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Weather in the Cockpit: Priorities, Sources, Delivery, and Needs in the Next Generation Air Transportation System

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16. Abstract

A study was conducted to identify/verify weather factors important to the conduct of aviation activities and that would be important to consider in systems intended to operate within the NextGen environment. The study reviewed weather-information systems available for General Aviation aircraft at that time. The report presents a listing of recognized aviation weather hazards followed by rankings, by General Aviation pilots, of weather data elements associated with these hazards.

This is followed by a listing of pilot-accessible sources for the relevant weather data and examples of graphical presentations of much of the data. Included is a brief listing and discussion of avionics systems able to host these graphical data. Recommendations are provided for the presentation of weather data in the cockpit, the incorporation of decision aids, forecasts, reliability labeling, and display strategies.

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EXECUTIVE SUMMARY

This report identifies important weather factors in aviation by reviewing the literature on this topic and by providing a new analysis of weather factors and their priorities in various phases of flight. The importance of weather information and its delivery in the Next Generation Air Transportation System (NextGen) is a primary focus of the report. The analysis includes a review of weather information available and systems available for the cockpits of general aviation aircraft as of the completion of this contract work (beginning of fiscal year 2010).

From a human factors perspective, it is vital that pilots and controllers have the right information at the right time. These goals, along with a concern over the potential problem of "too much information" lead to the suggestion that weather information systems should provide information focused on the safety of flight. The information should be presented in a meaningfully integrated way, reflecting all types of weather and all sources of weather information. The presentation of weather information should take other relevant factors into account (e.g., the type of aircraft and the 4-D profile of a particular flight) to focus on information pertinent to that flight with an emphasis on hazardous weather impinging it. The information should reflect the certainty of forecasts and areas with insufficient information to evaluate potential hazards. The information should be geared toward helping the pilot make decisions about executing a safe and efficient flight. While the information should directly relate to decisions, the system should also allow "drilling down" into the details of hazardous weather to allow an understanding of the nature of hazards, giving pilots access to the details of the weather they may need under some circumstances.

With currently available systems, pilots can access a great deal of the weather information available from the National Weather Service. Thus, the information available does cover what is needed for pilots to make decisions about weather affecting their flights. What is not found in most systems today is sufficient integration and filtering of the information to highlight what is relevant to a particular flight. Systems are needed that assist pilots in accessing relevant information to enable timely decisions without extensive searching and increased workload.

LIST OF ACRONYMS AND ABBREVIATIONS USED IN THIS REPORT

Acronym/ Abbreviation	Definition
ACARS	Aircraft Communication Addressing and Reporting System
ADDS	Aviation Digital Data Service
AFIS	Automated Flight Information System
AIRMET	Airmen's Meteorological Information
ARTCC	Air Route Traffic Control Center
ASOS	Automated Surface Observing System
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
AWC	Aviation Weather Center
AWOS	Automated Weather Observing System
AWRP	Aviation Weather Research Program
CFR	Code of Federal Regulations
CWA	Center Weather Advisory
CWSU	NWS Center Weather Service Unit
ESRL	NOAA Earth System Research Laboratory
FAA	Federal Aviation Administration
FMS	Flight Management System
GA	General Aviation (Part 91 operations)
GPS	Global Positioning System
GSD	NOAA/ESRL/ Global Systems Division
IAF	Initial Approach Fix
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
METAR	Aviation Routine Weather Report (from *MÉTéorologique Aviation Régulière)*
MIS	Meteorological Impact Statement
NAS	National Airspace System
NASA	National Aeronautics & Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDFD	National Digital Forecast Database
NEXRAD	NEXt Generation Weather RADar
NextGen	Next Generation Air Traffic System
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Airmen
NOWrad	National Operational Weather radar
NWS	National Weather Service
PIREP	PIlot REPort
RAP	NCAR Research Applications Program
SIGMET	Significant Meteorological Information
TAF	Terminal Aerodrome Forecast
TFR	Temporary Flight Restrictions
TRACON	Terminal Radar Approach CONtrol
VFR	Visual Flight Rules
VHF	Very High Frequency
WFO	Weather Forecast Office
WSI	Weather Services International

Weather in the Cockpit: Priorities, Sources, Delivery, and Needs in the Next Generation Air Transportation System

PURPOSE

This research project was intended to document pilot needs for weather information and the information available to pilots today with a focus on General Aviation (GA – as defined in Title 14 of the Code of Federal Regulations (CFR), Part 91) and scheduled air carrier (Part 121 – as defined in 14 CFR 121) in order to establish a baseline for current needs and usage in preparation for migration to the Next Generation Air Traffic System (NextGen) environment (Leader, 2007; Swenson, Barhydt, & Landis, 2006). Our earlier efforts (Beringer & Schvaneveldt, 2002; Schvaneveldt et al., 2000; Schvaneveldt, Beringer, & Lamonica, 2001; Schvaneveldt, Beringer, & Leard, 2003) were directed at determining the priorities associated with all of the information required for safe flight. In addition, we explored ways in which our analyses could inform the design of information systems.

NextGen, in its mature state, envisions pilots having control over their own flights during the en route phase of flight. One account (Swenson et al., 2006, p. 5) defines en route as starting on the initial turn on climb out during departure and finishing at the final approach fix on arrival. During the en route phase, pilots will be responsible for obtaining information about weather and traffic and adjusting their flight to accommodate these factors. Currently, this responsibility lies with Air Traffic Control (ATC) which accordingly assigns a 4-D flight path to the aircraft. To be sure, the path can be negotiated, but now ATC controls the flight path. Of course, the final authority for the safe conduct of flight operations belongs to the pilot in command.

How does weather information relate to NextGen? On the one hand, NextGen must ensure that pilots have the information they need to execute flights safely without the oversight of en route controllers. This is the primary focus of our analysis, but we also consider how pilots can manage flights safely and more efficiently when they have first-hand access to timely information about the weather ahead. We review several scenarios to illustrate how good weather information can positively affect the conduct of a flight.

BACKGROUND

Next Generation Air Transportation System

The proposed NextGen environment is a National Airspace System (NAS) in which a great deal of aviation-relevant information will be routinely available to pilots and air traffic controllers. Such information includes the flight plans of aircraft, positions of aircraft in the airspace, and spacing and sequencing of aircraft. In addition, current and forecast weather information will be available. All of this information is expected to increase the efficiency of the NAS by allowing pilots to have more control over their flights with the ability to monitor directly from the cockpit other aircraft positions and the weather. Flights will be able to go directly from point A to point B, rather than flying the grid of airways in use today. Of course, even today many flights, especially GA flights, fly direct using Global-Positioning-System (GPS) based navigation.

The following quote from Leader (2007) provides one view of the role of weather information in NextGen:

> The NextGen Network Enabled Weather will serve as the backbone of the NextGen weather support services, and provide a common weather picture to all NAS users. Approximately 70 percent of annual national airspace system delays are attributed to weather. The goal of this investment is to cut weather-related delays by at least 50 percent. The weather problem is about total weather information management, and not just the state of the scientific art in weather forecasting. The weather dissemination system today is inefficient to operate and maintain, and information gathered by one system is not easily shared with other systems. We must integrate predictive weather information with decision support tools and provide uniform real-time access to key common weather parameters, and common situational awareness. The benefits will be improved utilization of air space across all flight domains, and reduced flight delays.

Several studies have examined pilot decision making involving weather (Batt & O'Hare, 2005; Goh & Wiegmann, 2002; Latorella & Chamberlain, 2001; Madhavan & Lacson, 2006). These studies and others will be vital in understanding how to tie weather information to decisions. We address the need for such integration in later sections of the report.

Until recently, the sources of weather information in the cockpit have been from direct observation of the environment, special instruments in the aircraft, and the on-board thermometer together with radio communication. The pilot relied on contacting weather information services to obtain timely information enroute, including Flight Service, a dispatcher, online services, the control tower, the Air Route Traffic Control Center (ARTCC), the Automated Surface Observing System (ASOS), the Automated Weather Observing System (AWOS), the Automatic Terminal Information Service (ATIS), and unicom. Today, a number of avionics systems provide real-time weather information in the form of overlays on maps with controllable zoom levels, and studies have been conducted to examine pilot use of this information for making decisions about continuance of the flight (e.g. Beringer & Ball, 2004). Such information is readily available to aircraft with the appropriate equipment. One challenge for NextGen will be to provide the pilot the needed information to support effective decision making.

Croft (2007) characterizes the impact of weather information in NextGen as follows:

> By knowing the position of severe weather at a given time, pilots flying or planning a flight in the NextGen system will have the ability to select routes that are diversion-free in advance, or efficiently and safely divert around weather in mid-flight. The FAA plans to have these "probabilistic" forecasts, which will include a metric indicating the confidence in the prediction, as part of an online suite of weather tools accessible by all pilots. This should lead to less intervention by the FAA during the planning and execution of a flight, a basic tenet of the NextGen architecture.

McAdaragh (2002) emphasizes the relation of weather information to decision making:

> …system users will be able to acquire the type of weather information that is needed based upon the type of decision-making situation and condition that is encountered. The theoretical approach addressed in this paper takes the form of a model for weather information implementation. This model addresses the use of weather information in three decision-making situations, based upon the system user's operational perspective. The model also addresses two decision-making conditions, which are based upon the need for collaboration due to the level of support offered by the weather information provided by each new product or technology.

Although aircraft used for Part 121 operations had superior navigational and weather information (e.g., inertial navigation and weather radar) in the past, GPS technology and affordable weather detection and reporting systems have, to a large degree, given GA operators the advantage, with some GA aircraft having equipment with superior capability. In the future, with the development of technology, we may expect the capabilities of Part 91 and Part 121 operations to be equivalent if the business case for additional system investment can be made for Part 121 flight decks.

As we look toward NextGen, the problem of integrating multiple sources of information will become critical. We have information from ATIS, AWOS, ASOS, Terminal Aerodrome Forecast (TAF), Aviation Routine Weather Report (from MÉTéorologique Aviation Régulière; METAR), Notices to Airmen (NOTAMs), Pilot Reports (PIREPs), radar, XM radio, onboard laptops, etc. Air traffic controllers now provide much of the integration and, in the case of Part 121 operations, dispatchers access and integrate much of the information required for daily operations. Weather information systems of the future will have to assume this role.

With NextGen, the pilot and crew will be responsible for making decisions about weather and traffic in addition to the usual tasks of managing the aircraft and revising plans under changing conditions. It is vitally important to keep work loads at manageable levels. Good decision support systems can aid in accomplishing this goal, but effective information systems that integrate weather and traffic information are critical. There have been several discussions of issues surrounding the delivery and display of information (Ahlstrom, Keen, & Mieskolainen, 2004; Bussolari, 1994; Boyer & Wickens, 1994; Comerford, 2004). In our report we focus on the analysis of what information is needed and when it is needed, leaving the analysis of how that information should be delivered for later work. We decided that knowing what information should be provided is a prerequisite to exploring how to present it. Work has already been done that provides strategies and principles for the integration of data in displays (e.g., Roscoe, Corl, and Jensen, 1981; Boyer and Wickens, 1994).

The systems envisioned for NextGen make all information potentially available to all users, making it possible for all parties to have a common picture of the weather. As good as this sounds for coordination and communication, it is not clear that a common picture would provide the most relevant information to everyone concerned. In a later section, we discuss the problem of "too much information" along with the advantages of providing each individual with the right information at the right time. Meeting this goal requires factoring in the situation surrounding each player so that information affecting his or her decisions can be made readily available.

Weather in the Cockpit

Providing near real-time weather information to pilots and crews is known as "Weather in the Cockpit." Here are some views on what this means:

From the FAA (2006) we learn that:

> Weather in the Cockpit means we: Employ the aircraft as a node in the National Airspace System's communications, navigation, and surveillance (CNS) network. Enable flight deck weather information technologies that allow pilots and aircrews to engage in shared situational awareness and shared responsibilities with controllers, dispatchers, Flight Service Station (FSS) specialists, and others, pertaining to preflight, en route, and post flight aviation safety decisions involving weather.

