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PERSPECTIVE

WIREs CLIMATE CHANGE WILEY

Latent heat must be visible in climate communications

Tom Matthews[1] | **Michael Byrne**[2,3] | **Radley Horton**[4] | **Conor Murphy**[5] | **Roger Pielke Sr**[6] | **Colin Raymond**[7] | **Peter Thorne**[5] | **Robert L. Wilby**[8]

[1]Department of Geography, Kings College London, London, UK

[2]University of St Andrews, St Andrews, UK

[3]University of Oxford, Oxford, UK

[4]Columbia University, New York City, New York, USA

[5]Maynooth University, Maynooth, Ireland

[6]University of Colorado, Boulder, Colorado, USA

[7]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

[8]Loughborough University, Loughborough, UK

Correspondence
Tom Matthews, Department of Geography, Kings College London, London WC2R 2LS, UK.
Email: tom.matthews@kcl.ac.uk

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Abstract

Anthropogenic forcing is driving energy accumulation in the Earth system, including increases in the *sensible* heat content of the atmosphere, as measured by dry-bulb temperature—the metric that is almost universally used for communications about climate change. The atmosphere is also moistening, though, representing an accumulation of *latent* heat, which is partly concealed by dry-bulb temperature trends. We highlight that, consistent with basic theory, latent heat gains are outpacing sensible heat gains over about half of the Earth's surface. The difference is largest in the tropics, where global "hotspots" of *total* heat accumulation are located, and where regional disparities in heating rates are very poorly represented by dry-bulb temperatures. Including latent heat in climate-change metrics captures this heat accumulation and therefore improves adaptation-relevant understanding of the extreme humid heat and precipitation hazards that threaten these latitudes so acutely. For example, irrigation can lower peak dry-bulb temperatures, but amplify latent heat content by a larger margin, intensifying dangerous heat stress. Based on a review of the research literature, our Perspective therefore calls for routine use of *equivalent temperature*, a measure that expresses the combined sensible *and* latent heat content of the atmosphere in the familiar units of °C or K. We recognize that dry-bulb air temperature must remain a key indicator of the atmospheric state, not least for the many sectors that are sensitive to sensible heat transfer. However, we assert here that more widespread use of equivalent temperature could improve process understanding, public messaging, and adaptation to climate change.

This article is categorized under:

- Assessing Impacts of Climate Change > Observed Impacts of Climate Change
- Paleoclimates and Current Trends > Earth System Behavior

After our *Perspective* was first submitted, another paper (Song et al., 2022) expressing similar viewpoints was submitted to another journal, yet their final publication date precedes our own. We are therefore pleased to reference this recently published research article in this final version of the paper, but highlight that our *Perspective Article* was undertaken independently and without knowledge of their work.

KEYWORDS
climate change communication, equivalent temperature, extreme heat, heat accumulation, sensible heat

1 | INTRODUCTION

From its foundational (Arrhenius, 1896) and continued (Zelinka et al., 2020) use in summarizing climate sensitivity, to informing limits on greenhouse gas emissions (Seneviratne et al., 2016), dry-bulb temperature has become the de facto metric for climate change communications amongst scientists, policy makers, and the public alike. There is good reason for this popularity. It is a relatively straightforward quantity to measure using instruments or to reconstruct from paleoclimatic proxies, creating an observational record of more than three centuries in some locations (Mann et al., 2008; Parker et al., 1992). It also exerts significant control on key physical processes (e.g., phase transitions of water), and potential societal impacts—in fields as diverse as infrastructure planning (Underwood et al., 2017) and water resource management (Huss & Hock, 2018).

However, we assert that the limitations of dry-bulb temperature as a measure to track atmospheric heating are obscuring key features of climate change. We highlight that, in ignoring *latent* heat accumulation, the dry-bulb temperature (a) tracks a *minor* component of atmospheric heat gain over large swathes of the Earth's surface; (b) misses present and emerging "hotspots" of change; and (c) inhibits understanding of processes, including those relevant for extreme events and societal adaptation.

We organize our Perspective by providing context for latent heat accumulation in the atmosphere (Section 2), before outlining limitations of dry-bulb temperature for capturing total heat gains (Section 3). In Section 4 we then consider the importance of assessing latent heat for understanding extreme heat and precipitation potential in the tropics. We close with recommendations in Section 5. Throughout this review, we supplement insights from the literature by drawing on well-established theory applied to the ERA5 reanalysis (Hersbach et al., 2020) to illustrate concepts explored in the text.

