Chapter 23
Clear-Air Turbulence in a Changing Climate

Paul D. Williams and Manoj M. Joshi

Abstract How might the processes generating clear-air turbulence change in a warmer world? We know that observations support an association between clear-air turbulence and shear instability. We also know that the upper atmospheric wind shears are changing in response to greenhouse gas forcing. In particular, theoretical reasoning and climate model simulations both suggest that the vertical shear in horizontal wind is increasing in magnitude at typical aircraft cruising altitudes in the middle latitudes, especially in the winter months in each hemisphere. This increased shearing implies that clear-air turbulence may itself be changing as a consequence of climate change. This chapter reviews the various lines of observational and model-based evidence for trends in clear-air turbulence, by analyzing data from turbulence encounters with aircraft, turbulence diagnosed from reanalysis datasets, passenger injuries caused by turbulence, and turbulence diagnosed from climate models. The possibility of anthropogenic trends in clear-air turbulence opens up a whole new field of academic study, which exists at the interface between the two scientific disciplines of aviation turbulence and climate change. We call for future work to improve our understanding of this poorly understood but potentially important impact of climate change.

23.1 Introduction

Clear-air turbulence is, by definition, atmospheric turbulence on aircraft-affecting length scales that exists outside clouds and thunderstorms and their associated convective updrafts and downdrafts. Aircraft are estimated to spend roughly 3 %

P.D. Williams (✉)
Department of Meteorology, University of Reading, Earley Gate, Reading RG6 6BB, UK
e-mail: p.d.williams@reading.ac.uk

M.M. Joshi
Centre for Ocean and Atmospheric Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK
e-mail: m.joshi@uea.ac.uk

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of their cruise time in light-or-greater clear-air turbulence (Watkins and Browning 1973) and 1 % of their cruise time in moderate-or-greater clear-air turbulence (Sharman et al. 2006). Observations by Watkins and Browning (1973) support an association between clear-air turbulence and the Kelvin–Helmholtz shear instability. The fluid dynamical theory of this instability applies to stratified shear flows, such as those encountered in the vicinity of the atmospheric jet streams. According to the theory, if the shear is strong enough and the stratification is weak enough, then small, wavelike perturbations are able to grow in amplitude by extracting energy from the background flow. After an initial exponential growth that is governed by linear dynamics, the waves eventually enter the nonlinear regime and break down into turbulence.

The goal of this chapter is to bring together two separate ingredients. The first ingredient is the generally accepted belief, outlined above, that clear-air turbulence is generated by shear instabilities. The second ingredient is the notion that the atmospheric wind shears may be changing because of (or, more precisely, as part of) climate change. The implication of bringing together these two ingredients is that clear-air turbulence itself may be changing as a consequence of climate change. This possibility opens up a whole new field of academic study, which exists at the interface between the two scientific disciplines of aviation turbulence and climate change. This new field is still in its infancy, but our hope in writing this chapter is to spur on the research that will be needed to answer the many open questions.

The outline of the chapter is as follows. Section 23.2 discusses the basic science of climate change, focusing on the response of the upper atmospheric winds to anthropogenic forcing. A mechanism for climate-related trends in wind shear and clear-air turbulence is described, and the role of stratospheric ozone is considered. Section 23.3 discusses the various lines of observational and model-based evidence for trends in clear-air turbulence. Such trends are difficult to detect, but several attempts to do so are described, using data from turbulence encounters with aircraft, turbulence diagnosed from reanalysis datasets, passenger injuries caused by turbulence, and turbulence diagnosed from climate models. Section 23.4 concludes the chapter by calling for future work to improve our understanding of this poorly understood but potentially important impact of climate change.

23.2 Response of Upper Atmospheric Winds to Anthropogenic Forcing

23.2.1 The Changing Climate

It has become apparent from observations in recent decades that Earth's lower atmosphere has been warming globally since the end of the nineteenth century, with the warming trend accelerating in the latter half of the twentieth century (Hartmann et al. 2013). Although some natural factors such as variations in solar radiation have contributed a small amount to the warming, the primary cause is increasing anthropogenic emissions of greenhouse gases, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Myhre et al. 2013, Sect. 8.5). Increases in CO_2 mainly come from industrial processes such as fossil fuel combustion and cement manufacture, although other factors such as deforestation are also significant contributors (Ciais et al. 2013, Sect. 6.3.1; Le Quéré et al. 2013). Increases in CH_4 arise from sources such as rice paddies, ruminants, and climate-sensitive ecosystems such as wetlands (Ciais et al. 2013, Sect. 6.3.3), whereas increases in N_2O arise primarily from agriculture (Ciais et al. 2013, Sect. 6.3.4).

