The effects of regional weather patterns on the migration of birds and *Lepidoptera* to a coastal migration "hotspot" in East Kent and possible changes in occurrence in response to global climate change.

Greg Lee

Supervisors: Dr Robert Jehle & Dr Danielle Hinchcliffe

MSc by Research Environmental Studies

Thesis

Table of Contents

Acknowledgements

Through the journey of this thesis, a whole host of people have supported me and taken interest in my work to see that it is done. My thanks firstly go to Professor Philip James, Dr Danielle Hinchcliffe and Dr Robert Jehle who have been excellent supervisors to me and guided me through this fascinating topic and research and been patient with the progress I have made over the past two years, I would also like to thank my partner, Carrie Nicholls, for supporting and reassuring me during times when things seemed difficult, particularly during the pandemic and helping me stay grounded. Always providing an ear for me to talk to consistently about moths and birds must be a difficult task, but she achieved this with good grace. Also, helping me with my own garden moth-trapping and providing her scribing skills is commendable.

My parents too, Nick and Emma are worthy of mention as they put up with my disappearance into my bedroom for hours throughout the COVID-19 pandemic, while working away at my thesis. They also supported me in my decision to undertake this study and allowed me to set-up my bright MV trap in the garden through the pandemic. Cecil the cat deserves a mention, as he was always willing to have a cuddle and has been a brilliant pet for nearly 15 years.

Megan Longville, who helped read through my thesis and provided a fresh second perspective on what I had written, also deserves my full gratitude, especially with the number of other students she works with. I always was thankful for her eye for missing commas!

My good friend Alex White, who always took time to help me and showed me the ways of Python, cutting possibly weeks/months of looking through the raw data-set by telling me how to quickly sift through, without him the data collection progress would have been far more time-consuming. He deserves more than just a pint for his patience and determination. Likewise, my friends Richard Churchill, Seb Challinor, Jack Francis, James Campbell, Jon Carr and Ryan Johnson whose late night meet-ups on Discord kept the spirits lifted though the pandemic.

I would also like to take time to thank Steffan Walton, Ian Hunter, Ken Chapman and the rest of the committee at Sandwich Bay Bird Observatory, for sowing the seeds of my interest in moths three years ago, on internship. The former two, particularly for their hard-work in data collection, as well as the late John Beugg, Dennis Batchelor and all the others who trapped at the Bay and recorded the data which went into this thesis. Their willingness to allow me to study their data is the whole reason this thesis exists in the first place. My thanks also extend to their decision in hiring me as Assistant Warden at the Observatory in 2022. Under their expertise I hope to train to be a ringer and pay back the Observatory by finding some rare species of moths and birds that someday, may be someone else will study the data I collect.

Jonnie Fisk, Paul Collins, Tim Jones, Jacob Spinks, Liam Andrews and all the community of Spurn Bird Observatory require my gratitude, as my internship there only strengthened my passion about discovering more about migration. The distraction of birds such as Arctic Warbler, Greenish Warbler, Wryneck, Barred Warbler, Yellow-browed Warbler, Red-breasted Flycatcher, Common Rosefinch, Dusky Warbler, Rustic Bunting, Red-backed Shrike and my own self-found Western Bonelli's Warbler was simply an incredible experience at such a fascinating place.

In loving memory of James (Jim) Parke (19.12.1940- 25.12.2022)
Beloved grandfather and keen supporter of my endeavours and interests

Abstract

The phenomenon of long-distance migration is an important strategy for the survival of many species by maximising chances of breeding success in different climates. By analysing past literature covering the effects of weather on migration, a research gap was found that related to understanding between categorised, localised weather patterns on the migration of three groups: migratory breeding birds, vagrant birds and migratory moths and how climate change could affect the weather patterns and hence migration to the UK. Using long term-data (30 years – 1990–2020) provided by the Met Office and Sandwich Bay Bird Observatory (a site on the southeast coast of England), notable dates of migration and records of unusual species were compiled, as well as the corresponding weather patterns. ANOVA tests were undertaken to identify which weather patterns were linked to migration events in the three species groups. Correlations were used to determine if the rate of migrant moths and vagrant birds was changing over time and if the weather patterns that were favoured for migration were changing in frequency. There was an increase in the number of migratory moths and vagrant bird species annually over the study period, with ten weather patterns being favoured by all three species groups. Notably, for several migratory birds, such as pied flycatcher and redstart, there were shifts in the arrival and departure dates, possibly linked with climate-change. Three weather patterns linked to migration showed major trends in frequency over the period of investigation. This implies that there were subsequent factors such as population change or changes in climate driving increases in vagrancy/migration. In conclusion, the research shows that there has been an upward trend in the occurrences of vagrant bird species and migratory moth species, despite little evidence of weather patterns changing. Recommendations from the study include the incorporation of a longer study-period and other sites, to identify if these trends are more widespread.

Abstract Word Count: 313 words

Statement of originality

I declare that, with the exception of any statements to the contrary, the contents of this report/thesis are my own work, that the data presented herein has been obtained my experimentation and that no part of the report has been copied from previous reports/theses, books, manuscripts, research papers or the internet.

Signed:

Print Name: GREG LEE

Date: 29/12/2022

1. Introduction

The spectacular phenomenon of migration is a world-wide life strategy observed in a range of highly adapted taxa. Mammals can travel vast distances, such as the wildebeest (*Connochaetes taurinus*) that follow the rains across Africa (Serneels and Lambin, 2002) and grey whales (*Eschrichtius robustus*) that swim from their calving grounds off the coast of Mexico to their Arctic feeding grounds (Noakes et al., 2013). In fish, notable species such as Atlantic salmon (*Salmo salar*) return to the rivers where they hatched to spawn after spending their adult life in the ocean (Dadswell et al., 2010). Pelagic species such as the billfishes (*Istiophoriformes*) and tuna (*Scombridae*) are almost in a permanent state of migration as they move huge distances across the world's oceans in their search for food (Dell'Apa et al., 2018). Migration is one of the most prevalent and growing research topics in the current era, with some research even making national news in the UK (Eastham, 2021).

1.1 Bird Migration

Historically, bird migration has always been a topic of fascination, the vast distances such small birds can travel as well as the unpredictability of rare/unexpected species or large falls of commoner migrants bring many birdwatchers to migration hotspots annually. Indeed, the distances covered by birds are some of the greatest across the animal kingdom. Species such as the Arctic tern (*Sterna paradisaea*) travel from the Arctic to the Antarctic every year, covering a distance of 25,000 miles (Alerstam et al., 2019). Many migratory species are tiny, weighing only several grams, yet they are capable of flying from their breeding grounds in the north of Europe, Asia, and America to their wintering grounds below the equator. One of the most impressive examples is the North American blackpoll warbler (*Setophaga striat*a), which weighs only 12 grams yet covers a one-way migration distance of 2770 km over open water during three days of non-stop flight (DeLuca et al., 2015). Migration can be an innate activity as many juvenile birds, having hatched in the spring, instinctively, in autumn, begin the long passage to a place they have not previously visited (Newton and Brockie, 2007).

Besides the conspicuous large numbers of birds moving seasonally, the unpredictability of the falls of birds (i.e., the landing of birds *en route* or at the end of their migration) and the occurrence of unusual and rare species create a sense of wonder for many (Wernham, 2008). In the Middle Ages, the traditional belief around some of the UK's most obvious migrants, the Hirundines (swallows and martins), was that they spent the long, winter months dormant at the bottom of our ponds and lakes (Green, 2019). A goose species was thought to hide in mollusc shells during their absence, thus lending the name barnacle goose to the species (Patowary, 2020). The renowned Greek philosopher Aristotle similarly believed that the common redstart (*Phoenicurus phoenicurus*) transformed to over winter as the robin (*Erithacus rubecula*, Zimmer, 2017). Over time, understanding of the movements of birds has increased dramatically, with scientific projects such as ringing schemes and satellite-tracking increasing awareness of where many of our summer visitors have gone over winter. Tracking has especially benefitted through the development of technology with methods such as Motus towers, which notify when a bird tagged with the appropriate tracker has passed overhead allowing better visualization of movements (Taylor et al., 2017). This latter study has been used on not just sub-Saharan, migrants but also on species such as song thrush (*Turdus philomelos*) and yellow-browed warbler (*Phylloscopus inornatus*). However, despite these efforts, the underlying mechanisms still remain mysterious. Our understanding of where the birds go is more advanced but how they migrate is still elusive.

In modern times, visible migration has become one of the most exciting aspects of birdwatching. In North America, the famous hawk-watching as thousands of raptor species head down the Isthmus of Panama is considered a spectacular event (Kochert et al., 2011). In Europe, a similar occurrence happens in the Strait of Gibraltar, where species such as honey buzzard (*Pernis apivorus*), short-toed eagle (*Circaetus gallicus*), osprey (*Pandion haliaetus*) and black kite (*Milvus migrans*) congregate *en masse* to cross the narrowest point of the Mediterranean (Miller et al., 2015). In both continents, the areas known for mass arrivals in the passerines are revered by naturalists and ornithologists. In North America, sites such as Point Pelee (Ontario), Cape May (New Jersey) and Magee Marsh (Ohio) are famed for the vast falls of tiny North American wood warblers (*Parulidae*), each with their own spectacular variation of colour and niche. In Britain, since the middle of the 20th century, multiple bird observatories have been set up in the most rewarding areas to research and record the numbers of migrants passing through. Overall, 20 such sites exist in the British Isles (The Bird Observatories Council, n.d.). Data collected by these observatories has proved vital in informing understanding of long-term trends in the populations of migratory bird species. Examples are studies looking into the phenologies of migrants passing through as in the case of Marchant and Wernham (2003) or providing data for the publishing of books such as the Migration Atlas (Wernham, 2008).

The decision to migrate in birds does not seem to be clear-cut. To travel such long distances creates a considerable risk as the journey is fraught with various hazards and, consequentially, mortality rates are high (Wernham, 2008). Nonetheless, despite all these risks, migration appears to be the best option for many species, positively selected because of its benefits to individual fitness. In temperate zones, the food abundance declines markedly in the winter months, particularly of the insects which many bird species rely on to feed their young. Therefore, migration to the tropics, where the level of insect prey remains higher, provides the best option of survival in the winter period (Wernham, 2008). The more individuals that survive winter, the more the chances of breeding opportunities and population survival increase. Therefore, the benefits of such movements seem to eclipse the risk of mortality in many species. Indeed, most of the summer migratory species in the UK are insectivorous, with warblers, hirundines, and flycatchers included in this group.

Though this north-south migration is the most common form, other forms can be found in Britain. For example, high numbers of birds from continental Europe escape the harsher winters by travelling across the North Sea. In the autumn, the east coast particularly can see large falls of fieldfare (*Turdus pilaris*), redwing (*Turdus iliacus*), goldcrest (*Regulus regulus*) and woodcock (*Scolopax rusticola*) with passage vagrants from Siberia occasionally found within these movements, such as red-flanked bluetail (*Tarsiger cyanus*), Pallas's leaf warbler (*Phylloscopus proregulus*) and yellow-browed warbler. Other more familiar species, such as woodpigeon (*Columba palumbus*) and robin, can also see huge boosts in population through continental migrants (Murton and Ridpath, 1962).

For many European species, the Sahara is a vast and dangerous barrier to reaching the tropics in Central Africa. Therefore, many species drastically gain weight and body fat to build up energy reserves prior to their migration. For example, the garden warbler (*Sylvia borin*) can double its weight in body fat when preparing for migration (Wernham, 2008). Various predators also wait for migrants along the migratory route. One such species in the Palearctic is the formidable Eleanora's falcon (*Falco eleonorae*), which times its breeding season and rearing of its young to when the numbers of passing songbirds returning to northern latitudes are highest (Dimalexis et al., 2007). Humans also provide huge dangers. Illegal hunting activities, particularly in Mediterranean countries such as Malta and Cyprus, threaten many species crossing the Mediterranean. Birdlife Malta estimates 7000 birds are killed per square kilometre (BirdGuides, 2021), despite heavy pressure on these countries to crack down on such illegal activity (Briguglio, 2015).

Similarly, the fluctuation of food abundance for a migratory bird on transit can vary greatly, creating a huge risk of starvation or exhaustion if refueling opportunities are too sparse (Wernham, 2008). The unpredictability of the weather is one major factor; unseasonal extreme weather events (storms or dramatic changes in weather conditions) cause issues for birds, particularly weather phenomena against which no bird could fly, such as hurricanes or snowstorms (Newton, 2007). Weather patterns refer to a particular atmospheric circulation type that is responsible for differing characteristics in wind direction, wind-strength and also conditions such as heavy rainfall and prolonged sunshine, these patterns usually being present for several days at a time (Neal et al., 2016). Such weather patterns have caused migratory bird species to be blown far off course and arrive on shores which they do not usually migrate to. Over the past century, this has been the case where many Nearctic bird species have become stranded on European shores, often with dire consequences for the individual birds concerned. Major mass mortality events in birds have also been linked to migration and extreme weather (Newton, 2007).

Less extreme weather patterns can also have an impact on bird migration if they are unpredictable. Periods of adverse weather can delay migration or reduce the numbers of birds passing through a particular site (Newton, 2007). In some cases, the presence of a weather front may cause birds to be grounded as they are unable to fly further north through unsettled weather, such as heavy rain associated with the front (Newton, 2007). Raptors and storks rely on warm air and thermals to migrate as this allows the birds to expend the least amount of energy possible whilst covering the greatest distance (Newton and Brockie, 2007). Seasonality also causes the dependability of weather to fluctuate. In early autumn, migration is a more gradual process, with species slowly building up fat reserves (Wernham, 2008). In this case, when periods of good weather for movement occur, the passage can be gradual, with birds lingering. Later in the season, as the urge to migrate is stronger, such periods of weather can see mass departures of many birds as they attempt to head south quickly (Wernham, 2008). In spring, the desire to arrive in time for an adequate food supply at the breeding ground often results in a quicker journey. When this happens, migration may occur in sub-optimal weather conditions. However, if a bird arrives prematurely, they may return to a more southerly latitude where conditions are better and wait before heading north again (Wernham, 2008).

Due to their reliance on good conditions at both their wintering and breeding grounds, many British summer migrants are currently classed as threatened by the IUCN, especially those with highly seasonal habitats in both regions (Both et al., 2009). Declines in common cuckoo

(*Cuculus canorus*) populations have been linked to lack of caterpillars and the decline in turtle doves (*Streptopelia turtur*) to habitat loss and intense hunting pressure over the Mediterranean (Lormée et al., 2019). Similarly, the temperatures experienced in African wintering grounds have been found to affect the body conditions of other returning spring migrants (Aloni, Markman and Ziv, 2019). Many long-term UK migrants are susceptible to changes in climate, including the shift in timings of insect blooms (González-Braojos, Sanz and Moreno, 2017). Therefore, it is paramount to the conservation of British summer migrant species to provide and monitor suitable conditions in both breeding and wintering grounds.

Vagrancy in bird populations refers to the incidence of a species outside its breeding or wintering ground (Lees and Gilroy, 2009). The British Isles in particular is unique in its quantity of vagrant avifauna, particularly when the British List of birds consists of vagrants from southern Europe, far eastern Siberia, high Arctic, Central Asia and North America (Lees and Gilroy, 2009). In this study, the term vagrant is attributed to species designated as such by the BBRC (British Birds Rarities Committee). Founded in 1959, this organisation's key aims are to apply adjudication standards to reports of rare bird species throughout the British Isles to determine their legitimacy by either accepting or rejecting records via a committee of elected and skilled birders. In turn, a reliable and extensive database is collected on the rare taxa recorded in the British Isles, with an annual report created on all rarities/vagrants reported during a calendar year. Birdwatchers who are fortunate enough to find such rarities in the field are invited to submit a finder's report, detailing the identification of their rarity including plumage details, circumstances of their finding and any media such as photographs or sound recordings which may aid with identification. Once submitted to the BBRC, the record is assessed and either accepted or rejected based on the quality of the report provided.

The drive behind vagrancy can be attributed to a number of factors including breeding range expansion, changes to migratory routes, food shortages or unusual weather events (Lees, 2022). This aspect of bird ecology is fascinating, given some of the unintentional journeys undertaken by vagrant species who appear to be majorly disorientated and occurring in unusual areas far from their intended destination. On the other hand, the term "scarce migrants", applies in this report to birds categorised by the BBRC in their annual Scarce Migrants Report, which is produced annually with a list of all records of species that fall under this category. Many of species referred to as a scarce migrant are often observed as passage migrants simply passing through the British Isles on their way to and from their breeding/wintering grounds, though like vagrants, weather patterns may contribute to increased records albeit at a more consistent and substantial number. The yellow-browed warbler is one particular species whose numbers may exceed >3000 in a single autumn to Britain.

1.2 Insect Migration

Another animal group whose migration is far less understood or well-known, is the insects. Few insect movements are well known, the most prominent examples of migration being that of the monarch butterfly (*Danaus plexippus*) in the Americas (Zhan et al., 2014) and the painted lady butterfly (*Vanessa cardui*) in Europe. Knowledge of insect migration is limited due to an inability to study them across their vast spatial distribution. Only species with the most conspicuous movements, such as the significant arrivals of painted lady and monarch butterflies, are relatively well-studied. For example, research by Stefanescu et al. (2007), identified that the movement of painted ladies is a generational process with the first starting in north Africa. In the UK, several other butterfly species are also known migrants, such as clouded yellow (*Colias croceus*), red admiral (*Vanessa atalanta*) and large tortoiseshell (*Nymphalis polychloros*) (Sparks et al., 2005). Another smaller group is constituted of vagrant species that occur sporadically, for example, the long-tailed blue (*Lampides boeticus*), Queen of Spain fritillary (*Issoria lathonia*) and Camberwell beauty (*Nymphalis antiopa*) (Tolman and Lewington, 2013). Around 160 of our immigrant insect species are moths (Bretherton, 1983). Like the butterflies, some species are annual visitors, such as silver Y (*Autographa gamma*) and hummingbird hawk-moth (*Macroglossum stellatarum*), whilst others are exceptionally scarce, with very few records over the past two centuries (Waring et al., 2017). In late summer, coastal areas of the UK often experience arrivals of moth species that are non-breeding in this country (Waring et al., 2017). Areas of south coast headland, such as Durlston Head and Portland Bill in Dorset, Dungeness and Sandwich Bay in Kent, The Lizard in Cornwall and Prawle Point in Devon, are considered to be foci for the arrival of immigrant species. The mechanism for the movements of moths is considerably less understood than that of birds. In some species, the intent appears to be similar to the painted lady and the silver Y, where generations gradually move northwards during the summer (Chapman et al., 2012). The progeny of these generations then develops in the UK before heading south again to start the cycle again the following year. Other species, however, may have been recorded by pure chance, getting caught on strong winds and being transported across to the British Isles. Studies suggest that some moth species simply head northward once the food supply in mainland Europe has desiccated, very much like some bird species (Sparks, Roy and Dennis, 2005). Although the conditions for migration are well known, the localised weather patterns that allow passage are not so well understood. Further understanding into which weather patterns affect the arrival of particularly large numbers of birds or for them to be grounded is essential, as the characteristics and frequency of these patterns may change due to climate change and hence affect migratory birds and insects in the future.

1.3 Climate change and weather patterns

One of the key concerns of our changing climate has been the effect of global warming on our weather. Whilst research and predictions have been continuously developed on the expected increase in abnormal or extreme weather phenomena such as hurricanes and tsunamis, the effect of climate change on more regularly experienced weather conditions can also have major consequences. In the UK itself, some research has suggested via projections that increased heatwaves and droughts are likely as a consequence of climate change (De Luca et al., 2019). Indeed, the potential impacts could be far more disastrous such as increased drought and major forest fires caused by reduced rainfall. The expansion of the Sahara Desert would create an even vaster, more dangerous barrier for our long-distance migratory birds who are already seriously threatened and face pressure in their wintering grounds. With an increase of 0.18°C per decade since 1981 (Lindsey and Dahlmann, 2021), the global temperature has seen the spread of species to new breeding grounds and the contraction of others as former breeding sites become unusable (Martay et al., 2022). The colonisation of new species, particularly insects, is a feature throughout this current study and is likely to continue to be more a theme in the future. The creation of weather pattern indices to categorise expected patterns, has proved to be a valuable tool in predicting the variables created by changes in air pressure, such as wind direction/speed, temperature, and precipitation, with most systems referring to the daily circulation patterns over geographical areas to provide accurate forecasting. Further analysis of these patterns can also be used to determine which are responsible for major long-term effects such as drought and can possibly help aid in preparation for such weather events not just on a local scale, but a wider national scale (Richardson et al., 2017). This may also help with the studying of the effects such patterns can have on wildlife, with the conditions brought by some patterns benefitting more than others. Indeed, in the UK, recent research by the Met Office suggests that there has been a shift towards more weather patterns associated with drier, more settled conditions in the summer and warmer, milder conditions in winter (Met Office, n.d.). These winter conditions seem to favour patterns of that bring westerly, stormy type patterns suggesting a more active Atlantic jet stream in recent years. These milder, winters subsequently could have an impact on wildlife in various ways with conditions becoming more suitable for continental species to overwinter and also causing birds to remain longer in their breeding grounds before dispersal. In contrast, drier summer conditions could result in more droughts, affecting the breeding success of many species. Overall, the importance of the modelling of these weather patterns allows predictions to be made about the future of the climate and what alterations could occur to our environment as a result, the analysis of the trends of such patterns is vital to see the scale of climate change and the vast impact this phenomenon could have, including on our migratory wildlife.

1.4 Study aims and hypotheses

The research reported in this thesis attempts to address the gap in knowledge about the links between bird and moth migration and regional weather patterns, how they are related and if there are potentially shifts or changes to the movements of both taxa caused by alterations to our weather systems. Overall, the aims of this study are as follows:

1) To gain knowledge on the exact weather patterns that benefit migration in moths, birds and vagrant birds and whether seasonality sees difference in which patterns are favoured. Also are there links between the patterns favoured between the three groups?
2) Whether the rate of migration has changed over the study period (1990-2020), e.g. are more migrant moths and vagrant birds occurring on our shores than in previous decades due to changing patterns?
3) How the frequency and timing of weather patterns has changed through the study period and how much this possibly could affect the movements of the species groups.
4) Whether notable changes have occurred in the timings of migration in passage bird species as a result of climate change (e.g., arriving earlier or departing later).

The first hypothesis to be tested in this study is that moth and bird migration are both strongly linked to regional weather patterns (identified and designated by the Met Office). This will be tested by relating historical weather records with the occurrence of migration events. Furthermore, the study will consider what conditions these patterns bring that makes them so important for movement in these groups. Once determined, the next hypothesis is that there are discernible changes in the timing and frequency of regional weather patterns associated with moth and bird migration over the last 30 years. It is predicted those patterns associated with large migration movements are increasing in frequency and occurring earlier. By looking at the trends of the patterns identified during the study period, it can be determined by just how much our changing environment could be affecting our long-distance migrants. The final hypothesis is that there have been notable changes to the migration of commonly occurring species and an increase in the rate of vagrancy and moth migration over the decades. This will be achieved by looking at the numbers of migratory moths and vagrant birds over the decades and determining whether there have been changes in the occurrence of these phenomena. The significance of this study is that it will provide insight into how climate change may affect the movements of many of the species to our shores and whether we can expect further alterations in the community of our migrant bird and moth species in the future.

1.5 Structure of the thesis

Chapter 2 reviews extant literature to synthesise and evaluate the findings of studies that have analysed migration in birds and moths. This includes studies looking into the behavioural changes and physiological alterations observed in long-distance migrant species, the effects of weather observed on migration across the globe, the mechanics behind bird and moth migration, in addition to the overall impacts of weather on the distribution and abundance of moth species. By compiling and collecting studies of relevance to the topic, further understanding has been developed not only about the subject of migration itself but also where gaps in the knowledge exist around migration.

Chapter 3 discusses the research methodology and data analysis.

Chapter 4 presents the results and key findings of the thesis.

Chapter 5 concerns the overall findings of the thesis and an overview over the project including key points learnt from the study as well as possible future work.

2. Literature Review

The annual global mass migration of birds and insects (particularly Lepidoptera) is the culmination of millions of years of adapting long-distance migration as a strategy for survival (Newton and Brockie, 2007). The main objective of migration in birds is to take advantage of the mass insect blooms in the spring and early summer in colder zones and to avoid the absence of food in these areas in winter (Newton and Brockie, 2007). These temperate zones are where birds breed before heading to warmer climates where insect prey is abundant in the winter (Wernham, 2008). Therefore, weather plays a significant role in the migration of both groups, although it is still unclear to what degree. There appears to be little knowledge of whether the increased frequency of specific patterns due to climate change is causing more frequent and significant mass migration events in moths and birds.

2.1 Research on weather and its effect on bird migration

When it comes to rain and the effect on birds, research by Nisbet and Drury (1968) discovered that overall, rain suppressed migratory activity in passerines. However, there was a strong correlation with variables such as high and rising temperature and low and falling pressure. Bozo, Csörgo and Heim (2018) discovered that rain affected migration in four leaf warbler species in Siberia. Precipitation was found to limit the migration of all four species studied and the preferred conditions to migrate were warm, calm days. Interestingly, the preferred wind conditions used by the migrating warblers differed, depending on the season; a tailwind was associated with higher numbers of migrating individuals during the autumn. However, easterly crosswinds yielded the highest warbler numbers during the spring. Therefore, within this study, it should be expected that records of migratory bird species will be much more frequent in adverse weather conditions, such as heavy rain, thick cloud and high winds, when they are grounded.

Panuccio et al. (2019) noted the effect of low cloud and fog on migratory birds in the Strait of Messina (which separates Sicily from southern Italy). It seems visibility is key to the migration of many bird species, particularly the nocturnal migrants, such as the flycatchers and warblers that rely on the stars to guide them (Wernham, 2008). When bands of low cloud and fog occur, there can be many grounded migrants, particularly in exposed headlands, which are the first landmasses for many birds. Panuccio et al. (2019) raise evidence that migratory raptors, such as honey buzzard (*Pernis aviporus*), do not fly due to the lack of thermals to allow low-intensity soaring. They also emphasised the effects of wind on the passage of birds, with southerly tailwinds limiting numbers and westerlies providing the highest migration numbers. Stokke et al. (2005) explored the effects of severe weather on the autumn migration of house martins (*Delichon urbicum*). They found that harsh weather during the autumn migration had a severe, negative effect on the survival of house martins, particularly as they do not store fat reserves like many migrants. When the temperature dropped below 10°C, the mortality of juveniles increased; however, adults are unaffected, but the extreme weather severely reduced the numbers of insect prey. The increase in severe weather by climate change is also noted, as house martin populations may be more dependent in the future on the likeliness of these patterns (Stokke et al., 2005). This is important, as the weather patterns that may bring these extreme conditions could significantly affect the numbers of migrants recorded over the study period.

