Analysis of Satellite Signatures, Pattern Recognition, and Eddy Dissipation Rate In Determining Potential Areas of Convectively Induced Turbulence

Richard DiMaio
Department of Geography
Northern Illinois University

ABSTRACT

This study assists and improves the procedures of aircraft avoidance of turbulence near thunderstorms. Convectively induced turbulence (CIT) and near cloud turbulence (NCT) represents a significant hazard for the aviation industry and has shown to be responsible for over 60% of turbulence-related aircraft accidents (Cornman and Carmichael 1993). Current Federal Aviation Administration (FAA) avoidance guidelines do not properly address any formal tactical procedures when aircraft are more than 20 miles from a thunderstorm. However, CIT and NCT, often occur 200-300 miles downwind of large mesoscale convective systems (MCS).

Using pattern recognition associated with the development of MCSs, satellite imagery of transverse bands within the outflow cloud shield, pilot reports (PIREPS) and aircraft eddy dissipation rate (EDR) data, this study shows that certain sub-synoptic scale environments are more conducive to moderate or severe turbulence. By examining several case studies, it is hopeful that operational aviation forecasters, airline flight dispatchers, pilots and air traffic controllers can utilize these results by updating current procedures as well as those to be implemented into the FAA next-generation air transportation system (NextGen).

INTRO GRAPHICS:

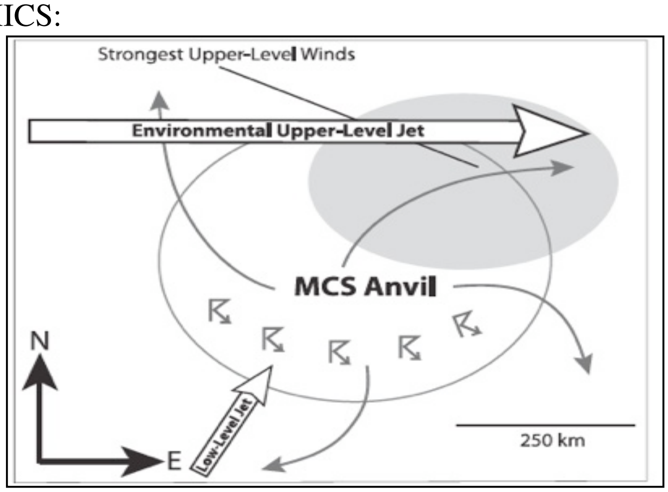

Figure 2. Schematic diagram illustrating spatial relationships among the environmental flow, strongest deep convection (thunderstorm symbols), MCS anvil cloud (thin oval-shaped curve), MCS divergent upper-level outflow streamlines (thick curves with arrowheads), and the location of strongest upper-level outflow winds (gray shading). Turbulence occurs most often in gray area. (From Trier and Sharman, 2008)

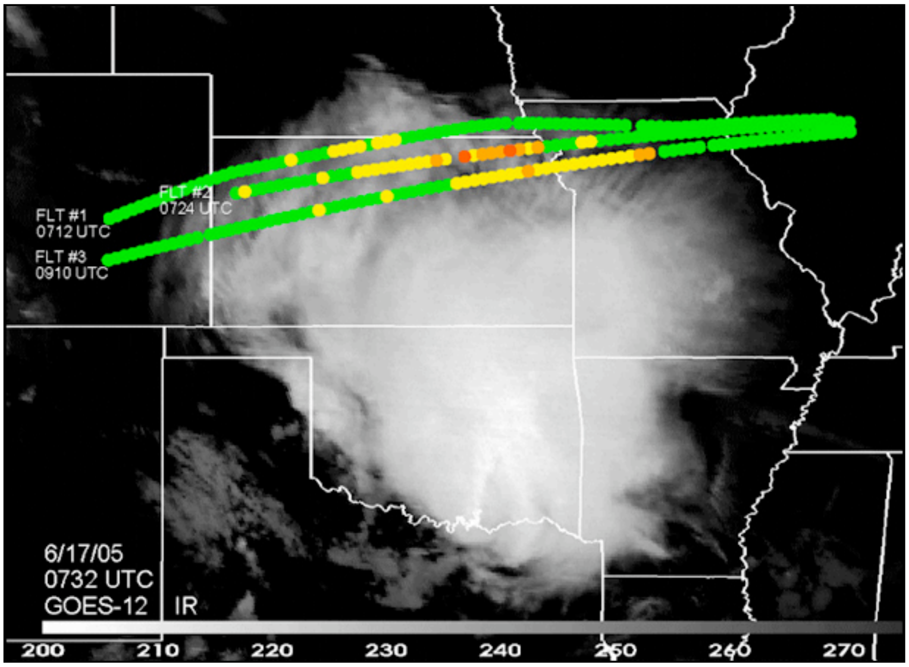

Figure 3. Turbulence measurements along the tracks of three EDR equipped aircraft superimposed on a 0732 UTC 17 June 2005 Geostationary Operational Environmental Satellite-12 (GOES-12) infrared satellite image. Color-coded dots represent intensity of turbulence related to EDR values; green: none, yellow: light, orange: moderate and red: moderate to severe (From Trier and Sharman, 2008).

