Abstract

The National Center for Atmospheric Research (NCAR) Research Applications Laboratory (RAL) is developing and implementing the tools that address six aviation weather hazard areas through emerging weather products: convection and convective hazards; in-flight icing; turbulence (terrain-induced, convective-induced, jet stream, and shear); winter weather hazard mitigation in the terminal and airport area including deicing decision making; remote and oceanic weather hazard diagnosis and forecasts; ceiling and visibility. These products are being transitioned to operations for use by pilots, dispatchers, flight service specialists, and air traffic controllers/managers. Underlying research, verification, dissemination methods, and user interface/display development have been sponsored primarily by the FAA Aviation Weather Research (AWR) Program, with joint sponsorship from NASA.

This paper describes integrated methods of diagnosing and forecasting aviation weather hazards using “fuzzy logic” or expert system framework techniques, and the current status of operational transition of these revolutionary new products. It also describes methods of getting the most current weather information to the end user, including data link and real-time display in the cockpit using 4-dimensional graphics; dissemination to all types of users including airline flight operations centers (FOCs) and air traffic controllers/managers; and the introduction of probabilistic forecasts to assist with managing risk—all to enhance collaborative decision support. Since these new products are four-dimensional, unique display concepts for the end user will also be covered. Finally, issues relating to how these new products can provide decision support to air traffic managers are identified.

Introduction

Although there has been significant research over the past twenty years relating to aviation weather hazards, weather is still identified as a causal factor in 33% of commercial air carrier accidents and 27% of general aviation accidents. Weather also has a large impact on the efficiency of air traffic management, and airspace and terminal capacity. For these reasons, the FAA and NASA are sponsoring a number of research programs that focus on the specific needs of aviation, emphasizing decision aiding and operational transition of improved weather products. Identified shortcomings of the current aviation weather system fall into two main areas: dissemination and information content. Specifically,

Weather information is usually presented to end-users like pilots and traffic managers in a format that is difficult to relate to a four-dimensional flight profile. Examples are textual products that cover large airspace volumes and
are written in 1950s-style teletype format.
Weather information is not spatially or temporally precise or accurate, making its use difficult as a decision support aid. Weather information is updated infrequently, missing the dynamic changes that often occur after an aircraft departs.
Weather information products are mostly created by humans, who are required to analyze and interpret large amounts of atmospheric data to subjectively describe current and forecast future hazard areas.
Sources of weather information are diverse, causing a non-meteorologist end-user to have to search for and interpret large amounts of data in order to identify hazard areas.
The only way for an airborne pilot to update weather information is via textual data link (for airlines) or verbal communications (for airlines and general aviation). Again, these formats are difficult to use as decision aids.
The major categories of end-users—pilots, dispatchers, air traffic controllers—do not have access to the same information when attempting to make collaborative decisions.

Addressing User Needs
One of the most successful FAA programs that focused entirely on addressing an aviation weather hazard was the Terminal Doppler Weather Radar (TDWR) program, which began in the 1980s as a result of a series of airline accidents that resulted in hundreds of fatalities world-wide. The hazard was wind shear near convection, or thunderstorm activity, in the terminal area. This program began with focused research and demonstration programs centered at Denver’s Stapleton International Airport, resulting in the scientific definition of severe wind shear now known as the microburst. It also established a clear understanding of what sensed data was needed in order to locate the hazard. Since the microburst is a very severe and highly localized phenomenon, it became quite clear during development that alerts given to controllers and pilots had to be temporally and spatially precise. Furthermore, the information transfer had to be immediate—that is, no time was available for human interpretation of the information. Simply, the information had to have high “glance value,” and the pilot’s response had to be rule-based and immediate.
The TDWR program resulted in the development and deployment of a highly successful alerting system and associated pilot training programs, essentially eliminating accidents caused by microbursts at airports equipped with the system. Also important, it revolutionized traditional thinking on how to create and present information on weather hazards for aviation users. The FAA’s AWR Program, in collaboration with NASA, continues to develop and deploy advanced aviation weather information using some of the underlying principles learned from the TDWR development:

Aviation users need weather information, not data. Data (large amounts of it) are used to create the information.
Information products come from numerous sources of data, each adding a particular skill component to the final product.
The above two points imply the use of automation to assimilate large amounts of varied data quickly. Information updates can be created whenever new data become available.
Most aviation users are not meteorologists—hence, the products must have high “glance value” and
minimize the amount of human interpretation needed. This implies the use of graphics that are tailored to the decision or task.

