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What are the implications of climate change for trans-Atlantic aircraft routing and flight time?

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ABSTRACT

The effect of wind changes on aircraft routing has been identified as a potential impact of climate change on aviation. This is of particular interest for trans-Atlantic flights, where the pattern of upper-level winds over the north Atlantic, in particular the location and strength of the jet stream, strongly influences both the optimal flight route and the resulting flight time. Eastbound trans-Atlantic flights can often be routed to take advantage of the strong tailwinds in the jet stream, shortening the flight time and reducing fuel consumption. Here we investigate the impact of climate change on upper-level winds over the north Atlantic, using five climate model simulations from the Fifth Coupled Model Intercomparison Project, considering a high greenhouse-gas emissions scenario. The impact on aircraft routing and flight time are quantified using flight routing software. The climate models agree that the jet stream will be on average located 1° further north, with a small increase in mean strength, by 2100. However daily variations in both its location and speed are significantly larger than the magnitude of any changes due to climate change. The net effect of climate change on trans-Atlantic aircraft routes is small; in the annual-mean eastbound routes are 1 min shorter and located further north and westbound routes are 1 min longer and more spread out around the great circle. There are, however, seasonal variations; route time changes are larger in winter, while in summer both eastbound and westbound route times increase.

Introduction

It is well-known that greenhouse gas emissions from transport contribute to climate change (e.g. Fuglestvedt et al., 2008; Lee et al., 2009); however climate change itself could have potentially large impacts on the transport sector. Despite this, the most recent Intergovernmental Panel on Climate Change (IPCC) report (Arent et al., 2014) notes that there have been few studies which quantitatively address the impacts of climate change on transport. The aviation sector in particular may be affected by changes to temperature, winds and extremes in weather (see reviews by Koetse and Rietveld (2009) and Peterson et al. (2008)), since its operations both on the ground and in the air are heavily weather dependent.

The focus of this paper is on changes to upper-level winds, particularly the jet stream, caused by climate change. There are several ways in which these could affect the aviation industry. Changes to the position and strength of the jet stream could affect both the incidence of wind storms and the variability in wind direction at airports, both of which influence runway

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capacity (Peterson et al., 2008; Koetse and Rietveld, 2009; Eurocontrol, 2013). A strengthened north Atlantic jet stream has been shown to have the potential to increase the incidence and strength of clear-air turbulence (Williams and Joshi, 2013). Several studies have identified upper-level wind changes as having the potential to impact aircraft routing (Love et al., 2010; Eurocontrol, 2013, 2009), but there is uncertainty as to the size of any impacts. Eurocontrol (2009) suggest that any wind changes will be small and therefore have minimal impacts on aircraft routing; however Eurocontrol (2013) note a potential for increased fuel costs and CO_2 emissions if the jet shifts become large enough that eastbound flights are less often able to take advantage of the strong tailwinds. Williams (2016) analyse the change to aircraft routing under a doubling of CO_2 from pre-industrial levels and find a decrease in eastbound route time and an increase in westbound route time such that the round-trip time increases. Karnauskas et al. (2015) inferred a small increase in route time for flights between Hawaii and the continental US, resulting from an increase in the mean strength of upper-level winds, but the effect on routing was not analysed. This study focuses on the changes to upper-level winds in the north Atlantic and, using multiple climate models with a high emissions scenario, provides quantitative estimates of the impact on trans-Atlantic flight routing, both in terms of route location and route time.

There is a growing scientific consensus that on average the northern hemisphere mid-latitude jet streams may shift northwards with climate change (Meehl et al., 2007; IPCC, 2013). In the near-term (early to mid twenty-first century), there is low confidence in these climate projections since the projected impact on the jet stream is very small compared to the natural variability in the jet stream. In the longer-term (by the end of the twenty-first century), there is medium confidence in a poleward shift of 1–2° in the mid-latitude jet streams if greenhouse gas concentrations remain high (IPCC, 2013). The degree of change to the jet stream is not uniform across the northern and southern hemispheres and also varies by region. For the north Atlantic sector, Barnes and Polvani (2013) estimated a mean poleward shift of 1° in the annual-mean. However on a seasonal timescale, there is less consensus between the models on the direction of the change in latitude or speed, particularly in winter (Woollings and Blackburn, 2012; Barnes and Polvani, 2013; Simpson et al., 2014).

Trans-Atlantic flight routing is strongly influenced by the jet stream. Since typical aircraft cruise altitudes coincide with the altitude of the jet stream, when the jet stream position is favourable eastbound flights can be routed to take advantage of the strong tailwinds in the jet stream, reducing the flight time and fuel use. Conversely, westbound flights can be routed away from the strong headwinds, which would otherwise increase the route time and fuel use. Considering minimum-time routes, Irvine et al. (2013) showed that the time taken to fly the New York to London routes can vary by over 60 min (assuming a constant true airspeed) due to the influence of the varying jet stream winds, and there are strong correlations between the location of the jet stream and the location of the quickest route.

From an economical perspective, changes to aircraft routing matter since wind changes that cause a systematic change in route time will likely change the overall fuel burn and operating cost (since this also has a component related to time in the air). There is an additional motivation, in that changes to fuel use imply changes to CO_2 emissions, since the two are directly related. Aircraft CO_2 emissions are currently around 2.5% of the total global CO_2 emissions and likely to be the largest impact of aviation on climate (Lee et al., 2009). There is substantial pressure on the aviation industry to reduce its CO_2 emissions. The question is, will climate change work for or against the aim of reducing CO_2 emissions? Fuel burn and related CO_2 emissions are not directly studied here. However, minimum-time routes minimise the air-distance flown at a constant altitude, which is equivalent to minimising fuel burn.

