Towards understanding Short-toed Eagle (*Circaetus gallicus*) Migration: Is meteorology influencing it?

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by

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Thesis submitted to the University of Twente, faculty ITC, in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation for Environmental Modelling and Management

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Abstract

Migration of birds has been explained and studied in an exclusive manner and a number of different ways of explanations and modelling have been adopted ranging from flight energy, aerodynamics and even on birds communication (calls) to adjust their flights. Some have assessed effect of meteorological variables such as wind and have explained migratory behaviour based on simulation. In this thesis the migratory flight of Short-toed eagle has been studied using the geo-locations based on GPS telemetry (Argos Tracking data system) and meteorological variables that are likely to affect the migratory journey from an idealized route of migration between departing site and destination site.

The meteorological variables were extracted from the NCEP/NOMAD's Global Forecast system in Integrated Data Viewer. Wind related variables in relation to the flight positions- crosswind and headwind were derived. The deviation in migratory journey from the ideal route was calculated for each geo-locations of the flight. The distance covered by the bird was calculated based upon the great circle distance. The assessment of wind related variables were done using Mann-Whitney Test and the deviation has been explained based upon Generalized linear modelling using Gaussian family with Identity function.

The Short toed eagle under study is juvenile which migrated for the first time to its wintering ground in Western mid-Africa from Southern Spain. The one way journey is completed in 11 days with 10 stopovers. Maximum distance covered is 131 km in four hours on the 2nd migratory day over Moroccan desert in North Africa. Though the numbers of geo-locations with crosswind from right are more, the speed of crosswind from right and from left are statistically similar (confidence interval of difference contains 0). Similar is with headwind and tailwind (median=3.41 m/s for headwind and 2.88 m/s for tailwind). And the deviation extent from an idealized route is also statistically similar (median=104.18 km for deviation to the right and 77.54 km for deviation to the left).

The Generalized linear model is based upon crosswind, surface lift index and wind speed. The Surface list index has the highest effect on deviation (coefficient. =-18.85, t value=-9.18, p=1.51e-12), followed by wind speed (coeff.=16.96, t value=3.54, p=0.000) and then surface lift index (coeff.=-5.12, t=-4.39, p=0.000). The alternative hypothesis that the crosswind and surface lift index effects negatively to the deviation so that deviation is to the left is accepted while for wind speed, the alternative hypothesis is rejected (p=0.999). Hypothesis related to headwind could not be tested because this variable is excluded in the stepwise modelling.

Theoretically, distribution of wind related opposing factors being equal in magnitude implies it is the bird's preference to fly through the observed geo-locations such that the effect from these is nullified towards the end of the migratory journey. However a separate study of the distribution of these meteorological variables along the migratory course range could bring deeper insight. We conclude that meteorology does determine the migratory route and the observation of flight position is likely to be an adjustment of the bird due to the effect of the meteorological factors.

Keywords: Migratory flights, Short-toed Eagle, Headwind, Crosswind, Surface lift Index, Deviation modelling

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Chapter 1. Introduction

1.1 Background

Dingle and Drake (2007) has conceptualized the meaning of migration as persistent, undistracted locomotary activity that includes all the level of migratory traits an animal has- the migratory syndrome, and its consequence for the dynamics of population and relationships between them. A migration can be at individual level including obligate or facultative or at ecological level involving sub/population. A migratory behaviour is characterized by morphological and physiological adaptations including the adjustment of the migrants, to make their migratory journey complete successfully(ÅKesson and HedenstrÖM, 2007). This "success" is possible with right adjustment to the various ecological, meteorological and other constraints that prevails along the migratory journey.

In birds, the migratory flight is associated with the available body energy and its conservation. Migratory journeys extends over few km to 10,000 km and coupled with navigation, the available body energy to fuel the migratory flight to reach the destination site from the departing site is the requirement (Newton, 2007a). The mechanics of bird migration described by Pennycuick (1969) is based upon the power consumption needed in a flight during a migration. This energy consumption is required to adjust for the flight constraints such as strong headwind that opposes the migratory flights or the unavailability of feeding sites on its long journey. For conservation of energy or covering larger distance with minimum energy has resulted in two strategy for birds for migratory flights-"minimal power speed" that allows the bird to stay airborne with minimal fuel consumption rate and "maximum range speed" which helps the bird to cover larger distance on given amount of fuel. These strategies are adopted by the birds depending upon the environmental conditions during its flight.

Weather effects the bird migration by influencing the onset of migration, energy costs for migration, visibility of geographical clues and risks along the migratory journey (Newton, 2007b). The same weather condition on different time of a year like in the migratory season does not provide strong relation of weather with migratory behaviour of a species. But the scale of migration mentioned by the author involves the higher, i.e. at the ecological level involving morphological or genetical structures (such as that includes biological clock within the bird for migration) conceptualized by Dingle and Drake (2007).

ÅKesson and HedenstrÖM (2007) mention that there exists a suite of adaptations to cope with their journeys for migrating animals which include not only the morphological features but also on behavioural adjustment to exploit winds to avoid drift away from intended route of migration. Koistinen (2000) has already explained migratory birds not only utilizes the favouring wind but also the thermals specially by the raptors that include the Short-toed eagle. There are still more factors to be assessed for greater understanding of migratory flight.

1.2 Research objectives

The overall objective is to assess the effect of meteorological variables during a migratory flight to understand the reaction of the bird to those effects. This is based upon the importance of the meteorological variables during migration recommended by Bowlin et al.(2010), Robinson et al. (2010), and Shamoun-Baranes et al. (2010) The specific objectives can be listed as follows.

1. To explain the deviation based upon the prevailing crosswind and headwind from observed geo-locations data.
2. To explain the deviation of migratory flight from an ideal route designed, with meteorological variables.
3. To assess the effect of the meteorological factors and to compare the effects on the deviations.

1.3 Problem Definition and Research Question

1.3.1 Problem Definition

Migration studies in literature are often independent and narrow in sense that the singularity of disciplines used in the studies. Some studies have considered the flight mechanics such as by Pennycuick (1969) where the explanation is based upon the energy consumption and conservation during a flight, whereas, Hedenström (2002) has assessed the response of the bird to the flight constraints based upon the morphological structure (wingspan, tail, body size etc) of the bird coupled with aerodynamics . Koistinen (2000) has explained the migratory birds as an immediate response for adjustment with the prevailing wind and other related factors such as the thermals and to conserve required flight energy. Griffin (1969) has explained the bird navigation based upon the echoes of flight call that helps the bird to differentiate the prevailing atmospheric conditions from adjacent flying members. This call ultimately helps the birds to orient themselves to a particular position in the air to reach their destination.

Not only the winds or thermals or the navigation skills, but there are certainly many factors that may interact continuously on a migratory journey. Even multivariate statistics cannot reveal which factors are critical and which are not, imposes a pitfall in assessing the weather effect on migration (Newton, 2007b). Although there is more knowledge about migration than before, still there are gaps needed to be fulfilled and one of them is how do local responses to environment affect large-scale movement patterns (Robinson et al., 2010) such as in migration.

Bowlin et al.(2010) have pointed out that the organismal response to the environment is one of the five grand challenges in migration studies and they recommend an integrative approach that addresses the migration from multidisciplinary perspectives. Following this, Shamoun-Baranes et al. (2010) have compared simulated models of migratory flights and has explained the stopover decision is affected by the prevailing wind along the migratory course. In addition they have tested the hypothesis that the flocking improves the identification and utilization of thermals more efficiently.

Any detour from the shortest path to the destination, of birds should not always be an effect of factors and are forced to drift but also could be a strategy or preference to fly over with favourable factors which may result in repeated detour from the ideal migratory path/route. Thus this study is explorative that seeks to quantify the effects of meteorological factors generated through GIS, using statistical modelling.

1.2.2 Research Question

The main research questions are centred about modelling the migratory deviations from its hypothetical shortest path between the departing site and the destination site using set of predictors from meteorology. Answering which factors explain the deviation to what extent through modelling is the purpose of this thesis work. The specific research questions are pointed as followings.

1. How are the crosswinds and headwinds distributed along the observed migratory positions?
2. Are the observed geo-locations reflecting a strategy to avoid unfavourable meteorological factors conditions?
3. What are important meteorological factors that can explain the migratory deviation for the species and to what extent?

3.2 Hypotheses

The deviations to the left and to the right are due to the difference in the crosswind from right and from left. Similar is with the headwind and tailwind. If the opposing wind related variables are acting with equal intensity, the deviation to the left and deviation to the right should be equal. If not then the crosswind from either side should be more dominating.

H_0: Median of crosswind from right = Median of Crosswind from left
H_A: Median of crosswind from right ≠ Median of Crosswind from left

In case of headwind and tailwind,
H_0: Median of Headwind = Median of Tailwind
H_A: Median of Headwind ≠ Median of Tailwind

Similarly the hypothesis related to deviation is,

H_0: Median of Right Deviation = Median of Left Deviation

H_A: Median of Right Deviation ≠ Median of Left Deviation

Hypothesises associated with the modelling:

H_0: For positive and higher crosswind (from right), the deviation will be to the left. i.e the coefficient of crosswind is zero or greater than zero.

i.e. H_0: $\beta_c \geq 0$

H_A : $\beta_c < 0$

H_0: Higher the headwind, deviation to the left will increase, i.e. the headwind has negative effect on deviation which means the coefficient of the headwind is negative.

i.e. H_0: $\beta_h \geq 0$

H_A :$\beta_h < 0$

H_0: The coefficient of the surface lift is negative.

This means, as the surface lift index increases, the bird tends to deviate more to the left from the idealized route. This is possible only if the coefficient of the surface lift index is negative.

H_0: $\beta_l \geq 0$

H_A :$\beta_l < 0$

H_0: The coefficient of the wind speed is negative.

This means if the wind speed increases, the bird will adjust itself by deviating to the left of the migratory course.

H_0: $\beta_w \geq 0$

H_A :$\beta_w < 0$

1.3 Research objectives

The overall objective is to assess the effect of meteorological variables during a migratory flight to understand the reaction of the bird to those effects. This is based upon the importance of the meteorological variables during migration recommended by Bowlin et al.(2010), Robinson et al. (2010), and Shamoun-Baranes et al. (2010) The specific objectives can be listed as follows.

- To explain the deviation based upon the prevailing crosswind and headwind from observations data.
- To explain the deviation of migratory flight from a hypothetical reference ideal route with significant meteorological variables based on GLM model.
- To assess the effect of the meteorological factors and to compare the effects on the deviations.

1.4 Contribution

Influence of atmosphere on migration is important for understanding the patterns in migration. This understanding is about the variability in individual behaviour and the atmosphere as recommended by Bowlin et al.(2010), Robinson et al. (2010)and Shamoun-Baranes et al. (2010). Further the authors have pointed out that the quantification of the variability in en-route migration has been rarely done. However their modelling is simulation based and this study intends to provide a quantified effect of meteorological variables based from the ordinal observation (all the observations are at 1 hour time interval) of migration.

