FLIGHT DECK WEATHER AVOIDANCE DECISION SUPPORT: IMPLEMENTATION AND EVALUATION

Shu-Chieh Wu and Rocio Luna, San Jose State University and NASA Ames Research Center

Walter W. Johnson, NASA Ames Research Center

Abstract

Weather related disruptions account for seventy percent of the delays in the National Airspace System (NAS). A key component in the weather plan of the Next Generation of Air Transportation System (NextGen) is to assimilate observed weather information and probabilistic forecasts into the decision process of flight crews and air traffic controllers. In this research we explore supporting flight crew weather decision making through the development of a flight deck predicted weather display system that utilizes weather predictions generated by ground-based radar. This system integrates and presents this weather information, together with in-flight trajectory modification tools, within a cockpit display of traffic information (CDTI) prototype. that the CDTI features 2D and perspective 3D visualization models of weather. The weather forecast products that we implemented were the Corridor Integrated Weather System (CIWS) and the Convective Weather Avoidance Model (CWAM), both developed by MIT Lincoln Lab. We evaluated the use of CIWS and CWAM for flight deck weather avoidance in two part-task experiments. Experiment 1 compared pilots' en route weather avoidance performance in four weather information conditions that differed in the type and amount of predicted forecast (CIWS current weather only, CIWS current and historical weather, CIWS current and forecast weather, CIWS current and forecast weather and CWAM predictions). Experiment 2 compared the use of perspective 3D and 2½D presentations of weather for flight deck weather avoidance. Results showed that pilots could take advantage of longer range predicted weather forecasts in performing en route weather avoidance but more research will be needed to determine what combinations of information are optimal and how best to present them.

Introduction

Weather related interruptions account for seventy percent of the delays in the U.S. National Airspace System (NAS) [1]. To meet the objective of expanding the capacity of the U.S. NAS in the Next Generation Air Transportation System (NextGen), new tools and technologies must be developed to help mitigate weather impact. A key component in NextGen's weather plan is to assimilate observed weather information and probabilistic forecasts into the decision making process of flight crews and air traffic controllers [2]. Here we report on two types of development that support flight deck weather decision making: enhancing information sources and improving information presentation. First, we discuss three concepts for enhancing weather information available to the flight deck. Second, we describe a prototype interface that implemented these concepts and a part-task experiment that evaluated the utility of these concepts. Third, we turn attention to the information presentation aspect, describing a part-task experiment that compared 2½D and 3D presentations of predicted weather. Finally, we discuss the implications of the results for how to best support pilot weather decision making in NextGen environments.

Concepts for Flight Deck Weather Information Enhancement

Weather information available to the flight deck today has limited range due to the constraint of airborne weather sensing technologies. One way to overcome the range limitation is to provide the flight deck with weather information collected using ground-based sensing technologies like NEXRAD. This idea is in line with NextGen's goal to provide NAS users with same-time access to a unified aviation weather picture through a proposed infrastructure called Common Support Services-

Weather (CSS-Wx) [3]. Access to NEXRAD weather has been made available mainly to general aviation cockpits through commercially available systems (e.g., Fore Flight, NOAA aviation weather system, etc). In the present research we explore the utility of presenting ground-based weather products on the commercial transport category flight deck. Our approach is to present current and forecast weather information from the Corridor Integrated Weather System (CIWS) on a flight deck weather and traffic display [4]. Developed by MIT Lincoln Laboratory, with funding support from the FAA and NASA, CIWS integrates thunderstorm forecasting technology with data from national weather service radars in the U.S. and Canada, and is used by air traffic controllers (ATC) to aid in the analysis of airspace congestion as a result of convective weather, the largest cause of air traffic delays in the NAS. CIWS is now in use at eight en route centers in the northeast U.S., six major terminal control areas, and the Aviation Research System Command Center.

In this research we also explore enhancing weather information by making predictions from the Convective Weather Avoidance Model (CWAM) available to the pilot [5-7]. CWAM outputs three-dimensional probabilistic weather avoidance fields, which identify regions of airspace that pilots are likely to avoid due to the presence of convective weather. The motivation for CWAM development was to provide controllers with predictions of how pilots are likely to deviate for weather given a certain weather pattern and intensity. Predictions of avoidance decisions by others pilots confronted with similar weather patterns provides a perspective different from avoidance decisions based solely upon a physical model of the weather hazard. Instead, it is grounded in how other pilots evaluated riskiness and benefits when confronted with these weather patterns, and thus takes into account not only the weather patterns per se but also pilots evaluations of these patterns, and their impacts on flight.

