AWE: Aviation Weather Data Visualization Environment

Lilly Spirkovska *

NASA Ames Research Center, MS 269-3, Moffett Field, CA, 94035-1000, USA

Suresh K. Lodha

Computer Science, University of California, Santa Cruz, CA 95064, USA

Abstract

Weather is one of the major causes of aviation accidents. General aviation (GA) flights account for 92% of all the aviation accidents. In spite of all the official and unofficial sources of weather visualization tools available to pilots, there is an urgent need for visualizing several weather related data tailored for general aviation pilots. Our system, Aviation Weather Data Visualization Environment (AWE), presents graphical displays of meteorological observations, terminal area forecasts, and winds aloft forecasts onto a cartographic grid specific to the pilot's area of interest. Decisions regarding the graphical display and design are made based on careful consideration of user needs. Integral visual display of these elements of weather reports is designed for the use of GA pilots as a weather briefing and route selection tool. AWE provides linking of the weather information to the flight's path and schedule. The pilot can interact with the system to obtain aviation-specific weather for the entire area or for his specific route to explore what-if scenarios and make "go/no-go" decisions. The system, as evaluated by some pilots at NASA Ames Research Center, was found to be useful.

Key words: weather visualization, general aviation, route selection, user evaluation.

1 Introduction

Weather is one of the major causes of aviation accidents. According to a NASA planning group, it is estimated that approximately 30 percent of commercial air-

* Corresponding author. Fax number: 650-604-4036.
Email addresses: spirkov@wolfie.arc.nasa.gov (Lilly Spirkovska), lodha@cse.ucsc.edu (Suresh K. Lodha).

craft accidents have weather as a contributing factor. Although, the percentage of accidents (0.4 accident per 100,000 departures), has remained flat in the past five years according to the National Transportation Safety Board, the total number of accidents will increase beyond public expectations due to the projected increase in the number of flights in a few years. Therefore, in 1997, a national goal was defined in the United States to reduce the fatal aviation accident rate by 80 percent by the year 2007. The US Federal Aviation Administration has launched an aggressive aviation weather research program and is pouring millions of dollars into different parts of the aviation weather research [25].

Significant advances have been made in the last decade in both weather forecasting and weather visualization for a variety of audiences including scientists, forecasters and the general public [11]. Professional TV production systems for weather presentations to the general public have been in existence for more than ten years and are constantly being upgraded. An example is the TriVis system operating since 1993 [33]. An interactive 3D weather visualization system VISUAL for scientists has been installed in the German Meteorological Office (DWD) in collaboration with Fraunhofer IGD since mid-1990s. Personalized Weather-on-Demand products are also being offered through the internet since 1998. Augmented reality weather visualization systems are being developed. Many of these systems also incorporate numerical weather prediction (NWP) forecasts and observations. However, the users are requesting tailored visualization tools for their specific needs. In particular, the existing and developing weather forecasting and visualization technology needs to be harnessed appropriately for the benefit of the pilots.

Broadly speaking, all aviation activities can be classified into commercial airline operations, general aviations (GA) and military operations. It is important to understand the differences between the needs of weather visualization and route selection for commercial and general aviation pilots. It is interesting to note that only 4% of aircraft are associated with commercial airline operations. Indeed, the rest of the aviation activities, referred to as general aviation, account for 96% of all aircraft. The general aviation aircraft range from single-seat, single-engine, piston aircraft to business jets that can fly as high as air carriers but typically carry less than 20 passengers. More importantly, GA pilots cover the full spectrum of flying experience, from student pilots with 20 hours of experience to accomplished pilots with tens of thousands of hours. In contrast, commercial pilots have substantial flying experience, fly powerful equipment such as the Boeing 747, and have a network of support people on the ground at the Airline Operations Center and the FAA's air traffic control centers. In addition, GA pilots often fly at lower altitudes, fly slower, carry less fuel on board, and thus cover shorter distances in a single flight. A typical flight covers about 400 miles in 4 hours. Because of the lower altitude and slower speed, they spend more time in adverse weather conditions. In contrast, air carrier aircraft are able to fly above much of the weather for a large portion of the flight. Commercial air carriers account for 85% of all the passengers carried, 67% of the total miles flown, but only 40% of the total hours flown due to the high speed. Indeed, although GA accounts for only 60% of the total hours flown, it accounts for over 92% of the total accidents. The fatal accident rate for air carriers is 0.15 accidents per 100,000 hours flown, whereas it is nearly an order of magnitude greater for GA at 1.4 accidents per 100,000 hours flown. Of these accidents, more than 15% can be attributed to weather [5].

The focus of this work is to provide weather graphics useful to the general aviation pilots for route selection and weather briefing. The most important official source of aviation weather reports to the GA pilots in the United States is Direct User Access Terminals (DUATs). In addition, weather briefings can be obtained via telephone, aircraft radio, or infrequently, in person from Flight Service Station (FSS) specialists (employees of Federal Aviation Administration (FAA)) [22,23,44], or via computer from the DUATs (Direct User Access Terminal) system [8]. Most of these briefings are textual or verbal and are obtained prior to flight. Face-to-face briefings with an FSS specialist have the advantage of access to graphical displays of the data. This advantage is outweighed by the limited availability of FSS facilities. Unfortunately, DUATs does not provide visualization of three of the most important elements of a weather briefing: airport-specific current weather observations (meteorological observations, or METARs), terminal area forecasts (TAFs), and winds aloft forecasts.

Perhaps the most important unofficial source of weather information to pilots is the National Weather Service (NWS) web sites [35]. Although these web sites provide a greater variety of weather graphics, the information provided to the pilots associated with airports and terminal areas is difficult to use. The pilot has to pick an airport in order to display the weather-specific information, which is then displayed textually without filtering as shown in Figure 1, which is difficult to grasp. Moreover, this weather information is hard to relate to the flight's schedule and path.

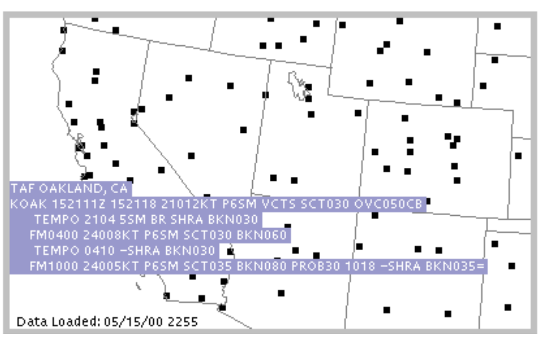

Fig. 1. The TAF squares can be selected with the mouse to obtain the full text associated with a NWS TAF display.

In a recent article [25], Perry states that "Unfortunately, the type of weather information available to a commercial pilot is scanty; a sheet of weather data printed out before takeoff, may be outdated and of minimal use." The inadequacy of the weather information provided to the pilots through the DUATs and the NWS often make them turn to several other unofficial sources of weather information such as the television news weather reports, the Weather Channel[6], or a variety of weather web sites [35,19,45,34,46]. However, these unofficial sources often provide only a general view of what the weather will be like.

In this work, we present AWE (Aviation Weather Data Visualization Environment) that focuses on extracting aviation-specific weather information from textual documents, visualizing this information, linking it to the flight's path and schedule, and providing a simple user interface to the pilot to control the display. To this purpose, we focus specifically on those weather products that have not been visualized or readily accessible through DUATs, NWS or many other sources mentioned before. Three main examples of these products are: airport-specific current weather observations (meteorological observations, or METARs), terminal area forecasts (TAFs), and winds aloft forecasts. AWE provides linking of this information to the flight's path and schedule, and thus facilitates answering of questions tailored to the pilot's needs which are difficult to address using current weather products. For example, AWE can be used to answer the following question quickly: Will the clouds be low enough to require flight under instrument flight rules, or can I fly under visual flight rules?.

It is possible to extend AWE by adding additional weather-related information such as the information on turbulence, wake vortices, icing, lightning and precipitation information, storm cells, ceiling, etc., or by adding numerous continuous weather informations based on numerical weather prediction systems. Later in Section 4, we report on some preliminary pilots' feedback on these questions. However, clearly additional research is needed to decide how much additional weather information (and which ones) can be presented in a display so that the visualization remains intuitive and uncluttered. Such a study is beyond the scope of this work. Rather, AWE is one step towards the important goal of ”providing weather information relative to the pilot's flight path, present it to the pilot in the cockpit in an easy-to-interpret graphical format, and give him decision-making aids to help him use that information ....” outlined by Stough, the manager of NASA's aviation weather information systems (AWIN) project at the Langley Research Center [25].

There is one additional very important question: the availability of in-flight weather information to the pilots. The most important issue here is the communication of the information to the pilots and the advancement in the datalink technologies. In this area again, currently the commercial pilot gets updates from the ground staff through a text printer via 2400 baud modem, or hears anecdotal reports from other pilots in the area. Currently, AWE is operational on the ground as a briefing and routing tool for pilots prior to flight. Because of the minimal data transfer requirements, AWE can be easily incorporated as an in-flight decision-making tool.

The rest of the paper is organized as follows. Section 2 describes the background, previous and related work. Section 3 presents Aviation Weather Data Visualization Environment (AWE) including graphical design, display and flight path planning issues. Section 4 describes users' feedback and experiences. Finally, Section 5 concludes with a summary and directions for future research.

2 Background and Previous Work

We begin by describing in detail the most important source of official weather information available to the pilots – Direct User Access Terminals (DUATs). We then describe an important unofficial source of weather information available to pilots – Aviation Digital Data Service (ADDS) by the National Weather Service (NWS).

2.1 DUATs

Till early 1990s, Flight Service Station Specialists (FSS) were the only official source of information to the pilots. With the introduction of the DUATs service in mid 90s, pilots were given the option of receiving more automated official briefings via a modem dial-in or through an internet browser. In the late 1990s, DUATs introduced graphical displays to help pilots visualize the ”big picture” using weather graphics.

DUATs, Direct User Access Terminal system, is offered by private companies under contract to the FAA. It is available to all pilots, from student pilot onward. We used the DynCorp (previously known as GTE) DUAT system. It obtains its data from the FAA, which in turn obtains some of its data from the National Weather Service. A DUATs area briefing provides the following information in a *textual* format:

- Area Forecast including position of fronts, pressure systems, wind conditions, cloud layers, weather (such as rain), and visibility conditions,
- Severe Weather Warnings,
- SIGMETs (Significant Meteorological Conditions) and Convective SIGMETs such as thunderstorms,
- AIRMETs (Airman's Meteorological Information) for turbulence, mountain obscuration, widespread low visibility conditions, and icing conditions and freezing levels,
- Surface Observations or METARs (Meteorological Observations) of current conditions, including ceilings, visibility, wind, barometric pressure, temperature and dew points for certain airports,
- Pilot Reports,
- Radar Summaries that textually provide information about echos, echo movement, and echo intensity,

- TAFs (Terminal Area Forecasts) including ceiling, visibility, and wind forecasts for certain airports,
- Winds Aloft Forecasts for relevant sites at altitudes of 3000 feet to 39000 feet, at various increments, and
- NOTAMs (Notices to Airmen), which provide information on such things as airport closures, unlighted obstructions, out of service equipment such as runway lights, etc.

