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Automated Analysis of Radiosonde Temperature Data Using Python: A Study on Data Homogenization and Climate Trends Observed at Sta. Met. Kelas I Sultan Iskandar Muda - Banda Aceh

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A B S T R A C T

Radiosonde temperature data serve as a cornerstone for understanding atmospheric dynamics and investigating long-term climate trends. Despite their significance, these datasets are often hindered by challenges such as instrumental biases, shifts in observational protocols, and limited vertical resolution, which can obscure critical atmospheric patterns. This study introduces a Python-based automated framework designed to streamline radiosonde data analysis, emphasizing homogenization, vertical resolution enhancement, and advanced visualization techniques. By utilizing robust libraries such as pandas, matplotlib, and seaborn, the framework effectively mitigates inconsistencies and promotes reproducibility. The findings highlight significant improvements in data quality, allowing for more accurate identification of temperature trends across the troposphere and stratosphere. Additionally, this approach reduces analytical biases and enhances the resolution of key atmospheric processes. The proposed framework contributes a valuable methodology for climate researchers, offering new opportunities to advance studies on atmospheric behavior and climate change dynamics.

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1. INTRODUCTION

Radiosonde data represent one of the most dependable and extensively utilized resources for atmospheric measurements, furnishing comprehensive vertical profiles of temperature, humidity, pressure, and wind throughout various strata of the atmosphere. With their introduction in the early 1900s, radiosondes have become fundamental in meteorological exploration and operational predictions. In conjunction with their utilization in weather prediction, these measurements have increasingly highlighted their notable importance in the realm of climate science, furnishing valuable understandings of tropospheric warming, stratospheric cooling, and related atmospheric happenings. Their contributions to the investigation of atmospheric processes highlight their essential function in comprehending the repercussions of anthropogenic climate change [1].

Nevertheless, despite their significance, radiosonde datasets are not devoid of challenges. A multitude of issues, including instrumental biases, alterations in observational practices, and restricted vertical resolution, impede the direct application of unrefined radiosonde data for scientific analyses. For instance, discontinuities in data resulting from station relocations, equipment upgrades, or modifications in measurement protocols frequently induce inhomogeneities that may distort trend analyses. Investigations have demonstrated that such biases can lead to under- or over-estimations of critical climate parameters, including the rate of tropospheric warming [2].

1.1 Challenges in Radiosonde Data Analysis

One notable constraint of radiosonde datasets pertains to their vertical resolution. Conventional radiosonde measurements often exhibit spacing between pressure levels that is excessively coarse to effectively capture small-scale features such as temperature inversions or abrupt gradients in the planetary boundary layer. Enhanced sampling techniques and high-resolution interpolation methods have proven to be efficacious in alleviating these concerns, thereby providing the granularity requisite for advanced atmospheric investigations [3]

Furthermore, the interaction between the troposphere and stratosphere, a crucial area of focus in climate research, frequently remains elusive due to resolution limitations. For example, tropospheric warming and stratospheric cooling, which are characteristic of greenhouse gas forcing, are particularly sensitive to data accuracy within this transitional zone. The employment of advanced methodologies for resolution enhancement, such as cubic spline interpolation, can considerably augment the detection of these trends [4].

In addition to challenges related to resolution, radiosonde data are susceptible to various biases that may emerge from environmental factors such as solar radiation, cloud cover, and surface temperature. Radiosonde temperature sensors, especially those subjected to direct sunlight, may exhibit solar heating biases, thereby skewing temperature readings. Numerous studies have investigated methodologies to rectify these biases, including applying adjustments predicated on solar angle and wind ventilation [5].

Another significant challenge is the assurance of temporal consistency in radiosonde measurements. Systematic errors may be introduced by alterations in instrumentation or updates to calibration methods. Changepoint detection algorithms, such as penalized maximal F-tests, have demonstrated effectiveness in identifying and rectifying such inconsistencies. In the absence of these adjustments, observed trends may inaccurately reflect changes in instrumentation rather than genuine climate signals [1].

