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# The dependence of minimum-time routes over the North Atlantic on cruise altitude

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## 1 Abstract

2 North Atlantic air traffic is broadly organised into a track system; daily sets of tracks are  
3 defined by air traffic control which are vertically stacked, such that the same set of tracks is  
4 used for all flight levels, regardless of any vertical variations in wind. This work uses minimum-  
5 time routes, previously shown to be a good proxy for the location of the North Atlantic track  
6 system, to understand whether vertical variations in wind speed and direction significantly  
7 affect minimum-time routes optimised at different altitudes; this is to examine whether (all  
8 other factors assumed equal) there is potential for improvements in fuel efficiency. The  
9 optimum cruise altitude over the North Atlantic is determined, focusing on the New York –  
10 London route. It is found that eastbound routes, which take advantage of the jet stream, are  
11 on average faster at 250 hPa (flight level (FL) 340) than at 300 hPa (FL300) or 200 hPa (FL390)  
12 by approximately 2 minutes (compared to the annual-mean route time of about 330 minutes,  
13 assuming a true air speed of 250 m s<sup>-1</sup>). For westbound routes, the route time increases with  
14 height: aircraft flying at 300 hPa are on average 3 minutes faster than at higher levels (the  
15 annual-mean optimum time being about 400 minutes). These estimates are compared with  
16 the time penalty which arises from flying a route optimized at 250 hPa at the other two  
17 altitudes. The time penalty is generally less than a minute, compared to the minimum-time  
18 routes calculated at those altitudes.

19 Keywords: Aviation, Weather-routing, Jet-stream, North Atlantic

## 20 1. Introduction

21 Air traffic over the North Atlantic is currently managed by the use of North Atlantic Tracks  
22 (NATs) (e.g. Attwooll, 1983; Attwooll, 1986; Lunnon and Marklow, 1992; Lunnon, 1998; ICAO,  
23 2017). These are a set of typically 5-7 flight routes running between the entry and exit points  
24 to oceanic airspace (roughly 10°W – 50°W) with multiple flight levels available on each route.

25 In the planning of NATs, vertical variations in the wind field are not considered despite the  
26 NATs system covering the range of cruise altitudes between about 315 to 190 hPa (FL290 to  
27 FL410, where FLxx0 stands for flight level at xx thousand feet, defined with reference to a  
28 standard atmosphere). NATs are defined twice daily by air traffic control, separately for east-  
29 and west-bound flights, in order to adapt them to the prevailing upper level winds and to  
30 meet the preferred routes requested by airlines. The upper-level winds over the north  
31 Atlantic are characterised by westerly winds and a strong jet stream; therefore, in order to  
32 minimize their flight time and maximise fuel efficiency, eastbound flights try to take  
33 advantage of the jet stream, whereas westbound flights try to avoid it or, at least, to minimize  
34 the headwinds. Both the strength and location of the jet stream vary seasonally (e.g., in  
35 winter, the jet tends to be more intense and located further south than in summer) and on a  
36 day-to-day basis (e.g. Woollings *et al.*, 2010). As shown in Irvine *et al.* (2013), these variations  
37 are important for aviation as they are reflected in the properties of both eastbound and  
38 westbound routes.

39 Several studies assessing the impact of the upper level winds on trans-Atlantic flights base  
40 their analysis on the minimum-time routes between New York and London rather than on the  
41 organized tracks system (Irvine *et al.*, 2013; Irvine *et al.*, 2016; Kim *et al.*, 2016; Williams,  
42 2016). In fact there is a good agreement between the two (Irvine *et al.*, 2013) and the  
43 properties of the former have the advantage of being more related to the state of the  
44 atmosphere, as they are only affected by the winds. Therefore, the minimum-time routes  
45 between these two cities will be the basis of this study.

46 This work seeks to answer two questions. First, taking into account only wind effects, what is  
47 the optimum (quickest) flight level, and what is the time penalty for deviating from this level?  
48 Second, are routes optimised at different flight levels significantly different?

49 There are two motivations for identifying the time-optimum flight level and whether the time-  
50 optimum routes differ between flight levels. If all else is considered equal, fuel burn and CO<sub>2</sub>  
51 emissions are directly related to the flight time hence there are both economic and climate  
52 change perspectives.

53 From an economic perspective, statistics from the International Air Transport Association  
54 ([http://www.iata.org/pressroom/facts\\_figures/fact\\_sheets/Documents/fact-sheet-industry-  
55 facts.pdf](http://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-industry-facts.pdf)) show that between 2010 and 2016, fuel costs for the industry worldwide varied  
56 from about US\$150-230 billion, constituting 21 and 33% of total expenses. Considering that  
57 operating profits and net profits are only a small fraction of the fuel costs (varying from  
58 US\$18-65 billion and US\$8-36 billion, respectively, over the same period), a simplistic analysis  
59 indicates that even a 1% saving in fuel costs due to reduced flight times could translate into a  
60 change in profits which is several times larger. If possibilities for reducing flight times can be  
61 identified, an alternative strategy would be to maintain the same flight time but achieve it at  
62 a lower cruise speed which, in general, also leads to a fuel saving.

63 From a climate perspective, the aircraft industry is now committed to achieving “carbon  
64 neutral growth” (i.e. maintaining total CO<sub>2</sub> emissions from international aviation at 2020  
65 levels via the CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation  
66 <https://www.icao.int/environmental-protection/Pages/market-based-measures.aspx>).  
67 Reductions in fuel burn from any reduction in flight time (or cruise speed) would map directly

68 onto a reduction in CO<sub>2</sub> emissions, and hence could make carbon-neutral growth easier to  
69 achieve.

70 Answering our two questions would then contribute to a broader consideration of the  
71 advantages and drawbacks of flying at particular levels, which would require multi-  
72 disciplinary input. Changes in flight altitude have implications for the occurrence of  
73 turbulence and for contrail production, and other non-CO<sub>2</sub> climate effects of aviation (e.g.  
74 Grewe et al. 2017). In addition, aircraft are optimised to fly at given altitudes (which depends  
75 on aircraft speed) and there are aircraft-dependent penalties for deviating from these (e.g.  
76 Airbus 2004). Hence any proposed change in flight altitude would require a consideration of  
77 the various trade-offs that such a change would cause.

78 Our study focuses on NATs, given that it is a major air traffic corridor with typically 600 flights  
79 per day (Irvine et al., 2013), which has been estimated to contribute about 6.5% to total  
80 aviation emissions (Wilkerson et al. 2010). Although our quantitative conclusions are specific  
81 to that region, they are indicative of the effects that may be found in other regions outside  
82 the tropics, where there are significant variations in wind speed with height.