One such weather phenomenon that can have a major effect on the weather are oceanic oscillations. Caused by variable sea temperatures, these can be responsible for years of heavy rainfall or drought across the world, one example being El Nino that affects the eastern Pacific, occurring every few years (Brönnimann, 2007). Grischenko (2019) investigated the effects of North Atlantic oscillation on migratory birds in Ukraine and Central Europe. The positive indices for this oscillation are responsible for mild winters bringing warm, moist air across Europe. However, negative indices can be accountable for harsh dry conditions. In the study, the periods of warm, humid weather were responsible for the earlier migrations of many bird species to the Ukraine. Such weather additionally facilitated the advance of spring and promoted migratory movement in the bird species studied. However, the positive indices of the oscillation could subsequently cause drought in the Mediterranean region, perhaps limiting or delaying migration for the birds in North Africa. For winter migrants, the mild winters also spurred an earlier departure from their wintering grounds, showing their preference for more favourable conditions to migrate in. Comparable results were found by Marra et al. (2005) who explored long-term data from bird-ringing stations over 40 years to assess arrival times for neotropical migrants in North America. Overall results showed that migration, in general, occurred earlier in warmer years and was delayed in particularly wintry conditions. This suggests that migrants seem to be stimulated by certain conditions that indicate they should migrate. The development of plant material has a substantial impact on the timing of emergence in insect populations. It remains unclear how weather patterns, such as the North Atlantic oscillation, might affect migratory moth species. However, there is little study into these weather patterns, particularly those that might have a considerable influence across Western Europe. A further study by Manola et al. (2020) explored the conditions that affected bird migration over the North Sea. In autumn particularly, the east of the UK sees passage from Scandinavia, species such as pied flycatcher (*Ficedula hypoleuca*) and redstart (*Phoenicurus phoenicurus*) (Manson, 2020); the former species mainly seems to pass through the UK to Iberia (Hope Jones, Mead and Durman, 1977). Many of the warbler and flycatcher species are indeed nocturnal and rely on suitable, clear weather conditions to cross over the North Sea. In this study, radar was used to detect large movements of birds across the North Sea during the spring and autumn. In spring, this study identifies that high pressure over Spain extending to Central Europe and over the southern United Kingdom and the Netherlands was noted on nights of heavy migration in spring.

Similarly, nights of low migration in spring are related to low-pressure conditions over the Netherlands and UK (Manola et., 2020). Unsurprisingly, precipitation was observed as a crucial factor in spring, nights with high migration were overall drier. Despite many birds relying on the night sky for migration, evidence shows they are willing to fly in cloud in dry conditions (Manola et al., 2020). In autumn, the same authors found that the conditions that aided bird migration were somewhat different. High-pressure systems over the Netherlands, which created easterly winds across the North Sea, were observed on all nights with high migration. Frontal systems, however, that passed over the Netherlands and Scandinavia hindered migration. Precipitation was a key factor with the potential departure areas remaining dry and cloudless in high migration nights. Overall, prevailing high-pressure systems bringing stable conditions were responsible for aiding migration across the North Sea. Tailwinds were also discovered to be important, particularly in the autumn when birds from the Netherlands would cross to the UK.

It appears that the North Sea is a frequently crossed barrier for many birds passing on migration in both spring and autumn, as there have been several other studies looking into the routes undertaken by migrants. A similar study by Lack (1963) looked at radar and bird passage across the North Sea. In this study, several different autumn migration periods were observed, with birds from Northern Britain and Scandinavia arriving in different waves. This study found that the movements of nocturnal migrating passerines were notably heavier in following, than opposing winds. As well as the wind, movement was more prevalent in clearer nights and anticyclonic conditions rather than disturbed weather although temperature seemed to not affect passage heavily. Overall, in support of Lack (1963), Manola et al., (2020) found that tailwinds were significant for spurring migration; opposing winds were generally avoided unless they were weak. Both the findings from these studies are essential as they will help explain what may allow the passage. However, conditions need to be investigated in what also causes the falls in birds and which weather patterns cause the right conditions that ground many migrants on the coast of Britain. Another study by Parslow (1969) discovered, via radar, that autumn migration seems to occur, mainly, in a S-SE direction. In spring, this is an N-NW direction. This helps explain why the numbers of migrants in the study area are so much higher in autumn.

Years of extremely heavy falls in Britain offer insight into conditions that caused large numbers of grounded migrant birds and help possibly explain why larger falls occurred in our own study area. One such study is the work of Davis (1966), whose paper offers an insight into a period of extraordinary migration experienced on the east coast of Britain in 1965. This period saw incredible numbers of common migrants such as redstart, garden warbler and pied flycatcher with 15,000, 4000 and 3000 respectively recorded in one location, as well as higher than average quantities of easterly drift migration rarities such as wryneck (*Jynx torquilla*), barred warbler (*Sylvia nisora*), red-breasted flycatcher (*Ficedula parva*), and icterine warbler (*Hippolais icterina*). Davis (1966) identifies that a period of cloudy unsettled weather had dominated Scandinavia until early September causing little arrival in the UK of migrants. However, the appearance of a high-pressure system heading in a north-easterly direction over the North Sea and Scandinavia allowed good conditions for emigration. However, these migrants were blocked by a curtain of rain and low-pressure areas over France, causing the migrants over the North Sea to be grounded on landfall on the east coast of Britain. The wind switched to a south-westerly direction, further preventing movement. Davis acknowledges that radar has shown that many Scandinavian migrants divert around south-east England in favourable conditions. Therefore, the poor conditions deflected these birds onto the East Coast. There seems to be disorientation in the migration of young birds in particular, which may help explain these falls. An older study reflects on the relatively sparse autumn passage in 1964 on east coast bird observatories (Davis, 1964). It identified that the overall fair-weather conditions of clear skies might have been responsible for migration to have been less notable.

From the literature examined, birds are able to determine and utilise favourable wind conditions that aid their migration. However, the presence of conditions such as heavy cloud or rain are likely to ground or limit migration, ultimately responsible for bringing down birds in concentrated areas creating large falls. During different times of year, the direction of the wind produces different results in migration, for example, easterly winds in the autumn are seemingly the most responsible for large falls of birds in the British Isles and of vagrancy in Eastern Palearctic species. Therefore, within this own study, it should be possible to link the indices created by the Met Office to the patterns associated with periods of increased migration in birds.

2.2 Climate change effects on timing in bird migration

There is convincing evidence that migratory bird species are starting to arrive earlier to compensate for the warmer climate. For example, Hedenström *et al.* (2007) investigated the arrivals of pied flycatchers (*Ficedula hypoleuca*) over 24 years and discovered that these birds are arriving earlier to compensate for the premature caterpillar blooms in the spring. These findings complimented the research by Marra et al. (2005), who also studied pied flycatchers and identified a shift in arrival times. This raises questions if there is a similar pattern with migratory moth species and weather. Like many bird species, they are arriving earlier to British shores, particularly if desiccation of nectaring plants on the continent is indeed a driving factor (Sparks, 2005).

Similarly, there is evidence to suggest a strong correlation between meteorological events impacting the timing of migration in bird species. Often, arrival in wintering grounds is found to be triggered by deteriorating conditions in breeding grounds. Large soaring birds such as raptors are particularly influenced by annual triggers in the weather (Shamoun-Baranes *et al*., 2006). Cold-fronts seem to influence departures of species in the autumn, with temperatures falling below a certain threshold and an increase in erratic weather, negatively impacting flight conditions. Erratic weather such as high winds, instability in atmospheric conditions and weather conditions such as hail, rain and lightning/storms were caused by the creation of low-pressure systems. The arrival of a cold front sweeping down from the north was considered to be the indicating factor to the migratory birds studied, that it was time to begin passage. For many species, the threshold pressure value was low (1013 hPa), showing the significance of the low pressure on the bird species, particularly due to the deterioration of flight conditions. The species covered are mainly large, soaring birds that require the right conditions to travel the most distance whilst expending the least amount of energy. Therefore, what spurs their migration could be vastly different to that which trigger migration in the much smaller passerine species, which may be much more susceptible to periods of unstable weather, with high winds and rain. Akesson and Biano (2021) found that swifts may experience mass departures as a response to unstable weather conditions as they are more subject to pressure from changing aerial conditions.

Research on climate change has shown evidence of the timing of autumn migration being impacted. Over a 42-year study period looking at 65 migratory species, Jenni and Kéry (2003) discovered that sub-Saharan species are departing earlier to avoid the significant and advancing dry season in Africa. Meanwhile, short-distance migrants are delaying their migration. The possible explanation for this may be due to increased time to rear more broods for short-distance migrants. While this may be considered beneficial to the populations of short-distance migrants, it is expected that there could be some severe repercussions for long-distance migrants, many of which are already threatened in Europe. This is important as it also shows the significant effect of weather patterns and climate in the wintering grounds, having a subsequent impact on many bird species' migrations. While there are no moths that migrate from as far as sub-Saharan Africa (Waring et al., 2017), several species have their origins in Northern Africa, such as the oleander hawk-moth (*Daphnis nerii*). Although this is an exceptionally rare immigrant (Waring et al., 2017), perhaps there may potentially be changes in these African species' timings.

2.3 Research on the changes in behaviour during bird migration and variance between species

The variation behind bird migration due to difference in behaviour also has the potential to see varying results within this study depending on the time of year. For example, Newton and Brockie (2007) note how the behaviour in migrating birds is vastly different, depending on the season. In spring, many species tend to pass through or indeed fly over land as they are pressed for time to begin breeding. The urgency to breed results in species consistently flying with little to no stops in the springtime. However, as migratory birds from sub-Saharan Africa travel to higher latitudes, they may face progressively worse weather conditions causing them to back-track, become held up or possibly be blown off-course, which may be the case for vagrants. Conversely, autumn migration appears to be a much more gradual affair for many UK species (Wernham, 2008). Many passerines will bulk up and develop high body fat counts to provide sustenance for their long journey. Furthermore, these birds may stop at suitable areas to fatten up before moving in more favourable conditions. The garden warbler (*Sylvia borin*), for example, fly short distances and refuel regularly, which means less body fat to slow them down (Wernham, 2008). The importance of stopover sites to fuel up means migration is gradual, with few birds completing the bulk of their journey in short periods (Newton and Brockie, 2007). This is interesting as the study area is at the most south-easterly tip of the United Kingdom, possibly helping to explain the heavier autumn passage occurring annually.

During the autumn migration, non-breeding birds are much more likely to be observed in regions of high passage than in spring. Some species that show examples of this include garden warbler and redstart (*Phoenicurus phoenicurus*). Autumn migration numbers are further bolstered by increased numbers of juvenile birds, some of which depart earlier than the adults (Newton and Brockie, 2007). In the UK, there also appears to be distinct differences in routes undertaken by migratory birds. In the spring, many species appear to head up the western side of the country, whilst in the autumn, heading more towards the east (Wernham, 2008); indeed, many autumn records come from east-coast bird observatories. This is an essential aspect of this study as the study area is in the far south-east of the country. Therefore, records of non-breeding passerines within the site are much more frequent in autumn, such as pied flycatcher, wood warbler (*Phylloscopus sibilatrix*) and redstart. However, the origin of many of these autumn migrants is possibly foreign; a peak in migration of Scandinavian birds has been reported in September (Wernham, 2008). Therefore, weather conditions over the North Sea must be considered. This aspect could be necessary as spring records of the species mentioned above could very much result from abnormal and influential patterns. However, which patterns are responsible is still unclear.

In preparation for departure and migration, most bird species go through significant physiological and behavioural changes. For example, the storing of fat reserves is a substantial part of the preparation for migration. Weight gain appeared to be quicker when a mixed diet of berries and insects is used (Bairlein 1998, Parrish 2000, Long and Stouffer 2003). This adaptation is essential to fuel the powerful flight muscles required. Also, the size of the muscles and the circulatory system increases, creating a much more efficient body for migration. The organs that are not so useful subsequently shrink in size at the same time (Newton and Brockie, 2007). One issue that is caused by having such a rapid weight gain is that flight efficiency is somewhat limited. Many birds undergo significant moulting to provide flight feathers that are strong enough for the long-distance journey. In many migratory species, this involves a complete moult of wing and tail feathers (Lars Svensson, 1975). Although all bird species moult at least once annually, many migrants have a complete moult in the autumn, before the bird begins to migrate (Lars Svensson, 1975). In juveniles, this is particularly notable; migratory species often experience rapid juvenile development compared to resident species (Wernham, 2008). Restlessness is also observed in many migratory species towards the period of their departure, often being considered the factor that indicates migration is about to occur and is probably caused by food availability, weather factors and hormonal responses (Eikenaar, Klinner, Szostek and Bairlein, 2014). These inbuilt circannual rhythms are so strong that studies in captive birds have shown that restlessness began to occur in hand-reared juvenile birds at the same time as in their wild counterparts. The captive birds then began trying to head in the same direction that wild birds would on migration, northwards in spring and southwards in the autumn (Gwinner and Wiltschko, 1980). A similar study on wheatears (*Oenanthe oenanthe*) from different populations showed that variation in body mass increase depends on the bird's origins; however, behaviour such as restlessness was at a consistent level (Maggini and Barlein, 2010).

There are different types of migratory birds that can largely fall into two categories: obligate and facultative (Newton and Brockie, 2007). Obligate migrants begin migration at a specific time of year and experience behavioural and physiological changes when their migration is due to be undertaken. Obligate migrants include species that return to the UK in the summer after overwintering in sub-Saharan Africa. Facultative migrants include species that possibly only migrate in harsh weather conditions, such as robin (*Erithacus rubecula)* and siskin (*Spinus spinus*) (Adriaensen & Dhondt, 1990). Facultative species may remain in the breeding grounds throughout the year but can be pressured to migrate due to external factors (Newton and Brockie, 2007). There may also be variance in migration between different sub-populations of species, for example migrant Blackcaps have notable physiological differences to their more resident counterparts. Such differences include longer wing-length, higher fat reserves and body mass (Gyurácz et al., 2021). It is not clear how the different weather patterns actually affect the migration of these species. However, this may be worth noting because extreme weather patterns might see an increased abundance of facultative migrants in some years of the study period. For example, harsh winters can be associated with significant facultative migration of goldcrest (*Regulus regulus*), firecrest (*Regulus ignicapilla*) and woodcock (*Scolopax rusticola*), all of which struggle in these conditions (Wernham, 2008). Due to this, it can be expected that numbers may be higher in significantly colder winters, such as February 2018. Other species include the finches and several raptor species, such as Merlin (*Falco columbarius*) that may overwinter in coastal areas less prone to harsh conditions, particularly those that breed in upland areas (Wernham, 2008). Therefore, it is vital to understand which types of weather pattern resulted in them needing to migrate from their breeding grounds or usual habitat.

The distribution of many migratory birds, particularly in the autumn season, can be affected by food availability. In the winter months, this is particularly important as species avoid starvation during this time of year. Calladine et al. (2011) studied the highly unpredictable movements of short-eared owls over 96 years, particularly the variation of individuals based on geographic origin. During mild winters, conditions are often suitable for small rodent populations, which attract species such as the short-eared owl (*Asio flammeus*) and hen harrier (*Circus cyaneus*). As in the case of the facultative passerine migrants, many wintering raptors are irruptive, meaning their distribution and abundance is very difficult to predict from year to year (Calladine et al., 2011). In the winter months, large numbers of wintering seed and fruit-eating species arrive to harvest the remnants of autumn. Many of these birds are simply migrating to explore food opportunities elsewhere, especially if the food supply in their breeding grounds has depleted (Wernham, 2008). Many of these birds escape the far harsher weather of Continental Europe to the relatively mild in comparison, British winter. This means that numbers of such species can vary greatly, with some years seeing much larger numbers than others. Therefore, other species such as short-eared owl will be driven not just by the weather conditions in their breeding grounds but will also be attracted to suitable hunting areas in the autumn. If the temperature drops early in their breeding grounds, it is expected that arrival in the autumn may be earlier than in other years. Similarly, if a late spring occurs, then it is expected that many of these overwintering species may continue to linger until quite late in the year.

The phenology of migrants can affect the journey undertaken and time taken to migrate. Akesson and Biano (2021) discovered that the migration journeys undertaken by more northerly populations of the common swift (*Apus apus*) was more direct than those at southerly latitudes. Similarly, in the spring, the use of stopover sites was far less regular than in autumn showing an increased urge to return to the breeding grounds. Like passerines, swifts were found to migrate by exploiting tailwinds to aid their passage. In spring, the routes undertaken by swifts enabled 20% more tailwind support than in autumn. Further studies into the phenology of different migrants on passage have been undertaken. One such study by Marchant and Wernham (2003) looked into the origins of willow warblers (*Phylloscopus trochilus*) passing through Dungeness, Kent, during autumn from 1960 to 2000. This study identified that pulses of migrants passing through were related to their origins. Birds passing through in late July, when the first movements of willow warblers are noted, are likely of local origin. In August, birds from as far as Scotland and Ireland are passing through, with the last wave of birds in September having a continental origin. Interestingly, this study also acknowledges the apparent shift in departure times, with the average departure time getting later through the decades. This study presents several hypotheses to explain this trend, including global warming and climate change; however, it also mentions the decline of breeding willow warblers in Kent, possibly resulting in declining numbers of local birds passing through in early autumn. A similar study by Norman and Norman (1985) discovered that continental willow warblers also passed in number through east coast observatories after Mid-August, potentially related to a later breeding season than British birds.

Another well-studied migrant through the UK is the redstart (*Phoenicurus phoenicurus*). Jones (1975) investigated the total numbers of redstarts recorded across eight bird observatories. His findings noticed that the east coast observatories such as Dungeness and Spurn saw markedly higher numbers of redstarts passing through in the autumn. This complements the studies with the radar, such as Parslow (1969), as it also shows a south-easterly direction in the autumn migration season. As Sandwich Bay is situated on an easterly peninsula, it is likely that a large bulk of the migrants are indeed of Scandinavian origin, although British migrants also pass through on their journey south. The route undertaken by migrating birds is not straightforward or direct. In many species, migration is undertaken at night for several reasons (Wernham, 2008). This allows time for feeding during the day when the birds are normally active and atmospheric conditions at night may allow reduced headwinds (which would otherwise slow down migration) and limit the evaporation of water in birds. The direction itself varies; radar studies have shown that whilst returning summer migrants will arrive from the south to the UK, in autumn, these same species will head in a southeast direction before heading southwest down through Iberia to Africa (Wernham, 2008).

2.4 Research on weather pattern effects on moth migration

While the passage of some migratory species of butterflies, such as the painted lady (*Vanessa cardui*), is well understood (Stefanescu et al., 2012), the large movements of moths are still relatively unclear. Some of the more common migratory moths that arrive in the United Kingdom make use of the summer by breeding a generation before, once again, heading southwards. Others seem to use migration to avoid starvation in their over-wintering habitat, flying to cooler climates where food may still be available in the late summer (Sparks et al., 2005). Some evidence suggests a strong association between migration and certain weather conditions within the more common migratory species but does not look at the broader perspective via weather patterns. Additionally, birds rely on weather conditions to ease the passage itself and trigger migratory behaviour (Wernham, 2008).

One critical study that attempts to address this issue is by Sparks et.al., (2005), who investigated several notable migratory moth species over 113 years and the causative factors for their occurrence. By looking at the weather conditions between mainland Europe and the UK on the nights that species arrived in Britain, it seemed that many Lepidoptera wait for optimal conditions. Long-term consequences resulting from climate change were discovered to be causing an increased abundance of vagrant species into the UK. A similar study focused on the moth records at Portland in Dorset over 23 years; over the two and a half decades, there was a marked increase in migratory species correlated with rising climate temperatures (Sparks et al., 2005). However, both studies are over 15 years old. Therefore, with the increase in temperature in recent years (Figure 4), it will be interesting to investigate whether the expected trends presented by these authors are realised. The reliance on weather conditions is argued by Akesson (2015), who found that migratory moths wait for high windspeeds to aid their migration by being blown by the wind. This appeared to be the same case with birds, although they were more flexible and able to adjust to wind drift. Additionally, they can fly higher than insects (between 400-1400 metres but up to 3600 metres in some circumstances), utilising colder and faster airstreams that have a significant impact on flight speeds. In another study Alerstam et al. (2011) investigated the migration of Noctuid moths which found that they had far more control than expected over their dispersal. They particularly favoured altitudes (200-800m) that would allow them to make use of the fastest airstreams, particularly those that were able to disperse them at a higher speed than their own flight speed, over 18 km/h. This ability to utilise such air currents for their benefits allows Lepidoptera to, relative to body-size, undertake migrations 25 times longer than that of the birds (Chapman, Reynolds and Wilson, 2015). Alerstam et al. (2011) stated that the evolution of this long-distance migration, whilst uncommon in European noctuids, is beneficial to the species who have adapted to use this strategy with many increasing in population. If this is the case, then the analysis conducted in this study should indicate increased numbers of commoner migrants through the study period.

Another study based in Europe, looking at the silver Y moth (*Autographa gamma*), attempts to explain the motive behind mass insect migration in some species. Chapman et al. (2012) argue that the migration recorded early in the year in areas of higher latitude in Europe, notably the UK, is in fact in response to allow winter breeding in the Mediterranean for this common migratory species. For example, the breeding of the initial spring generation enables caterpillars to be raised in the cooler summers of Northern Europe. Later in the summer and autumn, this generation of moths moves south to the Mediterranean, where breeding conditions are now more suitable in the winter months. Chapman et al. (2012) provide evidence that the 10-240 million diamondback (*Plutella xylostella*) immigrants favour moving in weather conditions of high airspeeds. In particular, the autumn months see many of these noctuid species waiting for conditions that would facilitate a southerly dispersal (Cardé, 2008). Thus, for many species, the driving factor for migration is attributed to when the benefit of moving for reproduction exceeds that of staying in the same habitat. This certainly provides another motive for some of the migratory species that arrive in the UK.

A similar study looked into the common migratory micro-moth species, the diamondback (*Plutella xylostella*). Evidence suggested an influx of adult moths arrived in the UK from continental Europe to set up a population in the spring. The second generation then heads southwards again to breed in the winter (Chapman et al., 2002). Therefore, it is expected with diamondbacks that the records from the study area should show a period of increased activity within the late spring-early summer period. Another interesting aspect of this study was the mention of unseasonable weather patterns during the study period. Chapman et al. (2002) describe a period of stable high pressure in Scotland and Scandinavia, combined with low pressure over continental Europe. This, in turn, caused abnormal surface temperatures and persistent warm easterly winds. This is particularly interesting to the study, as it claims that the moths would have been utilising the warm airstreams provided.

Similarly, weather patterns might have affected the movements of other migratory species and therefore the effects of different pressures across Europe should be investigated, which will allow some explanations about why there were periods of increased migration. Furthermore, given the diamondback is a micro-moth, it may require a narrower threshold of conditions than some macro-species. Therefore, although there may be a common group of favourable conditions for all moth migration, are some of the stronger fliers like the enormous Sphingidae species such as convolvulus hawk-moth (*Agrius convolvuli*) and death's-head hawk-moth (*Acherontia atropos*) able to migrate in more adverse conditions, such as stronger winds?

Since direct links with weather conditions and moth migrations have been well-evidenced, possibly the abundance of some of the migrants within the study can be explained by looking at what major weather patterns were influencing mainland Europe, where they breed. Although there are some links between desiccation of pollinating plants in mainland Europe and migratory behaviour in moths (Spark, 2005), there is little evidence of how the previous year's weather conditions could result in migrants having an excellent or poor year.

2.5 The effects of weather on moths in general and responses to light-trapping

Another investigatory question could focus on is how weather conditions affect the general abundance of moths in general. Do long-term factors affect the number of species on an annual basis? How susceptible are moths to short-term climatic changes? One study looks at a population of moths over three years in a Korean temperate forest and the various families responses to weather conditions (Choi, 2008). The increased rainfall in one year had a positive effect on the richness of species, although overall abundance was not affected; notably, *Geometridae* and *Sphingidae* were affected by rain as a whole. A UK-based study by Conrad et al. (2002) investigated the long-term decline of the garden tiger moth (*Arctia caja*) and discovered that mild winters were a significant factor in the development of the larvae, reducing the numbers of emerging adults in the summer months. They subsequently suggested an expected increase in many resident butterfly species with the rising temperatures. This shows the marked increase effects on climate can have on the populations of insect species; if butterflies are observed to expand their ranges than many moth species will do the same.

Other studies have shown relationships between catches in a light-trap and certain weather conditions. Steinbauer (2011) recorded the numbers of moths caught and the differences in wind direction and weather, finding that light winds seemed to provide the optimal yields using 250-watt light traps. The abundance of moth species strongly correlated with the temperature and relative humidity of a night's trapping. Wind speed also saw changes to variation in catch abundance and variability, with light winds below 10 km/h favoured by moths. Since this study was carried out in Australia, it is unclear whether it is the same conditions that also affect moth species in Europe. However, it is expected that European moths will be far more abundant in weather patterns that produce similar conditions to those in the study. Another study focused on the variations in catches using light-traps in western Germany (Jonason et al., 2014). This involved assessing the varying attractiveness of different types of light-traps and the study concluded that warmer nights were indeed a contributing factor to higher moth abundance, with the peak activity period of the year progressing from late May- late August in terms of diversity. This similarly coincides with the decision to exclude the winter months from this study, due to the extremely low abundance of moths during that time of year. Jonason et al. (2014) detail the superior effectiveness of a mercury vapour bulb compared to other forms of light used for trapping. This is important to this study as possibly there will be an array of different light traps used to collect the data over the study period. Therefore, this may also influence the findings as well as the weather patterns of the different nights examined. A mercury vapour, for example, can easily catch in excess of 1000 individuals on exceptional nights, whilst a weaker actinic light will struggle to attract even half these numbers (ALS Guide to Moth-Trapping, 2004). There appears to be variation in moth families attracted to lights. Merckx and Slade (2014) found that *Erebidae* moths were five times more likely to be recaptured at the same light than geometrids or noctuids. Furthermore, noctuids were attracted to the light from shorter distances than the other two families. Whether there are many cases of potential recaptures in our data is unclear. However, Sandwich Bay (the site used for this thesis' data collection) is very methodological with its releases of moths, often releasing the previous night's catch a substantial distance away from the trapping area.

Short-term weather variables are understood to have a significant effect on moth activity. For example, Yela and Holyoak (1997) studied the effects of wind and lunar-cycle on resident moth species within Spain over 120 nights in two years, using both bait and light traps. Yela and Holyoak (1997) found that the catch of light traps was influenced by cloud cover but not as much for bait-trapping. Furthermore, the numbers of moths caught in the traps increased as temperature rose. Both of the aforementioned studies provide significant evidence that the weather does affect the abundance of moths.

