Responses to reviewers – ESSD-2024-420

"**Global ocean surface heat fluxes revisited: A new dataset from maximum entropy production framework with heat storage and Bowen ratio optimizations**", by Yong Yang, Huaiwei Sun, Jingfeng Wang, Wenxin Zhang, Gang Zhao, Weiguang Wang, Lei Cheng, Lu Chen, Hui Qin, Zhanzhang Cai, submitted to ***Earth System Science Data***.

Dear Editors and Reviewers,

Thank you for your letter and for the reviewers' comments concerning our manuscript **ESSD-2024-420**. We appreciate editors and reviewers very much for the positive and constructive comments and suggestions.

Those comments are all valuable and very helpful for revising and improving our paper, as well as providing the important guidance for our researches. We have addressed all the comments carefully and made the revisions which we hope will meet your approval.

Below are our point-by-point responses to the comments raised by the referee. Comments of reviewers are marked with the blue color, and the corresponding responses are in black (begins with bold words of **"Response"**). Corresponding changes in the text of the manuscript appear in red font.

Responses to Reviewer #1

Reviewer #1: General Comments:

This research presents a new global ocean heat flux dataset developed using an innovative energy-balance-based method. The authors introduce a new approach grounded in energy allocation principles, utilizing modified Maximum Entropy Production (MEP) theory to estimate oceanic heat fluxes. The methodology is robust, the calculation process is well-structured, and the dataset is in good accuracy. The paper is well written, and the statistical and geographical analyses are conducted appropriately. The manuscript falls within the scope of the ESSD journal. Minor revisions need to be considered before publication. Please find details below:

Response: We appreciate reviewer's positive comments, and we will further improve our manuscript by fully address the reviewer's comments in the following.

Specific comments:

Title and Abstract:

(1) This paper develops a new global ocean heat flux dataset using the MEP framework, incorporating heat storage and Bowen ratio optimizations. I recommend the author designate a representative name for this dataset, such as "Maximum Entropy Production-based Global Ocean Heat Flux (OHF-MEP)."

Response: Thanks very much for your suggestion, which we strongly agree with. We decide to use the abbreviation (GOHF-MEP) to represent our dataset throughout the text.

"The 0.25° monthly global ocean heat flux dataset based on the Maximum Entropy Production method (GOHF-MEP) for 1988–2017, is publicly accessible at…"

(Line 44-45, in "1. Introduction" section)

"The GOHF-MEP dataset produced by the MEP method…"

(Line 801, in "6. Data availability" section)

"In this study, we developed a new global ocean heat flux product (GOHF-MEP) covering the period from 1988 to 2017"

(Line 806, in "7. Conclusions" section)

"The performance of the newly produced GOHF-MEP dataset was evaluated against extensive observations…"

(Line 814-815, in "7. Conclusions" section)

(2) Line 25, The author should provide a definition of the Bowen ratio upon its first mention to ensure clarity.

Response: Thank you for your comment. The corresponding revisions are as follows:

"This study derived global ocean heat fluxes using the MEP theory, incorporating the effects of heat storage and adjustments to the Bowen ratio (the ratio of sensible heat to latent heat)."

(Line 27-28, in "Abstract" section)

"B_o is crucial for understanding the global ocean energy partitioning process (Hicks & Hess, 1977)."

(Line 100, in "1. Introduction" section)

(3) Line 27-29, Consider rewording for better clarity. It should be "enhance/improve the model performance"

Response: Thank you for your helpful comment. The corresponding revisions are as

follows:

"The model was first evaluated using observed data from buoy stations, and the Bowen ratio formula that most effectively enhances the model performance was identified."
(Line 30-31, in "Abstract" section)

(4) Lin 29-31, The statement needs to be re-organized for better comprehension. Specifically, accounting for heat storage and adjusting the Bowen ratio were conducted within the MEP model or after the calculations?