A third concept of weather information enhancement that we explore arose in the process of our exploring the use of CIWS weather forecasts. As with any weather forecast products, CIWS forecasts are probabilistic with varied levels of accuracy in predicting various types of convective weather development. Specifically, the ability of CIWS to predict storm cell movements far exceeds its ability

to predict convective initiation [8]. Recognizing that securing enough bandwidth to reliably transmit ground-based weather data to the flight deck will be challenging, we examined a third concept for enhancing weather information on the flight deck by supporting pilots in generating their own storm movement predictions using information already available to them from airborne radar. Our proposal is to collect historical weather information along the flight path and allow pilots to visualize this information in a way that will support them in generating their own predictions of future weather development. Certainly pilots are not meteorologists and will not likely be able to generate forecasts at an accuracy level on par with weather forecast products like CIWS. However, this solution requires only existing information to implement. If this enhanced presentation of existing information proves useful to the pilots, it could become an affordable solution to improving flight deck weather decision making.

In the next section we describe how we implemented these three enhancements for weather information display on the flight deck.

Flight Deck Predicted Weather Presentation and Decision Interface

Cockpit Situation Display (CSD) and the Route Assessment Tool (RAT)

The Cockpit Situation Display (CSD), an extension of a Cockpit Display of Traffic Information (CDTI), is an interactive display prototype that has been in development in the Flight Deck Display Research Laboratory at NASA Ames Research Center for over a decade (Figure 1). The CSD supports both traditional 2D and advanced 3D visualization models, and depicts the 4D interrelationship of traffic, terrain, and weather using a cylindrical volume metaphor and fast time extrapolations. Designed to provide the basis for 4D Trajectory-Based Operation (TBO), the CSD also includes the Route Assessment Tool (RAT) which is integrated with the aircraft's Flight Management System (FMS), and allows for in-flight trajectory re-planning. A standard computer mouse is presently used to interact with the CSD prototype.

The RAT provides the functionality to create and visualize in-flight route modifications, downlink proposed route modifications to Air Traffic Control (ATC), receive route modifications from ATC, and execute modifications. The RAT supports the addition of waypoints at arbitrary latitudes-longitudes, and deletion of waypoints, through both clicking and dragging-and-dropping mouse operations. For each waypoint, pilots can also adjust an associated flight altitude and speed, thus enabling 4D trajectory in-flight planning.
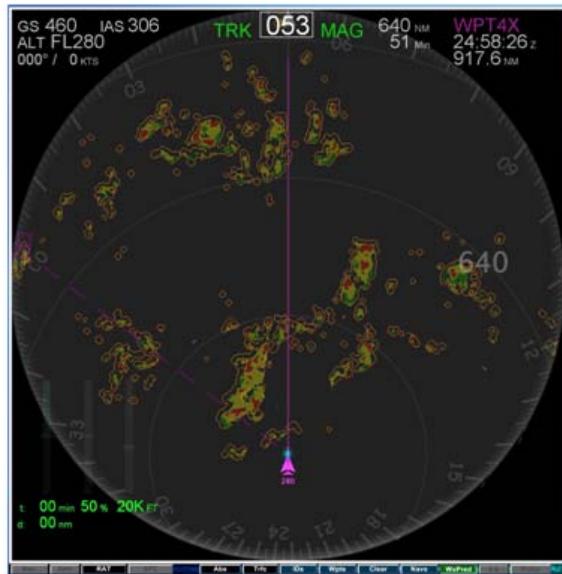

Figure 1. Screenshot of the CSD with CIWS and CWAM

Time, Hazard, and Altitude Control Sliders

Three control sliders were implemented in the CSD for the viewing of current and forecast weather information in 2½D and 3D presentation (seen in the lower left corner of Figure 1, and close up in Figure 2). A 2½D presentation is where weather data from one altitude slice at a time is viewed in 2D (shown in Figure 1). Users however can obtain a picture of the 3D weather information by consecutively viewing 2D weather over a range of altitudes. The three sliders are also available for controlling the viewing of perspective weather presentation shown in Figure 3.
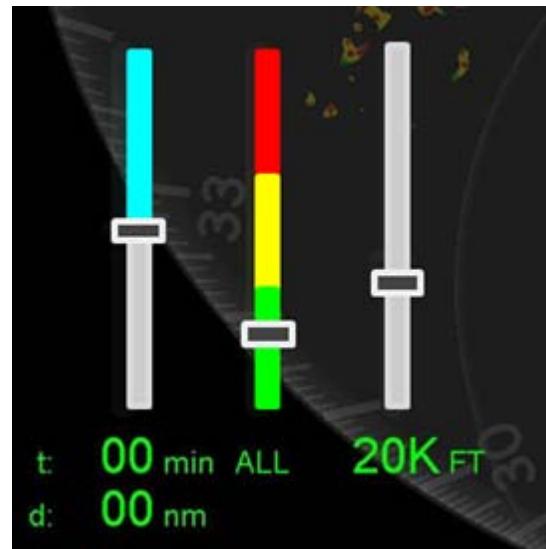

