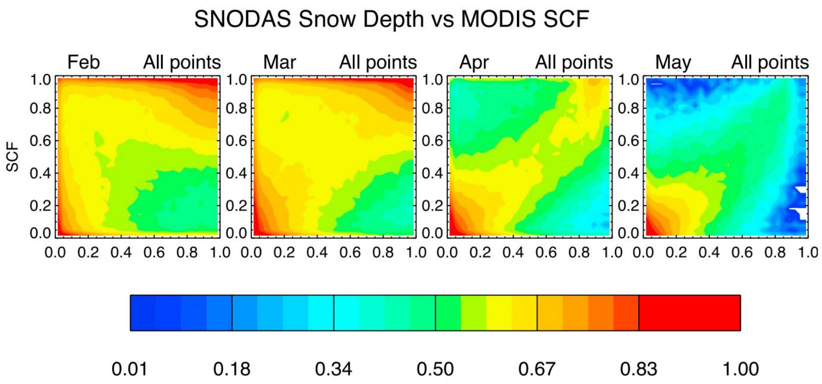


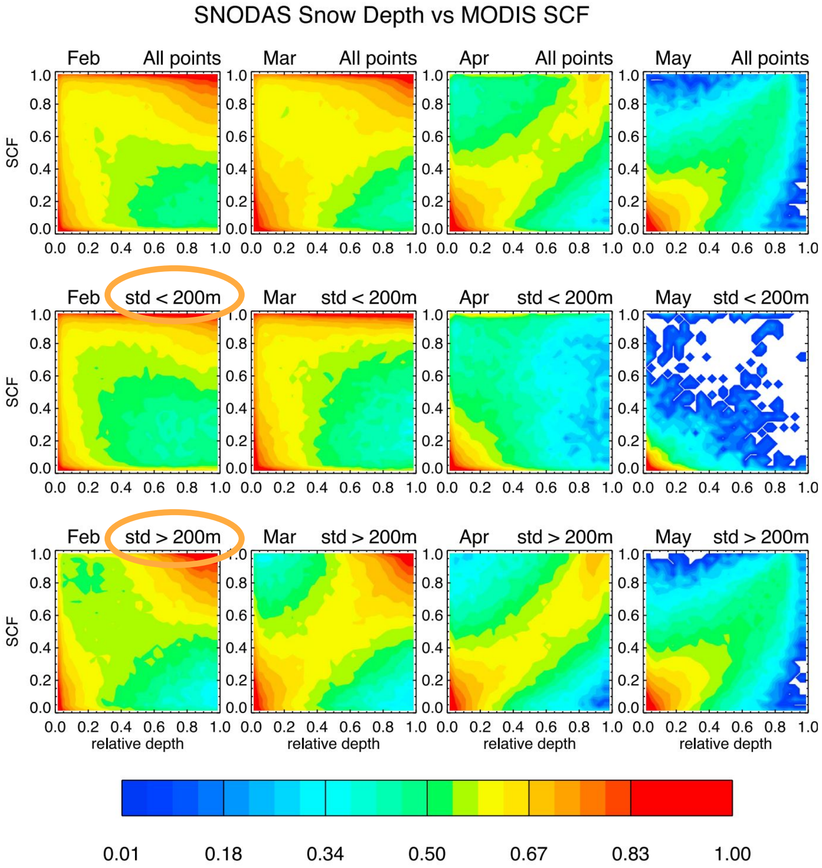
Figure 2. Relationship between AVHRR SCF (%) and CMC snow depth (m) in 1° × 1° grid cells of major NA river basins including the Mackenzie, Yukon, Churchill, Fraser, St. Lawrence, Columbia, Colorado, and Mississippi from October to May. The darker crosses stand for 1° × 1° grid cells where the standard deviation of topography σ_h < 150 m, and the lighter triangles stand for 1° × 1° grid cells where σ_h >150 m. The fitted lines are computed from equation (4) (m = 1.6) with the mean snow densities shown above each frame.

Snow cover in mountainous area: Swenson & Lawrence (2012) - SL12



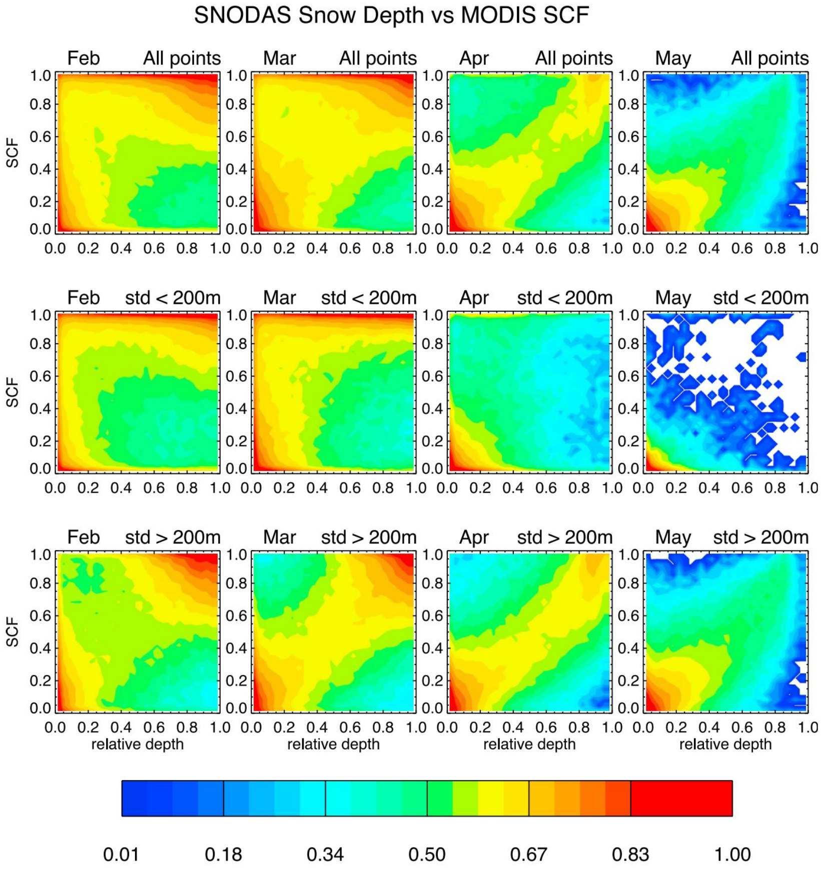
Swenson & Lawrence (2012)

Snow cover in mountainous area: Swenson & Lawrence (2012) - SL12



Swenson & Lawrence (2012)

Snow cover in mountainous area: Swenson & Lawrence (2012) - SL12



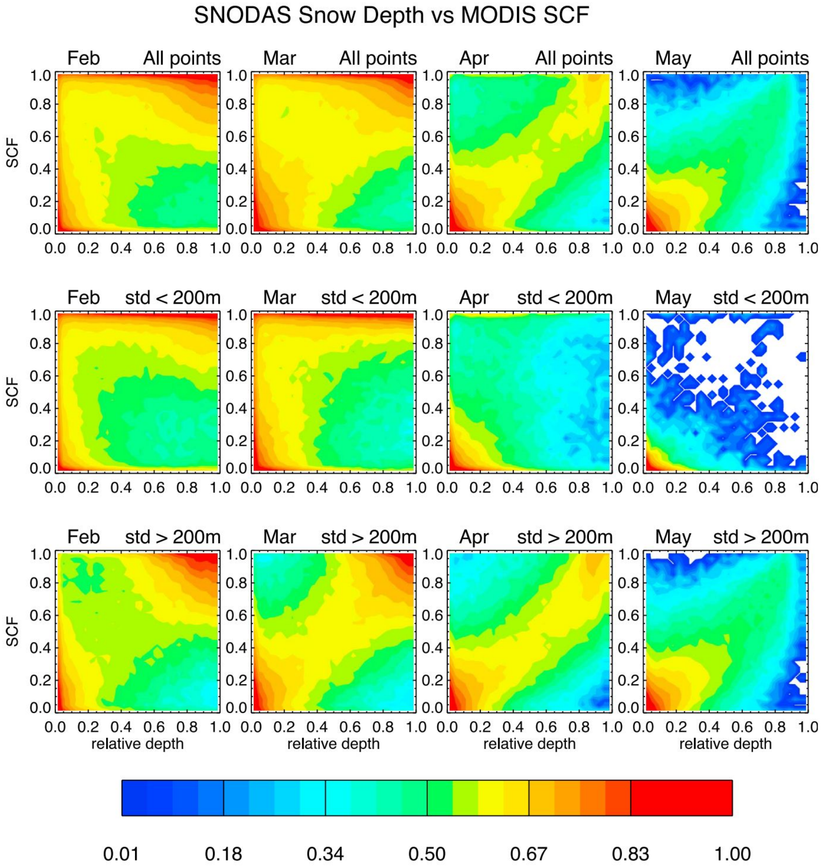
Swenson & Lawrence (2012)

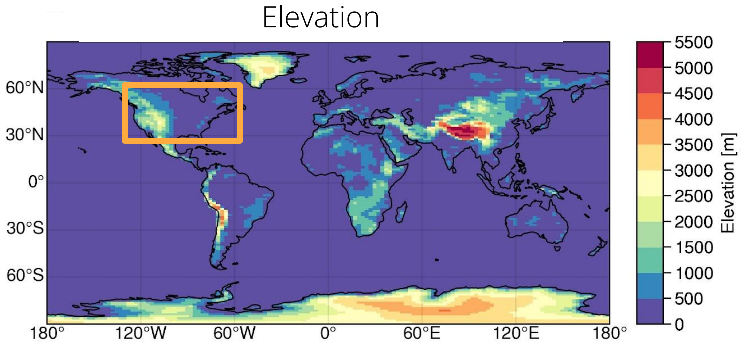
Standard deviation of topography (σ_{topo}) in SCF parameterization first introduced by Douville et al. (1995), then Roesch et al. (2001), etc.

