ABSTRACT: Exposure to weather extremes, such as heatwaves, can cause discomfort, harm, or death in grazing cattle in pastures. While the Australian Bureau of Meteorology issues sheep graziers alerts when there is an exposure risk to chill for livestock, there is no equivalent alert for heat stress for Australian cattle. Before any such alert system can be developed, a robust assessment and comparison of relevant cattle thermal stress indices is required. This study evaluates and compares the multiyear climatology of three cattle thermal heat stress indices across Australia in the warm season months (October–March). The same indices are then used to assess historical Australian heat events where cattle died from heat exposure. These events are based off official records and survey responses from northern Australian graziers. In the seven historical heat events studied, high relative humidity combined with low wind speeds, or high solar exposure combined with high surface temperatures, exacerbated the impact of heat stress on cattle. In the two historic events where multiple compounding weather factors combined (e.g., high humidity, low winds, and high solar exposure), the cattle mortality levels were significantly high. These events were characterized by rainy conditions followed by a rapid warming, meaning cattle were likely unable to acclimatize to such dramatic temperature changes. This study highlights the need for using more than one thermal stress index when verifying cattle heat stress events and, importantly, calls for further research on standardizing the risk classifications of these thermal indices for cattle in Australia’s variable climate.

SIGNIFICANCE STATEMENT: Cattle across Australia’s northern tropical and semiarid regions often experience extreme hot and humid conditions in the summer months, which increases the risk of heat stress. This is the first study of its kind to evaluate observations of cattle heat stress across Australia using indices that describe the combined effects of solar exposure, wind speed, relative humidity, and surface temperatures. These cattle heat stress indices can be used to evaluate historical cattle mortality events in feedlots and in grazed pastures. This study lays the groundwork for the development of Australian-wide cattle heat stress forecast products on the 7-day to multiweek time scales.

KEYWORDS: Extreme events; Climatology; Humidity; Temperature; Agriculture; Climate services

1. Introduction

The beef industry in tropical and semiarid northern Australia supports around 15 million cattle (Cobon et al. 2021). These livestock experience extreme weather conditions including extended heatwaves (Bureau of Meteorology 2019), flooding rains (Cowan et al. 2022), and flash droughts often associated with failed wet seasons (Nguyen et al. 2021, 2020). Alongside the impacts on forage production (McKeon et al. 2009), very hot days can cause heat stress in animals. In some cases, the heat impacts on the most vulnerable cattle, such as calves and malnourished animals, can be fatal. A recent overseas example of this occurred in mid-June 2022, when a heatwave in the southwest Kansas (United States) resulted in 2000 cattle deaths,1 reportedly exacerbated by cloudless skies (i.e., high solar exposure),2 driving cattle “feel like” temperatures well above 50°C. Similarly, in Australia’s northeast state of Queensland in February 1991, high temperatures, exacerbated by high relative humidity and low wind speeds, led to approximately 4000 cattle deaths, predominantly in feedlots (Lees et al. 2019). Such heat impacts on Australian grazing cattle in the northern tropics and semiarid regions can be difficult to measure because of the lack of suitable livestock data with cattle spread across often large (>5000 km²) cattle stations (Gaughan et al. 2019).

Heat stress indices developed for dairy and beef cattle generally factor in relative humidity or wet-bulb temperature, with the most well-known one being the temperature humidity index (THI), first developed in Scotland in the late 1950s.


By combining air temperature and relative humidity (or dewpoint/wet bulb) into one index, the THI is simple to calculate and easy to measure (Nidumolu et al. 2010; Wang et al. 2018). Values of THI > 72 (e.g., a temperature of 32°C and 0% humidity, or 25°C and 50% humidity) are considered stressful for dairy cows (Moran 2005). In tropical Brahman genotypes of northern Australian cattle, a THI > 79 over 2 weeks has been shown to cause calf mortality rates of 12%–17%, when the typical mortality in calves is between 6.5% and 11.1% depending on cow maturity (McGowan et al. 2016). Yet the THI is not appropriate for all Australian conditions as it neglects the compounding effects of solar load and wind speed on cattle comfort. This motivated the development of the heat load index (HLI) in the late 2000s (Gaughan et al. 2008, 2019). The HLI combines near-surface temperature, relative humidity, solar radiation, and wind speed into a single index. Critical upper HLI thresholds for cattle breeds under certain environmental conditions are based on animal respiration rates in unshaded feedlots (Gaughan et al. 2008). When the critical upper HLI threshold is exceeded over an hour, an animal’s heat load begins to accumulate, as detailed in section 2.

Another relatively new cattle thermal metric is the cattle comfort index (CCI), which spans both the cold and warm extremes. Like the HLI, the CCI combines temperature, solar radiation, humidity, and wind (Mader et al. 2010; Wang et al. 2018). It is currently used in forecasting cattle comfort levels across Oklahoma in the Midwest United States (Richards et al. 2016). In Australia, the CCI has been included in extreme cold weather event impact assessment (Cowan et al. 2022) and in evaluating shelter requirements for southern Australian cattle in cold weather (Lees et al. 2022). Yet, critical CCI thresholds for grazing cattle in northern Australia’s tropical and rangeland regions are yet to be fully established.

As of February 2024, Australian feedlots can receive location-based forecasts of cattle heat stress (i.e., HLI) out to 7 days via two different subscription services.1 The Bureau of Meteorology also generates daily and weekly prototype forecast maps of THI over Australia; however, these are unavailable to the general public while in their research trial phase. As such, there is a notable gap in the forecast availability of Australia-wide cattle heat stress where solar and wind effects are accounted for. There has also not been an assessment of the climatology of cattle heat stress conditions across Australia. Hence, quantifying the present-day heat stress for Australian cattle is an important first step, especially given climate projections suggest that livestock worldwide will face more extreme heat stress risk this century as a consequence of anthropogenic climate change (Thornton et al. 2021).

The main purpose of this study is to quantify the climatology and variability of cattle heat stress across Australia, given past studies have mainly focused on the feedlot scale and site-specific regions (Abellán et al. 2019; Wiebe et al. 2017; Gaughan et al. 2019; McCarthy and Fitzmaurice 2016), or exclusively on southern dairy cattle (Nidumolu et al. 2010). A secondary objective is to evaluate and compare cattle heat stress indices during periods of hot weather from the past 30 years across northern and eastern Australian locations that have recorded cattle losses. This will help answer the question as to what are the important weather conditions that contribute to heat stress events where cattle losses have occurred and been recorded. The study is as follows: data sources (e.g., observational and reanalysis datasets) and methods are described in section 2. This includes precise definitions of the cattle heat stress indices and their thresholds for heat risk above which leads to cattle discomfort, morbidity, and mortality. In section 3, a historical climatology of the heat stress indices is presented, as well as a comparison of the indices for a series of historical heat stress events and their association with estimated cattle losses. Later in section 3, utilizing nearly three decades of observations (1990–2017), the interannual variability in extreme cattle heat conditions is analyzed, in order to place the historical heat events in the context of the multidecade record. A summary of results and discussion of future research directions is presented in section 4.

