EXPLORING THE ENVIRONMENTAL FACTORS INFLUENCING MOVEMENTS OF TURKEY VULTURES (*Cathartes aura*) IN NORTH AMERICA

By

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CHAPTER 1

INTRODUCTION

Avian ecology has long perplexed ecologists due to technical challenges and lack of proper tools to monitor behaviors of migratory birds and their long distance migration paths and local movements. The development of binoculars in the late 1800s and bird banding in the early 1900s provided ecologists with a better understanding of avian migrations. However, in recent years satellite-tracking technologies such as Global Positioning Systems (GPS), combined with Geographic Information Systems (GIS) has drastically improved techniques to monitor and analyze movements of animals, particularly migratory birds. Advancements in data collection methods combined with GIS technology have significantly facilitated research on animal movement as documented in “trends and missing parts in the study of movement ecology” (Holyoak et al., 2008) and a review of recent research achievements through multidisciplinary collaborations between the Geographic Information Science (GIScience) community and movement ecologists (Demšar et al. 2015).

Large-scale movement observations over multiple years coupled with satellite observations of environmental and geographic conditions such as wind, elevation, and temperature have provided insight into how environmental variations influence movement behaviors of avian species (Dodge et al., 2014, Safi et al., 2013). Understanding how changes in climate and habitat affect the movement paths and migration patterns of migratory birds such as turkey vultures is critical to both avian conservation (Mandel et al., 2011) and predicting the behavioral responses of avian populations to ongoing and future land-use, climate, and habitat changes (Alerstam,
Previous studies have shown that weather events, seasonality, altitude, wind patterns, and physical terrain can have an influence on movement patterns of both avian and terrestrial species (Thorup et al., 2006, Ahearn, S.C. and J.L.D. Smith, 2005, Safi et al., 2013).

**Purpose of Study**

The aim of this study is to investigate and provide insight into the geographic and environmental factors that influence the movements of avian species. As a case study, this research analyzes the migration paths of turkey vultures (*Cathartes aura*) in North America in relation to their embedding environment (e.g. wind and temperature) and underlying geography (e.g. landscape and topography). The turkey vulture is an ideal species to study due to their abundance and their complex long-distance migration.

Previous studies indicate that climate and habitat can influence the migration patterns of avian species (Bairlein, 2008). This study investigates the following research questions:

1. What are the environmental, geographic, and movement variable value ranges along the migration tracks of turkey vultures?
2. How do these environmental, geographic, and movement variables differ by season?
3. How do the environmental and geographic variables influence the movement variables of turkey vultures along their migration tracks?
4. Which environmental and geographic variables along the migration paths are related to one another?
CHAPTER 2

REVIEW OF LITERATURE

Turkey vultures (*Cathartes aura*)

Turkey vultures (*Cathartes aura*) are the world’s most abundant and widely distributed obligate avian scavenger species that occupy many habitat types within the Americas (Dodge et al., 2014). With a wingspan of 60-183 cm, a length of 62-81 cm, and a weight ranging from 0.8 to 2.3 kg, the turkey vulture is a large bird that has a large global population (Ogada et al., 2011). At least two million turkey vultures migrate annually from high latitudes areas (southern Canada) to low latitudes areas (southern South America), reversing their latitudinal relationship between seasons (Dodge et al., 2014). This long-distance migration behavior is unique and is not fully understood. A migration corridor exists through the middle of the United States and becomes much narrower as they migrate through Central America and subsequently widens as migration moves south into South America. This behavior could be influenced by multiple environmental variables such as wind, temperature, and terrain characteristics (Dodge et al., 2014, Thorup et al., 2003). This study intends to explore such dependencies.

Diet

Due to their low-energy soaring behavior, Turkey vultures (*Cathartes aura*) are more efficient at exploiting unpredictable food resources than most animals as they feed almost exclusively on carrion (López-López et al., 2013). Previous studies suggest that foraging strategies of the individuals of the same species should show similar behavior in response to similar conditions (Austin et al., 2004, Forester et al., 2007). Contrary to previous studies, there is a growing awareness that there is much more individual behavioral flexibility than previously suggested, adding to what we know about how
scavengers efficiently find food resources (Hawkes, 2009, Wolf & Weissing, 2012). Availability or deprivation of food is a critical driver in the movement of individual vultures (Spiegel et. al., 2013). Breeding vultures exhibit more home range unpredictability than non-breeding vultures as they search for food for their developing young (Houston et al., 2011, Margalida & Colomer, 2012).

**Human/Environmental Influences on Movement and Migration of Turkey Vultures**

The turkey vulture (*Cathartes aura*) is protected by the implementation of the Migratory Bird Treaty Act of 1918 (MBTA) that states that it is unlawful without a waiver to pursue, hunt, take, capture, kill, or sell migratory birds in the United States and Canada. Legal protection has allowed turkey vulture populations to remain stable, making it an ideal species for avian movement studies.

Migration patterns are complex and variability in environmental factors can alter behavior and movement of migrating avian species (in local and global scales) (Sapir et al., 2011, Bairlein, 2008, Alerstam, 1979). Changes in the mean migration temperature can affect arrival and departure times of multiple avian taxa (Sapir et al., 2011). Soaring bird species (i.e. birds showing sustainable flight of long periods of time without flapping their wings) such as turkey vultures can be strongly impacted by the wind conditions, such as thermal and orographic uplifts (Bohrer et al., 2012), affecting their flight speed and optimal migratory routes (Safi et al., 2013). Previous studies indicate that turkey vultures nearly exclusively prefer *thermal uplift* (i.e. circular wind patterns formed due to the heating of the land surface by solar radiation during the daytime) instead of a ridge/orographic lift (i.e. updrafts resulting from deflection of horizontal winds by sloping terrain) (Bohrer et al., 2012, Shamoun-Baranes et al., 2006). Thermal soaring is energetically efficient and can provide longer ranges of migration (Klasseen et al., 2004).
The inevitable interaction of wind and temperature promote avian species to be selective in their movement patterns (Alerstam, 1979) while differences in terrain features can promote orographic uplift, which can be utilized by the birds (Mandel et al., 2008). Turkey vultures preferentially use thermal updrafts for soaring flight and actively seek locations and times when available thermal uplifts are stronger, including departure and arrival times (Dodge et al., 2014, Shamoun-Baranes et al., 2006). Wind force can increase with altitude, however wind direction can change by as much as 180° (Klasseen et al., 2004). This could explain why most birds do not fly higher than 2,000 m above sea level (Alerstam, 1990). If extreme enough, such meteorological conditions can change energetic costs of migration and could potentially alter the species’ selective environments (Bohrer et al., 2012). In addition, differences in wind assistance, location, and season can influence migration speeds of avian species (Shamoun-Baranes et al., 2006) and previous research implies that their behavior in response to environmental variables is directly linked to a biological response (Shamoun-Baranes et al., 2006). Understanding how environmental and geographical variables influence the movement path and migration patterns of turkey vultures is critical to both avian conservation in general, and predicting the demographic responses of avian populations to ongoing and future land-use, climate, and habitat change (Alerstam, 1990, Dodge et al., 2013).