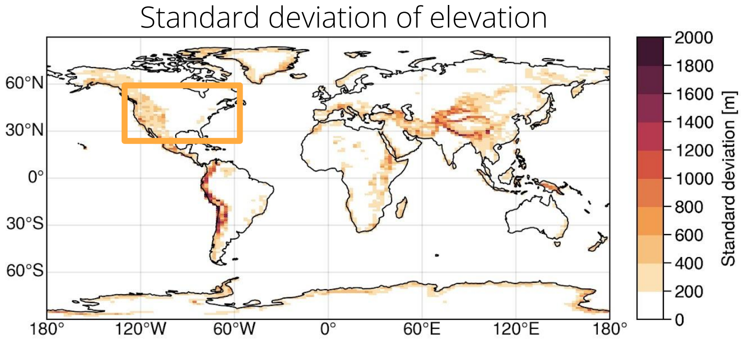
$$\mathrm{SCF} = 1 - \left[\frac{1}{\pi}\mathrm{acos}\left(2\frac{\mathrm{SWE}}{\mathrm{SWE_{max}}} - 1\right)\right]^{N_{\mathrm{melt}}}$$

$$N_{\mathrm{melt}} = \frac{200}{\max(30, \sigma_{\mathrm{topo}})}$$

Snow cover in mountainous area: Swenson & Lawrence (2012) - SL12

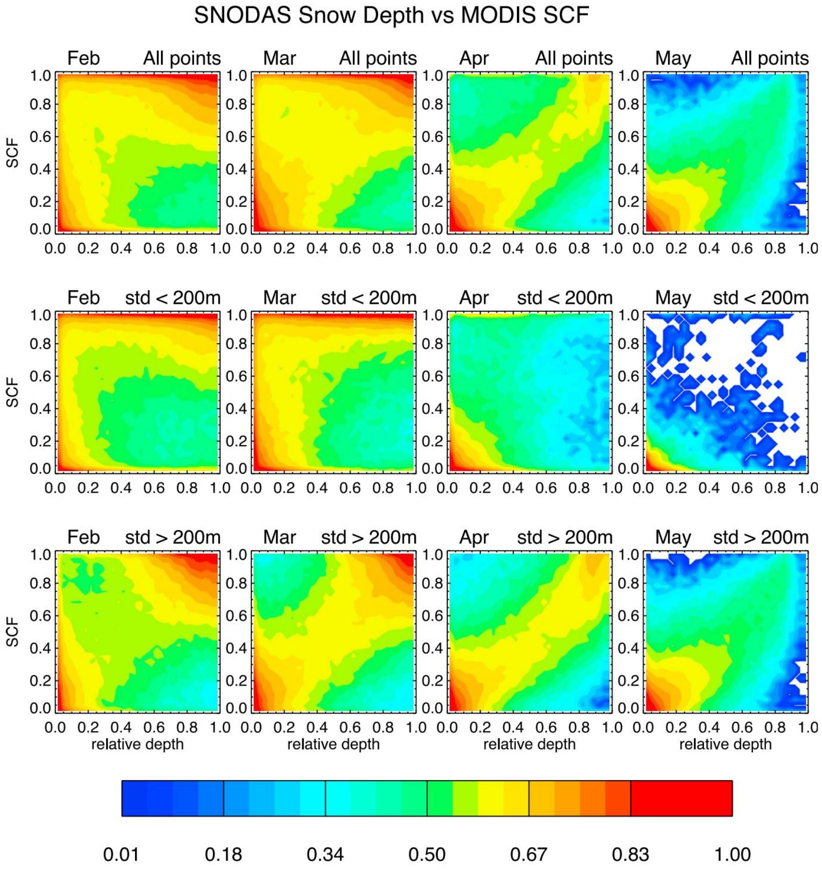




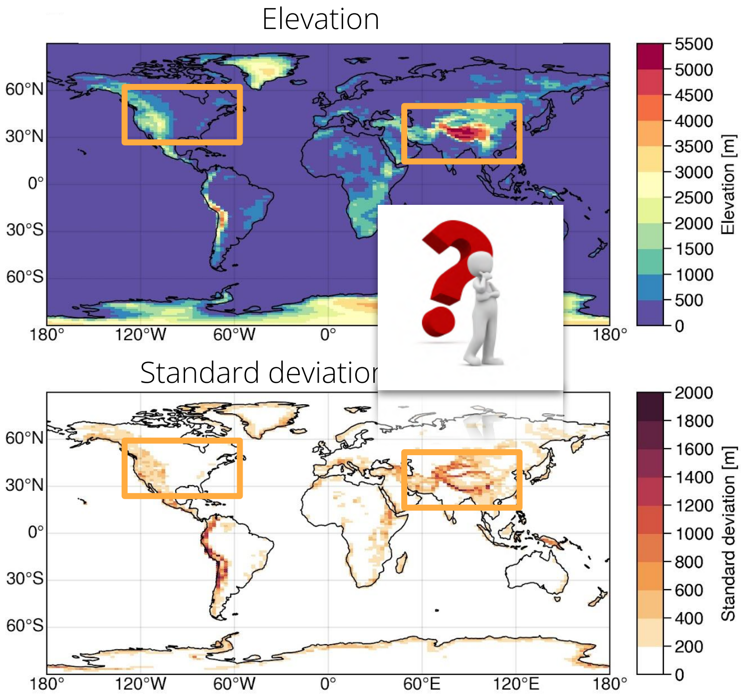


Swenson & Lawrence (2012)

Snow cover in mountainous area: Swenson & Lawrence (2012)



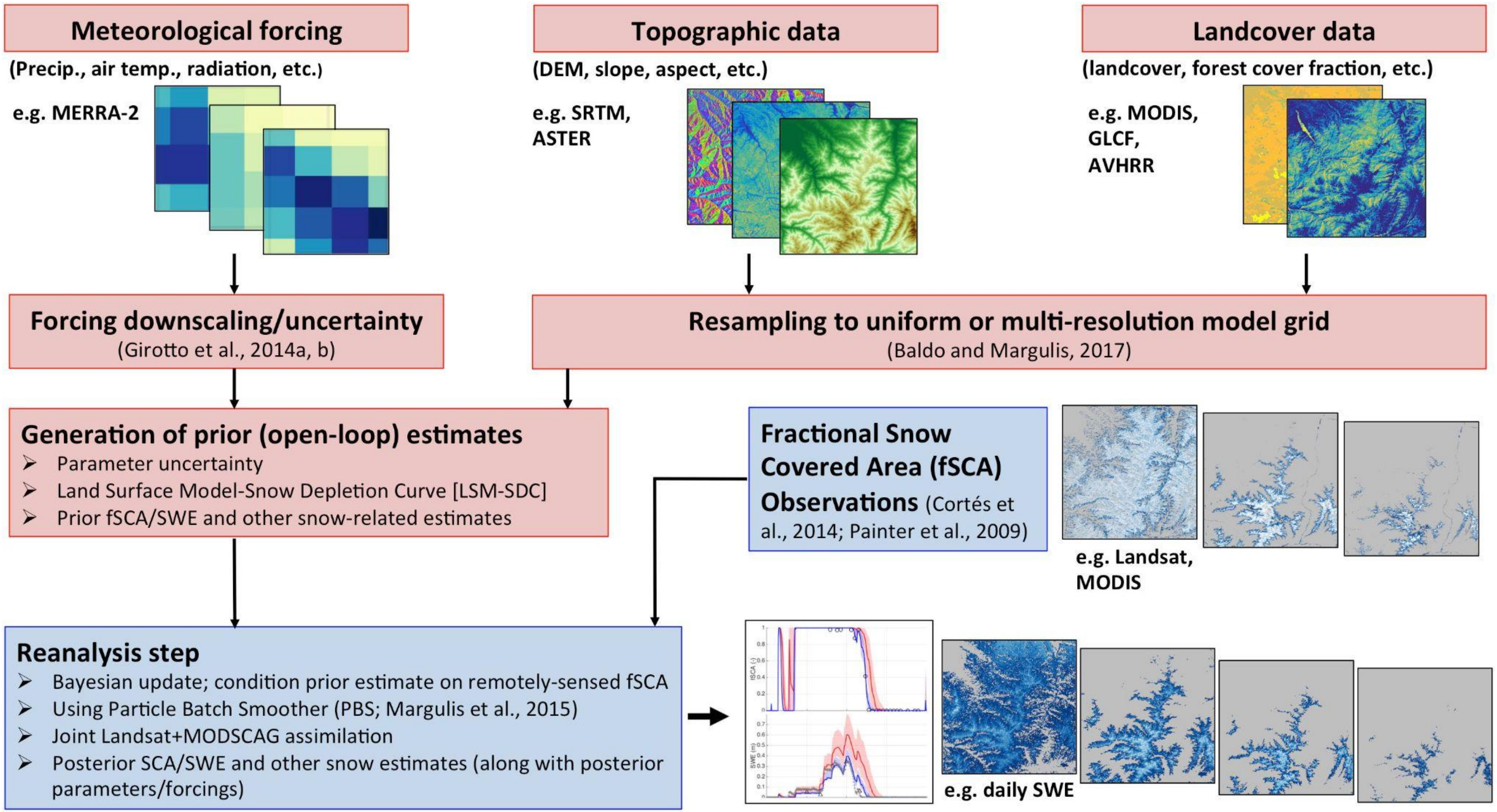
Swenson & Lawrence (2012)



“Estimating the spatial distribution of snow water equivalent (SWE) in mountainous terrain is currently the most important unsolved problem in snow hydrology.”