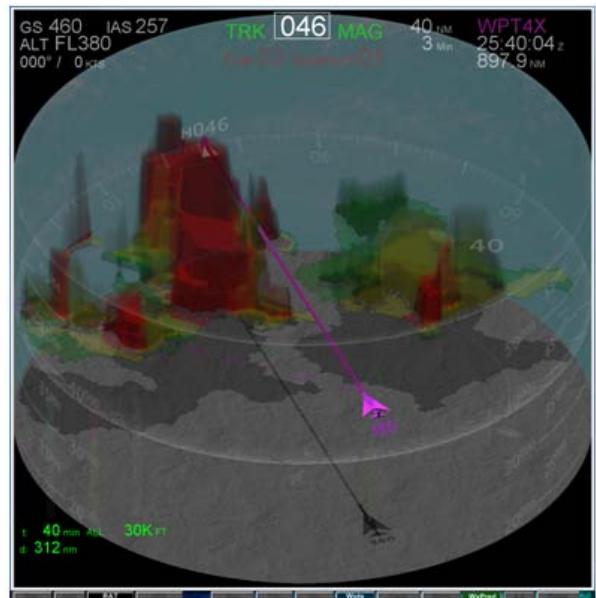**Figure 2. Screenshot of Time, Hazard, and Altitude Sliders**

Figure 3. Screenshot of 3D CIWS Presentation

The Time slider has a range of -120 minutes (the past) to +120 minutes (the future), with the 0-minute point (the present) in the middle. Sliding downward allows for the viewing of historical weather 120 minutes into the past; sliding upward allows for the viewing of predicted weather 120 minutes into the future. When the slider position is moved away from the 0-minute point, a blue bead representing ownship position appears at a time-corresponding position along ownship's trajectory (Figure 4). Therefore,

when the pilot uses the mouse to drag the slider to select different time intervals (past or future), weather and ownship position will update accordingly to reflect what happened (if sliding downward into the past) or is projected to happen (if sliding upward into the future) at the specified time interval.
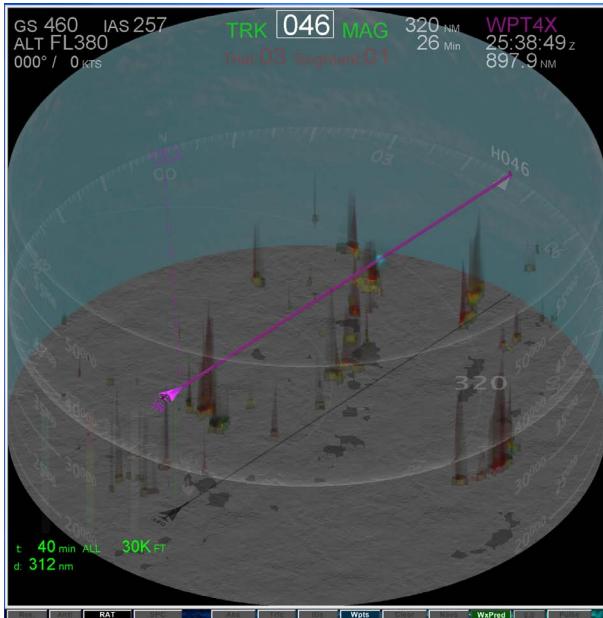

Figure 4. Blue Bead Shows Ownship Position 40 Minutes Ahead

The Hazard slider has two different types of implementations. When used in conjunction with the viewing of CIWS weather (as shown in Figure 2), it supports the viewing of three hazard levels: green, yellow, and red. Setting slider position at a given level shows weather hazards at that level and above. For example, setting slider position at the green level would show weather at the green, yellow and red hazard levels; setting slider position at the red level would only show weather at the red hazard level. When the Hazard slider is used in conjunction with CWAM predictions (not shown in Figure 2), it supports the viewing of CWAM polygons at different probability levels, ranging from 20% to 90%. The percentages indicate the proportion of pilots predicted by CWAM to avoid the associated polygon region. In general, higher percentage values are associated with smaller polygons centering on highly hazardous weather (red) because these areas are typically avoided by a greater proportion of the pilots (Figure 5).
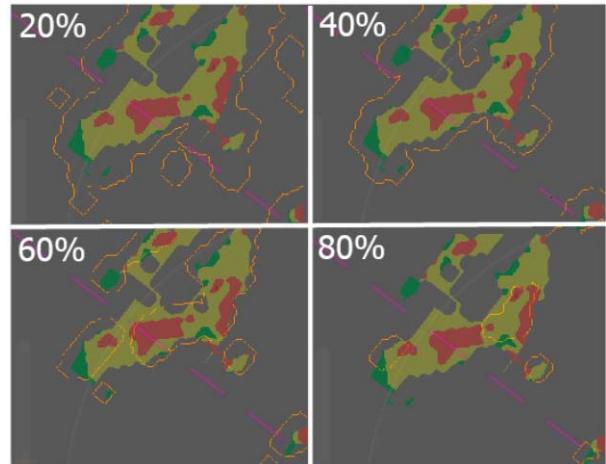

Figure 5. CWAM Polygons at Four Probability Levels

The Altitude slider supports the viewing of CIWS and CWAM information at a given altitude. When used in conjunction with CIWS in perspective 3D presentation, the altitude slider limits the viewing of 3D weather to the specified altitude and above.

