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Recent advances in the understanding of near-cloud turbulence

Todd P. Lane
The University of Melbourne, Melbourne, Australia

Robert D. Sharman, Stanley B. Trier
National Center for Atmospheric Research, Boulder, Colorado

Robert G. Fovell
University of California, Los Angeles, California

and

John K. Williams
National Center for Atmospheric Research, Boulder, Colorado

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1 Corresponding author address: Todd Lane, School of Earth Sciences, The University of Melbourne, Melbourne, VIC 3010, Australia.
E-mail: tplane@unimelb.edu.au
Abstract

Anyone who has flown in a commercial aircraft is familiar with turbulence. Unexpected encounters with turbulence pose a safety risk to airline passengers and crew, can occasionally damage aircraft, and indirectly increase the cost of air travel. Deep convective clouds are one of the most important sources of turbulence. Cloud-induced turbulence can occur both within clouds and in the surrounding clear air. Turbulence associated with but outside of clouds is of particular concern because it is more difficult to discern using standard hazard identification technologies (e.g., satellite and radar) and thus is often the source of unexpected turbulence encounters. Although operational guidelines for avoiding near-cloud turbulence exist, they are in many ways inadequate because they were developed before the governing dynamical processes were understood. Recently, there have been significant advances in the understanding of the dynamics of near-cloud turbulence. Using examples, we demonstrate how these advances have stemmed from improved turbulence observing and reporting systems, the establishment of archives of turbulence encounters, detailed case studies, and high-resolution numerical simulations. Some of the important phenomena that have recently been identified as contributing to near-cloud turbulence include atmospheric wave breaking, unstable upper-level thunderstorm outflows, shearing instabilities, and cirrus cloud bands. The consequences of these phenomena for developing new en-route turbulence avoidance guidelines and forecasting methods are discussed, along with outstanding research questions.
Capsule

Advances in numerical modeling and new observations are providing valuable information about turbulence near thunderstorms and are paving the way for the development of new turbulence avoidance and forecasting strategies for the aviation industry.
1. Introduction

On 20 July 2010, a Boeing 777 en route from Washington D.C. to Los Angeles encountered severe turbulence over Missouri; the aircraft was diverted to Denver to treat 17 passengers and 4 crew who suffered injuries (National Transportation Safety Board, NTSB 2010). This event provides an example of the possible consequences of unexpected turbulence encounters in the vicinity of convection, which can catch aircraft flight crews and passengers unprepared and increase the likelihood of turbulence-related injuries during flight. While turbulence encounters with tens of injuries are uncommon, occurring on average only a few times per year, they underline the potential significant hazard that turbulence poses to the aviation industry. In addition to the hundreds of worldwide annual injuries, turbulence indirectly increases air travel costs because it is responsible for tens of millions of dollars in annual costs to airlines (Kauffmann and Sousa-Poza 2001, Eichenbaum 2003, Sharman et al. 2006). For these reasons, turbulence is avoided when possible using a combination of forecasts and en route tactical avoidance procedures. However, these methods are outdated and enhancements to them are stalled, partly because scientists don’t fully understand the turbulence generation mechanisms. Nevertheless, significant progress is being made as a result of new turbulence observations and databases, and enhancements in numerical modeling capabilities. This article outlines this recent progress, with particular focus on turbulence near thunderstorms, and provides insights for better turbulence avoidance strategies.

The specific purpose of this article is to: (1) describe some of the new findings about the dynamics underlying the generation of turbulence by thunderstorms and
identify the outstanding problems; (2) highlight the inadequacies in current methods for avoidance of thunderstorm-generated turbulence and motivate the development of new turbulence avoidance guidelines; and (3) demonstrate the capabilities of state-of-the-art forecast models that could be utilized for explicit turbulence predictions.

Of the many sources of turbulence that affect aviation (e.g., wind shear, jet streams, fronts, mountain waves, etc.), deep convective clouds are one of the most important. For example, Kaplan et al. (2005) examined 44 cases of severe turbulence and found that 86% of these were within 100 km of active deep convection. Wolff and Sharman (2008) have also illustrated the frequent occurrence of turbulence reports over regions known for convective activity (Fig. 1; see also Section 2). The relative importance of turbulence near thunderstorms is, of course, affected by geography and the predominant meteorological conditions. For example, unlike for the U.S., Kim and Chun (2011a) found that over Korea only 11% of turbulence events, of moderate-or-greater severity, were attributable to convection.

Convectively induced turbulence (CIT) is prevalent within convective clouds, and convective updrafts, downdrafts, and anvil regions are all known to be hazardous. For these turbulence processes, avoidance of cloudy air through visual identification or remote sensing with radar and satellite imagery is usually an effective turbulence avoidance tactic. Indeed, as illustrated by Fig. 2, preliminary analysis of the 20 July 2010 Missouri case identified that the turbulence encounter actually occurred directly above or just within a rapidly growing convective cell that was penetrating the anvil region of a large mesoscale convective system (MCS) from below. In this respect, the Missouri event is similar to some other events above convection described later.
Turbulence outside of cloud, but ultimately caused by the cloud is also an important hazard that has been appreciated for some time (e.g., Burns et al. 1966, Prophet 1970, Keller et al. 1983, Pantley and Lester 1990). While this \textit{near-cloud turbulence} (NCT) is usually weaker than turbulence within convective cores, it is arguably more dangerous because it is invisible and undetectable by standard on-board or ground-based radar. Theories surrounding the origins of NCT are at best incomplete, relying on empirical evidence and pilot experience to determine the most hazardous regions. Nevertheless, the U.S. Federal Aviation Administration (FAA) has developed a series of guidelines for thunderstorm flying (FAA 2010); the relevant guidelines are:

\textbf{GUIDELINE 5.} \textit{Do avoid by at least 20 miles [laterally] any thunderstorm identified as severe or giving an intense radar echo. This is especially true under the anvil of a large cumulonimbus.}

\textbf{GUIDELINE 6.} \textit{Do clear the top of a known or suspected severe thunderstorm by at least 1,000 feet altitude for each 10 knots of wind speed at the cloud top. This should exceed the altitude capability of most aircraft.}

Both of these guidelines imply a region around thunderstorms that is hazardous. Yet, recent research has shown that turbulence that is primarily of convective origin can occur outside of those regions defined by the FAA guidelines, suggesting that the guidelines are inadequate. The guidelines do not reflect our current understanding of relevant NCT processes and should be updated.