This paper analyses climate model predictions of the change in flight-level winds between the present-day and 2100 under a high greenhouse gas emissions scenario, with a particular focus on the jet stream over the north Atlantic. This analysis uses freely-available climate model data used in the latest climate change assessment by IPCC (2013). A description of the climate model data, and method to calculate the position and strength of the jet stream are given in Section 'Jet stream analysis'. The associated impacts on trans-Atlantic air traffic are assessed by using modelled present-day and future flight-level winds input to flight routing software to calculate daily minimum-time routes between London and New York, and Madrid and Miami. This allows a quantitative estimate of the impact of climate change on flight routing, both in terms of changes to the location of the optimum routes and the time taken to fly them. The flight routing software is described in Section 'Route analysis'. Results are presented in Section 'Results' and conclusions in Section 'Discussion and conclusions'.

Methodology

Jet stream analysis

Wind data were used from climate model simulations of the present-day and future climates from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble (Taylor et al., 2012). These data are freely available through the Earth System Grid Federation (http://pcmdi9.llnl.gov/esgf-web-fe/). For the purposes of this study, daily-mean wind data were used. Of the few pressure-levels at which daily data are available, only 250 hPa, which equates to a pressure altitude of 34,000 ft, corresponds to typical aircraft cruise altitudes (the nearest alternative levels in the CMIP5 data archive are well above and below the range of standard aircraft cruise altitudes); hence model data on a pressure-level of 250 hPa were used here. Data were used from two experiments: to study the present-day climate, data were used from the historical simulation, for the period 1979–2005, and to study the impact of climate change data were used from the representative concentration pathway 8.5 scenario (RCP8.5) for the period 2073–2099. The historical simulation replicates the present-day climate by forcing the climate models with measured greenhouse gas concentrations. Of course, the exact future evolution of greenhouse gas concentrations is not known, and so the greenhouse gas concentrations used in the future climate scenario have to be estimated following various radiative forcing scenarios which represent possible future socio-economic scenarios. The RCP8.5 simulation used here simulates one possible scenario for the future climate where greenhouse gas emissions reach high levels with little mitigation, leading to an increase in global-mean surface temperature of about 4 °C and a radiative forcing of 8.5 W m^{-2} by 2100 (Taylor et al., 2012). This is the scenario with the highest greenhouse gas emissions and the largest degree of warming considered by IPCC (2013); using the RCP8.5 scenario allows us to estimate the maximum likely changes to the jet stream by the end of this century.

Due to the large computational requirements, we selected only a sub-set of the available CMIP5 models to analyse (Table 1). The 5 models selected for this study are: EC-EARTH (Hazeleger et al., 2010), GFDL-ESM2G (Dunne et al., 2012), HadGEM2-CC (Martin et al., 2011; Collins et al., 2011), MIROC5 (Watanabe et al., 2010) and MPI-ESM-MR (Stevens et al., 2013). The selection of these models was influenced by previous studies of this dataset. The chosen models have been shown to be able to represent, in a realistic manner, key large-scale features of the atmospheric circulation over the north Atlantic such as the north Atlantic oscillation (Lee and Black, 2013; Davini and Cagnazzo, 2013). They also show a range of jet stream behaviour (Barnes and Polvani, 2013). The horizontal resolution of the models chosen varies from 1.2° (EC-EARTH) to 2.0° (HadGEM2-CC). For the purposes of this study, the model data were used at their native resolution; an analysis of the possible effects of the different wind resolutions on the routing results is given in Section 'Route analysis'.

To analyse biases in the climate model simulations of the present-day climate, historical simulations from the climate model are compared to the European Centre for Medium-Range Weather Forecasts Interim re-analysis data (ERA-Interim; Dee et al., 2011). Unlike climate model data, which seeks to represent only the statistics of the mean climate over a time period, re-analysis data combines weather forecast models with observations to provide our best estimate of the state of the atmosphere over a time-period, and ERA-Interim is one such re-analysis dataset. It can therefore be used as the 'truth' against which to evaluate the ability of climate models to reproduce the statistics of key atmospheric circulation patterns and features, for instance the jet stream, in the present-day climate. ERA-Interim re-analysis data are available for the period 1979–2005 at 0.7° horizontal resolution and we use the same 250 hPa pressure level as the CMIP5 data.

A key feature of the wind pattern over the north Atlantic, in terms of its influences on trans-Atlantic flights, is the jet stream. The orientation of the jet stream in climate models is generally too zonal, such that the jet stream in the eastern north Atlantic is located on average further south than observed (e.g. Woollings and Blackburn, 2012). The analysis in this paper therefore calculates separately the daily position and speed of the jet stream in the east and west north Atlantic, using daily-mean wind data from both ERA-Interim and the CMIP5 models. We defined the west Atlantic sector as the region 40–60°W, bounded by 30–75°N latitude, and the east Atlantic sector as 0–20°W with the same latitude bounds. To find the jet stream latitude, we first zonally-averaged the wind speeds over the sector of longitude. We defined the jet stream as the speed and latitude of the maximum in the zonally-averaged wind speed, for each of the east and west sectors. This method identifies a jet stream every day, since there is no wind speed threshold applied. It is important to note that the wind speed values for the jet speed shown here will be considerably lower than the maximum wind speeds observed in the jet stream, since we average the wind speeds over a sector of longitude to find the jet stream.

