A Frequent-Updating Analysis System Based on Radar, Surface, and Mesoscale Model Data for the Beijing 2008 Forecast Demonstration Project

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(Manuscript received 16 July 2009, in final form 29 April 2010)

ABSTRACT
The Variational Doppler Radar Analysis System (VDRAS) was implemented in Beijing, China, and contributed to the Beijing 2008 Forecast Demonstration Project (B08FDP) in support of the Beijing Summer Olympics. VDRAS is a four-dimensional variational data assimilation system that produces frequently updated analyses using Doppler radar radial velocities and reflectivities, surface observations, and mesoscale model data. The system was tested in real time during the B08FDP pretrials in the summers of 2006 and 2007 and run during the Olympics to assist the 0–6-h convective weather nowcasting. This paper provides a description of the upgraded system and its Beijing implementation, an evaluation of the system performance using data collected during the pretrials, and its utility on convective weather nowcasting through two case studies. Verification of VDRAS wind against a wind profiler shows that the analyzed wind is reasonably accurate with a smaller RMS difference for 2006 than for 2007 due to better radar data coverage in 2006. The analyzed cold pools in three convective episodes are compared with surface observations at selected stations. The result shows good agreement between the analysis and the observations. The two case studies demonstrate the role that VDRAS could play in nowcasting convective initiation.

1. Introduction
In preparation for the 2008 Summer Olympics in Beijing, China, the Beijing Meteorological Bureau (BMB) of China upgraded its mesoscale-observing network in the vicinity of Beijing. The upgraded network includes four Doppler radars, five radiosondes producing soundings at 6-h intervals during the Olympics, about 150 automated weather stations, three profilers, and about 40 GPS–Met receivers. The Beijing 2008 Forecast Demonstration Project (B08FDP; information online at www.bo8fdp.org), organized by the World Weather Research Program (WWRP), with the emphasis on 0–6-h prediction of convective weather, took place during the summers of 2006–08. The demonstration includes state-of-the-art analysis and forecast systems for convective storms from China, Hong Kong, Australia, Canada, and the United States. These systems produced analyses, warnings, and forecasts of convective storms for the 2008 Olympics. The B08FDP pretrial was conducted during the summers of 2006 and 2007.

To provide better support for the game on convective weather forecasting and to participate in the B08FDP project, BMB collaborated with the National Center for Atmospheric Research (NCAR) to transfer the convective weather nowcasting technology of NCAR to BMB to enhance its capability of analyzing and forecasting very short-term convective weather events. The key component of the collaboration was the implementation and further development of NCAR’s Auto-Nowcast (ANC; Mueller et al. 2003) system at BMB. Other than the nowcasting system that aims at producing thunderstorm and convective precipitation nowcasts, the technology transferred to BMB and further developed also included a high-resolution Doppler radar analysis system called VDRAS.
Variational Doppler Radar Analysis System (VDRAS; Sun and Crook 2001) that provides frequent-updated high-resolution low-level analyses of wind, temperature, and humidity. In this paper, we evaluate VDRAS’s performance in the Beijing area and demonstrate its capability in analyzing some low-level atmospheric features that can potentially provide guidance for nowcasting thunderstorms.

In the last two decades, active research has been undertaken to infer detailed unobserved meteorological information from single–Doppler radar data, resulting in several single–Doppler radar retrieval techniques (e.g., Sun et al. 1991; Qiu and Xu 1992; Laroche and Zawadzki 1995; Shapiro et al. 1995; Gao et al. 2001; Liou 2007; Snyder and Zhang 2004). One of the major retrieval methods is the four-dimensional variational data assimilation (4DVAR) adjoint technique, which combines radar observations with a cloud-scale numerical model. By applying optimal control theory, this technique finds a solution that satisfies the model equations and simultaneously provides a best fit to all the observations in a specified assimilation window. The advantage of the 4DVAR technique over other simpler techniques is that it can retrieve not only the three-dimensional wind and convergence but also thermodynamical fields (Sun et al. 1991).

VDRAS is a 4DVAR-based system that assimilates observations from single or multiple Doppler radar(s) and produces unobserved meteorological fields of wind, temperature, and humidity at the convective scale with frequent updating of less than 20 min. The system has been continuously developed and used for convective-scale data assimilation research and applications for approximately 18 yr. VDRAS was used in research mode to demonstrate the potential of high-resolution data assimilation using Doppler radar data and its impact on short-term explicit forecasting of storms (Sun 2005; Sun and Zhang 2008). VDRAS has also been implemented in real-time operational environment for the assimilation of high-resolution data from operational Doppler radar and surface networks to produce low-level analyses since 1998. The real-time system was described in detail in Sun and Crook (2001, hereafter SC2001). It was implemented in three U.S. weather service offices (Sterling, Virginia; Dallas–Fort Worth, Texas; and Miami, Florida) and a number of U.S. Army test ranges. It was also been run at the Bureau of Meteorology in Sydney, Australia, as part of Sydney 2000 Forecast Demonstration Project (S2000FDP), which was similar to B08FDP (Crook and Sun 2002).

