Caribbean Heat Stress Atlas

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Abstract *— The Caribbean Heat Stress Atlas is an interactive, web-based visualization system designed as a Caribbean-scale framework and implemented here as a Puerto Rico pilot module. The prototype ingests NOAA station observations and computes interpretable heat metrics such as the annual number of hot days (Tmax ≥ 32 °C) and warm nights (Tmin ≥ 24 °C) for long-running stations across the island. For each station, metrics are summarized into early versus late windows (first vs. second half of available years) and displayed in a Leaflet-based web map where users can switch metrics, change units (°C/°F), and inspect station-specific popups. Complementary time-series plots for representative coastal/urban and interior highland stations illustrate how hot days and warm nights have evolved over 1960–2025, with stronger warming signals at coastal/urban stations (e.g., San Juan and Ponce) relative to interior stations in this station network. The system is hosted as a static web application on GitHub Pages, providing a lightweight and reproducible framework that can be extended to additional Caribbean locations and to humidity-informed indicators (like heat index) in future iterations.*

Keywords *— Climate Visualization, Extreme Heat Indicators, Heat Stress, Web Mapping.*

INTRODUCTION

Climate change is increasing the frequency and intensity of extreme heat and associated risks to human health, labor productivity, and energy demand, with elevated vulnerability in tropical regions such as the Caribbean [1]. Recent observational analyses also show statistically significant warming across Puerto Rico since the late twentieth century, with especially consistent increases in minimum temperatures [2].

This project addresses that gap by building the Caribbean Heat Stress Atlas – Puerto Rico module, an interactive web map that translates long-term weather station records into simple, locally meaningful indicators of heat stress. The core contribution is an end-to-end, reproducible pipeline that converts raw NOAA station observations into station-level heat metrics and delivers them through a browser-based spatial interface. This prototype focuses on temperature-based indicators; humidity-derived measures (like heat index or wet-bulb) are reserved for future work due to data availability and completeness considerations. Using daily minimum and maximum temperature data from NOAA stations across Puerto Rico (1960–2025) [3] [4], the system computes, for each station and year:

- "Hot days" – number of days with maximum temperature Tmax ≥ 32 °C
- "Warm nights" – number of nights with minimum temperature Tmin ≥ 24 °C

These thresholds were selected for interpretability and practical relevance: days with Tmax ≥ 32 °C (~90 °F) represent conditions that materially affect outdoor work and physical activity, while nights with Tmin ≥ 24 °C (~75 °F) reduce nighttime relief and are associated with poorer sleep and elevated health risk, especially under high humidity or limited access to cooling.

Notably, the World Health Organization recommends keeping indoor temperatures during heatwaves below 32 °C during the day and 24 °C at night, particularly for infants, older adults, and people with chronic conditions, supporting the public-health relevance of these thresholds [5]. These values are not presented as physiological limits; rather, they are pragmatic indicators chosen for clear interpretation, while recognizing that humidity, acclimatization, and housing conditions modulate experienced heat stress. The completed atlas provides a station-based spatial view of heat metrics across Puerto Rico, enabling comparison between coastal, urban, and interior highland stations and examination of multi-decade changes. By packaging these outputs in a lightweight, browser-based interface, the project makes climate-relevant information accessible to students, communities, and decision makers without requiring programming or GIS expertise.

BACKGROUND

Several open datasets from institutions such as the National Oceanic and Atmospheric Administration (NOAA) provide long-term records relevant to heat analysis, including daily temperature observations and derived heat-stress products. In this project, daily minimum and maximum temperature observations from NOAA's GHCN-Daily station network form the primary data source [3] [4]. After quality control and aggregation, station summaries are exported in tabular form (CSV) and as vector geospatial data (GeoJSON) for integration with web mapping tools.

Leaflet JS was selected as the visualization engine because it is lightweight, open source, and well-suited for interactive, client-side mapping. The prototype implements standard controls (time slider, metric selector, legend, and layer toggles) and renders station-level symbology directly in the browser. This client-side architecture supports deployment as a static site on GitHub Pages, lowering operational complexity while improving reproducibility and accessibility for end users [6] [7].

