

USE OF AIRCRAFT-BASED DATA TO EVALUATE FACTORS IN PILOT DECISION MAKING IN ENROUTE AIRSPACE

Bradley Crowe[†]

Rich DeLaura

Michael Matthews

*Massachusetts Institute of Technology, Lincoln Laboratory
Lexington, MA 02420*

1. INTRODUCTION

The Convective Weather Avoidance Model (CWAM), developed in collaboration with NASA, translates convective weather information into a Weather Avoidance Field (WAF), to determine if pilots will route around convective regions. The WAF provides an estimate of the probability of pilot deviation around convective weather in en route airspace as a function of time, horizontal location, and flight altitude [1][2]. The results of the WAF can be used to create reroutes around regions of convective weather where pilots are more likely to deviate. If reliable WAF information is provided to the cockpit and ground, pilot decisions may become more predictable, simplifying the task of air traffic control in convective weather.

The improvement and validation of CWAM requires inference of pilot intent from flight trajectory data, which is challenging. In the summer of 2008, a series of four research flights (three on 17 July and one on 14 August) were flown in and around convective activity in the upper Midwestern United States to gather aircraft data that could be correlated to validate WAF and provide further insights into the set of factors that affect pilot decision making in convective weather. The aircraft, a Rockwell Sabreliner Model 50 research aircraft (similar to the Sabreliner Model 40 production model) owned by Rockwell-Collins, flew through and around convective activity while recording on-board accelerations for comparison to the WAF deviation probabilities encountered along the flight trajectory. Aircraft state data, on-board weather radar images, video, photographs and pilot narrative from the cockpit were collected. A previous study [3] presented a statistical

comparison between the observed turbulence and WAF deviation probabilities from all four flights. The study also included a qualitative description of the factors observed from that flight deck during the flights on July 17.

This study presents a description of the factors observed from the cockpit during the flight on August 14, 2008. Data from this flight are significant, since the weather regime – scattered, moderately vigorous thunderstorms embedded in a larger stratiform shield – poses difficult challenges in the prediction of pilot weather avoidance behavior. The research aircraft flew several passes through and around the same complex of thunderstorms, gathering data from several different altitudes. In this analysis, radar data from the flight deck are compared ground-based weather radar and the WAF, a description of visual observations and pilot narrative from the flight deck is presented, and qualitative observations are compared with normal accelerations measured by the aircraft INS. Finally, conclusions and suggestions for further study are presented.

2. BACKGROUND

The Convective Weather Avoidance Model (CWAM) translates forecasts of convective weather information (VIL and echo top) into predictions of impact on aircraft by determining which convective regions pilots will choose to avoid. CWAM creates a Weather Avoidance Field (WAF), which estimates the probability between 0 – 1.0 (0 to 100%) of pilot deviation around convective weather in en route airspace as a function of time, location and flight altitude. High WAF probabilities indicate areas where pilots are more likely to deviate.

A previous study of data gathered from the 2008 flight missions found that there was a clear statistical relationship between convectively-induced turbulence and WAF deviation probabilities [3]. Light and moderate levels of turbulence were more likely to be associated with regions of high deviation probabilities, while negligible turbulence was more likely to be

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[†]Corresponding author address: Brad Crowe, MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420-9185; e-mail: bradc@ll.mit.edu

associated with regions of low deviation probability. A more recent, comprehensive evaluation of CWAM performance found that errors in the prediction of weather-avoiding deviations occurred most often where flight altitudes were near echo top heights, and in regions where convection was weak [4]. The factors that affect pilot decision making in these circumstances are not well-understood, and may not be easily incorporated into a pilot model. The view out the window and on-board weather radar displays that are the primary source of weather information for the pilot are not available for use by air traffic control and ground-based CWAM. Furthermore, some deviation decisions may be heavily influenced by opportunity. A pilot may be willing in one circumstance to take a small deviation to avoid moderate convection to ensure a smooth ride. In another circumstance, where finding clear air may require a deviation of one or two hundred miles, that same pilot may elect to fly through a 'best option' region of fairly vigorous convection. In order to create decision support systems that provide robust weather-avoiding reroutes and reduce the complexity of managing air traffic through regions of convection, it is important to identify the cockpit information that affects pilot decisions, and understand how best to integrate that information with ground-based CWAM to provide accurate common situational awareness between ground and cockpit.

