5.2 IMPLEMENTATION OF THE WRF MODEL FOR THE DUBAI INTERNATIONAL AIRPORT AVIATION WEATHER DECISION SUPPORT SYSTEM

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1. INTRODUCTION

In late 2007, Weather Decision Technologies, Inc. (WDT) installed the Aviation Weather Decision Support System (AWDSS) at the Dubai International Airport Meteorological Office (hereafter referred to as Met Office) in the United Arab Emirates (UAE). 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. A pictorial representation of the AWDSS is shown in Figure 1. A detailed description of the AWDSS is found in a companion paper by Barrere et al. (2008).

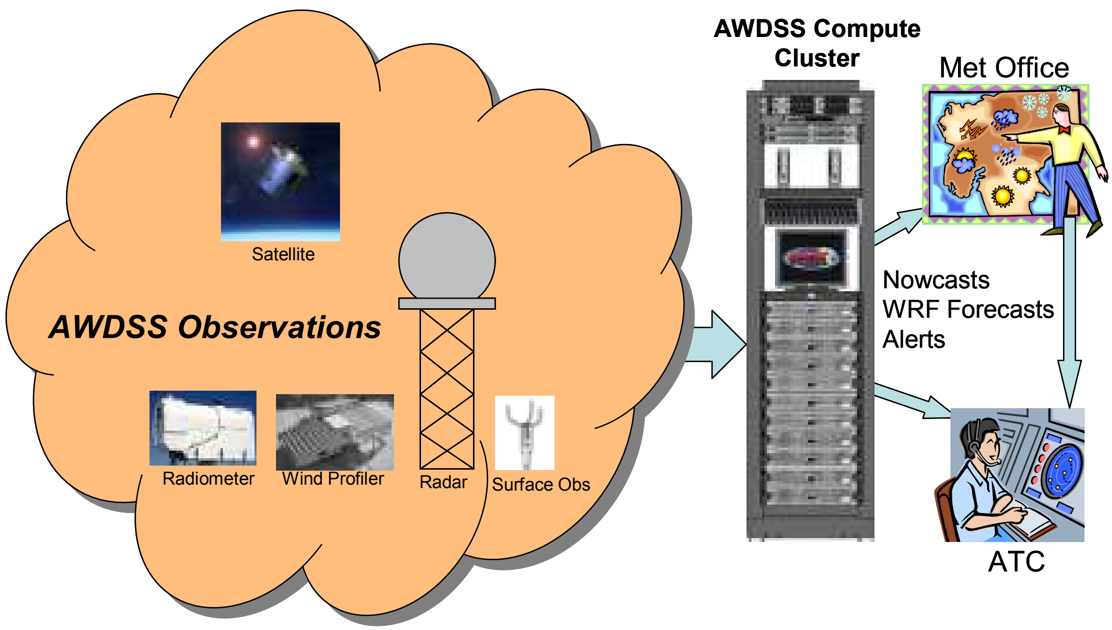

Figure 1. Overview of the Aviation Weather Decision Support System (AWDSS).

A major component of the AWDSS is a fully automated, operational mesoscale numerical weather prediction (NWP) system. Built around version 2.2 of the Advanced Research version of the Weather Research and Forecast (WRF) model (Skamarock et al. 2005), it employs advanced data assimilation techniques to take advantage of the new and existing data sources that are

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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

This paper provides an overview of the WRF system, the operational configuration, sample products, and our future plans.

2. SYSTEM OVERVIEW

2.1 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 2.2. 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.
- *WRF Three-Dimensional Variational (3DVAR) Analysis System* (Barker et al. 2004). Maintained as part of the WRF system by NCAR, this package provides a significant capability to provide optimum atmospheric analyses for initializing the forecast model. The strength of the 3DVAR technique is that it is able to consider a multitude of different types of observations. It combines these observations with a first-guess (either from a larger scale model in the case of a cold start or a previous forecast on the same WRF domain when running in "cycled" mode) and considers the three-dimensional error characteristics of both. This method is used at many of the operational meteorological NWP centers throughout the world.
- *Advanced Research WRF Version 2.2* (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. Finally, this version of WRF includes a new Four-Dimensional Data Assimilation (FDDA) capability (Liu et al. 2005). This technique is used in the AWDSS 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.
- *NCEP WRF Post Processor (WRFPOST).* 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.