The knowledge of the routes taken by birds is relatively well researched, with several studies using radar to detect visible passage across the ocean such as Lack (1963), Parslow (1969) and Manola (2020). Furthermore, the use of GPS trackers in contemporary times has allowed almost live visualisation of the routes undertaken by birds. However, such studies into the directions of moths are lacking. It appears that only a few select species of migratory moths such as the silver Y (Chapman et al., 2012) have been studied for their migration routes. In UK terms, there are 160 migratory moth species yet almost none of them have had their routes or behaviour for migration studied. This makes it unclear where the true origins of some migrant species are; for example, are the migrants recorded in Dorset from further west in continental Europe than those in east Kent? The lack of knowledge about specific routes or whether migrant moths congregate in the same way birds do at specific sites, means that it would be potentially difficult to explore links between both species' groups. Therefore, by seeing if there is a link between the weather patterns used by birds and moths, it might be possible to hypothesise that indeed there are similar directions and origins in both species' groups.

2.6 Research Gaps

Research into animal migration is ongoing as we seek to address a number of knowledge gaps. One persisting question is: are some weather patterns a major hindrance to some migrating birds and moths? Are others more responsible for overshoots during the spring migration season? There seems to be little exploring the spring migrations and the arrivals of

Mediterranean vagrants, whilst the North Sea appears to be a relatively well-studied area for bird migration. Whilst there are studies exploring how meteorological factors affect bird migration to some degree, moth migration is still unclear; do the weather patterns even have a major influence on the significant falls of migratory moths? Whilst the earlier arrival times have been noted with several migratory bird species, there is not much research looking into whether some migratory moths are arriving earlier than expected. With climate continuing to change, are the moths also having to move earlier than in previous decades? It is expected that weather will profoundly impact the migration of both birds and moths, and there could be a distinct change in the timing of migration through the decades.

2.7 Conclusion

In conclusion, evidence suggests that weather patterns have a major impact on migration and species occurrence. For example, similar temperatures between the ocean and land were found to increase migration in moth species (Sparks, 2005). This increase in temperature on the mainland continent could additionally be a driving factor for migration in many moth species whose foodplants may become desiccated in the south of Europe (Sparks, 2005).

An extensive literature review on moth and bird migration reveals that weather patterns may influence these phenomena, with a second issue identified in the literature indicating that there have been shifts in weather patterns' timing and frequency with climate change. This will be investigated in this study on how regional weather patterns over 30-years have changed in timing and frequency therefore affecting migration and possibly drawing links to changes induced by climate change. Furthermore, the implications migratory species may face in the future due to changes in climate and whether we may see further colonisation of continental species due to climate change, will need to be investigated. Overall, such research will be essential to understand how climate change impacts long-distant migratory routes of bird and moth species of conservation interest.

3. Data Collection and Methodology

3.1 Bird Recording

The data which formed the basis of this project were provided by Sandwich Bay Bird Observatory in East Kent, which has long-term records of both moths and birds starting from the 1950s to present. The data were collected by various birdwatchers who noted down the species and the quantity observed across the recording area every day, coverage was provided extensively by paid wardens of the Observatory. Although there is scope of observer bias potentially in sightings, those hired by the Observatory would be employed for their identification skills. The collection of data would be consistent as daily censuses are required as part of the duties by both Wardens and Assistant Wardens. The data were then inputted onto recording log sheets which have been subsequently digitised by the observatory.

Sandwich Bay is a Site of Special Scientific Interest (SSSI) based in the very south-east of the UK (Figure 1). The area is notable for its botanical and entomological interest with the British range of several species' endemic to the area, particularly in the dune grassland and saltmarsh habitat. Additionally, the geographical location of the area makes it a rich hotspot for migration of a wide range of birds and moths. The proximity of continental France sees many southern European bird species arrive in spring as well as rare migratory moth species. In the autumn, the easterly positioning allows drift migration to occur, with Scandinavian migrants arriving in significant number to stopover, as well as the potential for rarities from further east. Founded in 1952, the bird observatory was set-up as a ringing station to monitor the passage of birds in the area. In modern times, the observatory has now become a charitable trust (Sandwich Bay Bird Observatory Trust) and one of 20 current UK bird observatories, dedicated to monitoring all aspects of the SSSI with a warden team collecting the data and a field centre.

The recording area itself covers an area of approximately 22 km^2 and a wide-range of habitats including mixed scrub and bushes, freshwater marshland, saltmarsh, duneland, small areas of woodland, arable farmland and tidal mudflats. This impressive range of habitats in turn attracts a wide variety of bird species including waders, wildfowl and migratory passerines that all can be found in the suitable locations at Sandwich Bay. Over 350 bird species have been recorded at the Observatory since its inception.

The methods for recording of bird species at the observatory are varied. Although the majority of records are indeed observational records, bird-ringing is also a critical method undertaken to aid our understanding of the migratory patterns in many of our migratory species and represents a considerable proportion of some of the non-breeding species at Sandwich. The practice of bird-ringing is a vital study in assessing bird populations and the movements of our long-distance species (Bairlein, 2003). The scheme overseen by the BTO (British Trust for Ornithology) involves the practice of putting metal rings with codes around the legs of birds. The codes and data are then uploaded to a database. Should a ringed bird be recorded in another site, it is possible to obtain the data to uncover its origin, age and further data. At Sandwich Bay, the practice of ringing is usually carried out by setting mist-nets up in areas of scrub, in the autumn season. Audio playback of common migrant calls is used to lure birds in although this practice is forbidden during the breeding season. Any birds ringed are duly processed with weight, wing length, age and gender dated before release, the data is then uploaded to the BTO archives as well as kept by the Observatory.

Another survey approach is the relatively obscure but increasingly popular practice of recording nocturnal migration. This relatively simple method focuses on leaving a microphone pointing up at the sky overnight and examining the audio files the next day through software such as audacity, filtering out sonograms of calling birds passing overhead (Sanders & Mennill, 2014). Although this practice is not common, it has contributed between 10-20 impressive records at the Bay, including ortolan bunting (*Emberiza hortaluna*) and night heron (*Nycticorax nycticorax*). The validity and reliability of these records are high, as the observatory is supplied with records from extremely capable local birders daily and a Wardening team who are all professional-standard birdwatchers who have been hired on the basis of their bird identification skills.

Figure 1: Map of the Recording Area of Sandwich Bay Bird Observatory. (*Recording Area Map*, 2022)

3.2 Moth Recording

The primary collection of moth data is generated from light-trapping, where a light source is used to attract moths from a surrounding area (Fry and Waring, 2001). The type of light and style of trap can vary greatly, however, the main two light types used are actinic and mercury vapour. Mercury Vapor (MV) is the more attractive and powerful light source, with most MV bulbs producing an output of 150W. In recent decades, this has been the standard method for data collection at Sandwich Bay, with a Robinson-style trap deployed most nights in the car park (Fig 2). However, during nights that seem particularly promising for moth diversity, other traps are deployed and run off a generator in other parts of the study area. All moth data was provided by the Observatory. The trapping was conducted by several recorders over the study period, chiefly John Beugg and Ian Hunter in the 21st century, along with wardens Ian Hodgson and Steffan Walton.

Similarly, the observatory trap may also be joined by visiting moth-trappers who are permitted to trap at the observatory and submit their records. The process for trapping at the Bay involves the power supply plugged into a timer switch set for half an hour before sunset and is set to turn off at dawn (changes throughout the year). The moth trap is then collected at dawn and stored away with a towel covering the top to keep the contents inside. The location for the storage is essential, as direct sunlight on the trap can cause fatalities. In the mid-morning, the trap is inspected, with all species and the numbers of each noted down on a recording sheet. The only reason for not running the trap at the Bay is inclement weather, particularly nights where heavy rainfall is expected throughout the night, or the wind speed is too great for moths to be flying or there is a risk of damage to the trap and its electrics. In the case of light showers, trapping continues as the rain guard on the trap provides sufficient protection from precipitation. After the content of the trap has been analysed, the moths are released 40 metres away from the trapping site. The totals and numbers of the trap are then collected onto recording sheets which are subsequently digitised. Individuals or records are pictured or stored for genetic analysis where the County Moth Recorder will confirm or dispute the records.

Figure 2: The Robinson Moth-Trap set-up for deployment in the Observatory car park, note the Pyrex Bowl over the bulb to prevent shattering due to water contact (Gregory Lee).

Records collected by the observatory are passed onto County Recorders, who manage all records within a vice-county; for example, Sandwich is in VC15 and are subsequently passed onto the National Moth Recording Scheme.

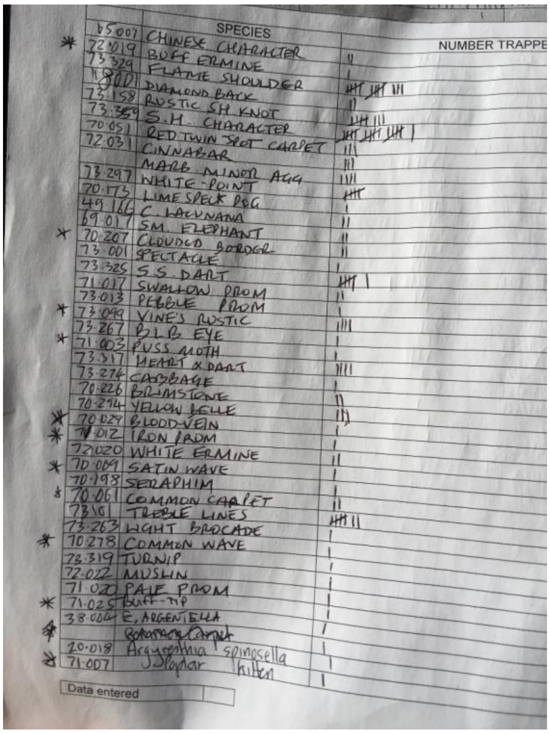


Figure 3: An example of the recording sheet used for moth-trapping at Sandwich Bay. These sheets are subsequently digitised. The numbers to the right of the species name are part of an implemented system of ordering in all UK moth species created by Agassiz et al., 2013. An asterisk denotes a new species recorded for the year. Tally represents the number of individuals. (Gregory Lee 20th May 2019)

3.3 Data Handling and Analysis

A vital source of the data collected came from annual reports created by the Bird Observatory over the 30 years. These offered monthly roundups of bird sightings, with notable species/dates with heavy passage noted. These were further supported with systematic data on each species recorded at the Bay over the year, often mentioning peak counts. As well as focusing on birds, most annual reports contained a section on the moth recording over the year, mentioning key species trapped and some even showing tables representing the more common migratory species. The *1990 Report* was the only one in the study period that did not contain this section. The annual report was dropped for a period of five years (from 2001 to 2006) before returning in 2007. The 2007 edition also covered the notable sightings and counts during this period.

These annual reports were provided by the Observatory. Since 2014, the online website has also provided sightings blogs for both birds and moths in the recording area (https://sbbot.org.uk/sightings/). The digitised moth data was also provided by the observatory but as it showed the records of all species, cleaning was required to extract the required data for migrants. A similar task was required for the bird records to separate the species of interest to the study.

3.4 Weather Analysis

As these substantial records have been obtained, the collected data created by the Met Office is critical to this study to be examined over the timeframe. The timeframe of 1990-2020 selected was based on previous research by the Met Office (Kaye, 2020), where the analysis of global annual temperature showed an increased spike post-1990 (Figure 4).

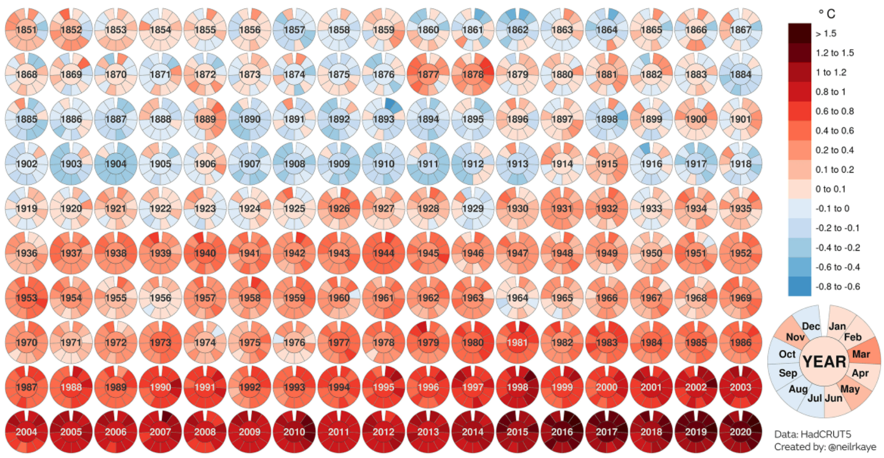


Figure 4: Monthly global mean temperature 1851 to 2020 (compared to 1850-1990 averages) (Met Office). This chart showed the distinct rise in global temperatures providing a good cut off for the study period.

Climate and Weather Data

For the first hypothesis, we predicted that the patterns favoured by moths and birds to migrate would differ between the two taxonomic groups. To determine if there was a difference, specific dates of heavy passage of both species' groups were collected to indicate the time of arrival over the thirty-year period. Dates were selected by either an overall arrival of a wide variety of migratory species, if there were large numbers of one species recorded or if there was the presence of a rare vagrant species. The summary of the weather on these dates was supplied by the Met Office archives, allowing viewing of daily synoptic charts for every year of the study and detailing the present pattern over Western Europe at 00:00 hours (*Daily Weather Report /Daily Weather Summary | Met Office UA*, n.d.).

A further spreadsheet was provided by Neil Kaye (2020) detailing the exact pattern on each date from 1990-2020, to allow a precise description of the patterns present on each day, reducing any possible user error through misinterpretation of the aforementioned synoptic charts. Additional data for more recent years includes Ventusky (*Ventusky - Weather Forecast Maps*, n.d.), which provides a virtual map of the wind direction on a particular night, helping to visualise what conditions caused by localised weather patterns may have aided migration. Whilst this data was not used for the statistical analysis, it helped provide a virtual animation of the weather patterns on some dates that might explain occurrences of vagrancy or falls in migrants, the data being provided live on the website. The weather patterns identified on the notable dates were then compared to those identified by the Met Office; their research identified 30 unique patterns that affected Europe that could be further condensed into eight patterns (Figures 5 & 6). The thirty weather patterns were decidedly used as this allowed thorough detail of the unique conditions provided by each pattern (e.g., wind speed and direction) instead of the basic overview created using the eight pattern-types (Figure 6) which provide a more generic summary of a weather system. The timeframe of each year (1990-2020) studied was between the 1st March and 31st October. This timeframe captures both the highest period of diversity for moths and the two critical periods of migration in birds to Britain, spring and autumn. In winter, the moth community is limited to an exceptionally sparse number of species; bird migration, as a whole, is also restricted.

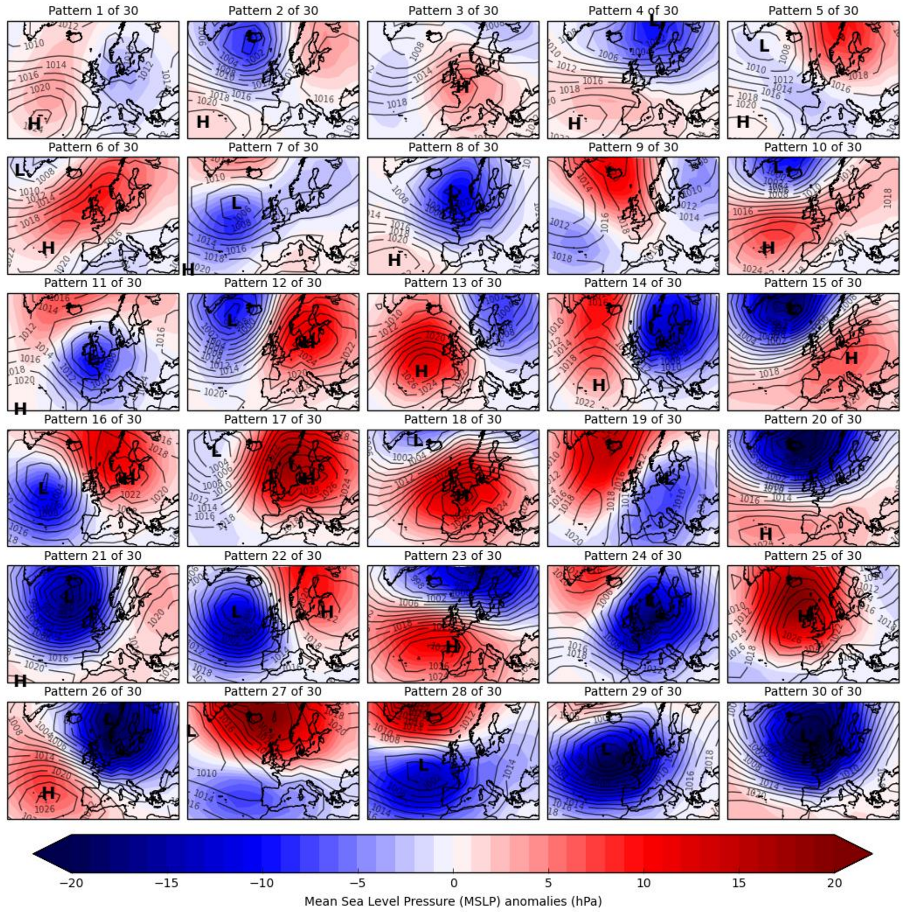


Figure 5: The 30 weather patterns designated by the Met Office (Image source: https://www.metoffice.gov.uk/research/news/2016/new-weather-patterns-for-uk-and-europe)

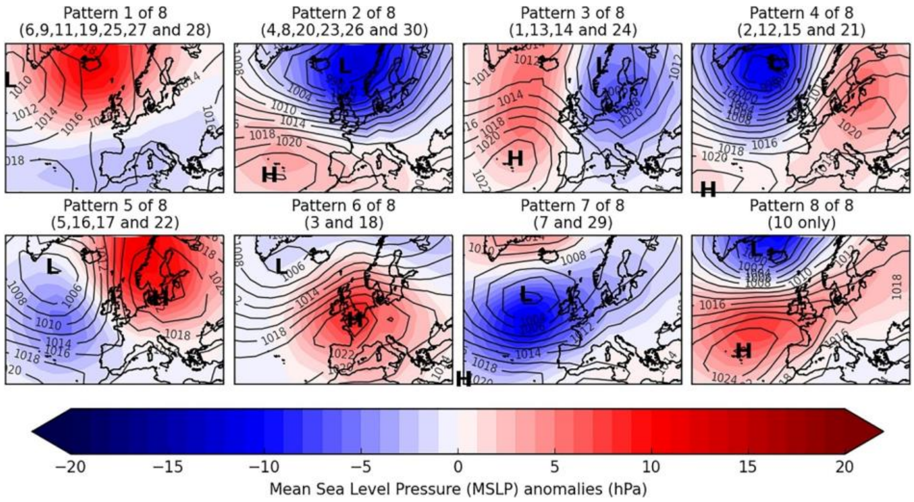


Figure 6: Eight weather patterns identified to affect Western Europe. Note how the weather patterns featured in Figure 5 are categorised into the eight. As the thirty-pattern designation provided more refined detail of exact conditions, this designation was not used examined in this study. (Image source: https://www.metoffice.gov.uk/research/news/2016/new-weather-patterns-for-uk-and-europe)

Table 1: Weather patterns and the wind conditions associated with each pattern (*Daily Weather Report /Daily Weather Summary | Met Office UA*, n.d.)

Pattern	Conditions experienced
1	Weak high pressure over the mid-Atlantic brings mild air from North Africa and the Azores. A weak area of low pressure over Scandinavia brings weak north/west winds to the UK.
2	High pressure over the mid-Atlantic brings southerly winds to the UK. The wind from the Atlantic high pressure meets a low pressure from the Arctic bringing south-westerlies to the UK. An area of high pressure over Northern Europe is responsible for easterly winds.
3	High pressure over the UK brings south/south-westerlies to the UK.
4	Strong low pressure over Scandinavia causes weak, cool northerly winds whilst an area of high pressure in the mid-Atlantic brings slow

	warm southerlies. These winds collide to create an overall westerly wind to the UK.
5	Calm easterly/southerly winds are formed from an area of high pressure over Europe which collide with gentle westerlies from low pressure over Greenland and high pressure over the mid-Atlantic.
6	Strong high pressure over the mid-Atlantic brings gentle westerlies over the UK although on occasion, air currents may loop over the UK in a clockwise direction causing easterlies.
7	Low pressure over the Atlantic brings gentle south-westerlies to the UK.
8	Low pressure over the UK causing strong westerly to the UK.
9	Gentle easterlies brought by low pressure over Scandinavia and high pressure over Iceland.
10	Calm westerly winds caused by high pressure over the Atlantic bringing warm air from Africa and low pressure near the North Pole may bring northerly-oriented winds.
11	Wet conditions caused by low pressure over the UK.
12	High pressure brings warm southerlies up from the continent and a low pressure over the Arctic brings warm air from the Atlantic
13	High pressure over the mid-Atlantic southwest of Ireland causing moderate north-westerlies to the UK
14	Low pressure over Scandinavia and high pressure over the mid-Atlantic causing north-westerly winds.
15	Very low pressure over Iceland and high pressure over mainland Europe brings strong south-westerly winds.
16	Low pressure over the mid-Atlantic and high pressure over the North Sea bringing southerly winds from the continent to the UK.
17	Southerly/easterly winds created by high pressure over the North Sea.
18	High pressure over Northern Europe bringing warm south-westerlies to the UK.
19	Low pressure over Northern Europe and high pressure over the North Atlantic bringing northerly winds to the UK.

20	Stormy westerlies caused by a very intense area of low pressure over the UK.
21	Stormy south-westerly winds caused by low pressure over the Arctic circle.
22	Low pressure in the North Atlantic causing strong southerly winds.
23	Strong westerlies caused by high pressure over the Bay of Biscay and a significant area of low pressure over Scandinavia.
24	Strong northerlies caused by low pressure over the North Sea.
25	High pressure over the UK causes north-easterlies to hit the east coast.
26	Very strong low pressure over Scandinavia creating very strong north-westerly winds.
27	High pressure over Iceland and low pressure over the Atlantic collide to bring easterly winds to the UK.
28	Low pressure over the North Atlantic and high pressure over Iceland causing south-easterly winds.
29	Low pressure over the North Atlantic creates high south-south-westerly winds to hit the UK.
30	Extremely strong north-westerly winds caused by very low pressure over Iceland.

3.5 Data Cleaning and Process

The flowchart in Figure 7 shows the steps of the data-cleaning process and how the large amount of raw data was condensed.

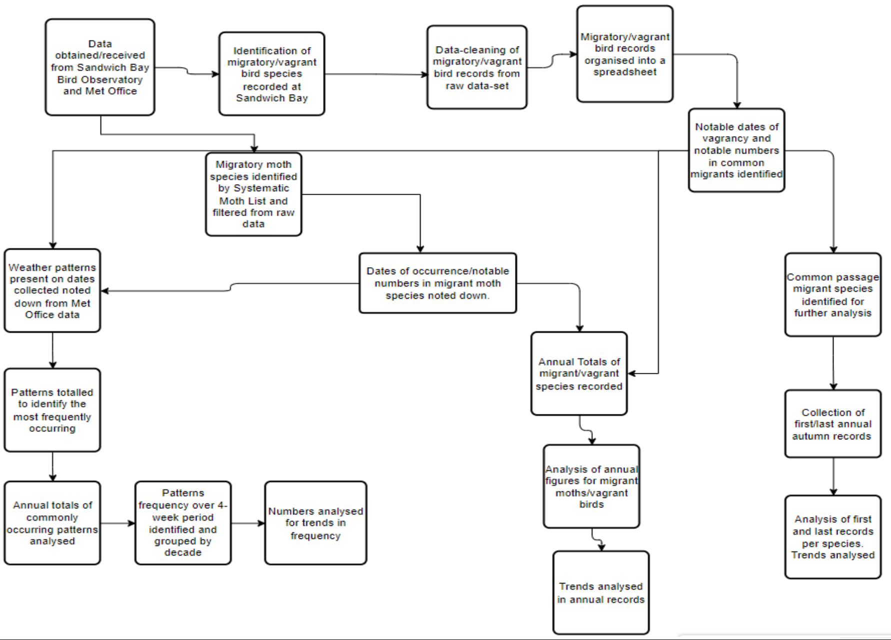


Figure 7: Flowchart detailing the data cleaning/analysis process in this study.

To address this study's hypothesis on moths, research involved looking at the conditions of the night of arrival in both the UK (United Kingdom) and mainland Europe, where their origins were. By looking at the weather patterns of good nights for migration, patterns should emerge about which regional weather patterns are considered best for these falls. Rarely, some moth species may even have their origin further away from North Africa. Therefore, the weather conditions around the Mediterranean over the previous week, before the arrival, also needed to be investigated. Occurrences of high counts of common migrant species were noted, as were nights where a rare species occurred. Alternatively, nights where moth activity on the migration front was deficient, were also explored to see which patterns limit passage; this is particularly interesting on nights when high numbers of resident species were recorded. To identify nights of limited migration, dates where high numbers of resident moths and little to no migrants were noted. Depending on the time of year, the benchmark for moth numbers varied; in the peak summer months June-late September where the number and diversity of moths is highest, nights of 500+ individual moths were recorded, this number being chosen as it reflects exceptional nights for moths. As the numbers will be considerably lower in March-May and also October, nights of over 250 individuals were recorded as again these were exceptional. This showed that the conditions were sufficient enough to provide substantial numbers of local moths, but an element was missing that enabled migration. Across the study period, there were 313 nights of heavy or interesting migration. Several common species were also identified to find noteworthy counts to indicate arrivals (Table 2). For nights of high resident counts, 227 were identified.

Table 2: Common migratory moth species recorded at Sandwich Bay according to the 2019 annual report. Many of these species were far more infrequent earlier in the study period.

Species	**Grouping**
Diamond-back (*Plutella xylostella*)	Micro
Rusty-dot pearl (*Udea ferrugalis*)	Micro
Palpita Vitrealis	Micro
Rush Veneer (*Nomophila noctuella*)	Micro
Convolvulus hawk-moth (*Agrius convolvuli*)	Macro
Hummingbird hawk-moth (*Macroglossum stellaratum*)	Macro
Vestal (*Rhodometria sacraria*)	Macro
Gem (*Orthonoma obstipata*)	Macro
Silver Y (*Autographa gamma*)	Macro
Bordered straw (*Heliothis peltigera*)	Macro
Scarce bordered straw (*Helicoverpa armigera*)	Macro
Small mottled willow (*Spodoptera exigua*)	Macro
Delicate (*Mythimna vitellina*)	Macro
Pearly underwing (*Pedridroma saucia*)	Macro
Dark sword-grass (*Agrotis ipsilon*)	Macro

A similar approach was taken to investigate bird migration. However, given birds are stronger fliers than moths, weather patterns from the previous week around southern Europe and the Mediterranean were taken into account, as this is where the sub-Saharan migrants are crossing in the spring. As spring migration is overall a rushed affair, and birds head to their breeding grounds as soon as the regional weather patterns show leverage. In the autumn, large numbers of birds of Scandinavian origin arrive at the study zone. Therefore, investigation of conditions over Scandinavia and the North Sea will be required 1-2 days prior to significant falls. Unlike with moth migration, there are two distinct periods of bird movement annually in spring and autumn. Therefore, records of note were separated into their corresponding season to allow insight into how the favoured patterns changed at these two key points in the year. This process was undertaken for both migratory breeding birds and vagrant birds. This allowed a distinction into which weather patterns were favoured during different times of year.

