Suitable indicator of heat stress for genetic evaluation of heat tolerance in Holstein cows in Japan

Research Article

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Running head: Heat-tolerance evaluation in dairy cows

ABSTRACT

Only a few, principal, weather stations in Japanese prefectures have the daily humidity records required to calculate the temperature–humidity index (THI) as a dairy cow heat-stress indicator. We compared three heat-stress indices: 1) THI calculated from daily average temperature and daily relative humidity at a principal weather station (PTHI); 2) daily average temperature at each herd’s closest local weather station (TEMP); and 3) THI calculated from daily average temperature at each herd’s closest local weather station and daily relative humidity at the principal weather station (HTHI). We used daily records from 532 provincial weather stations and test-day records of milk production from days 6 to 305 post-first-calving in Holsteins to compare the indices as indicators of heat-stress effects on milk yield and somatic cell score (SCS). The models used the BLUPF90 package to analyze the effects of herd–year, calving age, days in milk, and PTHI, TEMP, or HTHI. We estimated each model’s mean square error (MSE) and compared suitabilities among indices for each trait. TEMP heat-stress thresholds were ~18 °C (milk yield) and 15–20 °C (SCS). The MSE of the HTHI model was the smallest, but no significant differences were found among the indices for milk yield.

Keywords: dairy cow, heat stress, heat tolerance, Holstein, temperature–humidity index

1 INTRODUCTION

The Holstein—Japan's main dairy cow—excels as a dairy breed, producing 8 016 to 9 531 kg of average milk yield over 305 days during the first to third lactation periods (Yamazaki et al., 2016). However, many studies have shown that Holstein cows are very sensitive to heat stress and suffer negative effects of heat stress on their milk yield and reproduction (e.g., Fuquay, 1981; Ravagnolo et al., 2000; Boonkum et al., 2011; Bernabucci et al., 2014; Atagi et al., 2019; Hagiya et al., 2020; Negri et al., 2021). The temperature–humidity index (THI) is generally used to indicate heat stress in dairy cows. Heat stress in Holstein cows occurs when the THI is 68 or higher (West, 2003), and daily milk yield decreases by 0.72 kg for each unit of increase in the THI value (Bernabucci et al., 2010). Also, an increased THI is associated with an increased somatic cell score (SCS) (Lambertz et al., 2014), because heat stress can promote mammogenic udder infection (Giesecke 1985; Pragna et al., 2017). Hagiya et al. (2017) reported that heat stress affects milk yield, SCS, and fertility in Holstein cows in Japan. The economic losses incurred by dairy farmers in the United States as a result of heat stress amount to $1.5 billion annually without heat protection and $900 million annually with heat protection (St-Pierre et al., 2003). Therefore, to minimize the economic losses of dairy farmers, especially in the light of today’s climate warming scenarios, it is important to investigate the effects of heat stress on dairy cows (Negri et al., 2020).

In recent years, average temperatures in Japan have been rising because of global warming. Barn facilities such as sprinklers and fans can reduce the effects of heat stress (Armstrong, 1994), but installing these facilities is expensive. We therefore need to increase heat tolerance by genetically improving dairy cows.

Ravagnolo and Misztal (2010) reported that it is possible to evaluate the genetic ability of dairy cows to tolerate heat stress by using a random regression model. In Australia, HTABVg (the Australian breeding value for heat tolerance) has been proposed as a new genetic measure of heat tolerance in dairy cows (Nguyen et al., 2017); genetic improvement of heat tolerance is one of the important concerns. Hagiya et al. (2020) reported a suitable random regression model for genetic evaluation of heat tolerance in Japan. To evaluate genetic heat tolerance capacity, we need to identify traits that accurately reflect the effects of heat stress and to clarify the threshold value at which the effects of heat stress begin to be observed. Hagiya et al. (2019) reported that the threshold values for heat stress on dairy cows in Japan ranged from THI 60 to THI 63 for both milk yield and SCS, and the THI that they used was estimated from temperature and humidity data recorded at principal meteorological stations. In Japan, each prefecture has many meteorological stations and most of these record daily temperatures, but only one or two principal meteorological stations in each prefecture keep humidity records. Therefore, we sometimes have to assign THI values by using a meteorological station as far as 100 km away from a farm, instead of those from the nearest meteorological station.