1.5 Research Design

The research design for this thesis work consists of 6 components. These components have been represented in figure 1.

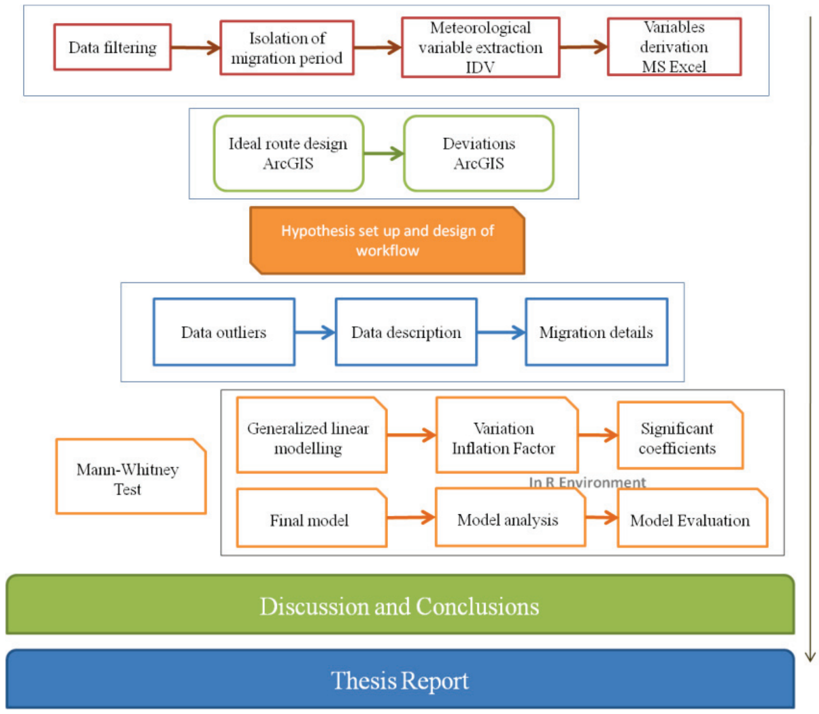

Figure 1: Research design

The research design for this thesis work consists of 5components.

- Data extraction and processing
- Hypothetical assumptions and design
- Data descriptions
- Statistical Modelling
- Inference and reporting.

The data extraction and processing is meant for base line data preparation for the thesis work. For analysis, some hypothetical assumptions were made such as the ideal route consideration that marked the left and right (marked by negative sign for left deviation) deviations of the bird flight during its one way migration.

The meteorological variables that affect this deviation are explored via hypothesis testing and modelling together with its evaluation for better understanding of the migration.

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Chapter 2. Literature Review

2.1 Drift and Migration

Pennycuick (1978) has presented fifteen testable predictions about bird flight. All his theoretical predictions are based upon the speed of flight with the bird's energy available. Prediction related to the wind can be stated as follows.

$$\text{Wind effect} = V_g - V_a \quad \text{eq. 1}$$

If there is no wind,

$$V_g = V_a \quad \text{eq. 2}$$

Where V_g and V_a are the speed of the flight over ground (groundspeed) and speed of flight in the air (airspeed). The difference in these two speeds is due to the wind. A simple interpretation would be if the speed is less, the distance covered is also less for given time, because the speed is function of distance with direct proportional relation. If the velocity increases, distance covered during a flight will increase. If tailwind exists, the airspeed of the flight may be slowed down than needed so that the "push" of the tailwind will compensate the speed required. This means that bird does not fly with the maximum flight speed it can under these conditions. Pennycuick (1978) has interpreted it as "presence of tailwind reduces the maximum range speed". If it's true then conversely, presence of headwind should force the bird to fly with greater speed so that the hindrance imposed by the headwind is minimized.

What is remarkable is that the maximum range speed (Vmr) is based upon the flight energy available for the bird. For a given bird, the flight energy it possesses remains constant until it stops its flight for next feeding and hence the Vmr also remains constant for that bird during that period. Variation in Vmr with changing wind speed is a pitfall in the Pennycuick's (1978) theory. The power curve (Pennycuick's) will result in inconsistent rate of change if the Vmr fluctuates with fluctuating wind speed because a power curve can have only one Vmr in a single flight. Unlike the aircraft, a bird can change direction of flight, can follow more favourable flight path in response to wind variations. Controversy exists in Pennycuick's theory (Videler, 2006).

Newton (2007a) has figured out that the ground speed of a bird during its flight is sum of its air speed and the tailwind speed, whereas this ground speed decreases if headwind prevails. Any wind which has angle with the path will make the bird blown off course. If not the bird may adjust its heading such a way that the wind direction and its heading will interact to compensate. Best strategy for the birds would be flying slowly when its tailwind and fast, when its headwind (Newton, 2007a). Or the bird deviates itself from the flight track, for favourable wind conditions.

Koistinen (2000) has observed that the heavy migration including Short-toed eagles occurs when the wind is northerly in autumn and southerly in spring for mid Europe. Since selecting the most profitable flight may result in additional gain of 40% in flight speed, migrants prefer a favourable wind for migration otherwise will make the migration unsuccessful. Soaring migrants like Short-toed eagle utilize the thermals and avoid crossing over areas with fewer thermals. The thermals which are the rising air parcel or "rising air bubbles" from the surface are glided into by birds so that they could acquire height where favourable wind conditions exits. If the air bubble is of lower strength, next air bubble is dived into by the birds and this way the thermals are utilized for flight in migration. But the question remains how does a bird sees the next thermal to which it is going to change for.

Gauthreaux (1991) has reported that the relationship between the longitude of the peak arrival of trans-Gulf migrants. They found that the highest densities of arriving migrants was at altitude of 1500-2500m where the atmospheric trajectories (air parcel movement based on meteorological variables) were the highest in direction of migrant's arrival. However, the few migrants arriving at 500 m were also significant which made the authors to conclude that the migratory path for the Trans-Gulf migrants may reflect the path being evolutionary rather than affected by wind aloft. Thus location of favourable condition in winds and thermals both are chosen by the birds rather than drifted to those due to meteorological forces.

Combination of high altitude drift and low altitude overcompensation is a general migratory strategy of migrants. Following this theoretical description of migration in birds, Alerstam (2000) has developed a theory as any detour during migration is result of its own flight capacity, wind and flight orientation. A large flight barrier is avoided by travelling along the detours by birds during its migration. Thus the drift could be in fact a detour where it is an adjustment or adaptation by the bird to maximize its flight efficiency. But whatever it could be, it's certainly a deviation from its shortest path between the departing site and the destination site.

Green and Alerstam (2002) have modelled and studied the wind drift and compensation done by birds during migration. Their definition of drift is in terms of angle and they have concluded that the linear regression between the geographic track and the heading direction provides reliable and robust results. According to them if this relation is established for individual flights, the results become biased. If mean direction is compared with the flight directions with cases of crosswinds then also the result becomes biased and spurious. Finally they recommend that the in reality, there is a need of modification of earlier definition of "drift" and probably the concept too. The Oxford online dictionary (Dictionaries) defines drift as any *deviation* from its intended route for an object that can remain airborne *due to currents of liquid or air*. This facilitates that the definition of drift can be expressed as fluctuating distances from a reference migratory track between departing site and destination site.

2.2 The need of meteorological effect in migration.

Flight during migration for a bird and its interaction with the prevailing wind has been studied and has been explained by Alerstam (1979). The drift during migration flight is strategic for the bird to save time. Allowing to be drifted with stronger wind at higher altitude birds compensate the drift caused by the wind by flying at lower altitude with weaker wind. This concept of Alerstam has been based upon the fact that wind increases with altitude. This strategy is more successful if the stronger wind is within 300 to 900, in relation to its goal direction. Though not mentioned by Alerstam (1979), wind within this range is definitely the crosswind.

Alertsam et. al (2006) studied the repeated journey of osprey (Pandion haliaetus) using satellite tracking data, that occurs from Europe to Africa during spring and autumn. They found that the landmarks did not play a role of cues evidenced by the limitation in the range of vision over repeated routes which were 120-405 km apart by same bird. However there existed some "goal areas" where the flight paths apart, converged. There are studies where the similar findings have been reported for White stork and Lesser spotted eagles (see Meyburg et al., 2003). The repeated migratory route being apart could be seen as the bird's preference or adjustment to the unfavourable meteorological conditions so that goal areas are not missed despite the routes being 120-405 km apart.

Purcell and Brodin (2007), analysed the probable reasons theoretically why Black brants (Branta bernicla nigricans) would choose a detour rather than the shortest path during its migration. They have concluded that the stochastic events may force them to choose a suboptimal migratory path otherwise; they would always use the optimal path (shortest path). Direct migration (along the optimal/shortest path) is an evolution to the prevalence of tailwind and the availability of the food on stopover grounds and that global warming could have detoured flight in the migration of these species. Anyway this detour is reaction of the bird to the prevailing meteorological conditions.

Bowlin et al.(2010) has described the challenges of migration studies where they have viewed that migration study needs to have an integrative approach which also includes modelling techniques of bird flight. Approach that includes multidisciplinary techniques to assess the migration of animals is suggested for greater understanding in migration. A need of multidisciplinary has arisen because for instance, the atmospheric phenomenon can be used to study the response of birds during its migration.

In this study drift of the bird has been measured as distances from the ideal route designed. As Green and Alerstam (2002) mention that the use of mean of the heading directions of individual birds may generate biased estimates and they are with view of evaluating the existing definition of drift, has been expressed in terms of distance from a reference ideal route.