The original dataset contained records of all species during the study period. Migratory species were searched for individually and extracted along with the dates in the study period in chronological order, with the daily records of each species examined implemented on the correct dates. This allowed visualisation of peaks in numbers in each year throughout the study period and helped identify days where a heavy passage was reported in multiple species. Overall, 139 migratory species records were collected, including vagrants. However, some species, like the offshore migrants such as the divers (*Gaviidae*), had their records omitted from the study.

Table 3: An example of the spreadsheet created organising migratory bird records. Along the columns are the individual days, whilst the rows contain the species. The most common summer migratory species are the first in the species column. The numbers in the columns represent counts of each species on that day.

1	Species	21/8/07	22/8/07	23/8/07	24/8/07	25/8/07	26/8/07	27/8/07	28/8/07	29/8/07	30/8/07	31/8/07
2	Chiffchaff	1				4	3	3	1		6	3
3	Willow W	40			30	15	11	14	6	12	7	7
4	Wood Wa											
5	Garden W						1			2	5	1
6	Blackcap						4	4	1	16	14	16
7	Sedge Wa						22	33	1	23	4	5
8	Grasshop	1				1				3		
9	Whitethr	8			6	6	6	8	4	25	22	12
10	Lesser W	2			4	4	6	6	2	2	2	1
11	Reed War	5			9	5	20	57	2	25	8	11
12	Redstart					1		2		1		
13	Pied Flyca	1										
14	Spotted F	1						1				
15	Nightinga											
16	Whinchat	10			2	5	26	21	2	9	9	7
17	Wheatea	3	1		5	5	11	6	1	3	6	
18	Stonecha				1		1	1			3	5
19	Sand Mar	8	2	13	18	45	24	14		9	50	82
20	House Ma	119		27	61	65	80	80	45	31	70	670

Amongst the migratory bird species, further division and cleaning of the data were required by separating breeding summer migrants and passage summer migrants (Table 3). For example, numbers of sedge warbler, lesser whitethroat and chiffchaff remained consistently high into early summer, as they breed in the study area. Therefore, a cut-off date was determined when birds no longer arrived at Sandwich Bay from the continent. By May 10th, most species have arrived at their breeding grounds, so this was a suitable cut-off for records. Other species, such as redstart, pied flycatcher, garden warbler and wood warbler, however, are non-breeders.

Therefore, records in both spring and autumn did indicate movement. The list of all bird species recorded at Sandwich Bay was key to identifying what category common migratory species need to be placed.

Further cleaning of the data was required to select the suitable dates for the study. In spring overall, the numbers of migrants are lower; this means that the values for what constitutes a fall are also lower (Table 4). For example, in March, a day where seven chiffchaffs were recorded is worth noting. However, a day in August-September where the same number is recorded would be ignored, as numbers during the autumn period can go into the hundreds. The annual reports also helped by mentioning days of particular heavy passage by monthly reports.

Table 4: Table showing the minimum spring and autumn count thresholds of breeding British summer migrants at Sandwich Bay across the study period.

Species	Spring Migration threshold	Autumn Migration Threshold
Chiffchaff (*Phylloscopus collybita*)	5+	50+
Willow Warbler (*Phylloscopus trochilus*)	3+	20+
Wood Warbler (*Phylloscopus sibilatrix*)	1+	1+
Common Whitethroat (*Sylvia communis*)	5+	5+
Lesser Whitethroat (*Sylvia curruca*)	3+	3+
Garden Warbler (*Sylvia borin*)	1	5+
Blackcap (*Sylvia atricapilla*)	10	50+
Reed Warbler (*Acrocephalus scirpaceus*)	5+	20+

Sedge Warbler (*Acrocephalus schoenobaenus*)	10+	10+
Grasshopper Warbler (*Locustella naevia*)	1+	1+
Redstart (*Phoenicurus phoenicurus*)	1+	1+
Nightingale (*Luscinia megarhynchos*)		
Pied Flycatcher (*Ficedula hypoleuca*)	1+	1+
Spotted Flycatcher (*Muscicapa striata*)	1+	1+
Wheatear (*Oenanthe Oenanthe*)	2+	10+
Whinchat (*Saxicola rubetra*)	1+	10+
Yellow Wagtail (*Motacilla flava*)	5+	10+
Tree Pipit (*Anthus trivialis*)	1+	5+
Swallow (*Hirundo rustica*)	20+	100+
House Martin (*Delichon urbicum*)	20+	100+
Sand Martin (*Riparia riparia*)	5+	20+
Cuckoo (*Cuculus canorus*)	1+	1+
Swift (*Apus apus*)	5+	20+
Turtle Dove (*Streptopelia turtur*)	2+	10+ (2010 onwards- 3+ due to severe decline)
Hobby (*Falco Subbuteo*)	1+	5+
Honey Buzzard (*Pernis aviporus*)	1+	1+
Osprey (*Pandion haliaetus*)	1+	1+

This also varied between species. Wood warblers are scarce in the study area; therefore, records of single individuals were worth noting in both spring and autumn. Species such as willow warbler, although commoner, also do not pass through in the numbers that chiffchaff and blackcap do. Therefore, a fall of 30 willow warblers in autumn is noteworthy, whilst 30 of the latter two species is also a low count during that same period.

Another category was vagrants, including records of non-breeding bird species in the UK, whose incidence in the British Isles is either accidental or sporadic. This was an important aspect, as species that are non-breeding in the UK recorded over the study period needed to be identified, as well as their origin. For example, species such as hoopoe, bee-eater and roller are birds of Southern Mediterranean Europe; therefore, an investigation into the regional patterns over Southern Europe was identified days before a record at Sandwich Bay was required. When it comes to determining which bird, species constituted as vagrants or scarce migrants, the designations created by the BBRC were used to determine the national status of the species (BBRC, 2022) as well as the 2018 report on scarce migrant birds (White & Kerhoe, 2020). The Sandwich Bay Systematic Bird List provided further information on species regarded as vagrants.

In autumn particularly, the numbers of many migratory species were higher on a daily basis. Therefore, dates that were considered noteworthy during the autumn consisted of either exceptionally large falls of one species (100+), such as enormous numbers of hirundines (1000+), or where there was a high species diversity with good numbers. A similar process was implemented for obligate migratory species. For example, suppose there is little movement of facultative migrants on a specific date but light-moderate passage of species such as meadow pipit, grey wagtail or robin (200+) which are not traditionally seen as migrants, then in that case, it was not used. However, if there was an exceptionally high quantity of these species with some facultative migrants, then the date was noted.

The majority of species used in this study were land-based. Sea-faring species recorded far out to sea during sea watches were not counted, as the conditions that affect the falls of migratory passerines will very likely not affect species that are adapted to spending the winter out on the open sea or are adapted to using high winds to travel exceptionally far distances. Therefore, it would be challenging to determine the conditions over the open ocean that would affect these species. Several wading bird species were also investigated; however, these only included passage migrants that do not stay in the area through the winter and vagrants. These include species such as curlew sandpiper (*Calidris ferruginea*) and wood sandpiper (*Tringa glareola*), which pass through to and from their breeding grounds, dropping onto inland water features. Overall, 1469 dates of bird migration were recorded; 487 dates of vagrants were also found, some of these being shared with regular bird migration.

Table 5: The breeding status of common summer migrant species in Sandwich Bay. All species are recorded annually on migration.

Species	**Status at Sandwich Bay**
Chiffchaff (*Phylloscopus collybita*)	Breeding
Willow Warbler (*Phylloscopus trochilus*)	Non-Breeder
Wood Warbler (*Phylloscopus sibilatrix*)	Non-Breeder
Sedge Warbler (*Acrocephalus schoenobaenus*)	Breeding
Reed Warbler (*Acrocephalus scirpaceus*)	Breeding
Common Whitethroat (*Sylvia communis*)	Breeding
Lesser Whitethroat (*Sylvia curruca*)	Breeding
Blackcap (*Sylvia atricapilla*)	Breeding
Garden Warbler (*Sylvia borin*)	Non-Breeder
Redstart (*Phoenicurus phoenicurus*	Non-Breeder
Pied Flycatcher (*Ficedula hypoleuca*)	Non-Breeder
Spotted Flycatcher (*Muscicapa striata*)	Non-Breeder
Wheatear (*Oeananthe oenanthe*)	Non-Breeder
Whinchat (*Saxicola rubetra*)	Non-Breeder

Several common migratory passerine species were chosen for further analysis due to their annual occurrence e.g., willow warbler, pied flycatcher and redstart (Table 5). This was because as non-breeders in the area with annual occurrence in the autumn, it would be interesting to see if there had been changes in timing of their autumn migration and passage throughout the study period. Autumn records were chosen as the autumn migration season experiences the main passage of migratory birds at Sandwich Bay. Breeding species in the area such as sedge warbler, were not focused on as their consistent recording of the breeding population through the summer months made it difficult to establish when the first annual pulses of southward-bound individuals from further afield occurred.

The community of moths was also expected to change over the study period. This is important as south-east England has been subject to the colonisation of several moth species previously designated as continental migrants. Examples of these include tree-lichen beauty (*Cryphia algae*), oak rustic (*Dryobota labecula*), white-point (*Mythimina albipuncta*) and l-album wainscot (*Mythimina l-album*) (Waring and Townsend, 2017). At which point these species became officially established as breeders in the area was also determined for inclusion/exclusion in migrants. Several migratory moth species are common annual occurrences, such as rusty-dot pearl, silver Y and rush veneer. Therefore, like the practice with the chiffchaff records, numbers of high counts were only considered useful to the study. Fortunately, many of these species did indeed have some notable dates of migration during the study period. One useful piece of literature for identifying migratory species was the Systematic List of Moths at Sandwich Bay. This list included every species ever recorded in the study area and also described their occurrence. For example, convolvulus hawk-moth is designated as a noted migrant. This list was also valuable for rarer species as it provided the exact dates such species were recorded. Using this list, such species were noted down to be cleaned out from the primary dataset, with dates also recorded of scarcer migrants, providing they fell within the study period. Additionally, the list also stated species that were recent colonists and former immigrants.

The dates collected for migration were divided into three groups: (i) moths, (ii) birds and (iii) vagrant birds. Birds consisted of migratory species that regularly breed in the UK or occur in large numbers on passage. Vagrants consisted of species that did not breed in the UK and were likely overshoots, with very sporadic records. When the three groups were created, the following process was to note down which weather patterns were present on the notable days recorded. This involved looking through the Met Office historical weather records and noting patterns and dates (patterns were based on the 30 designated by the Met Office). Data on the number of migratory species in notable frequency on that particular date was extracted. These identify which weather patterns occurred the most frequently for all three groups. At first, the top five most recorded weather patterns were noted; however additional patterns were added until there was a significant gap in occurrence. For the bird migration, the patterns were split into spring and autumn to identify which patterns were used at each time of year.

To investigate changes in the frequency/rate if weather patterns over the study period, each weather pattern's occurrence in every year of the study was recorded. Once the totals for each year were collected, the non-parametric Mann-Kendall correlation test was carried out to identify if there were any significant trends in occurrence. Similarly, totals were collected of patterns in 4-week periods to see if there was a shift in timing for these patterns to occur over the decades, possibly changing the timing of migration. For example, have the peak timings for a pattern beneficial to migration shifted earlier or later across the decades? When looked at, across the various decades of the study period, this allowed any trends to be identified. The nonparametric Mann-Kendall test was used as data did not meet parametric test assumptions. Similarly, the counts of occurrences of each weather pattern across the study period were collected to see which were the most commonly occurring in general.

By looking at notable dates for migration and the patterns responsible for such dates, it could be identified if the same factors responsible for sizeable migratory moth falls are similar to those required by birds to migrate. For example, whether the direction and strength of wind is a major limiting factor caused by the varying pressures of the weather patterns?

Finally, it was determined that the annual number of migratory moths and vagrant birds is increasing due to changes in weather pattern frequency. The numbers of species for each year were investigated and to see if there was a pattern or change in the numbers recorded over the study period. If so, future migration trends could be predicted. The annual totals of migratory moth species and vagrant bird species were recorded, and a Mann-Kendall test was used to identify trends. Regression lines were also created to determine the changes in annual frequency of both vagrants/rare migrants and migrant moths. Additionally, the first and last records annually of notable passage bird species in the autumn migration period, the reasoning behind this was to determine if there had been notable changes in their arrivals/departures over the study period. For example, species such as pied flycatcher do not pass through the study area in spring in more than singles, however, notable numbers do occur in the autumn. Therefore, the aim of collecting the earliest arrivals and latest departures of such species means it can be seen if there have been any distinct shifts in the timing of migration, either caused by pressures from climate change or by population declines. An ANOVA test was carried out to investigate the variation of dates (dates were turned into their Julian day numbers) between eight passage passerine migrants during autumn migration and a multiple-comparisons Tukey test was also carried out to identify the differences between the species.

4. Results

4.1 Annual Frequencies of Vagrant/scarce migrant birds

The annual numbers of vagrant/scarce bird species per year at Sandwich Bay were collected to determine whether there were any noticeable phenological trends in vagrant birds. An upward trend was observed over time, despite 2006 recording the fewest vagrant bird species (Figure 8). However, following 2006, the number of vagrants and scarce migrants recovered and increased above previous records from the early 1990s at Sandwich Bay. 2020 was an exceptional year for east coast bird observatories across Britain, with large numbers of vagrant species being recorded.

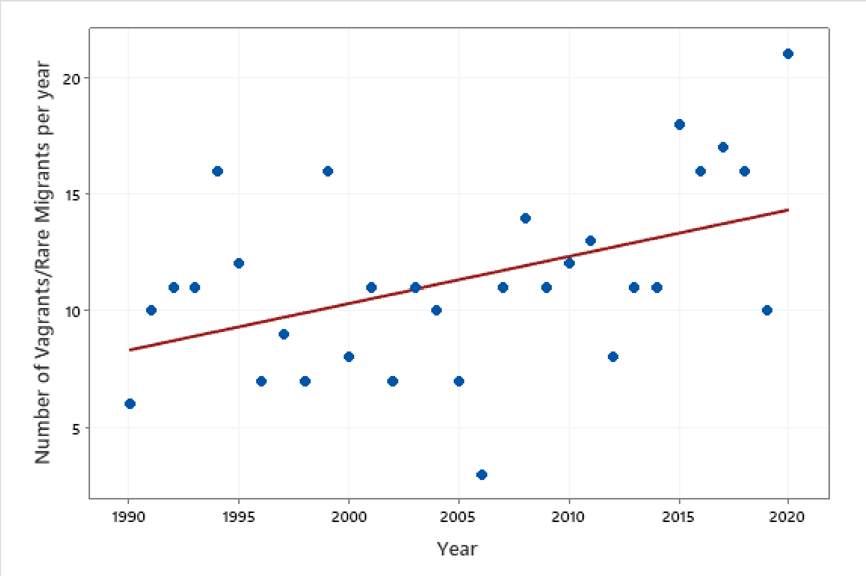


Figure 8: The number of vagrant bird species from 1990 to 2020. The linear regression line displays the correlation in the data, this particular one showing a significant increase (R^2: 0.209, p: 0.009).

There is a significant increase in migratory moth records through the study period. Initially, numbers of migratory moths are relatively stable before a sharp increase post-2005 (Figure 9). The year with the highest total before the sharp rise was 1998. The period 2015-2020 shows a large increase in numbers of species recorded. Interestingly, 1998 was the only year to surpass ten migratory species until 2010. Since 2013, every year has recorded at least ten migratory species (Figure 9).

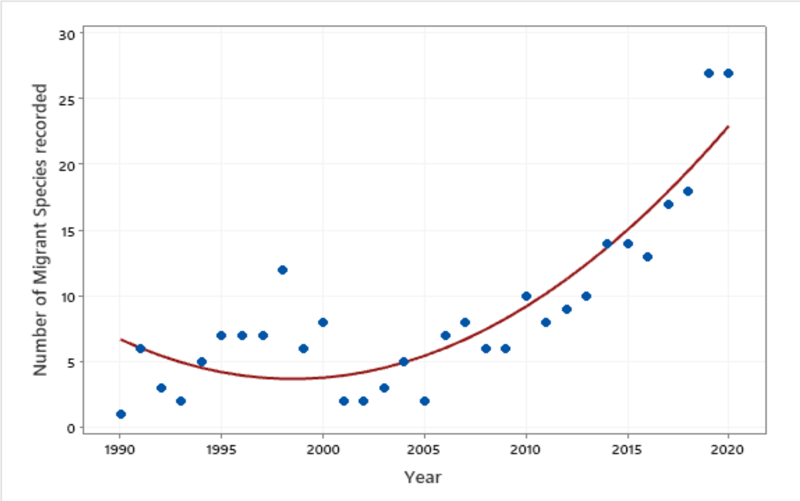
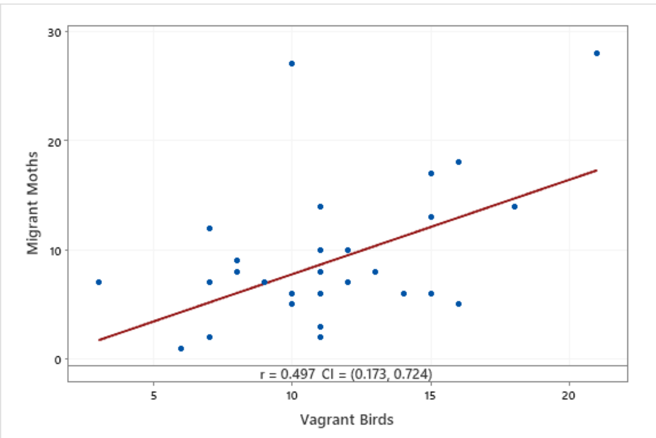


Figure 9: Annual counts of the diversity of migratory moth species recorded at Sandwich Bay. A second-order polynomial regression line was used based on a visual fit to the data (R^2: 0.56, $p<0.001$).

There is a clear upward trend in the numbers of vagrant bird species identified across the study period (Z: 2.460, upward $p < 0.05$, downward p: 0.933). Migrant moths showed a similar upward trend (Z: 4.817, upward $p < 0.05$, downward p: 1.00).

There is a positive correlation between the number of species of vagrant birds and migratory moths showing their population trends and occurrence in the study period with both increasing in number, r: 0.497 (Figure 10).



.

Figure 10: Matrix plot (R= 0.497, p <0.005) comparing the trends in vagrant birds and migratory moths over the study period.

Commented [RJ1]: I would expand this figure legend, to make the figure self-explanatory.

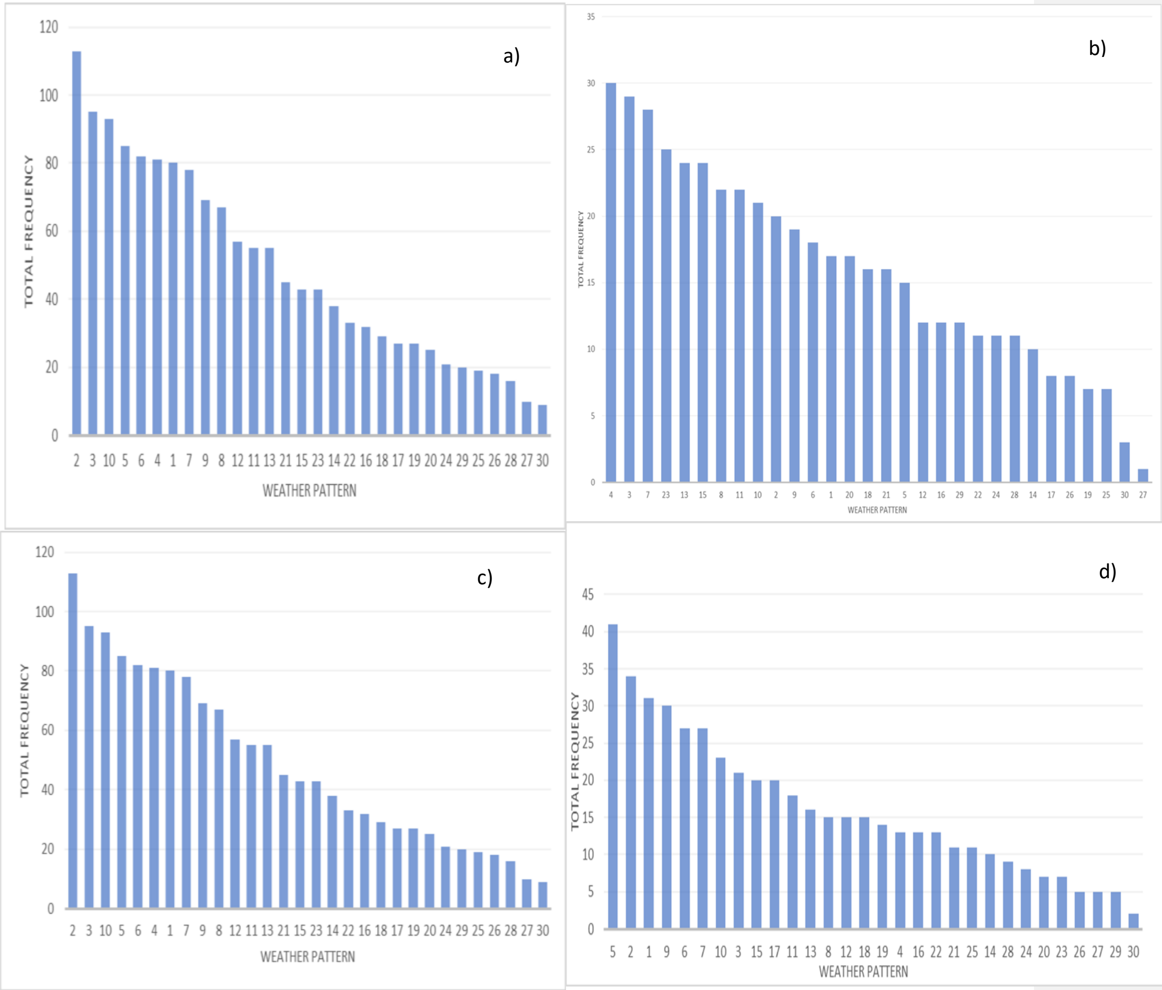


Figure 11: Absolute frequency of weather patterns on days of heavy bird migration overall (11a). Frequency of weather patterns during spring migration (11b). Frequency of weather patterns on autumn migration (11c). Frequency of weather patterns on notable dates of vagrancy (11d).

Pattern *2*, which consists of high pressure from the Azores colliding with low pressure over Iceland bringing a south-easterly wind across the English Channel, was the most frequently occurring weather system for bird migration (Figure 11a). This was followed by patterns *3*,*10*,*5* and *6*. Pattern *30*, which is responsible for cold Arctic winds being brought down across the UK, was the least occurring pattern in relation to bird migration.

Patterns *23*, *13* and *15* are unique to spring migration, showing a different preference of conditions for returning birds (Figure 11b). From those most frequently occurring in spring, only pattern *3* is in the top five most commonly occurring overall for bird migration. The most frequently occurring patterns in autumn are more reflective of the overall pattern frequencies of bird migration with patterns *2*,*10*, *5*, *3* and *1* being the five most commonly occurring (Figure 11c). The five most commonly occurring patterns for vagrants overall were *5*, *2*, *1*, *9* and *7* (Figure 11d). The variation was biased to those frequent in autumn due to substantially more autumn vagrancy records.

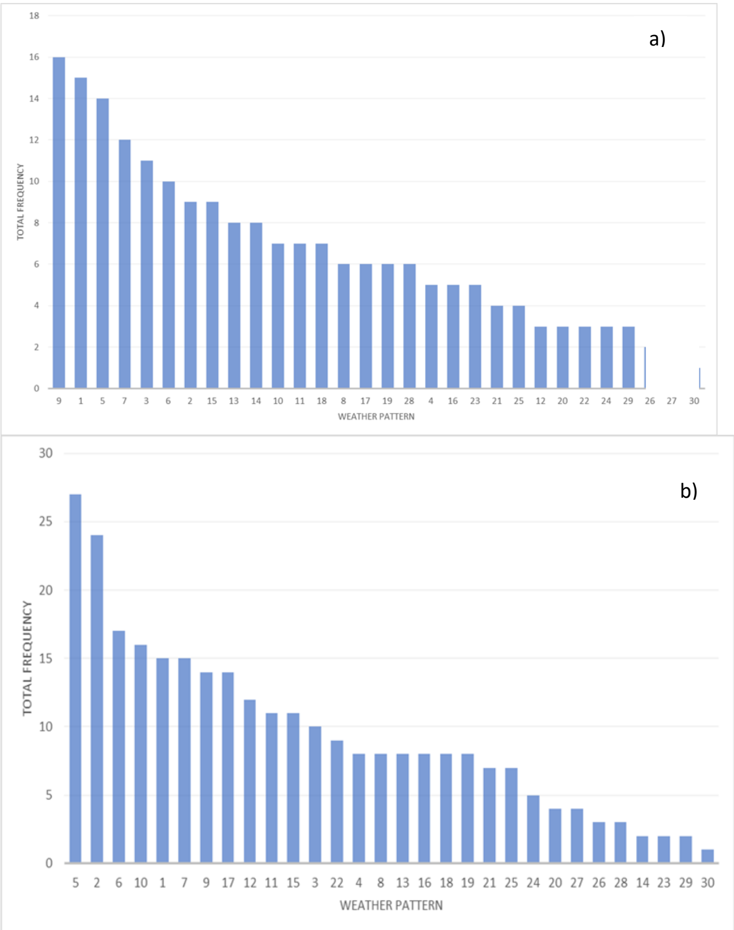


Figure 12: The most commonly occurring patterns during spring vagrancy (12a). The most commonly occurring frequency for dates of autumn vagrancy (12b).

The most commonly occurring patterns for spring vagrancy are *9*, *1* ,*5*, *7* and *3* (Figure 12a). When compared to Figure 11d, three of these are in the top five overall for vagrancy. Compared to Figure 12a, the top five most commonly occurring patterns in autumn differ with only patterns *5* and *1* being shared between the two (Figure 12b).