The frequently updated analyses from VDRAS provide useful information for nowcasting convective weather. The analyzed fields can be used directly by forecasters or as input into the ANC system to nowcast storm initiation and location (Mueller et al. 2003). To meet the time requirements for nowcasting, the real-time VDRAS is simplified from its research version to produce rapidly updated analyses within 10 min or so after the latest observations arrive. Previous real-time implementations of VDRAS used the dry version of the full cloud-scale model described by Crook and Sun (2002), emphasizing the analysis of three-dimensional wind and its convergence. After S2000FDP, VDRAS was improved in a number of aspects including the capability to analyze cold pools resulting from the inclusion of a simplified microphysics scheme. The implementation of VDRAS in the Beijing area also presents a number of unique challenges. One of them is the complex terrain in the area. The city of Beijing lies on a plain near the meeting point of two mountain ranges. The terrain height within the VDRAS implementation domain varies from sea level to over 2200 m. Hence, the VDRAS analysis in Beijing provides a good test on its performance over complex terrain. Another challenge is the quality of the radar data. The radars in Beijing and its vicinity were built in recent years. During the B08FDP pretrial years, the radar parameters were adjusted to produce the best quality data.

During the three summers of the B08FDP, VDRAS was run in real time on a domain that encloses the radar coverage areas of both the Beijing and Tianjin S-band radars with a spatial resolution of 3 km, producing three-dimensional wind, temperature, and humidity with a temporal frequency of ~18 min. These fields were displayed at the weather forecast office of BMB to assist the forecasters in issuing thunderstorm nowcasts. In addition, the vertical velocity field from VDRAS was ingested into the further developed ANC system at BMB (called BJANC) as one of the key interest fields needed to produce thunderstorm nowcasts, including the initiation, evolution, and dissipation of convective storms.

The main objectives in the pretrials were to ingest local data, evaluate and improve the data quality, and optimize the system’s performance. During the pretrials, VDRAS parameters were tuned based on the local data characteristics. The tuned final system was implemented during the Olympics in 2008. Reruns were conducted on a number of convective cases using this final system on data collected in the pretrial summers of 2006 and 2007. This paper is based on the results of these reruns. The main purpose is to describe the updated VDRAS and its Beijing implementation and evaluate the performance of VDRAS in Beijing over complex terrain. The evaluation is conducted by verifying wind analyses using observations from a profiler and the temperature analyses using observations from a local Beijing mesonet. In this paper, we also discuss the implications of VDRAS analyses on nowcasting convective initiation and evolution using two convective cases. A comprehensive study on the use of
VDRAS analyses for nowcasting is being conducted using VDRAS B08FDP 2008 data and will be reported upon in a separate paper. In section 2, we describe the data that were ingested into VDRAS and the data preprocessing. Section 3 provides a brief description of VDRAS and its recent refinement, as well as the implementation configuration employed for B08FDP. In section 4, the simplified real-time VDRAS analyses are compared with the full VDRAS results through a case study. In section 5, results of the verifications are presented. The implication of the VDRAS analysis to nowcasting is discussed in section 6. A summary and conclusions are given in the last section.

2. Description of data and quality control

The data source that is used for our study is shown in Fig. 1, along with the altitude plot and the VDRAS analysis domain. The observations include the following:

1) Two S-band China New Generation Radars (CINRADs) located at Beijing and Tianjin (BJRS and TJRS) that are very similar to the Weather Surveillance Radars-1988 Doppler (WSR-88Ds) of the United States—the two radars were run operationally using the same scan mode during the two summers, and produced reflectivities and radial velocities at nine elevation angles with a volume scan rate of ~6 min.

The other two radars (ZBRS and SJZRS) only became available in 2008; therefore, they were not used in the current study. Further, during the B08FDP trials in 2006 and 2007, it was found that the TJRS radar had a much smaller data coverage area and a 9-dBZ lower sensitivity than the BJRS. The problem was reported to the manufacturer and fixed before the Olympics. A sensitivity study with and without the TJRS data showed that the inclusion of the data did not make much difference to the VDRAS analysis. Therefore, the TJRS data are not used in this study although they were used in the real-time operational run.

2) Automatic Weather Stations (AWSs)—these mesonet stations provide wind, temperature, relative humidity, and pressure at 1-h interval during the summer of 2006 and at 5-min intervals during the summer of 2007. Note that only the surface stations within Beijing are available in 2006, but more stations surrounding Beijing became available in 2007 and during the Olympics. The available stations for 2006 and 2007 are marked differently in Fig. 1. Most of the available AWS data were assimilated in the mesoscale analysis portion of VDRAS as long as they passed a statistical quality control procedure.

3) Soundings extracted from mesoscale model analysis—In the first two B08FDP trials in the summers of 2006 and 2007, the operational fifth-generation Pennsylvania
State University–National Center for Atmospheric Research Mesoscale Model (MM5) with a 3DVAR initialization scheme was run at BMB from a 12-h cold start. The MM5 ingests data from both global and local observations and produced analysis and 48-h forecasts with a 9-km horizontal resolution. During the Olympics, the MM5 was replaced by the Weather Research and Forecasting (WRF; Skamarock et al. 2005) model with a 3-hourly Rapid Update Cycle and a 1-h forecast interval (BJRUC). In VDRAS, the extracted model soundings from BMB’s MM5 or BJRUC are used in conjunction with radar velocity azimuth display (VAD) profiles and surface observations to produce a first-guess background for the radar data assimilation.

4) A wind profiler with 6-min observational interval that is located in the Haidian District of Beijing. The profiler can produce wind observations in the boundary layer from 120 up to 3540 m with a 60–120-m interval in the vertical. We use the profiler data to verify the VDRAS wind analysis.