Chapter 4. Methodology

4.1 Research Method

4.1.1 Research workflow

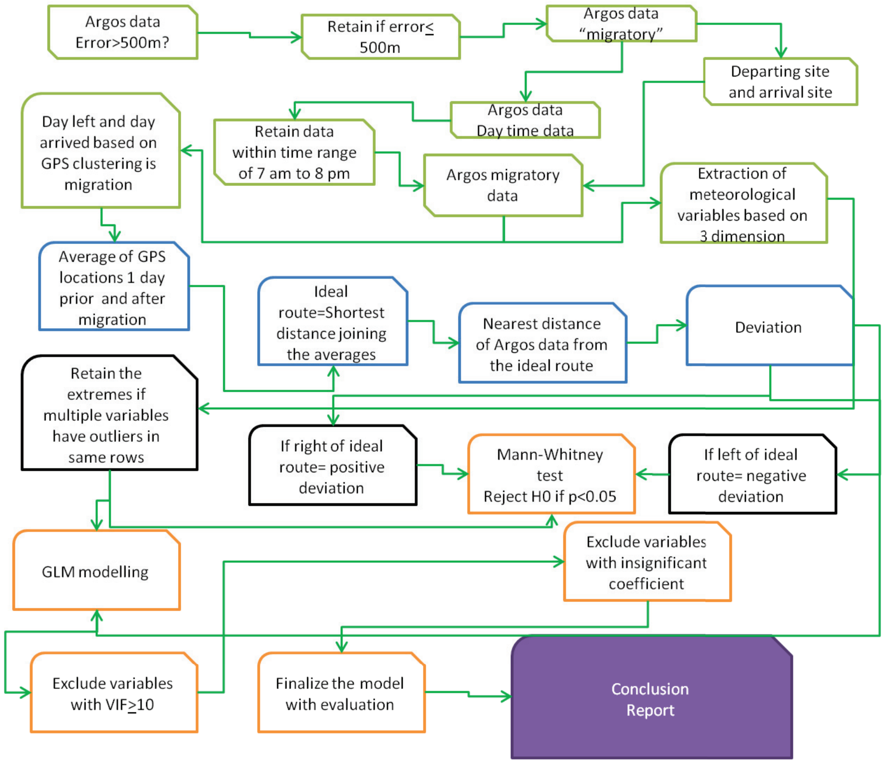


Figure 2: Research workflow

4.1.2 Information Gathering

A 10 day field work was carried out to understand the local information about the species during the migration season in mid-September 2010. Interactions were made with the locals, species experts and researchers in Spain. Followings were carried out during the field work from 13th September 2010 to 21st September 2010.

During the field trip, a total of 2 individuals (1 radio tagged) in Tarifa, and 5 in Malaga regions were observed. From the local experts, it was known that most of the Short-toed eagles had already left for their winter migration from their breeding ground in Spain. It is also known that not all the Short-toed eagles migrate and they remain in Spain throughout the migratory season. And in addition, the observed Short-toed eagles may not be the endemic species of Spain but from other regions such as from Italy that have come to Straits of Gibraltar for migratory crossing of the Mediterranean Sea.

4.1.3 Data Gathering

The short-toed eagle (PTT: 53725) is juvenile born in the study year 2010 in May. In comparison to the other Short toed eagles, the PTT 53725 has larger number of accurate GPS points. The first day on which the species crossed the Strait of Gibraltar and continued its flight toward mid-Africa, is considered as the first migratory day. The GPS fixes observed showed clustering in comparison to the migratory movement and this clustering is the basis for segregating the migratory GPS fixes and non-migratory GPS fixes. If the movement of the bird showed no further longitudinal movement but clustered at some location for a week, it is considered as end of migration. This was observed in the kml file of the Argos data in Google Earth (ver. 5.2.1.1588).

The extraction of the meteorological variables are based upon four dimensions namely latitude, longitude and altitude and time. The Jython code was developed so that if the altitude is less than 6 m, the variables values are extracted from the earth surface level. The extraction of the data is based upon weighted average, so that if the bird's geo-locations conflicted with the resolution of the meteorological grids, weighted average values are returned.

After the extraction of the data from Integrated Data Viewer (IDV), the data were tabulated in a matrix format with the columns as the variables and the rows as the geo-locations or "observations". The rows with missing values were excluded to avoid any miscalculation in the process. Further the data were sorted for the day-data only. For migratory flights, the data between 7:00 am to 8:00 pm were considered due to the time difference of Universal Coordinate Time (UTC) which is 1 hour less (the mean longitude of -50 is about 45 min late than UTC).

The Global Forecast System (GFS version 9.0.0) is a global spectral data assimilation and forecast model system which are gridded with Lat/Lon system produced by NOAA/National Centres for Environmental Prediction (NCEP). These are produced every three hours at 00, 03, 06, 12, 15, 18 and 21 hours of the Universal Time Coordinate (UTC). A forecast is for time interval of 192 hours.

The horizontal resolution is equivalent to 0.50 X 0.50 degree latitude and longitude, with vertical resolution of 15 levels below 800 hPa and 24 levels above 100 hPa. In total there are 64 unequally-spaced sigma levels (at surface, sigma=1 and, at atmospheric boundary, sigma=0). Since, the species in question may span a distance larger than the dimension of the data resolution (more than 100km) in a day during the migration, utilization of 0.50 X 0.50 spatial resolution data seems be reasonable in terms of temporal (3 hourly) resolution.

GFS contains a full suite of parameterized physics, sea-ice and land-surface models which can be taken as to be computationally efficient and ready for Earth System Modelling Framework (ESMF) and a hybrid (sigma, p) vertical coordinate (for detail see: http://www.nco.ncep.noaa.gov/pmb/products/gfs/). The Thematic Real-time Environmental Distributed Data Services (THREDDS) is a project at University Corporation for Atmospheric Research, Boulder, CO. which acts as bridge for the data providers and data users. The GFS data is used from the Unidata's THREDDS server (http://unidata.ucar.edu/) using its Integrated Data Viewer (IDV, version ITC).

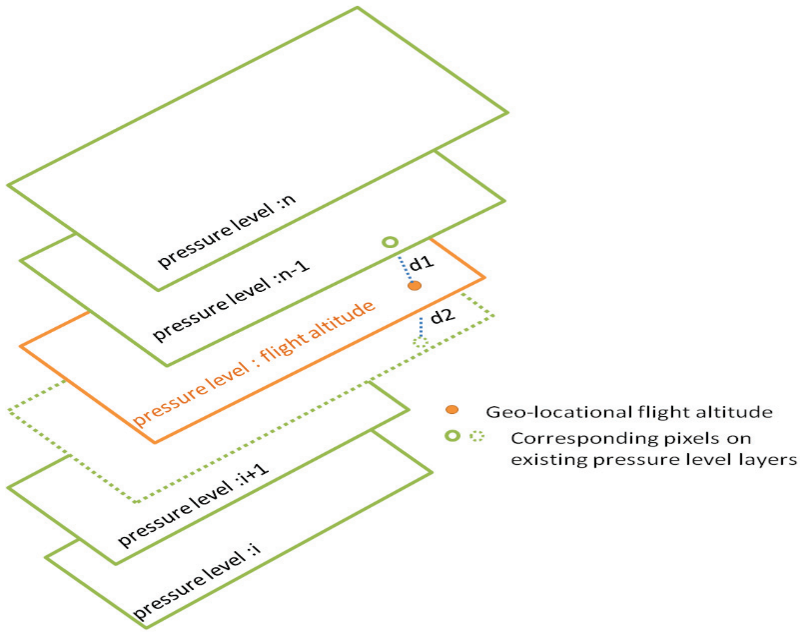


Figure 3: Weightage average sampling for the data extraction.
Value at geo-locational flight altitude = (d1*W1+D2*W2)/2
Where, if d1>d2, then w1<w2 because distance is farther away
If d1<d2, then w1>w2
Where d1 and d2 are distances to the adjacent pressure layers and w1 and w2 are the corresponding Weightage.

4.2 Assumptions and Data preparation

Wind is an influencing factor for the birds during its flight. When it is migration, the drift away from the track and the compensation undertaken by birds is purely explained by the wind effect in literatures (See, Alerstam (1979, 1991, 2000), Gauthreaux (1991) and Green and Alerstam (2002)). In this study, a route (ideal route, figure 4) is the shortest vector joining the departing site and destination site. The departing site and destination sites are the average of geolocation points one day earlier and 1 day after the migratory days (21st September 2010 to 1st October 2010). According Koistinen (2000), the track is resultant vector of heading and wind direction (Figure 3). Thus this resultant vector is the shortest line joining the destination point and the departing point.

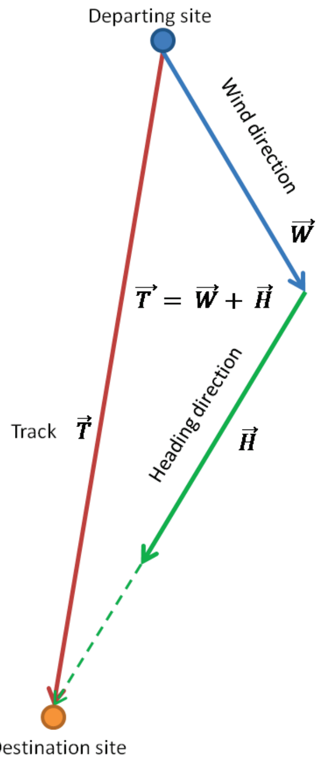


Figure 4: The sum of vectors W and vector H is the resultant vector T. The ideal route designed is analogous to this resultant vector (derived from Koistinen (2000).

Since a bird seldom follows this route due to assumed factor effects, and it is efficient because of its shortest distance, than any other route, the observed path during a migration has been considered as off route and hence it is drift in terms of deviation. Stronger the favouring wind, closer will be the distance between off route and ideal route for a migrating bird.

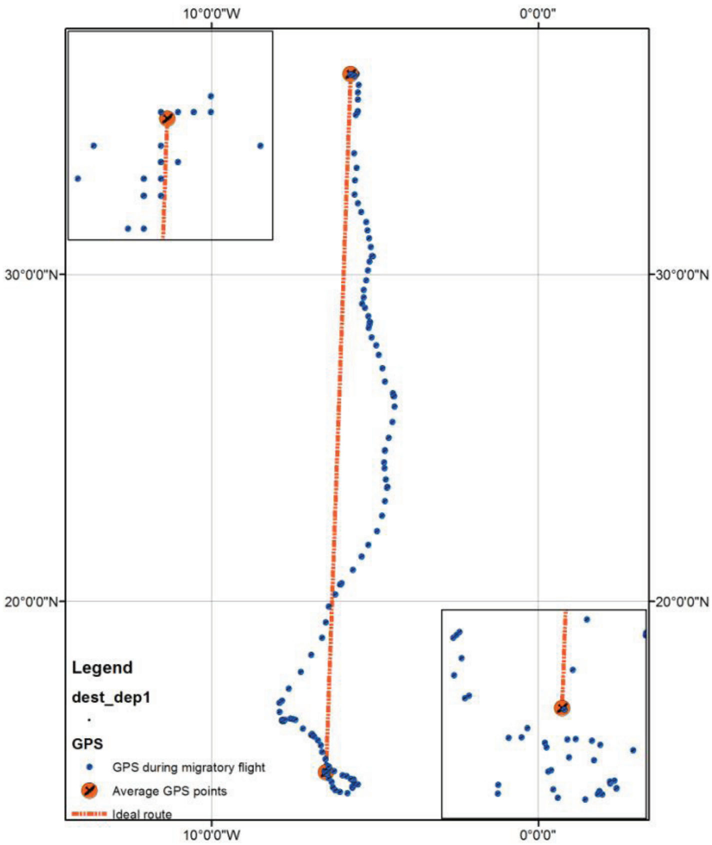


Figure 5: Departure point and Destination point with ideal route. The diagram in the box above and below show the mean (red) for the Birds position that marks the departing site (upper) and destination site (bottom).