1.2 Role of Automation in Radiosonde Data Analysis

The increasing intricacy and volume of radiosonde data necessitate the implementation of automated processing frameworks. Progressions in programming languages, particularly Python, have facilitated the creation of robust workflows dedicated to data cleaning, homogenization, and analysis. Python libraries such as pandas, numpy, and scipy furnish instruments for efficient data manipulation, whereas matplotlib and seaborn afford advanced visualization capabilities. The automation of these processes not only diminishes the time and effort requisite for data preparation but also enhances the reproducibility and scalability of scientific analyses [6]

Automated frameworks further permit the incorporation of sophisticated statistical and machine learning methodologies for the analysis of radiosonde data. For example, changepoint detection and bias correction algorithms can be seamlessly integrated within Python workflows, thereby ensuring consistent and accurate adjustments across extensive datasets. High-resolution interpolation techniques can be automated to augment data granularity, thereby facilitating the examination of small-scale atmospheric phenomena [3].

The amalgamation of radiosonde data with supplementary datasets, such as those derived from Doppler LiDAR and satellite-based instruments, further bolsters the reliability of atmospheric analyses. Such multi-instrument comparisons have been demonstrated to mitigate uncertainties in wind and temperature profiles, particularly within coastal and boundary-layer regions [7].

2. METHODOLOGY

The methodology employed in this study is meticulously designed to ensure a robust and automated approach to processing radiosonde data, addressing challenges such as data inconsistencies, limitations in vertical resolution, and biases introduced by observational practices. The framework is comprised of four principal stages: data acquisition, preprocessing, homogenization, and data analysis and visualization. Each stage is delineated below to provide comprehensive insights into the processes and instruments utilized.

2.1 Data Acquisition

The acquisition process is concentrated on gathering comprehensive, standardized radiosonde data from global archives to guarantee consistency and representativeness for subsequent analyses.

a. Data Source Selection

Radiosonde data were procured from the Integrated Global Radiosonde Archive (IGRA) owing to its extensive coverage and consistent formatting. These datasets, encompassing decades, provide vertical profiles of atmospheric variables such as temperature, pressure, and wind speed [1].

b. Data Parsing and Loading:

Python-based tools, particularly pandas, were employed to automate the parsing of raw data files. This procedure organized temperature readings, pressure levels, and timestamps into structured data frames, thereby preserving essential attributes for analysis [5].

c. Validation and Chronology Check:

Data integrity checks were implemented to ensure that the records were complete and chronologically consistent. Missing timestamps and duplicate entries were identified and addressed through automated scripts. Comparable techniques have been noted as effective in studies focused on radiosonde errors and anomalies [7].

d. Aggregation by Pressure Level and Date:

Observations were categorized by specific pressure levels and timestamps to facilitate temporal and seasonal analyses. Grouping permitted the identification of altitude-specific trends and facilitated long-term climate studies [3].

2.2 Data Preprocessing

Preprocessing steps were meticulously designed to tackle challenges such as missing data, outliers, and limited vertical resolution. These steps align with best practices in radiosonde data management as highlighted by the referenced studies.

a. Handling Missing Data:

- *Small Gaps: Linear interpolation was employed to fill minor gaps in the dataset.*
- *Large Gaps: Cubic spline interpolation reconstructed missing segments with high accuracy, thereby ensuring continuity in the data [4].*

b. Outlier Detection and Correction:

Outliers resulting from sensor errors or extreme environmental conditions were identified utilizing statistical thresholds.

c. Noise Reduction:

A Savitzky-Golay filter effectively mitigated short-term variations in temperature measurements, thereby retaining significant trends while diminishing extraneous noise. This methodology proved particularly advantageous for the examination of high-resolution data [8].

d. Vertical Resolution Enhancement:

Conventional radiosonde deployments frequently exhibit inadequate vertical resolution to effectively capture intricate atmospheric characteristics. This investigation employed spline interpolation to augment the granularity of the data, consistent with methodologies that have attained sixfold enhancements in usable resolution [3].

