SATELLITE SIGNATURES ASSOCIATED WITH SIGNIFICANT CONVECTIVELY-INDUCED TURBULENCE EVENTS

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Abstract

Convectively-induced turbulence (CIT) represents a significant hazard for the aviation industry. This project represents a collaborative effort between UW-CIMSS, NCAR, and UAH to enhance aviation safety by providing better diagnostics and forecasts of CIT using satellite and radar imagery. This paper will highlight signatures in satellite imagery frequently associated with moderate to severe turbulence observations. This analysis is done through comparison of GOES-12, MODIS, and AVHRR imagery with objective Eddy Dissipation Rate observations by commercial aircraft.

INTRODUCTION

Convectively-induced turbulence (CIT) represents a significant hazard for the aviation industry. For aviation interests between 1983-1997, all turbulence sources contributed to 664 accidents (609 fatal), in addition to 239 serious and 584 minor injuries, for an estimated annual societal cost of $134 million (Eichenbaum, 2000). Studies have shown turbulence in and around thunderstorms to be responsible for over 60% of turbulence-related aircraft accidents. (Cornman and Carmichael, 1993)

This project represents a collaborative effort between UW-CIMSS, NCAR, and UAH to enhance aviation safety by providing better diagnostics and forecasts of CIT using satellite and radar imagery. Unlike clear-air turbulence forecasts which can be developed to a large extent from NWP model output, CIT forecasts can benefit from the use of higher temporal and spatial resolution cloud observations provided by satellite and ground-based weather radar.

The goal of this effort is to develop satellite-derived interest fields using objective pattern recognition techniques that can be included for testing within the FAA-supported Next-Generation Graphical Turbulence Guidance (GTG-N) at NCAR. Improved GTG-N guidance will aid aviation meteorologists, dispatchers, and pilots in making strategic and tactical decisions for avoiding turbulent convection. This paper will highlight signatures in GOES-12, MODIS, and AVHRR imagery often found in association with moderate to severe turbulence.

DATA AND METHODOLOGY

A climatology has been developed using experimental Eddy Dissipation Rate (EDR) observations (Cornman et al. 1995) to identify highly turbulent convective events from January 2005 to June 2007. This EDR database, collected by United Airlines (UAL) Boeing 757 aircraft, represents an objective measure of the vertical accelerations induced by turbulent atmospheric phenomena. The objective nature and continuous reporting of turbulent and null EDR observations are essential to this effort, and provide a distinct advantage of the subjective and spatially disparate pilot reports (PIREPS) of turbulence. Peak EDR observations are normalized to values ranging from .05 to .95 (in .1 increments), with moderate turbulence (MOD) estimated from .25-.45 and severe (SVR) being ≥ .55.

EDR observations are plotted upon GOES, MODIS, and AVHRR VIS, IR window, and WV imagery to identify thunderstorm signatures frequently associated with MOD to SVR turbulence. Some examples shown in this paper highlight events with MOD to SVR EDR turbulence observations exceeding 2 SD from the seasonal mean. EDR observations in the climatology below are compiled from 1200 UTC on the day listed to 1159 UTC the following day. This is done to capture the full evolution of a convective event over the U.S., as daytime storms often evolve into turbulent Mesoscale Convective Systems (MCS) during the nighttime hours.

SIGNIFICANT TURBULENCE EVENTS

Turbulence Climatology:

Figure 1 shows the flight routes of EDR-equipped United Airlines Boeing 757 aircraft. The vast majority of the EDR observations occur in the region of most frequent convective activity over the U.S., between 70 and 110 W longitude. For this climatology, the domain is split up into 4 subregions, each spanning 10 degrees of longitude. Figure 2 shows a graphical representation of the turbulence climatology over the Rocky Mountain region, extending from 100-110 W. The number of MOD to SVR reports are expressed as a percentage relative to the total number of null + turbulent EDR observations. Table 1 provides a detailed summary of turbulence activity for each of the 4 regions. For the Rocky Mountain region, an average of 8162 null + turbulent EDR observations are collected per day. MOD to SVR turbulence occurs on average .35 % of the time, representing an average of 29 turbulent observations per day. The event with the highest number of turbulent observations occurred on May 3, 2007 with 286 MOD to SVR incidents (3.5% of 8162 total). The relative frequency of turbulence is significantly higher in the Rocky Mountain region than the other 3 regions.