Route analysis

Minimum-time routes are calculated using optimum-routing software. The method for finding the quickest route through a given wind field is based on Sawyer (1949) and Lunnon and Marklow (1992), who give the theoretical derivations for these calculations; a more basic description is given here. Given a wind field on a constant pressure level, the routing code seeks to solve an equation which relates the rate of change of aircraft heading (θ) to the curvature of the wind (Sawyer, 1949):

$$d\theta/dt = \partial u/\partial n \qquad (1)$$

where t is time, u is the tailwind (i.e. the component of the wind in the direction θ); and n is at right angles and left to the direction given by the nose heading θ. The direction that the aircraft travels relative to the ground is the ground-track angle which is the sum of the aircraft heading θ and the drift angle. In practice, optimum routes are found by iterating through a suitable range of starting angles from the start point, until a route is produced which passes through the destination.

The optimum routes produced by this software are comparable to those produced using the Met Office in-house optimum routing software, which has the same theoretical basis, and has been documented and used by previous studies (e.g. Lunnon and Mirza, 2007; Irvine et al., 2013). Since the route location and time taken to fly the route depend only on the wind field, this allows a clear investigation into the sole effect of any wind changes on the routing, which would be obscured by incorporating aircraft performance or air traffic control constraints.

There are several simplifying assumptions that are made to allow the fast computation of the routes. Firstly, we assume that the aircraft flies at a constant altitude between the origin and destination, thus neglecting both take-off and landing and any changes in flight-level. In practice, aircraft do not remain at a single level throughout a flight, but perform step increases in flight altitude as the aircraft burns fuel and becomes lighter during the flight. A fixed pressure altitude of 250 hPa (34,000 ft) was used, which is in the middle of the range of permitted cruise altitudes over the north Atlantic, and the pressure level for which daily climate model output was available. It is also assumed that aircraft fly at a constant true airspeed of 250 m s^{-1} (900 km h^{-1}, Mach 0.84) during the flight.

Table 1
Characteristics of the re-analysis data (top line, in bold) and CMIP5 models used in this study. The mean jet latitude and jet speed in the west Atlantic, plus/minus one standard deviation (calculated using daily-mean data) are shown for the present-day climate (1979–2005).

Model name	Centre	Horizontal resolution	Jet latitude (°N)	Jet speed ($m\ s^{-1}$)
ERA-Interim re-analysis	**European Centre for Medium-Range Weather Forecasts**	**0.7°**	**48.0 ± 9.1**	**49.7 ± 12.1**
EC-EARTH	EC-EARTH consortium	1.125°	47.7 ± 8.5	47.7 ± 11.5
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	2.0° lat, 2.5° lon	44.8 ± 7.9	44.1 ± 10.6
HadGEM2-CC	Met Office Hadley Centre	1.25° lat, 1.875° lon	48.4 ± 9.4	47.2 ± 12.3
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, Japan Agency for Marine-Earth Science and Technology	1.4°	45.9 ± 9.7	47.3 ± 11.0
MPI-ESM-MR	Max Planck Institute for Meteorology	1.875°	46.0 ± 8.7	50.1 ± 12.5

The optimum routing code was used to compute one eastbound and one westbound route for each day in the two time periods 1979–2005 and 2073–2099, using the daily-mean winds from the climate models (for both time periods) and ERA-Interim (for the present-day only).

For computational reasons it was not possible to calculate minimum-time routes for all city-pairs corresponding to trans-Atlantic routes. We therefore chose to calculate routes between New York and London, and use these as a proxy for the location of the bulk of the trans-Atlantic air traffic. In reality, there would obviously be some spread in the location of trans-Atlantic air traffic on any given day due to the varying start and end points of the flights, and the need to ensure safe separation between aircraft. However we have previously found good agreement between the location of the north Atlantic tracks, which are defined daily by air traffic control and on which a large proportion of trans-Atlantic air traffic fly, and the location of the New York to London minimum-time routes used in this study (Irvine et al., 2013). As a limited test that our results are generalizable for other trans-Atlantic city-pairs, the study was repeated with minimum-time routes calculated between two additional city pairs: London and Chicago, and Madrid to Miami. The great circle route between Madrid and Miami is to the south of the main north Atlantic air traffic but is still influenced by the movement of the jet stream. Comparable results were obtained to those shown for the New York to London route; some results for the Madrid to Miami route are discussed in Section 'Results'. We do not study the effect of wind changes on city pairs which are north of the bulk of the trans-Atlantic air traffic, since these are not influenced by the jet stream and therefore outside the scope of this study.

The daily optimum routes are run on the wind data from the CMIP5 models described in Section 'Jet stream analysis'. The wind data are input to the routing software at their own resolution (given for each model in Table 1), which varies by model from 1.2° to 2.0°. Lunnon and Mirza (2007) found minimum-time routes using their routing software to be relatively insensitive to changes in wind resolution from 40 km to 160 km (approximately 0.4–1.4°), but did not test resolutions coarser than this.

