1. Introduction

Aviation turbulence is the in-flight bumpiness due to vertical air motions induced by small-scale turbulent eddies, with sizes roughly 10 to 1000 m (Lester 1994). Unexpected turbulence encounters in the upper troposphere and low stratosphere (UTLS) are especially hazardous since commercial aircraft spend most of their flight time there and passengers and crews are more likely to be unbuckled (e.g., Tvaryanas 2003). This may lead to structural damage, occupant injuries, and occasional fatalities.

A major source of aviation-scale turbulence encounters in the UTLS is turbulence processes associated with moist convection (e.g., Sharman et al. 2012b; Lane et al. 2012; Kim and Chun 2011). Whereas turbulence in high reflectively regions of convective cloud can usually be avoided by timely use of available observations such as visible or satellite indicated cloud boundaries and/or onboard displays of radar echoes, turbulence outside of cloud or in low-reflectivity stratiform precipitation regions located away from the main convective region [which has been termed near-cloud turbulence (NCT) by Lane et al. (2012)] is more difficult to avoid.

One rule-of-thumb to mitigate NCT encounters is to avoid banded patterns within the anvil cirrus observed in satellite imagery (e.g., Ellrod 1985, 1989; Lenz et al. 2009). The banded patterns appear as brightness temperature gradients in satellite imagery and indicate
potential areas of strong flow deformation, gravity wave activity, and thermal instability, each of which are conducive to widespread turbulence. Lenz et al. (2009) showed that warm-season cirrus bands observed by the Geostationary Operational Environmental Satellite-12 (GOES-12) over the continental United States (CONUS) usually last for about 9 h, are most common during the mature and decaying stages of mesoscale convective systems (MCSs), and have horizontal wavelengths of \( \sim (5–50) \) km. They also found that the locations of these bands are well correlated with the automated eddy dissipation rate (EDR; Corman et al. 1995) turbulence intensity estimates from selected commercial aircraft. Lenz et al. (2009) referred to the banded patterns in the MCS upper-level outflow as transverse bands. However, Galvin (2009) and Knox et al. (2010) provided several examples of banded structures in cirrus clouds that were not associated with MCSs, and emphasized that these cirrus bands can exist not only near the outflow region of the MCSs but also within jet streams and upper-level outflow of tropical cyclones and midlatitude cyclones. In fact, Whitney et al. (1966) described cloud bands oriented transverse relative to the major axis of the cloud shield in jet stream cirrus, and the association of these transverse bands with aviation turbulence was noted shortly thereafter by Anderson et al. (1973).

The convection-permitting numerical simulations of Trier and Sharman (2009) suggested that widespread turbulence near cirrus bands in a MCS case was associated with enhanced vertical shear in the upper-level outflow of the MCS, where anticyclonic southwesterly outflow is superposed on environmental westerlies. A subsequent higher-resolution modeling study (Trier et al. 2010) simulated the observed cirrus bands near the northern anvil edge, which extended radially outward from the denser cirrus cloud shield located closer to the MCS center. The simulated radial cirrus bands in Trier et al. (2010) were organized by the vertical shear of the horizontal wind in the near-neutral to weakly convectively unstable outflow, and therefore shared similar dynamical characteristics with horizontal convective roll vortices (HCRs) in the planetary boundary layer (PBL).

Although recent case studies using numerical weather prediction models and satellite observations have described generation mechanisms for the cirrus bands and NCT near MCSs, case studies near other types of convective systems and in different environmental conditions appear to be lacking. In a recent example of a non-MCS cirrus band case, a commercial aircraft traveling between Hawaii and Tokyo encountered severe turbulence at 0300 UTC 9 September 2010 within or near cirrus bands in an anticyclonic upper-tropospheric ridge over the northwestern Pacific Ocean. Unlike the cases of NCT events within the northern part of the MCS-induced anvil cloud shield, this case occurred near the southern edge of the cirrus. The bands and NCT in the current case were associated with the dissipating stages of Tropical Cyclone Malou,\(^1\) which by this time had begun to acquire some characteristics of an extratropical cyclone. Included among these was an asymmetric cloud structure, in which the turbulent cirrus bands were contained, that was elongated eastward (Fig. 1) approximately parallel to a developing surface warm front (not shown).

The purpose of this study is to investigate the origins and atmospheric structure of this NCT using high-resolution numerical simulations that sufficiently resolve the possible sources of aircraft-scale turbulence. The Advanced Research Weather Research and Forecasting (ARW-WRF; Skamarock and Klemp 2008) Model with five nested domains having a finest horizontal grid spacing of about 370 m, is used to simulate simultaneously the atmospheric conditions that range from large-scale environmental flow to microscales associated with aircraft turbulence. Section 2 describes the observations of the NCT encounter within or near the cirrus bands, while section 3 provides the experimental design of the ARW-WRF simulations. Details of the evolution of the large-scale flows and turbulent areas are investigated in section 4 based on the simulation results. A summary and discussion are given in the last section.