2 | CLIMATE CHANGE AND ATMOSPHERIC ENERGY ACCUMULATION

Anthropogenic climate change is primarily driven by radiative imbalance at the top of the atmosphere causing energy to accumulate in the Earth system. Since the 1970s, the vast majority of energy gained has been used to warm the oceans (~89%), with the remainder heating the land (~6%) and cryosphere (~4%), and raising the total energy content (*TEC*) of the atmosphere (~1%) (von Schuckmann et al., 2020). The *TEC* is itself comprised of sensible (Q_h, ~97%) and latent (Q_l, ~3%) heat (together the "moist enthalpy"), with kinetic energy contributing less than 0.1% (Peixoto & Oort, 1992). Dry-bulb air temperature (T_a) is related to the sensible term $\left(Q_h = c_p T_a\right.$, where c_p is the specific heat of air at constant pressure) and therefore tracks by far the most important component of *TEC*. However, *changes* to *TEC* skew less toward sensible heat. Recent increases in the near-surface latent heat term—proportional to the amount of water vapor ($Q_l = L_e q$, where L_e is the latent heat of vaporization or sublimation, and q is the specific humidity)—nearly matched the global-mean increase in sensible heat at weather stations on land, and exceeded it in some tropical regions (Peterson et al., 2011). This pattern also emerges in our illustration using ERA5 (Figure 1), where we show the zonal changes in moist enthalpy. Of the 2.6 ZJ gain in *TEC* (one ZJ $= 10^{21}$ J) between the 1950–1969 and 2001–2020 periods, ERA5 indicates that over one-third (0.98 ZJ) was due to the increase in latent heat. This reflects the addition of 400 Gt (one Gt $= 10^{12}$ kg) of water vapor, equivalent to leaving the "tap" of Niagara Falls discharging its mean flow (~1700 $m^3\ s^{-1}$: Hayakawa & Matsukura, 2009) into the atmosphere for ~7 years! At low levels in the tropics, the gain in latent heat even exceeded the increase in sensible heat (Figure 1a), which counts heavily to the global total because surface area is concentrated at low latitudes (Figure 1b).

Just as the dry-bulb air temperature is proportional to the *sensible* heat component of *TEC*, the *equivalent temperature* (T_e) scales with the sum of the sensible *and* latent heat terms (Pielke et al., 2004):

$$T_e = T_a + \frac{L_e q}{c_p} \quad (1)$$

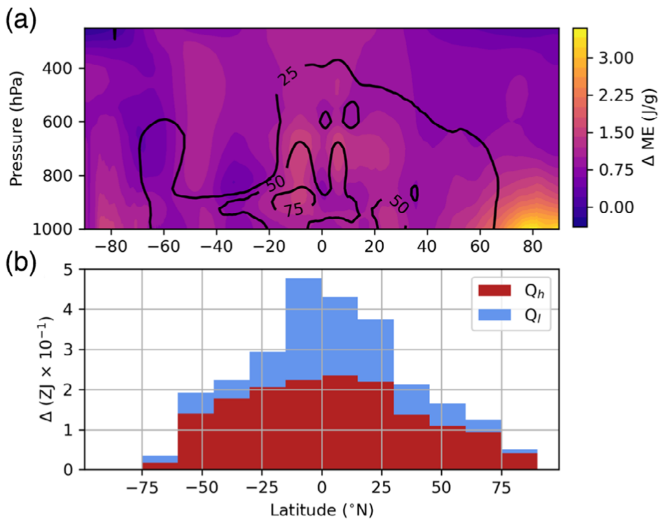

FIGURE 1 ERA5 changes to moist enthalpy (ME). (a) Zonal mean change in ME (2001–2020 minus 1950–1969). The contours show the percentage of the change in ME attributed to Q_{l}. (b) Zonal-sums of column integrated changes in ME, including their apportioning to sensible (Q_h) and latent (Q_l) terms