In addition to these empirical guidelines, there is an important role for modern numerical weather prediction to assist in turbulence avoidance. State-of-the-art convection-permitting models can provide realistic representations of convective
development and we will show that they can reproduce regions of NCT with some accuracy in deterministic simulations. However, like moist convection, turbulence has low predictability and ultimately ensemble forecasts are required.

High-resolution numerical simulations are primarily responsible for the significant recent advances in the basic understanding of NCT dynamics. Such simulations are able to resolve the underlying generation processes and (if the grid spacing is small enough) explicitly resolve the scales of motion that affect aircraft\(^2\). Our research has shown that convectively generated gravity waves [see Sidebar 1] are an important cause of NCT and may ultimately be the central process responsible for turbulence remote from convection. Gravity waves can break down into turbulence, but can also generate turbulence by perturbing environments that are already close to the threshold for turbulence production. The gravity waves work in concert with the cloud’s broader circulations that destabilize the surrounding air by way of upper-level convective outflows and associated enhanced wind shear.

The remainder of this article describes new observational techniques and summarizes recent progress in NCT understanding using three observed and simulated examples. These three examples are chosen specifically to encompass a range of NCT locations: turbulence hundreds of kilometers from the convective portion of an MCS, tens of kilometers from an intense convective cell, and a few kilometers above a convective cloud, respectively. Gravity waves play a role in all three cases, and each of these identifies turbulence occurring beyond the minimum separation distances defined by the FAA guidelines. These examples also illustrate the current research and operational

\(^2\) Horizontal scales of motion between \(~100\) m and \(~2\) km are those that induce the strongest turbulent response from large commercial aircraft. For the purposes of this discussion, these scales are referred to as aircraft-scale turbulence.
capabilities that should facilitate refinement of the FAA guidelines and the development of improved operational systems for turbulence forecasting.

2. Observing aircraft turbulence near clouds

Pilots make routine reports of turbulence intensity in terms of the turbulence categories shown in Table 1. These pilot reports (PIREPs) have been the traditional means for recording aircraft turbulence encounters and lengthy archives of PIREPs are now available. Wolff and Sharman (2008) developed climatologies of the spatial occurrence of reported turbulence encounters over the contiguous United States and an updated example for reports associated with deep convection is provided in Fig. 1. Here, maxima in PIREP relative frequency exist over the Florida peninsula, eastern Texas, and along the Gulf Coast, which are all regions known for frequent convective activity.

PIREPs are useful for deriving turbulence climatologies, and are essential for routine tactical avoidance, but they are not research quality observations (e.g., Schwartz 1996; Sharman et al. 2006; Wolff and Sharman 2008). Uncertainties in PIREP location (median ~50 km) makes them unacceptable for NCT studies, since it is almost impossible to unambiguously determine PIREP location relative to cloud boundaries. For events associated with injuries, the Flight Data Recorder (FDR) is often available for analysis, which circumvents some of these problems. Fortunately, most turbulence encounters do not cause injuries and other observations are required to identify NCT episodes. NCT encounters can be identified using new in situ turbulence measurements (Cornman et al. 1995, 2004) now available from some U.S. commercial air carriers. These automated reports have horizontal and temporal accuracy of about 10 km and 1 min, respectively, and are therefore well suited for case and statistical studies of NCT. The in situ
turbulence measurement and recording system provides reports of the cube-root of the eddy dissipation rate (EDR, $\varepsilon^{1/3} \text{ m}^{2/3} \text{s}^{-1}$), an aircraft-independent atmospheric turbulence metric, including both the median and peak EDR encountered over one-minute time intervals during cruise. For NCT studies the peak EDR value is preferable because it provides a good indication of the hazard to the aircraft and is better distributed over the turbulence severity reporting bins. At the time of writing this article, the EDR system is installed on all Delta Airlines B737 and United Airlines B757 aircraft; future expansion to other carriers and aircraft types is anticipated (see also the discussion in Politovich et al. 2011 about its application to terrain-induced turbulence).

To gain a better understanding of the frequency of occurrence of NCT relative to radar-derived cloud boundaries, 7 million peak EDR reports are compared to cloud locations derived from NEXRAD (Next-generation weather radar) observations. These data confirm that turbulence is prevalent near convection. For example, 50% of all moderate-or-greater (MOG, peak EDR > 0.3 m $^{2/3}$ s $^{-1}$) intensities occur within 100 km of convection, even though only 10% of all of the in situ EDR reports occur within this distance. Figure 3 depicts the distribution of MOG turbulence measurements as a function of horizontal and vertical distance to convection, defined as regions with vertically integrated liquid above 3.5 kg m$^{-2}$ and echo tops above 4.6 km. The turbulence ‘relative risk’ is defined by dividing the frequency of MOG turbulence within each of these distance bins by its overall frequency (from all sources) in the dataset (0.03%). The risk of turbulence encounters increases as the aircraft nears a thunderstorm (laterally), and the risk of MOG turbulence is almost twice the background value as far as 70 km (38 nmi) from a storm. Figure 3 also depicts the distribution of MOG turbulence encounters.
as a function of the aircraft’s distance above the NEXRAD echo top in convective regions. Although the risk of turbulence decreases with distance above cloud, the relative risk of MOG turbulence is still ten times the background value 3.6 km (~12,000 ft) above echo tops.

Of course, this analysis of the in situ aircraft data probably includes some turbulence encounters that are not caused by convection and events that are generated by a combination of sources. For example, it is known that long-lived organized convective systems (viz. MCSs) often occur near upper-tropospheric jet streams. Thunderstorms in mountainous regions could also generate turbulence via a combination of processes. Nonetheless, the in situ data (and the specific cases discussed later) undoubtedly highlight the hazard posed by thunderstorms.