2. Observations of the cirrus cloud bands and NCT events

Figures 1 and 2 show the evolution of the cirrus bands and their relation to the observed turbulence events. At 1800 UTC (Fig. 1a), a comma cloud associated with the oceanic cyclone with a minimum sea level pressure (SLP) of 1002 hPa is located off the east coast of Japan. As time progresses the cyclone moves eastward and cloud bands become prominent in the southern region of the cirrus cloud shield (Figs. 1c,d and 2b). The moderate and severe turbulence PIREPs were recorded near the southern cirrus bands at about 0300 UTC 9 September.

To quantify the characteristics of the observed bands, Figs. 2c,d show the one-dimensional power spectral density (PSD) of the observed brightness temperature (BT) as functions of horizontal wavenumber and wavelength.

\(^1\)A reviewer pointed out that the surface cyclone originated as Tropical Cyclone Malou, although according to the bulletin by the Joint Typhoon Warning Center (JTWC) issued at 0000 UTC 8 September (27h before the turbulence events), tropical storm Malou had already weakened to an extratropical system.
The one-dimensional PSD at two times [2100 UTC 9 September (Figs. 2a,c) and 0300 UTC 9 September (Figs. 2b,d)] was calculated by averaging five different PSDs of the BTs along the southwest–northeast cross-section lines in the black box in Figs. 2a,b. To calculate the PSD, data are interpolated into 100 segments of the given cross sections with 5-km horizontal grid spacing. The BT spectra are derived using a one-dimensional fast Fourier transform (FFT) with a second-order polynomial detrending and a Welch window (Press et al. 1992). The resolvable horizontal wavelengths range from ~10 to 1000 km. In Fig. 2c, enhanced power appears at about a 30-km horizontal wavelength, while in Fig. 2d at the later time the overall power in the longer wavelengths is significantly increased and the peak moves to larger scales at about a 50-km wavelength. This is consistent with the broader features of the observed bands in Fig. 2b compared with those in Fig. 2a. Although slightly wider, the banded structures in this case are similar to those in previous studies of banding in MCS anvils, where...
dominant wavelengths of the observed bands are 5 to 50 km (e.g., Lenz et al. 2009; Trier et al. 2010).

Though the National Weather Service’s (NWS) Family of Services (FOS) communication gateway contained only four archived pilot reports (PIREPs), they included one severe and two moderate turbulence intensities in the vicinity of this midlatitude cyclone within ±30 min around 0300 UTC 9 September 2010. The other PIREP indicated smooth conditions. Detailed information for the three moderate-or-greater (MOG)-level turbulence events is provided in Table 1. In particular, the severe event occurred at $z = 38,000$ ft ($\sim 12.3$ km and 200 hPa) near $32^\circ$N, $150^\circ$E in the vicinity of the cirrus bands (Figs. 1d and 2b). The altitude of the encounter was within or slightly above the thin cirrus in an area where radar reflectivity from conventional
onboard radar would be undetectable, so this case will be considered an NCT event.

3. Experiment design of the simulations

To understand the connection between the observed turbulence and cirrus bands, we perform a simulation using the ARW-WRF Model (Skamarock and Klemp 2008) version 3.2.1. This model is a finite-difference implementation of the nonhydrostatic fully compressible prognostic equations on an Arakawa-C grid with terrain-following sigma coordinates. In recent case studies of several turbulence encounters, ARW-WRF Model simulations have reproduced successfully both the environmental weather scenario and the small-scale structures responsible for several turbulence events (e.g., Trier and Sharman 2009; Trier et al. 2010, 2012; Kim and Chun 2010, 2012).

The placement of all model domains (Fig. 3) is based on the observed locations of the cirrus bands and the moderate and severe-level PIREPs. The horizontal grid spacings of domains 1, 2, 3, 4, and 5 are 30, 10, 3.3, 1.1, and 0.37 km, respectively. All domains have a model top of 20 hPa, and 113 sigma levels with the finest vertical grid spacing of about 100 m around \( z = 9-13 \) km where the turbulence events occurred. Above \( z = 13 \) km, the vertical grid spacing increases linearly to 500 m, while below \( z = 9 \) km the vertical grid spacing linearly increases to 300 m down to about 2 km AGL (above ground level) and remains constant at 200 m below 2 km AGL. A sponge layer with Rayleigh damping is applied to the uppermost 5 km. The WRF Model is integrated for 12 h from 1800 UTC 8 September 2010 to 0600 UTC 9 September 2010. Initial and lateral boundary conditions are obtained from 6-hourly reanalyses from the National Centers for Environmental Prediction (NCEP) global final (FNL) data assimilation system (GFS) with \( 1° \times 1° \) horizontal grid spacing. Two-way interactive nesting is applied within all domains in order to simulate several scales of atmospheric flow simultaneously.