Higher the negative cross wind (from left), greater will be right side deviation from the ideal route and if positive crosswind, the deviation from the ideal route would be towards left side. Since the resulting (observed path) depends not only birds own flight direction, but also on wind direction and speed (Alerstam, 2000), an assumption has been made, that possibly there are other driving factors that makes the bird to follow the observed path.

The departure location and the destination location are determined by the average of geo-locations prior and later to a day before and after the migration respectively. The line joining the two average points defines the ideal route for migration.

The extracted dataset was tabulated in spreadsheet for the preliminary processing such as sorting between day and night, and the migratory days. Based upon these extracted parameters, other relevant parameters were derived using the available common algorithms.

Wind direction: α= 900-(3600/C)*tan-1(V/U) + α0 eq. 3

Where, α0=1800 if U>0 but is zero otherwise, C is the angular rotation in a full circle (C=3600=2π radians).

Headwind = Wind speed (kt or kn)* COS (Wind direction-Bird direction) eq. 4

Where, the directions are in True-north and 1 knot= 0.514 m/s. A negative value will be Tailwind.

Crosswind: C= Wind speed (kt or kt)* SIN (Wind direction-Bird direction) eq. 5

A negative value will be crosswind from left.

4.3 Theoretical Basis and Variables.

4.3.1 Mann-Whitney test

Mann-Whitney test is non-parametric which tests two independent samples come from same population. This means that the median of the two samples are same and their difference is zero. It is considered as nonparametric equivalent to parametric t-test.

For two sets (groups) of samples of n_x and n_y observations, the possible number of pair wise comparisons of each x_i with y_i is $n_x n_y$. If the sample has same median then probability of observations x_i has equal chance of being greater or smaller than each y_i, i.e p=0.5.

$$H0: P(x_i>y_i) = 0.5 \text{ and } HA: P(x_i>y_i) \neq 0.5$$

If Wx and Wy represent the sum of number of times $x_i>y_i$ and sum of number of times $x_i < y_i$ where x_i and y_i are ordered by magnitude, then the Mann-Whitney statistic is given by:

$$W = \min(Wx, Wy) \qquad \text{eq. 6}$$

$$\text{where, } Wx + Wy = n_x n_y \qquad \text{eq. 7}$$

The probability of getting W is found from statistical table or from statistical softwares. If p value is small, the claim that difference in median being due to coincidence is rejected, i.e. alternative hypothesis is accepted. Alternatively if the confidence interval contains zero, null hypothesis can be accepted.

4.3.2 Theory of generalized linear models:

Generalized linear models (GLM) are the linear models made suitable for non normal conditional distribution of response variables. This generalization has three components.

1. Random component: It defines the distribution of response variables specifically conditioned on predictors. This distribution may be based upon the members of "exponential family" such as Normal, Binomial, Poisson, Gamma etc. Based upon nature of the data, the suitable family member is chosen for analysis and modelling.
2. Linear predictor (η): This is a linear function of the predictors on which the fit (expected value of μ_i of Y_i) depends.

$$\eta = \alpha + \beta_1 X_{i1} \dots\dots\dots + \beta_k X_{ik} = X_i{}' \beta \qquad \text{eq. 8}$$

3. Link function: This transforms the expected response to the linear predictor.

$$g(n_i) = \eta_i \qquad \text{eq. 9}$$

If the inverse of this link function is taken, it is called mean function. Link functions may be Identity, log, inverse, logit, probit etc.

There is condition on the variability of Y in GLM. This condition is the basis i.e, conditional variance of Y is function of mean μ and a dispersion parameter ϕ. A GLM is fit based upon maximum likelihood of the estimated parameters denoted by $\hat{\alpha},\ \hat{\beta}_1,\ \hat{\beta}_2 \dots\dots\dots\dots\dots$.

The log-likelihood for a model is obtained by maximized regression coefficient which is given by

$$\log L_0 = \sum_1^n \log_e p(\hat{\mu}, \emptyset; y_i) \qquad \text{eq. 10}$$

where $p\,(.)$ is the specific probability density function (pdf) for the family considered for modelling. Similarly a saturated model exists when single parameter is used for each observation during the modelling. This fits the data perfectly. But instead of $\hat{\mu}$, as in log likelihood of the model, individual response variables are used. The twice the difference between these two log-likelihoods is called Deviance. If Deviance is divided by the estimated dispersion ($\emptyset$), one gets scaled deviance.

GLM with Gaussian family with identity link produces normal linear model and the maximum-likelihood estimates are equal to the ordinary least-squares estimates.

4.3.2 Variables:

The variables based on which this study is carried out are from meteorology and

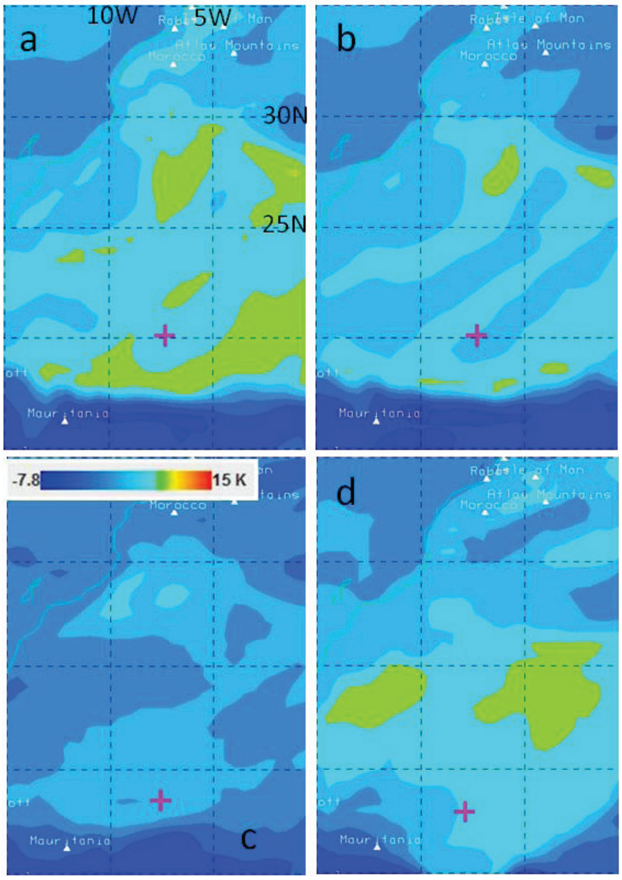


Figure 6: Surface lift index and the Short toed eagle position on 28th September 2010, over North Africa, at different time. a: 7 am, b:11 am, c: 15 pm and d: 8 pm. The pink cross marks the bird's position on same time and date. The bird has flown over lower surface index throughout the day. This figure is produced

as an example, one of the variables has been illustrated in figure 5 which illustrates the prevalence of surface lift index at different time of same day and the flight position of the bird on the same date and time. It is remarkable to notice that the flight position has been always with relatively lower surface lift index. Table 1, lists all the variables used in the study.

Table 1: List of the variables for the study

SN		*Name*	*Description and source*	*Unit*
1	Extracted from IDV	Wind Speed*	Wind speed@bird altitude, NCEP/GFS0.5,3hourly	m/s
2		U Comp	Westerly wind (U component of wind), NCEP/GFS0.5,3hourly	m/s
3		V Comp	Southerly wind (V component of wind), NCEP/GFS0.5,3hourly	m/s
4		Lift*	Surface lifted index, NCEP/GFS0.5, 3hourly	Kelvin
5		Temp*	Air temperature@bird altitude, NCEP/GFS0.5,3hourly	Kelvin
6		Shear*	Vertical wind shear@tropopause, NCEP/GFS0.5,3hourly	/s
7		RelHum*	Relative humidity@bird altitude, NCEP/GFS0.5,3hourly	%
8	Derived	Wind direction*	Wind direction from U and V components	True north
9		Headwind**	Wind component parallel and opposite to the destination, if negative, it is tailwind	m/s
10		Crosswind**	Wind component perpendicular to the journey path, if negative, it is from left	m/s
11		Deviation**	drift in km from the ideal route, derived from Argos data	km

*, ** are the variables used in modelling, ** are the variables used to analyze the Deviation.

4.4 Reliability and Validity

The modelling approach taken in this study is deductive, where a general proposition has been made such as the ideal route designed (see Skidmore, (2002)). With reference to the ideal route designed, the deviation with reference to it has been analyzed and modelled.

The data for the analysis has been tested for the normality using Shapiro-Wilk normality tests. The hypotheses test has been done using Generalized regression model that are unaffected by the demanding normality of data from real world.

The modelling approach has been selected such that the model incorporates non-linear and non normal distribution of the components. Since the chosen statistical tool is GLM with its random component being Gaussian and the link function being the identity, the random component must come from non-normal but from the exponential distribution (Cox et al., 1994) assuring that the model can address non-linear and non-normal nature of data. Further the link function used assures the relationship is monotonic differential function that assures linear relation between predictors and response variables.

The link function relates the linear predictor η with μ of response variable which can take any value on real line. A real line includes negative, zero and positive numbers which makes the function suitable for the analysis in this study as several variables are continuous and real numbers. Thus the GLM has been selected also because it outputs are based on Maximum Probability Likelihood. Beside this some predictor variables were denoted by signs "+" and "-"as are used in meteorology. Generalization is based upon the consistency in variance distribution rather than the normality criteria in data which was coined by Gauss in 1823 via his book "*Theoria combination*" and later on it was generalized on ordinary linear regression and is termed as Generalized linear modelling(Cox et al., 1994 pp:11). In this analysis the normality criteria has not been applied and assumption is based on consistency in variance distribution which is assessed through the pattern in error (deviance) distribution after a model is constructed.

The Short-toed eagle under this study is juvenile which migrated for the first time on its own. This limits the study that the findings cannot be interpreted for adults or for sex and for population. Further the analysis has been done for one way migration thus the study has not analysed for the complete (two way) migration due to incomplete availability of data during the period of this study.

Chapter 5. Results and Discussions

5.1 Data description

5.1.2 Variables description:

The descriptive statistics for the variables under this study were assessed for Altitude at flight, Relative humidity at flight, Temperature at flight, Vertical wind shear, Surface lift index, Wind direction at altitude of flight, headwind, crosswind and Deviation. All the variables are from duration of the migratory period, i.e 21st September 2010 to 1st October 2010.

The average of flight altitude is 837+68.58 m, for relative humidity it is 24.11+2.07 %, for temperature at flight, it is 304.55+0.77 K0, for Wind shear it is -0.0498+0.01 per second, for Surface lift index it is 2.20+0.47 K0, for wind direction it is 263.500+6.730, for headwind it is 0.44+0.57 m/s, for crosswind it is 0.29+0.80 m/s and for deviation it is -24.55+12.88 km.

