A package of momentum and heat transfer coefficients for the stable atmospheric surface layer

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Summary

The polar atmospheric surface layer is often stably stratified, which strongly influences turbulent transport processes between the atmosphere and sea ice/ocean. Transport is usually parametrized applying Monin Obukhov Similarity Theory (MOST) which delivers transfer coefficients as a function of stability parameters (see below). In a series of papers (Gryanik and Lüpkes, 2018; Gryanik et al., 2020,2021; Gryanik and Lüpkes, 2022) it has been shown that differences between existing parametrizations are large, especially for strong stability. One reason is that they are based on different data sets, for which the origin of differences is still unclear. In this situation Gryanik et al. (2021) as well as Gryanik and Lüpkes (2022) proposed a numerically efficient method, which can be used for most of the existing data sets and their specific stability dependences. A package of parametrization resulted that is suitable for its application in weather prediction and climate models. Especially, calculation of fluxes over sea ice were improved. Combined with latest parametrizations of surface roughness it has a large impact on large scale fields as shown recently by Schneider et al. (2021) who applied some members of the package.

Stable stratification is a common feature in polar regions and similarly, during night and whole day in snow covered mid-latitudes.

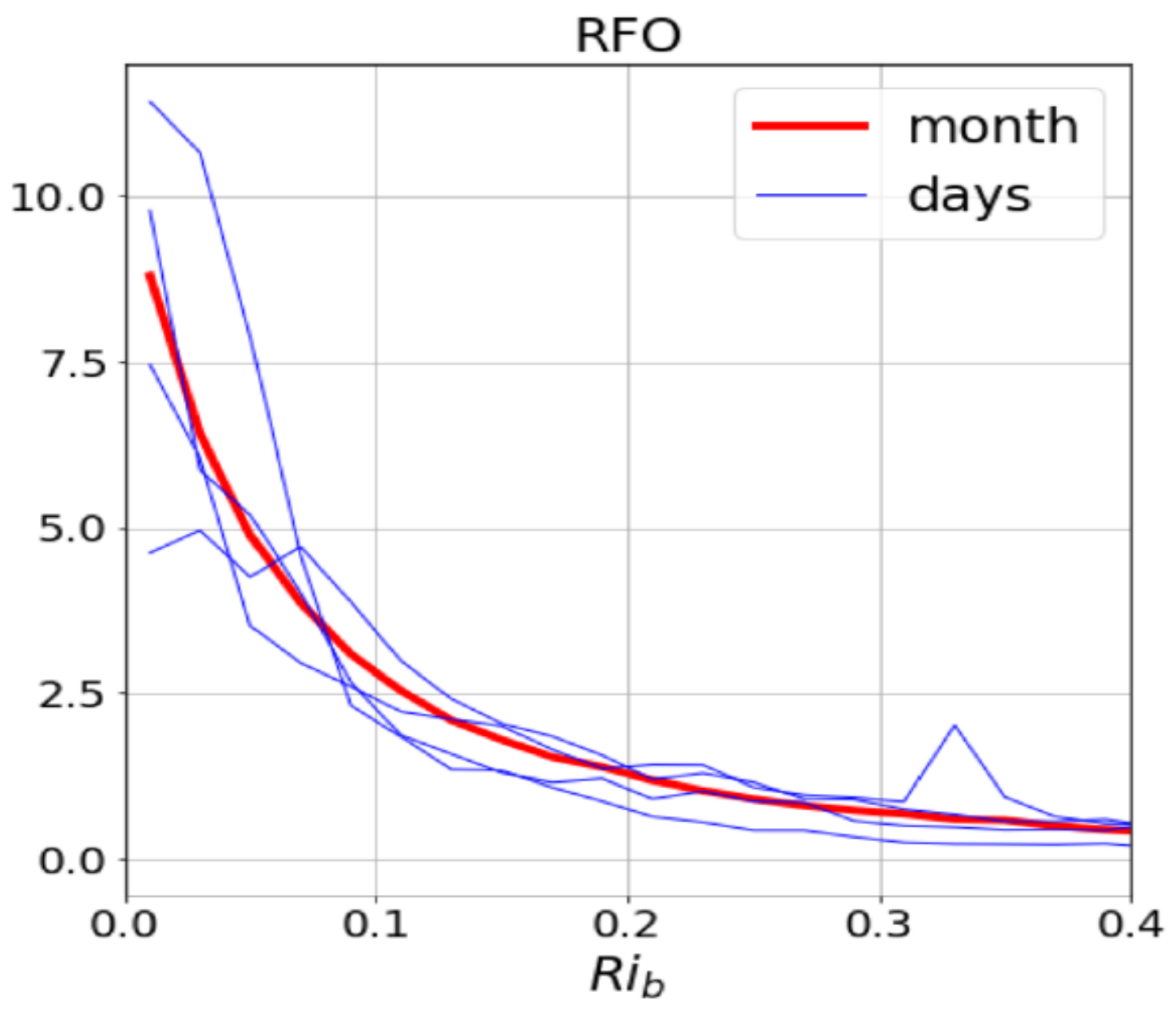


Figure 1: Arctic wide relative frequency of occurrence of the near-surface bulk Richardson numbers Ri_b in March 2019 (red) and during individual days (blue). Analysis based on ERA-Interim data (Gryanik et al., 2021).