4.2 Weather pattern effects on moth migration

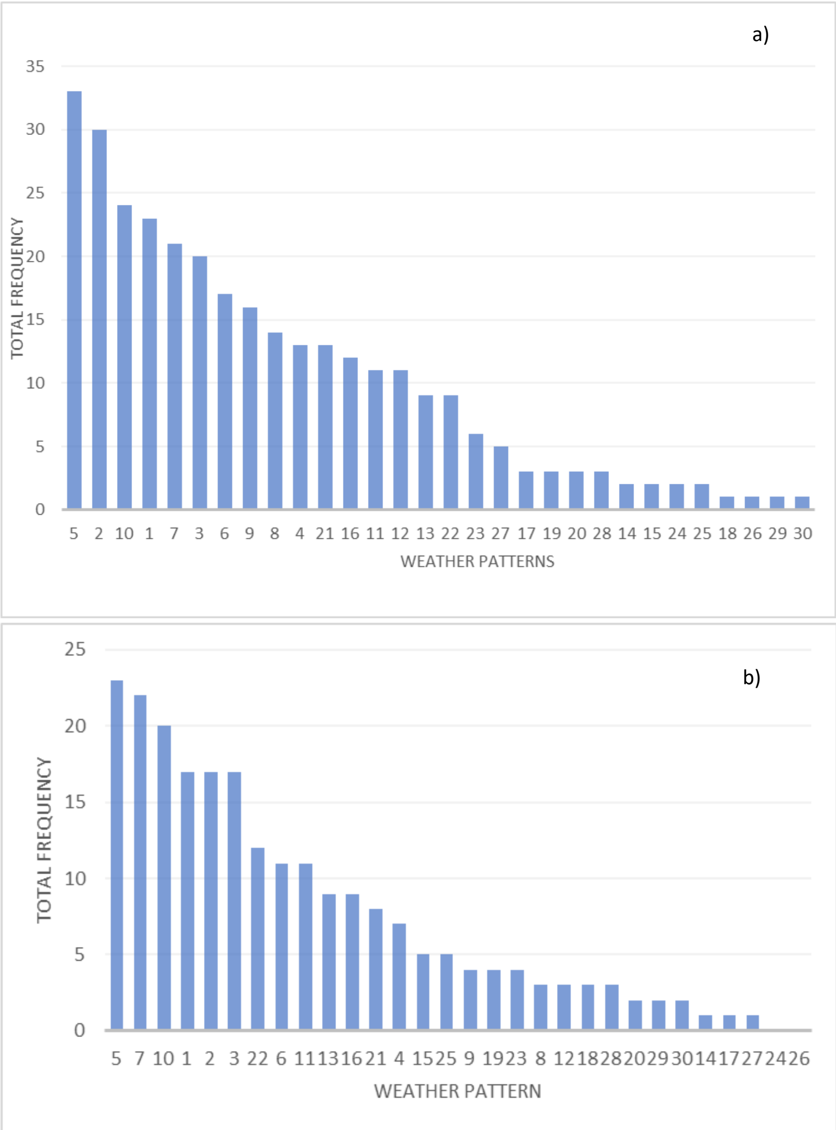


Figure 13: The patterns most frequently occurring on nights of notable moth migration (13a). The most frequently occurring patterns on night of high resident counts (14b).

Commented [RJ2]: Is this 14b? Unclear.

Figure 13a examined the notable nights of moth migration over the study-period. Pattern *5* is the most frequently occurring weather system (Figure 13a) followed by patterns *2, 1, 9, 7* and *6*, these patterns all being responsible for calmer winds to the UK though the direction varies. Similarly, to what was observed for migratory birds, however, pattern *30* was the least occurring with other patterns that bring cold, wintery conditions also being considerably low in occurrence. It is clear that pattern *5* is the most frequently occurring and consists of a strong low pressure over Scandinavia bringing southerly continental winds to the study area. The next most frequently occurring patterns are *2, 10, 1, 7* and *3* by some margin, both patterns *2* and *5* are ahead and rely on high pressure systems. Pattern *18,* which brings strong westerlies from the mid-Atlantic caused by high pressure over the UK, was the least frequent pattern, followed by *26, 29, 30* and *14*. It is worth noting that patterns *26, 29* and *30* are all caused by low pressure bringing cold winds from the Arctic to the UK, which may explain why their frequency of occurrence is so low.

The present weather patterns in nights of high resident moth counts at Sandwich Bay are shown in Figure 13b. Patterns *5,7* and *10* are the most frequently occurring in descending order, with patterns *1*,*2* and *3* tied equally. Resident moths share the same patterns as migrant moths but in different orders. Pattern *7*, for example, which is caused by an area of low pressure bringing a gentle south-westerly wind is more favoured by resident moths. Of the top five patterns, pattern *2* is the least occurring for resident moths, yet the second highest for migrant species

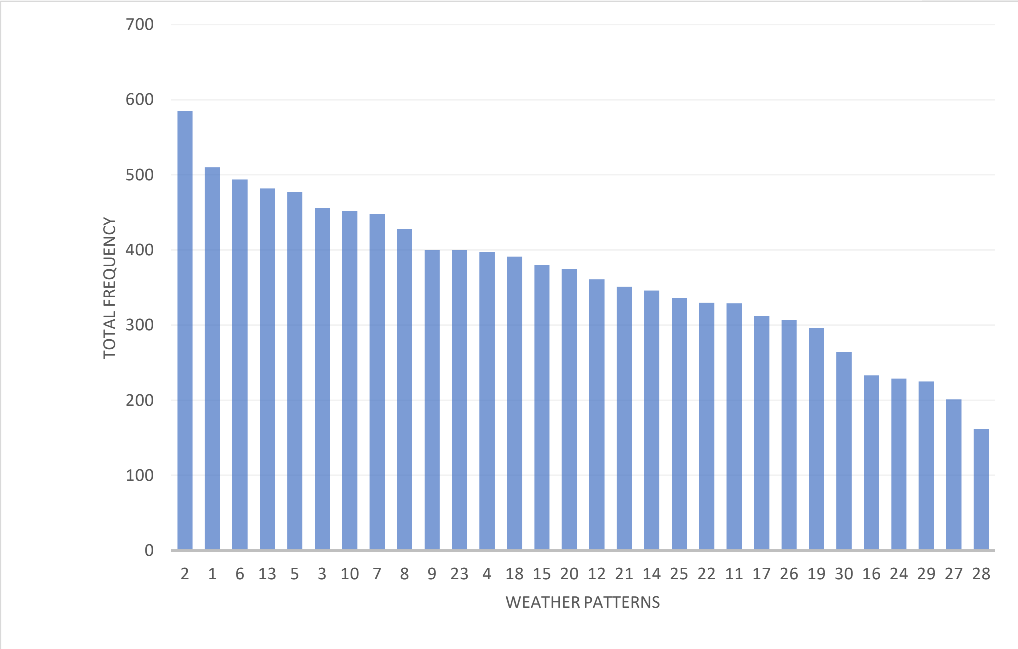


Figure 14: Frequency of all 30 weather patterns across the study period. Standard error bars included.

Pattern *2* was by far the most frequent followed by patterns *1*, *6*,*13* and *5*. Patterns *28*, *27*, *29*, *24* and *16* were the least occurring. The patterns in the late 20s are likely responsible for very harsh winter conditions which are less frequent to the British Isles.

Patterns *7*, *3* and *4* had discernible trends within the 30-year study period which were notable (Table 6). Pattern *7* was the only upward trend identified (Z: 2.466, $p < 0.001$).

Table 6: The top eleven patterns for migration in all groups (birds, moths and vagrant birds).

Weather Pattern	Z-Value	Trend	p-value (upward)	p-value (downward)
1	-1.113	None	0.867	0.132
2	-1.591	None	0.944	0.055
3	-1.696	Downward	0.955	0.044*
4	-1.863	Downward	0.968	0.031*
5	-0.855	None	0.803	0.196
6	-0.756	None	0.775	0.224
7	2.466	Upward	<0.001**	0.993
9	0.394	None	0.346	0.653
10	1.156	None	0.123	0.876
13	-0.286	None	0.612	0.387
15	0.068	None	0.473	0.527
23	0.608	None	0.418	0.581

* ≤ 0.05

*** ≤ 0.01

4.3 Weather pattern analysis

Analyses were conducted on the frequency and timings of weather patterns via Julian week by assessing the totals on a four-week basis for each year of the study period (Figures 15-22) The weather patterns selected where the ones showing the most marked trends that were linked with migration in both species' groups. Overall, there have been changes to these weather patterns over the 30-year study period, potentially providing insight into the changes in migration.

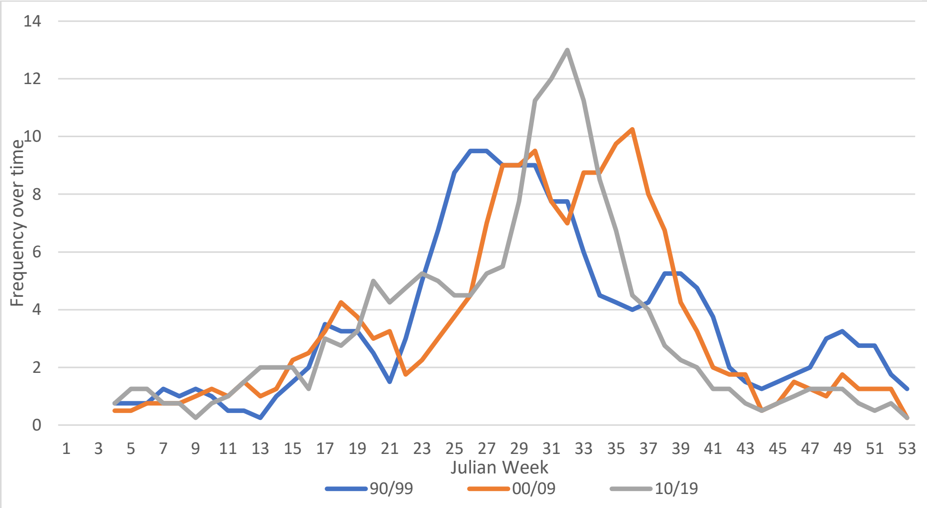


Figure 15: The peak totals via Julian week for Met Office Weather Pattern *1* sorted by decade. Pattern *1* brings westerly winds and mild air from Azores and Africa.

The peak count for pattern *1* is higher in the 2010s compared to previous decades demonstrated in Figure 15. The duration of annual peaks in pattern *1* however is longer and more stable in the 1990s and 2000s with the drop-off in occurrences of this pattern being more gradual. Pattern *1* appears to be a key component to early autumn migration with the peak occurring from late July- mid August.

Commented [RJ3]: Always check all formal details (you use italic letters elsewhere)

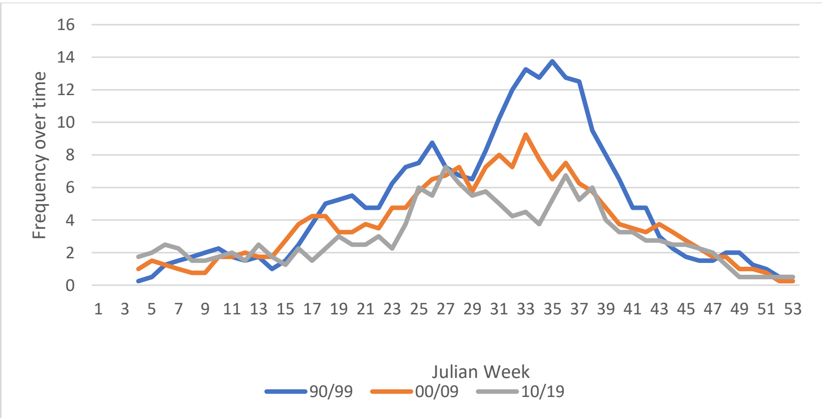


Figure 16: The peak totals via Julian week for Pattern 2 sorted by decade. This pattern can bring both easterly and southerly wind to Britain.

Compared to pattern *1*, the occurrence of pattern *2* is lower in the 2010s compared to the previous two decades (Figure 16). Over three decades, a small increase is notable around weeks 25-27 before a higher peak occurring later on. In the 2010s, this peak appears not only to be significantly lower, but also marginally later, with the 2000s appearing to show a pattern in between the trends shown in the 1990s and 2010s.

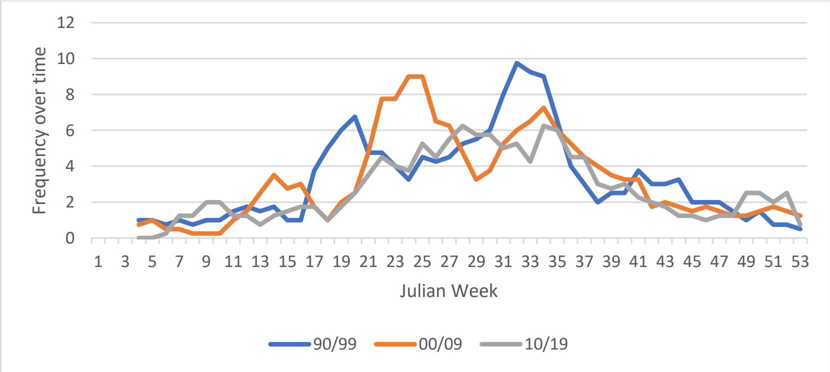


Figure 17: The peak totals via Julian week for Pattern *3* sorted by decade. Southerly/south-westerly winds are brought to the UK.

Trends shown in Figure 17 show that Pattern *3* has dropped in frequency in the 2010s. The trends in the 1990s and 2000s show a much more erratic pattern but there is a peak observed in all three decades around week 35, though this peak has declined during the decades.

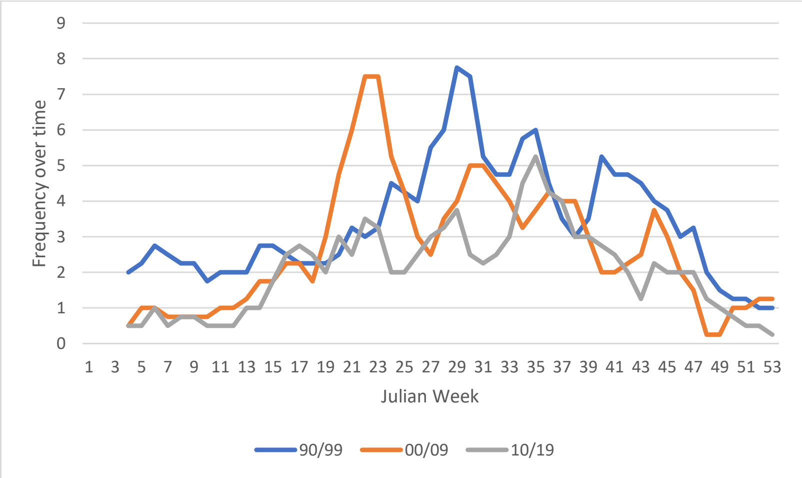


Figure 18: The peak totals via Julian week for Pattern *4* sorted by decade. Gentle westerly winds are brought to the UK in this pattern.

Pattern *4* shows a reduction in frequency through the study period, with the 1990s showing the highest trendline before a decrease through the decades.

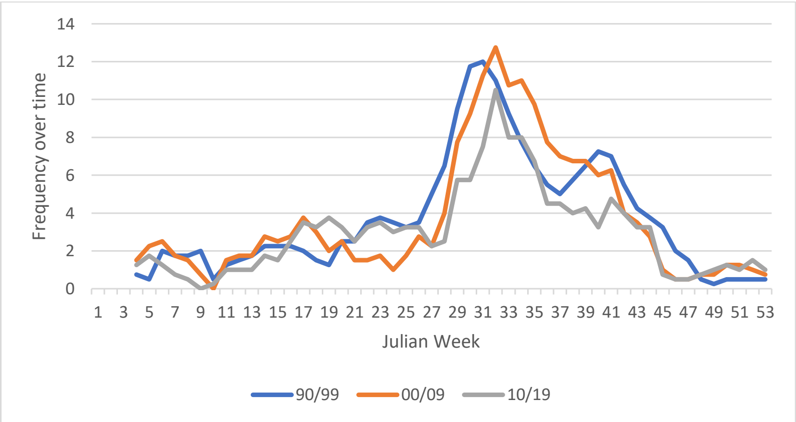


Figure 19: The peak totals via Julian week for Pattern *5* sorted by decade. This pattern brings westerly and on occasion, easterly winds to the UK.

Pattern *5* appears to one of the more stable patterns during the study period, with only a small decrease in peak count in the 2010s. The timing of these peaks also has become later by two weeks, although this pattern remains very common during migration in early August.

Commented [RJ4]: Be as specific as possible – better just "has"

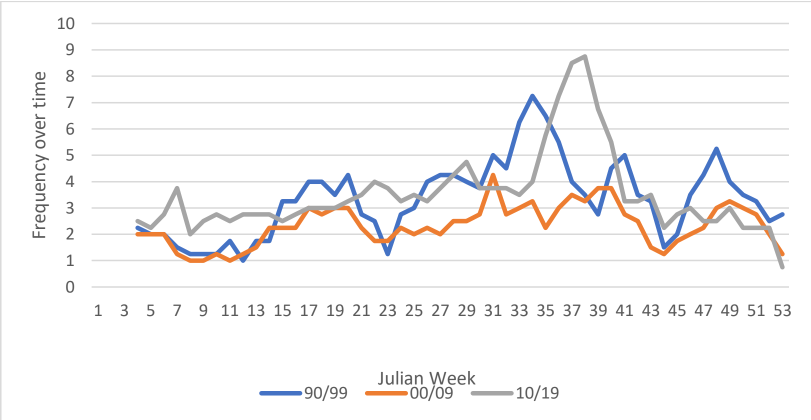


Figure 20: The peak totals via Julian week for Pattern *10* sorted by decade. Gentle westerly winds are brought to the UK.

Pattern *10* shows an increased peak in the 2010s than in previous decades, this peak is also later than the previous decades, with week 37 seeing the highest count.

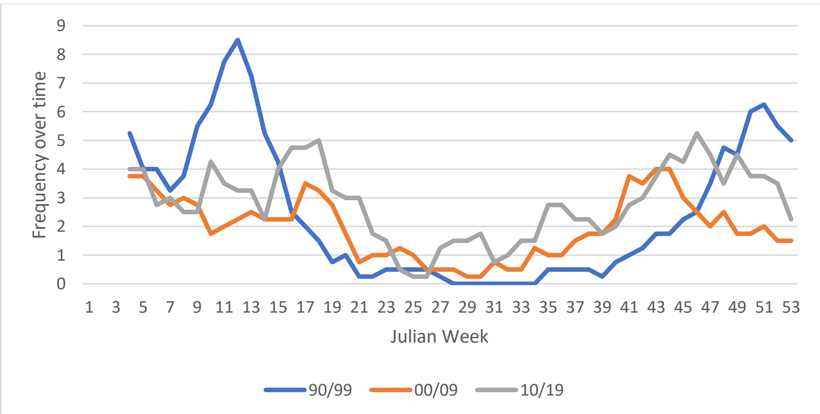


Figure 21: The peak totals via Julian week for Pattern *15* sorted by decade. Strong south-westerly winds are brought to the British Isles by this pattern.

In Figure 21, there was a drop in the frequency of pattern *15* over the study period with an early spring peak in the 1990s being considerably lower in the subsequent decades. A notable slump in this pattern's frequency is evident in the 2000s, however the 2010s saw an increase although not quite to pre-2000 levels.

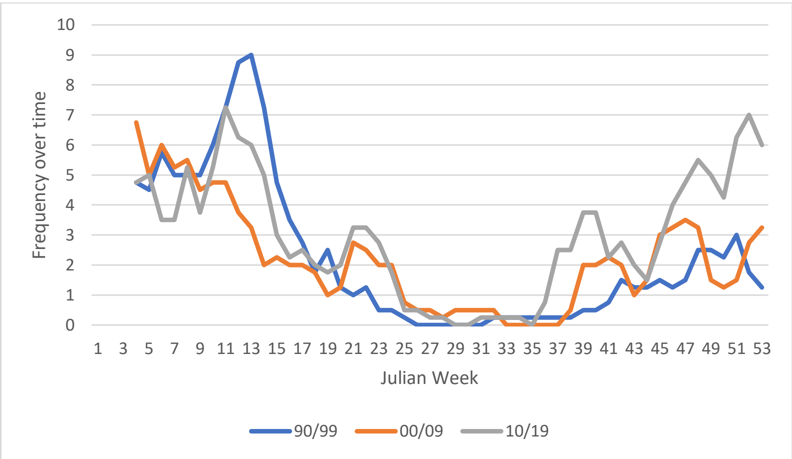


Figure 22: The peak totals via Julian week for Pattern *23* sorted by decade. Pattern *23* brings strong southerly winds.

Pattern *22* has a similar trend to that of *15* (Figure 21). Once again, the peak count in the 1990s is significantly higher, with week 13 seeing the highest average count (March 26th-April 1st). In the 2000s, there is an early peak in the winter, but no such peak in March. The 2010s show a significant peak also in March, although this is around week 11, showing an earlier shift in occurrence. Later in the year pattern *23* is becoming more prevalent, with both the 2000s and 2010s trendline being higher than in the 1990s in the latter weeks of the year.

4.4 Changes in the timing of migration

The study analysed the dates of the earliest autumn arrivals and latest departures annually in common summer migrants at Sandwich Bay (Figures 23-30). In each of the species, there appears to be a shift in departure times, with most being considerably earlier, compared to 30 years ago.

The annual autumn arrivals and latest departures in common redstarts are compared in Figure 23. From the records it shows that the arrivals are indeed shifting earlier, although only by less than a week. However, the mean occurrence of the first redstarts is during mid-August. There is a major shift in the departure times of redstarts, with records seldom being observed after the last week of October in recent decades, indicating a change of approximately ten days.

Common Redstart, Kilnsea,
East Yorkshire, 2021,
(Author's own)

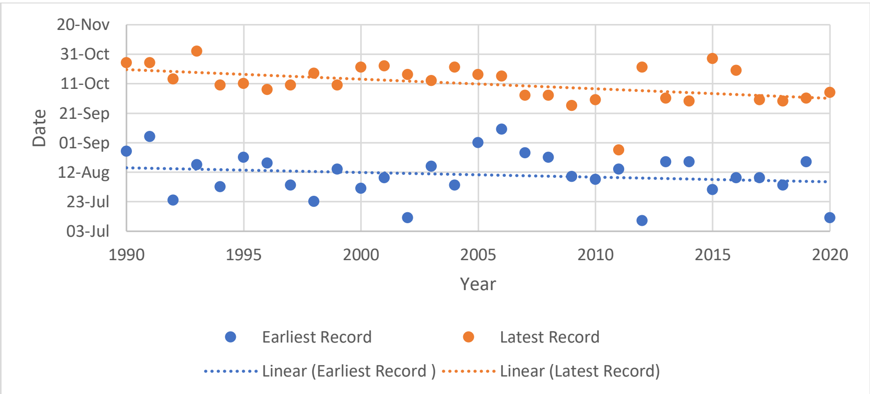


Figure 23: The annual records of earliest arrival and latest departure in common redstart (*Phoenicurus phoenicurus*) during autumn migration at Sandwich Bay (Earliest records R^2: 0.035, p <0.001; Latest records R^2: 0.206, p< 0.001).

The annual autumn records of pied flycatchers are examined in Figure 24. Similarly, to the redstarts (Figure 23), arrival dates remained consistent up until 2005, with birds arriving in early August. In the 2010s, pied flycatchers consistently arrive after August 12th, before, at the end of the decade, returning to early August. Only three of the 30 years had records in late July. There is a delayed arrival over the decades, although the last three years of the study period are going against that trend. There is also to be a shift in departure times of almost two weeks post-

2010, with most of the latest departures in late September, although this change might even be traced back to post-2000, with only four of the latest departures being in October.

Pied Flycatcher, Kilnsea, East Yorkshire. 2021 (Author's own)

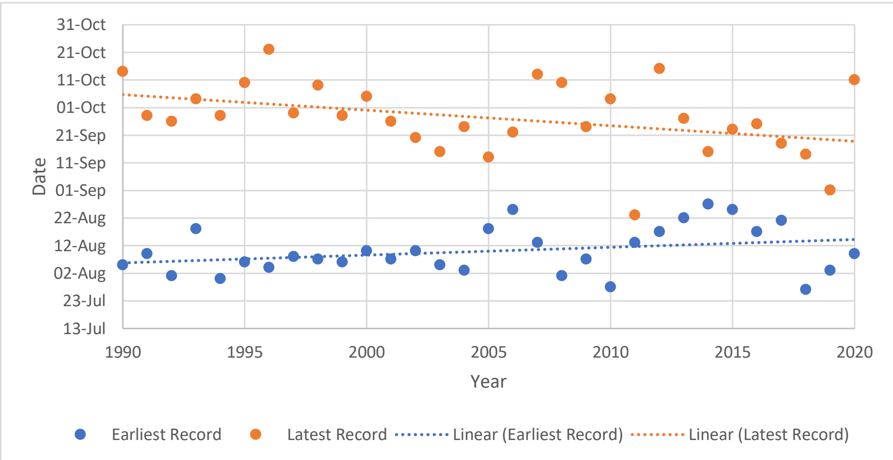


Figure 24: Scatterplot showing the earliest and latest autumn records of pied flycatcher (*Ficedula hypoleuca)* annually. The trendlines are linear regression, Earliest records (R^2: 0.093, p <0.001). Latest records (R^2: 0.154, p <0.001)

Commented [RJ5]: Be consistent with he use of capital letters (it is e.g. "earliest" in the previous figure)

The earliest autumn arrivals and latest autumn departures in garden warblers are shown in Figure 25. Unlike redstart and pied flycatcher, there appears to be more consistency through the study period in garden warbler. Early August and late July seems to experience the first pulses of movement making this species one of the earliest departing summer migrants. Late September also appears to be the usual departure time, with few records beyond late October and before September 21st. Both the change in arrival time and departure time does not appear to be as drastic as observed for pied flycatcher and redstart. Garden warblers are more widely distributed than the other two species and are present in Kent, therefore local birds may still be able to arrive at a consistent rate through the study period.


Garden Warbler. Sandwich Bay, S. Ray & SBBOT, (2012)

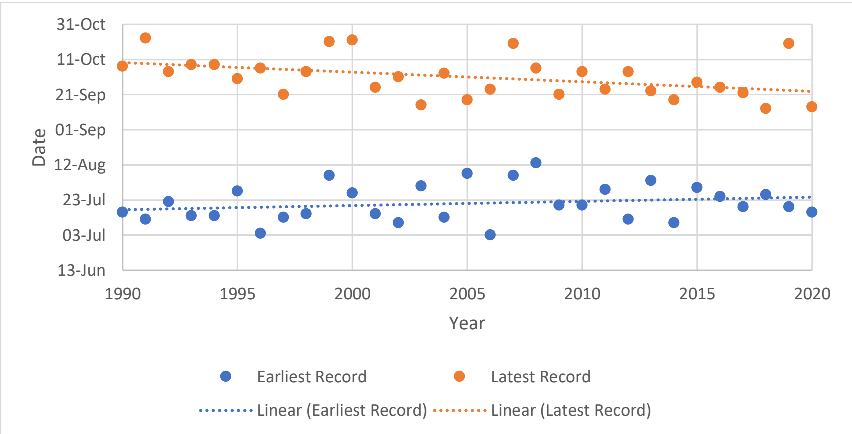


Figure 25: Scatterplot showing the earliest and latest autumn records of garden warbler (*Sylvia borin*). Earliest records (R^2: 0.043, p: <0.001). Latest records (R^2: 0.184, p <0.001).