The highest variation is for crosswind with coefficient of variation of 2110.26% followed by headwind (CV=1020.82%) and Deviation (CV= 409.88%). The least variation in data set is for temperature (CV=1.98%) and then with flight course (36.83%). Thus along the migratory course observed, the most diverse variable in this study are crosswind, headwind and Deviations. For details, please refer the Annexe C.

5.1.2 Normality issues:

The variables were tested if the population from which they are drawn are normally distributed using Shapiro-Wilk test. The null hypothesis is that they come from normal population. If the p-value is less than 0.05, the null hypothesis is rejected.

Majority of the variables come from non-normal population. The flight course and the headwind have normal population while other variables have significantly non normal distribution. In overall the data are non-parametric in nature (see Annexe D for detail)

5.2 Migration details:

The Short-toed eagle under study has migrated for the first time for its winter ground in mid-Africa on 21st September 2010 for the year from southern Spain. Remarkably in comparison to several other individual of same species, this eagle has the higher degree of accuracy for the GPS points. With a total of 11 days on its one way migration it has 10 stopovers during the journey covering a great circle distance of 2382 km from Tarifa region (36.1172N,5.7486W) of Spain (breeding ground) to Diabaly region in Mali of mid-Africa (14.702N, 6.519W) (wintering ground) in 11 days. The difference in longitude of the destination site has been less than a degree (0.7704 degree westward) from the departing site.

The distance covered has varied but the migratory distance covered is characterized by range of 28 km to 131 km in comparison to the beginning and towards the end of the migration. Since the distance covered is between two adjacent geo-locations with time difference of 1 hour, the distance covered can be considered as speed too. Higher the distance covered, higher is the speed. However due to outliers and data filtration not all the geo-location with time interval of 1 hour are represented in figure 7.

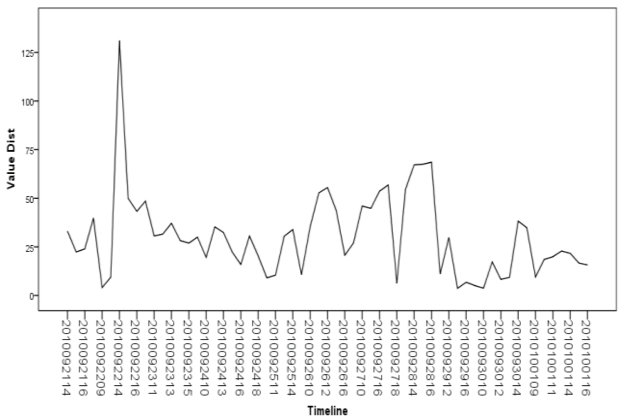


Figure 7: Run plot for the distance covered.

The average distance covered is 30.40+2.76 km between two adjacent geo-locations at 1 hour apart, which can be taken as speed too. The largest distance covered is 131 km on 22nd September 2010 day (Figure 6; between 10 am-2pm) on which the bird was above Morocco desert. ÅKesson and HedenstrÖM (2007) have reported similar speed range in other raptor-Lesser spotted eagle with speed of 133 km/day. But the Short-toed eagle has this speed in 4 hours on the day. Further the authors mention that the distance covered is based on diminishing return i.e. higher the food intake, higher energy required to compensate for drag and its own body weight. Since the bird started its migration on 21st September, the accumulated body weight should not have allowed it to gain that speed and distance coverage immediately next day because it takes time to digest the food and store it as body fat. Only rare literatures have addressed the time required to

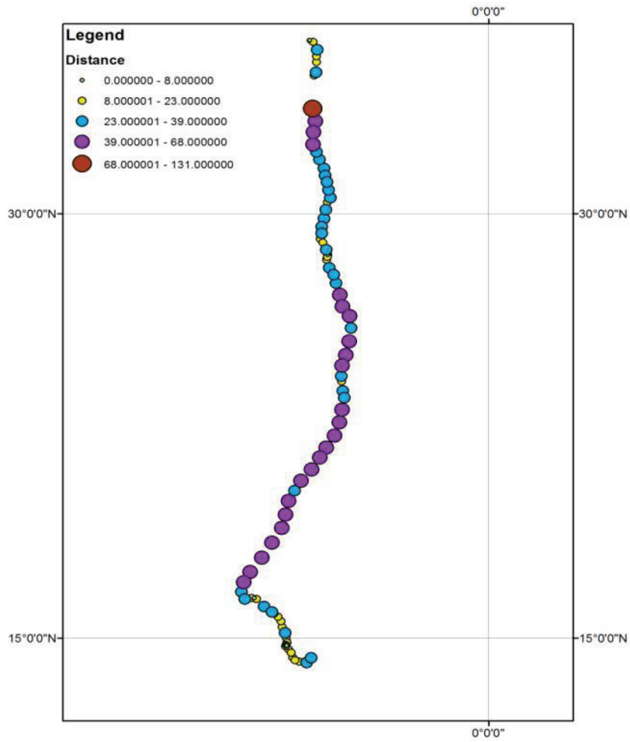


Figure 8: Distance covered between each geo-locations of minimum at 1 hour apart

convert the food intake to body fat that is crucial as energy required immediately for the flight next day at fuelling site.

5.3 Deviation Analysis

Along the migratory course, geo-locations with crosswind from right are more in number than geo-locations with crosswind from left. This could be the reason why the migratory deviations are mostly to the left of ideal route due to the push of the crosswind from right. Since the headwind is more in number than tailwind in the observations, the left deviation could be a strategy to balance out the effect in some way, by the bird.

The mean speed of crosswind from right and left, headwind and tailwind together with the deviation away from the ideal route is given in table 2. Though right crosswind is more in number than the left crosswind, the mean of crosswind from left is less than the mean of the crosswind from right. Headwind is stronger throughout the observed route than the tailwind and deviation to the left has been greater than the deviation to the right. The box plots (figure 8) shows the additional description of the variables in deviation analysis.

Table 2: Descriptive statistics for crosswind, headwind and deviations

Variables	*count*	*mean*	*Mean SE*	*CI 95.% lower*	*CI 95.% upper*
Rcros	35	4.79	0.45	3.87	5.70
Lcros	26	5.75	0.84	4.01	7.48
Hdwin	32	3.87	0.53	2.79	4.96
Tlwin	29	3.35	0.42	2.48	4.21
Rdev	20	93.76	12.82	66.92	120.60
Ldev	41	82.27	8.86	64.36	100.19

Rcros: Right crosswind, Hdwin: Headwind, Rdev: Deviation to the right

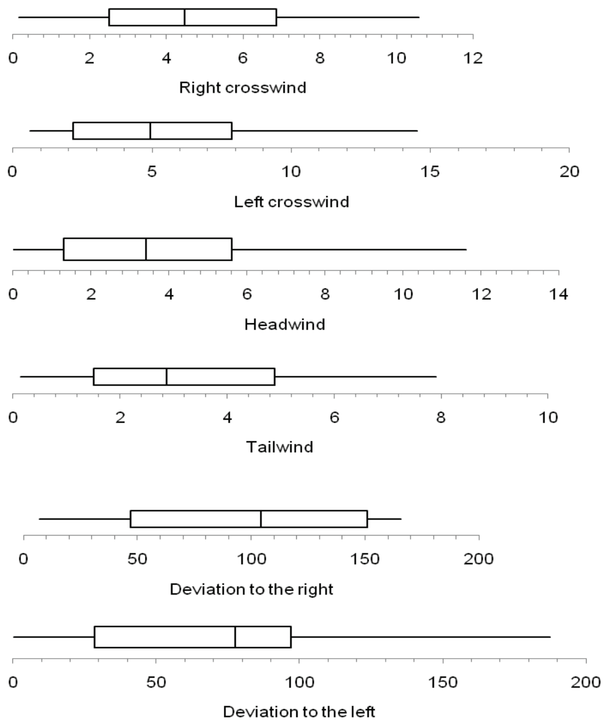


Figure 9: Box plots for the crosswind, headwind and deviations

Table 3: Mann-Whitney test for Deviation Analysis

Variables	*N*	*Median*	*Point estimate*	*Conf. Interval*	*W*	*P-value*	*Conclusion*
Right crosswind	35	4.46	-0.423	-2.15, 1.35	1084	0.75	Accept H_0
Left crosswind	26	4.95					
Headwind	32	3.41	0.287	-1.07, 1.71	1023	0.65	Accept H_0
Tailwind	29	2.88					
Right deviation	20	104.18	13.38	-20.67, 55.46	621.0	0.53	Accept H_0
Left deviation	41	77.54					

The hypothesis test regarding the crosswind and headwind has resulted that the crosswind from right has equal magnitude with the crosswind from left. The headwind is also equal in magnitude with the tailwind but the numbers of the flight positions with the headwind are more than the number of geo-locations with tailwinds.

Similarly the deviation to the left and right has similar magnitude. Since the majority of observed geo-locations have headwind, the migratory route has been against the headwind. This is in accordance with the review article done by Tinbergen and D. S (1950) that Chaffinches (*Fringilla coelebs*) which headed for migration towards West South-west direction when the headwind prevailed from South-east, South, South-west and West. In this scenario, it can be seen that headwind will occur most of the time than tailwinds. Similarly, Thorup et al. (2006) also have reported that during the migration of Ospreys (*Pandion haliaetus*), the birds fly without regard of wind and they have proposed that the strategy of no wind selectivity (travelling independently without wind) may be more favourable than stopping to rest when headwind prevails (travelling dependently with wind). Similar results can be inferred in this study too.

The flight position of the bird is in such a way that the net effect of crosswind and effect of headwind tends to be zero at the completion of journey. Without this, the bird would not reach to its destination goal for, prevalence of tailwind only is impossible along the migratory route and headwind opposes the migratory flights. Thus its the bird's strategy to fly is in a such way that the intensity of headwind is equal with intensity of tailwind and the magnitude of crosswinds from right and left are equal throughout the migratory flight.

5.4 Deviation modelling

The response variable is the deviation (state variable) which is signed continues number for the regression modelling. In the predictor variables Headwind, crosswind and Lift are signed continuous data and the rest are positively signed.

The first step modelling included all the 10 variables and produced significant coefficients for three variables. These are crosswind, surface lift and the wind speed. Others ranged from p value of 0.1444 (for headwind) to 0.9009 for (Wind direction). The residual deviance remained 177283 on 50 degrees of freedom (Table 4).

Table 4: Stepwise modelling achievements

Models	*AIC*	*Excluded variables*	*Predictors*	*Observations*
GLM.1	683.56	Non	10	61
GLM.2	682.35	Flight altitude, Relative humidity and Temperature	7	61
GLM.3	680.42	Flight course	6	61
GLM.4	678.57	Wind direction	5	61
GLM.5	621.59	Non	5	57
GLM.6	677.95	Head wind	4	61
GLM.7	677.97	Vertical wind shear	3	61
GLM.8	609.89	None	3	57

The Variation Inflation Factor (VIF) of the model illustrated that the altitudes of flight, the relative humidity and the temperature had severe influence due to multicollinearity (VIF>10) in the regression. The modelling after the removal of the predictors with higher VIF yielded the same number of significant coefficients. During the stepwise (see table 5) the variables with insignificant coefficients were removed namely, Course (p=0.81) and Wind direction (p=0.71), Headwind (p=0.27) and Vertical wind shear (p=0.17) to obtain the final model with details given in Table 5.