3.1 Weather and air traffic overview

In contrast to the thunderstorm events of July 17th 2009 [3], the atmospheric dynamics for thunderstorm development in Iowa and Minneapolis were relatively weak during the

August 14th flight. The main synoptic feature during this event was a deep cutoff low pressure center located in northwestern North Dakota with the axis of the trough extending into southern Minnesota. This feature provided limited instability from the surface to mid levels. CAPE values recorded from Davenport, IA and Minneapolis, MN at 12Z were in the 300 range indicating a fairly stable environment. Additionally, there was little shear aloft which worked to insure that any storm development would be limited in altitude. However, afternoon heating produced enough instability for thunderstorm development along the border of Iowa and Minnesota. The storms developed rapidly after 1800Z south of the Minneapolis TRACON and tracked south. The weak atmospheric environment provided for lower echo tops (between 35 and 44 kft.), a visual flight environment, and mid-range WAFs, where CWAM may not accurately predict how a pilot will react to the weather that they see out the cockpit window.

The flight experiment was flown in the region roughly bounded by jet routes J25 on the west, J34 on the north, J16 on the south, and J30 on the east, just south of the Minneapolis TRACON boundary. Air traffic flows that ordinarily fly through the experimental region into and out of the Minneapolis / St. Paul airport (MSP) generally deviated to avoid the weather. Thunderstorms also impacted higher altitude en route traffic on jet routes J34 and J25 during the experimental flights and there were a number of deviations observed in post analysis. Figure 1 shows a comparison of traffic in the area of the experimental flights on the day of the experiment and a fair weather day (July 15th 2008). A few aircraft were observed to fly over the experimental region at flight altitudes of 39 kft. or above.

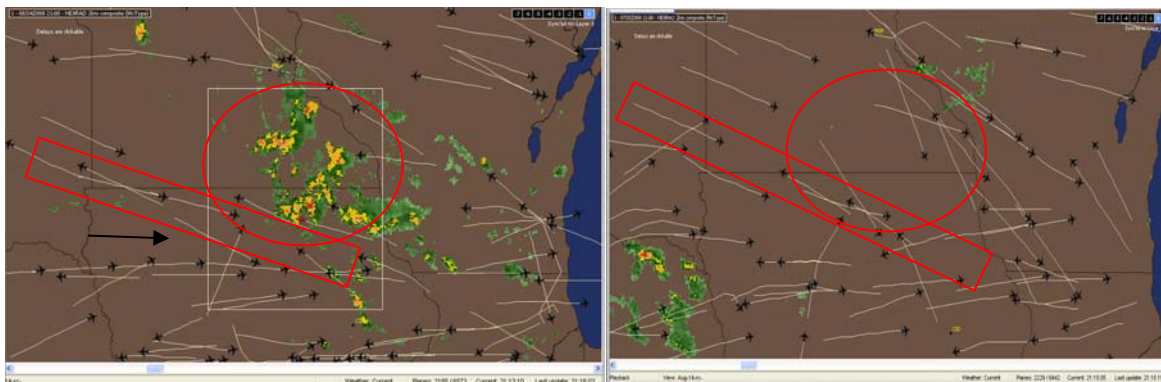


Figure 1. Illustration of the disruption to the nominal air traffic due to the thunderstorms on August 14th. The image on the left show storms on August 14th at 2116Z and the image on the right is of July 15th at 2116Z. The red elongated boxes highlight traffic on J16 and the red circle is the area the flight examined.

3.2 Flight observations

The flight departed Cedar Rapids, IA at 2000Z to collect data from a multi-cellular storm developing in southern MN (figure 2). The flight climbed to 39 Kft and turned eastbound to complete two passes along the leading edge of the storm complex, descending to 35 kft for the second pass. The flight then turned northward to fly along the upwind side of the storms complex. The flight circumnavigated the cells finally making three passes through the storms at three altitudes, 35 kft, 38 kft and 41 kft. During the flight there was little or no turbulence outside of the turbulence encountered near storm cells and the flight was mostly conducted in Visual Flight Rules (VFR). In the next two sections, the flight environment in each of these storm regions (leading edge and within the storm complex) is discussed, with a particular focus on the comparison of visual, on-board radar, and ground-based radar and WAF measurements. The on-board radar, a Rockwell Collins 2100 model that is widely used in commercial aviation, we set in an automatic mode that maintained a 2.25 degree downward tilt.



Figure 2. Developing storm complex in southern MN and northern IA investigated during the flight mission.

3.2.1 Case 1, leading edge of thunderstorm complex

Two passes were made along the leading edge of the storm complex (area A in figure 3) between 2048Z and 2112Z. The first pass was made from west to east at an altitude of 39 kft, positioning the aircraft above the cirrus blow off from the storms. The aircraft flew within 3 nmi. south of two storm cells, the tops of which were protruding through the cirrus shield. Figure 4

shows a comparison of the out-the-window view, an image of the Vertically Integrated Liquid (VIL) field from the Corridor Integrated Weather System (CIWS) [5], and the on-board Rockwell Collins 2100 weather radar. The first cell was encountered at 2050Z, and had a core represented as level 5 on the CIWS VIL and a strong (red) thunderstorm on the airborne radar. The echo tops reported by CIWS were 41 kft.

