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RESEARCH ARTICLE

Aircraft observations and reanalysis depictions of trends in the North Atlantic winter jet stream wind speeds and turbulence

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Abstract

Multiple studies have considered whether increased anthropogenic CO_2 will affect the wind speeds and turbulence associated with the winter North Atlantic polar-front jet stream in the upper atmosphere. Key questions are whether any effects can already be seen and, if so, can they be seen independent of computer models of the atmosphere. In this study we use two reanalyses, NCEP/NCAR and the ECMWF ERA5, and two large observational archives, AMDAR/ACARS and the Global Aircraft Data Set (GADS), to try to answer these questions for the period 2002–2020 when automated aircraft observations were plentiful over the North Atlantic. We focus on eastbound, New York to London, flights. No significant increase appears in reanalyses during the last roughly 40 years (1979–2020) which is our best estimate for the modern satellite era. In contrast, for the last roughly 20 years (2002–2020) both the ERA5 reanalysis (2.5% per year) and the GADS archive (1.2% to 1.4% per year) show a statistically significant rise in the wind speed in the North Atlantic jet streak exit region. These results must be considered in the context of atmospheric oscillations, changes to the North Atlantic Track System (NATS), and the effects of aircraft step climbs. We estimate that *up to* 0.5% of the rise may be due to improvements in the NATS operations and an unknown additional amount may be due to the substantial increase in automated aircraft observations starting in 1997. We also examine the impact of aircraft observations on one's confidence in drawing conclusions from secular changes in the reanalyses. For turbulence, the Light turbulence trends are not statistically significant. Our confidence in the turbulence results is more limited since these observations reflect medium-term changes in tactical and strategic aircraft operational procedures as well as the underlying prevalence of turbulence.

KEYWORDS

aircraft observations, climate change, GADS archive, jet stream, North Atlantic, turbulence, wind speed

1 INTRODUCTION

Multiple model-based studies of the winter North Atlantic polar-front jet stream have considered the effects of doubled CO_2 (Barnes and Polvani, 2013; Delcambre *et al.*, 2013; Williams and Joshi, 2013; Williams, 2016; Ceppi *et al.*, 2018). Three key questions are whether any effects can already be seen in observations, whether any effects can be seen independent of computer models, and whether the start of automated aircraft observations or air traffic control improvements also contribute. A major tool in the climate change community is model-based atmospheric reanalyses (National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR): Kalnay *et al.*, 1996, Kistler *et al.*, 2001; ECMWF ReAnalysis (ERA): Uppala *et al.*, 2005, Dee *et al.*, 2011, Hersbach *et al.*, 2020; Japan Meteorological Agency (JMA): Kobayashi *et al.*, 2015; National Aeronautics and Space Administration (NASA): Gelaro *et al.*, 2017) which provide an optimum depiction of the jet stream when the reanalysis model is held fixed for 40 to 50 years. But such reanalyses do depend on the underlying assimilation model and are subject to problems with systematic changes in the observations. In addition, any secular trends must be disentangled from other oscillations that affect the North Atlantic: the North Atlantic Oscillation (NAO: Hurrell *et al.*, 2003) and the Atlantic Multidecadal Oscillation (AMO: Trenberth and Shea, 2006; Msadek *et al.*, 2014).

We have addressed these issues by using four separate data sources: the NCEP/NCAR reanalysis, the European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis (ERA5), the Aircraft Meteorological DAta Relay/Aircraft Communication Addressing and Reporting System (AMDAR/ACARS) aircraft wind observation archive (Moninger *et al.*, 2003), and the Global Aircraft Data Set archive (GADS: Tenenbaum, 1991; Cardinali *et al.*, 2004; Gill, 2014; Gill and Buchanan, 2014). We focus on the eastbound, New York (JFK) to London (LHR), flights and start from 2002 when automated GADS observations became plentiful on this route. The reanalyses are somewhat correlated with AMDAR because those observations dominate the satellite radiance contributions in the eastern North Atlantic (Bormann *et al.*, 2019, their figure 14). The automated AMDAR/ACARS observations started in the mid- to late-1990s and, for reference, cannot be selected by route. The 3.2 billion GADS observations (200 million over the North Atlantic) during 2002–2020 taken from the flight data recorders of multiple carriers are independent of both reanalyses and AMDAR. The impact of aircraft observations on the reanalyses is discussed further below.

The impact of aircraft observations on forecasts, and especially the Covid-induced aircraft observation decrease, has been discussed by James *et al.* (2020), Chen (2020) and Ingleby *et al.* (2021). There is some disagreement on global versus regional results and the role of satellite versus aircraft inputs. More crucially, Ingleby *et al.* argue that the proper method of detecting changes in the presence of interannual variability is the use of data denial experiments. The GADS observations also provide direct (but not necessarily unbiased) measurements of the turbulence associated with the North Atlantic jet.

For the past roughly 20 years, our primary result is a statistically significant rise in the measured and analysed wind speed ranging from 1.2% to 1.4% (GADS, $p = 0.07$) and 2.5% (ERA5, $p = 0.04$)[1] per year during 2002–2020. The lower number for GADS is our raw result, less statistically significant ($p = 0.10$), and the larger number corrects for the decrease in measured wind speeds due to newly permitted air traffic control flight-level increases during 2018–2020. The wind speed increase appears in both the model-dependent ERA5 reanalysis and in the model-independent GADS observations. It is also consistent with anecdotal evidence given by the setting of multiple new eastbound subsonic flight time records, currently 4 hours 56 minutes from a British Airways 747–400 (hereafter 747) aircraft travelling from New York to London during February 2020 (Vigdor, 2020). That flight beat by 17 minutes a record that had been set in 2018 by a Norwegian Air Shuttle 787.

The AMDAR observations archive represents automated real-time meteorological reports that are digitally transmitted from cruise levels of most of the world's long-haul aircraft (referred to as ACARS by North American carriers). Typical report spacings are 7 min (~100 km). Their value relative to manually radioed Aircraft Weather Report (AIREP) (Pilot Report, PIREP) observations is that no additional errors are introduced by the human read-out or voice transmission steps. The GADS observation archive represents an alternate approach using flight data recorders. The underlying measurements are the same as AMDAR; only the data pathway changes. While not available in real time, they have spacings of 4 s (~1 km) and also include turbulence measurements similar to DEVG (derived equivalent vertical gust velocity: Gill, 2014). The GADS turbulence measure substantially matches (not shown) the World Meteorological Organization (WMO) aircraft independent standard of EDR (eddy dissipation rate: Sharman *et al.*, 2014, Sharman and Lane, 2016).

[1] To be conservative, probabilities are quoted for the two-sided Student's *t*-distribution.