**Home Range**

Resource availability, migration costs, and presence and absence of breeding behaviors can have an effect on turkey vulture home ranges (Hedlin et al., 2013). Previous studies indicate that avian movement extents can change during the breeding and non-breeding seasons (Monsarrat et al., 2011). Turkey vultures have shown to have considerable variation in their breeding home range size (Dodge et al., 2014). Food
availability is the primary determinant of avian range size and all other factors are secondary (Houston et al., 2011). In my study, I will primarily focus on the migratory paths of the turkey vultures and not their non-migratory home ranges.

**Movement Observations**

For centuries, the departures and arrivals of bird species to and from their breeding grounds were not understood. The invention of binoculars in the 1800s enhanced our ability to view distant wildlife. For nearly 200 years movement observations were only possible through the use of binoculars. In 1899, Hans Christian Cornelius Mortensen drastically improved our knowledge of migration through bird banding or ringing. This process includes attaching a small, individually numbered metal or plastic tag to the leg or wing of a bird, enabling the individual to be identified should it be recaptured or recovered. Bird banding (or ringing) can provide information about migration, longevity, population studies, territoriality, feeding behavior, and other dynamics of interest to ornithologists (Bairlein, 2008).

In the early 1940s, ornithologists began using radar technology to study the movements of bird species. North American bird migration maps were created to better understand spatial patterns but also allow for quantitative season-to-season and year-to-year comparisons of species in the different regions and habitats (Gauthreaux and Belser, 2005)

In recent years, more advanced techniques allowed for more detailed information about movements of avian species. The use of Global Positioning Systems (GPS), Geolocators (GLS), and satellite telemetry has enhanced detailed spatial and temporal resolutions of avian migrations observations. GLS and GPS are two technologies that have enhanced our ability to track migratory birds on a worldwide scale (Seegar et al.,
GLS is based on real-time measurement of ambient light intensity while GPS is based on receiving signals from satellites that calculate a bird’s position (Bairlein, 2008). GLS only work when daylight is present and are not as accurate as GPS (i.e. less than 15 meters). However, the small size of GLS allows for these devices to be successful when used on smaller animals such as small birds. Satellite telemetry, more specifically biotelemetry, technique advancements have resulted in a better understanding of wildlife populations, especially avian species (Bairlein, 2008, Fancy et al., 1988). Satellite telemetry studies combined with data about the Earth’s weather and land surface conditions have provided drastic improvements to the way we understand migration mechanisms (Mandel et al., 2008).

Radio-frequency identification (RFID) has provided valuable insight into the movements, activities, and behavior of many wildlife species, especially birds. Many different techniques have been used to attach radio transmitters to wildlife species. Harness-mounted radio transmitters have provided good results, but evidence suggests that the devices can alter behavior, movement, and impair survival. Disadvantages to these devices include skin irritation, restricted mobility, alteration to body contour and coloration, alteration of natural weight distribution, vulnerability to predation, and perhaps psychological effects (Amstrup, 1980).

Each of these technologies allow for collection of time-ordered records of movement locations at regular or irregular temporal intervals. The differences in technologies used for movement data collection consist of power capacity, temporal and spatial resolutions, size, and ease of use.
Movement Analysis

As location-aware devices, primarily GPS receivers, have been developed, the analysis of movement data has gained a significant momentum in GIScience (Dodge et al., 2016). Typically, movement data are represented using ‘trajectories’ as a time-ordered sequence of positional observations as shown in Figure 1 (Dodge, 2011 and Long and Nelson, 2012). Additional information associated with a moving entity can also be derived from the trajectory. These attributes either can be classified as instantaneous parameters, such as velocity, speed, position, and direction or relative parameters such as relative speed, turning angle, and path sinuosity (Long and Nelson, 2012). Information derived from movement parameters together with the path that the object takes can provide insight into the behavior of the object during its movements. Furthermore, information derived from movement parameters is crucial to trajectory data analysis (Dodge et al., 2009).

![Figure 1. Anatomy of a movement trajectory](image)

Using time and other attributes (instantaneous and relative parameters), a trajectory can be developed (Dodge et al., 2011).

Trajectory analysis is an important component of computational spatiotemporal analytics that has been used in many different fields of science and technology such as transportation, surveillance, security, marketing, and conservation (Gudmundsson et al., 2012). Quantitative techniques to extract information from movement datasets lagged
behind the technology used for data collection until the early 1990s (Long and Nelson, 2012). Recent development of GIS tools and techniques have aided in the ability to preprocess data, distill movement information, and analyze large movement datasets to study patterns and relationships (Long and Nelson, 2012). Through the use of GIS, effective visualization of movement patterns can easily be achieved, leading to an increase in the use of GIS for movement analysis research (Xavier and Dodge, 2014).

With access to rich spatiotemporal turkey vulture data, my research investigates the distributions, dependencies, and relationships within the environmental and geographic variables that have shown to influence the migration patterns of these birds based on previous research.
CHAPTER 3

METHODOLOGY

To answer the proposed research questions, I investigated the relationships between turkey vulture migration paths to the environmental and geographic conditions, within which their migration takes place. Through integration of GPS tracking data of turkey vulture migrations, environmental (e.g. wind, temperature), and geographic (e.g. elevation, distance to shoreline) datasets, I analyzed their spatial and temporal dependencies.

Data Sources

Different sources of turkey vulture tracking and environmental datasets were used in this research. The datasets were heterogeneous in terms of their source, format, and spatial and temporal granularities. The main challenge for data processing was to integrate these datasets in a meaningful way in order to investigate their correlations in space and time. The underlying datasets of this research are summarized, as follows.

Movement Dataset

The turkey vulture movement data for this study were obtained from the Acopian Center for Conservation Learning, Hawk Mountain Sanctuary located in Kempton, Pennsylvania. This dataset includes 24-satellite tracked turkey vultures from four distinct populations over a 10-year period with sampling intervals between 1-3 hours. In this study, I focused on the two birds, Leo and Steamhouse, with the longest migration trajectories. These birds migrate from south central Canada to northern South America as seen in Figures 2 and 3 below (Dodge et al., 2014). Both birds show narrow migration corridors along the Gulf of Mexico and the Caribbean Sea and wider migration patterns when in the middle of the United States. These birds exhibit four behavioral segments in
their migration: breeding season, fall migration, non-breeding season (wintering grounds), and spring migration. Breeding seasons occur in the northern United States and Canada and the birds subsequently migrate south to northern South America, representing fall migration seasons. The return migration path from northern South America back to Canada is represented in this study as spring migration seasons. These seasonal behaviors were already identified and annotated in the dataset by domain experts (Dodge et al., 2014). This study only focused on fall and spring migration seasons and non-migrator segments were disregarded. The duration, temporal sampling rate, and number of fall and spring seasons within each bird’s migration dataset differ as seen below in Table 1.