In the National Aeronautics & Space Administration (NASA) Aviation Safety Program: Weather in the Cockpit is defined as:

> "… a system combining and presenting various types of weather information obtained through multiple data-link sources, on-board remote sensors, and in-situ sensors to aid crews with effective flight management."

In work on weather in the cockpit at the National Center for Atmospheric Research (NCAR, 2008), they add risk management and decision support (either manual or automated) to further increase the power of accessing real-time weather information in the cockpit as important adjuncts to weather information.

Thus, the evolving conception of "weather in the cockpit" includes decision support in relation to weather information. In regard to decision support, we would like to emphasize the importance of considering the 4-D (3-D plus time) flight path of the aircraft in identifying aspects of the weather that impinge on a particular flight. Also, factoring in the threat to safety posed by weather can further reduce the information load on the pilot which will presumably lead to more rapid and better decisions regarding the safe continuation of a flight.

Phases of Flight

In our original work on weather, we analyzed 11 phases of flight, i.e., Preflight planning, Just before departure, Taxi, Takeoff, Climb, Transition to cruise, Cruise, In-flight planning, Descent, Approach, and Landing (Beringer & Schvaneveldt, 2002). As a result of this work, we discovered that most of the relevant priority information could be captured using just three phases, i.e., on the ground, near the ground, and in flight (Schvaneveldt, Beringer, & Leard, 2003). This three-part division is commonly found in analyses distinguishing phases of flight. In the present analysis, we have added a distinction between arrival and departure because of the importance of time (requiring weather forecasting for different points in time) giving us four phases of flight: Planning, Departure, Cruise, and Arrival. It seems important to distinguish departure and arrival because weather concerns are minimal during departure (weather is considered before takeoff), but weather concerns are paramount throughout arrival, and weather information pertinent to arrival involves forecasting both during planning and en route. Table 1 summarizes the phases.

Weather Factors in Aviation

There are many ways to classify weather in relation to aviation. In this section, we review past work on this issue that led to the classification system we adopted for this report. Several earlier studies have provided lists of important weather factors in aviation (Beringer & Schvaneveldt, 2002; Comerford, 2004; Heuwinkel, 1993; Krozel et al., 2003). Two of these (Beringer & Schvaneveldt, 2002; Heuwinkel, 1993) have also identified priorities associated with the factors. In the interest of bringing these analyses together in one place, summaries of each of these efforts will be presented here.

A summary of the Beringer and Schvaneveldt (2002) analysis of the priority of weather factors in various phases of flight is shown in Table 2, and the analysis from Heuwinkel (1993) is shown in Table 3.

Table 1. Phases of Flight and Weather Considerations

Planning	Entire flight plus 45 minutes. Planning should include potential changes in weather as a function of the time of the flight.
Departure	Weather concerns are limited because weather was considered before takeoff, but there is concern for the location and intensity of convective activity in the vicinity of the airport. Usually the departure controller, if available, provides this information.
En route	Confirming planned weather conditions and considering potential changes in weather as a function of the time of the flight. New planning is often involved.
Arrival	Constant weather concerns through approach plus concerns about potential missed approach and the weather factors associated with the alternate airport.

Table 2. Priorities of Weather Factors in Various Phases of Flight
Adapted from Beringer & Schvaneveldt (2002)

Weather Factor	Plan	Depart	Cruise	Arrive	Mean
freezing rain/sleet	1.1	1.1	1.1	1.1	1.1
hail	1.1	1.0	1.1	1.1	1.1
lightning	1.4	1.3	1.3	1.2	1.3
wind shear	1.3	1.3	1.8	1.2	1.4
snow	1.4	1.4	1.6	1.4	1.5
cloud ceiling	1.4	1.5	2.3	1.4	1.7
sand/dust storms	1.6	1.7	1.9	1.4	1.7
clear air turbulence	1.6	1.7	1.6	1.7	1.7
mountain rotors	1.5	1.8	1.6	1.8	1.7
downdraft	1.7	1.6	2.1	1.4	1.7
updraft	1.8	1.8	2.2	1.6	1.9
cloud coverage	1.6	1.9	2.3	1.8	1.9
cloud types	1.8	2.0	2.0	1.8	1.9
surface wind velocity	1.6	1.5	3.1	1.4	1.9
gusts	1.9	1.7	2.6	1.4	1.9
surface wind direction	1.5	1.4	3.2	1.6	1.9
rain	1.9	1.8	2.3	1.8	2.0
haze	1.9	2.0	2.4	1.8	2.0
present temperature	1.9	2.0	2.0	2.2	2.0
aloft wind direction	1.8	2.1	2.0	2.2	2.0
aloft wind velocity	1.8	2.2	1.9	2.4	2.1
cloud thickness	2.0	2.1	2.5	1.8	2.1
dewpoint	1.8	2.1	2.4	2.2	2.1
atmospheric pressure	2.1	2.3	2.4	2.1	2.2
rate of temperature change	2.2	2.2	2.4	2.2	2.3
rate of pressure change	2.2	2.4	2.5	2.4	2.4
vertical temperature gradient	2.2	2.4	2.6	2.4	2.4
geographical temperature gradient	2.5	2.6	2.9	2.8	2.7
percent ≤ 1.5	28.6	28.6	10.7	35.7	17.9
percent ≤ 2.0	82.1	67.9	42.9	67.9	71.4
percent ≤ 2.5	100	96.4	82.1	96.4	96.4
percent ≤ 3.5	100	100	100	100	100

Note. 1 is highest priority.

Table 2 shows that weather factors vary in their priority and the consistency of the priority throughout the various phases of flight. The very hazardous weather conditions at the top of the table are of constant concern, but it should be emphasized that they are really only of concern when they are present. Table 2 also reveals that several factors have high priority for only specific phases of flight. Taking surface winds as an example, one can see that it has high priority for all surface-related operations and planning, but surface-wind factors have above priority 3 for the en route phase. We will discuss the importance of limiting information to the essentials later in the report, but note that a phase-of-flight filter might "suppress" surface-wind information during climb, cruise, and descent but would present it prior to and during taxi/take-off and for approach and landing. It is also evident that some phases would have filters that are very similar, in that the importance of factors changes only slightly from one to another. The lower priorities associated with cruise should be qualified by the realization that additional planning is often involved in cruise, bringing the factors involved in planning into play again.

The analysis presented in Table 3 provides a slightly different slant on the weather factors, but there is marked agreement in the analyses provided by Tables 2 and 3.

Table 3. Weather Factors & Priorities During Phases of Flight From Heuwinkel (1993)

	Preflight	Departure	En Route	Approach & Landing
Significant Weather				
Convective Activity/Initiation	H	H	H	H
Lightning	M	H	M	
Microburst/Gust Front	H	H		H
Low Level Windshear	H	H		H
Icing and Freezing Level	H	H	H	H
Widespread Low Visibility	H		H	M
Clear Air Turbulence	H	H	H	H
Other Turbulence	H	H	H	H
Wake Vortex Detection/Dissipation	H	H		H
Volcanic Ash	H	H	H	H
Routine Weather				
Cloud Bases, Tops, Coverage	H	H	H	H
Ceiling	H	H	H	H
Surface Visibility	H	H	H	H
Runway Visual Range	H	H	H	H
Inflight visibility	H	H	H	H
Wx/Obstruction to Vision/Surface Conditions	M	H	M	M
Surface Temperature	H	H		H
Surface Dewpoint				
Surface Wind/Wind Shift Prediction	H	H	H	H
Altimeter Setting		H	H	H
Density Altitude	H	H		
Pressure Patterns/Fronts	H			
Winds and Temperatures Aloft	H	H	H	
Tropopause Height and Temperature	H			

Note. H = High Priority, M = Medium Priority

Table 4 summarizes the weather hazards noted by Krozel et al. (2003). By considering hazards such as the ones they identified, the delivery of weather information could focus on the weather that presents a threat to safety. As we remarked earlier, the amount of information presented could be reduced by focusing on the dangerous weather conditions that prevail relative to the specific flight.

Comerford (2004) summarizes several sources that have identified the types of weather having particular importance to aviation. The sources include FAA (2001), Honeywell (1999), Keel et al. (2000), and the Raytheon ATMSDI Team (2002). The 14 weather types identified from these sources include: Convection, Cyclones, Hail, Hurricanes, Icing, Lightning, Precipitation, Temperature, Thunderstorms, Tornados, Turbulence, Visibility/ceiling, Volcanic Ash, and Winds.

Comerford (2004) also presents several recommendations for providing weather in the cockpit. These recommendations and the reasons for them are important in planning for systems that enable NextGen. Her recommendations dovetail with many of the considerations that have emerged from our work on this problem. Here are her recommendations (with our comments added in italics).

- Obtain information that is based on multiple types of weather, E.g., the weather factors shown in Figure 1.
- Obtain information that is based on multiple sources of weather. Use all of the sources available.
- Utilize an algorithm based on meteorological principles to create a meaningful integration of the various types of weather and various sources of weather. Integrate the various sources into a meaningful picture of the weather.
- Include relevant, non-meteorological variables in the integration algorithm, E.g., the aircraft, the pilot's skill level, risk tolerance.
- Based on the algorithm discussed in the previous pages, create and display general "hazard zones." Provide direct information about factors that affect the particular flight.
- Create and display "insufficient data" zones to inform the user that there is either no data or insufficient data to determine if an area is hazardous. To help avoid the assumption that no news is good news.
- Provide the flight crew with the ability to access the list of weather variables that are responsible for "creating" a hazard zone and/or any weather variables that might be available about an "insufficient data" zone. Under some circumstances, pilots may be forced to negotiate encounters with weather hazards. Detailed information would be of value.
- Allow the flight crew to view weather variables in isolation on an as needed basis. Pilots may want to serve as their own forecasters in some circumstances.
- Display the age of weather information on the display. Provide some indication of the certainty associated with weather information. This may also include forecast uncertainties.

A distillation of our review of the literature and a new detailed analysis of our own leads to the weather factors shown in Figure 1. The links show salient relations between the factors. This final set of factors includes all of those identified in the various papers plus some additional factors to complete the coverage.

ANALYSIS: PRIORITIZING WEATHER DATA

Weather Hazards and Priorities of Weather Factors by Phase of Flight

In this section, we provide a new analysis of the priorities based on the judgments of expert pilots who reviewed the earlier work reviewed here. We have also identified specific hazards associated with each of the weather factors. A summary is presented in Table 5, with notations where ratings of weather factors differed between operating in visual flight rules (VFR) and operating in instrument flight rules (IFR). In characterizing the weather factors, we describe the weather at a level that directly feeds into decision making by the pilot. Instead of listing details of weather measurements, we identify systems of weather important to the safety of flight as well as a number of specific weather threats. Some details are embedded within weather systems. For example, hail and lightning are associated with thunderstorm activity so identifying the severity and location of thunderstorms will locate hail and lightning. Some of the factors identified in our earlier work were at too fine a resolution. For example, it is more helpful to know the type and location of fronts rather than rates of temperature and pressure changes along with the geographical temperature gradient.