83 This paper is organized as follows. Section 2 introduces the meteorological data used and how  
84 these have been analysed (Section 2.1). It also briefly describes the method used to compute  
85 the minimum-time routes (Section 2.2). Section 3 analyses what is the optimum flight level  
86 over the North Atlantic, taking into account wind effects, for eastbound (Section 3.1) and  
87 westbound (Section 3.2) flights, focusing on the minimum-time routes between New York and  
88 London. In Section 3.3 two further city pairs are assessed to see whether these conclusions  
89 can be more generally applied to a broader area of the North Atlantic air traffic. Section 4  
90 looks at the differences between minimum-time routes at different flight levels, looking first  
91 at how their location varies with altitude (Section 4.1). The time penalty arising from flying at  
92 a level different from that at which the route was optimised is analysed in Section 4.2. A  
93 general discussion and conclusions are presented in Section 5.

## 94 2. Data and Methodology

### 95 2.1 Jet stream analysis

96 An accurate knowledge of the vertical structure of the wind field over the North Atlantic is  
97 required in order to characterise the upper-level winds and to compute the minimum-time  
98 routes. Here, wind data were taken from the ERA-Interim reanalysis dataset (Dee *et al.*, 2011)  
99 of the European Centre for Medium-Range Weather Forecasts. These data have a horizontal  
100 spatial resolution of circa 0.7° ( $\approx$  80 km). Even though their temporal resolution is 6 hours, it  
101 was found that variations in weather conditions over the course of the day have little impact  
102 on trans-Atlantic flights. Therefore, daily averages have been considered instead.

103 This study uses ERA-Interim reanalysis data from the 33-year period between June 1979 and  
104 May 2012. However, the properties of the wind field between June 1990 and May 1992  
105 differed significantly from those observed during other years. Therefore, they have not been  
106 used here, meaning that this work is based on 31 years of data. The wind field at three  
107 different pressure levels have been considered: at 300 hPa (FL300), 250 hPa (FL340) and 200  
108 hPa (FL390), to span the altitude range of the NATs system.

109 Here, attention focuses on the eddy-driven jet stream because of its impact on the minimum-  
 110 time routes within the North Atlantic flight corridor (e.g. Irvine *et al.*, 2013). Woollings *et al.*,  
 111 (2010) proposed a simple method to determine the speed and the location of the lower  
 112 troposphere jet over the North Atlantic. Irvine *et al.* (2013) showed that this technique can  
 113 also be used for the jet stream in the upper troposphere-lower stratosphere and that, when  
 114 related to the properties of the routes, it is able to qualitatively explain their flight times and  
 115 locations. Therefore, this method has also been used here. Firstly, the North Atlantic is  
 116 defined as the region between 60°W and the prime meridian and between 35°N and 75°N.  
 117 Secondly, the zonal and meridional component of the wind field over this area is used to  
 118 calculate the wind speed at each grid point. The wind speed is then zonally averaged across  
 119 this sector and, for each day, the maximum value of the wind speed and the latitude at which  
 120 it is located are detected.

121 Although we use the jet stream definition simply as a diagnostic to help understand the  
 122 variation in minimum time routes (which are themselves calculated using the full daily-mean  
 123 horizontal wind speed field), a sensitivity analysis on the method has been performed to test  
 124 its robustness. To do this, the method has been applied to two additional domains both  
 125 covering 35°N and 75°N; the West North Atlantic, defined as the region between 60°W and  
 126 40°W and the Central North Atlantic, defined as the region between 45°W and 15°W. In  
 127 addition, the properties of the jet have been derived using only the zonal component of the  
 128 winds between 60°W and the prime meridian instead of the full wind speed (as in Woollings  
 129 *et al.* (2010)). While the absolute value of the diagnosed jet stream varies depending on the  
 130 choices (by typically 5 to 10 m s<sup>-1</sup>) the seasonal variation in jet stream speed, which is one of  
 131 the main foci here, is little affected.

## 132 2.2 Minimum-time route analysis

133 As stated in the Introduction, this study uses minimum-time routes. Irvine *et al.* (2013) noted  
 134 a good agreement between the location of the NATs and the minimum-time routes between  
 135 New York and London which is the principal focus here.

136 For each day, minimum-time routes have been computed at the 3 different pressure levels  
 137 for both east- and west-bound flights using the method described by Irvine *et al.*, (2016); this  
 138 method is also used operationally by the Met Office (Lunnon and Marklow, 1992) to derive  
 139 minimum-time routes. It is based on the theoretical work of Sawyer (Sawyer, 1949) who  
 140 derived an equation that an aircraft flying at a constant pressure has to satisfy in order to  
 141 minimize its flight time:

$$142 \quad \frac{d\theta}{dt} = -\frac{\partial u}{\partial n} - \frac{A + u}{S} \cdot \frac{\partial S}{\partial n}$$

143 The term on the left-hand side is the rate of change of  $\theta$ , the aircraft heading. The first term  
 144 on the right-hand side is the curvature of the wind ( $u$  is the tailwind,  $n$  is orthogonal and left  
 145 to the direction pointed by the aircraft), and the second term is associated with the Earth's  
 146 curvature ( $A$  is the true air speed,  $S$  is the scale factor of the projection used in the calculation).  
 147 For a specified origin (departure airport), the above equation is solved for a set of initial  
 148 heading angles. The software then selects the route that reaches the destination.

149 The results presented here are based on several assumptions. Even though the flight time of  
150 trans-Atlantic flights is affected by a number of elements, only the impact of the upper level  
151 winds has been considered here. Other factors, such as operational considerations, different  
152 types of aircraft, their take-off mass, or engine type have not been included here in order to  
153 isolate the meteorological component. Since our analysis focuses on winds at cruise altitude,  
154 our minimum-time calculations do not account for the time spent in the take-off and landing  
155 phases, and we assume a constant true airspeed of  $250 \text{ m s}^{-1}$  ( $900 \text{ km h}^{-1}$ , Mach number 0.84);  
156 small variations in these choices are unlikely to have an impact on our main conclusions. A  
157 simplification that might have more impact is our assumption of a constant cruise altitude  
158 (because flight altitude tends to increase during each flight as aircraft burn fuel and become  
159 lighter) and could be explored in future analyses in this area.

### 160 3. Optimum flight level over the North Atlantic

161 This section analyses the optimum cruise altitude (the flight level at which the flight time is  
162 minimum) within the North Atlantic Flight corridor.