PROJECT MOTIVATION AND PROBLEM STATEMENT

Residents, planners, and decision makers in Puerto Rico face three practical barriers when trying to understand how extreme heat is changing at the local scale: (1) many widely used climate portals emphasize regional or model-based views that are not granular enough for municipality level interpretation, (2) observational station data are publicly available but require technical steps that create access friction for non-specialists, and (3) common summary indicators (like annual mean temperature) are less actionable for everyday questions than metrics that reflect experienced heat. This project is motivated by the need to reduce those barriers with a station-based, reproducible, and browser accessible atlas focused on interpretable extreme-heat indicators.

1. Information at the wrong scale: Many climate dashboards and portals emphasize regional summaries or projection products that are valuable for broad assessments but are often too coarse to distinguish station-level contrasts relevant to Puerto Rico (for example, coastal, urban San Juan versus interior highland locations such as Aibonito). For heat risk communication and local planning, users frequently need observationally grounded, place-specific indicators that reflect the conditions people actually experience at representative stations rather than only regional averages.
2. Technical barriers to using observational data: NOAA and similar agencies provide high-quality open data, but converting raw station observations into interpretable metrics typically requires downloading and cleaning large daily datasets, reconciling station metadata, handling missing values, and implementing consistent aggregation logic. These steps are routine for technical users but prevent many non-technical stakeholders from performing even basic comparisons across locations or across time without a purpose built tool.
3. Mismatch between common climate summaries and lived experience: Many dashboards focus on annual mean temperature, which is scientifically useful but less intuitive for communicating heat stress than frequency-based questions such as "How many days exceed a high-heat threshold?" or "How often do nights remain warm enough to limit

recovery?" By centering on counts of hot days and warm nights, the atlas emphasizes indicators that are easy to interpret and that connect directly to household comfort, outdoor activity constraints, and potential health vulnerability.

The specific problem this project solves is the absence of a simple, station-scale, publicly accessible tool that summarizes how the frequency of very hot days and very warm nights has changed across Puerto Rico over multi-decadal station records and allows side-by-side comparison between locations. The Caribbean Heat Stress Atlas – Puerto Rico module addresses this by transforming daily station observations into annual counts and early-versus-late summaries, and by delivering these outputs through an interactive web map and station popups that run entirely in a standard browser.

Objectives

1. Data pipeline: Design and document a reproducible pipeline that ingests daily NOAA station data for Puerto Rico, performs basic quality control (missing/invalid value handling and coverage rules), and computes annual counts of hot days (Tmax ≥ 32 °C) and warm nights (Tmin ≥ 24 °C) for each station-year.
2. Spatial summary of long-term change: For each station, quantify change between the first and second halves of the available observation record by computing mean annual counts in early versus late windows for both hot days and warm nights, producing a compact summary suitable for spatial comparison across the station network.
3. Interactive web map: Implement a Leaflet-based web application that visualizes station-based heat metrics as map symbols with a clear legend and an information panel, and supports interaction through a metric toggle (hot days vs. warm nights), a year selector (time slider), and a unit toggle (°C/°F).
4. Temporal visualizations for key stations: Produce station-level time-series plots from annual aggregates for representative coastal, urban and interior (or highland) stations (like San Juan, Ponce, Ceiba, Fajardo, Arecibo, Arecibo Observatory, and Aibonito) to illustrate long-term behavior and interannual variability for both metrics.
5. Deployable prototype: Deploy the atlas as a static site (GitHub Pages) with version-controlled data artifacts and documentation, enabling end users to access the tool with a web browser and enabling future extension to additional stations, regions, or metrics.

Methodology and Implementation

The project uses daily minimum (Tmin) and maximum (Tmax) temperature observations from NOAA's Global Historical Climatology Network–Daily (GHCN-Daily) for stations in Puerto Rico, paired with station metadata (location and identifier) [3] [4]. Stations were selected to emphasize (i) long record length, (ii) geographic spread across coastal/urban and interior/highland settings, and (iii) sufficient daily coverage to support year-by-year aggregation. Daily observations are transformed into annual station-year summaries by counting threshold exceedances (hot days and warm nights), then organized into both year-specific layers (for the map slider) and multi-decadal summaries (early vs. late halves of each station's available record). This approach prioritizes transparent station-based evidence over model output, so users can compare locations using observed measurements rather than regional averages.