2. Data and methods

a. Daily observations and reanalysis

As the time scales associated with cattle heat stress events range from hourly to daily, these events are investigated using multiple observational and reanalysis datasets. For the daily observational analysis, 5-km gridded daily near-surface (1.2 m) maximum/minimum temperature (°C), from the Bureau’s Australian Gridded Climate Data (AGCD) version 1 (Evans et al. 2020), is used to calculate daily mean temperature. Daily relative humidity (RH; %) is defined as the percentage ratio of the vapor pressure (VP; hPa) to the saturation vapor pressure (SVP; hPa),3 the latter calculated using the dry-bulb mean temperature (T; °C):

\[
RH = \frac{VP}{SVP} \times 100\% \quad \text{and} \quad SVP = e^{(1.8096 + [17.26967/(237.3 + T)])}. \tag{2}
\]

Daily estimates of total surface solar exposure (SE; MJ m⁻²) from satellites are derived by the Bureau using a radiation model (Weymouth and Le Marshall 2001). Using satellite images of brightness, the radiation model estimates the surface solar irradiance by calculating the irradiance over groups of four pixels at the top of the atmosphere, the irradiance absorbed in the atmosphere, and the irradiance reflected at the surface and by clouds. The instantaneous irradiance values are then integrated over the day to give daily insolation amounts. The total daily surface (downwelling) shortwave solar radiation (SR; W m⁻²)


2. We note that this underrepresents the nighttime relative humidity.

is calculated from the SE estimate and bilinearly regridded to the 5-km AGCD grid:

\[ \text{SR} = \frac{\text{SE} \times 10^6}{(60 \times 60 \times 24)} \]  

(3)

The satellite-derived solar radiation data are only available from 1990, and due to data quality issues in the 2018 dataset (L. Majewski 2022, personal communication), we restrict our analysis of daily AGCD observations and their long-term climatology to the period 1990–2017. The latest solar data from 2019 onward from the Himawari-8 satellite estimates do not have the same quality issues, which allows an evaluation of heat events from 2019 onward.

For wind speed data, we use a new prototype gridded 5-km observational wind speed product, which is a mixture of 2-m winds and 10-m winds downscaled to 2 m (Sharples and Baron-Hay 2023). The 2-m observational wind product represents the heat conditions at cattle height and is on the same 5-km AGCD grid. Studies rely on the logarithmic wind profile to derive near-surface wind speeds from 10-m winds (Zhang et al. 2022; Allen et al. 1998). This is the same approach taken by Sharples and Baron-Hay (2023), using roughness lengths from wind observation sites around Australia. The Bureau also uses this approach when forecasting the livestock chill index, taking an average surface roughness length, and then applying a conversion ratio of 0.5 (based off the log wind profile) to 10-m wind forecasts to transform them to 2 m.

Daily observations from the Scientific Information for Land Owners (SILO) database6 are used as a comparison to AGCD. The SILO data are constructed from 4600 Australian weather station records back to the late 1800s, which are spatially infilled onto a 5-km grid using a two-pass interpolation scheme (Jeffrey et al. 2001). The available daily weather variables include 1.2-m maximum and minimum temperature (°C) and relative humidity (%) at the time of maximum and minimum temperature, from which the average daily relative humidity is calculated. Surface solar exposure (MJ m⁻²) is determined from measured solar radiation, sunshine duration, and cloud cover (Zajaczkowski et al. 2013). As SILO wind data (Zhang et al. 2022) were unavailable at the time of writing (14 February 2024), the same 2-m winds are used for calculating the HLI and CCI in the AGCD and SILO observations. A summary and comparison of the observed data spatial resolution, temporal resolution, and height levels is shown in the appendix (Table A1).

b. Subdaily reanalyses

To calculate heat accumulation in cattle, hourly or sub-hourly data are required, as the diurnal cycle in thermal conditions dictates if and when cattle gain or lose heat (Gaughan et al. 2019). For this, we utilize the Bureau of Meteorology Atmospheric high-resolution (12 km) Regional Reanalysis for Australia (BARRA-R, version 1; Su et al. 2019). This atmospheric reanalysis product uses boundary conditions from the European Centre for Medium-Range Weather Forecasts global atmospheric reanalysis product ERA-Interim (more information can be found in Su et al. 2019), and its resolution domain includes the Maritime Continent, southern India, and Australia/New Zealand. The BARRA-R data assimilation system uses 12-h forecast cycles at 6-hourly intervals that are constrained by observations (called an analysis cycle, completed at 0000, 0600, 1200, 1800 UTC time within a ±3-h period). At each analysis cycle, observations are assimilated with the model forecast from the previous cycle centered on the listed UTC times. The first 6 h after the UTC times are taken as the hourly observational analysis. The following variables are used: solar radiation (W m⁻²), 10-m wind speeds (m s⁻¹), 1.5-m screen dewpoint, and dry-bulb temperatures (°C), all at hourly time steps. The dewpoint temperature (Td; °C) and dry-bulb temperature (T; °C) are used to calculate the relative humidity (%) at 1.5-m height using the following equation:

\[ \text{RH} = \frac{e^{(1.8096 + [17.26986 T_d] (237.3 + T_d))}}{e^{(1.8096 + [17.26986 T_d] (237.3 + T))}} \times 100\%. \]  

(4)

The BARRA-R acts as a partly independent data source to AGCD and SILO; hence, it is used to investigate the magnitude of historical heat stress events through the heat load accumulation. The 0.5 conversion ratio is applied to 10-m BARRA-R winds in the subdaily analysis. We note that the 0.5 conversion ratio is a good estimate when compared to the Sharples and Baron-Hay (2023) 2-m transformed wind observations (as shown in Fig. 3f), as opposed to a conversion estimate based off short grassed surfaces (~0.75; Allen et al. 1998).

c. Thermal indices

1) Heat Load Index and Accumulated Heat Load Unit

The HLI measures instantaneous heat load and is derived at an hourly and daily time step, depending on the dataset used, from relative humidity, wind speed, and black globe temperature (BGT; °C). The BGT is a measure of the temperature within a black thin copper sphere, but given it is not routinely measured at Bureau weather sites (McCarthy and Fitzmaurice 2016), BGT can be derived from air temperature (T; °C) and SR (W m⁻²) (Gaughan et al. 2019):

\[ \text{BGT} = 1.337 - 2.65 \sqrt{T} + 3.21 \log_{10}(\text{SR} + 1) + 3.5. \]  

(5)

If the BGT ≥ 25°C, then the HLI is calculated as

\[ \text{HLI}_\text{HI} = 8.62 + (0.38 \times \text{RH}) + (1.55 \times \text{BGT}) + e^{(-\text{WS} + 2.4)} - (0.5 \times \text{WS}), \]  

(6)

where RH is the relative humidity (%) and WS is the wind speed (m s⁻¹) (Gaughan et al. 2019).

If the BGT < 25°C, then according to Gaughan et al. (2019), the HLI is calculated as
To account for the transition across the arbitrary 25°C BGT threshold, a blending function for BGT was introduced (Gaughan et al. 2019), where

\[
BGT_{bl} = \frac{1}{1 + \left( e^{-\left( BGT - 25 \right)^3} \right)}.
\]  

(8)

Using Eqs. (6)–(8), a blended HLI is calculated as

\[
HLI = BGT_{bl} \times HLI_{HI} + (1 - BGT_{bl}) \times HLI_{LO}.
\]  

(9)

Based on Eqs. (6) and (7), any increase in relative humidity or solar radiation increases the HLI. A higher wind speed acts to either decrease the HLI linearly if the BGT < 25°C, or nonlinearly if BGT ≥ 25°C; although for the latter, the HLI loss scales to 0.5 × WS for wind speeds > 5 m s⁻¹. Based on the HLI model, when the HLI < 50, the rate of heat loss in cattle discontinue (McCarthy and Fitzmaurice 2016), and the HLI is set to 50.