To investigate the impact of the resolution of the climate model wind data input to the optimum routing software on the resulting route time, we took the full 0.7° resolution ERA-Interim data and re-gridded it to the lower resolutions of 1.2°, 2.0°, 3.0° and 5.0°. Daily optimum routes for winters 1979–2005 were then run through these data. Fig. 1 shows the impact on the resulting optimum route time. The mean change in route time is −0.05 min for an input wind resolution of 2.0° compared to the full-resolution data, and changes to the minimum and maximum route times of 2 min. This is the approximate coarsest resolution of climate model data used in this study. 1.2° resolution wind data is approximately the resolution of the EC-EARTH data, the highest resolution climate model data used in this study. None of the data used in this study are as coarse as the 3.0° or 5.0° resolution data; these are shown to illustrate that the model resolution has a small impact on the mean route time, although it has larger impacts on the minimum and maximum times. We conclude from this that the optimum routing is relatively insensitive to reasonable changes in the resolution of the input wind data, and is therefore unlikely to impact the results of this study.

Results

Jet stream analysis

The jet stream latitude and speed were calculated every day for the present-day and future climate periods for the west Atlantic and east Atlantic sectors. Fig. 2 shows the annual-mean values for the present-day and future climate (present-day mean values for the west Atlantic are also shown in Table 1); the standard deviation in the daily values is shown as a measure of the variability in the jet stream in both time periods.

First, we assess the simulation of the jet stream in the present-day climate. The annual-mean jet stream latitude and speed in ERA-Interim are shown by horizontal lines on Fig. 2. The EC-EARTH and HadGEM2-CC models have a comparable climatological jet latitude to ERA-Interim in the west Atlantic, with other models showing a southward bias in their climatological jet position (Fig. 2a). All models have significant southward biases in the position of the jet in the east Atlantic; additionally the difference between the jet latitude in east and west sectors is smaller than in ERA-Interim, which confirms

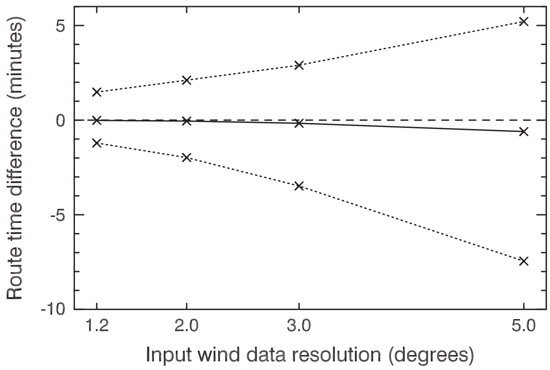

Fig. 1. The effect of the horizontal resolution of the wind data input into the optimum routing software on the resulting eastbound route times, for the New York to London route. Here, the resolution of the input wind data is given in degrees latitude. The route time difference is calculated as the route time using the full-resolution wind data (ERA-Interim at 0.7° resolution) minus the route time computed using ERA-Interim data at the reduced resolution. The difference in the mean (solid line), minimum (bottom dotted line) and maximum (top dotted line) route times are shown.

that in the present generation of climate models the orientation of the north Atlantic jet stream remains too zonally-oriented compared with observations. The jet streams simulated in the CMIP5 models are also generally weaker than in ERA-Interim; with the exception of MPI-ESM-MR, the modelled jet speeds are slower, although the variability in the jet speeds is similar (Fig. 2b).

The changes to the jet stream from the present-day to future climate are now discussed. The annual-mean location of the jet stream is predicted to move northwards in all models (Fig. 2a), with a mean increase of 0.8° in the west Atlantic (range: 0.3–1.1° from the five models), and 1.1° in the east Atlantic (range: 0.2–2.0°). The mean jet stream speed is also predicted to increase in all models (Fig. 2b), with a mean increase in the sector-averaged wind speeds of 0.9 m s^{-1} in the west Atlantic (range: −0.2 to 1.6 m s^{-1}) and 1.5 m s^{-1} in the east Atlantic (0.3–2.6 m s^{-1}). Note that these increases in jet stream latitude and speed are small compared to the size of the day-to-day variations in jet stream characteristics (the standard deviations in the daily values are shown by the vertical lines in Fig. 2). Since the speeds shown in Fig. 2 are averaged over a sector of longitude they do not reflect the magnitude of any possible increases in peak wind speed within the core of the jet stream.

The results shown in Fig. 2 are annual-mean changes. However, jet stream characteristics exhibit some seasonal dependency; for instance the jet stream is on average stronger and located further north in winter than summer (not shown). Therefore the annual-mean changes shown in Fig. 2 may have some seasonality to them. To investigate this, the jet stream analysis was repeated, but data selected for only winter (December, January and February) or summer (June, July and August). In winter, the climate models disagree on the direction of movement of the jet stream, but all show an increase in jet speed across the Atlantic sector. The mean increase in jet speed is 3.0 m s^{-1} in the west Atlantic and 2.5 m s^{-1} in