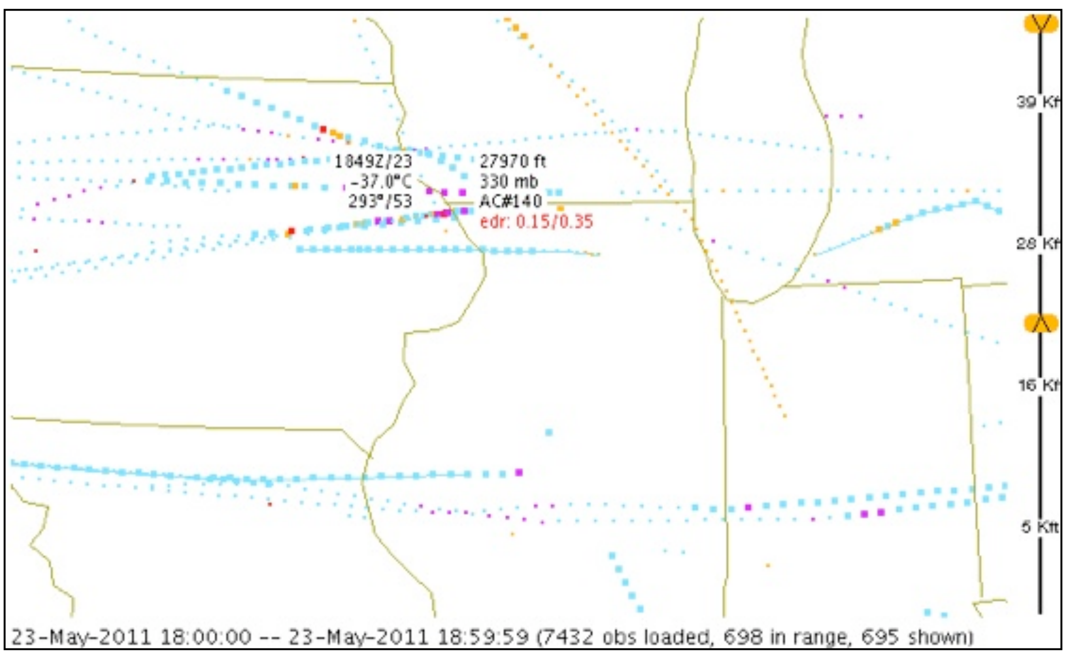

Figure 4. Sub-plot of AMDAR data, displaying peak EDR of 0.35 at 330 hPa or 27,970 feet over northwest IL at 1849 UTC 23 May 2011. This report was associated with moderate to severe turbulence. (Source: AMDAR)

D. Data Analysis

MCS and Short-Wave Troughs

Two cases of turbulence, 23 May and 16 June 2011, associated with a short-wave trough adjacent to the northern outflow portion of an MCS are examined. Each MCS existed during the time frame 12 - 21 UTC with initial development between 12 – 14 UTC. The precipitation core in both cases (not shown) exhibited a slightly east to southeast movement while the anvil and associated cirrus outflow developed an east to northeastward movement. Both MCSs developed within a westerly to west-northwesterly flow of 30 – 50kts from 500 to 300 hPa. In both cases, a well defined 500 hPa short-wave trough was progressively moving through the flow approximately 300 - 400 miles north and east of the track of the MCS and 200 – 300 miles from the edge of the cirrus outflow. Tropopause heights were generally 30-50 hPa lower in the vicinity of the short-wave trough in each case.

a) 23 May 2011

GOES Visible satellite imagery for 1445 UTC, 23 May 2011, shows a developing anvil spreading northward towards the MO/IA border associated with an MCS in southwest Missouri (Figure 7). No reported turbulence was associated with this system at this time. Note the well-defined cyclonic circulation over Minnesota and Wisconsin. At 1645 UTC (Figure 8), anvil cloud producing cirrus blow-off with an area of weakly developing transverse bands begins to move eastward into central Illinois. 9 PIREPS and 3 EDR reports of moderate turbulence between FL 310 – 390 from 1600 to 1730 UTC are evident in the northern flank of the expanding outflow at the same time transverse bands begin to multiply. Note the lower level cumulus cloud field in central Iowa is directly beneath the most northern turbulence reports. This is an example of two distinct streams of wind flow; a lower level wind flow related to the short-wave trough moving through the upper Midwest and the newly developing northern flank outflow associated with the developing MCS.

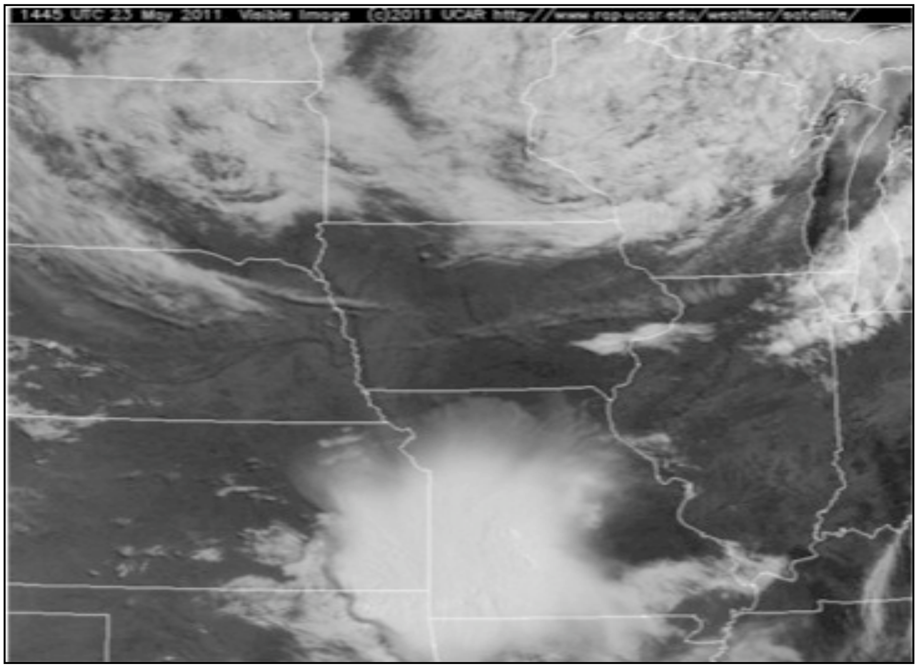

Figure 7. GOES Visible Satellite, 1445 UTC, 23 May 2011. (Source: UCAR)