While the HLI is an instantaneous, hourly, or daily heat load measure, it does not account for the continuous buildup of heat in cattle; this is called the accumulated heat load unit (AHLU). The AHLU is defined as the amount of heat accumulated in cattle over a 24-h period or longer, recording “...the number of hours that the HLI is above the upper critical threshold limit” (McCarthy and Fitzmaurice 2016). These critical upper limits vary across cattle breeds and have been determined from feedlot cattle respiration rates (Gaughan et al. 2008). Limits depend on multiple factors including cattle breed, coat color, nutrition, access to water, and acclimatization to local conditions (Gaughan et al. 2008). For example, the critical HLI threshold for unshaded Angus steers, which are a temperate breed, is 86 (unitless). If the hourly HLI remains above 86 over the course of a day and/or night, then an animal’s AHLU will increase. The lower threshold, at which an animal will dissipate its heat load, is 77 (Gaughan et al. 2008). If hourly HLI values sit between the low and high thresholds, known as the HLI neutral zone, then an animal’s AHLU will remain constant. For more tropical cattle breeds like Brahman, their upper HLI threshold is 90 or above (Wang et al. 2018). A more complete set of HLI thresholds is described in Gaughan et al. (2008).

The observed AHLU is determined from hourly HLI estimates (derived from BARRA-R) exceeding the aforementioned risk thresholds. There are three main AHLU classifications (Abellán et al. 2019): medium risk (21 units < AHLU < 50 units), high risk (51 units < AHLU < 100 units), and extreme risk (AHLU > 100 units). As each risk category is exceeded, this increases the likelihood of heat-induced stress within an animal, leading to reduced feed intake, hyperthermia (e.g., high core body temperature), and eventual death. For further information regarding the AHLU and its relationship to cattle respiration rates, refer to Gaughan et al. (2019).

2) CATTLE COMFORT INDEX

Introduced in 2010, the CCI (also called the comprehensive climate index) describes adjustments to dry-bulb temperature that give an “apparent temperature” used for monitoring hourly or daily cattle condition during hot and cold weather (Mader et al. 2010). The relative importance of the various CCI components can be assessed for weather events by analyzing daily weather variables. These include surface mean air temperature (T; °C)—taken as the mean of the daily maximum and minimum temperatures—and applying adjustments to T from daily mean relative humidity (RHadj), net surface radiation (RADadj), and daily mean surface wind speed (WSadj), which are conformed to the units of T (°C). Accordingly, the CCI is calculated as

\[
CCI = T + RH_{adj} + RAD_{adj} + WS_{adj},
\]  

(10)

where

\[
RH_{adj} = \left( 0.0182 \times RH + 1.8 \times 10^{-5} \times T \times RH \right) \times (0.000054 \times T^2 + 0.00192 \times T - 0.0246) \times (RH - 30),
\]  

(11)

\[
RAD_{adj} = 0.0076 \times SR - 0.00002 \times SR \times T + 0.00005 \times T^2 \times \sqrt{SR} + 0.1 \times T - 2,
\]  

and

\[
WS_{adj} = \left\{ \frac{1}{\left( 2.26 \times WS + 0.23 \right)^{0.46}} \times \left[ 2.9 + 1.14 \times 10^{-6} \times WS^{2.2} - \log_{10}(2.26 \times WS + 0.33) \right] \right\} - 0.00566 \times WS^2 + 3.33.
\]  

(13)

The units of the variables are as follows: RH (%), SR (W m⁻²), WS (m s⁻¹), and T (°C).

There is a small error in the WSadj equation in the original CCI description paper (Mader et al. 2010), as noted in Wang et al. (2018). For temperatures above 25°C, any increase in the relative humidity increases the CCI, whereas increasing wind speeds act to lower the CCI. However, the wind effect weakens as the relative humidity increases (Wang et al. 2018).

Heat stress level categories have been developed for the CCI by researchers using feedlot cattle data and weather observations from a network of weather stations (Mesonet) across Oklahoma (Richards et al. 2016), based on healthy
animals with a well-developed coat. If the CCI is between 30° and 40°C, the heat stress level is deemed to be in the heat caution category, leading to decreased production. If CCI values > 40°C, conditions are in the highest Heat Danger category (deaths may exceed 5%). Slightly different thresholds are presented in Wang et al. (2018), with extreme danger given when the CCI ≥ 45°C. Currently, daily CCI estimates across Oklahoma are derived from the U.S. National Weather Service forecasts and data from the Oklahoma Mesonet, the latter of which issues heat warnings when potential risks arise.

3) TEMPERATURE HUMIDITY INDEX

The final thermal index examined in this study is the THI, for which there are numerous methods of calculation (Wang et al. 2018). For this study, the THI (unitless) is defined using the daily mean surface air temperature (T, °C) and daily mean dewpoint temperature (Td; °C) as

\[ \text{THI} = T + (0.36 \times Td) + 41.2 \]  

(14)

THI thresholds are dependent on cattle breeds and are often related to reductions in milk yield in dairy cattle (Wang et al. 2018). For the Bureau of Meteorology prototype, their beef heat stress categories for THI range from 72 to 77 (mild for all breeds), 78 to 86 (significant stress for Bos taurus), 87 to 98 (significant stress for all breeds), and up to ≥99 (severe heat stress in all breeds). Stress levels are much lower for dairy cattle with the risk of death increasing when the THI > 77; this is based on cattle in northern/central Italy (Vitali et al. 2009). Heat stress thresholds for the THI are not well documented outside of southern Australia in dairy cattle (Nidumolu et al. 2010).

d. Daily-derived heat stress thresholds

To compare heat stress days across the different regions for the three cattle heat stress indices (excluding AHLU), we compare the daily variability for individual heat events against four classification levels using multiyear daily percentiles. This follows the approach used for the CCI in Cowan et al. (2022), as THI and CCI thresholds are not well defined in northern Australian regions predominantly featuring tropical beef cattle. The percentile levels defined are as follows:

- 80th → “moderate” category, likely some distress.
- 90th → “hot” category, moderate to high distress.
- 95th → “very hot” category, high distress and morbidity.
- 99th → “extreme” category, likely leading to mortality.

In some examples, the 20th, 10th, 5th, and 1st percentiles for the CCI are shown, to assess whether cooler conditions prior to hot days may have been a factor in exacerbating thermal stress in cattle, due to the lack of acclimatization to heat. The daily percentiles are calculated using a 15-day centered sliding window, with the percentile calculation window ramping up for the first and last 15 days of the record, similar to the Bureau’s seasonal prediction postprocessing method (Australian Bureau of Meteorology 2019). For example, the 8 January percentile is derived from all days from 1 to 15 January across 1990–2017, 9 January is derived from 2 to 16 January, and so on. Any residual noise in the percentiles is then smoothed across the same 15-day window using a Savitzky–Golay filter with a third-order polynomial fit.

e. Survey data

Historically, the impact of hot weather on cattle in northern Australia (grazing or feedlot) is not well recorded. For eastern and southeastern Australia, Lees et al. (2019) documented two feedlot cattle heat-mortality events: 1) Texas, Queensland (QLD), where 2680 cattle died in one feedlot in February 1991;7 and 2) Tabbita, New South Wales (NSW), where approximately 1250 cattle died over a 12-h period in one feedlot in February 20008 (see locations in Fig. 1). Information from these events comes from quite detailed QLD and NSW state parliamentary records (see footnotes).