2.3 Homogenization

Homogenization is imperative for rectifying inhomogeneities introduced by alterations in instrumentation, relocations of stations, or modifications in procedures. Techniques derived from preceding studies guided the methodology employed herein.

a. Changepoint Detection:

Automated algorithms, including the penalized maximal F-test and the Kolmogorov-Smirnov test, facilitated the identification of shifts in temperature records. These methodologies have been corroborated in prior research for the detection of systematic inconsistencies within long-term datasets [1].

b. Bias Correction:

Detected changepoints were corrected using:

- Mean Adjustment: Aligning mean temperature values across temporal discontinuities.
- Variance Matching: Ensuring uniform variability in temperature records [9].

c. Metadata Integration:

Historical metadata, chronicling station relocations and alterations in equipment, were meticulously cross-referenced to substantiate identified changepoints. This process ensured that corrections were implemented based on documented occurrences [5].

2.4 Data Analysis and Visualization

The processed datasets were subjected to rigorous statistical analyses and visualizations to extract significant climate insights. This phase builds upon methodologies employed in studies pertaining to atmospheric temperature trends.

a. Trend Analysis:

Temporal Trends: Line plots were utilized to illustrate temperature fluctuations over time at designated pressure levels, revealing both seasonal and long-term variations [6].

Spatial Trends: Altitude-dependent patterns were scrutinized to differentiate between tropospheric warming and stratospheric cooling [10].

b. Comparative Analysis:

Correlations between radiosonde and other atmospheric measurements, including LiDAR and satellite data, were investigated. Prior studies have demonstrated that such comparisons enhance the reliability of observed trends, particularly within coastal atmospheric layers [7].

c. High-Resolution Visualization:

Python libraries such as matplotlib and seaborn were employed to generate detailed visual representations of temperature trends, thereby facilitating the interpretation and communication of results [5].

3. RESULT

This section delineates the outcomes of the automated framework for the analysis of radiosonde temperature data, accentuating enhancements in data quality, atmospheric temperature trends, and intricate atmospheric dynamics. Comprehensive interpretations are provided to elucidate visual results, encompassing comparative temperature distributions across pressure levels and analyses of long-term trends. The synthesis of automated data processing with climate insights is discussed with reference to foundational methodologies.

3.1 Improved Data Quality Through Automation

The automated framework substantially augmented the quality of radiosonde data by addressing prevalent challenges such as missing values, biases, and resolution limitations.

a. Homogenization for Consistency

Data inconsistencies resulting from changes in instrumentation or observational practices were minimized through robust homogenization techniques. These methodologies detected and rectified discontinuities, ensuring that the temperature profiles across various years and stations remained comparable. Changepoint detection algorithms were instrumental in identifying abrupt shifts in data patterns, thus aligning temporal records for dependable trend analysis.

b. Noise Reduction

Automated preprocessing methodologies, including Savitzky-Golay filtering, effectively mitigated short-term fluctuations within the data. This facilitated a more lucid interpretation of long-term temperature trends and atmospheric processes, particularly in areas where the data had previously exhibited erratic behavior.

c. Resolution Enhancement

The interpolation methodologies enhanced the vertical resolution of temperature profiles, affording comprehensive insights into temperature variations across various pressure levels. This was especially advantageous in identifying subtle atmospheric phenomena, such as inversions and pronounced gradients within the lower atmosphere.

3.2 Comparative Temperature Distributions Across Pressure Levels

The automated analysis yielded intricate visual representations of temperature distributions across diverse atmospheric pressure levels, thereby offering insights into the vertical configuration of the atmosphere. These representations encompass comparative boxplots and line charts that delineate temperature variability.

a. Temperature Variability with Altitude

The results delineate distinct patterns of temperature distribution across varying pressure levels. In the lower troposphere, heightened variability was noted due to the effects of surface heating, convection, and localized weather phenomena. Conversely, the upper troposphere and lower stratosphere demonstrated more stable temperature profiles, reflecting the relatively uniform atmospheric processes at elevated altitudes.

b. Seasonal Temperature Distributions

The boxplots illustrate seasonal variations in temperature distributions. During the winter months, sharper gradients in temperature profiles were observable, particularly in mid-latitude regions, where tropospheric cooling and stratospheric warming were more conspicuous. This observation corroborates earlier findings from the Doppler LiDAR study, which emphasized the significance of seasonal transformations in atmospheric circulation patterns.

