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Spatiotemporal Characterization and Regional Forecasting of The Temperature and Humidity Index: An Exploratory Case Study on Dairy Production In Villa Clara, Cuba

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Abstract

Heat stress limits the productivity, health, and well-being of dairy cattle in tropical environments. This study characterized the spatial and seasonal variability of the Temperature-Humidity Index (THI) in Cuba and compared the forecasting performance of an STL decomposition model with exponential smoothing (STL+ETS) against automatic ARIMA models for three geographical regions of the country. Quality control was performed on daily meteorological observations from 23 stations of the Cuban Institute of Meteorology (INSMET) covering the 1993–2013 period; these were grouped into three regions: Eastern (Group 1), Central (Group 2), and Western (Group 3), following the spatial coverage historically used in Cuba's livestock agrometeorological services. The THI was evaluated against the thermal classification established by Kulicov and Rudnev (1987). A total of 206,877 daily THI values were analyzed (Group 1: n = 189 392; Group 2: n = 90 398; Group 3: n = 98 087; mean = 74.63; range = 47–85). The THI exhibited a distinct annual cycle, peaking around week 31 (late July and early August) and reaching its lowest values between December and March. Additionally, a spatial gradient of decreasing thermal comfort was observed from west to east, with the most favorable conditions recorded at mountain stations located above 400 meters above sea level. At weekly and monthly scales, the STL+ETS(M,N,N) model yielded lower RMSE, MAE, MAPE, and MASE values than automatic ARIMA models across most of the region-scale combinations evaluated, although STL+ETS showed a higher mean error (bias) in some instances. In an exploratory case study at the La Vitrina dairy unit (Villa Clara), the monthly THI was positively and significantly correlated with total milk production ($r = 0.496$, $p = 0.043$, $n = 17$) and production per cow ($r = 0.489$, $p = 0.046$, $n = 17$), but not with births, overall mortality, or calf mortality (all $p > 0.05$). These findings support the use of STL+ETS as a transparent statistical baseline for regional THI forecasting and confirm that thermal comfort conditions alone do not determine dairy productivity in this system.

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1. Introduction

Heat stress negatively affects the welfare, health, feed intake, milk production, and reproductive performance of dairy cattle [1-3]. These effects are particularly significant in tropical and subtropical production systems, where high air temperatures and humidity can persist for extended periods and where on-farm access to environmental monitoring and cooling infrastructure may

be uneven [4-6].

The temperature-humidity index (THI) is one of the most widely used indicators to describe the environmental heat load on livestock [7-9]. Originally developed to describe human thermal comfort (Thom, 1959) [10], it was later shown by Hahn & McQuigg (1967) [11] and Hahn & Osburn (1970) [12] to be clearly associated with losses in milk production; since then, it has been widely adopted in livestock bioclimatology (Nienaber & Hahn, 2007) [13]. However, THI thresholds are not biologically universal: their interpretation depends on genotype, milk production level, acclimatization, housing, solar radiation, wind speed, access to shade or cooling, and the duration of exposure (Khalifa, 2003) [14]. Consequently, fixed thresholds should be treated as screening values rather than universal physiological limits.

Cuban dairy systems face the combined challenges of a tropical climate, distinct wet and dry seasons, a spatially uneven station network, and locally adapted yet heterogeneous cattle populations [7,8,15]. Long-term meteorological records can support the identification of recurring periods of heat exposure and the development of parsimonious statistical forecasting tools for livestock management [3,5]. At the same time, a gridded or regional product derived from a sparse station network represents an interpolated or aggregated estimate; its uncertainty must be quantified before it is used as information at the farm scale [1,16,17].

The study had three objectives: (i) to characterize the spatial and seasonal variability of the THI in Cuba using daily observations from 23 INSMET stations grouped into three geographic regions during the 1993–2013 period; (ii) to compare the out-of-sample descriptive accuracy of an STL+ETS model against automatic ARIMA models for forecasting the THI at weekly and monthly scales in each region; and (iii) to examine, as an exploratory analysis, whether monthly THI was associated with milk production indicators recorded at a representative farm (La Vitrina, Villa Clara). The third objective was considered exploratory because herd management, physiological, and health-related covariates were not available to perform a causal adjustment.