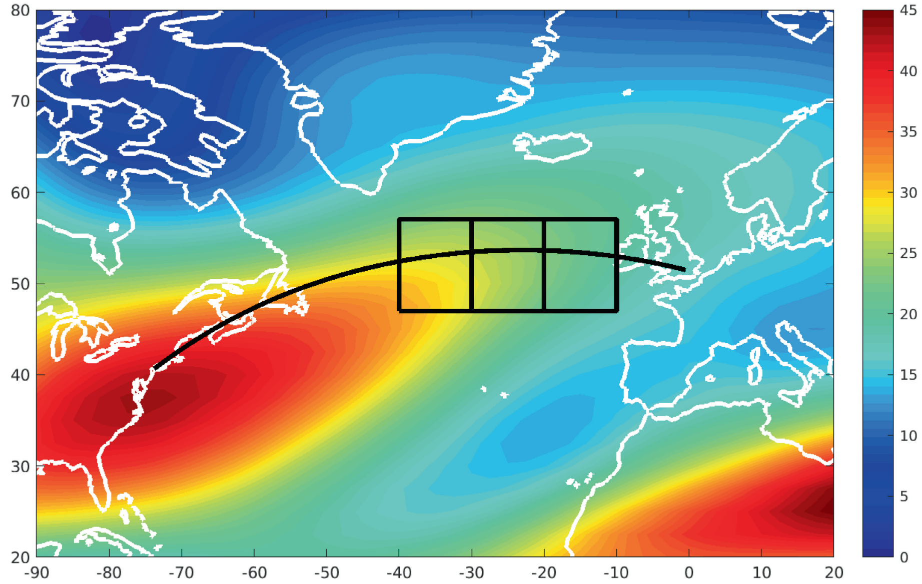


FIGURE 1 Total wind speed in m·s^{-1} at 250 hPa from the NCEP reanalysis for DJF 1981–2010. The three rectangular boxes are the eastern North Atlantic region used in this article, 52 ± 5°N, 40°W to 10°W. The curved line is the great circle route between New York (JFK) and London (LHR)

Multiple studies of the effects of doubled CO_2 and trends in global wind speeds have been carried out. Two that are directly relevant are Delcambre *et al.* (2013) using models that contributed to the then-current phase 3 of the Coupled Model Intercomparison Project (CMIP3) and Kim, J.-H. *et al.* (2021) using the Community Earth System Model version 2 (CESM2) that contributed to the subsequent CMIP6 project.

In a separate study that emphasizes changes in the waviness of the winter polar jet stream, Martin (2021) also addresses its wind speed changes. He finds no secular changes for three reanalyses (his figure 9) and little agreement on the presence or absence of such changes in the literature. While various years are included, all three of his reanalyses cover the interval 1980–2020 (roughly 40 years). Since our results do show such a change for GADS, AMDAR and the ERA5 reanalysis for roughly the last 20 years, a key question will be what could produce such a disagreement.

Delcambre *et al.* (2013) summarized multiple previous studies that suggest anthropogenic climate change impacts on the eddy–jet system including an intensified midlatitude jet stream, an elevated tropopause, and a poleward-shifted jet. To study the wind speed changes in more detail, they used 17 twenty-first-century projections of the ensemble mean zonal wind change at 300 hPa. They concentrate on the overall properties of the jet and "predict … an overall expansion of the Atlantic jet … [and that] zonal winds are projected to decrease in the core of the … Atlantic jets, with increasing zonal winds located primarily in the jet exit regions and the meridional flanks of the jets."

To roughly match the Delcambre *et al.* analyses we have concentrated on the polar-front jet exit region as illustrated in Figure 1. It shows the time mean 1981–2010 250 hPa wind speed for December, January and February (hereafter DJF) to convey the relative location of the GADS observations. Superimposed are three rectangular boxes extending from 40°W to 10°W in longitude and ± 5° in latitude centered on 52°N. The boxes contain a large number of observations from eastbound transatlantic routes which are used for the subsequent comparisons. Also depicted is the great circle route whose location is combined with the forecast winds to establish the North Atlantic Track System (NATS) tracks on a twice-daily basis (Williams and Joshi, 2013; FAA, 2019a). For typical eastbound flights, the actual track is a balance between maximizing tailwinds, conforming to the NATS rules, and not straying too far from the great circle route.

In contrast to Delcambre *et al.*, Kim, J.-H. *et al.* (2021) focus on the effect on transatlantic routes using a measured period of 1979–2014 versus a modelled period with various CO_2 increases during 2061–2100. While their major concern is changes in fuel usage, Kim, J.-H. *et al.* explicitly show an average zonal wind jet streak rise at 250 hPa of about 4 m·s^{-1} over the eastern North Atlantic boxes illustrated in Figure 1. Unlike their Pacific results, the Atlantic effects are not clearly monotonically increasing with increasing CO_2. This hypothetical multi-decadal increase should be compared with our already existing 2002–2020 increases described below.

2 | GADS ARCHIVE AND ERA5 SPECIFICATIONS

The GADS archive was started in 1989 (Tenenbaum, 1991), and in current form, 1998 (Cardinali *et al.*, 2004; Gill, 2014;

Gill and Buchanan, 2014). It captures meteorological observations from the flight data recorders of multiple long-haul carriers. Key quantities are time, 3-dimensional position, wind angle and speed, temperature, a proxy for turbulence, and (commercially sensitive) aircraft weight. The dense observations are captured every 4 s (~1 km) over about 95% of current long-haul routes. A key property is that unlike reanalyses, the GADS observations *do not depend on any computer model*. They are independent of real-time AMDAR observations but come from the same aircraft source. One additional advantage of GADS relative to AMDAR: we can explicitly select JFK-LHR flights (GADS) rather than relying on eastern Atlantic position and rough heading towards London (AMDAR).

One operational change that might affect both wind speed and turbulence occurred before the start of our primary 19-year period and was the reduction of the vertical separation over the Atlantic from 2,000 ft to 1,000 ft in 1997. One could argue that this should allow the aircraft to coalesce closer to the jet stream core level, and perhaps to more easily escape from turbulence. We have examined the root-mean-square (r.m.s.) vertical and horizontal distributions of the flights versus year for 2002–2020 and see only limited evidence of vertical coalescence as discussed below. A second operational problem concerns a data dropout due to a failed software upgrade for a 747 fleet during 2017. We have been able to work around this problem by using the proportional trends in the 777 fleet for that year for wind speed and turbulence.

Note that as global models approach resolutions of ~10 km, the ~1 km GADS observations will still provide a unique resource. For wind speed, multiple AMDAR reports provide a better than 100 km density but cannot be limited to specific (e.g. JFK-LHR) routes. For turbulence, following a specific, known airframe is crucial. Some AMDAR systems do increase the resolution to ~15 km for short distances associated with turbulence. Newer techniques (automatic dependent surveillance – broadcast, ADS-B out) have improved spatial resolution but do not directly transmit wind speed and turbulence data in their current form (FAA, 2019b). While the 1 km GADS resolution is not currently needed for comparisons, when global grids become finer the GADS resolution can keep up for almost another order-of-magnitude decrease in grid spacing in a way that single airframe AMDAR and the newer techniques retrospectively cannot. Finally, note that because of the 2020 retirement of almost all Boeing 747's, the 23-year GADS archive (19 years for the Atlantic) will be unique for at least another decade.

The ERA5 reanalysis is the most recent in a sequence of reanalyses carried out at ECMWF (Dee *et al.*, 2011; Hersbach *et al.*, 2020). It is based on the operational forecast model that came into use during 2016 (IFS CY41R2). The ERA5 High Resolution (HRES) atmospheric data has a resolution of 31 km. We used the 0600 UTC monthly wind speed means for December, January and February with the winter labelled by the January year. The vertical layout is 137 hybrid sigma/pressure levels which are also interpolated to 37 standard pressure levels on a 1° × 1° horizontal grid. Our primary results use these pressure level values but we have also checked the results directly from model levels, also using a 1° × 1° horizontal grid, as discussed in Supporting Information S1.

