Thermal circulation affects Black Vulture *Coragyps atratus* soaring behaviour in the vicinity of two airports in south-east Brazil.

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http://dx.doi.org/10.4314/vulnew.v82i1.1

Abstract

The growth of air traffic all over the world faces an increasing risk of aircraft collisions with birds. The Black Vulture (*Coragyps atratus*), being a large soaring species living across the Americas, presents a serious hazard to airplanes. The reduction of this threat without harm to birds is a complex task requiring thorough investigations of their behaviour. Various natural and anthropogenic factors can affect the distribution of soaring Black Vultures in the surrounds of airports. Here we focus on the impact of meteorological parameters (i.e. air temperature, relative humidity, wind speed and atmospheric pressure) on Black Vulture flight at two study sites. In the course of one year, from September 2012 to August 2013, we surveyed with binoculars the soaring activity of Black Vultures around Amarais and Presidente Prudente airports in the southeast of Brazil. The study areas were characterized by tropical climatic conditions with mild dry winter and hot rainy summer. We found that the frequency of soaring flights depended on the wind speed, a proxy of the strength of thermals (upward air flows). This finding is consistent with habits of Black Vultures using thermals for soaring. In contrast, air temperature, air humidity and atmospheric pressure did not affect their activity. We also showed that the different seasons affected the birds' behaviour, but the degree of their influence depended on the level of anthropogenic pressure in the soaring terrain. Two contrasting types of daily soaring activity appeared: a plateau-like trend and a tendency of two peaks at morning and afternoon with a pronounced drop between them. Our findings can be used to inform methods to reduce the risk of collisions between aircraft and Black Vultures at our study sites, and our analytical approach could be applied elsewhere.

Introduction

The rising number of aircraft collisions with birds caused by the global increase of air traffic is a serious problem for many countries in the world (Hedayati & Sadighi 2016). Strikes with the Black Vulture (*Coragyps atratus),* a large scavenging bird weighing approximately 1.6 kg (Buckley 1999), are considered one of the most substantial hazards to aviation in both Americas (Bastos 2001, Oliveira & Oliveira Pontes 2012, Dolbeer *et al.* 2016). In Brazil, 8200 aircraft accidents with birds were registered from 2011 to 2016. Among identified species, Black Vulture was found as a cause of 52% of collisions (Oliveira *et al.* 2017).

Most bird strike events occur in the airport surroundings inside a circular zone with a radius of 10-20 km, where airplanes fly at low altitudes performing landing and take-off operations (Bastos 2001, Oliveira *et al*. 2017). Due to the large size and behavioural traits of Black Vultures, the most common control measures (i.e. falconry and ground deterrents) do not work against them (Bastos 2001, Cauville 2010). As natural predation of vultures is infrequent (Platt *et al.* 2021), their use of space is largely dependent on the distribution and abundance of food sources (Bastos 2000, Blackwell & Wright 2006). To mitigate the risk of collisions, the Brazilian government established the airport safety area (ASA) or circular buffer zones around each airport with a radius of 20 km. Human activities that attract foraging vultures, including tanning and fish industries, garbage dumps, agricultural activities, and slaughterhouses, were prohibited within the ASAs (CONAMA 1995, Bastos 2001, Oliveira & Oliveira Pontes 2012). However, since ASA zones contain large and diverse urban and agricultural land uses, legal requirements are not always respected, and airport surroundings still attract Black Vultures. Therefore, novel specific measures to reduce the risk of collision with these birds are required.

Currently the Black Vulture is classed as Least Concern on the IUCN Red List of Threatened Species (BirdLife International 2016). However, during recent decades human impacts on the environment have caused catastrophic population declines of many vulture species (Ives *et al*. 2022). Presently, 13 of 23 (57%) of both New World and Old World vulture species are threatened with extinction (BirdLife International 2016). The Black Vulture, as with all avian scavengers, plays an important role in natural ecosystems and traditional agriculture, contributing to the regulation of epizootic diseases that could be harmful to nature, livestock farming and human health (Cortés-Avizanda *et al*. 2010, Plaza *et al*. 2020). Therefore, considering the large number of airports and the extended total area of ASA zones, the prevention of vulture-aircraft collisions must be implemented without harm to the population of Black Vultures in Brazil.

