Rijksuniversiteit Groningen

Master Thesis

Exploring the influence of climate change on the migration routes of Arctic Terns

rijksuniversiteit groningen

Author:
L. van de Straat

Supervisors:
Dr. M.J.J.E. Loonen
Prof. dr. R. Bintanja

Abstract

Arctic Terns (*Sterna paradisaea*) have a very long annual migration. The route of this migration can be influenced by factors such as food availability and weather conditions. Wind patterns are shown to be an important factor on the migration routes Arctic Terns take (Manche, 2019). This project looks at the impact of changing wind patterns due to climate change on these migration routes in the future.

Most climate models used by the Intergovernmental Panel on Climate Change (IPCC) provide projections of wind patterns up to the year 2100. These projections can be used to determine flight costs of Arctic Terns on current migrations routes taken by the birds as found by Egevang et al. (2010) and Fijn et al. (2013), both for the present and the future. A significant change in flight costs on these routes could indicate that birds might change their migration routes in the future.

There were no significant changes in flight cost found on the migration routes of Arctic Terns over the period 2010-2099. It was also found that most climate models seem to underestimate flight cost when compared to wind data by the European Centre for Medium-Range Weather Forecasts (ECMWF).

However, it must be stated that many simplifications were made to approximate the migration routes of the Arctic Terns. Predetermined migration tracks were used, it was assumed that all birds departed and arrived at the same time and the period over which the migration took place was limited to two months. Also monthly wind data was used, whereas birds encounter daily differences.

In conclusion, more in depth research must be done to give a conclusive answer to the question whether climate change will influence migration routes of Arctic Terns in the future.

Contents

1 Introduction **4**

2 Method **5**
2.1 IPCC Climate Models 5
2.2 Arctic Tern Migration 5
2.3 Global Wind Patterns 6
2.4 Calculating Flight Cost 7

3 Results **8**

4 Discussion **12**
4.1 Future research 13

5 Conclusion **14**

Appendices **17**

A Flight cost per climate model per migration track for the current and future situation **17**

B Flight cost broken into separate years per climate model per migration track for the current situation **21**

C Flight cost averaged over all climate models per migration track for the current and future situation **26**

D Comparison between the climate models with the highest and lowest flight cost for the current situation **28**

1 Introduction

Arctic Terns (*Sterna paradisaea*) have a very long annual migration with birds travelling up to 90,000 km per year. They travel from circumpolar Arctic breeding grounds to circumpolar Antarctic wintering areas (Egevang et al., 2010; Fijn et al., 2013). The route of this migration can be influenced by a number of different factors, such as food availability and weather conditions. One important factor that influences the migration route of Arctic Terns are wind patterns. By choosing not the shortest route but rather one which provides wind assistance, they can limit the cost of their migration (Manche, 2019).

In the past it was difficult to determine migration routes as they were based on sightings and ring recoveries. In the case of Arctic Terns there was the extra difficulty of their migration route being largely oversea. This way of inferring migration routes left large gaps of uncertainty in the data. Despite the difficulties in determining the migration routes, Salomonsen (1967) gave a comprehensive overview of the migration routes of Arctic Terns in which he already suggested a dependence on wind patterns.

In more recent years, the development of new tracking techniques has allowed scientists to track birds during their entire migration. Geolocators, or Global Location Sensing (GLS) loggers, record time and light intensity. With these data the location of a bird can be determined. These geolocators are attached to a bird and will record data during the whole migration trajectory. To retrieve the data, the bird must be recaptured the next year (Manche, 2019). The first study using geolocators to track Arctic Terns, by Egevang et al. (2010), seemed to largely confirm the migration routes inferred by Salomonsen (1967). More studies have followed with similar results (Fijn et al., 2013; Manche, 2019). The study performed by Manche (2019) looked specifically at the dependency of Arctic Terns on wind patterns during their migration. This study found that the differences in migration routes between different populations of Arctic Terns could be explained by varying wind patterns throughout the year.

When talking about climate change, much-discussed topics are temperature and sea level rise. A subject you hardly ever hear, is changing wind patterns. Even in the most recent report by the Intergovernmental Panel on Climate Change (IPCC) wind is hardly discussed. When it is discussed, it is mostly in the context of an increase in windstorms or as renewable energy source (IPCC, 2014). However, most of the climate models on which the IPCC report is based include projections of wind patterns up to the year 2100. These projections are of interest to this project.

Manche (2019) determined least cost migration routes for Arctic Terns by looking solely at current wind data. She did this for the years 2011 to 2018 and found striking similarities with the migrations routes that were recorded with the use of geolocators in that same period. By comparing the average migration routes found by Egevang et al. (2010) and Fijn et al. (2013) to the wind data provided by the climate models of the IPCC up to the year 2100, changes in the cost on these migration routes of Arctic Terns due to climate change can be determined. A significant change in cost on current migration routes might indicate a change of route in the future.

The goal of this project is to find out what effects climate change has on the migration patterns of Arctic Terns. This leads to the following research question:

How will climate change influence migration routes of Arctic Terns?

This paper is divided into several sections. In section 2, the method used for determining flight cost on current migration routes of Arctic Terns in the different climate models up to the year 2100 will be discussed. In section 3, the results of the research will be presented. In section 4, these results will be discussed and suggestions for further research will be given. And in section 5, the conclusion of the project will be given.

2 Method

2.1 IPCC Climate Models

The IPCC scenario used during this project, was the RCP8.5 scenario. This scenario is a so called "business as usual" scenario. That means that in this scenario no efforts are made to constrain or reduce the amount of carbon dioxide (CO_2) that is emitted (IPCC, 2014). The IPCC uses a total of 45 climate models for their report in 2014. 43 of these models have data for the RCP8.5 scenario. From these 43 models, there are 34 models that have provided wind data and thus can be used for this project.

Of these 34 climate models, 4 gave difficulties during processing. The 3 models by the Met Office Hadley Centre (MOHC) provided the data with a 360 day calendar instead of a 365 day calendar, which made them incompatible with the code used to process the models (Collins et al., 2008). The model by European EC-Earth consortium also gave problems with the code, but it was unclear what the exact cause was (EC-Earth, 2019). These 4 climate models were thus excluded from further analysis, which meant 30 climate models were eventually used.

2.2 Arctic Tern Migration

After establishing which climate models to use, the migration routes needed to be determined. Fijn et al. (2013) provide a schematic overview of the migration routes of Arctic Terns. Taking data collected by Egevang et al. (2010) and their own research, Fijn et al. (2013) created a map with the migration routes of birds breeding in the Netherlands and birds breeding around Greenland and Iceland. The Arctic Terns are separated in these two groups, not only because of their breeding location, but also because of the time period in which they migrate. The Dutch birds leave earlier on both their autumn and spring migration than the Greenlandic birds.

Figure 1 shows the migration tracks that were used during this project. The tracks are based on the schematic migration routes described by Fijn et al. (2013) and Egevang et al. (2010). The red track shows the southbound migration route followed by the birds breeding in the Netherlands. The blue track shows their northbound migration route. The birds breeding in Greenland and Iceland take one of two southbound migration routes that are shown by the green tracks. And they follow a single northbound migration route that is shown by the yellow track.

For calculating the cost of a flight path it is not only important where the Arctic Terns are flying, but also when the birds are there. It has been shown that the southbound migration of Dutch birds can span up to five months and the northbound migration up to two months (Fijn et al., 2013; Alerstam et al., 2019). The southbound migration of the Greenlandic birds can span up to four months and the northbound migration again up to two months (Egevang et al., 2010; Hensz, 2015; Hromádková et al., 2020). For this project, the time periods used by Manche (2019) are a good starting point. For the southbound migration, she uses the months August and September for the Dutch birds and the months September and October for the the Greenlandic birds. For the northbound migration, she uses the months March and April for the Dutch birds and the months April and May for the Greenlandic birds. The same time brackets were used during this project, with the first half of the track using data of the first month and the second half of the track using data of the second month. This simplifies the calculation of flight costs significantly.

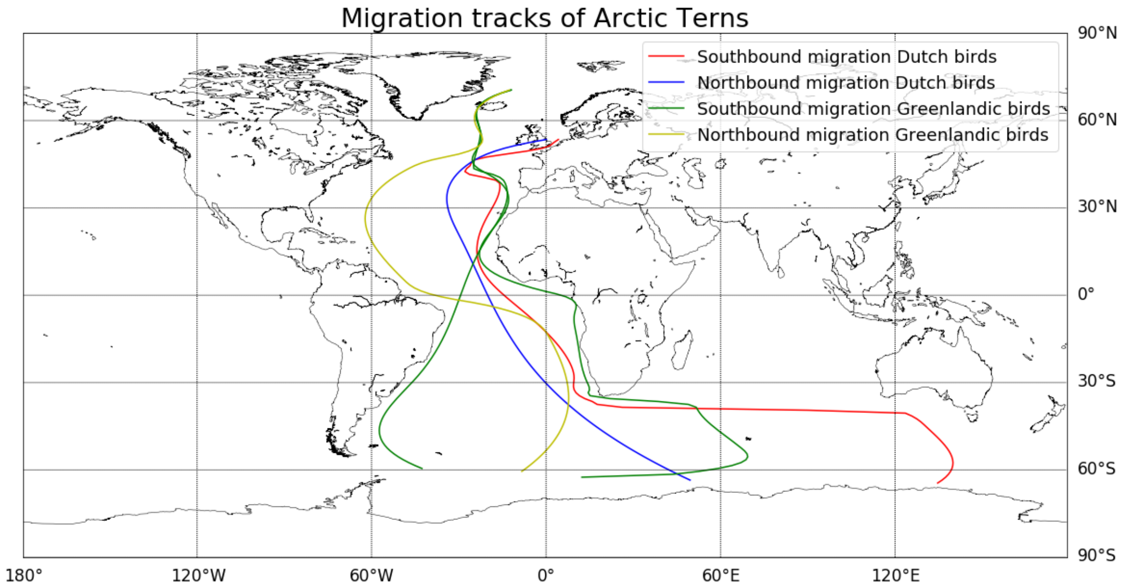

Figure 1: Migration tracks of Arctic terns breeding in the Netherlands (red, blue) (Fijn et al., 2013) and Arctic Terns breeding in Greenland and Iceland (green, yellow) (Egevang et al., 2010).

2.3 Global Wind Patterns

During their migration Arctic Terns encounter global wind patterns. Among these patterns are the North Atlantic jet and the Southern Hemisphere jet. These jets are found centered around 46°N and 48°S respectively and have prevailing eastward winds (Barnes and Polvani, 2013). Birds encounter the North Atlantic jet at the beginning of their southbound journey on their way to and from the North Atlantic staging area. When making their way towards the staging area, the birds will encounter these winds head on. When leaving the staging area, the birds will experience more tailwinds. The Southern Hemisphere jet is encountered when crossing from the southern tips of South America and Africa to Antarctica. It is likely that this jet influences how far East a bird will fly before crossing. This is especially relevant for the birds crossing from Africa.

Barnes and Polvani (2013) looked at changes in the North Atlantic and Southern Hemisphere jets between now and the year 2100. They did this by looking at the location of the center of the jets within the different climate models also used by the IPCC. They concluded that on average the center of the jets shift poleward by 1° latitude. This shift varies between the different climate models.

Another important global wind pattern encountered by the Arctic Terns are the Hadley Cells. A Hadley Cell consists of warm air rising at the equator, moving away from the equator while it cools down, the cooled air sinking around roughly 30° latitude and moving back towards the equator while the air warms again. When the air moves back towards the equator, it will start moving westward resulting in the westward trade winds (Hu et al., 2018). It is likely that the Greenlandic birds profit from the trade winds when crossing the Atlantic during their northbound migration.