Some of the above information is also presented to the pilots visually. In particular, DUATS provides weather charts including surface analysis and surface forecast charts that show the current and forecast location of high/low pressure systems and warm/cold fronts, areas of precipitation, and infrared satellite charts. An example chart is shown in Figure 2. In addition, these charts also display visibility conditions crucial to pilots. There are three types of visibility conditions that pilots typically use:

- Instrument flight rules (IFR). This is defined as visibility $<$ 3 miles and/or ceiling $<$ 1000 feet.
- Marginal visual flight rules (MVFR). This is defined as (3 miles $<$ visibility $<=$ 5 miles) and/or (1000 feet $<$ ceiling $<=$ 3000 feet).
- Visual flight rules (VFR). This is defined as visibility $>$ 5 miles and ceiling $>$ 3000 feet.

These visibility conditions are displayed as color-coded regions as shown in Figure 3. The charts are very effective in providing a broad (nation-wide) overview of the weather, but they do not provide information about specific locations, such as airports along the pilot's route. In particular, DUATs does not provide visual information on METARs and TAFs. Moreover, this weather information is not related to the flight's path or schedule.

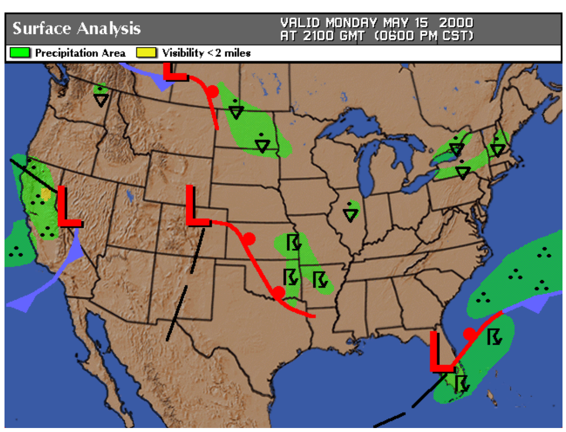

Fig. 2. An example of graphics available through DUATs. This surface analysis chart shows low pressure systems ("L"), cold fronts (the blue line across southern California) and warm fronts (the red line from Colorado, through Kansas and Oklahoma), areas of precipitation (such as the rain in Northern California and thunderstorms in eastern Kansas and eastern Oklahoma).

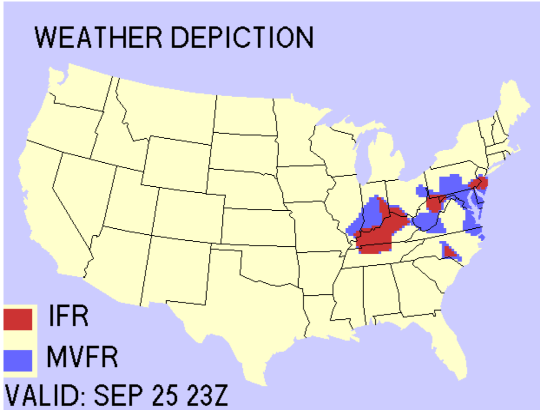

Fig. 3. Color-coded visibility conditions in DUATs. Poor visibility regions are shown in red and marginal visibility regions are shown in blue.

2.2 NWS

We now describe weather information and graphics available to pilots through the World Wide Web site by the Aviation Weather Center of the National Weather Service (NWS)[35] initially released in 1997. Unlike the DUATs site, the NWS site is experimental and unofficial. However, it provides a greater variety of graphics, and allows pilots to zoom in to get more specific information about an area of interest.

In addition to the standard charts provided by DUATs, NWS does attempt to provide more information visually on METARs and TAFs. Figure 4 shows a METAR display provided by the NWS site. The color coding reflects the visibility conditions. The amount the disk is filled reflects the cloud coverage amount, with empty disks representing clear conditions, partially filled disks representing few, scattered, and broken clouds, and completely filled for overcast conditions. Additional information such as wind speed and direction, temperature, dew point, and airport identifier can be associated with the disks by selecting the proper options through an interactive menu. Winds aloft display is shown as barbs (Figure 5) discussed later in Section 3.2.

The TAF display shown in Figure 1 is less powerful. The standard display shows a black square over airports that have TAF reports. No graphical display of the forecast is available. Rather, the pilot can get a textual display of an individual TAF by selecting the appropriate square. As shown in Figure 1, the textual display obscures the surrounding region.

In addition to DUATs and NWS, there are many other non-aviation weather web sites [6,19,45,20] that could also prove useful as a supplement to official pre-flight briefings. For example, weather graphics available to the general public, such as those shown on television newscasts or the Weather Channel, do a reasonable job of displaying lots of weather information that pilots find useful. Overall, all these

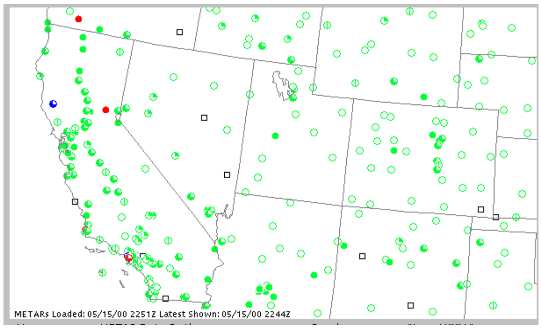

Fig. 4. A METAR display available through the National Weather Service web site. Each circle represents a METAR report. The color-coding provides some information on current visibility conditions, such as visual flight rules in effect (green circles) or instrument flight rules in effect (red circle). Cloud coverage is depicted by progressively filling in the disks for greater cloud coverage.

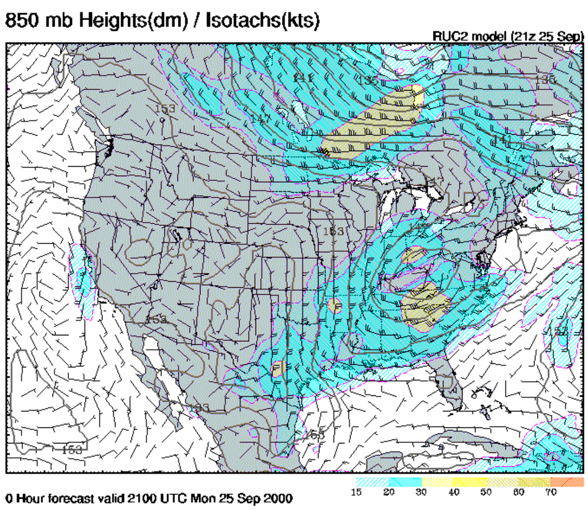

Fig. 5. Winds aloft display using barbs within ADDS system by NWS.

sources put together provide adequate information on low/high pressure systems, cold/warm fronts, clouds and cloud movement (through sequences of satellite images), and areas of precipitation (through sequences of radar images). Some of these sources also provide graphics for forecasts for wide-spread areas of thunderstorms, high wind speeds, or fog. Thus, visualization of most of the textual DUATs briefing is already available.

In this work, we focus on visualizing what has been neglected so far – the latest weather reports for selected airports (METARs), and the forecast reports for these airports (TAFs). To these displays, we also add a winds aloft display. Although NWS displays winds aloft reports, we provide additional functionality to help the pilot plan his flight. More importantly, the integrated visual display of these three elements allows a pilot to more quickly recognize and understand the current and forecast weather in an area of interest along the flight's path. AWE presents an intuitive, graphical presentation of these elements and provides an environment to determine alternate routes including altitude or alternate destinations, and explore his/her routing options with quick ”what-if” scenarios. We expect that the easy interaction improves the pilot’s understanding of current and forecast conditions during the pre-flight briefing in order to make an informed decision about whether to take off or delay the flight and to plan a safe route.

2.3 Related Work

There is a large body of literature on weather visualization and related products [37]. Visualization of large scientific data for earth sciences [12], oceanography [31], meteorology [39], climate modeling [17], and for environmental decision making [28,29,7,27] has been around for more than a decade. In addition to DUATs and NWS, we have also mentioned a number of weather related web sites [1,6,19,20,45,35,34,46] and professional weather presentation systems [33]. A number of research projects are under way to build more accurate weather forecasting tools [38,18]. Wood [48] describes a system for presenting environmental data over the world wide web. Haase [11] describes an interactive 3D weather visualization system for scientists. Treinish [40] emphasizes task-specific visualization and categorizes different weather visualization tools based on the type of visualization (2D or 3D) and support (level of interactive analysis and browsing capability) into different classes. In particular he mentioned Advanced Weather Information Processing System (AWIPS) by NWS, Vis5D developed by the University of Wisconsin, and efforts by Forecast Systems Laboratory (FSL).

The state-of-the-art in weather visualization for aviation-specific needs is also addressed by several researchers [25,8,13,22,23,44]. Numerous aviation weather visualization efforts are under way including those at NOAA, FAA, NRL, Rockwell Science Center, Honeywell International, WSI Corporation, BFGoodrich, EchoFlight, and the MIT Lincoln Lab.

In particular, Perry [25] emphasizes the need for developing more precise weather forecasting tools for turbulence, wake vortices, icing, and fog. We have already described DUATS and NWS in Sections 2.1 and 2.2 respectively. The weather visualization system described by Scanlon [32] perhaps comes closest to our work.

Scanlon presents four weather maps to the pilots. These maps are a national radar mosaic for precipitation data, an air-to-ground lightening strike map, a category map displaying visibility conditions relevant to commercial airline flights, and a ceiling/visibility map shown in Figure 6. Of these four maps, the last map is most relevant to our work. It presents four elements of a METAR/TAF: ceiling (lowest broken (BKN) or overcast (OVC) cloud layer), visibility, wind speed only if it is above 30 knots, and a notation for the existence of precipitation or another hazard known to exist at the airport. The glyph used is shown in Figure 6 and consists of two stacked rectangles color-coded to signify visibility and ceiling conditions with a gap which flashes white for winds above 30 kts, an adjacent red square if a flight hazard exists, and the character ”P” if precipitation is reported. Further information, in the form of the original METAR/TAF text, is available by selecting the glyph for an airport. By selecting a glyph, the pilot can have the METARs (a history of the last five reports) for a single airport displayed or the most recent TAF for that airport. The original TAF is displayed without any filtering based on anticipated arrival time. The textual information is displayed as a separate window that obscures the ceiling/visibility map so geographical context is temporarily covered. Scanlon designed his system for in-flight use by the commercial airline pilots and tested the system using simulated data. AWE, in contrast, is designed for general aviation flights.