Response: Thanks for your helpful comment. We have re-organized this sentence to improve the clarity. Accounting for heat storage and adjusting the Bowen ratio were conducted within the MEP model, and the corresponding revision is as:

"By incorporating the heat storage effect and adjusting the Bowen ratio within the MEP model, the accuracy of the estimated heat fluxes was significantly improved, achieving an R^2 of 0.99 (regression slope: 0.97) and a root mean squared error (RMSE) of 4.7 $W \cdot m^{-2}$ compared to observations"
(Line 32-34, in "Abstract" section)

Introduction:

(5) This section is well written and organized, it presents the significance of ocean evaporation estimation, the limitations of current bulk methods, the introduction of the MEP method, and the ways to improve the model estimation through Bowen ratio fitting. However, a brief overview of existing ocean heat flux datasets (such as algorithms and accuracy) would help clarify the necessity for developing a new dataset.

Response: We appreciate for your valuable suggestion. We have added a brief overview of the current accessible global ocean datasets, including the classification, resolution, algorithms and representative products (in the last paragraph of the

Introduction). Also, the necessity for developing a new dataset with a new method and fine spatial resolution is clarified. Moreover, we have included a detailed description on the current ocean heat flux datasets in the section of "3.3 Global turbulent heat flux datasets for evaluations", including the algorithms, resolution, and variables (Table 2). The corresponding revisions are given as follows:

"Current global ocean surface heat flux datasets can be classified into five categories based on their deriving approaches (Tang et al., 2023): remote sensing-based (e.g., J-OFURO3), atmospheric reanalysis-based (e.g., ERA5), machine learning-based (e.g., OHFv2), in-situ based (e.g., NOC), and hybrid-based (e.g., OAFlux) approaches. Compared to terrestrial flux products, these ocean flux products generally have a coarser spatial resolution ranging from 0.25º to 1.875º. Recent studies have conducted comprehensive assessments of global ocean heat flux datasets regarding their accuracy and error characteristics across spatial and temporal scales (Bentamy et al., 2017; Tang et al., 2023). However, substantial discrepancies remain among these datasets, particularly in terms of spatial patterns, annual means, and interannual variabilities. Therefore, developing a new global dataset using the innovative method could advance our understanding of deriving algorithms, improve temporal and spatial coverage of flux variables with a higher accuracy, and provide alternative reference to assess ocean surface heat fluxes in various applications."
(Line 117-127, in "Introduction" Section)

(6) Line 49, "A key component of this regulation is ocean evaporation (latent heat)", "latent heat" is repeated and not necessary.

Response: Thank you for pointing this out. The revised text reads as follows:

"A key component in this system is ocean evaporation, which accounts for approximately 86% of atmospheric water vapor, being the primary driver of the global hydrological cycle (Yu, 2011)."

(Line 50-52, in “Introduction” Section)

Methods:

(7) Line 177 and Line 194, Remove the space before “where”.

Response: Thank you for pointing this out. We have revised it and the text reads as follows:

“where B_o^* is the equilibrium Bowen ratio, which denotes the theoretical ratio of…”

(Line 194)

“where $B(\sigma)_{a1} \sim B(\sigma)_{a4}$ represent the four empirical Bowen ratio formulas for comparisons in this study.”

(Line 211)

(8) Line 195, Consider rewording for better clarity. “Thus, the improved MEP model is complemented as…”.

Response: Thanks for your careful checks. It is a writing error here, and we have revised it as:

“Thus, the workflow of the improved MEP model was conducted as:”

(Line 212)

(9) Line 309, “…at different depths with the observed G (derived as Rn-LE-H) (Fig.S1)”, Should it be Table.S1? check and make sure it.

Response: Thank you for correcting this writing error. It should be “Table S1” rather than “Fig.S1”, and the revision is as:

"…this study compared the OHC changes at different depths with the observed *G*, derived as *Rn-LE-H* (Table S1)."

(Line 327-328)

Results:

This section is well organized, followed by the order of the validation of modified MEP method at stations, comparisons of Bowen ratio formulas, evaluation of radiation and heat storage for model input, extended to global scale and analysis of new global estimates. However, additional analysis of spatial pattern variability across two different periods (before and after year 2003) can be considered.