Dissemination systems must be timely and reliable.

Training on the use of new information products must accompany operational transition.

The TDWR system, for the first time, analytically combined more than one source of data via algorithms developed by the team to optimize probabilities of detection and false alarm rates. Since then, research programs within the AWR Program product development teams have developed and verified a general methodology that can assimilate any number of data sources or diagnostics to optimize a defined objective function. We call these sources “interest fields” and the objective function is the skill in diagnosing or forecasting a particular weather hazard. The mathematical method used to integrate the interest fields into an information product falls into the broad category of “fuzzy logic” techniques, allowing for varied and even dynamic weightings of the various interest fields to account for differing mesoscale or synoptic situations. Finally, the algorithm’s output is formatted into uniform four-dimensional grids (three spatial, one time) that are easily compressed for transmission and allow for the creation of high-resolution, three-dimensional graphics. They can be easily related to a flight profile and allow for the creation of horizontal and vertical cross-sections.

To summarize, these new techniques actually try to mimic the expertise and experience of the meteorologist, using the same data sources and diagnoses known by humans to add skill to the desired product. But, because it is difficult for the human to assimilate large amounts of data, two things happen to the current product generation process. First, information gets updated infrequently and, second, the human tends to add spatial imprecision—conservatism—to the generation process to account for incomplete analysis of data. Automating the integration seems to solve these two weaknesses of current aviation weather products, while at the same time increasing accuracy of the information because all relevant data can be included in the formulation of the product.

The following section will provide brief descriptions of the products and status of their transition to operations.

Weather Hazards

The concept of integrating numerous diagnostic techniques and data sources to optimize a particular outcome (objective function, decision) is being used in a number of different hazard areas to improve weather information to end users. This paper will address six major aviation weather hazard areas: turbulence, convection, in-flight icing, ceiling and visibility, and oceanic/remote weather diagnoses and forecasts.

A significant amount of research on the physics of the atmosphere precedes any attempt to automate a particular process, as there must be some substantiated benefit to adding a data source or diagnostic to the integration. The fuzzy logic framework used was developed to accommodate essentially any interest field that has skill in optimizing the objective. As new interest fields are included in the process, formal verification is done to show that skill is indeed enhanced by the addition. Products can then become candidates for operational transition in an incremental way, as opposed to delaying benefit to the user community needlessly for complete implementation.
**Turbulence**

Despite over-forecasting and conservative piloting practices, aircraft turbulence encounters currently account for over 40 percent of all weather-related factors or causes cited in commercial air carrier accident and incident reports by the National Transportation Safety Board (NTSB). Industry-wide, airlines document over 1200 injuries per year to flight attendants and passengers due to unexpected turbulence encounters. A turbulence event that results in injuries costs the airlines an average of $750,000. A large percentage of these turbulence encounters and incidents might be avoided with air traffic controllers, airline flight dispatchers, and flight crews having access to better detection and forecast information.

Turbulence is a particularly difficult phenomenon to detect and forecast primarily because it is so dynamic and occurs on a very small scale. Also, turbulence can come from a number of sources—convection, convection-induced, jet stream interactions, wind shear, terrain interactions, mountain waves—many of which are not physically well understood. Turbulence is mentioned first, not because the technology is more mature, but rather because it provides a useful example of an integrated product.