To explore more historic cattle heat stress events, we draw on anonymous survey responses from 76 beef producers across northern Australia, as part of a wider heat load index survey. More information on the survey is presented in the online supplemental material. Among the questions regarding producer location and their role in the beef industry supply chain, recipients were also asked about their experience with heat or chill events that resulted in livestock losses on their property. Producers were also asked to provide further details on when the extreme event occurred (e.g., month and year), the approximate number of animals affected, and how frequently these event types occur. From this survey, five events across QLD, NSW, and northwest Western Australia (regions and town locations shown in Fig. 1) were selected for a comparison of the cattle heat stress indices. The two well-documented feedlot heat events in Texas (QLD) in 1991 and Tabbita (NSW) in 2000 were also examined and are documented in Table 1.

A number of other events were also reported in the survey, mostly in QLD; however, due to the lack of detailed information provided on the event date, they are not used here (see Table 2 in the online supplemental material). For all studied events, we only show historic events using AGCD data; however, the results are quite similar based on SILO (not shown). For the two significant cattle heat stress events and the five survey events, we compare the daily HLI, CCI, and THI and evaluate event severity using the subdaily AHLU. For each event, four different HLI thresholds from which the AHLU is calculated are overlaid; these are AHLU96, AHLU99, AHLU92, and AHLU95, representing HLI thresholds (e.g., HLI = 86, etc.) for four cattle breeds: British Bos taurus (i.e., Angus reference steer), European Bos taurus, 50% Bos indicus, and 100% Bos indicus genotypes (Gaughan et al. 2008). The CCI is also separated into each of its components (e.g., adjustments due to relative humidity, solar radiation, and wind speed) to investigate the weather conditions that contributed to each heat event.

---

3. Results

a. Cattle heat stress climatology, October–March
   northern hot-wet season/southern hot-dry season

We first compare the climatological wet season (October–March) patterns of the three cattle heat stress indices using AGCD (and 2-m transformed winds), seen in Fig. 2. The HLI decreases from the northern wet tropics to the central arid regions, with the peak values exceeding 90 over the Top End from December to March (peaking in February at 93.2) and HLI > 70 covering NSW during December–February (Figs. 2a–f). The CCI peaks over a broader area of northern Australia,

### Table 1. Locations and dates of seven historical cattle heat events taken from a heat load index survey and other records. The two historic cattle heat stress events (affecting >1000 heads) are shown in bold font. Other events from the survey but not investigated as part of this study due to lacking critical information are shown in supplemental Table 2. The town of Fitzroy Crossing represents the location for the West Kimberley Shire event in February 2016, although the cattle deaths listed (from the cattle heat load index survey) are not necessarily from that location. Dashes indicate where information was not supplied.

<table>
<thead>
<tr>
<th>State</th>
<th>Location (latitude, longitude)</th>
<th>Shire/region</th>
<th>Cattle breed</th>
<th>Date or month/year of heat event</th>
<th>No. of cattle deaths reported by producer/media</th>
<th>Frequency of event type</th>
</tr>
</thead>
<tbody>
<tr>
<td>QLD</td>
<td>Emerald (23.57°S, 148.18°E)</td>
<td>Central Highlands</td>
<td>Angus</td>
<td>February 2010</td>
<td>4</td>
<td>2–3 years</td>
</tr>
<tr>
<td></td>
<td>Longreach (23.44°S, 144.25°E)</td>
<td>Longreach</td>
<td>Brahman cross</td>
<td>27 Dec 2013–7 Jan 2014</td>
<td>Caused deaths, but number unknown</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charters Towers (20.08°S, 146.26°E)</td>
<td>Charters Towers</td>
<td>Brahman</td>
<td>16–19 Feb 2016</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NSW</td>
<td>Texas (28.86°S, 151.17°E)</td>
<td>Goondiwindi</td>
<td>Angus and Hereford</td>
<td>9–11 Feb 1991</td>
<td>2680 (4000 cattle across QLD)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carrathool (Riverina)</td>
<td>Carrathool</td>
<td>Angus and Hereford</td>
<td>25–26 Feb 2000</td>
<td>1255</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coonamble (30.95°S, 148.39°E)</td>
<td>Coonamble</td>
<td>Angus</td>
<td>January 2019</td>
<td>16</td>
<td>—</td>
</tr>
<tr>
<td>WA</td>
<td>Fitzroy Crossing (18.18°S, 125.56°E)</td>
<td>West Kimberley</td>
<td>Droughtmaster</td>
<td>February 2016</td>
<td>30</td>
<td>—</td>
</tr>
</tbody>
</table>
including the Top End, Cape York (far northeast), and the Kimberley region (far northwest). The CCI = 35°C level (middle of heat caution range) extends into the Pilbara region of Western Australia in January, while central/western QLD experiences climatological average CCI above 32°C from December to February (Figs. 2g–l). Across the Top End, the CCI peaks in December (36.4°C), 2 months before the HLI. The peak in the THI over the Top End occurs in November (84.9) due to the high surface temperatures close to the Tropic of Capricorn (supplemental Figs. 1a–f). The CCI, and to a lesser extent HLI, more closely follows the location of the apparent temperature peaks in December and January, with the highest temperatures along the far northern coast (supplemental Figs. 1g–l). Apparent temperature, calculated from dry-bulb temperature, relative humidity, and wind speed (excluding net radiation), is an estimate of the feel-like temperature in adults calculated from the Steadman (1994) model.

To assess the robustness of AGCD observations, we calculate the heat indices using SILO data together with the 2-m observational winds (Sharples and Baron-Hay 2023) over the same 1990–2017 climatological period (supplemental Figs. 2). In general, both the HLI and CCI values are higher in SILO than for AGCD across the wet season. Average HLI values over the Top End are 2–3 units higher in SILO than AGCD, and the CCI is 0.2–0.4°C warmer. For example, the HLI threshold of 90, when 25% Bos indicus cattle start accumulating heat (Gaughan et al. 2008), extends further south in SILO than for AGCD.

While the heat stress climatologies in AGCD and SILO are comparable, any differences between AGCD and SILO for the CCI and HLI must stem from the solar radiation and/or relative humidity estimates. To verify this, the 1990–2017 climatological (October–March) solar radiation and relative humidity from AGCD and SILO are compared for the Top End (Fig. 3). It is clear that heat stress differences between AGCD and SILO do not stem from differences between their respective average temperature estimates (Fig. 3a). As solar radiation estimates for SILO are lower than AGCD by between 30 and 50 W m⁻² (Fig. 3c), SILO exhibits both a cooler black globe temperature and solar radiation adjustment factor compared to AGCD (Figs. 3b,e). Yet as the SILO data are consistently more humid than AGCD (Fig. 3e), this produces a greater relative-humidity-based CCI adjustment in SILO of.
between 0.5° and 1°C (Fig. 3e). The solar and relative humidity adjustments to CCI offset each other, meaning averaged over the Top End, there is virtually no discrepancy in CCI between SILO and AGCD.

b. Historical cattle heat events

1) Texas, Goondiwindi Shire, QLD, 9–11 February 1991

As reported in QLD’s state parliament on 19 February 1991 by the Minister for Primary Industries (https://documents.parliament.qld.gov.au/events/han/1991/910219ha.pdf), 2600 cattle, mainly Angus and Hereford breeds, died at a feedlot near Texas during a significant heat stress event. The event began on the afternoon of 9 February and ended when the heat subsided on 11 February. The ministerial statement alluded to a sharp increase in relative humidity from 40% to 80% (6–8 February), with a lack of wind relief and temperatures ranging from 20° to 30°C. The HLI peaked at 95 on 8 February, with the AHLU_{80}, AHLU_{89}, and AHLU_{92} exceeding 51 (high-risk category) 2 days later (Fig. 4a).