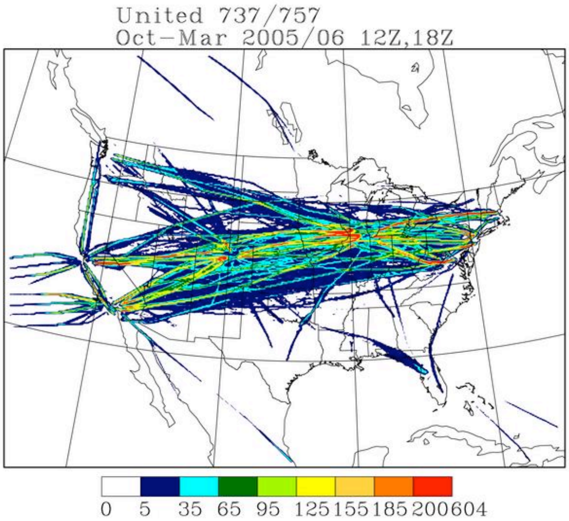

Figure 1: **Flight routes of EDR-equipped United Airlines aircraft from October 2005 to March 2006. Warm colors represent regions with higher flight density.**

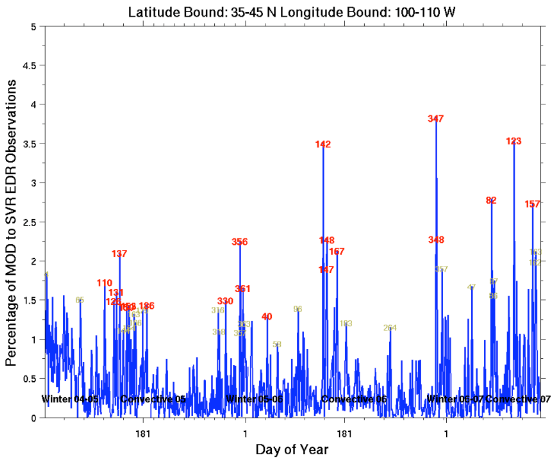

Figure 2: **A climatology of MOD to SVR EDR turbulence observations between January 2005 to June 2007 over the .S. Rocky Mountain region (100-110 West Longitude). Red (Green) numbers represent the Julian day of an event with the number of MOD to SVR observations exceeding three (two) standard deviations from the seasonal mean.**

Statistics Computed Per Day During Convective Seasons	***Mean # of Null + Turbulent EDR Observations Per Day***	***Mean % (Number/Day) of Moderate or Greater Turbulence***	***Max % of Moderate or Greater Turbulence, 2.5 Convective Seasons***	***Max % of Moderate or Greater Turbulence, Entire Database***
100-110 West Longitude	8162	0.35% (29 per day)	3.5% (JD 2007123: May 3)	3.8% (JD 2006347: Dec 13)
90-100 West Longitude	8110	0.19% (15 per day)	1.8% (JD 2007125: May 5)	2.7% (JD 2006096: April 6)
80-90 West Longitude	6745	0.20% (14 per day)	2.0% (JD 2006200: July 19)	3.0% (JD 2005005: Jan. 5)
70-80 West Longitude	3433	0.22% (8 per day)	2.6% (JD 2007105: April 15)	6.1% (JD 2005087: Mar 28)

Table 1: **A summary of statistics from the EDR turbulence climatology over 4 U.S. geographic regions, including the mean number of MOD to SVR observations per day and events with the highest relative percentage of MOD to SVR observations.**

Turbulence Events:

Figure 3 highlights light (LGT) to MOD intensity turbulence observed in association with convective gravity waves. Strong vertical motions are likely encountered as the aircraft fly through these wave features. Examination of the visible MODIS imagery reveals that the gravity waves induce a physical deformation of the cloud top. A infrared (IR) window brightness temperature (BT) transect along the dashed line (middle panel) is shown in Figure 4. The transect indicates a wavelength of ~5 km with a BT oscillation of ~.5-1 K. The maximum oscillation of ~4 K, found very near to the coldest cloud region, corresponds to a wave amplitude of 500 m when referenced to a nearby rawinsonde temperature profile. The waves are not resolved within GOES IR imagery, as this instrument does not have the necessary resolution to capture features with a 5 km wavelength.