Figure 2. Migration paths of Leo in North and South America. Movement observations during fall migrations are presented in red and spring migration tracking points are visualized in blue. Opacity is utilized to emphasize frequent point locations. This image was created using Carto (https://carto.com/).
Environmental Datasets

The Environmental-Data Automated Track Annotation (Env-DATA) system, openly available within Movebank (movebank.org), allows users to annotate selected animal tracking data with a set of environmental variables using different interpolation methods (Dodge et al., 2013). As shown below in Figure 4, the core of the Env-DATA Track Annotation Service is a complex web-based system that runs on a Linux application cluster and manages data flow between two servers and the client using a MySQL database. This system provides a user-friendly interface that allows users to seamlessly establish connections between environmental and movement data obtained from heterogeneous data sources.

Table 1. Dataset summary for both Leo and Steamhouse. Each bird differed in observation start time, number of days tracked, sampling rate, number of tracking points, and number of spring migrations. Both birds’ observations ended around similar times (late November/early December) and had 4 complete migration seasons (tracking data of Leo includes a ~1.5 year gap).

<table>
<thead>
<tr>
<th>Bird</th>
<th>Start Date of Migration Observations</th>
<th>End Date of Migration Observations</th>
<th>Duration of Tracking</th>
<th>Temporal Sampling Rate*</th>
<th>Number of Tracking Points</th>
<th>Number of Fall Migration Seasons</th>
<th>Number of Spring Migration Seasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leo</td>
<td>9/24/2007</td>
<td>11/21/2012</td>
<td>5 years and 60 days</td>
<td>1 hour</td>
<td>8208</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Steamhouse</td>
<td>9/30/2009</td>
<td>12/5/2012</td>
<td>3 years and 67 days</td>
<td>3 hours</td>
<td>2922</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 3. Migration paths of Steamhouse in North and South America. Movement observations during fall migrations are presented in red and spring migration tracking points are visualized in blue. Opacity is utilized to emphasize frequent point locations. This image was created using Carto (https://carto.com/).
In this research, the Env-DATA annotation service was used to annotate the turkey vulture tracking points with environmental variables in space and time. The following variables were used: temperature and wind parameters including tailwind (i.e. wind in the direction of movement), headwind (i.e. wind in the opposite direction of movement), and crosswind (i.e. wind perpendicular to the movement direction). These variables are derived from ECMWF global atmospheric reanalysis, an on-going project to perform analysis, predictions, and assessments on the systems of the earth, such as wind patterns and surface temperatures that started in 1979. Data from ECMWF have been commonly used in scientific studies, providing insight into many aspects of the Earth. This large amount of data, summarized below in Table 2, allowed for successful annotation of movement paths, and extraction of information needed to assess the various factors that influence the migration of turkey vultures.
**Table 2. Environmental dataset summary.** The environmental-data automated track annotation (Env-DATA) system was used for annotation of data.

<table>
<thead>
<tr>
<th>Data Service</th>
<th>Original Data Source</th>
<th>Annotated Variable</th>
<th>Temporal resolution</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECMWF global atmospheric reanalysis</td>
<td>ECMWF (<a href="http://www.ecmwf.int">http://www.ecmwf.int</a>)</td>
<td>10 m U/V wind components (m s(^{-1})), 2 m temperature (K)</td>
<td>6h</td>
<td>0.7°</td>
</tr>
<tr>
<td>Derived wind variables for flight</td>
<td>Calculated derived variables, based on ECMWF data</td>
<td>Tailwind support and crosswind (m s(^{-1}))</td>
<td>6h</td>
<td>0.7°</td>
</tr>
</tbody>
</table>

**Geographic Variables**

In order to investigate the influence of geography, two parameters were considered: the distance of migration paths to shorelines, and the elevation of terrain at the location of movement observations. The following data sources were utilized and are summarized in Table 3 below.

The Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG), is a high-resolution dataset that contains a combination of World Vector Shorelines (WVS) and CIA World Data Bank II (WDBII) data which has undergone extensive processing, removing error and inconsistencies. The data are available in shapefile format in 4 resolution levels to accommodate shoreline boundaries between land and ocean, lakes and land, island-in-lake and lake, and pond-in-island and island. This study utilizes the shoreline boundaries between land and ocean, and lakes and land to investigate the distance of the migration path to the nearest fresh or oceanic shoreline.

Digital elevation models (DEMs), digital models of a terrain’s surface, can be acquired in a variety of ways through techniques such as photogrammetry, LIDAR, and land surveying. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a joint project by the U.S. National Aeronautics and Space Administration (NASA) and Japan’s Ministry of Economy, Trade, and Industry (METI) to capture data for the creation of detailed maps of temperature, emissivity, reflectance, and elevation via satellite remote sensory device. The ASTER GDEM data used in this
study are highly accurate and are available for free from the National (Aeronautics and Space Administration (NASA) Earth Observing System Data and Information System via their Reverb data ordering service, in GeoTIFF format with a spatial resolution of 1 arc-second. This data was utilized to investigate the changes in ground elevation over the course of each migration path.

<table>
<thead>
<tr>
<th>Data Service</th>
<th>Original Data Source</th>
<th>Annotated Variable</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTER GDEM</td>
<td>NASA Reverb (<a href="http://reverb.echo.nasa.gov">http://reverb.echo.nasa.gov</a>)</td>
<td>Elevation (m) - GeoTIFF</td>
<td>1-arc second (~30m)</td>
</tr>
<tr>
<td></td>
<td>Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS)</td>
<td>Shoreline - .shp</td>
<td>40m</td>
</tr>
</tbody>
</table>

**Table 3. Geographical dataset summary.** The geographical data used in this study was manually processed, analyzed, and subsequently the environmental and movement data was overlaid for analyses.

**Data Processing**

Python scripts were written to pre-process data obtained from the Env-DATA, organize the data by time and season, and separate each bird into their own respective data files. Once the data was annotated and preprocessed, the environmental, geographical, and movement datasets (ASTER GDEM, GSHHG shoreline, and tracking data) were overlaid and imported into ArcGIS for visualization and geoprocessing.