The lower atmosphere has warmed by approximately 0.5–1.0 K since the nineteenth century (Hartmann et al. 2013), and projections of future change suggest an additional surface warming of 0.5–2.0 K by the 2050s or 0.5–4.5 K in the absence of reductions in greenhouse gas emissions (Collins et al. 2013, Sect. 12.4). These temperature ranges depend on three major uncertainties. The first uncertainty is the total anthropogenic emissions of greenhouse gases between now and the 2050s, which depends on socioeconomic factors such as economic growth and the development of renewable technologies (e.g., van Vuuren et al. 2011). The second uncertainty is the fraction of emitted carbon that remains in the atmosphere as CO_2, which depends on biogeochemical factors such as uptake of CO_2 by the ocean or the terrestrial biosphere (Friedlingstein et al. 2006). The third uncertainty is the sensitivity of the physical climate system to the CO_2 that remains in the atmosphere, which depends on how a warming world may alter processes such as the seasonal cycle of sea ice or cloud formation (Bony et al. 2006). The relative importance of these three factors is expected to change in time. For instance, changes in anthropogenic emissions of greenhouse gases in the near future will have a much greater bearing on climate change in the latter half of this century than on climate change before the middle of this century (Hawkins and Sutton 2009).

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) recommended achieving “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” The threshold chosen was a 2 K rise from preindustrial levels, although given the uncertainties discussed above, there are significant uncertainties in the greenhouse gas emissions needed to stay within this target (Meinshausen et al. 2009). Although at first sight 2 K seems like a small value, some profound effects are projected from even this small change, because even though climate change will affect the whole of the globe, some parts will warm more than others. For instance, the Arctic is projected to warm more than the tropics or Southern Ocean, and the land is projected to warm more than the ocean (Collins et al. 2013). Associated with such patterns in warming are changes to regional- and continental-scale atmospheric circulations, causing concomitant and potentially profound changes to other atmospheric processes such as winds and rainfall, in addition to changes expected from the direct temperature increase such as sea-level rise or heat waves. Climate model projections suggest that the 2 K rise will happen between 2050 and 2100, depending on future emissions of CO_2 this century (Joshi et al. 2011).

23.2.2 A Mechanism for Climate-Related Trends in Clear-Air Turbulence

A key question of interest to readers of this book will be: How might the processes generating clear-air turbulence change in a warmer world? In addition to spatial gradients in warming, the troposphere and stratosphere warm unevenly in response to climate change (e.g., Collins et al. 2013, their Fig. 12.12). The zonal-mean (i.e., longitudinally averaged) temperature response to climate change is shown in Fig. 23.1. The tropical troposphere is projected to warm more than the tropical surface, because a warmer atmosphere on average is projected to have a higher water vapor concentration, due mostly to the increase in saturation vapor pressure of water vapor with temperature. Associated with the higher concentration of water vapor is more latent heating due to condensation, resulting in the tropical atmosphere being more stable, i.e., having a less negative lapse rate (Bony et al. 2006). In the polar regions, the tropospheric amplification of warming is smaller because there is less water vapor present, but changes in atmospheric heat transport and strong climatic feedbacks associated with changes to sea ice and clouds do result in a strong surface warming (Taylor et al. 2013). The stratosphere, by contrast, cools in response to the addition of anthropogenic greenhouse gases, which is related to

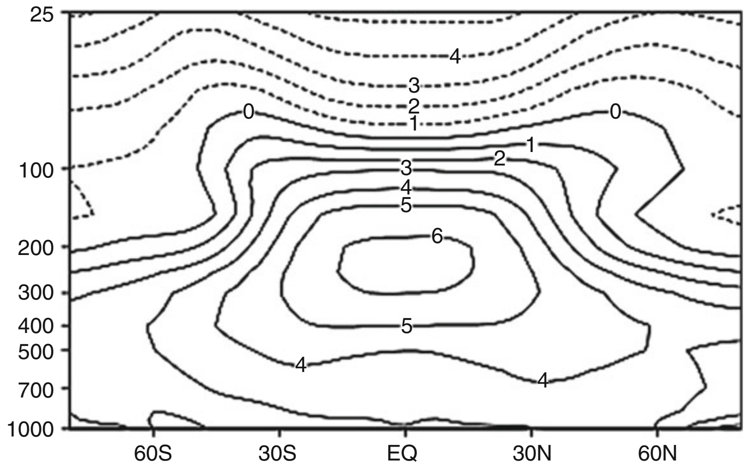

Fig. 23.1 Annual-mean zonal-mean temperature change (K) from 1980–1999 to 2080–2099 averaged over an ensemble of climate models. The horizontal axis is latitude, and the vertical axis is pressure in hPa. *Solid contours* indicate warming, and *dashed contours* indicate cooling. From Lorenz and DeWeaver (2007)

changes in the emission of infrared radiation to space by these increased gases (Fels et al. 1980).