The second cell was the stronger of the two storms that we examined on the first pass and was growing as we passed it. The ground observer noted a 2kft change in echo tops height to between 41kft 2051Z and 2052Z, and the flight observers noted that the tops were rising above the flights attitude during this time. Figure 5 shows the second cell as the flight was nearing the cell. The ground based radar shows a solid level 6 cell and the special extent of the storm and amount of heavy (red) precipitation in the airborne radar was much greater from the second cell. The normal acceleration recorded from the on-board INS showed very little turbulence (figure 6) as the aircraft passed by the cells, with G-forces of only +0.2 and -0.1 (light turbulence) between 2048 and 2051Z.

The flight turned back to the east at 2102Z to get a second look at the leading edge of the storm complex at a lower altitude (figures 7-9). The pilots lined up the aircraft for the leading edge of the storms and then stated, "When we get down there we may have to avoid that finger that is sticking out" (figure 7). As the aircraft approached these cells, the flight descended to 34 kft. and the winds increased before crossing in front of the leading edge of the storm complex (figure 8). As the flight flew over the cells at 2110Z (figure 9) the pilot stated that he would not normally fly this close to a storm like this at this altitude unless there was a significant advantage (e.g. avoiding a much longer deviation). The maximum difference in normal acceleration (+.16 to -0.33 G, light to moderate turbulence) encountered by the flights along the leading edge occurred at 2114Z (figure 6) as the flight passed in front of the cell, from IFR to VFR conditions. The WAF deviation probability (0.7) at this point was also the maximum encountered. In this instance, the visual cues out the cockpit window, airborne weather radar image, and WAF deviation probability showed a consistent picture of a region that a pilot would choose to avoid, but could penetrate if the cost of avoidance was deemed to be excessive.

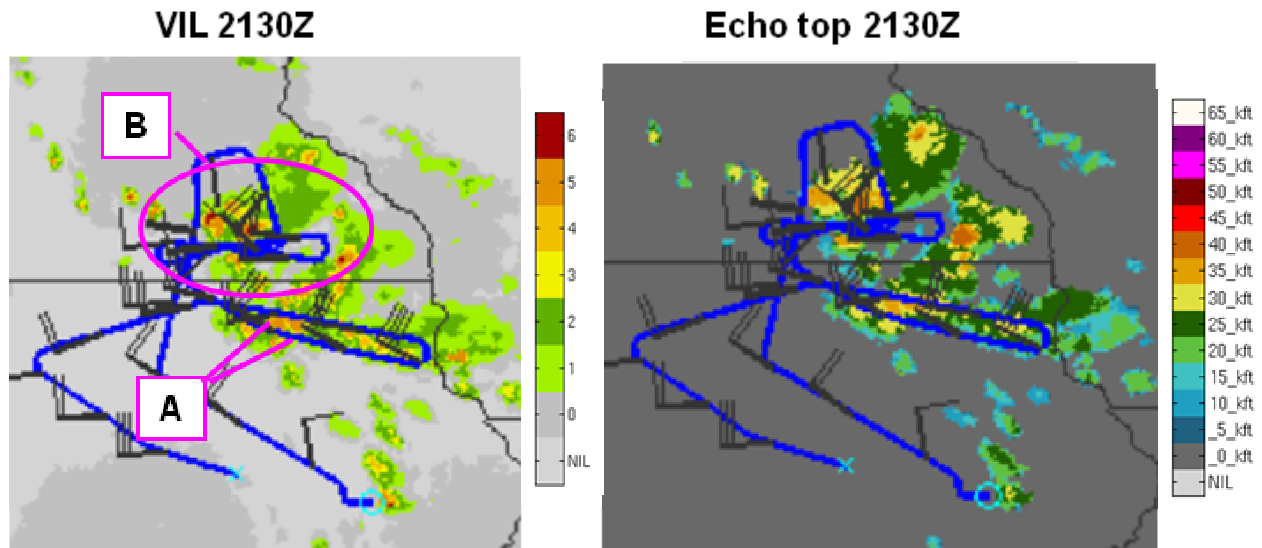


Figure 3. Flight path (blue line) overlaid on CIWS VIL on the left and Echo Tops on the right with associated wind barbs as from the aircraft sensors.