Nagamine and Sasaki (2008) reported that temperature had a greater negative effect than humidity on conception rate in Holstein cows in Japan. Therefore, here, to investigate suitable indicators of heat stress in Holstein cows under Japanese weather conditions, we compared the applicability of three mathematical models by using the following three heat stress indices: 1) THI calculated from the daily average temperature and daily relative humidity at one of the principal weather stations in each prefecture (PTHI); 2) the average daily temperature at the local weather station closest to each herd (TEMP); and 3) THI calculated from the daily average temperature at the local weather station closest to each herd and the relative humidity at the principal weather station (hybrid THI, HTHI).

2 MATERIALS AND METHODS

2.1 Data

Data on test-day milk yield and somatic cell count (SCC) collected by the National Livestock Breeding Center for domestic genetic evaluation purposes were used. The data consisted of monthly test-day records from days 6 to 305 after first calving of Holsteins in Japan between 2011 and 2015. When meteorological data were missing, production records for the corresponding dates were excluded. The number of test-day records was 4 112 791. SCCs were log-transformed into SCSs closer to a normal distribution. The following formula was used for logarithmic conversion (Ali & Shook, 1980):

$$SCS = \log_2(SCC/100\,000) + 3.$$

For the meteorological data, we used daily average temperature and relative humidity records obtained from 60 principal and 432 local meteorological stations in each prefecture from 2011 to 2015 and published by the Japan Meteorological Agency (Japan Meteorological Agency, 2020). Japan is situated from latitude 20°N to 46°N, and average monthly temperatures range from –8.9 °C in the north to 29.5 °C in the south (Table1). For PTHI, test-day records were assigned only one principal meteorological station in each of 46 prefectures, and 14 in the 47th prefecture, namely Hokkaido (the northern island containing more than half of the herds), according to the method of Hagiya et al. (2019). For HTHI, we used temperature records from the meteorological station closest to each herd and humidity records from the principal meteorological station for each prefecture or the 14 principal stations in the case of Hokkaido. On the basis of the results of our preliminary findings that THI calculated from daily average temperature and average relative humidity is suitable for use as a heat stress index, THI was calculated from these parameters by using the following formula (Thom, 1959):

$$THI = (1.8 \times T + 32) - (0.55 - 0.0055 \times RH) \times (1.8 \times T - 26)$$

where T is the daily average temperature (°C) and RH is the average relative humidity (%). On the basis of the results of reported by Hagiya et al. (2019), we set the duration of the lag in heat response on the test day as 3 days for mild yield and 8 days for SCS.

2.2 Model

The following mathematical model with reference our previous study (Hagiya et al. 2019) was used to analyze the effects of heat stress on milk yield and SCS:

$$Y_{ijklmn} = HY_i + M_j + A_k + DIM_l + T_m + a_n + e_{ijklmn}$$

where Y_{ijklmn} is the test-day milk yield or SCS; HY_i is the fixed effect of herd×year i; M_j is the effect of calendar month at calving, including the effects from calving to test-day (12 subclasses); A_k is the fixed effect of age at calving (18 to 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35 months); DIM_l is the fixed effect of l days in milk; T_m is each heat stress index [56 levels for TEMP (range, –23 to 33 °C), 76 levels for PTHI (range, 9 to 84), 86 levels for HTHI (range, 1 to 86)]; a_n is a random additive genetic effect containing the permanent environmental effect of cow n; and e_{ijklmn} are random residuals. Variance components estimated by Hagiya et al. (2019) were used in our analysis. Mean squared errors (MSEs) were estimated by using BLUPF90 (Misztal et al. 2002) to compare the suitabilities of indices for each trait.

2.3 Preliminary study

In a preliminary study, we investigated the combination of daily temperature and relative humidity records that was most suitable for use in a heat stress index. For this purpose, we compared THI's calculated by using a range of combinations of temperature and humidity records from principal meteorological stations. The various combinations are shown in Table 2. When meteorological data (maximum or minimum temperature, or minimum relative humidity) were missing, production records for the corresponding dates were excluded. The number of test-day records in the preliminary study was 2 466 440.

3 RESULTS

3.1 Preliminary study to select THIs

Table 3 shows the MSEs of mathematical models using each heat stress index [various combinations of temperature records (average, maximum, minimum) and relative humidities (average, minimum) observed at principal meteorological stations] for milk and SCS. For milk yield, there were significant differences between the MSE in the mathematical model without the heat stress index and the MSEs in the mathematical models with heat stress indices, except when we used average temperature data alone as an index. For SCS, there were no significant differences among any of the mathematical models. For milk yield, mathematical models containing THI_{aa} calculated from average temperature and average relative humidity or THI_{ab} calculated from average temperature and minimum relative humidity gave the lowest MSE value. The MSE calculated from THI_{ca} was the highest.