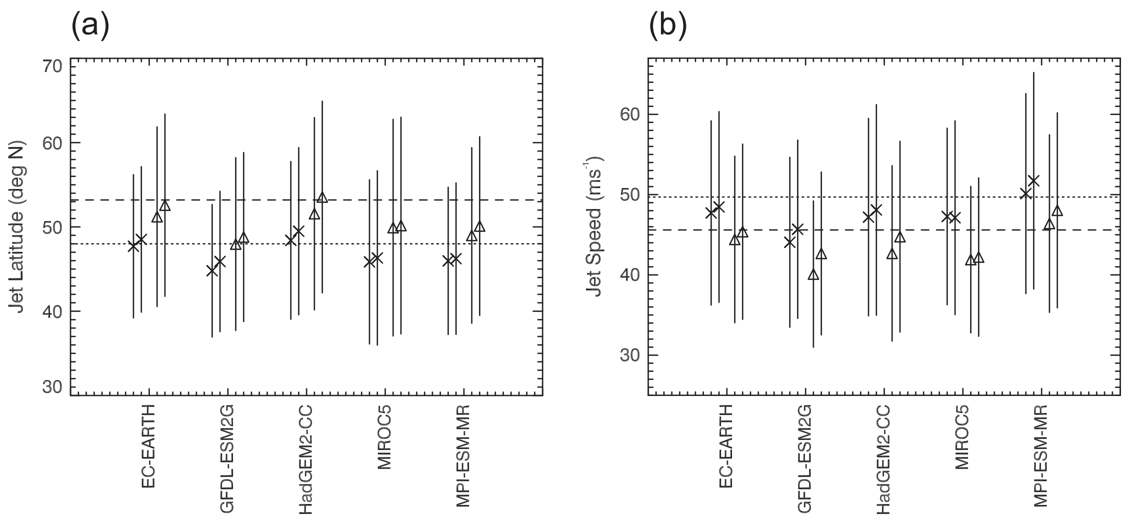

Fig. 2. (a) The mean jet latitude in the west Atlantic (cross) and east Atlantic (triangle) in five different climate models. For each pair of points, the mean value in the present-day climate (symbol) and daily variability given by the standard deviation (solid line) is on the left, and the mean value and its standard deviation in the future climate, 2073–2099, in a high greenhouse gas scenario is on the right. For comparison, the mean jet latitude in the ERA-Interim re-analysis data for the period 1979–2005 is shown for the west (dotted lines) and east Atlantic (dashed lines). (b) As (a) but for the jet speed.

the east Atlantic. However, in summer the climate models agree on a northward movement of the jet stream of 1.1° in the west Atlantic and 2.2° in the east Atlantic, but there are no consistent wind speed changes across the models.

Route analysis

There is considerable daily variability in the strength and position of the jet stream in the present-day climate, as shown in Fig. 2. The impact that this has on the variability in minimum-time route location in the present-day is shown in Fig. 3. Fig. 3 shows gridded minimum-time route data for the New York to London city pair, for every day in winter 1979–2005, where the route data were calculated using ERA-Interim winds. The data are gridded onto a regular latitude-longitude grid, and displayed as the number of days per winter per 100 km^2 area. In the absence of wind the quickest route would always be the great circle route (the black line connecting New York and London in Fig. 3); Fig. 3 shows considerable deviations away from the great circle route due to the influence of the jet stream winds. The spread in the route location corresponds to the variation in upper-level winds over the north Atlantic. The climatological (mean) winter winds in ERA-Interim are plotted as contours in Fig. 3. For eastbound routes (Fig. 3a), the distribution of routes is highest close to the core of the jet stream, to the south of the great circle route. However, there is also considerable variability in the location, caused by the daily movement of the jet stream winds. For westbound routes (Fig. 3b), the distribution of routes is more spread out, away from the departure and arrival points. The mean location of the routes is to the north of the great circle route, away from the strongest jet stream winds.

To assess the impact of the wind changes shown in Fig. 2 on the minimum-time routes, minimum-time routes were calculated from the climate model winds. Fig. 4 shows the change in the location of the time-optimum routes, between the present-day climate and future climate. For each model, daily time-optimum routes were calculated using the wind data from that model, and the routing data output gridded. The change in route location from present-day to future climate was then calculated from the gridded data, separately for each climate model, and the annual-mean results averaged. In Fig. 4 positive values indicate where, in a future climate, routes are more often located, and negative values where they are less often located. The impact of the wind changes on the location of the north Atlantic routes is on average small. There is a general northward shift in eastbound air traffic (Fig. 4a), but only on 2% of days. For westbound routes the changes are not a simple shift, but rather indicate that the distribution of routes becomes more spread out than at present (Fig. 4b).

The level of agreement between the five different models is shown by stippling in Fig. 4; areas which are stippled show where at least three out of the five models agree on the direction of the change (i.e. an increase in routes at that location or a decrease in routes at that location as a result of the change in winds). There is good agreement on the sign of the change for both eastbound and westbound flights. It is important to note that the results shown here for the route location will be to some extent affected by the bias in the wind data in the present-day climate shown in Fig. 2. The results shown in Fig. 4 are an average over the five models; individual models show larger changes, depending on the size of the simulated change to the winds.

The mean route times for routes using present-day winds from the different climate models are shown in Table 2. There is a range of 6–7 min in the mean route times from the different models. These differences between the models are two orders of magnitude greater than the differences in route time generated by routes run on the same winds given to the routing software at different horizontal resolution (Fig. 1). We can therefore be confident that the differences shown in Table 2 are due to the slightly differing representations of the atmospheric circulation in the climate models and not due to the differing horizontal resolution of the modelled wind data used in the routing software.