Hu et al. (2018) looked into changes of the Hadley Cells. They could not find any definite changes in the strength of the Hadley Cells. However, they did find evidence for a widening of the

Hadley Cells. Meaning the Hadley Cells will increase in size extending further poleward. This would be consistent with the poleward movement of the North Atlantic and Southern Hemisphere jets.

2.4 Calculating Flight Cost

Equation 1 was used for the cost calculation of each migration track. S is the wind speed, HRMF is the Horizontal Relative Moving Angle, or the angle between moving direction and wind direction and HF is the Horizontal Factor, a function that penalizes deviation from the wind direction (Felicísimo et al., 2008). To be able to do the cost calculation for each track, several things are needed.

$$Cost = \frac{1}{S} HF, where \begin{cases} HF = 0.1 & : HRMF = 0 \\ HF = 2HMRF & : HRMF \neq 0 \end{cases} \quad (1)$$

First, the wind speed and direction was calculated. The climate models provide wind data as a vector containing a variable for the eastward wind (U) and a variable for the northward wind (V). Using these variables, the overall wind speed and direction could be calculated using the Pythagorean theorem. The wind direction was given the unit of the angle in degrees between the y-axis, or latitude axis, and the wind direction. This way it could be compared to the flight direction of the Arctic Terns.

The flight direction of the birds was calculated by determining the slope between 2 neighbouring points on the flight track. Using this slope and the Pythagorean theorem, the flight direction as the angle in degrees between y-axis and the slope could be calculated.

The HRMF should be taken as the angle in degrees (Fernández-López and Schliep, 2019). The HRMF can be found by calculating the difference between the wind direction and the flight direction.

Once the HRMF was obtained, the HF could be calculated. Combining the HF with the wind speed S in equation 1 allowed for the calculation of the cost for moving from one degree latitude to the next. By expanding this calculation over a full flight track and adding the cost for each step, the full cost for that flight track could be calculated.

The wind data of the climate models was provided in 1° by 1° grids. However, the wind data of the current situation from the European Centre for Medium-Range Weather Forecasts (ECMWF) came in 0.5° by 0.5° grids. This meant that the wind data first needed to be regridded into a 1° by 1° grid.

To be able to compare the different climate models to the current situation, the cost was calculated for the 5 different tracks shown in figure 1 for each of the 30 climate models and the ECMWF wind data. This was done for a period of 10 years, 2010 to 2019, for the climate models and a period of 8 years, 2011 to 2018, for the ECMWF wind data. Then it was averaged over this period to account for yearly weather variations.

This process was repeated for two 10 year periods in the future for the climate models to see if there were significant changes in cost along the migration tracks. The periods chosen were from 2045 to 2054 and from 2090 to 2099. As the climate models provide data up until the year 2100, these periods best reflect the possible change in the near-future and far-future.

The last step in this project was to infer where in the migration tracks changes could be seen causing a model to provide high cost or low cost. By comparing the model with the highest cost to the model with the lowest cost for each migration track per degree of latitude, it was possible to make differences visible along the migration tracks.

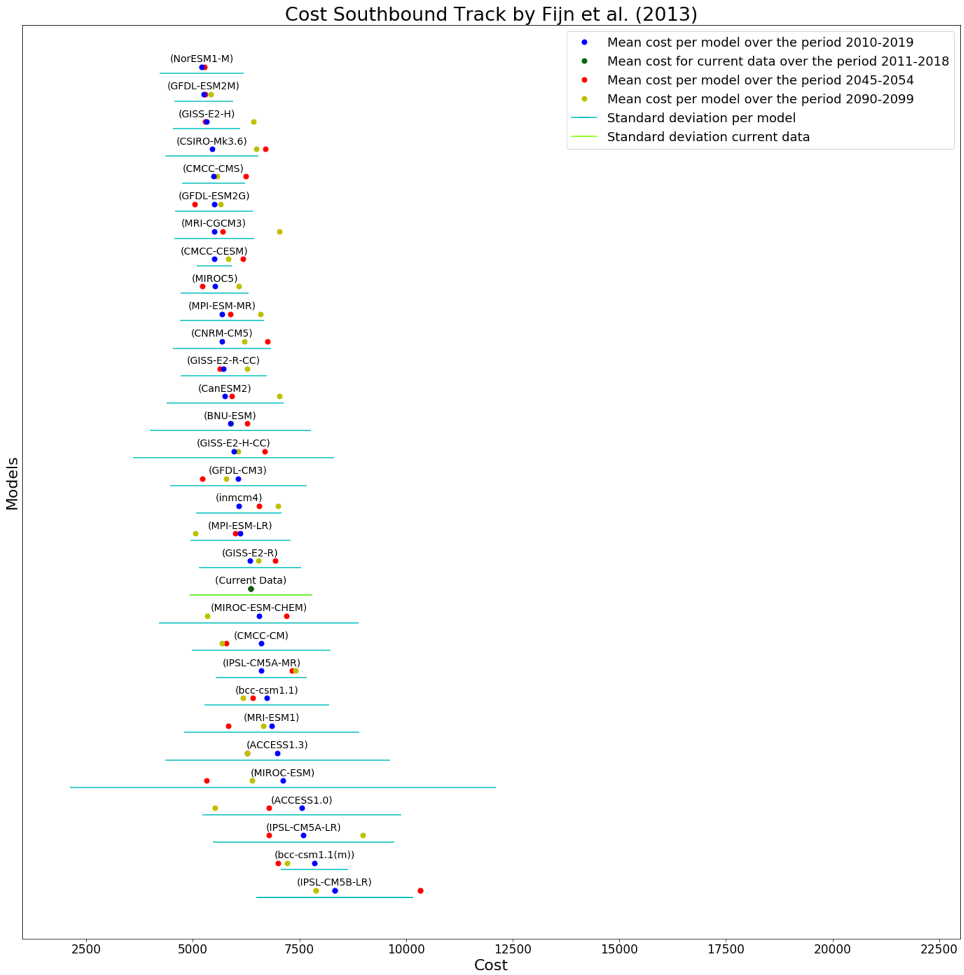

Figure 2: Average flight cost for the ECMWF data in the period 2011-2018 (green) and the climate models in the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the southbound migration track of the Dutch birds (Fijn et al., 2013; Felicísimo et al., 2008). The standard deviation is given for the period 2010-2019.

3 Results

First, the average flight cost for each climate model and the ECMWF wind data was calculated. This was done for the 5 different migration tracks shown in figure 1. The ECMWF wind data is currently measured data available for the period 2011-2018. However, as the climate models provide data up until 2100, the average cost was calculated for the periods 2010-2019, 2045-2054 and 2090-2099. The results of these calculations for the southbound migration track of the Dutch birds are shown in figure 2. The flight cost for the ECMWF wind data with its standard deviation is shown in green. The flight cost for the climate models with their standard deviation over the period 2010-2019 are shown in blue. These are compared to the flight cost over the period 2045-2054, in red, and the flight cost over the period 2090-2099, in yellow. It is immediately clear that the climate models differ greatly in flight cost. The ECMWF wind data has a relatively high flight cost compared to the climate models. Also there is no conclusive evidence for an increase or decrease in flight cost in the future. The results for the other four migration tracks can be found in appendix A. These results are similar to the results found for the southbound migration track of the Dutch birds. A further breakdown of the flight cost for the period 2010-2019 into separate years can be found in appendix B

To be able to distill more information from the results in figure 2 and appendix A, the flight cost was averaged over all climate models. This was done for all three time frames, 2010-2019, 2045-2054 and 2090-2099. Not only the flight cost was averaged this way, but also the standard deviation of this flight cost was averaged over all climate models. This resulted in figure 3. The average for the period 2010-2019 is shown in blue, the average for the period 2045-2054 is shown in red and the average for the period 2090-2099 is shown in yellow. A slight change in flight cost through the years can be observed. But this change lies within the standard deviation, meaning that the changes are not significant. Similar results were found for the other four flight tracks. These results can be found in appendix C.

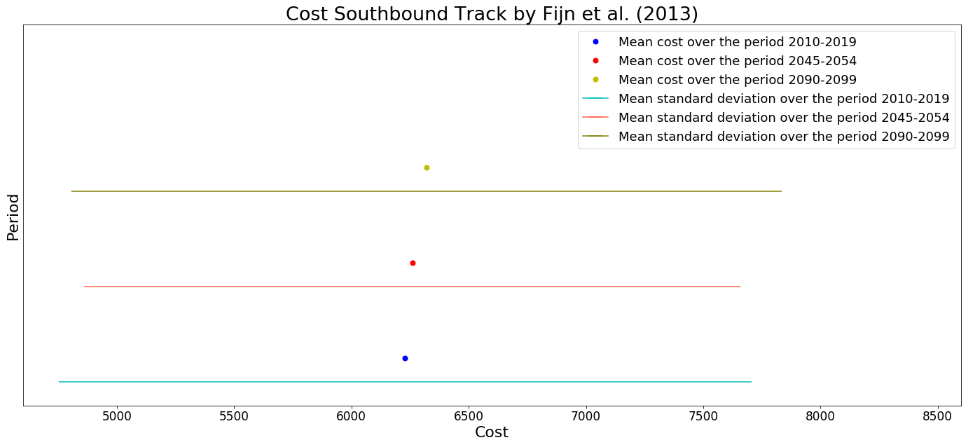

Figure 3: Flight cost and standard deviation averaged over all climate models for the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the southbound migration track of the Dutch birds.

Another method to get more information from the results in figure 2 and appendix A was by ranking the climate models. For each migration track the climate models were assigned a rank. A high rank for high flight cost models and a low rank for low flight cost models. These ranks were averaged over the five different climate models. This provided the final ranks with their respective standard deviation for the climate models shown in table 1. Models with a final rank over 20 have been coloured red and models with a final rank below 10 have been coloured blue. The ECMWF wind data has been coloured green. The ECMWF wind data has one of the highest ranks, showing that almost all climate models underestimate the flight cost if the ECWMF data are considered the "truth". Six climate models have an average high rank and two climate models have an average low rank, meaning that most climate models do not have a consistently high or low flight cost. Having an average rank (between 10 and 20) means that a climate model has either large variations in rank between the different flight tracks, shown by a large standard deviation, or an average rank for each flight track, shown by a small standard deviation. It is important to note that the rank of a climate model only tells something about the relation to other climate models. It does not tell anything about the actual flight cost within that particular climate model.

Rank	σ	Climate model
3.8	4.7	NorESM1-M
7.0	4.8	CanESM2
10.2	7.1	BNU-ESM
10.4	3.9	CMCC-CMS
10.8	3.1	MPI-ESM-MR
11.4	6.1	CMCC-CESM
12.4	8.7	GISS-E2-H
13.0	9.0	MIROC-ESM
13.0	8.7	bcc-csm1.1
13.4	12.4	GFDL-ESM2M
13.6	7.9	GFDL-CM3
13.8	9.3	CSIRO-Mk3.6
15.2	6.3	MPI-ESM-LR
15.6	8.3	ACCESS1.3
15.6	5.0	MRI-CGCM3
16.4	10.2	MRI-ESM1
16.4	8.2	inmcm4
17.2	4.0	GISS-E2-H-CC
17.2	8.2	MIROC5
17.8	8.2	IPSL-CM5A-MR
17.8	9.2	bcc-csm1.1(m)
18.0	9.0	GFDL-ESM2G
18.8	9.0	CNRM-CM5
19.6	5.9	CMCC-CMS
20.4	7.2	ACCESS1.1
20.6	2.9	MIROC-ESM-CHEM
20.8	2.9	GISS-E2-R
20.8	7.3	GISS-E2-R-CC
21.6	9.3	IPSL-CM5A-LR
23.0	6.5	Current Data
30.4	0.8	IPSL-CM5B-LR

Table 1: The average rank of each climate model, with models with a high rank (>20) shown in red, models with a low rank (<10) shown in blue and the ECMWF data shown in green.