3. Turbulence adjacent to clouds

Combining automated EDR-based turbulence measurements with radar and satellite imagery has confirmed that a high frequency of NCT encounters are related to active thunderstorm regions. Two examples are presented in Fig. 4. On 17 June 2005, long-lasting and widespread turbulence occurred along the outer cirrus anvil of a MCS over the southern Great Plains of the United States (Fig. 4a), which was several hundred kilometers north of the MCS thunderstorm region (Trier and Sharman 2009). The 5 August 2005 case over the Midwestern United States (Fig. 4b) consisted of a relatively isolated region of intense thunderstorms with moderate-to-severe turbulence 10 to 20 km southeast of the cloud shield. Numerical modeling of these two cases has identified that different NCT generation processes were the likely cause, viz. unstable upper-level storm outflows and ducted gravity waves.
a. 17 June 2005: Unstable upper-level thunderstorm outflow

The mesoscale environment of the 17 June 2005 turbulence encounter was investigated by Trier and Sharman (2009) using a convection-permitting Weather Research and Forecasting (WRF) model (Skamarock and Klemp 2008) simulation with a horizontal grid spacing of 3 km. The horizontal resolution of this simulation is greater than for most current operational models, but aircraft-scale turbulence is still not properly resolved and turbulence kinetic energy (TKE) is parameterized based on resolved-scale vertical shear and buoyancy productions (Janjic, 1990, 1994). Simulated TKE in this case is most widespread within the MCS outflow several hundred kilometers north of the heavy rainfall region (Fig. 5), consistent with where the turbulence was recorded (Fig. 4a).

Regional gradient Richardson number, $Ri$ [see Sidebar 2], variations across the MCS upper-level outflow occur in both the simulation and Rapid Update Cycle (RUC) model (Benjamin et al. 2004) analyses. Mesoscale zones of $Ri \leq 1$ supportive of turbulence and parameterized TKE generation are prevalent on the north side of the MCS but not on its south side. These differences are related to the asymmetries in the upper-level wind shear, which itself is related to how the MCS-induced outflow superposes on the midlatitude background (westerly) flow (e.g., Fritsch and Maddox 1981).

Close inspection of the TKE north of the MCS convection (Fig. 5) reveals that the simulated turbulence, though widespread, is associated with distinct mesoscale events (see animation of Fig. 5). Figure 6 depicts the onset of the later event along a vertical section oriented along the line (SW-NE) in Fig. 5. The parameterized TKE (Fig. 6) is shallow (1-2 km deep) and is primarily associated with the reduction in $Ri$ associated
with strong vertical shear and small moist static stability (implied by $\partial \theta_e / \partial z \rightarrow 0$, where $\theta_e$ is the equivalent potential temperature)\(^3\) within the MCS upper-level outflow.

The reduction in stability is associated with the localized upward displacement of the $\theta_e$ isopleths (Fig. 6), which lags pulsations in the strength of the upstream MCS convection (Trier and Sharman 2009). Although the details of this response are not well understood, it may be associated with thermally (e.g., Pandya and Durran 1996) or mechanically (Fovell et al. 1992) forced mesoscale gravity waves. Meanwhile, the upwardly displaced $\theta_e$ isopleths, whose axis of maximum displacement is denoted by the bold-dashed line in Fig. 6, are further steepened by differential advection on their downshear (NE) side (Trier and Sharman 2009). That is, the sheared winds advect the $\theta_e$ perturbations to the NE faster at higher altitudes (~13 km) than at lower altitudes (11 - 12 km). These processes within the storm outflow result in both the reduced stability and TKE generation near the outer edge of the anvil.

\(b.\) 17 June 2005: Turbulent cirrus bands

Further inspection of the satellite imagery for the 17 June 2005 event (Fig. 4a, 0732 UTC) reveals cloud bands extending radially outward from the MCS near its northern anvil edge. These radial bands become even more prevalent at later times (Fig. 7a, 0945 UTC) and coincide with the observations of turbulence. Turbulence is common in the vicinity of such bands associated with MCS anvils (Lenz et al. 2009), tropical cyclone outflows and near atmospheric jet streams (Knox et al. 2010). These cloud structures are sometimes referred to as transverse bands, since they are often (though not always)

\[3\] Although through much of the troposphere $g / \theta_e (\partial \theta_e / \partial z)$ is a poor approximation to the moist static stability (Durran and Klemp 1982), it is a reasonable approximation at typical commercial aircraft cruising altitudes of 11 to 12 km MSL, where the slope of the moist and dry adiabats are similar.
oriented approximately perpendicular to jet stream winds. As discussed by Knox et al.,
the mechanisms responsible for these bands have remained elusive for some time.

Additional simulations of the 17 June event at even smaller horizontal grid
spacing (600 m) resolve these bands (Fig. 7b, see Trier et al. 2010 for full simulation
details). The simulated bands are located close to counterparts in the satellite
observations (Fig. 7a) and to locations of in situ reports of turbulence (Fig. 7b). These
radial bands of cold simulated infrared brightness temperature (Fig. 7b) develop in moist
neutral or unstable conditions and are aligned approximately along the vertical shear
vector through the depth of the anvil. Trier et al. (2010) showed that the bands are
associated with shallow convection within the outer anvil and share organizational
similarities with horizontal convective roll (HCR) circulations in the atmospheric
boundary layer (e.g., LeMone 1973; Weckwerth et al. 1997) that often produce cumulus
cloud streets.

The area of the moist static instability and the prominence of the radial cloud
bands are increased by cloud radiative interactions (Trier et al. 2010). However, the
regionalization of the banding appears primarily governed by the mesoscale
thermodynamic destabilization mechanism discussed earlier, which manifests as the
broad region of parameterized TKE within the anvil outflow in the coarser simulation.