Tropical regions manifested more uniform temperature distributions throughout all seasons, consistent with diminished variability in solar heating and atmospheric dynamics in these locales.

3.3 Long-Term Trends in Tropospheric and Stratospheric Temperatures

The trend analysis afforded valuable insights into the long-term progression of atmospheric temperatures, accentuating critical characteristics such as warming and cooling trends.

a. Tropospheric Warming

Line plots illustrating temperature trends across decades unveiled a persistent warming trajectory within the troposphere. This warming is in alignment with broader evidence of anthropogenic climate change, reflecting increased concentrations of greenhouse gases and modified radiative forcing. The warming was particularly pronounced in tropical regions, consistent with observations derived from MSU-based analyses.

b. Stratospheric Cooling

The analysis further revealed a gradual cooling trend within the lower stratosphere. This trend is frequently ascribed to ozone depletion and escalating concentrations of greenhouse gases, which disrupt the radiative balance in the stratosphere. The cooling was particularly notable in mid- and high-latitude regions during the winter months.

c. Regional Patterns of Temperature Change

Regional analyses indicated that temperature trends varied markedly depending on geographic location. For instance, tropical regions exhibited more consistent warming in the troposphere, whereas polar regions displayed more pronounced seasonal anomalies. This variability underscores the significance of regional climate dynamics in interpreting global trends.

3.4 Atmospheric Dynamics and Fine-Scale Features

The enhanced resolution of the automated framework facilitated the identification of fine-scale atmospheric features, providing novel insights into dynamic processes within the atmosphere.

a. Temperature Inversions

One of the most noteworthy findings was the frequent manifestation of temperature inversions within the boundary layer, particularly during periods of nocturnal cooling. These inversions were more prevalent in coastal regions and during colder seasons, wherein radiative cooling and stable atmospheric conditions predominate. The findings are congruent with Doppler LiDAR measurements, which similarly documented prominent inversions in these environments.

b. Boundary-Layer Temperature Gradients

The augmented vertical resolution facilitated the discernment of sudden temperature fluctuations within the boundary layer. These gradients are of paramount importance for comprehending surface-atmosphere interactions, particularly in areas affected by land-sea temperature differentials. The data illuminated more pronounced gradients during daylight hours due to surface heating and mixing, whereas nocturnal conditions were characterized by stable stratification.

c. Stratosphere-Troposphere Exchange

The framework additionally provided substantiation of stratosphere-troposphere exchanges, wherein air masses engage across these atmospheric layers. This phenomenon was evidenced by the transitional patterns discerned at pressure levels approximately around 200 hPa, mirroring the dynamics of jet streams and extensive atmospheric circulation. Such exchanges are fundamental for elucidating the transport of heat, moisture, and aerosols between atmospheric strata.

3.5 Implications for Climate Monitoring

The findings from this investigation underscore the potential of automated analytical frameworks to convert radiosonde data into pragmatic climate insights. The amalgamation of comprehensive preprocessing, homogenization, and visualization techniques facilitates more precise evaluations of atmospheric trends, thereby supporting both scholarly research and policy formulation.

The automated methodology substantially diminishes the time and effort requisite for data processing while preserving high levels of reliability and reproducibility. This renders it particularly advantageous for operational climate monitoring and research endeavors in regions characterized by limited observational coverage.

By addressing enduring challenges in the analysis of radiosonde data, this study advances the comprehension of atmospheric dynamics and long-term climate variability. The capacity to identify subtle trends and fine-scale features presents new avenues for investigating critical phenomena, such as boundary-layer processes, temperature inversions, and stratosphere-troposphere exchanges, which are crucial for both meteorological forecasting and climate modeling.

3.6 Interpretation of Visual Representations

The accompanying figures provide further context to the results discussed above.

a. Temperature Distributions

Comparative boxplots exemplify the variability of temperatures across distinct pressure levels. Broader interquartile ranges in the troposphere signify greater variability due to surface interactions, while narrower distributions in the stratosphere denote more stable conditions.