The end-to-end workflow is summarized in Fig. 1.

Heat-metric computation and aggregation are implemented in Python using the pandas library [8]. Daily values are parsed into numeric form and handled with explicit missing-data logic so that only valid observations contribute to annual counts. For each station-year, the pipeline computes the number of days meeting the "hot day" threshold (Tmax ≥ 32 °C) and the number of nights meeting the "warm night" threshold (Tmin ≥ 24 °C), producing an annual summary table per station. To avoid misleading results from sparse years, the workflow applies a minimum-coverage rule at the station-year level: in this prototype, a station-year is considered valid when it contains at least 200 days (a conservative completeness threshold for a prototype) Tmax and Tmin (the same rule is applied across stations). Years below this threshold are excluded from early and late summaries and from exported station-year outputs used in plots. This design keeps the analysis reproducible while preventing artifacts driven by missingness rather than the climate signal.

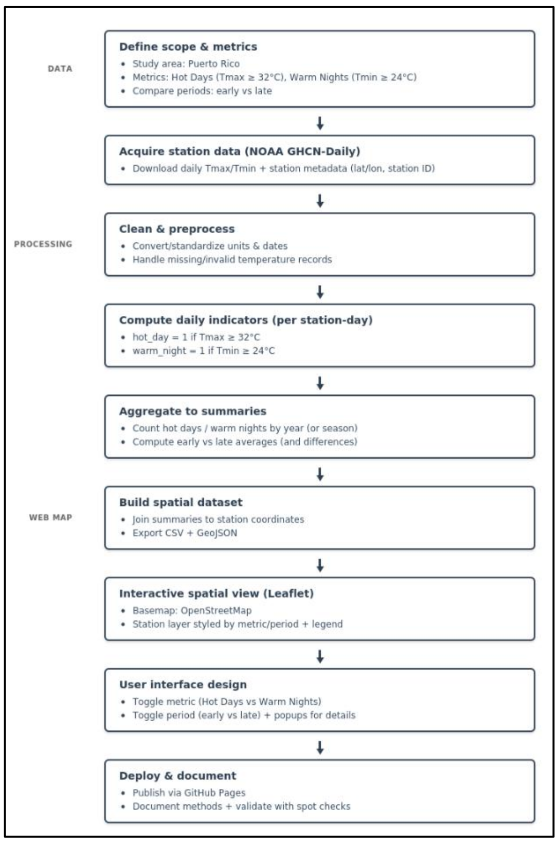

Figure 1

End-to-End Workflow for the Caribbean Heat Stress Atlas: Define Metrics, Acquire NOAA GHCN-Daily Station Data, Clean and Preprocess, Compute Daily Indicators, Aggregate to Annual Summaries, Build Spatial Datasets, and Deploy an Interactive Leaflet Web Map

To support long-term comparison while keeping the summary interpretable for non-specialists, each station record is split into an "early" and "late" window defined as the first versus second half of the station's available years after coverage filtering. Window assignment is computed per station from the ordered list of valid station-years; when the record length is odd, a floor and ceiling split is used so that the two windows differ by at most one year (the exact split logic is deterministic and implemented in the pipeline scripts). For each window, mean annual hot-day and warm-night counts are computed and displayed in the map popups so users can quickly compare long-run conditions at a station without relying on a single year.

Figure 2

Station-Based Spatial View of Hot Days (Tmax ≥ 32°C) in Puerto Rico for 1994 (7/7 stations; colors indicate days per year)

Figure 3

Station-Based Spatial View of Warm Nights (Tmin ≥ 24°C) in Puerto Rico for 1994 (7/7 stations; colors indicate days per year)

The web mapping interface is implemented as a static HTML and JavaScript application that runs entirely in the browser, using Leaflet for interactive spatial rendering [6] and OpenStreetMap as the basemap layer [9]. The spatial view is intentionally station-based: values are visualized as symbolized point markers whose color or size encode the selected heat metric for a given year, allowing direct comparison across observed locations. This avoids implying continuous spatial coverage that is not supported by the station network, and it makes uncertainty and sampling limitations easier to interpret for end users. The interface connects the spatial view to station popups and to complementary time-series plots, so users can validate patterns seen on the map against multi-decade station histories rather than treating the spatial layer as a standalone snapshot.