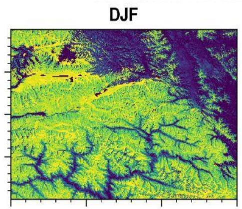
Dozier et al. (2016)

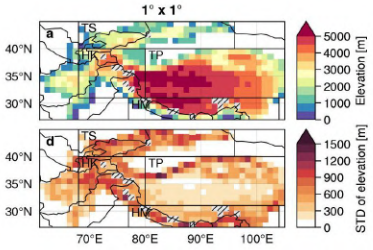
High Mountain Asia UCLA Daily Snow Reanalysis (HMASR)



Margulis et al. (2019)

HMASR -> snow cover parameterizations





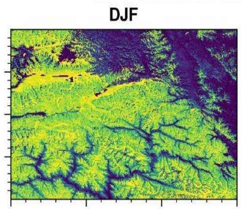
HMASR
SD / SWE / density
+ STD topo
at 1°x1°

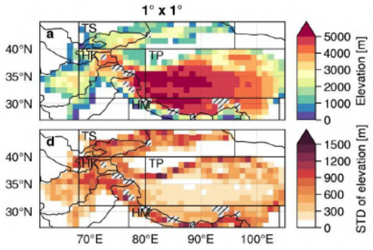
→

→

SCF

HMASR -> snow cover parameterizations





HMASR
SD / SWE / density
+ STD topo
at 1°x1°

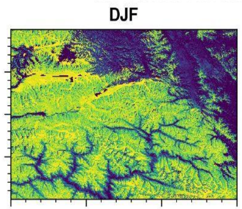
→

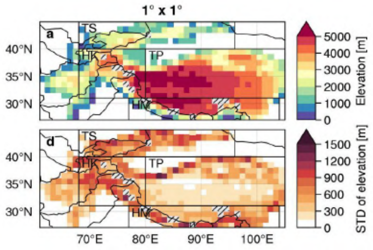
→

SCF

R01 ([Roesch et al., 2001])
$$\mathrm{SCF} = 0.95 \cdot \tanh(100 \cdot \mathrm{SWE})\sqrt{\frac{1000 \cdot \mathrm{SWE}}{1000 \cdot \mathrm{SWE} + \varepsilon + 0.15 \cdot \sigma_z}}$$

HMASR -> snow cover parameterizations





HMASR
SD / SWE / density
+ STD topo
at 1°x1°

SCF

R01 (Roesch et al., 2001)

$$\mathrm{SCF} = 0.95 \cdot \tanh(100 \cdot \mathrm{SWE}) \sqrt{\frac{1000 \cdot \mathrm{SWE}}{1000 \cdot \mathrm{SWE} + \varepsilon + 0.15 \cdot \sigma_z}}$$

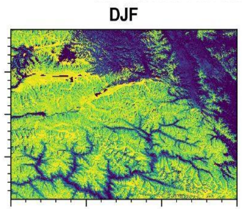
SL12 (Swenson and Lawrence, 2012)

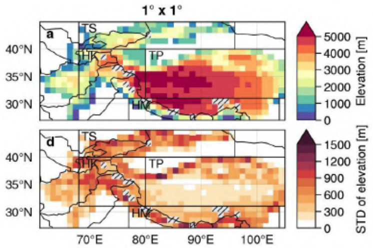
$$\mathrm{SCF} = 1 - \left[\frac{1}{\pi} \operatorname{acos}\left(2 \frac{\mathrm{SWE}}{\mathrm{SWE}_{\mathrm{max}}} - 1\right)\right]^{N_{\mathrm{melt}}}$$

$$N_{\mathrm{melt}} = \frac{200}{\max(30, \sigma_{\mathrm{topo}})}$$

$$\mathrm{SWE}_{max} = \frac{2 \cdot \mathrm{SWE}}{\cos\left[\pi(1 - SCF)^{1/N_{melt}}\right] + 1}$$

HMASR -> snow cover parameterizations





HMASR
SD / SWE / density
+ STD topo
at 1°x1°

SCF

R01 (Roesch et al., 2001)

$$\mathrm{SCF} = 0.95 \cdot \tanh(100 \cdot \mathrm{SWE}) \sqrt{\frac{1000 \cdot \mathrm{SWE}}{1000 \cdot \mathrm{SWE} + \varepsilon + 0.15 \cdot \sigma_z}}$$

NY07 (Niu and Yang, 2007)

$$\mathrm{SCF} = \tanh\left(\frac{\mathrm{SD}}{2.5 \cdot z_{0g} \left(\rho_{\mathrm{snow}} / \rho_{\mathrm{new}}\right)^m}\right)$$

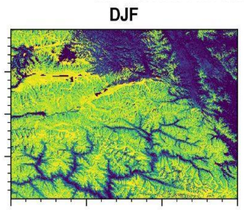
SL12 (Swenson and Lawrence, 2012)

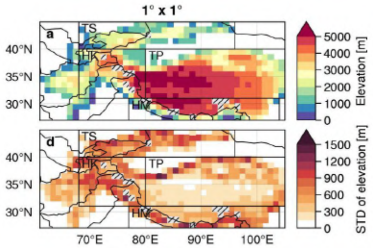
$$\mathrm{SCF} = 1 - \left[\frac{1}{\pi} \mathrm{acos}\left(2 \frac{\mathrm{SWE}}{\mathrm{SWE}_{\mathrm{max}}} - 1\right)\right]^{N_{\mathrm{melt}}}$$

$$N_{\mathrm{melt}} = \frac{200}{\max(30, \sigma_{\mathrm{topo}})}$$

$$\mathrm{SWE}_{max} = \frac{2 \cdot \mathrm{SWE}}{\cos\left[\pi(1 - SCF)^{1/N_{melt}}\right] + 1}$$

HMASR -> snow cover parameterizations





HMASR
SD / SWE / density
+ STD topo
at 1°x1°

SCF

R01 (Roesch et al., 2001)

$$\mathrm{SCF} = 0.95 \cdot \tanh(100 \cdot \mathrm{SWE}) \sqrt{\frac{1000 \cdot \mathrm{SWE}}{1000 \cdot \mathrm{SWE} + \varepsilon + 0.15 \cdot \sigma_z}}$$

NY07 (Niu and Yang, 2007)

$$\mathrm{SCF} = \tanh\left(\frac{\mathrm{SD}}{2.5 \cdot z_{0g}\left(\rho_{\mathrm{snow}}/\rho_{\mathrm{new}}\right)^m}\right)$$

$+ \sigma_{topo}$ (LA22)

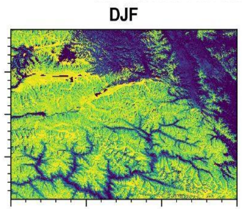
SL12 (Swenson and Lawrence, 2012)

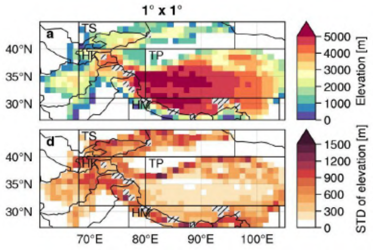
$$\mathrm{SCF} = 1 - \left[\frac{1}{\pi}\mathrm{acos}\left(2\frac{\mathrm{SWE}}{\mathrm{SWE_{max}}} - 1\right)\right]^{N_{\mathrm{melt}}}$$

$$N_{\mathrm{melt}} = \frac{200}{\max(30, \sigma_{\mathrm{topo}})}$$

$$\mathrm{SWE}_{max} = \frac{2 \cdot \mathrm{SWE}}{\cos\left[\pi(1 - SCF)^{1/N_{melt}}\right] + 1}$$

HMASR -> snow cover parameterizations





HMASR
SD / SWE / density
+ STD topo
at 1°x1°

SCF

R01 (Roesch et al., 2001)

$$\mathrm{SCF} = 0.95 \cdot \tanh(100 \cdot \mathrm{SWE})\sqrt{\frac{1000 \cdot \mathrm{SWE}}{1000 \cdot \mathrm{SWE} + \varepsilon + 0.15 \cdot \sigma_z}}$$

NY07 (Niu and Yang, 2007)

$$\mathrm{SCF} = \tanh\left(\frac{\mathrm{SD}}{2.5 \cdot z_{0g}(\rho_{\mathrm{snow}}/\rho_{\mathrm{new}})^m}\right)$$

+ σ_{topo} (LA22)

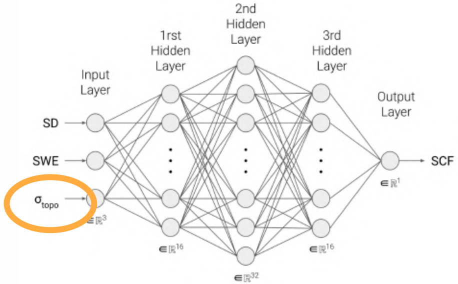
SL12 (Swenson and Lawrence, 2012)

$$\mathrm{SCF} = 1 - \left[\frac{1}{\pi}\mathrm{acos}\left(2\frac{\mathrm{SWE}}{\mathrm{SWE_{max}}} - 1\right)\right]^{N_{\mathrm{melt}}}$$

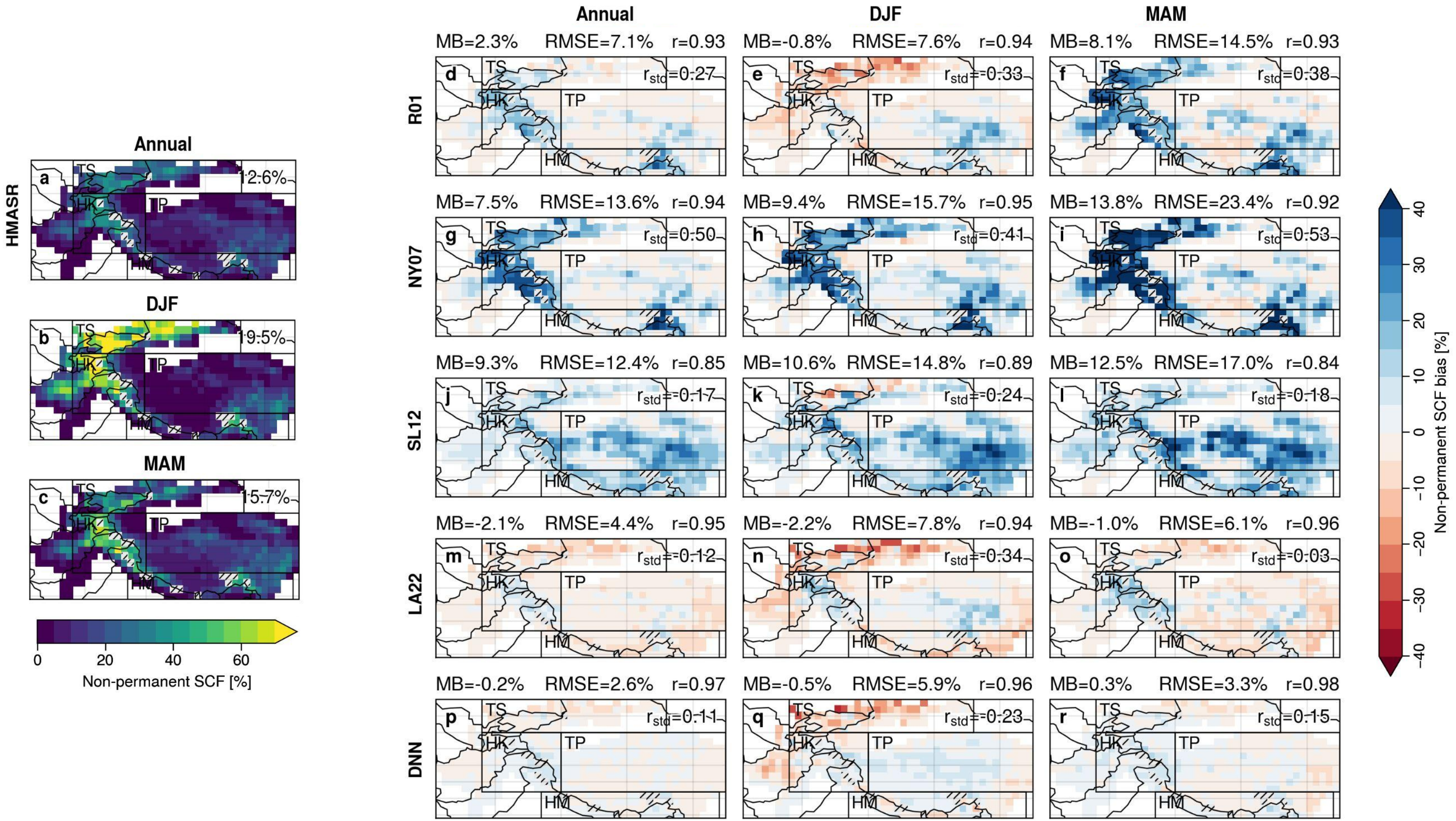
$$N_{\mathrm{melt}} = \frac{200}{\max(30, \sigma_{\mathrm{topo}})}$$