Several factors influence the foraging activity of Black Vultures and determine the temporal and spatial distribution of these birds over the surface. During daylight hours Black Vultures soar in flocks on thermals at high altitudes searching for food. Some researchers concluded that the presence of soaring Black Vultures is caused mainly by the distribution and abundance of human food waste (e.g., Novaes & Alvarez 2014). However, as recently reported, after the complete removal of all food waste on the ground, soaring vultures continue to occur in similar areas (Bastos 2001, Avery & Cummings 2004, Novaes & Cintra 2013). Soaring behaviour is an adaptation to minimize energy losses during flight (Schoener 1971, Ruxton & Houston, 2002). Whereas flapping flight is occasionally used at low altitudes, about 10 m above the ground (Buckley 1999, Novoselova 2016), the Black Vulture and the Turkey Vulture (*Cathartes aura*) prefer to use the ascending air flux of thermals to take-off and gain altitude in the morning and for soaring flights during the day. The soaring activity of both species coincides with the development of thermals. It starts after the local sunrise and finishes before the local sunset (Newman 1958, Pennycuick 1983, Mandel & Bildstein 2007, Freire *et al*. 2015, Novoselova 2016). Vultures often locate their large roosts near man-made structures that generate thermals (Thompson *et al*. 1990, Freire *et al*. 2015). The lack of strong and constant thermals can keep Turkey Vultures on the ground for several days or more (Mandel & Bildstein 2007). Also, there is a tendency for vultures to select thermals produced by artificial heating of air, such as flared methane vents in landfills or thermal power plants, which are much stronger than natural ones (Mandel & Bildstein 2007, Novaes & Cintra 2013, Freire *et al*. 2015). In particular, Turkey Vultures can continue to soar over artificial thermals (landfill methane vents) with illumination for 90-120 minutes after sunset (Mandel & Bildstein 2007). Previously we studied the spatial distribution of soaring Black Vultures around two airports in the southeast of Brazil (Novoselova *et al*. 2020) and confirmed that vultures tend to use the strongest thermals for soaring flight.

In the current study we tested the association of the same data from surveys of soaring Black Vultures from Novoselova *et al.* (2020) with meteorological factors, with the aim of informing management decisions to mitigate the risk of aircraft collision with soaring vultures at two airport study sites in southeast Brazil.

Methods

Study area

We studied the soaring behaviour of South American Black Vultures (*Coragyps atratus brasiliensis*) in the vicinities of the Amarais and Presidente Prudente airports in the southeast Brazil (Figure 1). Those airports were used by small- and medium-sized airplanes. The Amarais airport (22.86293°S, 47.10528°W) is located near Campinas city in the south-eastern part of São Paulo state. The topography is characterized by a transition from the large depression in the west to the plateau coming to Campinas from the east. The elevations of the area range from 450 to 1000 m above sea level (MASL). The average annual temperature and precipitations were 22°C and 1400 mm, respectively. The Presidente Prudente airport (22.17656°S, 51.427389°W) is located 7 km from Presidente Prudente city in the western part of São Paulo state. The surroundings are slightly undulating, turning into low hills with a branched river network. The elevations range from 300 to 540 MASL. The average annual temperature and precipitations were 24°C and 1300 mm, respectively. Both airports were in the vicinity of dense residential areas; the Amarais airport was surrounded by suburbs of Campinas and the Presidente Prudente airport was only 2 km from urban areas. Surrounding rural land uses were similar in both study sites. The main part of each area was occupied by pastures and agricultural fields. Native ecosystems were represented by small fragments of residual native forest, narrow corridors of degraded native vegetation along rivers and scattered trees. However, the degree of anthropogenic disturbance of the two study sites was quite different. The dominant landscape around Amarais airport was highly urbanized area (~60%), whereas the territory around Presidente Prudente airport mainly consisted of natural habitats and rural land uses (~85%). Therefore, we assigned the studied populations of Black Vulture as having the "natural and rural" type of habitat around the Presidente Prudente airport, and "urban" type of habitat around the Amarais airport (Novoselova *et al*. 2020).