Fig. 6. Ceiling/visibility map by Scanlon [32].

Many other researchers have focused on different aspects of aviation needs that are complementary to the weather visualization focus of AWE. Pruyn and Greenberg [26] visualized desired heading and altitude at different positions in the airspace surrounding the airport to facilitate the approach and landing at airports. Though their emphasis is not on visualizing weather data, they do consider showing the pilot a simulated wind sock (showing the wind direction and speed, similar to the wind sock at the airport) to give him extra preparation time for when he breaks out of the clouds and is ready to land. We considered utilizing a wind sock to represent wind velocity in AWE, but decided against it for reasons discussed in Section 3.2.3. Azuma et al. [2,3] utilize visualization techniques to present conflict resolution scenarios with other flights, leaving FAA air traffic controllers with more opportunity to do strategic planning rather than just immediate control.

Finally, the design of glyphs (shape, orientation, placement, color etc.) is an important, often a critical, element in the visualization of scientific data [4,42,43].

Appropriate use of color [16,36] and perceptual principles [10,41] is important to construct accurate and cognitively easy to decipher visual displays [30]. In AWE, we have given careful consideration to each glyph design and attempted to validate our designs by involving the users (pilots) through out the development process as discussed and reported later in this work.

3 AWE

In this section, we present AWE (Aviation Weather Data Visualization Environment). The input to the AWE prototype is a DUATs briefing for a specific area, for example, a 95 nautical mile (nm) radius from the Palo Alto airport, KPAO. We map this briefing onto a grid specific to the pilot's route or his area of interest and only include information relevant to his flight. For instance, for route-specific weather, rather than displaying current data available for his destination, we use forecasts available for his proposed time of arrival (automatically computed from his route and chosen departure time). We make careful and well thought out decisions using sound visualization principles [4,42,43] to design graphical displays in order to present the information to the pilots in a cognitively easy to decipher format. We validate our results through users' feedback.

AWE allows the user to specify his flight including route, desired altitude, true airspeed, and proposed departure time; select whether he wants to see current weather or forecast weather; and select whether the area of interest is just airports along the route or all airports in the area. The user is able to modify any of the route parameters and see the effect on weather he might encounter. We discuss each of these issues in the following sections.

Section 3.1 focuses on extracting aviation-specific weather information from textual documents. Section 3.2 discusses the graphical design choices we made and why. Section 3.3 describes the linking of the visual information to the flight's path and schedule, and providing a simple user interface to the pilot to control the display. Finally, Section 3.4 briefly describes the implementation of AWE.

3.1 Aviation-Specific Weather Data Extraction

As stated before, AWE focuses on extracting aviation-specific weather information from textual documents describing winds aloft display, METARs (Meteorological Conditions), and TAFs (Terminal Area Forecasts). We need to go through a pre-processing phase to clean the textual elements of these documents. The original textual document has three separate sections dealing with METARs, TAFs, and winds aloft information. We start by deleting the input format comments and extra notations associated with METARs and inserting semi-colons into TAFs so we can simplify our parser. For tacitly understood information, we make it explicit in the modified file. For instance, if no information is provided in the DUATs briefing regarding obstruction to visibility, we insert ”NO”. We also separate the original textual document into three separate documents. An example of each of these three textual documents (already slightly modified for ease of parsing) is shown in Figure 7, Figure 8, and Figure 9 respectively. The retrieval of relevant weather information from modified textual documents is straightforward. We now describe each of these three documents in detail.

```
KSFO 11 11 0 10 10 2 9 8 -4
     7 5 -10 27 7 -23 25 19 -34
     24 36 49 24 32 55 25 24 58
KSAC 11 12 0 20 20 1 18 19 -5
      15 29 -10 31 35 -24 16 29 -35
      24 33 49 24 31 55 26 20 58
```

Fig. 7. Sample winds aloft file. The airport identifier is followed by groups of three elements: wind direction, wind speed, and temperature. These groups of three are available for prespecified altitudes from 3000 feet to 39000 at various increments.

```
KSQL 181646Z 18014KT  8SM   NO FEW012 SCT050 BKN080 11/08 A3022
KSFO 181656Z 24008KT 10SM   NO FEW012 BKN060 11/08 A3022
KPAO 181646Z 00005KT 10SM   NO FEW015 SCT050 11/08 A3021
KSJC 181653Z 00000KT  9SM   NO FEW180 09/07 A3021
KRHV 181653Z 01000KT 10SM   NO FEW015 SCT100 10/07 A3022
KHWD 181654Z 04006KT 10SM   NO SCT050 OVC100 11/07 A3021
KOAK 181653Z 07007KT 10SM   NO FEW020 SCT040 OVC070 11/08 A3023
KLVK 181653Z 00000KT  5SM   HZ CLR    09/06 A3021
KCCR 181653Z 05004KT 10SM   NO FEW035 OVC060 11/08 A3023
KAPC 181659Z 03007KT 20SM   NO FEW030 SCT050 11/08 A3023
KSCK 181656Z 27006KT  1SM   NO OVC001 07/07 A3021
KSAC 181656Z 33004KT 0.25SM FG OVC001 07/07 A3022
KMOD 181650Z 06003KT  5SM   BR FEW015 SCT050 04/04 A3021
KMRY 181654Z 05016KT  3SM   RA BKN020 OVC040 16/04 A3014
KSNS 181653Z 11022KT  6SM   SH SCT020 BKN035 14/07 A3016
KWVI 181653Z 11012KT  9SM   BR FEW030 BKN060 16/07 A3016
KVCB 181653Z 35007KT 10SM   NO CLR    15/07 A3019
KSTS 181653Z 00000KT  4SM   HZ SCT012 BKN025 14/06 A3019
KMCE 181653Z 00000KT 7SM    HZ CLR    12/08 A3019
```

Fig. 8. Sample METAR file. Each line represents a METAR for a specific airport, specified by the airport identifier (first element). It also specifies the time of observation, wind direction and wind speed, visibility, visibility restrictions, cloud layers (with coverage amount and altitude), temperature, dew point, and barometric pressure.

Winds aloft: The winds aloft report begins with the airport identifier (i.e. KSFO) and then gives the direction the wind is coming from (in tens of degrees), the wind speed, and the temperature at each of the prespecified altitudes. It is implicit in these files that these three values are specified at altitudes from 3000 feet to 39000 at various increments. More precisely, the winds aloft values are associated with 3000, 6000, 9000, 12000, 18000, 24000, 30000, 34000, and 39000 feet. For example, the first row in Figure 7 example, the KSFO (San Francisco, CA) airport winds aloft report ”KSFO 11 11 0 10 10 2 9 8 -4 ...” states that the wind at 3000 feet is coming from 110 degrees at 11 knots. The temperature is not specified at 3000 feet; however, for the ease of uniform parsing, we have introduced a zero. Similarly, the wind at 6000 feet (the second set of 3 values) is from 100 degrees at 10 knots and the temperature is 2 degrees Celsius.

Since, DUATs only provides winds aloft for certain locations and for certain altitudes, there is a need to compute the wind speed and direction at the pilot-specified

```
KSFO 181730Z 181818 05007KT P6SM FEW010 SCT050;
     BECMG 2223 28010KT P6SM SCT100 SCT200;
     FM0300 30005KT P6SM SCT080 BKN100 BKN200;
     BECMG 0708 07005KT P6SM SCT200;
.
KSJC 181730Z 181818 00003KT P6SM SCT200;
     BECMG 2223 32017KT P6SM FEW050 SCT200;
     FM0300 32008KT P6SM SCT050;
     FM0600 00003KT P6SM SCT040 BKN080;
     FM0900 18020KT 3SM BR BKN020 OVC080;
     FM1600 00003KT P6SM SCT200;
.
KOAK 181730Z 181818 07007KT P6SM SCT200;
     BECMG 2223 28007KT P6SM BKN100 OVC200;
     FM0300 31005KT P6SM SCT100 OVC200 ;
     BECMG 0708 06005KT P6SM SCT200;
.
KSCK 181735Z 181818 30006KT P6SM SKC;
     BECMG 0102 00003KT P6SM SKC;
     FM0800 00000KT 3SM BR SKC ;
     FM1000 00000KT 1SM BR SKC ;
     TEMPO 1015 0.25SM FG VV002;
     FM1600 00003KT 3SM BR SKC ;
```

Fig. 9. Sample TAF file. A TAF for an airport extends from the airport identifier to the dot (”.”). Each TAF provides the time the forecast was created followed by the effective times of each forecast element. Each element specifies the wind direction and speed, visibility and restrictions to visibility, and cloud layers (with coverage amount and altitude).

altitude and location. In AWE, we have used distance-based interpolation, that is one of the methods used in meteorological computations [9,21], to fill in the missing values. We are aware of the data uncertainty problems arising due to this approach, but we have addressed these concerns elsewhere [24,47,15,14].

METAR: The METAR report also begins with the airport identifier. An example is shown in Figure 8. We will decipher the first row of this figure. KSQL stands for the San Carlos (CA) airport. ”181646Z” specifies the date (18) and the time of observation (16:46). The month and year is implicit in the file. All times are specified relative to the Greenwich Mean Time, also known as Universal Coordinated Time (UTC) and denoted by Z (or Zulu). ”18014KT” gives the surface wind direction (180 degrees) and the speed (14 knots) at the airport. The visibility is ”8SM” (statute miles). There are no restrictions to visibility. Compare this with the METAR for ”KSAC”, where ”FG,” or fog, is restricting visibility. The cloud layers are specified next. San Carlos has a few clouds at 1200 feet, scattered clouds at 5000 feet, and broken clouds at 8000 feet. The temperature is 11 degrees Celsius and the dew point is 8 degrees. Finally, the barometric pressure is 30.22 inHg (inches of Mercury).