Two special data quality issues arose during the Beijing implementation. One is the severe anomalous propagation (AP) of the TJRS radar. The TJRS radar site is located at the Bohai Sea seaside, where temperature inversions and strong humidity gradients usually occur and result in severe AP echoes on the lowest elevation angle for both reflectivity and velocity. The AP echoes have a distinct influence on VDRAS analysis. To remove data contaminated by AP, any velocity data with values less than 0.25 m s\(^{-1}\) and a decrease in reflectivity with values more than 25 dBZ between the lowest and second tilts were removed. The second issue was the data availability of the AWSs. The AWS stations within Beijing area were being built during 2006 and 2007. We selected only the 55 most reliable stations based on an evaluation using statistics.

3. Overview of VDRAS and its B08FDP implementation

The real-time VDRAS was described in detail in SC2001 and in Crook and Sun (2002). In this paper, only a brief summary of the system will be given. After S2000FDP, several new features were added to VDRAS in order to improve its performance and real-time applicability. These new features will be described in this section.

VDRAS was developed to retrieve those meteorological variables (3D wind, temperature, and microphysics) that are not observed by Doppler radar by assimilating observations (radial velocity and reflectivity) from single or multiple radars using a 4DVAR scheme and a cloud-scale model. Several studies have been conducted to demonstrate its capability in retrieving these variables during convective storms in the full troposphere. For real-time applications, however, VDRAS was implemented to retrieve only low-level wind and temperature due mainly to limited computation resources. The original VDRAS was developed to assimilate observations only from a single Doppler radar with a domain that covers a city or a county. Recently, VDRAS was enhanced to assimilate observations from multiple Doppler radars in operational networks and applied to larger domains. As a result, it became necessary to include data from in situ observations such as radiosondes, profilers, surface networks, VAD analyses, and mesoscale model analyses; that is, wherever these data were available (Crook and Sun 2002). These larger-scale observations are assimilated into VDRAS through an objective analysis to provide a mesoscale background prior to the 4DVAR radar data assimilation. Sun and Zhang (2008) gave a detailed description on how these data are blended in the objective analysis. A description of this objective analysis is also provided later in this section and the reasons for performing the objective analysis are explained. For the description of the cloud model used in VDRAS, the reader is referred to Sun and Crook (1997). The most updated description of the cost function, the background error and weighting specification, and the minimization procedure are also provided in Sun and Zhang (2008).

Compared with the version that was installed for S2000FDP, the current VDRAS has a few enhancements. First, the VDRAS installed for B08FDP includes rainwater evaporation and precipitation while the VDRAS used in S2000FDP did not include any microphysics processes. Note that the other warm-rain microphysics processes (cloud condensation, cloud to rain autoconversion, and cloud to rain accretion) are omitted because the objective of the VDRAS Beijing installation was to provide low-level analyses, and the rainwater evaporation and sedimentation play the most important role in the low level. In the next section, the impacts of this simplification will be examined. Second, soundings extracted from a mesoscale model are used in the background analysis for the Beijing implementation, as opposed to the use of observed radiosondes or profilers in previous implementations. In fact, an option is provided in the new version to allow the user to choose between the observed radiosonde soundings and the extracted soundings from a mesoscale model. An option is also given for the user to employ the original model data or thinned model data (extract soundings). It was found that when high-resolution model data are used, thinning the model data resulted in better convergence in the 4DVAR radar data assimilation. This new feature of using mesoscale model output in the mesoscale background analysis
helps in depicting the mesoscale environmental variation, which cannot be captured by radiosonde observations due to their insufficient spatial resolution. This is especially important for the Beijing area, which covers complex terrain, since VDRAS does not explicitly handle terrain variation using a terrain-following coordinate. In addition, the mesoscale model output is preferable than radiosonde data because it updates more frequently (usually 3 hourly) than radiosonde (12 hourly). Third, continuous cycles, with each cycle including a 12-min 4DVAR window and a 6-min forecast period, are executed in comparison to the cold-start cycles during S2000FDP. The continuous cycles are made possible by the implementation of a recursive filter (Hayden and Purser 1995) which is described in Sun and Zhang (2008).

One may wonder why the larger-scale observations are assimilated in a separate step using a classical Barnes technique in VDRAS. The reason is that the radar observations have much higher spatial resolution, which is believed to represent the convective-scale motion, than the others, which mostly capture the environmental conditions. The two-step approach allows a more detailed analysis of the convective-scale features from the radar observations by using a small assimilation window and a small scale length. This approach was also used in previous studies. For example, in the Local Analysis and Prediction System (LAPS) wind analysis, radar wind is analyzed in the second pass using the same successive correction technique but a different weighting function (Albers 1995). The mesoscale analysis in VDRAS that blends mesoscale model data, observed soundings, VAD profiles, and surface data is used as a background through a penalty term in the 4DVAR cost function for radar data assimilation. This penalty term ensures that the 4DVAR analysis is not too far from this background in the region where there is no radar coverage. It is used during both the cold start and in subsequent cycles, although the first guess in the subsequent cycles is from the short forecast following the previous analysis cycle.