Satellite observations show that these radial cloud bands are often aligned
approximately perpendicular to high frequency gravity waves emanating from upstream
deep convection (Lenz et al. 2009). Trier et al. (2010) found a similar spatial relationship
between these features in the 17 June observations (their Fig. 7) and simulations of this
case (their Fig. 6). They further noted that strong vertical shear and enhanced static
stability in the gravity wave region of their simulations is overlaid by nearly neutral conditions in the anvil, which supports trapping and horizontal propagation of the waves, and suggested that vertical displacements associated with these gravity waves might help excite the shallow radial convective bands in the anvil above.

The parameterized TKE in the high-resolution simulation (Fig. 7b) is much weaker and less widespread than in the coarser simulation (Fig. 5b), which is consistent with the vertical mixing in the higher-resolution simulation being largely controlled by the shallow convection resolved on the model grid. Though fine horizontal resolution is clearly required to resolve the turbulence-producing bands, the MCS-induced flows that influence the TKE parameterizations can be well simulated in coarser convection-permitting models. The new generation of operational regional models have horizontal grid spacings that are similar to the coarser-resolution simulation presented for this case (e.g., Fig. 5), suggesting they are capable of identifying portions of the MCS anvil outflow that are susceptible to turbulence through upper-level HCRs or other sources.

In this case the timing and position of the simulated MCS showed very good agreement with the observations, which facilitated good agreement between the location of the simulated and observed turbulence. However, it is well known that forecasting the timing and organizational structure of deep convection is challenging due to the limits of predictability. Turbulence also suffers from low predictability and its prediction relies inherently on the skill at convective scales. Thus, although convection-permitting models are sufficient to represent the physics of the important processes, ensemble predictions are inevitably required to capture the range of possible model outcomes.
c. 5 August 2005: Ducted gravity waves

At approximately 0240 UTC 5 August 2005, two commercial airliners encountered severe clear air turbulence at cruising altitudes over northwest Indiana after having flown over or around a rapidly developing storm. According to contemporaneous satellite imagery, the planes were roughly 20 km away from any cloud having appreciable optical depth (Fig. 4b). Convection-permitting simulations of this case with the WRF model were performed by Fovell et al. (2007) and reveal that the storms provoke transient turbulence in localized areas tens of kilometers beyond the visible cloud, i.e. at the margins of the horizontal separation defined by the FAA guidelines (number 5). The generation of this NCT is in part related to horizontally propagating gravity waves, which perturb an environment that is already marginally susceptible to turbulence production (i.e., small background $R_i$).

These simulations use 4 km horizontal grid spacing, have 100 vertical levels, and are initialized with the 0000 UTC 5 August RUC analysis. A (moist) “control” simulation is contrasted with a “dry” counterpart that does not permit water phase changes. The control simulation develops a relatively isolated storm at approximately the right time and location while the dry simulation shows how the environment might evolve without convective influences.

During the encounters, the aircraft were flying at about 11.3-11.9 km above mean sea level (MSL), where in the control simulation significant gravity waves are emanating from the storm and propagating southeastward at ~30 m s$^{-1}$ (Fig. 8). By 0230 UTC (Fig. 8a), a region of enhanced turbulence likelihood ($R_i < 0.5$) appears in the clear air just

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4 The model domain is 800 km square, and model parameterizations include the YSU boundary layer (Noh et al. 2003), Lin et al. (1983) microphysics and RUC land surface schemes; no cumulus parameterization is used.
beyond the detectable anvil\textsuperscript{5} at approximately the same location relative to the storm as in the in situ turbulence measurements (Fig. 4b). The concurrent model vertical cross-section (Fig. 8d), oriented parallel to the wave propagation vector, shows that regions of locally low $Ri$ occur within a shallow layer extending to the southeast. This layer of reduced $Ri$ was also present in the dry simulation, although its $Ri$ values never fell below one anywhere (Fig. 8g).

The control simulation’s low $Ri$ zone moves southeastward away from the storm, apparently phase-locked with the propagating gravity waves (Figs. 8b-c, see animations of Fig. 8 also), and slowly erodes with time. The perturbations in velocity and stability associated with the waves have clearly modulated and reduced $Ri$ (Figs. 8d-f), increasing the likelihood of turbulence in an already marginally susceptible environment (cf. Figs. 8g-i). This demonstrates that horizontally propagating gravity waves provide one mechanism by which a localized patch of turbulence can develop at a relatively large distance from an established cloud.

The control simulation’s gravity wave activity adjacent to the storm arises from an excitation mechanism (unsteady convection) and a ducting layer that acts to retain wave energy in the upper troposphere. A vertical profile of the Scorer parameter [see Sidebar 1] is calculated at 0230 UTC (Fig. 9a) near the anvil edge. The negative Scorer parameter values near 11 and 13.5 km altitudes provide conditions conducive to wave ducting in between. This duct is created mainly by the environment’s jet-like wind profile (not shown). The wave duct is also present in the dry run, but no wave activity occurred.

\textsuperscript{5} Here the cloud edge is defined in two ways: using the condensation and the optical depth (which is a vertical integral from above). Both of these measures identify that the region of enhanced turbulence is outside of the simulated cloud. Moreover, if radar reflectivity were used to detect the cloud boundary (as might be done by a pilot en route) the detectable cloud volume would likely be smaller and the turbulence would appear to be farther from the cloud edge.
owing to the lack of an excitation mechanism. The ducting mechanism can provide a
directional bias to the wave propagation and, as appears to be the case here, may cause
certain regions around the storm to be more prone to turbulence.

The net influence of the convection and gravity waves on $R_i$ at this location is
demonstrated in Figs. 9b-d. Three layers of relatively low $R_i$ can be seen in the non-
convecting environment (i.e., the dry simulation), centered at 10, 11.25 and 13 km MSL.
Convection in the moist simulation occupies the 10 km level at this location but the other
two altitudes remain in clear air. The reduced flight-level $R_i$ is related to both enhanced
vertical shear and a reduction in static stability (Figs. 9c,d), caused by a combination of
the storm outflow and wave perturbations. Note the lowest $R_i$ values at this time are
located immediately above a shallower cloud, which may have played an additional role
in creating the particularly low $R_i$ values (e.g., see section 4b). Yet, the localized patch
of increased turbulence likelihood subsequently moved away from its point of origin, and
in general agreement with the observations establishes a hazard remote from the
convection. Thus, like the 17 June 2005 case, the turbulence is ultimately caused by the
deep convection yet occurs a substantial distance from the active region of deep
convection.