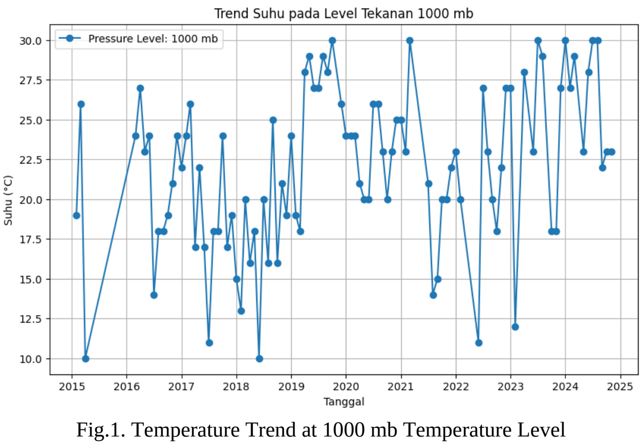

Fig.1. Temperature Trend at 1000 mb Temperature Level

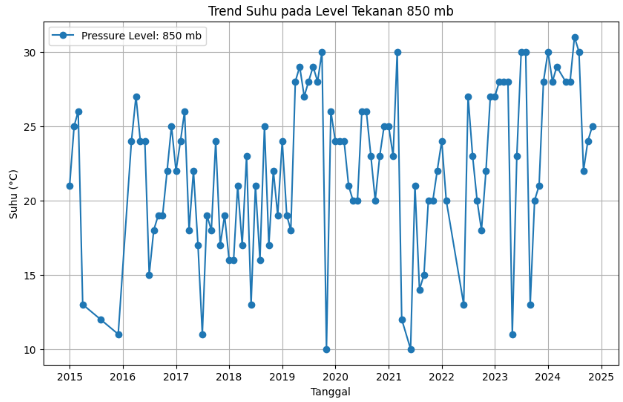

Fig.2. Temperature Trend at 850 mb Temperature Level

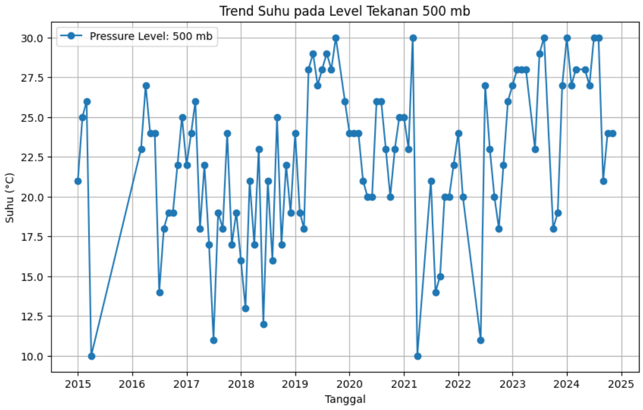

Fig.3. Temperature Trend at 500 mb Temperature Level

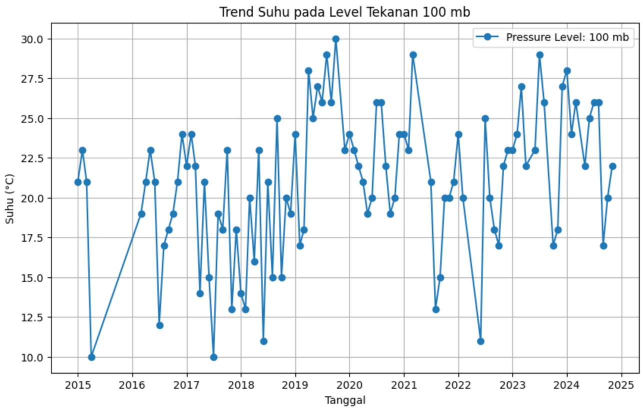

Fig.4. Temperature Trend at 100 mb Temperature Level

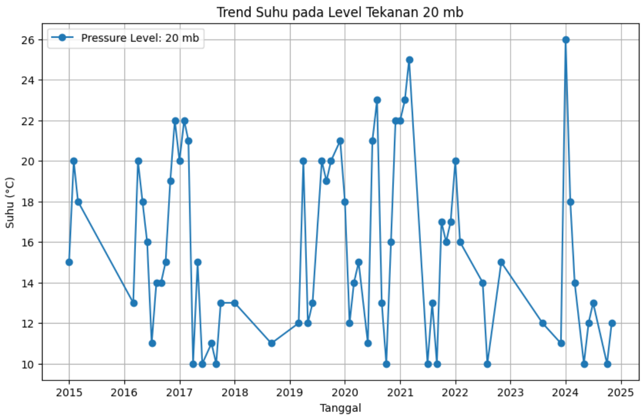

Fig.5. Temperature Trend at 20 mb Temperature Level

b. Trend Visualizations

Line plots illustrating long-term temperature trends reveal the consistent warming of the troposphere alongside the gradual cooling of the stratosphere. Seasonal variations are evident, with sharper transitions occurring during winter months in high-latitude regions.

These visualizations are indispensable for conveying intricate atmospheric patterns, rendering them accessible to a wider audience, inclusive of policymakers and researchers.

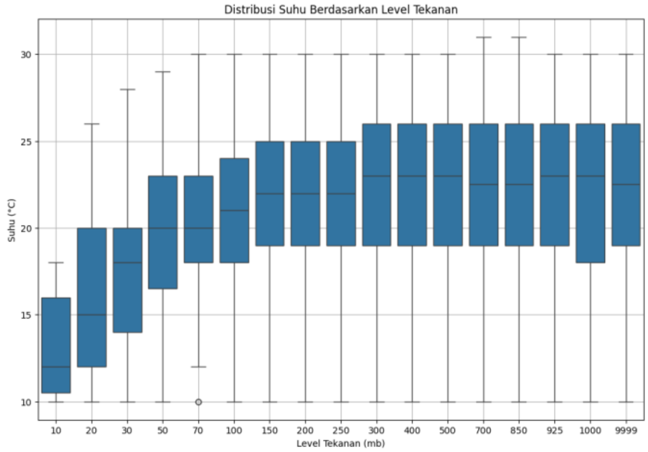

Fig.6. Temperature Distribution Based on Pressure Level

c. Interpretation of the Temperature Distribution

The boxplot presented in the figure offers a visual depiction of temperature distribution across various atmospheric pressure levels, articulated in millibars (mb). The horizontal axis delineates the pressure levels, extending from low pressures such as 10 mb—indicative of the upper atmosphere or stratosphere—to higher pressures, such as 9999 mb, which correspond to near-surface conditions. On the vertical axis, temperatures are charted in degrees Celsius, spanning from approximately 10°C to over 30°C.

From this figure, a general pattern can be observed where the temperature increases as the pressure level rises, which reflects the natural atmospheric temperature-pressure relationship. At lower pressures, which are indicative of higher altitudes, temperatures tend to be significantly lower. For instance, at pressure levels between 10 mb and 50 mb, temperatures consistently remain between 10°C and 15°C, and the distribution is quite narrow. This signifies stable atmospheric conditions, likely associated with the stratosphere, where temperatures are relatively homogeneous due to less turbulent air movement and radiative processes.

