TRACON Controller Weather Information Needs:

I. Literature Review

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June 2003

DOT/FAA/CT-TN03/18

U.S. Department of Transportation
Federal Aviation Administration

William J. Hughes Technical Center
Atlantic City International Airport, NJ 08405

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/CT-TN03/18		

4. Title and Subtitle	5. Report Date
TRACON Controller Weather Information Needs: I. Literature Review	June 2003
	6. Performing Organization Code ACB-220
7. Author(s) Ulf Ahlstrom, Ph.D., and Pam Della Rocco, Ph.D., ACB-220	8. Performing Organization Report No. DOT/FAA/CT-TN03/18
9. Performing Organization Name and Address Federal Aviation Administration William J. Hughes Technical Center Atlantic City International Airport, NJ 08405	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Federal Aviation Administration Chief Scientist for Human Factors (AAR-100) STARS Automation – (ATB-230) 800 Independence Ave., S.W. Washington, DC 20591	13. Type of Report and Period Covered Technical Note 14. Sponsoring Agency Code AAR-100 ATB-230

15. Supplementary Notes

16. Abstract

This report is the first in a series on the use of weather information by Terminal Radar Approach Control (TRACON) controllers and weather displays for the cockpit. The document provides a literature review with an emphasis on research relating to the specification of weather information needs for these controllers. Three problem areas are apparent from the review of current trends in weather information needs and weather information displays. First, research is lacking on the weather information needs for TRACON controllers. Second, no research has investigated and organized the regularities and lawful events that provide the TRACON controllers with goal-relevant options in their work domain. Third, although research is making progress on the identification and display integration of important weather information for the cockpit, there is a lack of research on how to display such information for the TRACON controller. The researchers provide discussions of these apparent deficiencies in relation to ecological interface design and guidelines for future research.

17. Key Words	18. Distribution Statement
Aviation, Display Integration, TRACON, Weather, Weather Displays,	This document is available to the public through the National Technical Information Service, Springfield, Virginia, 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	19	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Executive Summary

This report is the first in a series on the use of weather information by Terminal Radar Approach Control (TRACON) controllers and weather displays for the cockpit. The document provides a literature review summarizing current research with an emphasis on research that relates to the specification of weather information needs for TRACON controllers. It also addresses how to best display such weather information. Because TRACON controllers and pilots need to have access to similar weather information, this review also covers research that explored issues related to current weather displays for the cockpit, weather related controller/pilot communications, and weather situation awareness. Three problem areas are apparent from the review of current trends in weather information needs and weather information displays. First, research is lacking on the exploration and specification of the weather information needs for TRACON controllers. Second, no research has investigated and organized the regularities and lawful events (constraints) that provide the TRACON controllers with goal-relevant options (affordances) in their work domain. Third, although research is making progress on the identification and display integration of important weather information for the cockpit, there is a lack of research on how to display such information for the TRACON controller. The authors provide discussions of these apparent deficiencies in relation to Ecological Interface Design and guidelines for future research.

1. Introduction

This report is the first in a series on the use of weather information by Terminal Radar Approach Control (TRACON) controllers and pilots. The present document explored current research on the use of weather information with an emphasis on any research relating to the specification of weather information needs. It also explored research that addressed how best to display such weather information. Because TRACON controllers and pilots need to have access to similar weather information, this review also covers research that explored issues related to current weather displays for the cockpit, weather-related controller/pilot communications, and weather situation awareness (SA).[1] Although we briefly discuss the general topics of pilot weather information needs, reviews that are more specific to pilot information processing and pilot weather needs are available (Beringer & Schvaneveldt, 2002; Raytheon, 2002; Wickens, 2002; Yuchnovicz, Novacek, Burgess, Heck, & Stokes, 2001). Although the focus of this review was on TRACON controller weather needs and weather displays, this review also includes current research regarding how to display weather information for en route controllers because of the potential similarities in displays and crossover functionality.

1.1 User Weather Needs

Adverse weather conditions affect the National Airspace System (NAS) in many ways including flight safety and system effectiveness. According to the National Transportation Safety Board (NTSB, 1998), weather conditions caused 22% of the accidents involving major airlines and cargo carriers (large transport-category aircraft) in 1998. For commuter airlines, weather caused 62.5% of the accidents and, for air taxis and helicopters, weather-related accidents caused 30.5% and 27.3% of the accidents, respectively (NTSB). Therefore, it is immensely important that NAS users have accurate and timely information about weather to aid tactical and strategic planning for safe and judicious operations (Keel, Stancil, Eckert, Brown, Gimmestad & Richards, 2000).