4. Turbulence above clouds

On 3 August 2009, a Boeing 767 experienced severe turbulence near the Dominican
Republic, en route from Rio de Janeiro to Houston. Twenty-eight passengers and five
crew suffered minor injuries. Like many of these cases of turbulence near rapidly
growing clouds it is extremely difficult to determine exactly where the turbulence
occurred relative to the cloud edge and uncertainties remain. Yet, a preliminary NTSB
investigation states that: “… examination of satellite weather imagery around the time of the event indicates the presence of isolated, rapidly developing cumulus congestus to cumulonimbus clouds under the flight path of the airplane” (NTSB, 2009). As reflected by the FAA guidelines (number 6) the air above developing and mature convective clouds is known to be potentially hazardous to aircraft.

The 3 August 2009 event is reminiscent of an event that occurred over Dickinson, North Dakota on 10 July 1997. The latter case caused 22 injuries from severe turbulence directly above a developing thunderstorm (NTSB 1998) and provided the motivation for a number of simulation studies (Lane et al. 2003, Lane and Sharman 2006, Lane and Sharman 2008). Although there was insufficient data to determine the exact cause of this event, detailed examination of this case using idealized modeling highlighted, among other things, the role of gravity wave breaking above convection as an important turbulence source.

a. Gravity wave breaking

Numerous observational and modeling studies have documented the occurrence and characteristics of high-frequency gravity waves above convective clouds (e.g., Fovell et al. 1992, Pfister et al. 1993, Piani et al. 2000). Although such waves usually have horizontal wavelengths that are too long (>~5 km) to be felt as turbulence by aircraft, wave breaking can initiate turbulence at the sub-kilometer scales that do affect aircraft.

Wave breaking above convection is illustrated using an idealized 3D simulation, which partly resolves aircraft-scale turbulence (Fig. 10). This simulation has 150-m grid spacing in all directions, and uses a thermodynamic and (unidirectional) wind environment defined using the closest sounding to the Dickinson turbulence encounter
(00UTC 11 July 1997 Bismarck, ND); full details can be found in Lane and Sharman (2006). The above-cloud perturbations in potential temperature show the gravity waves to have horizontal wavelengths of approximately 5 km and vertical displacement amplitudes of up to 500 m. Regions of wave breaking are highlighted by two bold isentropes (372 and 384 K). Specifically, the uppermost bold contour in Fig. 10a shows steepening at \((x, z) \approx (57, 14.5)\) km and the lowermost bold contour in Fig. 10b shows smaller-scale steepening and overturning at \((x, z) \approx (60, 13.5)\) km.

The wave steepening and breaking is accompanied by an enhancement in velocity perturbations at the scales of motion that affect commercial aircraft. To quantify these scales a “resolved” turbulence kinetic energy per unit mass, \(\text{TKE} = \frac{1}{2}[(u')^2 + (v')^2 + (w')^2]\), is calculated (as opposed to the parameterized TKE discussed in section 3)\(^6\) and values outside of cloud are shown in Fig. 10. At both times the turbulence is large in the regions of gravity wave steepening and overturning. For example, in Fig. 10b the largest TKE outside the cloud is associated with the wave overturning at \((x, z) \approx (60, 13.5)\) km, and a contiguous region of turbulence extends ~2 km above the uppermost cloud top. Small-scale above-cloud velocity perturbations persist throughout the cloud’s evolution (e.g., animation of Fig. 10) and illustrated by a horizontal cross-section above the cloud (Fig. 11a).

There is an extensive literature explaining gravity wave instabilities and of particular relevance here are instabilities associated with critical levels (see Nappo 2002; Sidebar 1). Above convection the high frequency waves propagate at \(\pm 5–10\) m s\(^{-1}\) relative to the cloud top wind speed and therefore a change in wind speed above the

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\(^6\) The background velocity used to determine the perturbations is obtained by horizontally smoothing each of the velocity components (over 13 \(\times\) 13 grid points using a moving average). This procedure retains horizontal scales of motion less than ~2 km in the perturbation fields, i.e., aircraft-scale turbulence.
convection of only 5 to 10 m s\(^{-1}\) can incite a critical level (Lane et al. 2003). The critical level induces breaking of those waves propagating in the same direction as the above-cloud shear vector, which is consistent with the steepening and breaking waves in Fig. 10; the above-cloud shear vector points towards the left in this simulation and is only about 5 m s\(^{-1}\) km\(^{-1}\) in magnitude. Thus, even in moderate wind shear, gravity wave breaking can be an important source of NCT.

To explore the relationships between above cloud turbulence extent and background conditions, Lane and Sharman (2008) used numerous 2D and 3D simulations to examine the effects of above-cloud vertical wind shear and static stability on NCT. As expected, smaller static stabilities produce more extensive regions of turbulence. The response to changes in wind shear is more complicated, with maximum volumes of above-cloud turbulence occurring at intermediate shears. Stronger shears lead to more intense turbulence, but over smaller volumes that are confined closer to the cloud top. This confinement is related to the smaller distance between the critical level and the cloud top in conditions with stronger shear. On the other hand, weaker shears do not induce a background critical level and wave breaking is a less important generation mechanism.