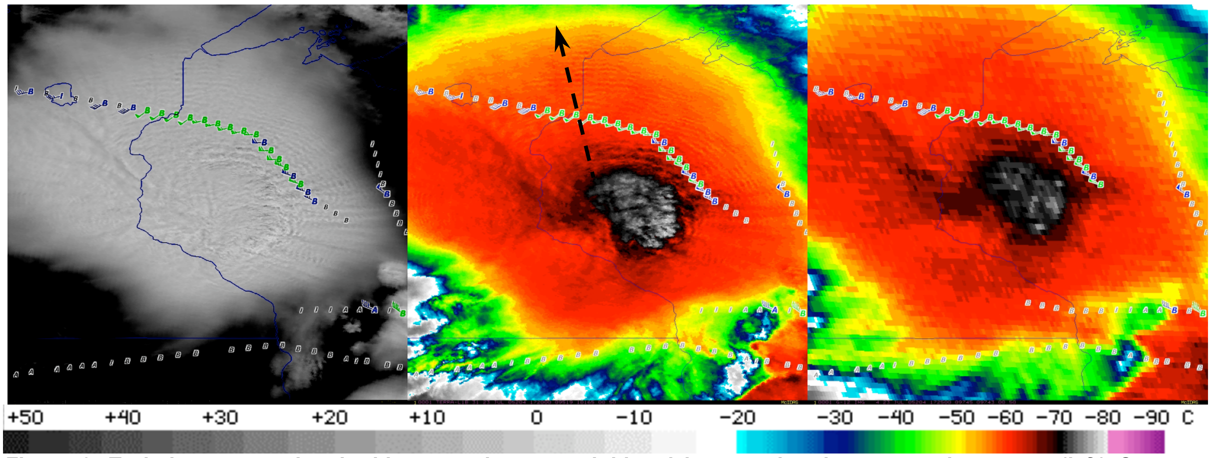

Figure 3: **Turbulence associated with wave signatures initiated by overshooting convective tops. (left) Contrast-enhanced Terra MODIS 1 km visible channel imagery (middle) Terra MODIS 1 km 10.7 micron infrared window imagery (right) GOES-12 4 km 10.7 micron infrared window imagery at 1725 UTC on 23 July 2005. The letters plotted upon the imagery represent the relationship between the aircraft-observed and IR window brightness temperatures. "A" indicates aircraft temperature colder than satellite, suggesting flight above cloud top. "I" indicates aircraft temperature within 2 K of satellite, suggesting flight within cloud top. "B" indicates aircraft temperature warmer than satellite, suggesting flight below cloud top. "C" indicates aircraft temperature significantly colder than satellite, suggesting flight in clear sky. The color of symbols indicates severity of turbulence as estimated by EDR with blue being light, green being moderate, and red being severe. Grey indicates no turbulence. EDR observations within +/- 30 mins from the image timestamp are shown.**

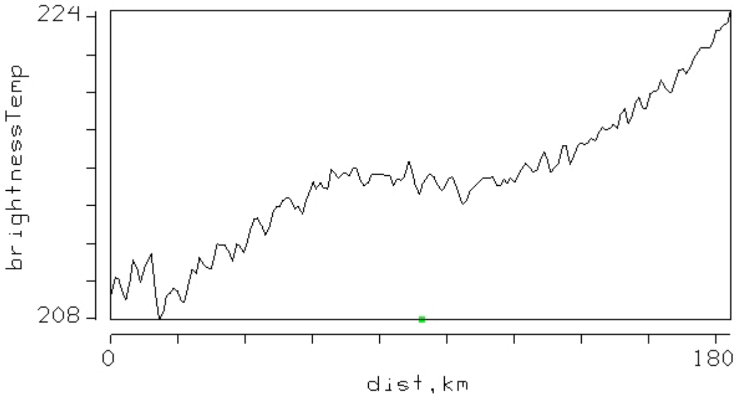

Figure 4: **An IR window BT transect for the dashed line upon the MODIS imagery in the middle panel of Figure 3.**