WDT has added algorithms and tuned some of the existing algorithms based on the Met Office requirements. The final step of WRFPOST is to output the fields in standard GRIB format so they can easily be imported into a variety of meteorological display systems.

- *WDT WRF Post-processor*. WDT has an internally-developed application for post-processing WRF output. For AWDSS, it provides forecast vertical profiles at user-specified locations for storage in a relational database. This database is accessed by various AWDSS 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.

2.2 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 2 shows sample screen shots from the WRF Management Portal.

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

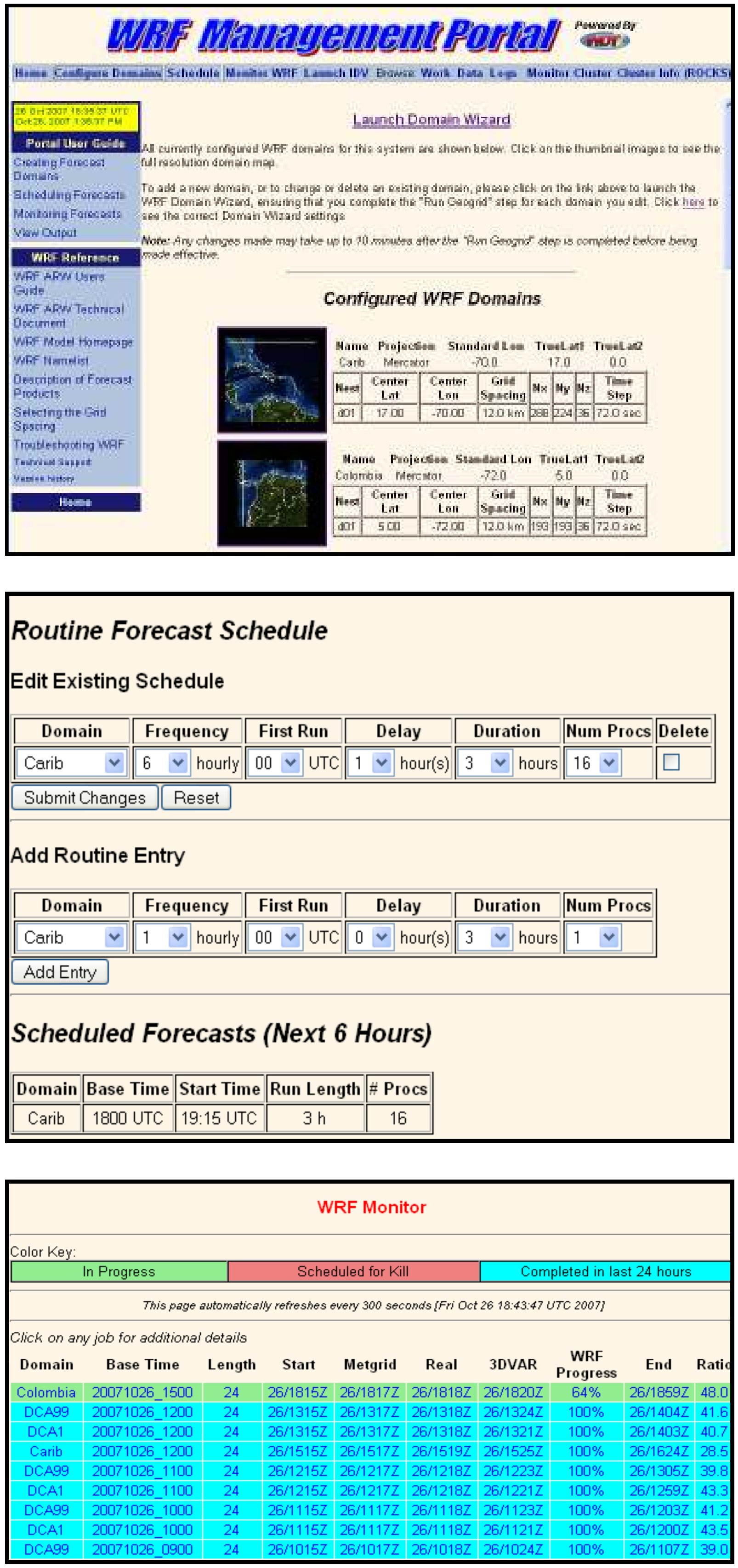

Figure 2. Sample screen shots of the WDT WRF Management Portal, including domain management (top), scheduling (middle), and monitoring (bottom).