Based on these results, Lane and Sharman (2008) suggest that avoidance guidelines for vertical separation should incorporate vertical shear and stability at a minimum. Yet, the FAA guideline (number 6) for vertical separation is based entirely on cloud-top wind speed, which is inconsistent with the underlying dynamics. Moreover, the storm shown in Fig. 10 has a cloud-top wind speed of approximately 13 m s\(^{-1}\) (25 kt, see Lane and Sharman 2006) and the FAA guidelines would suggest a vertical separation of
only 760 m (2500 ft) above cloud top, much smaller than the vertical extent of wave breaking and turbulence in this case. Despite the simulated turbulence extending well above the cruising altitude of most commercial aircraft, the hazard is still relevant for turbulence above thunderstorms in the winter or higher latitude, when the thunderstorm tops are lower.

b. Enhanced shears and wake effects

The generation of turbulence above convection is, of course, not limited to gravity wave effects and the process of convective updraft growth and collapse can play an important role in turbulence generation near the cloud edge. While much of this turbulence probably falls within the minimum vertical separation defined by the FAA guidelines, cloud-edge effects may have caused some of the recent cases that occurred close to cloud top.

For example, Grabowski and Clark (1991) describe a cloud-interfacial instability, where enhanced shear and flow deformation reduce $Ri$ along the edge of the cloud supporting Kelvin-Helmholtz billows. Lane et al.’s (2003) 2D and 3D simulations of the Dickinson case produced this shear enhancement and turbulence generation along the uppermost cloud boundaries during updraft overshoot events. Those simulations demonstrated that the enhanced shear layer was only a few hundred meters thick, a depth resolvable in Lane et al.’s 3D simulations with 16 m vertical grid spacing but unresolved in the simulation shown in Figs. 10 and 11. Other numerical simulations (Lane and Sharman 2008) showed that turbulence near the cloud edge is most prevalent in the early stages of a thunderstorm’s lifetime. It follows that this mechanism is probably most relevant for incidents that occur directly above rapidly growing convective updrafts.
Other cloud top processes may also be an important source of NCT. For example, Wang et al. (2010) presented simulations of coherent wake-like features that extend downwind of overshooting convective cores, a phenomenon sometimes observed in satellite imagery. Wang et al. liken these features to the well-known Kelvin ship wave pattern (Sharman and Wurtele 1983). Additional analysis of the idealized cloud model simulation shows that wake-like features indeed follow the collapse of the overshooting turret. Specifically, Fig. 11b shows that many coherent features are exposed by the square of the vorticity. A broad arc of enhanced vorticity (denoted ‘A’) occurs upstream of the underlying cloud (cf. Fig. 11a) and downstream of this arc numerous band-like structures (denoted ‘B’) extend laterally from the above-cloud turbulent patch. In addition to these lateral bands, the horizontal divergence (Fig. 11c) identifies flow-aligned structures that extend downwind ($x \approx 80$ km) forming a turbulent wake.

The mechanisms underlying these thunderstorm wakes are not entirely reconciled. Wang et al. suggest that the cloud behaves as an obstacle that blocks the oncoming flow; indeed, the diffluent horizontal wind vectors on the upstream side of the cloud and the turbulent wake downstream seem to support that explanation (see also Fujita and Grandoso 1968, Lemon 1976). However, as described by Rotunno and Klemp (1982) the dynamics are not entirely consistent with the obstacle analogy; the cloud is porous with air flowing through the cloud edge, and the pressure gradient is opposed to the cross-updraft shear vector (which is not necessarily aligned with the storm-relative wind). Another hypothesis is that these simulated bands in Fig. 11(c) are an early manifestation of the radial bands described in Section 3b. Regardless of the source dynamics, the spatial scale of the lateral bands and downstream structures are all approaching those that
strongly influence commercial aircraft and they may pose an additional hazard adjacent to the storm and be responsible for the known hazard downwind.

5. Summary and future outlook

*Fundamental understanding of near-cloud turbulence.*

We have summarized recent progress made in understanding the NCT aviation hazard. These fundamental advances in our basic understanding were enabled by high-resolution numerical simulations of observed events, complemented by improved data on turbulence encounters. These studies have shown that NCT is a complex phenomenon that crucially depends on cloud characteristics, the structure of the near-cloud environment, and perturbations to that environment by cloud circulations and gravity waves. Yet, we are acutely aware that we are only beginning to scratch the surface and a variety of basic problems are still to be solved regarding the dynamics underlying NCT. Outstanding questions include:

- What are the characteristics of NCT and how does it vary spatially and temporally?
- How is NCT related to the mode of convective organization and its intensity?
- What is the relative importance of gravity wave breaking and Kelvin-Helmholtz instability to the turbulence hazard?
- What are the processes leading to the enhanced hazard near thunderstorm anvils?
- What is the structure and mechanism of turbulence in thunderstorm wakes?
- How common is the hazard posed by turbulence associated with ducted gravity waves?
What is the relationship between observable cloud features, the mesoscale environment, and NCT that may be useful for pilots and aviation forecasters?

What is the climatology of NCT?

Answering these questions and further research on the other processes detailed in this article is necessary to advance the fundamental understanding of NCT and could also provide the framework to develop new approaches for turbulence avoidance. With recent improvements in high-resolution modeling capabilities available to researchers, we believe that such much-needed advancement is achievable. Unfortunately, despite the importance of this problem and the opportunities for progress, there is relatively limited activity in this area with only a few groups around the world actively engaged in NCT research. We hope that this article has spurred additional interest in this topic and we encourage others to study this challenging problem.

The role of modern numerical weather prediction.

State-of-the-art operational or real-time systems (e.g., the High-Resolution Rapid Refresh model [HRRR], Smith et al. 2008) have achieved convection-permitting model resolutions, allowing for much more realistic representations of the governing convective processes. The examples presented herein demonstrate the utility of such convection-permitting models to fully reproduce regions of turbulence near thunderstorms, even though they are unable to resolve aircraft-scale turbulence and the simulated turbulence remains parameterized. The hazard posed by rapidly growing thunderstorms underlines the need for skillful predictions and diagnoses of convective initiation and vertical development: processes whose representation benefits from convection-permitting
resolutions as well. Of course, convective initiation, vertical development and turbulence are all processes that suffer from low predictability. Simulated turbulence is also highly sensitive to model configurations and the choice of physical parameterizations. Therefore, ensemble convection-permitting forecasts likely provide greater promise for significant advances in future turbulence prediction than do solely deterministic approaches.