Changes to the route times in a future climate are shown in Table 2. The distribution of route times is approximately Gaussian, hence it is appropriate to consider a mean time. We also look at the change to the variability, using the minimum and maximum route times to examine changes to the extremes of the distributions. For eastbound routes, there is agreement between the models on a negligible or small reduction in route times. The future routes are on average 0.8 min shorter than the present-day routes, which corresponds to the small increase in jet speed in the climate model simulations. Conversely, the models agree on a small increase in route times for westbound routes, with the exception of routes calculated on winds from the HadGEM2-CC climate model. The mean change in westbound route time is an increase of 1.0 min. Since westbound routes avoid the jet stream, an increase in the strength of jet stream winds does not necessarily explain this result. In the absence of wind changes, an increase in mean flight distance of 15 km would be required to explain this change; however the mean increase in westbound flight distance is only 5.2 km. Hence it is a combination of small increase in flight distance from some flights being located further north, and a small increase in mean headwind along the route which contributes to this increase in route time.

Whilst there is little change to the variability of the route times in terms of the standard deviations (not shown), there are changes to the extreme values. For westbound routes, the models show an increase in the range of route times of around 7 min, mostly from an increase in the longest route time. MIROC5 shows a reduction in the range of route times (an increase in shortest route time and a decrease in the longest), but these changes are not significant at the 99% level. The changes to the minimum and maximum route times are smaller for the eastbound flights, with a mean increase in the range of route times of only 2 min. The time changes are statistically significant at the 99% level for the EC-EARTH, GFDL-ESM2G and MPI-ESM-MR models (calculated using a student *T*-test).

The effect of the wind changes in summer and winter on the route time was also analysed. The winter-mean changes in route time ranged from a mean decrease of 3 min to a mean increase of 3 min, depending on which climate model winds

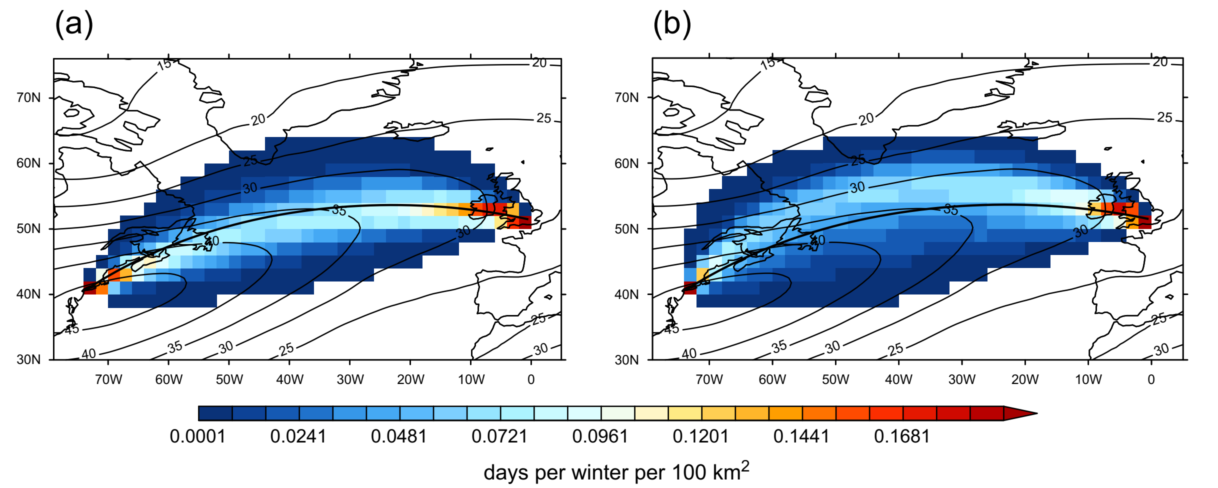

Fig. 3. Gridded daily optimum route data (colours) for (a) eastbound New York to London routes and (b) westbound London to New York routes. The gridded data show the number of days per winter that the daily optimum route passes through that area. The thick black line shows the location of the great circle route between the two cities. The mean wind field (black contours) shows the winter-mean location and strength of the jet stream at 250 hPa. Using daily-mean ERA-Interim data, 1979–2005 for winter (December, January and February). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