2. Materials and Methods

2.1. Study area and Station Network

The study covered the Cuban archipelago. Daily meteorological data from 23 INSMET surface stations for the 1993–2013 period (21 years) were grouped into three regions based on geographic coverage: Group ITH1 (Eastern), extending from Camagüey to Guantánamo; Group ITH2 (Central), spanning from Matanzas to Ciego de Ávila; and Group ITH3 (Western), extending from Pinar del Río to Isla de la Juventud.

Six stations were excluded from the final analysis due to sample sizes that were unequal compared to the rest of their group: 78361 (Group ITH1); 78308, 78335, and 78344 (Group ITH2); and 78315 and 78316 (Group ITH3).

Station elevations ranged from 0.90 m (Cape San Antonio, Pinar del Río) and 1 130.00 m (Gran Piedra, Santiago de Cuba); the lowest recorded ITH values were concentrated at stations situated above approximately 400–750 m a.s.l. (e.g., Topes de Collantes, 767.33 m; Gran Piedra, 1130.00 m; Palenque de Yateras, 440.00 m).

The exploratory production case study utilized monthly records from the La Vitrina livestock enterprise in Villa Clara province, Cuba, which is representative of the region's tropical dairy systems.

2.2. Meteorological Observations and Quality Control

Air temperature and relative humidity data were obtained from the INSMET Climate Center. Quality control assessed spatial, temporal, and statistical continuity and consistency, including the individual review of suspected cases (outliers) and the calculation of statistics regarding central tendency, dispersion, and frequency. Data were organized into daily (365 values/station/year), weekly (52 values/station/year), monthly (12 values/station/year), and annual (21 data points) series for each of the 23 stations.

Missing values were identified and replaced with the series mean (mean imputation). The final descriptive dataset comprised 206 877 daily THI observations: 189 392 in the THI1 Group, 90 398 in the THI2 Group, and 98 087 in the THI3 Group.

2.3. Temperature and Humidity Index

THI (referred to as ITH in the source records) was calculated from dry-bulb air temperature and relative humidity following Thom (1959) and NRC (1971), as reported by Nienaber and Hahn (2007) [13]:

$$THI = 0.8 \cdot T_{db} + RH \cdot (T_{db} - 14.4) + 46.4$$

where T_{db} is dry-bulb air temperature (°C) and RH is relative humidity expressed as a decimal fraction (0–1).

Calculated THI values were classified using two complementary schemes reported in the thesis: (i) the four-category operational scale of Cartwright et al. (2023) [6] applied directly to THI values (Table 1a), used in Section 3.2 to describe the proportion of “alert,” “danger,” and “emergency” conditions; and (ii) the air-temperature-based thermal classification of Kulicov & Rudnev (1987) [18] (Table 1b), used to characterize the animals’ physiological state independently of the composite index.

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Table 1: Operational classification of THI values (Cartwright et al., 2023) [6]

THI range	Classification
≤ 74	Normal
75–78	Alert
79–83	Danger
≥ 84	Emergency

Daytime (T_{foto}) and nighttime (T_{nicto}) temperatures, used to characterize diurnal thermal exposure, were calculated following Castillo & Castellví (2001) [19]:

$$T_{foto} = T_x - (T_x - T_n) / 4$$

$$T_{nicto} = T_n + (T_x - T_n) / 4$$

where T_x and T_n are the daily maximum and minimum temperatures.

Independently of the THI value itself, ambient air temperature was also classified using the thermal-comfort ranges of Kulicov and Rudnev (1987) [18] (Table 2), which describe animal state as a function of temperature alone.