Response: We gratefully appreciate for your valuable comment. We have analyzed the ET spatial pattern variability at two different periods (1988-2003, and 2003-2017). Based on your comments, we have revised Section 4.5. We have added two paragraphs to show the spatial variability before and after year 2003 (shown in Figure 11). The detailed revisions refer to the response to comment (11) below. For specific details regarding these revisions, please refer to our response to comment (11) below.

(10) Line 381, "This decision…", revised as "This choice…"

Response: Thank you for pointing this out. We have revised it as "This selection", and the revised text reads as follows.

"This selection was based on the site's long-term observational records…"

(Line 401)

(11) Line 620 - Line 632, From Fig.12, it seems that ocean ET from most ET datasets increased from 1988-2003, followed by fluctuations during 2003-2010, and then a consistent downward trend from 2010 to 2017. I am interested in the spatial variability for the periods 1988-2003 and 2003-2017, as 2003 appears to be a turning point for

evaporation changes. Providing a global spatial plot of ET trends for these two periods could be valuable for detecting spatial variability.

Response: We gratefully appreciate for your valuable comment. We have analyzed the ET spatial pattern variability at two different periods (1988-2003, and 2003-2017). The slowdown and transition of evaporation increase during 2003-2010 were consistent with the hiatus in global available energy and sea surface temperature. This phenomenon aligns with the concept of a "global warming hiatus" (Medhaug et al., 2017; Sung et al., 2023). This study supports the hypothesis that the hiatus in radiative forcing strongly affected the interannual variability of evaporation and surface temperature.

Based on your comments, we have made a major revision in Section 4.5. An additional analysis was conducted (before and after year 2003) and we have added more results to show the spatial variability in the Figure 11. Furthermore, we have added two paragraphs of content to analyze the spatial pattern variability at two different periods. The corresponding revisions in the Section 4.5 are listed as follows:

"However, global ocean evaporation experienced a notable shift around 2003, as illustrated in Figs.11b and 11c. The downward trend observed from 2003 to 2017 counteracted a significant portion of the growth trend that occurred during the previous 16 years (1988-2003), particularly evident in the mid-latitude regions (15ºS-20ºN). In the middle-to-low latitudes (0º-30ºN), nearly all ocean grids exhibited opposite trends around 2003. Spatially, regions that displayed the largest increasing trends during 1988-2003 transitioned to show the most substantial decreasing trends between 2003 and 2017. This includes regions associated with western boundary current systems, convergence zones of the East Australian Current and the South Equatorial Current, as well as equatorial regions of the Pacific and Atlantic Oceans (Fig. 11c). To further investigate the shift in ocean evaporation after 2003, we analyzed the interannual variability of global annual mean area-weighted evaporation using all available datasets (as shown in Fig.12)."

(Line 641-650)

"While different datasets revealed varying magnitudes of evaporation changes, most exhibited a similar temporal pattern: an increasing trend from 1988 to around 2003, followed by a hiatus during 2003-2010, and ultimately a decreasing trend after 2010 (Fig. 12a). Specifically, MEP indicated an increasing trend in evaporation of 3.58 mm/year from 1988 to 2010, followed by a decrease of 2.18 mm/year after 2010 (Fig. 12a). The slowdown and transition of evaporation during 2003-2010 aligned with the concept of a "global warming hiatus" (Medhaug et al., 2017; Sung et al., 2023), referring to the period when global mean surface air temperatures did not continue to rise between 1988 and 2012. Previous studies have proposed four potential explanations for this global warming hiatus: internal variability, external drivers, the Earth's response to CO_2, and radiative forcing (Medhaug et al., 2017). This study indicates that changes in radiative forcing (Fig. 12b) can significantly affect the interannual variability of evaporation (Fig. 12a) and surface temperature (Fig. 12c). This finding is consistent with previous research that attributed more than 50% of the uncertainty in MEP-modeled fluxes to the radiation term (Huang et al., 2017). Although surface temperature began to increase after 2012, the decrease in available energy remained the primary driver behind the decline in evaporation."