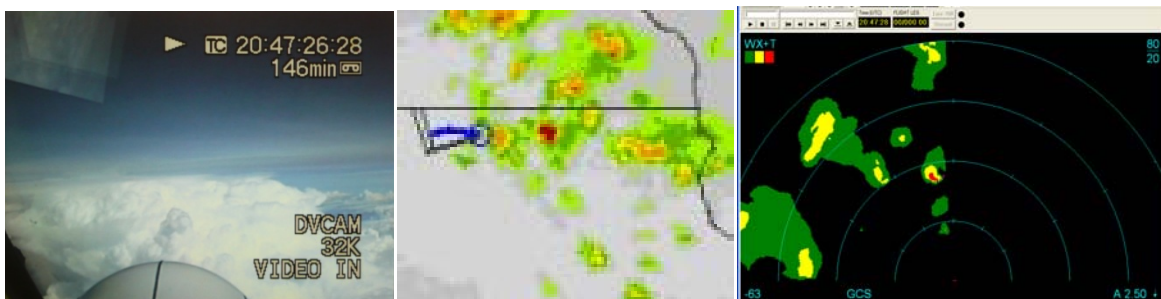


Figure 4. Storm environment and winds at 2047Z. The image on the right comes from the forward-looking, center cockpit camera. The image in the center is CIWS VIL data with the flight location (blue circle), 3 minute history of track, and wind data measured from the aircraft. The image on the right is the airborne radar image.

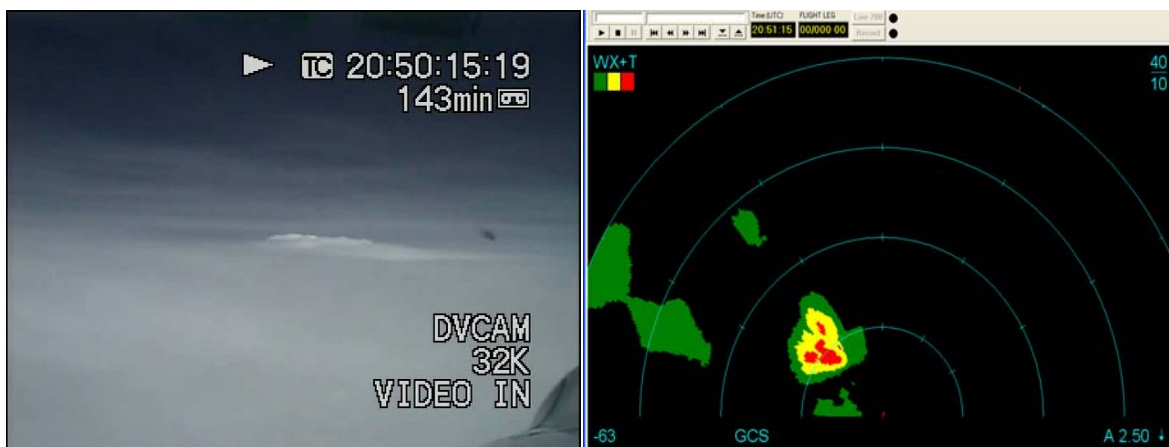


Figure 5. View from the left side cockpit camera left and the onboard radar picture right at 205115Z as the flight passed within 5 Nmi of the second cell on the first pass of the leading edge.

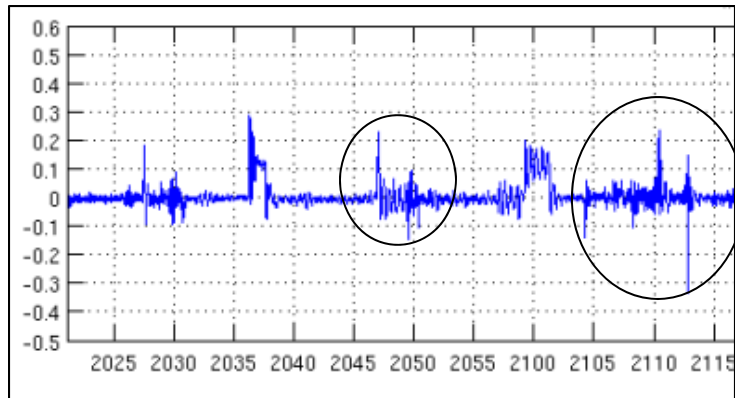


Figure 6. INS data showing turbulence during the passes the area 1 shows the associated motions on the first pass while area 2 shows the associated motions on the second pass.

