THE AVIATION WEATHER DECISION SUPPORT SYSTEM: DATA INTGRATION AND TECHNOLOGIES IN SUPPORT OF AVIATION OPERATIONS

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ABSTRACT

Weather Decision Technologies (WDT) is a private company that specializes in data integration, algorithms, processing, and displays with regard to operational aviation interests. WDT has developed and fielded a turn-key system specifically for aviation meteorologists and Air Traffic Control personnel termed the Aviation Weather Decision Support System (AWDSS). AWDSS integrates a number of surface based data sources including Doppler Weather Radars, Microwave Atmospheric Profilers, Radar Wind Profiles, runway and local airport surface sensors, and lightning data, along with other data sources such as satellite and numerical weather prediction grids. These data are processed through various algorithms to provide warnings of weather conditions hazardous to avaition operations. In addition to the algorithms developed by WDT, many of the detection and prediction algorithms within AWDSS were developed by leading research organizations for the US FAA Integrated Terminal Weather System program. AWDSS provides detections, predictions, and automated alerts of phenomena such as windshear, microbursts, gustfronts, fog, inversions, lightning, and general thunderstorm hazards. Data and algorithm products are viewed in displays customized for both operational meteorologists and Air Traffic Controllers. This paper will present the various aspects of the AWDSS including the use of surface based instrumentation, detection and prediction algorithms, and display systems.

1. INTRODUCTION

Weather Decision Technologies, Inc. (WDT) has developed a custom Aviation Weather Decision Support System (AWDSS) to support operations related to aviation interests. WDT's flagship installation of AWDSS was at the Dubai International Airport in the United Arab Emirates (UAE). The Dubai International Airport is affected by thunderstorms roughly 10 days per year, by fog during 4 months per year, and by sea breeze fronts and strong temperature inversions (with associated wind shear and turbulence) quite often. These weather phenomena can greatly impact operations at the airport, thus having the ability to detect, nowcast, and forecast these phenomena accurately and in a timely manner has immense value. Providing that information to both the meteorologists and air traffic controllers, in a manner they can use operationally, is also of great importance.

AWDSS collects meteorological data from several sources, integrates the data, runs a suite of detection and nowcasting algorithms, incorporates the Weather Research and Forecast Model (Shaw et al. 2008), and provides end-user interfaces, such as that shown in Figure 1, for real-time air traffic control operations as well as the support of operational meteorologist's work flow. The AWDSS utilizes real-time meteorological data from several data sources including Weather Surveillance Radars, Microwave Atmospheric Profilers, Radar Wind Profilers, local airport sensors, lightning data, surface observations, and all observations necessary for initialization of the WRF model.

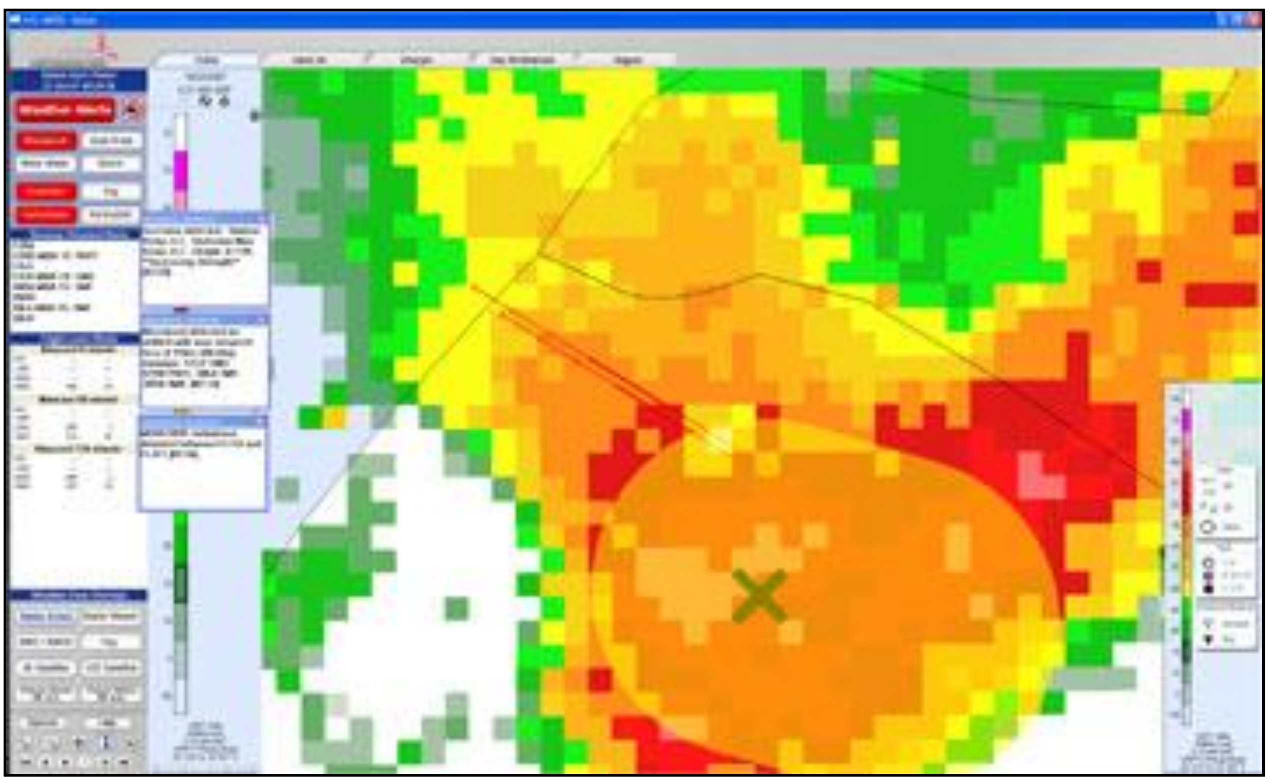


Figure 1. The AWDSS display showing a microburst affecting the Dubai International Airport.

2. AWDSS CONFIGURATION AND HARDWARE

Figure 2 shows an example AWDSS configuration consisting of instrumentation, hardware, and display locations. A typical installation, including WRF configuration, consists of a single rack of servers as shown in Figure 2. This hardware configuration is used for ingest and processing of all available instrumentation, data sets, algorithm and WRF processing, and serving of data and products to displays at both the meteorological offices and the ATC tower.