which represents the temperature that an air parcel would have if *all* its latent heat were converted to sensible heat. Therefore, T_e is directly proportional to the moist enthalpy, varying with both the dry-bulb temperature and specific humidity. Further elaboration of T_e is provided in Box 1, alongside an introduction to other relevant moist heat metrics. We address the critical benefits of using T_e throughout our Perspective, summarizing in Section 5. Here, we highlight that this metric can be used to include changes in latent heat content. For example, considering the entire depth of the atmosphere, T_e increased by 0.5°C compared with 0.3°C for T_a (2001–2020 relative to 1950–1969), meaning heat accumulation "hidden" in the latent term was equivalent to an additional 0.2°C increase in T_a. Note that these increases are perhaps more subtle than one would expect because they include the well-known cooling of the stratosphere (Steiner et al., 2020). The near-surface increase in T_a was indeed much larger over the same period (0.76°C) and so too was the amount of heat channeled into the latent term, with T_e rising by 1.49. These near-surface heating rates are in close agreement with those recently reported by Song et al. (2022) and Stoy et al. (2022).

BOX 1 The equivalent temperature and other common moist heat metrics

The *equivalent temperature* (T_e) varies linearly with the total sensible and latent heat content of the atmosphere. At high levels of humid heat, T_e tracks how hot it feels, because humans sweat to cool and so are sensitive to both the sensible *and* latent heat. It is similar to the "Heat Index" (HI; defined below), but changes by more than 1°C per 1°C increment in HI (see Figure 4).

The *heat index* (HI: Steadman, 1979) is a "feels-like" temperature, defined as the dry-bulb temperature required to produce the given thermal sensation if the atmospheric humidity was held to 1600 Pa (equivalent to 100% RH at 14°C).

The *wet-bulb temperature* (T_W) is defined as the value recorded by a thermometer wrapped in a wet cloth. For non-saturated conditions it is lower than the (dry-bulb) temperature due to evaporative cooling. It defines an upper limit to human tolerance: once T_W exceeds 35°C, evaporative heat loss can no longer maintain a safe skin temperature, regardless of sweat rate. However, T_W has a nonlinear relationship with HI, such that increments of T_W are ever more impactful for thermal discomfort at higher values.

The *wet-bulb globe temperature* (*WBGT*) is the International Organization for Standardization (ISO) metric for identifying conditions of heat stress (ISO, 2017), responding to radiative and evaporative heat exchange, as well as cooling potential via evaporation from a wet surface (Budd, 2008). Outside of direct sunlight, it is calculated as the weighted sum of the dry (weight = 0.3) and wet-bulb temperatures (0.7).