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.

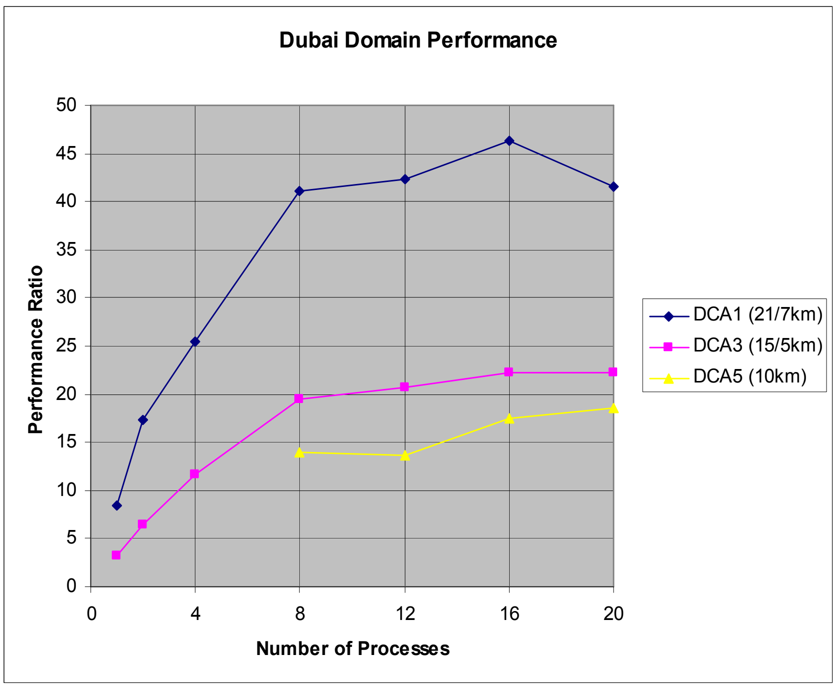

Figure 3. Benchmark results for three different grid configuration. The plot shows performance ratio as a function of the number of processor cores used (each node has 4 processor cores). DCA1 is represents the Met Office's minimum requirements for model resolution, with DCA3 and DCA5 both exceeding those requirements.

2.3 Computational System

The Dubai WRF system executes on a small cluster of eight commodity Linux servers. Each server contains two dual-core AMD Opteron processors for a total of four processing cores per server. To maintain cost-effectiveness, the servers utilize the on-board Gigabit Ethernet interfaces for all parallel process communications traffic.

During the customization effort prior to installation at the Met Office, numerous WRF benchmark cases were used to maximize the performance of the model on the cluster. The goals of this work were (a) to ensure that the system would meet the minimum requirements for model resolution, domain size, forecast length, and update frequency as specified by the Met Office; and (b) to determine the practical limits of the system. Simply using default parallelization options within the off-the-shelf WRF system and adding more processors does not necessarily improve performance, especially when using smaller clusters that do not contain specialized high-speed interconnects that larger supercomputers typically employ. In fact, our testing showed that the performance of the WRF model on these smaller, multi-core systems is extremely sensitive to how one allows the horizontal domain to be decomposed with respect to the number of nodes in use.

The Met Office required that WRF produce a new 36-h forecast every 3 h using a nested model domain. This infers that the model and all pre- and post-processing must be able to complete within a 3-h window. Accounting for the pre- and post-processing, we require the actual WRF execution to take no longer than 2.75 h, which results in a minimum required performance ratio of approximately 13 (where performance ratio is defined as the ratio of forecast length to the amount of actual time to execute).

Figure 3 shows the results of our benchmark tests. For each of the three cases plotted, the grids cover approximately the same geographical area (i.e., number of grid points increases as grid spacing decreases). Also note that the DCA5 grid does not include a nest, but covers the same area as the outer grid of the DCA1 and DCA3 cases.