Survey methods

Two professional ornithologists surveyed soaring Black Vultures with binoculars from 26 viewpoints (13 in each study site) located in the vicinities of two airports (Figure 1) during one year, from September 2012 to August 2013. In each viewpoint the observations were conducted during one day in each month from 8h00 to 18h00 except short periods of rainy weather when vultures did not fly. Every 15 minutes the sky around a viewpoint was visually scanned to count all soaring Black Vultures. Ornithologists could do this with high confidence of detection at a distance of up to 700 m. At a greater distance, the risk of missing a bird increased and the maximum limit for observations was constrained by technical characteristics of binoculars and visual capacity of the human eye (Land & Nilsson 2012). This potential variation in detection is therefore a limitation of the study to be aware of when interpreting the results. At the same time as the visual observations, the meteorological characteristics (i.e. air temperature (°C), relative humidity (%), wind speed (km h^{-1}), and atmospheric pressure (hPa)) were measured by a portable weather station, a WeatherLink Vantage Pro2 (Davis Instruments, USA) at the same viewpoints.

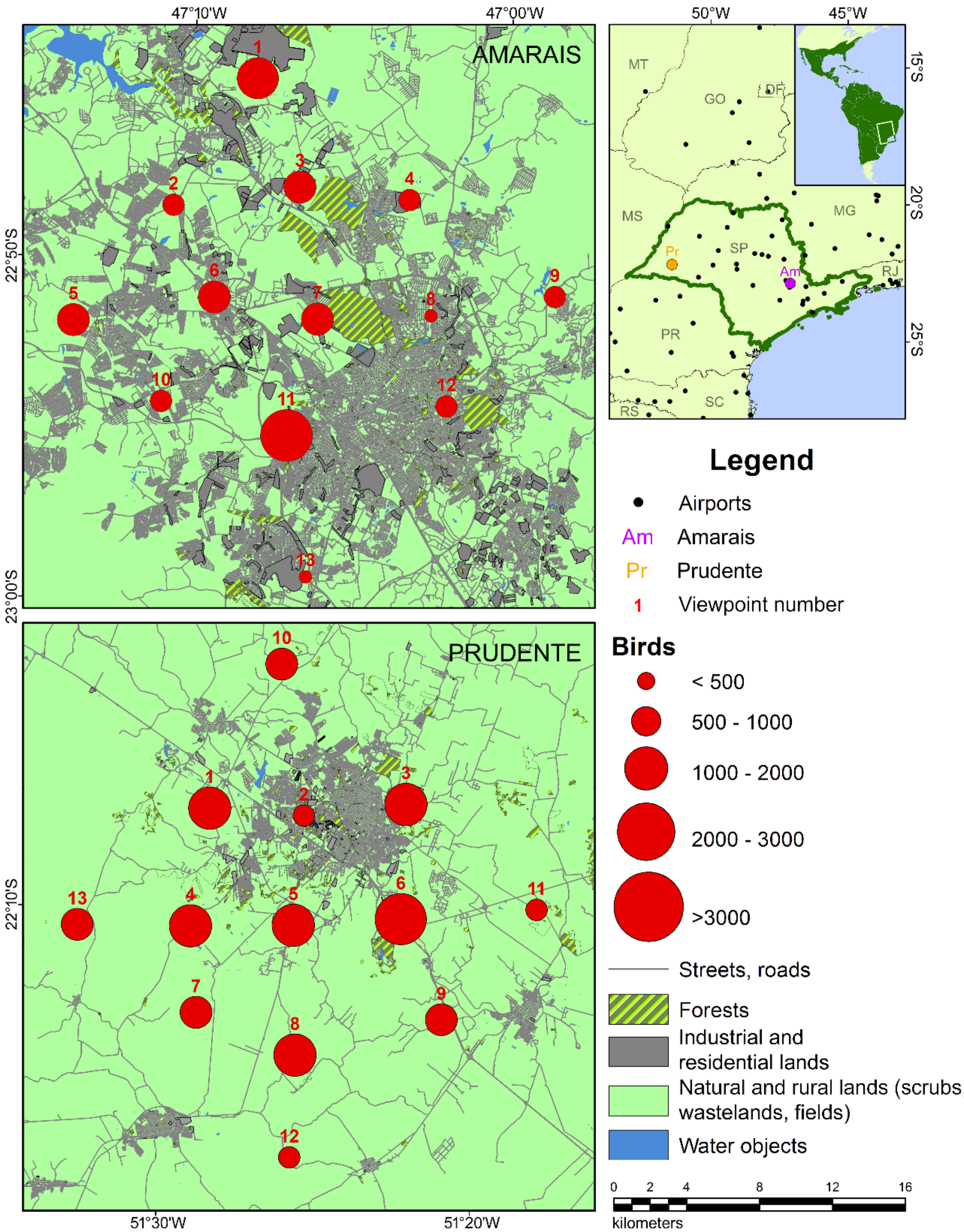

Figure 1: Study areas and the number of birds recorded in each viewpoint near Amarais (viewpoint 7) and Prudente (viewpoint 5) airports during the year of observations. The inset shows the location of study sites and the range of Black Vulture (BirdLife International 2016).

The time-series bird census was synchronized with meteorological data and tabulated in the database further processed with statistical methods in RStudio software version 1.2.5042 (RStudio Team 2020) using R 4.0.0 (R Core Team 2017). The variations in activity of soaring vultures during a day and the whole year and the relationship between weather conditions and flight activity of vultures were analysed. To test the links between meteorological parameters (independent variables) and the number of recorded vultures (a response variable), we applied descriptive statistics, Pearson correlation analysis, a principal component analysis (PCA) and a generalized additive model (GAM) with Poisson distribution. For PCA we used the FactoMineR package version 2.3 (Husson *et al.