163 As stated in the Introduction, eastbound and westbound routes interact with the jet stream  
164 in two distinct, almost opposite, ways. It follows that the location of the eastbound and  
165 westbound flights will be generally different and, therefore, the vertical structure of the winds  
166 experienced by them is also generally different. Hence, eastbound or westbound flights are  
167 considered separately.

#### 168 3.1 Eastbound flights

169 The flight times of the minimum-time routes at the three different levels have been  
170 compared. Specifically, for each analysis day, the time difference between flying minimum-  
171 time routes at different levels has been calculated by subtracting the 250 hPa route time from  
172 that at 300 hPa ( $\Delta t_{E-300}$ ) and 200 hPa ( $\Delta t_{E-200}$ ).

173 The probability density functions (PDFs) of the 4 route time differences are shown in Figure  
174 1. For the eastbound routes, the distributions peak at positive  $\Delta t$ , indicating that on average  
175 it is faster to fly at 250 hPa. The tail of the distributions have negative  $\Delta t$  but on 79% of days  
176 it is quicker to fly at 250 hPa than 200 hPa, and on 83% of days it is quicker to fly at 250 hPa  
177 than 300 hPa. Since the shape of the distributions is approximately Gaussian, their main  
178 properties can be summarised by using their mean values and their standard deviations (std).  
179 The annual mean time difference  $\Delta t_{E-300}$  is 1.7 minutes and  $\Delta t_{E-200}$  is 2.2 minutes (Table 1). To  
180 place these changes in perspective, the annual mean eastbound route time at 250 hPa is 334  
181 minutes (Table 1), hence these changes are of order 0.5 %.

182 The standard deviations of 2.7 minutes for  $\Delta t_{E-200}$  and 1.9 minutes for  $\Delta t_{E-300}$  highlights the  
183 day-to-day variability: on a daily basis, the route time differences can significantly diverge  
184 from the annual and seasonal averages. Although the time penalty from flying at altitudes  
185 other than 250 hPa appears small, as discussed in the Introduction, it does not mean that it is  
186 insignificant for airline operators in terms of both  $\text{CO}_2$  emissions and fuel use.

187 Since eastbound flights try to take advantage of the jet stream to reduce flight time, a  
188 qualitative explanation of these results can be obtained by comparing the difference in the  
189 jet stream speed at the different flight levels. Table 1 shows that the jet is on average stronger  
190 at 250 hPa than at 200 or 300 hPa, therefore explaining why the flight time is on average  
191 minimum at 250 hPa.

192 There is some seasonality to the route time differences. PDFs of the route time differences  
193 for each season show similar features to the annual-mean plots (not shown). Table 1 shows  
194 that both  $\Delta t_{E-300}$  and  $\Delta t_{E-200}$  follow a seasonal cycle and suggests a relationship between them  
195 and the seasonal variations of the vertical structure of the jet. The jet speed difference  
196 between 300 hPa and 250 hPa is maximum in summer ( $-2.2 \text{ m s}^{-1}$ ) and is a minimum in spring  
197 ( $-0.4 \text{ m s}^{-1}$ ). This pattern is also found in  $\Delta t_{E-300}$ : it is maximum in summer (2.6 minutes) and  
198 minimum in spring (0.9 minute). Similarly, when the jet speed difference between 200 hPa  
199 and 250 hPa is most negative ( $-4.0 \text{ m s}^{-1}$  in spring)  $\Delta t_{E-200}$  reaches 3.2 minutes, whereas when  
200 it is at its least negative ( $-2.7 \text{ m s}^{-1}$  in summer)  $\Delta t_{E-200}$  is only 1.5 minutes. It follows that also  
201 on a seasonal basis, 250 hPa remains the fastest level and that, interestingly, the seasonal  
202 patterns of  $\Delta t_{E-300}$  and  $\Delta t_{E-200}$  seem to be in anti-phase. However, it should be noted that there  
203 are some discrepancies between the properties of the routes and of the jet. These might arise  
204 because of the complex relation between the routes and the upper level winds.

205 It is noteworthy that the eastbound minimum-time routes are shorter in summer than in  
206 spring, despite the mean jet speeds being stronger in spring (Table 1). This is because the  
207 minimum-time routes are affected not only by the intensity of the jet, but also by its location.  
208 For example, the influence of the jet stream on the minimum-time routes is diminished when  
209 the jet is located further from the great circle route between New York and London; because  
210 the time saved by taking advantage of the strong tailwinds might not compensate for the time  
211 lost because of the longer distance that has to be covered. We find that at  $40^\circ\text{W}$  the latitude  
212 of the jet core is on average  $7.1\text{-}7.6$  degrees from the New York-London great circle latitude  
213 in March-April-May, while in June-July-August it is  $3.7\text{-}4.9$  degrees away; in addition, within a  
214 few degrees of the great circle latitude itself, the zonal-mean zonal wind is stronger in  
215 summer, rather than in spring, even though in general the opposite is the case. In Section 4,  
216 where the Miami-Madrid route is considered, it will be shown that the eastbound minimum  
217 time routes are shorter in spring than summer, consistent with the fact that the great circle  
218 route for this city pair is closer to the peak wind speeds in spring.

### 219 3.2 Westbound flights

220 For westbound routes, the distribution of  $\Delta t_{W-300}$  peaks at negative values (Figure 1), meaning  
221 that it is generally quicker to fly at 300 hPa than 250 hPa. For  $\Delta t_{W-200}$  the distribution is centred  
222 closer to zero (Figure 1), and it is quicker to fly at 250 hPa than 200 hPa on 59% of days (Table  
223 2). In the annual mean, routes at 250 hPa are approximately 3 minutes longer than those at  
224 300 hPa and 0.7 minute shorter than those at 200 hPa (these differences are less than 1 % of  
225 the typical time for a westbound route). Hence, for westbound routes, the optimum cruise  
226 level is 300 hPa, in contrast to eastbound routes where the optimum cruise level was 250 hPa.  
227 300 hPa is the optimum cruise level in each season (Table 2) and this result is also consistent



228 for individual years (not shown). Both  $\Delta t_{W-300}$  and  $\Delta t_{W-200}$  are seasonally dependent.  $\Delta t_{W-300}$  is  
229 least negative in spring (-2.3 minutes with  $\Delta t_{W-300}$  positive 13 % of the days) and most negative  
230 in winter (-3.7 minutes, or about 1% of  $t_{W-250}$ , and positive on only 7 % of days). For  $\Delta t_{W-200}$   
231 the average route time difference is slightly negative in spring (-0.3 minute) and reaches its  
232 most-positive value in autumn (1.3 minutes). Interestingly, as for the eastbound routes, the  
233 changes in  $\Delta t_{W-300}$  and  $\Delta t_{W-200}$  appear to be in anti-phase.