→ Strong stability ($Ri_b > 0.07$) occurs approximately as often as weak stability ($0 < Ri_b < 0.07$) (compare areas below red curve)

Calculation of fluxes based on Monin Obukhov Similarity Theory (MOST) (Iterative Method)

$$\mathrm{M} = -\,\mathrm{C_d\,U^2}$$ momentum flux

$$\mathrm{H} = -\rho\,\mathrm{c_p}\,\mathrm{C_h}\,\mathrm{U}\,[\Theta(\mathrm{z}) - \Theta_\mathrm{s}]$$ heat flux

$C_d = C_{dn}\, f_m$ $\quad$ $C_h = C_{hn}\, f_h$ $\quad$ transfer coefficients

Normalized stability dependent transfer coefficients

$$\mathrm{f_m} = \left[1 - \frac{\psi_\mathrm{m}(\zeta) - \psi_\mathrm{m}(\zeta/\epsilon_\mathrm{m})}{\ln \epsilon_\mathrm{m}}\right]^{-2}$$

$$\mathrm{f_h} = \left[1 - \frac{\psi_\mathrm{m}(\zeta) - \psi_\mathrm{m}(\zeta/\epsilon_\mathrm{m})}{\ln \epsilon_\mathrm{m}}\right]^{-1} \left[1 - \frac{\psi_\mathrm{h}(\zeta) - \psi_\mathrm{h}(\zeta/\epsilon_\mathrm{t})}{\ln \epsilon_\mathrm{t}}\right]^{-1} \quad (1)$$

ψ-functions are the stability correction functions, for which many different versions exist (see Fig. 2)
ε_m and ε_t are roughness parameters for momentum and for heat

Since ζ = z/L depends on M and H, iteration is necessary

New parametrization: universal non-iterative method

$$\zeta = \frac{\ln^2 \epsilon_m}{\ln \epsilon_t}\,\hat{Ri}_b + \frac{(\ln \epsilon_m - \psi_{ma})^{2(\gamma-1)}}{\zeta_a^{\gamma-1}(\ln \epsilon_t - \psi_{ha}/Pr_0)^{\gamma-1}}\left[\frac{(\ln \epsilon_m - \psi_{ma})^2}{\ln \epsilon_t - \psi_{ha}/Pr_0} - \frac{\ln^2 \epsilon_m}{\ln \epsilon_t}\right]\hat{Ri}_b^{\gamma}$$

ψ_{ma} and ψ_{ha} are MOST stability functions for prescribed $\zeta = \zeta_a$

$$\hat{Ri}_b = \frac{Ri_b}{Pr_0}\,\frac{1 - 1/\epsilon_t}{(1 - 1/\epsilon_m)^2}$$

Ri_b is the bulk Richardson number,
Pr_0 is the neutral-limit turbulent Prandtl number

Only two constants have to be fitted (γ and ζ_a) to obtain the detailed iterative solution $\zeta(Ri_b)$.