An earlier heat event was also observed around 24–25 January, with two AHLU_{90} peaks on 22 and 26 January. Both January and February HLI values exceeded the 99th “extreme” percentile; however, the extent to which the January heat contributed to the deterioration of cattle condition in February is unknown.

The February 1991 event was also captured by CCI and THI, both exceeding their respective 90th and 95th percentiles (Figs. 4b,c). While the daily average temperature of the event does not appear severe (~29°C, ~90th percentile) (Fig. 4d), the HLI and CCI suggest that the event was >90th “moderate” percentile from 8 to 14 February (Figs. 4a,b). It is clear that in the days before the recorded cattle deaths (i.e., 6–8 February), relative humidity was the major contributing factor, adding 4°C warming to the CCI (Fig. 4e). Solar radiation rapidly dropped prior to the event (Fig. 4f), associated with significant rainfall\(^9\); although during the heat event, solar radiation also contributed a

\(^9\) From 7 to 9 February 1991, Texas Post Office (Station 41100) recorded 93.6-mm accumulated rainfall.
4°C warming to the CCI (>90th percentile). The written evidence suggesting a lack of any breeze is also confirmed by the wind speed adjustment of 1°C to the CCI (Fig. 4g). In combination, the CCI adjustments raised the cattle feel-like temperatures to above 36°C, which are harsh conditions for Angus and Hereford breeds. The cattle faced similar conditions during 24–25 January, with a strong contribution from relative humidity and the calm conditions but were not exposed to the compounding effect of high solar exposure in the immediate aftermath (due to rainfall). To summarize the February 1991 Texas event: high relative humidity and low wind speeds before and during the event, and high solar radiation during the event, led to cattle comfort temperatures well above the recorded ~29°C average temperatures. The event was best captured by the HLI, AHLU, and CCI. It is possible that the January heat weakened the cattle prior to February, but this is somewhat speculative.

2) TABBITA, CARRATHOOL SHIRE, NSW, 25–26 FEBRUARY 2000

The Tabbita event in late February 2000 contributed to the deaths of 1250 cattle, over a relatively short time of 12 h, according to a NSW parliamentary statement (https://www.parliament.nsw.gov.au/Hansard/Pages/HansardResult.aspx#docid/HANSARD-1323879322-22611/link/2139). As detailed in that statement, “the deaths were related to extreme heat stress. The environment at the time was of high humidity, high day and night temperatures,
and no wind.” The event is captured by the HLI and CCI but not the THI (Figs. 5a–c, respectively). The HLI exceeded the 95th percentile for 4 days (23–26 February), but the CCI only exceeded the 95th percentile for 2 days (25–26 February), peaking at 35°C (Fig. 5b). The AHLU peaked on 25 February (AHLU = 58), surpassing the 50 units needed for an alert for HLI > 86. The HLI 86 threshold for Angus cattle is close to the 99th percentile for Tabbita, whereas for Texas, QLD (in February), HLI = 86 lies between the 80th and 90th percentiles. The THI reached 81 but barely exceeded the 80th percentile (Fig. 5c), which is surprising given the reports of high humidity and warm temperatures.

Focusing on the weather conditions, the event’s average temperature only marginally exceeded 30°C, making it an 80th percentile event (Fig. 5d). The relative humidity, however, added an extra 2.5–3°C warming (Fig. 5e), confirming the parliamentary report that the humid conditions exacerbated the event’s severity. While not anomalously high, solar radiation still contributed 3°C of warming to the CCI (Fig. 5f) and the low wind speeds adding a further 1–2°C (Fig. 5g). In the weeks leading up to the Tabbita heat event, the CCI and its components fluctuated from cold (<20°C) in late January to warm conditions (>30°C) in early February before returning to relatively cool conditions in late February. Any unacclimatized or malnourished/weaker cattle would have been affected to some degree by these extreme variations. Given the HLI threshold for cattle that have health issues is less than 80, it is perceivable that the cattle were not “previously healthy” as the parliamentary statement suggests.

To summarize the February 2000 Tabbita event: the combination of high relative humidity and low wind speeds resulted in cattle facing feel-like temperatures above 30°C and 1 day of high-risk AHLU conditions (noting that the reference HLI is likely lower than 86 for the Riverina region). As with the Texas QLD event, the THI suggests that this event was only a “moderate” 80th

![Fig. 5. As in Fig. 4, but for a significant cattle heat event in Tabbita during 25–26 Feb 2000.](image-url)
percentile event. We hypothesize that large swings in cattle comfort temperatures preceding the heat stress event contributed to the accumulated cattle fatigue, noting that animals were in unshaded feedlots and unable to escape the heat, making them highly susceptible to sudden temperature spikes. The Tabbita event is evidence that even relatively short episodes can have devastating consequences.

3) COONAMBLE, COONAMBLE SHIRE, NSW, JANUARY 2019

Based on respondents from the heat load index survey, the heat event in Coonamble is perhaps the most significant event. The January 2019 event led to the loss of 16 Angus cattle for the survey respondent, although animal condition prior to the event is unknown, or if the losses were predominantly calves. January 2019 was Australia’s hottest month on record (Bureau of Meteorology 2019), part of what became known as the Angry Summer of 2018/19 due to the continental-wide heat extremes. For example, the town of Bourke, 300 km northwest of Coonamble, experienced 21 days above 40°C (Steffen et al. 2019). For Coonamble, mid-December peaks in all three cattle heat indices (>99th percentile) were followed by close to one month of extreme conditions, as captured by the AHLU, CCI, and THI (Figs. 6b,c). While the HLI suggests that the January conditions were mostly “moderate” (>80th percentile; Fig. 6a), the AHLU remained high and peaked on 27 January for a HLI = 86. For 3 days (15–17 January), a number of NSW locations broke their all-time January maximum temperatures, including Griffith (570 km southeast of Coonamble) reaching 46°C on the 16th (Bureau of Meteorology 2019). The predominant breed of cattle for Coonamble is Angus (Table 1), and the HLI threshold is 86 (base AHLU). The AHLU90 remained near or above 20 for 3 weeks from 9 to 30 January and above 50 from
15 to 30 January (Fig. 6a). This represents a medium risk to cattle health when the AHLU lies between 20 and 50 and a high risk when the AHLU is between 51 and 100 (Abellán et al. 2019).

Aside from 2 days in January 2019, the average temperatures for the month were above the 80th percentile (~30°C). For up to a week at a time, average temperatures exceeded the 95th percentile (~32.5°C; Fig. 6d). The CCI peaked twice at 37.5°C, with a strong heating effect from the solar irradiance, adding 5.2°C to the CCI (Fig. 6f). Both the relative humidity and wind speed adjustments contributed little to this event. By 25 January, the heat had reintensified from the west, reaching inland NSW (Bureau of Meteorology 2019), which closely coincided with the second solar radiation adjustment peak around 26 January. Distinct from the Tabbita and Texas events, the January 2019 period featured protracted heat, enhanced by lengthy clear-sky and sunny periods, leaving any unshaded cattle highly vulnerable. It is unclear as to why the HLI does not capture this extended nature of this event, despite almost reaching the 95th percentile on 25 January, when the AHLU clearly shows heat accumulation in mid-January.

4) OTHER NOTABLE CATTLE HEAT EVENTS FROM THE
HEAT LOAD SURVEY

We briefly detail the remaining four cattle heat stress events from the heat load index survey. The accompanying indices plots are shown in supplemental Figs. 3–6, utilizing AGCD observations, noting that all events are similar in SILO observations (not shown).