In this study, we use cloud microphysical (Hong and Lim 2006), land surface (Chen and Dudhia 2001), shortwave radiation (Dudhia 1989), and longwave radiation (Mlawer et al. 1997) parameterizations in all domains. The Kain (2004) cumulus parameterization scheme is used only in domains 1 and 2. The Mellor–Yamada–Janjić (MYJ) PBL parameterization (Janjić 2002) is used in each domain. This PBL scheme is used since it predicts local vertical mixings [subgrid-scale turbulent kinetic energy (SGS TKE)] not only in PBL but also in free atmosphere via Mellor–Yamada 2.5-level turbulence closure scheme. Horizontal mixing is calculated

<table>
<thead>
<tr>
<th>No.</th>
<th>Time (UTC)</th>
<th>Lat (°N)</th>
<th>Lon (°E)</th>
<th>Flight level (km)</th>
<th>Turbulence intensity</th>
<th>Approx ( e^{1/3} ) (m(^{2/3}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0259</td>
<td>32.00</td>
<td>150.000</td>
<td>12.3</td>
<td>Severe</td>
<td>0.5–0.7</td>
</tr>
<tr>
<td>2</td>
<td>0315</td>
<td>33.00</td>
<td>150.000</td>
<td>12.0</td>
<td>Moderate</td>
<td>0.3–0.5</td>
</tr>
<tr>
<td>3</td>
<td>0322</td>
<td>30.00</td>
<td>140.950</td>
<td>12.0</td>
<td>Moderate</td>
<td>0.3–0.5</td>
</tr>
</tbody>
</table>

FIG. 3. Horizontal locations of (a) the coarsest three domains: 1 to 3 with \( \Delta x = 30, 10, \) and 3.3 km, respectively, superimposed on the terrain height (m, contour interval = 300 m). (b) The finest three domains: 3 to 5 with \( \Delta x = 3.3, 1.1, \) and \( 0.37 \) km, respectively. Locations of the reported turbulence encounters are depicted by the asterisks.
using the Smagorinsky first-order closure scheme (Skamarock and Klemp 2008).

4. Model results

Trier et al. (2010) showed that the cirrus bands on the northern part of an MCS with widespread upper-level turbulence had the character of thermal-shear instability, similar to daytime HCRs in the PBL (e.g., Kuettner 1971; Etling and Brown 1993), with the shear vector parallel to the longitudinal axis of the rolls. Trier et al. (2010) also found the rolls were significantly enhanced by radiative cooling at the anvil top and warming below it, but the cloud–radiative feedback did not determine in which specific sector of the MCS anvil the rolls occurred. In this section we discuss how the rolls in the current case have a similar origination mechanism to the MCS case of Trier et al. (2010) even though both environmental conditions and the location of the bands relative to the parent deep convection are quite different. As we shall see, in the current case, cloud–radiation feedback is more critical to the formation of the cirrus bands than in the MCS case. And the vertical shear that influences band organization within the cirrus in the current case is induced predominately by the background large-scale flow rather than recent convectively induced upper-level outflow, which had a major influence on the vertical shear in the MCS case.

a. Large-scale environmental flow

Figures 4a,b show model results from domain 1 at 0300 UTC 9 September 2010. In Fig. 4a the reflectivity calculation assumes that particles of rain, snow, and graupel are spheres of constant density with exponential size distributions, following the formulation in the Reisner-2 bulk microphysical scheme (Reisner et al. 1998). Consistent with the satellite image in Fig. 1d, a spiral rainband structure with a well-organized reflectivity region greater than 20 dBZ (Fig. 4a) is located along the warm and cold fronts (not shown) within the oceanic cyclone. Note that the moderate and severe turbulence reports are within the anticyclonic flow of a large-scale upper-level ridge (Fig. 4b) and are located in very low reflectivity several hundred kilometers away from the main convective region (Fig. 4a). This implies that the observed turbulence is not directly associated with the main deep convective activity, but rather is associated with other processes within or near the outer edge of the cirrus.