$$\mathrm{SWE}_{max} = \frac{2 \cdot \mathrm{SWE}}{\cos\left[\pi(1 - SCF)^{1/N_{melt}}\right] + 1}$$

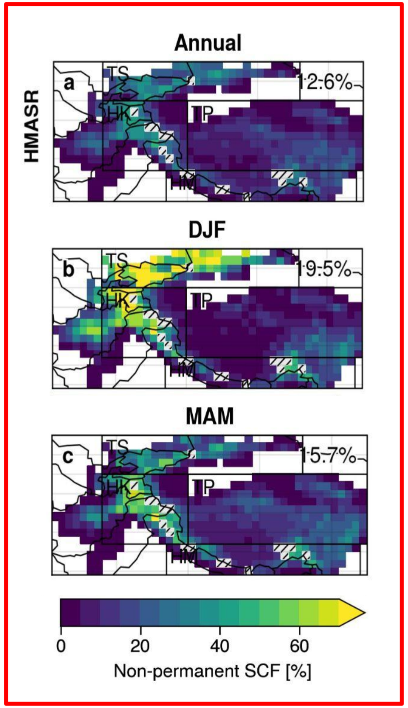
DNN (deep neural network)

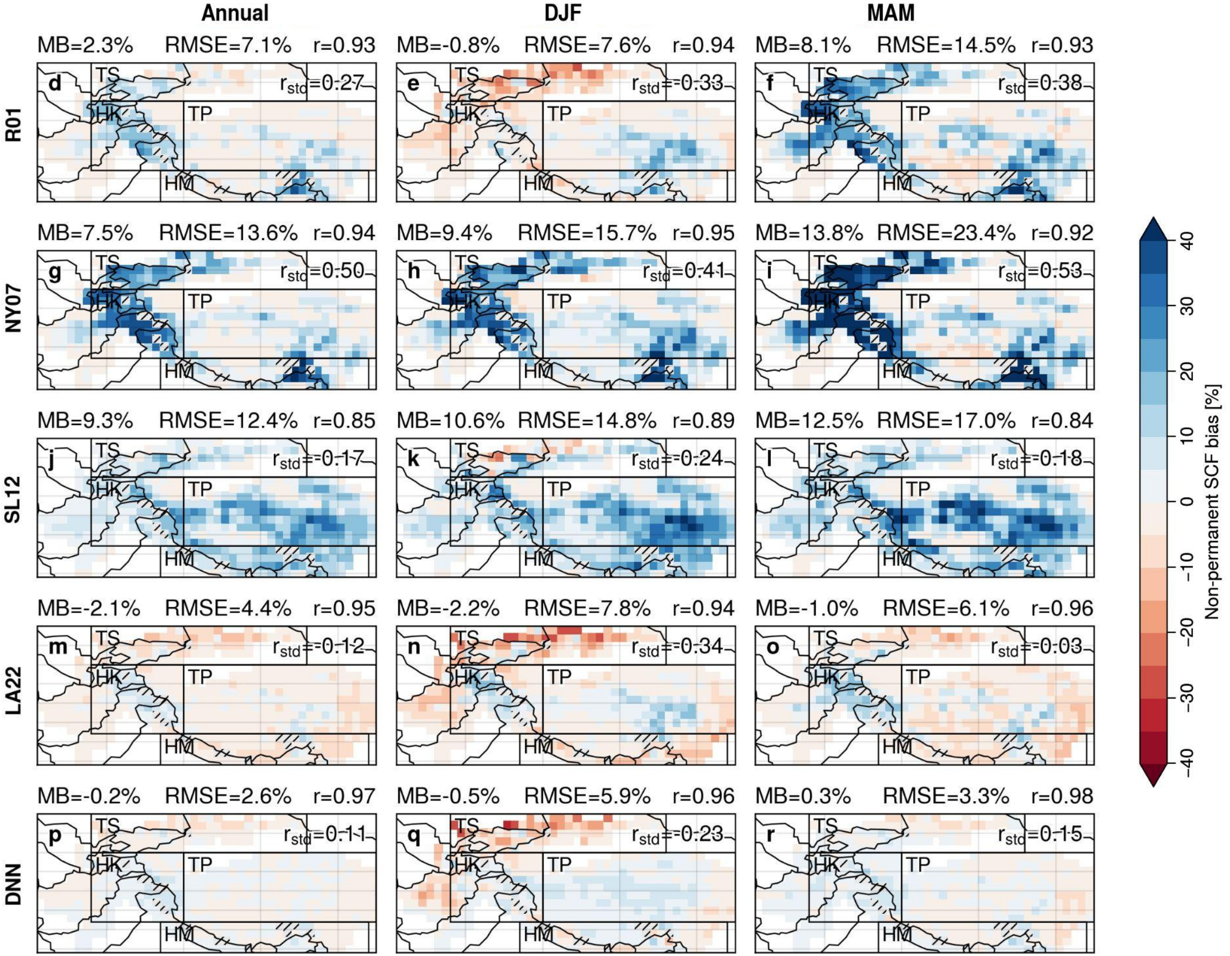


HMASR -> snow cover parameterizations

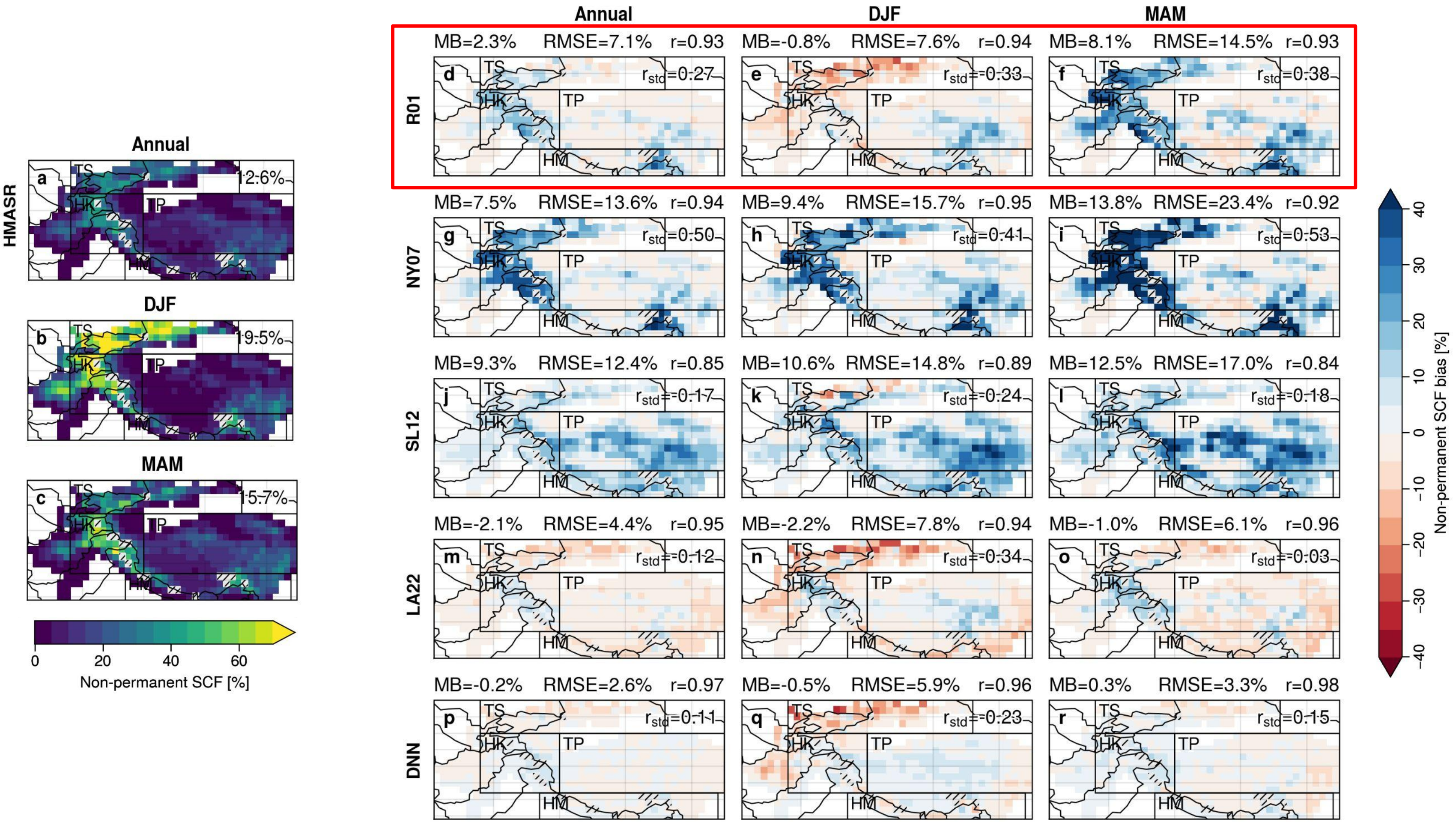


HMASR -> snow cover parameterizations

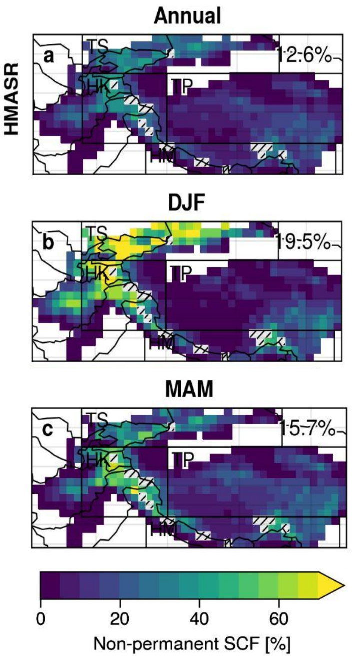


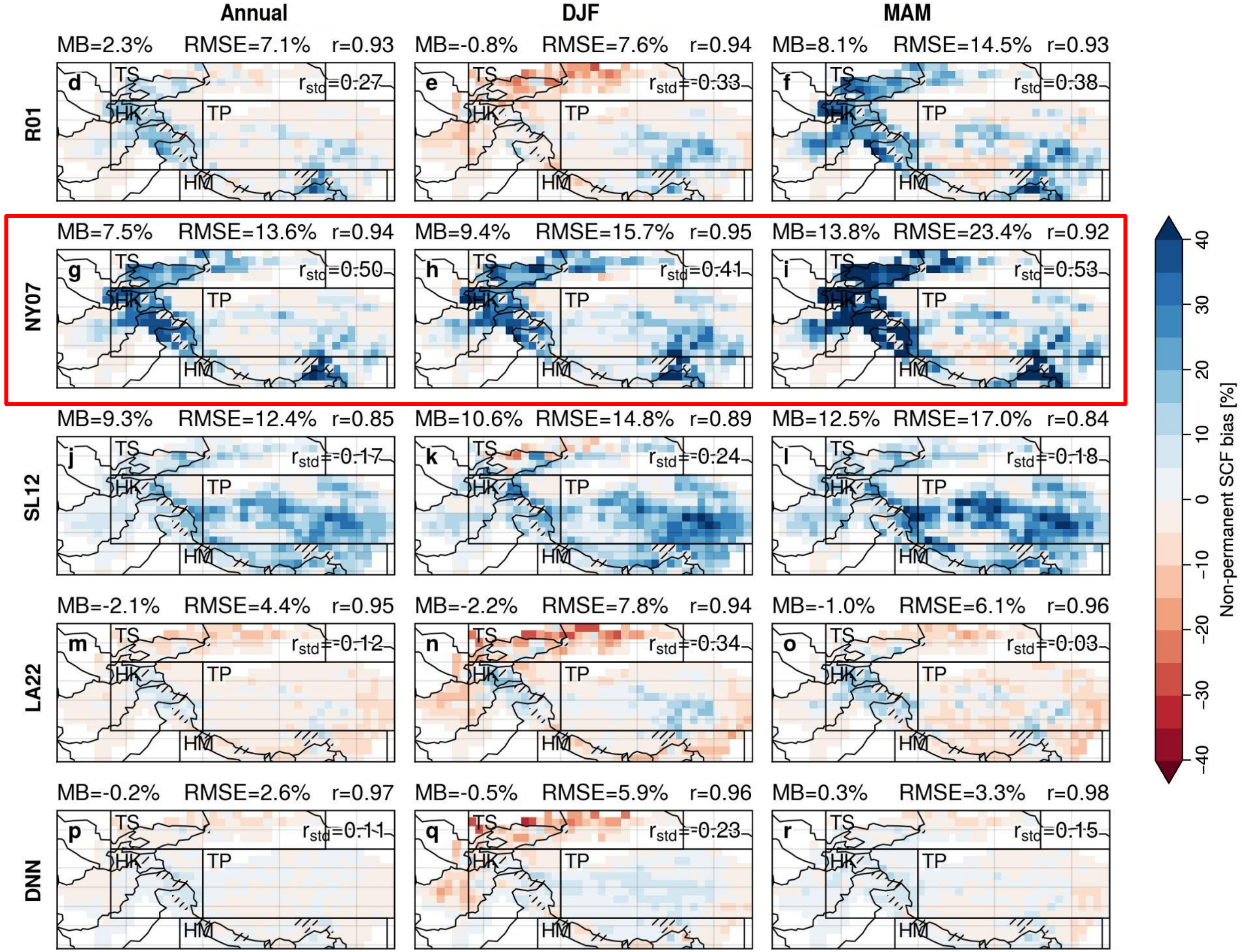


HMASR -> snow cover parameterizations

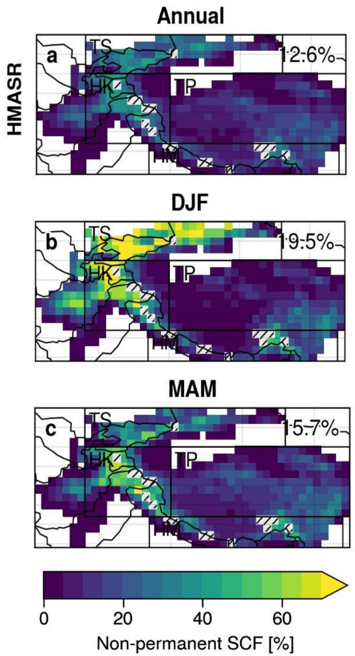


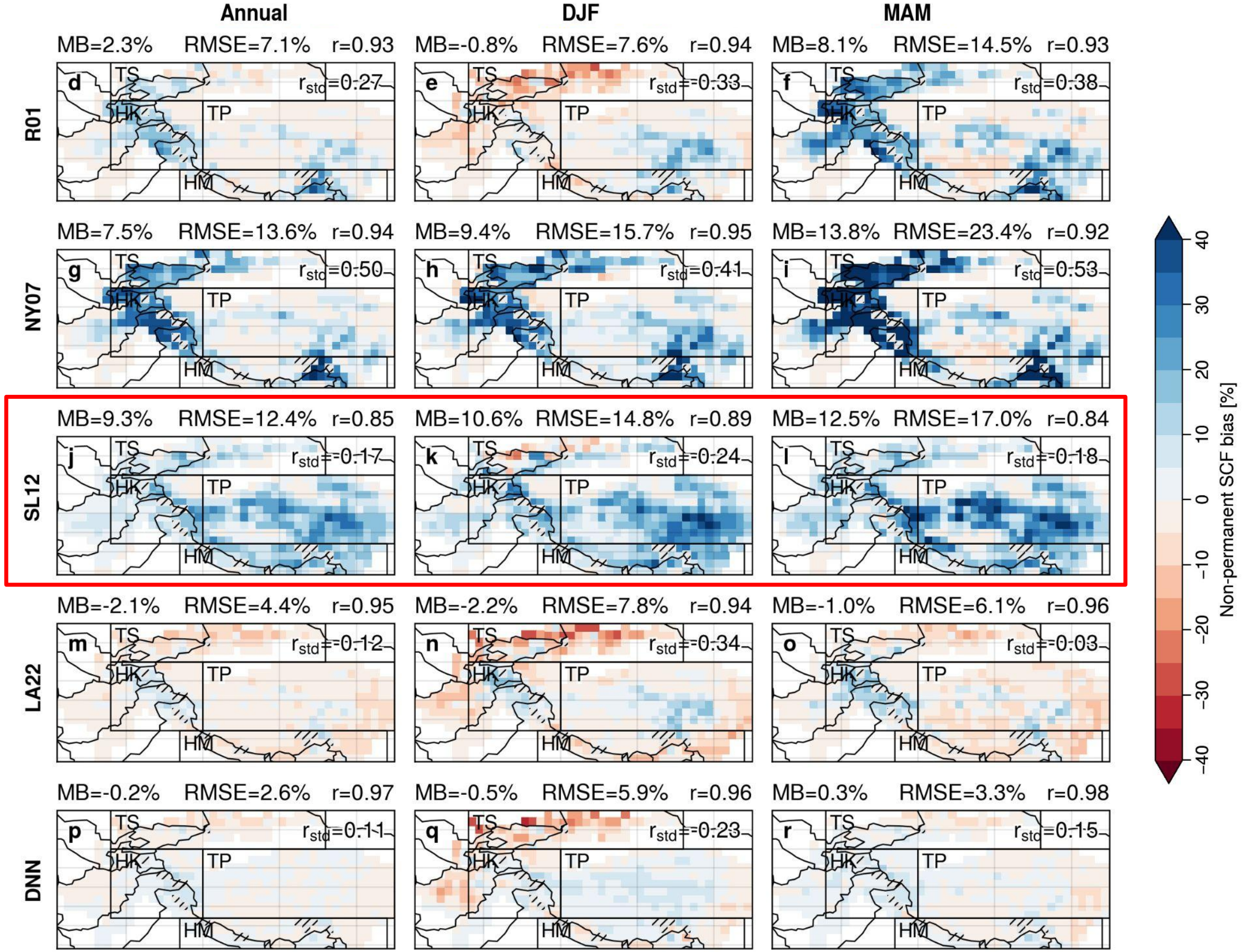
HMASR -> snow cover parameterizations



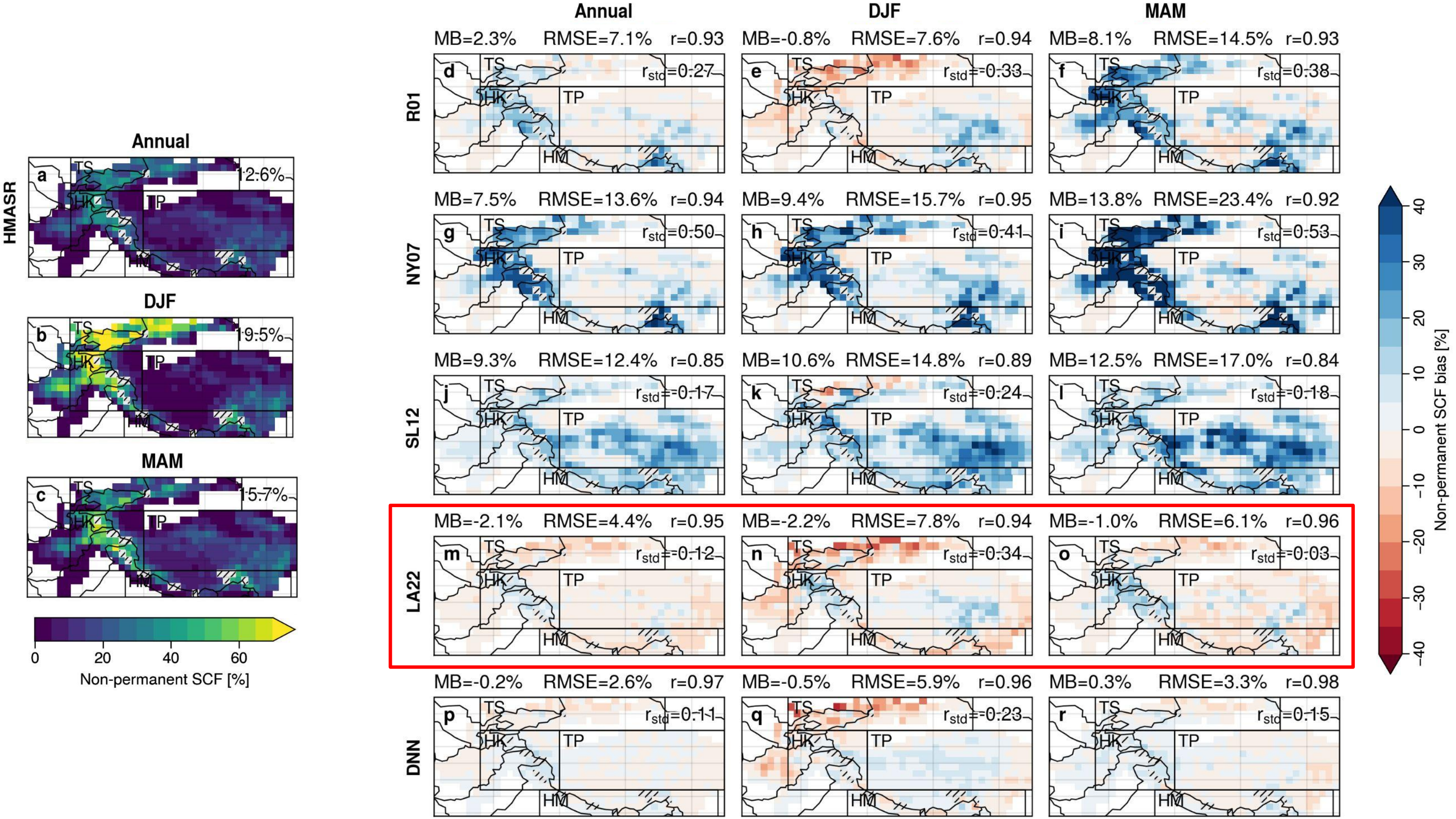


HMASR -> snow cover parameterizations

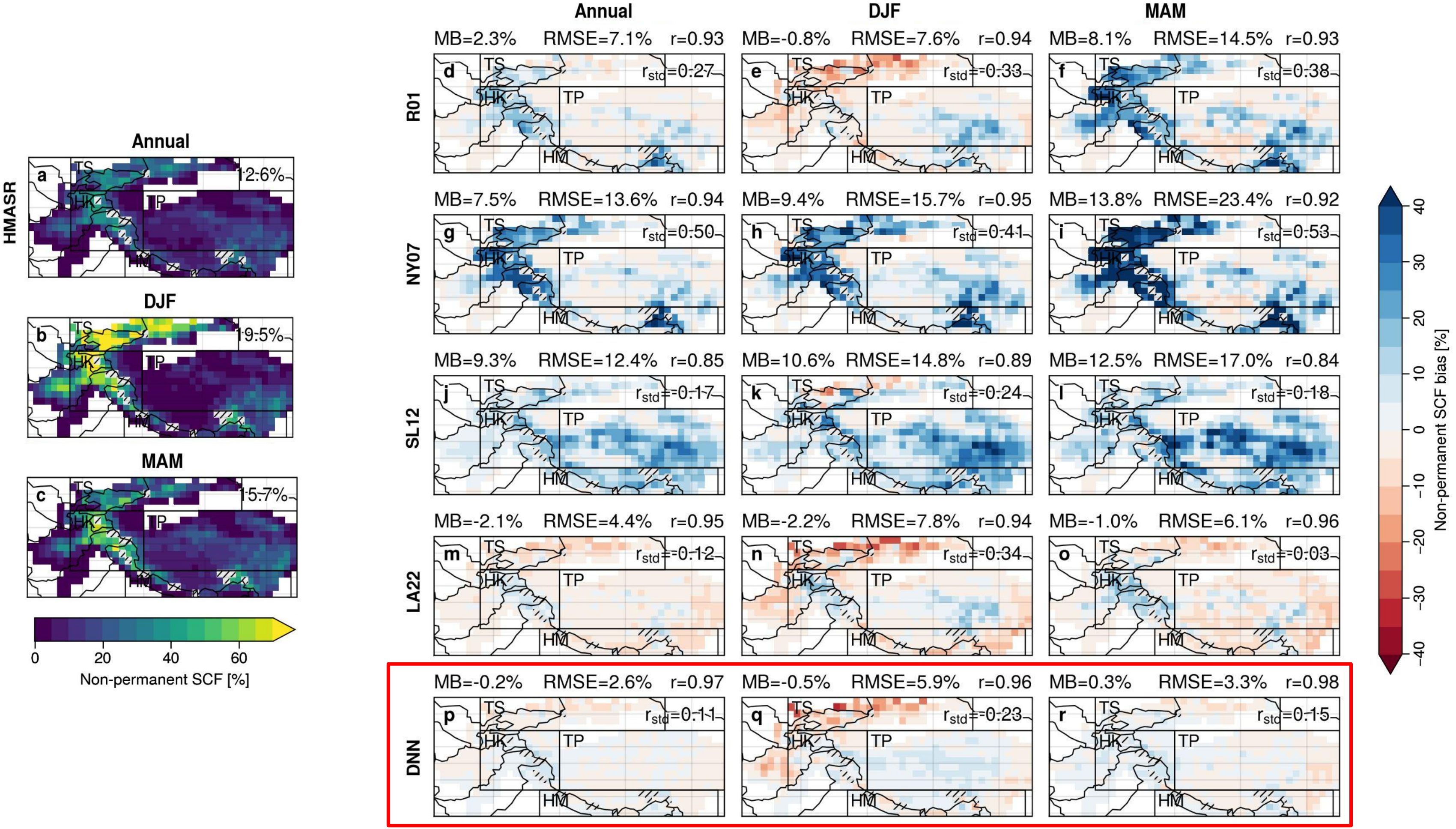




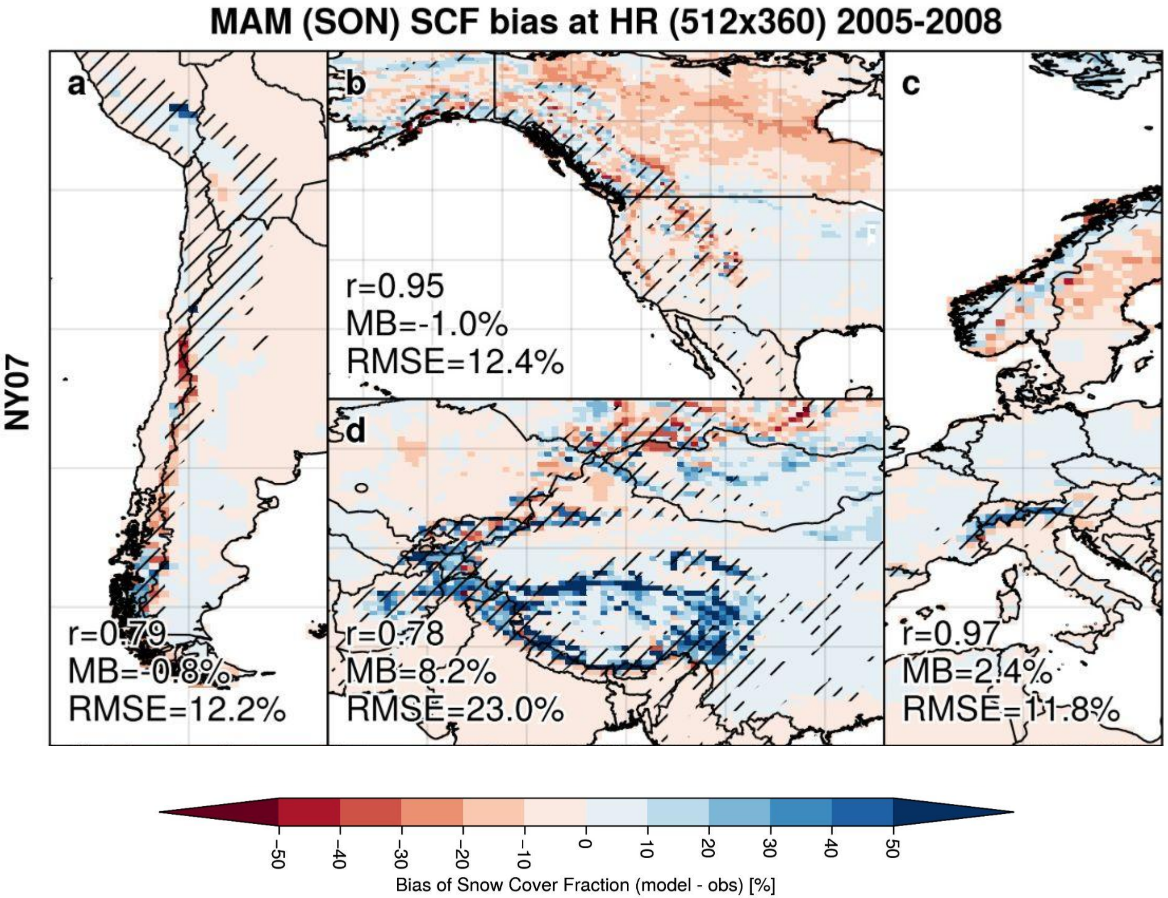
HMASR -> snow cover parameterizations



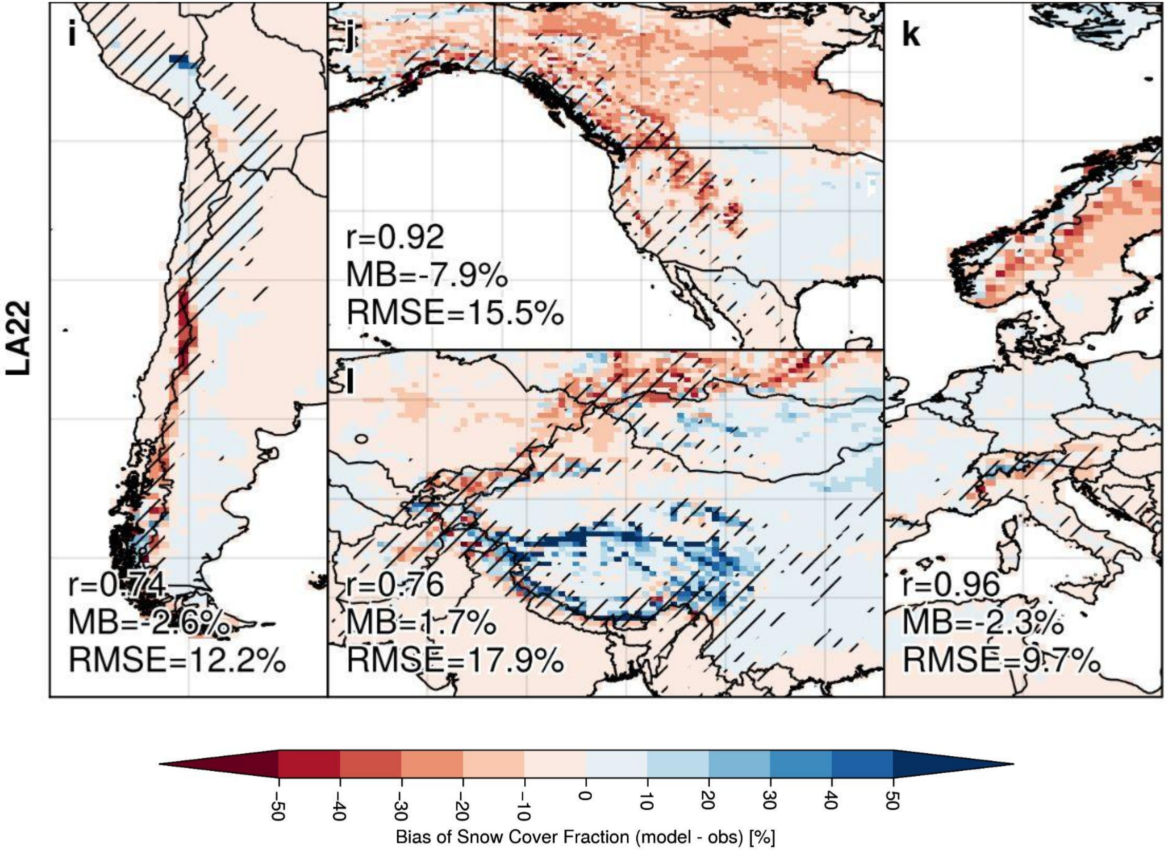
HMASR -> snow cover parameterizations



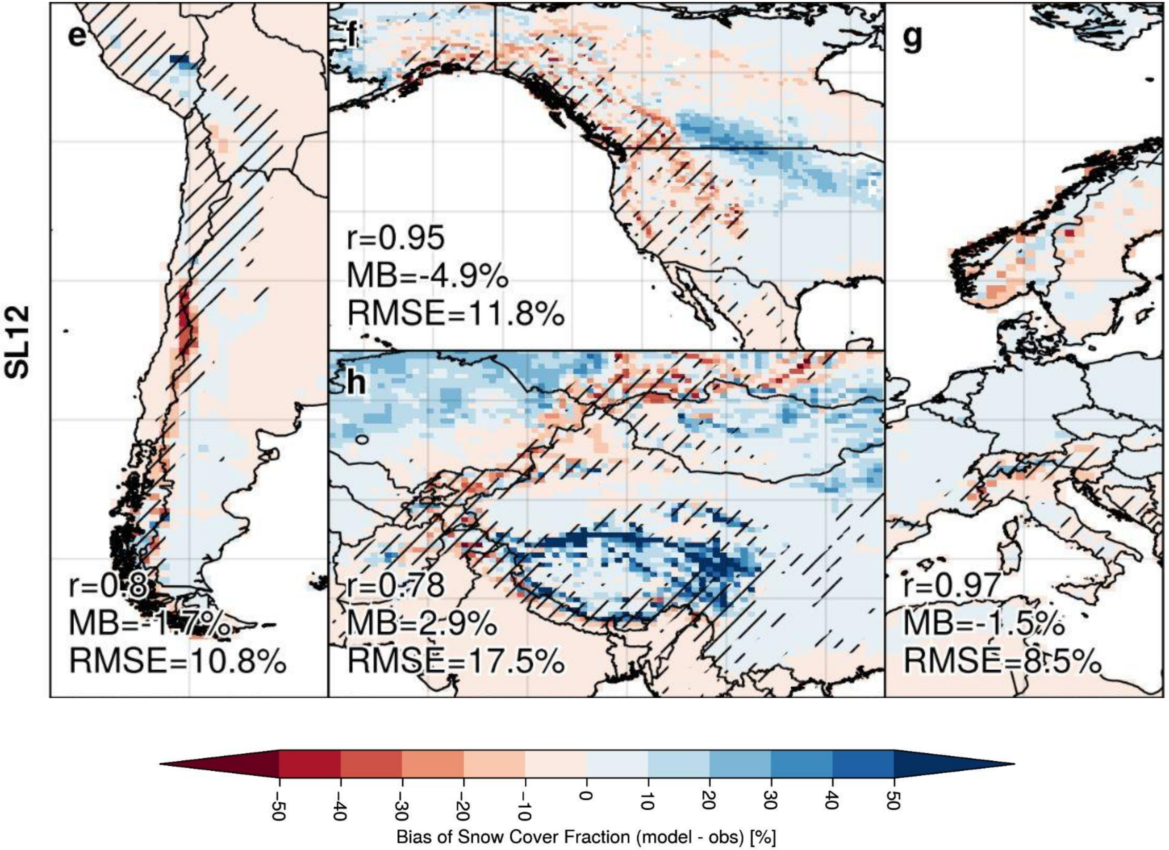
