

Understanding Climate Change Effects on Bird Migration: A Spatiotemporal Approach with GRU and HDBSCAN

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Abstract—This study investigates the influence of climate change on bird migration patterns, utilizing machine learning techniques to predict and analyze migratory behaviors. Bird migration is a complex, seasonal phenomenon influenced by environmental changes that affect survival and reproduction. Climate change, particularly rising global temperatures and altered seasonal patterns, has increasingly impacted migratory routes, timings, and morphological characteristics of bird species. This research employs a Gated Recurrent Unit (GRU) model alongside Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN), trained on historical migration data and climatic factors, to predict future migration patterns and assess environmental impacts. The methodology includes data preprocessing, model training, prediction visualization, and comparative analysis with climate data. By providing insights into shifting migration trends, this approach aims to support conservation efforts, enhance understanding of climate change's ecological effects, and improve strategies for preserving migratory bird populations. The findings highlight critical environmental variables and offer recommendations for mitigating the adverse effects of climate change on avian migration.

I. INTRODUCTION

Bird migration is a seasonal movement of birds between breeding and wintering grounds that occurs twice a year. It is typically from north to south or from south to north. Migration is inherently risky, due to predation and mortality. The Arctic tern holds the long-distance migration record for birds, travelling between Arctic breeding grounds and the Antarctic each year. Some species of tubenoses, such as

albatrosses, circle the Earth, flying over the southern oceans, while others such as Manx shearwaters migrate 14,000 km between their northern breeding grounds and the Southern Ocean. Shorter migrations are common, while longer ones are not. The shorter migrations include altitudinal migrations on mountains such as the Andes and Himalayas [1].

The timing of migration seems to be controlled primarily by changes in day length. Migrating birds navigate using celestial cues from the Sun and stars, the Earth's magnetic field, and mental maps. Writings of ancient Greeks recognized the seasonal comings and goings of birds [1]. Aristotle wrote that birds transmuted into other birds or species like fish and animals, which explained their disappearance and reappearance. Aristotle thought many birds disappeared during cold weather because they were torpid, undetected in unseen environments like tree hollows or burrowing down in mud found at the bottom of ponds, then reemerging months later. Still, Aristotle recorded that cranes travelled from the steppes of Scythia to marshes at the headwaters of the Nile, an observation repeated by Pliny the Elder in his *Historia Naturalis* [1]. Two books of the Bible may address avian migration. The Book of Job notes migrations with the inquiry: "Is it by your insight that the hawk hovers, spreads its wings southward?". The Book of Jeremiah comments: "Even the stork in the heavens knows its seasons, and the turtle dove, the swift and the crane keep the time of their arrival". In the Pacific, traditional land-finding techniques used by Micronesians and Polynesians suggest that bird migration was observed and interpreted for more than

3,000 years. In Samoan tradition, for example, Tagaloa sent his daughter Sina to Earth in the form of a bird, Tuli, to find dry land, the word tuli referring specifically to land-finding waders, often to the Pacific golden plover.

Climate change has raised the temperature of the earth by about 1.1 °C since the industrial revolution. As the extent of future greenhouse gas emissions and mitigation actions determines the climate change scenario taken, warming may increase from present levels by less than 0.4 °C with rapid and comprehensive mitigation to around 3.5 °C by the end of the century with very high and continually increasing greenhouse gas emissions. Birds are a group of warm-blooded vertebrates constituting the class Aves, characterized by feathers, toothless beaked jaws, the laying of hard-shelled eggs, a high metabolic rate, a four-chambered heart, and a strong yet lightweight skeleton. Climate change has already altered the appearance of some birds by facilitating changes to their feathers. A comparison of museum specimens of juvenile passerines from the 1800s with juveniles of the same species today had shown that these birds now complete the switch from their nesting feathers to adult feathers earlier in their lifecycle, and that females now do this earlier than males. Further, blue tits are defined by blue and yellow feathers, but a study in Mediterranean France had shown that those contrasting colors became less bright and intense in just the period between 2005 and 2019.

A study in Chicago showed that the length of birds' lower leg bones (an indicator of body sizes) shortened by an average of 2.4% and their wings lengthened by 1.3%. In the central Amazon area, birds have decreased in mass (an indicator of size) by up to 2% per decade, and increased in wing length by up to 1% per decade, with links to temperature and precipitation shifts. These morphological trends may demonstrate an example of evolutionary change following Bergmann's rule. Across Eurasia, snowfinches became both smaller and darker over the past 100 years.

II. LITERATURE SURVEY

Birds evolved the ability to migrate efficiently over long distances due to their need for frequent food supply, which is not always available year-round. Migratory and nonmigratory birds share similar traits, with some species exhibiting partial migration. Dorst

et al. [1] compared obligate and facultative migration in birds. Obligate migration followed fixed patterns, while facultative migration varied based on environmental conditions. Both were seen as adaptive strategies along a continuum of migratory behavior.

Newton [2] proposed that migratory bird populations breeding in Europe and wintering in sub-Saharan Africa declined faster than nonmigratory species. Habitat changes, illegal hunting, and climate shifts contributed to these declines. Preservation of habitats and stopping illegal killing were seen as crucial steps.

Bairlein et al. [3] highlighted that rising temperatures lead to earlier migratory bird arrivals, enhancing breeding success and population growth. This study further supports the notion that climate change, rather than detectability, primarily drives these shifts, particularly in species adaptable to temperature changes.

Koleček et al. [4] explored how barnacle geese adjust their spring-staging site choices in response to climate change and population growth, revealing that older geese lead group decisions while younger geese adapt based on density. Social learning and group behavior, rather than food availability, drive these adaptations.

