RESPONSE TO RC1

The MELT index, Moisture Elevated Temperature, is designed to evaluate potential heatwaves and diagnose dry and moist heat events. Categories range from 0 (no heat event), <0.5 (dry enhanced), to ≥1 (moist elevated) scale. The intent is for use to help meteorologists and decision makers to determine the threat to health outcomes. The manuscript then uses 3 recent heatwaves that were recently scrutinized by multiple researchers to showcase the metric. Two of the events, the 2021 Pacific Northwest Heatwave and the 2016 South Korean heatwave were consistent with elevated moist heatwaves. The 3rd event, the 2019 European heatwave, was identified as a dry heatwave. Overall, a straightforward synoptic scale analysis was conducted, and the metric shows promise in meteorological applications.

From the scientific objectives and demonstration, the manuscript is well written and straightforward. I appreciate the authors efforts in readability! From this standpoint, the paper is good, and some minor adjustments which I detail below would be fine.

Response

We thank the reviewer for these very constructive comments. We have addressed the reviewer comments in this response and have made modifications to the manuscript to prepare the manuscript for a larger audience with more practical application.

However, there are 3 a fundamental 'elephant-in-the-room' aspects to the paper from an editorial point of view that perhaps should be addressed.

1. The authors discuss physiological responses to moist heat, and that their metric can identify a moist or dry heatwave. But without showing human responses to the moist or dry heatwave examples, it can be hard to determine whether their classification would correctly address the societal outcomes from these heatwaves.

   Response

   We thank the reviewer for their thoughtful comment. We agree that our proposed index, MELT, does not directly capture physiological outcomes of heatwaves. Rather, the primary aim of our index is to serve as a physically-based tool that can be used **in conjunction with health outcome data and other heat stress metrics** to better define and characterize heatwaves.

   We acknowledge that MELT is not a direct measure of human heat stress response. However, one of its key strengths lies in its use of readily available meteorological data (air temperature and relative humidity) which allows for broad application, including in **data-sparse regions** where more complex indices may not be feasible.

   To address the reviewer's concern, we have clarified throughout the manuscript that **we do not claim MELT to be the best or universal index**, but rather a complementary method for identifying multi-regional heatwave regimes within a consistent climatological framework. We have added language in several key sections (Introduction, Discussion, and Conclusions) to highlight this nuance and emphasize that MELT should be interpreted as one component within a broader toolkit of heatwave and heat stress metrics.

We believe that MELT offers a useful approach for regional climate studies, particularly in contexts where observational constraints limit the use of more sophisticated heat stress measures, and appreciate the opportunity to clarify this point.

2. There are 100s of heat stress metrics. The authors mention that metrics are not quite universal or are region-specific. But this gets into the nuances of heat stress: there are 100s of heat stress metrics because humans respond to heat in a myriad of ways. A dry heatwave can be just as deadly as a wet heatwave. Exposure, duration, activity, health status, age, etc., all interplay into heat stress. It is very difficult to generalize heat stress on humans to an individual index. Fundamentally, this is because the thermo-physiological system is complex, and there are many 'paths' that lead to negative outcomes, many of which are non-linear. So, I am skeptical that this index would be universally applied. What is interesting is the interplay with meteorology, which is clearly demonstrated from the authors' synoptic analysis.

Response

We thank the reviewer for this comment. We agree that multiple heat stress metrics exist, reflecting the fact that humans respond to heat in diverse ways, and it is therefore difficult to generalize a single metric for all contexts. While the current form of our manuscript may have implied otherwise, that was not our intention.

The goal of our proposed method is not to replace existing metrics, but to provide a novel, simple, efficient, and computationally accessible approach to characterizing heatwaves, particularly by using a specific climate regime as a benchmark. We have clarified this point in the revised manuscript to better motivate the rationale behind the development of this index. Specifically, we have added the following to the text:

"Furthermore, in regions where observational data is sparse or unavailable, it can be challenging to quantify certain heatwave or heat stress metrics. For example, the use of wet-bulb temperature, which is a commonly used indicator for heat stress, involves complex computations and approximations (e.g., Stull 2011) that may not be readily accessible, particularly in developing countries. Our method is not intended to replace existing approaches, but rather to complement them. It offers a more accessible and practical means of identifying heatwaves by benchmarking against a reference climate regime, especially in data-scarce regions or where computational resources are limited."

3. Lastly, there is the aspect of applying MELT to future climate change. Buzan and Huber, 2020 show that relative humidity scales negatively with global mean temperature change. This does not mean that future heatwaves would switch from moist to dry in the future. There are a lot of issues with relative humidity as a basis for a metric, and one of those is that absolute humidity increases non-linearly with temperature. Even if extreme relative humidity goes down in the future, the danger from the heatwave is enhanced due to the unusually elevated moisture.