The procedure for the mesoscale background analysis is given below:

1) compute VAD profiles for each radar on the VDRAS vertical grid,
2) interpolate the model data to the VDRAS vertical grid,
3) blend the model data and the radar VAD profiles to produce a gridded analysis using a Barnes (Barnes 1964) interpolation technique with a radius of influence of 200 km,
4) interpolate the surface observations horizontally onto the VDRAS grid using the Barnes interpolation scheme with a radius of influence of 2 times the average station spacing (~20 km), and
5) a local-linear least squares fit is applied vertically at each grid point to combine the surface analysis and the upper-air analysis.

The mesoscale analysis obtained by the above procedure does not result in significant changes from the mesoscale model background except at the lower levels (below 2 km) because the VAD data and surface observations are only in the low levels. The current operational model analysis–forecast does not have adequate accuracy in the low levels for the purpose of convective analysis and forecasting. Therefore, a modified background, based on the frequently updated observations such as the VAD and surface data, is necessary for better high-resolution low-level analysis.

The inner square in Fig. 1 is the VDRAS analysis domain. The radars operate with nine scanning elevations: 0.5°, 1.5°, 2.5°, 3.5°, 4.4°, 6.1°, 9.9°, 14.6°, and 19.6°. Each scanning volume completes in about 6 min; thus, the length of the 4DVAR window is set to 12 min, which covers three volumes of radar observations. A 6-min forecast follows each of the 4DVAR analyses to forward the time to the next observation data volume. Figure 2 shows the data and analysis sequence. With the chosen domain size, each VDRAS analysis (including the 6-min forecast) is complete in less than 18 min of wall-clock
time, which enables the data assimilation to keep pace with the arrival of new radar volumes.

4. Test of a shallow domain versus a deep domain

To reduce the analysis latency, VDRAS was implemented on a domain with a vertical extent of 5.625 km with a simplified microphysical scheme that only includes rainwater evaporation and precipitation. Our target was to obtain an accurate analysis at the lowest 3 km by using clear-air and storm observations. The additional 2.625 km is added because a sponge layer is required in the model to alleviate wave reflection from the top boundary. Doppler radars typically provide nonprecipitation returns (by bugs or small raindrops) below a height of less than 3 km unless there is deep convection. Whenever VDRAS
is applied with a shallow domain for low-level analysis, radar data above 3 km are not used. Therefore, VDRAS analysis above 3 km basically corresponds to the mesoscale background and a dynamical adjustment through the constraining model integration in 4DVAR. The dynamical adjustment enables a smooth transition between the layers with and without radar data. To investigate how much impact was made by the simplification of the microphysics and the shallow domain, in this section, we compare the experiment that uses the same configuration as in the real-time implementation with an experiment that uses the full microphysics on a domain that extends to 11.25 km.

An intense thunderstorm that occurred on 1 August 2006 was used for our comparison. This storm produced 53 mm of rain in less than 3 h and hail in Haidian District, causing traffic congestion on major roads across central Beijing. On the 0000 UTC (0800 LT) synoptic map, there was a weak but deep, slow-moving trough at 500 hPa, and a surface low centered just east of Beijing. Some convective storms that were induced in the northwest mountains organized into a convective line by 1533 local time (LT) (Fig. 3b), just prior to reaching the foothills. Between 1609 and 1721 LT, the storm at the northeast end of the line dissipated while rapid intensification at the southwest end of the line occurred (Figs. 3c–f). In section 6, we will describe in detail what caused this intensification based on VDRAS analysis.

In Figs. 4 and 5, we compare the results from the shallow and deep domain experiments by plotting the vertical velocity and perturbation temperature fields. In both figures, the shallow domain run is compared with the deep domain run at two different times (1627 and 1745 LT).
From Fig. 4, we can see that the main patterns of the vertical velocity field are similar from the two runs. Both runs capture the line of updraft that is responsible for the development of the northeast–southwest convective line at both times. The vertical velocity from the deep domain run is generally noisier, presumably because the deep domain better resolves the clouds due to more complete microphysical processes. The horizontal wind does not show significant differences between the two runs, although some small-scale differences can be observed. For example, at the northeast corner of the domain, the wind directions and magnitudes are rather different between the two runs (Figs. 4b and 4d). Because the main purpose of the VDRAS analysis is capturing the features that trigger convection rather than obtaining the updrafts and downdrafts within convective cells, we believe that the smoother analysis obtained from the shallow domain experiment can serve the purpose better.

In contrast to the vertical velocity field, the perturbation temperature field (Fig. 5) shows much less difference between the shallow and deep domain runs at both times (cf. Figs. 5a and 5c with Figs. 5b and 5d). The only noticeable difference is that the cold pool near the north boundary of the analysis domain is about 1°C colder in the deep domain run at both times. The comparison of the two experiments indicates that running VDRAS with a relatively shallower domain does not degrade the low-level (below 3 km) analysis and it is a reasonable approach when the purpose of the application is to obtain low-level analyses for nowcasting. It is worth noting that the simplified microphysics for the low-level analysis does not show much difference from the full warm rain microphysics because the model integration is very short in each analysis cycle. This conclusion does not apply to the situation when a long period of model integration is used.