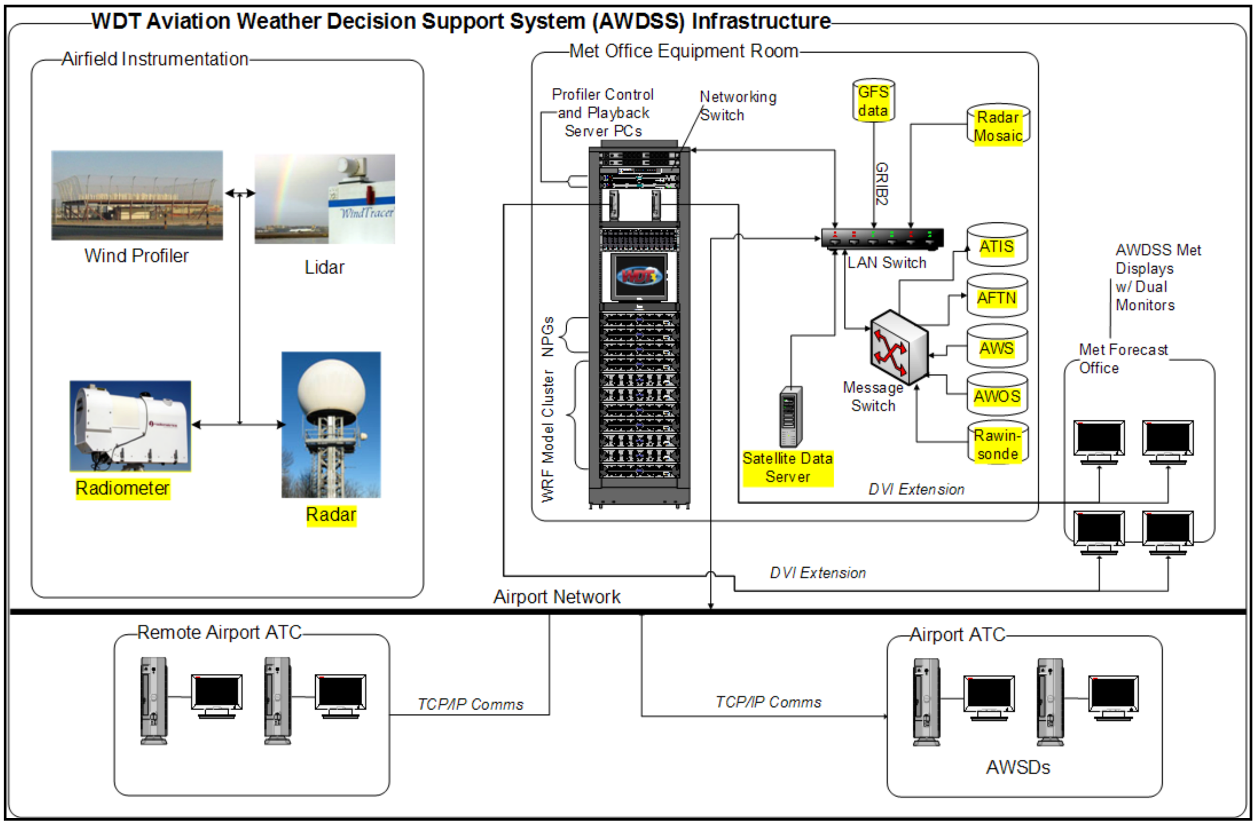


Figure 2. AWDSS configuration and hardware.

3. THE SUITE OF AWDSS ALGORITHMS

The AWDSS contains of a collection of algorithms either licensed from leading research organizations and subsequently enhanced and tuned by WDT, or proprietary technologies developed by WDT and then deployed as part of the AWDSS. At the heart of the AWDSS is the Nowcast Product Generator (NPG). The NPG is a WDT proprietary system comprised of commercial-off-the-shelf hardware and custom software that facilitates the data ingest, data decoding and storage, and proper execution of the algorithms.

3.1. *Microburst Detection Algorithm*

A version of the ASR-9 Microburst Detection Algorithm (AMDA; Cullen et al. 1999) which is similar to the MDA implemented as part of the Integrated Terminal Weather System (ITWS, Evans and Ducot 1994) was licensed by WDT from the Massachusetts Institute of Technology /Lincoln Laboratory (MIT/LL). AMDA provides the detection of divergent wind shear phenomena and estimates wind shear loss through those wind shear phenomena along the runway and along the arriving and departing flight corridors. The main input for the algorithm is the radar data from the EEC radar at the Dubai International Airport. The runway alerting component of the software analyzes each microburst detection in relation to the runways and flight paths. Techniques to determine the flight path expected air speed loss are utilized to provide this information for alerting and display. Runway alerts are only generated if a microburst is overlapping the runway or if any part of it is within 500 meters of the runway (this buffer is variable).

3.2. *The Machine Intelligent Gust Front Algorithm (MIGFA)*

MIGFA was developed by MIT/Lincoln Laboratory (Delanoy and Troxel, 1993). Slightly different versions have been fielded as part of the TDWR system, the ASR-9 Wind Shear Processor (WSP), and the Integrated Terminal Weather System (ITWS). WDT has licensed this software, along with the runway alerting component, and made them part of the AWDSS. The main input for the algorithm is radar data. MIGFA detects and predicts the movement of gust fronts and other synoptic and mesoscale fronts, sometimes only seen as “fine lines” of reflectivity on radar. Gust front detections (Figure 3) are executed utilizing an artificial intelligence technique called “functional template correlation”; this technique was adapted from a technique to automatically identify military vehicles utilizing satellite data.

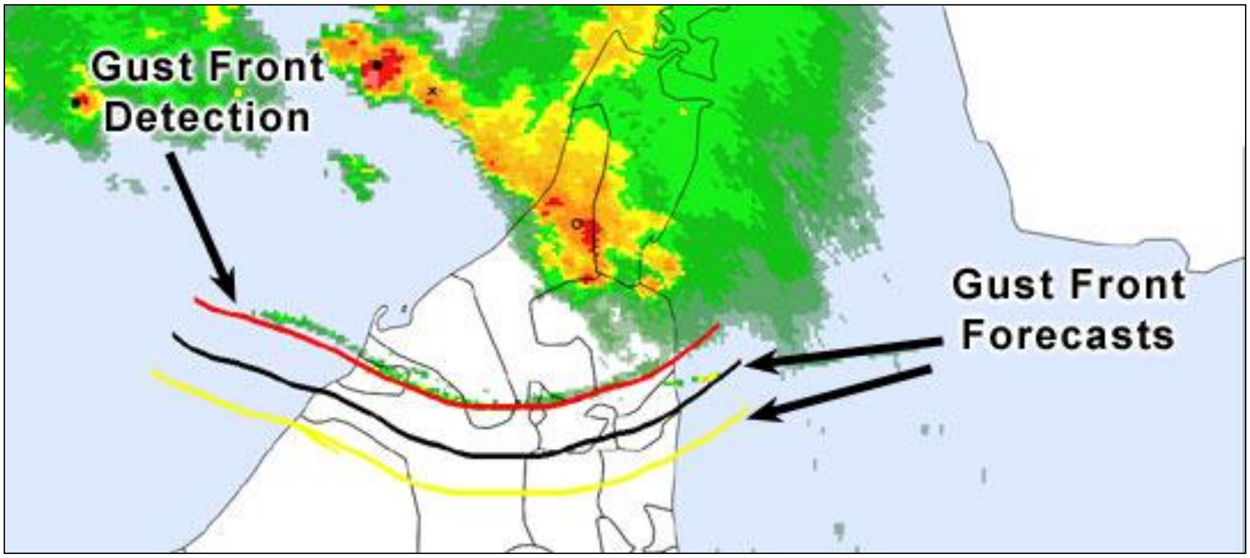


Figure 3. Gust front detection and forecasts 10 (black line) and 20 (yellow line) minutes.

The runway alerting portion of MIGFA compares gust front detections and predictions and determines when the gust front is projected to impact the runways and/or flight paths. The algorithm also determines the strength of wind shear along the runway and along the arriving and departing flight paths for alerting and display.

3.3. *Radar-Based Storm Detection and Nowcasting Algorithms*

Several of these algorithms have been licensed from the National Severe Storms Laboratory (NSSL), the University of Oklahoma (OU), and McGill University. They have been adapted by WDT to work with any radar data from a number of different manufacturers.

3.3.1. *Radar Artifact Removal and Gridding Algorithm*

This algorithm was licensed and adapted as part of the NSSL Warning Decision Support Integrated Information (WDSS-II Lakshmanan et al. 2007) software suite. It ingests radar data in real-time and provides a “clean” high-resolution 3-D grid of radar reflectivity by utilizing several sub-algorithms to ingest the data, perform quality control, and convert the data into a Cartesian dataset. Radar artifacts such as Anomalous Propagation (AP) and ground clutter are removed. This algorithm is an important quality control pre-processor applied to the radar data before they are assimilated into any of the AWDSS algorithms.