* 2010, Kassambara 2017). The functions of this package are able to plot the number of birds as a supplementary variable in PCA factor maps. The GAM fitting smooth curves (s()) and their twice-standard-errors in logit units were estimated with the GAM package (Hastie 1992). The smoother scores can be interpreted in the probability terms; i.e. the neutral probability to survey a soaring bird corresponds to s() equal to 0, positive and negative scores reveal respectively the higher or lower probability. The effect of different weather variables on the soaring activity can be compared by their s() scores.

In order to highlight the general patterns in the flying activity of vultures (denoted by F_{birds} = *Number of birds observed / Number of sky surveys*) during daylight at different months, we recalculated time of observations to relative 12 hours timescale where time of local sunrise was taken as a zero point. This scale shows the "hours" (i.e. 1/12 parts of daylight) after sunrise. Values "0", "6", "12" at this timescale correspond to a local sunrise, noon and sunset, respectively. This procedure allowed us to compare the changes of the birds' soaring activity and values of meteorological parameters throughout daylight and their dependence on the position of sun (i.e. sunrise, noon and sunset).

Results

The soaring activity of vultures was different within the vicinities of the two studied airports through the observation period. The total number of vulture records in Prudente (n = 26072) exceeded by 44% the number of records in Amarais (n = 18129). We registered an increase in the number of flights near Prudente airport during the colder months (April-August), although at the same time Black Vultures were less active in the Amarais site (Figure 2).

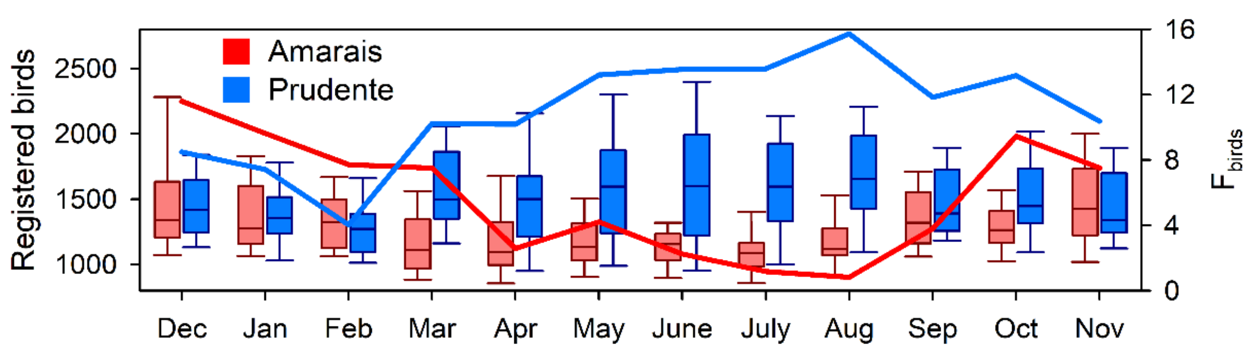

Figure 2: The annual variation of total number of soaring Black Vultures (lines) and their flying activity (denoted as F_{birds} = *Number of birds observed / Number of sky surveys*; box plots) recorded around Amarais and Prudente airports, southeast Brazil.