The 1994 maps are included as a high-coverage snapshot that enables a clean, spatial comparison across all stations in the current network (7/7 stations meeting the coverage requirement for that year). This figure functions as a visual anchor: it demonstrates how the system renders a complete station layer and helps users interpret coastal versus inland contrasts without the confounding effect of missing stations in a given year. However, the atlas is not intended to encourage single-year conclusions; the snapshot is paired with station time-series plots and early-versus-late summaries so that spatial patterns can be interpreted in the context of long-run behavior and year-to-year variability.

Interpretation note: throughout this report, the term "spatial heat map" refers to a map-based spatial view of heat metrics using station symbols (points) rather than an interpolated raster surface. With limited station density, interpolation can create false precision and may visually imply coverage in unsampled areas. The station-symbol design therefore emphasizes transparency: users see exactly where observations exist and can connect each mapped value to station metadata and to its underlying time series.

As a basic validation step, several station-years were checked by manually counting exceedance days from the daily record and confirming agreement with the pipeline's annual totals. Although this was time consuming, this validation was crucial in developing confidence in the scripts made and ensuring automaticity when reproducing the results for different stations added later.

User Interface and Spatial Visualization Design

The Puerto Rico module is designed for non-technical users to explore station-based heat-stress indicators through a small set of high-impact controls while keeping the map as the primary analytic surface (Fig. 4(a)). The interface exposes three primary choices: year, metric (Hot Days vs. Warm Nights), and units (°C/°F), so users can quickly switch between questions such as "Where are warm nights most frequent?" and "How do hot days differ across stations in a given year?" The design intentionally prioritizes interpretability: the legend and value bins provide a clear mapping from color to annual counts, and the layout keeps controls visible without obscuring the spatial view. Throughout the interface, the spatial "heat map" is implemented as a station-symbol layer (points), so mapped values correspond directly to observed station locations rather than interpolated coverage.

Interaction follows a "select–view–inspect" workflow that supports comparison and drill-down. Users select a year with the slider and choose a metric, after which station markers and legend bins update immediately to reflect the active view (Figs. 2–3, Fig. 4(a)). This interaction pattern encourages rapid exploration across years and locations while maintaining a consistent visual encoding, making coastal–interior contrasts easier to assess within the station network shown.

Selecting a station opens a popup that provides station metadata and computed values, enabling the user to connect the spatial view to specific locations (Fig. 4(b)). For stations where embedded charts are available, the popup also provides immediate access to annual time series, allowing users to inspect interannual variability and longer-run shifts without leaving the map. This design links overview (spatial comparison) with local inspection (station detail) in a single interface.

Key UI Components

Controls include a metric selector, temperature-unit selector, layer toggles, and a reset view option that returns the map to a consistent framing (Fig. 4(a)). Keeping controls minimal reduces cognitive load while supporting core analytic tasks: comparing coastal versus interior stations, identifying high-frequency warm-night locations, and drilling down into station-level values through popups. This balance of simplicity and inspection capability is central to the tool's goal of making observational heat metrics accessible without requiring GIS or programming expertise.

To complement the spatial view, station time series are generated from annual aggregates and presented in the Results section (Figs. 5–8). Pairing spatial snapshots with multi-decade station trends reduces the risk of over-interpreting any single year and provides context on both long-term change and year-to-year variability.

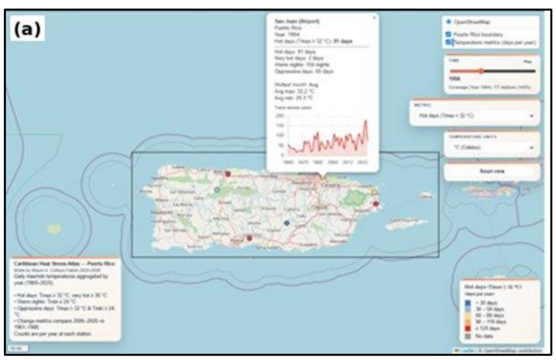

Figure 4
User interface of the Caribbean Heat Stress Atlas: (a) main controls (layer toggles, time slider, metric selector, units selector, and legend), and (b) example station popup with time-series chart used to inspect local values.

