Response to Referee 2

The manuscript titled "A revised ocean mixed layer model for better simulating the diurnal variation of ocean skin temperature" focuses on the fine-tuning and validation of an ocean mixed layer model (OMLM) used at ECMWF. The authors initially describe the shortcomings of the existing OMLM, then rectify the typographical errors in the model, and subsequently validate the results.

Comments and suggestions

1. However, the manuscript, in its current form, lacks proper organization and sequence. The methodology is described before the dataset is introduced, leading to confusion. Various SST definitions and terminologies are introduced without context, puzzling the reader. The authors should first provide a detailed description of the data used, including sources, resolution, etc., followed by the methodology. This should include defining various SST terms and explaining each term's source from the dataset.

Manuscript organization and sequence:

Thanks for the suggestion. We initiated this work upon discovering that the ERA5 skin temperature data exhibited erroneous features, particularly the changing spatial patterns at 10 UTC and 22 UTC. Further investigation revealed errors in the prognostic scheme employed by the ECMWF model. As a result, our initial presentation in the previous version focused on these erroneous features before detailing our corrective measures, which may have seemed awkward. Other reviewer also suggested restructuring the manuscript.

Following your suggestion, in the revised version, we introduced the data set used after the introduction, identified model errors, detailed the subsequent revisions, validated the revised model, and presented the results, including the erroneous features in the ERA5 data.

Recognizing that the various definitions and abbreviations of SST may have caused confusion, we defined only the relevant temperatures at their points of use. We removed the SST definition section (previously subsection 2a) and simplified the overall SST terminology in the revised manuscript. A new Fig. 1 visually presents the SST terms and aids in understanding the OML model structure. Thus, all temperature-related definitions/acronyms are limited to five shown in Fig. 1: T_s, T_{cool}, T_{warm}, T_z, and SST. Other IR and buoy-measured temperatures are referred to as the temperatures at 10 μm and 1 m depths, respectively, without additional acronyms.