3 | EXAMINING WIND SPEEDS OVER DECADES

Figure 2 shows the ERA5 and NCEP/NCAR winter wind speed reanalyses averaged over the three boxes depicting the North Atlantic jet stream exit region for 1979–2020. Throughout this article the Northern Hemisphere winters are labelled by the January year. Note that in this data-dense region there is a close agreement between the two reanalyses. The two curves have been offset for clarity. There is also a striking correlation with the North Atlantic Oscillation (NAO), with Pearson correlation coefficients of 0.88–0.89. Martin (2021) has pointed out that changes in polar jet stream waviness also bear some relation to the NAO. In some sense the wind speeds in our three eastern North Atlantic boxes are a rough proxy for the NAO index. The anomalous wind speeds and NAO index for 2010 are well documented and have been widely studied (Madonna *et al.*, 2019, and references therein). The period 1979–2020 is currently the longest "modern" winter interval corresponding roughly to the modern satellite era. There is a small secular increase in reanalysis wind speeds which is not statistically significant. Note that because of the negative and positive values of the NAO index, calculating its slope would be somewhat arbitrary.

Given the concern with the apparent disagreement between 40- and 20-year results, it is instructive to note a recent third independent study including the North Atlantic polar jet: Hallam *et al.* (2022). While that paper also uses winters as DJF, it defines the geography slightly differently, 60°W–0°. Their figure 9d only covers roughly 30 of the 40 most recent years (1979–2011). But their apparent slope for 2000–2011, the first 10 years of the most recent 20-year period, is suggestive.

For shorter periods, confounding natural oscillations could mask any real signal (Stendel *et al.*, 2021, Woolings and Blackburn 2012). Two widely studied examples are the NAO in Figure 2 and the Atlantic Multidecadal Oscillation in Figure 3 (AMO; also referred to as the Atlantic Multidecadal Variability). While we are considering periods that cover multiple NAO cycles, the AMO is more

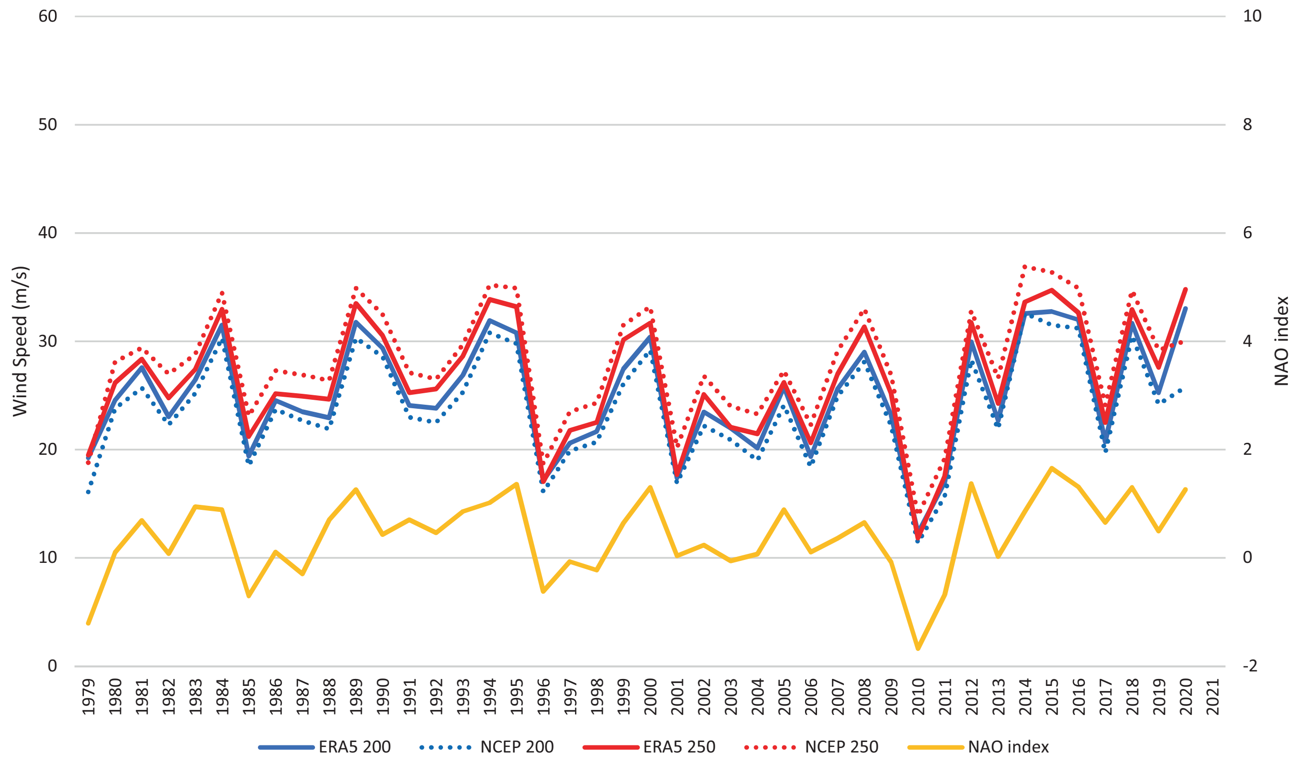
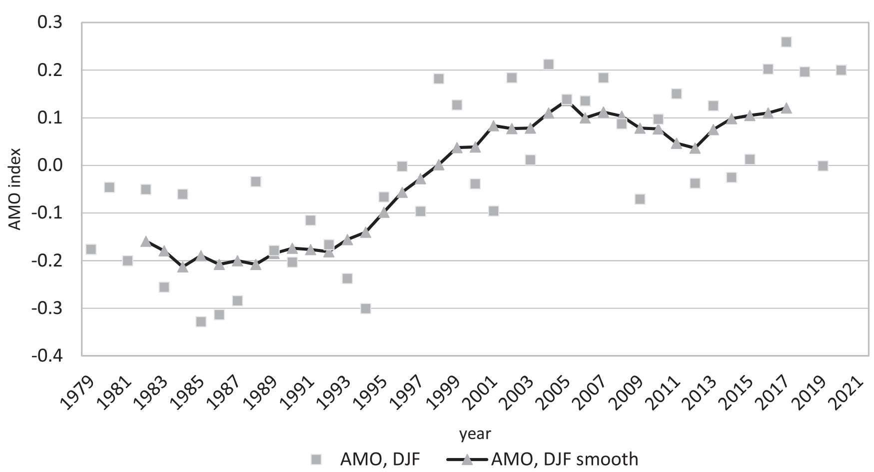


FIGURE 2 ERA5 and NCEP reanalysis wind speeds for 200 and 250 hPa and NAO index averaged over the three eastern North Atlantic boxes (40°W to 10°W) for DJF labelled by January year. For clarity, the NCEP values are offset by $-1.5\ \mathrm{m{\cdot}s^{-1}}$ (200 hPa) and $+1.5\ \mathrm{m{\cdot}s^{-1}}$ (250 hPa). On average the 250 hPa wind speeds are slightly greater than 200 hPa values, an effect which will be clearer in subsequent figures. Note the striking correlation of the wind speeds with the NAO index (Pearson correlation coefficient of NAO index with ERA5 200 hPa, 0.88; 250 hPa, 0.89). See Hurrell *et al.* (2003) for link to the current NAO data source