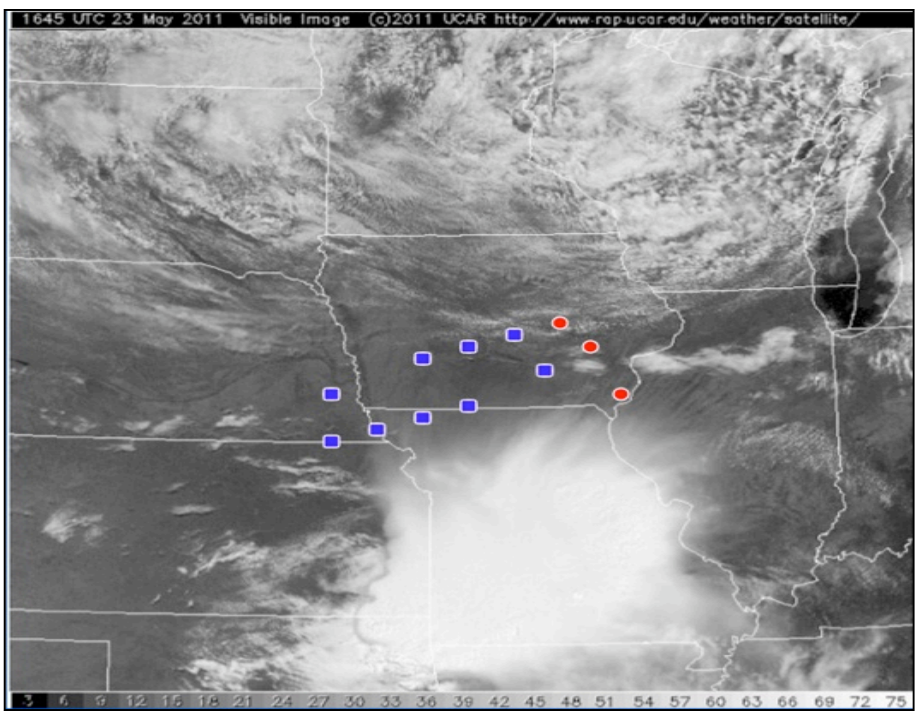

Figure 8. 1645 UTC, 23 May 2011, superposed with EDR reports from 0.15 to 0.35 (squares) and PIREPS (circles). Both indicate moderate turbulence at Flight Level (FL) 310 – 390 feet from 1600 to 1730 UTC. Note the majority of reports occurring in cirrus outflow and edge of transverse bands.

At 1845 UTC visible satellite imagery shows the larger MCS sinking southward towards northern Arkansas while a second cluster of convective activity develops over western Illinois (Figure 9). Additional streaks of transverse bands now develop further northward through Illinois. 12 PIREPS and 7 EDR reports of moderate turbulence occur between FL 240 – 390 at 1800 – 1945 UTC from central IA into northern IL and southern WI. Turbulence closer to the short-wave trough tends to be at a lower altitude, FL 240 – 330, while closer to the anvil, turbulence is at a higher altitude, FL 330 – 390. Single reports of moderate to severe and severe turbulence occurred at FL 270 and FL 290, respectively, between 1914 and 1928 UTC over southern Wisconsin where it appears the transverse bands were directly overhead the strongly cyclonic lower level flow.

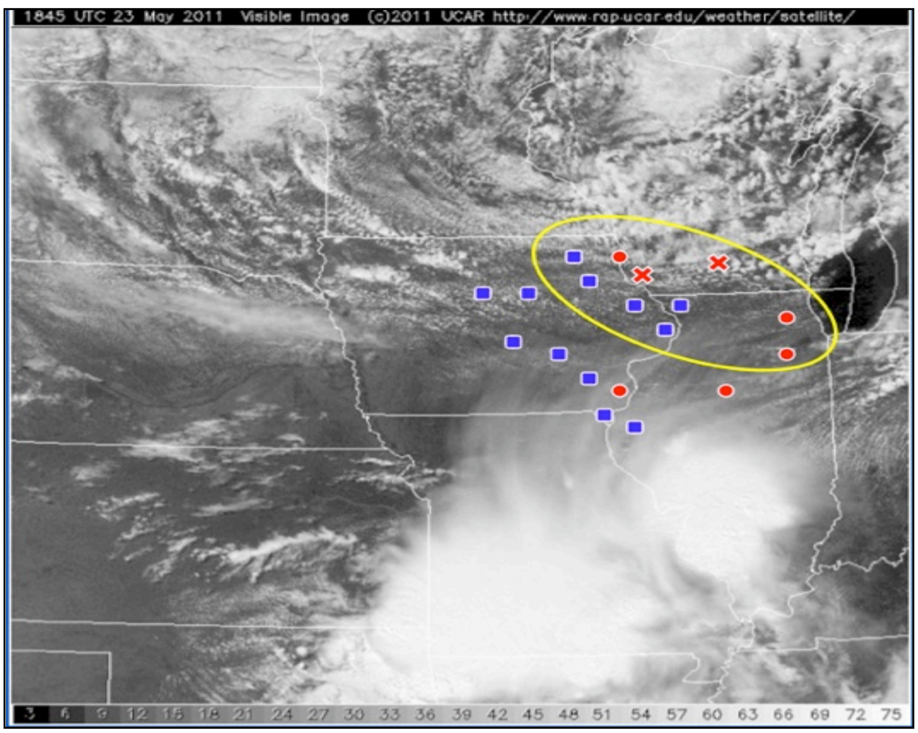

Figure 9. 1845 UTC, 23 May 2011, superimposed with EDR reports of 0.15 to 0.35 (squares) and PIREPS (circles). Area inside oval indicates moderate turbulence at FL 240 – 330 from 1800 to 1945 UTC. Area outside oval indicates moderate turbulence FL 330 – 390. Red X's indicate moderate to severe and severe turbulence FL 270 – 290, 1914 to 1928 UTC.