TAF: Interpreting the TAF report is similar to the METAR report. An example is shown in Figure 9. As an example, we will translate part of the second set of data associated with the KSJC (San Jose) airport. The report time is on the 18th of the month at 17:30 Zulu. The forecast is valid for the 18th from 18:00Z to the 19th (next day is implicit) at 18:00Z. The wind is from 0 degrees at 3 knots, visibility 6 statute miles or greater, with scattered clouds at 20000 feet. The second row states that between 22:00Z and 23:00Z the winds will become (”BECMG”) 320 degrees at 17 knots, plus 6 sm visibility, with a few clouds at 5000 feet and scattered clouds at 20000 feet. The fifth row in this set starting with FM0900 states that from 09:00Z (the following day), the wind will be from 180 degrees at 20 knots, the visibility will be 3 statute miles with mist ("BR"), with broken clouds at 2000 feet and overcast clouds at 8000 feet. Note that the FAA provides a standard interpretation of the cloud cover amount: FEW means 1/8 of the sky or less is obscured by clouds, SCT means between 1/8 and 3/8 of the sky has clouds, BKN means 4/8 to 7/8 of the sky, and OVC means the entire (8/8) sky has clouds. The FAA also provides a list of standard contractions for visibility obscurations. Our examples are not for comprehensive coverage, but rather for general understanding. Hence, only a few options are discussed.

3.2 Graphical Design and Display

We now turn to the display formats. We begin by describing the background of our graphical display. We then discuss the display of winds, METARs and TAFs.

3.2.1 Background

Both DUATs and the NWS weather graphics use a state outline of the continental US as the background image. This approach provides little contextual information useful to pilots. AWE uses a VFR (Visual Flight Rules) aeronautical chart for its background. One can obtain these charts at different resolutions of 3-1/2 miles (terminal), 7 miles (sectional) and 14 miles (world) per inch. Currently, AWE uses VFR sectional aeronautical charts. Figures 10, 11, and 12 show the VFR sectional aeronautical chart for San Francisco in the background.

We considered other options such as IFR (Instrument Flight Rules) charts, and 3D depiction of terrains as well. We felt that the 3D depiction of terrains will require much more interaction and perceptual understanding of 3D displays before these displays can be adapted for the pilots' use. Although IFR charts are much less busy than the VFR charts (described below), they do not provide adequate data for low-altitude flights that can be crucial in avoiding weather-related accidents. We also report on users' feedback regarding our choice of VFR as the background image.

The VFR sectional chart shows the location of airports (magenta or blue circles or short lines that mimic the runway layout), airways ("highways" in the sky as light blue straight lines), navigation aids (such as VHF Omni Ranges also known as VORs and mostly depicted by a compass rose), controlled and special use airspace, obstructions, natural terrain features (such as water and hills, depicted using color coded altitudes), demographic features (such as cities, depicted in yellow), and maximum elevation in each area (depicted with numbers with superscripts). Finally, the horizontal white lines appearing in Figures 10, 11, and 12 indicate that a detailed terminal area chart is also available for the encompassing region. Although

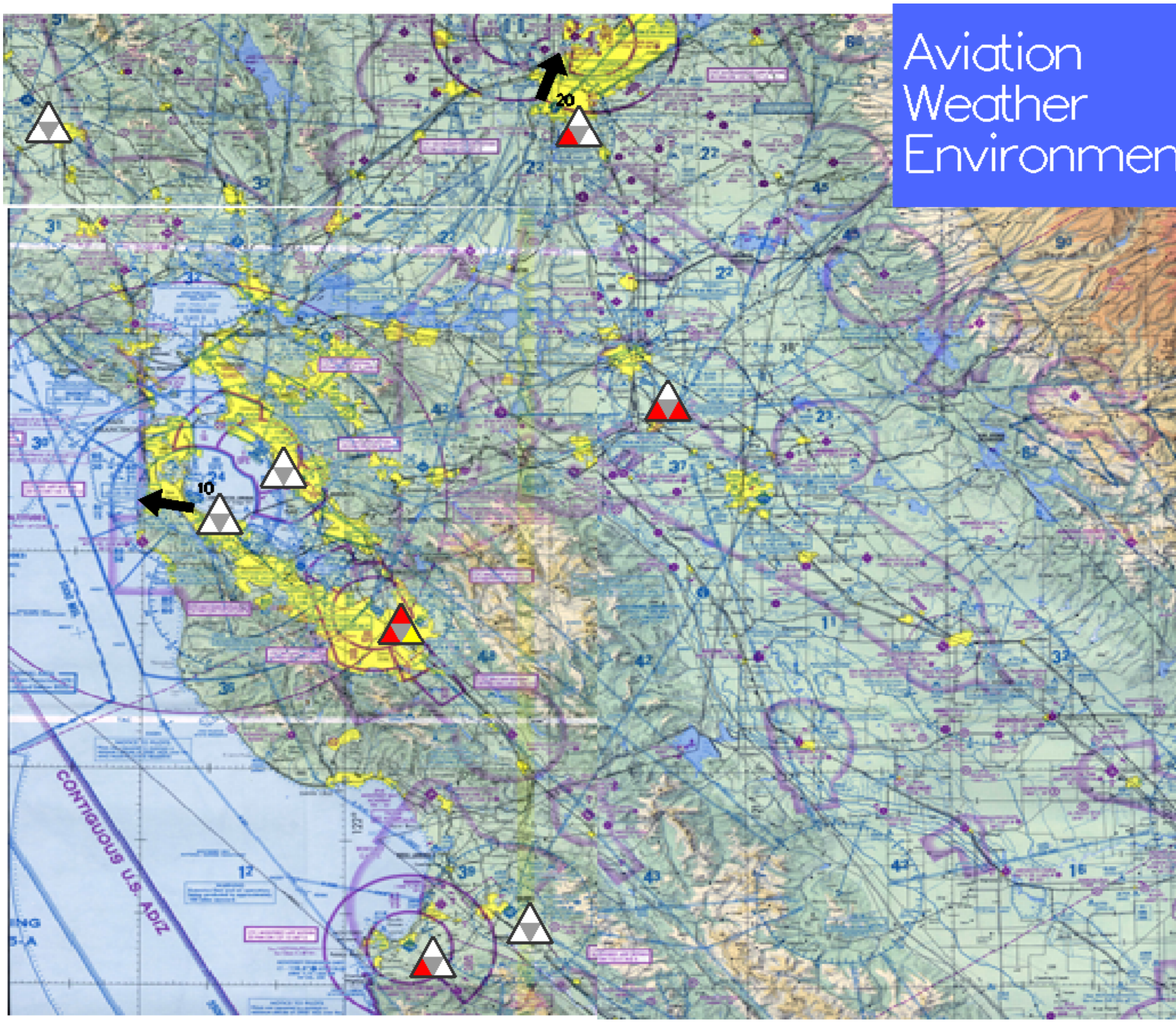

Fig. 10. Area TAF display using triangular warning icons. The top, lower left, lower right, and the middle subtriangles represent winds, visibility, clouds and temperature/ dew point spread conditions respectively. Red, yellow, and white colors indicate alert, caution and normal conditions respectively. Grey color indicates that the information is not available.

the background may look cluttered and complex, the chart background texture gives pilots a familiar environment with which to interact and provides them with additional information for making their ”go/no-go” decision. For example, a 2000 foot ceiling presents a different situation if the airport is in a flat region versus a narrow valley surrounded by tall mountains. Overlaying the weather on the chart consolidates the weather and the terrain surrounding the airport allowing the pilot to make a decision by looking only at one source.

In particular, we expect that this display will be very useful in route selection. The

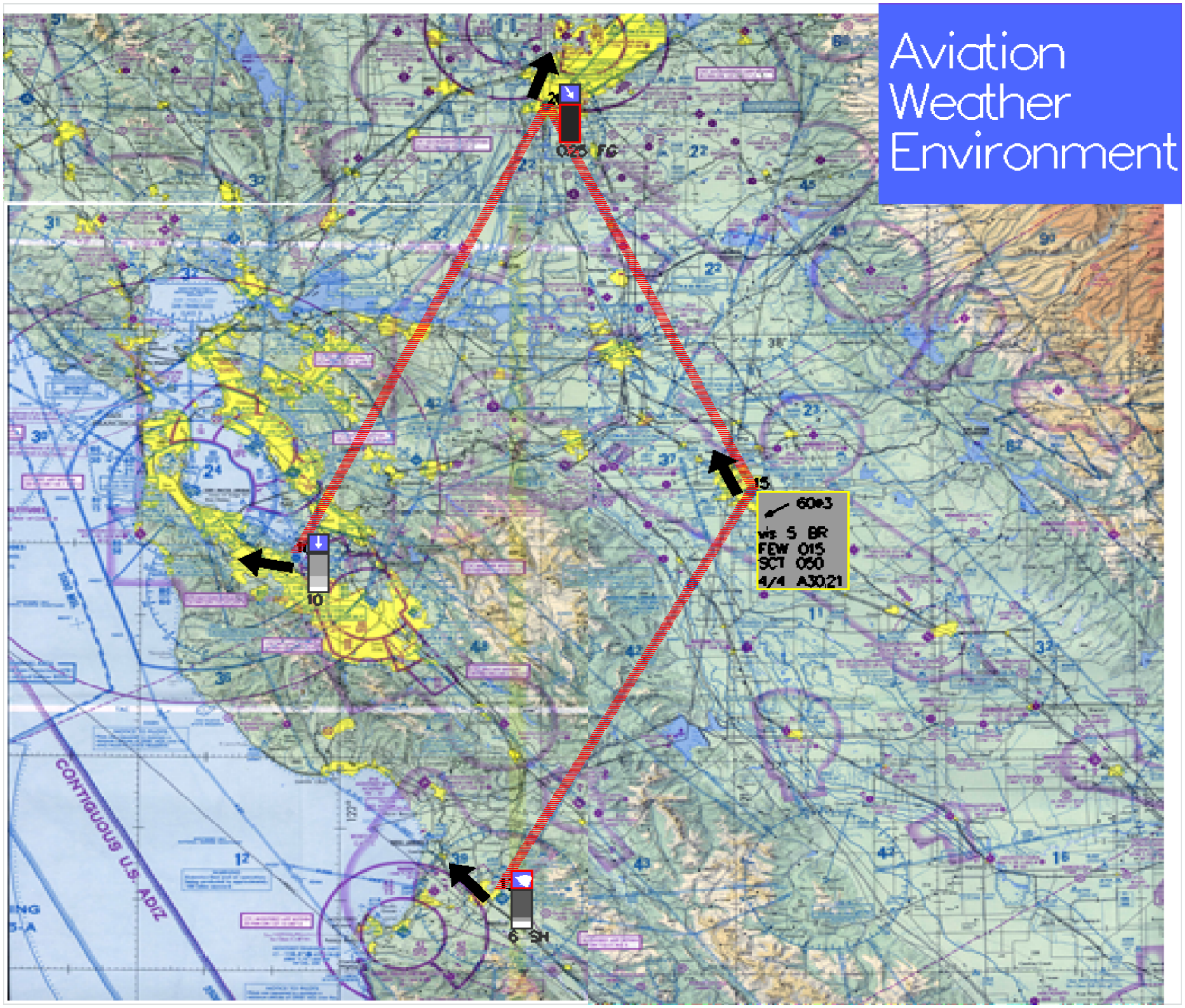

Fig. 11. Route METARs and winds aloft shown alongside a pilot-selected route. A combination of textual METAR at KMOD (Modesto, California) and symbolic METARs at KPAO (Palo Alto, California), KSAC (Sacramento, California), and KSNS (Salinas, California) is shown. The red border at KSAC indicates poor visibility due to fog, and the yellow border indicates marginal visibility at KMOD.

route selection process typically involves determining a minimum distance path that avoids the above hazards, as well as any hazards presented by adverse weather conditions. Seeing each of these elements on one display simplifies the process. Using AWE, a pilot is able to plot a path that has accessible navigation aids; avoids special use, prohibited, or restricted airspaces; approaches mountainous terrain at the proper angle and altitude based on the winds aloft; avoids flight over inhospitable terrain; optimizes his emergency landing choices; and avoids flight through adverse weather.