Application in GCM (LMDZ/ORCHIDEE)



Application in GCM (LMDZ/ORCHIDEE)



Application in GCM (LMDZ/ORCHIDEE)



Discussion

- Evaluating SCF parameterizations is not easy in GCMs because depends on correct snowfall / SD / SWE estimates

- These later snow related parameters (snowfall / SD / SWE) does not necessarily take into account subgrid topography:

  ↳subgrid parameterization of snowfall, snow distribution with elevation, surface energy budget, small scale orographic drag?

- Hard to evaluate!

↳Crucial need of snowfall, SD/SWE observations over mountainous areas!

Conclusion

- Taking into account the sub-grid topography in SCF parameterization seems essential over mountainous areas (Swenson and Lawrence, 2012 ; Miao et al., 2022 ; Lalande et al., in prep)
- Other processes might be involved in current biases over HMA:
  - precipitation (orographic drag; e.g, Wang et al., 2020) / aerosol deposition on snow (e.g., Usha et al., 2020) / boundary layer (e.g., Serafin et al., 2020) / tropospheric cold bias, etc.
- Further calibration -> other regions / datasets (+ other variables, forested areas?, etc.)
- Limitation over permanent snow areas? (glaciers, etc.)
  - elevation bands (e.g., Walland and Simmonds, 1996; Younas et al., 2017)
- Other parameterizations not tested, e.g.: Liston (2004), Helbig et al. (2021), etc.
- Deep learning very promising for such parameterizations (+ help to test the influence of other parameters)

Bibliography

References

Cortés, G., & Margulis, S. (2017). Impacts of El Niño and La Niña on interannual snow accumulation in the Andes: Results from a high-resolution 31 year reanalysis. Geophysical Research Letters, 44(13), 6859–6867. https://doi.org/10.1002/2017GL073826

Douville, H., Royer, J.-F., & Mahfouf, J.-F. (1995). A new snow parameterization for the Météo-France climate model. Climate Dynamics, 12(1), 37–52. https://doi.org/10.1007/BF00208761

Dozier, J., Bair, E. H., & Davis, R. E. (2016). Estimating the spatial distribution of snow water equivalent in the world's mountains. WIREs Water, 3(3), 461–474. https://doi.org/10.1002/wat2.1140

Helbig, N., van Herwijnen, A., Magnusson, J., & Jonas, T. (2015). Fractional snow-covered area parameterization over complex topography. Hydrology and Earth System Sciences, 19(3), 1339–1351. https://doi.org/10.5194/hess-19-1339-2015

Liston, G. E. (2004). Representing Subgrid Snow Cover Heterogeneities in Regional and Global Models. Journal of Climate, 17(6), 1381–1397. https://doi.org/10.1175/1520-0442(2004)017<1381:RSSCHI>2.0.CO;2

Liu, Y., Fang, Y., & Margulis, S. A. (2021). Spatiotemporal distribution of seasonal snow water equivalent in High Mountain Asia from an 18-year Landsat–MODIS era snow reanalysis dataset. The Cryosphere, 15(11), 5261–5280. https://doi.org/10.5194/tc-15-5261-2021