3.2 Changes in annual average temperature

We plotted the transition of the annual average temperature in Japan up to 2020 (Fig. 1) by using temperature data released by the Japan Meteorological Agency (2020). Average temperatures in Japan rose over a range of 13 to 17 °C from 1876 to 2016 because of global warming. We also plotted average temperatures in 2020 by calendar month (Fig. 2); average temperatures in August were about 20 °C higher than those in January. The average monthly temperature in Hokkaido, which contained more than half the herds studied, was about 5 °C lower than that in the other prefectures.

3.3 Summary statistics

Means, standard deviations (SDs), and minimum and maximum values for test-day milk yield and SCS and for the three heat stress indices are given in Table 4. The mean daily milk yield (± SD) was 27.99 ± 6.4 kg, and the mean SCS (± SD) was 2.27 ± 1.69. Figure 3 shows the numbers of TEMP records used. The average daily temperature ranged from –19 to 30 °C, with the greatest number of records at about 20 °C. The shapes of the distributions of THIs (data not shown) used in the analysis were consistent with those of the THI values used in our previous study (Hagiya et al., 2019).

3.4 Threshold values for effects of PTHI, TEMP, and HTHI on milk yield and SCS

We obtained BLUEs (best linear unbiased estimations) of test-day milk yield and SCS against PTHI, HTHI, or TEMP (Fig. 4). The threshold PTHI and HTHI values for an effect on milk yield ranged from 65 to 70; that for TEMP was about 18 °C. The threshold PTHI and HTHI values for an effect on SCS were about 65; that for TEMP ranged from 15 to 20 °C. For milk yield and SCS, the BLUEs were close to constant at PTHI, HTHI, and TEMP values below the thresholds.

3.5 Applicability of indices of heat stress

The MSEs of the mathematical models were calculated for each of the heat stress indices for milk yield and SCS (Table 5). For milk yield, but not SCS, there was a significant difference between the MSEs for no HS index and the mathematical model for each heat stress index. For milk yield, the MSEs estimated from the models increased in the order HTHI < TEMP < PTHI < no HS index. For SCS, the MSEs increased in the order HTHI < TEMP = PTHI < no HS index.

4 DISCUSSION

4.1 Effects of heat stress on milk yield and SCS

Our preliminary analysis revealed that THI_{aa} calculated by using average temperature and average relative humidity and THI_{ab} calculated by using average temperature and minimum relative humidity in Japan’s meteorological environment were useful for both milk yield and SCS. The MSEs from THI_{ca} calculated by using minimum temperature and average relative humidity were large for both milk yield and SCS. In the model considering THI_{ca}, we found extremely slow convergence. Therefore, the BLUEs from the model containing $\mathrm{THI}_{\mathrm{ca}}$ were not suitable in comparison with those from other mathematical models including THI.

Decreased dry matter intake is one cause of heat-associated decreases in milk yield (Schneider et al., 1988). Rhoads et al. (2009) have shown that 35% of all declines in milk production are due to reduced dry matter intake. According to West (2003), the dry matter intake of dairy cows in a hot environment decreases by 0.85 kg/°C. Moreover, changes in metabolism due to heat stress change the homeostasis of dairy cows: for example, heat stress increases plasma insulin levels (Wheelock et al., 2010) and decreases plasma growth hormone levels and milk yield (Igno et al., 1988; McGuire et al., 1991; Rhoads et al., 2009; Wheelock et al., 2010). Here, we found that the threshold values of both PTHI and HTHI for an effect on test-day milk yield ranged from 65 to 70. This was similar to the thresholds for milk production loss (THI about 68 to 74) in a worldwide comprehensive review by Herbut et al. (2018). The wide range of THI thresholds in that review was due to differences among study areas in breeding environment, breed, and type of winter housing. Atagi et al. (2019) reported somewhat different threshold THI values linked to the daily mean temperature and relative humidity for first-lactation Holstein cows in Japan (72 for milk yield and 64 for SCS) because they used segmented-regression analysis (Muggeo, 2008). Our estimated threshold TEMP (i.e., air temperature) value for decreased test-day milk yield was about 18 °C. This value corresponds to a THI of 63, assuming an average relative humidity of 70% (Japan Meteorological Agency 2010). From the monthly average temperatures in Hokkaido and other prefectures in 2020 (see Fig. 2), we inferred that effects of heat stress on milk yield would appear from June to September in Hokkaido and from May to October in other prefectures.