The last method used to gain information from figure 2 and appendix A was by breaking down the flight cost of the different migration routes into degrees of latitude. By doing this for the climate model with the highest flight cost and the climate model with the lowest flight cost, a comparison between these could be made. This shows where on the migration tracks the largest difference in cost can be found. Figure 4 shows this comparison for the southbound migration track of the Dutch birds. The green dots show the flight cost for the climate model with the lowest total flight cost and the red dots show the flight cost for the climate model with the highest total flight cost. In addition, figure 4 also shows the month in which the birds fly and indicates the flight direction with the black arrow. The results for the other four migrations tracks can be found in appendix D. The largest differences between the climate models in figure 4 and appendix D can be seen around the locations where the Arctic Terns encounter the North Atlantic and Southern Hemisphere jets. This corresponds with the variation in location of these jets between climate models found by Barnes and Polvani (2013).

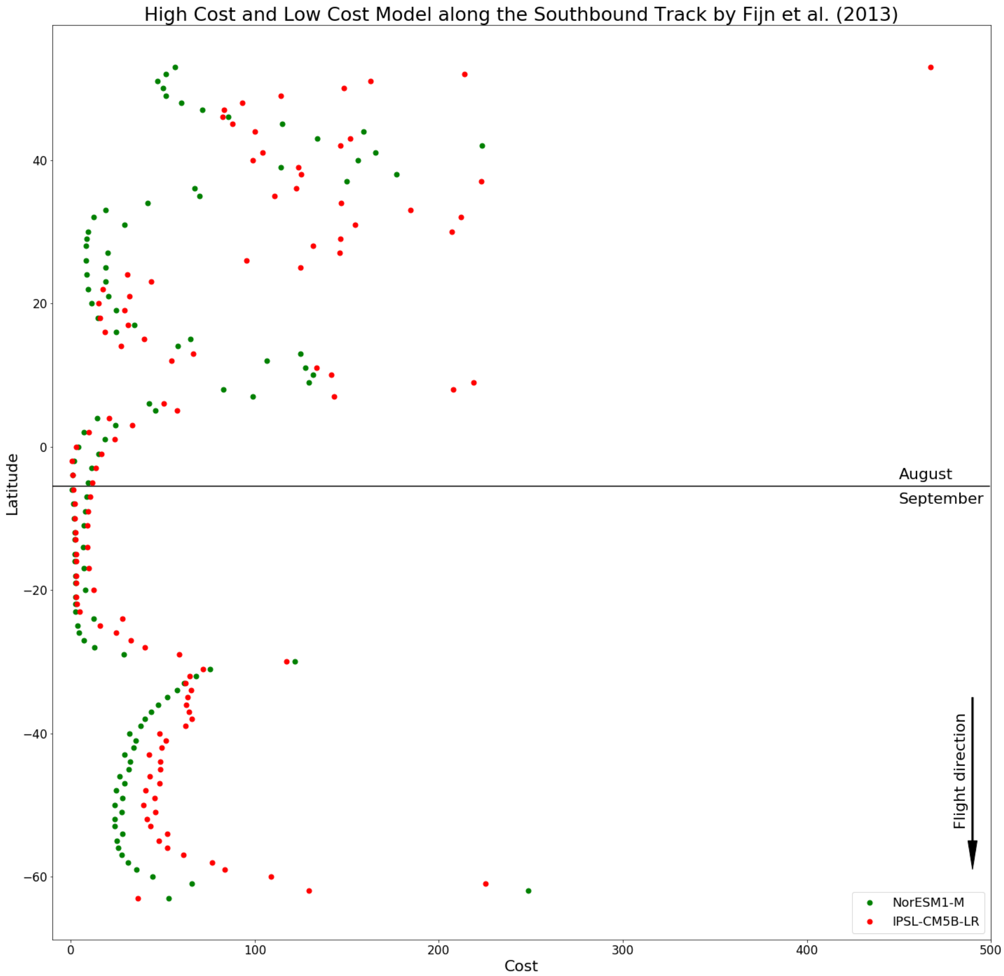

Figure 4: Flight cost per degree latitude for the southbound migration track of the Dutch birds. Green indicates the climate model with the lowest flight cost on this track. Red indicates the climate model with the highest flight cost on this track.

4 Discussion

There were no significant changes found in flight cost on the migration routes of Arctic Terns as determined by Fijn et al. (2013) and Egevang et al. (2010). As seen in figure 2 and appendix A the set of 30 climate models used in this project do not show a consistent increase or decrease in flight cost over the period 2010-2099. As mentioned in section 2.3 there seems to be a trend in the shift of the North Atlantic and Southern Hemisphere jets and the widening of the Hadley Cells. However, these changes are averaged over the different climate models, while each climate model separately shows different changes. These differences could account for the inconsistencies in the increase and decrease in flight cost over the period 2010-2099 between the different climate models.

Figure 3 and appendix C confirm that there is no consistent increase or decrease in flight cost by showing that the average changes over the years fall easily within the standard deviation of the flight cost for each time period. It was also found that most climate models underestimate the flight cost on the migration routes of Arctic Terns. This is striking as the climate models are able to accurately predict, for example, the rise in temperature over the years.

There are certain factors that were not taken into account during this project, mainly due to time constraints, which would influence the calculation of flight costs during the migration of the Arctic Terns. The first factor that was not taken into account, was the fact that the birds depart at different times on migration. This means that each bird encounters unique wind patterns on their migration, which influences the total flight cost on each migration track. There are a multitude of factors that can influence the decision of individual birds about when to depart. Favorable winds can mean that a bird will depart earlier or unfavorable winds can mean that a bird will depart later. Local wind conditions can also give an indication of what a bird can expect further afield and thus influence the decision that way. However, it are not only wind conditions that influence the decision to depart. Other factors can be precipitation and temperature. How selective a bird will be depends strongly on how long they can afford to wait for suitable conditions (Shamoun-Baranes et al., 2017). And also the arrival date can be influenced by varying wind patterns. Barrett (2016) found that the arrival date of the spring migration of Arctic Terns in Troms Norway was influenced by the presence of head- or tailwinds in the 10 days prior to the arrival of the birds. This difference was found to be up to four days.

The second factor that was not taken into account, was that Arctic Terns stop at staging areas to feed. The birds have been measured to spend from 6 up to 32 days at these staging areas, with the two most important staging areas found in the North Atlantic and west of Southern Africa (Fijn et al., 2013; Egevang et al., 2010). The time a birds chooses to spend at a staging area influences when a bird will be where on their migration route, thus contributes to the uniqueness of the wind patterns that birds will encounter. These staging areas are especially important on the southbound migration of the birds. Hromádková et al. (2020) found that Arctic Terns migrate between different staging areas on their southbound migration, making use of the abundant food availability in these areas. On their northbound migration, they mainly make use of favorable wind patterns, which results in a much faster migration. This means that the calculation of flight costs is likely more accurate on the northbound migration tracks.

There is a third factor that influences the prediction for flight costs significantly. As stated before, climate models are able to accurately predict the change in temperature over the years. Temperature is one of the influencing factors in wind patterns. However, the wind patterns in the climate models do not change in the same way between the different climate models, while the temperature does. This suggests that the wind patterns in the different climate models are not as well developed as the temperature is. By further developing the wind patterns in the climate models, more accurate predictions on the change in flight costs in the future can be made.

Another step that was taken within this project, was the use of monthly data for the wind patterns and the averaging of flight cost over periods of 10 years. This accounts for outliers caused by yearly weather differences, but also removes the nuances that can be caused by slight differences in the wind patterns for each year.

4.1 Future research

As previously discussed, there are several factors that were not taken into account because of time constraints. Also, the migration routes of the Arctic Terns were restricted to specific tracks, monthly data was used and flight cost was averaged over periods of 10 years. In addition, there are a number of figures that have the potential of yielding more information than they do in their current form. Mainly figure 4 can be improved to reveal how bird behaviour and wind patterns connect.

In section 2.2 it was stated that the southbound migration of Arctic Terns can be spread over a period of up to five months. However, in this project a period of two months was used to simplify the calculations. It was also assumed that the first month transitions into the second precisely halfway through the migration. By including more months in the flight cost calculation and randomizing the moment of transition, it will be possible to obtain more accurate numbers for the flight cost. Manche (2019) applies a method similar to this when she calculates the optimal flight tracks for the period 2011-2018. This randomization of the transition from one month to the next during both the southbound and the northbound migration means not only the difference in departure and arrival (Shamoun-Baranes et al., 2017; Barrett, 2016) is taken into account, but also the stopover time in staging areas (Hromádková et al., 2020).

Again in section 2.2 it was explained that the flight cost over the average migration routes as determined by Fijn et al. (2013) and Egevang et al. (2010) was calculated. By using this method, the Arctic Terns were restricted to a single track on each migration route. As shown by a number of studies this is not a realistic approximation. Each bird takes a different route depending on the unique wind patterns they encounter (Egevang et al., 2010; Fijn et al., 2013; Hensz, 2015; Alerstam et al., 2019; Hromádková et al., 2020). An alternative method was used by Manche (2019). She restricted only the points of departure and arrival and determined the least cost path between these two points. By repeating this process for the 8 years within the period 2011-2018 and for several different transition points between the months, she was able to obtain a flight path that would be most likely for the Arctic Terns to take. Using this process for the different climate models and the different time periods, a most likely flight path can be determined for each model and each time period. Differences that might show up between these flight paths can then be attributed to changes in the wind patterns. It will also be easier to locate were the biggest changes can be found.

Using the method described above also solves the possible problem of information loss due to the averaging of the flight cost over periods of 10 years. However, it still uses only monthly data, despite the fact that wind patterns can change within a much shorter period of time.

As stated previously, figure 4 can be improved to yield more information. This can be done in a number of different ways. Firstly, adding wind vectors to the different latitudes can give several insights. If wind vectors are given relative to where North is, it can reveal the differences between the different climate models in more detail. By adding vectors, it becomes visible whether the differences are to be found in wind direction or speed. In addition, if wind vectors are given relative to the bird's flight direction, it will give a better idea of where the birds encounter headwinds or tailwinds. This can then be related to the global wind patterns the birds encounter.

Secondly, a version of figure 4 can be made that includes the data from the ECMWF. It can be interesting to add wind vectors in this version as well. This can reveal where the differences between the climate models and the ECMWF data is located and how significant these differences are. And again it can show whether the differences are caused by a change in wind direction or speed.

Lastly, figure 4 can show not a comparison between separate models for a single time period, but a comparison of the mean values of all climate models per time period. This shows where on the different flight tracks the changes are largest. These changes can then be linked to the wind patterns on those locations.

5 Conclusion

This project has looked at the flight cost of Arctic Terns on their annual migration. This was done by comparing the flight cost calculated with ECMWF data to data from 30 IPCC climate models in the RCP8.5 scenario for the period 2010-2019. To see how flight costs might change in the future, the previous results were compared to the 30 IPCC climate models for the periods 2045-2054 and 2090-2099. No significant changes in flight cost were found in the five different migration tracks of Arctic Terns provided by Fijn et al. (2013) and Egevang et al. (2010). It was also found that the climate models consistently underestimated the flight cost for the period 2010-2019.