3.3.2. *Storm Cell Identification and Tracking Algorithm*

The SCIT algorithm (Johnson et al., 1998) was also licensed from NSSL. It automatically identifies individual storm cells and diagnoses parameters associated with them, such as height, depth, echo top, echo base, Vertically Integrated Liquid (VIL), movement speed and direction, etc. In addition, the SCIT algorithm forecasts the movement of the identified storms.

3.3.3. *Storm Nowcasting*

WDT has licensed from McGill University a software system called MAPLE (Germann and Zawadzki, 2002) that predicts the evolution and movement of storms with great accuracy out to two hours in advance. The MAPLE system is a sophisticated expert system/artificial intelligence algorithm that was designed, developed, and thoroughly tuned and tested by a group of scientists over a 10 year period at McGill University in Montreal Canada. MAPLE examines a time sequence of up to six hours of radar data utilizing highly-tuned filtering, expert system, and artificial intelligence techniques to determine the movement and evolution of storms and their radar echoes. An important component of MAPLE is the capability to determine the different scales of storms and predict the lifetime of those scales based upon recent past history and the stability of the present environment. In this way, the motion and evolution of small scale storms are predicted out to 30-60 minutes while the motion and evolution of larger scale events are predicted to sustain for the entire nowcast length. The output of MAPLE consists of nowcasts of radar reflectivity out to 2 hours in advance in 5 minute increments. These nowcasts are then utilized by other algorithms within the AWDSS.

3.3.4. *GIS-Based Asset Monitoring System (GAMS)*

GAMS utilizes a GIS database of locations and the output from MAPLE and the other algorithms to provide alerts and Estimated Time of Arrival and Departure (ETA/ETD) information for any number of locations in the database. These locations can either be point locations, line segments (runways), or polygons. GAMS compares predicted threat areas with the location of each of the assets. If there is overlap between the predicted threat areas and an asset, an alarm is provided by the AWDSS. The content of the alarm is generated automatically by GAMS. This content includes which “asset” is threatened and the ETA/ETD information.

3.4. *Fog Detection, Nowcasting, and Forecasting Toolkit*

WDT has developed a proprietary fog detection, nowcasting, and forecasting package. The Fog Detection and Nowcasting Toolkit (hereafter, “Fog Toolkit”) alerts for the presence of fog and makes short term forecasts of fog formation and fog burn-off. The primary instrumentation used by the system is the radiometer, which provides vertical profiles of temperature, relative humidity, and liquid water content that update every 2 minutes.

One primary sub-algorithm utilizes satellite data to detect the presence of fog using the temperature difference between the 3.9 μm and 10.7 μm infrared channels. The IR temperature data are utilized by the toolkit directly. Additionally, the IR temperature difference data are advected forward in time using the K-Means method (Lakshmanan et al. 2001) developed by NSSL as part of the WDSS-II. This output is also provided to the Fog Toolkit.

Inputs to the Fog Toolkit include trends of surface temperature, relative humidity, and cloud base height, along with the depth of the liquid water content, satellite-based fog detection and diagnosis, local surface observations, and the WRF forecast profiles from the AWDSS WRF system (Shaw et al. 2008). These data are then weighted using several fuzzy logic systems, which make decisions regarding the presence of fog, the short term threat of fog (1-3 hours), and the estimated burn-off time. If fog is present, the user will be alerted via a standard alert message which also includes the estimated burn-off time. If fog is not present, but expected to form within three hours, the user will be issued an alert which indicates the expected formation time.

3.5. *Detection and Forecasting of Wind Shear Experienced by Aircraft While Arriving*

The wind profiler produces automatic, near-continuous monitoring of the wind field throughout the bottom one-half of the troposphere and is therefore an excellent tool for estimating wind speed and the vertical shear of the horizontal wind. The issue for arriving aircraft is that while attempting to land they can descend into differing wind regimes. For example, a low level jet may form at the top of a night time inversion causing an acceleration of the winds just above the inversion. As aircraft approach the field, they can descend through the accelerating winds and into the inversion where there are very light winds. The aircraft can quickly lose airspeed thus causing the pilots to execute a missed approach. It is this type of wind shear that this particular algorithm detects. The vertical wind shear vector is calculated as the difference in horizontal winds between two successive heights normalized by the altitude difference of the measurements.

The effect of wind shear to a given aircraft is dependent on the shear along the glide slope. The Degreane wind profiler provides a wind shear calculation that was developed by Meteo-France (http://www.meteo.fr). This algorithm is utilized to calculate wind shear along the direction of the flight paths at each airport using the wind profiler data. From these wind speed and wind shear calculations, software developed by WDT calculates the estimated loss expected by an aircraft over a distance of a few hundred meters along the glide slope. The algorithm then provides estimates of the height the wind shear will be first experienced the location on the glide slope (e.g., 2 Mile Final) and the magnitude of the expected loss. If these calculations indicate a loss expected that is more than 20 kts (user threshold) then an alert is generated. Additionally, the WRF modeling system also provides forecasts of low-level wind shear, as well as types of weather phenomena that lead to vertical wind shear.

3.6. *Turbulence Forecasting System*

Unpredictable and rapid aircraft movements during flight that pose a safety risk to the crew and passengers are caused by atmospheric turbulence. WDT's Turbulence Detection and Forecasting Toolkit ("Turbulence Toolkit") consists of a suite of applications that use data from the wind profiler, radiometer, and WRF model output to detect, diagnose and predict the occurrence of atmospheric turbulence. The Turbulence Toolkit provides a suite of intermediate products to be used by meteorologists to assist them in diagnosing and forecasting the occurrence of turbulence, and provides automated detections (Figure 6) and forecasts of turbulence for non-meteorological users for alerting and support purposes.