EDR reports of 0.15 to 0.35 indicating moderate or greater turbulence from 14 – 19 UTC from FL 240 – 390 shows an excellent spatial relationship with transverse bands and lower level cyclonic flow during this time frame (Figure 10). Several reports of 0.35 to 0.45 were within 50 km of the two reports indicating moderate to severe and severe turbulence. Note the spatial relationship of the EDR within the inner circle with the transverse bands overlaying the lower level cumulus cloud field.

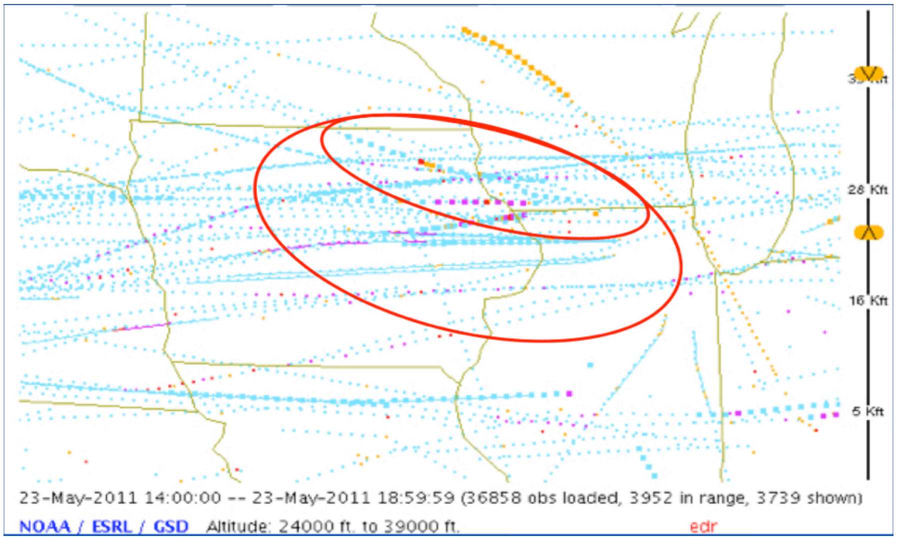

Figure 10. Sub-plot of AMDAR EDR data, 23 May 2011, 14 – 19 UTC, displaying peak EDR from 0.15 to 0.45 from FL 240 - 390. Large circle indicates region of moderate turbulence FL 270 – 390. Sub-circle indicates concentration of of moderate-severe and severe turbulence at FL 240 - 270. (Source: AMDAR)

In the AMDAR wind plot at FL 180 – 290 from 1800 – 2000 UTC (Figure 11), northwesterly flow of 50 kts depicts the western edge of the short-wave trough. Two reports of moderate-severe and severe turbulence occurred during this time frame at FL 270 – 290. The enhanced southwesterly jetstream due to the outflow from the MCS can clearly be seen from IA into WI and IL (Figure 12). Not only does the wind velocity increase to nearly 110kts but also the wind direction in this layer varies by almost 50 degrees from the lower layer, FL 180 – 290.

Comparison of the AMDAR wind data from FL 180 - 290 to earlier 1200 UTC 500 hPa analysis shows that wind velocity in the lower layers did not increase more than 10 kts (Figure 13).   Evidence suggests, that the enhanced jetstream due to the developing MCS did not have any effect on this layer. However, wind velocity did increase by almost 50 kts from FL 290 - 390 in 6 to 8 hours compared to earlier 1200 UTC 250 hPa winds (Figure 14).

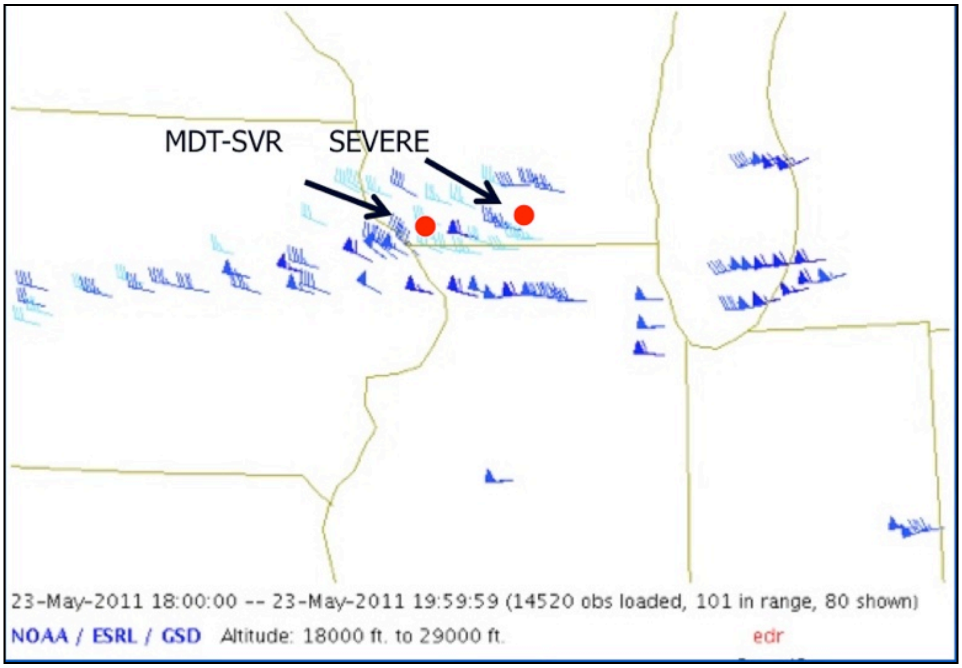

Figure 11. AMDAR wind plot FL 180 – 290, 1800 – 2000 UTC, 23 May 2011 at time of two reports of MDT-SVR and SVR turbulence. (Source: AMDAR)