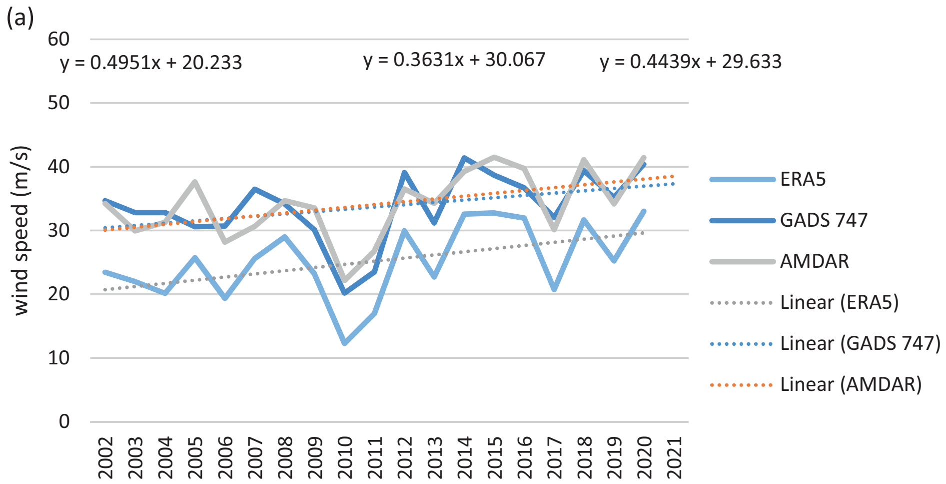
FIGURE 3 The Atlantic Multidecadal Oscillation (AMO) index for the DJF months of 1979–2020 labelled by the January year. Boxes are individual winters; line uses a seven-point smoother. See Enfield *et al.* (2001) for link to current AMO data source



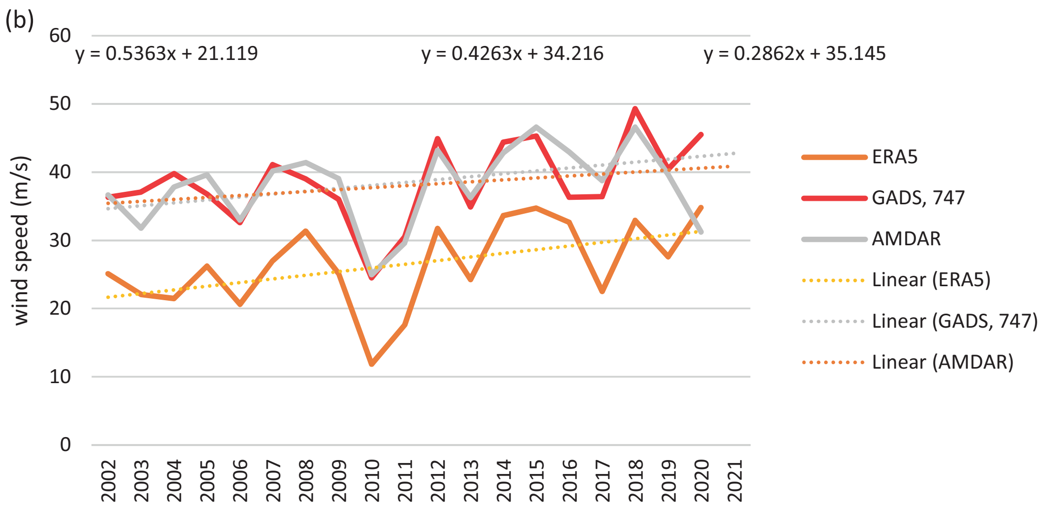
problematic for secular changes. It is somewhat fortuitous that the AMO graph appears approximately flat over our primary period of interest, 2002–2020. In addition, should the AMO undergo its likely flip over the next year or two there will be additional problems in drawing any further conclusions about medium-term secular changes in the wind speed. For reference, our finish date of 29 February 2020 was chosen several years ago unrelated to the very large coronavirus-related drop-off of North Atlantic air traffic starting in March 2020.

4 | WIND SPEED RESULTS

Our key results answer the questions posed in the Introduction affirmatively: measured wind speeds in the



ERA5	0.4951	20.233	2.4%
GADS 747	0.3631	30.067	1.2%
AMDAR	0.4439	29.633	1.5%



ERA5	0.5363	21.119	2.5%
GADS 747	0.4263	34.216	1.2%
AMDAR	0.2862	35.145	0.8%

FIGURE 4 Wind speed ($m\cdot s^{-1}$) averaged over the eastern North Atlantic boxes, 52 ± 5°N, 40°W to 10°W, for the ERA5 reanalysis and two observational archives, GADS 747 and AMDAR, at (a) 200 hPa and (b) 250 hPa. Fitted equations for ERA5 and GADS 747 are in same order as legends

exit region of the North Atlantic polar-front jet stream do show a statistically significant rise each year during the period 2002–2020 even though the ~40-year period (Figure 2) does not. This result appears in both the model-independent GADS observations and the model-dependent reanalyses. Figure 4 shows our initial wind speed results for the ERA5 reanalysis, GADS 747 and AMDAR, separated by height. Plotted are the wind speeds averaged over the three eastern North Atlantic boxes from the ERA5 reanalysis, GADS observations, and AMDAR observations at (a) 200 hPa and (b) 250 hPa, for 2002–2020. Within the figures are the linear fits to ERA5 and GADS 747 series and their corresponding equations in the same order as the legends where x is the year minus 2002 and y is the wind speed.

Two major results are conveyed by these graphs. First, the reanalysis wind speeds are consistently lower than the individual aircraft observations in absolute value but larger in their slopes. That difference in absolute value is not surprising given that the reanalysis has smoothing appropriate to its spatial resolution of 31 km (ERA5). In contrast, the GADS and AMDAR measurements are effectively point observations and are not implicitly smoothed. Second, we can quantify the secular increase by dividing

TABLE 1 Initial wind speed results

(a) Initial 200 hPa wind speed from Figure 4a			
	ERA5	**GADS 747**	**AMDAR**
Degrees of freedom	17	17	17
F value	4.79	2.75	4.70
p value	0.043	0.115	0.044
Coefficient of x	0.4951	0.3631	0.4439
Fitted 2002 wind speed	20.233	30.067	29.633
Initial slope at 200 hPa	**2.4%**	**1.2%**	**1.5%**
(b) Initial 250 hPa wind speed from Figure 4b			
	ERA5	GADS 747	AMDAR
Degrees of freedom	17	17	17
F value	5.03	3.33	1.43
p value	0.039	0.086	0.249
Coefficient of x	0.5363	0.4263	0.2862
Fitted 2002 wind speed	21.119	34.216	35.145
Initial slope at 250 hPa	**2.5%**	**1.2%**	**0.8%**

The initial secular wind speed slopes at (a) 200 hPa and (b) 250 hPa for ERA5, GADS 747, and AMDAR from Figure 4a and 4b that are statistically significant. Listed are the degrees of freedom, F value, and corresponding p value followed by the secular slope calculation.

the coefficient of x in the fitted equation by its constant term. The statistics and secular slope calculation are summarized in Table 1. For the GADS 747 observations (second equations in Figure 4a, b), the recent roughly 20-year initial wind speed result is

200 hPa, GADS	0.3631 / 30.067 = 1.2%	p = 0.115
250 hPa, GADS	0.4263 / 34.216 = 1.2%	p = 0.086

yielding an average annual increase for GADS 747 observations of 1.2% for 2002–2020. We have checked the autocorrelation function with varying lags to verify that the 19 years show no significant autocorrelations. The coarser-resolution ERA5 reanalysis also average a statistically significant increase of 2.5% per year over 2002–2020. It is not immediately obvious why the smoothed AMDAR-dependent ERA5 reanalyses yield even larger values. But see also the discussion in the following Section 5. As described below, this is not our final GADS result.