Experiment 1: Utility of Historical and Forecast Weather Information on Flight Deck Weather Decision Making

The purpose of Experiment 1 was to evaluate pilot weather avoidance performance using three different types of weather information: CIWS, CWAM, and History. In a part-task setting, participants flew 48 flight scenarios that were 2 hours long in simulated time (but varying in real time duration) in the en route phase, and modified the trajectories when necessary to deviate for weather. To simplify matters, only a single aircraft (ownship) was present in the scenarios; traffic was not a consideration in this experiment. We evaluated objectively measured weather avoidance performance as well as subjective ratings of the various sources of weather information.

Method

Participants

Sixteen transport pilots with high-altitude flight experience participated in the study and were compensated $25/hr.

Apparatus

The experiment was conducted using a personal computer (PC) equipped with a 30" LCD display. Pilots manipulated the CSD using a computer mouse.

Design

On each trial, pilots were presented with a 2-hour segment of an en route flight with one of four types of weather information:

- Basic: Pilots only had access to CIWS current weather information updated every 2.5 minutes.

- History: In addition to CIWS current weather information and its updates, pilots had access to historical weather information from the past 2 hours at 10-minute resolution.

- CIWS: In addition to CIWS current weather information and its updates, pilots had access to 2-hour CIWS weather forecast information with forecast updated every 5 minutes.

- CWAM: In the CWAM condition, in addition to CIWS current and forecast information and its updates, pilots had access to CWAM predictions. Because CWAM predictions are computed based on CIWS information, CWAM predictions were updated at the same cycles as CIWS information.

Weather Scenarios

Historical CIWS weather data obtained from the NASA NextGen ATM Data Warehouse provided the source of weather scenarios [9]. More than 50 samples in 2-hour long segments were taken from July to August in 2011. Weather scenario samples included all information from CIWS product's native update cycles (current weather updates every 2.5 minutes and 2-hour forecast updates every 5 minutes). Custom software was developed to convert raw CIWS data format (netCDF-4/HDF5) to formats usable by the CSD and to generate CWAM predictions.

Once the weather samples were collected, the next step was to design 2-hour long flight trajectories that traversed a section of the weather impacted airspace. Because the 2-hour flight trajectory was meant to simulate a segment of a possible en route flight where, as part of an experimental constraint, pilots were not allowed to modify the end points, one criterion for designing the trajectories was that they began and ended with ownship flying clear of weather conflicts.

One criteria used for the selection of the weather impacted airspaces used in this experiment was the associated accuracy of the weather forecasts for those airspaces. Attempts were made to select weather scenarios that varied in terms of forecast accuracy to reflect the probabilistic nature of forecasts in general. CIWS datasets include a Forecast Accuracy Score Product, which indexes accuracy by comparing 30, 60, and 120 minute weather predictions with the actual weather. Scores come in 5% increments (up to 100%) [10], [11], with higher percentage values corresponding to a greater match between forecast and current weather. Because forecast accuracy scores are only available for a 300x300NM area around each of the 77 defined home regions (mostly major airports in the U.S. and Canada) [12], flight trajectories were designed to fly through at least one home region so to make it possible to associate a forecast accuracy score with each of those trajectories.

Among those weather scenarios collected, 48 were used for experimental trials and 3 were used for practice. The 48 trials were divided into 4 groups of 12 with roughly matching mean forecast accuracy (40% to 42%). For different pilots, the 4 groups of scenarios were paired up with different weather information conditions so that across participants different weather scenarios were used in all 4 weather information conditions.

Procedure

On each trial, pilots were presented with a unique weather scenario and a 2-hour section of flight plan in the en route phase. Their task was to guide their flight safely and efficiently through weather using the provided thunderstorm avoidance criteria:

These are minimum standards:
If Tops < FL 300 avoid thunderstorm by at least 5 NM

If Tops > FL 300 avoid thunderstorm by at least 20 NM, clear tops by at least 5000'

Pilots had access to the applicable slider controls for manipulating the viewing of historical or forecast weather information, and the RAT for planning and executing path modifications.

To accommodate 48 trials of 2-hour weather/flight scenarios within a reasonable amount of testing time, scenarios were fast-forwarded at non-critical periods of the flight. Specifically, each 2-hour scenario was divided into 6 20-minute segments. The beginning of each segment was a "real-time" period, during which pilots could evaluate ownship trajectory for weather impact and modify it if necessary. Once pilots made a modification, or decided that none was needed, they executed the modified or unmodified trajectory using RAT, and the scenario was automatically fast forwarded to the beginning of the next segment. During the fast-forward period, pilots could view the progression of the flight and the evolution of weather but could not make path modifications. Pilots were made aware of this procedure during training and asked to plan their paths to avoid weather accordingly.

A total of 48 trials were divided into 4 blocks, one for each weather information condition. The order of the weather conditions was counterbalanced across participants. Pilots received the corresponding training for a particular weather condition right before that block of trials. The training involved verbal instructions and hands-on exercises, followed by self-paced practice runs. Pilots were asked to practice until they felt comfortable using the newly learned information source. After pilots completed all blocks of trials, they filled out an online questionnaire designed to solicit their subjective evaluations on various aspects of the scenario.