Gryanik and Lüpkes (2022) provide the values of constants γ and ζ_a for the most famous sets of stability correction functions ψ_m and ψ_h.

After inserting these values in the above equation for ζ and using this ζ in equation (1) the system is closed and fluxes can be determined.

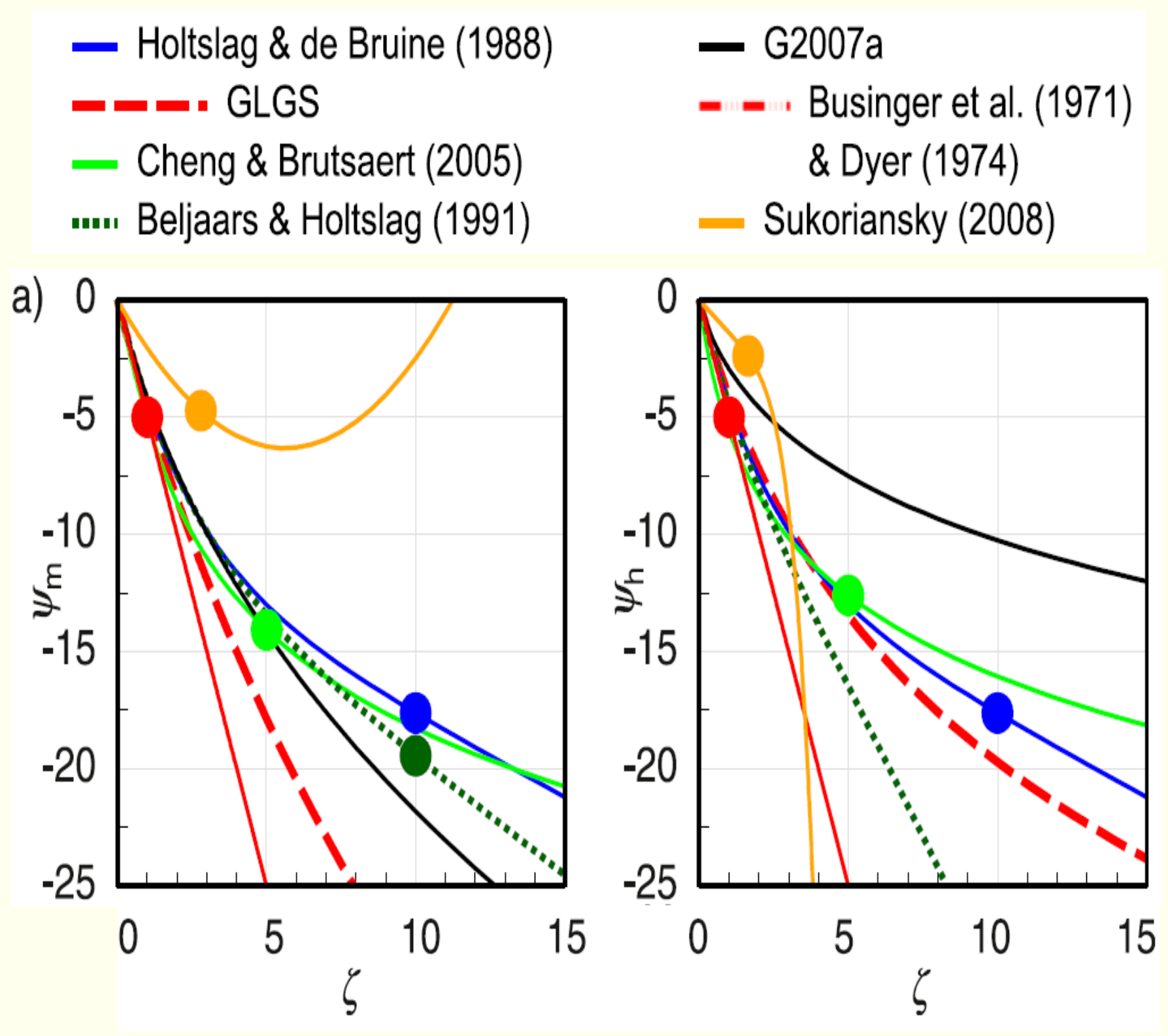
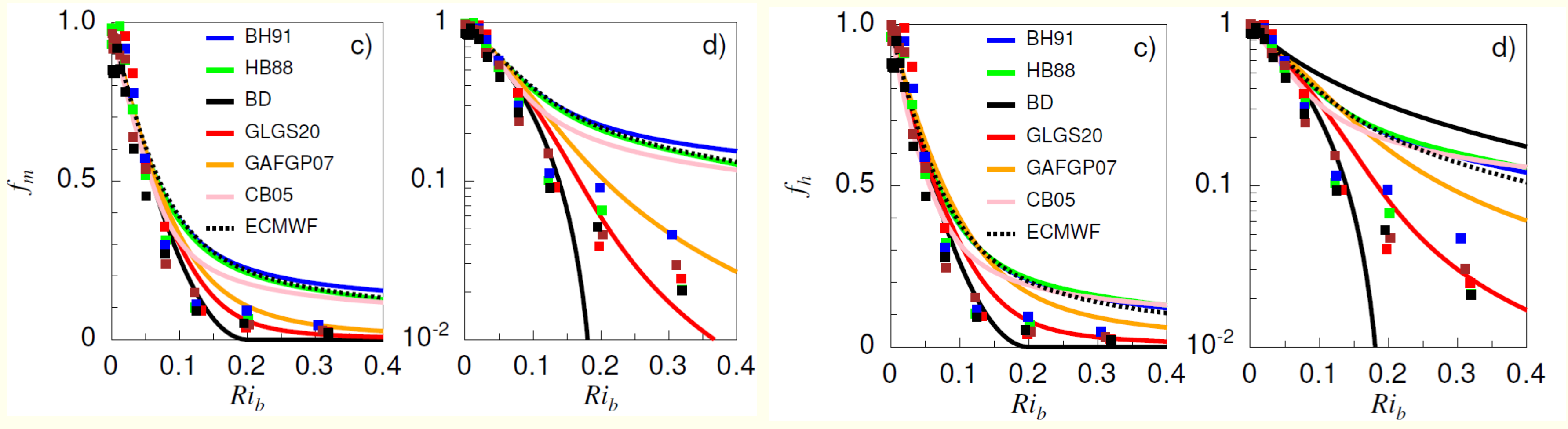