From this graph, several conclusions can be drawn about the performance of this particular hardware platform in relation to the operational requirements of the Met Office. First, it can be seen that the minimum requirements of a 21 km regional outer grid with a 7 km nest centered on the UAE can be met using a single node (4 processor cores). Second, the system can support higher resolution runs, as demonstrated by the DCA3 and DCA5 cases plotted. Finally, in all cases it appears there is a point of diminishing returns beyond 8 to 12 processors (2-3 nodes). This is due to communications latency between processes becoming the dominating factor. This could potentially be addressed by using a specialized, low-latency interconnect dedicated to parallel processing message traffic between the nodes in lieu of the standard Gigabit Ethernet interface currently in use. However, such networks are somewhat cost prohibitive on smaller systems, and are generally used on much larger super computers consisting of multiple tens to thousands of nodes.

3. OPERATIONAL CONFIGURATION

3.1 Domain and Schedule

Although the system delivered provides the capability to exceed the minimum requirements specified by the Met Office, the initial configuration matches the specifications, using an outer grid with 21-km spacing and an inner nest with 7-km grid spacing. For the vertical coordinate, there are 36 terrain-following levels, with highest resolution concentrated in the boundary layer and near the tropopause. Minimum vertical spacing in the boundary layer is approximately 20 m, and the maximum vertical spacing is approximately 1 km near the middle of the troposphere. First-guess fields and boundary conditions are provided by the NCEP Global Forecast System (GFS) which is automatically retrieved and processed four times per day via customized WRFControl scripts. Current limitations in network bandwidth at the Met Office necessitated the use of the GFS grid that uses 1 deg grid spacing (providing an approximate grid spacing of approximately 100 km at that latitude), so using a finer outer grid would exceed the maximum recommended nesting ratio of 5:1. There are plans to increase the bandwidth to the Met Office, at which time the 0.5 deg GFS files (approximately 50 km) will make a higher-resolution outer grid feasible. The initial operational domain is shown in Figure 4.

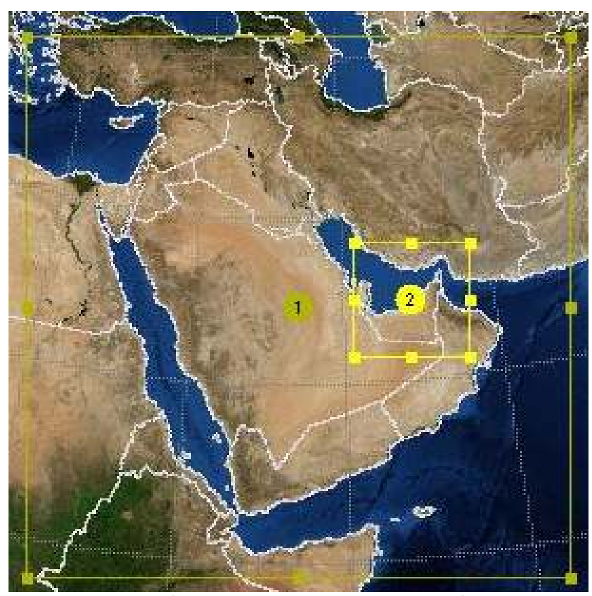

Figure 4. Map of the initial operational domain for the Dubai Met Office. The outer grid is 161 x 161 points with 21-km grid spacing. The inner grid is 103 x 103 with 7-km spacing.