As the pressure escalates toward the mid-range levels, particularly from 100 mb to 300 mb, the temperature distribution begins to exhibit increased variability. The median temperatures within these levels progressively rise to an approximate range of 20°C to 25°C. This segment pertains to the upper and mid-troposphere, a region wherein convective processes, wind interactions, and radiative effects exert substantial influence on temperature dynamics. In contrast to the stratosphere, the troposphere is characterized by a greater level of dynamism, as it is subject to the influences of weather systems, cloud cover, and solar radiation. This heightened variability is manifested in the dispersion of the data, as evidenced by the broader interquartile range (IQR) presented in the boxplots. The occurrence of maximum temperature values attaining up to 30°C at these levels further underscores the dynamic At elevated pressure levels, specifically between 400 mb and 9999 mb, the temperature distribution becomes increasingly pronounced and stabilizes. Median temperatures at these levels consistently attain values ranging from 25°C to 27°C. This range is indicative of lower tropospheric and near-surface atmospheric conditions, wherein processes such as diurnal solar heating, boundary layer turbulence, and surface-atmosphere energy exchanges predominate in determining temperature variability. In contrast to the upper atmospheric layers, temperature values at these levels exhibit a considerably broader range, with maximum values frequently reaching 30°C. This observation accentuates the impact of daytime heating, surface radiation, and localized weather phenomena, such as cloud cover or winds, which contribute to the noted variations. The extensive spread of the boxplots further illustrates the variability of surface conditions across diverse regions and temporal contexts.