Table 2: Classification of air-temperature regime and associated animal thermal state (Kulicov & Rudnev, 1987) [18]

Lower limit (°C)	Upper limit (°C)	Classification	Animal state
—	16–24	Ideal	Best condition, maximum productivity
10–16	24–27	Favorable	Active animals, satisfactory state, normal productivity
7–10	27–30	Not fully favorable	Insignificant depression, mainly at midday
—	30–35	Unfavorable	Visible depression, reduced productivity
—	35–40	Very unfavorable	Significant depression, minimal productivity

2.4. National-Scale Gridded Thi Mapping (Short-Range Operational Component)

In parallel with the regional statistical analysis described below, the source methodology also describes a short-range (24, 48, 72, 96, and 120 h) operational THI mapping service, integrating six-hour forecast fields (12 UTC initialization) of the GFS (Global Forecast System) numerical weather-prediction model with the station-based THI/thermal-classification scheme, following the approach of Domínguez et al. (2017) [20]. This component used a national network of 68 INSMET stations, distinct from, and broader than, the 23-station regional network used for the time-series characterization and forecasting analysis reported in Sections 3.2–3.3.

Station temperature and specific humidity were reduced to mean sea level using the static-equation formulation of Matveev (1984) [21]:

$$T_0 = -0.06815 \times [h_{est} / \ln(P_1/P_0) + 14.6730 \times T_{est}]$$

$$S_0 = S / 10^{\wedge} (-h/9 - h^2/120)$$

where T_0 is temperature reduced to sea level (K), T_{est} is station-level temperature (K), h_{est} is station elevation, and P_1, P_0 are station-level and sea-level-reduced pressure (hPa); S is specific humidity computed from station-level pressure and dew point, and S_0 is specific humidity reduced to sea level.

Reduced values were interpolated onto a regular 118 × 44-node grid (approximately 10-km spacing) covering the Cuban archipelago using Shepard's inverse-distance-weighting method (power μ = 2) (Shepard, 1968) [22], then re-elevated to each grid node's true height. For graphical display only, the 118 × 44 grid was further interpolated to a 718 × 324-pixel map using bicubic spline interpolation; this step did not generate additional independent observations and did not enter the statistical evaluation reported in Section 3.

2.5. Regional Time-Series Forecasting Models

For each of the three regions (Eastern, Central, and Western), the aggregated weekly and monthly ITH series were examined for stationarity using the Augmented Dickey–Fuller test and the KPSS test (Table 3). Both tests indicated that all six series (three regions × two-time scales) were stationary (Dickey–Fuller: $p < 0.05$ in all cases).

Table 3: Dickey–Fuller and KPSS stationarity tests by region and time scale

Escale	Group	Dickey–Fuller	Lag	p	KPSS	KPSS truncation lag	KPSS p
Daily	I	−27.509	55	0.01	1.3020	95	0.01
Daily	II	−12.249	48	0.01	1.4743	78	0.01
Daily	III	−24.970	48	0.01	1.8322	77	0.01
Weekly	I	−8.6862	10	0.01	2.1199	7	0.01
Weekly	II	−8.7354	10	0.01	0.0760	7	0.01
Weekly	III	−8.7835	10	0.01	4.3920	7	0.01
Monthly	I	−5.4499	6	0.01	2.1262	3	0.01
Monthly	II	−8.6185	6	0.01	0.1005	3	0.01
Monthly	III	−5.1948	6	0.01	3.6182	3	0.01

Two forecasting approaches were compared: (i) an automatic seasonal ARIMA model, with orders (p,d,q) (P,D,Q) selected via the auto. Arima function in R, and (ii) an STLETS(M,N,N) model, combining Seasonal-Trend decomposition using LOESS with a multiplicative-error, no-trend, no-seasonality exponential-smoothing model applied to the seasonally adjusted series, following the Holt–Winters family of exponential-smoothing methods [...] Forecast accuracy was assessed using mean error (ME), root mean squared error (RMSE), mean absolute error (MAE), mean percentage error (MPE), mean absolute percentage error (MAPE), and mean absolute scaled error (MASE), following Hyndman & Koehler (2006) [23]. Model residuals were evaluated using ACF and PACF diagnostics.

$$y_t = \text{Trend}_t + \text{Seasonality}_t + \ell_{t-1} \cdot (1 + \eta_t)$$

where ℓ_t is the level at time t and η_t is a multiplicative error term, normally distributed with mean 0 and variance σ^2.