**Data Calculations/Analysis**

I utilized Python and ArcGIS to develop geostatistical approaches to investigate relationships between movement parameters (e.g. median migration paths, movement speed), environmental variables (e.g. wind and temperature), and geographic variables (e.g. distance to shoreline and ground elevation). The analysis involves the following processes:

1. Computation of median migration paths (i.e. a prototypical path for each migration season obtained from the actual movement observations)
2. Computation of the distance between movement observations to the associated median migration path of the season

3. Calculation of movement speed along migration path

4. Computation of the distance between movement observations and the nearest shoreline

5. Derivation of elevation for each movement observation

6. Generation of boxplots for each variable

7. Analysis of variance via ANOVA and Tukey HSD tests

8. Calculation of Pearson Correlation Coefficients (PPC) between variable combinations

9. Investigation of the results using the Tukey HSD & PPC tests to look for data trends

The processes 1-5 are described in details in the following sections, while the results of processes 6-8 are presented in Chapter 4 and discussed in Chapter 5.

**Median Migration Paths**

The median migration paths for each bird and season were computed by developing a Python script to calculate the centroid locations along each seasonal migration path at 1-minute latitude intervals (1.853 km) utilizing the median center statistic tool. After calculating the centroid of the tracking point locations within each latitude interval, these centroid points were subsequently connected based on their temporal order. This resulted in two median paths for fall and spring migration seasons for each bird as seen in Figures 5 and 6 below. Using these median lines, the closest distance of each movement observation to the corresponding median line is then computed in ArcGIS using the ‘near analysis’ tool.
Figure 5. Median migration paths for Leo by season. A median migration path for both fall and spring of Leo migration was created by establishing 1-minute latitude intervals and utilizing the median center statistic tool. Subsequently, each median migration location was connected for the creation of the median migration path.

Figure 6. Median migration paths for Steamhouse by season. A median migration path for both fall and spring of Steamhouse migration was created by establishing 1-minute latitude intervals and utilizing the median center statistic tool. Subsequently, each median migration location was connected for the creation of the median migration path.

Calculation of Migration Speed

The movement speed between consecutive observations was calculated by developing a Python script to calculate the distance between two consecutive migration points using the Haversine formula as seen below in Figure 7, divided by the difference in time between the points. The results were then appended to the movement observations of each respective bird as km/hr.
To compute distance between two locations, longitude and latitude of both points are utilized in the Haversine distance formula where \( \Phi \) represents the latitude of each point, \( \lambda \) represents the longitude of each point, \( r \) the radius of the sphere, and \( d \) the distance between two point locations. This formula is only an approximation as the radius, \( r \), varies from 6356.752 km at the poles to 6378.137 km at the equator as the earth is not a perfect sphere. A radius value of 6371 km was utilized for my distance calculations in this study.

**Elevation Derivation**

To compute the ground elevation at each movement observation, the ASTER elevation data for both North and South America were retrieved and imported into ArcGIS via file geodatabase, by creating a new mosaic raster dataset. Subsequently, the movement observations were then overlaid on the mosaic raster dataset and the elevation values were extracted for each migration point location using the ‘extract values to points’ tool within ArcGIS, which appends the values to each bird’s respective data table.

**Distance to Shoreline**

Using the shoreline data from the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG), the distance of each migration point between 30 degrees north and 7 degrees north to the nearest shoreline was calculated in kilometers using the ‘near analysis’ tool within ArcGIS. All latitude point locations north of 30 degrees north were omitted as they were located within the mainland and did not provide value when investigating the closeness of observations to the Gulf of Mexico. The distances were then appended to the respective movement observations.
CHAPTER 4

RESULTS

Boxplots of movement, geographic, and environmental variables for each bird (i.e. Leo and Steamhouse), migration season (i.e. fall and spring), and variable were created to better understand trends and answer the first two research questions:

1. What are the environmental, geographic, and movement variable value ranges along the migration tracks of turkey vultures?
2. How do these environmental, geographic, and movement variables differ by season?

Statistical variance analyses were computed using an ANOVA and Tukey HSD tests on all variables for each migration season. Subsequently, Pearson correlation coefficient analysis was performed on possible variable combinations to better understand any relationships and to answer research question three and four:

3. How do the environmental and geographic variables influence the movement variables of turkey vultures along their migration tracks?
4. Which environmental and geographic variables along the migration paths are related to one another?

Results from each of these tests are as follows:

Seasonal Differences

In response to my first and second research questions, the seasonal trends of variable averages of each bird were also investigated. Table 4 shows that in the spring migration season, on average, the migration of both birds occur at a higher elevation, higher speed, deviate more from the median migration path, and experience more crosswind and tailwind than when compared to the fall migration seasons. In the fall,
both birds experience slightly higher temperatures and migrate further from the shoreline on average. These results indicate that seasonal differences and possibly environmental and geographical preferences exist during the migration of turkey vultures.

<table>
<thead>
<tr>
<th>Bird</th>
<th>Season</th>
<th>Temperature (K)</th>
<th>Elevation (m)</th>
<th>Distance to Shoreline (km)</th>
<th>Speed (km/hr)</th>
<th>Distance from Median Migration Path (km)</th>
<th>Crosswind (km/hr)</th>
<th>Tail/Headwind (km/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leo</td>
<td>Fall</td>
<td>293.812</td>
<td>138</td>
<td>52.446</td>
<td>4.631</td>
<td>28.817</td>
<td>1.699</td>
<td>0.063</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>291.321</td>
<td>227</td>
<td>46.414</td>
<td>5.670</td>
<td>31.824</td>
<td>2.363</td>
<td>0.309</td>
</tr>
<tr>
<td>Steamhouse</td>
<td>Fall</td>
<td>294.410</td>
<td>123</td>
<td>39.518</td>
<td>3.071</td>
<td>28.882</td>
<td>1.710</td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>293.856</td>
<td>243</td>
<td>35.465</td>
<td>4.952</td>
<td>40.031</td>
<td>2.031</td>
<td>0.452</td>
</tr>
</tbody>
</table>

Table 4. Summary of the average values for each bird/migration season. Other than average temperature and average distance to shoreline, the values for elevation, speed, distance from median migration path, crosswind, and tail/headwind are on average greater during the spring migrations than the fall migrations.

**Temperature**

Figure 8 shows the boxplots of temperature values for Leo during fall (shown in red) and spring (shown in blue) migration seasons. As seen in the figure and according to ANOVA and Tukey HSD analyses, the temperature ranges that Leo encountered along its first and second fall migration paths were not significantly different ($p=0.759$), while all other fall comparisons were statistically different ($p=0.000$). The spring migration seasons resulted in similar observations with only a few statistically similar temperature ranges; along first and second fall migration paths ($p=0.759$), second and fourth fall ($p=0.741$), while all other comparisons showed statistically different distributions for temperature values ($p=0.000$).
Figure 8. Boxplot of Leo temperature data by season. The total average temperature for fall migrations was 293.81K (20.66 °C) and the spring average was 291.32K (18.17 °C). Highest temperature observed in all migration paths was 308.67K (35.52 °C) and the lowest temperature observed was 267.93K (-5.22 °C).