The dynamics of flights throughout daylight revealed two types of soaring activity for vultures (Figure 3): (i) two well-defined peaks in soaring activity in the morning and afternoon, with a notable depression at midday in Amarais; (ii) a plateau-like plot of frequency of soaring flights in the Prudente site. In both areas the soaring activity started ~1-1.5 hours after sunrise and finished ~1-1.5 hours before sunset. The start of Black Vulture soaring activity corresponded with the increase in air temperature. Also, the increase in relative air humidity, caused by rainy weather, often coincided with a decrease in flight activity. However, the correlation analysis did not show a significant relationship between those parameters.

Through the year, the ornithological census depicted a Gaussian distribution versus air temperature, pressure and humidity, and a log-normal distribution in the case of wind speed. 90% of soaring vultures were recorded at temperatures of 19.9-34.6°C, atmospheric pressure of 1004-1021 GPa, relative humidity of 31-79% and wind speed of 1.3-7.1 ms^{-1}. Those meteorological parameters represent the ecological soaring niche of the surveyed populations of Black Vulture. Vultures did not fly at humidity higher than 90%, linked with rainfall, and at relatively low temperatures typical for morning hours.

The Pearson test revealed a significant negative correlation only between temperature and relative humidity (R = -0.56) and between temperature and atmospheric pressure (R = -0.68). There was no correlation between the number of soaring birds and any meteorological parameter. Depicting those variables, the PCA factor map also outlined the inverse correlation of temperature versus relative humidity and atmospheric pressure, although there was not any linear relationship between weather variables and the number of soaring vultures (Figure 4). The GAM results revealed that variables such as wind speed, temperature and humidity affected vulture soaring activity in a nonlinear way (Figure 5). The number of soaring vultures increased with wind speed, reaching a peak at 9 ms^{-1} and decreasing thereafter. The optimal temperature for vulture soaring activity was 25°C, while it decreased during colder weather (T < 20°C). The curve elevations at highest temperatures and lowest wind speeds corresponded to agglomerations in flocks of several dozen individuals that were relatively rare. There are two peaks of vulture soaring activity linked with humidity of 39% and 76%. The first peak might be explained by optimal conditions for the vulture soaring at this air humidity. The highest humidity values corresponded to rainfalls. Therefore, this likely reflected the behaviour of birds that had not flown during periods of rainy weather and then climbed into the air immediately after weather conditions became more favourable.

Discussion

Our study reveals that the temporal distribution of soaring Black Vultures at two airports in south-east Brazil is not uniform. Understanding the factors driving vulture soaring activity can help to elaborate a strategy of sustainable development for airport surroundings, especially those in which small to medium aircraft operate, as is the case in this study. The aircraft schedules of take-off and landing can be designed to avoid the main hours of vulture activity, thus decreasing the risk of collisions with these birds. In cases where flight routes and timings cannot be adapted to avoid peaks of vulture flight activity, other mitigation measures such as vulture repelling systems combining acoustic and visual cues could be used (Seamans *et al*. 2013, Boycott *et al*. 2021).

We found two types of daily soaring activity for Black Vultures: (i) two peaks of activity, at morning and afternoon, with a notable depression at local midday; and (ii) a plateau-like activity.