In the current NAS, terminal controllers maintain their weather SA by receiving weather briefings from the supervisor and by viewing six independent levels of precipitation on the Standard Terminal Automation Replacement System (STARS) Terminal Controller Workstation (TCW) or the ARTS Color Display. If the controller uses older TRACON display systems, he/she can only display two precipitation levels simultaneously (out of six possible). In addition to this information, controllers get pilot reports of hazardous weather conditions that pilots

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[1] Weather Situation Awareness (SA) is defined here for the controllers as the combined perception of time, current weather location, airspace volume, weather movements in the near future, sector traffic flow, and the available control options. A high weather SA would imply that the controller knows where the heavy weather areas are, making it easier to adjust the traffic flow. With high SA, the controller also comprehends the projected weather movements, therefore, it will aid vector planning and allow the controller to give clearer directions to the pilots. The definitions for weather SA for the pilot is the combined perception of time, current weather distribution along the present and alternative routes, available areas that are free of hazardous weather, weather locations in the near future, and tactical options to avoid hazardous weather areas.

encounter during flight. Controllers also provide weather information to pilots when possible. However, separating aircraft from weather is not a requirement for terminal or en route controllers (Amis, 2002; Krebs & Ahumada, 2001; Lindholm, 1999).

With numerous advanced weather products entering the market (Fritts, 2002) and with an increasing capability to display graphics, several key issues need to be resolved before designers can plan an optimal TRACON weather information system. First, a systematic and objective analysis of the TRACON controller weather needs is required. What weather information is essential for increased operational safety and capacity? Second, how should weather products be displayed to the controller? Should they be integrated into the computer-human interface (CHI) so that it produces unambiguous and easily accessible information to the user? Finally, what procedures are optimal for appropriate use of the information? Although the greater aviation community has proposed various answers to these questions, they currently have adopted no single solution.

We know a great deal about weather conditions affecting TRACON operations (Collins, 1991; Gormley, 1999; Keel et al., 2000; Lawson, Angus & Heymsfield, 1998; Liu; Golborne, Bun & Bartel, 1998; Williams et al., 1999). However, very little empirical research is available on what actual weather information TRACON controllers need to maintain weather situational awareness (SA), operational safety, and efficiency. The Federal Aviation Administration (FAA) has outlined the concepts of operations for weather in the NAS domain (FAA, 2002a). This document describes operational decisions by different NAS users that are affected by weather. It also outlines the weather information needed by NAS decision makers to mitigate the effects of weather. FAA (2002b) has also documented the mission-need statement for aviation weather information and identified deficiencies in the current NAS. The result of this effort is a business case for a cost-effective strategy for propagating needed weather information products to NAS users. Although these documents provide a summary of conceptual weather information needs and a strategy to mitigate current deficiencies, they provide no validation of requirements or empirical data on operational use. Therefore, more in depth research is needed to refine different user weather needs and the associated impact on operational services. There is also a lack of a detailed plan for integrating multiple sources of weather information onto user displays.

According to Lindholm (1999), job functions within the general area of Air Traffic Control (ATC) have different needs with regard to weather information. The TRACON controllers, for example, are executing tactical control where they keep aircraft separated within a limited geographical region. Lindholm furthermore argues that given adverse weather conditions, the incomplete and imprecise weather information currently displayed on their workstations limit their job function. A better weather display could increase the controller weather SA and possibly increase their strategic planning role. Results from a pilot survey of convective weather needs by Forman, Wolfson, Hallowell, and Moore (1999) support Lindholm's conclusion. Pilots frequently chose enhanced real-time weather displays for controllers when asked to rank different sources of important weather information.

Chornoboy, Matlin, and Morgan (1994) defined controller weather information needs in simple terms. All that controllers want are good weather products that they can use without interpretation and coordination. Controllers furthermore need to know where adverse weather is and where it is going.

