Short Comment 2: Improved moist thermodynamic calculations

From Reviewer #1 major comment #2:

> "What I really want to see in this paper is a demonstration of the value added by what the authors have done. How do online, time-step level metrics improve on what we could have done with archived model output? If we had daily or 3-hourly model output would that be enough to get the same results? Are the results they have shown, also evident in daily or even monthly mean fields?"

From Reviewer #2 major comment #1:

> "The author emphasize the implementation of more accurate moist thermodynamic calculations. However, based on the results shown here I am not yet convinced that this is particularly relevant. At least Fig.1 suggest that there is hardly any difference in the typical range of tropospheric temperatures. Please quantify the effect for the application here."

From Reviewer #2 major comment #2:

> "The discussion of the existing literature on page 5200, line 4-22 is misleading. It suggest that there are major issues in the existing literature on heat stress, pointing to the inaccurate moist thermodynamic calculations. However, from Fig.1 it seems that this effect is either small or even completely irrelevant for the findings… Also the criticism of the studies looking at monthly values is not justified as for instance Dunne et al. are carefully motivating why they choose the monthly time scale."

We agree that we did not sufficiently show evidence of the added value of our research. The added value of our approach is:

1) our implementation of the Davies-Jones (2008) method to calculate wet bulb temperature is an improvement over the Stull (2011) approximation.

2) online calculation of the heat stress metrics is an improvement over calculating these metrics using monthly or 4x daily model output.

To illustrate these points, we present our new Preliminary Figure 1 (below). Figure 1a shows the difference in the Stull (2011) wet bulb temperature calculated using the saturated vapor pressure from Davies-Jones (2008) (QSat_2) and Flatau et al. (1992) (QSatMod). The differences are minimal, as pointed out by both reviewers.

However, our point is that the Davies-Jones (2008) method for wet bulb temperature is preferred. We show the difference between wet bulb temperatures using Stull (2011) calculated with QSat_2, and Davies-Jones (2008) (which requires QSat_2) (Figure 1b). Differences are greater than 1K between Stull (2011) and Davies-Jones (2008) methods, and they are temperature dependent (Figure 1b).

Lastly, we show the difference between calculating Davies-Jones (2008) T_w using monthly and 4x daily averaged model data vs the model instantaneous calculations (Figures 1c and 1d, respectively). Using model averaged data instead of the instantaneous data systematically overestimates T_w by more than 1K for monthly output and up to 0.5K for 4x daily output.

The overestimation of T_w implies that previous studies that use monthly and even 4x daily averaged data vs the instantaneous data may systematically overestimate heat stress for future climates. This is a major issue because heat stress is a threshold phenomenon. Humans respond to heat stress in a non-linear fashion with step-wise responses (Kjellstrom et al., 2009b, Figure 3; Liang et al., 2011, Figure 1). For example, a ~2°C T_w change (30°C to 32°C) can drop safe exercise time from 240 minutes to 30 minutes (Liang et al., 2011). This is dependent on region and environmental conditions in the work place, however, this overestimation could potentially exaggerate the danger due to heat stress. Even if heat stress impacts are modeled as more smooth functions, these kinds of differences are important.

We use results from a landmark paper published in Nature Climate Change, Dunne et al. (2013) (Figure 2), to illustrate the issue. The authors use WBGT (although, there is a terminology issue, which we explain in the next paragraph). Assuming a 0.5°C T_w overestimation (our Preliminary Figure 1c, below), a WBGT value of 28 (2001-2010 India Figure 1b) becomes 27.65. Using the labor capacity equation in Dunne et al. (2013), there is a 4% gain in labor capacity. If the WBGT value is 25.5 (2001-2010 Florida Figure 1b), the new value is 25.15. This corresponds to a 8.6% gain in labor capacity. At the limit of labor capacity, zero (WBGT at 33, now 32.65), there is a 2.9% gain in labor capacity. These are large values; economic productivity change on a yearly basis is on the order of a few percent (The World Bank, 2014).

One aspect of the Dunne et al. (2013) study that is noteworthy and relevant to our proposed inclusion of standardized metrics in land surface models. The authors use the heat stress metric WBGT, however, they assume the input globe temperature (GT) is equal to the air temperature. This has been criticized in the literature for using the WBGT name, but omitting the GT term:

> "…like all equations that omit GT without changing the index's name, has corrupted the terminology, causing confusion in the literature and doubtless on the sports field as well. It cannot be strongly emphasised that GT is part of the definition of WBGT. Estimates of WBGT without the GT are clearly invalid, and should never be referred to as 'WBGT'." (Budd, 2008).

Even in conditions where there is no direct exposure to sunlight (aka indoors), the GT replaces T, not the other way around (Parsons, 2006, Eq. 5). The construction of WBGT, and other heat stress metrics, are carefully calibrated to responses in the human body. The authors are fitting a regression through WBGT data, but not using WBGT as measured.

The wet bulb temperature (Eq. 6) that Dunne et al. (2013) use is Davies-Jones (2008) Wet Bulb Potential Temperature (Eq. 3.6). However, Eq. 3.6 is valid only for equivalent potential temperatures (θ_e) less than 377K. Yet, θ_e exceeds the calibration by as much as 20K in various areas of the world (such as the Himalayan Wall). Equation. 3.7 (Davies-Jones, 2008) extends the valid calibration to a θ_e of 478.4K. We use wet bulb temperature Eq. 4.8-4.11 (Davies-Jones, 2008), and iterate these equations 2x using Eq. 2.6 (Davies-Jones, 2008). This expands the range of valid wet bulb temperatures, increasing its utility in land models.