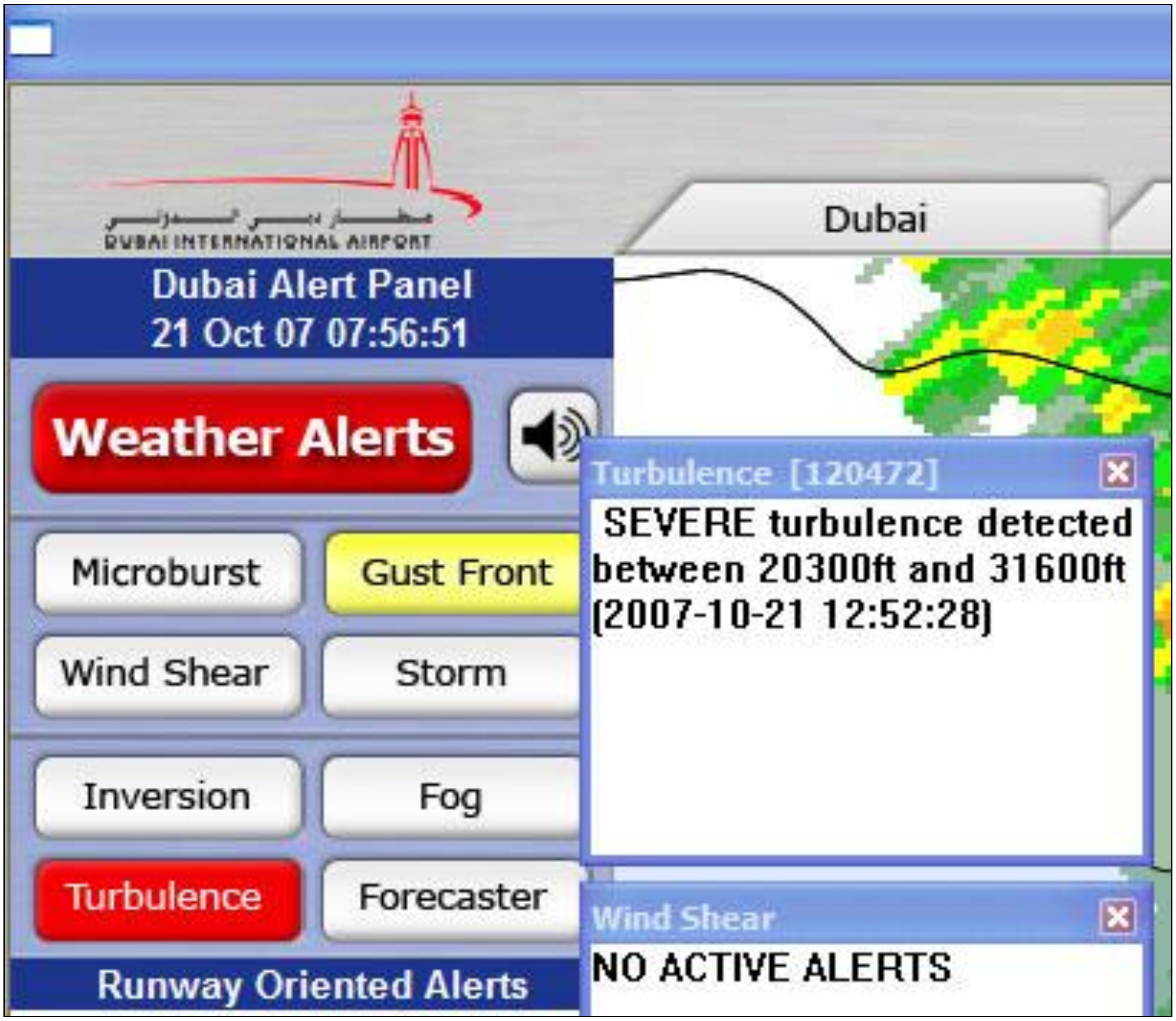


Figure 4. Turbulence alert in the AWDSS display.

3.6.1. *Turbulence Diagnosis from Wind Profiler Data*

A primary culprit for dangerous turbulence is strong vertical wind shear, defined as a rapid change with height of the horizontal wind vector. The wind profiler produces automatic, near-continuous estimates of the wind field throughout the bottom one-half of the troposphere. From these data, rapidly-updating vertical wind shear estimates are available at numerous heights simply by computing the magnitude of the wind shear for each vertically adjacent set of wind observations within a profile. When the magnitude of the vertical wind shear exceeds a user-defined and adjustable threshold alerts of hazardous wind shear are generated.

3.6.2. *Turbulence Nowcasting from Wind Profiler Data*

Useful short-term forecasts (up to about 2 hours) of turbulence are made possible by performing a linear extrapolation of the wind field at all levels provided by the wind profiler. By extrapolating the most recent wind profiler data forward in time and computing the vertical wind shear from these extrapolated winds, short-term forecasts of increasingly dangerous—or increasingly benign—turbulence may be obtained. Beyond the time frame of about 2 hours, such extrapolated values are likely to deviate beyond acceptable error limits, especially during important, rapidly evolving situations such as the passage of troughs and frontal systems. For this reason, WRF model data must be employed to produce useful forecasts of turbulence beyond this time frame.

3.6.3. *Turbulence Forecasting from WRF Model Output*

The WRF modeling system (within the AWDSS) produces forecasts of turbulence for each grid point within the model three-dimensional domain. The turbulence index is computed using the algorithm of (Ellrod and Knapp, 1992). This index, which is the product of the vertical wind shear and horizontal deformation, has proven itself useful in identifying regions of hazardous turbulence.

3.7. *Flight Level Wind Diagnosis and Nowcasting System*

The Flight Level Wind Diagnosis and Nowcasting System predicts wind speed and direction changes based on a linear trend of wind profiler data. This combination of past and present wind data provides useful short-term nowcasts (up to about 3 hours) of the wind field at user-selected flight levels interrogated by the wind profiler. Beyond this time frame, however, such predicted values are likely to deviate beyond acceptable error limits, especially during important, rapidly evolving situations such as the passage of troughs and frontal systems. For this reason, the WRF numerical model forecasts are utilized for any forecasts beyond 3 hours.

3.8. *Inversion Detection and Nowcasting*

The radiometer provides continuous vertical profiles of temperature, humidity, and liquid water. Diagnosing the temperature sounding directly from the radiometer is an elementary process. This algorithm utilizes the radiometer temperature profiles and the trend of those profiles to detect and alert for inversions. The alerts generated by the Inversion Detection and Nowcasting Algorithm include the temperature at the surface, the temperature at the height of the inversion (highest temperature in the sounding), and the height of the inversion. In addition, trend information is provided including the direction of the trend (e.g., is the inversion strengthening or decaying?) and a short-term nowcast (up to 3 hours) of expected inversion strength (difference between the temperature at the bottom and top of the inversion layer).

3.9. *Low Altitude Wind Shear Detection*

WDT's Low Altitude Wind Shear Detection Algorithm (LAWSDA) is designed to alert users to low altitude wind shear based on two sub-algorithms. The first uses multiple wind observations from spatially adjacent observing stations and identifies sharp spatial gradients in wind vectors. The vector gradients are then projected on the different runway orientations and compared to user adaptable warning thresholds. The second sub-algorithm identifies rapid temporal shifts in wind vectors being observed at any given observing station, and compares them to user adaptable thresholds. Identifications of either wind shear type exceeding the corresponding LAWSDA thresholds are then issued to the NPG database for distribution to forecasters and air traffic controllers.

A motivation behind such an algorithm is to facilitate detection of shallow sea breezes that often move inland from the Persian Gulf and adversely affect arriving and departing air traffic. The same system will also aid in diagnosis of the strength of low altitude shear resulting from a convectively forced density current (i.e. gust front). The LLWSDA was tested using a sea breeze model, as well as by ingesting Oklahoma Mesonet observations during active cases of scattered convective storms.

4. THE AWDSS DISPLAY SYSTEM

Two different display configurations are utilized in this implementation of the AWDSS, one for the meteorologists, and the other for use by the air traffic controllers.

4.1. *The AWDSS Air Traffic Control Display*

The AWDSS Air Traffic Control Display (ATC AWSD) has similar functionality to the Terminal Doppler Weather Radar (TWDR) and Integrated Terminal Weather System (ITWS) displays fielded by the United States Federal Aviation Administration. However, the AWDSS includes many more weather phenomena that need to be alerted for. As a result, managing these alerts in an innovative manner was critical. Importantly, the ATC AWSD is laid out in a simple, highly functional fashion with limited buttons and maximum visual cues when any weather phenomenon impacts or is expected (via the automated algorithms described above) to impact any flight or ground operations (Figure 5). The ATC AWSD is not a "sit-down" tool, but is instead an advisory tool for strategic as well as tactical planning of the terminal airspace. The ATC AWSD was developed to alert Air Traffic Control personnel to changing and hazardous weather conditions in the terminal area. The upper left portion of the display is an “Alert Panel”. In the case of potentially hazardous weather being detected or nowcasted in the terminal area, the large button on the top of the Alert Panel and one or more of the eight different boxes will turn a specific color to alert the user to specific conditions and an audible alert will be sounded. By changing the color of these boxes and providing an audible alert, the ATC AWSD draws the attention of the supervisor/manager to a situation that may be potentially dangerous or may require a change in the runway configuration or airspace.