5 | CHANGES IN NORTH ATLANTIC AIRCRAFT OBSERVATIONS AND REANALYSES

Several broad issues must be dealt with when using aircraft observations to detect secular changes in jet streams over the eastern North Atlantic. The first broad issue is how do we know that the measured wind speed increases that we see are not due to improvements or other operational changes in the North Atlantic Track System. The second broad issue is the same question for the start of extensive automated aircraft observations. We thank Larry Cornman at NCAR for stressing the first point (Cornman, 2019, personal communication). That system provides a mandatory set of parallel tracks and multiple levels to handle the dense diurnal flow.

Briefly, the NATS system sets the horizontal location of the mandatory tracks approximately 36 hours in advance for the dominant eastbound flow (near 0000 UTC) used in this article and the dominant westbound flow (near 1200 UTC). The eastbound tracks reflect a balance between optimum flight levels, picking up tailwinds, not straying too far from the great circle route illustrated in Figure 1, and matching the bids of the air carriers. At peak times one was dealing with approximately 800 eastbound aircraft per day (pre-coronavirus). In the subsequent subsections we deal with the issue of improvements over the 19 years (Section 5.1), the start of automated aircraft observations (AMDAR/ACARS, 5.2), operational changes during the most recent few years (5.3), and the results and implications for reanalyses (5.4).

5.1 | Possible improvements during 2002–2020

Cornman's query is whether our initial roughly 20-year period wind speed results, at least in part, reflect an overall improvement in this process over 2002–2020. We argue that two results imply an actual change in the atmosphere rather than only NATS improvements. Figure 5 again shows our wind speed results for both levels, both fleets (747 and 777), and the DJF NAO index. First, as already seen in Figure 2, the correlation of our wind speed slope and value with the NAO index and its rise is again striking. Clearly, the rising values for the NAO index are not the result of NATS improvements. The NAO index fit shows a positive slope though, because of the negative values, a numerical value for the slope and its graphical appearance is arbitrary. Second, intuitively NATS improvements – doing a more accurate depiction of the height of the jet stream core – should result in a decreased r.m.s. height spread vertically in the "as-flown" tracks.

While sometimes all levels around the jet stream for eastbound flights will be filled, on balance there should be more clumping closer to the better-predicted jet stream core height. Figure 6a shows the time history of the as-flown r.m.s. height departure values. Putting aside the anomalous behaviour for 2006, one can summarize the

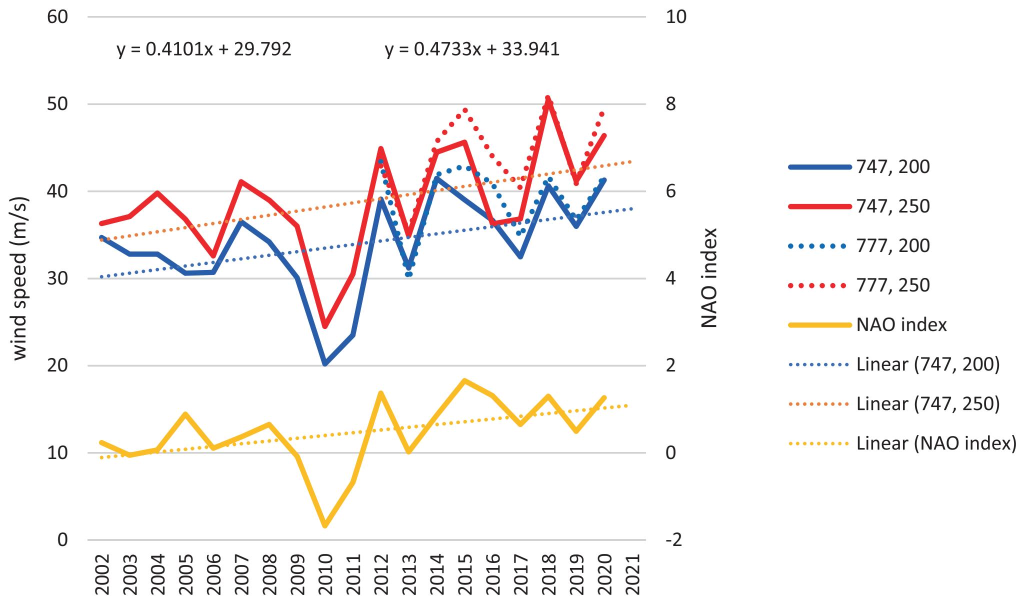


FIGURE 5 GADS 747 (2002–2020) and 777 (2012–2020) wind speed and NAO index averaged over the three eastern North Atlantic boxes, 52 ± 5°N, 40°W to 10°W, at 200 and 250 hPa including the GoFli height correction. Note that 777 observations only became available in 2012. Fitted equations for 747, 200 hPa and 250 hPa are in same order as legends. No slope is given for the NAO index since negative values would make it arbitrary