• Emerald (QLD), February 2010 (supplemental Fig. 3): For this event, the beef producer lost four Angus cattle, but no information was provided on the loss dates. For this event, the HLI captures two main peaks in mid and late February, briefly exceeding the 99th percentile. Following both peaks, the AHLU86 and AHLU89 enter the high-risk AHLU category (51 < AHLU < 100) for between 3 and 5 days. Despite average temperatures not reaching extreme values, the high relative humidity and lack of wind lifted the CCI to the 90th percentile threshold around 24 February, but notably, the event was not extreme according to the THI (supplemental Fig. 3e). In summary, the minimal cooling effect of the winds and protracted high relative humidity contributed to cattle heat stress; however, it was only deemed to be extreme by the HLI and AHLU.

• Longreach (QLD), 27 December–7 January 2013/14 (supplemental Fig. 4): No cattle loss information was provided, although the grazier noted that heavy rainfall on 9 January caused further cattle losses, implying that the previous 12 hot days also caused cattle deaths. For this event, there are two distinct heat peaks in all three indices on 30 December and 3 January, and, respectively, in the AHLU 1 day later. Both the CCI and THI exceeded their 99th percentile threshold, while AHLU86 to AHLU89 exceeded 51 in late December (AHLU86 and AHLU89 also exceeded 51 in January). For 2 days from 29 December, the AHLU89 exceeded 25. Adding to the extremely high average temperatures above 38°C, the solar radiation increased the CCI by more than 5.5°C. This event was driven by warm dry conditions, which likely weakened cattle prior to the heavy rainfall.

• Charters Towers (QLD), 16–19 February 2016 (supplemental Fig. 5): As with Longreach, no additional event information was recorded about cattle losses for Charters Towers. Intriguingly, the dates listed (16–19 February) do not correspond with extreme HLI peak, only for THI and CCI. Instead, the HLI and AHLU show deteriorating conditions from late January to early February. For the second peak (16–19 February), solar radiation is the main contributing factor to the CCI, adding 4.5°C of warming. The early February heat event saw humid conditions and weak winds pushing the CCI above 36°C. For the second February event, hot, sunny, and dry conditions resulted in the CCI reaching 37.5°C. This was a prime example of two cattle heat stress events within a 4-week period that reached similar thresholds but were enhanced by different factors.

• Fitzroy Crossing (WA), February 2016 (supplemental Fig. 6): The survey information provided does not provide the grazer’s location, other than being based in Kimberley and losing 30 Droughtmaster cattle in February 2016. As such, we focus on the town of Fitzroy Crossing, to represent the Kimberley region (Fig. 7). We show an average over the entire West Kimberley Shire. A distinctive feature of this event is the extended period of extreme temperatures and high THI. We do not display the AHLU because the HLI thresholds here are too low for tropical cattle breeds and AHLU values exceed 1000 (i.e., reaching saturation because the HLI rarely goes below 77 in the wet season). The THI exceeds its 90th percentile threshold on four separate occasions in February, whereas the CCI predominantly exceeds its 80th percentile. On each of the four occasions, the average temperature exceeds the 95th percentile, with solar irradiance the main contributing factor to the CCI. This event is a prime example of where anecdotal or on-ground evidence does not necessarily match with the HLI; however, this is a region with sparse observations, and the event may have been quite localized.

We next compare the AHLU evolution of the six inland east coast events listed above: Texas, Tabbita, Coomamble, Emerald, Longreach, and Charters Towers. Figure 7 shows time–latitude plots of the summer AHLU, averaged over eastern Australia (140°–152°E; see Fig. 1), with respect to the HLI threshold that best matches the breed of cattle likely found at each location. For the NSW locations and Texas and Emerald (QLD), which are mainly Bos taurus regions, AHLU86 is shown. Breeds in Longreach are likely to be part Bos indicus and tolerate higher HLI thresholds; hence, AHLU89 is shown. For Charters Towers, AHLU86 is shown, accounting for the Brahman breeds that tolerate the highest HLI thresholds. For each panel in Fig. 7, the approximate town location is denoted as a horizontal gray line.

For the Texas event in February 1991, there are 4–5 pulses of tropical heat with a gradual increase throughout the summer (Fig. 7a), which accounts for the high contribution from relative humidity (see Fig. 4e). The pulses in early 1991 are in the
extreme risk AHLU category for *Bos taurus* breeds. Likewise, the late February 2000 Tabbita event appears to have originated from the tropics, yet it was shorter and more rapid than for Texas (Fig. 7b). The Tabbita event that caused 1255 cattle deaths was in the medium risk category (21 < AHLU < 50). The January 2019 Coonamble event was not directly connected to the northern tropics but associated with a heatwave over Australia’s arid center (see Fig. 4 in Bureau of Meteorology 2019). The heat penetrated as far south as the state of Victoria (Fig. 7c), with the AHLU86 reaching the extreme risk category twice, in mid and late January 2019. The three central QLD events are each associated with an excursion of tropical heat (Figs. 7d–f), linked with extreme conditions across the far northern tropics (north of 18°S). For Emerald and Charters Towers, the February events were preceded by heat pulses in January, as seen in the AHLU, although the Charters Towers event in February 2016 barely reaches the low-risk category. The Charters Towers event was, however, preceded by several days in the extreme risk category relative to HLI50 threshold, which likely weakened cattle. Therefore, it is possible that the grazer in question may be recalling the earlier heat event in the month. This analysis shows that, during the heat stress events, or at least in their lead-in, the AHLU category reached the high or extreme risk categories. Furthermore, for the Texas and NSW heat events, there were multiple heatwaves throughout the summer, and as four of these six heat events occurred in February, we suggest that accumulated heat fatigue across the summer likely exacerbated stock losses. In the next section, we investigate the historical frequency of cattle heat stress events for four regional shires to provide a historical comparison across the 1990–2017 period.

**c. Historical frequency of cattle heat events**

We compare four of the seven historical events in the context of every summer season across the 1990/91–2016/17 period, to assess how unusual or extreme the historical heat events were in the context of the 27-yr record. We focus on two metrics: 1) Heat frequency: the percentage of days above the multiyear daily 95th and 99th percentiles for the summer (DJF); and 2) heat duration: the longest run of consecutive days above the 95th and 99th percentile for the summer. The metrics are the three cattle heat indices derived from AGCD, and AHLU derived from BARRA-R, averaged over four of the regional Shires outlined in Fig. 1. We focus only on the 95th and 99th percentiles because we want to examine the most extreme conditions. Coonamble, Longreach, and Central Highlands Shires are excluded from the analysis because the objective is to highlight the variability in the heat stress indices across different climatic regions.

For the Carrathool Shire in NSW (encompassing Tabbita), the summer of 1999/2000 was comparatively mild, with only 2%–6% (0%–1%) of days above the 95th (99th) percentile, during which the AHLU86 was in the high-risk category 12% of the time (highest across the historical record). Although substantial covariations exist between the three AGCD-derived heat indices, some exceptions occur. For example, in 2010/11, the HLI was above the 95th percentile for

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**Fig. 7.** Hovmöller diagram of AHLU from BARRA-R hourly observations over December–February for six cattle heat stress events in eastern Australia, averaged over 140°–152°E. Shown are (a) AHLU86 at Texas in 1990/91, (b) AHLU86 at Tabbita in 1999/2000, (c) AHLU86 at Coonamble in 2018/19, (d) AHLU86 at Emerald in 2009/10, (e) AHLU86 at Longreach in 2013/14, and (f) AHLU86 at Charters Towers in 2015/16. The horizontal dashed line marks the latitude of each location, and the vertical dotted lines show approximately when the heat stress event occurred. The BARRA-R 10-m wind speeds have been transformed to 2 m by a conversion ratio of 0.5.
17% of the season, compared to <6% for the THI and CCI, and the main contributor was a run of 4 days above the 95th percentile and almost 4 days of the AHLU$_{95}$ > 50 (supplemental Fig. 7a). Interestingly, from 1990/91 to 1999/2000, the AHLU$_{95}$ never spent more than 12 h in the high-risk category; since 2000/01, the AHLU$_{95}$ has been deemed high risk for more than two consecutive days in six separate summers.