Along the top of the display shown in Figure 5 are 5 tabs, the first 4 allow the user to choose which airport in that region (Dubai, Jebel Ali, Sharjah, Ras Al Khaimah in the case of the Dubai International Airport system) they are viewing in a “local view”. The fifth tab (Regional) shows a regional view.

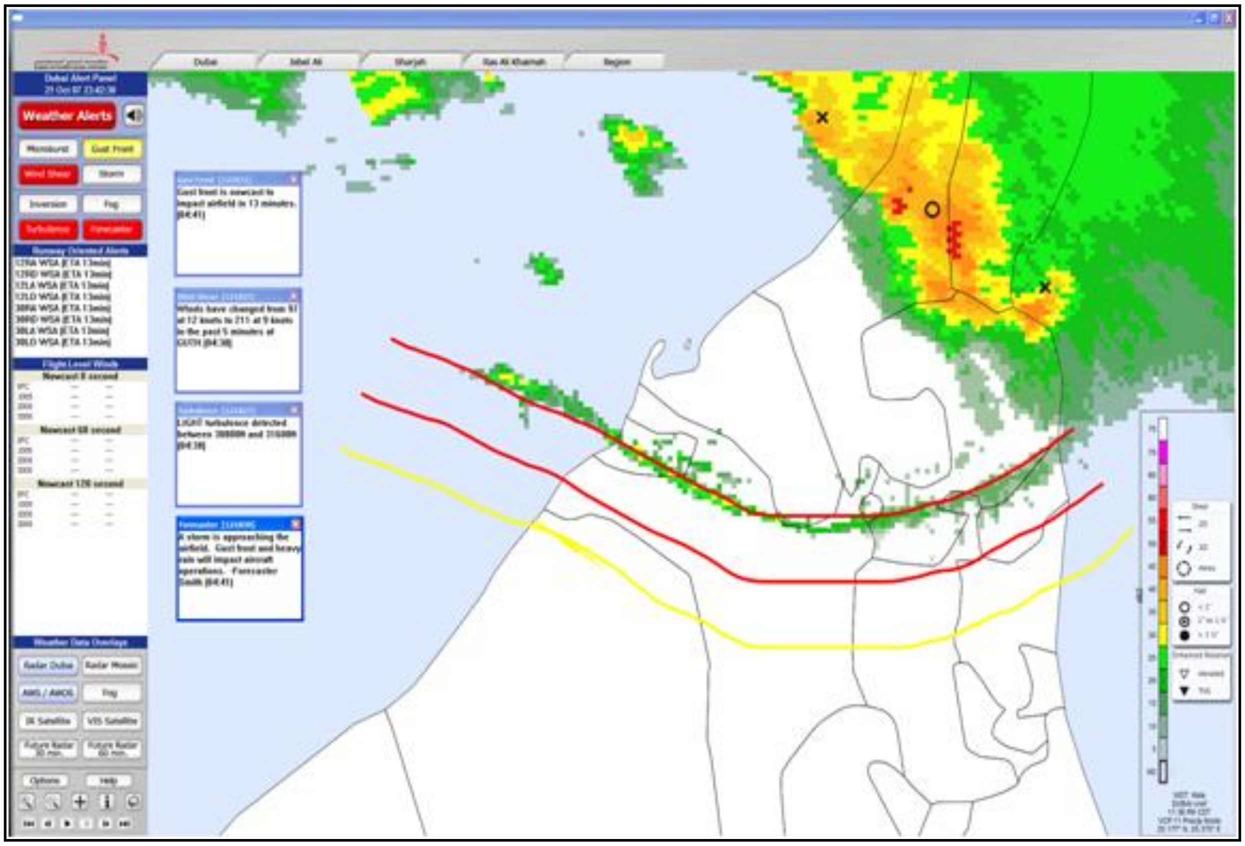


Figure 5. The ATC AWSD.

On the upper part of the left column is a label that clearly defines which airport the alerts are issued. Below the label, the date and time are clearly displayed and are updated continuously. Under the date and time is a large button that is grey when there are no active weather alerts but changes to red and stays red for the duration of any weather phenomena impacting the area shown in the display. Otherwise, it will turn yellow if weather is nowcasted to impact the local area in the next 60 minutes (user selectable threshold). Any “red alert” will override a “yellow alert” causing the Weather Alert bar to stay red as long as any weather alert is active for the local area. To the right of the Weather Alert bar is a toggle for turning on and off audible alerts. Under the Weather Alert and Audible buttons are a series of “Individual Weather Phenomena Alert” buttons identifying what weather alert is occurring at that time. Buttons turn red when a weather alert is detected or yellow when a weather phenomenon is nowcasted to occur within 60 minutes. If there are no detections or nowcasts for that phenomenon, the button remains grey. Clicking on any of these buttons brings up a small window that provides information about the alert that was generated as well as Estimated Time of Arrival and Departure information about the weather phenomena if it is available. These button labels indicate the type of alert being generated, the “forecaster” button is an alert sent manually by a forecaster at the Dubai Met office.

4.1.1. ***Runway Oriented Alerts***

Below the center field wind line is a series of lines of text. These lines of text are simple coded messages that are specific to each possible flight path for arriving and departing aircraft. For example, “12RA” is decoded as the flight path for arriving aircraft on the runway 12 R. If a weather alert of any kind is generated on this runway or along the expected flight path out to 3 nautical miles from the runway a coded message will be placed to the right of the moniker. For example:

12RA MBA 30K- 1MF

This message is decoded as: “on 12 right approach there is a Microburst Alert, expect 30 knot loss beginning at 1 Mile Final.” If the alert is for the actual runway then the letters “RWY” will be used instead. These designations are set to indicate the location where the aircraft will first experience the hazard.

4.1.2. ***Weather Data Overlay***

In the column under the Runway Oriented Alerts is a section labeled “Weather Data Overlays” consisting of a series of buttons which allow the user to toggle on or off the overlay of various weather data including radar reflectivity data, surface observations, radar mosaics, fog identified from Satellite, MSG IR Satellite data, MSG Visible Satellite imagery, 30 minute nowcasted reflectivity and 60 minute nowcasted reflectivity (from MAPLE forecasts). The forecasted reflectivity is displayed in a different color scale than the present reflectivity so that the user can easily distinguish between the two and avoid confusion.

4.1.3. ***Main AWDSS Display***

The larger display is a version of the WeatherScope™ display capability developed by the Oklahoma Climatological Survey and licensed by WDT. WeatherScope integrates real-time weather and GIS data into a single display. WeatherScope is an interactive display capability that is delivered as a dynamically linked library (DLL) component of a stand-alone application. WeatherScope can inherently display many meteorological data streams in their standard format whether the data are point observations, gridded, or in azimuth/range format. The core functionality of WeatherScope is that it allows a user to interact with the weather data by zooming, panning, etc. even while images are animating. Also, any GIS map layer can be displayed within WeatherScope allowing the user to toggle on and off those layers as they choose.

Within WeatherScope, the runways are color coded to indicate weather alerts on the runway or along the flight path. When no weather alerts are present, the runways and flight paths are black (user adaptable). When alerts occur, the runway and the flight path are changed to red. Only detections of hazardous weather phenomena will cause the runway colors to change, and nowcasts of those phenomena will only change the color of buttons on the left. This can be configured differently depending on the preferences of the meteorologists or air traffic control personnel.