234 Westbound flights tend to avoid the jet stream or, at least, to minimize the headwinds (see  
235 e.g. Fig. 7 of Irvine et al. 2013). At 40°W, and 300 hPa, about 55% of flights divert to the north  
236 of the jet core, and 45% to the south (with the frequency of diversions peaking at  $\pm 10^\circ$  from  
237 the jet core) and with only 3% of routes within  $\pm 2.5^\circ$  of the jet core. Therefore, it is not  
238 possible to find a simple relationship between the route time and the jet speed. However,  
239 since the route time is equal to the ratio between the route distance and the velocity, some  
240 insight can be gained by analysing the intensity of the headwinds and the length of the  
241 minimum-time routes (see Table 3). Table 3 contains two main messages: the intensity of the  
242 headwinds increases with height and the 200 hPa minimum-time routes are on average 30  
243 km shorter than the 250 and the 300 hPa routes (whose length, on the other hand, is similar  
244 to 250 hPa). Weaker headwinds allow the 300 hPa routes to be systematically faster. On the  
245 other hand, the averaged time difference between the 200 hPa and the 250 hPa routes is less  
246 pronounced because the stronger headwinds at 200 hPa are partly compensated by the  
247 shorter extension of the 200 hPa routes.

### 248 3.3 Properties of the minimum-time routes for other city pairs

249 The analysis thus far has focused on the New York to London city pair, since this is  
250 representative of the bulk of the North Atlantic air traffic. The analysis is extended to include  
251 two additional city pairs: Miami - Madrid and Chicago - Copenhagen. Because their great circle  
252 routes are, respectively, further south and north of the core of the North Atlantic air traffic,  
253 they are used to assess whether the results found for the New York to London route are  
254 applicable to a broader area.

255 The results for eastbound routes for both city pairs are summarized in the upper part of Table  
256 4. As for New York - London, the optimum flight level between Chicago and Copenhagen is  
257 250 hPa. This result suggests that this property of the trans-Atlantic flights is also satisfied  
258 over the northern flank of the North Atlantic even though minor differences between the two  
259 city-pairs exist (for example, for Chicago - Copenhagen, the 200 hPa flights are on average  $\approx$   
260 1 minute longer than those at 250 hPa when compared to New York - London).

261 By contrast, the optimum flight level for the Miami - Madrid route is 200 hPa (Table 4); on  
262 average, the 200 hPa routes are 1.4 minutes faster than those at 250 hPa and 4.6 minutes  
263 faster than those at 300 hPa. This result can be qualitatively explained by analysing the  
264 horizontal and the vertical structure of the upper level winds. As the Miami - Madrid great  
265 circle route is to the south of that for New York - London, the flights between Miami and  
266 Madrid might be more influenced by the sub-tropical jet stream than by the mid-latitude jet  
267 stream. To consider the properties of the strong westerly winds affecting the Miami - Madrid  
268 minimum-time routes, a different area to Section 3.1 has therefore been defined, this time  
269 between 20°N - 55°N and between 70°W and the prime meridian (i.e. the area is shifted south  
270 and extends further west). Even though the results obtained from this new analysis are not

271 as clear as in the New York - London case, two main features were found. First, the jet appears  
272 to be located on the northern flank of the region in summer (not shown). This is reflected in  
273 the properties of the eastbound and westbound routes: between June and August, the route  
274 time of the eastbound routes reaches its maximum (about 450 minutes), whereas it is  
275 minimum ( $\approx 483$  minutes) for the westbound routes (not shown). Second, between February  
276 and May, the jet is located further south and has more influence on the properties of the  
277 routes at the different levels. The analysis of the jet speed over this period shows that the  
278 stronger winds are located at 200 hPa and that their intensity decreases with height (not  
279 shown).

280 The properties of the westbound routes are summarised in the lower part of Table 4, where  
281 only the annual averages are shown. Seasonal means and standard deviations are not  
282 included because they do not provide any additional information: for both city pairs, the  
283 optimum flight level is not seasonally dependent (the Miami – Madrid westbound routes in  
284 the summer seasons are an exception: their route times are not altitude dependent and an  
285 optimum flight level is not easily identifiable). On average, the difference between the route  
286 time of the 300 hPa and 250 hPa minimum-time routes seems not to be strongly latitude  
287 dependent:  $\Delta t_{W-300}$  is -2.9 minutes for Chicago - Copenhagen and New York - London and -2.5  
288 minutes for Miami - Madrid. By contrast, the difference between the route time at 200 hPa  
289 and 250 hPa depends on the city pair considered:  $\Delta t_{W-200} \approx 2.4$  minutes for Chicago -  
290 Copenhagen, 0.7 minute for New York - London and 3.7 minutes for Miami - Madrid.

291 An important conclusion is that the optimum flight level for the westbound routes for all the  
292 city pairs studied (Chicago - Copenhagen, New York - London and Miami - Madrid) is 300 hPa.  
293 Thus, it is a particularly robust property of the trans-Atlantic flights as it shows little route  
294 dependence.

#### 295 4. Time penalty for not optimizing routes at each flight level

296 When the NATs are produced, vertical variations in the upper level winds are not taken into  
297 consideration: the same set of organised tracks is used at all altitudes. This section aims to  
298 understand whether the current procedure can be improved by evaluating the benefit of  
299 optimizing (and hence potentially having different NATs) at each flight level.

##### 300 4.1 Variation of location of minimum-time routes with altitude

301 First, the preferred locations of the minimum-time routes optimised at each pressure level  
302 (200, 250 and 300 hPa) are analysed to see whether the routes location varies with altitude.  
303 This analysis is based on the following method. The latitude at which the routes intersect the  
304  $40^\circ\text{W}$  meridian is used as a proxy for their location (as in Irvine *et al.*, 2013). Then, for each  
305 analysis day, the location of the minimum-time routes at each pressure level is identified and  
306 the result is used to produce the PDFs of the 200, 250 and 300 hPa route locations for both  
307 eastbound and westbound flights (Figs. 2a and 2b respectively).