Figure 2: Examples of stability correction functions $\psi_m(\zeta)$ for momentum and $\psi_h(\zeta)$ for heat with ζ= z/L, where z is height and L is Obukhov length.

Curves agree well for near-neutral conditions but strongly diverge for growing stability.

→ All curves are based on famous data sets, thus climate models should test their sensitivity to parametrizations of transfer coefficients based on the different ψ-curves obtained at different places in the world. An efficient method for this test is provided by our new parametrization..

Figure 3: Results for normalized transfer coefficients valid for sea ice conditions



Red curves (functions of Gryanik et al. 2021) (our development) shows best agreement with SHEBA measurements (symbols).
Scheme used in the ECMW-model strongly overestimates mixing for $Ri_b > 0.1$.

Figure 4: Normalized transfer coeffcients for momentum valid for sea ice (blue curves) and very rough (green) and very smooth surfaces (red).
Solid lines represent iterative and dashed lines non-iterative (new) schemes.

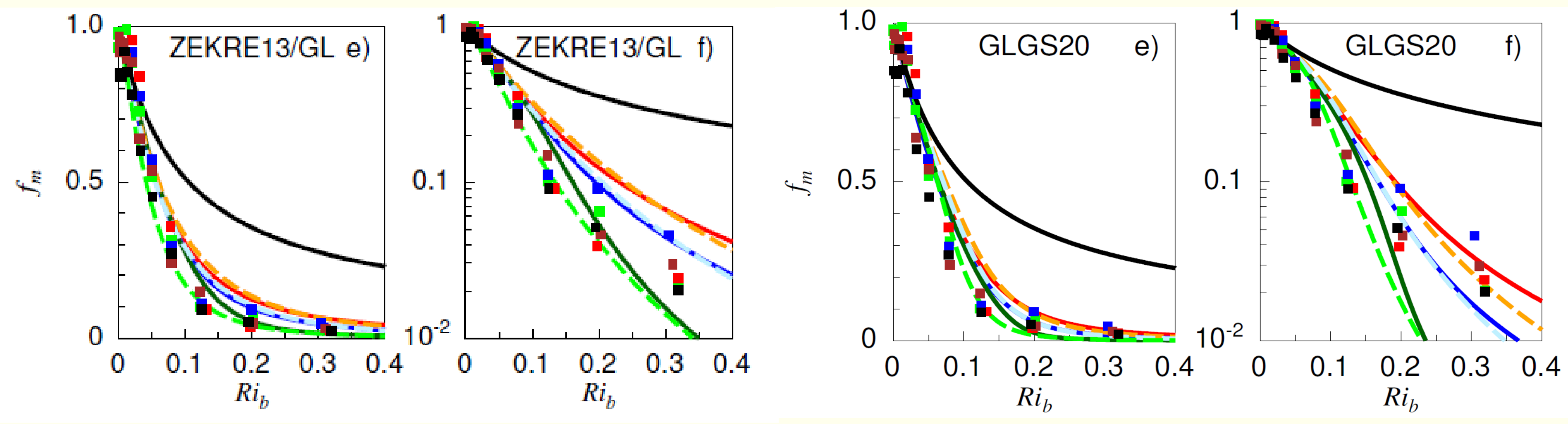
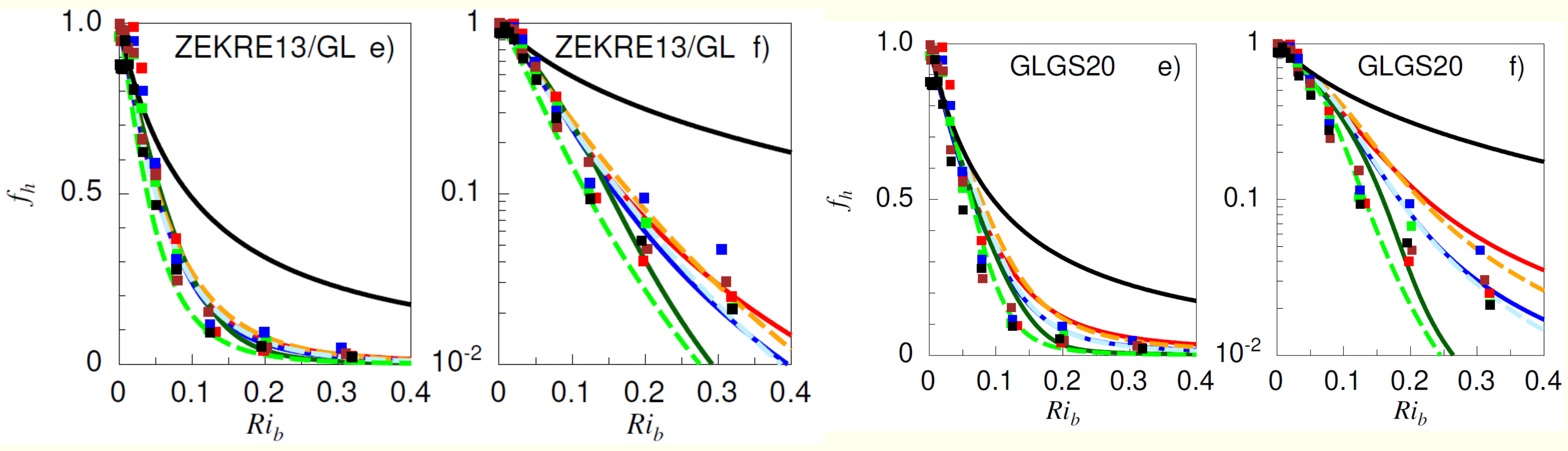