Model residuals were evaluated using ACF and PACF diagnostics.

2.6. Exploratory Analysis of Dairy-Production Records

Monthly production and demographic records from the La Vitrina farm, Villa Clara, Cuba, number of milking cows, total milk production (L), total births, general mortality, and

calf mortality, were compiled from the corresponding livestock indicator bulletins.

Associations between monthly THI and each production/demographic indicator were assessed using Pearson correlation coefficients (two-tailed significance). Losses attributable to theft or slaughter were excluded from the mortality counts.

3. Results

3.1. Data Completeness and Station Distribution

After quality control, the final data set comprised 206,877 daily THI observations from 23 stations (six additional stations excluded for unequal sample size, as noted in Section 2.1). Group-level descriptive statistics are show in table 4.

Table 4: Descriptive statistics of daily THI by region

Groups	n	Range	Minimum	Maximum	Mean	SD
ITH1 (Oriental)	189 392	30	55	85	75.39	3.784
ITH2 (Central)	90 398	40	43	83	73.85	4.621
ITH3 (Occidental)	98 087	31	51	83	74.10	4.521

Overall, the series ranged from 47 to 85 (mean = 74.63; n = 206,877). The absolute minimum (THI = 47) occurred on 10–11 January 2010 at stations 78342 (Topes de Collantes, Sancti Spíritus, 767.33 m a.s.l.) and 78366 (Gran Piedra, Santiago de Cuba, 1,130.00 m a.s.l.), coinciding with the passage of the season's tenth cold front under La Niña and negative North Atlantic Oscillation conditions. The absolute maximum (THI = 85) was sustained for three consecutive days (25–27 August 2010) at Punta Lucrecia, Holguín (4.00 m a.s.l.), associated with increased low- and mid-level humidity, strong afternoon heating, and afternoon sea-breeze convergence. Station elevation across the full 23-station network (see Section 2.1) ranged from 0.90 to 1,130.00 m.

3.2. Spatial and Seasonal Variability of THI

THI followed a unimodal annual cycle in all three regions, with maxima in July–August (values consistently above 75, classified as alert/danger for the animals) and minima from December to March (values below 74, classified as normal conditions). At the weekly scale, the highest values occurred around week 31 (late July–early August), consistent with the monthly pattern.

A spatial gradient of decreasing thermal comfort from west to east was observed: Group ITH1 (Oriental) showed the least favorable conditions, followed by Group ITH2 (Central), with Group ITH3 (Occidental) showing the most favorable conditions overall. This deterioration was more pronounced during July–August regardless of region. The most favorable stations in each group were located above approximately 400 m a.s.l. (e.g., Palenque de Yateras, 440.00 m, and Pinares de Mayarí, Group ITH1; Topes de Collantes, 767.33 m, Group ITH2), consistent with the expected effect of altitude and montane climate on temperature and humidity.

Anomaly-detection (X-bar) analysis of daily THI series identified 12.5% (21,264 of 170,566 cases), 15.7%, and 21.6% (24,161 cases) of observations outside the established control limits for Groups ITH1, ITH2, and ITH3, respectively, predominantly below the lower control limit. Correspondingly, 87.5%, 84.3%, and 78.4% of observations for Groups ITH1, ITH2, and ITH3 fell within the "alert" or "danger" range for animal thermal comfort, indicating that unfavorable conditions predominate for most of the year across all three regions, with Group ITH3 (Occidental) showing the smallest proportion of such conditions. Weekly CUSUM analysis showed an increasing trend in cumulative anomalies for Group ITH1 (12.5% of points outside limits, mostly above the upper bound), no defined trend for Group ITH2 (no points outside limits), and both excess and deficit anomalies for Group ITH3, concentrated below the lower bound.

3.3. Regional THI Forecasting Performance

Table 4 summarizes forecast-accuracy statistics for the STL+ETS(M,N,N) and automatic-ARIMA models, by region and time scale.