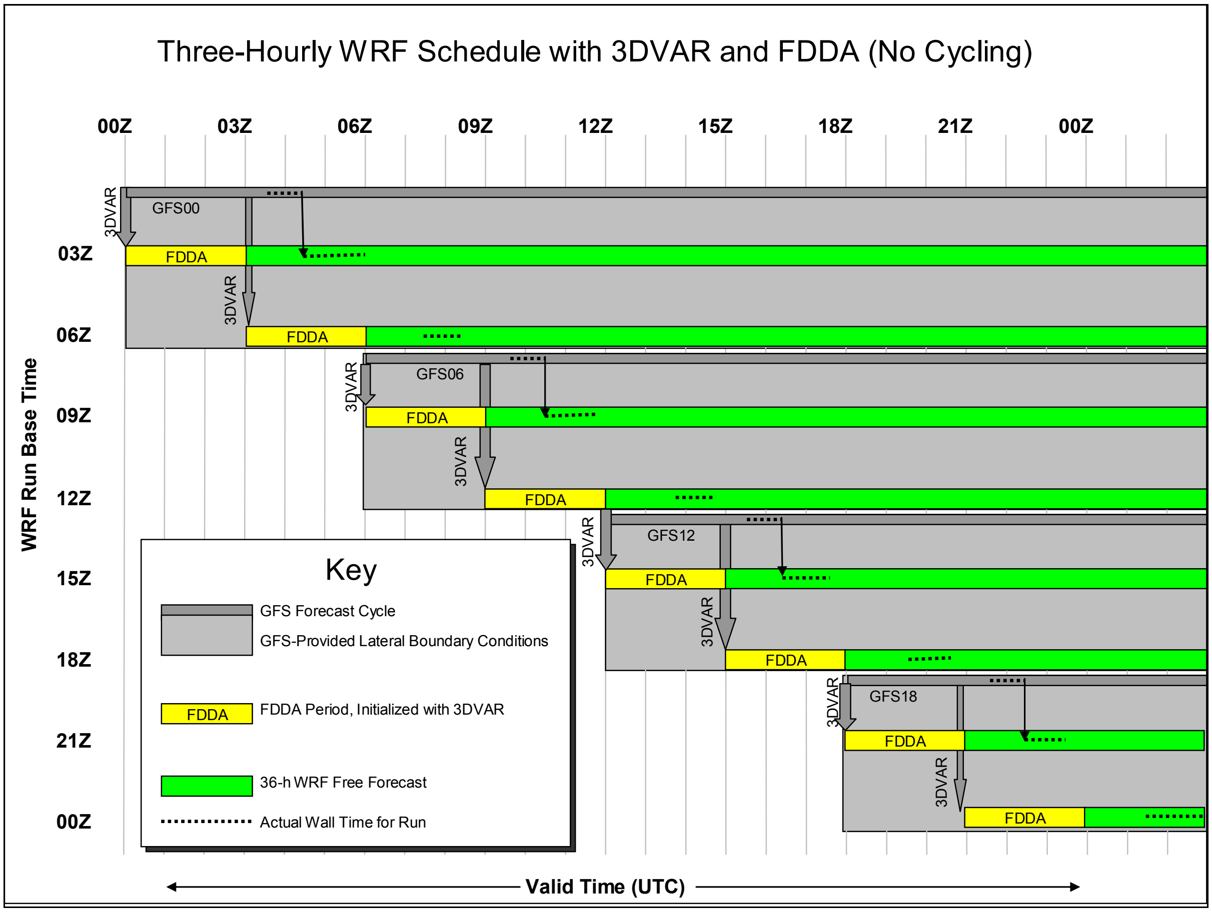

Figure 5. Operational WRF forecast schedule for the Dubai Met Office. The yellow and green bars depict the valid time range of the FDDA and free forecast period for each WRF run. Dotted lines show the actual wall time the run begins and ends. The gray boxes show which GFS cycle provides boundary conditions for the WRF runs contained within them.

Per the Met Office requirements, this domain is routinely schedule to produce a 36-h forecast every three hours. To maximize the number of observations included in the data assimilation, processing is delayed 1 h 15 min after the desired initial time. Figure 5 provides a graphical depiction of the schedule, relating valid times to wall time and the GFS cycles providing boundary conditions.

3.2 Data Assimilation

An important and unique aspect of the Dubai WRF implementation is its data assimilation system, both in terms of the data ingest and the methods used. Many local implementations of WRF and similar NWP models include no data assimilation at all. Rather, data assimilation is "inherited" from the model providing initial and lateral boundary conditions. WRF users who do perform data assimilation typically use a separate data analysis package, the WRF 3DVAR, or the new FDDA capability. However, the Dubai WRF is using both 3DVAR and FDDA observational nudging. It is believed that this is the first operational implementation of WRF that uses both of these capabilities.

The goal of using both methods is to leverage the strengths of each to offset their different weaknesses. For example, the current FDDA observation nudging capability requires observations to be on pressure levels and uses the approach of adding non-physical "nudging" terms to certain model equations to drive the model solution toward observations as it proceeds through the pre-forecast period. However, it is much less complicated than 3DVAR, easy to implement, and has been shown to be a very effective mechanism for eliminating model spin-up issues. Additionally, it is able to make use of observations with high temporal frequency (e.g., the wind profiler and radiometer), whereas 3DVAR selects only the value that is closest in time to the analysis time.

