<u>Response to the comments from Reviewer#2</u>

We thank the reviewer for his/her critical evaluation of the manuscript. A point-wise reply to the comments of the reviewer is given below:

General Comment

Summary: The paper discusses how the free convection limit needs to be implemented in NWP models, i.e. that fact that in case of vanishing wind speed the friction velocity drops out of the Monin Obukhov scaling. Within the context of the WRF mesoscale model several formulations are discussed and implemented in the surface layer scheme of WRF and tested for a long period of offline and online simulations. It is shown the model is (moderately) sensitive to the selected similarity functions for operational forecasts for a 3 month period.

Reply: We thank the reviewer for carefully going through the manuscript and for his/her valuable comments and suggestions.

Major Comments

Comment 1: Earlier studies, especially the ones done in the GABLS model intercomparison projects have studied the impact of the shape of the stability functions on the modelled profiles and fluxes (though for stable conditions mostly). However, they learnt that applying different stability functions in the surface layer parameterization and in the boundary-layer parameterization may trigger unnatural kinks in the wind speed profiles in models like WRF. This happens in practice quite often in modelling approaches for all kind of reasons. It would be good if the authors can add some discussion about this aspect, and check for (in)consistency of phi-functions in PBL and SL in their updated KY90 formulation. And whether kinks are seen in temperature and wind profiles in the WRF output.

Reply: We sincerely accept the reviewer's concern regarding the unnatural kinks in the wind speed and temperature profiles by using different similarity functions in the surface and boundary layer parameterizations. We wish to highlight that the present study focused on evaluating the impacts of different similarity functions in the revised MM5 surface layer scheme in WRF model version 4.2.2 on the simulation of surface turbulent fluxes and near-surface variables. For the simulations, we have utilized the YSU (Yonsei University) PBL scheme proposed by Hong et al. (2006). This scheme utilizes similarity functions suggested by Dyer (1974) for both unstable and stable conditions in the gradient form; those are different from the ones used in surface layer parameterization.

We have analyzed the behaviour of 10-m wind and 2-m temperature profiles predicted from the WRF model using different forms of similarity functions in the surface layer scheme for the whole simulation period (March-April-May). It is observed that the unnatural kinks have not been observed in cases of both 10-m wind speed and 2-m temperature (Figures R1 and R2). However, the relatively higher magnitudes of 10-m wind speed simulated from the WRF model have been observed for some hours, which may be linked with the localised weather phenomenon characterized by rapid changes in weather, including strong wind, lightning, and thunderstorms. However, the 2-m temperature values are found to be in line with the observed data. Thus, both 10-m wind speed and 2-m temperature values simulated from the WRF model are justifiable, and no unnatural kinks have been observed. Moreover, further investigation is needed in this direction.

As per the reviewer's suggestion, we have added text in the revised version of the manuscript and presented it here for the reviewers' reference:

Lines 338-349…Note that earlier studies, especially the ones done in the GABLS model intercomparison projects, have studied the impacts of the similarity functions on the modelled profiles and fluxes (though for stable conditions mostly). However, they learnt that applying different stability functions in the surface and boundary layer parameterizations may trigger unnatural kinks in the model simulated wind speed and temperature profiles. Here, we have analyzed the profiles of U_{10} and T_{2m} simulated from the WRF model using different similarity functions in the surface layer scheme for the occurrence of unnatural kinks in their values. We observed that the U_{10} predicted from CTRL simulation, along with various experiments corresponding to different similarity functions at specific hours, exceeds its observed maximum value of approx. 8 m s^{-1} (Figure S3). Some localized weather phenomena, such as strong wind, lightning, and thunderstorms, may link these relatively higher magnitudes to rapid changes in weather, making them justifiable. However, the simulated T_{2m} from different similarity functions is found to be in line with the observed values across the whole simulation period (Figure S4). This suggests that the values of U_{10} and T_{2m} predicted from the WRF model are found to be in a justifiable range, and no unnatural kinks have been observed.