Table 4: Comparison of STL+ETS and automatic-ARIMA forecasting models for regional THI series

Region	Scale	Model	ME	RMSE	MAE	MPE	MAPE	MASE	ACF1
Oriental	Weekly	ARIMA(1,1,2)(0,0,1)[52]	0.672	219.585	157.204	−0.017	1.365	0.678	0.012
Oriental	Weekly	STL+ETS(M,N,N)	2.686	165.983	121.093	0.003	1.052	0.523	0.133
Oriental	Monthly	ARIMA(0,0,1)(0,1,1)[12]	−14.166	855.504	632.339	−0.059	1.257	0.852	0.079
Oriental	Monthly	STL+ETS(M,N,N)	49.050	622.743	450.127	0.082	0.897	0.606	0.046
Central	Weekly	ARIMA(1,0,1)(1,0,0)[52]	0.913	184.729	127.795	−0.057	1.710	0.795	−0.008
Central	Weekly	STL+ETS(M,N,N)	1.000	132.319	93.092	−0.019	1.243	0.579	0.171
Central	Monthly	ARIMA(1,0,2)(0,0,2)[12]	−2.698	947.129	723.374	−0.143	2.203	1.584	−0.001
Central	Monthly	STL+ETS(M,N,N)	26.451	414.355	285.782	0.063	0.878	0.626	0.081
Occidental	Weekly	ARIMA(1,1,2)(0,0,2)[52]	0.041	196.756	141.097	−0.049	1.921	0.701	0.025
Occidental	Weekly	STL+ETS(M,N,N)	−1.567	148.721	108.583	−0.061	1.481	0.540	0.155
Occidental	Monthly	ARIMA(1,0,0)(1,1,0)[12]	2.936	782.174	566.681	−0.028	1.785	0.926	−0.027
Occidental	Monthly	STL+ETS(M,N,N)	−35.084	523.995	374.277	−0.132	1.175	0.612	0.031

Note: ME, RMSE, and MAE are expressed in the same units as the underlying weekly/monthly summed ITH series (not standardized to individual daily THI units); MPE and MAPE are percentages; MASE and ACF1 are dimensionless.

In all three regions and at both time scales, STL+ETS(M,N,N) achieved lower RMSE, MAE, MAPE, and MASE than the corresponding automatic-ARIMA model, indicating smaller and proportionally more accurate forecast errors. However, STL+ETS showed a larger mean error (ME) than ARIMA in most region–scale combinations, indicating greater systematic bias despite its lower overall error magnitude. ACF1 values were generally low for both model families, indicating limited residual autocorrelation, although STL+ETS tended to show slightly higher ACF1

than ARIMA. Group Central (ITH2) showed the lowest error levels overall, while Group Occidental (ITH3) showed comparatively larger errors at the monthly scale.

3.4. Exploratory Association with Dairy-Production Records

At the La Vitrina farm, total milk production peaked during the rainy season (July–August) and was lowest during the dry season (February–April), despite THI being classified as "alert" or "danger" in both periods. Monthly THI was significantly and positively correlated with total milk production ($r = 0.496$, $p = 0.043$, $n = 17$) and with per-cow milk production ($r = 0.489$, $p = 0.046$, $n = 17$) (Table 5). No statistically significant correlations were found between THI and calf/heifer sales, births, general mortality, or calf mortality (all $p > 0.05$), although weak positive correlations were observed with sales-related variables ($r = 0.272$–0.293) and weak negative correlations with mortality and births ($r = -0.126$ to -0.327).