Cross sections from domain 1 of the simulation through the location of the observed severe turbulence report (32°N, 150°E) are shown in Figs. 4c–f. Areas of inertial instability (AVOR = ζ + f < 0, where \( \zeta = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \) is the relative vorticity and \( f \) is the planetary vorticity), which are influenced by strong meridional gradients of zonal wind (\( \partial u/\partial y > 0 \)) in Fig. 4c, and weaker zonal gradients of meridional wind (\( \partial u/\partial x < 0 \)) in Fig. 4d, are enclosed by the solid red contours and occur near the turbulence reports (Figs. 4e,f). Vertically propagating gravity waves are also evident above \( z = 14 \text{ km} \) (Figs. 4e,f), although they do not appear to be directly related to observed turbulence in this case.

A polar jet at \( z = 13.5 \text{ km} \) (near the top of the anvil cirrus) stretches southeastward into the region of turbulence at 32°–33°N, 150°E (Figs. 5a,b). This supports inertial instability (AVOR < 0) on the equatorward side of the jet streak (Fig. 5b). The inertial instability is generally located south and downwind of the deep convection in the cyclone and is coincident with areas of the bands and turbulence encounters. However, the jet at \( z = 11 \text{ km} \) (near the bottom of the anvil cirrus) lacks anticyclonic curvature (Figs. 5d,e) evident within the exit region of the jet at 13.5 km (Figs. 5a,b). These differences in jet morphology at different vertical levels contributes to strong vertical shear greater than 20 m s\(^{-1}\) (2.5 km\(^{-1}\)) beneath the anticyclonically curved jet (Figs. 5g,h), located within the regions of the bands and near the reported turbulence encounters.

To investigate whether the deep convective activity in the cyclone affects upper-level flow and vertical shear near the bands and turbulence, we performed another simulation (DRY) that was identical to the control run (CTL) except that it disables cloud microphysics and convection parameterizations in all computational domains. The results from DRY are shown in Figs. 5c,f,i. When we compare CTL (Figs. 5b,e,h) with DRY (Figs. 5c,f,i), there are no significant flow differences between the two. This implies that the large vertical shear near the cirrus bands and reported turbulent areas are driven primarily by the synoptic-scale flow and are not significantly strengthened by moist convection-induced divergent upper-level outflow within the cyclone. This is one of the differences in environmental conditions between the current case and the MCS case where the MCS-induced upper-level outflow (Trier and Sharman 2009) was the most important factor contributing to large vertical shears in the vicinity of the bands (Trier et al. 2010). A caveat to this finding is that the large-scale flow, itself, was likely influenced by the presence of Tropical Cyclone Malou for several days prior to the NCT event.

The evolution of the vertical structure of large-scale flow across the convective system and upper-level jet near the bands and turbulence are shown in Fig. 6. During 1900–2100 UTC, strong horizontal shear occurs on the equator side of the polar jet (Fig. 6a), which favors widespread areas of inertial instability (red contour) due to large anticyclonic relative vorticity (\( \zeta < 0 \))
FIG. 4. Simulated results in domain 1 ($\Delta x = 30$ km) at 0300 UTC 9 Sep 2010: (a) column maximum radar reflectivity (shading, dBZ) and SLP (black contours). (b) Horizontal wind speed (shading, m s$^{-1}$) with horizontal wind vectors (barbs) and pressure (black contours with 4 hPa intervals) at $z = 12.3$ km. (c),(d) Vertical cross sections of $u$ ($v$) [black (red) contours with 10 m s$^{-1}$ intervals, negative values dashed] wind components and total cloud mixing ratio ($QC$, shadings) along (c) meridional (AB) and (d) longitudinal (CD) cross-section lines through the severe PIREP shown in (b). (e),(f) Potential temperature ($\theta$, black contours with 4 K intervals) and the absolute vorticity = 0 isoline (AVOR; red) with total cloud mixing ratio ($QC$, shadings) along transects as in (c),(d). Locations of the severe and moderate turbulence reports are depicted as the red and black asterisks, respectively.
Fig. 6b) combined with decreases in planetary vorticity toward the equator. Strong vertical shear near the turbulence region is mainly associated with large magnitudes of $\frac{\partial u}{\partial z}$ beneath the southwardly stretching jet located at $z = 14$ km, which is consistent with the findings shown in Fig. 5. By 2300–0100 UTC, the vertical and horizontal shears strengthen as the polar jet moves eastward and extends southward. As a result of the latter, the area of inertial instability and cirrus extends farther south by 2300–0100 UTC (Fig. 6d).