**FIG. 5.** As in Fig. 4, except that the color shading shows the perturbation temperature analysis.
5. Verification of VDRAS wind and temperature analyses

Verifying the high-resolution VDRAS analysis using independent data is challenging because the lack of data sources that can provide similar spatial and temporal resolutions. In this study, we use a wind profiler located in Haidian District, as shown in Fig. 1. This profiler has high temporal and vertical resolution, but it is only a point measurement in the horizontal. For temperature analysis, observations from the AWS surface network are used for the verification. We do not verify the humidity due to the fact that radar data assimilation is unable to infer water vapor information outside the convective storms. Hence, the humidity analysis in the current VDRAS only provides a large-scale distribution based on the background analysis. Inside the storms, the water vapor analysis is sensitive to the first guess. Other data, such as radar refractivity (Roberts et al. 2008) and GPS precipitable water, should be assimilated to obtain an accurate high-resolution water vapor analysis.

a. Wind verification against profiler data

Since the main purpose of B08FDP is to nowcast convective weather, the verification of VDRAS was done on selected episodes when severe storms occurred. Four convective cases that occurred during the summer of 2006 and represent different convective regimes and six convective cases that occurred during the summer of 2007 were rerun after a few parameter settings were optimized. These reruns were verified against the measurements from the profiler that was described in section 2. These 10 cases are summarized in Table 1, which lists the period of the convection that is seen in the VDRAS domain, the number of VDRAS analyses, and the accumulated rainfall, and also summarizes the forcing and triggering mechanisms.

Because the vertical resolution of VDRAS (375 m) is much coarser than the profiler (60 ~ 120 m), interpolation using a spline function is done to fit the profiler wind onto every model level. The VDRAS analysis results at the profiler site are obtained by calculating the distance-weighted mean of the four closest grid points to the site. We only calculate the verification using the data below 2625 m because much of the profiler data above this level is void. In addition, the profiler wind with an observational time closest to the output from the VDRAS cycle is used for verification. The maximum time difference is less than 3 min because the time interval of the profiler observation is 6 min. We compute the following quantities for both wind speed and direction: 1) bias from the profiler wind and 2) root-mean-square difference (RMSD) of the VDRAS wind and profiler wind.

First, we present the data reliability of the profiler by comparing wind observations from the profiler with those from a radiosonde, VAD analysis of the BJRS radar, and the MM5. The radiosonde is collocated with the BJRS radar and has a short distance of 28 km to the profiler site. We also select the MM5 sounding point closest to the profiler site. It is commonly known that the radiosonde data are available only at 0000 and 1200 UTC of every day. The MM5 3DVAR analysis is also available only at those two times. Therefore, the wind data are compared only at 0000 and 1200 UTC. In addition, smoothing of the profiler wind data is performed by using a five-point smoothing method before comparing the results with the other data sources because the profiler wind has a much finer resolution than the other data. We compared winds from the profiler, radiosonde, VAD of BJRS, and MM5 3DVAR analysis at six different times near the periods when the convective cases of 2006 occurred. The $u$ and $v$ winds at 0000 UTC 10 July 2006 are shown in Figs. 6a and 6b, respectively. We can see that the different profiles have a similar trend, but clear differences exist. The largest difference in the $u$ wind between these profiles exceeds 5 m s$^{-1}$. The difference between the two observed profiles (radiosonde and profiler) can also exceed 3 m s$^{-1}$ on some levels. Even after the smoothing, the profiler sounding still shows more vertical variation and generally higher values than the others.
observations apply in a general sense to five other times during the profile comparison as well, although they are not shown here. The uncertainty (maximum wind difference between the observations) ranges from 2 to 5 m s$^{-1}$. This comparison indicates that there is no perfect instrument and uncertainties could also exist for the profiler observations, so caution needs to be exercised when explaining our verification results shown below.

Figure 7 shows the verification results of the bias and RMSD for the four cases from the 2006 summer on every model level. Figure 7a shows that the bias of the wind speed is less than 2.5 m s$^{-1}$ for all cases and at all levels and that the RMSD is generally less than 2.5 m s$^{-1}$ except for the 11 July case in which the value is nearly 3.5 m s$^{-1}$ at some levels. The negative bias in the wind speed is expected because the VDRAS analysis is a three-dimensional fitting to the observations, which inevitably involves smoothing by the model and the limited grid resolution, while the profiler data are a point measurement. Figure 7b shows the bias and RMSD of the wind direction. The bias and RMSD for the 9 and 11 July cases are generally less than 15$^\circ$ except at the lowest level. However, the values are much larger for those of the 27 June and 1 August cases, especially for the RMSD, which exceeds 90$^\circ$ at some levels.

To find out the reason for the larger RMSDs on 27 June and 1 August in the wind direction verification, we plotted the wind profiler data every 18 min for the analysis period and found the profiler winds were contaminated...
by the heavy precipitation that hit the site during both cases. Figure 8 shows the profiler winds from 1549 to 1719 UTC on 27 June when there is precipitation at the profiler station. These winds are compared with the VDRAS winds in each of Fig. 8's six panels. The winds from the profiler display a large temporal directional variability in the layer between 2 and 4 km while the VDRAS winds are consistent with time except for the lowest level where the wind shift is associated with the cold pool outflow. A similar plot was made for the 1 August case (not shown) and the same findings were obtained.