The earliest autumn arrivals and latest autumn departures of willow warbler across the study period are shown in Figure 26. The dates for this species have remained consistent throughout the study periods; late July experiences the first movements with late September usually seeing the end of passage.

Willow Warbler,
Leckhampton Hill,
Gloucestershire,
2021 (Author's own)

Commented [RJ6]: I assume you have taken all the photos? If not, then you would need to quote a source

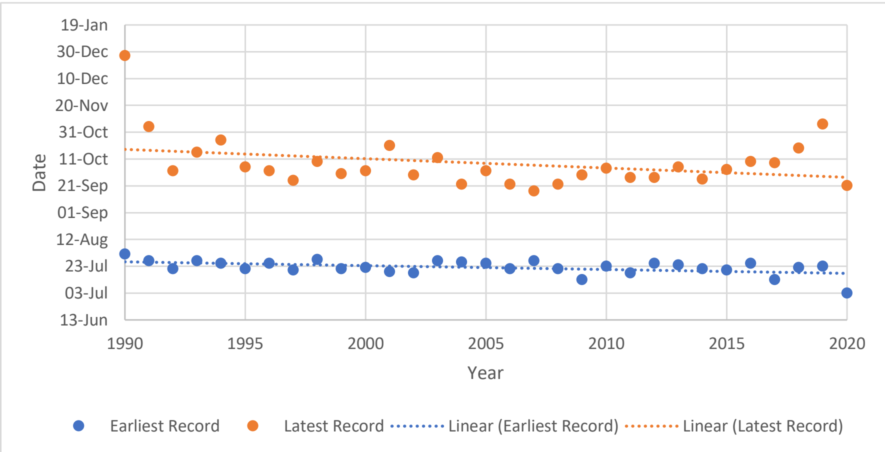


Figure 26: Scatterplot showing earliest and latest autumn records of Willow Warbler (*Phylloscopus trochilus*). Earliest records (R^2: 0.233, p <0.001). Latest records (R^2: 0.107, p <0.001).

Commented [RJ7]: Be consistent with the sue of capital letters (record vs. Record)

The earliest arrivals and latest departures of spotted flycatcher in autumn through Sandwich Bay, during each year of the study period are displayed in Figure 27. The arrival dates for this species have become more consistent over the decades, whilst the departure times have become less so. Mid-August is the most commonly occurring arrival time, with late September and early October being the usual departure. The earlier departure time and later arrivals may simply be linked to this species' marked national decline resulting in less numbers passing through. In later decades, a period of six weeks observes most of the spotted flycatcher passage, whilst in the 1990s this was as much as ten weeks.

Spotted Flycatcher, Kilnsea, East Yorkshire, 2021 (Author's own)

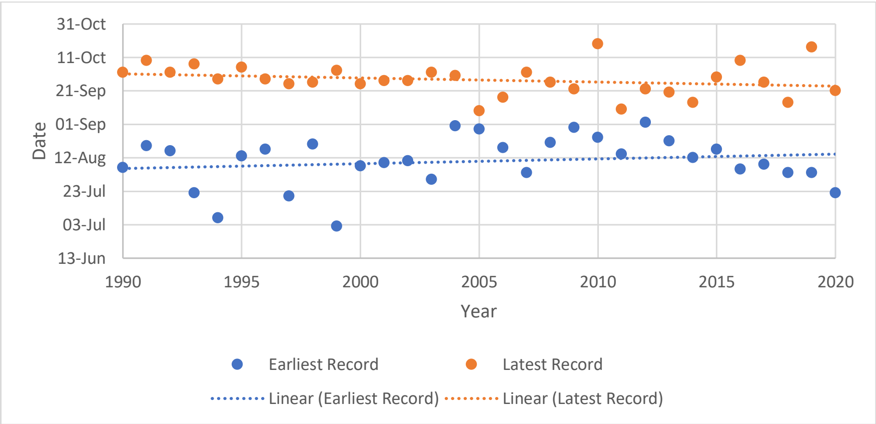


Figure 27: latest and earliest autumn records of spotted flycatcher (*Musciapa striata*) (Earliest records R^2: 0.030, $p <0.001$; Latest records R^2: 0.055, $p <0.001$).

Commented [RJ8]: = or <?

The earliest arrival and latest autumn records, annually, of whinchat through the Sandwich Bay recording area are shown in Figure 28. The late 2000s saw later arrivals than previous years, however post-2010 late July appears to be the usual date for arrivals. The departure dates are more consistent over the study period.

Whinchat, Spurn Point, East Yorkshire, 2021 (Author's own)

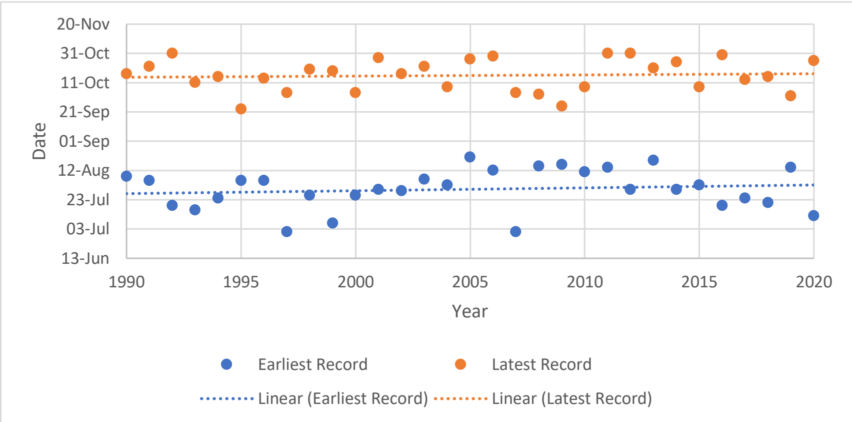


Figure 28: Scatterplot showing earliest and latest autumn Whinchat (*Saxicola rubecula*) records. Earliest records (R^2: 0.017, p:<0.001). Latest records (R^2: 0.004, p <0.001)

The annual records of first autumn arrivals and latest autumn departures in wheatear are displayed in Figure 29. Later departure dates were observed in the 1990s than in subsequent decades. The arrival dates remained consistent, with late July-early August being the peak time. Like whinchat, this is a bird of uplands, however it does appear that the departure time has crept forward by a week.

Wheatear, Spurn Point,
East Yorkshire, 2021
(Author's own)

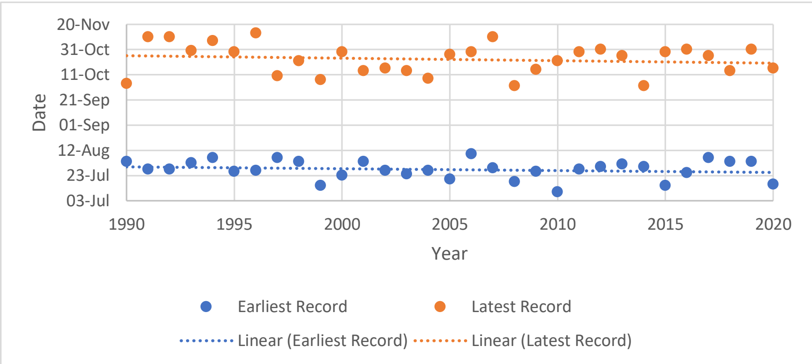


Figure 29: Scatterplot showing latest and earliest autumn wheatear (*Oenanthe oenanthe*) records. Earliest records (R^2: 0.032, p: <0.001). Latest records (R^2: 0.021, p <0.001).

The earliest and latest records of sand martins during the autumn migration period annually are displayed in Figure 30. The arrival dates appear to have gotten earlier post-2005, with the first individuals being recorded in late June. The departure dates appear to be more inconsistent with records fluctuating from early-mid October, yet they are also becoming earlier.

 (Sand Martin-Ray & SBBOT, 2015)

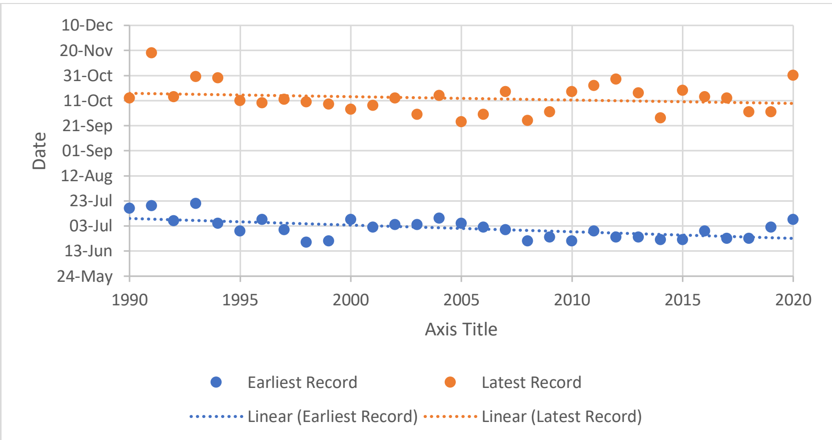


Figure 30: Scatterplot showing the earliest and latest autumn records of Sand Martin (*Riparia riparia*). Earliest records (R^2: 0.023, p: <0.001). Latest records (R^2: 0.040, p <0.001).

Commented [RJ9]: Again a picture is missing for this species?

Between the passage summer migrants at the study site there is variation between the arrival dates for these species. (F: 48.81, p <0.001).

Table 7: Summary table of the Tukey post-hoc test grouping eight passage summer migrants.

Factor	**N**	**Mean**	**Grouping**			
Redstart	31	44418.3	A			
Spotted Flycatcher	31	44418.2	A			
Pied Flycatcher	31	44418.0	A			
Whinchat	31	44407.2		B		
Wheatear	31	44404.7		B	C	
Willow Warbler	31	44399.3		B	C	
Garden Warbler	31	44398.1			C	
Sand Martin	31	44378.1				D

The departures dates were also tested between the species to observe the differences in migration. There was a statistical significance between the species and their autumn departure dates (P: <0.001, F: 14.24).

Commented [RJ10]: P cannot be zero, also “f” needs tp be “F”

Table 8: Tukey post-hoc test examining the autumn departure times in eight passage passerine species.

Grouping Information Using the Tukey Method and 95% Confidence

Factor	**N**	**Mean**	**Grouping**				
Wheatear	31	44491.3	A				
Whinchat	31	44483.7	A	B			
Sand Martin	31	44481.1	A	B			
Redstart	31	44479.8		B	C		
Willow Warbler	31	44476.6		B	C	D	
Garden Warbler	31	44469.6			C	D	E
Spotted Flycatcher	31	44466.4				D	E
Pied Flycatcher	31	44465.8					E

5. Discussion

5.1 Effects of weather patterns on bird migration

The present study, for the first time, was able to link the long-term data available from Sandwich Bay Bird Observatory with weather patterns, revealing new findings around the phenology of birds and moths, while also supporting previous findings documented in the literature. Long-distance summer migrants such as pied flycatcher, garden warbler and redstart were found to be advancing their migration times, a trend previously noted by Jenni & Kéry (2003) in Switzerland. This could reflect the mounting pressure to compensate for the advancing and harsher dry seasons brought by global warming. The influence of wind also complemented previous findings in that wind direction affects falls. The importance of easterly winds in large falls of autumn migrants to Britain was first presented by Lack (1965), who described the effects of prolonged spells of north-easterly winds on migrant numbers. This was complemented here in this study through the patterns identified to be the most productive for numbers in both common migrants and vagrant birds in autumn. The patterns involving easterly winds were tightly linked to such occurrences, with the new Met Office designations allowing for more refined predictions of when suitable conditions for large bird numbers may occur. In contrast, the results for spring migrations identified the presence of southerly-winds for vagrancy during the season, highlighting the importance of tailwinds as noted by Manola et al., (2020) and Lack (1965).

Based on the results of the present study, there has been a considerable increase in moth migration and vagrancy in birds The annual numbers of rare and/or vagrant bird species have increased throughout the study period (Figure 8). This increase has not been linear, with the early 1990s (1990-1995) recording an impressive number of rare species before a drop between 1996 and 2006, where the average annual totals saw less than ten rarities per annum. Post-2006, the totals again, appear to increase to 22 rare species recorded in 2020.

The importance of weather patterns on bird migration is particularly well-demonstrated for vagrant species (Figures 12a and 12b). In autumn, the predominant patterns for vagrancy include patterns *2*, *5*, *6*, *10* and *1* (Figure 12b). Of these, five (*2*, *5*, *6* and *10*) are responsible for bringing easterly winds, from the continent across the North Sea. These winds are exceptionally important as many Scandinavian passerines will travel across the North Sea in favourable conditions; easterly tailwinds can cause the phenomenon known as drift migration (Lees, 2022). In this instance, migrating birds are blown off-course by winds and arrive in unintended areas. In autumn, this is a more common occurrence as a high percentage of all birds are inexperienced juveniles that are making the journey for the first time (Thorup et al., 2003). In such conditions at Sandwich Bay, eastern European drift migrants such as icterine warbler, red-backed shrike, wryneck and barred warbler were associated with these weather systems that brought easterly winds. Anticyclonic conditions further play a large part in the occurrence of vagrants in the British Isles (Elkins & Johnson, 2005). If easterly airflows across the continent are present, birds of Siberian/Eastern Palearctic origin are displaced with species such as yellow-browed warbler, Pallas's warbler and red-flanked bluetail, some of the more expected migrants. These findings support Manola et al. (2020) who show that autumn migration was particularly prevalent when the conditions provided tailwinds across the North Sea (easterlies/north-easterlies).

In spring vagrancy, the favoured patterns (*9*, *1*, *5*, *7* and *3*) differed to those in autumn (Figure 12a). For example, patterns *3*, *5* and *7* are associated with bringing southerly winds to the UK. This is interesting as many of the rarities experienced in the spring migration season are overshoots from southern latitudes, particularly the Mediterranean. In particular, species such as hoopoe, bee-eater, red-footed falcon and great spotted cuckoo appear to be rare vagrants recorded throughout the study period. Notably, pattern *5* may also bring south-easterly winds, which appears to be a major factor in the arrival of continental birds in the spring months (Elkins & Johnson, 2005). Red-footed falcons were particularly plentiful in 2020, with at least five different individuals recorded at Sandwich Bay in May and June, after a prolonged spell of easterlies from the continent. These birds are breeders in Central and Eastern Europe, as opposed to the Mediterranean (Hanžel, 2015).

The reasoning behind the large increase in vagrants is unclear but several species, formally considered very rare, appear to be becoming more regular to the United Kingdom (UK) and western Europe, in autumn. One of the key species reflecting this is yellow-browed warblers. Despite being a breeder in Siberia and wintering south-east Asia, this leaf-warbler is appearing with greater numbers to the Western Paleartic (Thorup, 1998). In the UK, most of the birds ringed appear to be juveniles, suggesting there has been disorientation responsible for driving the movements, although it is unclear where these migrants travel to or if they survive the winter (Wernham, 2002). At Sandwich Bay, this rise has been notable, with records increasing throughout the study-period. For example, 2007 was a record autumn for the Bay, with 10 individuals recorded. In 2018, the peak count was as much as 53 records of yellow-browed warbler, showing a startlingly dramatic increase. The rarer, but closely related Pallas's warbler has been following a similar trend, with increasing records since the 1960s (Bell & Howey, 1985), with both species associating and linking with large falls of goldcrests. Indeed, one of the reasons for such vagrancy, at least in autumn, could be attributed to the phenomenon of "reverse migration" (Lees, 2022). As a hypothesis, it may be most juvenile birds mistake the orientation of their migration route and head in the opposite direction. For species such as red-breasted flycatcher, this is a likely occurrence, as their autumn direction is usually south-easterly; when reversed this would see individuals migrate into north-west Europe. In comparison, the related collared flycatcher has a more southerly-orientated autumn migration. Therefore, according to the reverse migration theory, this would see vagrancy of this species occur in eastern Europe (Lees, 2022). This appears to be true, as red-breasted flycatcher is an annual autumn vagrant to the British Isles, whilst collared flycatchers are extremely rare; there are however few records of the former species in the study area. For yellow-browed warblers this could also be a reason for their occurrence in north-western Europe, however other theories suggest a new migration route is beginning to be used, where individuals are now perhaps wintering in Africa (Thorup, 1998). This is further endorsed by the build in numbers of yellow-browed warblers in Iberia after earlier peak movements have been recorded in the British Isles, suggesting there is a filtering of birds heading in a similar direction (Lees, 2022).

The red-flanked bluetail is another species whose westward expansion may bring increased migration and occurrence at the study area. Over the past four decades, this species has seen a continued expansion out of the Siberian taiga into north-western Europe, causing an increase in vagrancy (Ferlini & Malling Olsen, 2021). However, during the study-period there was only one record of this species in 2015, with an individual occurring for seven days in the recording area. With the population and overall national occurrences of this species increasing, a similar trajectory to yellow-browed warblers could occur and possibly bring an increased frequency of this rare species to the recording area. Other species with similar trends include common rosefinch (*Carpodacus erythrinus*) and citrine wagtail (*Motacilla citreola*), which similarly are scarcities to the recording area that may see increased records due to range expansion.

Another hypothesis to the increase in vagrancy may also be linked to increased knowledge of rare species, due to increased networking in birding communities via social media and the availability of resources for identification of even the infrequent species. The use of mobile applications with not just the identification features of vagrants but also the calls, provide readily accessible guides on the identification of rarer species. Particularly, those that look superficially similar to the inexperienced eye, for example, red-breasted flycatcher (*Ficedula parva*) and taiga flycatcher (*Ficedula albicilla*) and the rarer *Phylloscopus* warbler species (e.g., greenish (*P. trochiloides*), Arctic (*P.borealis*), two-barred (*P. plumbeitarsus*) , green (*P. nitidus*) and Hume's (*P. humei*). As bird-watching is a growing hobby in the UK (Beament, 2021), further information and awareness can lead to birds being observed more regularly than in previous decades.

The weather patterns favoured by common migrants differ significantly between seasons. In the autumn, the patterns favoured (*2*, *5*, *10*, *3* and *1*) were similar to those preferred by vagrants, with only pattern *3* differing between the two groups by being absent from the top five for vagrants (Figure 11c). This is most likely due to the origin of the majority of birds passing through, coming from Scandinavia. Therefore, the presence of easterly winds across the North

Sea or slack winds in general may spur departure from the continent before drift migration pushes them into the study area. Certainly, side-winds appear to be important for bringing passerine species to Sandwich Bay. Pattern *1* being favoured is interesting, as the conditions brought are predominantly northerly winds. These winds may act as a crosswind to birds crossing the North Sea, pushing them towards the UK as they attempt to migrate south from Scandinavia (higher latitude) as argued by Manola et al., (2020). For birds leaving their breeding grounds, the use of these tailwinds would allow faster movement, concurring with previous studies such as those which confirmed that birds make use of tailwinds to migrate (Åkesson, 2015). For spring, several patterns were unique to the season, with *13*, *15* and *23* only linked with migration at this time of year (Figure 12a). Each of these patterns are linked with strong westerly/northerly winds to the UK; this suggests that perhaps large falls of spring migrants at Sandwich Bay may be the result of displacement by strong winds. Spring migration is indeed much quieter at the study area, with only small numbers of chiffchaff, wheatear and willow warbler an annual occurrence. Meanwhile, species such as redstart, pied flycatcher and garden warbler are not classified as annual spring migrants. Records of the latter three species may be linked with poor weather conditions, either grounding birds or forcing them to fly in a more easterly direction as a result from strong westerly winds. Spring records are most likely more dependent on the occurrence of poor weather for migration; this is due to birds being less likely to use stopovers, such is their rush to return to their breeding grounds (Newton, 2008). One such case occurred on the 1st May 2018, where overnight, westerly winds across the English Channel and a belt of rain over the North Sea caused a small fall of five pied flycatchers and three redstarts. The origins of these birds and other spring records could possibly be Scandinavian, with these individuals forced to ground as they cannot travel across the North Sea.

5.2 Timing of migrants

When looking at the timings of common autumn passage migrants through the recording area, there have been several interesting results (Figures 23-30). Relationships in the arrival and departure times between eight species were examined to determine if there had been significant changes over the study period. There was distinct grouping in the arrival dates, such as for redstart, spotted flycatcher and pied flycatcher that were considered to be related and grouped together (Table 7). Whinchat was only designated under group "B" with wheatear and willow warbler, which were also designated under group "C" with garden warbler. This implies that the arrival times differ between the species, with certain weeks of the autumn likely to bring only one set of birds. A similar result was found for departure dates (Table 8). Although there was more overlap between the groups, none of the species were in their own unique group, however, there still appears to be distinct differences in departures. In the eight species tested, all species showed increasingly earlier departure times throughout the study-period, although to what degree this was apparent varied between species. In pied flycatchers, the 1990s saw departure times around the 26th of September- 11th October; in the 2010s only 2010 and 2012 have October records, with the rest of the decade seeing the last records around the 21st of September, although three years had their last record before the 15th of September (Figure 24). Over the study-period, there appears to be a defined advance of their autumn departures by almost a fortnight. The autumn of 2011 was a notably poor year for pied flycatcher, with only three records, and such years may affect the trendlines. Pied flycatchers' occurrence in the study area is relatively early, with the first birds usually arriving in early August, often in conjunction with other early species such as willow warbler and garden warbler. As this species favours mature oak woodland to breed (Nicolau et al., 2021), the suitable habitat is absent from Kent, resulting in this species being only a passage migrant in the region. In the UK, there is a strong bias to the west and north, particularly in Wales, of the breeding population. As a result, spring occurrences are far more sporadic at Sandwich Bay. It seems unlikely that the birds encountered in autumn, which are nearly all juveniles, are indeed of British origin and in fact reflects the large-scale arrivals further north on the east coast, with areas like Spurn point experiencing triple-figures falls on occasion (Roadhouse and Spurn Bird Observatory, 2016). Overall, this species has been researched and proven to be sensitive to climate change, shifting its arrival dates to match the earlier caterpillar blooms (Marra et al, 2015). Therefore, it could be possible that the earlier triggers that cause this species to migrate from climate change, drive an earlier return migration to Africa. Though this is interesting, the recent population trends of these species need to be considered, as there are heavy declines across Europe of this species (Both et al., 2006), and the apparent bottlenecking may be resultant of simply fewer numbers passing through, compared to previous decades.

In redstarts, a similar trend was found in the departure times (Figure 23). At the start of the study period, the 22nd of October was the average date of the latest records, but this increased markedly to the 1st of October by 2020. This species is more localised in Britain to the west, though not as dependent on mature forest as pied flycatcher, though like the flycatcher, the phenology of most autumn birds to the UK is Scandinavian. This species is a little later as migrant in autumn, with passage peaking in the last week of August/first week of September

(Hope Jones, 1975). Unlike the pied flycatcher, however, this species is more stable with populations not showing any long-term trends (Gillings et al., 2007). Despite this, the changes in timings are interesting as it appears they are moving earlier as a result of an external factor such as the deterioration of weather conditions, an influence found to affect the migration of bird species. The trends of spotted flycatchers appear to be less drastic, with the 2nd of October being the 1990s average departure date dropping to the 24th of September by 2020. The reasoning for this may be due to the species still being present breeders in south-eastern England (although only present at Sandwich Bay as a passage migrant), despite heavy population declines (Figure 27). Therefore, local birds are still passing through at a similar rate to previous years instead of arriving from further afield. It is possible that many of the insectivorous long-distance migrants like spotted flycatcher are struggling with reduced numbers of prey, resulting in young juveniles and adults being in poorer condition in preparation for their movements leading to higher mortality *en route* to the wintering grounds. Overall, this species is declining across the country, with possible links to loss of insect abundance rather than loss of habitat (Freeman & Crick, 2003), and it could be expected that the arrival and departure dates will continue to merge, if populations continue to shrink.

Garden warblers have also shown a distinct reduction in departure dates (Figure 25). These warblers are some of the earliest departing migrants in the autumn, with the first birds arriving at coastal sites typically in late July (Wernham, 2008). Compared to their close relatives, blackcaps, the development of the juveniles is more rapid, allowing for a quicker departure to wintering grounds. In the study-period at Sandwich, garden warblers were never very numerous, with peak daily counts never exceeding a maximum of twenty (2017 annual report), with 7-9 the peak counts in most years. In the 1990s, the average departure date dropped from the 11th of October to the 21st of September, showing an advance of nearly three weeks in migration. Again, it is possible that the species is beginning to migrate earlier in accordance with seasonal changes advancing. If this is true, then we may expect so see garden warbler passage becoming more frequent in even July. Interestingly, this species has a relatively long period of migration; it might be that the birds at Sandwich Bay in late July are progeny of local populations, whilst the later birds in September could be further afield or of Scandinavian origin. Garden warblers are particular exponents of stopovers, able to put on high amounts of fat relatively quickly, thus making their migration a more gradual affair as they need to spend time gaining weight (Wernham 2008). If birds arriving later in Sandwich Bay are of

Scandinavian origin, than they would need to refuel and build-up the fat reserves depleted after crossing the North Sea, resulting in individuals lingering for a few days.

Willow warblers are the most common migrants in the recording area during the early autumn period, despite being sparse in spring, with the first pulses generally occurring in the last week of July. Over thirty years, some of the largest daily counts have passed the 100-mark, with 174 recorded in 2017, the record for the study period. Interestingly, whilst there has been an earlier average departure time from the 22nd of October-27th September in 2020 (Figure 26), the general arrival dates have been very stable, with only a slight increase in dates. These findings are somewhat surprising, as the study by Marchant and Wernham (2003) found that in general, the autumn passage was shifting later at nearby Dungeness. It was expected a similar case would be found at Sandwich as Marchant and Wernham (2003) discovered that the phenology of July-arriving willow warblers consisted of local birds. Willow warblers are generally in heavy decline in southern England, with northern populations faring better (Morrison et al., 2016). In this case, it was expected with declining numbers of local breeders, there would be a shift towards mid-August when continental birds make up the bulk of passage.