There are only minor differences in the vertical structures between CTL (Figs. 6c,d) and DRY (Figs. 6e,f), which further supports our finding that the strong vertical shear through anvil cloud depth in the current...
case is driven primarily by the large-scale flow rather than convectively induced upper-level outflow. Within the leading edge of the anvil region ($y = 500–700$ km, $z = 10–14$ km in Figs. 6b,d), the vertical gradient of potential temperature becomes less than for other layers, indicating smaller static stability in this layer.

b. Generation mechanism for the cirrus bands

Strong vertical shear $>20$ m s$^{-1}$ through the anvil depth between $z = 11–13.5$ km at 1900 and 2000 UTC (Figs. 7a,b) approximately coincides with the location where bands occur in domain 3 of CTL (Fig. 7c). At this
later time (0300 UTC) the area of large vertical shear has expanded southward along the southeastern part of the midlatitude cyclone. These bands of small reflectivity \([-20 \text{ to } 10 \text{ dBZ}\)] are approximately aligned along the vertical shear vectors (Fig. 7c) and the spacing between the bands increases with time consistent with the observed satellite imagery features shown in Figs. 2a,b.

Development of the simulated bands occurs continually from 2100 to 0300 UTC near the southeastern edge of the upper-level cirrus cloud. The simulated band development is illustrated during a 2-h period near their onset in Fig. 8. At 2140 UTC (Fig. 8a), the moist static stability $N^2_m$, as defined by Durran and Klemp (1982), is less than zero near the portion of the cloud edge located upshear from a small area of preexisting (mature) bands. During the next 40 min new bands initiate within this statically unstable region (Fig. 8b) and continue to grow during the following 80 min (Figs. 8c,d). The region in which the bands grow near the cloud edge eventually becomes approximately conditionally neutral as a result of the widespread nature of the explicit shallow convective overturning. The bands also become elongated toward areas of positive static stability ($N^2_m > 0$) as a result of advection of ice particles along the vertical shear vector, itself indicated by the barbed symbol in Fig. 8d.
To determine the effect of cloud radiative feedback on the formation of the bands, we follow Trier et al. (2010) and conduct an additional numerical simulation (NCR) that disables the cloud–radiative feedback but is otherwise identical to CTL. Comparing the two simulations at 0300 UTC 8 September (Figs. 7c,d) reveals bands only in CTL. This implies that the cloud–radiative feedbacks are crucial in generating the cirrus bands in this case.

In CTL (Figs. 9a,b), a region of nonzero SGS TKE coincides with the region of overturning isentropes on top of the well-developed convective cells, while the anvil cirrus stretches downstream near z = 10–13 km and x > 700 km. The relatively large spacing of isentropes near the cloud top (~10–13 km) indicates small static stability near the onset of the banding around 2000 UTC in CTL (Fig. 9a).

The smaller static stability in this upper portion of the CTL anvil (Fig. 9a) than at similar elevations in DRY (Fig. 9d) indicates the important effects of anvil cloud processes on the static stability. Moreover, comparing...
CTL and DRY with NCR (Fig. 9c) suggests that a significant portion of these stability reductions near the southeast edge of the CTL anvil \((x \approx 700 \text{ km})\), where it is thinnest, may be influenced by cloud–radiative feedback occurring in this location just upstream of where the actual turbulence was reported (red asterisk).

The small static stability is highlighted by the especially large spacing between the 346- and 350-K isentropes (red contours) near the \(x \approx 700\)-km anvil edge in CTL (Fig. 9a) compared with those at the same location in NCR (Fig. 9c) as banding is becoming evident in the cloud water of CTL. At this time, largest magnitudes of vertical velocity within the \(z = 10–14\)-km layer for \(x > 300\) km in CTL are about 1 m s\(^{-1}\), which is significantly larger than the corresponding values of 0.2 m s\(^{-1}\) in NCR and 0.1 m s\(^{-1}\) in DRY. Therefore, we conclude that effects of the cloud–radiative feedback on thermodynamic destabilization (e.g., longwave cloud-top cooling and cloud-base warming) and the synoptically forced strong vertical shear, along which the bands are approximately aligned (Fig. 7c), are primary factors influencing the onset and subsequent organization of the bands in this case.

Figure 10 compares the CTL and NCR simulated fields in domains 3 (\(\Delta x = 3.3\) km) and 4 (\(\Delta x = 1.1\) km). In both domains the vertical shear vectors in CTL are aligned approximately along the bands, consistent with the proposed thermal instability mechanism. In domain 3, there is similarity in general features of the main convective region between CTL (Fig. 10a) and NCR (Fig. 10b), which implies that cloud–radiative feedback processes do not significantly affect the character and intensity of the deep convection. However, note that in both simulation domains [domain 3 (Figs. 10a,b) and domain 4 (Figs. 10c,d)] only CTL has the widespread bands near the southern edge of the cirrus cloud shield, and only CTL has nonzero simulated turbulence (SGS TKE) in that area. So in this case, cloud–radiative feedback processes are crucial to the formation of the bands and the bands are crucial to the formation turbulence on the southern edge of the cloud shield. This is to be expected given the convectively unstable nature of the bands themselves (cf. Fig. 8).