(Line 653-666, in Section 4.5)

Reference:

[1] Medhaug, I., Stolpe, M. B., Fischer, E. M., & Knutti, R.: Reconciling controversies about the 'global warming hiatus'. Nature, 545(7652), 41-47, https://doi.org/10.1038/nature22315, 2017.

[2] Sung, M. K., An, S. I., Shin, J., Park, J. H., Yang, Y. M., Kim, H. J., & Chang, M: Ocean fronts as decadal thermostats modulating continental warming hiatus. Nature communications, 14(1), 7777, https://doi.org/10.1038/s41467-023-43686-1, 2023.

(In the Section "References")

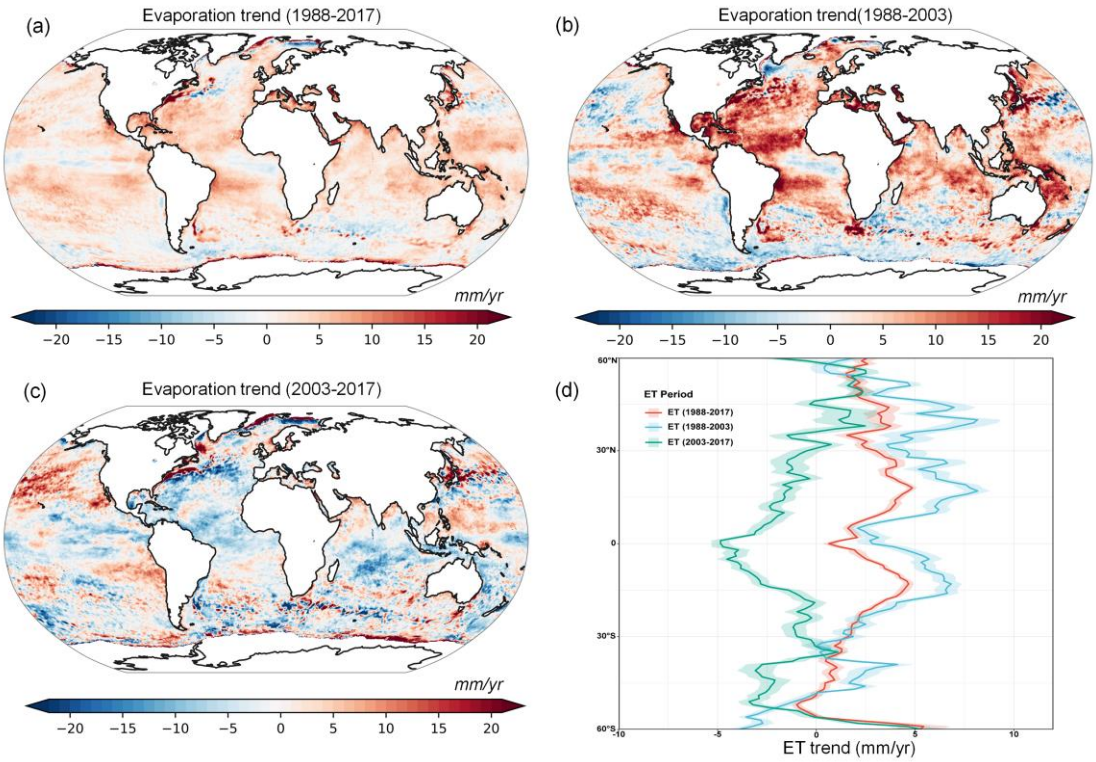

Figure 11. Spatial distribution of multi-year trends in ocean evaporation estimated by the improved MEP method during (a) the period 1988-2017, (b) the period 1988-2003, (c) the period 2003-2017, and (d) the latitudinal average changes across three different periods.