One of the causes of increased SCS is weakened immunity due to heat stress (Roma et al., 2009). An increase in SCS is associated with increased prevalence and development of both latent and clinical mastitis (Dohoo & Meek, 1982). The thresholds of the two THI indicators for increased SCS were about 65. This is consistent with a previous report that used domestic cattle herd data to calculate threshold THI values on the basis of daily mean temperature and relative humidity; the values were 60 to 65 for increased SCS (Hagiya et al., 2019). Our estimated TEMP threshold values (15 to 20 °C) meant that the effect of heat stress on SCS appeared from about May to October in Hokkaido and from about April to November in other prefectures (Fig. 2). Thus our results for milk yield and SCS show that dairy cows in Japan are exposed to heat stress for approximately half a year.

4.2 Weather records suitable as indicators of heat stress

Nagamine and Sasaki (2008) reported that the significant effect of heat stress on conception in Japanese Holstein cows occurs only through the disturbance of body temperature. The effects of heat stress include a decrease in food intake and an increase in production of active enzyme due to an increase in body temperature (Collier et al. 2006). The resulting increased oxidative stress leads to disturbance of homeostasis and consequently a decrease in conception rate. This physiological phenomenon also causes milk loss (Sakatani et al., 2011) and mastitis (Lykkesfeldt & Svendsen, 2007). For milk yield, we found significant decreases in the MSEs of the mathematical models for the three heat stress indices compared with that for no HS index (Table 5). This suggests that three indices are suitable choices of heat stress index for analyzing the effects of heat stress on milk yield.

5 CONCLUSION

Effects of heat stress on milk yield in Holstein cows in Japan appeared when the temperature was 18 °C or higher. For SCS, the threshold TEMP values of heat stress were in the range of 15 to 20 °C. The average temperature in Japan is now about 17 °C, and our findings suggest that dairy cows in Japan are exposed to heat stress for about half a year. To estimate the effects of heat stress in terms of decreasing milk yield, PTHI calculated by using daily mean temperature records and relative humidity records obtained from nearest principal meteorological station, TEMP obtained by using mean temperature records from nearest meteorological station, and HTHI calculated by using daily mean temperature records from the nearest meteorological station and relative humidity records from the nearest principal meteorological station are applicable.

CONFLICTS OF INTEREST

The funding source had no role in the design, practice or analysis of this study.

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Legends

Figure 1 Changes in annual average temperature in Japan, 1876 to 2016

Figure 2 Monthly average temperatures in Hokkaido and other prefectures in 2020

Figure 3 Numbers of daily mean temperature records used in the analyses

Figure 4 Best linear unbiased estimates of test-day milk yield and somatic cell score (SCS) obtained by using the models PTHI, HTHI, and TEMP

Table 1 *The number of records, means, standard deviations (SD), and minimum and maximum values for temperature and humidity[1] in each region[2]*

Region	N	Temperature				Humidity		
		Mean	SD	Min	Max	Mean	SD	Min
Hokkaido	2 773 188	6.6	11.2	-23	29	76.2	12.3	25
Tohoku	252 873	10.5	9.7	-12	31	73.4	11.5	29
Kanto	327 313	15.0	8.7	-10	33	66.0	15.2	22
Chubu	169 695	14.0	9.2	-13	33	68.7	12.6	22
Kinki	73 432	15.3	8.5	-4	31	66.3	11.6	34
Chugoku	132 697	15.0	8.7	-7	32	68.7	11.5	33
Shikoku	40 279	17.9	7.5	-5	32	68.6	12.0	26
Kyusyu	343 341	19.0	7.0	-6	32	71.7	11.9	25

[1] Maximum humidity : 100 in all regions

[2] Tohoku : Aomori, Iwate, Miyagi, Akita, Yamagata, Fukushima
Kanto : Ibaraki, Tochigi, Gunma, Saitama, Chiba, Tokyo, Kanagawa
Chubu : Nigata, Toyama, Ishikawa, Fukui, Yamanashi, Nagano, Gifu, Shizuoka, Aichi, Mie
Kinki : Shiga, Kyoto, Osaka, Hyogo, Nara, Wakayama
Chugoku : Tottori, Shimane, Okayama, Hiroshima, Yamaguchi
Shikoku : Tokushima, Kagawa, Ehime, Kochi
Kyusyu : Fukuoka, Saga, Nagasaki, Kumamoto, Oita, Miyazaki, Kagoshima, Okinawa