The safety of flight can be compromised when high-priority weather factors are not taken into account during planning or in flight. The pilot's work load would be lighter if the information provided led directly to decisions rather than requiring interpretation and inference to arrive at the needed information. Ideally weather information systems might directly indicate critical information, e.g., the location and severity of thunderstorms. In general, the priority of weather factors together with the state of the factors in the world determines the criticality of each factor. For example, density altitude is particularly important when the temperature is high or, more generally when the density altitude becomes too high for safe operations. Thus, density altitude only needs to be displayed when it is above the safety-critical level. In summary, concerns for safety

Table 4. Aviation Weather Hazards From Krozel et al. (2003)

Phenomena	Risk to Pilot/Passengers and/or Aircraft
Fog/Haze/Smoke	Visibility hazard; Pilot has difficulty with landing, taxi, or takeoff.
Clouds	Visibility hazard; Pilots not trained to fly according to Instrument Flight Rules (IFR) may become disoriented, possibly leading to loss of control.
Thunderstorms	Hazards associated with thunderstorms include: lightning, hail, heavy rain, wind gusts, microbursts, CIT, tornadoes, waterspouts, and icing.
Hurricanes	Hurricanes combine the hazards of gust, strong winds, and heavy rain. Problems associated with severe convection (turbulence, tornadoes, etc.) occur over a wide-spread area.
Lightning	Could temporarily blind a pilot; Can cause physical damage to airframe or avionics.
Hail	Causes physical damage to the windshield, wing leading edges, and other aircraft surfaces. Physical damage could lead to loss of control of aircraft. Could cause physical damage to aircraft while parked or taxiing. Not much of a visibility hazard.
Heavy Rain	Associated mainly with thunderstorms, but could also come from stratiform clouds. Could be a visibility hazard for the pilot. Could degrade engine performance for jets. Could cause flooding at airports or cause hydroplaning during landing or takeoff. Also has a minor impact on aerodynamics performance (loss of lift).
Icing (Clear, Rime, or Mixed)/ Graupel/ Sleet	Degrades aerodynamic performance causing a loss of climb or possibility tail instability. The stall speed increases, the lift decreases, and the drag increases – an airplane flies contrary to pilot expectations. Some jet engines cannot tolerate a lot of ice crystals – engine flame out is possible. Ice particles can clog engine filters. Blocks of ice on leading edges of wings can break off and enter a tail mounted engine. Intermittent icing may be associated with thunderstorms and convection and continuous icing may be associated with stratiform clouds. When associated with convection icing adds to the risks associated with thunderstorms and with stratiform or continuous icing, it adds to the risks associated with reduce visibility.
Wind Shifts	A sustained change in the wind, which can cause problems during takeoff and landing if the runway configuration/takeoff direction is not adequately addressed.
Wind Gusts	A quick change in the wind speed and/or direction. Can cause control problems during takeoff or landing. Gusts at takeoff quickly degrade aerodynamics and can cause fatal accidents.
Jet Stream	Turbulence regions may exist near jet stream boundaries.
Convective Induced Turbulence (CIT)	CIT is caused by the instability and resulting up and down drafts. Could physically damage the aircraft if strong enough. Even light turbulence causes passenger discomfort. Extreme turbulence could cause physical injuries to pilot/passengers who are not wearing seat belts.
Clear Air Turbulence (CAT)	CAT could damage aircraft if strong enough. Even light turbulence causes passenger discomfort. Extreme turbulence could cause physical injuries to pilot/passengers who are not wearing seat belts. Generally caused by wind shear in the atmosphere where no clouds are present.
Mountain Waves	Fast change in vertical wind velocity, eddy currents, and rotors could cause turbulence or shifts in wind that greatly affect aircraft aerodynamics. Frequently results in moderate or greater turbulence. Could lead to a loss of aircraft control or at the extreme, structural failure.
Microburst/ Wind Shear	Wind shear is dangerous to the aerodynamics and can cause loss of control or uncontrolled impact with the earth. Microbursts are a specific kind of wind shear which results in an increase in performance, a downdraft and a strong decrease in performance, possible leading to a loss of control and uncontrolled impact with the earth.
Tornado/ Waterspout	High vorticity wind conditions associated with tornado/water spout are very dangerous. Very difficult to control the aircraft potentially leading to a loss of aircraft. Wind and/or flying debris can damage or destroy aircraft on the ground (even if tied down or in hangars).
Snow	Could be a visibility hazard (white out) for the pilot, possibly causing loss of control. Likely (possibly) to be coupled with icing. If snow on the aircraft is not removed before takeoff, could degrade aerodynamics performance. Snow/ice on runways could cause an aircraft to slide off the runway during landing, taxi, or takeoff.
Blizzard	Blizzards combine the hazards of wind gusts, icing, and heavy snowfall. Reduced visibility may adversely affect the pilot.
Volcanic Ash	Visibility hazard if near the eruption. Could damage engine parts leading to flame out and scratch/pit wind shield leading to loss of visibility for pilot. Encounters with volcanic ash can destroy the airplane even if landed safely.

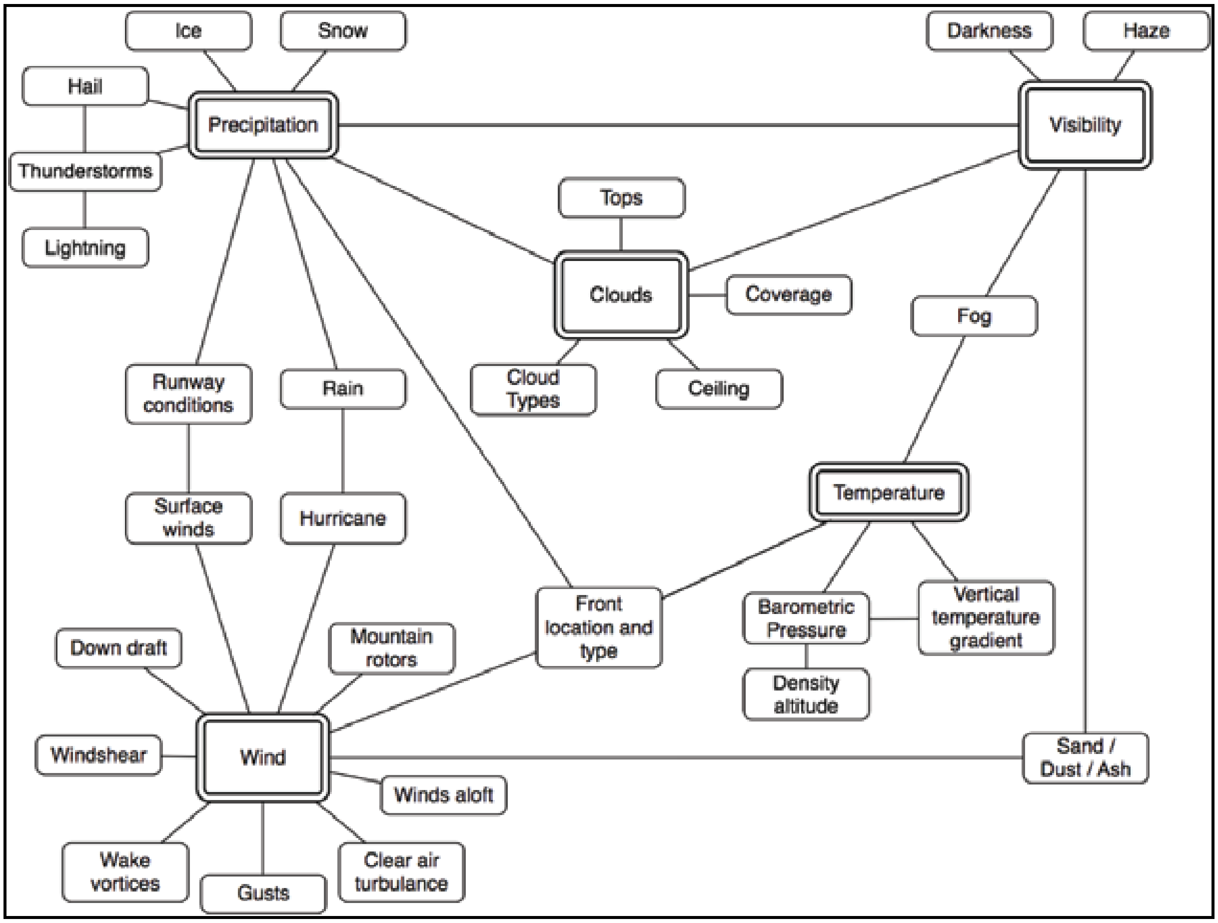

Figure 1. Weather Factors and Some Salient Relations Between the Factors

should drive the delivery of weather information. When a weather condition could compromise the safety of flight, it should be rapidly and clearly communicated to the pilot. In the context of a control hierarchy, a good display for flight control shows the pilot how to move the controls to achieve the desired goal state. Thus, a good fully integrated navigation display system should contain sufficient data, in a coherent reference frame, to show the pilot how to position the aircraft in 4-D space-time to achieve the goals of the flight: (1) separation from hazardous weather conditions, (2) separation from traffic, (3) separation from restricted-use airspace, and (4) separation from terrain, while progressing, in a timely fashion, toward the flight's intended destination (Roscoe, Corl, & Jensen, 1981).

Aside from the Planning phase which is usually accomplished without severe time pressure, pilot concern with weather is greatest during the Arrival phase (20 factors with Priority 1), followed by Departure (13 factors with Priority 1). These are the times during flight when workload is highest (Corwin, 1992). Concern with weather factors certainly contributes to this workload, but clearly several other factors are involved as well. A weather factor is actually only at issue when some hazard or threat associated with the factor is in play. Consequently, the static priorities probably overestimate the impact of weather factors in all but the worst of conditions.

The combination of weather factors, their priorities, the threats to safety associated with the factors, and the actual weather conditions in effect can be used to further prioritize information to help avoid providing too much information, as discussed in the next section.

Too Much Information

Along with a concern for delivering timely and accurate weather information to pilots, we should note that presenting too much information can compromise safety. The goal is to avoid trouble (Ramsey, 2003). Too much information can make it difficult to locate safety-critical information. An exhaustive presentation of all the weather from every possible source (including other aircraft) can easily hinder the ability to locate the information relevant to a particular flight at a particular time. Similarly, when weather information is presented in different layers, requiring a search through layers to find needed information, the likelihood of missing critical information is increased. What is needed are integrated systems providing safety-critical

Table 5. Weather Information Priorities by Phase of Flight and Hazards (1 is Highest Priority)

Weather Factor	Plan	Depart	Cruise	Arrival	Hazardous Conditions / Effects
Barometric pressure	**1**	**1**	**1**	**1**	Pressure change / erroneous altimeter setting, wrong altitude
Clouds/ceiling	**1**	**3**	**4**	**1**	Ceiling too low / below IFR minimums, VFR too low
Clouds/coverage	**4/1**	**3**	**4/1**	**4/1**	Large area with low clouds / no alternate airport
Clouds/tops	**2**	**3**	**2**	**4/2**	Turbulence, hail, icing / VFR not able to be on top
Clouds/types	**2**	**3**	**2**	**4/2**	Nimbostratus, cumulonimbus / thunderstorms, precipitation
Density altitude	**1**	**1**	**4**	**3**	High density altitude / decrease performance, need longer runway
Front location & type	**1**	**1**	**3**	**1**	Cold fronts (wind, gusts, precip.) / loss of control, poor braking
Precipitation/Ice/freezing rain/sleet	**1**	**1**	**1**	**1**	Ice / poor aerodynamics, loss of control
Precipitation/Rain	**3**	**3**	**3**	**2**	Driving rain / poor visibility, hydroplaning, poor braking
Precipitation/Snow	**3**	**3**	**3**	**1**	Blizzard / poor visibility, poor steering & braking
Present/Forecast temperature	**1**	**1**	**4**	**1**	Extremes / poor performance, icing conditions
Runway conditions	**1**	**1**	**4**	**1**	Water, ice / loss of control, hydroplaning, poor braking
Thunderstorms/Hail/Lightning	**1**	**1**	**1**	**1**	Hail, lightning / damage, loss of control, blindness
Vertical temperature gradient	**3**	**4**	**4**	**4**	Freezing levels / ice, poor aerodynamics, loss of control
Visibility	**1**	**4/1**	**4/1**	**1**	/ loss of visibility, limits navigation, strike obstacles, illusions
Visibility/Fog (dew point)	**1**	**1**	**4/1**	**1**	/ Ditto plus carburetor icing, forecasting precipitation
Visibility/Haze	**1**	**3**	**4/2**	**1**	/ loss of visibility, limits navigation, strike obstacles, illusions
Visibility/Sand/Dust/Ash	**3**	**3**	**2**	**1**	/ Ditto plus damage to aircraft/engine
Wind/Clear air turbulence	**3**	**4**	**1**	**4**	/ damage to aircraft.
Wind/Downdraft	**4**	**1**	**4**	**1**	/ loss of control, impact
Wind/Gusts	**3**	**2**	**4**	**1**	/ loss of control, structural failure
Wind/Hurricanes	**1**	**1**	**1**	**1**	/ damage to aircraft and passengers, loss of control
Wind/Mountain rotors	**3**	**1**	**3**	**1**	/ damage to aircraft and passengers, loss of control, impact
Wind/Surface Winds	**3**	**1**	**4**	**1**	/ directional control, runway distance for tailwinds
Wind/Tornadoes	**1**	**1**	**1**	**1**	/ damage to aircraft and passengers, loss of control
Wind/Wake Vortices	**4**	**2**	**4**	**1**	/ damage to aircraft and passengers, loss of control
Wind/Winds Aloft	**1**	**4**	**2**	**4**	/ fuel exhaustion, undesirable alternates
Wind/Windshear	**4**	**2**	**4**	**1**	/ damage to aircraft and passengers, loss of control, stall
Number of items ranked #1	***16***	***13***	***7***	***20***	