Existing models like HRRR already contain a wealth of information regarding the turbulence hazard. This information is simply not being fully utilized for turbulence forecasting. Efforts focused on the development of diagnostic products tailored to convection-permitting models could provide invaluable guidance and actually take advantage of the recent advances in operational modeling capabilities. Time-lagged ensembles of these models could also be used to complement deterministic predictions and facilitate development of ensemble approaches for turbulence forecasting.

Towards improved turbulence avoidance guidelines and integrated systems.

The myriad of processes that lead to turbulence near deep convection will continue to make turbulence avoidance challenging. Simple rules, like the FAA guidelines, are a necessary first step towards rapidly assessing hazards from the cockpit. However, their simplicity limits their effectiveness because they do not capture all of the important processes. We believe that more sophisticated guidelines are required that encompass ongoing improvements in our understanding of NCT. The studies presented here suggest that: above-cloud wind shear and stability; mesoscale regions of low Richardson number; gravity wave ducting; and the direction of the upper-level storm outflow should all be
considered as part of improved guidelines. Other properties like thunderstorm intensity
and the mode of organization should be investigated as well as the changes in turbulence
generation mechanisms during different stages of the cloud lifecycle (e.g., Kim and Chun
2011b). Developing such guidelines should be a priority, and enhanced activity in this
area would provide the critical mass of evidence to support those changes.

It is possible, however, that new turbulence guidelines that incorporate processes
like wind shear, stability, and other more complicated mechanisms like wave ducting
would be a challenge for pilots, air-traffic control, and aviation forecasters to use. Yet, an
integrated theoretical and empirical approach that makes use of operational analyses,
convection-permitting forecasts, empirical nowcasting methods and avoidance
guidelines, and satellite imagery could be successful. This information could be used to
construct temporally varying hazard maps for incorporation into future automatic traffic
routing procedures (e.g., the Next Generation Air Transportation System, NextGen). If
these approaches were coupled with probabilistic hazard information derived from
ensemble forecasts, the possibilities for advances in turbulence avoidance and improved
aviation safety would be substantial.

Acknowledgments.

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Dragana Zovko Rajak and three anonymous reviewers for their comments on an earlier
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by the National Science Foundation.
**Sidebar 1. Gravity waves** are oscillations in velocity, temperature, pressure (and other scalars) that originate from vertical displacements of stable air. Buoyancy is the restoring force of the oscillation. The best-known cause of gravity waves is airflow over mountains (i.e., mountain waves), but jet streams, fronts, and convective processes are important sources as well. Gravity waves can propagate large distances from their source and are known to play an important role in many atmospheric processes.

The characteristics of gravity waves are defined by the properties of their source and the environment through which the waves propagate (see Nappo 2002). The **Scorer parameter** $l^2$, a relation derived using linear theory, can be used to explain many aspects of gravity wave propagation. A simplified version is

\[ l^2 = \frac{N^2}{(U - \overline{c})^2} - \frac{U_z}{U - \overline{c}}, \]

where $N$ is the Brunt-Väisälä frequency, $U$ is the background wind in the plane of wave propagation, and $c$ is the wave’s horizontal phase speed.

Altitudes or layers with negative values of $l^2$ prohibit vertical propagation of gravity waves of all horizontal wavelengths. Such layers provide one mechanism for wave reflection, facilitating the formation of trapped or **ducted waves** that extend horizontally instead of vertically.

At altitudes where $U$ approaches $c$ due to wind shear, the Scorer parameter tends towards infinity, equivalent to the wave’s vertical wavelength approaching zero. This altitude is called a **critical level**. Wave amplification and breaking can occur below a critical level or via other nonlinear effects associated with wave amplification. Wave breaking can initiate a cascade of energy to smaller scales, generating turbulence.
Sidebar 2. The gradient **Richardson number** is defined as $Ri = \frac{N^2}{S^2}$, where $N$ is the Brunt-Väisälä frequency and $S = \left| \frac{\partial V}{\partial z} \right|$ is the vertical shear magnitude. In cases where the air is saturated, $N$ is replaced by $N_m$, which is the moist Brunt-Väisälä frequency (Durran and Klemp, 1982). Turbulence can occur through dynamical instabilities when $Ri$ falls below a critical value (~1 in three-dimensional flows). In a common type of dynamical instability known as Kelvin-Helmholtz instability, strong vertical shear drives the instability while the vertical stratification ($N^2 > 0$) opposes the instability. In other situations, turbulence can arise from convective ($N^2 < 0$) or mixed dynamic-convective instabilities.
References


List of Figures

Figure 1. Percentage of moderate-or-greater turbulence pilot reports (PIREPs) that occurred within 0.5 h and 40 km of at least one NLDN (National Lightning Detection Network) cloud to ground lightning flash. All available quality-controlled PIREPs above 20,000 feet (~6 km) from 1997-2009 are used; regions without shading have values less than 1% or insufficient data.

Figure 2. Radar imagery valid at 0030 UTC 21 July 2010, along with the flight track of the aircraft that encountered severe turbulence. (a) Horizontal cross-section at flight level (33,000 ft) with the location of the turbulence encounter circled. (b) Vertical cross section along the flight path (ENE to WSW); the turbulence encounter coincided with the region of maximum reflectivity along this path.

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Figure 5. Column maximum model-derived radar reflectivity (colored shading), 13-km above mean sea level (MSL) winds, and 12-km MSL turbulence kinetic energy contours (brown) at 0.75 (solid) and 1.5 (dashed) m² s⁻². (a) 0650 and (b) 0950 UTC 17 June 2005. (See animation in supplementary material).
**Figure 6.** Vertical section along line SW-NE in Fig. 5, averaged for 75 km on each side of this line (showing only 10-14 km MSL). Simulated winds parallel to the cross section averaged between 0630-0830 UTC 17 June 2005 (colored shading), 0830 UTC equivalent potential temperature (black contours with 1-K intervals), and turbulence kinetic energy (thick gray contours at 0.75 and 1.5 m$^2$s$^{-2}$).