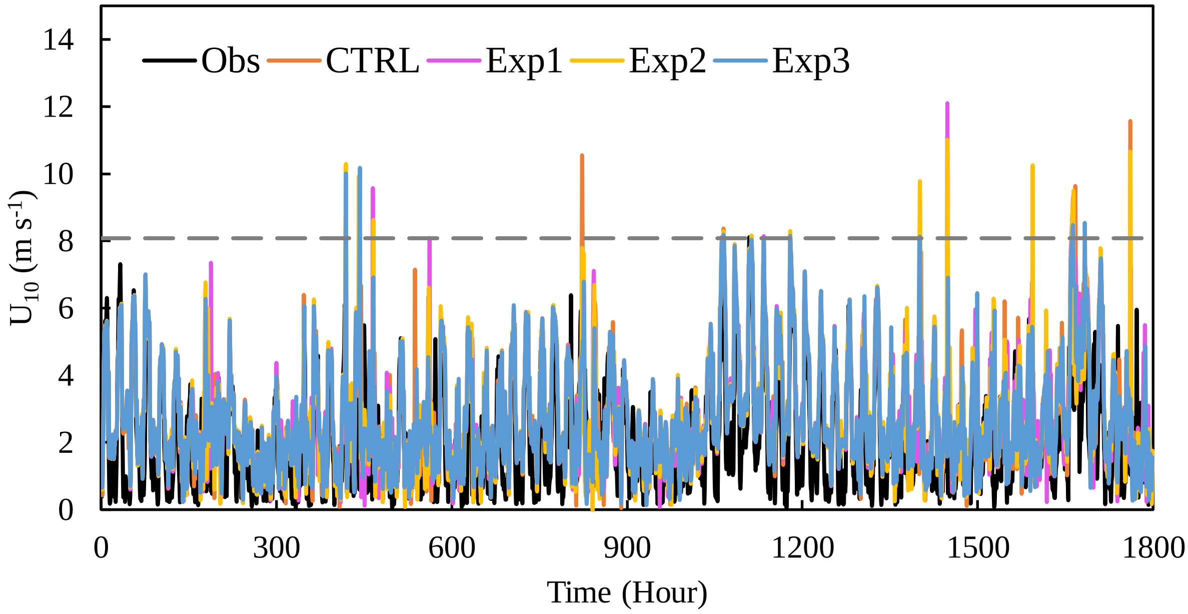

Figure R1: Time variation of 10-m wind speed predicted from different similarity functions in the surface layer scheme of WRF model. The maximum value of wind speed in observational data is shown by dotted grey line.