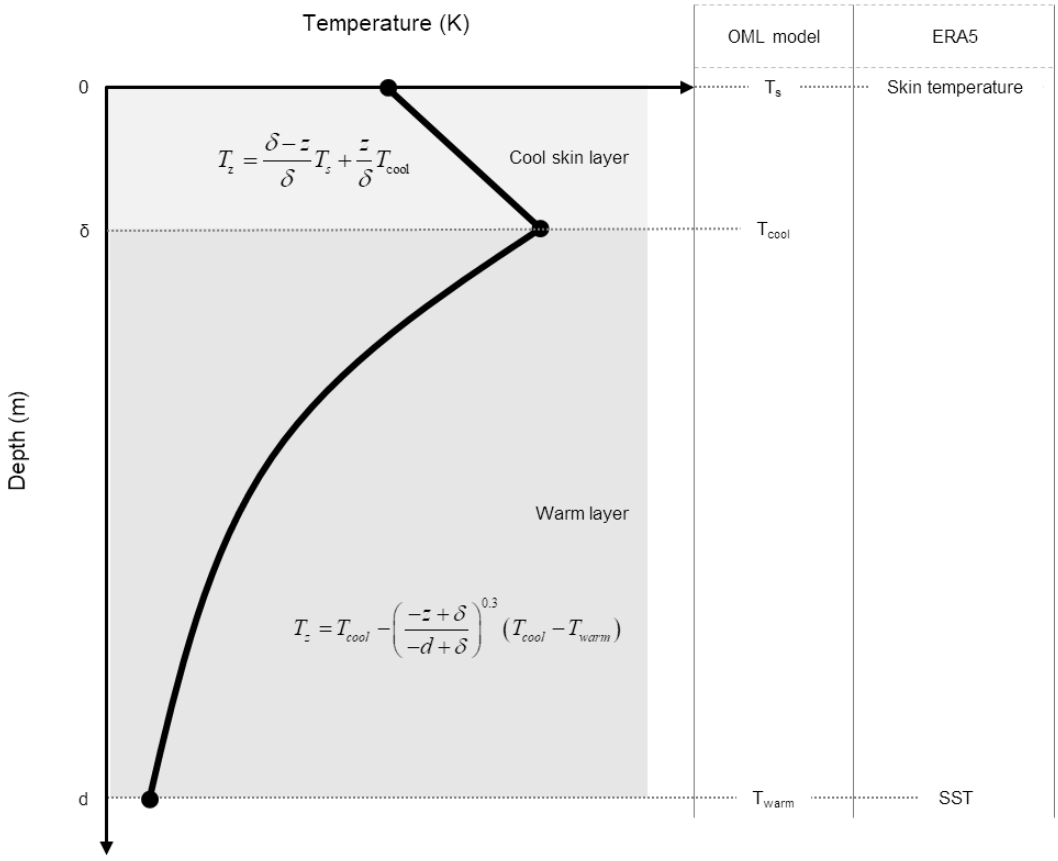

Figure 1. Schematic diagram illustrating the ocean mixed layer (OML) model. T_s, T_{cool}, and T_{warm} represent the temperatures at three levels of the OML model. In ERA5, skin temperature and SST correspond to T_s and T_{warm}, respectively. Temperature T_z represents the temperature at depth z. The thick solid lines depict the temperature profiles as expressed by two equations in the cool skin and warm layers.

2. Figures 3 and 4 should also include comparisons with the original ECMWF model. Although the authors state that the revised model has the same error range, it would be beneficial to compare the scatter plots from the original model for clarity.

It would be ideal to make a direct comparison between T_s from the original ERA5 and observations, as shown in Figs. 3 and 4. Note that the two temperatures at two depths (10 μm and 1 m) used for comparison against IR and buoy observations in Figs. 3 and 4 are from the OML model-based temperature profile within the cool skin and warm layers. However, since the ECMWF model does not save the intermediate output (here ocean temperature profile), a direct comparison is not possible.

Although direct comparison is not allowed, significant underestimates of T_s by ECMWF are evident in Fig. 9. We have now explained this in the revised version. The ECMWF model incorrectly used thermal diffusivity as 0.6 instead of approximately 1.40×10^{-7}, in addition to a unit inconsistency. Thus, the denominator on the right-hand side of Eq. (2) is roughly 4×10^{6} times larger than the correct value. Additionally, the incorrect assignment of thermal diffusivity affects the depth of the cool skin layer (δ). Our calculations indicate that the wrong coefficient

causes δ to be approximately 1×10^{-4}–3×10^{-4} times that of the correct model. Overall, the incorrect assignment induces "$T_s - T_{cool}$" to be about 10^{-3} of the expected values, approaching near zero (i.e. $T_s \approx T_{cool}$) regardless of the heating magnitudes at the surface.

$$T_s - T_{cool} = \frac{\delta}{h_w \rho_w c_w}\left(Q + f_s\ SW\right) \tag{2}$$

This effectively eliminates the role of cool skin layer in the diurnal variation, resulting in T_s being equal to T_{cool}, leading to erroneous T_s simulations in the ECMWF model. This explanation is now included in the conclusion and discussion section as follows:

"The unreasonable features noted in ERA5 T_s may be attributed to the failure to simulate the temperature within the cool skin layer due to the incorrect equation and the wrong assignment of diffusivity. In addition to the unit inconsistency, the wrong diffusivity value (i.e., 0.6 instead of 1.40×10^{-7} m^2 s^{-1}) may result in T_s being nearly equal to T_{cool} (i.e., $T_s \approx T_{cool}$). However, in reality, as expressed in Eq. (2), T_s variation should be much larger than T_{cool} during the daytime due to incoming solar flux. Such expected difference is confirmed by observing that ERA5 T_s is not well responsive to solar radiation flux (Fig. 9). Since the diurnal variation of T_{cool} should be smaller than T_s in accurate simulations, the diurnal variation of the current ERA5 T_s should be smaller than the new ones, as revealed in Fig. 9. Furthermore, the ERA5 T_s diurnal variation may not follow the solar flux variation, whose direct influence is on T_s. Because the cool layer physics was effectively suppressed in ECMWF model (as shown in $T_s \approx T_{cool}$), the ERA5 T_s variation may follow the variation of the warm layer, which is more complex due to the competing influences of solar radiation and turbulent mixing. This might result in more irregular patterns as shown in Fig. 9. It appears that the problems in the current ECMWF may not be confined to the assignment of wrong values for the heat diffusivity, but also may reside in the warm layer temperature variation. It is because the warm layer process might have been developed based on incorrect equations of the cool skin process."