Vertical cross sections of total cloud mixing ratio and the \(y\) component of vorticity \((\partial u/\partial z - \partial w/\partial x)\) across the bands (along the line between A and B in Figs. 11a,b) indicate counter-rotating vortices within the anvil cirrus.
(Figs. 11c,d). Here, rolls are implied by the presence of counter-rotating vortices within the anvil cirrus; and the ascending branches of the rolls contribute to the enhanced density of total cloud condensate, which leads to the banded structures evident in the BT. Figure 12 shows the one-dimensional PSD of the simulated BT as a function of horizontal wavelength across the cirrus bands. There is enhanced power near horizontal wavelengths of 50 and 20 km, which is consistent with the observed BT pattern shown in Fig. 2d. From Figs. 10 and 11, the aspect ratio (spacing–depth) of the rolls is \(~\) (10–20), which is at the large end but still within the range of aspect ratios observed in planetary boundary layer rolls (e.g., Miura 1986; Etling and Brown 1993).
Additional sensitivity tests using different microphysical parameterizations were performed to determine the robustness of the current results. A comparison between the CTL simulation results with the WRF single-moment 6-class microphysics scheme (WSM6; Hong and Lim 2006) scheme and another simulation with the WRF double-moment 6-class microphysics scheme (WDM6; Lim and Hong 2010) scheme showed no significant difference near the cirrus bands, although the simulated column maximum reflectivity in the main convective region along the well-organized surface fronts was locally larger in the experiment with the WDM6 scheme (not shown). The similarity between the two simulations is likely due to the fact that the cirrus comprises mostly ice phase particles that are treated identically in both the WSM6 and WDM6 schemes (Lim and Hong 2010).

In summary, the differential radiative forcing and vertical shear in the near-neutral to convectively unstable layer within the anvil cirrus produces counter-rotating vortices (rolls), which in turn produces the observed cirrus bands in the satellite imagery. This is consistent with the thermal-shear instability mechanism for the cirrus bands in the northern outflow area of the MCS case described in Trier et al. (2010). However, in the current case vertical shear is mainly driven by the large-scale flow rather than by convectively induced
upper-level outflow in the MCS case. Furthermore, cloud–radiative feedbacks are more crucial to the generation of the bands in the outer anvil in this case than in Trier et al. (2010). Although areas of inertial instability are present, the most direct generation mechanism for the bands appears to be thermal-shear instability.

c. Generation mechanism of aircraft-scale turbulence within the cirrus bands

The relationship of the observed turbulence to the bands was investigated by inserting a still finer grid (domain 5, $\Delta x = 370$ m) in the CTL simulation. Figure 13 shows the simulated BT, vertical-shear vectors and SGS TKE at 0300 UTC 9 September 2010 in the four different domains, and allows us to assess the sensitivity of the simulated bands to horizontal grid spacing. As expected, the detailed structure of the cirrus bands is more apparent in the finer resolution domain.

In Fig. 13d, smaller-scale irregular patterns in the simulated BT especially those lower than $-50^\circ$C, are embedded within each segment of the shallow-banded convection, although these irregularities do not appear as clearly in the Japan Meteorological Agency (JMA) Multifunctional Transport Satellite (MTSAT) data shown in Figs. 1 and 2 due to the coarser 4-km horizontal grid spacing of the MTSAT IR channel. However, irregular patterns in satellite imagery along cirrus bands in other cases have been reported (e.g., Knox et al. 2010), so the simulated results are not unreasonable. To examine these structures more closely, Figs. 14a,b present the vertical velocity, total model-estimated EDR ($= \varepsilon^{1/3}$) values, and vertical shear vectors within the anvil cirrus at 0300 UTC 9 September 2010. Here, the total EDR is calculated using both SGS TKE and resolved TKE, since in these domains with finer horizontal grid spacing some of the small-scale turbulent eddies directly affecting aircraft motion are explicitly resolved. The energy dissipation rate $\varepsilon$ can be roughly estimated by $\varepsilon = 0.84 e^{2/3} \Delta$, where $\varepsilon$ and $\Delta$ are the total TKE (SGS TKE + resolved TKE) and length scale ($\Delta x \Delta y \Delta z)^{1/3}$, respectively (e.g., Schumann 1991; Sharman et al. 2012a). The resolved TKE $\{[(u')^2 + (v')^2 + w^2]/2\}$ is computed in domain 5 by using the $u$ and $v$ components averaged over $5 \times 5$ grid points subtracted from the local values (i.e., $u' = u - \bar{u}$). Several averaging regions for the resolved TKE were tested ranging from $5 \times 5$ to $15 \times 15$ gridpoint regions. The spatial structure of total EDR did not appear very sensitive to the averaging region and varied little from that shown in Fig. 14b, although the maximum value of the total EDR linearly increased from using gridpoint-averaging regions of $5 \times 5$ (0.678 m$^{2/3}$ s$^{-1}$) to $15 \times 15$ (0.94 m$^{2/3}$ s$^{-1}$), because the perturbation magnitude is generally larger with more averaging (not shown). This simulated maximum total EDR value is near the severe-level EDR threshold value (0.7 m$^{2/3}$ s$^{-1}$) for the turbulence experienced by relatively large aircraft such as B757s and B737s (International Civil Aviation Organization 2010).