308 The PDF of the location of the 250 hPa eastbound routes is approximately Gaussian and its  
309 peak is slightly further south than the great circle (Fig. 2a). The distribution of the 250 hPa  
310 westbound routes is skewed towards high latitudes and peaks at circa  $55^\circ\text{N}$  (Fig. 2b). Both  
311 Figs. 2a and 2b show that the 250 and 300 hPa routes have a similar distribution, suggesting

312 only a small difference between the location of the routes at these two levels. By contrast,  
313 the distribution for the 200 hPa routes shows some differences. Figure 2a shows that the PDF  
314 for the 200 hPa eastbound routes is centred circa  $1^\circ$  further south than that for the 250 and  
315 300 hPa flights and it is also more peaked, indicating less variability in the route locations at  
316 this level. Figure 2b shows that westbound routes at 200 hPa do not extend as far north as  
317 those at 250 and 300 hPa and they are located closer to the great circle than the lower level  
318 routes.

319 A qualitative explanation of Figs. 2a and 2b can be obtained by noting the preferred jet  
320 locations over the North Atlantic. These have been derived by using a simple technique. For  
321 each day, the 200, 250 and 300 hPa wind speed over the North Atlantic (defined as in Section  
322 2.1 as the region between  $60^\circ\text{W}$  and the prime meridian and between  $35^\circ\text{N}$  and  $75^\circ\text{N}$ ) has  
323 been computed and zonally averaged. Then, the mean over the 31-year period has been  
324 calculated and plotted as a function of latitude (Fig. 3). A comparison between Figs. 2 and 3  
325 shows that the eastbound routes, for which the minimum-time routes tend to maximize the  
326 tailwinds, are located in proximity of the wind speed maximum (which is further south than  
327 the great circle between New York and London). A closer look at the peaks of the wind speed  
328 profiles shows that the jet appears to be tilted in the vertical and to shift southward with  
329 height: this is consistent with the routes at 200 hPa being located slightly further south than  
330 those at 250 and 300 hPa. On the other hand, westbound flights aim to reduce the headwinds  
331 to a minimum and are therefore located further north than the great circle, where the wind  
332 speed is lower. Interestingly, the wind speed at 200 hPa is weaker than at 250 hPa and 300  
333 hPa (by approximately  $5 \text{ m s}^{-1}$ ): weaker headwinds might explain why it is possible for the 200  
334 hPa minimum-time routes to fly closer to the great circle.

335 Figures 2 and 3 suggest that vertical variations in the horizontal structure of the wind field  
336 cause the locations of the minimum-time routes to change with height. It is therefore  
337 important to assess whether these can be exploited to improve the NATs system.

#### 338 4.2 Penalty for using 250 hPa minimum-time routes at different altitudes

339 The vertically-stacked nature of the current NATs structure (where the same NATs are used  
340 irrespective of altitude) has been reproduced by using the 250 hPa minimum-time routes  
341 between New York and London at all altitudes (therefore flying at 300 hPa and 200 hPa along  
342 routes optimised using 250 hPa winds). Since Section 4.1 shows that the location of the  
343 minimum-time routes may change with height, flying the 250 hPa-optimised route at a  
344 different altitude (so that it is a 'non-optimised route') instead of the actual minimum-time  
345 route for that particular level should lead to a time penalty. The time penalty for flying a non-  
346 optimised route at, for example, 200 hPa is computed as the time taken to fly the 250 hPa  
347 route at 200 hPa minus the time taken to fly the 200 hPa minimum-time route. The results  
348 are summarized in Table 5.

349 Since the distributions of daily time penalty are not Gaussian, the median (50<sup>th</sup> percentile)  
350 and the 80<sup>th</sup> percentile of the data have been used to give information about the centre and  
351 the spread of the distributions. For eastbound routes, the median time penalty for flying the  
352 250 hPa-optimised route at 300 hPa rather than the 300 hPa-optimised route is 0.1 minute,  
353 whereas it is circa 0.5 minute at 200 hPa. Figures 2 and 3 suggest that there is greater  
354 similarity in the location of the 250 and 300 hPa minimum-time routes than of the 250 and

355 200 hPa routes, and therefore could explain why the time penalty for not optimizing at 300  
356 hPa is smaller than at 200 hPa.

357 For westbound routes, the penalty for not optimizing at 200 hPa and 300 hPa is similar: in  
358 both cases, the 50<sup>th</sup> and the 80<sup>th</sup> percentiles are comparable and approximately equal to 0.3  
359 minute and 0.8 minute respectively.

360 In addition, it has been found that the penalty for not optimizing at each flight level is not  
361 seasonally dependent.

## 362 5. Summary and Conclusions

363 Flights between North America and Europe are strongly affected by the winds at cruise level.  
364 Here the properties of trans-Atlantic minimum-time routes were analysed in order to detect  
365 any change with height. The aim of this work is to better understand whether the vertical  
366 variations in the properties of the routes can be used to make the North Atlantic oceanic  
367 airspace more efficient.

368 This work aimed to answer two main questions: considering only the effect of winds, and  
369 therefore assuming all other factors are equal, what is the optimum flight level for trans-  
370 Atlantic flights? And, is there a significant advantage at designing separate sets of NATs for  
371 each flight level to exploit vertical variations in the wind field?

372 First, the minimum-time routes between New York and London were analysed. It was found  
373 that the 250 hPa eastbound routes are on average faster than those at 300 hPa and 200 hPa  
374 by approximately 2 minutes (i.e. about 0.5 % of the mean flight time). Moreover, the  
375 eastbound routes at 200 hPa are located slightly further south than at 250 and 300 hPa: this  
376 agrees with the structure of the jet core. The properties of the westbound routes are also  
377 altitude dependent. The 300 hPa flights are on average faster than those at 250 hPa and 200  
378 hPa by circa 3 minutes and 3.5 minutes (i.e. between 0.5 and 1 % of the mean flight time)  
379 respectively. Vertical variations in the properties of the jet cannot be used to understand  
380 these features because westbound routes tend to avoid the jet. However, these results can  
381 be qualitatively explained by the fact that the intensity of the averaged headwinds increases  
382 with height. Interestingly, it was also found that the 200 hPa routes are able to partly  
383 compensate the stronger headwinds by flying closer to the great circle (possibly because the  
384 intensity of the jet at 200 hPa is weaker than at 250 and 300 hPa therefore allowing the  
385 location of 200 hPa minimum-time routes to be less affected by the winds). For both east-  
386 and west-bound routes, the route time difference between different levels is, on average, less  
387 than 1 % of the typical route time of trans-Atlantic flights.

388 The minimum-time routes between Chicago and Copenhagen and between Miami and  
389 Madrid were also analysed. They are located further north and further south than New York  
390 – London, respectively, and are used to understand whether the conclusions above could be  
391 extended to a broader region over the North Atlantic. It was found that some of the properties  
392 of the routes depend on the city-pair considered (and, therefore, on the latitude). For  
393 example, the optimum flight level for the eastbound routes between Miami and Madrid is  
394 200 hPa and not 250 hPa as for New York - London. However, some of the features appear  
395 not to be latitude dependent: notably, the optimum flight level for westbound flights is 300  
396 hPa, regardless of the city-pair considered.