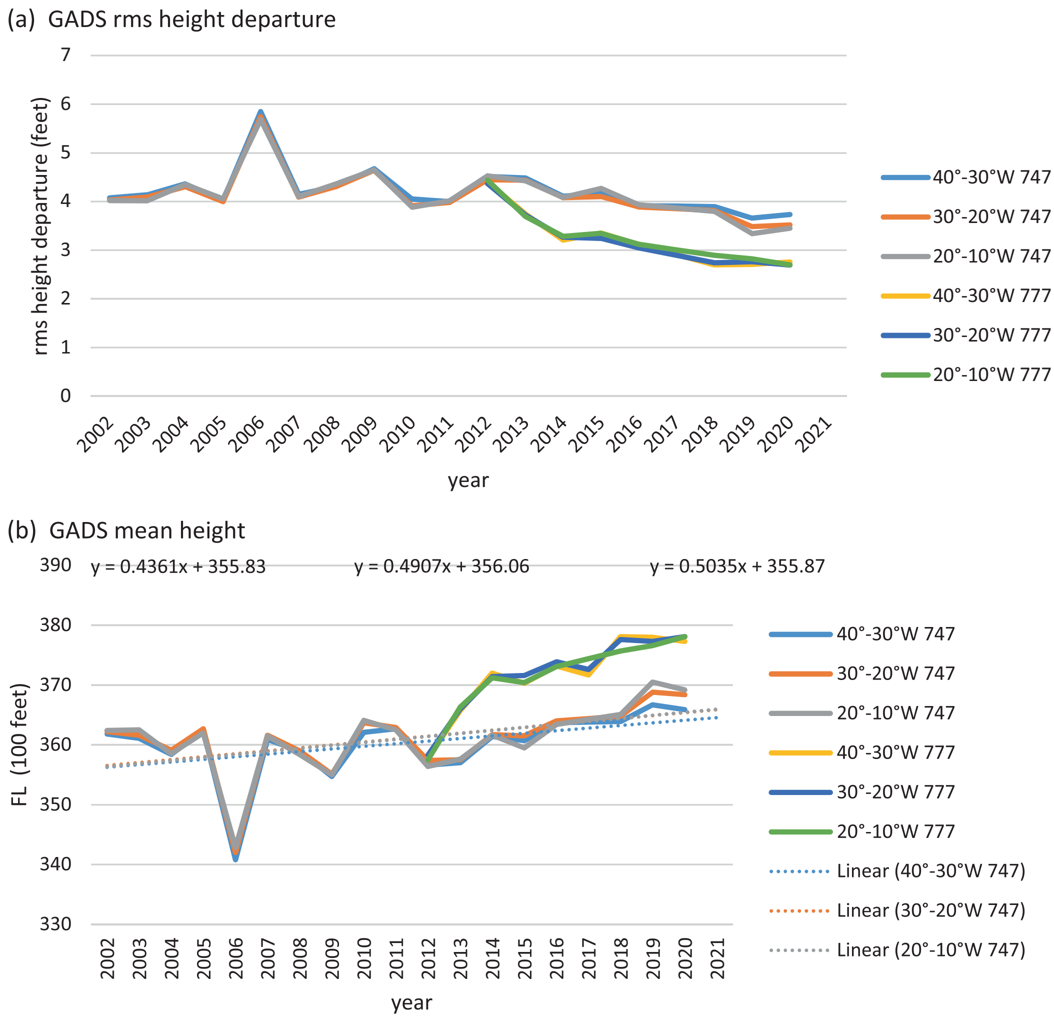


FIGURE 6 GADS r.m.s. height departure and mean height observed values, 747 (2002–2020) and 777 (2012–2020) for the eastern North Atlantic boxes. Note slight longitudinal variation for 2018–2020. (a) R.m.s. height departure values, units are feet. (b) Mean height values, units are hundreds of feet. Starting in 2012 the upper triplet is 777's and the lower triplet is the continuation of 747's

747 result as flat to 2016 or 2018 and a possible shrinkage thereafter (upper triplet for 747's). Supporting Information S2 gives the detailed calculation of the bounds on NATS improvement effects on GADS wind speed results with an upper limit of −0.4% to −0.5%.

This result implies only limited evidence for secular improvements producing better NATS routing to flight levels with stronger tailwinds. Some slight indication of a longitudinally dependent behaviour shows for 2018–2020. A similar near-null result occurs for r.m.s. latitude values (not shown) where one is much more constrained by the 1° latitudinal separation used for most of the 2002–2020 period.

5.2 | Start of automated aircraft observations (AMDAR/ACARS)

While GADS observations became plentiful over the eastern North Atlantic starting in 2002, their AMDAR/ACARS equivalent started only a few years earlier in the mid-1990s. See figure 2 in Moninger *et al.* (2003), also Supporting Information S1. One possibility is that this new data source, especially over the eastern North Atlantic, produced the discrepancy between 1980–2020 and 2002–2020 results. Figure S1.1 shows that if we extend the starting year back from 2002 to the mid-1990s, we still get a statistically significant rise in the ERA5 wind speed with the exact value depending on the choice of the starting year.

5.3 | Operational 747 changes during 2018–2020

Perhaps more indicative of recent operational changes is the corresponding mean height graph, Figure 6b. Until 2018 the fitted 747 height level is again dominated by the 2006 anomaly but is otherwise flat (lower triplet). Note the indications of some increase for 747 heights during 2018–2020 and, again, some longitudinal dependence of that increase. The biggest effects, decreased r.m.s. height departure (Figure 6a) and increased mean heights (Figure 6b), occur closest to the congested European airspace (20°–10°W). The 777 fleet shows a substantial jump for 2012–2020, in contrast to the 747 fleet, and a decrease in the r.m.s. height departure, but is not relevant to our 747-based results. As discussed in the remainder of this subsection concerning the likely source of these changes, these height alterations counterintuitively cause an underestimate of the actual secular measured wind speed changes. These changes exist because given the opportunity, the flight crews want the aircraft to improve fuel economy by flying higher. No significant decrease in the 747 r.m.s. latitude occurs (not shown).

To pursue the implications of the height changes, one must reconsider the concentration on the three easternmost boxes (52° ± 5°N, 40°–10°W). Part of the explanation is that is where the largest number of eastbound flights come closest to the core exit region of the climatological jet streak per Figure 1. But the other part of the explanation concerns normal long-haul aircraft operations and, in particular, step climbs. For some time after take-off, long-haul aircraft are too heavily loaded with fuel to be able to reach their optimal cruise altitude. Thus, they usually do one to three step climbs to improve fuel economy as they progress eastward across the Atlantic and it is in the latter half of their flight that they can reach the 747 optimal cruise altitude, FL350–FL390 (FL = flight level corresponding to 35,000 ft – 39,000 ft), depending on aircraft weight. Such a level tends to be at or just above the typical jet streak core. The results shown in Figure 6b represent a change in the mean height above and beyond the usual step climbs. But more crucially, since we are increasing the number of measurements above the mean jet core, any such height rise will on average *lower* the measured wind speed increase.

In discussions with the Shanwick oceanic air traffic control centre (Hillan, 2020, personal communication) two likely explanations were suggested for the increased heights. First was the introduction of a "GoFli" computer program that aids the controllers. Second was the use of flight deck computers that aid tactical decision making. The GoFli program prompts the air traffic controllers to proactively offer higher flight levels as fuel is burned off in a way that could not easily be done when the process was manual. Figure 6a,b show that 777 aircraft are better able than 747 aircraft to take advantage of this increased flexibility.

This seeking out of higher flight levels occurs because multiple factors improve fuel efficiency as the aircraft altitude increases – less parasitic drag and lower temperature up to the tropopause producing better thermodynamic efficiency (Davies, 1979, figures 2.4, 2.5) But there is a trade-off. A typical penalty from the decreased tailwind above the core is a loss of about one-eighth of the gain due to increased fuel efficiency. Note that one must also subtract the energy costs of the extra climb. The detailed calculation is given in the Supporting Information S3.

5.4 | Primary results and implications for reanalyses

The GADS 747 value of 1.4% per year for the secular wind speed increase (Figure 5) starts out as an averaged 1.2% per year (Figure 4a, b) prior to correcting for the GADS

TABLE 2 Final GADS wind speeds at 200 and 250 hPa from Figure 5

	200 hPa	250 hPa
Degrees of freedom	17	17
F value	3.41	3.92
p value	0.082	0.064
Coefficient of *x*	0.4101	0.4733
Fitted wind speed	29.792	33.941
Final slope	**1.4%**	**1.4%**

The final GADS 747 wind speeds at 200 hPa and 250 hPa after correction for tailwind loss during 2018–2020 due to increased height above the jet stream core. See text for discussion of GoFli program which produced this effect.

747 as-flown mean heights shown in Figure 6b. The overall effect on the GADS 747 results is small, about 1.0 $m\cdot s^{-1}$, for 2018–2020. We note that after applying this height change correction in Figure 5 the 200 hPa results seem to flatten out along with the NAO index while the 250 hPa results keep rising. The same correction has been applied to both levels. Table 2 again summarizes the detailed statistics and secular slope calculation. For the GADS 747 observations, the recent roughly 20-year final wind speed result is

200 hPa, GADS	0.4101 / 29.792 = 1.4%	p = 0.082
250 hPa, GADS	0.4733 / 33.941 = 1.4%	p = 0.064

A third broad issue is the correlation of the GADS (model-independent) wind speed trends with the (model-dependent) reanalysis results. We take this as a welcome result reinforcing the use of reanalyses in climate change studies. But there is clearly a caution needed here. The reanalyses combine background forecasts with multiple types of observations to provide the best depiction of the atmospheric state for that date. Reanalyses are independent of GADS observations but do use AMDAR observations extensively over the upper levels of the eastern North Atlantic. As noted previously, multiple studies by ECMWF have shown that the AMDAR observations have more impact on the short-term forecasts than the satellite radiances in the eastern North Atlantic (Bormann *et al.*, 2019, their figure 14). Specifically, the *in situ* observations, their figure 14a, do have a substantial effect, while both types of satellite observations, their figure 14c and 14d, do not. With rare exceptions, AMDAR reports are the only *in situ* observations in the eastern North Atlantic. Thus, the reanalyses, which depend on the accuracy of the short-term forecasts, can be affected by AMDAR height rises corresponding to the GADS height rises in Figure 6b.