The spatially varying response described above, when allied to the fact that the tropopause, which separates the stratosphere and troposphere, itself decreases in height from equator to pole, gives rise to one key possible change to clear-air turbulence due to the large-scale relationship between wind and temperature. The zonal-mean zonal wind response to climate change is shown in Fig. 23.2. Meridional (north–south) gradients in temperature are related to vertical shear in zonal (east–west) winds, because of geostrophic and hydrostatic balance. Therefore, near the tropopause, which is the approximate cruising altitude for commercial aircraft, climate change causes both the meridional temperature gradient and vertical wind shear to increase in magnitude in the middle latitudes, especially in the winter months in each hemisphere (Lorenz and DeWeaver 2007; Delcambre et al. 2013). This mechanism is at the heart of the projected increases in wind shear and hence clear-air turbulence studied by Williams and Joshi (2013), which will be described in Sect. 23.3.5.

The response described above assumes that both hemispheres warm evenly, which is not the case. In fact, the southern extra-tropics are expected to warm at a

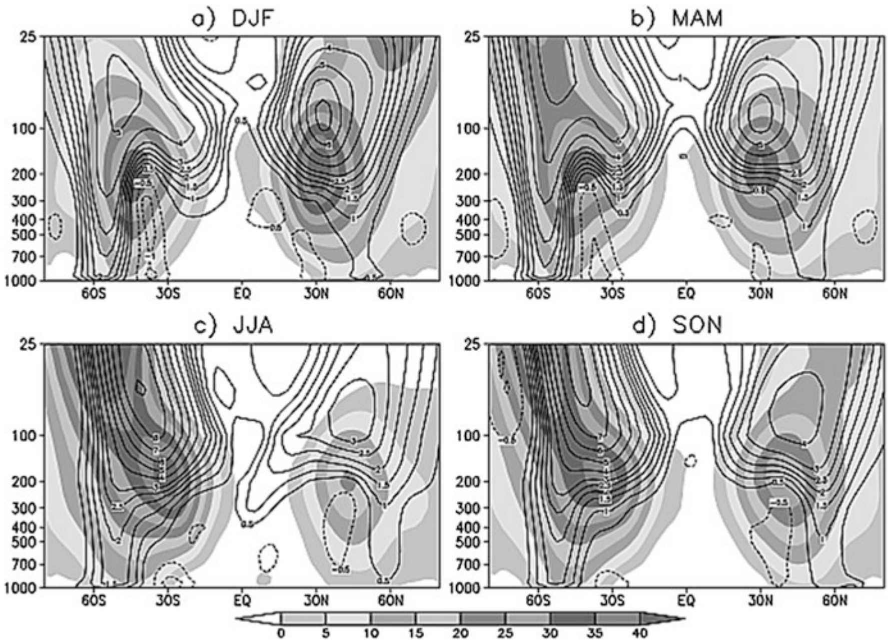

Fig. 23.2 Zonal-mean zonal wind speed for the twentieth century (*shaded*) and change from 1980–1999 to 2080–2099 (*contours*), both averaged over an ensemble of climate models in (**a**) December, January, and February; (**b**) March, April, and May; (**c**) June, July, and August; and (**d**) September, October, and November. The units are m s^{-1}. The horizontal axis is latitude, and the vertical axis is pressure in hPa. *Solid contours* indicate increases, and *dashed contours* indicate decreases. From Lorenz and DeWeaver (2007)

slower rate than the rest of the world, because of the efficiency at which heat is transported away from the surface by the circulation of the Southern Ocean. However, in the upper troposphere, this asymmetry is much less marked, suggesting that the winds in the southern hemisphere's upper troposphere will warm in a similar manner to the northern hemisphere. The zonally averaged picture conceals the fact that the northern hemisphere's upper tropospheric jet stream displays considerable longitudinal variability. The response of the Pacific and Atlantic jet streams will depend to some extent on the differing responses of these respective ocean basins to climate change (Lorenz and DeWeaver 2007), which projections suggest are very different. While climate models project a robust warming of the Pacific Ocean, the response of the North Atlantic Ocean varies more among models (Collins et al. 2013, their Fig. 12.11) because of the added complexity of the ocean circulation's response to climate change (Weaver et al. 2012).