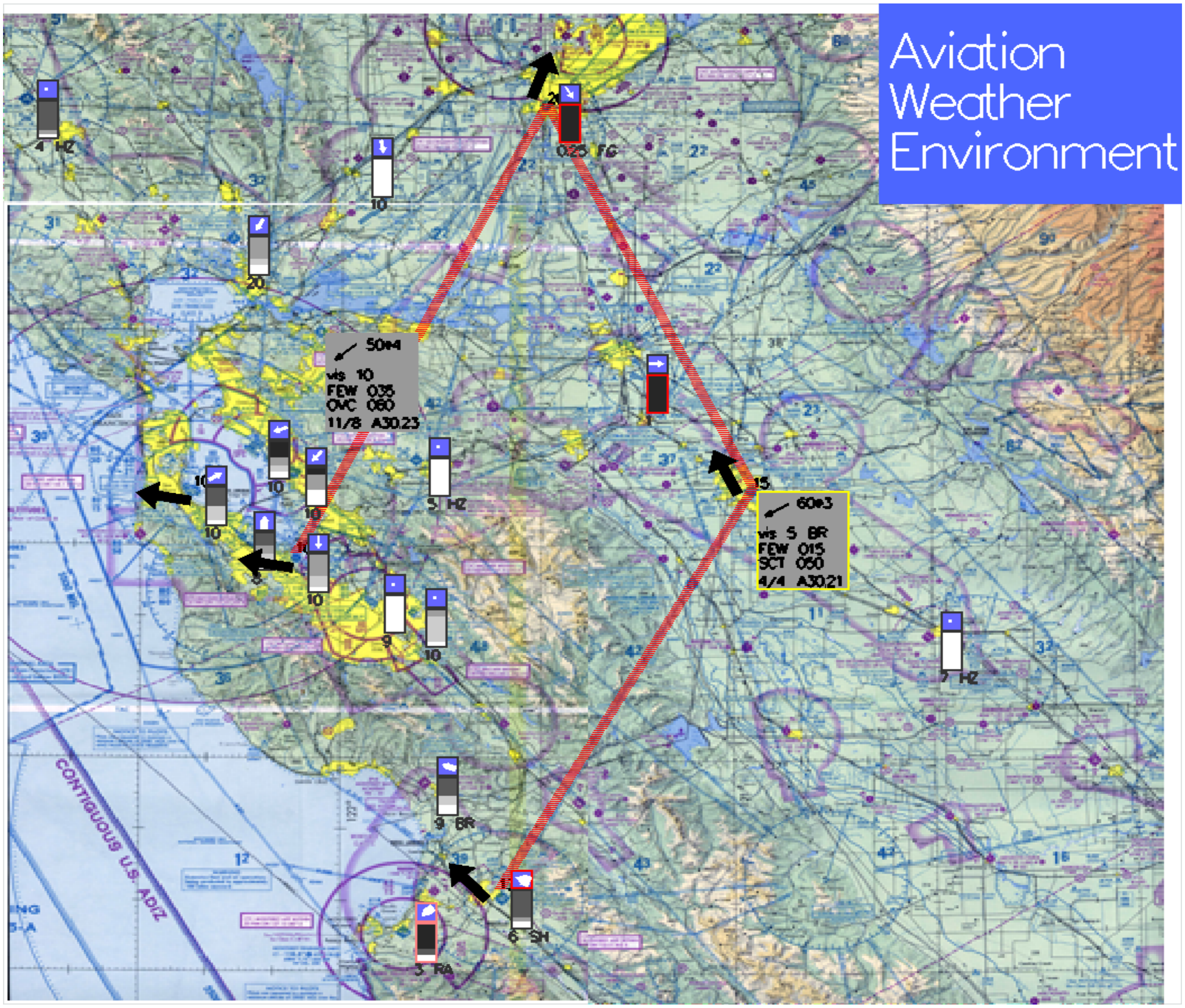

Fig. 12. Area METARs. All the METAR reports available for the charted area. METARs can be displayed in symbolic or textual format as shown here.

3.2.2 Winds Aloft Display

The most common method of displaying winds for aviation purposes, also adopted by FSS, DUATs and NWS, is the use of wind arrows with barbs as shown in Figure 5. Each barb represents either 5 knots or 10 knots, depending on its length. Although this representation is familiar to pilots, one has to count the barbs and try to determine whether it's a short barb or a long one. The direction of the wind is encoded in the tilt of the arrows.

In AWE, we considered two choices for displaying winds aloft data. The two choices were barbs and wind arrows. After some initial discussion with pilots, we decided to use wind arrows over the barbs. We rotate the wind arrow to show the direction of the wind at that location and display the wind speed alongside. Most pilots find this display simpler than the barbs display. In this method, it is easier to quickly read a number (the wind speed). Furthermore, this method seems to bring out wind direction more clearly than the barbs. Later in Section 4, we report on this choice by providing users' feedback.

In AWE, we have used the winds aloft display in both the route specific weather and the area wide weather. If the pilot requests route weather, we display wind information alongside each airport along his route, as illustrated in Figure 11 by the black arrows. This visual representation allows a pilot to compare his flight path to the path of the wind and determine whether to expect a tailwind, headwind, or crosswind. He/she can then compensate for a crosswind easily, or expect to go slower and use more fuel for a strong headwind, or slow down to save fuel but still arrive at the scheduled time in case of a strong tailwind. If the pilot has requested area wide weather, AWE displays all known winds aloft forecasts for central California.

Because winds aloft are altitude dependent, in AWE, the pilot can modify his selected altitude to determine where the winds are most favorable. This helps the pilot to choose an appropriate flight path for cruising.

3.2.3 METAR/TAF Display

Determining how to display a METAR or a TAF to make it easily decipherable yet provide all the necessary information is challenging. The FAA approach, used with charts available at Flight Service Stations, are very informative, yet very cryptic. Their symbols, shown in Figure 13, require a lot of memorization and can be easily forgotten if not used regularly. Instead, we could choose to follow the Weather Channel approach and display only a small set of symbols. One disadvantage of this approach is that much of the available information is not represented.

In AWE, we present options to the pilot to view all the information available or to view only part of it. In particular, the pilot has the option to ask for all the information, ask for part of the information in a visual representation that provides him/her with a ”feel” for the weather, that helps in making ”go/no-go” decisions prior to flight, or ask for a visual presentation which provides him with an overview of the weather, that is helpful in making routing and path planning decisions. We now discuss these options in greater detail.

Textual METAR/TAF Display with Color-coded Borders: When the pilot asks for all the information related to the METAR/TAFs, we choose to display the information mostly in a textual manner by presenting the essentials in a compact way. A textual display of METAR information is shown in Figure 14. Contrast this with the textual display of TAFs using NWS used currently (Figure 1). To make the task of recognizing crosswind conditions quicker, we still represent the surface wind

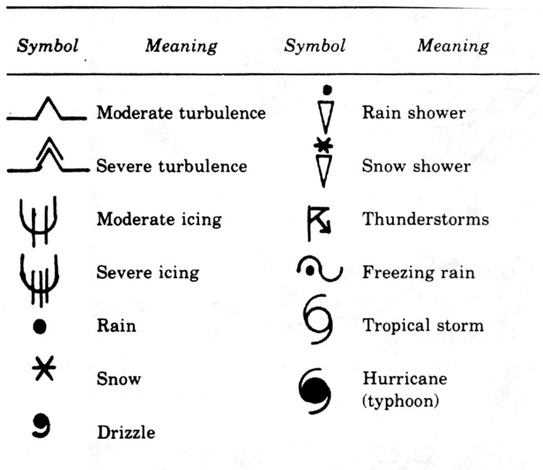

Fig. 13. FAA weather symbols and their associated meanings. These symbols are used on charts available at Flight Service Stations, and more recently on DUATs and NWS charts available on the web.

direction (not to be confused with the winds aloft, which is at varying altitudes) graphically as well as textually. The details of the textual display are described in the caption of Figure 14.

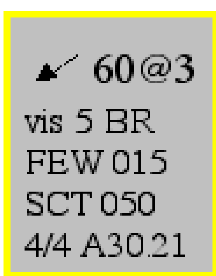

Fig. 14. Close-up view of a textual representation of a METAR. The wind direction is shown by the arrow. The wind direction and wind speed are also shown by the text in the upper right corner. In this case, the wind is coming from 60 degrees at 3 knots. The visibility is 5 miles with 'BR' or mist. Cloud layers are given as a few clouds at 1500 feet and scattered clouds at 5000 feet. Finally the temperature and dew point are both 4 degrees and the barometric pressure is 30.21 inHg. The colored rectangle (yellow) represents marginal visual flight conditions (MVFR). It would be colored red for poor visibility conditions (IFR) or gray for good visibility (VFR).

The textual displays are supplemented with color-coded borders to warn the pilot of possible adverse visibility conditions. We described the visibility conditions, namely IFR, MVFR and VFR in Section 2.1. Many pilots are prevented either legally (by not having appropriate certification) or practically (by not being proficient) from landing at airports with IFR conditions. MVFR conditions are only a practical, not a legal, deterrent (many pilots feel less safe in marginal conditions). AWE displays airports with IFR conditions with a red border, airports with MVFR conditions with a yellow border, and those with VFR conditions without a border.