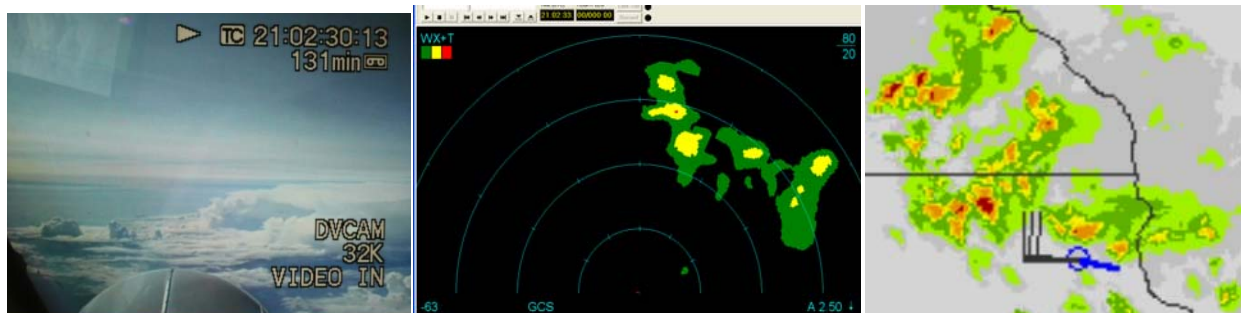


Figure 7. Three panel view of leading edge of storms after turn back to the west for the second pass.

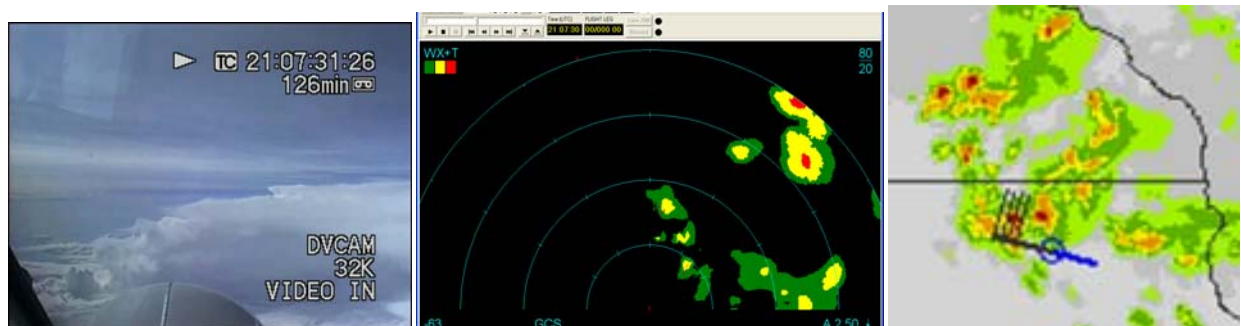


Figure 8. Three panel view at 2107Z. Note the increase in wind speeds near the cells.

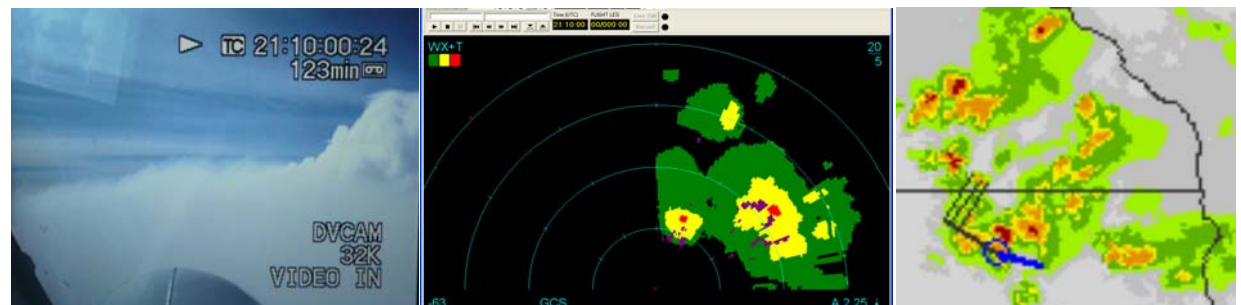


Figure 9. Three panel view at 2110Z.

3.3.2 Case 2, multiple passes on cells at the three different altitudes.

Following the second pass on the southern most leading edge of the storms, the decisions was made to circumnavigate the storm complex to examine the upwind and crosswind storm structures within the complex. First the flight crossed the upwind side of the storm complex at 2120Z (Figure 10) at an altitude of 34 kft. At this time the pilot commented that he would not fly as close to this cell and that he would give it at least 5 miles more distance between the storms and the clouds at this level. Then he went on to state that he believed that we would get into the "blow off from these cells". Figure 10 shows the winds at the flight level to be 5 kts or less from a westerly direction so the cirrus that the pilot was observing was most likely a spreading out along the tropopause, and not a turbulent downwind anvil. The flight continued through the cirrus, with negligible turbulence; in this instance, a pilot inference based primarily on the view out the window was incorrect.