397 The second part of the paper focused on the present structure of the NATs and, more  
398 precisely, on whether it can be improved by building a set of routes which is optimized at each  
399 flight level. The time penalty for using the 250 hPa-optimised minimum-time routes to fly at  
400 200 hPa and 300 hPa (rather than routes optimised at 200 hPa and 300 hPa) was computed.  
401 It was found that, for eastbound and westbound routes, the median time penalty was under  
402 30 seconds or less. For eastbound routes the time penalty was larger for flying the 250 hPa  
403 routes at 200 hPa than the equivalent situation at 300 hPa, which might be a consequence of  
404 the 250 hPa routes locations being more similar to those at 300 hPa than at 200 hPa. This  
405 time penalty appears small in comparison to the effect of the variation in wind with altitude,  
406 and suggests that there would be little advantage to defining different sets of North Atlantic  
407 tracks at different altitudes.

408 The savings appear to be a small percentage of total route time. On the one hand, our results  
409 could act to reassure airline operators and air traffic managers that any inefficiencies arising  
410 from wind variations with height may be small compared to other operational factors (see,  
411 for example, Poll (2017)). On the other hand, and as discussed in the Introduction, given  
412 ambitious international targets to reduce the growth in aviation CO<sub>2</sub> emissions under CORSIA,  
413 and the generally small profit margins in this industry, even small savings in CO<sub>2</sub> emissions  
414 (or, equivalently, fuel use) could be beneficial enough to consider changes in practice, such  
415 as improved practice in matching aircraft to routes (e.g. Poll, 2017), which could consider the  
416 time-optimum cruise altitude. Clearly other factors would also have to be considered; this  
417 includes the effect of changing flight levels on aircraft safety (for example, due to the  
418 frequency and severity of turbulence (e.g. Jaeger and Sprenger 2007)) and fuel efficiency, and,  
419 potentially, the climate impact of non-CO<sub>2</sub> emissions (e.g. Grewe *et al.*, 2017). Even if there is  
420 no clear advantage for the present fleet, our results are relevant for design considerations of  
421 future aircraft, most particularly in the choice of the aerodynamic optimum cruise altitude;  
422 this could be more closely matched to the altitudes for which winds speeds are most  
423 beneficial for achieving minimum-time routes, or alternatively, minimising the penalty for  
424 variations in cruise altitude.

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478 *Table 1: For the eastbound minimum-time routes, annual and seasonal mean and standard deviation*  
479 *of the route time for the 250 hPa routes ( $t_{E-250}$ ), and the time difference between the 200 hPa and 250*  
480 *hPa routes ( $\Delta t_{E-200}$ ) and between the 300 hPa and 250 hPa routes ( $\Delta t_{E-300}$ ), using 31 years of daily*  
481 *minimum-time routes between New York and London. For these routes, the percentage of days when*  
482 *the route time difference is positive is also shown ( $\%>0$ ). The annual and seasonal mean and standard*  
483 *deviation of the jet speed at 250 hPa ( $jet\_speed_{250}$ ) and the difference in jet speed between 200 hPa*  
484 *and 250 hPa ( $\Delta jet\_speed_{200}$ ) and between 300 hPa and 250 hPa ( $\Delta jet\_speed_{300}$ ) are also shown. Times*  
485 *are in minutes, jet speeds are in  $m\ s^{-1}$ .*

	$t_{E-250}$	$jet\_speed_{250}$	$\Delta t_{E-200}$		$\Delta t_{E-300}$		$\Delta jet\_speed_{200}$	$\Delta jet\_speed_{300}$
	Mean $\pm$ std	Mean $\pm$ std	Mean $\pm$ std	$\%>0$	Mean $\pm$ std	$\%>0$	Mean $\pm$ std	Mean $\pm$ std
Year	334.2 $\pm$ 14.0	39.9 $\pm$ 8.6	2.2 $\pm$ 2.7	79%	1.7 $\pm$ 1.9	83%	-3.3 $\pm$ 3.0	-1.4 $\pm$ 2.2
Spring	339.5 $\pm$ 13.8	38.0 $\pm$ 7.5	3.2 $\pm$ 2.9	87%	0.9 $\pm$ 1.7	71%	-4.0 $\pm$ 3.5	-0.4 $\pm$ 2.4
Summer	337.1 $\pm$ 11.2	34.5 $\pm$ 6.1	1.5 $\pm$ 2.2	76%	2.6 $\pm$ 1.8	93%	-2.7 $\pm$ 2.7	-2.2 $\pm$ 1.8
Autumn	331.7 $\pm$ 12.6	41.6 $\pm$ 7.5	1.4 $\pm$ 2.4	72%	2.2 $\pm$ 1.8	90%	-3.2 $\pm$ 2.6	-1.9 $\pm$ 1.9
Winter	328.2 $\pm$ 15.1	45.6 $\pm$ 9.0	2.6 $\pm$ 3.0	81%	1.2 $\pm$ 1.8	77%	-3.4 $\pm$ 2.9	-1.3 $\pm$ 2.0

486

487 *Table 2: For the westbound minimum-time routes, annual and seasonal mean and standard*  
488 *deviation of the route time for the 250 hPa routes ( $t_{W-250}$ ), of the time difference between the*  
489 *200 hPa and 250 hPa routes ( $\Delta t_{W-200}$ ) and between the 300 hPa and 250 hPa routes ( $\Delta t_{W-300}$ ),*  
490 *using 31 years of minimum-time routes between New York and London. The percentage of*  
491 *days when the time differences are positive is also shown ( $\%>0$ ). Times are in minutes.*

	$t_{W-250}$	$\Delta t_{W-200}$		$\Delta t_{W-300}$	
	Mean $\pm$ std	Mean $\pm$ std	$\%>0$	Mean $\pm$ std	$\%>0$
Year	398.5 $\pm$ 17.2	0.7 $\pm$ 3.5	59%	-2.9 $\pm$ 2.6	11%
Spring	393.0 $\pm$ 16.6	-0.3 $\pm$ 3.4	49%	-2.3 $\pm$ 2.2	13%
Summer	393.8 $\pm$ 12.7	0.7 $\pm$ 2.8	60%	-2.5 $\pm$ 2.3	13%
Autumn	400.9 $\pm$ 15.8	1.3 $\pm$ 3.2	66%	-3.3 $\pm$ 2.8	9%
Winter	406.4 $\pm$ 19.4	1.0 $\pm$ 4.1	62%	-3.7 $\pm$ 2.8	7%