Visual METAR/TAF Display for Overview: There are four primary elements that affect a pilot's "go/no-go" decision: wind conditions, visibility, cloud altitude, and temperature / dew point spread. The first three elements are available both in METARs and TAFs. The fourth element (temperature/dew point spread) is only available in METARs. We have already mentioned the importance of wind conditions, visibility, and cloud conditions earlier. We now briefly comment on the fourth element – the spread between temperature and dew point, that is temperature minus dew point. The temperature/dew point spread provides information regarding fog, and is clearly an important piece of information, particularly in areas where morning and evening fog is common for example in the San Francisco Bay Area. If the airport is currently experiencing fog, the spread gives information on when it may become clear (especially if you have the previous hour's METAR and can see a trend in how the spread is changing). There are conditions under which temperature may be an important piece of information as well. For example, in the heat of the summer, temperature is important, particularly at high altitude airports, since it has a direct effect on aircraft flight characteristics. Similarly, low temperatures have an effect on starting the engine and they can contribute to possible ice on the airframe. Usually, though, temperatures can be safely classified as non-critical information and are not represented in the iconic format in AWE.

Our icons are designed to present a quick overview of all four primary elements. We first considered some of the icons in use such as colored regions in DUATs (Figure 3), color-coded disks, and weather channel representation. All these representations seem to do a good job of providing one piece of information such as visibility conditions; however, they fall short of providing lower level details such as cloud information or winds etc. Color-coded disks with auxiliary information as utilized in ADDS attempt to overcome this difficulty; however, this method depends upon a key and also the dense barbs often overlap with other information.

Therefore, in order to present the four quantities in an integrated manner, we considered some additional graphical options for displaying them – rectangular representation stacked on top of each other, rectangular representation stacked horizontally, circular representation with one quarter assigned to each element, and triangular representation subdivided into four subtriangles with each triangle assigned to each element. We chose the rectangular representation stacked on top of each other for the detailed METAR/TAF visual display (to be discussed next), because this representation is ideally suited for cloud layers at different heights. Therefore, we wanted to choose an alternative representation for distinction. Of the remaining three, an earlier discussion and user feedback seemed to favor the circular or the triangular representations which appeared to be more wholistic and easier to process. We finally decided on the triangular icon because triangular icons are used for warnings and are more familiar to the pilots. Also, the temperature/ dew point spread information is not available for TAFs and is not as crucial as the rest of the information. Therefore, we assigned the center subtriangle to this information.

An area-wide TAF display using triangular icons is shown in Figure 10. The top, lower left, lower right and the middle triangles represent wind, visibility, clouds, and temperature/ dew point spread respectively. Figure 15 describes the color coding used in the triangular icon. In the TAF displays, since they do not provide temperature or dew point forecasts, the center triangle is always shown in gray. In each of these cases, the color coding serves to alert the pilot of possible adverse conditions. The thresholds were chosen to coincide with the FAA definitions of IFR and MVFR conditions for visibility and ceiling. The thresholds for wind speeds and temperature dew point spreads were chosen based on a typical pilot and weather profile. A more flexible user interface would allow each pilot to set his/her own thresholds for caution and alert conditions.

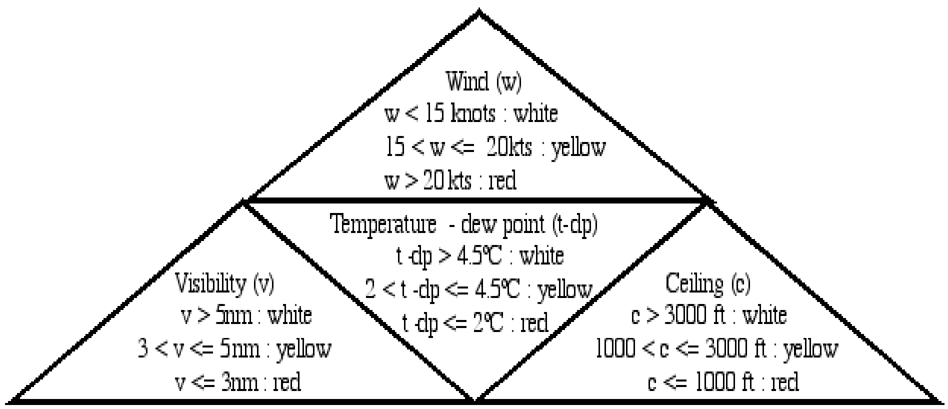

Fig. 15. Triangular icon color coding scheme.

Visual METAR/TAF Display with Details: AWE also uses visual displays for presenting detailed METAR/TAF information. Several examples are shown in Figure 11. Figure 16 shows a close-up view of the symbolic representations. This METAR/TAF display encodes surface wind speed and direction, cloud conditions at different altitudes, and visibility conditions.

Winds: We considered several alternatives for displaying this information. An important decision was to choose between arrow glyphs and wind socks to represent wind speed and direction. Every airport has a wind sock and pilots are able to interpret them readily. The direction is displayed by the orientation of the wind sock and the speed is displayed by the amount the wind sock is straightened to the 90 degree orientation (with respect to the pole holding it up). We attempted to use a wind sock to display wind information as suggested by Pruyn and Greenberg[26] but found the 3D wind sock did not merge well with the overhead perspective of our 2D view. Also, one of the advantages of displaying the wind direction is diminished when using the wind sock: when using a wind arrow, the pilot can easily compare the wind

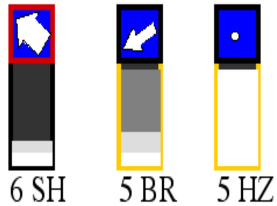

Fig. 16. Close-up view of symbolic representation of METARs. The wind is coming from the SouthEast at about 20 knots in the left symbol, from the NorthEast at about 5 knots in the middle symbol and is calm in the right symbol. The red border in the left symbol shows indicates strong winds. The left symbol shows a broken layer of clouds at about 3000 feet, the middle symbol shows a scattered layer at about 4000 feet, and the right symbol indicates clear conditions below 12000 feet. Finally, the text below the symbols corresponds to 6 miles visibility with showers, 5 miles visibility with mist, and 5 miles visibility with haze.

direction with the orientation of the runways as displayed on the sectional chart (AWE's background image). Thus, crosswind landing conditions become visually obvious. The 3D wind sock requires more analysis to extract similar information. Therefore, we decided in favor of the arrow glyphs. These arrow glyphs are similar to glyphs used in winds aloft display, but with the following modifications. In winds aloft display, we use the same size arrow and the wind speed is presented textually adjacent to the arrow. We felt that this approach is justified because the wind direction is typically much more important than the wind speed. The winds aloft display thus facilitates the quick detection of altitudes at which the direction of the winds are most favorable to the flight path. The speed of the wind is also important at the selected altitude and is used to compute the time of arrival at various checkpoints. However, in recent practice, this task is often delegated to the on-board GPS (global positioning system) unit, further reducing the importance of displaying the wind speed.

In contrast, in METAR/TAF display, the width of the surface wind arrow varies with the speed of the wind. Light winds (that is, low wind speeds) are represented by thin arrows, whereas strong winds are represented by thick arrows. Compare the wind symbol (20 knots) shown in the left symbol of Figure 16 and (5 knots) shown in the middle symbol of Figure 16. Also notice the winds shown in the right symbol of Figure 16. The wind vector in the right symbol 0 degrees at 0 knots, or calm. Calm winds are represented with just a dot since no direction is associated with them.

Finally, the border of the wind square is color coded. A red border signifies strong winds (>= 20 knots), an orange/yellow border signifies medium winds (>= 15 knots), and black border signifies winds below 15 knots.

Clouds: The next element of the METAR/TAF symbol is a rectangle that presents the cloud layers. The rectangle represents the sky from 0 to 12,000 feet. We chose 12,000 feet because automated weather observation systems (AWOS) use the same height threshold for reporting clouds. We then pseudo-color the rectangle to show the cloud layers[16,36]. As suggested by Bertin[4] and Tufte[42], we chose a gray scale to represent the cloud amounts so pilots do not need to remember a color key. Darker colors represent thicker coverage. Hence, white represents a clear sky. Very light gray represents a few clouds, a darker light gray represents scattered clouds, medium gray represents broken clouds, and finally, very dark (nearly black) gray represents an overcast sky. Ceilings (defined as broken or overcast layers) are thus quickly recognized by scanning for darker grays.

Visibility: The border of the rectangle is color coded to instantly show whether the visibility conditions are poor (IFR with red border), marginal (MVFR with orange/yellow border), or normal (VFR with black/no border).

The final element of a METAR/TAF symbol is the text specifying the visibility and obstructions to visibility. That information is presented in black and blends in more with the background than the rest of the symbol. In this way, the information is there if it is needed, but it is not overwhelming.

The METAR/TAF symbols do not represent the temperature, dew point, or barometric pressure values. Also, the values for cloud altitudes are shown only indirectly (by the amount of rectangle filled). If any of those values are desired exactly, the symbol can be transformed into a text box containing all available information as discussed previously.

3.3 User Interface and Path Planning

The Aviation Weather Data Visualization Environment, AWE, provides an environment for the pilot to interact with and obtain the information he/she needs to effectively plan a flight. The user interface for the system is shown in Figure 17. The pilot is able to set the true airspeed of his airplane, select an altitude for the flight, and specify a departure time. He can also select whether he wants to display weather for the entire area or just along the flight path. Moreover, he can choose to view any of the graphical displays discussed earlier such as METARs with overview, details or textual, TAFs, or winds aloft. Finally, he can specify to display the graphics only for selected airports or use the closest airport in case the information is unavailable from a selected airport. These selections are used to determine what specific information to display, as discussed below.

3.3.1 Selecting Information Overlays

AWE provides the pilot with a number of options in selecting what information to display. These include:

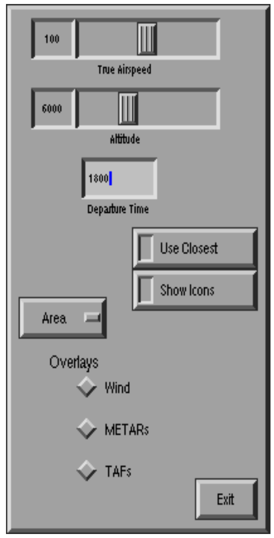

Fig. 17. User interface of AWE

- Display focus: display area wide weather vs. route specific weather;
- Type of weather: display current weather observations (METAR) or forecast weather (TAF), and/or winds aloft;
- Display formats: display an overview visual representation, a detailed visual representation, or a textual representation of either METARs or TAFs.
- Report locality: display only weather for airports with reporting capability or also display closest available weather for airports without reporting capability.

We now describe each of these options below.

Display Focus: The pilot can choose to display weather at airports either just along his route of flight, as shown in Figure 11 or at airports in the entire area known by AWE, as shown in Figure 12. The area wide weather option is especially useful during the route selection phase. The pilot can view all available weather and then choose a route of flight. Conversely, if he has already chosen a route, route specific weather shows him only information relevant to his flight.