Our agreement between model-independent wind speeds (GADS) and model-dependent wind speeds (reanalyses) does not prove that secular trends in the reanalysis wind speeds can be trusted, even though the reanalyses still provide the best description of the atmosphere for a given day and year. Clearly the same problem occurs because of secular changes in satellite instrumentation (Gelaro *et al.*, 2017). It is less common for *in situ* observations to have difficulty with secular changes.

6 | TURBULENCE RESULTS

When the GADS experiment was started in 1989 (Tenenbaum, 1991) an effort was made to capture turbulence information. Since that time, there has been general agreement by the International Civil Aviation Organization (ICAO) that the quantity to report is the aircraft-independent value of the Eddy Dissipation Rate (EDR: Sharman *et al.*, 2014, Sharman and Lane. 2016). While recent progress has been substantial, early efforts were more typically reported as equivalent gust velocity, DEVG, which is aircraft specific. Because the original version of the GADS observations relied on the on-board computer capability, a simpler measure was adopted. This consisted of the minimum and maximum values of the vertical acceleration, a_{zn} and a_{zx}, during the 1 s preceding the every 4 s GADS measurement. Subsequent work showed that these quantities can be converted to DEVG even though it is still aircraft specific (Gill, 2014).

Notwithstanding the issue of the desired turbulence measure, we can still examine the time dependence of the GADS turbulence measure. For context it is important to realize that most of a long-haul aircraft's turbulence reports will be "Nil" because "Light" turbulence is relatively rare and "Moderate or Greater" (MOG) even rarer. Complicating the issue is that the boundary between the various categories is still subject to change even if one focuses on the ICAO EDR measure (ICAO, 2020).

A separate problem is changes in the tactical and strategic avoidance procedures of forecast turbulence areas using information supplied by the global significant weather (SIGWX) charts issued by the two World Area Forecast Centres (WAFC, 2017). One only need think of the growing ubiquitousness of "please keep your seat belt fastened at all times" flight crew announcements. Note that this problem is more prevalent for turbulence than for the eastbound New York-London wind speed studies where the rules of NATS constrain the tactical decisions of the flight crews.

Because of the large number of North Atlantic observations in the GADS archives, we can at least check on the time dependence of the "Light" event fraction. Statistically valid MOG results are beyond our capabilities and are being pursued in separate studies over a

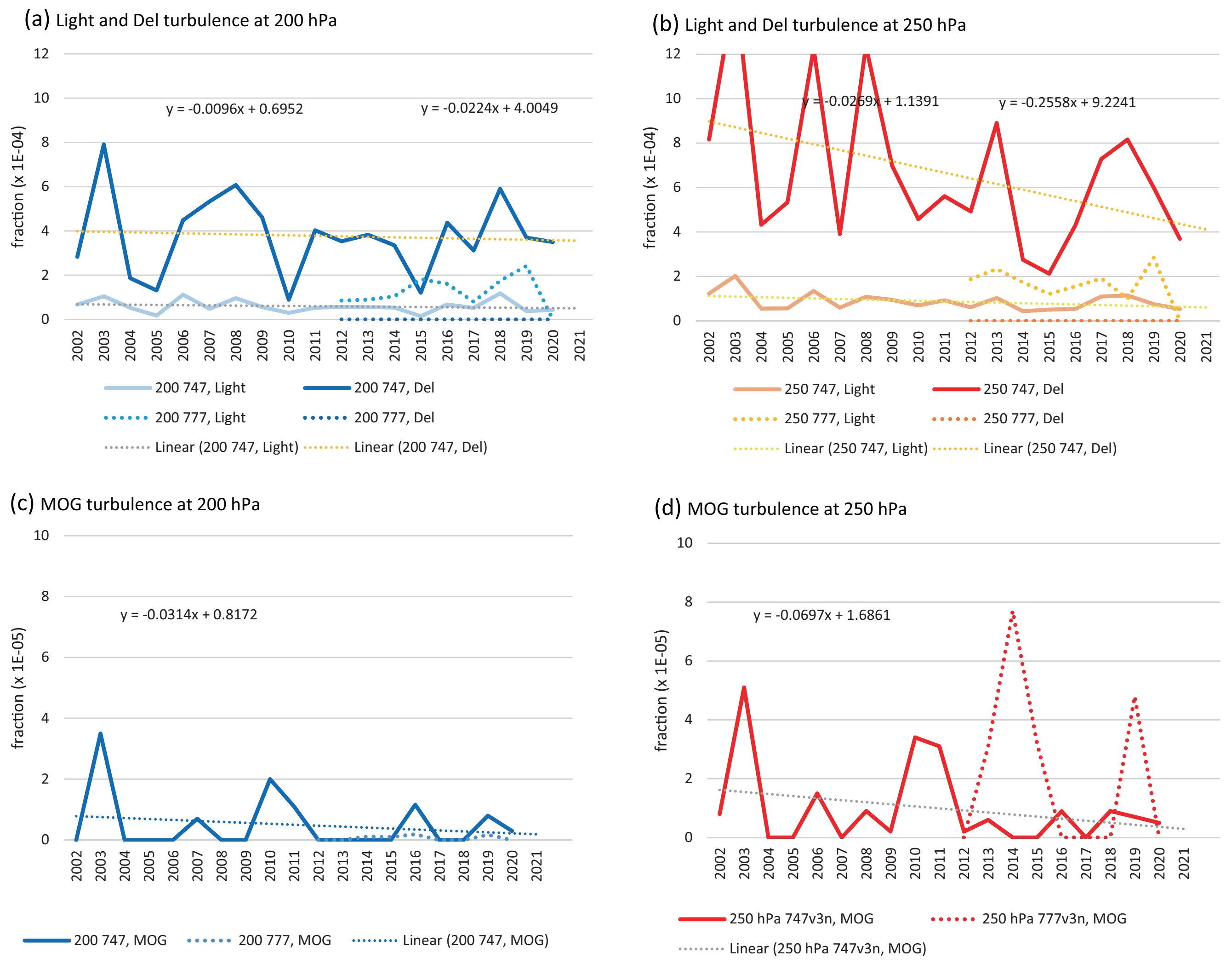


FIGURE 7 GADS turbulence events for 747 (2002–2020) and 777 (2012–2020) aircraft. Light and Del events at (a) 200 hPa and (b) 250 hPa. MOG events at (c) 200 hPa and (d) 250 hPa

wider geographical area by the United Kingdom Meteorological Office (UKMO) (Buchanan, 2020, personal communication).

One additional problem enters into studies of Light turbulence. An event exceeds the Light threshold when the a_{zn} or a_{zx} departure from $1.000 \times g$ exceeds 0.150 which is equivalent to DEVG exceeding 2.0 m·s^{-1} (Truscott, 2000; Overeem, 2002). But, this threshold poses two related problems. The first is that the vertical acceleration measurement is not claimed to be calibrated. We remedy this difficulty by examining the long-run average for each aircraft. If there is a small but stable bias, we renormalize the readings from that aircraft. If there is not a stable bias, we exclude that aircraft from the turbulence computations.