Table 2 *Weather data included in the heat stress index calculations in our preliminary study*

Heat stress index	Weather data				
	Temperature			Humidity	
	Mean	Maximum	Minimum	Mean	Minimum
No heat stress index	–	–	–	–	–
TEMP_a	○	–	–	–	–
TEMP_b	–	○	–	–	–
TEMP_c	–	–	○	–	–
THI_{aa}	○	–	–	○	–
THI_{ab}	○	–	–	–	○
THI_{ba}	–	○	–	○	–
THI_{bb}	–	○	–	–	○
THI_{ca}	–	–	○	○	–
THI_{cb}	–	–	○	–	○

Weather data are from principal weather stations.

Table 3 *MSEs[1] of mathematical models using each heat stress index[2] for milk and SCS[3] in our preliminary study*

Heat stress index	Trait	
	Milk	SCS
No heat stress index	9.8722^{b}	1.1355
$\mathrm{TEMP}_{\mathrm{a}}$	9.8433^{ab}	1.1350
$\mathrm{TEMP}_{\mathrm{b}}$	9.8522^{a}	1.1351
$\mathrm{TEMP}_{\mathrm{c}}$	9.8406^{a}	1.1350
$\mathrm{THI}_{\mathrm{aa}}$	9.8392^{a}	1.1350
$\mathrm{THI}_{\mathrm{ab}}$	9.8392^{a}	1.1350
$\mathrm{THI}_{\mathrm{ba}}$	9.8482^{a}	1.1350
$\mathrm{THI}_{\mathrm{bb}}$	9.8446^{a}	1.1350
$\mathrm{THI}_{\mathrm{ca}}$	9.9389^{c}	1.1373
$\mathrm{THI}_{\mathrm{cb}}$	9.8425^{a}	1.1350

Different superscript letters indicate significant differences between values ($P < 0.05$).

[1] Mean squared errors

[2] See Table 2

[3] Somatic cell score

Table 4 *Means, standard deviations (SD), and minimum and maximum values for test-day milk yield, SCS[1], PTHI[2], HTHI[3], and TEMP[4] (N = 4 112 818)*

Trait or heat stress index	Mean	SD	Min	Max
Milk (kg)	27.8	6.5	0.2	88.3
SCS	2.2	1.7	–3.6	12.5
PTHI	50.3	18.5	0.0	84.0
HTHI	50.6	17.0	1.0	86.0
TEMP	9.4	11.3	-23.0	33.0

[1] Somatic cell score

[2] Temperature–humidity index (THI) calculated from the daily average temperature and daily relative humidity at one of the principal weather stations in each prefecture

[3] THI calculated from the daily average temperature at the local weather station closest to each herd and the relative humidity at the principal weather station

[4] The average daily temperature at the local weather station closest to each herd

Table 5 *MSEs[1] of mathematical models obtained by using each heat stress index for milk and SCS[2]*

Heat stress index	Trait	
	Milk	SCS
No heat stress index	9.9124^{a}	1.1291
PTHI[3]	9.8899^{b}	1.1287
TEMP[4]	9.8859^{b}	1.1287
HTHI[5]	9.8848^{b}	1.1286

Different superscript letters indicate significant differences between values ($P < 0.05$).