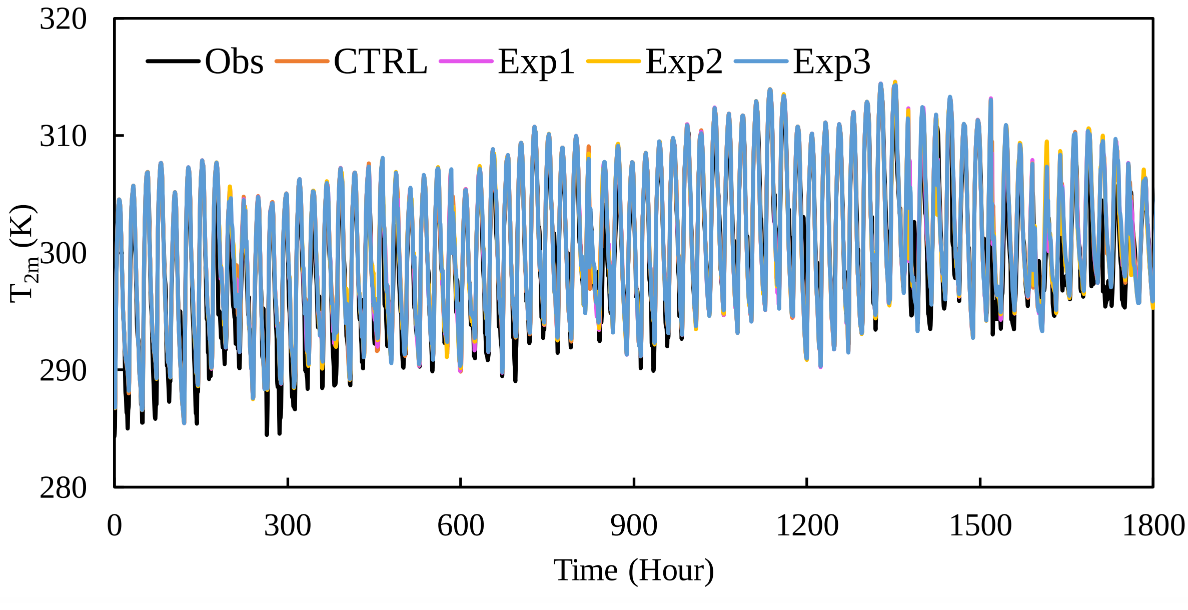

Figure R2: Time variation of 2-m temperature predicted from different similarity functions in the surface layer scheme of WRF model.

Comment 2: The paper is silent on the impact of potential clipping that is present in the WRF model. In many schemes the stability (psi) is kept in a certain range, as is the friction velocity, and some other parameters. Hence it is interesting to learn whether the WRF model got the complete freedom to show its sensitivity to the tested similarity functions. Hence please add some discussion to what is the range of -zeta the model could reach.

Reply: Various surface layer schemes in different numerical models have restrictions on the values of the stability parameter (ζ)/bulk Richardson number (Ri_B), as well as on the friction velocity and some other parameters. The present study utilizes the revised MM5 surface layer scheme (Jimenez et al., 2012), which is an updated version of the MM5 (fifth-generation Pennsylvania State University-National Centre for Atmospheric Research Mesoscale Model) surface layer scheme. It is observed that the MM5 scheme has several restrictions on the values of ζ, Ri_B, friction velocity (u_*), and mean wind speed (U). In the MM5 surface layer scheme, U is restricted by a lower limit of 0.1 m s^{-1} to control Ri_B values from being inordinately high. The similarity functions for stable conditions are restricted by a limit of -10 on the values of both ψ_m and ψ_h, and a limit on ζ (> -10) for unstable conditions is applied to prevent the use of similarity functions in strong stable and unstable conditions, respectively. Apart from this, a lower limit on $u_*(> 0.1 \text{ m s}^{-1})$ is also applied to control the value of heat flux from becoming zero in strong stable conditions.

On the other hand, in the revised MM5 surface layer scheme, most of these restrictions have been relaxed. For instance, the restrictions on both ψ_m and ψ_h in stable conditions as well as on ζ (> -10) in unstable conditions have been relaxed. This implies that the WRF model with the revised MM5 surface layer scheme has no restrictions on ζ or Ri_B under stable as well as convective conditions and has complete freedom to show its sensitivity to the tested similarity functions. Moreover, the restriction on the values of u_* is also reduced from 0.1 to 0.001 m s^{-1} to allow smaller values of u_*, which can be common during the night. The restriction on the mean wind speed is as it is (i.e., U $>$ 0.1 m s^{-1}) in the revised MM5 scheme.

As the reviewer has suggested, we have included a text regarding this in the revised version of the manuscript and presented it here for the reviewers' reference:

Lines 107-110…Note that the revised MM5 surface layer scheme has lower limits on the values of $u_*(> 0.001$ m $s^{-1})$ and U($>$ 0.1 m s^{-1}) that allow nocturnal values of u_* at night and control Ri_B values to be inordinately high, respectively (Jimenez et al., 2012). However, the stability parameter ζ or Ri_B is not restricted in the revised MM5 surface layer scheme, which gives complete freedom to the WRF model to show its sensitivity to the tested similarity functions (Jimenez et al., 2012).