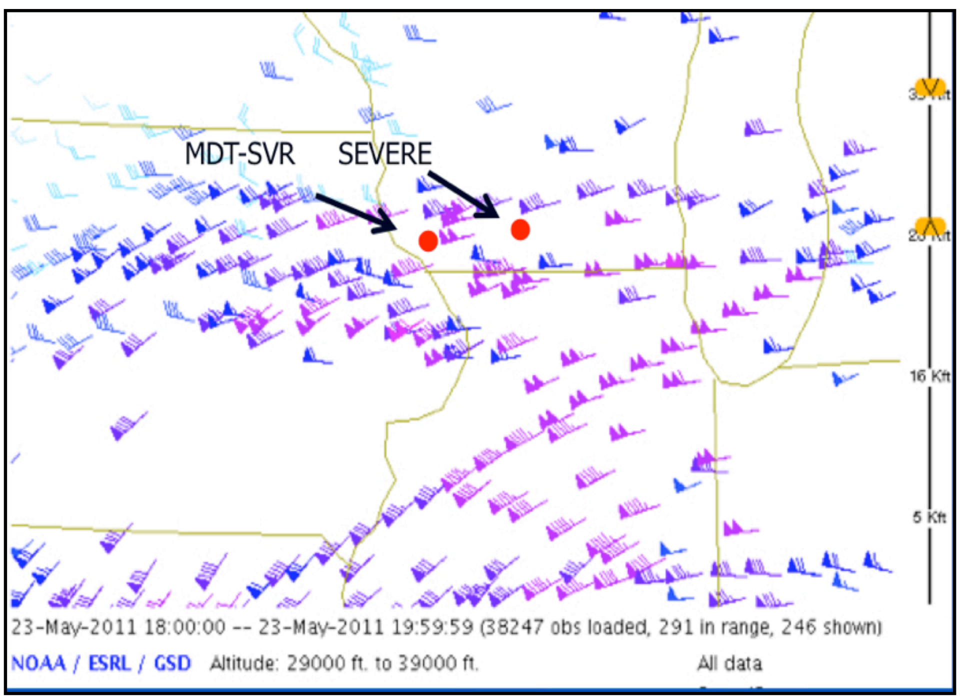

Figure 12. AMDAR wind plot FL 290 – 390, 1800 – 2000 UTC 23 May 2011.
Note westsouthwesterly flow of 110 kts in area of severe turbulence.
(Source: AMDAR)

The nature of the tropopause is also examined in this case. The nearby sounding at Davenport (DVN), IA at 1200 UTC indicates a tropopause height of 250 hPa, FL 340, (Figure 15). At 0000 UTC the tropopause has increased to 220 hPa, FL 370, due to the departing short-wave trough. Increasing stability above the tropopause due to tended to constrain the upper levels of the enhanced jetstream. This increase in tropopause height allowed turbulence and the jetstream to occur at higher flight levels over southern IA from 1200 UTC to 1800 – 2000 UTC.

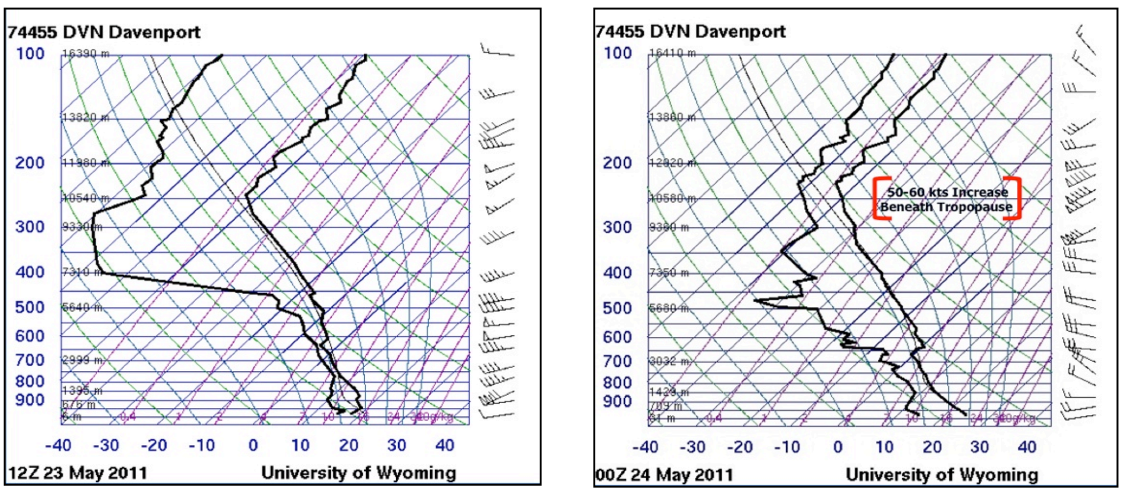

Figure 15. Davenport (DVN), IA soundings for 12 – 00 UTC, 23 - 24 May 2011. Note the increase in wind speed due to outflow from MCS. Most turbulence remained below tropopause. (Source: University of Wyoming)

3rd Case…..(2nd case removed from this manuscript)

c) MCS and Southern Flank Outflow 29 May 2011

In this example, a large MCS developed in the early morning hours over IA and moved rapidly into IL and IN eventually reaching southern MI by the afternoon. While radar imagery is extremely helpful in identifying intense areas of precipitation, it can be misleading to most operational aviation specialists when trying to determine safe route of aircraft travel in non-turbulent air. Nearly 20 PIREPS and 10 EDR reports of moderate turbulence occurred between FL 340 – 400 within a six-hour period in the oval area as the MCS moved almost due easterly (Figure 26). This event shows that convectively induced turbulence is possible several hundred miles from the leading edge of the heaviest precipitation core in rapidly developing MCSs.