On the other hand, 3DVAR is able to use any observation for which a forward operator can be created that converts the observation into variables represented explicitly in the model. Furthermore, it elegantly considers observational and first-guess error characteristics to optimize the final analysis. However, in the absence of observations and in cold start mode (first guess provided by external model forecast of coarser resolution), it is not able to solve the spin-up issue. Additionally, while WRFControl provides a cycling option whereby the previous WRF forecast can be used as the first-guess for the next 3DVAR analysis, our testing revealed that significant feedback problems can occur when the model incorrectly forecasts areas of precipitation that either did not materialize or are in a different location. Figure 6 shows an example of this problem from real-time runs performed over the data-rich U.S. during the development process. In areas containing less data, we expect this would cause even more problems. In the future, enhancements to the 3DVAR to do full radiance assimilation as well as the use of digital filters may alleviate this issue, making 3DVAR cycling a viable option. Such enhancements are currently planned for WRF version 3.

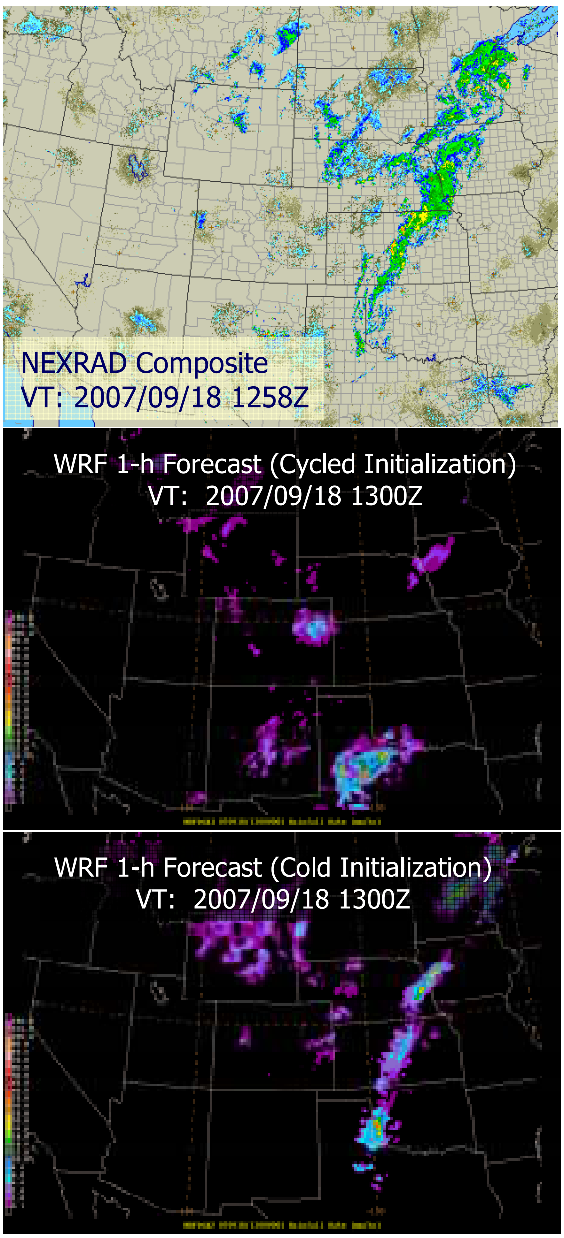

Figure 6. Example of problems that can occur with a 3DVAR cycled initialization. The cold initialization (bottom) compares much more favorably with the actual radar (top) than the cycled initialization (middle).

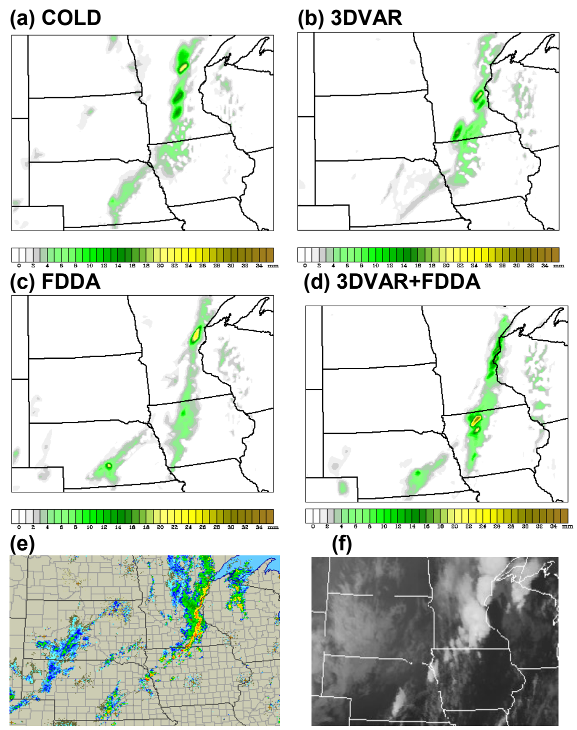

Figure 7. One-hour accumulated precipitation (mm) at 2300 UTC 24 September 2007 from the (a) COLD, (b) 3DVAR, (c) FDDA, and (d) 3DVAR+FDDA simulations. Radar and satellite imagery valid at the same time are shown in (e) and (f).

