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# Using operationally synthesized multiple-Doppler winds for high resolution horizontal wind forecast verification

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[1] The potential value of operational Doppler radar networks for high resolution wind forecast verification is investigated through comparing wind outputs of the cloud resolving model AROME against newly available operational multiple-Doppler winds in northern France. Quantitative comparisons of radar and model winds for a 16-h frontal precipitation event show good agreement, with differences in wind speed (resp. direction) generally comprised between $\pm 2.5$ m.s$^{-1}$ (resp. $\pm 15°$). Power spectra deduced from the scale decomposition of radar and model outputs also show good agreement through all scales. The method is also applied to validate the divergence structures as analyzed by AROME's 3Dvar assimilation system that considers, among a comprehensive set of observation types, the same radial velocities than those considered in the wind retrieval. **Citation:** Bousquet, O., T. Montmerle, and P. Tabary (2008), Using operationally synthesized multiple-Doppler winds for high resolution horizontal wind forecast verification, *Geophys. Res. Lett.*, *35*, L10803, doi:10.1029/2008GL033975.

## 1. Introduction

[2] The upcoming operational deployment of very high resolution (~1–3 km), limited area, numerical weather prediction (NWP) systems such as AROME (Applications of Research to Operations at MesoscalE) or WRF (Weather Research and Forecasting) [*Skamarock and Klemp*, 2008] models, is expected to provide significantly more accurate short to medium range forecasts of precipitation, temperature and winds, as well as to improve the structure and realism of predicted rain events in an unprecedented way. Yet, several recent studies have shown that model forecast skill assessed from traditional objective verification scores (e.g., threat scores, mean, biases, among others) did not necessarily improve – and sometimes even worsen - as the grid spacing decreases [e.g., *Colle et al.*, 2003; *Mass et al.*, 2002]. Part of this surprising result can be attributed to means of verification used to evaluate the skills of these models, which are very sensitive to timing and position errors and are generally computed from sparsely located local measurements (rain gauges, soundings). Because high resolution NWP systems produce more localized structures than coarser resolution ones, phase and time shift errors tend to be more strongly amplified - and thus further penalized - in such models. Poor observational network density also negatively impacts on their skill since it does not allow to capture – and thus to benefit from - the produced additional spatial variability [e.g., *Colle et al.*, 2000]. These studies, which have raised some questions about the current means of verification, suggest that non traditional tools and data may be needed to demonstrate the benefits of higher horizontal resolution [*Mass et al.*, 2002]. Such means may consist in using observations from satellites and operational weather radars, which are both useful tools to overcome the limitations of current verification datasets [*Vasic et al.*, 2007; *Bousquet et al.*, 2006].

[3] The use of ground-based weather radars for NWP model verification is a promising field that has received considerable interest in the last few years, notably with respect to quantitative precipitation forecast (QPF) verification. The major benefit of radars lies in their unique ability to provide extensive mapping of observed rain events at high spatial resolution, which makes them natural complement to more traditional verification data (e.g., rain gauge and reanalysis) despite uncertainties ensuing from Z-R relationships used to get quantitative precipitation estimates. Although less used than reflectivity measurements, velocity data collected by Doppler weather radars can also be quite useful to evaluate model wind forecasts, especially those performed with high resolution NWP systems. Indeed, while conventional wind verification datasets such as operational analyses or surface data are often suitable to assess synoptically driven winds predicted by global or, to a certain extent, regional scale operational NWP systems, they can hardly be used to evaluate the realism of mesoscale features produced by high resolution models. This point is essential as the skill of the latter strongly depends on their ability to properly generate and position mesoscale wind structures, such as convergence or vortices, that will trigger or enhance the formation of precipitation. In this context, radar operators that mimic the behavior of real Doppler radar systems have been proposed to assimilate and perform direct model validation from radial wind data [e.g., *Lindskog et al.*, 2004]. A basic difficulty with such operators, however, is related to the measurement principle of the Doppler radars. As radars only provide one component of the wind (i.e., the projection of the wind vector along the radar beam axis), the radial velocity at a given point depends as much from the structure of the observed system as to the position of the radar. Small timing and positioning errors in the model can thus have a strong impact on the model-derived radial velocity field and ruin both objective and subjective comparisons against real radar measurements even so the forecast is otherwise perfect. A possibly efficient way to overcome this problem is to use complete 3D wind fields instead of radial velocity data. Although such data are generally restricted to field experiments, recent advances in radar signal processing now allow to routinely retrieve