In the Goondiwindi Shire, in terms of frequency of days above the daily 95th percentile, the summer of 1990/91 was a third ranked event according to the AGCD-derived HLI (dashed vertical line, Figs. 8b,d,f). Using the 99th percentile, 1990/91 was the most extreme summer, with more than 4% of days above the threshold. Similarly, the 1990/91 AHLU$_{95}$ was the second highest ranked in terms of frequency (22% of summer hours in high risk). While 1990/91 ranks further down for the THI and CCI, 3%–4% of summer days were above the 99th percentile. The 2016/17 summer features the highest frequency of extreme days for CCI and THI, with between 19% and 22% (6%–8%) of days above the daily 95th (99th) percentile. Other notable summers with a high percentage of extreme heat days include 1997/98 and 2003/04, the latter summer experiencing a run 4–5 days of conditions above the 95th percentile for all AGCD-derived indices and almost 2 weeks of AHLU$_{95}$ > 50 (supplemental Figs. 7b,d,f).

February 2016 was an extreme month in northern Australia, with impacts observed from the Charters Towers (east coast) to the West Kimberley (west coast). For the Charters Towers Shire, the summer of 2015/16 was not overly extreme in the context of other summers for all three AGCD-derived indices (Figs. 9a,c,e). Yet, based on the AHLU$_{92}$ (a risk category for tropical cattle breeds), more than 30% of the summer was in the extreme risk category (Fig. 9a), as a result of all of February 2016 featuring an AHLU$_{92}$ > 100 (supplemental Fig. 8a). Interestingly, Charters Towers experienced more extreme conditions, including higher frequency and longer duration, in the 1990s than other decades for HLI, CCI, and THI. This might indicate a strong driver like the interdecadal Pacific oscillation (Heidemann et al. 2022) in modifying the teleconnection of El Niño–Southern Oscillation on heat extremes.

In the far northwest of Australia (West Kimberley Shire), there was more frequent heat stress activity in the 2000s, compared to the 1990s (Figs. 9b,d,f). Like Charters Towers, 2015/16 does not appear to be an anomalous summer; however, the AHLU$_{95}$ nearly always sits in the extreme risk category in the majority of summers (Fig. 9b). This suggests that either an HLI = 95 threshold is inappropriate for this region, or AHLU > 100 should not be considered extreme risk. In other regions, such consistently high AHLU values would cause widespread cattle losses. For the West Kimberley, the summers of 2005/06 and 2012/13 are the most extreme seasons of the record based on the HLI and CCI, in terms of frequency and duration of heat above the 99th percentile (supplemental Fig. 8b). Since 1990, there is a clear tendency toward an increase in the frequency and duration of the HLI and CCI being above the 95th percentile, whereas this trend is not observed in THI (Fig. 9f, supplemental Fig. 8d). This analysis has shown that some historical cattle heat stress events do not appear as anomalous or outstanding events when performing a broader temporal and spatial assessment. Clearly, cattle heat stress events are examples of compound extremes, whereby anomalous heat might only last a
few days but if occurring in the midst of relatively mild or cool conditions, then the impacts can be profound (e.g., Tabbita event in February 2000, Fig. 5).

4. Discussion

This study has interrogated gridded observational and surface weather reanalysis data from 1990 to 2017 to derive and assess cattle heat stress indices in Australia. We first quantified the monthly climatology of our three daily-derived indices, HLI, CCI, and THI, across the warm austral months of October to March, and found that the peak heat in the far tropical north for each heat index occurs in different months. For example, averaged over the Northern Territory’s Top End, the HLI peaks in February, the CCI in December, and the THI in November. This reflects the competing effects of solar irradiance (peaking before November), relative humidity (February peak), and surface temperatures (November peak).

We then explored seven historical cattle heat stress events between 1990 and 2019 across northern and eastern Australia and identified the important weather factors that exacerbate cattle heat stress, namely, high relative humidity, high solar irradiance, and calm (i.e., low or no wind) conditions. The factors that contributed to each event are presented in Table 2, including if rain

<table>
<thead>
<tr>
<th>Location and event</th>
<th>High surface temperature</th>
<th>High RH</th>
<th>High SE</th>
<th>Lack of wind</th>
<th>Rain during/prior to event</th>
<th>Daily heat index order of severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas, February 1991</td>
<td>&gt;80</td>
<td>&gt;95</td>
<td>&gt;90</td>
<td>&gt;95</td>
<td>Y</td>
<td>HLI &gt; CCI &gt; THI</td>
</tr>
<tr>
<td>Tabbita, February 2000</td>
<td>&gt;80</td>
<td>&gt;95</td>
<td>—</td>
<td>&gt;99</td>
<td>Y</td>
<td>HLI &gt; CCI &gt; THI</td>
</tr>
<tr>
<td>Coonamble, January 2019</td>
<td>&gt;99</td>
<td>—</td>
<td>&gt;99</td>
<td>—</td>
<td>—</td>
<td>CCI &gt; THI &gt; HLI</td>
</tr>
<tr>
<td>Emerald, February 2010</td>
<td>—</td>
<td>&gt;99</td>
<td>—</td>
<td>&gt;90</td>
<td>Y (16–19 Feb during event)</td>
<td>HLI &gt; CCI &gt; THI</td>
</tr>
<tr>
<td>Longreach, December–January 2013/14</td>
<td>&gt;99</td>
<td>—</td>
<td>&gt;99</td>
<td>—</td>
<td>—</td>
<td>CCI &gt; THI &gt; HLI</td>
</tr>
<tr>
<td>Charters Towers, February 2016</td>
<td>&gt;99</td>
<td>—</td>
<td>&gt;99</td>
<td>&gt;90</td>
<td>—</td>
<td>THI &gt; CCI &gt; HLI</td>
</tr>
<tr>
<td>Fitzroy Crossing (West Kimberley), February 2016</td>
<td>&gt;95</td>
<td>—</td>
<td>&gt;95</td>
<td>—</td>
<td>—</td>
<td>THI &gt; CCI &gt; HLI</td>
</tr>
</tbody>
</table>
occurred in the five days preceding the events or during the event.

Four of these events were classified as extreme (above the 99th percentile) in terms of their average daily surface temperature. Yet only one event, Texas in February 1991, featured all three factors (i.e., humid, calm, and sunny) and high temperatures, as well as precipitation prior to the event. The remaining six events can be separated into two groups based on the thermal stress factors: 1) events that featured high surface temperatures and high solar exposure (Coonamble, Longreach, Charters Towers, and Fitzroy Crossing) and 2) events with not overly high surface temperatures but high relative humidity and lack of winds (Tabbita and Emerald). In group 2, these events also experienced rainfall during or just prior to the heat event, which aligns with high relative humidity. The Texas event lies in the juncture of both groups, as the conditions transitioned rapidly over 1–2 days from wet and humid to hot, cloudless, and calm conditions. Similar conditions also prevailed in Tabbita, although the thermal effects of solar radiation on CCI were not above the 80th percentile. The relatively cool conditions in the lead-in to the heat stress event likely exacerbated the heat-related impacts, due to the inability for livestock to acclimatize quickly.