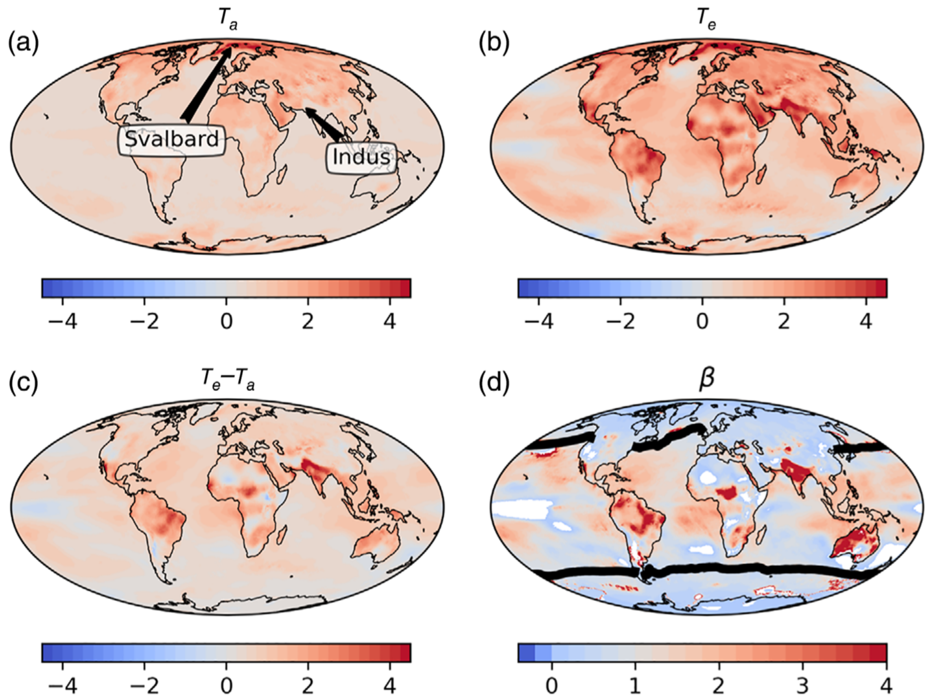

FIGURE 2 ERA5 trends in near-surface (2 m) heat content per degree of global mean 2 m T_a from ERA5. (a) 1950–2020 trends in mean annual dry-bulb temperature (T_a). Annotated arrows identify regions mentioned in the text and plotted in Figure 3. (b) As in (a) but for the equivalent temperature (T_e). (c) As in (a) but for the latent heat contribution to equivalent to T_e. (d) Ratio of trends in latent heat to sensible heat (β: See Equation (2)). The black line is the mean 10°C contour for ocean pixels (1950–2020). White shows regions where trends are of different sign. Note that all fields are dimensionless, and that trends in (a)–(c) are defined as the slope coefficient in a regression of mean-annual grid-point values versus the global mean annual (2 m) dry-bulb temperature

For about 48% of the Earth's surface, the increase in latent heat even *outpaced* the gain in sensible heat (Figure 2). Therefore, for people living in these (generally more equatorial) locations, recent atmospheric heat accumulation was experienced more through an increase in water vapor than via rising dry-bulb temperature. To understand this behavior, note that under the assumption of constant relative humidity (RH), the ratio (β) of changes in latent heat (dQ_l) to changes in sensible heat (dQ_h) under warming can be approximated by (cf. Priestley, 1966):

$$\beta = \frac{dQ_l}{dQ_h} = \frac{L_e}{c_p} RH \alpha e_s(T_a) \frac{\varepsilon}{P} \tag{2}$$

where ε is the ratio of gas constants for dry air and water vapor (0.622), e_s is the saturation vapor pressure (which increases with T_a according to the Clausius Clapeyron relation), P is the air pressure, and α is the fractional increase in e_s per degree of T_a (6–7% K^{-1}). Note also that the quantity $\alpha = 1 + \beta$ provides the change in equivalent temperature per degree of warming in dry-bulb air temperature.

Equation (2) indicates that climates with higher RH and T_a will be characterized by greater partitioning to Q_l at the expense of Q_h. For example, if RH is fixed at a value typical over the oceans (0.80) and $c_p = 1013\,J\,kg\,K^{-1}$, changes in Q_l should exceed those in Q_h wherever T_a exceeds ~10°C. This simple threshold approximately delineates marine latitudes where latent-heat increases have dominated the total (Figure 2d) and therefore highlights that the observed ratios of latent and sensible heat gains are consistent with basic theory.

Another interesting feature made clear by Equation (2) is that atmospheric heat should be channeled ever more into the latent term as the climate warms (due to rising e_s with rising T_a). Reductions in RH would offset this to some extent, but in the global mean RH is expected to remain approximately constant under continued warming, albeit with decreases over land (Byrne & O'Gorman, 2016) continuing the observed downward trend (Vicente-Serrano et al., 2018). We return to this as a motivation to employ T_e more widely in climate communications in Section 5.

3 | AIR TEMPERATURE TRENDS CAN OBSCURE CLIMATE CHANGE "HOTSPOTS"

T_a trends generally downplay moist enthalpy gains most substantially in tropical and subtropical regions (Figure 2), which risks obscuring global hotspots of change that emerge for these latitudes (Figure 3a). Amplification of moist enthalpy trends nearer the equator is indeed a robust feature of model projections (Matthews, 2018; Song et al., 2022) and consistent with known feedbacks (Shell et al., 2008), but is perhaps an under-appreciated feature and hazard of climate warming. It is distinct from the T_a-based conclusion that the tropics will see the greatest signal to noise ratio in heat gains due to low noise (interannual variability: Hawkins & Sutton, 2009); T_e identifies that the signal in the tropics is amplified.

The greater increase in T_e relative to T_a for more equatorial (warmer) latitudes has been highlighted in the research literature (Song et al., 2022) and is consistent with the theory outlined in Section 2, as shown by the reference lines in Figure 3b. Interestingly, the greater partitioning of energy to the sensible term for more polar (colder) latitudes implies that at least some of the well-documented Arctic amplification of T_a trends (Previdi et al., 2021) should be expected, even if moist enthalpy accumulated uniformly across latitudes. Similarly, some elevation-enhancement of T_a warming (Pepin et al., 2015) should be anticipated because of the colder climate that prevails at higher altitudes. In contrast, the large increase in T_e at high northern latitudes (Figure 3a) helps clarify the importance of regionally unique positive feedback mechanisms in driving up total heat accumulation in the Arctic.