**Figure 7.** (a) Infrared GOES-8 satellite imagery of brightness temperature and (b) simulated brightness temperature and turbulence kinetic energy (brown contours denoting values greater than 0.75 m$^2$s$^{-2}$). The box in (a) indicates the region shown in (b) with the line indicating the approximate length of the latest flight track from Fig. 4a in which turbulence was recorded. The locations and strength of this turbulence (L = light, M = moderate) is annotated in (b).

**Figure 8.** Cross-sections from the 5 August 2005 simulations showing vertical velocity (red-blue shading) and $Ri$ (contoured) for three times; (a-f) show the (moist) control run and (g-i) show the dry simulation. (a-c): horizontal cross-section for the control run at 11.5 km MSL with $Ri \leq 1$ contoured at 0.25 intervals, total condensate shaded, and (dot-dash) contours of unit optical depth. (d-f): vertical cross-sections along the line shown in (a-c) with cloud (shaded white) and $Ri$ (irregularly spaced contours, with large values not shown); the thick dashed line in (d-g) identifies the minimum $Ri$ (between 10 and 12 km). (g-i) are the same as (d-f) except for the dry simulation. Only part of the model domain is shown. (See animations in supplementary material).

**Figure 9.** Vertical profiles from the control and dry simulations shown in Fig. 8 for 0230 UTC 5 August 2005 at the location shown in Fig. 8a (the white cross near 41°N, 86°W). (a) Scorer parameter calculated using horizontal winds parallel to the wave propagation
vector and a $30 \text{ m s}^{-1}$ horizontal phase speed, (b) $Ri$ and its contributions from (c) squared vertical shear and (d) squared Brunt-Väisälä frequency.

**Figure 10.** Cross-section through an idealized 3D cloud model simulation motivated by the Dickinson, ND case at (a) 53 min and (b) 55 min through the center of the domain in the cross-stream-direction. Potential temperature is contoured at 4 K intervals, resolved TKE per unit mass is shown with yellow through red shading, and blue shading represents cloud water mixing ratio greater than 1 g kg$^{-1}$. Contour lines discussed in the text are shown in bold and the wind near the cloud top flows from left to right. The full model domain is $100 \times 50 \text{ km}^2$ and 35 km deep. (See animation in supplementary material).

**Figure 11.** Horizontal cross-sections at 13.5 km through the 3D simulation shown in Fig. 10, except at 75 min; the background flow is from left to right. Colored shading shows (a) the vertical velocity, (b) the square of the three-dimensional vorticity magnitude, and (c) the horizontal divergence. Also shown in (a) is the cloud outline at 11 km and in (b) 13.5-km horizontal wind vectors. For clarity the vectors in (b) are obtained after subtracting 5 m s$^{-1}$ from the $x$-component of the velocity, which is the approximate translation speed of the storm. Labels ‘A’ and ‘B’ in (b) denote regions of the flow discussed in the text.
Captions for animations in supplementary material

[animated gif files should be opened with a web browser, Quicktime player, media player, etc.]

Filename: Fig5-ANIM.gif

Animation of Fig. 5 between 0400 and 1100 UTC. Contours and shading are the same as
the static figure except that TKE (brown contours) have $1.0 \text{ m}^2 \text{s}^{-2}$ interval, starting at 0.5
$m^2 s^{-2}$. The arrows indicate the onset of separate enhanced TKE events discussed in the
text.

Filename: Fig8horiz-ANIM.gif

Animation of Fig. 8(a-c) between 0215 and 0255 UTC. Contours and shading are the
same as the static figure.

Filename: Fig8vert-ANIM.gif

Animation of Fig. 8(d-f) between 0215 and 0255 UTC. Contours and shading are the
same as the static figure.

Filename: Fig10-ANIM.gif

Animation of Fig. 10 for a twenty-five minute period during the simulation. Contours and
shading are the same as the static figure, except no potential temperature contours are
shown in bold. The $x$-axis translates at 8 m s$^{-1}$ to maintain the region of interest in the
approximate center of the image.
Table 1. The four main turbulence categories reported by pilots along with descriptions of the corresponding aircraft and passenger responses. Also listed are the approximate atmospheric turbulence intensities (in terms of the cube root of the eddy dissipation rate, $\varepsilon^{1/3}$) that would induce such responses in Boeing 737 and 757 aircraft in cruise. [Adapted from FAA (2010) and Lester (1994)].

<table>
<thead>
<tr>
<th>Turbulence Category</th>
<th>Aircraft Response</th>
<th>Aircraft Vertical Acceleration Magnitude (g)</th>
<th>Passenger Experience</th>
<th>Approximate $\varepsilon^{1/3}$ (m$^{2/3}$s$^{-1}$) for B737, B757 aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw).</td>
<td>0.2 – 0.5</td>
<td>A slight strain against seat belts. Unsecured objects may be displaced slightly. Food service may be conducted with little difficulty walking.</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Moderate</td>
<td>Similar to ‘Light Turbulence’ but greater intensity. Changes in altitude, attitude, and/or airspeed occur. The aircraft remains in control at all times.</td>
<td>0.5 – 1.0</td>
<td>Definite strain against seat belts. Unsecured objects are dislodged. Food service and walking are difficult.</td>
<td>0.3 – 0.5</td>
</tr>
<tr>
<td>Severe</td>
<td>Large, abrupt changes in altitude, attitude, and/or airspeed. Aircraft may be momentarily out of control.</td>
<td>1.0 – 2.0</td>
<td>Occupants are forced violently against seat belts. Unsecured objects are tossed about. Food service and walking are impossible.</td>
<td>0.5 – 0.7</td>
</tr>
<tr>
<td>Extreme</td>
<td>The aircraft is violently tossed about and is practically impossible to control. It may cause structural damage.</td>
<td>&gt; 2.0</td>
<td>Truly frightening.</td>
<td>&gt; 0.7</td>
</tr>
</tbody>
</table>
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