(In Figure 11)

(12) Line 639-642, Fig.12, the author should clarify the meaning of "S=2.31…" in the figure legend.

Response: Thank you for pointing this out. The "S=2.31" means the regression slope of MEP estimated evaporation global multi-annual mean evaporation increased with a rate of "2.31 mm/year" during 1988-2017. We have explained it in the caption of Fig.12 and the revised text reads as follows:

"Figure 12. Time series of area-averaged multi-annual mean evaporation from the improved MEP method (a), available energy (b), and sea surface temperature (c) over the global oceans during 1988-2017. The black dotted line in panel (a) marks the year 2010, and the label "S = 2.31" indicates that the MEP-estimated global multi-annual

mean evaporation increased at a rate of 2.31 mm/year during 1988-2017, with change rates of different ET datasets represented by various colors. The black dashed lines in panels (b) and (c) denote the linear regression lines."

(Line 673-678, in Figure 12)

Conclusions:

(13) I recommend including a brief clarification of the limitations of this research in this section.

Response: We sincerely appreciate your constructive comments. We agree that it is important to include a description of the limitations of this research. In response to your suggestion, we have added a subsection titled "5.4 Limitations" within the "Discussion" section. We believe this placement is more appropriate as it allows for a comprehensive evaluation of our findings alongside their limitations. In this new subsection, we have clarified the limitations from three perspectives: (1) Uncertainty of Driving data, (2) Heat Storage Determination, and (3) Bowen Ratio Improvement. Each of these aspects has been discussed in detail, providing a balanced perspective on the constraints and challenges encountered in this study. The corresponding revisions are as follows:

"**5.4 Limitations**

The improved MEP method proposed in this study offers a novel approach for estimating ocean heat fluxes, producing a validated long-term global dataset with high accuracy and spatiotemporal continuity. Despite its advancements, the proposed MEP method has several limitations that require further refinement: (1) Uncertainty of Driving data: The input variables of net radiation, heat storage, and sea surface temperature for the MEP model were sourced from the state-of-the-art satellite-based J-OFURO3 dataset. This dataset was constructed using observations from multiple satellite sensors. The net radiation in J-OFURO3 was derived by combining data from the CERES and the International Satellite Cloud Climatology Project (ISCCP) via the creeping sea fill method, along with twelve global sea surface temperature products (Tomitta, 2019). Consequently, the uncertainty of the MEP-estimated fluxes may arise

from biases in input data derived from various satellite sensors and their associated analysis methods. Therefore, it is essential to integrate multiple approaches to assess the uncertainty associated with the input datasets. Moreover, due to the limited temporal duration of the J-OFURO3 dataset, future work should utilize input datasets with longer time series, finer spatio-temporal resolution (Liang et al., 2022), and higher accuracy to advance ocean heat flux estimations using the MEP method. (2) Heat Storage Determination: This study did not employ a direct calculation method to obtain heat storage. Given the unclear relationship between heat storage and changes in ocean heat content at varying depths (as shown in Table 4), we utilized an energy balance residual-based approach to indirectly estimate heat storage. Consequently, this may render the MEP method susceptible to uncertainties in heat storage data derived from auxiliary flux datasets. Future research should focus on understanding the relationship between ocean heat content changes in the upper 100m and heat storage, with the goal of establishing a functional relationship between water column temperature at different depths and heat storage. (3) Bowen Ratio Improvement: Accurate determination of the Bowen ratio in high-latitude regions remains challenging. The Bowen ratio derived from the MEP method showed significant discrepancies with other datasets in these areas (Fig. 10), particularly in sea-ice-covered Arctic regions, where other datasets exhibited notable overestimations and irregular fluctuations. Therefore, incorporating more observational data from high-latitude regions is essential for a better understanding of energy partitioning patterns."

(Line 773-799, in Section 5.4)

Once again, thank you very much for your valuable comments and suggestions. We hope that the revisions in the manuscript and our accompanying responses will be sufficient to make our manuscript suitable for publication in *ESSD*.