A focus on trends in T_a does not just risk systematically underestimating total heat accumulation in the tropics and subtropics where it is warmer, but also jeopardizes identifying *relative* hotspots of change within these regions. Empirically, the proportion of spatial variance in dT_e explained by dT_a (Figure 3b) reaches 98% within the polar latitudes, and 92% within the mid-latitudes (40°–60° of the equator), but only 39% and 34% within the subtropics (between 20° and 40° of the equator), and tropics (within 20° of the equator), respectively. This is also consistent with theory because

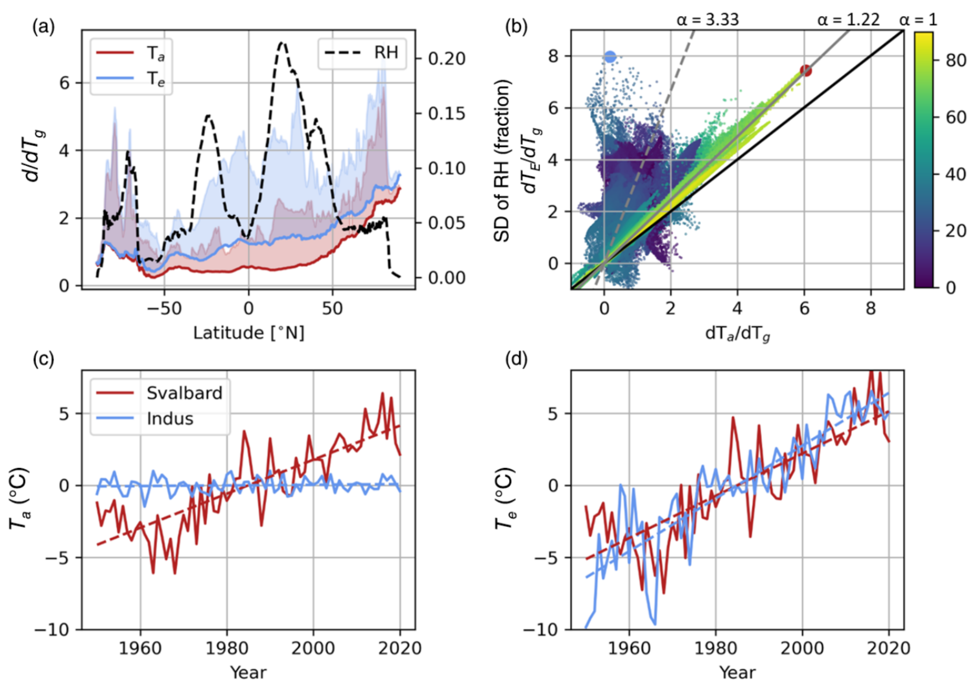

FIGURE 3 Spatial variation in ERA5 heating trends. (a) 1950–2020 changes in dry-bulb temperature (dT_a) and equivalent temperature (dT_e) per change in global mean 2 m T_a from ERA5 (dT_g) as a function of latitude. Solid line is the median and shading extends to the 90th percentile of the longitudinal distribution at each latitude. We also show the longitudinal standard deviation in the 2001–2020 mean relative humidity (RH) as a function of latitude. (b) 1950–2020 ERA5 grid-point values of dT_e/dT_g versus dT_a/dT_g, shading represents the absolute latitude of the grid cell. The reference lines represent the theoretical scaling (α) between dT_a/dT_g and dT_e/dT_g expected from applying Equation (2) to the ERA5 mean climate (1950–2020) for polar (solid gray-line: Within 23° of the poles) and tropical (dashed gray line; within 20° of the equator) regions. Note that the blue and red circles highlight the "Indus" and "Svalbard" locations discussed in the text (and Figure 2 caption). (c) Annual mean anomalies of T_a for the Indus and Svalbard locations shown in Figure 1 and discussed in the text. Dashed lines indicate the least-squares linear fits. (d) As in (c) but for T_e