So just using this study as an example, different assumptions about how to calculate WBGT and what temporal sampling to use can lead to large differences in the estimates of heat stress. To ensure accurate and consistent calculations, are addressed by the approach we use:

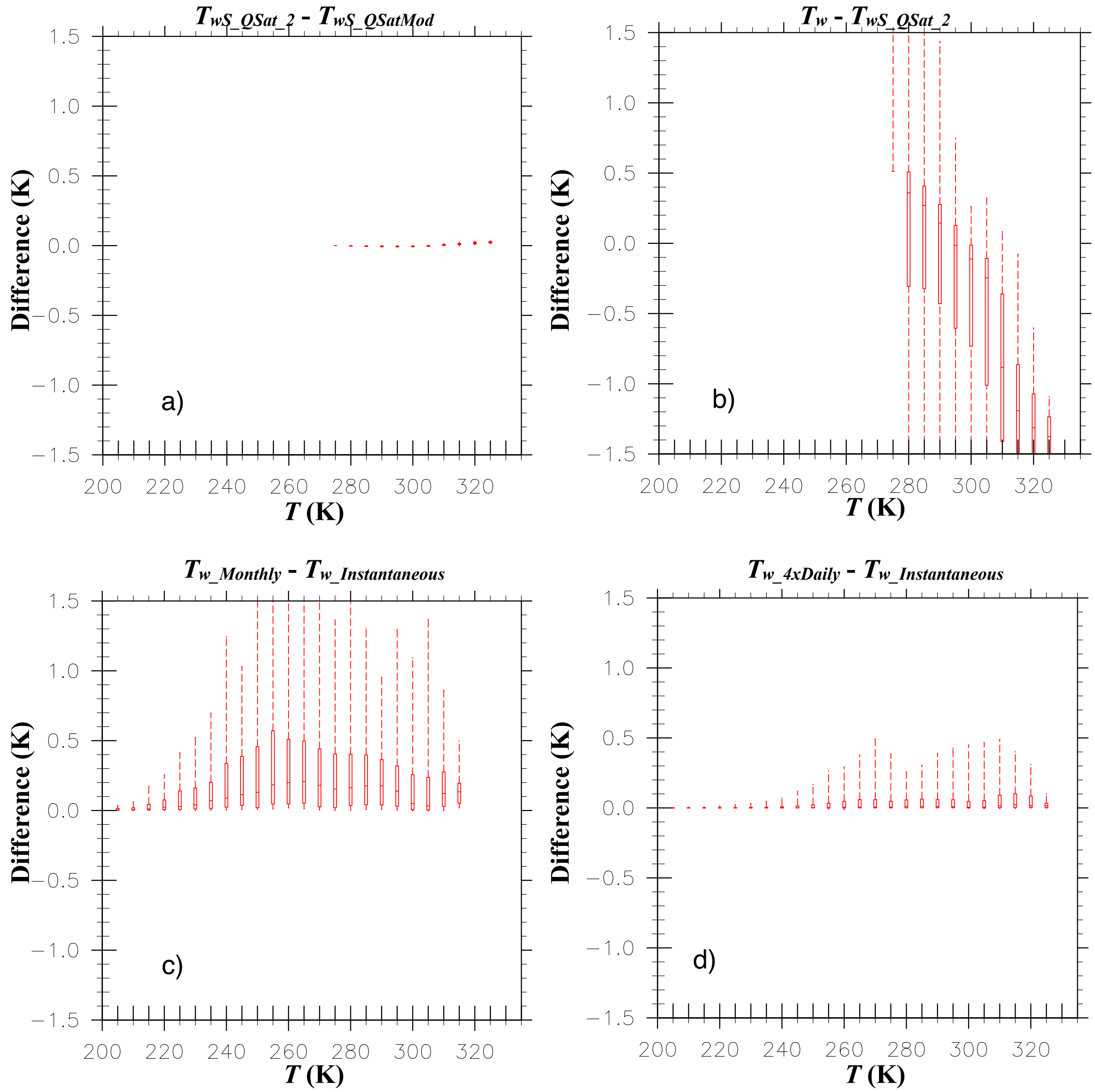
1) We standardize the moist thermodynamics by including the equations in Appendix I into the HumanIndexMod.

2) With the HumanIndexMod incorporated into CLM4.5, we overcome the issue of overestimating heat stress due to temporal resolution.

3) The HumanIndexMod is calculated at the sub grid level in CLM4.5, such that heat stress is calculated in every environment independently (e.g. urban and rural areas)—something that is impossible with 4x daily or even higher temporal resolution standard model output.

We hope that other Earth system models will adopt the HumanIndexMod for these advantages.

Wet Bulb Evaluation



Preliminary Figure 1. Evaluation of wet bulb temperatures. The boxes represent the 90% confidence interval. The upper and lower tails represent the 100% confidence interval. The horizontal line in each box is the median value. a) difference between T_{wS} using QSat_2 saturated vapor pressure and QSatMod saturated vapor pressure over the valid range for T_{wS}. b) difference between T_w (Davies-Jones, 2008) and T_{wS} (Stull, 2011) (both using QSat_2 saturated vapor pressure calculation) over the valid range for T_{wS}. c) is the difference between using model monthly averaged input fields and model instantaneous fields to calculate monthly T_w. d) difference between using model 4x Daily averaged input fields and model instantaneous fields to calculate 4x Daily T_w. For a), b), and d) the inputs of T, P, and Q are derived from model 4x Daily fields from the year 2009. For c) the inputs of T, P, and Q are derived from model Monthly fields from the year 2001-2010.

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The World Bank: http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG/countries/1W?display=graph , last access October 18th, 2014.