Note. Two priorities separated by a slash (e.g., 4/1) indicate different priorities for IFR and VFR flight. The values are in the order IFR/VFR.

information without requiring a search. Such information certainly goes beyond weather to traffic and conditions of the aircraft, to name two other broad areas. A combination of ground-based systems designed to collect and summarize a vast amount of weather information and on-board systems designed to filter what is relevant to the flight should be able to present salient information at the appropriate level of detail. Similarly, the role of an individual in the system may affect what information is relevant to the decisions the individual must make. Pilots probably need different information than do controllers. In summary, meeting the goal of presenting the right information at the right time requires:

- Defining what information is needed.
- Defining when that information is needed.
- Combining the priority of weather information factors with the actual state of the world to identify what information is critical to decisions enabling safe flight during the 4-D profile of the flight.
- Making flight plans part of the weather information system so the system can take into account the planned 4-D course of flight, thus providing forecast information appropriate to the flight. Such plans can be updated in real time as the actual flight unfolds. Current conditions and decisions made in flight can change the flight plan. Ideally, a current flight plan would affect what to display and when to display it. The uncertainty associated with forecasts must be conveyed to enable effective decision making. If pilots know sooner about problems ahead (thunderstorm cells, airports expected to be below minimums, etc.), they can employ more effective and efficient means of coping with the problems. With enough advance information, a small heading change can avoid potential trouble at small cost.
- Additional constraints to consider in deciding what information to display include characteristics of the aircraft and the pilot. The severity of threats clearly varies as a function of the nature of the aircraft and the experience of the pilot. As an extreme example, consider the difference between VFR and IFR flights.
- Timeliness is central to weather information. The generic phrase "stale weather" translates to "lack of weather information." The time interval for forecast phenomena should be within about 10 minutes to be considered useful. The time from the Initial Approach Fix (IAF) to landing is about that long.

Ahlstrom and colleagues (Ahlstrom & Della Rocco, 2003; Ahlstrom, Keen, & Mieskolainen, 2004) proposed an approach to organizing weather information for Terminal Radar Approach CONtrol (TRACON) controllers using Rasmussen's (1985) means-end hierarchy, which provides an organization of goal-relevant constraints. While the details of the approach have yet to be provided, characterizing constraints can help lead directly to decisions about the design of information systems. Realizing the goal of tying weather information to the dynamics of particular flights will require the development of intelligent systems to manage, integrate, filter, and present the information. Several studies have begun to explore the requirements of such intelligent systems (e.g., Comerford, 2004; Evans, Weber, & Moser, 2006; Honeywell, 1999; Krozel et al., 2003; Kulkarni et al., 2004; Swenson et al., 2006).

SOURCES OF WEATHER INFORMATION

As a background to specifying the weather information potentially available to pilots, it will be useful to review the way in which the United States government collects and distributes the weather. To this end, we review the several weather reports and forecasts available from the National Weather Service. While there are several ways in which weather information is distributed, much of the information originates from this agency.

The National Weather Service

The National Weather Service (NWS) is a scientific agency within the National Oceanic and Atmospheric Administration (NOAA) of the United States government. The NWS provides "weather, hydrologic, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy" (mission statement from the NWS website: www.nws.noaa.gov/mission.php). The NWS maintains national and regional centers and more than 122 local weather forecast offices (WFOs). Because the NWS is a government agency, most of its products are in the public domain and available free of charge. Each of the 122 WFOs send their graphical forecasts to a national server to be compiled in the National Digital Forecast Database (NDFD). The weather elements collected include: maximum and minimum temperature, humidity, cloud cover, probability of precipitation, amount of precipitation and wintry precipitation, weather type, and wind direction and speed.

Although the NWS is the original source of much of the information about the weather, commercial weather vendors often provide enhanced means of presenting the information in graphical form. The provision of free graphical forecast data by the NWS has led some commercial vendors to complain that their commercial efforts can be undermined by the NWS offerings. With uncertainty over the limits to what the NWS will provide in the future, commercial innovation may be curtailed. There is something of a quandary here because it is vital that the government does what it can to promote the safety and welfare of its citizens, which suggests that the NWS provide information in the most effective forms. At the same time, innovation in the commercial sector should be encouraged. Perhaps future commercial efforts will focus more on the delivery and presentation of information than on the design of displays. In aviation, there appears to be room for developing weather information systems that are tailored to the specifics of individual flights. This would require selecting and displaying information that might affect the flight. Displays could also be designed to indicate clearly just where weather problems exist for a specific flight, thus aiding pilot decision making. Such information systems seem more likely to be developed by commercial enterprises than by the government.

The NWS supports the aviation community through the production of several specific forecast products. The Aviation Digital Data Service (ADDS) provides aviation-related weather (see adds.aviationweather.gov/). Each WFO issues TAFs for one or more airports in their jurisdiction. TAFs are concise, coded 24-hour forecasts for specific airports, issued every six hours with amendments as needed. As opposed to a public weather forecast, a TAF only addresses weather elements critical to aviation. These elements are: wind, visibility, weather, sky condition (clouds), and optional data such as wind shear.

Twenty-one NWS Center Weather Service Units (CWSUs) are collocated with the FAA ARTCCs. Their main responsibility is to provide up-to-the-minute weather information and briefings to the Traffic Management Units and control-room supervisors. Special emphasis is given to weather conditions that would be hazardous to aviation or would impede the flow of air traffic in the National Airspace System. Beside scheduled and unscheduled briefings for decision makers in the ARTCC and other FAA facilities, CWSU meteorologists also issue two unscheduled products. The Center Weather Advisory (CWA) is an aviation weather warning for thunderstorms, icing, turbulence, and low cloud ceilings and visibilities. The Meteorological Impact Statement (MIS) is a 2- to 12-hour forecast for weather conditions expected to impact ARTCC operations.

The Aviation Weather Center (AWC), located in Kansas City, MO, is a central aviation-support facility operated by the National Weather Service. The AWC issues two primary products, AIRMETs (Airmen's Meteorological Information) and SIGMETs (Significant Meteorological Information). An AIRMET provides information on icing, turbulence, mountain obscuration, low-level wind shear, Instrument Meteorological Conditions (IMC), and strong surface winds. AIRMETs are primarily aimed at smaller aircraft with limited capability, often flying under VFR. SIGMETs provide both convective and non-convective information about significant weather activity. Convective warnings are issued for thunderstorms affecting an area of 3,000 square miles or greater, a line of thunderstorms at least 60 nm long, and/or severe or embedded thunderstorms affecting any area that are expected to last 30 minutes or longer. Non-convective warnings are issued for severe or greater turbulence over a 3,000-square mile area, severe or greater icing over a 3,000 square mile area, or IMC over a 3,000 square mile area due to dust, sand, or volcanic ash.

Delivery of Weather Information

Pilots can obtain weather information from many sources. In this section, we summarize delivery of the information both on the ground and in the cockpit. The technology for delivering weather information is in an extremely active state of development today. New systems, both installed and portable, are appearing frequently. Thus, we can provide just a snapshot of what is available as of August 2008. We consider three primary methods of delivery: via the Internet, via VHF (Very High Frequency) broadcast, and via satellite broadcast.

The Internet. A great deal of weather information can be obtained from the Internet. This information is certainly useful in flight planning, and with the development of technology, it seems likely that pilots will be able to access the internet in flight giving them access to all of the information provided by the NWS. Because much of this information can be delivered via other methods including satellite radio, we provide some details about what is available to indicate what can be potentially provided in the various systems.

The NWS website provides an overview of weather information available for the USA (www.weather.gov/). The AWC (http://aviationweather.gov/) is focused on reports and forecasts of direct relevance to aviation. The ADDS (adds.aviationweather.noaa.gov/) makes available to the aviation community text, digital and graphical forecasts, analyses, and observations of aviation-related weather variables. ADDS is a joint effort of NCAR Research Applications Program (RAP), Global Systems Division (GSD) of NOAA's Earth System Research Laboratory (ESRL), and the National Centers for Environmental Prediction (NCEP) AWC. The FAA funds and directs the continuing development of ADDS as well as other experimental products being developed by the FAA Aviation Weather Research Program (AWRP). The results of the latest ADDS development efforts along with new experimental AWRP algorithm results can be viewed on the experimental ADDS site (http://weather.aero/).

Aviation Digital Data Service (ADDS). On the ADDS website, the NWS provides weather reports and forecasts in digital form. Graphical displays are available showing turbulence, icing, convective activity, winds and temperatures, prognosis charts, radar images, satellite images, AIRMETs, SIGMETs, PIREPs, TAFs, and METARs. Text forms are also available for TAFs, METARs, PIREPs, SIGMETs, and AIRMETs. Translated forms are provided for most, but not all of the text reports. The coded forms can be difficult to assimilate, especially by novice pilots, and pilots with limited currency can also find the coded forms difficult to interpret. It is interesting to note that the coded text forms are still found in many of the reports, and some display systems provide the coded forms in the cockpit. Today's technology can certainly support sending the longer translated forms, and yet it is not the standard.

Tables 6 and 7 provide some examples of text reports with translations. The TAF (in Table 7) shows both current and forecast conditions.

The graphical forms of the information are illustrated in Figures 2 and 3. They convey the information about geographical location more directly, but they cover large areas. It would be good to have them focused on the relevant areas for a flight. It is also more difficult to get the details from the graphical display as compared to the text forms. It is recommended that an option for a more localized display be implemented to facilitate getting at the relevant details.

Table 8 shows the connections between the weather factors we have identified and the information provided by the NWS. The good news is that the weather factors are generally well covered by the information provided. None of the reports provides information about density altitude, downdrafts, or mountain rotors. Of course, density altitude can be calculated from altitude, temperature, barometric pressure, and dew point, making it specific to a particular location. Still, it helps to have that information about a specific airfield. The ATIS report would provide this information, as would communication with a controller. Downdrafts and mountain rotors are short-lived phenomena that cannot be captured in reports covering longer durations. These, too, would be provided by ATIS or controllers with the information. In the interest of integrating relevant information, we recommend that ATIS information, as well as other information from controllers, be integrated into flight management systems in the cockpit.