Table 5: Pearson correlations between monthly THI and production/demographic indicators, La Vitrina farm

Variables	r	p (bilateral)	n
Potential litres per cow (LXVR)	0.278	0.280	17
Calf/heifer sales, real (VESTR)	0.293	0.253	17
Births, real (NACR)	0.103	0.704	16
General mortality, real (MTR)	−0.327	0.201	17
Calf mortality, real (MCR)	−0.015	0.955	16
Total milk production, real (LP)	0.496	0.043	17
Milk per cow, real (LR)	0.489	0.046	17
Milking cows (VOP)	0.154	0.555	17
Cows in herd (VOR)	0.199	0.443	17
Potential litres per cow, plan (LXVP)	0.272	0.291	17
Calf/heifer sales, plan (VESTP)	0.276	0.284	17
Births, plan (NACP)	−0.126	0.643	16
General mortality, plan (MTP)	−0.265	0.272	19
Calf mortality, plan (MCP)	−0.051	0.851	16

Bold values are significant at $p < 0.05$. These results should be interpreted cautiously: the analysis used aggregate monthly farm-level records and did not include individual-animal physiological status, feeding, disease incidence, pasture availability, shade, or cooling interventions. It therefore describes temporal co-variation, not a causal effect of heat stress on milk production.

4. Discussion

This study documented a pronounced seasonal cycle and a west-to-east spatial gradient in THI across Cuba, and compared two forecasting approaches for regional THI series. The STL+ETS(M,N,N) model was more accurate than automatic ARIMA models by conventional scale-dependent and percentage error metrics (RMSE, MAE, MAPE, MASE) in the majority of the region–time-scale combinations examined, although it showed greater bias (ME) in several cases, a trade-off that should be weighed against the intended operational use of the forecasts (e.g., whether systematic bias or overall error magnitude is more consequential for livestock-management decisions).

The apparent paradox of milk production peaking during the period of least favorable thermal conditions (July–August) may reflect several non-mutually exclusive factors, which have also been discussed in the context of other tropical systems [5,7,23]. These include the genetic adaptation of locally raised cattle to heat and humidity; physiological adjustments (e.g., increased respiratory rate and peripheral blood flow) that partially offset productivity losses, and possibly the dominant factor, the greater availability of feed and pasture during the rainy season, which coincides with the period of highest heat load [2,3,9]. This aligns with the observation that the Temperature-Humidity Index (THI) showed a moderate yet significant association only with milk production variables, and no significant association with mortality, births, or animal sales; this suggests that factors other than thermal comfort (e.g., nutrition, management) are more decisive for those outcomes in this system [24,25,29].

The findings contrast with reports describing significant associations between the season of the year and calf mortality in Mexican livestock systems [26,28]; however, such relationships depend on the context and the system and should not be generalized without local validation [26,28,30].

Two components of the broader agrometeorological service described in the original methodology, the "leave-one-station-out" validation of spatial interpolation and the quantitative assessment of the skill of GFS/NCEP-based THI forecasts for the 24–120 h range, could not be evaluated. Given that the national grid (68 stations, 10 km nominal spacing) relies on a station network that is considerably sparser than the grid resolution, interpolation uncertainty likely varies by region and should not be assumed negligible; reporting this uncertainty is a priority before the gridded product is used for farm level decision making.

5. Conclusion

Daily THI in Cuba (1993–2013, 23 stations) exhibited a clear unimodal seasonal cycle, peaking in late July to early August, and a spatial gradient of decreasing thermal comfort from west to east, with the most favorable conditions recorded at mountain stations. At weekly and monthly scales, the STL+ETS(M,N,N) model outperformed automatic ARIMA models in terms of scale-dependent and percentage-based accuracy metrics across most region-scale combinations evaluated, albeit with higher bias in several instances. Thermal comfort is one of several contributing factors, rather than the dominant one regarding the production and demographic outcomes examined. Validating the spatial interpolation and the short-term forecasting service based on numerical weather prediction models remains a necessary step before both can be considered operationally validated.

Institutional Review Board Statement
Not applicable.

Transparency
The authors confirm that the manuscript is an honest, accurate, and transparent account of the study, and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Competing Interests
The authors declare that they have no competing interests.

Author contributions
Ismabel María Domínguez Hurtado: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, writing – original draft, writing – review and editing. César Soto Valero: Formal analysis (statistical analysis). David del Valle Laveaga: Writing – review and editing, Funding acquisition. Rigoberto Fimia Duarte: Writing – review and editing. Neilys González Benítez: Methodology, Writing – review and editing.

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