Migratory Deviation from shortest path between departing site and destination site:

= -50.59 + (-5.12* Crosswind) + (-18.85* surface lift index)
+ (16.96*Wind speed) eq. 11

with residual deviance: 124179 on 53 degrees of freedom

Table 5: The result model from stepwise modelling.

GLM.8				
Deviance Residuals				
	1Q	Median	3Q	Min, Max
	-31.47	-2.84	20.2	-84.68,195.35
Coefficients				
	Estimate	Stud. Residuals	t value	Pr(>|t|)
(Intercept)	-50.59	16.30	-3.104	0.003065 **
Crosswind	-5.12	1.16	-4.394	5.37e-05 ***
Surface Lift In.	-18.85	2.05	-9.185	1.51e-12 ***
Wind speed	16.96	4.78	3.544	0.000831 ***

Signif. codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**
Dispersion parameter for gaussian family taken to be 2342.993
Null deviance: 479480 on 56 degrees of freedom
Residual deviance: 124179 on 53 degrees of freedom
AIC: 609.89

From table 5, the coefficient of crosswind being negative ($\beta_c<0$) is probability of getting t value lesser than -4.394 which is 2.62e-5 obtained by dividing the two tailed p value (5.37e-05) which is again significant. Thus, the alternative hypothesis that the positive crosswind has negative effect on the deviation is accepted.

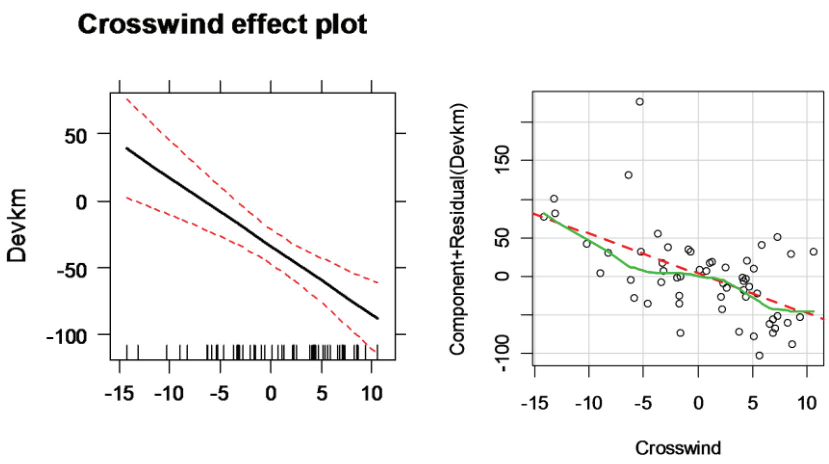
Similarly the coefficient of the lift ($\beta_l<0$) is also significant with p value of 7.55x10-13 obtained by dividing the two tailed p value (1.51e-12). Thus the null hypothesis cannot be accepted and the alternative hypothesis that the effect of lift on the deviation is negative is accepted. But for wind speed (HA: $\beta_w<0$) is p of getting t<3.544 which is 1-(0.000831/2)=0.999. This makes probability of getting t-value less than 3.544 insignificant. Hence the directional hypothesis regarding the wind speed that wind speed has negative effect on the deviation is insignificant. For the headwind, since it was excluded in the stepwise modelling because of its insignificant coefficient, the hypothesis related to it could not be tested.

Crosswind alone affects by magnitude of 5.28 to the deviation. Positive values of crosswind (i.e. crosswind from right pushing the bird to the left) will affect the drift of flight to the left. If it is positive i.e., crosswind is from left side, the deviation is to the right, of the ideal route designed.

Surface lift increases the deviation to the left by 18 units but the wind speed reduces it by 16.96. If all the predictors are positive and unity, the overall deviation will have negative sign, i.e the deviation will be to the left. This implies the deviation is biased towards left side in the winter migration of this Short-toed eagle.

5.5 Model Analysis and goodness of fit:

Model analysis and goodness of fit for generalized linear models are done via the Deviance analysis.



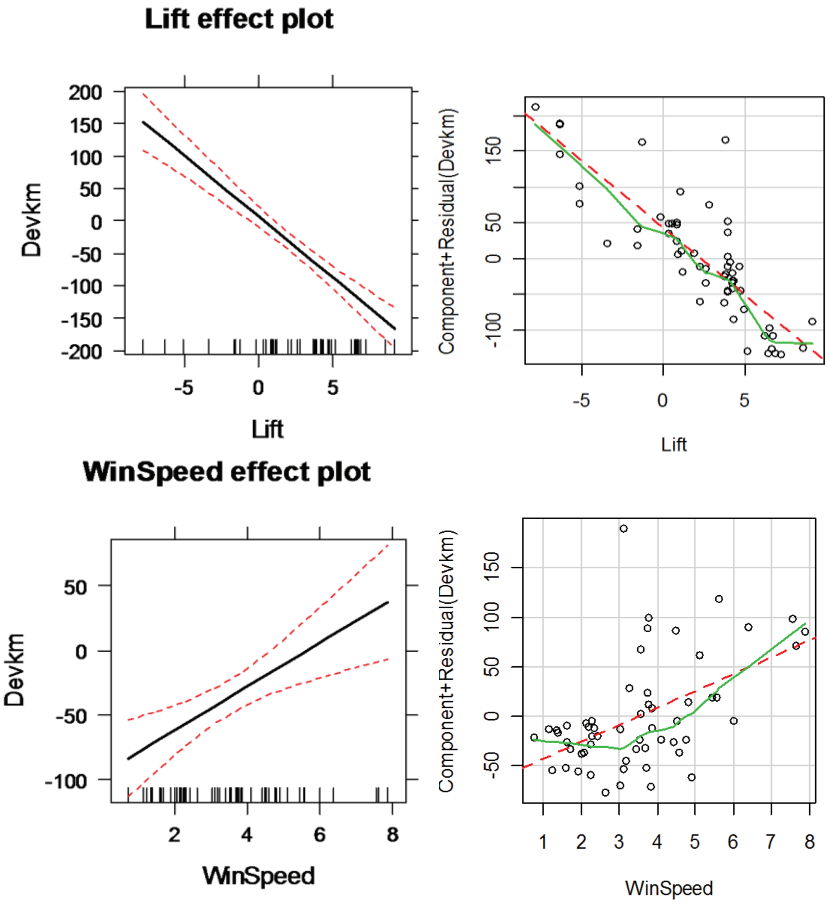


Figure 10: Effect plots (left) and Component+ residual plots (right) from the final model

The effect of the individual variables on the deviation fit from the ideal route (figure 10) shows the effect has been higher and centred around 0 and above for crosswind and lift. The confidence bands for the fit also, are narrower in these regions. For wind speed, the effect on the model has been from the wind speed lesser than 6 m/s. The confidence bands are narrower in mid region and as one go further away the confidence band widens increasing unreliability towards the extremes.

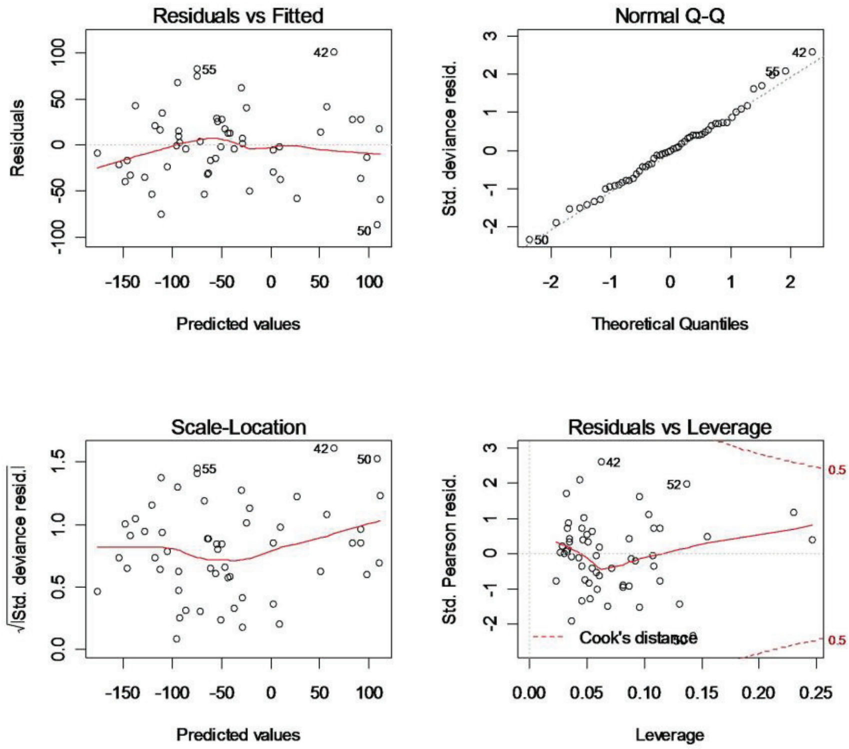


Figure 11: Model checking plot

Component in addition with the residuals ((residuals from full model + βiX) against Xi) gives the fit marked by the green smoothed line between the chosen variable and the regression line considering all the variables. Without the residuals, the relationship is shown by the marked red dashed line.

The model checking plot (Figure 11) shows the residual distribution are normal except some observation clustered namely, observation number 42, 52 and 55. Each observation is within the cook distance and there are no clear trends in the residual distribution. The QQ plot clearly marks the extreme points.

The analysis of deviance (anova, type I) test has result in the following table 8.

Table 6: Analysis of deviance for the model

Terms added sequentially (first to last)						
	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
NULL			56	479480		
Cross wind	1	149827	55	329653	63.95	1.133e-10 ***
Surface lift index	1	176039	54	153614	75.13	9.738e-12 ***
Wind speed	1	29436	53	124179	12.56	0.0008311 ***

Significance Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '

Table 6 indicates the significance in deviance reduction when the variables are added sequentially. In other sense it is nested model test with the three variables shown in the table. The sequential inclusion for the individual variables has reduced the residual deviance and the results are statistically significant. This indicates the model is good and that the resulting variables do explain better when taken together.

5.3 Model Evaluation

The table 9 presents the confidence intervals for the regression coefficients at 95%. If looked at the intercept, it does not permit the intercept to have zero or positive. This implies the migration starts always with deviation to the left if there is no meteorological effect in the model.