For Dubai, each cycle begins with a 3DVAR analysis at T-3 h, where T represents the desired initial time. For example, when running the 1200 UTC WRF, a 3DVAR analysis is created for 0900 UTC. Input to the 3DVAR is a GFS forecast valid at the analysis time, which provides a relatively accurate forecast of the synoptic scale conditions without adding smaller scale (and potentially incorrect) features. This first guess is then blended with the wind profiler, radiometer and conventional observations from throughout the region.

Upon completion of the 3DVAR analysis, WRF is initialized for the T-3 h time and uses FDDA observation nudging for the period from T-3 h to T. As the simulation approaches time T, the FDDA function ramps down and the model continues forward to produce forecast conditions from T to T+36 h. The resulting "initial condition" at T-0 has thus benefited from the advanced capabilities of the 3DVAR while taking advantage of other local data during a spin-up period.

During the next few months, we will be tuning the 3DVAR and FDDA assimilation, but as delivered we have subjectively observed the value being added using the combination of 3DVAR and FDDA. A test case comparing runs with no assimilation (COLD), FDDA only, 3DVAR only, and FDDA with 3DVAR was performed. The one-hour accumulated precipitation forecasts ending at 2300 UTC on 24 September 2007 from each of the four simulations are presented in Figure 7. Although the patterns from the simulations are rather similar, each indicating a line of precipitation from northeastern Minnesota extending south-southwestward, the line of precipitation from the COLD simulation is farther west than the other three simulations, especially along the northern portion of the line. Radar and satellite observations indicate that the line of precipitation at this time is indeed farther east, near the Minnesota and Wisconsin border where the 3DVAR, FDDA, and 3DVAR+FDDA simulations each place the precipitation.

Although this is only a single case from which broad conclusions should not be drawn, it does illustrate that 3DVAR and FDDA analysis/assimilation techniques can be used with the WRF model to make notable improvements in precipitation forecasts. As the system is used operationally in Dubai over the next few months, we will be able to evaluate it in more detail.

3.3 Operational Application

The primary weather hazards that impact the Dubai airport include fog, low-level wind shear due to sea-breeze penetrations, severe temperature inversions that impact aircraft performance during takeoff, and thunderstorms and their associated hazards. Additionally, airline clients of the Met Office require forecasts of standard aviation hazards such as turbulence and icing. Finally, the office is responsible for issuing Terminal Aerodrome Forecasts (TAFs) for Dubai and other nearby airports. The WRF modeling system contributes information related to all of these.

As mentioned earlier, WRF forecast profiles are stored in a relational database for use in the various detection and nowcasting algorithms. It provides a state-of-the-science NWP forecast at higher resolution and with more frequent updates than any other indigenous or foreign data source available to the Met Office, making it a valuable general forecasting tool for both aviation and general public products.

Via the WRFPOST program, all required aviation parameters including turbulence, icing, flight-level winds, ceiling, visibility, thunderstorms, and low-level wind shear potential are made available in the GRIB files for use on the Met Office display systems. The version of NAWIPS delivered with the system includes custom scripts for generating user-friendly renderings of the various required products. It is anticipated that this suite of products will be tuned as forecasters