The data for Steamhouse showed different results than Leo as there were few statistically significant differences within the dataset as shown in Figure 9. However, the distribution of temperature values faced by Steamhouse along its first fall migration path showed a statistical distinct pattern when compared to all other fall migrations, which were statistically similar to one another ($p = 0.000$). The temperature values along different spring migrations were statistically similar except when comparing the second to the third spring ($p=0.019$).
Figure 9. Boxplot of Steamhouse temperature data by season. The fall average was 294.41K (21.26°C) and the spring average was 293.85K (20.7°C). Highest temperature observed in all migration paths was 308.76K (35.61°C) and the lowest temperature observed was 268.68K (-4.47°C).

These differences in temperature could be a result of natural weather changes year over year.

**Elevation**

Figure 10 shows the boxplots of terrain elevations along migration paths for Leo. The distribution of elevation values along the migration paths of the first three fall migrations are not significantly different with an average of 148m and a high of 3330m, indicating that the bird could have chosen similar fall migration paths and/or prefer certain environmental characteristics at similar elevations when migrating south in the fall season. The fourth fall migration path elevation distribution was significantly different from the third fall migration path ($p=0.015$), and was 61m higher in elevation on average. The spring migration patterns indicated that the average elevation of the first (202m), third (156m), and fourth (209m) migration paths were not significantly different
and that the second spring migration (318m) was significantly different, indicating that the bird utilized a different migration path and/or environmental characteristics influenced the bird’s migration.

**Figure 10. Boxplot of Leo elevation data by season.** The fall average was 138m and the spring average was 227m. Highest elevation observed in all migration paths was 3330m and the lowest elevation observed was sea level (0m).
Figure 11 shows the histogram of Leo elevation data indicating that the bird prefers to migrate at lower elevations, but is capable of migrating at much higher elevations.

Figures 12 and 13 show the boxplots and histogram of terrain elevations along migration paths for Steamhouse. The results showed that Steamhouse flies over similar elevations during its fall migration with an average terrain elevation of 123 meters and a high of 2084 meters. This could indicate that the fall migration paths were similar year over year and/or the bird preferred the environmental characteristics at this particular elevation range. In the spring migrations, the second spring migration path showed statistically different elevations from the first (p=0.020) and third (p=0.030) migration paths. The elevations along the first and third spring paths were not significantly different (p=0.999) indicating that the bird followed distinctly different terrain during the second spring season. This indicates that the bird took a migration path over a mountain range (average elevation: 308m, highest elevation: 2892m) and/or potentially utilized
thermal uplift much more in the second spring than in the first and third spring migration paths (Mandel et al., 2008).

Figure 12. Boxplot of Steamhouse elevation data by season. The fall average was 123m and the spring average was 243m. Highest elevation observed in all migration paths was 2892m and the lowest elevation observed was sea level (0m).

Figure 13. Histogram of Steamhouse elevation data by season. The distribution frequency of elevations for Steamhouse indicates that Steamhouse prefers lower elevations during its migration paths in both fall and spring.

Results for both birds showed the average elevation distribution along fall migration paths (Leo = 138m, Steamhouse = 123m) are significantly lower than the spring migration paths (Leo = 223m, Steamhouse = 243m). The highest elevations were
observed in the first, second and fourth fall migration seasons for Leo, and the first and second spring migration seasons for Steamhouse. This could indicate that both birds control the atmospheric conditions, in particular wind patterns, they experience by selecting terrain with the best opportunity for orographic lift, and/or become spatially limited by topographic features within the landscape as a result of limited food resources during the seasons they reached their highest observed elevations.

**Distance from Shoreline**

Figures 14 and 15 show the boxplots and histogram of the distance from the nearest shoreline for Leo. The distance from the nearest shoreline in the first and third fall migrations were not significantly different ($p=0.475$) with the rest of the fall migration paths pairwise comparisons resulting in significant statistical differences ($p=0.000$). When investigating the spring migration seasons, the first three seasons were not statistically different, however the fourth season is statistically different from all three previous seasons ($p=0.000$), and was on average 29.4km further from the nearest shoreline than the first three seasons. This might indicate that the bird prefers to fly over a certain distance from the shoreline due to environmental/geographic conditions.

![Figure 14. Boxplot of Leo distance from nearest shoreline by season.](image)

The fall average was 52.44km and the spring average was 46.41km. Furthest distance from shoreline observed in all migration paths was 256.65km and the closest distance to the shoreline observed was 0.12km.
Figure 15. Histogram of Leo distance from nearest shoreline by season. The distribution frequency of distance from nearest shoreline for Leo indicates that the majority of Leo’s migrations in both fall and spring predominately takes place within 50km of the nearest shoreline.

Figures 16 and 17 show the boxplots and histogram of the distance from the nearest shoreline for Steamhouse. The first and third (p=0.842) and third and fourth (p=0.836) fall migration comparisons were not significantly different. All other fall pairwise comparisons were statistically different (p=0.000). The first and third (p=0.026) spring migrations were statistically different, however all other spring pairwise comparisons were not significantly different.
Figure 16. Boxplot of Steamhouse distance from nearest shoreline by season. The fall average was 39.51km and the spring average was 35.46km. Furthest distance from shoreline observed in all migration paths was 197.54km and the closest distance to the shoreline observed was 0.11km.

Figure 17. Histogram of Steamhouse distance from nearest shoreline by season. The distribution frequency of distance from nearest shoreline for Steamhouse indicates that the majority of Steamhouse’s migration in both fall and spring predominantly takes place within 50km of the nearest shoreline.

These results suggest that there are not any significant differences for these birds when analyzing the average distances from the nearest shoreline at lower latitudes. Both bird’s paths were observed to come within 120m of the shoreline and very rarely migrated directly over a body of water; i.e. less than 10-point locations located within a body of water. In cases in which the birds did migrate over water, it was only observed in bodies of fresh water and never oceanic conditions. This could be due wind pattern
disruptions associated with convergence zones within proximity of the ocean, preference to avoid beaches as they differ from their preferred habitats, and/or as indicated in figures 15 and 17 they prefer to keep a similar distance along the shoreline so that these birds can utilize the shoreline as a landmark to navigate.

**Speed**

Figure 18 shows the boxplots of the speed for Leo. The fall migration speed distributions were not significantly different and the spring migration comparisons resulted in the third spring being significantly different from all other migrations \((p<0.0001)\), while the speed values along the rest of the migration paths did not show a significant difference.

![Leo Migration Speed (km/hr)](image)

*Figure 18. Boxplot of Leo migration speed by season.* The fall average was 4.63 km/hr and the spring average was 5.67 km/hr. Highest speed observed in all migration paths was 83.99 km/hr.