Vertical velocity (Fig. 14a) and total EDR (Fig. 14b) have substantial variability along each segment of the shallow-banded convection, which is not unlike the longitudinal structure of atmospheric rolls in the boundary layer (e.g., Kuettner 1971). Figure 14d shows the vertical velocity, total cloud, and potential temperature within the black box in Fig. 14c. The northerly wind increases from $z = 10$ km to $z = 14$ km (Fig. 14c, resulting in upward vertical tilt of the shallow-banded cloud toward the south (bold red lines in Figs. 14c,d). This implied vertical shear results in strong flow deformations and vertical mixing, evident in the steep and overturning isentropes near the upper part of the anvil around $z = 12$–13 km (Fig. 14d). This leads to strong updrafts and downdrafts of very small horizontal scale ($\sim 2$ km) at $z \approx 12.3$ km and $x \approx 24$ km in Fig. 14d. These vertical velocity perturbations may be felt as a sudden jolt and/or bumpiness to aircraft passing through this area, which a pilot might report as moderate-to-severe-level turbulence. This effect is consistent with previous studies of NCT due to the flow deformation induced by the convection (e.g., Lane et al. 2003; Kim and Chun 2012).
5. Summary and conclusions

On 0300 UTC 9 September 2010, commercial aircraft traveling between Tokyo and Hawaii encountered moderate and severe intensity turbulence at about 12-km elevation in or just above the cirrus anvil associated with a precipitation system that was undergoing a transition from a weakening tropical cyclone to an extratropical cyclone off the east coast of Japan. Satellite observations indicated a large comma-shaped convective system aligned along the surface warm and cold fronts within the emerging midlatitude cyclone. The moderate and severe turbulence experiences reported by pilots were several hundred kilometers south of the active deep convection, and occurred within or above the banded cirrus structures that extend southward from the main area of cloudiness. In this region the radar reflectivity is very low and the turbulence hazard would not be detectable by onboard radar, and is thus classified as a near-cloud turbulence (NCT). Although there is always some uncertainty in PIREP locations (e.g., Sharman et al. 2006), the region of cirrus bands is rather widespread, indicating enhanced levels of turbulence was likely present in the vicinity.

The generation mechanisms for the NCT in the vicinity of the cirrus bands were investigated using the high-resolution ARW-WRF Model with five nested domains having a finest grid spacing of 370 m, which...
were collectively able to simultaneously simulate both the large-scale environmental forcing and aircraft-scale turbulent flow. We compared a DRY simulation without cloud microphysics to a control run to understand how microphysical processes and moist convection within the oceanic cyclone can affect the upper-level environmental flow. To isolate the generation mechanism for the cirrus bands, an experiment that disables the cloud–radiation feedback (NCR) was also performed.