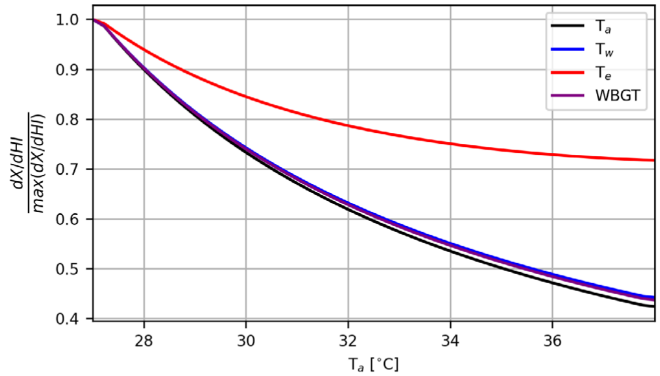

FIGURE 4 Changes in the respective heat metrics (dX) defined in Box 1: Dry bulb air temperature (T_a), wet-bulb temperature (T_w), equivalent temperature (T_e), and the wet-bulb globe temperature ($WBGT$) with respect to changes in the heat index (dHI), as a function of T_a. Note that (i) relative humidity was held at 80% to compute the derivatives; and (ii) the derivatives are normalized by dividing by the maximum value (achieved at the lowest value of T_a)

Equation (2) indicates that, for higher values of T_a, energy partitioning is increasingly sensitive to changes in RH, which in turn exhibits appreciable spatial variability in the tropics and subtropics according to ERA5 (Figure 3a).

The potential limitations of using T_a to infer hot spots of total heat gains are communicated vividly by considering the grid cell with the largest gains in moist enthalpy according to ERA5 (Figure 3b, 28.5°N, 68.0°E). This occurs within the Indus Valley (see Figure 2a for location), a densely populated region home to more than a quarter of a billion people (Wang et al., 2020), characterized by extremely high vulnerability to climate change (Immerzeel et al., 2019), where communities already endure some of the world's highest values of T_e (Matthews, 2020). However, the drastic change here is obscured by the annual mean T_a series (Figure 3c). Only when T_e is examined does the heat accumulation appear (Figure 3d), exceeding that in the most rapidly warming Arctic regions (e.g., near to Svalbard: 80.25 °N, 13.75°E). T_e is closely related to human heat stress (Box 1), and has a relationship with how hot it feels that is more linear than other commonly used metrics (Figure 4). In line with concerns raised in the literature (Stoy et al., 2022), Figure 3d therefore communicates that moist enthalpy is climbing fastest in a region already with the highest values worldwide and on the frontline against the threat from deadly humid heat. This critical, impacts-relevant message is obscured entirely by the dry-bulb temperature trend.

4 | INCLUDING LATENT HEAT IMPROVES PROCESS UNDERSTANDING

Not only does dry-bulb temperature fail to provide a robust assessment of where heat accumulation is occurring most rapidly, it also hinders process understanding for key features of climate change that are of critical societal relevance. Below we outline the urgency of studying total heat content by highlighting the extreme heat and precipitation hazards most prevalent in low-latitude regions.

4.1 | Extreme heat

The spotlight of total heat content has recently helped illuminate physical limits on deadly humid heat stress in the densely populated lower latitudes. Consistent with dynamical controls, it has been shown that changes to the highest values of moist static energy (MSE: the sum of moist enthalpy and geopotential) are approximately spatially uniform in the tropics due to the role of deep convection (Zhang & Fueglistaler, 2020), and limited by the amount of tropical sea-surface warming (Zhang et al., 2021). This insight reduces uncertainty in projections of extreme heat because moist enthalpy is tied to wet-bulb temperature (Box 1), leading to the conclusion that the limits to human heat tolerance are unlikely to be exceeded in the tropics for global warming less than 1.5°C above preindustrial (Zhang et al., 2021). An MSE perspective has also helped explain the amplified warming of extreme dry-bulb temperatures in the tropics under the so-called "drier get hotter" mechanism (Byrne, 2021).

The improved process understanding that comes from assessing total atmospheric heat content also helps inform other factors that modulate extreme heat with relevance for adaptation. For example, enhanced transpiration and physical evaporation from increased vegetation cover (greening) and irrigation have been shown to reduce dry-bulb temperature (Piao et al., 2020; Pielke et al., 2011), with some studies highlighting the potential to mitigate heat waves (Thiery et al., 2020; Zeng et al., 2017). However, elevated water vapor flux into the atmosphere also implies an increase in the latent heat content, meaning a decline in moist enthalpy is not self-evident. Theory and modeling even suggest that, if total surface heat fluxes are unchanged as the latent fraction increases, near-surface moist enthalpy may *rise* as it becomes trapped in a shallower boundary layer (Rappin et al., 2021; Segal et al., 1998). Land surface modifications such as irrigation (Mishra et al., 2020) and urban greening (Sharma et al., 2016) may, therefore, reduce peak dry-bulb temperature, but *not* human heat stress if this simply reflects a trade-off between sensible and latent heat (Wouters et al., 2022). Rather than being an effective means of mitigating heat stress, irrigation could instead accelerate the arrival of widespread conditions beyond human thermal tolerance in some regions (Kang & Eltahir, 2018).