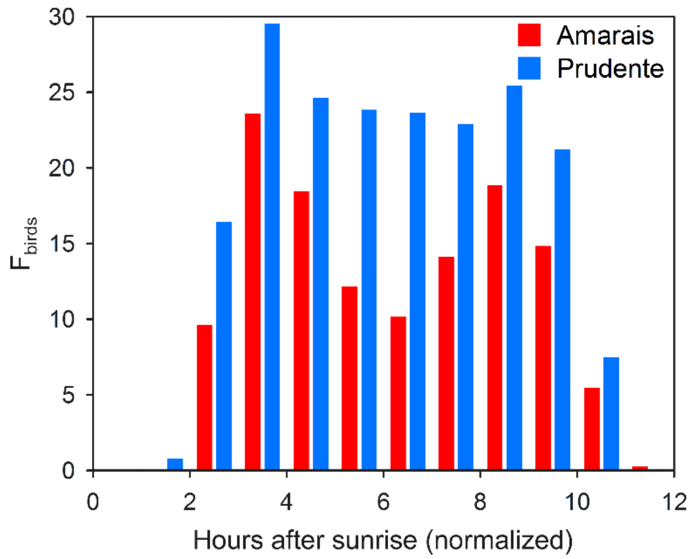

Figure 3: Daily variation in the soaring activity of Black Vultures (denoted as F_{birds} = *Number of birds observed / Number of sky surveys*) averaged for a year of observation. The relative time was calculated through normalization of the actual daylight length to 12 hours. It shows the hours after sunrise. Values 0, 6 and 12 correspond to a local sunrise, noon and sunset, respectively.

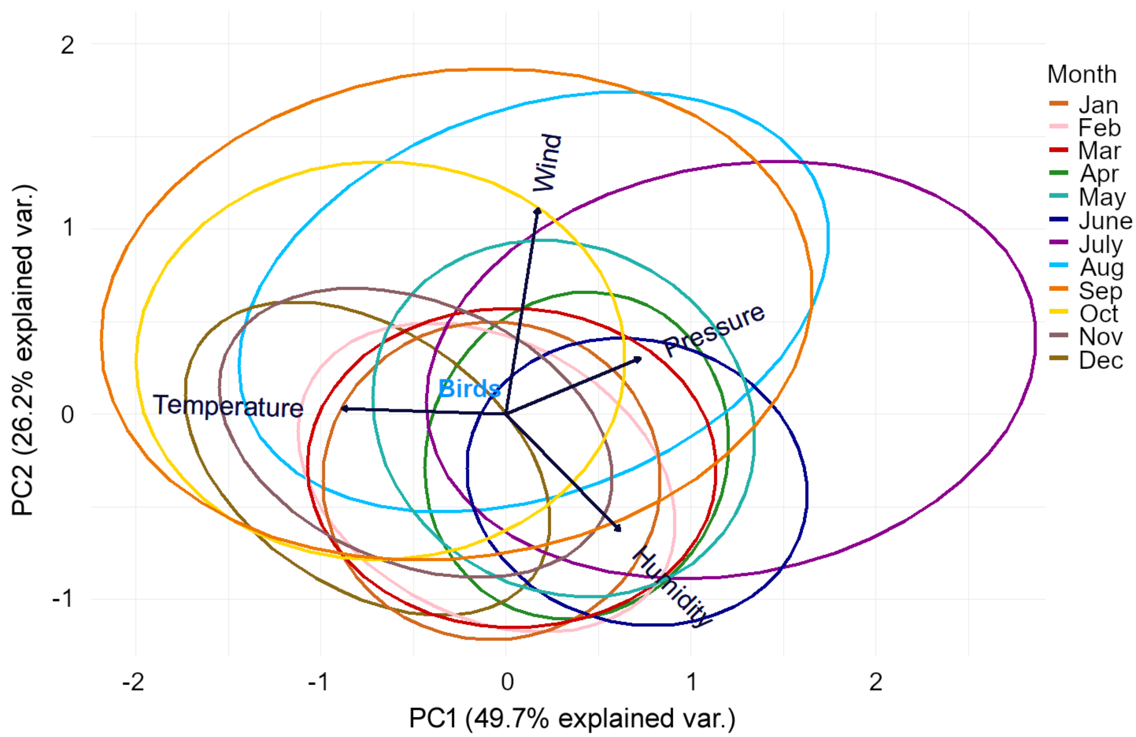

Figure 4: The factor map obtained by means of Principal Component Analysis revealing the relationship between meteorological characteristics and soaring activity of Black Vultures in the study sites during the year.