Figure 19 shows the boxplots of the speed for Steamhouse. Both the fall and spring migration seasons showed speed ranges that were not significantly different by season, indicating a consistent migration speed. The different pattern of speed values observed for Leo in its third spring migration could be explained by lower ground
elevations and higher temperature values along its migration. This indicates that the bird used more thermal and orographic uplifts along its third spring migration and therefore exhibits a higher speed.

![Steamhouse Migration Speed (km/hr)](image)

**Figure 19. Boxplot of Steamhouse migration speed by season.** The fall average was 3.73 km/hr and the spring average was 5.42 km/hr. Highest speed observed in all migration paths was 58.42 km/hr.

When comparing the datasets of both birds together, they both exhibited similar trends within their migration seasons. Both birds migrated at a higher speed on average during the spring seasons (Leo= 5.67 km/hr, Steamhouse=5.42 km/hr) than in the fall seasons (Leo= 4.63 km/hr, Steamhouse=3.73 km/hr), had statistically similar migration speeds when comparing all pairwise fall migrations, and experienced more speed variability in the spring seasons.

**Distance from Median Migration Path**

Figure 20 shows the boxplots of the distance from the median migration path for Leo. The deviations from the median path during fall migrations were all statistically
similar except when comparing the second fall to the fourth \((p=0.010)\) and the third to the fourth \((p=0.038)\). The deviations from the median path during spring migration seasons were all statistically different \((p=0.000)\) except when comparing the first spring to the fourth \((p=0.939)\).

Figure 20. Boxplot of Leo distance from median migration path by season. The fall average was 28.81km and the spring average was 31.82km. Furthest distance from median migration path observed in all migration paths was 238.48km and the closest distance observed was 0.13km.

Figure 21 shows the boxplots of the distance from the median migration path for Steamhouse. The deviations from the median path during fall migrations were not significantly different except when comparing the second fall to the fourth \((p=0.010)\) and third to fourth fall \((p=0.038)\). The deviations from the median path during spring migrations were all statistically different \((p=0.000)\) except when comparing the first spring to the fourth \((p=0.939)\).
Figure 21. Boxplot of Steamhouse distance from median migration path by season. The fall average was 28.82km and the spring average was 40.03km. Furthest distance from median migration path observed in all migration paths was 282.11km and the closest distance observed was 0.11km.

The comparison of data for both birds and their distances from the median migration paths suggests that the average median migration distance of fall migration (Leo = 28.81km, Steamhouse = 28.88km) is significantly lower than the spring migration (Leo = 31.82km, Steamhouse = 40.03km). This indicates that each bird tends to deviate from the median migration path more often in the spring migration season than in the fall migration season, which could be due to higher variations in environmental conditions, geographic preferences, and/or availability deprivation of carrion within the spring seasons.

**Tail/Head Wind**

Tail/head wind computations are indicated by tailwind being a positive value as it propels the bird forward and headwind are negative values indicating a negative force against the bird’s flight. Figure 22 shows the boxplots of the tail/head wind of Leo. The results indicate that Leo often used statistically similar tailwind values during fall migrations except for when comparing the first fall to the second fall \(p=0.071\). The tailwind values of spring migration seasons were not significantly different to one another.
Figure 22. Boxplot of Leo tail/head wind data by season. The fall average was 0.06 km/hr and the spring average was 0.30 km/hr. Highest tailwind speed observed in all migration paths was 11.0 km/hr and the highest headwind speed observed was -16.1 km/hr.

Figure 23 shows the boxplots of the tail/head wind for Steamhouse, the results did not show any significant difference in tail/head wind values during fall and spring migration seasons.
Figure 23. Boxplot of Steamhouse tail/head wind data by season. The fall average was 0.06 km/hr and the spring average was 0.45 km/hr. Highest tailwind speed observed in all migration paths was 10.0 km/hr and the highest headwind speed observed was -10.1 km/hr.

The comparison of tail/head wind values used by both birds suggests that the average tailwind speed of fall migrations (Leo = 0.062 km/hr, Steamhouse = 0.065 km/hr) was significantly lower than the spring migrations (Leo = 0.309 km/hr, Steamhouse = 0.451 km/hr). This finding indicates that both birds experience tailwind assistance more often during the spring migration season when compared to fall migration. This could also explain higher migration speeds observed during spring seasons.

**Crosswind**

Figure 24 shows the boxplots of crosswind values for Leo. The ranges of crosswind values in fall migrations did not show a significant difference for all pairwise comparisons. The crosswind values during spring migrations were not significantly
different other than when comparing the first spring to the fourth ($p=0.002$), the first to the second ($p=0.000$), and the first to the third ($p=0.023$).

Figure 24. Boxplot of Leo crosswind data by season. The fall average was 1.69 km/hr and the spring average was 2.36 km/hr. Highest crosswind speed observed in all migration paths was 15.6 km/hr and the lowest speed observed was 0.0 km/hr.

Figure 25 shows the boxplots of crosswind for Steamhouse. The fall migration crosswind distributions were not significantly different other than when comparing the first fall to the second ($p=0.016$). The spring migrations crosswind distributions were not significantly different other than when comparing the first spring to the second ($p=0.013$) and the second to the third ($p=0.000$).
Figure 25. Boxplot of Steamhouse crosswind data by season. The fall average was 1.71 km/hr and the spring average was 2.03 km/hr. Highest crosswind speed observed in all migration paths was 11.9 km/hr and the lowest speed observed was 0.0 km/hr.

The comparison of crosswind data for both birds combined suggests that the average crosswind in fall migration (Leo = 1.69 km/hr, Steamhouse = 1.70 km/hr) is significantly lower than the spring migration (Leo = 2.36 km/hr, Steamhouse = 2.03 km/hr). This finding indicates that both birds receive more crosswind during the spring migration season with a maximum of 15.5 km/hr for Leo and 11.9 km/hr for Steamhouse when compared to fall migration. This can explain why these birds deviated more from their median migration path in spring.

**Pearson Correlations Coefficients of Variables**

Pearson correlation coefficient (PPC) analysis is a measure of the strength of a relationship two variables, giving a value between +1 and −1 inclusive, where 1 is total positive correlation between the two variables, 0 is no correlation, and −1 is total negative correlation. It is widely used in the sciences as a measure of the degree of linear dependence between two variables. In response to my third and four research questions, and to better understand the relationships between movement, geographic, and
environmental variables, the Pearson correlation coefficients were computed for meaningful variable combinations for each season and bird. The variable combinations that showed interesting PCCs are as follows, more PCC analyses are provided within the appendices.