The verification procedure was also applied to six convective storm cases observed during the summer of 2007. The results are shown in Fig. 9. Larger RMSDs and biases are seen for both the wind speed and the direction compared with those of the 2006 cases. Generally speaking, the greater RMSD and bias in speed occur in the higher levels above 1500 m while they are quite comparable with the 2006 results in the low levels. From Fig. 9b, one can observe that the values of the wind direction bias on 31 July 2007 have large fluctuations and the RMSD is larger on all vertical levels than the other days. This is again due to the degraded quality of the profiler data when a thunderstorm passed over the instrument, as explained in the last paragraph. The larger RMSDs and biases for the 2007 cases are attributed to the poorer radar data coverage.
and quality. In 2007, BJRS experienced interference from an unknown military source, which forced the engineer to use a high signal-to-noise ratio, resulting in the loss of sensitivity of approximately 7.5 dB. (P. I. Joe 2008, personal communication). Figure 10 compares the radial velocity observation at the third elevation angle (2.4°) at 0303 UTC 1 August 2006 with that at the same time and on the same day of 2007. It is clearly seen that the data coverage in 2007 is significantly reduced.

The above wind verification suggests that the VDRAS wind retrieval in Beijing over the complex terrain is reasonably accurate. The magnitude of the uncertainty is in good agreement with results from previous studies (e.g., Crook and Sun 2002) that were conducted under relatively flat surface conditions. It is worth noting that the verification was conducted on convective days when strong low-level wind prevails and sharp wind shifts are usual phenomena.

b. Temperature verification against surface data

The temperature verification was done for three 2007 cases (30 July, 31 July, and 1 August) in which strong cold pools passed through the analysis domain. As mentioned in section 2, the 5-min surface AWS data in Beijing and its
surrounding areas were received in 2007. We explained in section 3 that these data were used in our VDRAS mesoscale background analysis but not in the 4DVAR assimilation. The mesoscale background analysis is intended to provide an environmental background for the convective-scale radar data analysis. Therefore, it does not capture the cold pool structure but only depicts the general cold and warm temperature contrast as shown in the mesoscale analyses in Figs. 11a, 11c, and 11e for the three cases, respectively. After the radar data assimilation, the cold pools are evidently seen in Figs. 11b, 11d, and 11f. Note that the perturbation temperature from the horizontal mean at the first model level (0.1875 km) is plotted in Fig. 11 to represent the cold pools. The horizontal mean temperatures for the three cases are 25°, 26°, and 28°C, respectively. By comparing the final VDRAS analyses with those from the mesoscale analysis, we can conclude that these cold pools are clearly a result of the 4DVAR radar data assimilation. It is therefore justifiable to treat the surface observations as “independent data” for the verification of the cold pool. In Fig. 11, the values of the surface temperature observation are overlaid on the temperature analysis. By comparing the surface observations with the VDRAS analysis, the locations of the cold pool analyzed by VDRAS agree quite well with the observations. It should be noted that the surface network in the Beijing area has a high density that is rarely available elsewhere. The VDRAS analysis is especially valuable wherever the surface network has a low density. Even with a high-density surface network as in Beijing, VDRAS analysis still has added value because its three-dimensional result presents the depth of the cold pool, which could be an important predictor for the intensity of convective storms.

To further verify the cold pool accuracy, we chose two surface stations that were passed by the cold pool for each of the three verification cases and we compare the temperature changes with time between the VDRAS analysis and the AWS observation. The results are shown in Fig. 12. The VDRAS temperature at the AWS station was interpolated using the nearest four grid points. A bias caused by the height difference between the VDRAS analysis at 187.5 m and the AWS surface observation was removed before plotting Fig. 12.

The temperature trends from 0600 to 1500 UTC 30 July are shown in Fig. 12a, from 1200 to 1800 UTC 31 July in Fig. 12b, and from 0830 to 1200 UTC 1 August in Fig. 12c. The general trends of the analyzed temperature agree quite well with those of the AWS data at all of the stations for all three cases. However, differences of around 2°C are shown at a few times, for example, at the beginning of the verification period before the passage of the cold pool on 30 July at both stations and on 1 August at station 54416. The colder analyzed temperature before the cold pool passage is explained as follows. In the prestorm environment, VDRAS analysis depends mostly on the mesoscale analysis background, which results from a combination of mesoscale model data and surface data, because radars only provide a limited amount of data from clear-air reflectors. The temperature deviation from the surface observation is a reflection of the combined error from the mesoscale model and from the vertical least squares interpolation of the surface data to the VDRAS model grid. A new vertical interpolation technique that takes into account more of the surface observation than the mesoscale model data is being developed in order to increase the impact of the surface data on the low-level analysis. Another difference between the VDRAS temperature and the surface observations that can be seen from Fig. 12 is on the small-scale fluctuations. For example, the observed temperature fluctuation between 0700 and 1000 UTC 30 July is missed in the VDRAS analysis. This is not surprising because the use of the cloud model in VDRAS results in at least a 6Δx (18 km) spatial smoothing of the analysis.

The above comparison suggests that VDRAS is capable of analyzing the low-level cold pools with a good degree of accuracy above certain spatial scales. The favorable comparison of the VDRAS temperature analysis with the surface observations indicates that the analysis provides a valuable dataset for studying the characteristics of cold pools and their roles in convective initiation and maintenance. It is anticipated that conceptual models can be developed from VDRAS analysis for nowcasting thunderstorms.