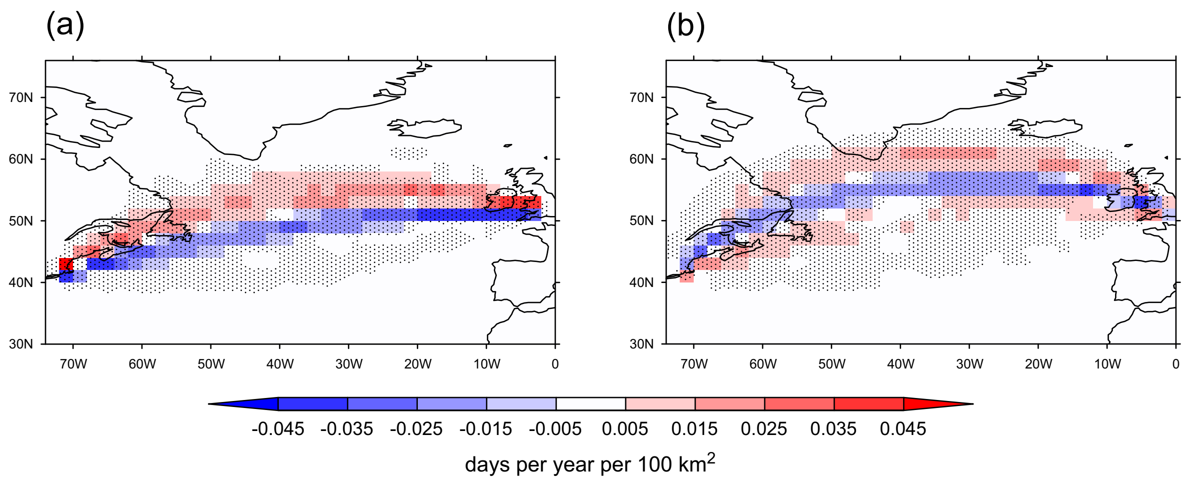

Fig. 4. The annual-mean change (in colours) in the location of (a) eastbound and (b) westbound New York to London optimum routes, from a present-day climate (1979–2005) to future climate (2073–2099). Calculated as the change in the number of days a year that the daily optimum route would go through that area, where positive (negative) values represent more (fewer) routes in that area per year. This is the mean change, averaged over all five climate models. To indicate the level of agreement between the different climate models, black stippling shows locations where at least three out of the five models analysed agree on the sign of the change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

were used. All models except HadGEM2-CC showed a decrease in route time for eastbound flights. For summer, the maximum change in mean route time was 2 min. For both eastbound and westbound flights, four out of five models showed increases in route time, although these were small. Note that these results differ from Williams (2016) who did not find any seasonality to his route time changes, using an older climate model and different emissions scenario.

To put the route time changes into perspective, it is useful to examine the year to year variability in the seasonal-mean route time (Fig. 5). Fig. 5 shows, for the EC-EARTH climate model, the departure of the winter-mean route time from the long-term winter-mean route time, calculated for the present-day period 1979–2005 (Fig. 5a) and 2073–2099 (Fig. 5b), and separately for eastbound and westbound flights. There is considerable year to year variability in the route time, which we know to be due to the large variability in jet stream location due to the large-scale circulation patterns in the north Atlantic (Irvine et al., 2013). Also of note is the anti-correlation between eastbound and westbound route time; in seasons where the eastbound route times are shorter than average the westbound route times are longer than average and vice versa. The variability in route times in the future climate is just as large as that in the present-day climate; the standard deviation in

Table 2
For the time-optimal routes, the annual mean route time, minimum and maximum route times in route times in the present-day climate (1979–2005) and changes to these quantities, calculated as future (2073–2099) minus present-day climate. Units are minutes.

Model	Mean route time	Change in mean	Minimum route time	Change in minimum	Maximum route time	Change in maximum
Eastbound						
EC-EARTH	334.4	−0.7	283.1	−0.1	383.6	0.4
GFDL-ESM2G	335.9	−2.4	292.4	−0.6	378.9	5.1
HadGEM2-CC	336.5	−0.01	286.4	1.4	385.0	0.2
MIROC5	339.7	0.03	295.2	−2.2	385.8	−3.0
MPI-ESM-MR	333.7	−1.1	282.6	0.4	380.3	6.3
Mean	*336.0*	*−0.8*	*287.9*	*0.2*	*382.7*	*1.8*
Westbound						
EC-EARTH	395.4	1.1	343.3	1.9	457.2	6.6
GFDL-ESM2G	397.0	2.7	349.4	−3.5	452.2	6.2
HadGEM2-CC	393.8	−0.7	345.7	−2.1	451.5	9.4
MIROC5	389.9	0.3	341.6	4.6	452.7	−5.3
MPI-ESM-MR	394.1	1.4	344.5	−10.7	460.4	6.5
Mean	*394.0*	*1.0*	*344.9*	*−2.0*	*454.8*	*4.7*

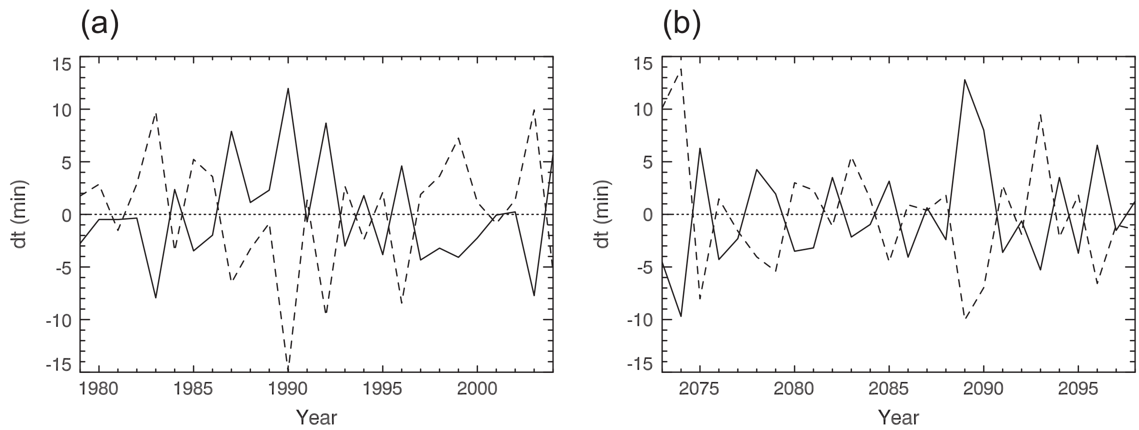

Fig. 5. For the New York to London optimum routes calculated using EC-EARTH winds, a time series of the departure of each individual winter-mean route time from the (a) 1979–2005 and (b) 2073–2099 winter-mean route time. These are calculated and shown separately for eastbound (solid line) and westbound (dashed line) routes.

daily route times in each winter in both present-day and future climates ranges from 8 min to 20 min in this climate model. It is clear then that the mean changes in route times of a few minutes caused by climate change are small compared to the variability in the route times.