Type of Weather: The pilot can choose to view either current (METAR) or forecast (TAF) weather, as well as winds aloft information. Most (probably all) airports that provide TAF forecasts also provide METAR observations. Therefore, we implemented the options to display METARs or to display TAFs to be mutually exclusive to avoid screen clutter; that is, either METARs or TAFs can be displayed, but not both simultaneously. Winds aloft, on the other hand, provide complementary information to both sources and can be displayed either alone or with a TAF or METAR. METARs and TAFs provide surface winds associated with the reporting airport. Winds aloft reports provide winds at various altitudes and are associated with a much wider area around the airport.

Display Formats: AWE provides the pilot with three options on how to display the METAR and TAF reports. We discussed these options in detail in Section 3.2.

Report locality: Not all airports AWE knows about have weather reporting capabilities. If the pilot is viewing route specific weather, we provide him with the option of choosing to display the nearest report (METAR or TAF) for airports that fit this criteria. To accomplish this, the pilot chooses the ”show closest available weather” option.

3.3.2 Route Selection

In contrast to the route selection process of a commerical airliner, which is mainly controlled by the flight controllers on the ground, a general aviation pilot has considerable flexibility in choosing the flight path. As stated before, a typical general aviation flight lasts about 4 hours and covers about 400 miles. Depending upon the purpose of the flight – pleasure or business – the pilot also has the flexibility of choosing the landing airport. Weather plays a major role in determining a safe as well as a fuel-efficient or a time-efficient route.

In AWE, the pilot can explore what-if scenarios by choosing alternate routes and observing the weather conditions along the different routes. The pilot specifies his route of flight by selecting (with the mouse) a sequence of airports. The user is able to extend his route by adding an airport to the end, modify his route by deleting airports off the end until the modification point is reached (eventually backtracking to the beginning if desired), or specify a new route. As airports are added or deleted, the interface is updated to reflect the current specified route. The background screen with a route selected by the pilot is shown as a solid line in Figure 11.

Flight Schedule and Time-dependent Information: Pilots need the forecast weather at the time of arrival at each en-route checkpoint (airport, in AWE), not the forecast for the departure time. To eliminate the need for the pilot to specify a full flight plan with expected arrival times, we calculate arrival times automatically based on the specified true airspeed and departure time. If the pilot is looking at route-specific TAFs, he will be given the appropriate forecast based on this information.

Choosing an Appropriate Forecast: Determining the appropriate forecast is not as simple for a computer as it is for a person. DUATs forecasts are not specified at mutually exclusive time ranges. Rather, as illustrated in Figure 9, the general forecast (given first) covers a 24 hour period. Forecasts for more specific times are then given. Even these specific time periods can overlap. As in the KSCK (Stockton airport) TAF of Figure 9, we see that three forecasts apply for 10:30. First, the general one that spans the range 18:00 on the 18th of the month to 18:00 on the 19th states that the weather will be {wind 300@6, visibility 6 statute mile (sm) or better, sky clear}. Then, the ”FM1000”, states that from 10:00, the weather will be {wind calm, visibility of 1 sm with mist, sky clear}. Finally, the ”TEMPO 1015” states that there will be a temporary condition from 10:00 to 15:00 of weather {visibility 1/4 sm with fog, and a vertical visibility of 200 feet}. AWE must determine which one of these to present to the user. Currently, AWE uses a set of rules which consider the visibility, cloud covers, and wind speeds to extract the most cautious scenario. Thus, in this case, it chooses the temporary foggy condition as the representative weather. More research is needed to extract and represent the information for overlapping time periods.

3.4 Implementation

AWE is written using C++, OpenGL, and Xforms and runs on an SGI workstation. It was also easily ported to a Sony Superslim Pro Notebook computer running Mandrake Linux. This platform will be useful to provide AWE during in-flight use with the help of data-link technology. The underlying capability, or AWE's foundation, consists of object-oriented programming classes that deal with information about airports, METAR, TAF, and winds aloft. It also includes supporting classes that know how to deal with latitude and longitude coordinates and can find distances between lat/long locations. Four data files are used by AWE. Airport identifiers as well as the latitude and longitude coordinates of the airport are specified in a user readable data file, and the DUATs briefing is translated into three separate files: one containing current METARs, one containing TAF forecasts, and one containing winds aloft forecasts.

The two final foundation classes are Awe_interface and Awe. Awe_interface deals with interactions with the user, properly updating the input forms. The Awe class maintains a list of known airports, and reads and updates winds aloft, METAR, and TAF reports. It also provides various search methods, such as finding the closest airport to an arbitrary latitude/longitude position; getting the METAR/TAF for an airport with reporting capability; getting a representative METAR/TAF for non-reporting airports; finding the closest and second closest winds aloft forecasts; or keeping track of the user's chosen route. Each of these methods is used by other foundation classes to help provide what the user wants.

4 Users' Feedback and Experiences

The first author of this paper is a general aviation pilot herself with a commerical license with instrument rating and over 800 hours of flight experience. During the design of AWE, feedback was taken on many issues discussed below at several stages from different pilots to ensure that the system remains pilot-friendly and usable.

AWE, as discussed in this work, was also evaluated by six general aviation pilots (five of them work at NASA Ames Research Center, California). Four of the pilots have a commercial license, two have a private license, and one also has a flight instructor license. Four of the pilots are instrument rated and are hence qualified to fly under poor visibility conditions (IFR). The flight instructor is qualified to teach under poor visibility conditions as well. The approximate total flight time of the pilots ranged from 120 hours to 2000 hours with an average of 675 hours. Each pilot reported that nearly half his hours was outside his local area.

Each evaluation session consisted of a formal demonstration of AWE followed by a practice session and a question/answer period. Each of the pilots was then requested to fill out a questionnaire. Finally, more feedback was obtained through an open-ended discussion of current and desired features.

The first section of the questionnaire aimed to gather information about each pilot's flying background as well as his familiarity with DUATs and ADDS. We have already described the flying background above. The familiarity of the pilots with the DUATs system varied from 1 (very familiar) to 4 (not familiar) on a scale of 1 to 5 (not familiar at all) with an average score of 2.33. Most pilots stated that they were not familiar with the ADDS system at all with an average of 4.67. In an open-ended question as to which weather visualization systems they are most familiar with, five of the pilots mentioned that they use DUATs for their pre-flight briefings. A few also used other methods, such as talking with an FSS specialist and getting unofficial information via television or the World Wide Web.

The rest of the questions sought their opinions on various aspects of AWE's design as well as how it compared to other weather visualizations. We compared AWE to Scanlon's work, ADDS, graphics available through DUATs, and the Weather Channel graphics. We have described all of these systems in Section 2. Rather than asking about each system by name, we presented the pilots with a representative display of these systems and an explanation when needed. As a memory aid and to allow for side-by-side comparisons, we presented a representative display for AWE displays as well.

We begin by presenting the results of the survey in the order that the questions were asked in the questionnaire. Overall, the evaluation of the individual pieces of information in AWE were rated as better than other options in all cases. The first set of questions were designed to evaluate the background, winds aloft display, METAR display, and TAF display. Among the four choices – VFR sectional chart (used by AWE), IFR chart, generic US/state/point-of-interest map (such as used by the GPS units) and 3D depiction of terrain/airports/points-of-interests – the VFR sectional chart as used by AWE was rated as ”very desirable” (1.33) on a scale of 1 to 5 (not at all desirable). The second choice was an IFR chart with a mean of 2.0. This is not surprising because the majority of the pilots are instrument rated and often fly IFR. The remaining two choices – a generic US/state/point-of-interest map and a 3D depiction of terrain/airports/points-of-interest – earned 3.17 and 3.0 and appear to be neutral. In an open-ended question, some pilots expressed desire to selectively declutter some of the background material.

AWE's winds aloft display (black arrow) rated 1.67 on a scale of 1 (very desirable) to 5 (not at all desirable). All other options – arrow with color-coded wind speed, FAA wind speed with barbs, and 3D Windsock – rated worse with a rating of 2.33, 3.0 and 4.17 respectively. Some of the suggested changes in displaying winds aloft display was to include thinner arrows and length-encoded wind speeds.

For the METAR display, we presented the pilots with nine choices including AWE's design and the designs used by other systems as mentioned above. These choices included color-coded disks, color-coded disks with textual information, weather channel type graphics, color regions presenting only IFR/MVFR/VFR etc. AWE's rectangular cloud/wind symbols with color-coded borders were preferred (rating of 1.67) over the other representations, followed by AWE's textual display (1.83) and AWE's triangular icons (2.0). The next best liked representations were a simple textual overlay as you mouse over the airport (2.67), the DUATs representation showing regions of IFR/MVFR/VFR (2.83), and the representation used by ADDS (3.0). A desirable feature not currently included in AWE is the presentation of trends in weather with the ability to extract the more recent METARs.

Not as many systems currently graphically encode forecasts, hence the pilots were presented with fewer choices for the TAF display. Of the five choices, AWE's detailed display was preferred (rating of 1.67) along with AWE's overview display (also a rating of 1.67 but a worse minimum rating). The next best option was considered the ADDS presentation; that is, a textual overlay as you mouse over the airport (2.5).

We also asked about the user interface. The "Use closest" functionality was found to be useful (rating of 1.5) but almost everyone commented that there should be a visual reference that lets the pilot know which airport's report is being used. The automatic selection of the TAF sub-forecast based on arrival time was also considered useful (rating of 1.5). Because arrival times are not precise, the automatic selection of a TAF sub-element would be considered even more useful if the pilot had the option to look at the other forecasts for that time frame or around that time frame.

The second set of questions evaluated the overall utility of different capabilities of AWE in comparison to the other systems as judged by the pilots. AWE was well rated in all categories and was found to be better or much better than the other options presented. For weather briefings, AWE earned an average rating of 1.5 on a scale of 1 ("much better") to 5 ("much worse") for overall comparison to their current system. The pilots also found AWE useful (rating of 1.67) for route selection. For possible in-flight briefings, it was rated a 1.33 on the same scale.

In an open-ended question to determine for what purposes would AWE be most useful, the pilots listed initial planning especially in unfamiliar areas, helping with the go/no-go decision, and enroute decision making such as continuing to fly the original plan, replanning, or choosing an alternate destination. All pilots thought it would be useful both in their local area as well as in an unfamiliar area with a couple of them stressing its greater usefulness in unfamiliar territory.