These results would suggest that the wind patterns are less accurately simulated by the IPCC climate models compared to for instance temperature. However, during the project major simplifications were made to the simulation, such as taking the same moment of departure for all birds, limiting the number of months in which the birds migrate and not taking the time spend at staging areas into account. These simplifications can be another explanation for the lack of significant changes in flight cost.

Thus, this project cannot give a conclusive answer to the research question stated in section 1. Further development of the wind data in the climate models and a more realistic simulation of bird behaviour is needed to provide a reliable answer.

References

Alerstam, T., J. Bäckman, J. Grönroos, P. Olofsson, and R. Strandberg (2019). "Hypotheses and tracking results about the longest migration: The case of the arctic tern". In: *Ecology and Evolution* 9.17, pp. 9511–9531. DOI: 10.1002/ece3.5459. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/ece3.5459.

Barnes, E.A. and L. Polvani (Sept. 2013). "Response of the Midlatitude Jets, and of Their Variability, to Increased Greenhouse Gases in the CMIP5 Models". In: *Journal of Climate* 26.18, pp. 7117–7135. DOI: 10.1175/JCLI-D-12-00536.1. URL: https://doi.org/10.1175/JCLI-D-12-00536.1.

Barrett, R.T. (2016). "Upwind or downwind: the spring arrival of Arctic Terns Sterna paradisaea at Troms, north Norway". In: *Ringing & Migration* 31.1, pp. 23–29. DOI: 10.1080/03078698.2016.1190610. URL: https://doi.org/10.1080/03078698.2016.1190610.

Collins, W.J., N. Bellouin, M. Doutriaux-Boucher, N. Gedney, T. Hinton, C.D. Jones, S. Liddicoat, G. Martin, F. O'Conner, J. Rae, C. Senior, I. Totterdell, S. Woodward, T. Reichler, and J. Kim (2008). *Evaluation of the HadGEM2 model.* Tech. rep. 74. Hadley Centre.

EC-Earth (2019). *About EC-Earth.* URL: http://www.ec-earth.org/about/ (visited on Oct. 22, 2019).

Egevang, C., I.J. Stenhouse, R.A. Phillips, A. Petersen, J.W. Fox, and J.R.D. Silk (2010). "Tracking of Arctic terns Sterna paradisaea reveals longest animal migration". In: *Proceedings of the National Academy of Sciences* 107.5, pp. 2078–2081. DOI: 10.1073/pnas.0909493107. URL: https://www.pnas.org/content/107/5/2078.

Felicísimo, Á.M., J. Muñoz, and J. González-Solis (2008). "Ocean Surface Winds Drive Dynamics of Transoceanic Aerial Movements." In: *PLoS ONE* 3.8, pp. 1–7. URL: http://search.ebscohost.com.proxy-ub.rug.nl/login.aspx?direct=true&db=aph&AN=55664430&site=ehost-live&scope=site.

Fernández-López, J. and K. Schliep (2019). *rWind: Download, Edit and Include Wind and Sea Currents Data inEcological and Evolutionary Analysis. R package version 1.1.3.* URL: https://cran.r-project.org/web/packages/rWind/rWind.pdf.

Fijn, R.C., D. Hiemstra, R.A. Phillips, and J. van der Winden (2013). "Arctic Terns Sterna paradisaea from The Netherlands migrate record distances across three oceans to Wilkes Land, East Antarctica". In: *Ardea* 101.1, pp. 3–12. DOI: 10.5253/078.101.0102. URL: https://doi.org/10.5253/078.101.0102.

Hensz, C. (Jan. 2015). "Environmental factors in migratory route decisions: a case study on Greenlandic Arctic Terns (Sterna paradisaea)". In: *Animal Migration* 2. DOI: 10.1515/ami-2015-0004.

Hromádková, T., V. Pavel, J. Flousek, and M. Briedis (Jan. 2020). "Seasonally specific responses to wind patterns and ocean productivity facilitate the longest animal migration on Earth". In: *Marine Ecology Progress Series.* DOI: 10.3354/meps13274.

Hu, Y., H. Huang, and C. Zhou (2018). "Widening and weakening of the Hadley circulation under global warming". In: *Science Bulletin* 63.10, pp. 640–644. DOI: https://doi.org/10.1016/j.scib.2018.04.020. URL: http://www.sciencedirect.com/science/article/pii/S2095927318301919.

IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Ed. by Core Writing Team, R.K. Pachauri, and L.A. Meyer. IPCC, Geneva, Switzerland. 151 pp.

Manche, P. (2019). "The migration of Arctic Terns, Do windconditions explain variation within- and among populations?" MA thesis. the Netherlands: Rijksuniversiteit Groningen.

Salomonsen, F. (1967). “Migratory movements of the Arctic Tern (Sterna paradisaea Pontoppidan) in the Southern Ocean”. In: *Biologiske Meddelelser* 24.1, pp. 1–42.

Shamoun-Baranes, J., F. Liechti, and W.M.G. Vansteelant (2017). “Atmospheric conditions create freeways, detours and tailbacks for migrating birds”. In: *Journal of Comparative Physiology. A, Neuroethology, Sensory, Neural, and Behavioral Physiology* 203, pp. 509–529.

Appendices

A Flight cost per climate model per migration track for the current and future situation

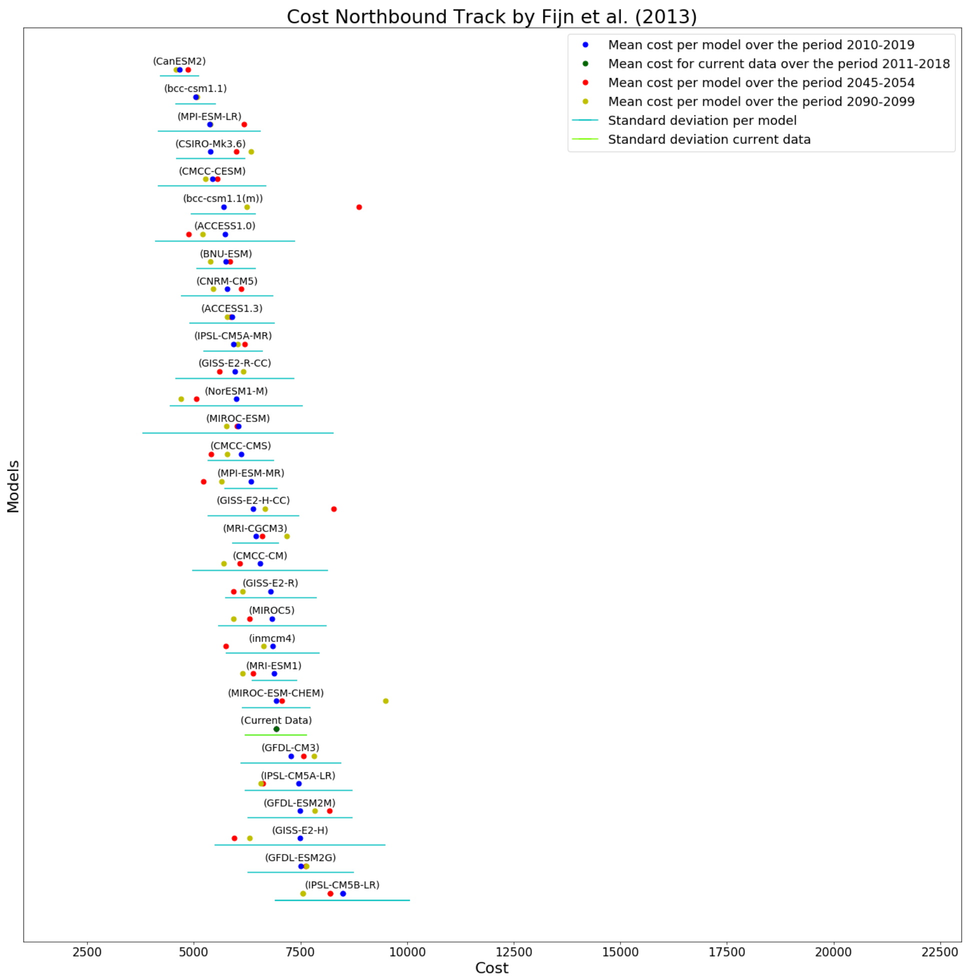

Figure 5: Average flight cost for the ECMWF data in the period 2011-2018 (green) and the climate models in the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the northbound migration track of the Dutch birds (Fijn et al., 2013; Felicísimo et al., 2008). The standard deviation is given for the period 2010-2019.

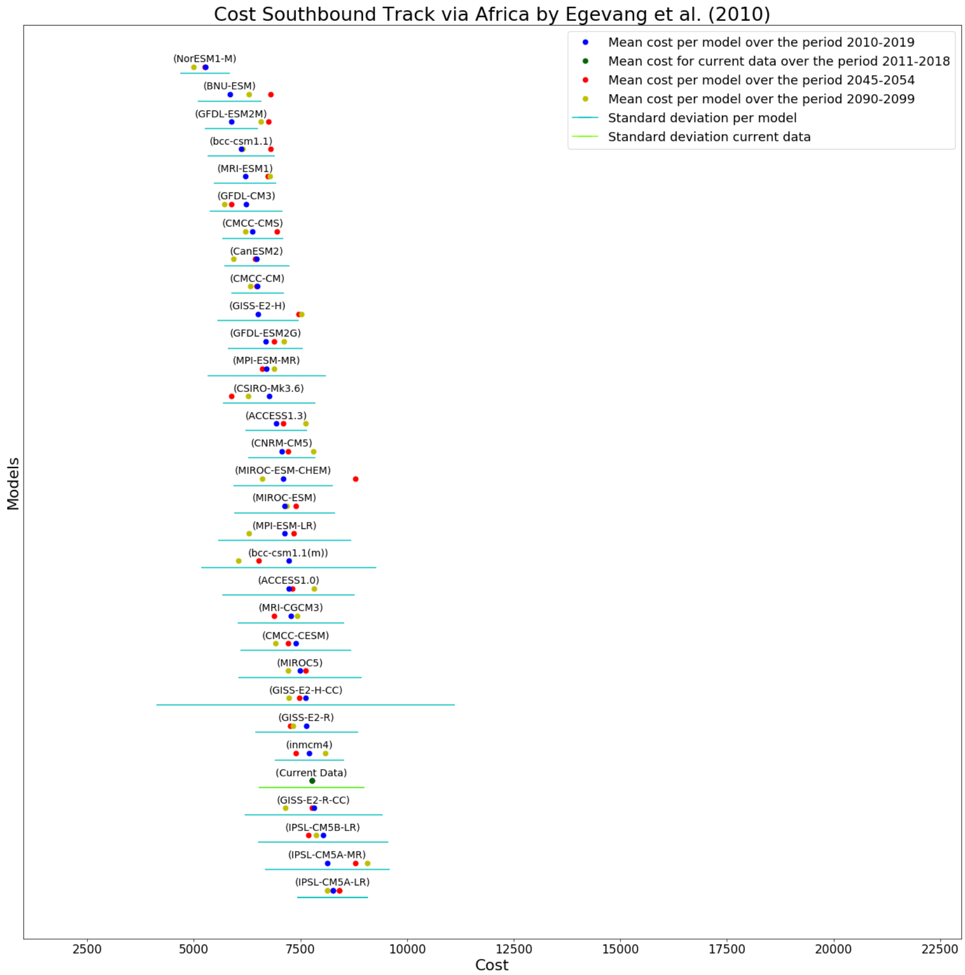

Figure 6: Average flight cost for the ECMWF data in the period 2011-2018 (green) and the climate models in the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the southbound migration track via Africa of the Greenlandic birds (Egevang et al., 2010; Felicísimo et al., 2008). The standard deviation is given for the period 2010-2019.