The second problem is specific to Light events (as opposed to MOG). Calling an event Light if and only if the a_{zn} or a_{zx} departure from $1.000 \times g$ exceeds $0.150 \times g$ does not do justice to the nature of the GADS observations and the nature of turbulence. The GADS turbulence measurements are taken during the 1 s interval preceding the every 4 s wind speed recording. If there are really both downward and upward excursions during that 1 s time interval, we argue that the relevant measurement of the turbulence is the difference, $|a_{zx} - a_{zn}|$, since that is what our stomachs would feel. Specifically, an overall excursion, referred to as Del of

$$\text{Del} = |a_{zx} - a_{zn}| = 1.050 - 0.875 = 0.175,$$

whose value using the cut-off of $0.150 \times g$, does exceed the "Light" threshold even though neither a_{zx} or a_{zn} do.

With these caveats, the results for the turbulent fraction defined as the number of events in that category divided by the number of observations for that winter are shown in Figure 7 for Light, Del and, with much less statistical confidence, MOG categories at 200 hPa and 250 hPa. Note the differing scales for Light and Del versus MOG. Note also that as expected the Del results are significantly larger than the Light results. See also Kim, S.-H. *et al.* (2020).

Whether these results represent a real change in the upper troposphere, or much more careful turbulence avoidance tactical and strategic actions, must be determined. The fall-off to zero for MOG events during recent years needs further study and may represent changed tactics or random fluctuations. Aircraft are biased samplers of turbulence, attempting to avoid it whenever possible. Improved turbulence avoidance strategies over the decades may explain the apparent lack of increase in turbulence, even if the amount of clear-air turbulence in the atmosphere has been increasing as we expect (Williams and Joshi, 2013; Storer *et al.*, 2017; Williams, 2017; Lee *et al.*, 2019). These improved strategies may stem from improved turbulence forecasts, the skill of which has been gradually increasing decade on decade (Kim, J.-H. *et al.*, 2018) from improved communication of real-time turbulence information between pilots (the IATA Turbulence Aware project: IATA, 2020); or from modified airline safety policies that increasingly require pilots to avoid areas of suspected turbulence for fear of injuries and litigation.

7 | CONCLUSIONS AND DISCUSSIONS

Our primary conclusion is that we see a small but statistically significant measured increase of between 1.2% and 1.4% per year over 2002–2020 from the GADS 747 observations of the exit region of the North Atlantic jet stream wind speeds. Of this *up to* 0.5% might be due to NATS changes. We also see a rise in the independent 777 fleet but the record (2012–2020) is too short for statistically valid fits. Note that 19 years at 1.4%–0.5% = 0.9% per year implies a more than 17% cumulative change. A solidly statistically significant ($p = 0.04$) larger change of 2.5% per year occurs in the coarser-resolution AMDAR-dependent ERA5 reanalysis. If we move the ERA5 starting year back to the mid-1990s, we obtain slopes of 1.2%–1.8% depending on the starting year. Our uncertainty here is in part, when did the early AMDAR/ACARS observations become quantitatively important over the eastern North Atlantic.

Such a cumulative change is consistent with recent anecdotal subsonic transatlantic speed records. The increase shows up both in the model-dependent ERA5 reanalyses and in the model-independent GADS observations and at both 200 hPa and 250 hPa. The turbulence results show little or no apparent change. Unlike wind speeds, however, the turbulence results can be more readily confounded by difficult-to-quantify changes in aircraft procedures – specifically, changed tactical and strategic actions as a result of improvements in the significant weather guidance and the height changes mentioned in Section 5.

An obvious concern is whether the polar-jet wind speed observation results could be confounded by other non-NATS factors. Not surprisingly, the AMDAR reports dominate the satellite observations in the upper-level reanalyses of the eastern North Atlantic. First, we also see the increase in the reanalyses though they could be influenced by changes in the AMDAR reports feeding the data assimilation step. But it is worth remembering that because of the size of the GADS archive, we have a large and unusually homogeneous dataset independent of computer models in general and reanalyses in particular. Specifically, we deal only with eastbound flights connecting a fixed pair of cities, New York-London (JFK-LHR), and two independent homogeneous fleets (747 and 777). If given the choice, such flights would seek out the jet stream core and balance such a choice only with not departing too far from the great circle route. Because of the NATS track set-up, typically five parallel tracks during most of the 2002–2020 period at 1° latitude intervals (2020: likely to shrink in the future), most aircraft are offset by 1–2° poleward or equatorward of the optimal track and/or multiples of ±1,000 ft vertically.

Given the lack of a statistically valid wind speed increase in the roughly 40-year Figure 2, we cannot argue that our results prove an actual trend in the atmosphere. Four possibilities are: (1) no change in the atmosphere over the 40 years; (2) an increase during the last roughly 20 years in the reanalyses within the GADS sectors due to the very large increase in automated aircraft observations probably starting in 1997; (3) a small increase during the last 20 years due to improvements in the NATS system; and (4) a small increase during the last 20 years in the actual atmospheric wind speeds.

Thus, on average we argue that our eastbound wind speed increase of 1.2% to 1.4% per year fairly samples recent secular changes in the North Atlantic polar jet stream reanalyses of which *up to* 0.5% might be due to NATS changes. This result is true even after accounting for the mean height changes from 2012 to 2020. As illustrated both by the secular rise in the NAO index and its close correlation with the measured GADS wind speeds and by the near-zero vertical shrinkage of the 747 as-flown tracks, the analysed wind speed increase is not due to just changes in the NATS operations. In combination with two increased CO_2 model studies (Delcambre *et al.*, 2013; Kim, J.-H. *et al.*, 2021; the ERA5 results; and the GADS results), we now have four independent tests showing increased wind speeds in the recent analysed winter North Atlantic jet exit region.

For turbulence, we must still be concerned with the effects of the aircraft step climbs and the tactical changes in turbulence avoidance even though such changes are limited by the rules of the North Atlantic track system. Finally, our perhaps most worrisome result is that secular changes in eastern North Atlantic wind speed reanalyses are also subject to the biases due to NATS operational changes in the dominant AMDAR *in situ* reports. Stated as an admonition: reanalyses still provide the best estimate of the actual state of the atmosphere at a given time but continue to treat secular changes with caution.

DATA AVAILABILITY STATEMENT

The contents of the GADS (Global Aircraft Data Set) archive are proprietary to the air carriers and are covered in part by two licensing agreements between (1) the air carriers and State University of New York, Purchase (SUNY Purchase) and (2) the air carriers and the United Kingdom Meteorological Office (UKMO). The two agreements differ slightly but essentially require that the GADS observations not be passed on to other entities and not be placed onto a publicly available server. We are permitted to use the data in scientific publications provided individual flights cannot be directly identified. The GADS archive is currently maintained by the UKMO in Exeter, Devon, UK.

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Joel Tenenbaum: Conceptualization; funding acquisition; investigation; software; supervision; writing – original draft; writing – review and editing. **Paul D. Williams:** Investigation; methodology; software; validation; writing – original draft; writing – review and editing. **Debi Turp:** Data curation; investigation; methodology; software; validation. **Piers Buchanan:** Investigation; methodology; project administration; software; supervision; validation. **Robert Coulson:** Data curation; software; validation. **Philip G. Gill:** Conceptualization; investigation; methodology; resources; software; supervision; validation. **Robert Lunnon:** Conceptualization; funding acquisition; investigation; methodology; resources; software; supervision; validation; writing – review and editing. **Marguerite G Oztunali:** Data curation; investigation; methodology; software; validation. **John Rankin:** Conceptualization; funding acquisition; investigation; methodology; resources. **Leonid Rukhovets:** Data curation; investigation; methodology; software; validation.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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