Comment 3: There is some discussion about the free convection limit that could be added to the paper. On one hand the idea is that if the mean wind drops completely, then the CH should go to zero to allow the friction velocity to become zero too, so it disappears from the problem. However there are some other LES studies that show that despite the mean wind speed can drop to zero, the friction velocity will NOT drop to zero, i.e. that there is a

"minimum friction velocity " that is proportional the w* (see Schumann 1980). Please discuss how the KY90 approach and implementation matches the minimum friction velocity approach.

Reply: Studies reported in the literature suggest that friction velocity (u_*) cannot be zero when the mean wind drops to zero in free convective conditions; i.e., there should be a minimum friction velocity that is proportional to the w_*. We wish to highlight that the minimum value of u_* is prescribed as 0.001 m s^{-1} in the existing version of the revised MM5 scheme based on the recommendations by Jimenez et al. (2012) to avoid the complexity that arises when mean wind drops to zero. Thus, the updated revised MM5 surface layer scheme with KY90 functional forms proposed in the present study also utilizes a minimum value of u_* (> 0.001 m s^{-1}) as suggested by Jimenez et al. (2012).

As suggested by the reviewer, we have added text regarding this in the revised version of the manuscript and presented it here for the reviewers' reference:

Lines 110-116…Moreover, some of the LES studies reported in the literature suggest that the friction velocity cannot be zero when the mean wind drops to zero; i.e., there should be a minimum friction velocity that is proportional to the w_* (Schumann, 1980). For this purpose, the existing version of the revised MM5 scheme sets 0.001 m s^{-1} as the minimum value of u_* based on the recommendations by Jimenez et al. (2012). Thus, to avoid the complexity that arises when mean wind drops to zero, the updated revised MM5 scheme proposed in the present study also utilizes a minimum value of u_* (> 0.001 m s^{-1}) as suggested by Jimenez et al. (2012) in the existing version of the revised MM5 scheme.

Comment 4: ***I find the description of the observational site too limited. Please extend. What is the time frequency of the output of the obs? 10-min or 60 min? What is the vegetation of the measurement site? Idem for typical roughness length.***

Reply: The needful is done. The revised text is presented here for reviewers' reference:

Lines 169-184…For the evaluation of different simulations corresponding to newly installed similarity functions, observational data derived from the micrometeorological tower installed at Ranchi (India) has been utilized (Srivastava and Sharan, 2019; Srivastava et al., 2020; 2021). The dataset (Ranchi data) is derived from an instrument mounted on a 32-m tall tower at the Birla Institute of Technology Mesra in Ranchi, India with an average elevation of 609 m above sea level in a tropical region. The site has a few buildings in between east and northwest; agriculture land in between northwest and west; a residential area; and dense trees in between southeast and east. The site also has a relatively flat area in between southeast and west, which is free from any obstacle (Srivastava and Sharan, 2015). A fast-response sensor (CSAT3 Sonic Anemometer) at a height of 10 m with an average elevation of 609 m above sea level provides the temperature and the three components of wind at a 10 Hz frequency. The eddy covariance technique (Stull 1988) is used to estimate heat and momentum fluxes at one-hour time resolution; however, the hourly temperature at 2 m is determined by averaging temperature observations available at a temporal scale of 1 minute from the slow response sensors located at logarithmic heights on the same tower. The time frequency of the output of the observation is 60 min. The roughness length for momentum (z_0) over the Ranchi domain is found to be around 0.009 ± 0.007 m during the summer, as suggested by Reddy and Rao (2016), who utilized the profile method to compute the values of z_0 based on the observed data from June 2011 to May 2012. However, we have also computed the value of z_0 based on the observational data utilized in the present study, but the value comes out to be higher than that suggested by Reddy and Rao (2016) and needs to be further validated.

Comment 5: Concerning the real cases, it would be good to add some discussion about how many model grid cells are affected by the changed psi functions for how many time slots in the simulations, and in which weather regimes this occurs. That offers a more detailed insight in the modelling impacts.