NCAR has been applying fuzzy logic techniques to turbulence forecasts and diagnostics for over ten years. A four year research and development program to help mitigate terrain-induced hazards at the Hong Kong Chek Lap Kok airport motivated the development of a fuzzy logic approach because of the limited and diverse atmospheric sensors available. Although the Hong Kong system was sensor-based, the concept of integrating data sources forms the basis for the model-based Graphical Turbulence Guidance (GTG) product. As a result, the GTG provides aviation users much more precise diagnostic and forecast turbulence information. There are essentially four steps in the current implementation of GTG:

First, GTG computes a set of diagnostics based on numerical weather prediction output. Currently, GTG uses model output plus 10 diagnostics relevant to diagnosing clear air turbulence. Some of these diagnostics have been used for years by aviation weather forecasters to forecast turbulence, but individual diagnostic performance has generally been less than adequate.

Next, GTG determines a mapping from the diagnostics to turbulence potential. This is the most difficult task, and is still an area of active research to determine turbulent thresholds in different situations.

Next, GTG scores the performance of each individual diagnostic against available observations. Currently, available observations are subjective pilot reports and objective eddy
dissipation rate (edr) measurements routinely reported from commercial aircraft. Currently, the edr measurements are taken every minute by commercial aircraft, downlinked, and are used by GTG in this step.

Finally, GTG combines the different diagnostics as a weighted sum with the weights determined dynamically in step 3. The overall procedure amounts to determining the best fit of the weighted sum of the individual diagnostic indices to the available observations. Clearly, the more available observations, the more GTG will reflect current reality. Other NCAR programs are in place to dramatically increase objective turbulence measurements.

Extensive verification, which is still in progress, has shown that GTG consistently outperforms any of the current diagnostics individually. At this time, GTG specifically addresses the clear air turbulence threat. Other types of turbulence will be added to the algorithm as the relevant diagnostics are developed and verified. Figure 1 shows an example output graphic from GTG, a composite mapping of turbulence potential intensity from FL200-450.

The GTG output is available to anyone on the web site. It was declared operational for meteorologists and dispatchers in 2002, and can be used for flight planning guidance. A second version to become operational in early 2007 will provide forecasts from 10,000 feet MSL to FL450.

**Convection**

Convection and its associated hazards—hail, high winds, turbulence, lightning, heavy precipitation, wind shear—are the most disruptive weather phenomena to aviation when they are present. Convection is also responsible for as much as 60% of the large number of turbulence accidents and incidents. Essentially all commercial passenger aircraft are equipped with on-board weather radar to provide the flight crew a real-time indication of where convection exists in front of the aircraft. However, because radar energy attenuates in the presence of heavy precipitation, many times the flight deck indication will only show the leading edge of a line of thunderstorms. A national ground-based system of Doppler weather radars also provides a near real-time graphic of the location of precipitation indexed to 16 levels of intensity. This information is available to ground support stations such as Flight Service, ATC, and dispatch, but not directly to the flight crew. Again, this product is based solely on reflected radar energy and has a time lag from time sensed to time displayed of as much as 30 minutes. What is needed is a convective information product that updates frequently and shows more than where radar reflectivity is highest—it needs to show hazard areas that aircraft need to avoid.

The National Convective Weather Forecast (NCWF) product uses the integrated, fuzzy logic approach to combine radar imagery, satellite imagery, and lightning information to produce an indication of where the most dynamic convection, and hence most severe hazard, exists. Ongoing research has shown that lightning occurs where the most severe updrafts and downdrafts occur, which usually coincides with where the most severe turbulence, hail, and precipitation exist. Furthermore, lightning strike data (cloud to ground) is currently available with one-minute updates. Lightning data provides the real-time update to satellite and radar data needed to mitigate the time lag inherent
in these two data sources, allowing a five minute update to NCWF diagnosis and forecast products.

To provide the forecast component of the product, NCAR has integrated a well-tested trending algorithm to provide one and two hour extrapolations, including probabilistic forecasts, of storm position. Soon, the NCWF will be able to provide storm initiation, growth, and decay information as well. Figure 2 shows an example 1-hour extrapolation graphic.

![Figure 2. NCWF and 1-hour Extrapolation](image)

The NCWF is also available to anyone on the [http://adds.aviationweather.gov/](http://adds.aviationweather.gov/) website, and is used for guidance by aviation users. It became fully operational in 2001.