Response

We thank the reviewer for highlighting that some studies (e.g., Buzan & Huber 2020) report a negative trend in relative humidity (RH) with global warming, which

could bias an RH-based metric toward “dry” classifications. However, recent work demonstrates that conditional RH, i.e., RH given a particular high temperature, often increases in a warming climate. For example, Matthews et al. (2018) demonstrated that both temperature and RH exhibit an upward trend in a warming climate. Similarly, Yuan et al. (2020) showed that *"in a warming climate, a future day will tend to have higher RH than a day of the same temperature under the historic climate."*

Consequently, even at the same temperature, increased RH in the future will amplify heat stress. Ignoring this conditional increase in RH, as done in some recent assessments of heat impacts, may lead to underestimating the severity of future heatwaves. Therefore, the observed negative scaling between temperature and RH in certain studies may reflect regional or temporal variability, rather than a consistent global response to rising temperatures. Moreover, the Clausius-Clapeyron relation suggests that with increasing temperature, the atmosphere's capacity to hold moisture increases, which generally supports a rise in humidity.

Citations

Yuan, J., Stein, M. L., & Kopp, R. E. (2020). The evolving distribution of relative humidity conditional upon daily maximum temperature in a warming climate. Journal of Geophysical Research: Atmospheres, 125(19), e2019JD032100.

Matthews, Tom. "Humid heat and climate change." Progress in Physical Geography: Earth and Environment 42.3 (2018): 391-405.

To me, what I discuss in the 3 paragraphs above is an editorial decision on the status of the manuscript, because, as stated before, the paper is well written and is self-contained with clear scientific objectives, construction, and application. Below are the minor comments that should be addressed.

Best regards,

-Jonathan R. Buzan

Response

We thank the reviewer for these insightful and constructive comments. We have revised the manuscript with the above suggestions in mind.

Line 10: may want to remove the mention of accurately assessing physiological heat stress. The paper does not compare with health data. Emphasize the meteorological applications instead.

Response

We thank the reviewer for the comment. In the context of this statement, we are stating the importance of moisture and temperature for physiological heat stress and not

necessarily the MELT index. We have revised this statement to clearly articulate the intent of the sentence.

Line 42—50: Buzan et al., 2015 shows that batteries of heat stress metrics cover a larger swath of societal outcomes. Furthermore, the manuscript also comes up with methods that address the dry vs wet heat through this battery of metrics. The utility of using multiple metrics also allows for broader applications, such as the interplay of infrastructure, climate change, and heat stress (Parkes et al., 2022). Additionally, Ivanovich et al., 2024 also created a new index called 'stickiness' that also goes into splitting heatwaves into dry and wet classifications. These manuscripts should be mentioned and discussed.

Response

We thank the reviewer for the comment. We have added further discussion on these papers as described by the reviewer in the revised manuscript.

Line 59-66: WBGT and UTCI go one step further than temperature-humidity covariance, they also include radiation… as long as they are calculated correctly (Cvijanovic incorrectly calculates WBGT, even with the assumptions about "radiation free" environment). Buzan, 2024 highlights the temperature-humidity-radiation relationship.

Response

We thank the reviewer for the comment.

Line 86: The reference period includes the climate events. Does this change when choosing a different reference period? Or climate change?

Response

We thank the reviewer for the comment. This is one interesting aspect of the MELT index. When using this index, a preferred climate regime can be selected for inference and heatwaves calculated using that period. Hence, we would expect that a different reference period would yield heatwaves that are characteristic of that reference regime. This makes the MELT index applicable across different climate regimes.

Line 100-106: The temporal resolution of RH is not stated, and daily maximum is not stated for temperature. I recommend making each step explicit on what data is used. I found it confusing. Buzan and Huber, 2020 and Buzan, 2024 demonstrate that changes in precision can change the outcomes.

Response

We thank the reviewer for the comment. In the manuscript, we give detail to the dataset and temporal resolution used in this work in the "Synoptic, dynamics and thermodynamics drivers associated with MELTS" section. We have further added the temperature and relative humidity resolutions to the methods section as well.

Figure color bars: use less colors, especially with the MELT figures. The patterns should become easier to see. For example, Figures 4 and 6. The color bars here become important. There are a lot of sign changes for specific humidity, but it looks like the elevated specific humidity corresponds with the wet heat in the MELT. I was a little confused by this. It will likely become clearer with less color steps.

Response

We thank the reviewer for the comment. We have addressed this in the revised manuscript.