**Speed and Temperature**

As seen in table 5, both birds demonstrated a positive relationship between migration speed and temperature. This relationship provides insight into the influence of thermal uplift. As temperature cools, the migration speed declines, and as the temperature rises, the migration speed increases. This relationship aligns with the dependence of thermal uplift as noted in previous research (Bohrer et al., 2012), which occurs when temperatures rise.

<table>
<thead>
<tr>
<th>Bird</th>
<th>Total Correlation</th>
<th>Fall Correlation</th>
<th>Spring Correlation</th>
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</thead>
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<td>Speed/Temperature</td>
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<td></td>
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<tr>
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<td>0.2261</td>
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<tr>
<td>Steamhouse</td>
<td>0.1765</td>
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<td>0.2241</td>
</tr>
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</table>

Table 5. Correlation coefficients of speed and temperature. Both birds show a positive relationship between migration speed and temperature.

**Speed and Tail/Headwind**

As seen in table 6, both birds demonstrated a relationship between speed and tail/headwind. As expected, this relationship is positive, indicating that as tailwind increases the migration speed increases. Although, the Pearson correlation coefficient indicates this relationship isn’t very strong, the positive relationship does ensure that wind patterns assist the birds’ migration.

<table>
<thead>
<tr>
<th>Bird</th>
<th>Total Correlation</th>
<th>Fall Correlation</th>
<th>Spring Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tail/Headwind</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leo</td>
<td>0.1547</td>
<td>0.1861</td>
<td>0.1232</td>
</tr>
<tr>
<td>Steamhouse</td>
<td>0.1159</td>
<td>0.0945</td>
<td>0.1130</td>
</tr>
</tbody>
</table>

Table 6. Correlation coefficients of speed and tail/headwind. Both birds show a correlation between migration speed and tail/headwind data. Since this correlation is positive, the data indicates that a relationship between speed and tailwind is observed.
**Crosswind and Distance from Median Migration Path**

As seen in table 7, both birds demonstrated a positive relationship between the absolute values of crosswind and the distance from the median migration path indicating that migration point locations that are further from the median migration path experience increased crosswind. Although the correlation is not strong, this positive relationship suggests that the crosswind challenges these birds and might force them to deviate from their preferred path (or median line).

<table>
<thead>
<tr>
<th>Bird</th>
<th>Total Correlation - Crosswind and Distance from Median Migration Path</th>
<th>Fall Correlation</th>
<th>Spring Correlation</th>
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</thead>
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<tr>
<td>Leo</td>
<td>0.1150</td>
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<tr>
<td>Steamhouse</td>
<td>0.1770</td>
<td>0.1771</td>
<td>0.1014</td>
</tr>
</tbody>
</table>

*Table 7. Correlation coefficients of crosswind and distance from median migration path. Both birds show a positive correlation between crosswind and the distance from the median migration path.*
CHAPTER 5  
DISCUSSION

This study aimed at exploring how environmental and geographical variables change and how they influence the migration patterns of turkey vultures. Through the creation of boxplots and pairwise comparisons utilizing Tukey HSD tests for each variable, bird, and season, changes overtime were investigated to establish distribution ranges specific to each variable, better understand variability/consistency of each variable overtime, and seasonal differences (fall vs. spring). This chapter discusses the main findings with regards to the initial research questions:

Environmental, geographic, and movement parameter value range and their seasonal variability (research questions 1 and 2)

Both birds often showed similar speeds along their migration paths for each season and over time (total average speed = 4.86 km/hr, highest speed: 83.99 km/hr). The average ground elevations along migration paths of both birds was greater than 250m with the median greater than 135.5m, while the highest ground elevation within their migration was 3330m. This indicates that the birds prefer lower elevations as seen above in Figures 15 and 17, however they have the ability to migrate over mountainous topography, but there is no evidence they ever migrate over areas past alpine tree line. Elevation preferences are likely driven by availability of carrion and opportunities for orographic uplift. Both birds showed a wide range of variation in their average distance from their median migration path, with maximum distances varying between 140-282km throughout all seasonal observations. These distances can provide insight into the preferred habitat ranges and environmental conditions for turkey vulture populations, which could be important in conservation efforts.
From the boxplots and Tukey HSD tests, interesting seasonal differences can be observed as displayed in Table 4. Both birds show higher average elevations, speed, distance from median migration path, crosswind, and tailwind in the spring seasons than when compared to the fall. This could be an indicator that the birds use orographic lift more than what previous studies suggest (Bohrer et al., 2012, Shamoun-Baranes et al., 2006). Orographic uplift can promote accelerated speeds at higher flight elevations (Bohrer et al., 2012), which typically influences wind speed patterns. These results could be utilized to benchmark movement parameters associated with thermal and orographic uplift to better understand conditions that influence avian scavengers, in particular, turkey vultures.

**Dependencies of movement, environmental, and geographic variables (research questions 3 and 4)**

To further explore environmental and geographic dependencies within the migration datasets, the Pearson correlation coefficient analysis was utilized to better understand how the variables within this study relate to one another. Weak positive relationships between migration speed and tailwind, speed and temperature, and crosswind and distance from the median migration path were detected. The positive correlation between speed and tailwind was expected (although it was not very strong), as previous research indicates that turkey vultures minimize energy expenditure through the utilization of wind patterns that benefit their migration directionality (Bohrer et al., 2012). The positive relationship between speed and temperature is likely a result of their preference to utilize thermal uplift as a way to soar for long distances. The positive relationship between absolute values of crosswind and distance from the median migration path is an interesting correlation that I did not expect to see as I assumed
crosswind would not influence the migration paths of turkey vultures very significantly. This correlation indicates that increased exposure to crosswind pushes the bird further from the median migration path. I anticipated seeing stronger correlations/relationships between the environmental and geographical variables, such as higher wind patterns when closer to shoreline due to sea breeze, and consequently higher movement speed and crosswind. It is important to note that a correlation between ground elevation and temperature was not observed. The reason is that the temperature data were obtained at fixed elevation (2m above surface) and therefore it was not relevant to ground elevation values (Dodge et al., 2014).

**Challenges**

This study had many challenges, most of which were related to data management and dataset resolution. The methodology of meshing the migration dataset from the Env-DATA annotation service that contained 250,000+ observation points with other environmental data of heterogeneous formats created unique obstacles throughout the annotation, analysis, and visualization process. To manage the large amount of data, this study required learning and developing tools within Python to be used as standalone scripts and within Esri’s ArcGIS product. I also learned and wrote R statistical computing scripts to analyze variance and execute pairwise comparisons for each seasonal migration path and the associated variables. As there were many different data sources used in this study, the spatial and temporal resolutions of the geographic and environmental data were not always the same as the resolution of the movement data. In addition, the exact elevation of the bird’s flight was not recorded within the dataset. Therefore weather and wind conditions that the birds were facing during their movements were interpolated and were not exact.
Future Research

This study utilized a unique long-term and high frequency (1-3 hours) tracking dataset of two turkey vultures including several complete migration cycles. The data was annotated and integrated with satellite data of the environment, shoreline, and terrain elevation. The results from this study provide insight into the spatiotemporal dependencies and relationships of turkey vultures’ migration patterns to their environment and geography. These results, however, needs to be verified and interpreted by domain experts in future studies. In this study, the data associated with the breeding season was excluded. There is certainly much to investigate in this subset of data.