23.2.3 The Role of Stratospheric Ozone

The above picture describes a change to the tropospheric jet stream arising from changes in temperature primarily as a result of CO_2 emissions. While the role of other well-mixed greenhouse gases on the temperature distribution of the upper troposphere and lower stratosphere (UTLS) is smaller, one greenhouse gas whose changes are anthropogenic in origin must be mentioned: stratospheric ozone (O_3). Emissions of chlorofluorocarbons during the twentieth century led to an increase in the concentrations of such gases in the stratosphere. These gases are able to destroy O_3 in a reaction that is catalyzed on surfaces such as cloud particles, which can form in the lower stratosphere in winter and spring, usually in the southern polar lower stratosphere, since this is significantly colder than its northern counterpart. The resulting drop in springtime polar stratospheric O_3 is known as the ozone hole.

The reason why this process is relevant to clear-air turbulence changes is that destroying O_3 cools the polar lower stratosphere (Fels et al. 1980), enhancing the equator-to-pole temperature gradient, associated with which is a strengthening of the tropospheric jet stream wind shear. Depletion of O_3 is thought to have significantly contributed to recent changes in the southern hemisphere's jet stream (e.g., Arblaster and Meehl 2006). However, changes in the northern hemisphere are smaller, so while O_3 depletion is of interest to understanding the behavior of the UTLS region, it is perhaps of less interest to understanding future changes to clear-air turbulence in the regions where aviation traffic is highest.

The above picture also brings into focus how the spread in the projections of regional changes associated with global warming is related to differences between the models. The spread is associated with different model formulations of small-scale processes such as cloud formation and sea ice as described above, as well as differences in the large-scale advection or movement of momentum or tracers in the atmosphere and ocean. These factors also give rise to inter-model spread in projections of exactly how phenomena such as jet streams may change both in position and strength under climate change. Quantifying such uncertainty is a task that is being carried out by the climate research community.

It is perhaps ironic at a time when aviation is being described as part of the climate change problem due to emissions associated with air travel—especially given projected future trends in air traffic—that changes to climate may affect aviation through increases in turbulence. This should not be a surprise though: changes to clear-air turbulence are simply dynamical consequences to changes in the large-scale state of the atmosphere–ocean system, which are to be expected when the system is perturbed significantly over many decades, as humankind has done and is continuing to do.

23.3 Evidence of Trends in Clear-Air Turbulence

23.3.1 The Problem of Detecting Historic Trends in Turbulence

The suggestion of anthropogenic changes in clear-air turbulence according to the mechanisms discussed in Sect. 23.2 naturally leads us to search for turbulence trends in historic data. The detection of historic trends in atmospheric variables such as temperature and precipitation is possible partly because of the existence of high-quality gridded reanalysis data covering at least the past few decades. Reanalysis datasets contain the best estimates of the large-scale state of the three-dimensional global atmosphere, constrained by a wide variety of observations that have been assimilated into a comprehensive general circulation model. In contrast, the detection of historic trends in clear-air turbulence is complicated by a number of problems concerning the quality of the available data. Although global atmospheric reanalysis datasets have finer resolutions than climate models, they are still too coarse in space and time to resolve turbulence on the scales affecting aircraft. The only direct observations of clear-air turbulence are in situ measurements from weather balloons and aircraft.

Radiosondes suspended from weather balloons are widely deployed to obtain operational soundings for weather forecasts. As they ascend, they respond to turbulent eddies that are an order of magnitude smaller than the eddies that affect aircraft. However, under the assumption that the turbulence is in equilibrium, the downscale cascade of three-dimensional turbulence implies that wherever and whenever there is aircraft-affecting turbulence, there will also be balloon-affecting turbulence. Therefore, turbulence measured by weather balloons could offer insights into aviation turbulence. Unfortunately, commercial radiosondes currently have no capability to directly measure and record the atmospheric turbulence they experience.

Motivated by the above capability gap, Harrison and Hogan (2006) proposed a method for adapting conventional meteorological radiosondes to detect atmospheric turbulence. The method involves adding a Hall-effect magnetometer to the instrument package. These inexpensive geomagnetic sensors are able to monitor the terrestrial magnetic field. Rapid fluctuations in the magnetic field measurements are related to the motion of the radiosonde, which is strongly influenced by atmospheric turbulence. Harrison et al. (2007) developed the method, by using three mutually orthogonal Hall-effect magnetometers instead of one, allowing the detection of all three dimensions of the turbulent fluctuations.