The flight continued northward around the storm complex's north end (area B on figure 2) before making a turn to the east and finally to the south and entering Instrument Meteorological Conditions (IMC) by 2127Z. As the flight entered the cirrus blowoff of these storms it encountered mixed precipitation. While in the IMC conditions the pilots informed the observers that they didn't want to get "too close to the strong storm" core (figure 11). As the flight continued south the pilots initially reported that the turbulence was only light chop but then at 2131Z, as the aircraft flew through the downwind of a strong cell, the pilot stated that they were getting altitude deviations. As the flight exited the cirrus shield at 2133Z the pilot stated "There goes the auto pilot - that was moderate bump".

Figure 12 illustrates flight through a gap between two thunderstorm cells that was difficult to identify from either the on-board or ground-based weather radars, but was readily identified by the pilots based on the view out the cockpit window. The pilots immediately pointed out how fast the growing cell to the south of the aircrafts track was building:

Pilot: "That one I would avoid".

Copilot: "Yea that is really building fast."

However, the pilot indicated before flying through the gap that "I would be confident in doing this with passengers on board", and didn't believe there would be any turbulence. In fact, the flight was smooth. As the flight passed through the gap, echo tops on the neighboring cells were nearing the flight altitude of 34 kft. The WAF deviation probability was 0.8; the WAF did not have sufficient resolution to identify the gap.

A second pass was made of the same thunderstorms approximately 10 minutes later, at a flight altitude of 38 kft. As the flight approached the storm complex, the gap could still be identified visually (at 2144Z), and was now apparent on the on-board radar as well (figure 13). The echo tops associated with the cell were now well above the flight altitude and as the flight approached the storm at 2146Z, the pilot made a sharp right turn to stay VMC and fly through the gap once again. By this time, however, there was no visual gap at our flight altitude. The over-shooting tops could be identified on the on-board radar, and the pilot was able to clear the cells quickly. A brief period of moderate turbulence (+0.4 to -0.2 G) was experienced during the pass through the closing gap.

The flight made one final pass near the echo tops of the same cells at a flight altitude of 41 kft. By this time, the two separate storm cells had grown together in to a single storm. Figures 14-16 show a sequence of cockpit views and on-board radar images as the flight approached the overshooting top of a growing cell. In figure 14 (approximately 2156Z), two thunderstorm cells are apparent on the on-board radar image: one at a range of 15 nmi, and a second at a range of 30 nmi. The pilot and crew expected that the first cell would pose no problems in over flight, but were concerned that they would need to avoid the second cell. Approximately one minute later, the overshooting tops of the first thunderstorm appear (figure 15), and in the next minute (figure 16), it becomes apparent that the first cell was growing very rapidly, and the pilot made a sharp right turn to avoid it. The INS normal acceleration recorded on this encounter was the highest of the flight, ranging from +0.6 to -0.4 G (moderate to heavy turbulence). Figure 17 shows the INS normal acceleration recorded from all three encounters of the storm.

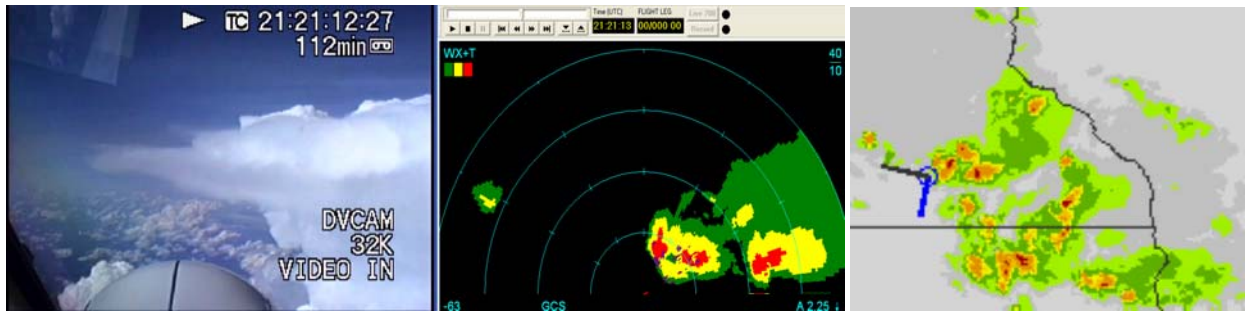


Figure 10. Cockpit view and VIL on the upwind edge of the storm at 2120Z. The pilot mistook the spreading cirrus straight ahead for a turbulent downwind anvil.