492

493



494 *Table 3: For the westbound minimum-time routes, annual and seasonal mean and standard deviation*  
 495 *of the headwinds along the 250 hPa minimum-time routes and of the difference between the*  
 496 *headwinds at 200 hPa or 300 hPa and the 250 hPa routes. Annual and seasonal mean and standard*  
 497 *deviation of the 250 hPa minimum-time route distance and of the difference between the 200 hPa or*  
 498 *300 hPa route distance and the 250 hPa route distance. The analysis uses 31 years of daily minimum-*  
 499 *time routes between New York and London.*

	Headwind (m s <sup>-1</sup> )			Route Distance (km)		
	250 hPa	200 – 250 hPa	300 – 250 hPa	250 hPa	200 – 250 hPa	300 – 250 hPa
Year	11.7 ± 9.3	2.0 ± 2.7	-1.7 ± 2.4	5649 ± 94	-30 ± 48	0 ± 43
Spring	9.3 ± 9.1	1.7 ± 2.4	-1.7 ± 2.1	5627 ± 78	-33 ± 39	7 ± 37
Summer	9.5 ± 7.5	1.6 ± 2.7	-1.0 ± 2.3	5647 ± 90	-22 ± 49	-9 ± 43
Autumn	12.4 ± 8.7	2.2 ± 2.8	-1.7 ± 2.6	5663 ± 103	-27 ± 51	-4 ± 47
Winter	15.4 ± 10.3	2.5 ± 2.9	-2.4 ± 2.3	5659 ± 101	-37 ± 49	8 ± 42

500

501 *Table 4: For eastbound routes (upper), annual and seasonal mean and standard deviation of the 250*  
 502 *hPa route time ( $t_{E-250}$ ) and of the route time difference between the 200 and 250 hPa routes ( $\Delta t_{E-200}$ )*  
 503 *and between the 300 and 250 hPa routes ( $\Delta t_{E-300}$ ) for the (left) Chicago - Copenhagen and (right) Miami*  
 504 *– Madrid city pairs. For westbound routes (lower), annual mean and standard deviation of the 250 hPa*  
 505 *route time ( $t_{W-250}$ ) and of the route time difference between the 200 and 250 hPa routes ( $\Delta t_{E-200}$ ) and*  
 506 *between the 300 and 250 hPa routes ( $\Delta t_{W-300}$ ) for the (left) Chicago - Copenhagen and (right) Miami –*  
 507 *Madrid city pairs. Times are in minutes.*

	Chicago - Copenhagen			Miami - Madrid		
	$t_{E-250}$	$\Delta t_{E-200}$	$\Delta t_{E-300}$	$t_{E-250}$	$\Delta t_{E-200}$	$\Delta t_{E-300}$
Year	423.5 ± 14.3	3.3 ± 3.1	1.6 ± 2.6	437.0 ± 18.0	-1.4 ± 2.9	3.2 ± 3.3
Spring	427.5 ± 14.3	4.7 ± 3.3	0.3 ± 2.3	435.1 ± 16.6	-1.9 ± 3.4	3.7 ± 4.1
Summer	428.1 ± 11.0	3.3 ± 2.6	2.7 ± 2.2	450.1 ± 11.4	-0.6 ± 1.9	1.9 ± 1.9
Autumn	419.7 ± 13.1	2.8 ± 2.7	2.3 ± 2.4	438.8 ± 15.3	-1.5 ± 2.8	3.5 ± 3.2
Winter	418.7 ± 15.5	2.6 ± 3.3	1.3 ± 2.8	423.8 ± 17.6	-1.5 ± 3.2	3.7 ± 3.5
	$t_{W-250}$	$\Delta t_{W-200}$	$\Delta t_{W-300}$	$t_{W-250}$	$\Delta t_{W-200}$	$\Delta t_{W-300}$
Year	473.9 ± 15.4	2.4 ± 3.4	-2.9 ± 2.2	500.0 ± 21.1	3.7 ± 4.9	-2.5 ± 3.5

508

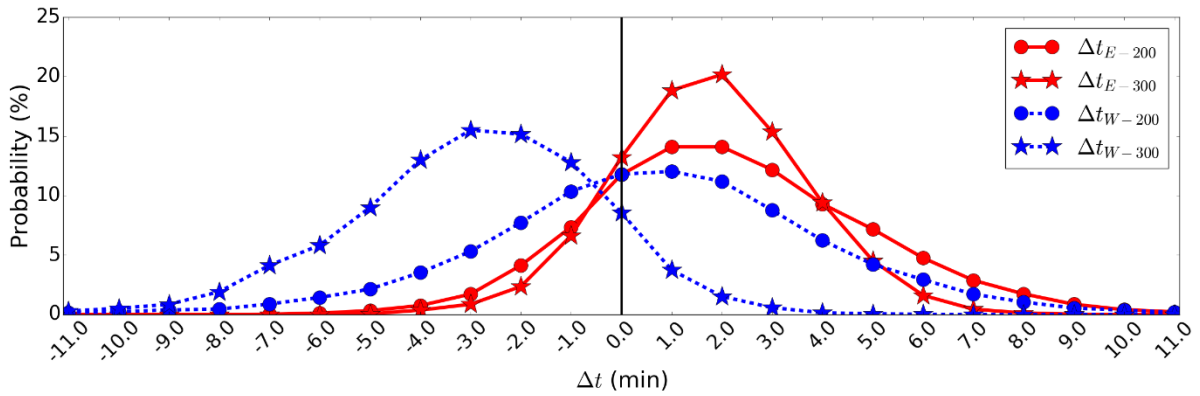
509

510 *Table 5: Time penalty for flying at 200 hPa and 300 hPa along non-optimized routes (the 250 hPa*  
 511 *minimum-time routes) for east- and west-bound routes. All the 31-year data have been used. In each*  
 512 *case, the median (50<sup>th</sup> percentile) and the 80<sup>th</sup> percentile of the data are shown. Units are minutes.*

Flight altitude	Time penalty (minutes)	
	Eastbound	Westbound
200 hPa	0.5 - 1.1	0.3 - 0.8
300 hPa	0.1 - 0.4	0.2 - 0.7