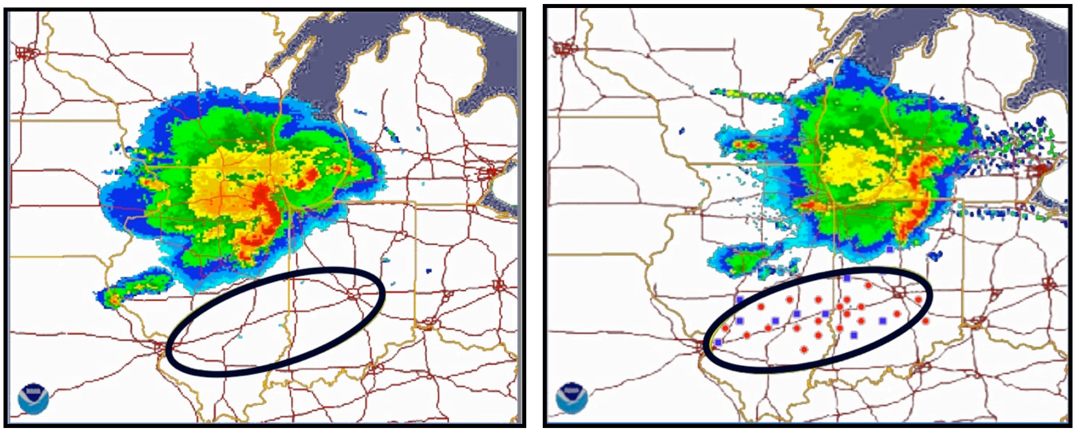

Figure 26. NexRad composite imagery from KLOT, IL at 248nm range. Image on left is 1800 UTC, 29 May 2011 showing large MCS. Image on right is 2000 UTC with associated region of turbulence (PIREPS in circles, EDR in squares) from 16 – 22 UTC from FL 340 – 400.

In addition to values of turbulent kinetic energy from EDR reports, wind and temperature information is also transmitted through the AMDAR system.
Real-time verification of the altitude of NCT using EDR values and AMDAR temperature can be accomplished by co-locating the position of the aircraft with the IR imagery (Figures 28 and 29). This occurrence of moderate turbulence on the leading edge of an expanding anvil is similar to the results of Bedka (et al. 2008) where it was shown that a surge of northward expanding outflow, using IR imagery, was responsible for moderate to severe turbulence and a large disruption to air traffic. Information such as this can be extremely useful for operational aviation specialists who are looking for smooth altitudes “down-wind” of advancing thunderstorm complexes.

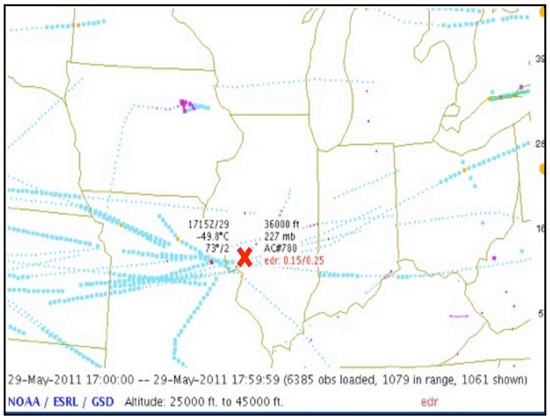

Figure 29. AMDAR report at FL 360 at 1715 UTC with temperature of -49.8 C. Several aircraft nearby reported moderate turbulence.

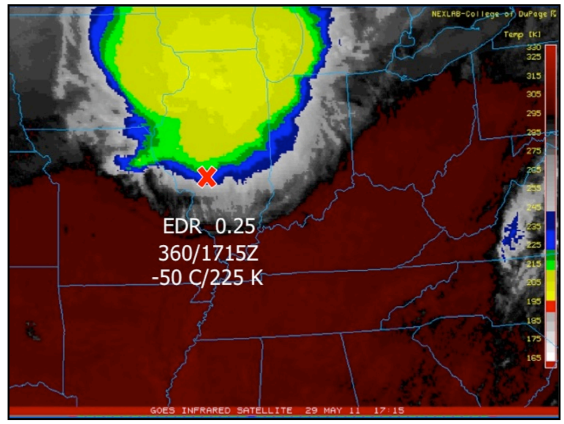

Figure 30. IR satellite imagery, 1715 UTC, with AMDAR data superposed over edge of cirrus outflow indicating temperature of 225K or -50 C.

Much of the focus on NCT research relating to MCSs is with the enhanced jetstream and the presence of transverse bands within the northern flank outflow. In the two cases from 23 May 2011 and 16 June 2011, the northern flank jetstream increased by over 50-60 kts in less than 6 hours. However in this case, although EDR values were associated with moderate turbulence, 0.15 to 0.35, AMDAR winds were less than 40 kts with little directional shear in the southern flank outflow area (Figures 31 and 32).

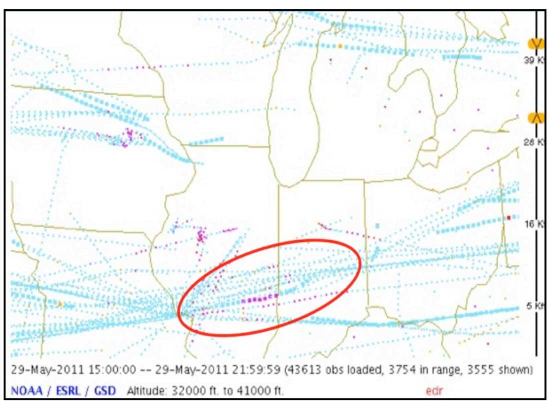

Figure 31. EDR reports from 0.15 to 0.35 from 15 – 22 UTC, FL 320 – 410. Oval represents region of moderate turbulence.