The application is deployed via GitHub Pages [7] and version-controlled in a public repository [10], enabling transparent reproducibility and straightforward extension to additional stations, metrics, or Caribbean locations. Static deployment also supports broad accessibility by allowing the atlas to run in a standard browser without specialized software or local installation.

KEY RESULTS

The analysis reveals systematic spatial patterns and temporal trends in extreme heat across Puerto Rico's station network.

Spatial Patterns Across the Station Network: Coastal/Urban Versus Interior/Highland Contrasts

The atlas reveals clear contrasts in heat metrics across the station network that align with Puerto Rico's elevation and coastal/urban geography (Figs. 2–3). Within this network, interior (highland) stations exhibit substantially fewer threshold exceedances than coastal stations, supporting the value of reporting frequency-based heat indicators at the station scale for interpretable comparisons.

In the interior highlands, represented by Aibonito 1 S, hot days (Tmax ≥ 32 °C) are rare: in the early half of the station record the site averages roughly 1–2 hot days per year, and in the later half this falls to near zero. Warm nights (Tmin ≥ 24 °C) are effectively absent at this station across the record. This contrast is reflected in the spatial views (Figs. 2–3), where Aibonito appears among the lowest-frequency locations for both metrics, emphasizing the moderating role of elevation on heat extremes within Puerto Rico's station network.

In contrast, northern and eastern coastal stations like San Juan, Ceiba, and (historically) Fajardo show substantially higher frequencies of both hot days and warm nights. San Juan (Airport) exhibits the strongest warm-night signal: mean annual warm nights increase from roughly 120 nights in the early half of the record to about 200 nights in the later half (approximately a 60% increase), while hot days increase from approximately 47 to about 84 per year. Ceiba (Roosevelt Roads) shows a similar direction of change, with hot days increasing from roughly 22 to about 50 per year and warm nights rising from about 132 to roughly 166 nights annually. Fajardo's record ends in the mid-1990s, but it already displays frequent hot days and warm nights during its operating period, indicating that coastal heat exposure has been persistent for decades at some locations. These coastal–interior contrasts are visible in the spatial views (Figs. 2–3).

Southern and north-central stations add additional nuance to the elevation and coastal pattern. Ponce stands out as one of the hottest locations in the station network, with mean hot days increasing from about 110 to over 200 days per year between early and late windows, and warm nights increasing from roughly 22 to about 31 nights annually. The original Arecibo station (1960–1998) records more than 100 hot days per year on average during its operating period but relatively few warm nights. Arecibo Observatory, located inland at higher elevation, shows fewer hot days and almost no warm nights, consistent with a cooler microclimate despite proximity to the broader Arecibo region. Overall, the station network suggests that coastal/low-elevation stations experience far higher frequencies of hot days and warm nights than interior/highland stations (Figs. 2–3), reinforcing the importance of distinguishing between warmer coastal environments and milder highland areas when communicating heat exposure.

Temporal Trends at Representative Stations

Figure 5 highlights both long-term change and strong year-to-year variability at San Juan (Airport). Warm nights show the clearest multi-decade shift: earlier decades include many years with fewer than ~100 warm nights, whereas many recent years exceed ~200, indicating that a large fraction of nights remain at or above 24 °C. Hot-day counts increase as well, with more frequent years above ~80–100 hot days in the last two decades. Together, these patterns indicate that warming is expressed not only through hotter days but also through reduced nighttime recovery at a major coastal/urban location.

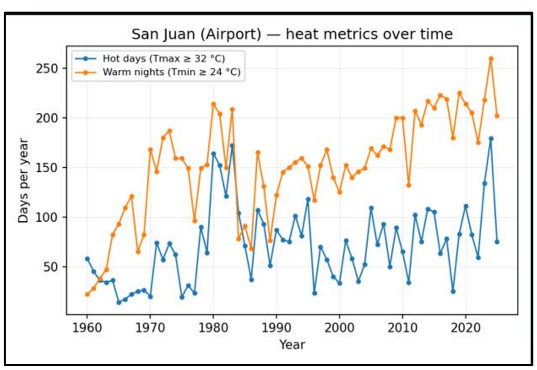

Figure 5

Annual Number of Hot Days (Tmax ≥ 32 °C, blue) and warm nights (Tmin ≥ 24 °C, orange) at San Juan (Airport), 1960–2025