Table 7: Confidence interval for the coefficients

GLM.8 level=.95			
	Estimate	2.50%	97.50%
Intercept	-50.59	-82.54	-18.64
Crosswind	-5.12	-7.40	-2.83
Surface Lift Index	-18.85	-22.87	-14.82
Wind Speed	16.96	7.58	26.34

Crosswind and Surface lift index have negative coefficient but the product will not be negatives only because crosswind has two sides with opposite signs in the data. Hence the deviation is affected by these from and by, both sides.

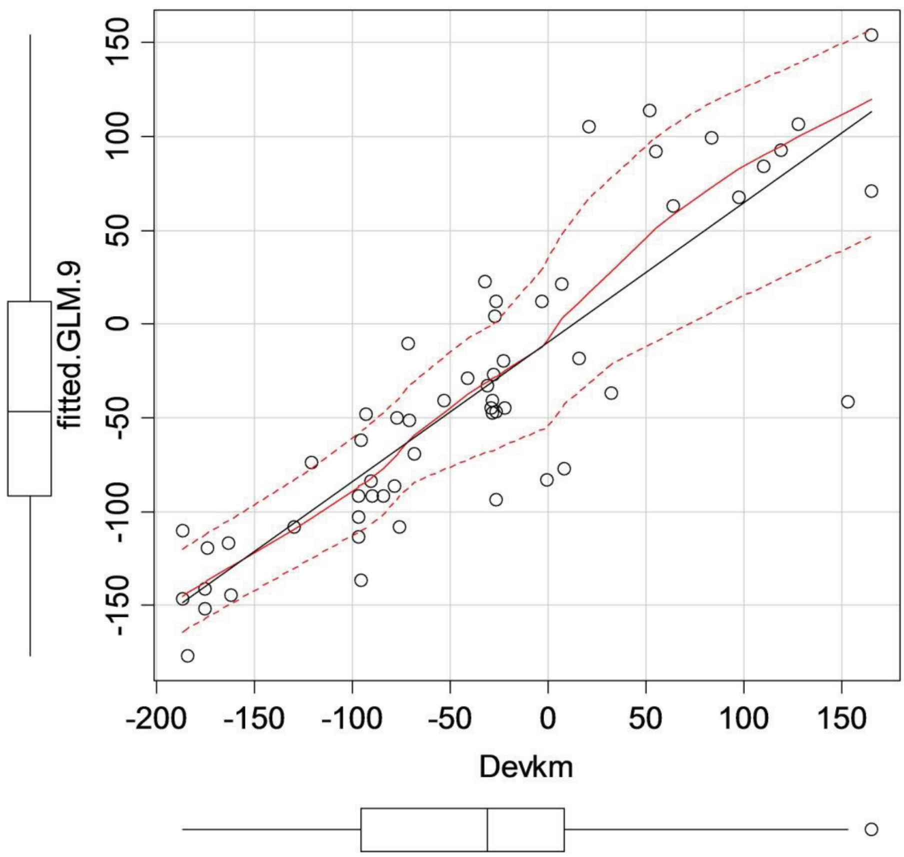


Figure 12: The predicted vs. observed deviations

Figure 12 demonstrates the fit, smoothed line and the confidence interval band for the smooth line. Thus the model can be considered as satisfying. The left deviations from the shortest route have better fit, since they have narrower confidence band around belonging to negative values of deviation as the median lies nearly at same intervals and in negative region of deviation in this study (refer the box plots).

According to Pennycuick (1978, in Koistinen (2000)) the tailwind and the headwind are responded by the birds by adjusting itself with altitude rather than deviating away from main track, this could be the reason why headwind was insignificant in the modelling process.

Chapter 6: Conclusions and Recommendations

The distance coverage per unit time has ranged up to 131 km in 4 hours with mean distance coverage per hour as 30.4+2.76 km in time intervals ranging from an hour to four hours. The highest distance coverage has been on the 2nd day of migratory journey over Moroccan desert in North Africa on 22nd September 2010.

The distribution of crosswind, headwind and tailwind has been equal in magnitude throughout the migratory journey. Crosswind from right is more ($n=35$, $N=61$) but it is statistically equal in magnitude with crosswind from left throughout the journey ($W<1085$, $p=0.7539$ and Confidence interval (CI) for the difference can have value 0, which is possible if the the opposite wind factors are equal). The headwinds has prevailed more than tailwinds ($n=32$, $N=61$). Alike the crosswind, the magnitude of headwind and the tailwind are equal in the journey ($W=1023$, $p=0.6596$ and CI~0). The magnitude of deviation to the left and to the right are also statistically equal ($W>620$, $p=0.5338$ and CI~0).

This could be a strategy of the bird to conserves energy. Every flight position chosen by the bird goes in way that opposing wind forces tend to cancel each other at the end. The majority of the deviation being left sided is due to the higher number of geo-locations with crosswind from right side.

The migratory course would start from the left (50 km) of the ideal route that joins the departing site and destination site in absence of wind effect. Higher the crosswind (i.e. positively higher = from right), the deviation to the left will increase by 5.12 km. With higher surface lift index, this deviation will again increase to the left by 18.85 km to the left. However, higher the wind speed disregarding the direction, the left side deviation would decrease by 16.96 km to the right. Wind speed does not determine the deviation to the left. Deviation is determined by the crosswind, surface lift index along the geographical region of the migration.

The left deviation observed even if there is no wind effect could be an effect of surface lift index. It is likely that the surface lift index towards the eastern side of the ideal route is less and the bird has preferred it. A separate assessment of the surface lift index over the migratory region would bring deeper insight in explaining the observed deviations.

The deviation considered here is based upon the geographical distance from the ideal route. Since the headwind is adjusted by the birds with altitudinal variation, considering the wind related parameters in relation to altitudinal variation may explain migration more in addition with other meteorological variables.

Meteorological factors do determine the migratory route of the bird and the bird adjusts its flight position and route such that the total effect from wind related variables tend to cancel out each other in the end of journey. So any drift from the idealized route, is in fact an adjustment to the prevailing meteorological conditions. The deviation from the ideal route could be in fact a search for unstable air parcel that eases the bird to carry out its migratory journey. This search makes the bird to deviate more to the left than right.

Analysis of migratory behaviour including the return migration may reveal better information on migratory behaviour of this bird. Comparison of the model in this study with a model that integrates the return migration as well could increase our understanding in migration behaviour of Short-toed eagle.

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Appendices

Appendix A: Data table

SN	Timeline	Lat	Long	Flight alt m	Course degree	Rel Hum %	Temp K	Win Speed m/s	Shear /s	Lift K	Wind dir degree	Headwind m/s	Crosswind m/s	Dist km	Dev km
1	2010092114	35.79	-5.51	573	183	78	293.60	3.17	-0.19	1.20	262	-0.32	-6.16	33.11	-26.90
2	2010092115	35.56	-5.53	554	61	70	295.38	2.43	-0.31	0.30	235	4.14	2.29	22.41	-27.85
3	2010092116	35.34	-5.53	1097	189	69	292.54	2.18	-0.15	0.30	236	0.66	4.19	23.96	-28.28
4	2010092208	34.98	-5.54	149	67	56	298.66	1.38	0.36	0.80	310	2.47	1.05	39.77	-28.40
5	2010092209	34.95	-5.54	356	294	49	298.58	1.62	0.28	0.80	326	-2.88	1.28	4.07	-22.03
6	2010092210	34.88	-5.60	413	192	45	299.30	1.72	0.13	0.80	338	-0.69	-3.27	9.43	-22.58
7	2010092214	33.70	-5.64	1400	238	43	296.26	3.70	-0.46	-1.60	327	6.10	3.82	131.10	-32.21
8	2010092215	33.26	-5.57	1780	169	37	294.89	3.44	-0.71	-1.60	327	-1.28	6.57	49.97	-27.17
9	2010092216	32.87	-5.63	430	188	27	306.43	2.14	-0.13	0.50	339	0.58	4.12	43.23	-29.00
10	2010092220	32.43	-5.63	1613	246	42	294.07	2.01	0.00	1.10	283	-3.57	-1.59	48.53	-41.20
11	2010092311	32.17	-5.53	986	141	36	301.61	2.07	-0.25	2.20	351	2.54	-3.13	30.58	-53.44
12	2010092312	31.90	-5.43	1329	180	32	300.24	3.04	-0.40	2.20	354	0.00	-5.91	31.60	-71.41
13	2010092313	31.59	-5.28	1390	144	25	300.61	3.26	-0.21	4.60	188	-3.73	5.13	37.12	-75.77
14	2010092314	31.34	-5.25	1642	130	25	298.59	3.76	-0.13	4.30	197	-5.60	4.70	28.26	-84.50
15	2010092315	31.11	-5.18	1636	136	25	298.99	3.86	-0.16	4.20	197	-5.21	5.40	26.90	-90.06
16	2010092316	30.84	-5.14	1327	244	22	302.06	3.04	-0.06	4.20	197	5.32	2.59	30.02	-96.76
17	2010092410	30.40	-5.18	881	80	22	302.94	2.34	0.05	3.80	219	4.48	0.79	19.61	-78.66
18	2010092412	29.81	-5.28	1319	226	20	301.32	1.59	-0.05	0.90	212	2.23	2.15	35.30	-70.89
19	2010092413	29.53	-5.36	1408	197	19	301.11	2.28	0.04	1.90	245	1.30	4.24	32.37	-68.16
20	2010092415	29.10	-5.40	1014	24	13	306.56	1.91	-0.06	2.60	252	-1.51	-3.39	22.40	-77.54