6. Implication of VDRAS analyses to nowcasting

It is well known that the lower-tropospheric ascent at some horizontal scale is crucial for the initiation of convection and to allow it to persist significantly beyond the lifetime (~1 h) of a single cumulonimbus cloud. One of the challenges in successfully nowcasting convective weather initiation and maintenance is in identifying the triggering mechanisms of convection and their associated convergence in the lower atmosphere. Wilson and Schreiber (1986) showed that 80% of the thunderstorms in the Denver, Colorado, area formed along radar-detected convergence lines. Although the radar reflectivity observations can be used to identify some of the convergence lines, they are not adequate in that they do not detect all the convergence lines and they are not quantitative. VDRAS cannot only analyze the full three-dimensional wind and derive the convergence field but it can also retrieve the temperature field and hence the cold pool that is a distinct feature of most convective systems (e.g., Wakimoto 1982; Mueller and Carbone 1987). The
interaction of downdraft outflows with environmental air can initiate convective cells and thus affect the dynamical structure and life cycle of long-lasting and organized convection (e.g., Thorpe et al. 1982, Rotunno et al. 1988). The outflow boundary is capable of triggering convection at great distances from the source if it travels into a thermodynamically favorable environment (Carbone et al. 1990), is affected by mesoscale oscillations (Crook et al. 1990), or collides with other outflow boundaries. In this section, we describe how the VDRAS analysis reveals the

Fig. 11. Snapshot of the VDRAS-analyzed cold pool (temperature perturbation from the horizontal mean) that passed through the analysis domain on (a),(b) 30 Jul, (c),(d) 31 Jul, and (e),(f) 1 Aug 2007. The left panels are taken from VDRAS mesoscale background analysis before the radar data are assimilated. The right panels are from the final VDRAS analysis. Values of the surface temperature observed by the AWS mesonet are overlaid. The station numbers that are used for verification in Fig. 12 are marked in yellow. The red symbol indicates the center of Beijing.
convective triggering processes using two convective storm cases that were observed during B08FDP periods.

a. Convection due to the collision of cold pools on 1 August 2006

The convective storm that occurred on 1 August 2006 was described in section 4 and used for the sensitivity test. This case was characterized by a rapid intensification when the convective line that developed over the northwest mountainous region approaches the urban districts of Beijing. The challenge for nowcasters was whether the system would intensify or weaken when it moved to the foothills and the plain, where most of the population lives. The key for successfully forecasting the retriggering of the storm near central Beijing is the identification of the two colliding cold pools (see Fig. 13a, marked CP1 and CP2) produced by the storms located northeast and northwest of Beijing, respectively. The leading edges of the cold pools are partially detected by the reflectivity observations (marked as GF1 and GF2 in Fig. 3c). GF2 is better observed and identifiable in Figs. 3a–c. Figure 13 illustrates the colliding process of the cold pools by showing the perturbation temperature field overlaid with the horizontal convergence contours greater than $0.2 \times 10^{-3}$ s$^{-1}$ and the horizontal wind vectors. The collision of the two convective boundaries caused the intensification of the convective line as shown in Fig. 3c and a new convective cell as marked in Fig. 3d. The new convective cell expands into a convective line that passes over downtown Beijing (Figs. 3e and 3f). Through VDRAS wind and temperature analyses, the cold pools and their leading edges are clearly shown by the perturbation temperature field and the horizontal convergence field, respectively. As the two cold pools continue to merge, the convergence near the center of Beijing is enhanced, which results in the ascending motion in the area as shown by Fig. 14. Another distinct feature shown in Fig. 13 is the warm tongue over central Beijing, which might be associated with the “urban heat island” effect. The warm temperature anomaly near the center of Beijing and its associated wind convergence is a feature analyzed by VDRAS on a large number of days, particularly when there is light wind around Beijing. The new cell shown at 1645 LT in Fig. 3d is marked by an asterisk in Fig. 13. It can be clearly seen that the initiation occurs in the warm tongue and between the two merging gust fronts. Figure 14 shows the vertical velocity field at

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**FIG. 12.** Comparison of temperature changes with time at selected stations between the VDRAS analysis and surface observations for (a) 30 Jul, (b) 31 Jul, and (c) 1 Aug 2007. The locations of the stations are marked in Fig. 11.
the level of 1.6875 km above ground. The black contour shows the observed 35-dB reflectivity 1 h behind the vertical velocity field. The overlapping of the two indicates that the vertical velocity field is a good predictor for convective initiation with a 1-h lead time. As mentioned previously, the vertical velocity is also ingested into the BMB’s BJANC system as one of the key fields of interest for producing storm nowcasts. Studies are being conducted to find other predictor fields from VDRAS analyses that can be used in BJANC to improve storm nowcasting.

b. Nighttime terrain-induced convection on 27 July 2007

At 0000 UTC 27 July 2007, the 500-hPa analysis showed a west–east-oriented shear line across the northern districts of Beijing. This shear line corresponded with a low pressure center situated to the west of Beijing. The center of Beijing was under the influence of the southwesterly wind that brought moisture to Beijing. The convergence and vertical motion associated with the shear line was fairly weak and there was no substantial moisture convergence. Near the surface, the air was dominated by moist and warm southerly flow, favorable for convective weather. Figure 15 shows the evolution of the convective system that occurred on 27 July 2007. The initial convective cell was developed around 2200 LT along the foothill about 150 km southwest of Beijing’s city limits. The system expanded to multiple cells and stayed locally for a few hours (Figs. 15a–c). At about 0130 LT, it extended to the northeast to form a line and then moved rapidly toward the center of Beijing (Figs. 15d–e), reaching the valley to

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**FIG. 13.** VDRAS analyses of the perturbation temperature (colors), horizontal convergence (contours), and wind vectors at 0.1875 above ground at (a) 1515, (b) 1533, (c) 1609, and (d) 1630 LT 1 Aug 2006. The contours for convergence start from 0.2 m s\(^{-1}\) km\(^{-1}\) with an interval of 0.5 m s\(^{-1}\) km\(^{-1}\). The asterisk indicates the location of the new cell that is shown in Fig. 3d. The length of the reference wind vector is shown near the top of each panel.
the north of Beijing by 0400 UTC (Fig. 15f). The system weakened as it moved to the northeast and up the mountains.