Banded convectively-induced outflow, often called "transverse bands", has been well recognized by aviation weather forecasters as a signature of turbulence in satellite imagery. This signature can be observed in both 1-4 km GOES and higher resolution polar-orbiting satellite imagery, as the spacing between bands is often 10 km or greater. Two examples of this turbulence signature are shown in Figure 4. For both examples, aircraft had not observed turbulence until they encountered the banded cirrus structures and subsequently experienced LGT to MOD turbulence while progressing through the bands. Transverse bands are found in association with a variety of atmospheric phenomena such as thunderstorms, tropical cyclones, and strong upper level streaks. Little documentation is available describing the physical mechanism for this banding. Cases studied by the authors noted that banding was often associated with rapid lateral anvil expansion from long lived mesoscale convective systems.

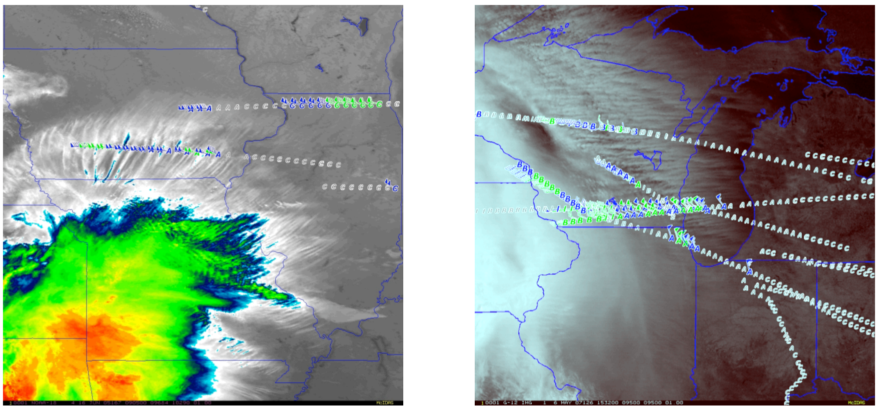

Figure 5: **Turbulence associated with banded convectively-induced outflow (i.e. "transverse bands"). (left) NOAA-18 1 km infrared window channel imagery at 0905 UTC on 16 June 2005 (right) Contrast-enhanced GOES-12 1 km visible imagery at 1532 UTC on 6 May 2007. Symbol descriptions are the same as those described for Figure 3.**

Rapid lateral expansion of a cold convective anvil cloud has also been recognized as a signature associated with turbulence. A sequence of lower resolution geostationary IR window imagery is sufficient to observe this signature as we are simply looking at expansion rates of the anvil cloud pattern. Figure 6 shows an example of such a signature, where a surge of outflow to the north and northwest of the primary convective activity impacted air traffic and induced MOD to SVR turbulence. Rapid anvil expansion indicates strong upper-tropospheric divergence associated with developing convection. Strong vertical wind shear between the outflow layer and the atmosphere above/below would induce turbulent mixing which could be responsible for the turbulence observed in this case.