**In-flight Icing**

In-flight icing, although not a constant threat to commercial jet aircraft, has a significant impact to small general aviation and commuter aircraft operations. Current in-flight icing diagnostics and forecasts frequently cover large areas of the country, severely limiting the use of aircraft not able to circumnavigate the areas or climb through the forecast icing conditions. Icing is also listed as a cause or contributing factor in an average of 30 accidents a year, and nearly half of these are fatal.

Although airline operations are not as impacted by in-flight icing conditions, airliners frequently have to descend through icing layers as they approach airports, resulting in a buildup of icing that has to be removed prior to subsequent takeoff. The question of the presence of icing during a planned flight segment also determines the legality of dispatch without full deicing capability. Therefore, determining the precise likelihood of in-flight icing for airline operations has a large, daily affect on aircraft utilization, even though the safety impact may not be as great as that for general aviation.

![Figure 3. CIP Product](image)
weaknesses of individual data sources. The Current Icing Potential (CIP) product integrates numerical model data and diagnostics (such as temperature and relative humidity profiles), radar and satellite imagery (presence of visible moisture, liquid water content, droplet size distribution), ground observations, and pilot reports, to produce diagnostic three-dimensional grids indicating the potential for in-flight icing and the potential for supercooled large droplet (SLD) icing, the most hazardous type of icing.

Figure 3 shows an example of a vertical cross-section of icing potential, SLD potential, and the combination of the presence of visible moisture and temperature less than 10 degrees Centigrade, as computed by the CIP. The value of three-dimensional graphics and cross-sections is also illustrated in Figure 3. A forecast product generated by the Forecast Icing Potential (FIP) algorithm is also available.

The CIP is also available to anyone on the [http://adds.aviationweather.gov/](http://adds.aviationweather.gov/) web site and has been declared operational for aviation users. The FIP product is also available, and an icing severity product will be available in late 2006.

**Remote/Oceanic Diagnoses and Forecasts**

Addressing aviation weather needs in remote and oceanic areas is a unique problem, as available data is extremely limited. Typically, the only data sources available are visible and infrared satellite imagery, and, in some areas of the world, limited lightning and low-resolution model sounding data. This limited data, however, can be integrated to infer the presence of convection, including cloud top heights, turbulence, and icing, plus high resolution winds useful for flight planning. Currently, the individual application of these data sources offers only very coarse results. However, automating the product generation process and integrating available data allow more frequent updates of hazard location relative to flight profile as new data become available.

At present, aircrews for long-range oceanic flights receive a general weather briefing before departure, including a summary of flight level winds and expected en route weather conditions. Frequently, the main products are a series of text summaries of the expected weather along the flight path, augmented by a facsimile copy of a hand drawn weather summary produced by the Aviation Weather Center in Kansas City, or equivalent products provided by a foreign weather service, commercial vendor, or an airline weather office. Once aloft, the aircrew can receive updated weather information in the form of text messages via the ACARS multi-purpose data link, or when in contact with an air traffic control center via HF or VHF radio communication. While the current weather products do provide valuable information for strategic planning, the information is already hours old by the time the aircraft depart and only the most general weather updates are provided during the flight. In particular, little or no information can be provided about rapidly changing weather systems that may be encountered.

A current NCAR-led research and demonstration program, sponsored by the FAA’s AWR Program, is generating an integrated convection diagnostic that is available to ATC, airline dispatch, and the airborne flight crew. United Airlines, the Oakland Air Route Traffic Control Center (ARTCC), and the Aviation Weather Center (AWC) are participating in the initial demonstration in the South and Central Pacific. These capabilities could expand globally in the next few years. Research and development are also addressing turbulence...
(all types), in-flight icing, and volcanic ash dispersion, both diagnoses and forecasts for each hazard.

Figure 4. Convective Diagnosis Character Graphic

The web-based oceanic convective diagnosis product can be viewed at

http://www.rap.ucar.edu/projects/owpdt

A simplified version of the product (character graphic, Figure 4) are being data linked to the flight decks of United 747-400s en route to/from Australia and New Zealand. Convective diagnoses are also available for the North Pacific and the Gulf of Mexico, and will be available soon for the North Atlantic.