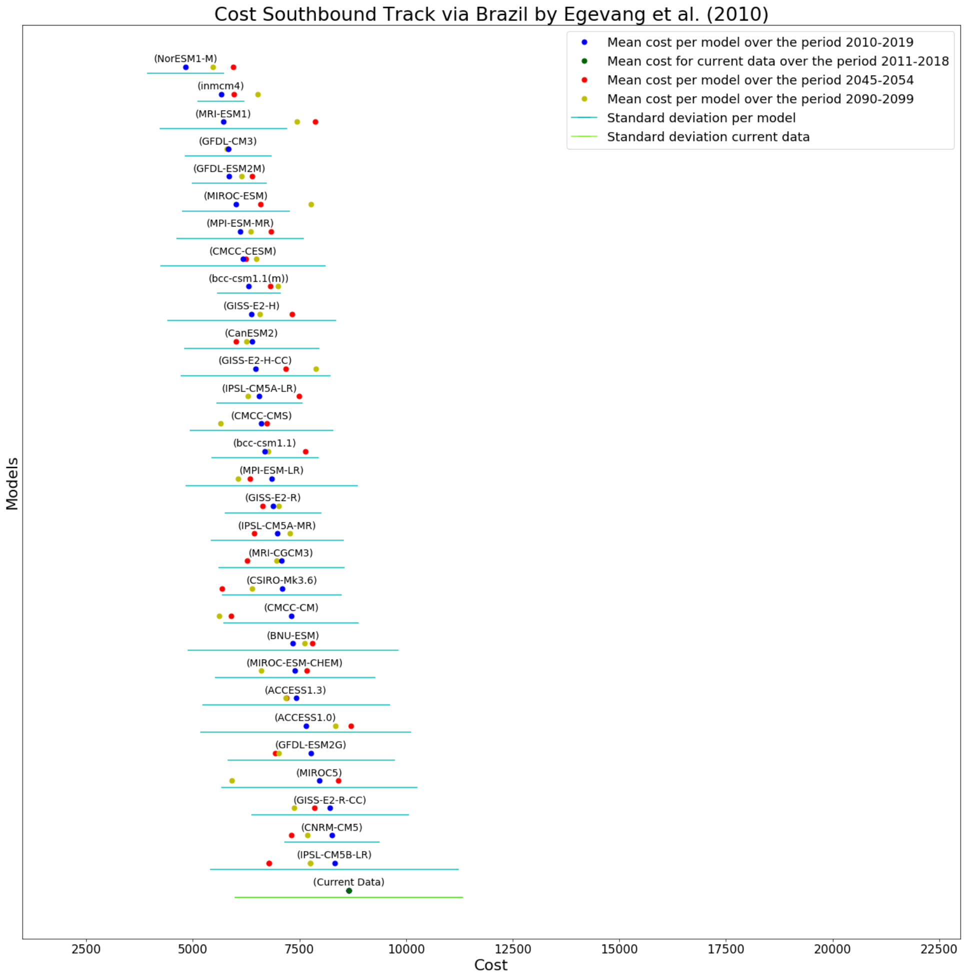

Figure 7: Average flight cost for the ECMWF data in the period 2011-2018 (green) and the climate models in the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the southbound migration track via Brazil of the Greenlandic birds (Egevang et al., 2010; Felicísimo et al., 2008). The standard deviation is given for the period 2010-2019.

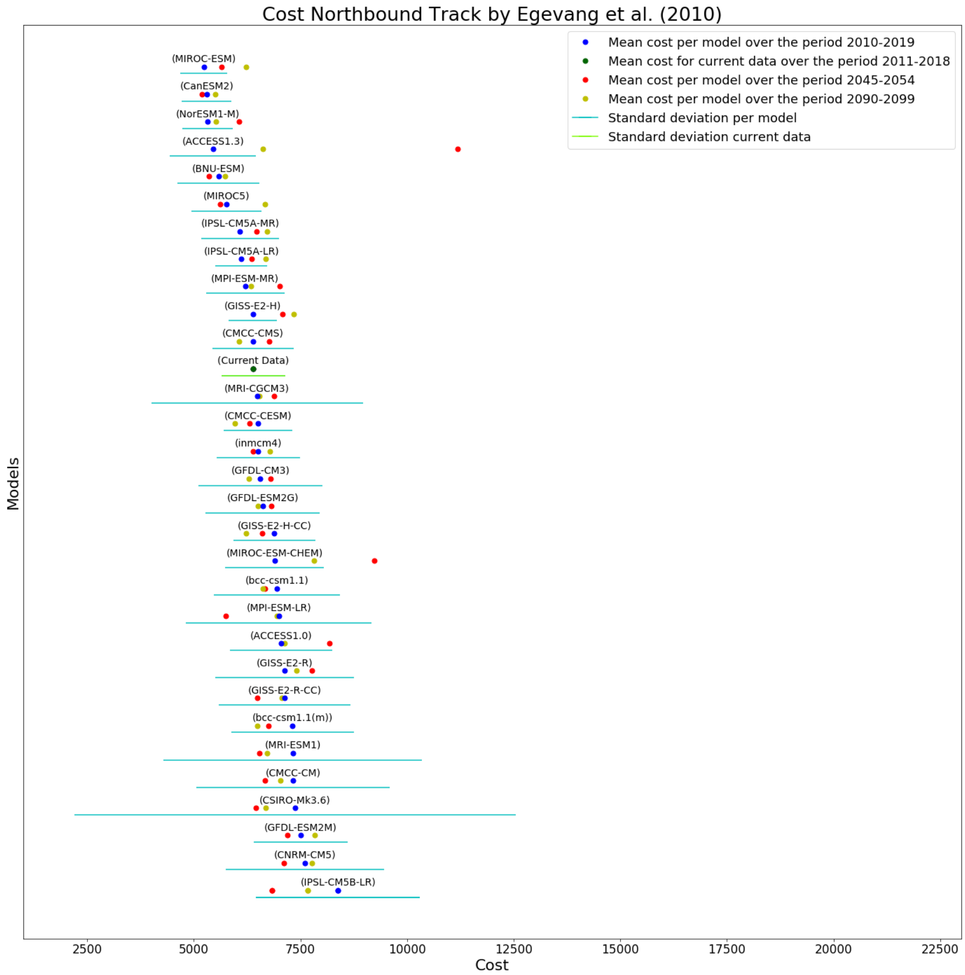

Figure 8: Average flight cost for the ECMWF data in the period 2011-2018 (green) and the climate models in the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the northbound migration track of the Greenlandic birds (Egevang et al., 2010; Felicísimo et al., 2008). The standard deviation is given for the period 2010-2019.

B Flight cost broken into separate years per climate model per migration track for the current situation