Although the focus of this paper is on the weather needs and displays for TRACON controllers, some interesting developments have occurred for the en route domain that bear similarity and crossover functioning with the terminal domain. For example, Ahlstrom, Rubinstein, Siegel, Mogford, and Manning (2001) created a weather display prototype with six independent levels of precipitation and an animated prediction of a 30-minute weather cell movement. In addition to the weather graphics, the prototype showed text-based information about precipitation intensity, thunderstorms, turbulence, radar echo tops, and upper level winds. The results from the Ahlstrom et al. study showed that controllers rated the weather display as producing a moderate-to-large task-complexity reduction when controlling traffic in adverse weather conditions. Controllers furthermore expressed the need to know the weather trends, the direction of movements, and the intensity of the weather within their sector. Having this information would increase the controller weather SA, enhance vector planning, and allow clearer directions to the pilots.

Forman et al. (1999) explored different user needs with regard to forecast lead-time and accuracy. For example, tower personnel need a forecast accuracy of ~90% in order to operate and reconfigure the runway and can work with a lead time of 10 to 20 minutes. However, the TRACON personnel can deal with a ~70% forecast accuracy because they have more flexibility in controlling arrivals and departures. A functional lead-time for the TRACON is 30 min, whereas airline dispatchers like to have the flight time plus an additional 2 hours. Pilots have a special problem because weather forecasts are not commonly generated with enough accuracy and timeliness so that pilots can avoid weather hazards before they are encountered (Bass & Minsk, 2001).

Current area-based weather forecasts are given for a specific geographical area over certain time periods. An assessment of the forecast accuracy is made by statistically comparing the spatial coordinates of observed weather movements with the weather forecast. According to Fritts (2002), future weather forecasts will be much more accurate than today, with improved ocean-surface wind measurements, cloud and precipitation sensors, and improved upper-air measurements of pressure, temperature, and winds. In contrast to the current area-based forecast method, Vigeant-Langlois and Hansman (2002) have proposed a trajectory-based forecast method. In their model, four-dimensional (4D) hypertubes represent aircraft trajectories, and 4D unsafe hypervolumes represent weather areas. The authors developed a test to see if the aircraft trajectory and weather volumes are intersecting. If there is an aircraft-weather interaction, controllers can make a decision about accepting or rejecting the trajectory as well as creating a new trajectory without aircraft-weather interactions. Vigeant-Langlois and Hansman believe their framework to be important for future work on the development of trajectory-based weather forecasts. It could furthermore serve as a useful framework for the development of graphical weather displays.

1.2 Display Integration of Weather Information Products

Several different weather systems are currently in operation at airports to increase forecast accuracy and safety. One system that integrates weather data from several Federal Aviation Administration and National Weather Service sensors and weather information systems is the Integrated Terminal Weather System (ITWS) (Evans & Ducot, 1994). For the end user, this system provides timely and accurate information on current storm locations (updated every 30 sec), motion (10- and 20-min extrapolated locations), microbursts, gust fronts, storm cells, and wind conditions. As an example, when the ITWS is coupled with an enhancement like the Terminal Convective Weather Forecast capability, the annual delays due to convective weather can be reduced by 1.2 million min per year as was the case at the New York terminal area (Evans, 2001).

Although individual weather information systems are available, it has proven difficult to integrate products into a system that enhances weather SA for pilots and controllers. Arend (2003) concludes that it is no longer a shortage of weather information in the cockpit - the problem is how to integrate and present the information to pilots in such a form that they can make use of it. Currently, there is a separation of weather information in the cockpit by time or location or both, putting the burden of integration on the pilot. There is also a lack of consensus in the aviation community regarding the priority of hazard information and a lack of standardization for displaying and color coding variables such as terrain, weather cells, and special use airspace. According to Arend, this will be a much greater problem in the future when pilots, TRACON controllers, and dispatchers will have to collaborate in a different way that requires an even greater weather SA. Without a homogenization of weather information and displays, this task will be very difficult (Latorella, Lane, & Garland, 2002).

Bass and Minsk (2001) have provided a solution to the problem of integration of cockpit weather information. Their answer is the Weather Hazards Integrated Display System. Rather than displaying all weather data available, this pilot-centered system would let the pilot be in charge of what information to display. For example, the pilot should be able to display only the weather information relevant to his route of flight, thereby reducing extraneous information and avoiding unnecessary clutter. This would make it easier for the pilot to maintain weather SA resulting in greater decision-making capability.