4.2. *The Met Aviation Weather Situation Display*

The Meteorologist AWDSS Display (hereafter "Met AWSD") has three core functions. These core functions include 1) providing the same display and functionality as is used in ATC operations, 2) providing capabilities to analyze and interrogate meteorological data and algorithm products in detail, and 3) providing a method whereby meteorologists can have the option of verifying alerts before they are sent to the ATC Display as well as allowing them to send their own alerts to the ATC display.

4.2.1. *Overview*

The Met AWSD is optimized for a display on dual widescreen monitors. Figure 6 is a sample of the Met AWSD Launch Pad that first appears when you start the display. From the Launch Pad, the user can select any one of the 16 buttons. On the left of the AWSD Launch Pad is a Weather Alert button, that turns Red (weather hazard detected at any airport) or Yellow (weather hazard nowcasted at one of the airports) depending upon weather conditions at any of the airports. Clicking on the Weather Alert Button opens up a small window with information about the alert or alerts. The Audible Alarm Function operates the same as the ATC AWSD version, with alerting for one airport or for multiple airports (user adaptable option). The application buttons launch software to control the radiometer and profiler, display a system status page, view model output, launch the sounding analysis program, and launch the radar analysis program. The system status button is color-coded to indicate the overall health of the system.

Figure 6. "Launch Pad" user interface.

4.2.2. *Sounding Analysis Software*

Figure 7 shows a custom version of the RAOB software, developed by Environmental Research Services, has been implemented as part of the Met AWSD. RAOB is a multi-functional sounding analysis program. Data from the radiometer and wind profiler are displayed in RAOB and color-coded time-height diagrams are available. In addition, the user can create a variety of sounding diagrams, 3-D hodographs, time & distance based vertical cross-sections, mountain wave turbulence diagrams, and view forecast soundings from WRF output.

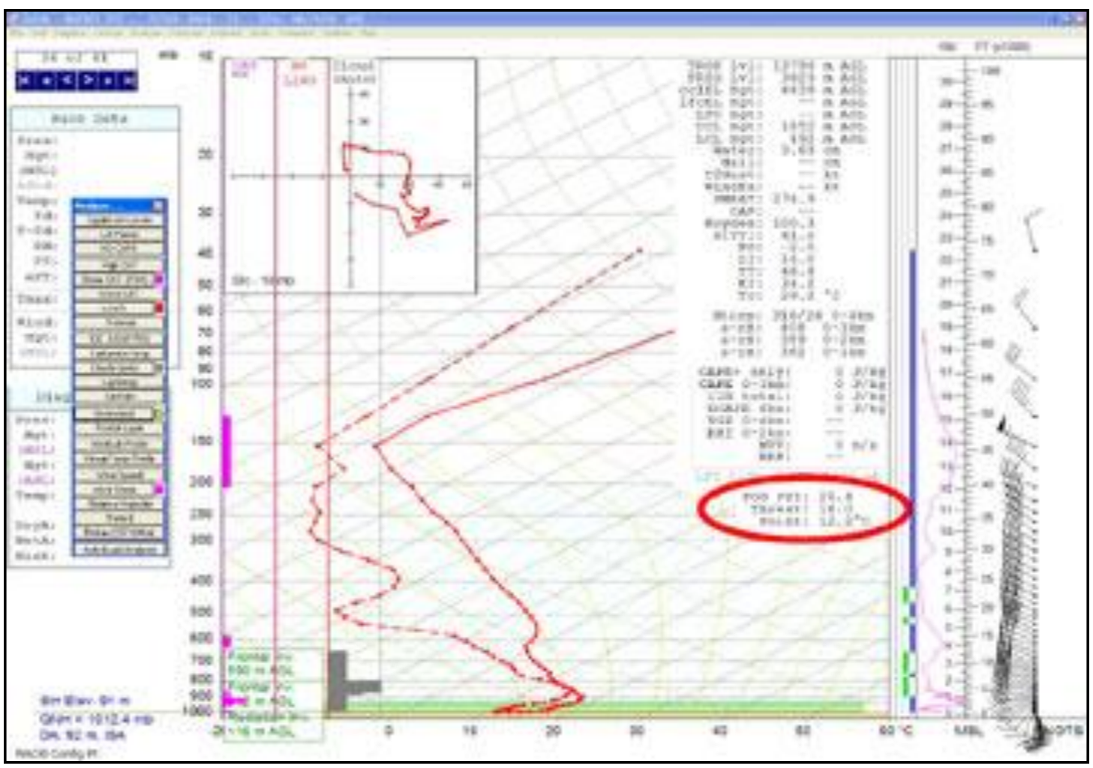


Figure 7. Customized RAOB display.

4.2.3. *Radar Analysis Toolkit*

The Radar Data Analysis Toolkit (hereafter “Radar Toolkit”) is built upon the WeatherScope plug-in capability that was described earlier. The Radar Toolkit has a robust capability to examine and analyze every elevation angle of reflectivity and velocity data from radar data as well as the radar-based algorithm output (Storm Tracking, MAPLE nowcasts, gust front detections, etc.). The radar data can be displayed overlain upon high resolution terrain and any GIS layers (roads, streams, runways, flight paths, power utility lines, etc.). WDT has delivered this capability as part of our Weather Decision Support Systems to many clients including the Italy ARPAV Centro Meteorologico di Teolo, the Lower Colorado River Authority, over 100 electric utilities in the United States and many other organizations.

4.2.4. *Nowcast Product Generator Browser*

WDT has developed a custom web-based system status monitor. This monitor allows the user to monitor the overall health of the servers, Met displays, ATC displays, and algorithm performance (Figure 8). Additionally, the user is able to view some of the raw data and algorithm output.