(a) **(b)**

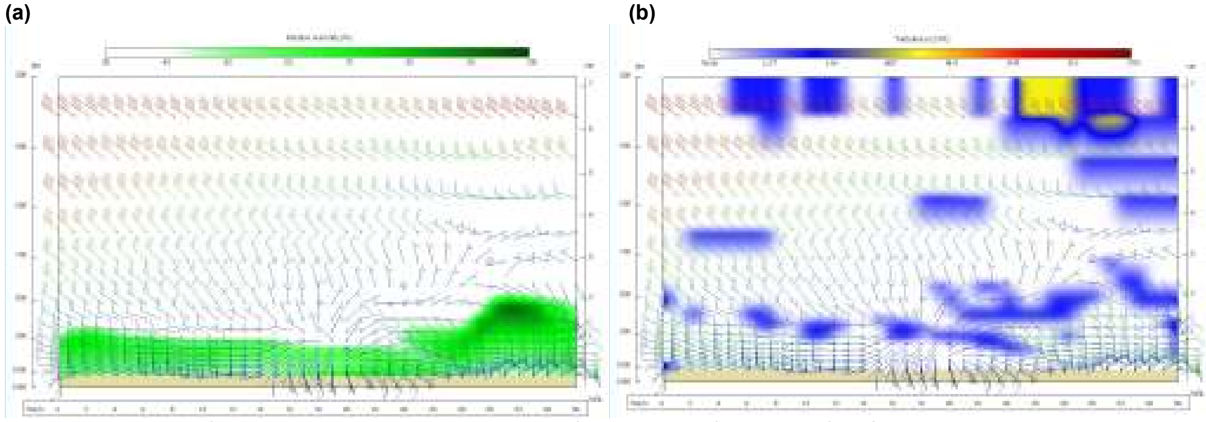

Figure 8. Example of time-height cross sections generated from the WRF forecast profiles for Dubai Airport: (a) relative humidity, (b) clear-air turbulence. Time scale is from 0-36 h at 1-h intervals.

become comfortable with using them and can provide feedback.

In addition to the products within the GRIB files, the forecast staff has become accustomed to using time-height cross-sections of model output to forecast sea-breeze entrance/exit and fog potential. The combination of hourly temporal output from WRF and the ability to view forecast profiles within the AWDSS sounding toolkit make WRF a powerful tool for this application. Figure 8 shows example time-height cross sections generated from the WRF output.

Within hours of the WRF system being activated in the Met Office and even before formal training had been performed, an example of how the system will benefit the operations was observed by the first author. On that particular day, there was some uncertainty as to whether or not fog would impact the terminal in the early morning hours of the next day, as had been the case for several days. The additional forecast problem was whether or not a marine wind advisory was needed for the offshore area east of the UAE peninsula. Prior to viewing the WRF model, there was some thought that winds would be increasing overnight, which might help prevent fog as well as create winds exceeding advisory criteria. Forecasters utilized WRF time-height cross sections in the AWDSS sounding toolkit to view the evolution of wind and humidity in the low levels of the atmosphere. Additionally, standard maps of low-level winds, humidity, and pressure were viewed in the NAWIPS display. All indications from WRF were that fog would not form and offshore winds would indeed reach advisory criteria. Based on this information, the forecasters produced a forecast for no fog and the issuance of a marine wind advisory, both of which verified correctly.

4. CONCLUSIONS AND FUTURE WORK

The AWDSS WRF installed in Dubai is one of the most advanced operational implementations of WRF known to date, both in terms of the science and its integration into the operational systems. Although the system has been operational in Dubai for less than a month, anecdotal evidence has already shown that AWDSS and its WRF subsystem have the potential to provide significant benefit to the Dubai airport operations, and can serve as a prototype for future, larger systems. One can easily envision a larger, regional or continental scale AWDSS and WRF system that provides automated input into air traffic management systems, flight planning guidance, etc.

During the first half of 2008, we will be focusing on tuning the system to maximize its utility and accuracy specifically in Dubai. These efforts will include:

- Adding additional data types to the assimilation process, including the EUMETSAT satellite-derived winds
- Tuning the 3DVAR background error co-variances. This tuning process requires a minimum of 30 days of forecasts, which are being archived on the system. This tuning will result in improved initial conditions and more accurate forecasts than the default statistics provided with the 3DVAR system
- Adjusting the various derived product algorithms (e.g., visibility, turbulence, etc.) as feedback is obtained on the performance of the existing algorithms
- Assisting the staff with improving how the data are displayed for operational effectiveness
- Additional forecaster training as required.

The AWDSS WRF will continue to grow in capabilities, taking advantage of the newer versions of WRF as they are released, providing a continuous infusion of the latest NWP research. As the system is installed at other future locations, new ideas and applications will be integrated, benefiting existing and future clients and thus making terminal and in-flight operations safer for all.

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