3. The manuscript does not present any significant scientific advancements in the present form beyond correcting typographical errors in the original model. While the authors have contributed by identifying and fixing these mistakes, this could have been addressed in a technical internal note rather than a peer-reviewed publication. Furthermore, the practical implications of the errors in the mixed layer model are not clearly articulated, aside from the improper simulation of diurnal variability. The authors should emphasize the practical benefits gained from correcting the OMLM.

We respectfully disagree with your opinion that this paper merely addresses typographical errors in the original model. As detailed in the revised model section, especially in the Appendix, the corrections are far more extensive than simple typographical fixes. Correcting the erroneous equations used in the original model is only part of the revision process. Since the original model was developed based on incorrect equations, which do not even have unit consistency, the entire simulation process was flawed. As discussed in #2, the current ECMWF version seems to have no functioning cool skin layer. Therefore, rectifying the identified errors required a comprehensive overhaul of the model, including the development of corrected equations, model configuration, and new stability functions.

Additionally, we have included a new discussion on why ERA5 shows significant underestimates compared to T_s simulations with the revised model, as discussed in #2. Further, we provided error statistics for T_s, demonstrating the reliability of these values. By comparing the temperatures obtained from simulations against IR-based SST retrievals and buoy observations, we were able to demonstrate that T_s error statistics are comparable to errors in satellite measurements of SST. This study presents the first instance of such error statistics for T_s diurnal variation obtained from model simulations.

To convey the importance of these error statistics, we compared them with observational errors, as observational data serve as a reliable reference. In this study, the model results were compared with M-AERI and 1-m depth buoy data. Existing comparisons between satellite-derived SST and the same M-AERI and buoy observations allow us to understand the significance of the current error statistics better. Error statistics for three satellite SST products based on longwave nonlinear algorithm (Aqua-MODIS, Terra-MODIS, and S-NPP-VIIRS) compared to M-AERI and buoy observations are presented in Tables 1 and 2, respectively. It is important to note that SSTs from these three satellites are derived from IR measurements, which represent the temperature at a depth similar to the IR-based M-AERI (~10-μm depth), but differ from the 1-m depth buoy-observed SSTs. Consequently, a larger bias is expected when comparing IR-based satellite products with buoy observations. As expected, IR-based satellite products show a larger bias against buoy observations, which is typically corrected when buoy-like SSTs are produced from satellite measurements.

Considering this, we conclude that the errors of model-produced temperatures at two levels are similar to those of satellite observations. Therefore, the model-produced skin temperature in this study would be comparable to satellite measurements, if such satellite data were available.

In conclusion, this work is not a mere correction of typographical errors but involves developing a corrected model whose T_s simulation accuracies are comparable to satellite observations.

We added following sentence in the subsection 3a:

"With the corrections and modifications mentioned above, the implemented OML model is referred to as the "revised" OML model in this study. Correcting the erroneous equations used in the original model, which do not show even unit consistency, is only part of the revision process. Since the original model was developed based on incorrect equations, the entire simulation process was also considered flawed. Therefore, rectifying the identified errors requires a comprehensive rebuilt of the model, including the development of corrected equations, model configuration, and new calculation of stability functions with revised model. A detailed description of the model structure and configuration can be found in Appendices A–B."

Table 1. Statistics of errors in SSTs at the sub-skin layer over global ocean: comparison of this study and satellite sensor-retrieved temperatures vs. M-AERI-measured temperatures for best quality level only (NASA ATBD; https://oceancolor.gsfc.nasa.gov/resources/atbd/sst/#sec_4, last accessed on July 24, 2024).

SST	Mean Deviation	Standard Deviation	Count

This study	**-0.08 K**	**0.49 K**	**32,647**
Terra MODIS	−0.06 K	0.48 K	3,069
Aqua MODIS	0.04 K	0.49 K	2,070
S-NPP VIIRS	0.03 K	0.20 K	81

Table 2. Same as in Table 1 except for 1-m depth buoy-measured temperature.

SST	Mean Deviation	Standard Deviation	Count
This study	**-0.07 K**	**0.28 K**	**6,241,008**
Terra MODIS	−0.17 K	0.44 K	538,918
Aqua MODIS	−0.19 K	0.42 K	508,950
S-NPP VIIRS	−0.21 K	0.48 K	473,498