On all of the trials, ownship was initialized with an altitude of 28000 feet and a ground speed of 464 knots. No wind information was provided; pilots were instructed to infer wind direction based on the observed or forecasted movement of the storm cells.

Only the Altitude slider, initially preset to 25000, was activated and implemented in the same way in all four weather conditions. The Time slider was not activated in the Basic condition. It was activated for sliding between 0 and -120 minutes (the

past) in the History condition, and between 0 and 120 minutes (the future) in the CIWS and CWAM conditions. The Hazard slider showed green, yellow, and red hazard levels in the Basic, History and CIWS conditions, and was preset at the yellow level at the beginning of each trial. In the CWAM condition the Hazard slider was used for controlling the weather avoidance polygon probabilities instead of the three CIWS hazard levels. Because no slider control was available for the selective viewing of CIWS hazards in the CWAM condition weather from all hazard levels (green, yellow, and red) were continuingly shown. The initial CWAM percentage was set at the 50% level.

Results and Discussion

Four of the sixteen pilots were excluded from most analyses: three due to failure to follow instruction to utilize historical weather information in the History condition, and one due to failure to follow instruction to minimize numbers of climbs.[1] Results reported here are based on the remaining twelve pilots, who together fulfilled a complete counterbalancing of the four weather information conditions.

Weather Avoidance Performance

In our examination of weather avoidance, our measures only capture how the presentations affected strategic and not tactical guidance since pilots were only allowed to modify their path every 20 minutes in the simulated scenarios. Therefore, these results reflect the utility and acceptance of the various presentations for making strategic guidance decisions without the luxury of fine tuning their trajectories by requesting deviations as they approach weather systems.

Weather avoidance performance was evaluated with regard to the safety and efficiency of flight paths. We used proximity to weather as the measure for safety. Specifically, for proximity we examined 1) the percentages of time flight paths came closer than

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[1] We were informed by the early participants that the echo tops of some of the storms in our scenario were low enough that they could be bypassed altogether through a simple climb operation given the appropriate types of aircraft. As a result we instructed the participants to avoid climbs by having them assume the initial altitude was most efficient for their flight.

20NM to the green and red hazard level regions of weather and, 2) the closest a flight came to each of these regions during a trial. We chose to focus on the green and red hazard levels because proximity to green measures proximity to weather of any intensity, while proximity to red signifies proximity to an extremely hazardous region. We examined coming within 20 NM because keeping 20NM from the green hazard level is often used as the guidance for weather avoidance as recommended by FAA's Aeronautical Information Manual with regard to thunderstorm flying (although the actual recommended guidance given to pilots allowed for closer approaches if echo tops were below 30000 feet) [13].

Overall, pilots flew rather safely around weather, and penetration of the 20NM stand-off boundary rarely occurred (less than 10% and 5% penetration with respect to the green and red hazards, respectively). Table 1 summarizes the percentage of penetration and closest distance to weather by weather condition (shown as figures outside the parentheses). Results from a repeated measure within-subject Analysis of Variance (ANOVA) on the percentage of time penetrating the green hazard found a marginal main effect of weather information condition, $F(3,33) = 2.83$, $p < .06$. No difference was found for the percentage of time penetrating the red hazard level ($p > .2$). Echoing these results, results from an ANOVA on the closest distances to weather at the green hazard level found a significant main effect of weather information condition, $F(3,33) = 5.42$, $p < .01$, while no effect of weather information condition was found for the closest distances to weather at the red hazard level ($p > .2$). As shown in Table 1, pilots flew closest to the green and red hazards when they had CIWS forecasts (mean closest distances 2.0 NM and 9.8 NM), and furthest from the weather when they had CIWS forecasts with CWAM (mean closest distances 7.4 NM and 12.0 NM).

We also examined the closest proximity to weather with regard to CIWS forecast accuracy by doing a median split and dividing weather scenarios roughly into two halves based on their prediction accuracy scores. The results are summarized in the parentheses in Table 1 (based on scenarios with relatively low and high prediction accuracy, respectively). Note that the number of weather scenarios within each condition was already limited (12 each), thus results based on further reduced sets

that contained as few as 4 scenarios should be interpreted with caution. Nonetheless, some patterns appear to emerge. First, pilots in general came closer to weather on trials with forecasts that had relatively lower prediction accuracy than on trials with forecasts that had relatively higher prediction accuracy. However, because the same pattern is observed in the Basic condition, where forecasts were not presented to the pilots, it is likely that the differences were due largely to a correlation between the type of convective activities and forecast accuracy (i.e., lower accuracy associated with prediction of growth and decay vs. higher accuracy associated with prediction of movement). Second, the closest distances to weather scenarios of similar prediction accuracy were equivalent across the four conditions (except in the case of green hazard, CWAM condition). The differences in the closest distance to weather observed in the aggregated results were mostly due to scenarios with higher prediction accuracy. Understandably, pilots did not have information on accuracy scores and thus could not have approached weather differently according to how accurate the predictions were. It is likely though that pilots approached weather differently based on the predominant type of convective activities they perceived.