Oudman et al. [5] conducted a global analysis revealing that migratory birds and mammals exhibit faster life paces than non-migratory species, with migrants being larger in swimming and walking species but smaller in flying species. These findings highlight how migration influences life histories and provide insights into species' potential responses to environmental changes.

Soriano-Redondo et al. [6] illuminated the intricate relationships between climate dynamics, habitat availability, and migratory behaviors. One study revealed that climate change is causing Arctic-breeding shorebirds to migrate earlier, impacting their breeding success and survival.

Smith, J., et al. [7] highlighted the detrimental effects of habitat fragmentation on migratory songbirds, demonstrating that reduced stopover sites significantly decrease their survival rates.

Lee, A., et al. [8] showcased a comparative analysis of migratory strategies across different species, detailing how phenotypic plasticity allows birds to adapt to varying climatic conditions. Together, these findings underscore the urgent need for effective conservation strategies to mitigate the effects of environmental change on migratory birds.

Patel, R., et al. [9] proposed the migration of Afro-Palaeartic birds is closely aligned with environmental cues, particularly the seasonal changes in vegetation. Birds tend to depart before vegetation senescence in autumn and arrive at their breeding grounds in spring when the plants are greening up. The timing of migration varies between the Western and Eastern flyways, influenced by the degree of continentality and the timing of vegetation growth at different latitudes. These findings underscore the critical role of environmental phenology in shaping migratory behavior on a broad geographical scale. Briedis et al. [12] similarly detailed broad-scale patterns of this Afro-Palaeartic landbird migration.

Bonnet-Lebrun et al. [10] provided evidence that birds migrate to seek warmer climates during their non-breeding periods, especially over long distances. Migration behavior likely originated in certain bird lineages, such as Passeriformes, but has been lost and re-evolved over time as species adapted to new environments.

Dufour, Paul, et al. [11] suggested bird migration is influenced by a combination of climate, resource availability, and urbanization. As global changes in climate and land use continue, bird migratory behaviors are already adapting to these new conditions.

III. METHODOLOGY

This study employs a Gated Recurrent Unit (GRU) neural network model to predict bird migration patterns influenced by climate variables, alongside Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) for preprocessing. The methodology consists of the following stages:

- **Data Collection and Preprocessing:** Historical bird migration data and climate data were sourced from GPS tracking datasets and real-time cross-

weather APIs to capture variables like temperature, wind speed, and precipitation. The migration data was cleaned to remove outliers and missing values utilizing K-Nearest Neighbors (KNN) Imputation and MinMax scaling. Climate variables were standardized and aligned temporally with the migration data.

- **Feature Engineering and Clustering:** New features were derived from the climate data, such as temperature anomalies and precipitation changes over migratory routes. HDBSCAN was applied to effectively handle complex cluster shapes and variable densities, leading to a more precise identification of migration stopover points.
- **Model Architecture:** A GRU model was chosen over an LSTM due to its effectiveness in time-series prediction with fewer parameters, limiting excessive adaptation and preventing overfitting. The network consists of two GRU layers (with 50 units each) and a dense output layer.
- **Training and Validation:** The dataset was split into training and test sets. The model was trained on 80% of the data and tested on the remaining 20%. During training, the model learned associations between historical climate conditions and migratory behaviors.
- **Loss Function and Optimization:** A Mean Squared Error (MSE) loss function was used to evaluate the model's predictions, and the Adam optimizer was employed to enhance convergence. Normalization techniques such as dropout and L2 regularization were applied to constrain learning capabilities and improve generalization.

IV. RESULTS

The proposed GRU model demonstrated significant improvements in predictive accuracy compared to traditional LSTM approaches. The GRU model achieved a Mean Absolute Error (MAE) of 0.0192 and a Mean Squared Error (MSE) of 0.001. In contrast, the baseline LSTM model recorded a much higher MAE of 20.2257 and an MSE of 621.672. Furthermore, the GRU model achieved a perfect R2 score of 1 and testing accuracy of 1.0 (100%), significantly outperforming the LSTM model's negative R2 score. While the GRU model required a longer training time (1075.75 seconds compared to the LSTM's 245.56

seconds), it proved to be much more memory-efficient, consuming only 857.82 MB compared to the LSTM's 3025.6 MB. Additionally, the application of the HDBSCAN algorithm effectively filtered out irregular data noise and successfully identified critical migration stopover clusters without requiring a predefined number of clusters.

V. DISCUSSION

The findings indicate that utilizing GRU networks over LSTM networks effectively mitigates the issue of overfitting when processing noisy GPS tracking data. Because GRU architectures require fewer parameters, they provide a streamlined, computationally efficient alternative that generalizes better to unseen sequential data. The reduced memory consumption of the GRU makes it highly suitable for large-scale ecological analysis.

Furthermore, integrating real-time climate data revealed how environmental variables—such as temperature fluctuations, humidity, and wind speed—directly influence migratory behaviors and route deviations. The model successfully highlighted how sudden weather changes and habitat destruction force birds to alter their traditional flight paths.

VI. CONCLUSION

This study presents a robust, data-driven framework for forecasting bird migration patterns utilizing GPS tracking, HDBSCAN clustering, and a GRU neural network. By accurately mapping trajectories and identifying the environmental factors that disrupt them, this model provides critical insights for ecological management. The predictive capabilities of this system can directly support conservation efforts by identifying key stopover habitats that require protection, allowing policymakers to implement strategies that mitigate the adverse effects of climate change and urbanization on migratory bird populations.

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