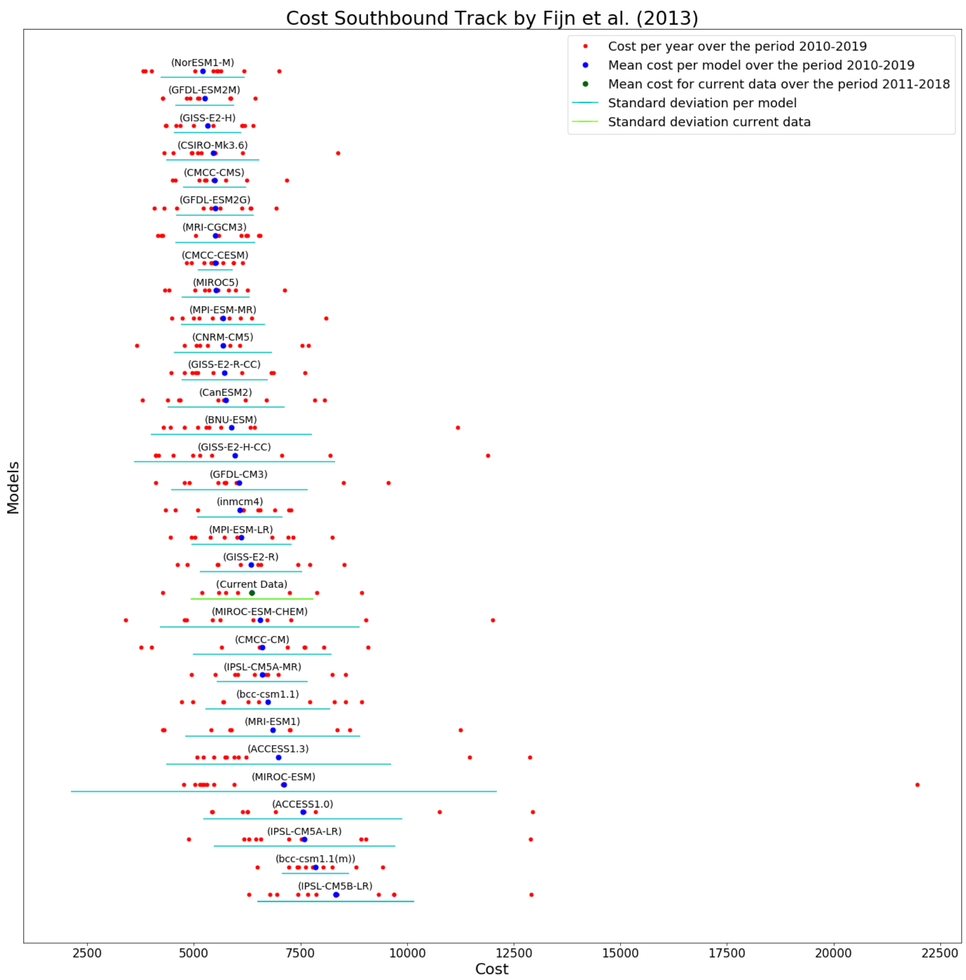

Figure 9

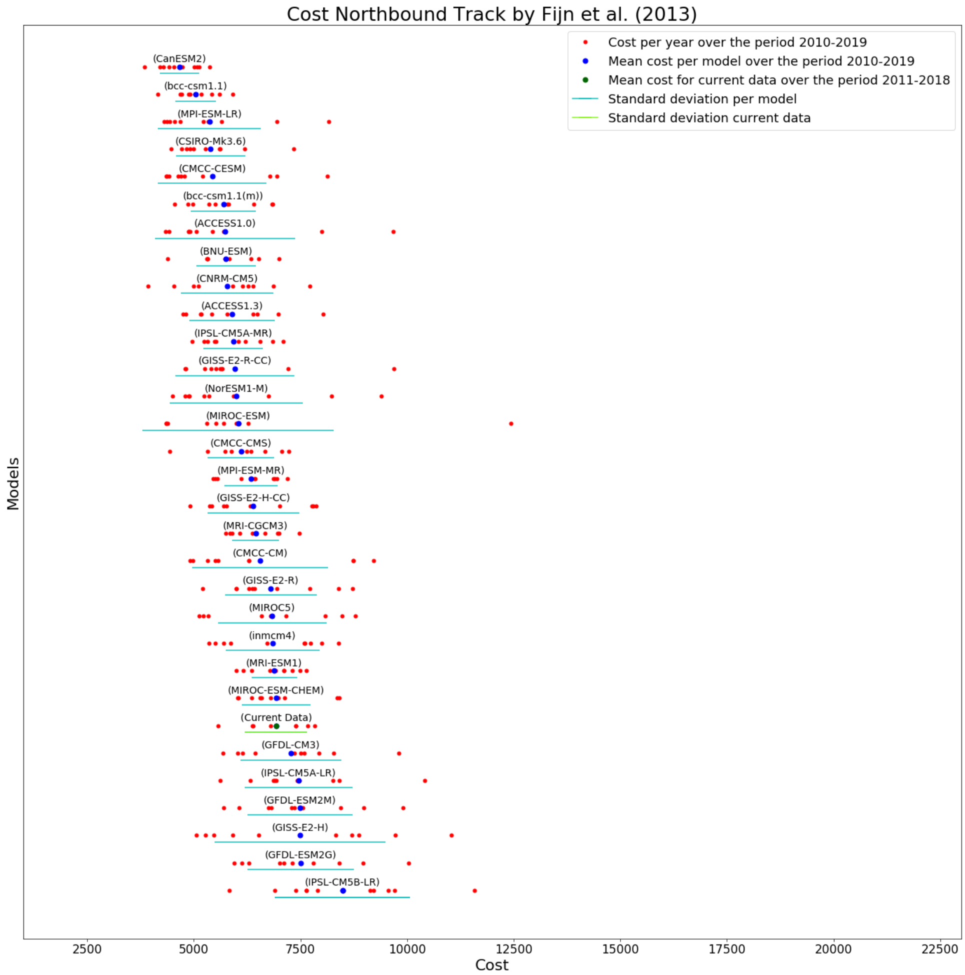
Cost Northbound Track by Fijn et al. (2013)
Cost per year over the period 2010-2019
Mean cost per model over the period 2010-2019
Mean cost for current data over the period 2011-2018
Standard deviation per model
Standard deviation current data
(CanESM2)
(bcc-csm1.1)
(MPI-ESM-LR)
(CSIRO-Mk3.6)
(CMCC-CESM)
(bcc-csm1.1(m))
(ACCESS1.0)
(BNU-ESM)
(CNRM-CM5)
(ACCESS1.3)
(IPSL-CM5A-MR)
(GISS-E2-R-CC)
(NorESM1-M)
(MIROC-ESM)
(CMCC-CMS)
(MPI-ESM-MR)
(GISS-E2-H-CC)
(MRI-CGCM3)
(CMCC-CM)
(GISS-E2-R)
(MIROC5)
(inmcm4)
(MRI-ESM1)
(MIROC-ESM-CHEM)
(Current Data)
(GFDL-CM3)
(IPSL-CM5A-LR)
(GFDL-ESM2M)
(GISS-E2-H)
(GFDL-ESM2G)
(IPSL-CM5B-LR)
Models
2500
5000
7500
10000
12500
15000
17500
20000
22500
Cost

Figure 10

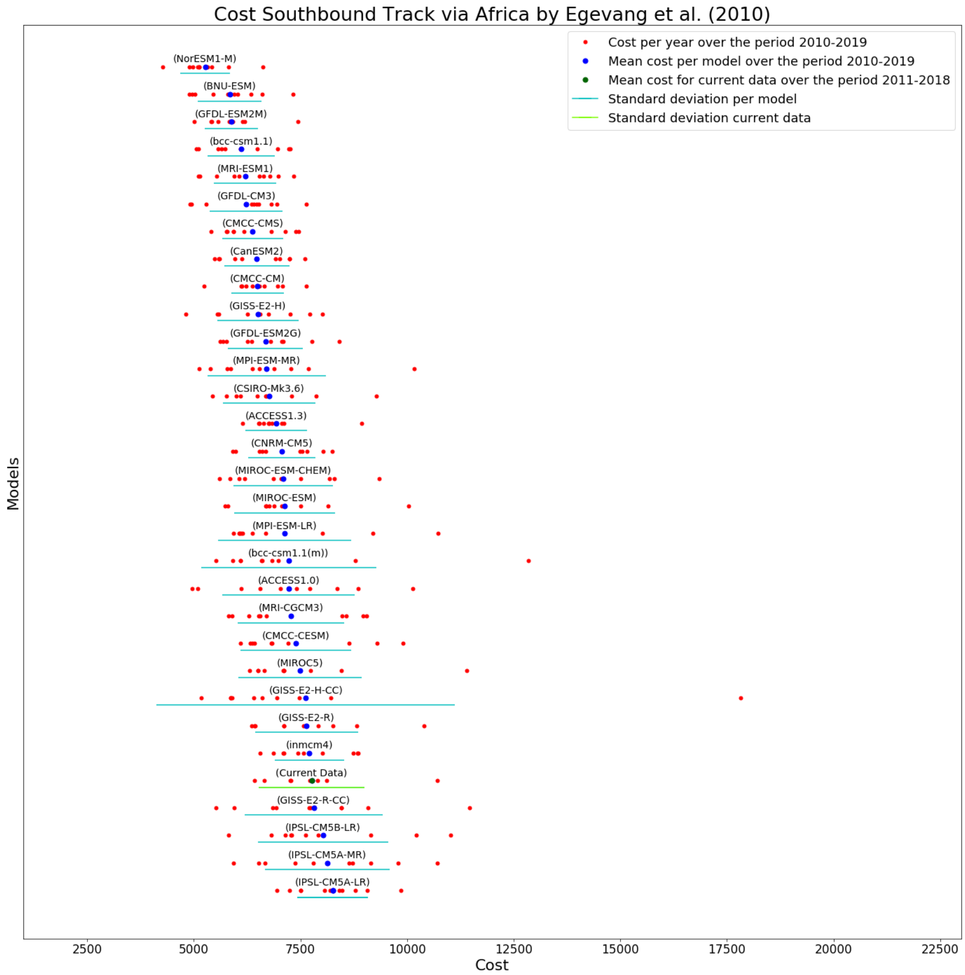
Cost Southbound Track via Africa by Egevang et al. (2010)
Cost per year over the period 2010-2019
Mean cost per model over the period 2010-2019
Mean cost for current data over the period 2011-2018
Standard deviation per model
Standard deviation current data
(NorESM1-M)
(BNU-ESM)
(GFDL-ESM2M)
(bcc-csm1.1)
(MRI-ESM1)
(GFDL-CM3)
(CMCC-CMS)
(CanESM2)
(CMCC-CM)
(GISS-E2-H)
(GFDL-ESM2G)
(MPI-ESM-MR)
(CSIRO-Mk3.6)
(ACCESS1.3)
(CNRM-CM5)
(MIROC-ESM-CHEM)
(MIROC-ESM)
(MPI-ESM-LR)
(bcc-csm1.1(m))
(ACCESS1.0)
(MRI-CGCM3)
(CMCC-CESM)
(MIROC5)
(GISS-E2-H-CC)
(GISS-E2-R)
(inmcm4)
(Current Data)
(GISS-E2-R-CC)
(IPSL-CM5B-LR)
(IPSL-CM5A-MR)
(IPSL-CM5A-LR)
Models
2500
5000
7500
10000
12500
15000
17500
20000
22500
Cost

Figure 11

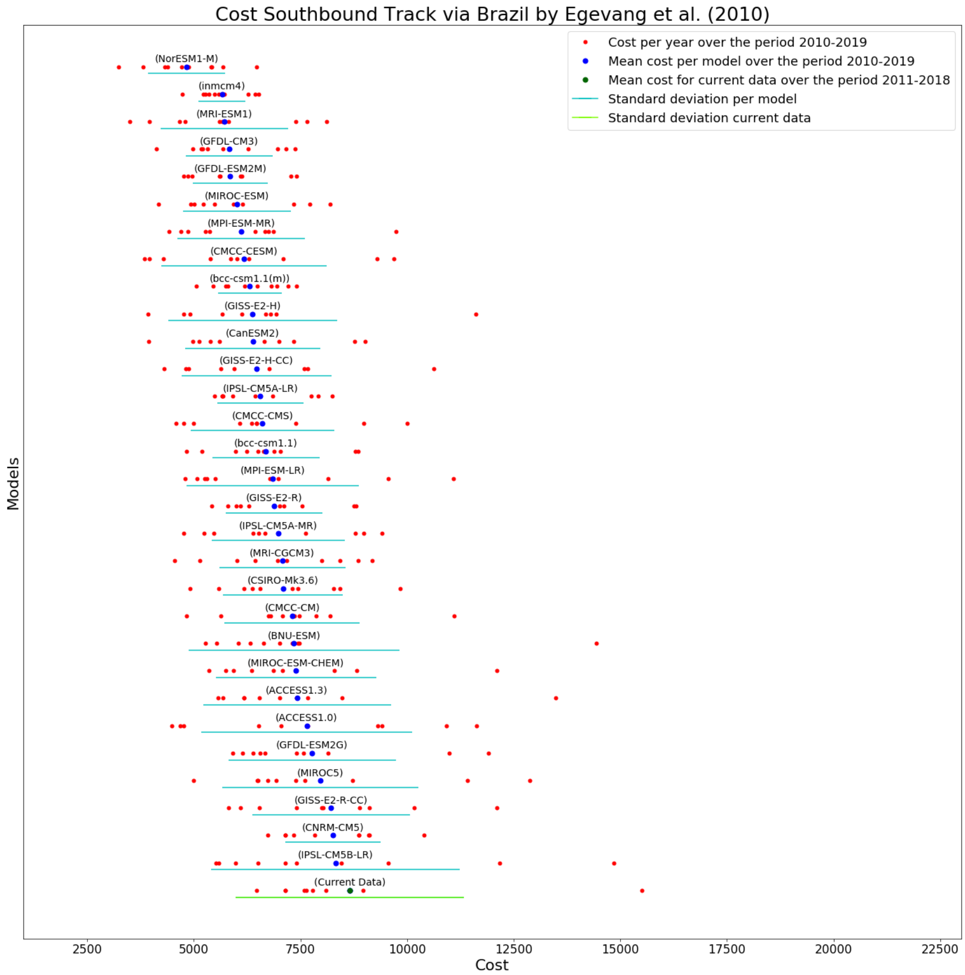
Cost Southbound Track via Brazil by Egevang et al. (2010)
Cost per year over the period 2010-2019
Mean cost per model over the period 2010-2019
Mean cost for current data over the period 2011-2018
Standard deviation per model
Standard deviation current data
Models
Cost
(NorESM1-M)
(inmcm4)
(MRI-ESM1)
(GFDL-CM3)
(GFDL-ESM2M)
(MIROC-ESM)
(MPI-ESM-MR)
(CMCC-CESM)
(bcc-csm1.1(m))
(GISS-E2-H)
(CanESM2)
(GISS-E2-H-CC)
(IPSL-CM5A-LR)
(CMCC-CMS)
(bcc-csm1.1)
(MPI-ESM-LR)
(GISS-E2-R)
(IPSL-CM5A-MR)
(MRI-CGCM3)
(CSIRO-Mk3.6)
(CMCC-CM)
(BNU-ESM)
(MIROC-ESM-CHEM)
(ACCESS1.3)
(ACCESS1.0)
(GFDL-ESM2G)
(MIROC5)
(GISS-E2-R-CC)
(CNRM-CM5)
(IPSL-CM5B-LR)
(Current Data)
2500
5000
7500
10000
12500
15000
17500
20000
22500