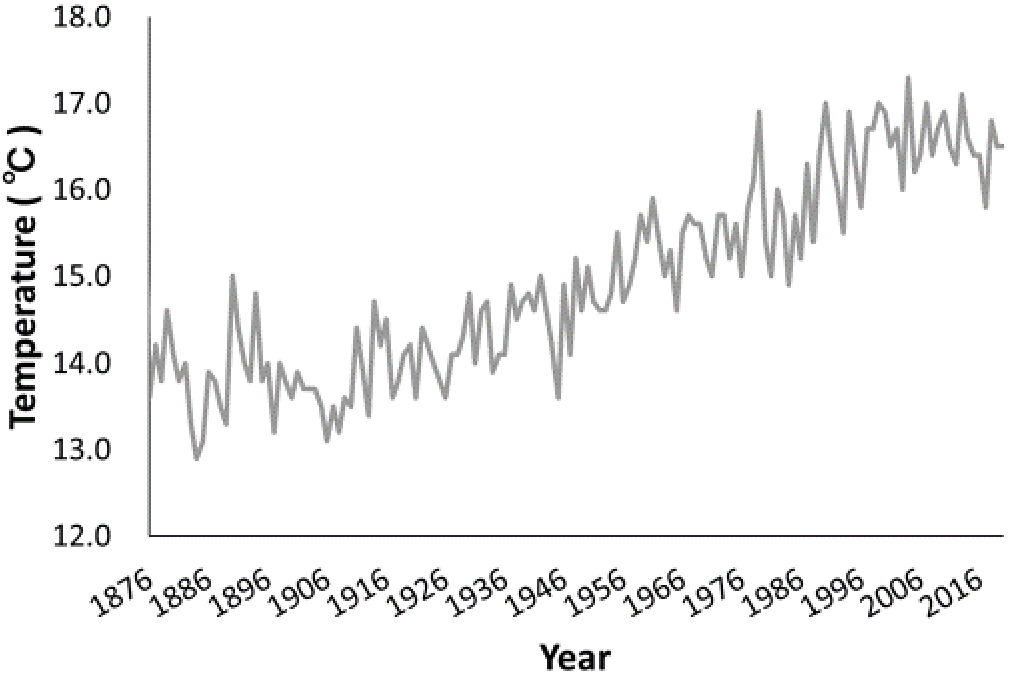
[1] Mean squared errors

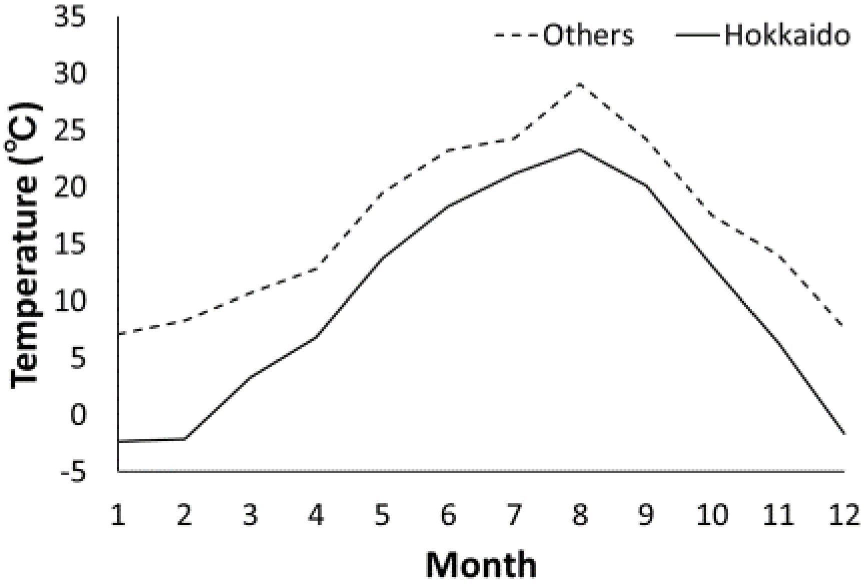
[2] Somatic cell score

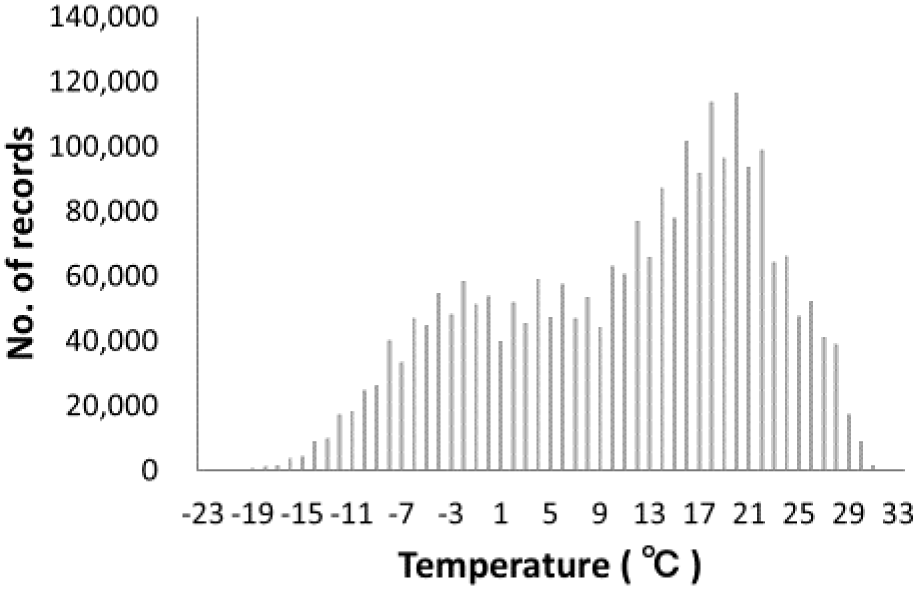
[3] Temperature–humidity index (THI) calculated from the daily average temperature and daily relative humidity at one of the principal weather stations in each prefecture