VHF Broadcast. Communication between controllers and pilots uses VHF radio. Controllers provide weather information, along with other things such as clearances and instructions. Automated systems such as ATIS rely on VHF communication as well. ATIS provides localized information near airports including: barometric pressure, clouds (ceiling, coverage, types), density altitude, fronts, precipitation (ice, freezing rain, sleet, rain, snow), present temperature, runway conditions, thunderstorms (hail, lightning), visibility (fog, haze, sand, dust, ash), wind (downdrafts, gusts, surface winds, tornadoes, wind shear). Other systems use VHF frequencies to transmit information such as ACARS (Aircraft Communication

Table 6. METAR Text Report and Its Translation

Aviation Digital Data Service (ADDS) Output produced by METARs form (1608 UTC 22 August 2008) found at adds.aviationweather.noaa.gov/metars/index.php	
METAR text:	KTPA 221553Z 23012KT 9SM -RA FEW025 SCT039 OVC150 28/25 A2982 RMK AO2 RAE31B50 SLP098 P0000 T02780250
Conditions at:	KTPA (TAMPA, FL, US) observed 1553 UTC 22 August 2008
Temperature:	27.8°C (82°F)
Dewpoint:	25.0°C (77°F) [RH = 85%]
Pressure (altimeter):	29.82 inches Hg (1009.9 mb) [Sea-level pressure: 1009.8 mb]
Winds:	from the SW (230 degrees) at 14 MPH (12 knots; 6.2 m/s)
Visibility:	9 miles (14 km)
Ceiling:	15000 feet AGL
Clouds:	few clouds at 2500 feet AGL scattered clouds at 3900 feet AGL overcast cloud deck at 15000 feet AGL
Weather:	-RA (light rain)

Table 7. A Portion of a TAF Report and Its Translation

Aviation Digital Data Service (ADDS) Output produced by TAFs form (1606 UTC 22 August 2008) found at adds.aviationweather.noaa.gov/tafs/index.php	
Forecast for:	KTPA (TAMPA, FL, US)
Text:	KTPA 221314Z 221312 26014G24KT P6SM -RA SCT015 BKN045 OVC060
Forecast period:	1300 to 1600 UTC 22 August 2008
Forecast type:	FROM: standard forecast or significant change
Winds:	from the W (260 degrees) at 16 MPH (14 knots; 7.3 m/s) gusting to 28 MPH (24 knots; 12.5 m/s)
Visibility:	6 or more miles (10+ km)
Ceiling:	4500 feet AGL
Clouds:	scattered clouds at 1500 feet AGL broken clouds at 4500 feet AGL overcast cloud deck at 6000 feet AGL
Weather:	-RA (light rain)
Text:	TEMPO 1316 2SM +RA BKN015
Forecast period:	1300 to 1600 UTC 22 August 2008
Forecast type:	TEMPORARY: The following changes expected for less than half the time period
Visibility:	2.00 miles (3.22 km)
Ceiling:	1500 feet AGL
Clouds:	broken clouds at 1500 feet AGL
Weather:	+RA (heavy rain)
Text:	FM1600 25017G27KT P6SM -RA SCT015CB BKN030 OVC050
Forecast period:	1600 to 2000 UTC 22 August 2008
Forecast type:	FROM: standard forecast or significant change
Winds:	from the WSW (250 degrees) at 20 MPH (17 knots; 8.8 m/s) gusting to 31 MPH (27 knots; 14.0 m/s)
Visibility:	6 or more miles (10+ km)
Ceiling:	3000 feet AGL
Clouds:	scattered clouds at 1500 feet AGL broken clouds at 3000 feet AGL overcast cloud deck at 5000 feet AGL
Weather:	-RA (light rain)
Text:	TEMPO 1620 2SM +RA BKN015
Forecast period:	1600 to 2000 UTC 22 August 2008
Forecast type:	TEMPORARY: The following changes expected for less than half the time period
Visibility:	2.00 miles (3.22 km)
Ceiling:	1500 feet AGL
Clouds:	broken clouds at 1500 feet AGL
Weather:	+RA (heavy rain)

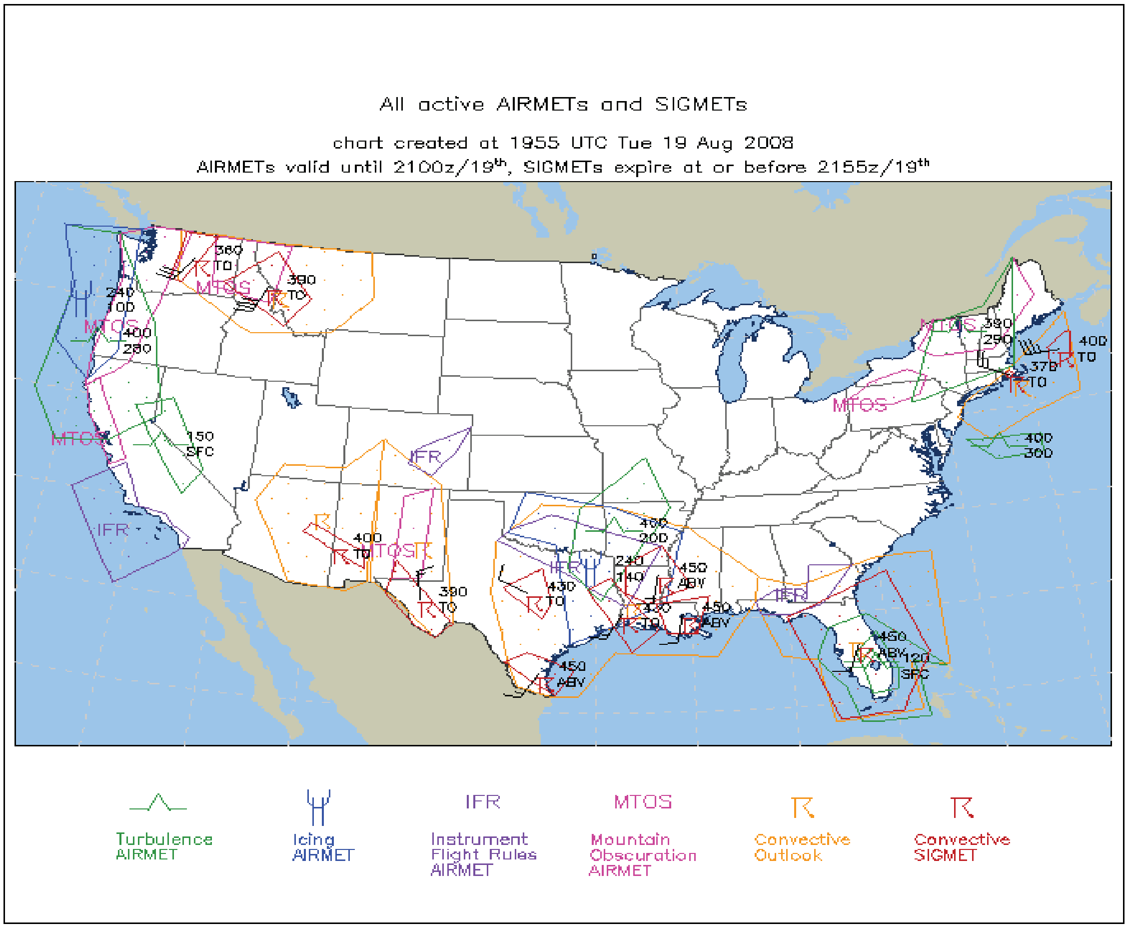

Figure 2. Display of AIRMETs and SIGMETs in the Lower 48 States

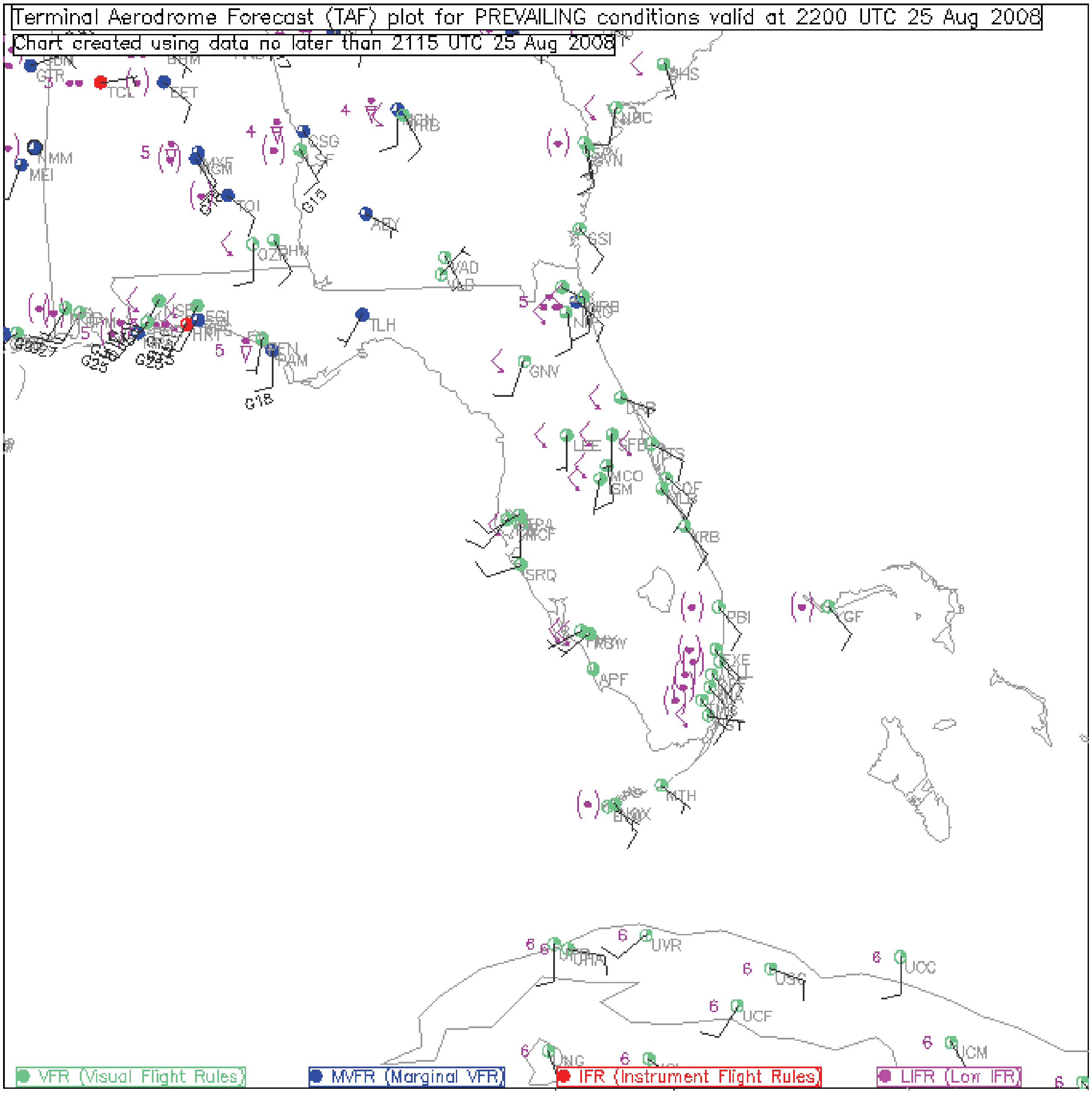

Figure 3. Display of TAF Reports in the Lower Southeastern United States

Table 8. NWS Reports for Each Weather Factor

Weather Factor	NWS Source(s)
Barometric pressure	METARs Surface Pressure
Clouds/ceiling	AIRMETs METARs TAF
Clouds/coverage	TAF METARs Satellite Mosaic
Clouds/tops	METARs TAF
Clouds/types	TAF
Density altitude	
Front location & type	Surface Analysis Weather Maps METARs
Precipitation/Ice/freezing rain/sleet	TAF SIGMETs METARs Precipitation Type (at surface)
Precipitation/Rain	TAF Precipitation Type (at surface)
Precipitation/Snow	TAF Precipitation Type (at surface)
Present/ Forecast temperature	METARs (present)
Runway conditions	METARs
Thunderstorms/ Hail/ Lightning	TAF METARs County Warnings Lightning Severe Weather Storm Tracks

Weather Factor	NWS Source(s)
Visibility	AIRMETs METARs SIGMETs TAF Visibility Forecast
Visibility/Fog (dew point)	METARs TAF (fog)
Visibility/Haze	METARs
Visibility/Sand/Dust/Ash	METARs AIRMETs SIGMETs
Wind/Clear air turbulence	AIRMETs SIGMETs
Wind/Downdraft	
Wind/Gusts	METARs
Wind/Hurricanes	Hurricane Track
Wind/Mountain rotors	
Wind/Surface Winds	METARs Surface Wind Speed and Direction TAFs
Wind/Tornadoes	METARs County Warnings NEXRAD
Wind/Winds Aloft	Winds Aloft
Wind/Windshear	Severe Weather Storm Tracks Wind Shear Detection

Addressing and Reporting System). ACARS is primarily used in commercial aviation which is beyond the scope of the present report. VHF has also been used in various flight information systems from Bendix/King and Allied Signal, but most of these are transitioning to satellite-based systems.