Marlton et al. (2015) have recently developed the weather balloon method further, by proposing the use of an accelerometer instead of a geomagnetic sensor. This modification is beneficial because it allows the turbulent motions to be measured in standard units of acceleration. In a series of test flights, strong turbulence was found to induce accelerations of magnitude greater than 5 g, where $g = 9.81$ m s^{-2}. Calibration of the accelerometer data with a vertically oriented lidar has allowed eddy dissipation rates (ε) of between 10^{-3} and 10^{-2} m^2 s^{-3} to be derived from the acceleration measurements. Data from one of the test flights by Marlton et al. (2015) is shown in Fig. 23.3. In-cloud turbulence, identified as such because the relative humidity is near 100 %, is present at 2–6 km. Clear-air turbulence, identified as such because of the low relative humidity, is present within the fast winds of the jet stream at 8–10 km.

Accelerometer measurements of turbulence have been made routinely by Marlton and colleagues since 2013. However, the launches are made from only a few geographic points, and the record is too short to seek climate-related trends. If inexpensive accelerometers were fitted to the thousands of radiosondes that are launched around the world daily, then the result would be a growing record of direct turbulence measurements with considerable geographic coverage. At the present

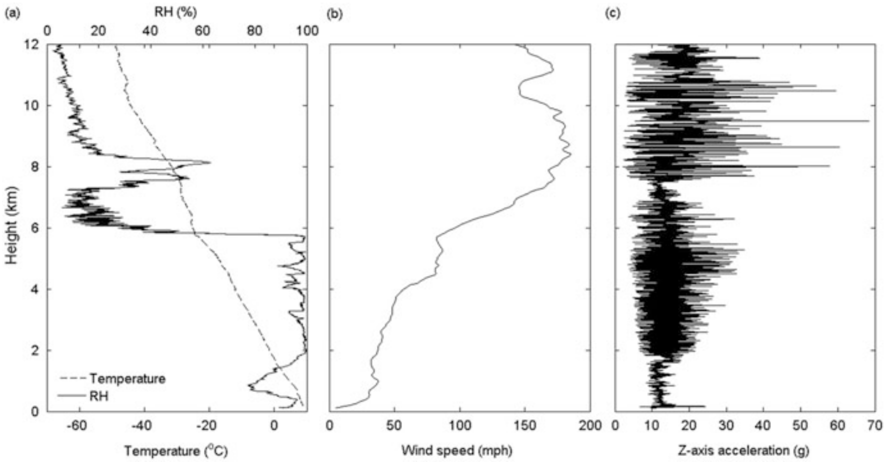

Fig. 23.3 Vertical profiles from a radiosonde balloon flight launched on 5 November 2013 in Reading, UK, showing (**a**) temperature (*dashed*) and relative humidity (*solid*), (**b**) horizontal wind speed, and (**c**) acceleration measured by the vertical axis of the accelerometer. From Marlton et al. (2015)

time, however, datasets of turbulence encounters with aircraft appear to offer the best opportunity for seeking historic trends.

23.3.2 Historic Trends in Turbulence Encounters with Aircraft

Datasets from turbulence encounters with aircraft fall into two categories: automated measurements and pilot reports (PIREPs). In the first category, some aircraft have recently been fitted with appropriate hardware and software to make automated measurements of the atmospheric turbulence through which the aircraft is flying. The measures provide estimates of the eddy dissipation rate (e.g., Sharman et al. 2014) and derived equivalent vertical gust (e.g., Gill 2014). The measures are quantitative and objective and are logged automatically by the aircraft at regular intervals. The eddy dissipation rate is an attractive quantity to measure and analyze, because it is an intrinsic property of the atmosphere and is independent of the specific aircraft flying through it. Unfortunately, these automated measures have only been available for a few years and are not yet amenable to a trend analysis. However, they are likely to become so as more data are acquired over time and as the facility to make automated measurements is installed on more aircraft.

In the second category, PIREPs indicate a turbulence intensity that is estimated by the pilot. The estimates are typically recorded on a calibrated scale in which 0 represents null turbulence, 1 is smooth-to-light, 2 is light, 3 is light-to-moderate, 4 is moderate, 5 is moderate-to-severe, 6 is severe, 7 is severe-to-extreme, and 8 is extreme. PIREPs are known to suffer from a number of limitations (e.g., Schwartz 1996; Sharman et al. 2014). In contrast to automated measurements, PIREPs are only semiquantitative, and, because they inevitably depend upon the experience and knowledge of the pilot, they are also subjective. PIREPs must be interpreted with some caution, because they are a property of the specific aircraft being flown: a small aircraft will experience stronger turbulence than a large aircraft when flying through airspace with a given turbulent eddy dissipation rate. PIREPs can have significant spatial and temporal errors. There may also be cultural biases, with pilots from some countries or airlines less likely to log PIREPs. A final limitation is that aviation hazard forecasts are available to help aircraft avoid flying through suspected regions of strong turbulence, and recent PIREPs from previous aircraft in the same airspace are also available for the same purpose. The usage of this prior information in route planning introduces a bias in PIREPs against the stronger turbulence categories.