Margulis, S. A., Cortés, G., Girotto, M., & Durand, M. (2016). A Landsat-Era Sierra Nevada Snow Reanalysis (1985–2015). Journal of Hydrometeorology, 17(4), 1203–1221. https://doi.org/10.1175/JHM-D-15-0177.1

Margulis, S. A., Liu, Y., & Baldo, E. (2019). A Joint Landsat- and MODIS-Based Reanalysis Approach for Midlatitude Montane Seasonal Snow Characterization. Frontiers in Earth Science, 7(October), 1–23. https://doi.org/10.3389/feart.2019.00272

References

Miao, X., Guo, W., Qiu, B., Lu, S., Zhang, Y., Xue, Y., & Sun, S. (2022). Accounting for Topographic Effects on Snow Cover Fraction and Surface Albedo Simulations Over the Tibetan Plateau in Winter. Journal of Advances in Modeling Earth Systems, 14(8). https://doi.org/10.1029/2022MS003035

Niu, G.-Y., & Yang, Z.-L. (2007). An observation-based formulation of snow cover fraction and its evaluation over large North American river basins. Journal of Geophysical Research, 112(D21), D21101. https://doi.org/10.1029/2007JD008674

Roesch, A., Wild, M., Gilgen, H., & Ohmura, A. (2001). A new snow cover fraction parametrization for the ECHAM4 GCM. Climate Dynamics, 17(12), 933–946. https://doi.org/10.1007/s003820100153

Serafin, S., Rotach, M. W., Arpagaus, M., Colfescu, I., Cuxart, J., De Wekker, S. F. J., … Zardi, D. (2020). Multi-scale transport and exchange processes in the atmosphere over mountains. In Multi-scale transport and exchange processes in the atmosphere over mountains. https://doi.org/10.15203/99106-003-1

Swenson, S. C., & Lawrence, D. M. (2012). A new fractional snow-covered area parameterization for the Community Land Model and its effect on the surface energy balance. Journal of Geophysical Research: Atmospheres, 117(D21), n/a-n/a. https://doi.org/10.1029/2012JD018178

Usha, K. H., Nair, V. S., & Babu, S. S. (2020). Modeling of aerosol induced snow albedo feedbacks over the Himalayas and its implications on regional climate. Climate Dynamics, (0123456789). https://doi.org/10.1007/s00382-020-05222-5

WALLAND, D. J., & SIMMONDS, I. (1996). SUB-GRID-SCALE TOPOGRAPHY AND THE SIMULATION OF NORTHERN HEMISPHERE SNOW COVER. International Journal of Climatology, 16(9), 961–982. http://doi.wiley.com/10.1002/%28SICI%291097-0088%28199609%2916%3A9%3C961%3A%3AAID-JOC72%3E3.0.CO%3B2-R

References

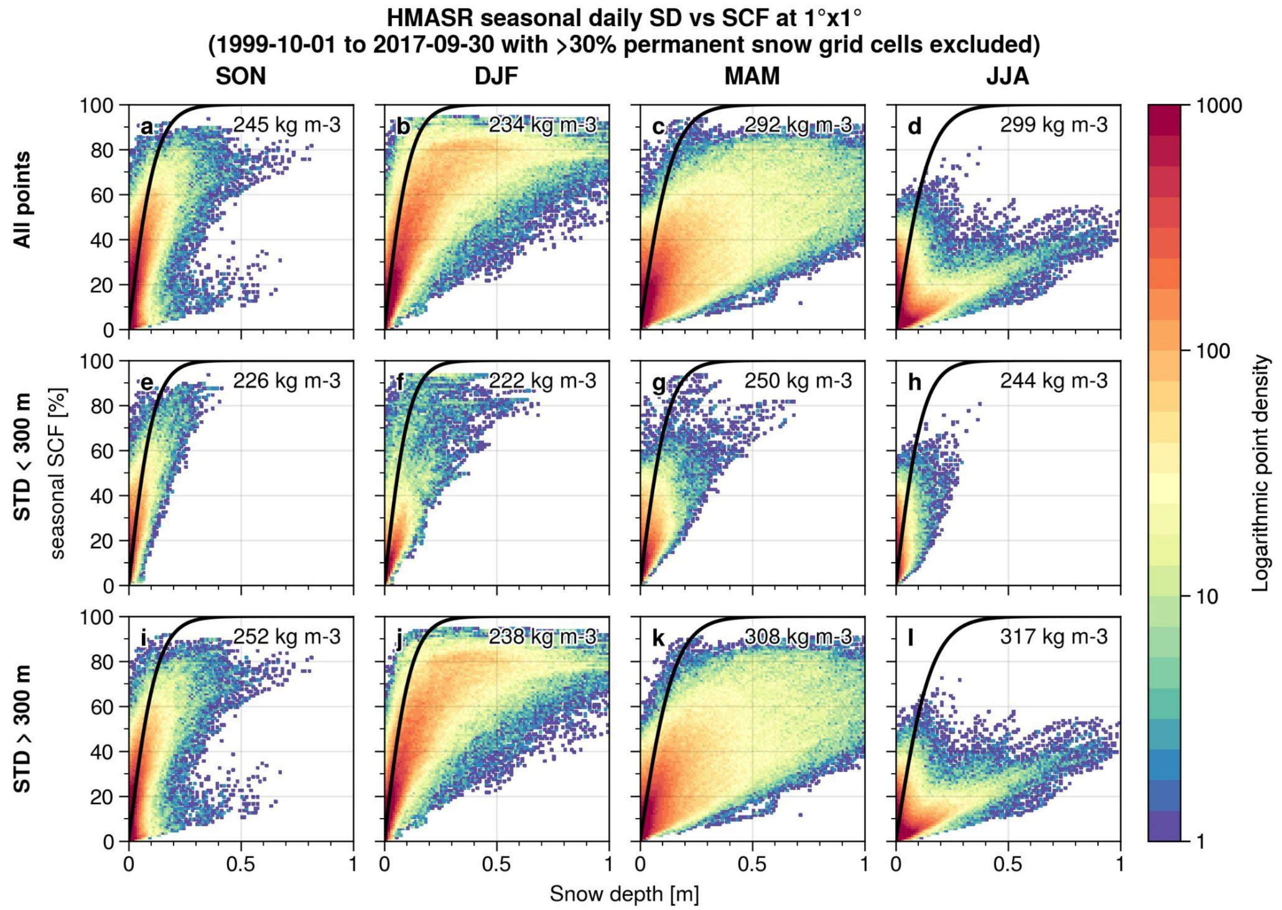
Wang, T., Ottlé, C., Boone, A., Ciais, P., Brun, E., Morin, S., ... Peng, S. (2013). Evaluation of an improved intermediate complexity snow scheme in the ORCHIDEE land surface model. Journal of Geophysical Research: Atmospheres, 118(12), 6064–6079. https://doi.org/10.1002/jgrd.50395

Wang, Y., Yang, K., Zhou, X., Chen, D., Lu, H., Ouyang, L., ... Wang, B. (2020). Synergy of orographic drag parameterization and high resolution greatly reduces biases of WRF-simulated precipitation in central Himalaya. Climate Dynamics, 54(3–4), 1729–1740. https://doi.org/10.1007/s00382-019-05080-w

Younas, W., Hay, R. W., MacDonald, M. K., Islam, S. U., & Déry, S. J. (2017). A strategy to represent impacts of subgrid-scale topography on snow evolution in the Canadian Land Surface Scheme. Annals of Glaciology, 58(75pt1), 1–10. https://doi.org/10.1017/aog.2017.29

Complementary Slides

High Mountain Asia UCLA Daily Snow Reanalysis

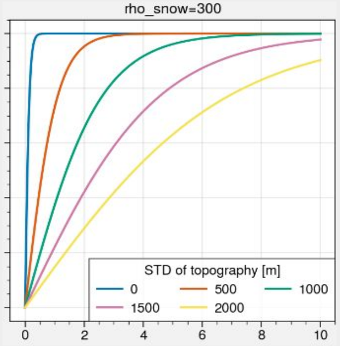


Other snow cover parameterizations

Niu and Yang (2007) custom

$$F = \tanh\left(\frac{d}{2.5 z_{0g}\left(\rho_{snow}/\rho_{new}\right)^{m}}\right)$$

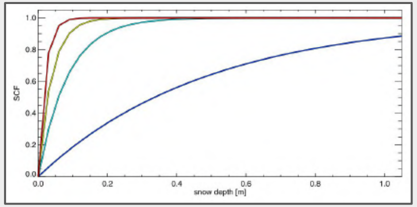
STD topo



Swenson and Lawrence (2012)

Accumulation

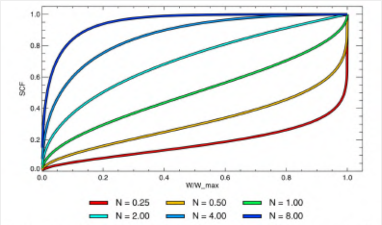
$$F_{N+1} = 1 - (p_{N+1})(p_N) = 1 - (1 - s_{N+1})(1 - F_N)$$



Depletion

$$F = 1 - \left[\frac{1}{\pi}\operatorname{acos}\left(2\frac{W}{W_{\max}} - 1\right)\right]^{N_{melt}}$$

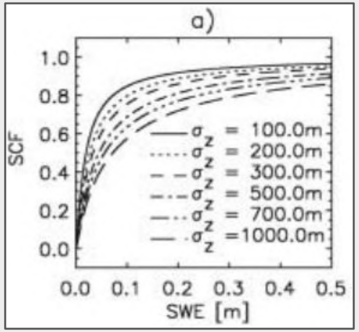
$$N_{melt} = \frac{200}{\sigma_{topo}}$$



Roesch et al. (2001)

Mountainous areas

$$f_s = 0.95 \cdot tanh(100 \cdot S_n)\sqrt{\frac{1000 \cdot S_n}{1000 \cdot S_n + \epsilon + 0.15\sigma_z}}$$



Depends only on SWE so no hysteresis

High Mountain Asia UCLA Daily Snow Reanalysis