Satellite. There are many satellite-based systems in use today including AFIS (Automated Flight Information System) from Allied Signal which uses both VHF and satellite methods to communicate with aircraft. AFIS is a world-wide system that includes weather services. Echo Flight also provides data messaging via satellite communication. Weather Services International (WSI) provides weather information via SIRIUS Satellite Radio. Their systems provide information about precipitation, lightning, METARs, TAFs, SIGMETs, AIRMETs, PIREPs, winds, and temperatures aloft. Options are shown in Table 9.

The most commonly used delivery vehicle for weather information in general aviation today is XM Satellite Radio. This information can be presented in either text or graphical form by the various display systems that receive the XM signal. Table 10 shows all of the weather information available from XM Radio along with the rate at which the information is updated.

AVAILABLE WEATHER INFORMATION SYSTEMS

Many avionics systems now provide weather information and some rudimentary means of integrating the disparate types of information such as overlays, picture in picture, split-screen views, and zooming capabilities. But do these avionics systems provide the information pilots need, when they need it, in a useful way? This section reviews the weather capabilities of avionics products on the market now, in light of the suggestions proposed earlier in this paper. The suggestions and, therefore, our evaluation criteria are:

- Weather is customized by phase of flight — Different weather information should be presented or highlighted according to the phase of flight.
- Weather source information is integrated and summarized — Weather from multiple sources should be

Table 9. Weather Information From WSI

	Basic	Standard	Premium
WSI NOWrad®	●	●	●
Precipitation Type	●	●	●
Dynamic Radar Coverage Mask	●	●	●
Radar Summary		●	●
Lightning	●	●	●
METARs	●	●	●
TAFs	●	●	●
TFRs	●	●	●
Winds Aloft		●	●
Temperatures Aloft		●	●
PIREPs			●
SIGMETs		●	●
AIRMETs		●	●
Canadian Radar		●	●
International METARs		●	●
International TAFs		●	●
Icing			●
Cloud Top (Satellite IR)		●	●
Surface Analysis		●	●

Table 10. Weather Information Available From XM Radio

AIRMETs (AIRman's METeorological Information) AIRMETs advise of weather that may be hazardous to single engine, other light aircraft, and Visual Flight Rule (VFR) pilots. This advisory affects an area of at least 3,000 square miles at any one time and provides data in ceiling, obscuration and turbulence 12 minutes
Buoy Data Buoy observations are taken from marine buoys and coastal observation stations to determine wind speed, direction and gusts; air and sea surface temperature; dewpoint; sea level pressure; wave height, period and direction; visibility; pressure tendency and tide change 12 minutes
City Forecasts Shows current conditions in available cities 12 minutes
County Warnings Specific public awareness and protection weather warnings for Tornados, Thunderstorm, Floods and Flash Floods 5 minutes
Echo Tops A display derived from NEXRAD that indicates the highest altitude at which precipitation is falling 7.5 minutes
High Resolution NEXRAD Composite data from all the radar sites in the U.S. composed of the maximum reflectivity from the individual radar sweeps. Color-coded to indicate storm level severity. Also provides information on which NEXRAD sites are in operational mode or are offline. 5 minutes
Hurricane Track Provides the latest hurricane and tropical storm information, showing location, forecasted track and track errors (current 12, 24, 48, and 72-hour periods for 5 days) *Data image represented by WxWorx.* 12 minutes
Lightning Indicates the location, time, polarity and amplitude of cloud-to-ground lightning strikes, and uses 3 colors to determine the age of the strike (varies by hardware). 5 minutes
METARs (METeorological Aviation Reports) or Surface Observations Surface Observation reports provide information on current sky and weather conditions, including temperature, dew point, winds and visibility 12 minutes
NWS Marine Zone Forecast Displays expected weather conditions, water choppiness and wind speeds. NWS forecasts include NWS Special Marine Forecasts, Marine Weather Statements, Coastal Marine Forecasts, Offshore Marine Forecasts, Great Lakes Forecasts and more 20 minutes
Precipitation Type (at surface) Indicates whether rain, snow or a mix is most likely to occur on the ground anywhere precipitation is falling 5 minutes
Satellite Mosaic Infrared composite images of cloud cover taken by geostationary weather satellites providing eight levels of cloud cover data and can be presented in 5,000 foot increments 15 minutes
Sea Surface Temperature Temperature of the water surface measured in one-degree increments with equal temperature points connected with isobars. 12 minutes
Severe Weather Storm Tracks Arrow-like indicators that identify the location of stronger storms, and provide information on forecasted direction/speed, hail size probability and wind shear. This is a patented technology 1.25 minutes
SIGMETs (SIGnificant METeorological Information) SIGMETs advise of potentially hazardous weather, other than convective activity, to all aircraft. This advisory affects an area of at least 3,000 square miles at any one time and provides data on icing, turbulence, dust and volcanic ash 12 minutes
Surface Analysis Weather Maps High ("H") and Low ("L") pressure systems at the earth's surface are shown; the pressure is measured at the center of the system in millibar units; cold and warm fronts are indicated along with the front's direction of movement 12 minutes
Surface Pressure Nearest hour forecast of Surface pressure. 12 minutes
Surface Wind Speed and Direction Provides Wind speed and direction measured at 10 meters above sea level. 12 minutes
TAFs (Terminal Aerodrome Forecasts) or NWS Forecasts TAFs are issued by the National Weather Service for pilots. They include 24-hour forecasts on wind; visibility; expected weather conditions and wind shear 12 minutes
TFRs (Temporary Flight Restrictions) Volumes of airspace where all aircraft are temporarily restricted from entering into unless a waiver has been issued. TFRs are routinely issued for occurrences such as sporting events, dignitary visits, military depots and forest fires 12 minutes
Visibility Forecast Forecasts probability of visibility, stated in miles or kilometers with isobars to define regions of equal visibility 12 minutes
Wave Direction Provides information on the mean wave direction. 12 minutes
Wave Height Nearest hour forecast of highest waves: units are in feet or meters with isobars connecting areas of equal wave height. 12 minutes
Wave Period Provides information on the amount of time between swells in the ocean with isobars for area of equal wave period. 12 minutes
Winds Aloft (at altitude) Provides wind speed and direction from the surface up to 42,000 feet in altitude, presented in 3,000 ft increments 12 minutes
Wind Shear Detection Provides information on severe twisting of the winds in the atmosphere 5 minutes

integrated to provide the big picture, yet still enable zooming in for additional information.
- Weather information is presented at the appropriate level of detail — Pilots should not be overwhelmed by the volume of weather information presented.
- Hazard information is provided on an exception-only basis — Hazards should be highlighted, whereas non-hazardous weather should not be focused on unduly.
- Weather presentation is tied to 4-D flight profile.
- Probabilistic forecasts are provided and the level of uncertainty of the information is indicated.
- Recommendations are provided about how to avoid bad weather.*

Framework for Product Review: Get the Gist, Explore the Details

The review framework focuses on what information a pilot needs, when it is needed, and the degree of detail needed to be useful. At the least, pilots need information about:

- Relevant, current weather.
- Recommendations about how to avoid dangerous weather.*
- More detailed information upon request.

**Note: While it is generally considered useful to provide information about how to resolve conflicts or avoid problems in most system operations, it is recognized that cases where system failures occurred and influenced the user, in this case the pilot, to choose an incorrect course of action that resulted in aircraft loss, injury, or fatality could be subject to litigation. This, however, could be ameliorated to some degree by the use of conservative and stringent algorithms not unlike the logic used in TAWS today. This is, certainly, an area that requires further exploration.*

Simply put, pilots need the *gist* of the situation. For any point along a 4-D flight profile, they might need to answer the following questions:

- How dangerous is the weather?
- Why is it dangerous?
- What is happening?
- Why is it happening?
- How long is the danger likely to continue?
- What should I (the pilot) do about it?
- What are my options?

The *gist* is crucial because it:

- facilitates situational awarenes focuses on critical situations rather than minute details,
- enables rapid and effective decisions,
- integrates multiple weather sources, types, and formats,
- reduces pilot workload, and
- focuses on critical situations rather than minute details.

Developing the gist requires integrating weather from disparate sources, which are currently displayed in varying formats. The system would intelligently integrate information from radar, satellite, and reports such as METARS, TAFS, PIREPS, AIRMETS, SIGMETS, winds aloft and others. This would enable the pilot to maintain situational awareness, manage workload, and make rapid decisions. The information feeding the algorithm and the format in which it is communicated to the pilot would need to adhere to Grice's maxims of quality, quantity, relevance and clarity (Grice, 1975). It should be noted that we are discussing actual sensed/detected weather data, not forecast (or probabilistic) weather data, for the purpose of achieving and maintaining a sense of near-to-actual (immediate past) weather conditions.

From a quality perspective, the above data will need to be accurate and timely, and the degree of certainty and timeliness will need to be conveyed. From a quantity perspective, it will need to provide just the right amount of detail, and that detail will likely vary according to phase of flight (i.e., planning, departure, en route, arrival). To a large degree, the weather information should be exception-based. That is, unless the weather is present and a threat to safety, it should not be provided on the top-level displays. Providing too much detail simply serves to increase noise. Moreover, the system must enable the pilot to retrieve more detail. This can be provided by zooming, cluttering/de-cluttering, and providing several types of reports. However, the default display should remove all unnecessary detail.

All information on the default displays needs to be relevant. It should indicate the situation's level of danger, why it is dangerous, and what the pilot should do about it. Further queries by the pilot could provide more information about what is happening, why it is happening, how long it is likely to continue, and even suggest alternative actions. Finally, the way in which this information is displayed will need to be clear to the pilot. Again, this helps to reduce workload.

From a clarity perspective, the pilot is not likely to obtain the gist from reading multiple displays, even when they conform to the principles of proximity compatibility (Wickens, 1992) and integration (Roscoe et al., 1981). They will need to surpass those principles and provide decision aiding -- making recommendations and providing rationale for the recommendations. This provides situational awareness while significantly reducing the number of mental operations required. Then, if desired, the pilot can bring up additional displays to explore the detailed weather. In fact, obtaining the gist first enables people to interpret the details better (Bransford & Johnson, 1973).

Products Reviewed

We reviewed several products. Some of the products were designed to be installed in the instrument panel of the aircraft and others were portable. We included a combination of popular equipment and new and news-worthy products. Most products were designed for Part 91 use. There are several reasons for this. First, 90% of all flights are GA flights. Second, many Part 121 carriers use custom equipment and dispatchers. Third, there is significant innovation right now in avionics for Part 91 use.

Reviewed —

- Garmin: G-1000 (installed); 396/496 (portable)
- Honeywell-Bendix/King: AV8OR (portable)
- L3: SmartDeck (installed)
- WxWorx (portable; laptop or tablet PC)

On the market but not reviewed —

- Garmin: 430/530 (installed)
- Universal Avionics FMS (installed)
- Garmin 1000

Garmin 1000. The G1000 (McClellan, 2004), shown in Figure 4, enables the display of weather information using the GDL69A sensor and XM Wx satellite weather. This section evaluates the G1000 in light of the recommendations made in this paper. A rating scale of 0 to 5 was used (where 0 indicates that information is absent and 5 indicates information is present and is excellent). This is only a rough ordinal ranking to indicate if one system presents data any better, per our criteria, than any other system. A ranking of "3" should be considered average and "4" above average. Scores are presented as x/5, indicating that x points of a possible 5 were awarded.

- *Content appropriate to Phase of flight.* Although the G1000 enables the pilot to show many kinds of weather information, the types of information shown are not customized to the phase of flight unless pilots make adjustments on the device as they change phases, the types of information shown are the same. This increases the mental and physical workload on the pilot. The pilot needs to remember to make these adjustments and how to make them. Score: 3/5.
- *Integrated and Summarized Source Information.* The G1000 enables the pilot to see only one source of weather information at a time. For example, the pilot may be able to display satellite weather and then switch over to another display that shows radar, but both cannot be displayed at once. In this sense, it is not well integrated, and information is not summarized. Admittedly, integrating more than one type of weather information in the same display — for example through the use of overlays — runs the risk of making the display too busy. On the other hand, other approaches, such as a window-in-window display, could be considered. Score: 3/5.
- *Information is displayed in appropriate detail.* With this system information can be displayed at many levels of detail. The problem is that the pilot needs to explicitly control the level of detail that is displayed. So, the detail does not change automatically to suit or anticipate the level that the pilot will need at that time. In addition, information is not summarized in a way that will facilitate the pilot comprehending the gist of the weather situation. That is, it displays weather information without providing much in the way of decision aiding. Score: 3/5.