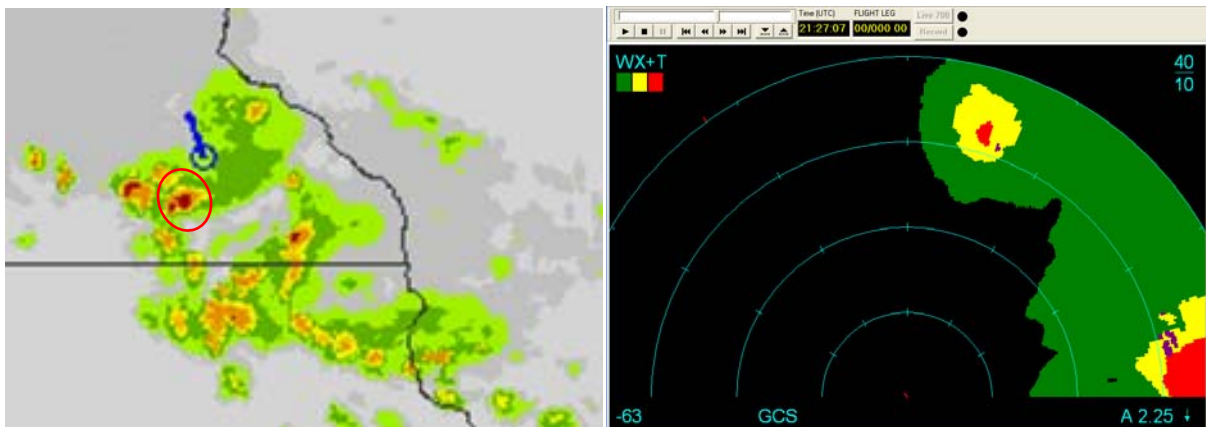


Figure 11. Entering downwind region of a thunderstorm at 2127Z.

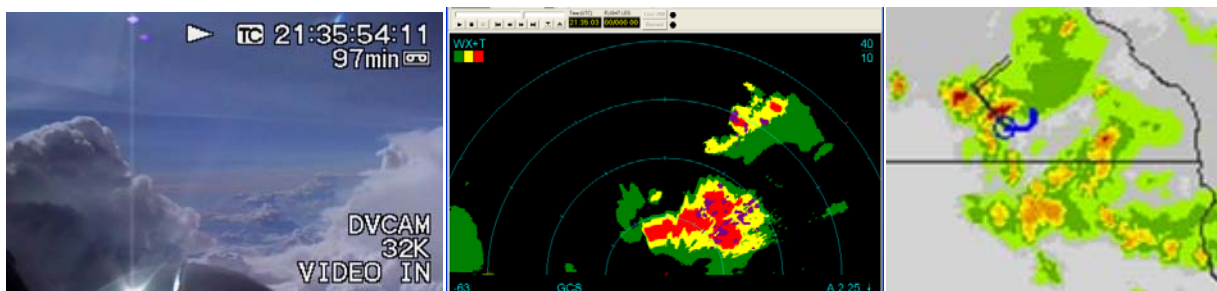


Figure 12. Flying through a gap.

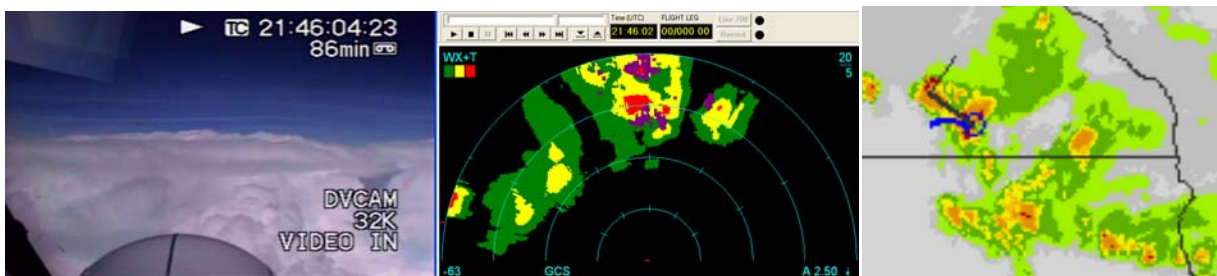


Figure 13. Three image view storms during second pass, approaching two rapidly growing cells and a closing gap between them.



Figure 14. Approaching a growing cell.



Figure 15. First appearance of overshooting tops.

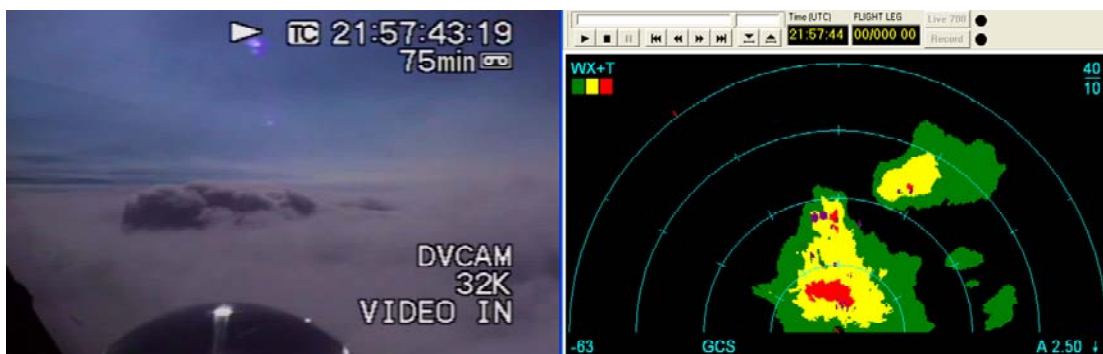


Figure 16. Overshooting tops of a rapidly growing thunderstorm cell, resulting in the decision to turn right and avoid.