The two passage chat species, whinchat and wheatear, appear to have more gradual changes (figures 28 and 29). Both species are later migrants in autumn, with wheatear records remaining until mid-November and the whinchat passage continuing to the end of October. The latest departure times for wheatears has the most notable change between the two; 1991-1996 records were the earliest 31st October with records lasting until early November. It is worth noting however that in 1990, the latest record was a rather early 5th October. In the 2000s and 2010s, it was only 2007 that recorded a November wheatear record. Interestingly, 2001-2004 recorded earlier departure dates of wheatears with the records getting later on average. The arrival time also appears to be getting earlier, although this is more marginal. Whinchats appear to be getting later in both their departure and arrival times, the only species of those studied to follow this trend. Again, this is quite marginal however with a bias for the 2nd half of October.

As a hirundine, sand martins are considerably stronger fliers than the other species discussed, and this species differs in its preference as a diurnal migrant. They are sensitive in the timing of their migrations, with Sparks & Tryjanowski (2007) discovering that despite being historically earlier on spring arrival than barn swallow (another hirundine species), the two species appear to have switched around. At Sandwich Bay, sand martins are a passage migrant despite efforts to entice them to breed in the study area. Fortunately, they are still a local breeding bird in Kent. Over the study period, the species has shown a preference for the first autumn arrivals in late July. Between 2006 and 2011, however, there was a period of arrivals in mid-August, with only 2007 having a July record. After this period, the remaining eight years again recorded the first birds arriving in July. The departure dates appear to be less consistent, with no real noticeable pattern across the study period, and only a slight delay in departures noticeable in Figure 30.

It is interesting to note that of the species analysed for timings, the long-distance sub-Saharan migrants appear to be the most prone to changes in their movements. Redstart, pied flycatcher, spotted flycatcher, garden warbler and willow warbler all appear to be departing earlier at the end of this decade, than 30-years prior. The arrival dates are more mixed, however, with pied flycatcher, garden warbler and spotted flycatcher on average arriving later. This differs to willow warbler and redstart who appear to arrive earlier through the decades. The case for this is uncertain but in garden warbler, the food source may be a reason for the delay in movement. In autumn, garden warblers switch their diet to include fruits such as elderberries, which facilitate the gaining of weight and fat reserves (Bairlein, 1987). These reserves are particularly vital for the long-distance migrants to provide the fuel for their bodies, but garden warblers particularly employ this strategy with a weight gain of up to 80% (Bairlein, 1987). If climate change is prolonging our summer conditions, then the ripening of the necessary fruits is delayed; consequently, this could be changing the behaviour of this species in response to the food source being impeded. This could be a similar case for the two flycatcher species, with both also observed to supplement their diet with seeds and berries during autumn migration (Hernández, 2009). Additionally, the other species will adopt frugivory in autumn if necessary and appear to be arriving earlier. The advancing departure dates may be attributed to an advancing dry season in their African wintering grounds, as these long-distance migrants need to cross the Sahara before the dry-season reduces the amount of food available during stop-over. As many of these species overwinter in the tropics of Africa, the Sahara, and dry conditions north of the equator provide a huge barrier to species crossing (Åkesson et al., 2016).

Population trends may also be responsible for changes in timings. Many of our migrant species are declining, with our sub-Saharan migrants faring worst (Morrison et al., 2016). Potentially, this implies that with reduced numbers of individuals in the migration flyways, we are seeing less pass through and the window of passage in many species becomes smaller. In Figures (24, 25 and 27) a bottlenecking pattern with pied flycatchers, spotted flycatchers and garden warbler is observed; this tightening of their migration seasons is concerning and certainly could reflect the national declines of both flycatcher species and the moderate decline in garden warbler. This may be less evident in the other species as they are more numerous; the willow warbler in particular, has such large numbers that a decline may be less noticeable, despite there being evidence of a substantial rapid decline in southern England (Peach et al., 1995). Redstarts too are more common in the study area than the two flycatcher species and garden warblers, with a national population fluctuating with no notable trends (Woodward et al., 2020) and a slightly increasing European population. As a result, the two species who are not as sparse, may not be as sensitive to changing climates.

Both wheatears and sand martins are arriving and departing earlier. In the case of wheatears, the earlier departure, though relatively marginal, might be simply that, the stopover conditions are not suitable, resulting in quicker passage to other areas (Maggini & Bairlein, 2010). The population of wheatears in Britain is relatively stable, with only small declines in lowland Britain (Gillings et al., 2007). With this stability, similar numbers have been passing through the study area regularly each year, possibly explaining why the timings have not changed significantly. In sand martins, the national population is fluctuating but with no long-term trends (Woodward et al., 2020), possibly explaining why their arrivals and departures are only becoming marginally earlier. An issue with the arrival times is that it is unclear whether birds recorded at the end of June in recent years, are late arrivals or failed breeders heading back south. As they are one of the earliest spring migrants, however, (mid-March) it seems more likely that failed breeders are passing through during the end of June. Another possible explanation to why sand martins are arriving slightly earlier could be due to localised breeding populations being established, allowing local birds to arrive in the recording area at a slightly earlier time of year, instead of birds from further afield. Sand martins, particularly juveniles, are gradual in their southbound migration, with birds often using stopover roosts for several days before moving several hundreds of kilometres (Wernham, 2008). This may also help explain why juvenile dispersal is not seeing more of a marked change in arrival times.

Interestingly, whinchats are declining birds across Britain, yet they are arriving and departing later (Figure 28). It is possible that, as the breeding population in the UK has declined, birds of British origin are not so frequent passage migrants and instead Scandinavian whinchats are responsible for the bulk of records, with many making landfall on the east coast in autumn (Wernham, 2008). In return this may cause a slight delay in arrivals and departures. An alternative is due to lack of food abundance or suitable stop-off sites, which is a common strategy also used in wheatear. Overall, the trends shown in this species appear to be very marginal and stable, despite the population declines. As these are birds from upland areas of the UK, there have not been any local declines, unlike that of spotted flycatcher and willow warbler, therefore this could explain why this migratory species is more consistent.

5.3 Weather patterns and effects on moth migration

The findings with moths also reflected those by Sparks et al., (2005) who identified the preference for southerly-oriented winds in migratory *Lepidoptera*. Again, using the new system by the Met Office can facilitate those wishing to trap and study moths to prepare and set-up their research. Further complementing Sparks et al., (2005), it appears the prediction concerning the increase of migrant moths to the UK has been realised. Similarly, as observed with birds, the use of conditions that provide tailwinds are favoured for migration to occur, in agreement with findings by Alerstam (2011).

When comparing the occurrences between vagrant birds and moths, a positive correlation was found with both increasing groups (Figure 10) and the increasing occurrence of both to the study area might be due to external factors. In Figure 9, it can be seen that throughout the 1990s, the number of migrant moth species recorded at Sandwich Bay annually remained under 10, aside from 1997 where 13 migrants were recorded. The years 1990-1994, in particular, seemed to catch only a low number of migratory species, a theme that was echoed in the early 2000s (2000-2004), before a sharp increase post-2005 in the species was recorded. The 2010s has seen a significant surge in moth numbers (Figure 9). This increase is so dramatic that upwards of 25 migratory species have been recorded in 2019 and 2020. The weather patterns most commonly occurring for moth migration to Sandwich Bay all appear to be responsible for gentle winds brought to the UK (Fig 13a). Of the top five patterns identified, four of these brought winds of a southerly-direction. This is a not an immediate surprise to the findings, as the origins of nearly all 160 migrant moth species to the UK are either continental or from North Africa, save a few American species such as Stephen's gem (*Megalographa biloba*) (Waring and Townsend, 2017). The only pattern that did not bring direct southerlies was pattern *10*, which is responsible for westerlies. However, with this pattern, there is high pressure over the mid-Atlantic which brings in warm air from Africa and the Azores, possibly resulting in migratory moths being hitched on these winds. Interestingly, when these patterns are contrasted with high counts of resident moths, they share the same patterns albeit in a different order (Figure 13b). The reasoning for this might be the gentle conditions at play, suggesting that patterns which bring stronger or cooler winds (such as northerlies) may be less favourable for moths to be flying in significant numbers. It is worth noting that in terms of the total frequencies of all thirty weather patterns (Figure 14), patterns *1*, *2* and *5* are in the top five. The other patterns are less frequent, although still in the top 50% of the 30 patterns in abundance. Therefore, with the study area's proximity to the continent, the occurrence of southerly-oriented winds to the region appears to be a key factor in the mass arrivals of many migrant moth species. Unusually however, many of our even migrant common species see a sharp increase in the 21st century. One prime example in this study is the convolvulus hawk-moth (*Agrius convolvuli*). This large visitor to our shores is a stalwart to trapping on the south-coast in modern times but appears to have been far scarcer in the earlier years at Sandwich Bay. In the 1990s, just three records of convolvulus hawk-moth were noted down, whilst the early 2000s appears to be almost as sporadic, despite the national counts of 2671 individuals in 2003 and 2335 in 2006, being the two highest counts ever recorded (Atropos, 2021). In stark contrast, the species appears to be a regular fixture of late summer moth-traps at Sandwich Bay in the 2010s, with some years, such as 2019 recording 12 over the season (2019 annual report). It appears this species could be potentially seeing an expansion northward in its range, putting the south-coast of England in closer proximity to breeding populations. Rarer migrants also have appeared to be increasing, with species such as death's-head hawk-moth having a handful of four records in the 21st century, compared to none recorded in the 1990s. Two of these were caught by trapping and two individuals found dead in the recording area. Yet another rare migrant that also appears to be increasing is the clifden nonpareil (*Catocala fraxini*), becoming an annual species since 2018 after sporadic records through the previous study period. This, however, marks a nationwide colonisation with the species now almost certainly breeding in some areas of the country.

Aside from this, the 2010s also experienced a wealth of new migrants recorded in the area, some of which are exceptionally rare for the UK. Just some examples include the black v moth (*Arctornis l-nigrum)* (5th for UK), the shining marbled *(Pseudeustrotia candidula)* and the dark crimson underwing (*Catocala sponsa*). Another key example is the beautiful marbled (*Eublemma purpurina*), which since its first record in 2015 has now been recorded a further five times at Sandwich Bay, showing a marked increase and possible northward spread with new annual records being broken every year since 2018. Further noted are several species have now also been further categorised into the adventist (recent colonist) category, having colonised the south-east successfully, including white-point, tree-lichen beauty and jersey tiger (*Euplagia quadripunctaria).* All of these species are now recorded annually at the Bay despite being rare migrants in earlier times. This follows recent research showing that since 1900, 137 moth species have colonised Britain, 53 of these first becoming established in the 21st century (Waring and Townsend, 2017). Whilst some of these species are linked to imports and accidental introductions, such as the light brown apple moth (*Epiphyas postvittana*), colonisations have been able to occur naturally, with the three formerly mentioned species becoming established in this way. One possible explanation for this apparent increase in migrant moth species might also be linked to the development of knowledge. For example, one of the most highly-acclaimed books into British moth species is that by Waring et al., (2003) being updated several times over the years. This book provided detailed illustrations of migrants in their resting pose, as well as the status of all species recorded in the UK. Therefore, identification of migratory species was much more available than in previous years.

It might be argued that the increasing popularity and the increased resources for moth-trapping might be responsible for the rising number of these migrants being recorded. However, many of these species mentioned are extremely distinctive and in actuality the technology around moth-trapping has changed very little since the 1990s. The same mercury vapour bulbs today would have been present in the 1990s, which is still relatively recent, given that trapping has been consistent at Sandwich Bay since at least the 1950s. Therefore, it seems that the reason for this influx of new migratory species and increases in both common and rare migrants are not due to changes in trapping or technology over the 30-year study period, but instead linked to the changes in climate experienced. The south-east itself is the driest region of the UK, matching temperatures closest to continental Britain (Met Office, 2014). This makes it an ideal colonisation area for not just new moth species but other insect families as well, such as *Odonata*, with several species at their northernmost range.

5.4 Changes in weather pattern frequency

Overall, the frequency of the patterns identified as benefitting migration appear to have very little change (Table 6). Only three patterns showed any discernible trends in the Mann-Kendall tests. Patterns *3* and *4* were identified as having downward trends, whilst pattern *7* had a noticeable upward trend. Despite the importance of weather conditions on migration, there do not appear to be obvious changes over the study period. This also does not appear to link with the rise in annual average global temperatures since 1990 (Figure 4) which possibly could have resulted in changes in weather patterns. Sparks (2005) suggests that the desiccation of southern European food sources for *Lepidoptera* could be a better indicator of the increasing records of migrant *Lepidoptera* species to UK shores, with temperature being a more deciding factor in their movements instead of changes in wind patterns. Whilst there appears to be little in the way of changes in total frequency, further analysis focused on shifts in the timings over 4-week averages in each weather pattern.

In pattern *1*, the analysis showed that the peak of the pattern in the 1990s was more gradual and earlier than in subsequent decades. In the 2010s, however, the peak frequency was higher in number and sharper in the decline, with the instances of pattern 1 declining rapidly. This peak was also later, around week 32. In the 2000s, there was an initial peak at week 30 and then a second, larger peak at week 36, something that was not observed in the other decades. Overall, however it appears this pattern is becoming more prevalent later in the autumn, with increased records (Figure 15). This makes it an important pattern during the early autumn migration period in mid-august, when species such as willow warbler, pied flycatcher and garden warbler are the commonest passage migrants (Wernham, 2002). The trends for pattern *2* are also particularly noteworthy (Figure 16). In all three decades, it appears there are two main peaks, the second being higher. In the 1990s this is most evident with the first spike at week 25 and the second at week 35. In the following decades, these peaks were lower in frequency and a week later. The second peaks are far lower than in the 1990s, with the frequency in the 2000s calculated to 9 and the 2010s only at 7 at their highest. This shows evidence of this pattern's decline through the study period, despite initially being a prevalent pattern during autumn migration bringing southerly/ easterly winds.

Pattern *3* is also similar, with the 1990s total frequency and peak being highest, the subsequent decades would see a decline in frequency, so much so that the 2010s trendline has barely noticeable peaks (Figure 17). These peaks, once again, appear to be occurring later with the first occurring at week 19 in the 1990s; in the next two decades this first peak would occur at week 21. The second peak is even more noticeable, with week 32 seeing the largest peak during the 1990s and week 34 observing smaller peaks in the 2000s and 2010s. Week 32 is also during the mid-August when the earlier autumn migrants are passing through, week 34 entails the last week of August when species such as redstart and spotted flycatchers enter their peak numbers. This pattern is responsible for bringing southerly winds to the UK.

The trends for pattern *4* showed distinct changes (Figure 18). Like the other patterns mentioned so far, the trendline for the 2010s was again lower on average with the 1990s. Every decade showed three different peaks during the autumn and were fairly consistent with the first peak occurring at week 28 and the second at week 33. The final peak saw the greatest changes during the study-period, with the 1990s observing a spike in number at week 39, but in the two subsequent decades this occurred more around week 43. The trends in pattern *5* were more consistent with the peaks delayed by a week across the study period; the frequency however was lower in the 2010s (Figure 19).

Pattern *10* showed a higher trendline in the 2010s compared to previous decades; the 2000s had the lowest with no noticeably apparent peaks in frequency (Figure 20). When comparing the peaks in the 1990s and 2010s there is a 4-week difference, with the 2010s occurring later at week 38 (the last week of September, the frequency is also higher within the 2010s).

Pattern *15* also has an interesting trend with a noticeable early spring peak at week 12 in the 1990s; in the subsequent decades this peak appears to be occurring at week 16 showing a delayed timing in such an occurrence as well as a reduction in frequency (Figure 21). In the latter half of the year pattern *15* appears to be becoming more numerous through the decades, with the 1990s seeing a lower rise in late autumn. In the 2010s the late autumn peak, also appears to be later than in the 2000s by two weeks. However, as this is at the end of October-early November, the effect on migration may be less obvious, as movement of birds is beginning to wane by that stage in the season (Wernham, 2002).

Pattern *23* shows an increase through the decades in occurrence. The notable early spring peak in March is not present in the 2000s but is observed in the 2010s, marginally earlier than the 1990s though at a lower frequency overall (Figure 22). In the autumn, the most notable trend shows an increase in frequency, with the 2010s trendline higher in autumn than the previous decades. Overall, it appears that pattern *23* is becoming less of a prevalent pattern in spring, but becomes more frequent in autumn and winter, although in spring it is slightly earlier in the 2010s than the start of the study period.

It is difficult to gauge just how significant of an effect further weather pattern change may have to migration and how they contribute to the changes brought by climate change in general. For example, although autumn passage migrants have shown clear changes in arrival and departure, is this a result of favoured weather patterns shifting or more linked to changes in population through the study-period, or simply an amalgamation of both? For autumn vagrancy, some of the key patterns appear to either shifting later or becoming prevalent (patterns *3* and *10*). If easterly winds were becoming more numerous during the autumn due to pattern 10 becoming more frequent, than it may be expected that eastern vagrant species should increase in occurrence (Gilroy & Lees, 2003). Spring vagrancy may be expected to occur less however as several patterns associated with this phenomenon appear to decrease, such as patterns *3* and *9*, or become more prevalent later in the year e.g., pattern *5*. Moth migration may be difficult to predict as it is more of a random occurrence, as many species are recorded across several months of the year as migrants. Therefore, there is not a set season for moth migration, aside from being more common in the summer months, when insect life, in general, is more abundant. It is very plausible that the increase in moths is spurred simply by the increasing temperatures, rather than changes in weather pattern frequency or occurrence, as suggested by Sparks et al, (2005). Until we know the true factor in driving for moth migration and whether they truly wait for certain patterns it will be difficult to provide assumptions on their vulnerability to changing patterns.

5.5 Future opportunities

There are several suggestions that could potentially provide future opportunities following on from this thesis. Firstly, looking at older data may provide more evidence of changes to our climate and migratory species. Thirty years is a relatively brief window into investigating changes in weather patterns and climates and, though trends were certainly identified in some patterns, perhaps these would become more apparent with climate data from further years. Though this study did not see major changes in the annual frequencies of weather patterns, this could be due to the study-period not being substantial enough in length to identify changes. The addition of several decades of meteorological data could identify much more apparent changes in frequency.

The limitations of the dataset regarding moths and birds influenced the findings of this study, with digitised data not available pre-1990. The population changes in bird numbers are far longer term than just the 1990s, therefore the incorporation of data collected from even earlier would greatly benefit the results of the study. Indeed, a clearer indication of the changes in the timings of bird migration may be possible or perhaps alter the conclusions. Additionally, the use of data from future decades may also provide further insights into what has been discovered in this study, particularly for moths, whose recording is continuing to increase. For example, in 2022, moth migration was exceedingly heavy at Sandwich Bay with several new migrant species recorded for the area such as Dorset cream wave (*Stegania trimaculata*), crimson speckled (*Utetheisa pulchella*) and flame brocade (*Trigonophora flammea*). In addition to these, records of other rare migrant species such as striped hawk-moth (*Hyles livornica*), orache (*Trachea atriplicis*), death's-head hawk-moth and great brocade (*Eurois occulta*) and high numbers of common migrant species, e.g. rush veneer (*Nomophila noctuella*) and hummingbird hawk-moth all occurred. Therefore, investigating the patterns to determine why it was such a good year for moth migration could prove to hold extremely invaluable data.

One way to advance this study would be to incorporate data from other sites. With 20 bird observatories around the UK, there is a wealth of data that possibly could be collected, and whose findings may complement or disagree with those of Sandwich Bay. Most interestingly, UK bird observatories with a different geographical location could differ in which patterns bring large falls of each species group. For example, at the Portland Bird Observatory in the south-west in Dorset, in spring, migration is far more prominent than that of Sandwich Bay whilst the frequency of migrant moths is also high (Sparks et al., 2005). Another possibly interesting location would be Spurn Bird Observatory, whose position on the East Yorkshire coast and general geography of the region brings exceedingly heavy autumn migration and far more vagrancy than Sandwich Bay, with higher numbers of species such as little bunting, red-breasted flycatcher and greenish warbler, as well as extreme vagrants (Roadhouse & Spurn Bird Observatory, 2016). By also being on the east coast, it is predicted conditions responsible for falls of common migrants would be very similar. If these given locations also had higher numbers of passage migrants, then similar investigations into arrivals and departures could be achieved. One example is the inclusion of species where data at Sandwich Bay was too sporadic to annually compare species such as wood warblers, which in a good year has a handful of records (mainly in July) but can be absent in many others in the recording area. This species is particularly unusual, as despite a fairly large but decreasing UK population, it is incredibly difficult to detect on migration, with few birds even recorded at observatories in spring or autumn. Several bird observatories are also based on more remote islands such as Bardsey, North Ronaldsay and Fair Isle. It would be intriguing to see if their geographical location affected the prominence of certain patterns. One particular aspect that was missing from the dataset was the occurrence of Nearctic vagrants, with none recorded at Sandwich Bay over the 30 years, the single historical record being a Swainson's thrush (*Catharus ustulatus*) in 1976. Autumn in particular, can see the occurrence of North American passerine species in the British Isles with several species such as red-eyed vireo (*Vireo olivaceus*), yellow-billed cuckoo (*Coccyzus americanus*) and hermit thrush (*Catharus guttatus*) on the British Bird List (McLaren et al., 2006). Though the occurrence of such passerines is extremely rare, there appears to evidence that Nearctic vagrancy is increasing (McLaren et al., 2006). The patterns that occur over the Atlantic to cause such vagrancy is a potentially interesting aspect to explore as it could potentially differ majorly to the Siberian/Mediterranean vagrants that were examined in this thesis. This is particularly due to the much more substantial distance needing to be covered by these migrants and much more severe weather required to remove them off their standard migration routes (Elkins, 2008). Despite this, the most commonly occurring species, red-eyed vireo, has over 100+ records in Britain (McLaren et al., 2006). If incorporating data in the future, the autumn of 2022 would be an interesting dataset, which saw considerable numbers of Nearctic passerines make landfall on the west coast of Britain and Ireland. This was the result of strong westerly winds across the North Atlantic which brought species such as baltimore oriole (Icterus galbula), tennessee warbler (*Leiothlypis peregrina*), blackburnian warbler (*Setophaga fusca*) and myrtle warbler (*Setophaga coronata*) between the Scilly Isles in the far south-west to the Shetland Isles in the extreme north-east of the British Isles. It is interesting to add that during this period of weather in 2022, the extremely rare yellow-browed bunting (*Emberiza chrysophrys*) was recorded at Sandwich Bay, this being a vagrant from far-east Asia. The use of such data from other bird observatories that have recorded Nearctic vagrants would help build an idea about the patterns that could potentially bring these species to our shores and whether we should expect more rarities in the future. Overall, there is huge scope for finding and developing this dataset further, to allow further understanding into the changes in migration in both birds and moths and additionally, the alterations on our weather patterns to potentially influence our environment.

5.6 Conclusion

In conclusion, regional weather patterns have a very strong effect on migration in both birds and moths, with certain patterns correlated with large falls of both species' groups. It also appears that in the following decades, dramatic changes may occur as a result of timings in weather patterns but also climate change in general agreeing with the hypothesis. The 2nd hypothesis in this study concerning an increase in vagrant birds and migrant moth species over the study-period can be also accepted, with both groups showing a notable increase over the 30 years. It certainly would not be implausible to suggest that further colonisations of new moth species will continue to occur in the study area, with species such as beautiful marbled and convolvulus hawk-moth being particularly notable. This will also affect the designation of such species, potentially seeing them no longer classified as immigrant species. Following on from this, predictions can be made supporting the occurrence of new migratory species occurring to Britain in subsequent decades, with northward expansion resulting in further species beginning to arrive and becoming classed as migrants. The timings of passage migrants also have changed significantly over the study-period. It can be expected that the patterns identified in passage migrants may also continue to occur if their changes in populations continue. Pied flycatchers, in particular, have already been proven to be sensitive to climate-change and alter their arrivals in occurrence. Therefore, it is predicted that continued bottle-necking of their arrivals and departures may occur as a result of climate change and population declines, as with the other species studied. The trends of willow warbler would be noteworthy to follow, to see if their decline eventually begins to mirror the trends identified in this study in the scarcer passage species i.e. garden warbler and spotted flycatcher. Vagrancy itself may continue to increase, as species previously considered rare become more common, due to range expansions and observers becoming more aware of the rarities encountered during the migration season.

The application of this data for bird observatories could be beneficial in predicting when conditions are beneficial for big falls of migrants or are looking suitable for vagrancy of rarer bird species. For example, those wishing to study birds with methods such as ringing may find the data useful as it incorporates the new designations by the Met Office, allowing better predications about adequate dates to conduct ringing. Likewise, as many record moths too, it may help to identify suitable nights to trap and collect the valuable data for this threatened group of insects. Looking at the timings of the migrants that pass through also holds extremely important value, as this can identify the huge effects that further changes in climate or population declines may have on species and their movements, particularly if species are adapting their migration routes as argued by Lawrence at al., (2021). For example, the common migratory warbler, the blackcap has been observed to be over-wintering in higher numbers in the UK than in previous decades (Leach, 1981), likewise for chiffchaff, with several other species also observing this behaviour. Lawrence et al. (2021) also found that migratory bird species were spending longer in Europe, on average, than in previous years, showing delays in returns to their wintering grounds and possible changes in their migration strategy. It may be anticipated that other, previously known summer migrants, may also begin to over-winter in the increasingly milder conditions of Britain. Knowledge of how these weather patterns are changing can facilitate when to expect the changes in migration in response and determine just how much bird populations are being altered by these occurrences. However, it is difficult to predict, in the long-term when accounting for the ebbs and flows often shown in bird populations. Further, long-term analysis of weather patterns should certainly be undertaken, to determine if the changes in timings are continuing to occur and if there are changes in frequency that may require a longer-term studying. If there are dramatic changes due to climate change occurring, then the results of these alterations could substantially alter the ecology of many of our bird and moth species.

6. Bibliography

6.1 References

Adriaensen, F., & Dhondt, A. A. (1990). Population Dynamics and Partial Migration of the European Robin (Erithacus rubecula) in Different Habitats. *The Journal of Animal Ecology*, *59*(3), 1077.

Åkesson, S. (2015). Flying with the winds: differential migration strategies in relation to winds in moth and songbirds. *Journal of Animal Ecology*, *85*(1), 1-4. https://doi.org/10.1111/1365-2656.12450

Åkesson, S., & Bianco, G. (2021). Wind-assisted sprint migration in northern swifts. *Iscience*, *24*(6), 102474. https://doi.org/10.1016/j.isci.2021.102474

Åkesson, S., Bianco, G., & Hedenström, A. (2016). Negotiating an ecological barrier: crossing the Sahara in relation to winds by common swifts. Philosophical Transactions of the Royal Society B: *Biological Sciences*, 371(1704), 20150393. https://doi.org/10.1098/rstb.2015.0393

Alerstam, T., Bäckman, J., Grönroos, J., Olofsson, P., & Strandberg, R. (2019). Hypotheses and tracking results about the longest migration: The case of the arctic tern. *Ecology and Evolution*, *9*(17), 9511-9531. https://doi.org/10.1002/ece3.5459

Alerstam, T., Chapman, J., Bäckman, J., Smith, A., Karlsson, H., & Nilsson, C. et al. (2011). Convergent patterns of long-distance nocturnal migration in noctuid moths and passerine birds. *Proceedings of The Royal Society B: Biological Sciences*, *278*(1721), 3074-3080. https://doi.org/10.1098/rspb.2011.0058

Aloni, I., Markman, S., & Ziv, Y. (2019). Autumn temperatures at African wintering grounds affect body condition of two passerine species during spring migration. *PLOS ONE*, *14*(5), e0217619. https://doi.org/10.1371/journal.pone.0217619

Anglian Lepidopterist Supplies. (2004). *ALS Beginners Guide to Moth Trapping* [PDF]. ALS.