Figure 4. Garmin G-1000

- *Emphasizes hazards.* The color display of the G1000, which actually varies intensity, as well as hue, does a good job of highlighting potential hazards. Score: 4/5.
- *Tied to a 4-D profile.* Current weather information such as satellite weather can be integrated with a map that shows the pilot's flight plan. However, all information is current, rather than forecast, information. Often it is more useful for the pilot to know not what the weather is like at a particular location now, but what it will be like when they get there. That is not provided in any type of 4-D profile. It can be pieced together by the pilot from various reports, but it is not summarized and integrated onto the pilot's display. Score: 3/5.
- *Suggestions to avoid bad weather.* The best weather management system would provide suggestions on alternate routes, waypoints, airports and so on, to avoid weather hazards. The G-1000 does not do this. Score: 0/5.
- *Probabilistic information is indicated.* The G-1000 does not include any indication of the certainty surrounding weather information. Score: 0/5.

Garmin 386/496. With a subscription to XM WX Satellite Weather the Garmin 496 (Figure 5) (Garmin, 2008) provides access to constantly-updated, high-resolution weather data. Weather information includes Radar (NEXRAD), METARs, TAFs, TFRs, Lightning and Winds Aloft. These graphical data can be layered over Jeppesen and topographic map databases. The weather capabilities of this product are reviewed below.

- *Content appropriate to Phase of flight.* As with the G1000, the pilot can display many types and sources of weather information. However, the type of weather information displayed does not change automatically with the phase of flight. Unless the pilot makes adjustments explicitly, the type and source of weather information stays the same. Score: 3/5.
- *Integrated and Summarized Source Information.* The GPSMAP 496, like the G1000, enables the pilot to see one source of weather information at a time. For example, the pilot may be able to display satellite weather and then switch over to another display that shows radar, but both cannot be displayed at once. Score: 3/5.
- *Information is displayed in appropriate detail.* Information can be displayed at many levels of detail, but the pilot needs to select that level of detail. It does not change automatically. Further, information is not summarized so that the pilot can get the gist of the weather situation. Score: 3/5.
- *Emphasizes hazards.* As can be seen in Figure 5, the color display highlights potential hazards. Score: 4/5. Tied to a 4-D profile
- *Current, but not forecast, weather information can be integrated with a map showing the flight plan.* No specific 4- D profile. Score: 3/5.
- *Suggestions to avoid bad weather.* The GPSMAP 496 does not provide suggestions on how to avoid weather hazards. Score: 0/5.
- *Probabilistic information is indicated.* The GPSMAP 496 does not provide any indication of the certainty surrounding weather information. Score: 0/5.

Figure 5. Garmin 496

Honeywell-Bendix/King AV8OR. The Honeywell-Bendix/King AV8OR (Bendix/King, 2008), Figure 6, provides real-time satellite weather, including NEXRAD, graphical METARS, AIRMETS, SIGMETS, METAR/TAF at nearby airports, storm cell track, and cloud tip information. One benefit offered by AV8OR is its touch screen and object-oriented user interface. That is, it enables pilots to touch items on the screen to gain more information. It is reviewed next.

Figure 6. Bendix/King AV8OR

- *Content appropriate to Phase of flight.* As with other avionics systems, the pilot can display many types and sources of information, but the type of weather information does not change automatically with the phase of flight. Unless the pilot makes adjustments explicitly, the type and source of weather information stays the same. However, the touch-panel interface of the unit allows the pilot to access information spatially by point along the flight plan, bringing up additional weather information about the location on the map that was touched. Although the display does not change automatically, it does reduce the burden of navigating among displays during various phases of flight. Score: 3/5.
- *Integrated and Summarized Source Information.* The AV8OR enables the pilot to see one source of weather information at a time. However, the ability to touch a portion of the screen corresponding to a point on the flight plan makes it easier for pilots to navigate through the weather information and should reduce their work load. Score: 3/5.
- *Information is displayed in appropriate detail.* Information can be displayed at many levels of detail, but the pilot needs to select that level of detail. Score: 3/5.
- *Emphasizes hazards.* As can be seen in Figure 6, the color display highlights potential hazards. Score: 4/5.
- *Tied to a 4-D profile.* Current, but not forecast, weather information can be integrated with a map showing the flight plan. No specific 4-D profile. Score: 3/5.
- *Suggestions to avoid bad weather.* The AV8OR does not provide suggestions on how to avoid weather hazards. Score: 0/5.
- *Probabilistic information is indicated.* The AV8OR does not provide any indication of the certainty surrounding weather information. Score: 0/5.

L3 SmartDeck. The L3 SmartDeck (L3 SmartDeck, 2008) avionics package, Figure 7, offers real-time satellite weather, including NEXRAD, graphical METARS, AIRMETS, SIGMETS, METAR/TAF at nearby airports, storm cell tracking, and cloud top information. Further it enables the pilot to tap on screen items on the screen to gain more information about them. It is reviewed below.

- *Content appropriate to Phase of flight.* The pilot can display many types and sources of weather information, but the type of information does not change automatically with the phase of flight. Unless the pilot makes adjustments, the type and source of weather stays the same. Score: 3/5.
- *Integrated and Summarized Source Information.* SmartDeck uses picture-in-picture displays and pop-up windows to show multiple types of weather information at a time. Score: 3/5.
- *Information is displayed in appropriate detail.* Information can be displayed at many levels of detail, but the pilot needs to select that level of detail. Score: 3/5.
- *Emphasizes hazards.* As can be seen in Figure 7, the color display highlights potential hazards. Score: 4/5.
- *Tied to a 4-D profile.* Current, but not forecast, weather information can be integrated onto a map showing the flight plan. No specific 4-D profile. Score: 3/5.
- Suggestions to avoid bad weather. SmartDeck does not provide suggestions on how to avoid weather hazards. Score: 0/5.
- *Probabilistic information is indicated.* SmartDeck does not provide any indication of the certainty surrounding weather information. Score: 0/5.

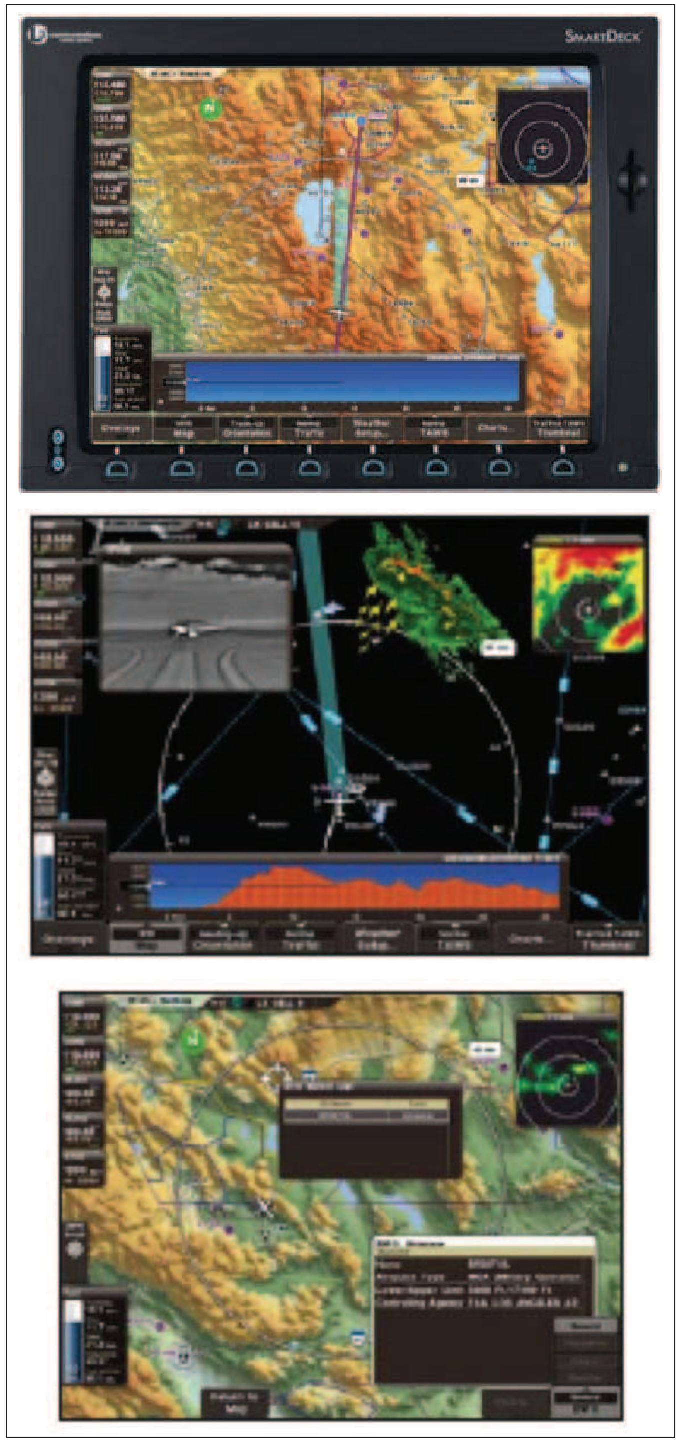

Figure 7. L3 SmartDeck

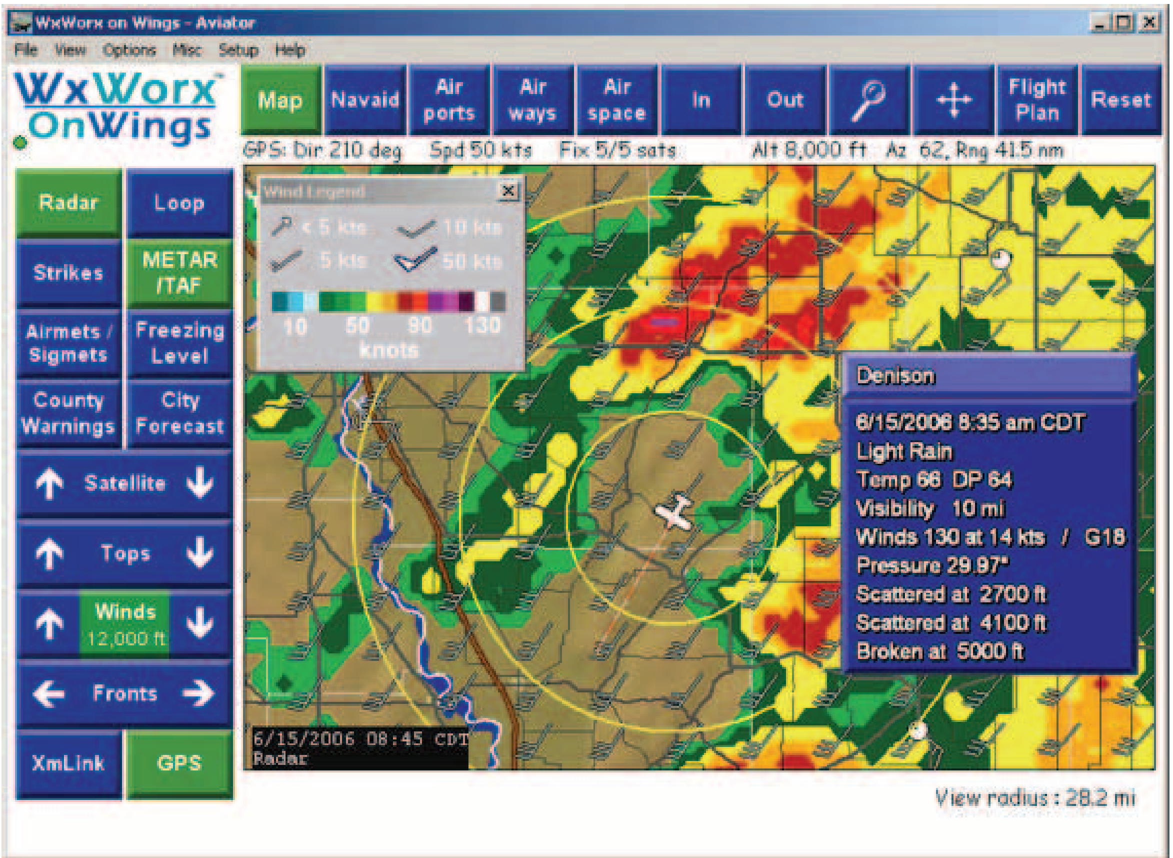

Figure 8. WxWorx display

WxWorx. WxWorx (WxWorx, 2008), Figure 8, provides real-time weather via an XM satellite radio receiver. It enables pilots to display multiple sources of information on various types of displays. Often it is displayed on a laptop or tablet computer in the cockpit. The system is reviewed below.