Spirkovska and Lodha (2002) presented another way to improve upon pilot weather SA in their Aviation Weather Data Visualization Environment (AWE). This system graphically displays meteorological observations, terminal area forecasts, and winds aloft. This system is interactive, and the pilot can display weather data for any area or very specifically along his route of flight. Furthermore, the AWE system has a speech-based user interface (Spirkovska & Lodha, 2003) that reduces head-down time for the pilot while getting weather updates. An evaluation of the system showed that pilots could answer pre-flight route planning questions 2.5 times faster compared to doing the same task under the usual pre-flight weather reports.

Similarly, the Aviation Weather Awareness and Reporting Enhancements (AWARE) by Uckun, Ruokangas, Donohue, and Tuvi (1999) is another example of a tool that they devised to enhance the weather SA for general aviation pilots. AWARE integrates both text-based and graphical weather data that will be ported to an Electronic Flight Instrument System display. The tool will improve the pilot weather SA because pilots are alleviated from the task of integrating the huge flow of independent weather data that they have to do today.

The relationship between weather SA and decision making has proven crucial for many aspects of aviation. For example, Wiegmann, Goh, and O'Hare (2003) found that visual flight rules flights into instrumental meteorological conditions could, in part, be an effect of poor weather SA and experience from the pilots. Results from their study showed that pilots who flew into deteriorating weather early flew longer in the weather before deviating. These pilots were much more optimistic in their projection of the weather than the pilots who experienced the worsening weather conditions later in their flight. Wiegman et al. suggest that training pilots to recognize critical weather cues could increase their weather evaluation skills and, thereby, reduce this major safety hazard.

Much research has focused on developing weather displays for the cockpit; however, far less research has been devoted to the development of display concepts for the TRACON controllers. Furthermore, the current research has focused on *how* to display weather information (e.g., CHI issues) rather than *what* information to display. An example is the CHI designs for advanced weather products developed by the NAS Human Factors Group (2002). The group created weather data graphics for the STARS TCW. Although the study examined the best ways to display these products in the user interface, no empirical data on the usefulness and benefits from these weather products are available. Therefore, the TRACON controllers' weather information needs and the possible effect from these products on controller weather and traffic SA are largely unknown. An important part of the CHI development was to take into account the existing TCW symbols, colors, and controls when creating the display prototypes. The goal was to find a weather display representation that would not obscure, overlap, or, in any way, distract controllers from extracting the vital sector traffic information. Being a very flexible concept design, the system can take weather data input from several external sources such as ITWS, the Weather System Processor, Low-Level Wind Shear Alert System, or any other compatible weather system processors. The weather prototype displays several new weather products: six levels of precipitation, microburst, wind shear, storm motion, storm extrapolated position, gust front and wind shift, terminal winds, storm cell information, terminal weather text, wind shear ribbon display, and highlighted runways. The inherent problems with so many graphical objects on top of the weather display are color coding, clutter, and legibility (Arend, 2003). Designers have to be cautious with color coding and make sure that the critical traffic data are still legible as different overlay graphics are superimposed. Krebs and Ahumada (2001) have proposed a background masking metric that researchers and designers can use when creating good color schemes for weather displays. The metric will predict how colors used in the weather display mask aircraft data block text. Other measures developed specifically for the prediction of text readability are also available (Krebs, Xing, & Ahumada, 2002; Scharff & Ahumada, 2003).

Another related CHI issue concerns the format of the weather display itself. Most ATC weather is displayed in two-dimensions (2D); however, research has been exploring the possible effects of representing weather information in three dimensions (3D). Such display formats could have favorable effects on weather SA because a weather presentation in 3D reveals all constraints with regard to the spatial X-Y-Z positions of the weather object, something that is not possible to show in a 2D representation. This could be particularly useful for the TRACON controller because of the greater dynamics, aircraft density, and vertical maneuvers in the terminal airspace. Wickens, Campbell, Liang, and Merwin (1995) investigated the possible effects on weather SA from display dimensionality by having participants run weather penetration scenarios and vectoring tasks. The result showed no difference between the two display formats with regard to participant accuracy in vectoring aircraft to avoid weather hazards. However, a small speed advantage for the 2D display showed up for some of the tasks. Wickens et al. concluded that a 2D weather display that the controller could 'rotate' into a 3D format, and then 'rotate' back into the 2D format could be the best option. The 2D and 3D formats provide different weather information that is best suited for different controller tasks. St. John, Cowen, Smallman, and Oonk (2001) also found differences in display formats from their research on 2D and 3D displays for shape-understanding and relative-position tasks. 2D displays are superior for judging relative positions (e.g., positions between aircraft), whereas 3D displays are superior for shape understanding. Hanson (1997) envisions 3D volumetric displays that would show air corridors between storm cells, information that controllers would not be able to perceive in 2D displays. The 3D display would also present information regarding in-trail climb and in-trail descent that would more realistically represent the real environment.