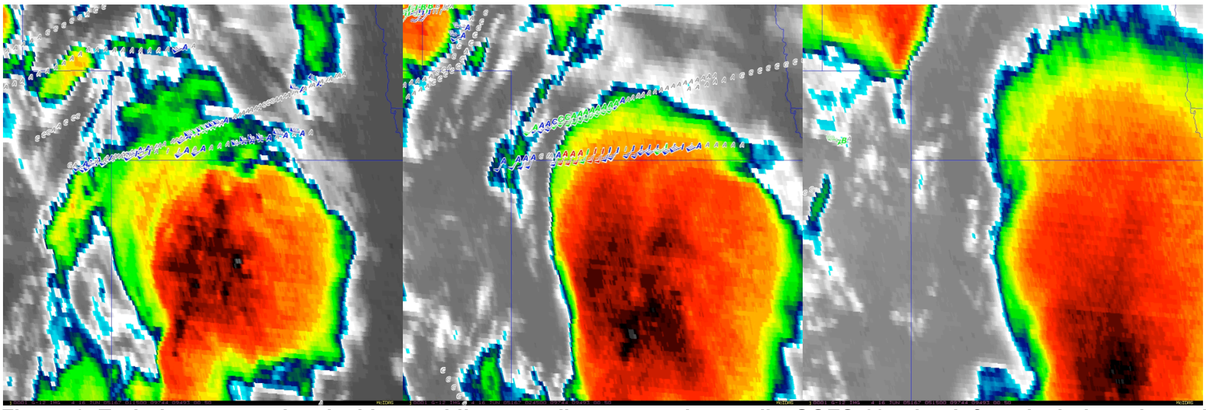

Figure 6: **Turbulence associated with a rapidly expanding convective anvil. GOES-12 4 km infrared window channel imagery at (left) 0115 UTC, (middle) 0245 UTC, (right) 0515 UTC on 16 June 2005. Symbol descriptions are the same as those described for Figure 3.**

Rapidly developing convection (i.e. convective initiation) is another signature often associated with turbulence. Figure 7 shows two examples where SVR turbulence was observed when aircraft passed through developing convection. For the example in the left panel, the satellite IR window BT at the location of the SVR turbulence was 235 K and the aircraft observed temperature was 205 K, indicating that the aircraft flew far above the convective cloud tops. Vertically propagating gravity waves are generated by developing convection and could be responsible for producing turbulence for aircraft. The example on the right depicts a two separate SVR turbulence encounters; one where an aircraft flew below cloud top and may have interacted with the updraft region of newly mature convection, and a second to the south flew above cloud top, similar to the example shown in the left panel.

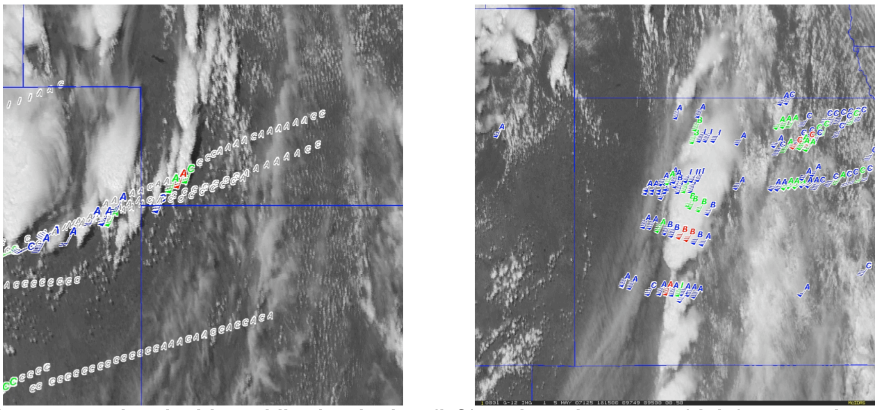

Figure 7: **Turbulence associated with rapidly developing (left) and newly mature (right) convection. GOES-12 1 km visible channel imagery at (left) 1945 UTC on 7 May 2005 and (right) 1815 UTC on 5 May 2007. Symbol descriptions are the same as those described for Figure 3.**

CONCLUSIONS

Results of the climatological analysis show that the Rocky Mountain region (100-110° W) exhibited a significantly higher frequency of MOD to SVR turbulence incidents than any of the other three regions. 99.65% of all EDR observations were either LGT or null in the Rocky Mountain region. The regions from 70-100° W exhibit near equal relative percentages of MOD to SVR observations.

Analysis of satellite imagery reveals that the following phenomena are often found in association with highly turbulent convective events:

1) Rapidly vertical convective development
2) Rapidly expanding anvil clouds indicative of strong outflow/divergence
3) Banded cirrus outflow structures (i.e. transverse bands)

4) Convective gravity waves

Future work involves the development of objective satellite-derived to identify rapidly expanding cirrus anvils, convective cloud top growth, and overshooting tops in support of current and future generation aviation turbulence nowcasting.

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