4.2 | Extreme precipitation

Precipitation rate is determined by the low-level convergence of moisture (Held & Soden, 2006). It is, therefore, no surprise that the highest precipitation rates are generally experienced in the tropics (O'Gorman & Schneider, 2009), where specific humidity (i.e., latent heat content) is greatest. The tropics are also anticipated to experience the greatest *increases* in precipitation intensity under climate warming (O'Gorman, 2015), consistent with the tropical amplification of latent heat accumulation simulated by climate models (Matthews, 2018). However, the magnitude of the increase is particularly uncertain in the tropics due to the importance of other features of convection (e.g., updraft velocities) (Fowler et al., 2021; Pfahl et al., 2017), which operate at scales too fine for global climate models to simulate directly (Tabari et al., 2019).

Given this physical context, observed *declines* in precipitation intensity with increasing T_a at higher temperatures in some tropical areas have been noted with interest (Maeda et al., 2012; Utsumi et al., 2011). These trends were initially poorly understood (Wang et al., 2017) and considered "controversial" by the Intergovernmental Panel on Climate Change (IPCC) (Boucher et al., 2013). It is now appreciated, though, that the surface energy balance can help explain this unexpected result. In the tropics, the highest dry-bulb temperatures generally result from limited surface moisture availability, causing more of the surface heat fluxes to be apportioned to sensible rather than latent heat, and therefore driving up T_a at the expense of specific humidity and precipitation intensity (Fowler et al., 2021; Moustakis et al., 2020).

Declines in tropical precipitation intensity with increasing T_a are therefore *not* evidence for less intense precipitation extremes under climate change. Rather, they can reflect scaling against the wrong (sensible) component of atmospheric heat. Although the sensible term sets the upper limit for moisture content, the two do not track each other directly. If instead some measure of the atmosphere's latent heat content is used as the covariate—for example, the dewpoint air temperature (Ali et al., 2018; Lenderink et al., 2011) or total column moisture (Roderick et al., 2019)—a positive relationship with precipitation intensity generally emerges. Hence, just as tracking latent heating deepens understanding of emerging deadly heat in the tropics, it also improves understanding of possible future changes in extreme precipitation events.

5 | RECOMMENDATIONS

The previous sections demonstrated important consequences of neglecting latent heat. We therefore propose that *equivalent temperature* be incorporated as a primary metric within assessments of climate change. As a measure of moist enthalpy it is closely related to thermal discomfort, allowing for an accurate identification of hotspot regions and quantification of anticipated impacts, whilst retaining a physical (rather than empirical) basis. By contrast, dry-bulb air temperature risks drifting ever further from people's lived experience as the amount of heat "hidden" in the latent term grows with warming (Equation (2)). Other widely used heat metrics like T_W and *WBGT* (Box 1) may also become less sensitive to increments in feels-like temperature as heat stress climbs (Figure 4).

The more complete picture provided by T_e would also explain heating contributions across sources and scales, including: unpacking the roles played by greenhouse gases, aerosols, and land management/use (e.g., urbanization, irrigation, and deforestation) to explain spatial variation in heating patterns (Gogoi et al., 2019; Matsui & Pielke Sr, 2006); the processes responsible for deadly heatwaves in the densely-populated mid-latitudes (Wehrli et al., 2019); and the drivers of heat accumulation at different heights throughout the atmosphere (Steiner et al., 2020).

In addition, the *difference* $T_e - T_a$ is linearly related to moisture content, so precipitation extremes increasing at the Clausius Clapeyron rate would appear as a straight line when plotted against this quantity. Departures from linearity could therefore diagnose situations where dynamical changes (e.g., increased updraft speeds) are important in driving the climate change response (Pfahl et al., 2017). While this applies equally to specific humidity, rescaling to the difference $T_e - T_a$ enables results to be communicated in the familiar units of changes *per degree of warming*—only this time "warming" refers to the increase in the latent heat content. Another attractive feature of integrating T_e into the study of precipitation extremes is that vertical gradients in the closely related *potential* T_e (T_e adjusted adiabatically to a reference air pressure) govern moist static stability, such as is used to compute convective available potential energy (CAPE). Greater awareness of T_e may therefore advance the understanding and communication of changes in tropical convection (Song et al., 2022). Combined, we assert that these attributes make T_e a more appealing metric to track latent heat than other thermodynamic variables like the wet-bulb and dewpoint temperatures.