Reply: The present study is focused on evaluating the impacts of different similarity functions under convective conditions in the surface layer scheme of the WRF model. For this purpose, various functional forms of similarity functions have been newly installed in the surface layer scheme of the WRF model under convective conditions, and the similarity functions for stable stratification remain the same in all the experiments and CTRL simulation. This suggests that most of the changes due to different functional forms are expected to be visible in the convective regime (i.e., daytime). Due to this, we have considered the summer (MAM) season and analyzed the model output using different similarity functions in the WRF model for various variables during daytime only (i.e., unstable conditions). From Figure 4, it is observed that the differences between different similarity functions are more pronounced in strong unstable conditions. Thus, we have also analyzed the model output for various experiments during those hours in which strong convective conditions occur over most of the study domain.

Regarding the number of model grids affected by the changed similarity functions, we have shown the mean spatial distribution of model simulated variables and their differences with respect to the CTRL simulation utilizing the default version of the similarity functions in the revised MM5 scheme. For instance, a figure is also attached herewith, which shows the mean spatial differences of simulated ζ, C_D, and C_H between CTRL simulation and other newly installed similarity functions. Note that no fixed pattern has been observed for the model grids that are being affected by the changed similarity functions; however, the changes are dependent on the considered variable and experiment. For instance, $\frac{z}{L} (= \zeta)$ simulated from the KY90 functional forms (Exp3) shows substantial differences over the whole study domain (i.e., all the model grids are affected) with respect to CTRL simulation (Figure R3).