21	2010092416	28.98	-5.32	2028	178	22	295.95	2.25	-0.21	2.60	254	-0.15	4.37	15.93	-90.82
22	2010092417	28.72	-5.21	1654	189	18	299.79	2.27	0.07	4.20	251	0.69	4.36	30.58	-97.10
23	2010092418	28.54	-5.16	466	267	10	312.17	1.63	0.01	4.20	220	3.17	0.17	20.39	-97.10
24	2010092510	28.46	-5.18	694	13	12	306.90	4.76	0.00	6.60	241	-2.08	-9.02	9.08	-93.33
25	2010092511	28.37	-5.20	1391	222	14	301.90	6.01	0.11	4.30	246	7.82	8.69	10.47	-121.02
26	2010092513	27.84	-4.97	1405	160	15	302.17	4.53	0.13	4.90	247	-3.01	8.28	30.44	-130.00
27	2010092514	27.54	-4.90	266	139	9	314.22	3.83	-0.10	5.10	252	-4.89	5.62	33.92	-187.24
28	2010092518	26.28	-4.43	386	217	9	312.57	4.42	-0.05	7.20	257	5.18	6.87	10.74	-187.24
29	2010092610	25.96	-4.41	556	185	12	307.74	4.82	0.03	8.50	318	0.81	9.34	35.32	-184.75
30	2010092611	25.49	-4.48	746	235	10	307.89	4.59	0.03	6.40	301	7.31	5.12	52.78	-174.40
31	2010092612	25.00	-4.59	785	165	9	307.86	3.87	0.03	6.50	297	-1.95	7.27	55.51	-162.52
32	2010092613	24.62	-4.71	221	286	7	314.11	3.13	-0.01	6.80	286	5.85	-1.68	43.83	-163.71
33	2010092616	24.07	-4.72	1688	187	12	299.68	3.69	0.05	6.20	273	0.87	7.13	20.68	-175.75
34	2010092618	23.49	-4.63	303	185	7	313.39	3.54	0.00	6.70	279	0.60	6.86	26.97	-175.75
35	2010092710	23.06	-4.70	451	249	19	306.15	6.40	0.03	9.10	358	11.62	4.47	46.02	-95.87
36	2010092714	21.37	-5.42	223	286	9	314.03	4.11	0.03	3.70	187	-7.69	2.21	44.78	-95.87
37	2010092716	20.96	-5.69	971	220	10	306.84	3.55	0.00	3.70	182	-4.44	-5.29	53.62	-31.04
38	2010092717	20.56	-6.03	545	248	8	311.32	3.73	-0.03	3.90	182	-6.73	-2.72	56.83	-26.74
39	2010092718	20.52	-6.07	291	212	8	313.22	3.55	-0.05	3.90	354	3.66	5.86	6.19	-26.74
40	2010092813	18.89	-6.63	1361	197	19	300.59	7.64	-0.17	4.70	216	-4.35	-14.21	54.60	64.28
41	2010092814	18.36	-6.96	1760	206	20	297.32	7.55	-0.11	4.10	226	-6.44	-13.20	67.18	97.97
42	2010092815	17.84	-7.28	1574	185	18	299.44	7.49	-0.05	2.60	225	-1.27	-14.52	67.51	137.30
43	2010092816	17.34	-7.65	1710	211	19	298.00	7.88	0.02	-0.20	224	-7.90	-13.14	68.54	165.73

44	2010092818	16.90	-7.92	230	210	11	312.22	3.78	0.01	-1.30	213	-3.68	-6.37	11.04	165.73
45	2010092912	16.38	-7.82	450	147	16	307.30	4.06	-0.03	0.50	246	4.30	-6.63	29.80	152.64
46	2010092915	16.36	-7.86	250	66	16	311.98	3.12	0.00	1.70	265	5.55	2.47	3.69	150.37
47	2010092916	16.35	-7.80	546	280	20	308.85	3.47	-0.01	1.70	279	-6.65	1.17	6.83	153.82
48	2010092917	16.38	-7.83	422	208	19	310.12	3.13	-0.03	3.80	288	-2.86	-5.38	5.07	153.75
49	2010093010	16.38	-7.76	229	165	42	305.99	1.36	-0.01	-7.80	238	-0.68	2.56	3.78	128.34
50	2010093011	16.41	-7.60	436	66	39	305.50	1.16	-0.02	-6.30	234	-2.06	-0.92	17.28	119.44
51	2010093012	16.41	-7.52	410	296	33	307.14	0.75	-0.03	-6.30	238	1.31	-0.64	8.29	110.39
52	2010093013	16.37	-7.44	769	144	37	304.16	1.25	0.00	-6.30	295	1.43	-1.97	9.33	83.85
53	2010093014	16.11	-7.21	852	113	36	304.18	2.24	-0.03	-5.10	282	4.01	-1.70	38.27	55.35
54	2010093015	15.92	-6.96	618	206	29	307.52	2.64	-0.02	-5.10	275	-2.25	-4.62	34.81	52.08
55	2010100109	15.87	-6.88	399	192	30	304.71	4.48	-0.01	1.00	322	1.81	8.53	9.51	32.48
56	2010100110	15.75	-6.76	378	280	25	307.03	4.92	-0.02	-3.40	336	9.43	-1.66	18.57	20.77
57	2010100111	15.59	-6.66	269	292	19	310.20	5.12	-0.04	3.90	349	9.24	-3.73	19.93	15.59
58	2010100112	15.39	-6.62	355	166	13	311.52	5.61	-0.04	3.90	360	-2.65	10.59	22.87	-0.32
59	2010100114	14.99	-6.49	547	140	12	310.79	5.55	-0.03	3.90	194	6.94	-8.27	21.70	-3.05
60	2010100115	14.85	-6.47	833	166	12	308.43	5.45	-0.07	3.90	206	2.56	-10.29	16.68	6.95
61	2010100116	14.71	-6.51	308	356	11	313.41	3.74	-0.01	2.80	189	-0.50	7.26	15.72	8.31

Appendix B: R scripts;run in library (Rcmdr), version: 1.6-3.

```
>setwd("C:/Users/Nirmal/AnlThes/forR/Doublecorefile/Modelli
      ng")
>Dataset <-
      read.table("C:/Users/Nirmal/AnlThes/forR/Doublecorefi
      le/Modelling/backmodelling/migdrift.csv",
      header=TRUE, sep=",", na.strings="NA", dec=".",
>strip.white=TRUE)
      >GLM.1 <- glm(Devkm ~ Balt + Course + Crosswind +
      Dist + Headwind + Lift +
      RelHum + Shear + Temp + Winddir +
      WinSpeed,family=gaussian(identity),
      data=Dataset)
>summary(GLM.1)
>Dataset <-
      read.table("C:/Users/Nirmal/AnlThes/forR/Doublecorefi
      le/Modelling/backmodelling/migdrift.csv",
      header=TRUE, sep=",", na.strings="NA", dec=".",
      strip.white=TRUE)
>GLM.2 <- glm(Devkm ~ Balt + Course + Crosswind + Headwind
      + Lift + RelHum +
       Shear + Temp + Winddir + WinSpeed,
      family=gaussian(identity), data=Dataset)
>summary(GLM.2)
>vif(GLM.2)
>GLM.3 <- glm(Devkm ~ Course + Crosswind + Headwind + Lift
      + Shear + Winddir
      + WinSpeed, family=gaussian(identity), data=Dataset)
>summary(GLM.3)
      >GLM.4 <- glm(Devkm ~ Crosswind + Headwind + Lift +
      Shear + Winddir +
      WinSpeed, family=gaussian(identity), data=Dataset)
>summary(GLM.4)
>GLM.5 <- glm(Devkm ~ Crosswind + Headwind + Lift + Shear +
      WinSpeed,
      family=gaussian(identity), data=Dataset)
>summary(GLM.5)
>influencePlot(GLM.5, id.method="identify")
      library(relimp, pos=4)showData(Dataset, placement='-
      20+200',font=getRcmdr('logFont'),maxwidth=80,
      maxheight=30)
>Dataset <-
      read.table("C:/Users/Nirmal/AnlThes/forR/Doublecorefi
      le/Modelling/backmodelling/migdrift1.csv",
      header=TRUE, sep=",", na.strings="NA", dec=".",
      strip.white=TRUE)
>GLM.6 <- glm(Devkm ~ Crosswind + Headwind + Lift + Shear,
```

```
       family=gaussian(identity), data=Dataset)
>summary(GLM.6)
>Dataset0 <-
      read.table("C:/Users/Nirmal/AnlThes/forR/Doublecorefi
      le/Modelling/backmodelling/migdrift.csv",
       header=TRUE, sep=",", na.strings="NA", dec=".",
      strip.white=TRUE)
>GLM.7 <- glm(Devkm ~ Crosswind + Lift + Shear + WinSpeed,
      family=gaussian(identity), data=Dataset0)
>summary(GLM.7)
>GLM.8 <- glm(Devkm ~ Crosswind + Lift +
      WinSpeed,family=gaussian(identity),
      data=Dataset0)
>summary(GLM.8)
>par(mfrow=c(2,2))
>plot(GLM.8)
>influencePlot(GLM.8, id.method="identify")
>GLM.9 <- glm(Devkm ~ Crosswind + Lift +
      WinSpeed,family=gaussian(identity),
      data=Dataset)
```

Appendix C: Descriptive statistics for the variables under study.

	Balt	Course	RelHum	Temp	Wind Speed	Shear	Lift	Wind Direc.	Head wind	Cross wind	Dist	Deviation
count	61	61	61	61	61	61	61	61	61	61	61	61
mean	837.26	187.93	24.11	304.56	3.57	-0.05	2.21	263.61	0.44	0.30	30.41	-24.56
minimum	149.00	13.00	7.00	292.54	0.75	-0.71	-7.80	182.00	-7.90	-14.52	3.69	-187.24
maximum	2028.00	356.00	78.00	314.22	7.88	0.36	9.10	360.00	11.62	10.59	131.10	165.73
standard error of the mean	68.58	8.86	2.07	0.77	0.22	0.02	0.48	6.74	0.58	0.80	2.77	12.89
confidence interval 95.% lower	700.09	170.21	19.97	303.01	3.14	-0.09	1.25	250.12	-0.71	-1.31	24.87	-50.34
confidence interval 95.% upper	974.43	205.66	28.26	306.10	4.01	-0.01	3.16	277.09	1.60	1.90	35.95	1.22
skewness	0.56	-0.33	1.51	-0.10	0.76	-1.44	-0.88	0.29	0.27	-0.64	1.85	0.34
coefficient of variation (CV)	0.64	0.37	0.67	0.02	0.47	-3.11	1.69	0.20	10.20	21.12	0.71	-4.10
1st quartile	399.00	147.00	12.00	299.68	2.25	-0.07	0.80	224.00	-2.86	-3.39	15.93	-93.33
median	618.00	189.00	19.00	305.50	3.54	-0.02	2.80	252.00	0.58	1.28	28.26	-28.40
3rd quartile	1361.00	226.00	32.00	308.85	4.48	0.01	4.20	301.00	3.66	5.12	39.77	32.48
interquartile range	962.00	79.00	20.00	9.17	2.23	0.08	3.40	77.00	6.52	8.51	23.84	125.81

Appendix D: Normality of the data

R code:

```
>require (stats)
>shapiro.test(x) # x is a variable from the data matrix
```

Shapiro-Wilk Normality tests results

Reject “Ho: population is normal” if $p<0.05$

Vairables	W	P value	Remark
Alittude at flight	0.8915	5.71E-05	Ho rejected
Course	0.9742	0.2245	*Ho accepted*
Rel hum	0.8468	2.10E-06	Ho rejected
Temperature	0.9609	0.04887	Ho rejected
Wind speed	0.9456	0.008926	Ho rejected
Vertical wind Shear	0.8401	1.34E-06	Ho rejected
Surface lift index	0.9278	0.001455	Ho rejected
Wind direction	0.9495	0.01371	Ho rejected
Headwind	0.9869	0.761	*Ho accepted*
Crosswind	0.9516	0.01711	Ho rejected
Distance covered	0.8648	7.41E-06	Ho rejected
Deviation	0.9467	0.0101	Ho rejected