FIG. 14. Simulated results from domain 5 ($\Delta x = 0.37$ km) of CTL at 0300 UTC 9 Sep 2010: Vertical shear vectors (barbs) between $z = 11$ and 13.5 km superimposed onto (a) vertical velocity (shading) and (b) estimated eddy dissipation rate (EDR, shading) computed from the subgrid-scale turbulent kinetic energy (SGS TKE) and resolved TKE. (c) Estimated EDR (shading) and total cloud mixing ratio $> 0.01$ g kg$^{-1}$ (red contours) with meridional winds (black contours with 4 m s$^{-1}$ intervals) along transect AB in (a). (d) Estimated EDR (shading) with potential temperature (black contours with 0.5-K intervals) and total cloud mixing ratio exceeding 0.01 g kg$^{-1}$ (red contours) within the black box in (c). Locations of the observed severe and moderate turbulence events are indicated by the red and black asterisks, respectively.
The simulations demonstrate that the observed cirrus cloud bands are manifestations of horizontal roll vortices that formed in near-neutral to convectively unstable layers of the outer anvil. The bands and associated roll circulations are oriented approximately parallel to the vertical shear vectors within the outer anvil layer and have aspect ratios (width/depth) of ~\((10\) to \(20\)). These aspect ratios are similar to horizontal convective rolls (HCRs) in the atmospheric boundary layer, which result from thermal–shear instability. Similar structures have been simulated for a more isolated warm-season continental MCS case (Trier et al. 2010). Since the rolls owe their existence to thermal instability induced by cloud–radiative feedback within the cirrus shield, it is not surprising that model-simulated turbulence is most pronounced within the vicinity of the rolls. Indeed in the NCR case, rolls were not produced, and SGS turbulence did not develop.

A novel aspect of the current study is the simulation of cirrus bands arising from convection contained in a much larger-scale oceanic cyclone. The current work also extends the results of the earlier MCS case of Trier et al. (2010) by documenting simulated eddy dissipation rates (EDRs) within the banded structures that are consistent with severe turbulence levels reported by pilots.

Despite the similar proposed thermal–shear instability mechanism, there are several important differences between the current case and the MCS case of Trier et al. (2010). Cloud–radiative feedbacks were critical to the thermodynamic destabilization that allowed band formation in the current case, as evidenced by the lack of band formation in the NCR run. In the MCS case, though cloud–radiative feedbacks clearly enhanced cirrus band formation, they were not essential because the region in which the bands formed was already statically unstable due to differential temperature advection associated with strong vertical shear resulting from the MCS-induced upper-level outflow (Trier and Sharman 2009; Trier et al. 2010). The vertical shear through the simulated anvil depth in the current case was similar in the control simulation (CTL) to its counterpart in the DRY run. This represents another significant difference between the current case and the MCS case, and implies that the vertical shear that helped organize the cirrus bands in the current case resulted primarily from largescale (adiabatic) processes. This difference between cases also has possible implications for the primary location of the cirrus bands, which, unlike the MCS case, are on the south side of the convective system in the current case.

An additional difference from the MCS case concerns the synoptic upper-tropospheric environment in which the convection and cirrus bands formed, which in the current case consisted of a strong upper-level anticyclone situated to the south and southeast of a strong upper-level jet streak. Here, both the scale and the intensity of upper-level anticyclone were likely influenced by Tropical Storm Malou, which was located in the area several days earlier. This region possessed large pockets of negative absolute vertical vorticity, leaving open the possibility that inertial instability (e.g., Knox 1997) could have also played a role in the formation of the bands by perhaps influencing the environmental vertical shear via associated horizontal accelerations. The current case suggests that both vertical and horizontal shears could somehow act synergistically to create instability, as has been noted in some earlier studies (e.g., Ciesielski et al. 1989). Moreover, previous studies (e.g., Schultz and Knox 2007; Schumacher et al. 2010) have discussed the possibility that multiple instabilities could simultaneously influence the generation of cloud and precipitation bands. However, the contribution of these multiple effects to the turbulence generation processes is often difficult to isolate and remain an important area of ongoing and future research.

More case studies of cirrus bands in different weather regimes such as strong anticyclonic jet streams (both with and without convective activity) and upper-level outflows from midlatitude and tropical cyclones are still required to further understand the underlying generation mechanisms for cirrus bands and NCT events. It seems clear though, that in this case and the MCS case of Trier et al. (2010) the presence of banded structures in satellite imagery can be useful indicators of elevated levels of turbulence (e.g., Anderson et al. 1973; Ellrod 1990). Current (e.g., GOES-R) and planned future [e.g., Meteorological Satellite (Meteosat) second generation] geostationary satellites have infrared (IR) resolution of ~\(2\) km, which should allow better detection of these bands.

A promising aspect of the current simulations is that the turbulence-producing cirrus bands were reasonably well resolved at horizontal grid spacing of \(\Delta = 3.3\) km (Fig. 13b), which is comparable to the horizontal grid spacing used in next-generation limited-area numerical weather prediction (NWP) models (e.g., Smith et al. 2008). Though this resolution is clearly not adequate in many cases (e.g., Trier et al. 2010), and accurate cirrus band formation also depends on the model’s ability to simulate the parent deep convection, our findings suggest that examination of detailed model cloud and hydrometeor fields may be useful for real-time prediction of aviation-scale turbulence using automated predictive algorithms (e.g., Sharman et al. 2006; Kim et al. 2011, 2014).

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