Despite the above limitations, PIREPs have been used to create statistical climatologies of clear-air turbulence within given geographic regions. For example, Wolff and Sharman (2008) have constructed a climatology of upper-level turbulence over the contiguous USA. To create their climatology, over 2.3 million PIREPs were analyzed covering the 12-year period from 1994 to 2005. To ensure that the constructed climatologies were as robust as possible, light turbulence reports were ignored, and moderate, severe, and extreme turbulence reports were combined into a single category of moderate-or-greater (MOG) turbulence. The analysis showed that the fraction of PIREPs reporting MOG turbulence increased over this time period, suggesting a trend of increasing turbulence. However, the authors call for a more thorough analysis to verify the existence of the trend because, given that there are only 12 years of PIREP data in the analysis, the statistical significance is unclear.

In a similar manner, Kim and Chun (2011) have analyzed the statistics of PIREPs over South Korea from 2003 to 2008. Korea and eastern Asia have significant potential for turbulence events, because the jet stream there is the strongest on the planet. In the analysis by Kim and Chun (2011), the absolute numbers of PIREPs reporting turbulence are normalized by the total number of PIREPs for each year, to attempt to account for any changes in the volume of air traffic. Their analysis finds that the fraction of PIREPs reporting light-or-greater (LOG) turbulence events increased from around 29 % in 2003 to around 41 % in 2008. In addition, the fraction of PIREPs reporting moderate-or-greater (MOG) turbulence events increased from around 2 % in 2003 to around 6–7 % in 2008. By analyzing jet stream winds, the authors show that the atmospheric conditions over South Korea probably were more conducive for generating turbulence in 2008 than they were in 2003. Although this analysis is objective and the increase in turbulence encounters over the 5-year period appears to be statistically significant, whether the increase reflects inter-annual variability or is indicative of a longer-term climate-related trend is unclear.

23.3.3 Historic Trends in Turbulence Diagnosed from Reanalysis Data

In the absence of multi-decadal records of turbulence encountered directly by aircraft, we must resort to less direct methods to investigate possible trends associated with climate change. As we noted in Sect. 23.3.1, atmospheric reanalysis datasets are too coarse to explicitly resolve turbulence on the scales that are relevant to aircraft. However, this subgrid-scale turbulence can be diagnosed with demonstrable success from the larger-scale synoptic and mesoscale atmospheric flow, which is resolved in reanalysis datasets. Jaeger and Sprenger (2007) exploit this capability to present a 44-year climatology of four clear-air turbulence indicators in the Northern Hemisphere, as diagnosed using ERA-40 reanalysis data from 1958 to 2001. The four turbulence indicators that are calculated are the Richardson number, which diagnoses Kelvin–Helmholtz instability; the Brunt–Väisälä frequency, which diagnoses static instability; the potential vorticity, which diagnoses symmetric instability; and the first Ellrod and Knapp (1992) index, which is an empirical indicator that is commonly used for predictions.

A 44-year climatology of diagnosed clear-air turbulence is long enough to seek climate-related trends. A statistical analysis of all four turbulence indicators by Jaeger and Sprenger (2007) for the North Atlantic sector over the period 1958–2001 found large increases in the frequencies with which thresholds corresponding to significant turbulence were exceeded. The increases were roughly 70 % for turbulence calculated from the Ellrod and Knapp diagnostic, 90 % for the Richardson number diagnostic, 40 % for the Brunt–Väisälä diagnostic, and 60 % for the potential vorticity diagnostic. The trends are shown in Fig. 23.4. Similar trends were found in the US and the European sectors, and the trends were found to be insensitive to the choice of thresholds.