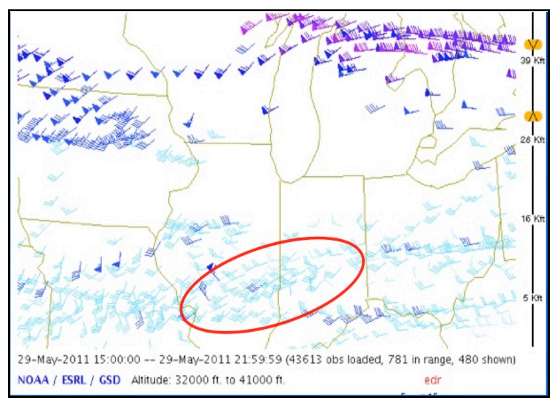

Figure 32. AMDAR wind reports from 15 – 22 UTC, FL 320 – 410. Oval represents region of moderate turbulence.

This poses some interesting questions as how widespread turbulence can be generated without any increase in vertical wind speed or directional shear remaining weak. The Ri calculates changes in potential temperature with height compared to the change in the horizontal wind with height. However, very little change in temperature or wind speed was observed using several aircraft AMDAR reports within the turbulent area compared to nearby 1200 UTC soundings and 500 hPa and 250 hPa analysis (Figures 33 & 34).

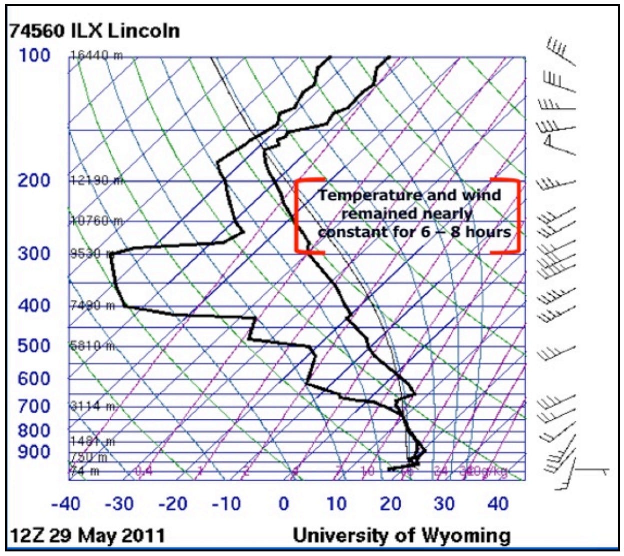

Figure 33. Lincoln, IL sounding, 1200 UTC, 29 May 2011. Comparison of AMDAR wind (Figure 32) and temperature data show very little change with sounding data.

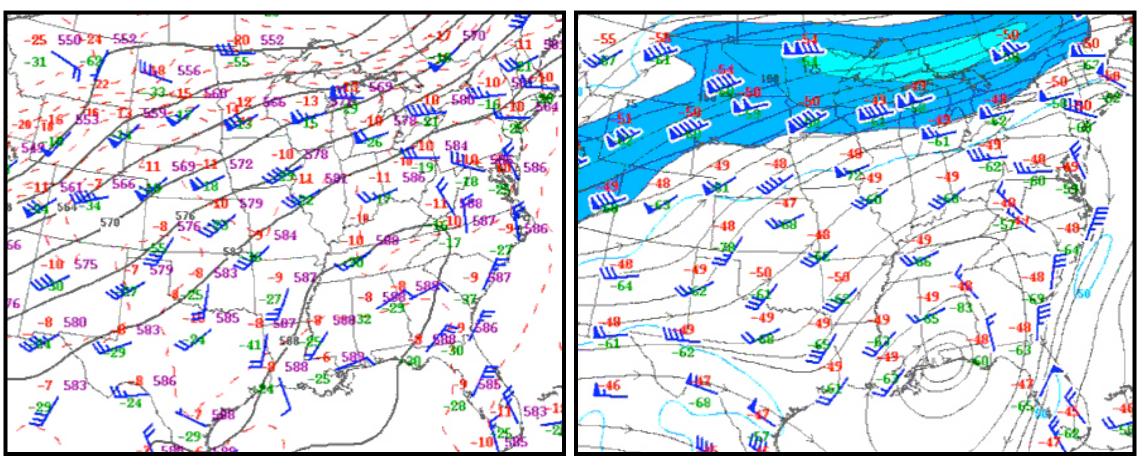

Figure 34. 500 hPa (FL180) and 250 hPa (FL 340) analysis for 1200 UTC, 29 May 2011. Weak southwest flow over IL and IN of 30 – 40 kts at 1200 UTC did not show any appreciable increases between 15 – 22 UTC in turbulent area in Figure 32.

So what was the reason for this turbulence? In the time series of IR imagery from 1745 – 2045 UTC, the southern flank of the expanding anvil appears to weaken as transverse bands begin to develop. At the same time, cloud-top IR window brightness temperatures begin to warm from 1945 – 2045 UTC. During this time, transverse bands begin to develop and extend southward. Between 1900 - 2000 UTC ten aircraft reported moderate turbulence within the proximity of the developing bands. Similar results were found by Lenz, (et al. 2009), where warming cloud top temperatures were coincident with the development of transverse bands on the southeast side of the anvil. The 29 May 2011 case can again be misleading to operational aviation specialists who might see the weakening of the MCS as a sign of decreasing possibility for NCT associated with the anvil. However, it is clear that the development of the transverse bands on the southern flank of the anvil is not related to the maturation of the MCS but rather the beginning of the dissipation stage.