The challenging question for nowcasters was whether the system that was initiated southwest of Beijing and stayed locally for a few hours would propagate toward Beijing and initiate convective activities. The triggering process on this day was vastly different from that on 1 August 2006. The VDRAS vertical velocity field shows an area of ascending motion in the plain of Beijing (Fig. 16a) at 0045 LT. The weak northerly flow down from the mountains north of BJRS is believed to be a result of the nighttime cooling over the mountains. This area of ascending motion slowly moves southward as the wind from the mountains becomes stronger with time. Meanwhile, the convection southwest of Beijing produces a cold pool with a magnitude of over $-4^\circ$C (see Fig. 17b)

The outflow from the cold pool increases the southwesterly wind and the convergence at the leading edge. The increases in the northerly from the mountain and the southerly flow from the convection result in the enhancement of the convergence in the area south of the Beijing border at 0157 LT (Fig. 16b) and in central Beijing at 0251 LT (Fig. 16c). As a result, the convective system moves rapidly northeastward, arriving at the valley to the north of downtown Beijing at 0403 UTC. At this time, the downdraft dominates in the region surrounding the convection and the system begins to dissipate. Figures 17b–d show how the propagation of the convection (35-dBZ white contour) corresponds to the propagation of the cold pool. Although the band of the upward motion in the southeast of the domain persists for a few hours, it does not trigger any convection because the cold pool does not propagate to the east.

**FIG. 14.** Analyzed vertical velocity field (colors) overlaid with the 35-dBZ reflectivity (black contours) 60 min ahead at 1.6875 km above ground. The time shown at the top of each panel is the valid time for the vertical velocity at (a) 1627, (b) 1645, (c) 1703, and 1721 LT 1 Aug 2006. The valid time for the 35-dBZ reflectivity is 1 h ahead of the vertical velocity time.
FIG. 15. Observed reflectivity from the BJSR radar’s first elevation angle (0.5°) at (a) 2345, (b) 0045, (c) 0027, (d) 0057, (e) 0251, and (f) 0403 LT 27–28 Jul 2007. The yellow contour shows the 100 m terrain height.
7. Summary and conclusions

The high-resolution low-level analysis system VDRAS was implemented at BMB during the B08FDP’s pretrial periods during the summers of 2006 and 2007 in preparation for providing nowcasting support during the 2008 Summer Olympics. During those periods, VDRAS produced analyses of three-dimensional winds, temperatures, and humidity fields with a 3-km horizontal resolution and an 18-min update cycle by assimilating Doppler radar radial velocities and reflectivities and surface observations. This paper provided a description of the real-time implementation and an evaluation of VDRAS analyses using data collected during the pretrial periods. The implications of these analyses to thunderstorm nowcasting were examined using two convective cases.

The real-time VDRAS has always been implemented with a shallow domain configuration in order to reduce the computational cost such that the analysis can be produced in a timely fashion for nowcasting users. In this paper, the analysis from the shallow domain run was compared with that from a deep domain experiment using a case observed during the summer of 2006. The results showed that the velocity and temperature patterns produced from the two experiments were quite similar in the low levels, which justified the use of the shallow domain configuration for nowcasting applications.

The wind analyses for four convective days in the summer of 2006 and six convective days during 2007’s summer were verified against data from a wind profiler that was located northwest of the Beijing radar. It was found that the retrieved VDRAS wind was reasonably...
accurate and both the RMS difference and the bias are smaller for the 2006 cases. The larger differences in the wind speed and direction for the 2007 cases were likely caused by the poorer radar data coverage due to radar parameter changes. The analyzed temperature was compared with surface observations at selected stations featuring three convective periods of cold pool passage. The results showed good agreement between the VDRAS analysis and the surface observations.

The rapidly updated wind and temperature fields from VDRAS provide detailed analyses for monitoring convection-triggering features in the low levels. How the VDRAS analysis can be used as guidance for nowcasting convection is illustrated by two convective cases in this paper. More comprehensive and statistical study on the role of low-level convergence, cold pool, and low-level wind shear is being conducted using B08FDP data collected during the 2008 Summer Olympics. A similar study is also being conducted using International H2O Project (IHOP_2002; Weckwerth et al. 2004) data. It is anticipated that conceptual models for convective initiation/strengthening will be developed based on these studies. These conceptual models can be used in automated nowcasting systems or directly by severe weather forecasters.

Acknowledgments. This work has been supported by Beijing Meteorological Bureau through a grant to the National Center for Atmospheric Research. The authors are grateful for the engineering support of Feng Gao and Sue Dettling for the VDRAS installation at BMB. We also acknowledge grants from the China
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