Figure 12

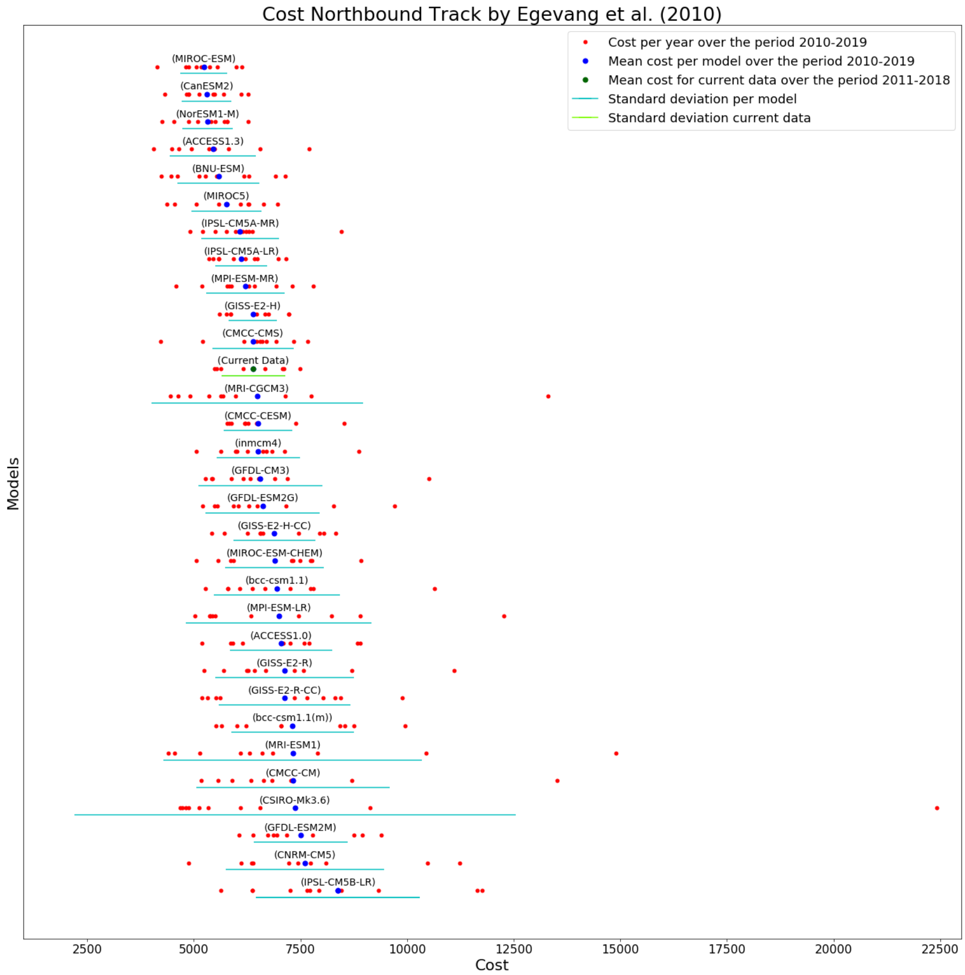
Cost Northbound Track by Egevang et al. (2010)
Cost per year over the period 2010-2019
Mean cost per model over the period 2010-2019
Mean cost for current data over the period 2011-2018
Standard deviation per model
Standard deviation current data
(MIROC-ESM)
(CanESM2)
(NorESM1-M)
(ACCESS1.3)
(BNU-ESM)
(MIROC5)
(IPSL-CM5A-MR)
(IPSL-CM5A-LR)
(MPI-ESM-MR)
(GISS-E2-H)
(CMCC-CMS)
(Current Data)
(MRI-CGCM3)
(CMCC-CESM)
(inmcm4)
(GFDL-CM3)
(GFDL-ESM2G)
(GISS-E2-H-CC)
(MIROC-ESM-CHEM)
(bcc-csm1.1)
(MPI-ESM-LR)
(ACCESS1.0)
(GISS-E2-R)
(GISS-E2-R-CC)
(bcc-csm1.1(m))
(MRI-ESM1)
(CMCC-CM)
(CSIRO-Mk3.6)
(GFDL-ESM2M)
(CNRM-CM5)
(IPSL-CM5B-LR)
Models
2500
5000
7500
10000
12500
15000
17500
20000
22500
Cost

Figure 13

C Flight cost averaged over all climate models per migration track for the current and future situation

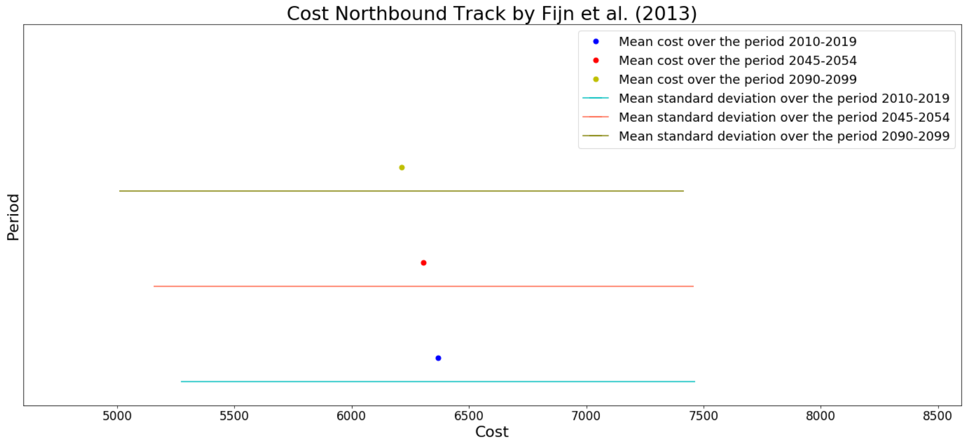

Figure 14: Flight cost and standard deviation averaged over all climate models for the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the northbound migration track of the Dutch birds.

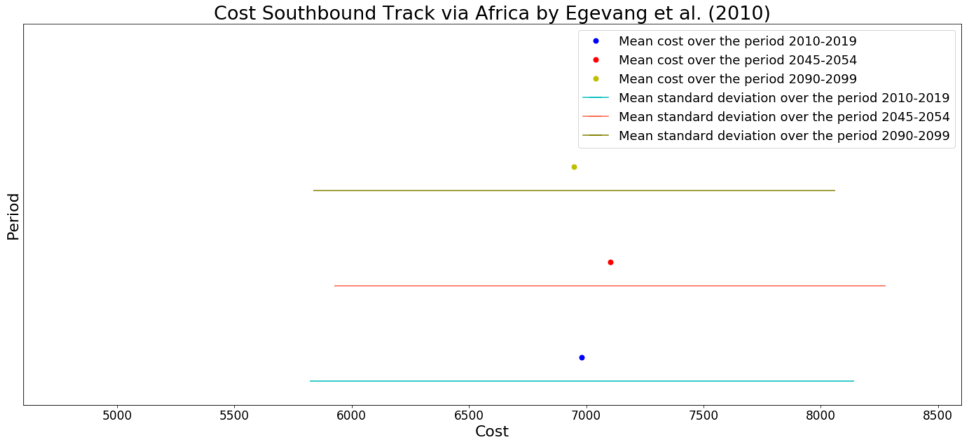

Figure 15: Flight cost and standard deviation averaged over all climate models for the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the southbound migration track via Africa of the Greenlandic birds.

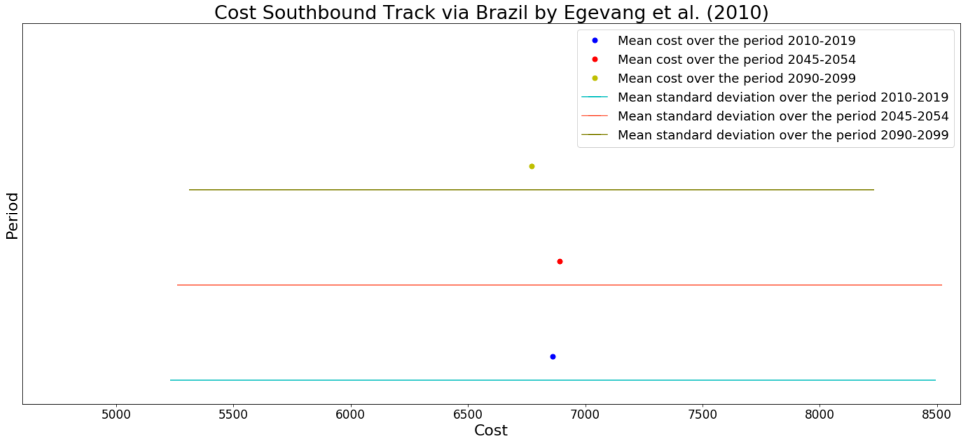

Figure 16: Flight cost and standard deviation averaged over all climate models for the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the southbound migration track via Brazil of the Greenlandic birds.

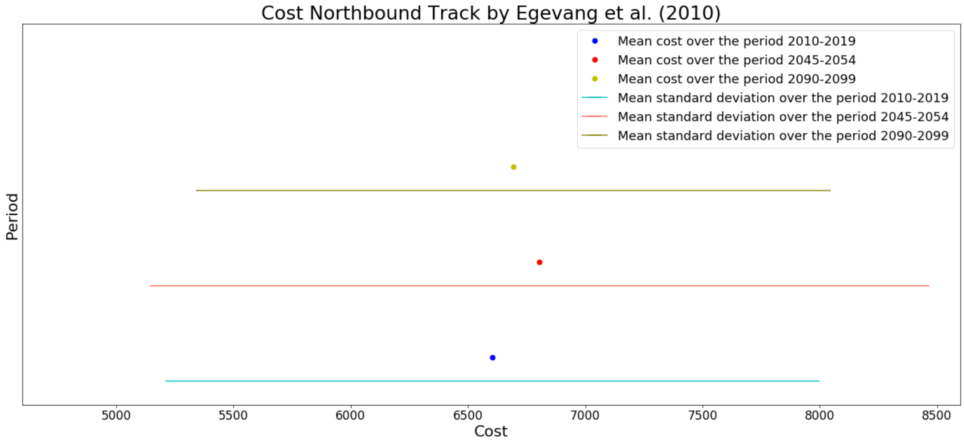

Figure 17: Flight cost and standard deviation averaged over all climate models for the periods 2010-2019 (blue), 2045-2054 (red) and 2090-2099 (yellow) for the northbound migration track of the Greenlandic birds.

D Comparison between the climate models with the highest and lowest flight cost for the current situation

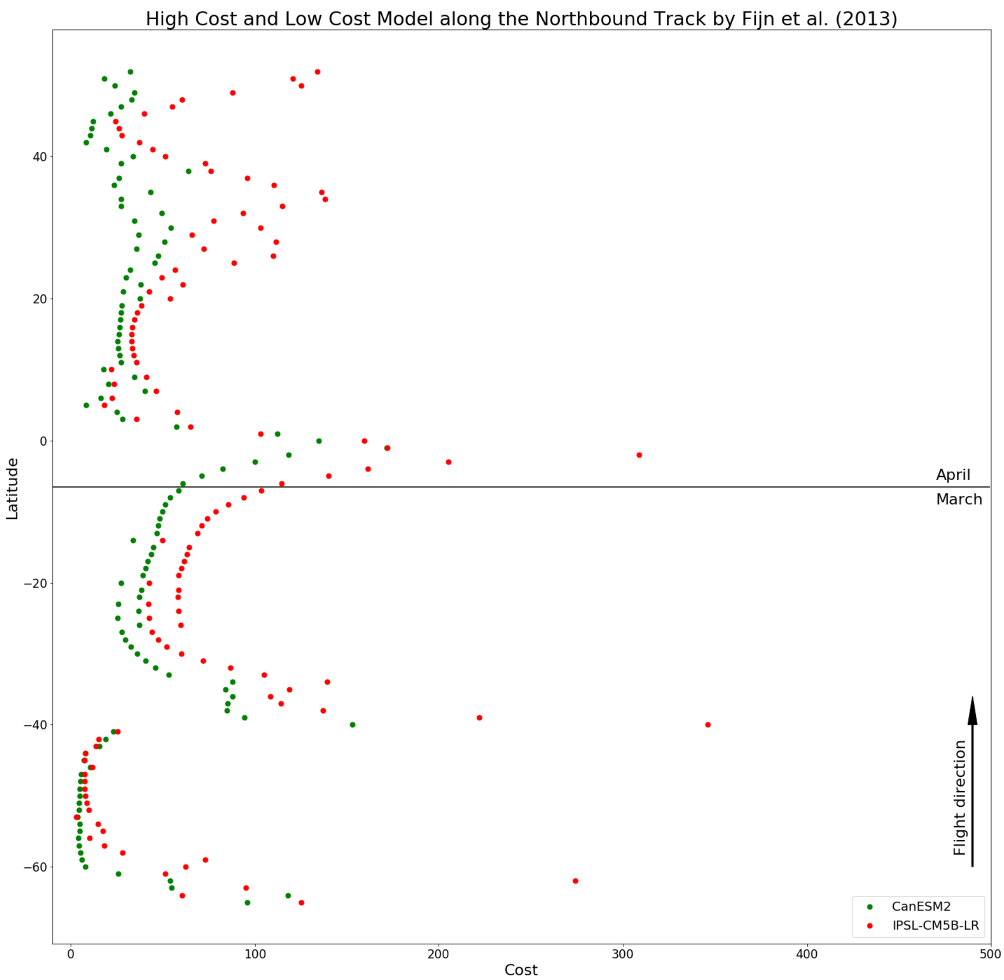

Figure 18: Flight cost per degree latitude for the northbound migration track of the Dutch birds. Green indicates the climate model with the lowest flight cost on this track. Red indicates the climate model with the highest flight cost on this track.