In the context of summer events over 1990–2017, nearly all the case study heat events were not record-breaking in terms of the frequency and duration of hot days, despite the confirmed loss of livestock. In fact, the only record-breaking event was in Goondiwindi Shire (Texas) in 1990/91, based on the frequency of days that the HLI was above the 99th percentile. The 1990/91 summer also featured the longest duration of days that the HLI, CCI, and THI were all above their respective 99th percentiles. Other events, like Tabbita in February 2000, were locally extreme but fairly rapid in their timing and occurred during relatively mild summers, as opposed to 2018/19 for Coonamble (Fig. 7c). Future work will explore the drivers of the extreme heat conditions during the worst summers (e.g., El Niño–Southern Oscillation). Research has shown that La Niña events bring more wet and humid conditions over eastern Australia, particularly during decadal periods when the tropical Pacific is anomalously cool (Heidemann et al. 2022) but also a greater heatwave risk in southeast Australia (Parker et al. 2014). The opposite is true for El Niño, which is associated with clear skies, increased solar radiation and lower winds over eastern Australia, and an increased likelihood of heatwaves over the northeast (Perkins et al. 2015).

For graziers and feedlot managers over Australia, the question of which cattle heat stress index to use is open to discussion. Of the three heat stress indices, the CCI is the easiest to interpret as its units are the same as the temperature and its heat thresholds are relevant to northern Australia. Additionally, each of the weather factors that exacerbate a heat event, like solar irradiance, wind, and relative humidity, can be separated and quantified. The CCI can be used to assess the potential risk of heat stress to a herd, particularly for cattle regularly exposed to high solar irradiance and where natural shade is unavailable (e.g., at a water point). The one caveat for the CCI was that it was developed and validated for feedlot cattle and based on limited heat stress event data from the United States (Mader et al. 2010). Hence, more research is required for understanding thresholds in grazing cattle in Australian conditions (e.g., hot and humid wet seasons and warm dry seasons). For feedlots, the HLI and AHLU are perhaps more suitable for subdaily monitoring, with a range of thresholds based on cattle breed and condition. These range from values of 80 for Bos taurus breeds in warmer conditions or cattle with underlying health issues to values above 96 for healthy, acclimatized Bos indicus cattle in harsher tropical climates (Gaughan et al. 2008). One limitation of the HLI is that the producer or farmer needs to know their threshold to interpret an event’s severity. Breed-specific thresholds are easy to find (e.g., 86 for Angus and 96 for Brahman); however, gauging the health status of cattle based on feed and manure management or warmer drinking water, all that effectively lower the HLI threshold, is more challenging. Issues related to saturation of the AHLU values beyond 1000 in the far northern tropics (as seen in the Kimberley) also need to be addressed.

Given its ease of use, the THI is appropriate for graziers in humid/wet tropics or with cattle in shaded walled feedlots (Wang et al. 2018). The benefit of the THI over the HLI and CCI is its simplicity, and, as shown in this study, it displays similar variability to the CCI, which is more complex to calculate. The one drawback of the THI is the numerous ways of calculating the index [see index definitions in Wang et al. (2018)]. This also means that the absolute thresholds for THI are likely dependent on which formula is used for the calculation. The advantage of referencing THI peaks against percentile-based thresholds (to elucidate days of extreme conditions as demonstrated in this study) is that it removes the need to match absolute thresholds, derived for southern dairy cattle, to northern beef cattle.

5. Conclusions

In this research, we have demonstrated the complexity, assumptions, and overall performance of three cattle heat stress indices that are applicable to beef cattle. Our findings show the importance of utilizing multiple cattle heat stress indices, including those that encompass the effects of wind speed and solar irradiance, to identify high-risk cattle heat-mortality events. We evaluated seven historical cattle heat events, mostly across eastern Australia, and showed that either the combination of high relative humidity and a lack of winds, or high solar irradiance with high surface temperatures, compounded the cattle heat stress conditions. In the two historic events where rainy conditions were followed by a rapid warming, cattle mortality was significantly high. Although the focus of this study was on the impact of heat stress on beef cattle, the broader implications of the findings can be applied to other livestock (e.g., dairy cattle, sheep, goats, pigs, and horses) that are affected by the combination of heat and humidity (Kang et al. 2023). Yet, as noted by the HSRA Technical Reference Panel (2019), the THI and AHLU thresholds have not been applied to other livestock industries such as sheep. Furthermore, there is limited quantitative or qualitative evidence of the use of the CCI or HLI in cattle grazing regions in Europe, South America, and Asia, meaning further field work and validation against observations is required, similar to feedlot trials in the Midwest United States (Arias and Mader 2023).

For Australia, there is a need to develop a cattle heat stress gridded forecast, given the strong community support in the
Anthropogenic climate change has increased temperature extremes including across Australia and will continue to do so this century (Perkins-Kirkpatrick and Gibson 2017). This will expose human populations to a greater health risk (Nishant et al. 2022). The heat risk also extends to livestock, including cattle, with regions like Kimberley, the Top End, and the Gulf of Carpentaria likely to experience more days above what are considered current extreme THI thresholds by the 2090s (Thornton et al. 2021). Warmer temperatures in the north will likely reduce the livestock-carrying capacity and reduce the amount of grazing time in the solar exposed regions (McKeon et al. 2009; Cobon et al. 2020). Increases in cattle heat stress in the future will undoubtedly impact Australia’s dairy and beef industry, hence the growing need for information such as forecasts to help with managing heat impacts on cattle.

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**Data availability statement.** Daily AGCD temperature and vapor pressure data are available from https://dapds00.nci.org.au/thredds/catalog/zv2/agcd/v1/catalog.html, while solar irradiance, humidity, and temperature data from SILO are available from the LongPaddock website: https://www.longpaddock.qld.gov.au/silo/. BARRA-R data are available from https://dapds00.nci.org.au/thredds/catalogs/cj37/BARRA/BARRA_R/v1/v1.html. The 2-m wind and solar irradiance observations, as well as the survey results, are available on request. All codes to calculate the heat stress indices and figures are available from https://github.com/tcowan80/Code-for-cattle-heat-load-study-in-JAMC. The data in this study were analyzed and plotted using Python3 and Xarray.

**APPENDIX**

**Variables and Datasets in this Study**

Table A1 shows the height, spatial resolution, and temporal resolution of the variables used in this study. The gridded datasets include the Australian Gridded Climate Data (AGCD), the Scientific Information for Land Owners (SILO), and the Bureau’s Atmospheric High-Resolution Regional Reanalysis for Australia, version 1 (BARRA).

**TABLE A1. Summary table of the variables and datasets used in this study.**

<table>
<thead>
<tr>
<th>Variables</th>
<th>AGCD and SILO</th>
<th>AGCD and BARRA</th>
<th>Temporal resolution (dy = daily, hr = hourly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>1.2</td>
<td>1.5</td>
<td>dy</td>
</tr>
<tr>
<td>Spatial resolution (km)</td>
<td>5</td>
<td>12</td>
<td>dy</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>1.5</td>
<td>dy</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>1.5</td>
<td>dy</td>
</tr>
<tr>
<td></td>
<td>Surface</td>
<td>Surface</td>
<td>dy</td>
</tr>
<tr>
<td>Wind speed</td>
<td>2</td>
<td>10</td>
<td>dy</td>
</tr>
</tbody>
</table>

* Solar irradiance in SILO is derived from cloud oktas and sunshine hours, while the AGCD gridded product is from satellites and the Bureau’s radiation model.