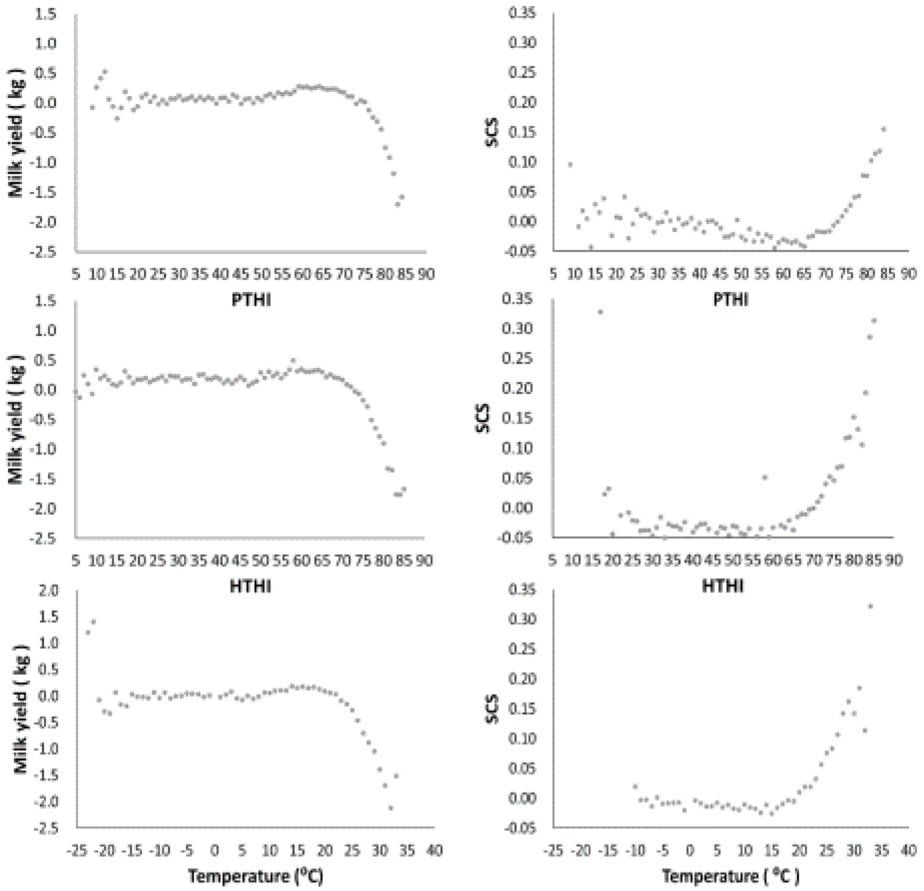
[4] The average daily temperature at the local weather station closest to each herd

[5] THI calculated from the daily average temperature at the local weather station closest to each herd and the relative humidity at the principal weather station


18.0
17.0
16.0
15.0
14.0
13.0
12.0
Temperature (°C)
1876
1886
1896
1906
1916
1926
1936
1946
1956
1966
1976
1986
1996
2006
2016
Year


Others
Hokkaido
Temperature (°C)
35
30
25
20
15
10
5
0
-5
1
2
3
4
5
6
7
8
9
10
11
12
Month


140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
No. of records
-23
-19
-15
-11
-7
-3
1
5
9
13
17
21
25
29
33
Temperature (℃)


Milk yield (kg)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
SCS
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
PTHI
PTHI
Milk yield (kg)
SCS
HTHI
HTHI
Milk yield (kg)
2.0
SCS
-25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40
Temperature (⁰C)
Temperature (⁰C)