Table 1. Experiment 1 Weather Avoidance Performance Results

Weather Condition	Hazard Level	
	Green	Red
Basic % penetration	8.5% (9.0%/8.0%)	3.3% (3.8%/2.5%)
closest distance	4.8 (2.7/6.9)	11.3 (9.3/13.4)
History % penetration	8.0% (8.0%/8.0%)	3.3%(3.8%/2.5%)
closest distance	4.1 (2.2/6.1)	11.2 (8.8/13.6)
CIWS % penetration	9.1%(8.0%/10.0%)	3.9%(3.8/%/4.5%)
closest distance	2.0 (2.7/1.2)	9.8 (8.6/10.9)
CWAM % penetration	6.6% (8.0%/5.0%)	3.0% (3.6%/1.9%)
penetration	7.4 (4.3/10.5)	12.0 (8.9/15.2)

closest distance		

Overall, the results of the weather proximity analysis showed that the predicted CIWS with CWAM condition resulted in pilots planning routes that held the greatest distance from the weather. Conversely, predicted CIWS without CWAM resulted in planned routes with least separation from the weather. The CWAM result was not unexpected since it presented a contour that surrounded the weather cells, providing effectively an additional buffer. Thus if pilots attempted to stay outside of the contour they would be even further from the weather. The performance with the predicted CIWS alone was less expected. One explanation for this may be overconfidence in the CIWS prediction, leading pilots to attempt to plan routes that skirt closer to the storms.

Similarly, the results of path stretch, used as the measure for efficiency, showed a corresponding inverse relationship with those of proximity to weather. Path stretch was measured by the percentage of increase in length of the actual path flown relative to the planned path. Overall the actual paths flown were about 5% longer (5.6%, 5.2%, 5.0%, and 7.0% in the Basic, History, CIWS, CWAM conditions, respectively). Specifically, the results showed the greatest path stretch when pilots flew with CWAM predictions (7.0%) and the least when they flew with CIWS forecasts (5.0%), compared to the basic current weather only condition. Results from an ANOVA confirmed the significant effect of weather condition, $F(3,33) = 3.20$, $p < .05$.

Subjective Evaluations

Pilots rated the weather information in terms of utility in improving flight efficiency and safety, as well as reducing time on task and workload on a 5-point Likert scale, from strongly disagree (1) to strongly agree (5). They were instructed to rate the information relative to specific comparison conditions (History relative to Basic, CIWS relative to Basic, and CWAM relative to CIWS). Overall pilots showed relatively favorable opinions on these information sources (greater than 3.5 on average) (Table 2).

Table 2. Experiment 1 Subjective Evaluation Results

Weather Condition	Areas			
	Efficiency	**Safety**	**Time**	**Workload**
History	4.17‡ (*3.81*†)	4.17‡ (*3.75*†)	3.50‡ (*3.25*)	3.58 (*3.44*)
CIWS	4.50‡ (*4.63*‡)	4.33‡ (*4.50*‡)	3.83 (*3.88*†)	4.00‡ (*3.94*†)
CWAM	3.75 (*3.56*)	3.92† (*3.69*)	3.92† (*3.63*)	3.92† (*3.63*)

Table 2 summarizes pilot ratings on weather information in areas of efficiency, safety, time, and workload. Means in parentheses were from all 16 participants, including those who did not use history information. Means outside parentheses were from 12 participants whose data were used for all other analyses. A rating of 3.0 signifies a neutral rating, meaning that the condition did not differ from the comparison condition on the dimension being rated. Therefore, significance ratings are assessed for difference between mean rating and 3.0. (†p < .05, ‡p < .01).

Interpretation of the subjective ratings must take into account that four subjects were excluded from the analysis, in particular the three that were excluded because they did not utilize the historical weather information, even though they were trained in its use and instructed to use it. For the ratings data this exclusion introduces a potential bias, because some of these pilots found the weather history of insufficient value to use it. It is not clear if their evaluation of History would have risen (or fallen further) if they had used it, so mean ratings with and without these four participants' data, are shown in Table 2. Table 2 also reports the results of t-tests of the significance of the difference between the mean ratings and a neutral value of 3.0.

Relative to the Basic condition, pilots found it more useful to be given forecast information with CIWS. Seven of the eight tests comparing the means

with the neutral rating (3.0) found statistical significance.

Relative to the CIWS with forecast condition, pilots' mean ratings indicate that they believed presentations adding CWAM weather avoidance fields were often better but not by much. Only three of the eight tests comparing the means with the neutral rating (3.0) found statistical significance.

Although the History condition did not seem to affect safety and efficiency of flight based on the performance results, pilots who used it overwhelmingly found it useful to be able to visualize weather history relative to relying on their own memory (4.17). Tests for the History condition showed that participants' ratings for weather history information were significantly above neutral (3.0) for efficiency and safety, even when the three excluded participants were added to the analysis. However, for time and workload only the rating for time with the four participants excluded was significantly greater than 3.0.