Ceiling and Visibility

The final example of the use of fuzzy logic integrating techniques in describing aviation weather hazards is in the area of forecasting ceiling and visibility. This is not a critical safety problem for airlines, but does have a large impact on terminal capacity at some airports that have IFR operational constraints. Low ceilings and visibilities severely limit general aviation operations and is a critical safety hazard—non-instrument flight into instrument conditions almost always results in a fatal accident.

The research in diagnosing and forecasting ceiling and visibility is a very complex problem, and is just beginning. The initial version of this algorithm integrates surface observations, Doppler radar data, satellite imagery, pilot reports, terminal area forecasts, and numerical model results to produce a national map of operationally significant ceiling and visibility categories ranging from visual conditions to low instrument conditions. The initial version of this product may be viewed at

http://www.rap.ucar.edu/projects/cvis

Dissemination to the End-user

The Aviation Weather Center

The Aviation Weather Center (AWC) in Kansas City is the official agent of the National Weather Service and FAA for disseminating aviation weather information to end-users. Currently, AWC has near-global responsibility for providing weather information to support all facets of aviation operations, including flight planning and the identification of weather hazard areas. AWC collects data from all sources, including satellite imagery, radar imagery, automated ground observations, terminal forecasts and observations, and state of the atmosphere model output. Meteorologists then create and disseminate numerous weather products via an international communications infrastructure. This “family of services” is accessible to users through a number of communication links, including the Internet. Further information on AWC capabilities and weather products may be viewed at

http://aviationweather.gov/

The NCAR and AWR Program research and development effort to improve aviation weather products depends extensively on the
AWC to ensure users have access to the new capabilities. In partnership with AWC, NCAR has developed and implemented a unique web-based service called the Aviation Digital Data Service (ADDS). This highly interactive web site has been designed especially for aviation users and their need for flight profile-specific, graphical weather, and provides links to most traditional AWC products as well as the new integrated products. Users can actually “click” in a route of flight, select a desired altitude, and view weather hazard graphics in vertical cross-section along a route of flight. ADDS may be viewed at http://adds.aviationweather.noaa.gov/.

As implied, ADDS provides an immediate service to aviation users while at the same time allows new, experimental products to be viewed and verified. In partnership with the AWC, NCAR, and other AWR Program participants, the FAA and National Weather Service have implemented a formal process that quickly transitions experimental products to operational use. Called AWTT—Aviation Weather Technology Transfer—this process ensures users can derive benefit from this important research without delay.

Weather to the Cockpit

NCAR, NASA, FAA, many service providers and avionics manufacturers, and the NWS also participate in a number of important programs that are focusing on providing high-resolution weather graphics to the airborne pilot. A long recognized shortfall of the aviation weather infrastructure, weather in the cockpit was a primary thrust of the NASA AvSP. The Aviation Weather Information (AWIN) segment of the AvSP and follow-on integrated flight deck programs target all classes of aircraft—general aviation through military and commercial airliners—to ensure the pilot can share in the benefits of improved weather information. The NASA AvSP and FAA have also sponsored a number of programs demonstrating and implementing the use of airborne aircraft as atmospheric sensors, which can provide real-time in-situ measurements of temperature, relative humidity, winds, turbulence, and icing conditions. This data is extremely valuable to human and automated diagnostic and forecasting processes.

There are two challenges to implementing an international capability of uplinking/downlinking weather information and data. The first is the data link itself, in terms of bandwidth and communications costs. A number of NASA programs have sponsored testing and development of new digital communication and networking technologies and techniques. These include satellite digital radio and high bandwidth very high frequency communications which have the capability to efficiently transmit the large amount of data needed. Industry is also exploring the use of high bandwidth communications to provide passenger services, such as Internet-in-the-sky, that can provide the needed infrastructure to support weather to the cockpit.