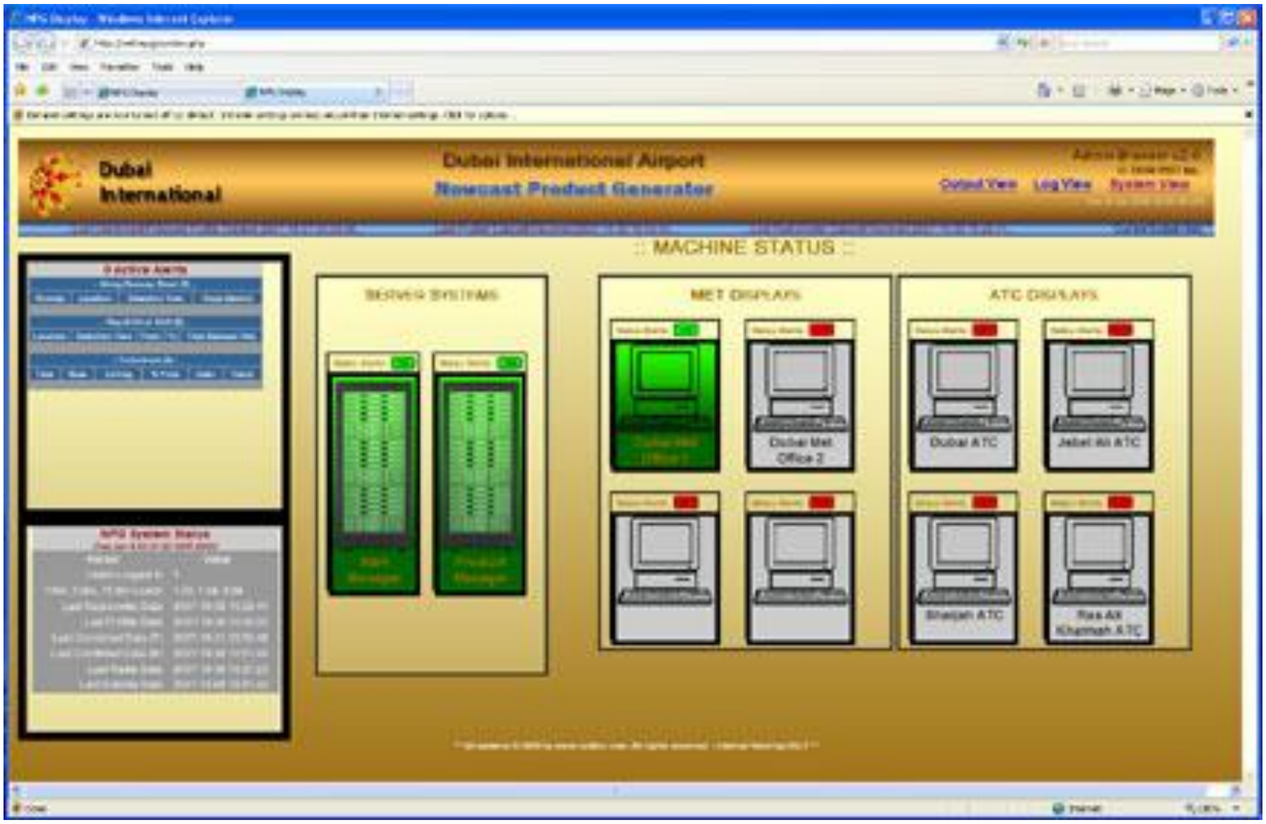


Figure 8. System status monitoring web site.

5. MESOSCALE DECISION SUPPORT SYSTEM

A critical component of the AWDSS is the implementation of the Mesoscale Decision Support System (MesoDSS). MesoDSS is a customized implementation of the Weather Research and Forecast (WRF) modeling systems (Skamarock et al. 2005). The AWDSS provides seamless integration of new sensing capabilities, advanced meteorological algorithms, and display systems for both the air traffic control (ATC) tower and meteorologists. In addition, integrated communications tools allow the Met Office to more effectively analyze and disseminate critical weather information to the ATC and flight operations personnel, thereby maximizing the safety and efficiency of flight and ground operations. The system employs two new state-of-the-art observational systems: a radiometer for providing nearly continuous profiles of temperature, moisture, and liquid water, and a wind profiler for nearly continuously updated vertical profiles of wind. These new sensors are combined with existing systems (radar, satellite, and surface observations) as input to meteorological applications that provide detection, short-range forecasts ("nowcasts"), and planning forecasts, along with automated alerting of hazardous conditions to the meteorologists and ATC personnel.

WDT's customized version of WRF employs advanced data assimilation techniques to take advantage of the new and existing data sources that are integrated by AWDSS. The WRF subsystem is designed to provide:

- "First-guess" input to several of the nowcast algorithms within AWDSS, including the fog detection/prediction and flight-level wind algorithms
- Forecasts of specific aviation hazards in the region, including low-level wind shear, turbulence, icing, ceiling, visibility and convective storms
- An operational, indigenous source of mesoscale NWP information for general forecast operations at the Met Office

6. SYSTEM OVERVIEW

6.1 WRF Modeling Software Components

The AWDSS WRF system contains several sub-components, most of which are part of the publicly-available WRF software system. The entire system is fully managed by WDT's proprietary WRFControl software package, discussed in more detail in Section 6.2. WRFControl manages the configuration, user-interface, and execution of the following sub-components:

- *WRF Domain Wizard* (Smith et al. 2007). The Domain Wizard is a Java-based graphical user interface (GUI) program used for setting up the WRF horizontal grid. It allows the user to select an area from a global map, apply one of the available map projections, specify the grid spacing, dimensions, and any nests, and run the "geogrid" program from the WPS (described below).
- *WRF Pre-processing System (WPS).* NCAR's WPS contains three programs for processing gridded data sets for input into the WRF model. The "geogrid" program performs this function for a variety of static geographical data sets (e.g., terrain, land use category, vegetation fraction, etc.) when initially creating a WRF domain. The other two programs ("ungrib" and "metgrid") are used for extracting and interpolating data from GRIB-format files from the model used to provide the first-guess and/or lateral boundary conditions to WRF, and are run for each new WRF simulation.

- *Custom DataAssimilation*. WDT's WRFControl system supports multiple data assimilation methods that can be implemented based on data available and the user's requirements. WDT's primary initialization system is based on the Local Analysis and Prediction System (LAPS) analysis package (http://laps.noaa.gov) which provides a unique capability of assimilating the infrared imagery channels from geostationary satellite systems as well as WDT's quality-controlled three-dimensional radar mosaics. Additionally, WDT has also used the WRF Three Dimensional Variational (3DVAR) system (Barker et al. 2004) and can combine either 3DVAR or LAPS with the WRF's built-in Four Dimensional Data Assimilation (FDDA, Liu et al. 2005) capability. FDDA allows WRF to take advantage of the high-temporal frequency of the radiometer, wind profiler, and surface mesonet data to improve the WRF initial conditions using a 3-h pre-forecast "spin-up" period as part of each forecast cycle.
- *Advanced Research WRF* (Skamarock et al. 2005). This is the core capability that integrates the analyzed state of the atmosphere forward in time to produce the forecast. It is a highly flexible, state-of-the-science, parallelized mesoscale NWP model designed for both research and operations. It employs an advanced numerical solver that uses the full equations of motion on a compressible, terrain-following vertical coordinate and a suite of available physics packages resulting from the latest research in NWP. The WRF code also includes a program ("real") that prepares the initial (or first-guess when using 3DVAR) and lateral boundary conditions using the output of WPS*WDT PostWRF Program*. This program is used to convert the raw model output state variables into parameters useful for meteorologists. This requires interpolating winds to the same horizontal grid as the thermodynamic variables, vertically interpolating from the terrain-following coordinate to constant pressure and/or constant height levels, and diagnosis of all required variables, some of which require specialized algorithms that have been implemented within the program by WDT. PostWRF outputs the fields in standard GRIB (edition 2) format so they can easily be imported into a variety of meteorological display systems. It also outputs point data in a variety of formats, including vertical profiles for use by the AWDSS nowcasting algorithms.
- *Display Tools*. Since the AWDSS WRF provides data in GRIB format, the WRF forecasts can be easily imported into numerous meteorological display tools. For convenience, the AWDSS WRF system includes an installation of the Unidata NAWIPS system customized specifically for aviation applications. In addition, the Unidata Interactive Data Viewer (IDV) is available on the display workstations, and the forecast vertical profiles have been made compliant with the format required by the AWDSS sounding analysis toolkit.

Within the public codes, WDT has made some modifications to either enhance integration with the WRFControl package or to add or enhance output from the post-processing to fulfill specific algorithm needs of the AWDSS and the Met Office. However, maintaining the core software structure of these packages allows WDT to more quickly integrate advancements from the WRF research community into the operational systems. Indeed, this more rapid transfer of science into operations is one of the overarching goals of the WRF project within the U.S.