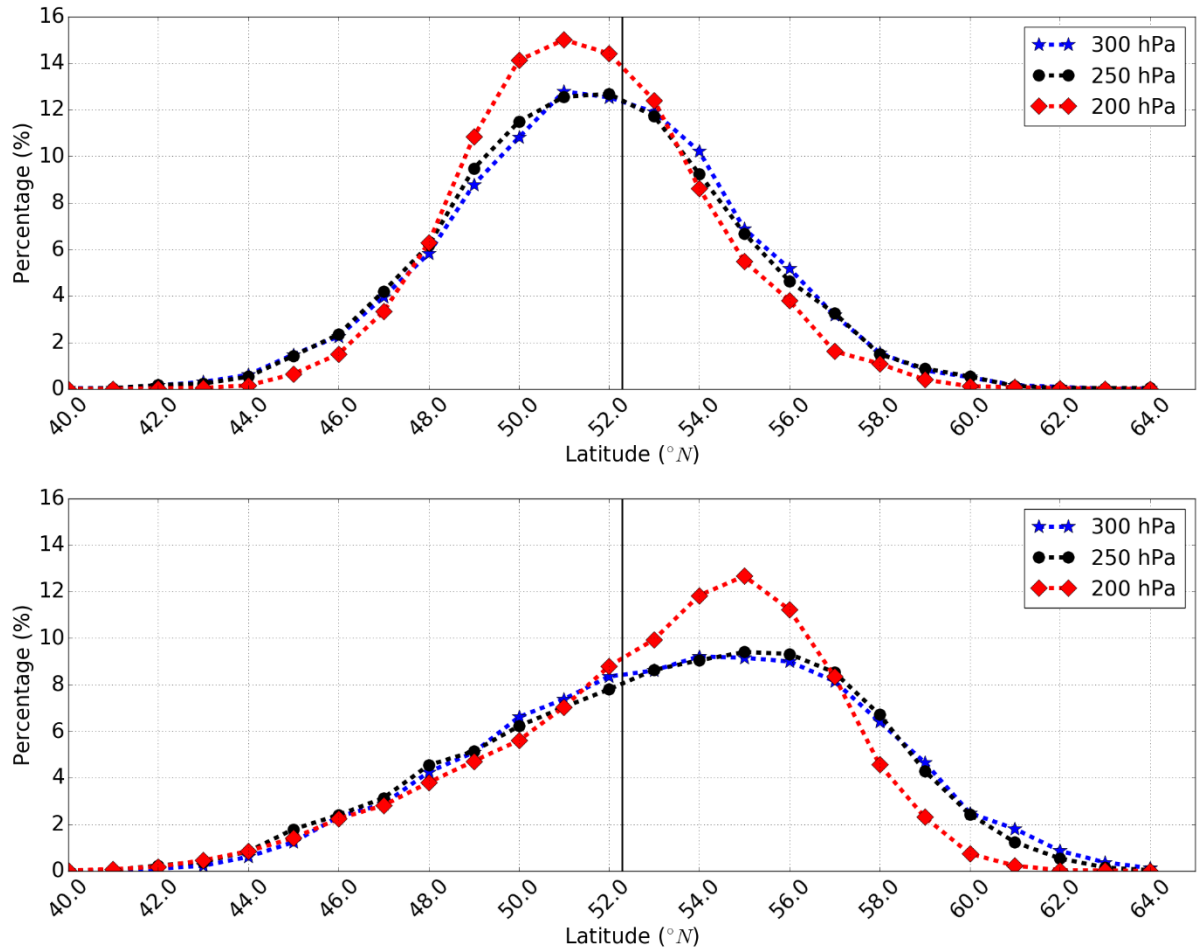
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514 FIGURE CAPTIONS



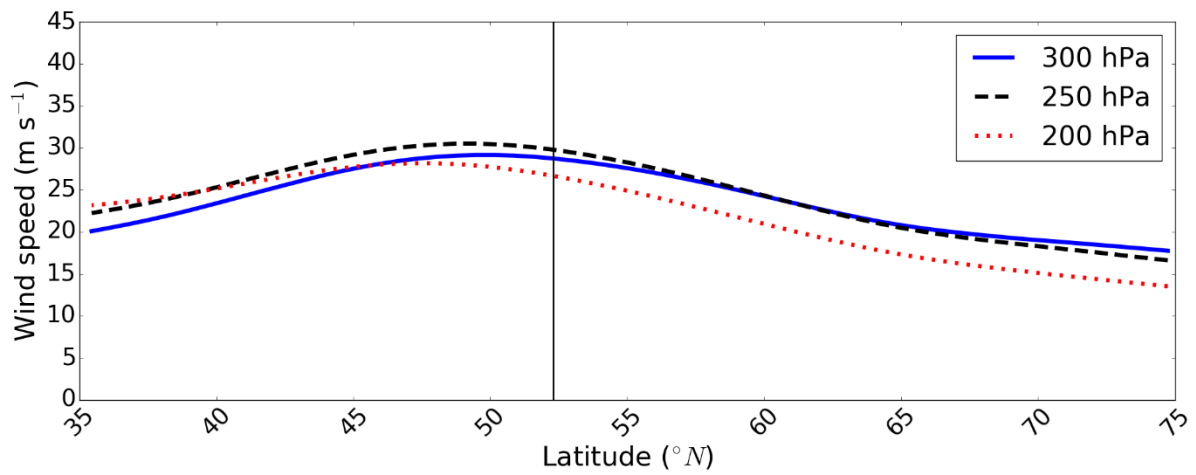
515

516 *Figure 1: Probability density functions of the route time difference (in minutes) between the 300 hPa*  
 517 *and 250 hPa minimum-time routes (stars) and between the 200 hPa and 250 hPa minimum-time routes*  
 518 *(circles) using 31 years of daily data for flights between New York and London. Eastbound flights are*  
 519 *indicated by a red, straight line, westbound flights by a blue, dashed line.*



520

521 *Figure 2: Probability density functions of the latitude at which the (a) eastbound and (b) westbound*  
 522 *minimum-time routes at 300 hPa (blue stars), 250 hPa (black circles) and 200 hPa (red triangles)*  
 523 *intersect the 40°W meridian. The vertical line located at circa 52°N represents the latitude of the great*  
 524 *circle route between New York and London at 40°W. The analysis uses 31 years of daily minimum-time*  
 525 *routes between New York and London.*



526

527 *Figure 3: Zonally and annually averaged wind speed ( $m s^{-1}$ ) over the North Atlantic at 300 hPa (blue*  
 528 *solid line), 250 hPa (black dashed line) and 200 hPa (red dotted line). The vertical line located at circa*  
 529 *52°N represents the latitude of the great circle route between New York and London at 40°W.*

530