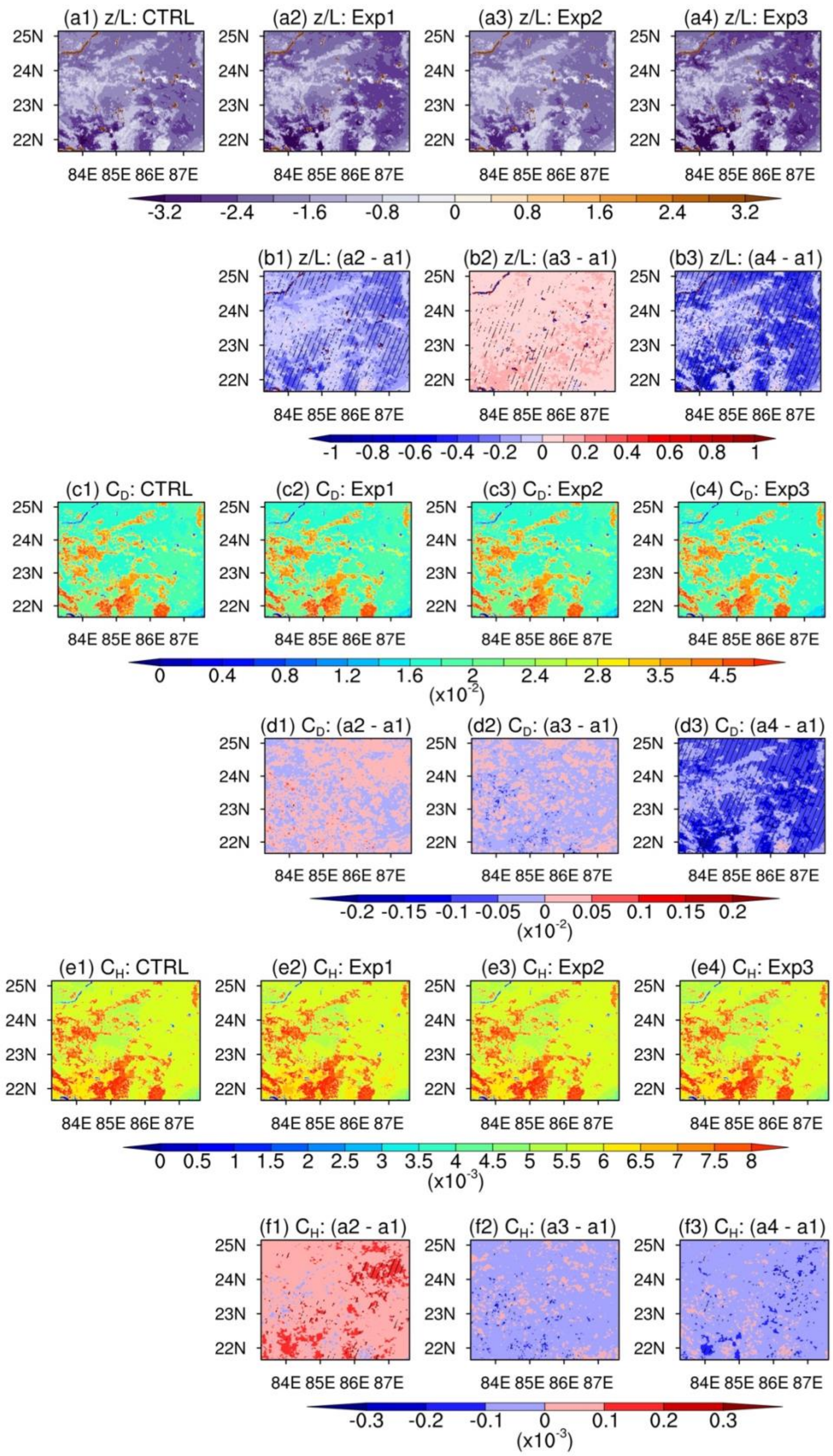

Figure R3: Mean spatial distribution of model simulated $\boldsymbol{\zeta}$ (1st row), $\mathbf{C_D}$ (3rd row) and $\mathbf{C_H}$ (5th row) from different experiments and their differences with respect to CTRL simulation averaged during daytime for whole simulation period. Hatched regions show significant differences at 95% confidence level in experiments with respect to CTRL simulation.

As per the reviewer's suggestion, text has been added to the revised version of the manuscript for better presentation and clarity of results. The modified text is presented here for reviewers' reference:

Lines 409-414…The results presented so far suggest that the changes corresponding to different functional forms of similarity functions under convective conditions in the surface layer parameterization of the WRF model are more pronounced in convective conditions during daytime hours. For the number of grid points over the study domain that are being affected by the changed similarity functions, no fixed pattern was observed; however, the changes depend on the considered variable and similarity functions. Furthermore, we observe that the changes are more pronounced in grids that experience strong instability during the daytime.

Minor comments

Comment 1: C_D and C_H are never formally defined in the paper. I think it is good to add that for a more easy read.

Reply: The mathematical expressions for both C_D and C_H are now added to the revised manuscript.

Comment 2: Ln 28: tuned. I think this is not the right wording in the sense that to fit the relation between dimensionless groups, one must use observations

Reply: The text has been modified accordingly in the revised version of the manuscript.

Comment 3: Ln 84: Appendix B was referred to before Appendix A was referred to.

Reply: The appendices A and B are interchanged in the revised text.

Comment 4: Ln 86: …the CASES-99 dataset

Reply: The necessary changes are made to the modified text.

Comment 5: Equation 7: something seems to be missing between the brackets for the formula in the upper regime

Reply: Equation 7 has been modified accordingly in the revised version of the manuscript.

Comment 6: Equation 8: Same here, they look like loose hanging minuses.

Reply: The needful is done.

Comment 7: Ln 132: here the notations for phi's are suddenly in italic, while they are not in the rest of the manuscript so far.

Reply: The phi's are accordingly changed throughout the text.

Comment 8: Ln 169: For the computation, z is taken as 10 m and RiB is in the range $-2 \leq$ RiB ≤ 0. Can you justify the 10m and the RIB regime?