We recognize that dry-bulb temperature is a familiar quantity with an excellent measurement legacy, and that it will continue to play an important role in understanding and monitoring the climate system. For example, planetary emissions of longwave radiation to space are proportional to the fourth power of T_a, and the rates of chemical reactions in the atmosphere are temperature dependent. There are also many instances where T_a will remain the most relevant metric from a societal impacts perspective, for example wherever the rate of sensible heat transfer is of interest (e.g., human thermal tolerance to extreme cold; bridge-expansion; and railway buckling; growing degree days).

However, these considerations do more to highlight the importance of T_a for specific applications, than to downplay the significance of T_e as a key metric for climate change communications. Indeed, using both quantities alongside one another may be most informative in some instances. For example, beyond the extreme precipitation scaling mentioned already, the magnitude of T_a and its difference from T_e could be relevant for assessing the potential dryness of the land surface, a key variable in the assessment of wildfire risk (Anderson, 2010). The answers to high-level questions powerfully framed in terms of T_a might also be refined with T_e in mind. As uncertainty in climate model projections is lower for T_e than T_a (Fischer & Knutti, 2013), societal impacts from radiative forcing may, for example, be determined more robustly with the latter, which in turn could help constrain estimates of allowable CO_2 emissions (Seneviratne et al., 2016). The relative unfamiliarity of equivalent temperature may pose a near-term practical challenge for widespread public messaging, but on the positive side the quantity has familiar units of °C (or K), and its magnitude is more similar to T_a if focusing on *changes* (rather than absolute values).

6 | CONCLUSIONS

First, we have illustrated that despite its status as a benchmark metric, dry-bulb temperature poorly identifies hotspots of atmospheric heat accumulation by underplaying changes in *total* heat content, especially in more equatorial latitudes. This is particularly of concern because total heat content is already highest in the tropical atmosphere, where it drives some of the most severe extremes in humid heat and precipitation worldwide. Outside the Arctic, a simple but important narrative appears when the latent heat term is included: consistent with regional patterns in radiative forcing, energy is generally accumulating fastest where it is already highest, and where major climate and other environmental hazards already pose significant threats to vulnerable and populous societies.

Second, we have shown that the specific hazards associated with humid heat and extreme precipitation become more apparent when including a measure of the latent component. In warmer climates, dry-bulb temperature can be very poorly correlated with variations in both total and latent heat, meaning humid heat stress and extreme precipitation could climb more where dry-bulb temperatures increase less. Under these circumstances, there is a high potential for underestimation of risk in vulnerable tropical and subtropical regions, as well as implementation of inappropriate adaptations. Inclusion of latent heating could therefore help inform questions around attribution, legal liability, as well as loss and damage (Burger et al., 2020).

No variable encompasses all aspects of climate change, and certain risks are more closely linked to dry-bulb temperature than a moist heat measure. However, just as ocean heat content is a more complete metric of energy accumulation in the Earth system (Pielke, 2003), equivalent temperature is a superior measure to research and communicate total heating of the near-surface atmosphere. We, therefore, call for its wider use in climate communications.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Tom Matthews: Conceptualization (lead); formal analysis (lead); investigation (lead); methodology (lead); writing – original draft (lead). **Michael Byrne:** Conceptualization (supporting); writing – review and editing (equal). **Radley Horton:** Conceptualization (supporting); writing – review and editing (equal). **Conor Murphy:** Conceptualization (supporting); writing – review and editing (equal). **Roger Pielke Sr:** Conceptualization (equal); writing – review and editing (equal). **Colin Raymond:** Conceptualization (supporting); writing – review and editing (equal). **Peter Thorne:** Conceptualization (supporting); writing – review and editing (equal). **Robert Wilby:** Conceptualization (supporting); writing – review and editing (equal).

DATA AVAILABILITY STATEMENT

All data and codes used to illustrate ideas in this perspective are available from the corresponding author upon request.

ORCID

Tom Matthews https://orcid.org/0000-0001-6295-1870
Colin Raymond https://orcid.org/0000-0003-3093-5774

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