Finally, in another question pilots were asked to indicate the extent of forecast range that they consider could be used effectively (Figure 6). Results showed that almost all of the pilots thought they could effectively use forecasts of up to an hour in the future.
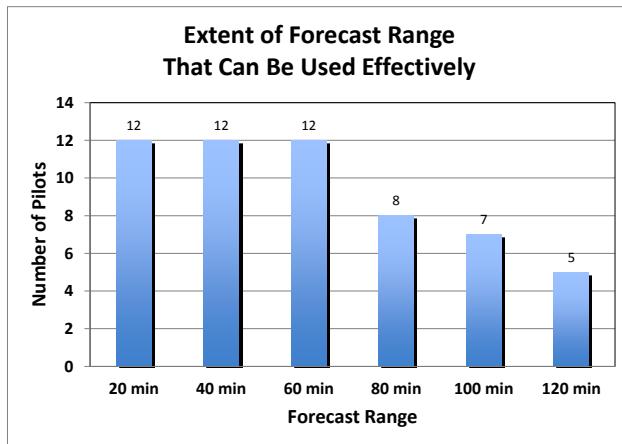

Figure 6. Experiment 1 Subjective Effective Forecast Range

In summary, even without any weather information enhancement, as in the Basic condition, pilots flew the scenarios safely through weather with minimal penetration. However, weather information enhancements, particularly CIWS and CWAM, affected weather avoidance decisions in opposite ways. Specifically, the addition of CIWS forecasts resulted in more penetration into weather at the green hazard level and less path stretch. Conversely, the addition of CWAM predictions resulted in less penetration into weather at the green hazard level and more path stretch. Lastly, avoidance performance based on weather history in general did not differ from that based on current weather only. However, pilots found it useful to be able to visualize weather history.

Experiment 2: 2½D vs. Perspective 3D CIWS Presentations on Weather Decision Making

Advances in computer graphics technologies combined with the increasing availability of affordable hardware solutions make it possible to render and present complex perspective 3D images for real time use. For phenomenon like weather which is highly spatial in nature, there is an intuitive appeal to present it in perspective 3D, rather than 2D, to get closer to how it appears in the physical world. However, research has shown that 2D and perspective 3D displays each has advantages and disadvantages depending on the tasks and situations [14–16]. Specifically, 3D presentation is better for shape and layout information whereas 2D presentation is better for precise orientation and positioning [16] and understanding the relative locations between objects [14].

The purpose of Experiment 2 was to evaluate the use of 2½D and perspective 3D presentations of weather for flight deck weather avoidance. In particular, we were interested in how these two presentation modes fare in a task like weather avoidance that demands both an understanding of the general layout of weather and precise positions between the trajectory of ownship and weather hazards. The task was identical to that of Experiment 1, flying multiple 2-hour segments of trajectories in en route airspace safely through weather. There were two weather presentation conditions, 2½D and perspective 3D. Sixteen participants flew 30 flight scenarios, 15 in each of the conditions. We evaluated the same objective and subjective measures as well as

how much time pilots spent in 2D vs. 3D viewing (in perspective 3D condition).

Method

The method in Experiment 2 was identical to that of Experiment 1 with the following exceptions. First, there was a total of 30 trials divided into 2 blocks, one for each weather presentation condition. These 30 trials featured new weather scenarios sampled from June to September, 2012. Each trial began with the display preset in the presentation mode being tested (top-down 2D view for 2½D and perspective view for perspective 3D). In the 3D condition pilots could freely rotate the display, turning it into 2D if so desired. The 2½D presentation could not be rotated out of the 2D view. The hazard level was preset to include red, yellow, and green levels (i.e., ALL). The altitude of ownship was preset to 38000 feet and altitude changes in the planned trajectory were not discouraged as they were in Experiment 1. CIWS current and predicted weather were used as the source of weather information in both presentation conditions.

Results and Discussion

All analyses were based on all sixteen participants.

Weather Avoidance Performance

Overall, the two presentation conditions produced equivalent results in terms of avoidance performance (Table 3). Penetration within 20NM of the green and red hazard regions occurred 12.0% and 8.2% of the time respectively with 2½D presentation and 12.0% and 7.8% of the time with perspective 3D presentation. The closest proximity to weather was also equivalent in the two conditions, around 1.1NM and 1.2NM for the green and 4.0NM and 4.5NM for the red hazard regions, respectively. Not surprisingly, the amount of path stretch was also equivalent in the two conditions, both around 4.2%. The two different presentations also did not result in any difference in the amount of time spent on weather evaluation, both around 33 sec. The two conditions however had a small difference on the average number of altitude changes per trial. The altitude of ownship changed 1.5 times on average per trial in the 2½D condition and 1.3 times in the perspective 3D condition, $F(1,15) = 6.05$, $p < .05$.