Discussing the positive trends in diagnosed clear-air turbulence, Jaeger and Sprenger (2007) caution that the amount and type of assimilated data were not constant over the 44-year period of study. For example, the sudden onset of assimilation of data from radiosondes and satellites partway through the analysis period may have caused spurious trends. Indeed, Bengtsson et al. (2004) show that the assimilation of additional satellite data produces a kink in approximately 1979 in the time series of total kinetic energy calculated from ERA-40. However,

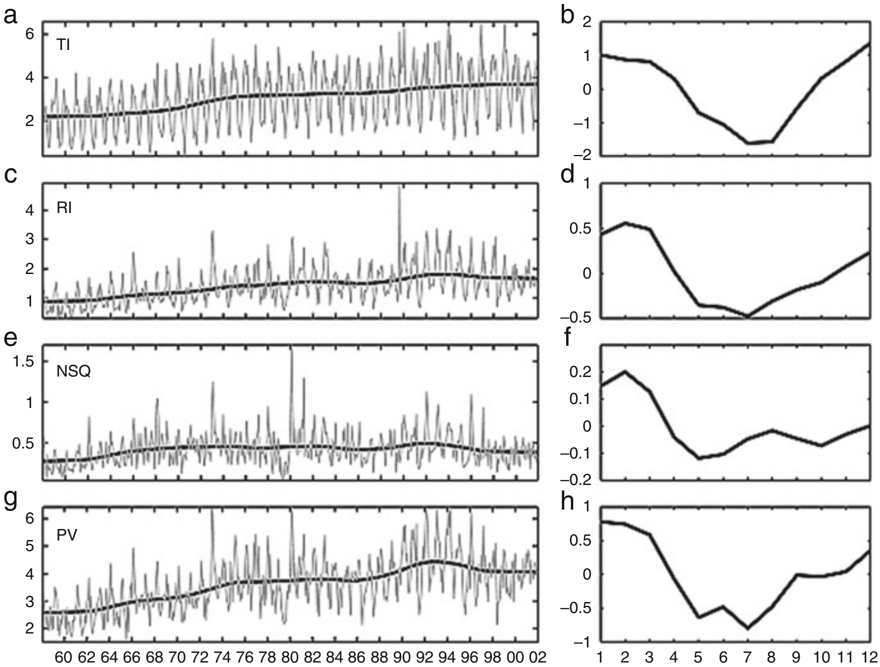

Fig. 23.4 Time series for the period 1958–2001 showing the frequency (%) of clear-air turbulence estimated using the Ellrod and Knapp index (TI), Richardson number (RI), Brunt–Väisälä frequency (NSQ), and potential vorticity (PV). *Gray lines* show the raw data, and *black lines* show the nonlinear trend estimates. The geographic region is the North Atlantic sector from 90°W to 10°E and 30 to 70°N in the tropopause region. The panels on the *right* show the mean seasonal cycle as a deviation from the nonlinear trend. From Jaeger and Sprenger (2007)

because the trends calculated by Jaeger and Sprenger (2007) are reasonably constant throughout the reanalysis period, rather than exhibiting a step change at the start of the satellite era, they appear to be more than merely artifacts of the data assimilation.

23.3.4 Historic Trends in Passenger Injuries Caused by Turbulence

A key source of information on historic trends in passenger injuries caused by turbulence is the US Federal Aviation Administration (FAA) and in particular their advisory circular on preventing injuries caused by turbulence (Ballough 2007). This advisory circular analyzes accident statistics, where an "accident" is defined to be "an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage." In turn, a "serious injury" is defined to be "any injury that (1) requires the individual to be hospitalized for more than 48 hours, commencing within 7 days from the date the injury was received; (2) results in a fracture of any bone (except simple fractures of fingers, toes, or nose); (3) causes severe hemorrhages, nerve, muscle, or tendon damage; (4) involves any internal organ; or (5) involves second- or third-degree burns, or any burns affecting more than 5 per cent of the body surface."

A graph of accident statistics from the FAA report is reproduced in Fig. 23.5. The graph shows that, on average over the 22-year coverage period, in terms of order of magnitude, there was roughly one accident caused by turbulence for every million flight departures by US carriers. Superimposed on this average, however, is a linear trend in which the accident rate more than doubles from 0.5 to 1.2 per million over the 22 years. Ballough (2007) speculates that the controlling factor behind this increase might be load factors. We speculate, however, that at least part of the controlling factor could be an increase in the amount and strength of turbulence in the atmosphere. Incidentally, Ballough (2007) notes that seatbelts play a crucial role in reducing accident rates, stating that in the period 1980–2003, only four people who were seated with seatbelts fastened received serious injuries during turbulence (excluding cases of other people falling onto and injuring properly secured occupants).