Figure 6 indicates that Ponce experiences persistently high hot-day counts across the record, with multiple years exceeding ~200 hot days even in earlier decades. Warm nights remain comparatively modest until the 2010s, after which they increase sharply; recent years exceed ~100 warm nights, suggesting a recent intensification of nighttime heat in the south. This divergence–-high baseline hot-day exposure with a later rise in warm nights–-illustrates how daytime and nighttime warming can evolve differently across stations.

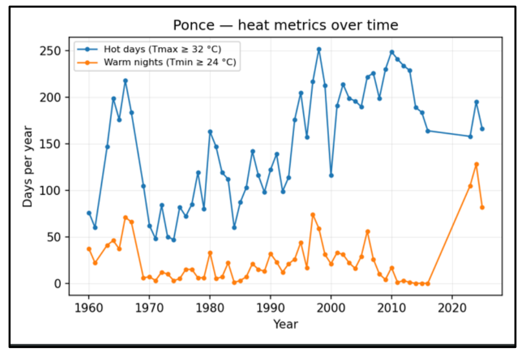

Figure 6

Same Metrics for Ponce, Highlighting Persistently High Hot-Day Counts and the Recent Jump in Warm Nights

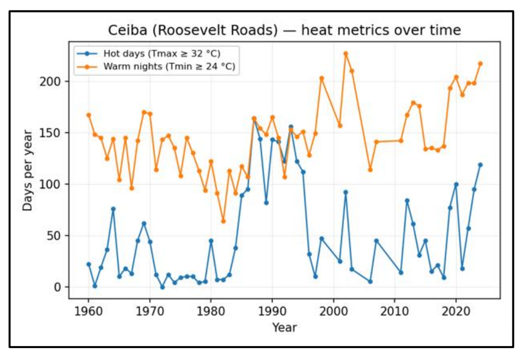

Figure 7

Annual Hot Days and Warm Nights at Ceiba (Roosevelt Roads), Illustrating High Warm-Night Frequency and Increasing Hot Days

Figure 7 shows that Ceiba (Roosevelt Roads) maintains high warm-night frequency across much of the record (often ~130–180 warm nights per year), with a modest upward shift in recent decades. Hot days intensify after the late 1980s, with more years exceeding ~80–100 hot days annually. As a coastal station, Ceiba illustrates how warm nights can be persistently common even before the most recent decades, while hot-day frequency increases more noticeably over time.

Fajardo and the original Arecibo station have shorter records that end in the mid-1990s, but they provide valuable historical context for coastal and north-central conditions. Fajardo already shows frequent warm nights and hot days during its operating period, and the original Arecibo station exhibits high hot-day frequency with comparatively fewer warm nights. These shorter records are therefore useful for interpreting the station network as evidence of long-standing coastal exposure alongside more recent intensification at other sites.

Figure 8 underscores the moderating effect of elevation: at Aibonito 1 S and Arecibo Observatory, hot days occasionally occur but remain low in most years, while warm nights remain near zero across the record. Together, these inland stations provide a strong counterexample to coastal and urban locations and help validate that the 32 °C and 24 °C thresholds behave as expected across Puerto Rico's topographic gradients.