The single-peak activity associated with local midday was reported for Black and Turkey Vultures in South Carolina (Avery *et al*. 2011, Walter *et al*. 2012). Also, Freire *et al*. (2015) detected the two-peak type activity in the Manaus area (Central Amazon, Brazil). Both types of soaring activity were observed during a time interval between ~1-1.5 hours after local sunrise and ~1-1.5 hours before local sunset. These timescales match the time of convective response in the boundary layer of atmosphere (~1 hour) and likely correspond to the development of thermals (Stull 1988). Therefore, as expected, soaring vultures are likely to be absent from the airspace in the vicinity of airports during dark and twilight hours. However, this pattern of soaring activity is only expected in landscapes that do not have artificial thermals working at night, especially in combination with artificial illumination, since the prolongation of soaring activity after sunset in those conditions was reported for Turkey Vultures (Mandel & Bildstein 2007).

We propose that the variation observed between the patterns of soaring activity of vultures at the two different airports can be explained by the different levels of anthropogenic pressure controlling the availability of food and roosting locations (DeVault *et al*. 2004). The "two-peak" type of soaring activity was seen in the Amarais site. The highly urbanized lands impacted with strong anthropogenic pressure dominate in the suburbs of Campinas city. As there are very few natural resting areas for vultures around this airport, many birds may fly away to look for roost sites, causing a decrease in flight activity at midday. In contrast, the second "plateau-like" type of daily soaring activity was observed in the Prudente site. The natural and rural areas predominating around this airport are less exposed to anthropogenic pressure. As vultures may find enough quiet natural refuges, they do not need to fly as far away, allowing roosting and soaring activity to be more evenly distributed throughout the day. An alternative explanation is that a greater diversity and abundance of food resources across the more heterogeneous Amarais landscape may mean that vultures find food there more quickly. This corresponds to previous studies that have shown that many bird species are forced to travel larger distances in homogeneous rural environments (Tucker *et al*. 2019). However, the factors underlying these different soaring patterns require further investigation.

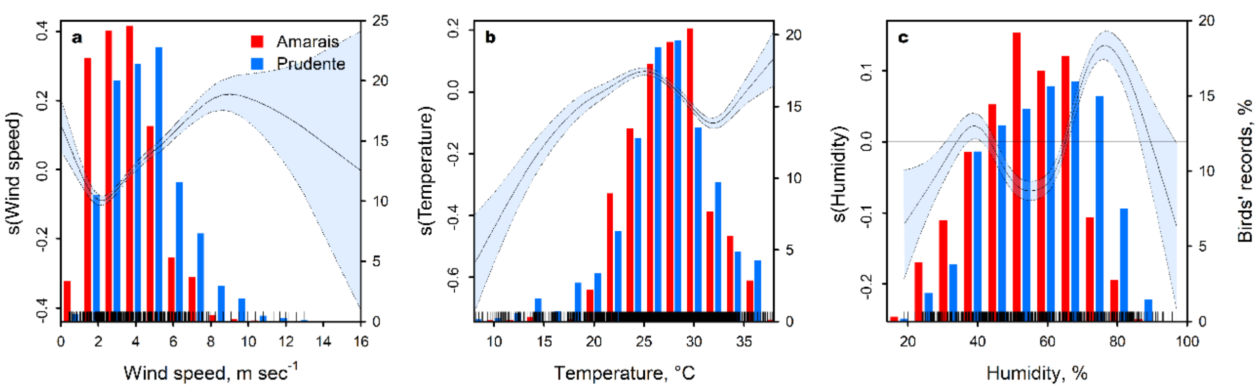

Figure 5: Exposure-response curves (s()) obtained by means of Generalized Additive Modelling for significant effect of weather variables (wind speed, air temperature and humidity) over soaring activity of Black Vultures (right ordinate axis).

Different seasonal conditions affected the soaring activity of Black Vultures. The numbers of soaring birds recorded during the year correlate negatively between Amarais and Prudente regions. The inverse correlation was stronger during the cold and shorter daylight period of the year from April to August (Figure 3). In those months the F_{birds} values were the largest through the year in Prudente and the lowest in Amarais. Considering the similar climatic conditions, the difference in levels of urbanization between the two areas may be a reasonable explanation (Novoselova *et al*. 2020). Black Vultures may migrate from more anthropogenic landscapes to more rural and natural areas during cold months. At this time of year infectious and parasitic diseases cause the highest mortality in beef cattle (Molossi *et al*. 2021), possibly leading to an increase in carrion availability for vultures. Also, as thermal formation during winter is limited and daylength is shorter, vultures may tend to stay closer to the roost sites, often located in natural or less disturbed areas. At relatively low temperatures and during rainfall vultures may not fly until weather conditions improve. This behavioural pattern can be interpreted as a form of ecological adaptation of the Black Vulture as an avian scavenger in order to minimize its energy loss due to flight activity (Schoener 1971, Ruxton & Houston 2002).