- *Content appropriate to Phase of flight.* The pilot can display many types and sources of weather information all at once on the same display, but the type of information does not change automatically with the phase of flight. Score: 3/5.
- *Integrated and Summarized Source Information.* WxWorx integrates many types and source of information into one display. However, it does not summarize the information for the pilot. Score: 4/5.
- *Information is displayed in appropriate detail.* Information can be displayed at many levels of detail, but the pilot needs to select that level of detail. Score: 3/5.
- *Emphasizes hazards.* As can be seen in Figure 8, the color display highlights potential hazards. Score: 5/5.
- *Tied to a 4-D profile.* Current, but not forecast, weather information can be integrated with a map showing the flight plan. No specific 4-D profile. Score: 3/5.
- *Suggestions to avoid bad weather.* WxWorx does not provide suggestions on how to avoid weather hazards. Score: 0/5.
- *Probabilistic information is indicated.* WxWorx does not provide any indication of the certainty surrounding weather information. Score: 0/5.

Table 11 summarizes the scores for the products reviewed. Recall that 0 = function absent, 3 = presentation average, and 4 and 5 are presentation above average.

As evidenced in these reviews, technological advances have enabled the display of multiple sources of weather all in one unit. However, there are still several areas in which the current products fall short of our criteria. By examining Table 11, one can see similar patterns of results for most of the products. This is probably because they rely on the same information provided by XM weather. As a result, although most products enable the pilot to zoom in and select weather information and detail that is appropriate to their phase of flight, this is not done for them automatically.

Further, while there is some degree of integration of information from multiple sources on these products, the integration is superficial. On the least integrated end of the continuum, one toggles among windows that show various weather displays. On the slightly more integrated end of the continuum, one can have a split display or picture-in-picture display of the weather along with a topographic map. This is the approach taken by

Table 11. Quality of Weather Information for Various Systems on a 1-5 Scale

	Content Appropriate to Phase of Flight	Source information Integrated and Summarized	Appropriate Detail	Emphasizes Hazards	Tied to 4-D profile	Suggestions provided to avoid bad weather	Probabilistic Information	Total
Garmin 1000	3	3	3	4	3	0	0	16/35
Garmin 386/496	3	3	3	4	3	0	0	16/35
Bendix/King AV8OR	3	3	3	4	3	0	0	16/35
L3 SmartDeck	3	3	3	4	3	0	0	16/35
WxWorx	3	4	3	5	3	0	0	17/35
Total	15/25	16/25	15/25	21/25	15/25	0/25	0/25	

SmartDeck. WxWorx provides the best integration of the group by enabling the user to select what pieces of information will be displayed on the screen at any one time. However, a better approach would be the "get the gist, explore the detail" approach described above. In such a situation, the product would summarize the problems for the pilot, provide the appropriate display, and suggest options. Then the pilot could explore the weather information for more details, if needed.

Most of the products do a good job of emphasizing hazards, indicating storms in red and, so on; however, they do not tie it well to a 4-D profile. Though they provide current weather along a three-dimensional profile, they fail to provide current and forecast information along a four-dimensional profile. Finally, none of the systems provide overt suggestions for avoiding weather hazards (i.e., possible rerouting). ARTCC controllers have historically supplied this suggestion of an alternate route, and they are not likely to continue doing so during NextGen. This review suggests that, although a plethora of weather information is now available in the cockpit, systems do not yet automatically integrate disparate sources of information, match the phase of flight, or align with the four-dimensional flight profile. Further, the systems provide little indication of the level of uncertainty associated with particular forecasts, nor do they suggest ways to circumvent weather based on the forecast. Adding these capabilities should improve the pilot's ability to avoid weather hazards by getting the gist and exploring the details.

WEATHER INFORMATION IN NEXTGEN

While the pilot-in-command always has the ultimate responsibility for safety of flight, ATC plays a major role in providing pilots with information about traffic and weather that may threaten the safety of flight. The NextGen air transportation system envisions removing the need for continuous ATC monitoring by giving pilots the responsibility to monitor traffic and weather using on-board information systems during the en route phase of flight. However, as weather information systems exist today, there are several issues surrounding the differences between what pilots need and what systems provide.

Current weather information systems for general aviation are generally geared to delivering weather products from the NWS. Traditionally, weather information has been delivered via broadcast from ground stations, and some systems still use this form of delivery. Increasingly, satellites are used to transmit information. Often, weather products are supplied via XM Satellite Radio.

While the available products provide a reasonably thorough analysis of current and forecast conditions, there is little attempt to adapt the information to the needs associated with a particular flight. This means that pilots are required to: (1) have current subscriptions to the appropriate information services, (2) review the information pertaining to their flight, which most likely is contained in a number of different weather information products, (3) identify the factors that may impinge on the planned flight, and (4) make the decisions required to execute the flight safely.

In preflight planning, pilots have the time and lack of urgency to gather, process, and interpret information about the weather. However, when conditions during a flight do not correspond to the anticipated conditions from planning, further analysis of the weather and its impact on the flight must be done under time pressure. During such times, bad decisions can easily result from having insufficient time to digest and interpret multiple sources of weather information. In short, simply having access to all of the weather information will not necessarily aid the pilot in times of urgency. In such times, contextually relevant information is what is needed.

Human Factors Challenges for NextGen

When the pilot must monitor weather and traffic, in addition to the requirements to aviate, navigate, communicate, and manage systems, the potential for overload is always present. Perhaps the most effective way to keep the workload within bounds is to provide information that is meaningfully integrated so that navigation decisions follow directly from the consideration of destination, weather, traffic, and terrain. In short, this information should be as integrated as possible. As we have suggested, this will require some intelligent systems to accomplish the integration and to filter out less relevant information, but it will also require extensive work in human factors to determine the details of effective methods of presenting information and ways to relate the information directly to decisions.

Today, pilots are often faced with using one set of information sources for flight planning, another set of sources as they communicate with ATC concerning clearances and departure instructions, and yet other sources while en route to monitor weather and to aviate, navigate, communicate, and manage systems. ATIS provides critical information about weather and other factors concerning the arrival airport. Developers of new systems should attempt to bring this information together into a single system that could be used throughout all phases of flights. Efforts at integrating all of these sources could be focused on providing information at the right level of detail to allow pilots to obtain the information needed quickly to facilitate the best decisions concerning the weather, traffic, and terrain. Flight management systems (FMSs) are moving in this direction.

Adding information about weather and traffic to that already needed to fly the aircraft creates a major human factors challenge. There is a potential conflict between making all relevant information salient to the pilot while not constructing overly cluttered displays that defeat this very purpose. Some of the means of filtering information that we have begun to outline in this report should be helpful in this effort.

While we have emphasized ideal qualities of weather information systems, it is important to recognize the impact of economic factors in enabling individuals and businesses to acquire and deploy such systems. There are often trade-offs between the ideal and the affordable. To be sure, developing technology has helped to reduce the cost of very capable systems, but there are still budgets and profit margins to be considered as NextGen comes into operation. Good information systems can help reduce costs, but they also have their costs. We hope that our analysis here can help guide future technological developments to move toward the systems that assist in conducting safe and efficient flights.

The Impact of Good Weather Information

Our analysis of the weather information needs of pilots aims at identifying what a pilot needs to know to fly safely. Certainly, the quality of the information a pilot has will affect the safety of flight. The NextGen scheme for operation appears based upon the availability of accurate weather information, both current and forecast. If availability is guaranteed, the critical issue becomes the effective delivery of the information. Our analysis of weather information priorities in different phases of flight should provide a framework for deciding which data to present, along with when it should be presented. It can also provide guidance for the development of such information systems and provide one basis for evaluating existing technology.

In what follows, we assume that the systems envisioned for NextGen are in place and information systems on aircraft operate according to the principles we have outlined. The following scenarios and situations illustrate how the systems could affect the efficiency and safety of flight.

- With good information about dangerous weather ahead, a slight change in heading could suffice to avoid the weather with a minimum cost in time or fuel. Such en route adaptations would be facilitated by information about the rate and direction of movement of weather systems that directly impinge on the planned flight of the aircraft in question.
- It would be valuable to communicate changes in flight plans (diversions, changes in speed with winds aloft, etc.) to the air transportation system as a whole to allow adjustments to be made in expected traffic, arrival times, etc. Of course, the weather pertaining to a particular flight may require updating (e.g., changes in forecast times, changes in route) as the flight plan changes.
- Diverting from the planned airport without a missed approach would be more likely with better weather information, including better weather information at the alternate airport. Decisions to go to the alternate could be made earlier, saving fuel and congestion at the planned airport. While this clearly applies to GA flights, it is less applicable to Part 121 operators.
- For Part 121 operations, diversion to alternates is less desirable, but good weather information could help time departures to avoid forecast problems at the destination airport. Good weather information could also help to determine possible holding times when arrival is delayed.

- Good current weather information and accurate forecasts would help in finding an airport with acceptable weather when planned alternates are not available.
- Good/believable information will help avoid IMC for VFR flights. Advanced forecasting systems are beginning to be developed to provide better information (Wolfson & Clark, 2006).
- Communication failure in handoff between controllers (especially approach to tower) could be mitigated by having needed weather information independently of controllers.
- Deviations from flight plans can be assisted by knowing where weather problems are located.

Coping With Weather Now and in NextGen

Some examples may help to illustrate how an ideal weather system would affect some situations that arise in flight. We are assuming that such a system would provide timely, accurate, and focused information. In the NextGen environment, such onboard systems would be needed to replace communication about weather available from ATC in the present environment.

VFR into IMC. Having reliable, valid, and timely weather information onboard can forestall the temptation to venture too far into deteriorating weather conditions in the attempt to learn, first hand, just how bad the situation is. In general, having reliable information about where danger lies should prevent encounters with it.

Icing encounters. Information about icing requires good resolution to be usable. In the current system, potential icing is often forecast over very wide areas, presumably to err on the side of safety. Unfortunately, the knowledge that the icing may not extend as far as forecast encourages some pilots to see if the situation is not as bad as forecast. Better resolution and accurate estimates of certainty of forecasts from onboard weather information systems would help lead pilots to believe the forecast information.

Diversions. A major challenge for NextGen concerns the way diversions will be handled. For example, when thunderstorms are active, ATC must handle multiple requests for deviations, sometimes leading to unacceptable workloads for controllers. Simply closing areas of airspace is one way to cope with such problems; pilots effectively do that now by reacting to current situations. Clearly, better forecasts that are widely available should help by allowing earlier reactions to emerging situations. Still, diversions will require coordination among pilots and between pilots and ATC. NextGen systems will require effective means of achieving the coordination.

RECOMMENDATIONS

1. Provide integrated display of weather data
2. Incorporate decision-making aids referenced to a specific pilot and flight profile
3. Emphasize hazardous weather directly relevant to flight profile (per known pilot prioritizations)
4. Indicate reliability of forecast information (i.e., probabilities associated with specific forecasts)
5. Provide access to lower levels of detailed data without full-time display of same.

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