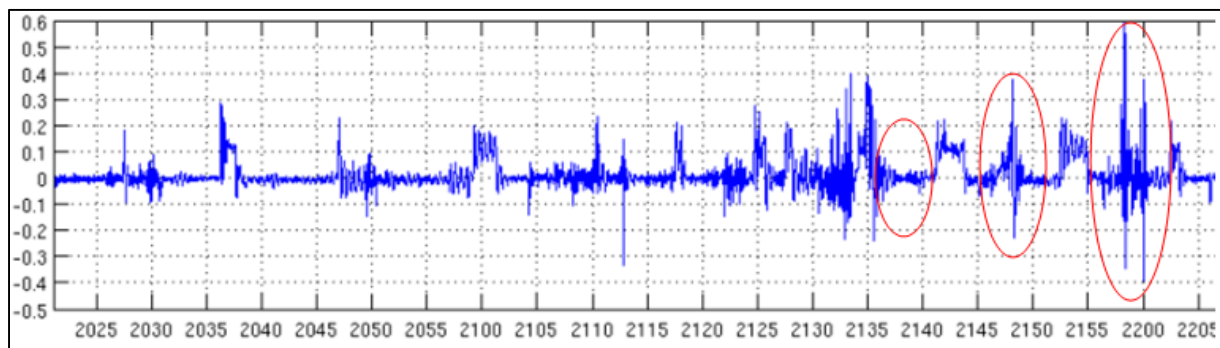


Figure 17. INS normal acceleration data. The three circles indicate the three passes that were made on the storm area B: flying the gap at 2135Z to 2140Z, the second pass on the gap (+.4 to -.2 G) between 2147Z to 2152Z and the storm over flight between (+.6 to -.4 G) 2155Z and 2200Z.

4. CONCLUSIONS AND FUTURE WORK

The Convective Weather Avoidance Model (CWAM) provides a means of partitioning airspace into regions that pilot are willing to penetrate and regions that they will choose to avoid due to convective weather. Current CWAM often have difficulty predicting pilot behavior when flight altitudes are near the height of thunderstorms (as determined by the echo top height), when pilots are presumed to be operating according to Visual flight Rules (VFR) and basing their decisions on information seen out the cockpit window that ground-based systems cannot readily discern. A flight mission was flown on August 14, 2008, through a region of moderate convection and mostly VFR conditions in southern MN and northern IA, to gather data that might provide insights into pilot decision making in such an environment. Synchronized cockpit video, pilot narrative, on-board weather radar images, INS acceleration data, and weather information from ground-based systems (CIWS VIL, echo tops, and weather avoidance fields) were analyzed.

The study revealed that the cockpit is a very fluid decision making environment in and around convective weather. The rapid, unanticipated development of thunderstorms can result in a pilot decision to avoid a storm that (s)he had decided to penetrate only minutes ago. In some circumstances, storm growth below the cloud deck may be obscured from the pilot (and on-board radar) view. Pilots may also misjudge what they see out the window; in one instance during the flight, the relatively benign spreading of a cloud at the tropopause was mistaken for a turbulent downwind anvil. In such instances, supplemental information from ground-based systems may provide critical information that alerts a pilot that all is not what it seems to be in the cockpit.

On the other hand, visual cues enable pilots to identify and take advantage of small gaps through thunderstorms that are nearly impossible to identify using ground-based systems. Furthermore, the pilot's decision to fly through a gap (instead of avoiding the weather altogether) will depend not just on the weather itself, but on the pilot's judgment about the cost of deviation versus the risk of penetrating the gap. Determining the pilot 'cost function' in these circumstances is a challenge, to say the least.

Improving the predictability of pilot decisions in convective weather is likely to involve both CWAM improvements based on cockpit information, and an increase in shared common situational awareness between ground and cockpit. In

addition to working to improve the CWAM, it would be worthwhile to develop systems that provide the pilot with the best options through or around convective weather identified by CWAM and allow the pilot to select and transmit back to air traffic control his / her preferred option. Such a system could reduce both the uncertainty in predicting pilot decisions and would reduce the workload required to control air traffic moving through regions of dynamic convection.

5. REFERENCES

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