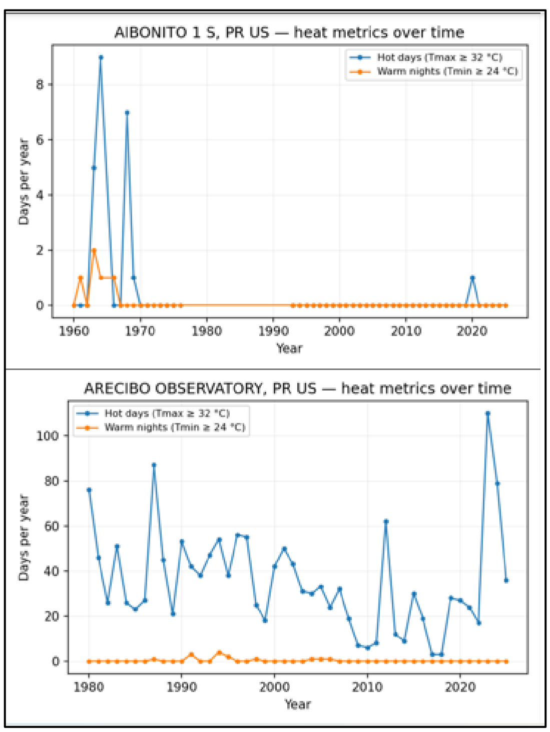

Figure 8

Time Series for (a) Aibonito 1 S and (b) Arecibo Observatory. Both show very few hot days and almost no warm nights, emphasizing the moderating effect of elevation.

Limitations and Future Directions

Station coverage and representativeness: The current prototype uses a small subset of stations chosen for record length and continuity. As a result, the spatial views represent differences among observed station locations rather than a continuous map of conditions across all municipalities. Some microclimates and under-instrumented areas remain under-represented, and station metadata changes (relocations, instrument upgrades, observing practice shifts) may introduce non-climatic artifacts. A publication-grade climate analysis would benefit from more formal homogenization checks and sensitivity tests to quantify the impact of station history on computed trends and early–late comparisons [4].

Metric scope and heat-stress realism: Hot days and warm nights are intentionally simple temperature-threshold indicators that support interpretability and rapid comparison, but they do not incorporate humidity, wind, solar radiation, or acclimatization—-factors that strongly influence experienced heat stress. A future iteration should integrate humidity-informed metrics (e.g., heat index or wet-bulb proxies) where data coverage permits, and should document the tradeoff between metric realism and data completeness, particularly for older station records [1] [5].

Observations-only analytics: The atlas currently visualizes historical observations and derived summaries. Extending the framework to incorporate downscaled projections would enable "what-if" exploration under different emissions pathways, but would require careful communication of uncertainty, model dependence, and the differences between observed station records and gridded projection products [1].

Product and usability extensions: The current interface is optimized for exploration, but several additions would increase utility for applied users: (1) export/download of station-year tables and station summaries (CSV/GeoJSON) directly from the UI, (2) a comparison mode for selecting multiple stations and plotting them in one view, (3) sectorspecific story views (health, energy, labor) that interpret metrics for practical contexts, and (4) automated expansion to additional stations and additional Caribbean locations through a repeatable ingestion configuration and validation routine. These extensions are feasible within the existing architecture because the pipeline already separates computation (offline) from visualization (client-side) and maintains derived outputs in a version-controlled repository [7] [10].

These limitations do not undermine the current contribution; rather, they clarify that the Puerto Rico module functions as a defensible prototype and a scalable foundation for a broader Caribbean Heat Stress Atlas.

CONCLUSION

The Caribbean Heat Stress Atlas – Puerto Rico module demonstrates how an end-to-end computer science workflow can transform raw climate observations into an interpretable, browser-accessible decision-support prototype. The project's primary contribution is a reproducible pipeline that converts NOAA station observations into frequency-based heat indicators (hot days and warm nights), publishes station-based spatial views, and supports station-level inspection through interactive popups and multi-decade time-series plots. By emphasizing transparent computation and lightweight deployment, the system makes station-scale heat information accessible without requiring GIS software or programming expertise.

Across the station network analyzed, results show pronounced contrasts between coastal and urban lowlands, and interior and highland environments. Coastal and urban stations such as San Juan, Ponce, and Ceiba exhibit substantially higher frequencies of hot days and warm nights, while highland and inland stations such as Aibonito and Arecibo Observatory exhibit far fewer exceedances, consistent with Puerto Rico's topographic gradients and published temperature-trend findings [1], [2]. The paired spatial and temporal views help interpret both long-run change and year-to-year variability, reducing reliance on any single-year snapshot.

More broadly, this capstone illustrates a scalable template for applied climate informatics: data acquisition and cleaning, metric definition, station-year aggregation, interactive geospatial visualization, and reproducible deployment. The Puerto Rico module serves as a working foundation that can be extended to additional Caribbean locations, increased station coverage, and more heat-realistic metrics (some future steps might be humidity-informed indicators) in future work.

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