Similar data on accident rates from turbulence were analyzed by Kauffmann (2002), except that in his case they were normalized by the number of flight hours rather than the number of flight departures. The use of this normalization makes the trend less pronounced, and consequently calculations by Kauffmann (2002) indicated a lack of statistical significance, although only data up to 1999 were analyzed. Neither the FAA study by Ballough (2007) nor the academic study by Kauffmann

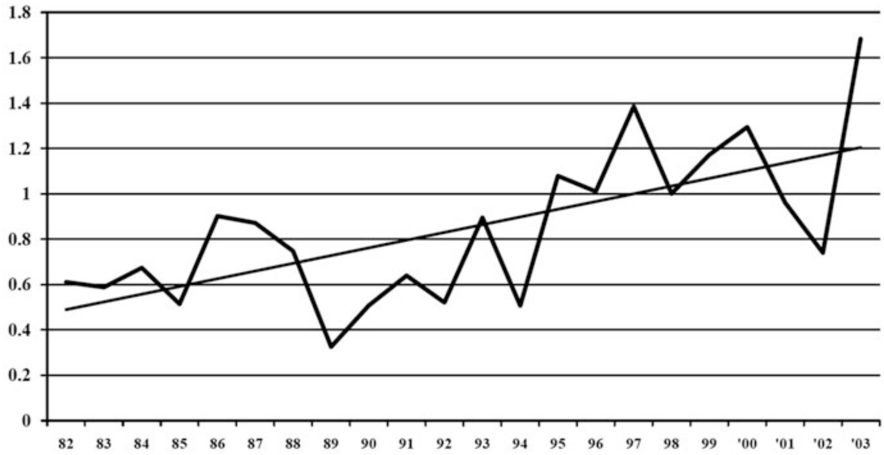

Fig. 23.5 Time series of the number of turbulence accidents per million flight departures. The data are for US air carriers, covering the 22-year period from 1982 to 2003. The data for each year are connected by *lines* and are over-plotted with a *straight line* showing the linear trend. From Ballough (2007)

(2002) appears to have been updated to bring the coverage period up to the present day, despite the present availability of at least a decade's worth of additional data.

23.3.5 Future Trends in Turbulence Diagnosed from Climate Models

The possible existence of historic climate-related trends in turbulence, whether they are inferred from PIREPs (Sect. 23.3.2), reanalysis data (Sect. 23.3.3), or passenger injuries (Sect. 23.3.4), naturally raises the question of what the future holds. To investigate the response of clear-air turbulence to future climate change, Williams and Joshi (2013) used computer simulations from the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 coupled atmosphere–ocean model. Twenty years of daily-mean data were analyzed from two model integrations, in which the concentration of atmospheric CO_2 was held constant at its preindustrial level and twice its preindustrial level. The study focused on the 200 hPa pressure level within the busy North Atlantic flight corridor in winter.

Williams and Joshi (2013) used the climate model simulations to calculate a basket of 21 clear-air turbulence diagnostics, including the Richardson number, the relative vorticity advection, the residual of the nonlinear balance equation, the negative absolute vorticity advection, and the horizontal temperature gradient. The central finding of the analysis was that the statistics of the diagnosed clear-air turbulence change significantly when the concentration of carbon dioxide in the atmosphere is doubled. For example, in the doubled-CO_2 integration compared to the preindustrial integration, most of the 21 diagnostics showed a 10–40 % increase in the median strength of turbulence and a 40–170 % increase in the frequency of occurrence of moderate-or-greater turbulence. These results suggest that climate change will lead to bumpier transatlantic flights (along the northern corridor) by the middle of this century.

23.4 Discussion

This chapter has surveyed the current stock of scientific knowledge about the possible long-term trends in clear-air turbulence driven by anthropogenic climate change. Increases to the magnitudes of the jet stream wind shears in the midlatitude upper troposphere and lower stratosphere in each hemisphere are a robust expectation, in the sense that they are not only understood from basic physical principles but also simulated by comprehensive climate models. Given the documented association between wind shears and clear-air turbulence (e.g., Watkins and Browning 1973), it seems inevitable that the result of this process will be an increase in clear-air turbulence. The only study so far to produce a quantitative estimate of the future increase found that the volume of wintertime transatlantic airspace containing moderate-or-greater clear-air turbulence could double by the middle of this century (Williams and Joshi 2013).

Clearly, more work is needed to verify, refine, and extend these predictions and to quantify the range of uncertainty originating from model error and other sources. As this is a multidisciplinary problem, it will require aviation turbulence scientists and climate scientists to work together and collaborate across the usual disciplinary boundaries. It will also require research scientists in academia to collaborate with airline operators. In addition to clear-air turbulence, convective turbulence might also be affected by climate change, but we are not aware of any published research in this area. A key limitation holding back research progress is access to turbulence data collected by the airlines. We call on the airlines to roll out automated turbulence measurements across their fleets of aircraft. Furthermore, in these days of open access to scientific data, we call on the national aviation regulators to make the collected turbulence data available for academic research, to help ensure the long-term safety of air passengers and crew as the climate changes.

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