Table 3. Experiment 2 Weather Avoidance Performance

Presentation Condition	Hazard Level	
	Green	Red
2½D % penetration	12.0% (11.0%/12.7%)	8.2% (7.1%/9.2%)
closest distance	1.1 (1.2/0.9)	4.0 (4.3/3.8)
3D % penetration	12.0% (12.5%/11.7%)	7.8%(7.8%/8.0%)
closest distance	1.2 (-0.2/2.4)	4.5 (3.7/5.2)

Subjective Evaluations

Although there was no difference in weather avoidance performance between the two presentation conditions, pilots consistently preferred the perspective 3D presentation to the 2½D presentation. In particular, they preferred 3D in terms of their ability to assess the height and spread of weather and the ability to plan alternative trajectories (Table 4). As a whole, pilots overwhelmingly preferred perspective 3D presentation over 2½D (80% vs. 20%). Perspective 3D presentation was also considered significantly easier to use than 2½D presentation for assessing the height of weather ($t = -4.53$, $p < .001$), assessing the penetration of weather by ownship's planned trajectory ($t = -4.03$, $p < .005$), assessing the penetration of weather by ownship's trajectory being planned while using RAT ($t = -4.39$, $p <.001$), getting a complete picture of weather ($t = -3.14$, $p < .01$), and planning vertical maneuvers using RAT ($t = -3.52$, $p < .01$). Perspective 3D and 2½D presentations received similar ratings in terms of their support for assessing the spread of weather and planning lateral maneuvers.

Table 4. Experiment 2 Subjective Evaluation Results

Presentation Condition	Weather assessment					Route planning	
	Height of Wx	Spread of Wx	Penetration of planned trajectory	Penetration of trajectory being planned	Complete picture of Wx	Lateral maneuvers	Vertical maneuvers
2½D	3.00	4.17	3.25	3.18	3.62	4.25	3.25
Perspective 3D	4.18	4.33	4.18	4.12	4.31	4.18	4.18

In Experiment 2 pilots were also asked to indicate the extent of forecast range that they consider could be used effectively (Figure 7). Again almost all of the pilots considered forecasts of up to an hour in range to be useful.
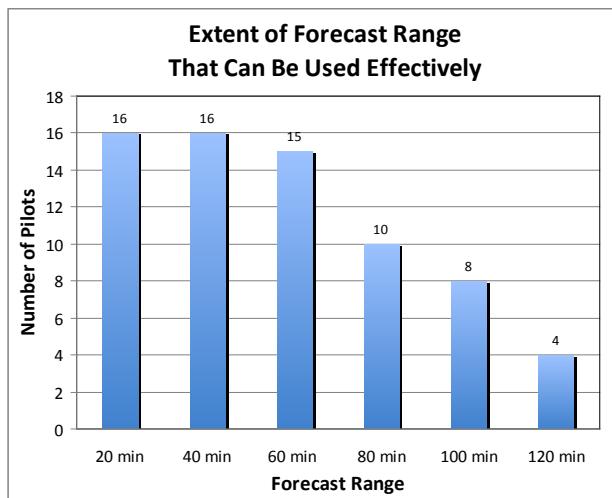

Figure 7. Experiment 2 Subjective Effective Forecast Range

Presentation Mode Usage (Perspective 3D Condition Only)

In the perspective 3D condition pilots could freely change the viewpoint of CSD and set its view to 2D if desired. Although the majority of pilots preferred perspective 3D over 2½D, almost all of them set the presentation mode to 2D some portion of the time. While the proportion of time spent in 2½D view varied widely among pilots, on average they spent about 40% of the time viewing weather in 2½D. The time portion of 2½D viewing increased even more, to around 47%, when pilots were actively using the RAT to modify trajectories.

In summary, despite a lack of objective performance benefits, pilots expressed a preference for perspective 3D presentation of weather. It should be noted that the perspective 3D presentation condition used in the present experiment also included 2½D presentation. Therefore, it is not surprising that pilots might prefer a presentation condition that provides more ways to view weather. However, giving this additional information to the pilots did not appear to hurt performance, nor did it lengthen the amount of time needed to complete the task. All in all the present results suggest that a presentation mode combining 2½D and perspective 3D has the potential for providing a more comprehensive weather picture for the pilots without negative impact on performance

General Discussion

The results of two part-task experiments showed that pilots could take advantage of the additional forecast information while performing en route weather avoidance but more research will be needed to tailor the presentation mode to pilots' use. In particular, one issue that arose unexpectedly from the course of the study concerns the scale of weather displays. In the experiments pilots were able to visualize the complete 2-hour segment of the trajectory to be flown and the surrounding weather, as far as 1000 NM ahead. Because pilots are used to seeing only about 300 NM ahead, the scale of our display may have led them to misjudge distances. Because of the scale issue, it is probably important that in the NextGen Trajectory-Based Operation (TBO) environment, pilots have access to features like panning and zooming so that they have a better indication of when their routes will take them within some unacceptable distance to the storms. The ability

to pan over to weather impacted portions of their trajectory will allow pilots to examine them at a much lower scale.

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Acknowledgements

participants. We also thank Vernol Battiste and Joel Lachter for comments on an earlier draft of the paper.