The discussion following the questionnaire focused on high level advantages and shortcomings of AWE. Overall, the pilots were pleased with AWE, specifically its displays allowing for the quick interpretation of the data, and its helpfulness in choosing routes of flight as well as alternates. Several suggestions were mentioned to add to the existing functionality. The most important ones included the display of (or at least access to) weather trends encoded by METARs and TAFs, an option to display winds aloft for all (DUATs prespecified) altitudes simultaneously, selective de-clutter of the background and displayed symbols, and a method of interacting with AWE in the cockpit that did not rely on a keyboard and mouse. A touch screen and voice interaction were both mentioned as possible alternatives.

5 Conclusions and Future Work

We have presented an Aviation Weather Data Visualization Environment (AWE) for General Aviation (GA) pilots. The system was designed keeping the needs of the pilots in mind. The focus is to display winds aloft, METARs and TAFs information against a useful background in an integrated manner to assist the pilots in making useful decisions. The system can be used for pre-flight weather briefings, route selection, and to make a ”go/no-go” decision prior to the flight. The system was evaluated by pilots and found to be very useful in comparison to several other systems including DUATs which is the most common method for pre-flight weather briefings.

An important step forward would be to make this weather visualization environment available during flights. The Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), and aviation industry are currently developing data link technology which promises to bring much needed data directly to the in-flight pilot [13]. The driving goal for data link is the Free Flight program that will allow commercial and general aviation pilots to determine their route of flight with minimal coordination with FAA air traffic controllers. Besides traffic data[3], data link can be used to transfer weather data to the pilot or send weather data from on-board sensors to a central location for dissemination (as pilot reports) to other flights in the general area. As mentioned earlier, AWE has been ported to a Sony Superslim Pro Notebook computer running Mandrake Linux. We are able to access the aircraft’s current position by connecting the laptop to a GPS (global position system) unit. AWE can use this real-time position data to automatically scroll the area displayed on the chart. We expect that the weather updates in AWE will not require much head-down time (Head-down time is time spent focusing on instruments or data inside the cockpit rather than scanning outside for traffic). We hope to provide AWE for in-flight weather briefings and route modification plans for GA pilots. An important component for interaction would have to be a touch screen or voice interaction capability.

The user evaluation study pointed out some areas of improvement. Noteworthy amongst them are the availability of weather trends as encoded by METARs and TAFs, to display all winds aloft simultaneously, and to selectively declutter the background or displayed symbols. In addition, we are investigating visualization of two additional elements of DUATs briefings that are currently being displayed only textually – pilot reports and notices to airmen. PIREPs are useful in confirming the forecast or pointing out areas where it was not accurate. They are especially helpful for determining the extent of icing conditions and the top of the cloud layers. Notices to airmen (NOTAMs) provide a variety of information potentially helpful to a pilot. Some examples are unlighted obstructions near the airport, acrobatic practice areas, active parachute jumping sites, temporarily prohibited areas, and areas of possibly reduced GPS reception. We believe that the combination of these features will make AWE a very useful tool for local and non-local pilots alike.

6 Acknowledgement

The authors gratefully acknowledge the suggestions from fellow pilots David Iverson, Cedric Walker, and Butler Hine. This research was partially supported by LLNL Agreement No. B347879 under DOE Contract No. W-7405-ENG-48 and the Multidisciplinary Research Initiative (MURI) grant by DOD.

References

[1] Federal Aviation Administration. Word Wide Web. www.faa.gov/aua/awr.

[2] R. Azuma, H. Neely III, M. daily, and R. Geiss. Visualization tools for free flight air-traffic management. *IEEE Computer Graphics and Applications*, 20(5):32–36, September-October 2000.

[3] R. Azuma, H. Neely, M. Daily, and M. Correa. Visualization of conflicts and resolutions in a ’free flight’ scenario. *Proc. of IEEE Visualization*, pages 433–436, October 1999.

[4] Jacques Bertin. *Semiology of Graphics: Diagrams, Networks, Maps*. University of Wisconsin Press, Madison, WI, 1983.

[5] AOPA 1998 Aviation Fact Card. 1998.

[6] The Weather Channel. World Wide Web. www.weather.com.

[7] R. Denzer. Graphics for environmental decision making. *IEEE Computer Graphics and Applications*, pages 58–64, March 1993.

[8] DynCorp DUATS. World Wide Web. www1.duats.com.

[9] Dennis Glaeser, Sanford Gum, and Bruce Walters. *An Invitation to Fly: Basics for the Private Pilot*. Wadsworth Publishing Co., 1985.

[10] G. Grinstein and H. Levkovitz. *Perceptual Issues in Visualization*. Springer, Berlin, 1995.

[11] H. Haase, M. Bock, E. Hergenrother, C. Knopfle, H.-J. Koppert, F. Schroder, A. Trembilski, and J. Weidenhausen. Meteorology meets computer graphics – a look at a wide range of weather visualizations for diverse audiences. *Computers and Graphics*, 24:391–397, 2000.

[12] W. Hibbard and D. Santek. Visualizing large data sets in the earth sciences. *IEEE Computer*, 1989.

[13] Thomas A. Horne. Beaming up the weather. *AOPA Pilot*, pages 97–102, March 2000.

[14] S. K. Lodha, A. T. Pang, R. E. Sheehan, and C. M. Wittenbrink. UFLOW: Visualizing uncertainty in fluid flow. In *Proceedings of IEEE Visualization '96*, pages 249–254, October 1996.

[15] S. K. Lodha, C. M. Wilson, and R. E. Sheehan. LISTEN: sounding uncertainty visualization. In *Proceedings of IEEE Visualization '96, San Francisco, California*, pages 189–196. IEEE, October 1996.

[16] L.W. MacDonald. Using color effectively in computer graphics. *IEEE Computer Graphics and Applications*, pages 20–35, July/Aug. 1999.

[17] N. Max, R. Crawfis, and D. Williams. Visualization for climate modeling. *IEEE Computer Graphics and Applications*, pages 34–40, July 1993.

[18] P. T. McCaslin, P. A. McDonald, and E. J. Szoke. 3d visualization development at noaa forecast systems laboratory. *Computer Graphics*, pages 41–44, February 2000.

[19] MIT. World Wide Web. cirrus.mit.edu/ gempak/forecast_maps.html.

[20] NASA. World Wide Web. http://awin.larc.nasa.gov.

[21] W. Nuss and D. W. Titley. Use of multiquadric interpolation for meteorological objective analysis. *Monthly Weather Review*, pages 1–21, August 1994.

[22] U.S. Department of Transportation. *Aviation Weather: AC 00-6A*. US Government Printing Office, Washington, D.C., 1975.

[23] U.S. Department of Transportation. *Aviation Weather Services: AC 00-45C*. US Government Printing Office, Washington, D.C., 1985.

[24] A. Pang, C.M. Wittenbrink, and S. K. Lodha. Approaches to uncertainty visualization. *The Visual Computer*, 13:370–390, November 1997.

[25] T. S. Perry. Tracking weather's flight path. *IEEE Spectrum*, 37(9):38–45, September 2000.

[26] P.W. Pruyn and D.P. Greenberg. Exploring 3d computer graphics in cockpit avionics. *IEEE Computer Graphics and Applications*, pages 28–35, May 1993.

[27] T. M. Rhyne. Scientific visualization in the next millenium. *IEEE Computer Graphics and Applications*, 20(1):20–21, January-February 2000.

[28] T. M. Rhyne, M. Bolstad, P. Rheingans, L. Petterson, and W. Shackelford. Visualizing environmental data at the epa. *IEEE Computer Graphics and Applications*, pages 34–38, March 1993.

[29] P. K. Robertson and D. J. Abel. Graphics and environmental decision making. *IEEE Computer Graphics and Applications*, pages 25–33, March 1993.

[30] B. Rogowitz and L. Treinish. How not to lie with visualization. *Computers in Physics*, 10(3):268–274, May-June 1996.

[31] L. Rosenblum. Visualizing oceanographic data. *IEEE Computer Graphics and Applications*, pages 14–19, May 1989.

[32] Charles H. Scanlon. Cockpit graphical weather information shown to enhance efficiency, safety, and situationl awareness. In *Proceedings of the 39th Annual Corporate Aviation Safety Seminar (CASS), Flight Safety Foundation*, pages 83–94, April 1994.

[33] F. Schroder and M. Lux. Trivis: Professional television weather presentation. World Wide Web, October 1997. http://www.igd.fhg.de/www/igd-a4/projects/docs/trivis/trivis_e.html.

[34] Aviation Digital Data Service. World Wide Web. adds.awckc.noaa.gov/projects/adds/index.html.

[35] NOAA National Weather Service. World Wide Web. www.awc-kc.noaa.gov/awc/aviation_weather_center.html.

[36] Shubin, Falck, and Johansen. Exploring color in interface design. *ACM Interactions*, pages 36–48, July/Aug. 1996.

[37] P. Stough, M. Rudisill, P. Schaffner, and K. Martzaklis. Aviation weather information systems research and development. SAE Paper No. 1999-01-1579, April 1999.

[38] P. Stough and C. Scanlon. Numerous research projects support efforts to overcome weather-related hazards. *ICAO Journal*, pages 20–29, January-February 1999.

[39] L. A. Treinish. Visualization of scattered meteorological data. *IEEE Computer Graphics and Applications*, 15(4):20–26, July 1995.

[40] L. A. Treinish. Task-specific visualization design. *IEEE Computer Graphics and Applications*, 19(5):72–77, September-October 1999.

[41] L. A. Treinish. Multi-resolution visualization technqiues for nested weather models. In *Proceedings of the IEEE Visualization Conference, San Francisco, CA*, pages 513–516. IEEE Computer Society Press, October 2000.

[42] Edward R. Tufte. *The Visual Display of Quantitative Information.* Graphics Press, Cheshire, CT, 1983.

[43] Edward R. Tufte. *Envisioning Information.* Graphics Press, Cheshire, CT, 1990.

[44] S. Uckun, C. Ruokangas, P. Donohue, and S. Tuvi. Aware: Technologies for interpreting and presenting aviation weather information. In *Proceedings of the IEEE Aerospace Conference, Snowmass, CO,* March 1999.

[45] Aviation Weather. World Wide Web. aviationweather.com.

[46] K. Whitehouse. Weather without the weatherman. *IEEE Computer Graphics and Applications*, pages 12–15, March 1996.

[47] C. M. Wittenbrink, A. T. Pang, and S. K. Lodha. Glyphs for visualizing uncertainty in vector fields. *IEEE Transactions on Visualization and Computer Graphics,* September 1996. 266–279.

[48] J. Wood, K. Brodlie, and H. Wright. Visualization over the world wide web and its application to environmental data. In *Proceedings of the IEEE Visualization Conference, San Francisco, CA*, pages 81–86. IEEE Computer Society Press, October 1996.