Although display format is an issue that requires additional research and development, there is currently little doubt regarding the usefulness of newly developed weather displays. Most of the benefits were recently experienced at the Fort Worth Air Route Traffic Control Center (ARTCC) (Amis, 2002) using Next Generation Weather Data (NEXRAD). The Weather and Radar Processor (WARP) integrates data from several NEXRAD radar sites to display the 'big picture' in ARTCCs. Subsequently, this weather data is displayed to controllers on their Display System Replacement (DSR) consoles in 3 varying shades of blue. During a thunderstorm affecting the Dallas Forth Worth TRACON, controllers were able to direct 15 additional aircraft all the way to the airport before the operations closed due to the thunderstorm. Besides being an aid for the controller during thunderstorms, they also reported that the weather display increased the controller weather SA and confidence level.

2. Discussion

Three problem areas are apparent from the present review of current trends in weather information needs and weather information displays. First, research is lacking on the exploration and specification of the weather information needs for TRACON controllers. What weather information do controllers need to ensure operational safety and maximum efficiency? Second, no research has investigated and organized the TRACON domain constraints and affordances that support goal-directed behavior. Consequently, research is needed to organize the regularities and lawful events (constraints) that provide the TRACON controllers with goal-relevant options (affordances) in their work domain. Third, research is making progress on the identification and display integration of important weather information for the cockpit, but there is a lack of research on how to display such information for the TRACON controller.

Researchers encountered several broad definitions of controller weather information needs in the literature, along with proposed weather products that are said to satisfy these needs. However, very little detail is presented regarding the ATC domain constraints and affordances that constitute the basis for the needs. Environmental constraints, or regularities, are the foundation of information; they make the coupling between organisms and the environment upon which perception relies (Jacobs, Runeson, & Andersson, 2001). ATC domain constraints include, but are not limited to, local aspects such as runway configurations, physical obstacles (e.g., mountains and high buildings), hazardous weather, control procedures, and aircraft performance characteristics. Affordances of things are what they provide or give the observer. They are action-relevant properties of the environment relative to an observer (Gibson, 1979; Runeson, Juslin, & Olsson, 1997). ATC domain affordances specify what they afford the controller (i.e., what actions can be taken by the controller). They are properties of the ATC system domain relative to a controller. For example, a heavy storm cell affords weather incursion and bars aircraft penetration, and spaces or openings between storm cells afford aircraft penetrations. Therefore, there needs to be a consideration of weather in the context of the ATC domain that determines what affordances weather information specifically provides the controller.

The task of identifying goal-relevant constraints in the ATC domain is a gigantic enterprise. However, frameworks are available for this undertaking. Rasmussen (1985) developed a means-end hierarchy that provides a framework for organizing descriptions of goal-relevant constraints for a given work domain. The means-end hierarchy represents the functional structure of a domain (i.e., the set of constraints that are available for an operator to achieve the system goal) (Vicente & Rasmussen, 1990; Vicente & Wang, 1998). This hierarchy has been used successfully to define work environments in several different domains: aviation, power plants, engineering design, medicine, and nuclear power plants, to name a few (Vicente, 1999). Currently, we do not have a clear understanding of the constraints and affordances that affect TRACON controllers, and therefore, there is no rational guidance for implementing weather information into the CHI. The starting point must be a structuring of constraints and affordances in the TRACON domain. Then the designer can turn to the task of building these constraints into the display interface. The important thing is to make use of the powerful capacity of the visual system and to reduce operator problem solving.

Research is progressing on the integration of weather products for the cockpit display. For the TRACON display, very little research is available on weather products, and no research has explored the effects of weather data integration. There is also a lack of research showing alternatives for displaying TRACON weather information. In fact, there is still no answer to the core question of whether the display should present different types of weather information to the controller or simply provide support for automated weather probes and weather advisories.