Reply: We would like to point out that the turbulent measurements at both Ranchi (India) and the CASES-99 sites are used at a height of 10 m. Accordingly, z is taken as 10 m for the calculation of ζ, C_D, and C_H in offline simulations. In principle, there are no restrictions on the Ri_B values under convective conditions; however, for practical consideration, the range of Ri_B is taken as -2 to 0, which can cover all the different sublayers considered in convective conditions, from DNS ($\zeta > -0.04$) to FCS ($\zeta < -2$).

Comment 9: Ln 347: typo in "moemntum"

Reply: The needful is done.

Comment 10: Ln 487: the bias is the mean of the difference between model and observations, so better to type the overbar over (p_i - o_i).

Reply: It is corrected in the revised text.

Comment 11: Figure 1: In the box for the stable boundary layer, "Change" should be "Cheng"

Reply: "Change" has been replaced by "Cheng" in Figure 1.

Comment 12: Figure 2: From these plots and the captions it is not directly clear which of the lines represents the new model implementation.

Reply: The caption of Figure 2 has been modified accordingly and is presented here for reviewers' reference:

Figure 2: Integrated similarity functions $\psi_{m,h}(\zeta)$ for momentum and heat for default (F96; black line) and newly installed (BD71, CL73, and KY90; orange, gray, and blue lines) functions for unstable atmospheric surface layer.

Comment 13: Figure 2: the caption says "default", but none of the labels in the figure indicates which of the four is the default.

Reply: Figure 2 has been modified accordingly, and the caption of Figure 2 is presented in the previous reply.

Comment 14: Figure 4: the legend box is overlying the vertically dashed lines three times

Reply: It is corrected in the revised text.

Comment 15: Figure 4: the caption is incomplete since the explanation is missing for DNS, DFS, FCS, DCS-FCS, DNS-DCS. I must say I find these graphs rather chaotic since these texts about the regimes are scattered all over the place. Can this not be solved by coloring the background of the diagram for the regimes in contrasting color. The caption is also incomplete since it does not explain what are Exp1-3. Better to label these BD71, CL73, and KY90. This applies to all figures afterwards.

Reply: The caption of Figure 4 is modified in the revised version of the manuscript and presented here for reviewers' reference:

Figure 4: Variation of ζ with Ri_B (upper panel), C_D (middle panel), and C_H (lower panel) with ζ calculated from bulk flux algorithm (offline simulation) for different functional forms of ψ_m and ψ_h corresponding to BD71, CL73, KY90, and F96 forms for smooth (z_0 = 0.01 m; 1st column), transition (z_0 = 0.1 m; 2nd column), and rough (z_0 = 1 m; 3rd column) surfaces. The background colour corresponds to different sublayers in convective conditions (Kader and Yaglom 1990), from the dynamic sublayer ($0 \geq \zeta > -0.04$; light gray) to the free convective sublayer ($\zeta < -2$; dark gray).

Comment 16: Figure 4: headers: z0 must have a unit.

Reply: The unit for z_0 is meter, and Figure 4 has been accordingly modified.

Comment 17: Figure 4: the vertical axes have somewhat unnatural steps. Why not start at y=0?

Reply: Since the differences in the simulated ζ, C_D, and C_H from different functional forms of similarity functions are smaller. So, for better visibility and clarity, we haven't started the y axis from zero for some of the subplots in Figure 4.

Comment 18: Figure 8: RMSE must have a unit.

Reply: Units have been included for RMSEs in Figure 8.

Comment 19: All tables: Put the table caption above the caption.

Reply: In all the tables, the captions are now moved from bottom to top in the revised version of the manuscript.

Comment 20: Table 2: The number of decimals is really too large in this table. The typical measurement error of a temperature measurement including its representativeness error is about 0.3K, then 3 decimals for RMSE and MAE is really high. Friction velocity does not have more than 2 decimals significance, so 3 is too many here. Please reconsider also for the other variables, and in Table 3.

Reply: Table 2 and 3 have been modified accordingly, and the values of bias, RMSE, and MAE for considered variables up to two decimal places are now used in the revised version of the manuscript.

References:

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