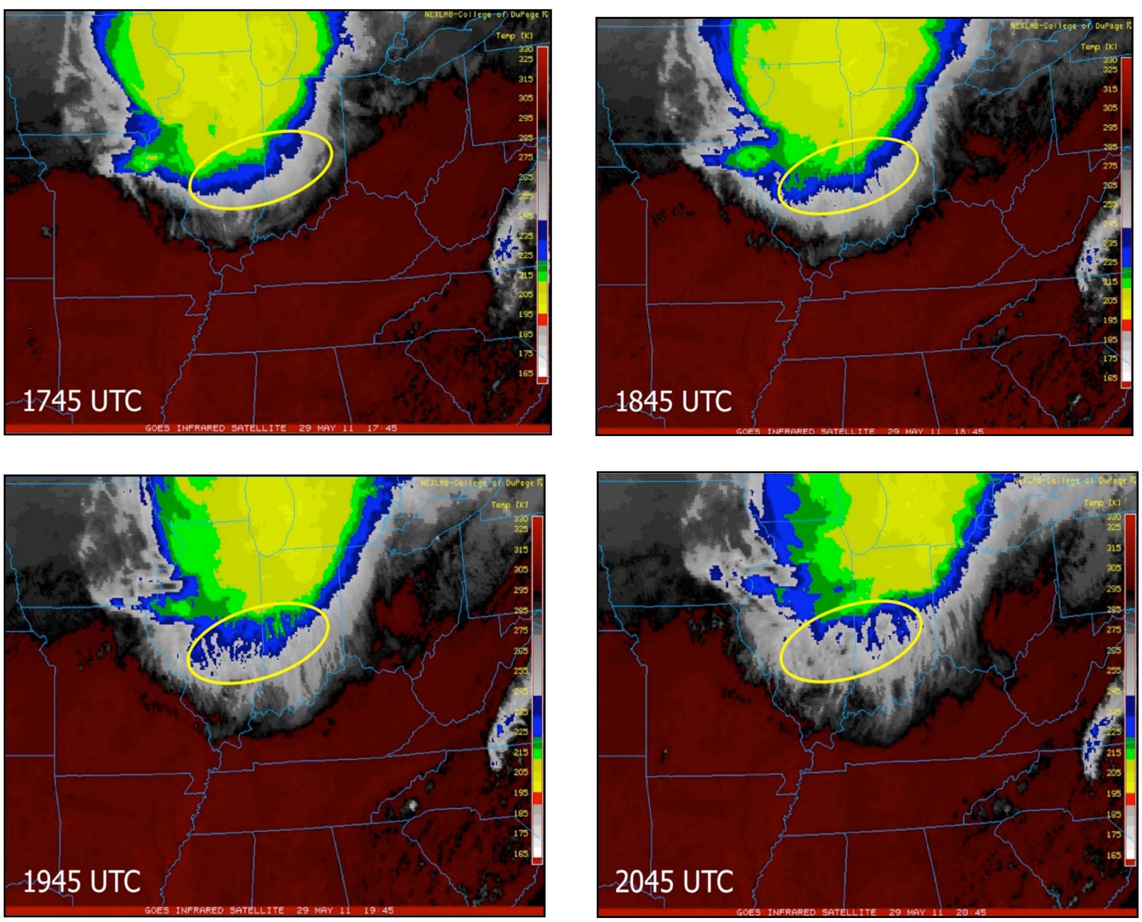

Figure 33. IR imagery, 1745 – 2045 UTC with area of moderate turbulence highlighted with oval.

E. Summary and Conclusions

It is well known that transverse bands, rapidly developing vertical convection, and rapidly expanding anvil clouds are responsible for CIT and NCT (Bedka et al.

2008). Through comparison of satellite imagery and time-matched (+ /- 15 min. of imagery) EDR turbulence observations, Lenz (et al. 2009) found that aircraft in 38 of 41 transverse band events reported light turbulence and moderate turbulence occurred in 18 of 41. As with this study and Lenz (et al. 2009), it is very difficult to objectively determine the vertical proximity of the aircraft relative to the bands without precise knowledge of the cloud height and band vertical thickness. However, it is possible using these three cases combining EDR, AMDAR wind data, identifying certain cloud signatures relating to a developing MCS and sub-synoptic pattern recognition, a developing turbulence event can be better identified.

Current FAA guidelines suggest aircraft avoid by at least 20 miles any thunderstorm identified as severe or giving an intense radar echo. Recent research, (Bedka et al. 2008, Lenz et al. 2009, Williams et al. 2008, Lane et al. 2012) and the results of this study have shown that turbulence primarily of convective origin, especially that associated with an MCS, can occur well outside of those regions defined by the FAA guidelines~~.~~ The guidelines do not reflect the current understanding of relevant NCT processes and should be updated (Lane et al. 2012).

This study examines a sub-synoptic scale environment capable of enhancing CIT associated with a MCS. Short-wave troughs more typical of the early convective season in the upper Midwest when adjacent to the northern outflow of an MCS have been shown to increase the areal coverage of turbulence beyond the cirrus outflow due to increased vertical and horizontal wind shears. The combination of pattern recognition and EDR data can prove useful to aviation forecasters in regional CWSUs that might be more affected by this sub-synoptic scale situation. In addition, real-time EDR and AMDAR wind data continues to demonstrate valuable potential nowcast capabilities by providing the aviation forecaster with the ability to verify cloud-top temperatures and wind fields associated with an expanding outflow anvil.

The demands of NextGen will continue to provide challenges for the aviation meteorological industry to become more effective in providing near real-time updates for potential NCT and CIT in the future. It is the hope of this study that these results will be useful to aviation forecasters at regional CWSUs when assessing the short-term dynamics of the atmosphere and possible re-routes of aircraft as well as forecasters at the AWC when assessing the synoptic scale environment and considering the spatial and temporal extent of turbulence forecast products.