The second challenge relates to aircraft equipage limitations and the cost to reequip for communications and display capabilities. For this reason, a full spectrum of options are being explored that will permit weather in the cockpit for “legacy” aircraft as well as new, integrated displays for new technology aircraft.

For older aircraft, simple graphics are being created using text characters and existing on-board printers. The Oceanic Weather Product Development Team is demonstrating this technique to avoid aircraft modification and to show that even this simple type of information transfer is valuable to the pilot (Figure 4). Figure 5 is
an example of the “electronic flight bag” concept, with weather graphics, being demonstrated on a United Airlines A-320. All of these systems and techniques have been designed to accommodate the emerging, integrated weather products.

Figure 5. “Electronic Flight Bag”

ATM Decision Support

Everyone agrees that improved weather information will have a positive effect on air traffic management decision support. How the information is employed in both automated and manual air traffic functions is not well understood. There are a number of groups and organizations studying the problem in terms of the human factors and decision support aspects with an industry goal of defining an evolving concept of operations for new, more precise weather information.

The problem, of course, is the uncertainty of weather prediction that will never go away. The TDWR development mentioned earlier is somewhat different than the diagnosis of turbulence, for example, as the microburst could be detected with near certainty and the decision being supported was binary—go or no-go. This is not the case for en route weather hazards, as there are a number of decisions that could apply. And because of the uncertainty of weather prediction, in most cases airspace will not be totally closed based on a forecast. A good example of this is the disruptive nature of convection, which severely limits the flow of traffic but very seldom totally closes off a point-to-point flight route.

Here are some considerations and challenges facing the national airspace system as more precise weather information is integrated into decision support for air traffic management:

First, weather information is essential for effective ATM decision support. Weather becomes a constraint on the system.

Weather products should be of high information content and high “glance value.” They should be 4-dimensional (space and time) so that a 4-D flight profile can be related to the weather information.

Even with much improved resolution and precision, the weather information will still have some degree of uncertainty. Therefore, effective ATM will most likely not tolerate deterministic-type decisions (like closing airspace).

Giving consideration for the uncertainty, an operational concept for the use of integrated weather products is essential for both automated and semi-automated decision support (they will be different). This is something that will evolve and cannot be defined without trying out various concepts. This suggests rapid prototyping decision support systems (DSS) to evolve a concept of use.

To take advantage of the uncertainty characteristic of weather information,
consideration should be given to generating probabilistic forecasts and then basing decisions on expected value (or cost) of a particular course of action. This concept is familiar to us all—risk management as opposed to risk avoidance. Expected value thresholds for decisions such as metering or limiting traffic through hazardous weather areas should be established through experience (prototyping) or customer tolerance to cost. This concept allows for “shades of gray” between binary decision extremes.

Consideration should be given to keep the human in the ATM decision loop to take advantage of human judgment. It will be difficult to arrive at a complete set of rules for all situations needed to fully automate ATM functions.

Implementation of an ATM DSS that includes weather must consider that rules/thresholds will be different for different regions and weather hazards.

An en route DSS must include consideration for the terminals as well. En route traffic flows will impact terminal input and output. Further, weather decision support for when terminals are impacted by hazardous weather must be included. For example, decision support to enhance arrival capacity improves nothing if there are thunderstorms along the standard terminal arrival and the DSS doesn’t know it.

Conclusion

The improvements to weather information products and dissemination systems introduced in this paper are revolutionary in every sense of the word. Most significantly, impacts to national airspace system efficiency, safety, and increased capacity are poised to happen in the very near term. The concept of automated, integrated, informational weather products has been shown to provide end-users the decision support they need without burdening them with data that is either not needed or difficult to interpret. Although these products are being introduced just as soon as verification shows improvement from traditional weather products, research will continue to incrementally add more skill to the algorithms as necessary to support more efficient and safe aircraft operations.

An important area of active research continues to study the human factors and efficiency aspects of using the new weather technologies within ATM decision support systems. An expected result of this work will be an evolving concept of operations for both automated and manual decision support. Once this occurs, the national airspace system can expect to realize the full potential benefit of enhanced weather information.

Reference


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