A weather display presents various sources of weather data that controllers have to interpret. An automated weather probe provides warnings and solutions that they can act upon directly. For the en route controllers, automatic problem resolution capabilities like the User Request Evaluation Tool, the Problem Analysis Resolution and Ranking function (Kirk, Bowen, Heagy, Rozen, & Viets, 2001), and the Direct-To decision support tool (McNally et al., 2001) all probe for severe weather areas and allow the controller to rapidly visualize and evaluate safe routes for aircraft. Similarly, Kuchar, Walton, and Matsumoto (2002) have developed a generalized model of objective (terrain and traffic) and subjective (weather) hazard information that can be incorporated into an automated weather decision-aiding system. Along similar lines, work by Vigeant-Langlois and Hansman (2002) presents an abstraction for probing and assessing potential interactions among aircraft and hazardous weather fields. In their framework, the authors present information about the spatial distribution of hazardous weather fields along the flight path and at locations along the path in a future situation. Future research could evaluate analogous solutions and the effects of automatic weather probes for the terminal ATC domain.

Finally, the strength of display integration (a many-to-one mapping) lies in the move from human cognitive load to effortless information pick-up. There should be no need for tedious mental integration of different sources of weather information. The weather display should unambiguously provide the user with information that is meaningful. Consequently, the information that controllers pick up should directly be usable for goal-relevant behaviors. Ecological Interface Design (EID) is a framework that aims at providing such information of domain affordances in the CHI (Vicente, 2002). The goal is to "make visible the invisible" and to create a one-to-one mapping between perception of the display and the unobservable status of the work domain (Vicente & Burns, 1996). To assist the operator, the framework puts great emphasis on the importance of creating systems that offer the operator computer assistance to avoid arduous problem solving (Vicente & Rasmussen, 1990). It is important to note that the EID's goal is to create an interface based on a means-end hierarchy. The operator acts directly upon the interface and determines for each situation what means are obtainable to satisfy the goal. Therefore, the EID framework is based on structure (affordances) rather than behavior that is the hallmark of traditional task-analysis techniques. Applications of EID have successfully been adopted to control of nuclear power plans, thermal-hydraulic process control systems (Vicente & Rasmussen), pasteurization processes (Reising & Sanderson, 2002a; 2002b), and medicine (Vicente, 1999). There has also been a successful implementation of EID principles for the development of an ATC planning aid. Moertl, Canning, Gronlund, Dougherty, Johansson, and Mills (2002) designed a planning aid that reduced uncertainty by perceptually linking spatial information (e.g., aircraft location, distances between aircraft) and discrete information (e.g., flight identifier, sequence of aircraft, aircraft type). As a result, the planning aid presented a constraint (the perceptual link between spatial and discrete information) in the ATC domain that was not previously visible to the controller. According to Moertl et al., the planning aid made controllers' actions less repetitive and resulted in a much more integrated information retrieval.

New forecast technologies and weather products will bring an ever-increasing bag of tricks for developers in their quest for building effective weather displays. However, the diverse group of NAS users requires different weather information needs. A means-end hierarchy could organize TRACON domain affordances into a coherent structure, thereby disentangling controller needs in a structured way. EID provides a framework for mapping these domain affordances into the display. By virtue of the EID display, controllers can directly pick up goal-relevant information that supports their goal. Automated weather probes could provide a predominant part of the controllers' weather information. There would be no 'many-to-many' mappings of weather information and no need for tedious mental integration. Although this outline for future weather displays sounds a bit revolutionary, a variety of researchers in the greater aviation community have already touched upon this idea. All that future research needs to do is to bring it all together in a form that will serve controllers, pilots, and airline dispatchers.

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Acronyms

2D	Two Dimensions
3D	Three Dimensions
4D	Four Dimensions
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
AWARE	Aviation Weather Awareness And Reporting Enhancements
AWE	Aviation Weather Data Visualization Environment
CHI	Computer-Human Interface
EID	Ecological Interface Design
FAA	Federal Aviation Administration
ITWS	Integrated Terminal Weather System
NAS	National Airspace System
NEXRAD	Next Generation Weather Data
SA	Situation Awareness
STARS	Standard Terminal Automation Replacement System
TCW	Terminal Controller Workstation
TRACON	Terminal Radar Approach Control