Atropos. (2021). *Migrant Totals*. Www.atropos.info. Retrieved January 25, 2022, from http://www.atropos.info/site/index.php?option=com_content&view=article&id=99&Itemid=114Bairlein, F. (1987). The migratory strategy of the Garden Warbler: A survey of field and laboratory data. *Ringing & Migration*, *8*(2), 59–72. https://doi.org/10.1080/03078698.1987.9673903

Bairlein, F. (2003). The study of bird migrations – some future perspectives. *Bird Study*, *50*(3), 243–253. https://doi.org/10.1080/00063650309461317

BBRC. (2022). British Birds Rarities Committee (BBRC) | BBRC Species / taxa. British Birds Rarities Committee (BBRC). https://www.bbrc.org.uk/main-information/species-taxa

BirdGuides,. (2021, March 23). Osprey photographed being shot down over Malta. *BirdGuides*. https://www.birdguides.com/news/osprey-photographed-being-shot-down-over-malta/

Beament, E. (2021, February 1). Locked-down Britons turn to bird watching [Review of Locked-down Britons turn to bird watching]. The Independent. https://www.independent.co.uk/news/uk/home-news/lockdown-bird-watching-rspb-b1795853.html

Bell, M., & Howey, D. H. (1985). Pallas's Warblers and other migrants in Britain and Ireland in October 1982 [Review of *Pallas's Warblers and other migrants in Britain and Ireland in October 1982*]. *British Birds*, *78*, 381–392. British Birds. https://britishbirds.co.uk/wp-content/uploads/article_files/V78/V78_N08/V78_N08_P381_392_A091.pdf

Both, C., Van Turnhout, C., Bijlsma, R., Siepel, H., Van Strien, A., & Foppen, R. (2009). Avian population consequences of climate change are most severe for long-distance migrants in seasonal habitats. *Proceedings of The Royal Society B: Biological Sciences*, *277*(1685), 1259-1266. https://doi.org/10.1098/rspb.2009.1525

Bozó, L., Csörgő, T., & Heim, W. (2018). Weather conditions affect spring and autumn migration of Siberian leaf warblers. *Avian Research*, *9*(1). https://doi.org/10.1186/s40657-018-0126-5

Bretherton, R. F. (1983). The incidence of migrant lepidoptera in the British Isles. In J. Heath, & A. Maitland Emmet (Eds.), *The Moths and Butterflies of Great Britain and Ireland, 10 Noctuidae (Part II) and Agaristidae* (pp. 9-34). Harley Books.

Briguglio, M. (2015). The bird hunting referendum in Malta. *Environmental Politics*, *24*(5), 835-839. https://doi.org/10.1080/09644016.2015.1055880

Brönnimann, S. (2007). Impact of El Niño-Southern Oscillation on European climate. *Reviews of Geophysics*, *45*(3), n/a-n/a. https://doi.org/10.1029/2006rg000199

Cardé, R. (2008). Insect migration: Do migrant moths know where they are heading? *Current Biology*, *18*(11), R472-R474. https://doi.org/10.1016/j.cub.2008.04.018

Calladine, J., du Feu, C., & du Feu, R. (2011). Changing migration patterns of the Short-eared Owl *Asio flammeus* in Europe: an analysis of ringing recoveries. *Journal of Ornithology*, *153*(3), 691-698. https://doi.org/10.1007/s10336-011-0786-y

Chapman, J., Reynolds, D., & Wilson, K. (2015). Long-range seasonal migration in insects: mechanisms, evolutionary drivers and ecological consequences. *Ecology Letters*, *18*(3), 287-302. https://doi.org/10.1111/ele.12407

Chapman, J., Reynolds, D., Smith, A., Riley, J., Pedgley, D., & Woiwod, I. (2002). High-altitude migration of the diamondback moth *Plutella xylostella* to the U.K.: a study using radar, aerial netting, and ground trapping. *Ecological Entomology*, *27*(6), 641-650. https://doi.org/10.1046/j.1365-2311.2002.00472.

Chapman, J., Bell, J., Burgin, L., Reynolds, D., Pettersson, L., & Hill, J. et al. (2012). Seasonal migration to high latitudes results in major reproductive benefits in an insect. *Proceedings of the National Academy of Sciences*, *109*(37), 14924-14929. https://doi.org/10.1073/pnas.1207255109

Choi, S. (2008). Effects of weather factors on the abundance and diversity of moths in a temperate deciduous mixed forest of Korea. *Zoological Science*, *25*(1), 53-58. https://doi.org/10.2108/zsj.25.53

Dadswell, M., Spares, A., Reader, J., & Stokesbury, M. (2010). The North Atlantic subpolar gyre and the marine migration of Atlantic salmon *Salmo salar*: the 'Merry-Go-Round' hypothesis. *Journal of Fish Biology*, no-no. https://doi.org/10.1111/j.1095-8649.2010.02673.

Daily Weather Report /Daily Weather Summary | Met Office UA. (n.d.). Digital.nmla.metoffice.gov.uk. Retrieved November 22, 2020, from https://digital.nmla.metoffice.gov.uk/SO_86058de1-8d55-4bc5-8305-5698d0bd7e13/

Davis, P. (1964). Aspects of autumn migration at the bird observatories, 1963. *Bird Study*, *11*(2), 77-122. https://doi.org/10.1080/00063656409476061

Davis, P. (1966). The great immigration of early September 1965. *British Birds*, *59*(9), 353-374. Retrieved 4 May 2021, from https://britishbirds.co.uk/wp-content/uploads/2013/02/Davis-1966.pdf.Davis, P. (1967). Migration-seasons of the Sylvia warblers at British Bird Observatories. *Bird Study*, *14*(2), 65-95. https://doi.org/10.1080/00063656709476149

De Luca, P., Harpham, C., Wilby, R. L., Hillier, J. K., Franzke, C. L. E., & Leckebusch, G. C. (2019). Past and projected weather pattern persistence with associated multi-hazards in the British Isles. *Atmosphere*, *10*(10), 577. https://doi.org/10.3390/atmos10100577

DeLuca, W., Woodworth, B., Rimmer, C., Marra, P., Taylor, P., & McFarland, K. et al. (2015). Transoceanic migration by a 12 g songbird. *Biology Letters*, *11*(4), 20141045. https://doi.org/10.1098/rsbl.2014.1045

Dell'Apa, A., Carney, K., Davenport, T., & Carle, M. (2018). Potential medium-term impacts of climate change on tuna and billfish in the Gulf of Mexico: A qualitative framework for management and conservation. *Marine Environmental Research*, *141*, 1-11. https://doi.org/10.1016/j.marenvres.2018.07.017

Dimalexis, A., Xirouchakis, S., Portolou, D., Latsoudis, P., Karris, G., & Fric, J. et al. (2007). The status of Eleonora's Falcon (*Falco eleonorae*) in Greece. *Journal of Ornithology*, *149*(1), 23-30. https://doi.org/10.1007/s10336-007-0207-4

Eastham, J. (2021, October 25). Europe's birds may stop migrating because of global warming, new research shows. *The Telegraph*. https://www.telegraph.co.uk/news/2021/10/25/europes-birds-may-stop-migrating-global-warming-new-research/

Effects of climate change. (n.d.). Met Office. https://www.metoffice.gov.uk/weather/climate-change/effects-of-climate-change#:~:text=UK%20winters%20are%20projected%20to

Eikenaar, C., Klinner, T., Szostek, K., & Bairlein, F. (2014). Migratory restlessness in captive individuals predicts actual departure in the wild. *Biology Letters*, *10*(4), 20140154. https://doi.org/10.1098/rsbl.2014.0154

Elkins, N. (2008). Further thoughts on the transatlantic vagrancy of landbirds to Britain & Ireland [Review of *Further thoughts on the transatlantic vagrancy of landbirds to Britain & Ireland*]. *British Birds*, *101*(9), 458–477. British Birds. https://britishbirds.co.uk/wp-content/uploads/article_files/V101/V101_N09/V101_N9_2_21.pdf

Elkins, N., & Johnson, R. (2005). *Weather and bird migration*. https://britishbirds.co.uk/wp-content/uploads/article_files/V98/V98_N05/V98_N05_P238_256_A003.pdf

Freeman, S. N., & Crick, H. Q. P. (2003). The decline of the Spotted Flycatcher Muscicapa striata in the UK: an integrated population model. *Ibis*, *145*(3), 400–412. https://doi.org/10.1046/j.1474-919x.2003.00177.x

Fry, R., & Waring, P. (2020). *A Guide to Moth Traps and Their Use* (3rd ed.). Amateur Entomologists' Society.

Gillings, S., Newson, S. & Sellers, R.M. (2007) Breeding population estimates for Northern Wheatear in Britain. *British Birds* 100: 179–181.

Gilroy, J., & Lees, A. (2003). Vagrancy theories: Are autumn vagrants really reverse migrants? *British Birds* 96 (9): 427-438.

González-Braojos, S., Sanz, J., & Moreno, J. (2017). Decline of a montane Mediterranean pied flycatcher *Ficedula hypoleuca* population in relation to climate. *Journal of Avian Biology*, *48*(11), 1383-1393. https://doi.org/10.1111/jav.01405

Google Maps. (n.d.). (Google Maps, Sandwich Bay Bird Observatory, Sandwich, Kent, UK). Retrieved November 22nd 2021 from: https://www.google.com/maps/place/Sandwich+Bay+Bird+Observatory+Trust/@52.0480259

Green, A. (2019). Cultural responses to the migration of the barn swallow in Europe. *ANU Historical Journal II*, (1), 87-107. https://doi.org/10.22459/anuhjii.2019.10

Grishchenko, V. (2019). Influence of global weather conditions on timing of the spring migration of birds in the Kaniv Nature Reserve (Central Ukraine). *Vestnik Zoologii*, *53*(2), 141-148. https://doi.org/10.2478/vzoo-2019-0014

Gwinner, E., & Wiltschko, W. (1980). Circannual changes in migratory orientation of the garden warbler, *Sylvia borin*. *Behavioral Ecology And Sociobiology*, *7*(1), 73-78. https://doi.org/10.1007/bf00302521

Gyurácz, J., Bánhidi, P., Góczán, J., Illés, P., Kalmár, S., Lukács, Z., Molnár, P., Németh, C., & Varga, L. (2021). Temporal Changes in Wing Length, Fat Reserves and Body Mass of Migrating Eurasian Blackcaps Sylvia atricapilla at a West Hungarian Stopover Site. *Acta Ornithologica*, *56*(1). https://doi.org/10.3161/00016454ao2021.56.1.005

Hanžel, J. (2015). The influx of Red-footed Falcons Falco vespertinus in Slovenia in spring 2015. *Acrocephalus*, *36*(166-167), 179–183. https://doi.org/10.1515/acro-2015-0012

Hedenström, A., Barta, Z., Helm, B., Houston, A., McNamara, J., & Jonzén, N. (2007). Migration speed and scheduling of annual events by migrating birds in relation to climate change. *Climate Research*, *35*, 79-91. https://doi.org/10.3354/cr00715

Hernández, Á. (2009). Summer-autumn feeding ecology of Pied Flycatchers *Ficedula hypolueca* and Spotted Flycatchers Muscicapa striata: the importance of frugivory in a stopover area in north-west Iberia. *Bird Conservation International*, *19*(03), 224. https://doi.org/10.1017/s0959270909008351

Hewson, C., Thorup, K., Pearce-Higgins, J., & Atkinson, P. (2016). Population decline is linked to migration route in the Common Cuckoo. *Nature Communications*, *7*(1). https://doi.org/10.1038/ncomms12296

Hume, R. (2006). *DK RSPB Complete Birds of Britain and Europe*. Dorling Kindersley.

Jones, P. (1975). The migration of redstarts through and from Britain. *Ringing & Migration*, *1*(1), 12-17. https://doi.org/10.1080/03078698.1975.9673693

Jones, P., Mead, C., & Durman, R. (1977). The migration of the Pied Flycatcher from and through Britain. *Bird Study*, *24*(1), 2-14. https://doi.org/10.1080/00063657709476526

Jenni, L., & Kéry, M. (2003). Timing of autumn bird migration under climate change: advances in long–distance migrants, delays in short–distance migrants. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *270*(1523), 1467-1471. https://doi.org/10.1098/rspb.2003.2394

Jonason, D., Franzén, M., & Ranius, T. (2014). Surveying moths using light traps: Effects of weather and time of year. *Plos ONE*, *9*(3), e92453. https://doi.org/10.1371/journal.pone.0092453

Lack, D. (2008). Migration across the southern North Sea studied by radar Part 4. Autumn. *Ibis*, *105*(1), 1-54. https://doi.org/10.1111/j.1474-919x.1963.tb02473.

Lars Svensson. (1975). *Identification guide to European passerines*. Naturhistoriska Rikskmuseet.

Lawrence, K., Barlow, C., Bensusan, K., Perez, C., & Willis, S. (2021). Phenological trends in the pre- and post-breeding migration of long-distance migratory birds. *Global Change Biology*. https://doi.org/10.1111/gcb.15916

Leach, I. H. (1981). Wintering Blackcaps in Britain and Ireland. Bird Study, 28(1), 5–14. https://doi.org/10.1080/00063658109476693

Lees, A. (2022). *Vagrancy In Birds.* Princeton University Press.

Lees, A & Gilroy, J. (2009). Vagrancy mechanisms in passerines and near-passerines. Rare Birds, Where and When: An Analysis of Status and Distribution in Britain and Ireland. 1. 1-23.

Lindsey, R., & Dahlmann, L. (2021, March 15). Climate Change: Global Temperature (J. Blunden, Ed.) [Review of Climate Change: Global Temperature]. Climate.gov; Climate.gov. https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature#:~:text=August%2012%2C%202021-,Highlights,land%20areas%20were%20record%20war

Lormée, H., Barbraud, C., Peach, W., Carboneras, C., Lebreton, J., & Moreno-zarate, L. et al. (2019). Assessing the sustainability of harvest of the European Turtle-dove along the European western flyway. *Bird Conservation International*, *30*(4), 506-521. https://doi.org/10.1017/s0959270919000479

Kochert, M., Fuller, M., Schueck, L., Bond, L., Bechard, M., & Woodbridge, B. et al. (2011). Migration patterns, use of stopover areas, and austral summer movements of Swainson's Hawks. *The Condor*, *113*(1), 89-106. https://doi.org/10.1525/cond.2011.090243

Maggini, I., & Bairlein, F. (2010). Endogenous rhythms of seasonal migratory body mass changes and nocturnal restlessness in different populations of Northern Wheatear *Oenanthe*

oenanthe. *Journal of Biological Rhythms*, *25*(4), 268-276. https://doi.org/10.1177/0748730410373442

Manola, I., Bradarić, M., Groenland, R., Fijn, R., Bouten, W., & Shamoun-Baranes, J. (2020). Associations of synoptic weather conditions with nocturnal bird migration over the North Sea. *Frontiers in Ecology and Evolution*, *8*. https://doi.org/10.3389/fevo.2020.542438

Mayson, S. (2020). *Migration blog (August – September)*. BTO - British Trust for Ornithology. Retrieved 17 August 2020, from https://www.bto.org/community/blog/migration-blog-august-%E2%80%93-september.

Marchant, J. H., & Wernham, C. V. (2003). Phenology of autumn passage of Willow Warblers at Dungeness, 1960–2000. *BTO Research Report No.323.*, (323), 34pp. https://www.bto.org/sites/default/files/shared_documents/publications/research-reports/2003/rr323.pdfMarra, P., Francis, C., Mulvihill, R., & Moore, F. (2004). The influence of climate on the timing and rate of spring bird migration. *Oecologia*, *142*(2), 307-315. https://doi.org/10.1007/s00442-004-1725

Martay, B., Pearce-Higgins, J. W., Harris, S. J., & Gillings, S. (2022). Breeding ground temperature rises, more than habitat change, are associated with spatially variable population trends in two species of migratory bird. *Ibis*. https://doi.org/10.1111/ibi.13101

McLaren, I. A., Lees, A. C., Field, C., & Collins, K. J. (2006). Origins and characteristics of Nearctic landbirds in Britain and Ireland in autumn: a statistical analysis. *Ibis*, *148*(4), 707–726. https://doi.org/10.1111/j.1474-919x.2006.00574.x

Merckx, T., & Slade, E. (2014). Macro-moth families differ in their attraction to light: implications for light-trap monitoring programmes. *Insect Conservation and Diversity*, *7*(5), 453-461. https://doi.org/10.1111/icad.12068

Met Office (2016). Southern England: climate. Met Office. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/southern-england_-climate---met-office.pdf

Miller, R., Onrubia, A., Martín, B., Kaltenecker, G., Carlisle, J., Bechard, M., & Ferrer, M. (2015). Local and regional weather patterns influencing post-breeding migration counts of soaring birds at the Strait of Gibraltar, Spain. *Ibis*, *158*(1), 106-115. https://doi.org/10.1111/ibi.12326

Morrison, C. A., Robinson, R. A., Butler, S. J., Clark, J. A., & Gill, J. A. (2016). Demographic drivers of decline and recovery in an Afro-Palaearctic migratory bird population. *Proceedings of the Royal Society B: Biological Sciences*, *283*(1842), 20161387. https://doi.org/10.1098/rspb.2016.1387

Murton, R., & Ridpath, M. (1962). The autumn movements of the Woodpigeon. *Bird Study*, *9*(1), 7-41. https://doi.org/10.1080/00063656209476010

Neal, R., Fereday, D., Crocker, R., & Comer, R. E. (2016). A flexible approach to defining weather patterns and their application in weather forecasting over Europe. *Meteorological Applications*, *23*(3), 389–400. https://doi.org/10.1002/met.1563

Newton, I. (2007). Weather-related mass-mortality events in migrants. *Ibis*, *149*(3), 453-467. https://doi.org/10.1111/j.1474-919x.2007.00704.

Newton, I, & Brockie, K (2007). The Migration Ecology of Birds. Elsevier Science & Technology, San Diego. Available from: ProQuest Ebook Central. [27 September 2020].

Nicolau, P. G., Burgess, M. D., Marques, T. A., Baillie, S. R., Moran, N. J., Leech, D. I., & Johnston, A. (2021). Latitudinal variation in arrival and breeding phenology of the pied flycatcher Ficedula hypoleuca using large-scale citizen science data. Journal of Avian Biology, 52(2). https://doi.org/10.1111/jav.02646

Noakes, S., Pyenson, N., & McFall, G. (2013). Late Pleistocene gray whales (Eschrichtius robustus) offshore Georgia, U.S.A., and the antiquity of gray whale migration in the North Atlantic Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *392*, 502-509. https://doi.org/10.1016/j.palaeo.2013.10.005

Norman, S., & Norman, W. (1985). Autumn Movements of Willow Warblers ringed in the British Isles. *Ringing & Migration*, *6*(1), 7-18. https://doi.org/10.1080/03078698.1985.9673849

Patowary, K., 2020. *Barnacle Goose: The Bird That Was Believed to Grow on Trees*. [online] Amusingplanet.com. Available at: <https://www.amusingplanet.com/2020/03/barnacle-goose-bird-that-was-believed.html> [Accessed 27 January 2021].

Parslow, J. (2008). The migration of passerine night migrants across the English Channel studied by radar. *Ibis*, *111*(1), 48-79. https://doi.org/10.1111/j.1474-919x.1969.tb01604.

Peach, W. J., Crick, H. Q. P., & Marchant, J. H. (1995). The demography of the decline in the British willow warbler population. Journal of Applied Statistics, 22(5-6), 905–922. https://doi.org/10.1080/02664769524702

Pope, J. O., Brown, K., Fung, F., Hanlon, H. M., Neal, R., Palin, E. J., & Reid, A. (2021). Investigation of future climate change over the British Isles using weather patterns. *Climate Dynamics*. https://doi.org/10.1007/s00382-021-06031-0

Ray, S., & SBBOT. (2012). Garden Warbler [Review of Garden Warbler].

Ray, S., & SBBOT. (2015). Sand Martin [Review of Sand Martin].

Richardson, D., Fowler, H. J., Kilsby, C. G., & Neal, R. (2017). A new precipitation and drought climatology based on weather patterns. *International Journal of Climatology*, *38*(2), 630–648. https://doi.org/10.1002/joc.5199

Sanders, C. E., & Mennill, D. J. (2014). Acoustic monitoring of nocturnally migrating birds accurately assesses the timing and magnitude of migration through the Great Lakes. *The Condor*, *116*(3), 371–383. https://doi.org/10.1650/condor-13-098.1

Serneels, S., & Lambin, E. (2002). Impact of land-use changes on the wildebeest migration in the northern part of the Serengeti-Mara ecosystem. *Journal Of Biogeography*, *28*(3), 391-407. https://doi.org/10.1046/j.1365-2699.2001.00557.

Shamoun-Baranes, J., Van Loon, E., Alon, D., Alpert, P., Yom-Tov, Y., & Leshem, Y. (2006). Is there a connection between weather at departure sites, onset of migration and timing of soaring-bird autumn migration in Israel? *Global Ecology and Biogeography*, *15*(6), 541-552. https://doi.org/10.1111/j.1466-8238.2006.00261.

Sightings | Sandwich Bay Bird Observatory Trust. (n.d.). Retrieved November 22, 2020, from https://sbbot.org.uk/sightings-2/

Sparks, T., Dennis, R., Croxton, P., & Cade, M. (2007). Increased migration of Lepidoptera linked to climate change. *European Journal of Entomology*, *104*(1), 139-143. https://doi.org/10.14411/eje.2007.019

Sparks, T., Roy, D., & Dennis, R. (2005). The influence of temperature on migration of Lepidoptera into Britain. *Global Change Biology*, *11*(3), 507-514. https://doi.org/10.1111/j.1365-2486.2005.00910.

Sparks, T., & Tryjanowski, P. (2007). Patterns of spring arrival dates differ in two hirundines. *Climate Research*, *35*, 159–164. https://doi.org/10.3354/cr00722

Steinbauer, M., Haslem, A., & Edwards, E. (2011). Using meteorological and lunar information to explain catch variability of Orthoptera and Lepidoptera from 250W Farrow light traps. *Insect Conservation and Diversity*, *5*(5), 367-380. https://doi.org/10.1111/j.1752-4598.2011.00170.

Stefanescu, C., Alarcón, M., & Àvila, A. (2007). Migration of the painted lady butterfly, Vanessa cardui, to north-eastern Spain is aided by African wind currents. *Journal Of Animal Ecology*, *76*(5), 888-898. https://doi.org/10.1111/j.1365-2656.2007.01262.

Stefanescu, C., Páramo, F., Åkesson, S., Alarcón, M., Ávila, A., & Brereton, T. et al. (2012). Multi-generational long-distance migration of insects: studying the painted lady butterfly in the Western Palaearctic. *Ecography*, *36*(4), 474-486. .

Stokke, B., Møller, A., Sæther, B., Rheinwald, G., & Gutscher, H. (2005). Weather in the breeding area and during migration affects the demography of a small long-distance passerine migrant. *The Auk*, *122*(2), 637-647. https://doi.org/10.1093/auk/122.2.637

Stouffer, P. (2003). Diet and preparation for spring migration in captive Hermit Thrushes (Catharus guttatus). *The Auk*, *120*(2), 323-330. https://doi.org/10.2307/4090184

Taylor, P., Crewe, T., Mackenzie, S., Lepage, D., Aubry, Y., Crysler, Z., Finney, G., Francis, C., Guglielmo, C., Hamilton, D., Holberton, R., Loring, P., Mitchell, G., Norris, D. R., Paquet, J., Ronconi, R., Smetzer, J., Smith, P., Welch, L., & Woodworth, B. (2017). The Motus Wildlife Tracking System: a collaborative research network to enhance the understanding of wildlife movement. *Avian Conservation and Ecology*, *12*(1). https://doi.org/10.5751/ACE-00953-120108

The Bird Observatories Council. (n.d.). Home. Www.birdobscouncil.org.uk. Retrieved October 29, 2022, from https://www.birdobscouncil.org.uk/

Thorup, K. (1998). Vagrancy of Yellow-browed Warbler *Phylloscopus inornatus* and Pallas's Warbler *Ph. proregulus* in north-west Europe: Misorientation on great circles? *Ringing & Migration*, *19*(1), 7–12. https://doi.org/10.1080/03078698.1998.9674155

Thorup, K., Alerstam, T., Hake, M., & Kjellén, N. (2003). Bird orientation: compensation for wind drift in migrating raptors is age dependent. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *270* (PP S8-S11). https://doi.org/10.1098/rsbl.2003.0014

Tolman, T., & Lewington, R. (2013). *Collins British butterfly guide*. Collins.

Ventusky - Weather Forecast Maps. (n.d.). Www.ventusky.com. https://www.ventusky.com/

Waring, P., Townsend, M., & Lewington, R. (2017). *Field guide to the moths of Great Britain and Ireland* (3rd ed.). Bloomsbury.

White, S., & Kerhoe, C. (2020). Scarce migrant birds in Britain in 2018. *British Birds*, *113*(8), 461–482.

Woodward, I.D., Massimino, D., Hammond, M.J., Barber, L., Barimore, C., Harris, S.J., Leech, D.I., Noble, D.G., Walker, R.H., Baillie, S.R. & Robinson, R.A. (2020) BirdTrends 2020: trends in numbers, breeding success and survival for UK breeding birds. BTO Research Report 732. BTO, Thetford. www.bto.org/birdtrends

Williamson, K. (1959). *THE SEPTEMBER DRIFT-MOVEMENTS OF 1956 AND 1958 Part 1-General Summary and Weather Conditions*. Retrieved November 29, 2021, from https://britishbirds.co.uk/wp-content/uploads/article_files/V52/V52_N10-11/V52_N10_11_P334_377_A067.pdf

Yela, J., & Holyoak, M. (1997). Effects of moonlight and meteorological Factors on light and bait trap catches of Noctuid Moths (Lepidoptera: Noctuidae). *Environmental Entomology*, *26*(6), 1283-1290. https://doi.org/10.1093/ee/26.6.1283

Zhan, S., Zhang, W., Niitepõld, K., Hsu, J., Haeger, J., & Zalucki, M. et al. (2014). The genetics of monarch butterfly migration and warning colouration. *Nature*, *514*(7522), 317-321. https://doi.org/10.1038/nature13812