6.2 WDT WRFControl System

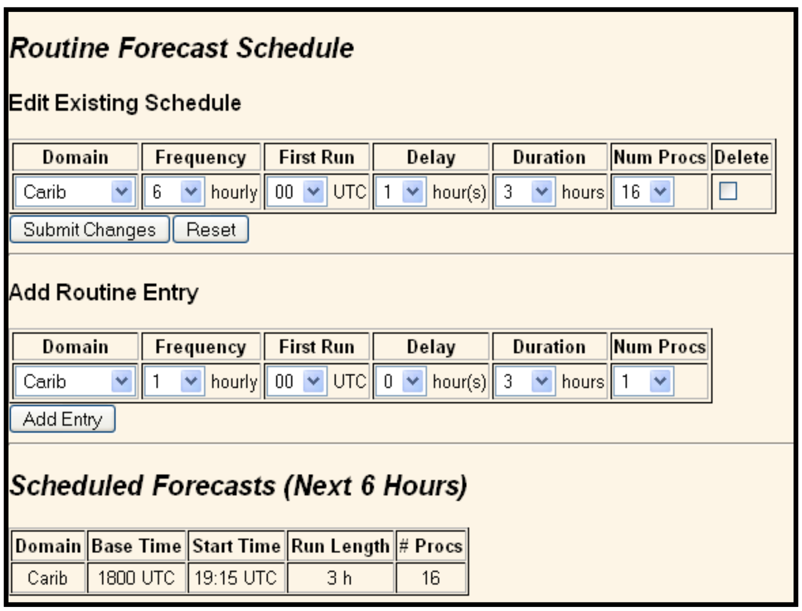
The WDT WRFControl package is the workhorse that integrates all of the internal WRF components described above into a robust, operationally reliable system. While the public WRF package is scientifically advanced and extremely flexible, it does not include any facility for easily automating and managing all of the processes for real-time, operational users. WRF-Control fills this void, while providing custom interfaces specific to the client's environment and allowing integration within AWDSS, both as a receiver of data (observations and user configuration input) and as a provider of data (forecasts). WRFControl leverages WDT's years of experience in operationalizing NWP models and other meteorological applications. It is maintained in version control by a team of meteorological software engineers and continues to be upgraded as customer needs change and/or as new releases of the public WRF codes become available.

The complexity of the WRF system (or any NWP system) generally requires specialized training and/or experience to reach a level of expertise required for configuring and managing it. The challenge is to build a system that can be used within the operational aviation forecasting office without burdening any of the staff members with having to develop a significant amount of detailed knowledge on the "care and feeding" of the system. To address this issue, WRFControl includes the web-based WDT WRF Management Portal that allows the local AWDSS administrator to easily configure and monitor the system via a web browser. Key features provided by the WDT WRF Management Portal, include:

- *Domain Management*. On a single web page, all domains configured are shown using thumbnail images of the domain along with a summary of all the key parameters that specify the domain. From the same page, there is one click access to launch the WRF Domain Wizard to accomplish the desired changes. The domain management web page is fully integrated with the job scheduling web page and the operational WRFControl run scripts in a way that is transparent to the user, which minimizes the potential for operational problems due to domain changes.
- *Scheduling*. This provides the user the capability to schedule any of the configured WRF domains for routine operations. It allows the user to select the domain, forecast length, run

frequency, and number of processes to allocate for each run using a simple, intuitive interface. It also performs error checking to ensure there are no scheduling conflicts.

- *WRF Monitor*. This page provides a quick look at all WRF jobs that have completed in the previous 6 hours, as well as any jobs currently in progress. The information is presented in a user-friendly tabular view, and includes start and stop time information for each of the individual processes, including estimated end time for a run in progress. Clicking on any of the jobs in the list provides a new page with additional job details, links to allow browsing of the working data directories, final output data, and log files, and in the case of in-progress runs, a button to terminate execution.
- *Cluster Monitor*. This page provides a link to the open-source Ganglia cluster monitor, allowing the user to quickly see the state of all nodes on the system using graphical time-series plots.
- *Quick Reference*. The portal provides quick links to instructional material, reference information, technical support contact information, and WRF documentation.
- *Data Browser.* Links are provided to quickly browse the working directories as well as the directories containing the output GRIB data. This makes it easy to download data files to a local computer for diagnostic purposes, meteorological case studies, etc. without having to log onto the system or have any knowledge of the directory structures.



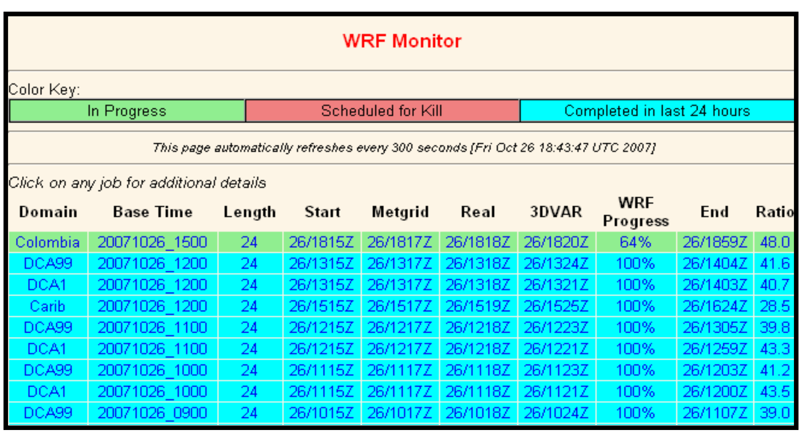


Figure 9. Screenshots from the WRF Management Portal.

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Behind the scenes and transparent to the user, the WRFControl system includes a robust library of software that manages the end-to-end processing of the system. Features of the run-time environment include:

- *Integration with Sun Grid Engine (SGE).* The open source SGE package is used to manage cluster resource allocation for the processing tasks. This allows for automated state-of-health monitoring for each node and dynamic allocation of resources that are known to be functioning properly. The run scripts are tightly integrated with SGE. Because the cluster includes more capacity than is required to meet the minimum operational WRF requirements, this makes the system able to tolerate the failure of one or more computational nodes without any operational interruptions or manual intervention.
- *Alerting.* WRFControl includes an automated alerting capability that notifies a user-defined set of users via e-mail when run-time problems are encountered.
- *Data Management.* This includes scripts for ingesting, reformatting, and storage of various incoming and outgoing data sets, as well as volume management for the file systems and databases used by the WRF system.
- *Graceful Handling of Missing or Late Data.* Because WRF relies on external data for first guess and lateral boundary conditions, WRFControl includes the capability to automatically deal with missing data in the event some or all of the expected data are not received. For example, the user can specify an amount of time to wait for an expected data set. If it does not become available within that time period, an alternate source (e.g., an older run of the external model) that satisfies the requirements will be searched for and used if found. This helps ensure the operational forecasters will always have a WRF run to use.
- *Processing Efficiency.* WRFControl scripts have been designed to maximize processing efficiency to ensure the most timely availability of forecasts possible. For example, the WPS "ungrib" process is separated from the routine WRF run, and is configured to process multiple incoming GRIB files simultaneously. This eliminates redundant processing when a WRF domain is run more frequently than the model providing boundary conditions or when running multiple domains. Additionally, WRFControl supports concurrent post-processing of the WRF forecast model as it is running. This allows operational forecasters to begin viewing model output within minutes of the forecast process starting, with updates occurring as it runs.

7. SUMMARY

The AWDSS is designed to support airport operations through forecasts at any size airport using all available data sources. The primary purpose is to provide timely guidance to the forecasters and ATC personnel concerning meteorological hazards and a common situational awareness between them. The system combines the latest meteorological hazard prediction technology with state-of-the-art remote sensing hardware and a user-friendly interface.

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