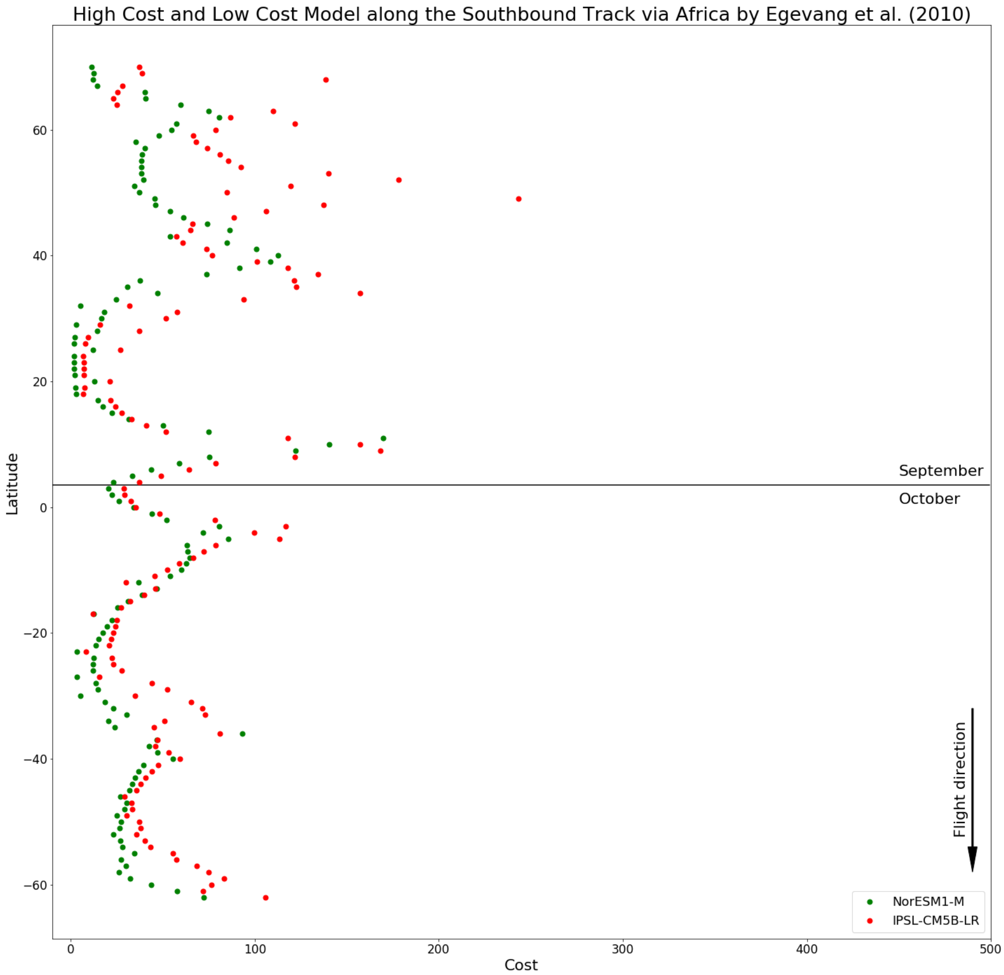

Figure 19: Flight cost per degree latitude for the southbound migration track via Africa of the Greenlandic birds. Green indicates the climate model with the lowest flight cost on this track. Red indicates the climate model with the highest flight cost on this track.

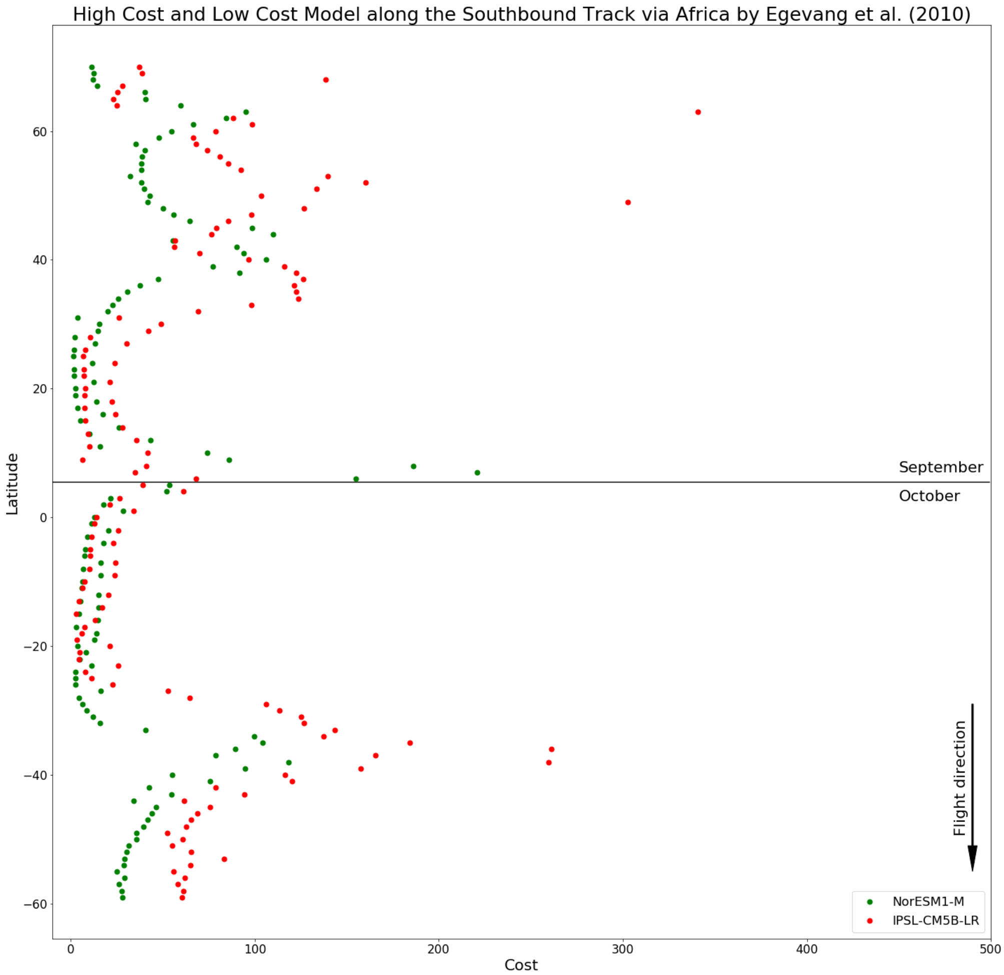

Figure 20: Flight cost per degree latitude for the southbound migration track via Brazil of the Greenlandic birds. Green indicates the climate model with the lowest flight cost on this track. Red indicates the climate model with the highest flight cost on this track.

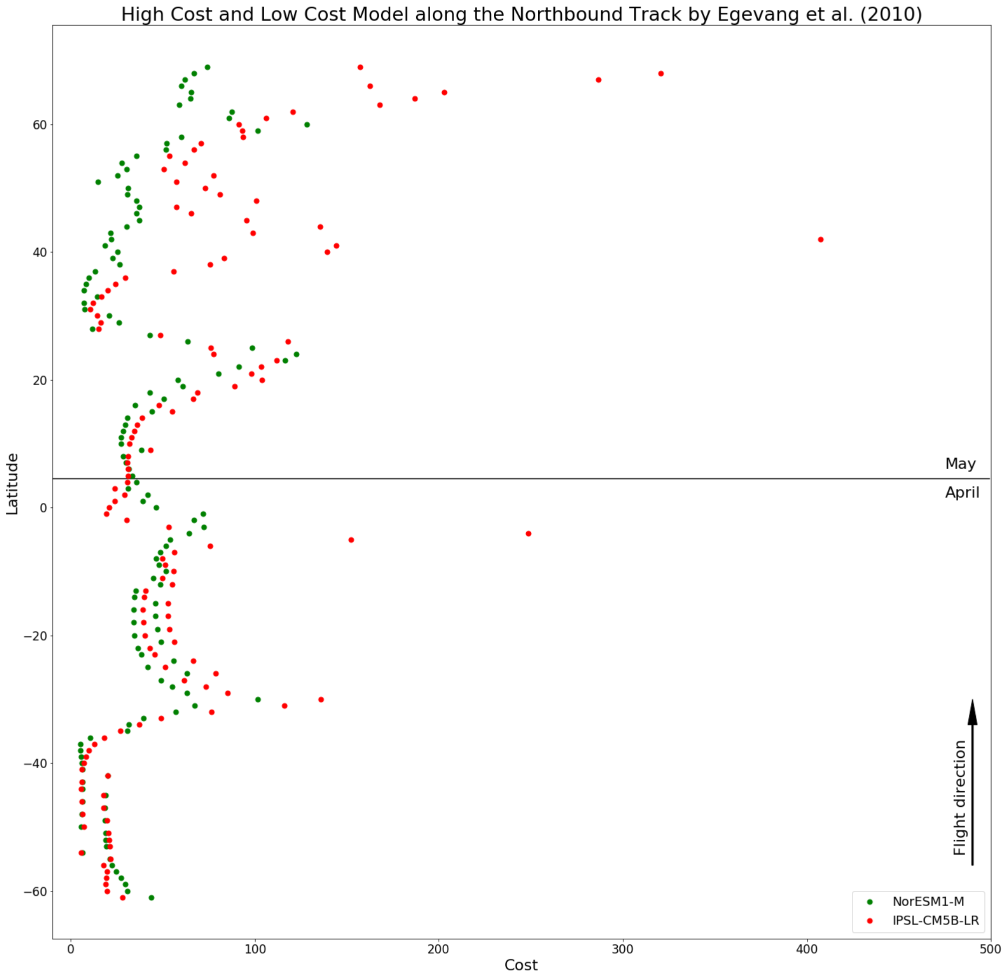

Figure 21: Flight cost per degree latitude for the northbound migration track of the Greenlandic birds. Green indicates the climate model with the lowest flight cost on this track. Red indicates the climate model with the highest flight cost on this track.