Thus far results have been presented for the New York to London route. To test the applicability of our results to other trans-Atlantic routes, we calculated routes between Miami and Madrid, for winter and summer using winds from the GFDL-ESM2G and EC-EARTH climate models. The great circle route between these cities is to the south of the New York to London route and is therefore also further south than the bulk of the trans-Atlantic air traffic; however the influence of the jet stream is still important. Indeed, for winters with very different jet stream behaviour, the eastbound and westbound route distributions agree with those for the New York to London route. For a more northerly jet stream in a positive NAO the eastbound minimum time routes are located mostly to the north of the great circle; for a southerly jet stream in a negative NAO eastbound routes are located mostly to the south of the great circle route. The change in route time under the future climate winds was consistent with those for the New York to London route. In winter, the mean eastbound route time was 3–4 min quicker, and the mean westbound route time was slower by 5–6 min. In summer, the mean route time increased by up to 2 min, regardless of route direction. That these changes are consistent with the changes found for the New York to London route adds strength to the argument that the results shown here are generalizable for the bulk of trans-Atlantic air traffic.

Discussion and conclusions

Changes to upper-level winds, in particular the jet streams, have been identified as one possible impact of climate change that could have an effect on aviation, through aircraft routing (Eurocontrol, 2009, 2013; Love et al., 2010). This is of particular interest for trans-Atlantic flights, since their location and duration are strongly influenced by the strength and location of the jet stream (Irvine et al., 2013). This study provides a quantitative assessment of both the changes to flight-level winds in the north Atlantic, and the impact of these changes on trans-Atlantic flight routing and flight time.

Wind data from five climate models in the CMIP5 multi-model archive were analysed to assess the size of projected changes to the wind at flight level. Data from the future climate simulation RCP8.5 were used, which represents the scenario where greenhouse gas emissions continue at a high level. These models agree on a poleward movement of the jet stream of around 1° latitude in the annual-mean, and an increase in the mean strength of the jet stream. There is little change to the daily variability in jet stream strength and location, which is much larger than the magnitude of the predicted changes due to climate change. There is some seasonality to these results; in winter the climate models agree on a strengthening of the jet stream but not on any change in location, whilst in summer, when the jet stream is on average weaker, the models agree on a more northerly jet stream but not on changes to its strength.

The climate model winds were used to calculate minimum-time routes for the New-York to London city pair, as a proxy for the location of the bulk of trans-Atlantic air traffic. The mean northward movement in the jet stream was reflected in a greater proportion of eastbound routes being located further north in the future climate, whilst the westbound routes were more spread out. The impact on annual-mean route times was minor; eastbound routes were on average less than one minute quicker, and westbound routes around one minute slower. These changes are somewhat smaller than those found by Williams (2016), who found route time changes on the order of 5 min using an older climate model and different emissions scenario. Additional computations for the more southerly Madrid to Miami route showed similar changes. These long-term changes are an order of magnitude smaller than the daily variations in route time caused by the movement of the jet stream. From these results, we conclude that it is likely that changes to upper-level winds simulated by the CMIP5 models under a high greenhouse gas emissions scenario will have minimal impact on trans-Atlantic flight routing, at least in terms of route location and time taken. Although fuel use and related CO_2 emissions have not been explicitly studied here, given the small impact on route times, it seems unlikely that fuel use would be significantly affected given these wind changes.

The use of the RCP8.5 scenario, and end of 21st century time period means that we analysed the jet stream at the point of the highest greenhouse gas concentrations considered by the IPCC in its latest climate assessment (IPCC, 2013). The changes to the jet stream shown here could therefore be considered as somewhat of an upper bound, at least in as far as current climate models are able to simulate these changes, and in as far as the RCP8.5 scenario is broadly representative of maximum emissions. Use of a more moderate emissions scenario, which includes a higher level of mitigation of greenhouse gas emissions, or an intermediate time period, would likely show smaller changes to the upper-level winds, and therefore smaller impacts on flight routing than shown here.

The changes to the upper-level winds, in particular the jet stream, as a result of climate change have been shown here to be sufficiently small as to have minor impacts on the routing of trans-Atlantic flights. The results shown here are specific to the north Atlantic, and may not apply to other regions; other flight corridors where routes are affected by a jet stream may experience different impacts and should be investigated separately. Over the north Pacific, for example, the jet stream is also expected to move poleward in the annual-mean (Barnes and Polvani, 2013), but could experience different seasonal changes to the north Atlantic jet (Simpson et al., 2014). In addition, climate change may have more significant impacts to aircraft routing than shown here. For example a strengthened jet stream is projected to increase the median strength of turbulence over the north Atlantic by 10–40% (Williams and Joshi, 2013), which as the authors note could result in longer routes being flown to avoid the turbulent regions.

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