Figure 5: Normalized transfer coeffcients for heat valid for sea ice (blue curves) and very rough (green) and very smooth surfaces (red).
Solid lines represent iterative and dashed lines non-iterative (new) schemes.



It is remarkable that the scheme obtained with adjusted Zilitinkevich et al. (2013) functions (ZEKRE13, two left hand panels) shows similar agreement with SHEBA (symbols) as our functions (GLGS20, two right hand panels), although they were developed on the basis of different data sets (ZEKRE13 based on LES, GLGS20 based on SHEBA).

References

Gryanik VM, Lüpkes C (2022) A Package of momentum and heat transfer coefficients for the stable surface layer extended by new coefficients over sea ice, BLM, https://doi.org/10.1007/s10546-022-00730-9
Gryanik VM, Lüpkes C, Sidorenko D, Grachev A (2021) A universal approach for the non-iterative parametrization of near-surface turbulent uxes in climate and weather prediction models. JAMES, 13(8):e2021MS002,590
Gryanik VM, Lüpkes C, Grachev A, & Sidorenko D (2020). New modified and extended stability functions for the stable boundary layer based on SHEBA and parametrizations of bulk transfer coefficients for climate models. *J. Atmos. Sci.*, *77*, 2687–2716.
Gryanik VM, Lüpkes C (2018) An efficient non-iterative bulk parametrization of surface fluxes for stable atmospheric conditions over sea-ice , Boundary Layer Meteorol. 166:301-325.
Beljaars ACM, Holtslag AAM (1991) Flux parameterization over land surfaces for atmospheric models. J Appl Meteorol 30(3):327–341
Businger JA, Wyngaard JC, Izumi Y, Bradley EF (1971) Flux-profile relationships in the atmospheric surface layer. J Atmos Sci 28(2):181–189
Cheng Y, Brutsaert W (2005) Flux-profile relationships for wind speed and temperature in the stable atmospheric boundary layer. Boundary-Layer Meteorol 114(3):519–538
Dyer A (1974) A review of flux-profile relationships. Boundary-Layer Meteorol 7(3):363–372
Holtslag A, De Bruin H (1988) Applied modeling of the nighttime surface energy balance over land. J Appl Meteorol 27(6):689–704
Grachev AA, Andreas EL, Fairall CW, Guest PS, Persson POG (2007) SHEBA flux-profile relationships in the stable atmospheric boundary layer. Boundary-Layer Meteorol 124(3):315–333
Louis J-F, Tiedtke M, Geleyn J-F (1982) A short history of the operational PBL-parametrization at ECMWF. In: Proceedings of the ECMWF workshop on boundary layer parametrization. November 1981, ECMWF, Shinfield Park Reading, UK, 59-79.
Schneider T, Lüpkes C, Dorn W., Chechin D, Handorf D, Khosravi S, Gryanik VM, Makhotina I., Rinke A (2021) Sensitivity to changes in the surface-layer turbulence parameterization for stable conditions in winter: A case study with a regional climate model over the Arctic, Atmos. Sci. Lett., DOI: 10.1002/asl.1066
Sukoriansky S (2008) Implementation of the quasi-normal scale elimination (QNSE)model of stably stratified turbulence in WRF. Report on WRF-DTC Visit
Zilitinkevich S, Elperin T, Kleeorin N, Rogachevskii I, Esau I (2013) A hierarchy of energy-and flux-budget (EFB) turbulence closure models for stably-stratified geophysical flows. Boundary-Layer Meteorol. 146(3):341–373