The overall trend in this temperature-pressure relationship aligns with the atmospheric lapse rate, a fundamental concept in meteorology, which describes how temperature decreases with altitude. In simpler terms, as pressure decreases—indicating higher altitudes—the temperature also drops. This behavior is a direct consequence of adiabatic cooling, where rising air expands and loses energy in the process, causing a temperature decrease. Conversely, near the Earth's surface, where pressures are higher, the energy input from solar radiation and surface heating causes temperatures to rise significantly.

4. DISCUSSION

The results presented in this study illustrate a distinct relationship between temperature distribution and atmospheric pressure levels. The temperature values exhibit an inverse trend with decreasing pressure, which aligns with the theoretical principles of the atmospheric lapse rate. At lower pressure levels (10–50 mb), representing the stratospheric region, temperatures remain consistently low, typically between 10–15°C, with minimal variability. This stability reflects limited vertical mixing and energy transfer in the stratosphere, consistent with findings from previous satellite studies such as the S-N Microwave Sounding Unit [6]. In contrast, the mid-pressure levels (100–300 mb), corresponding to the mid-troposphere, reveal higher temperature variability due to dynamic atmospheric processes, such as convection, large-scale wind systems, and cloud-related energy exchanges, findings echoed in Doppler LiDAR wind profiling research [10].

The boxplots further show increased temperatures and broader spreads at higher pressure levels (400–9999 mb), which correspond to the lower troposphere and near-surface regions. These levels exhibit median temperature values of up to 30°C, primarily driven by surface solar heating and boundary layer turbulence. The variability in this region is influenced by factors such as daytime heating, cloud cover, and geographical conditions. Such behavior aligns with previous studies evaluating radiosonde temperature data for climate monitoring [11], which highlighted enhanced near-surface variability during daytime conditions. Furthermore, the consistent presence of upper temperature limits (~30°C) across various layers suggests localized thermal extremes, possibly driven by heatwaves or surface-induced warming, as has been observed in radiosonde-based high-resolution studies [3].

The findings presented here emphasize the value of high-resolution radiosonde observations for analyzing vertical thermal structures within the atmosphere. The automated analysis framework applied in this study ensures consistency and accuracy in data processing, reducing biases from instrumentation and environmental factors. This approach aligns with earlier research, such as HadAT radiosonde analysis [1], which underlines the importance of homogenizing temperature records to detect long-term trends accurately. By revealing clear patterns of tropospheric warming and stable stratospheric cooling, the results further corroborate the well-documented impacts of anthropogenic greenhouse gas emissions and ozone depletion on atmospheric temperature distribution.

5. CONCLUSION

This study demonstrates the importance of radiosonde temperature measurements in analyzing vertical temperature distributions across different atmospheric pressure levels. The findings reveal distinct thermal patterns, with lower temperatures and reduced variability observed at low-pressure levels in the stratosphere, while higher temperatures and greater variability occur at high-pressure levels in the lower troposphere. These observations align with established atmospheric dynamics, such as the lapse rate and surface-driven heating processes.

By applying an automated Python-based framework for data preprocessing, analysis, and visualization, this research successfully mitigates inconsistencies and biases often associated with radiosonde data. The use of homogenization techniques ensures the accuracy and reliability of long-term climate trend analyses. Such automated approaches pave the way for more efficient, reproducible, and scalable methods in climate research, contributing to better monitoring of atmospheric changes.

In conclusion, the study underscores the critical role of radiosonde data in understanding tropospheric warming and stratospheric stability, both of which are key indicators of climate change. Future work should focus on integrating additional observational tools, such as satellite measurements and LiDAR systems, to improve spatial and temporal resolution. Continued refinement of automated analysis techniques will further enhance the ability to detect and interpret atmospheric trends, providing valuable insights for climate modeling and mitigation strategies.

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