There was a nonlinear relationship between wind speed and number of soaring birds with its maximum at 9 ms^{-1}. During light winds the soaring activity increased together with increasing wind speed, but decreased during strong winds. We registered the horizontal wind flux and this is necessary to clarify the link with factors controlling the vertical circulation in the atmospheric boundary layer. The average daily variation of wind speed resembles the dynamics of surface heating by solar radiation, which starts to increase at ~1 hour after sunrise, reaches the maximum at midday, then begins to decline and drops to the minimum during the sunset. Since thermals develop due to surface heating, their intensity should directly correlate with a curve of solar activity (Stull 1988). Therefore, the wind speed reflects to a great extent the thermal circulation of atmosphere. Light winds, less than 5 ms^{-1}, indicate the rising thermals, although moderate winds of 5-15 ms^{-1} distort them. Wind gusts of 20 ms^{-1} completely cease the thermal circulation (Heise *et al*. 2009). Thereby, the strongest sustained thermals form at winds of ~5 ms^{-1} and this wind speed value is most suitable for effective soaring (Woodcock 1975, Elkins 2004). This observation indicates that the wind speed is the best proxy of the thermal circulation, the soaring activity depends on availability of thermals and vultures tend to select the strongest thermal in their surroundings (Novoselova *et al*. 2020). The maximal height of soaring Black Vultures (558 m - DeVault *et al*. 2005; 550 m – Novoselova 2016) coincides with the maximum lift in thermals and the mean cloud base ranging in tropics from 300 to 700 m with a mean value of 500 m. Above this level the buoyancy and vertical velocity of rising thermals decrease (Stull 1988). Since thermals save energy of birds during take-off and flying, this behavioural trait can also be interpreted as an ecological adaptation of the Black Vulture to minimize its energy losses.

Conclusions

The following main results can be used to inform management decisions to mitigate the risk of aircraft collision with soaring vultures at our two airport study sites. The altitudes higher than 550 m or the cloud base and night hours were usually free from flying vultures. We detected two types of soaring activity attributed to urbanized and rural habitats, respectively: (i) an activity plot with morning and afternoon peaks and a notable decline at local midday; and (ii) a plateau-like activity plot with a single smooth peak at midday. For both types, the soaring activity starts at ~1-1.5 hours after the local sunrise and finishes at ~1-1.5 hours before sunset. Seasonality impacts the soaring foraging activity of Black Vulture. We found a difference in flight behaviour of these birds between mild dry (April-August) and hot rainy (September-March) periods. The soaring activity of Black Vultures was influenced by wind speed, an indicator of thermal strength, and peaked at a wind speed of ~9 ms^{-1}. The presence of soaring vultures is not only determined by the availability of feeding sources, but also by meteorological conditions that control thermal development and flying conditions for foraging activity. Hence, these factors should be considered when planning aircraft flight routes and schedules so that the risk of vulture-aircraft collisions can be reduced by avoiding peak soaring periods for vultures.

Acknowledgements

We wish to acknowledge Angelo Benaglia for his assistance in developing the methodology for vulture observation. The Aviation Department of the São Paulo state (DAESP) provided the portable weather station, the funds for fieldwork and the permits to work inside Amarais and Presidente Prudente airports. We are also grateful to all members of the internet community GIS-Lab of Russian-speaking GIS and remote sensing specialists (http://gis-lab.info) for their valuable assistance in solution of technical and scientific questions in GIS and remote sensing technologies. NSN acknowledges CAPES, the Brazilian Research Foundation, for the financial support.

Data accessibility

Supplementary Datasets including all data collected in field are deposited at https://data.mendeley.com/datasets/8s3fps4vvb/2.

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