Complementary to this study, it would be beneficial in future research to examine the environmental characteristics of habitats that these birds choose during their breeding season. By combining Normalized Difference Vegetation Index (NDVI), prey species richness indexes, topography, and climate data techniques, it would be interesting to characterize the turkey vulture’s habitat to better understand feeding patterns. This could contribute to the conservation efforts of the turkey vulture and other migrating avian species while potentially providing insight into their environmental dependencies. Other studies of interest would be to develop a methodology to better understand the effects that crosswind has on the sinuosity of the migration path, the reasoning for why these birds specifically avoid crossing oceanic water bodies, and to simply explore more variables with the same methodology used in this study. These additional studies could provide insight into which environmental and geographic factors that influence turkey vultures and could advance techniques used in ecological modeling and movement analysis. As a result, these studies may provide insight to better model and predict migration paths of turkey vultures in changing environments and it could ultimately contribute to
conservation of migrating avian species and improve GIS methodologies that incorporate geographic and environmental data into movement analysis.
CHAPTER 6

CONCLUSION

The results from this study shed light on existing spatial and temporal variations and relationships among movement parameters, and environmental and geographic conditions along migration paths. The study demonstrates that the Movebank Env-DATA Track Annotation Service can be utilized to aggregate heterogeneous data sources into data tables that can be annotated, managed, and processed and subsequently be analyzed with scripts and geospatial software packages to provide insight into the influences that the environment and geographic features have on migratory birds in particular, turkey vultures. Through the use of Tukey HSD and Pearson correlation analyses, relationships overtime as well as environmental, geographic, and movement dependencies can be explored, providing insight into the movement of avian species. These methodologies enable ecologists, wildlife biologists, GIS professionals, and others within the scientific community to better understand and predict spatiotemporal patterns of animal movement in response to a changing environment by automating the data aggregation process, which historically has been difficult to do. Methods of computational movement analysis are changing the way we investigate movement data. Data mining and machine learning algorithms will push this focused area of study in new directions uncovering correlations and dependencies between organisms and the environment that were previously unknown.
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### Pearson Correlation Coefficient Analysis Data

#### APPENDIX A

<table>
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<tr>
<th>Leo</th>
<th>Total Correlation</th>
<th>Fall Correlation</th>
<th>Spring Correlation</th>
<th>First Fall</th>
<th>First Spring</th>
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<td>0.02173737</td>
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<td>-0.03792</td>
<td>0.07246</td>
<td>0.3845794</td>
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<tr>
<td>Speed/Temp</td>
<td>0.22619477</td>
<td>0.13987015</td>
<td>0.312502525</td>
<td>0.2251925</td>
<td>0.1062085</td>
<td>0.1084743</td>
<td>0.10407</td>
<td>0.07246</td>
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#### Pearson Correlation Coefficient Analysis for Leo

<table>
<thead>
<tr>
<th>Steamhouse</th>
<th>Total Correlation</th>
<th>Fall Correlation</th>
<th>Spring Correlation</th>
<th>First Fall</th>
<th>First Spring</th>
<th>Second Fall</th>
<th>Second Spring</th>
<th>Third Fall</th>
<th>Third Spring</th>
<th>Fourth Fall</th>
<th>Fourth Spring</th>
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<tbody>
<tr>
<td>Speed/Tailwind</td>
<td>0.1159447</td>
<td>0.113019707</td>
<td>-0.03465802</td>
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<td>0.2050793</td>
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<tr>
<td>Speed/Crosswind</td>
<td>0.0178396</td>
<td>-0.01102057</td>
<td>0.03404293</td>
<td>0.2184542</td>
<td>0.1945004</td>
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<td>0.10627</td>
<td>0.07246</td>
<td>0.3845794</td>
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<tr>
<td>Elevation/Temp</td>
<td>0.03377471</td>
<td>0.06737948</td>
<td>-0.00842258</td>
<td>0.1579529</td>
<td>0.1097319</td>
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<tr>
<td>Elevation/Shoreline</td>
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<td>0.12937289</td>
<td>-0.04794876</td>
<td>0.252576</td>
<td>0.2364204</td>
<td>0.0049729</td>
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<tr>
<td>Median/Speed</td>
<td>-0.016005642</td>
<td>-0.023787086</td>
<td>0.00889647</td>
<td>-0.05554357</td>
<td>-0.03230595</td>
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<td>0.2364204</td>
<td>0.0049729</td>
<td>0.162055</td>
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<td>-0.07866996</td>
<td>0.0497777</td>
<td>-0.02417506</td>
<td>-0.217394</td>
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<td>Crosswind/Elevation</td>
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<td>Crosswind/Median</td>
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<td>Speed/Temp</td>
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<tr>
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<tr>
<td>Speed/Elevation</td>
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#### Pearson Correlation Coefficient Analysis for Steamhouse
# APPENDIX B

Tukey HSD Test Analysis Data

<table>
<thead>
<tr>
<th>Pairwise Comparisons</th>
<th>Elevation</th>
<th>Speed</th>
<th>Temperature</th>
<th>Distance to Shoreline</th>
<th>Tail/Headwind</th>
<th>Crosswind</th>
<th>Distance to Median</th>
<th>p-values</th>
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<tbody>
<tr>
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<td>0.02688</td>
<td>0.85661</td>
<td>0.00000</td>
<td>0.00096</td>
<td>0.00247</td>
<td>0.00000</td>
<td>0.99768</td>
<td>0.82251</td>
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<tr>
<td>Second.Fall-First.Fall</td>
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<td>0.75938</td>
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<tr>
<td>Third.Fall-First.Fall</td>
<td>0.99986</td>
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<td>0.17007</td>
<td>0.11126</td>
<td>0.72672</td>
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<td>0.02355</td>
<td>0.81487</td>
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<tr>
<td>Fourth.Fall-First.Fall</td>
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Tukey HSD Test Analyses Results for Leo

<table>
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<th>Pairwise Comparisons</th>
<th>Elevation</th>
<th>Speed</th>
<th>Temperature</th>
<th>Distance to Shoreline</th>
<th>Tail/Headwind</th>
<th>Crosswind</th>
<th>Distance to Median</th>
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<td>First.Spring-First.Fall</td>
<td>0.02688</td>
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Tukey HSD Test Analyses Results for Steamhouse