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these so called “multiple-Doppler wind fields” from operational weather radar systems [*Bousquet et al.*, 2007; 2008]. The aim of this paper is to evaluate the potential of these wind fields for wind forecast verification through comparing AROME outputs against newly available operational radar analyses performed in northern France. Section 2 describes radar and model datasets used in this study. Model and radar wind outputs are compared in Section 3 for two different precipitation regimes. A concluding discussion is provided in Section 4.

## 2. Data Sets

### 2.1. Model Forecasts

[4] Forecasts presented herein have been performed using the non-hydrostatic cloud resolving model AROME (information on the AROME modelling project are available at http://www.cnrm.meteo.fr/arome). This NWP system covers the French territory with a 2.5 km horizontal resolution and will run operationally at Météo-France in mid 2008. Its main goals are to improve the local meteorological forecasts of potentially dangerous convective events (e.g., storms, unexpected floods, wind burst) and of lower tropospheric phenomena (e.g., wind, temperature, turbulence, visibility). AROME uses the physical parameterisations of the non-hydrostatic MesoNH model [*Lafore et al.*, 1998] that considers, in particular, a complete representation of the water cycle with five hydrometeors governed by a bulk microphysical parameterisation. Nowadays, AROME makes use of the dynamical core and of the complete 3Dvar data assimilation system of Météo-France’s operational limited area model ALADIN that uses a 10 km horizontal resolution [*Fischer et al.*, 2005]. AROME is also coupled with the ALADIN model, which provides lateral boundary conditions every 3 h.

[5] The simulated precipitating cases presented in this paper were obtained using AROME both in its spin-up (e.g. starting from an extrapolated ALADIN analysis) and its data assimilation configurations. The latter uses a 3 h RUC (Rapid Update Cycle) based on several cycled assimilation steps prior to the verifying forecast, allowing to analyse an atmospheric state from the previous 3h forecast and from observations. The 3 h time period between two assimilation steps has been chosen to ensure the stability of the background fields, the spin-up of the model being around 1 hour of integration for the scale of interest. The observation types that are considered in this study are detailed in section 3.2.

### 2.2. Radar-Derived Wind Observations

[6] Wind verification data are taken from operational multiple-Doppler analyses performed within a domain of 320 × 320 × 12 $km^3$ centered near Paris, France. The principle of these analyses is to combine reflectivity and radial velocity data collected by 5 (before April 2007) or 6 (from April 2007) operational Doppler weather radars to reconstruct, in real-time, the 3-D airflow within observed precipitating systems between 1 and 10 km altitude (all heights are given above mean sea level). The temporal and horizontal grid resolution of the retrieved 3D wind fields are set to 15’ and 2.5 km, respectively. More details about data processing and analysis techniques relied upon to perform these wind syntheses are given by *Bousquet et al.* [2007].

[7] Before verifying model wind forecasts against radar observations, precise knowledge of measurement uncertainties is required. This task is however complicated as no other instruments can provide wind measurements at the space-time resolution achieved by Doppler radars. An alternative to this problem is to use simulated radar observations to estimate errors based on uncertainties in raw measurements and geometric principles inherent to the wind synthesis. Using simulated input data, *Bousquet et al.* [2008] estimated that errors on horizontal winds retrieved in the greater Paris area range from about 4 m $s^{-1}$ near 1 km altitude down to ~1 m.$s^{-1}$ between 2.5 and 10 km. The higher uncertainty at low levels is mostly a consequence of the poor radar coverage below 1 km. Errors in retrieved vertical velocities are significantly higher due to assumptions required to perform wind syntheses in a fully operational framework. Therefore, only retrieved horizontal winds can be used for model wind verification purposes. Although these estimates provide a reasonable assessment of uncertainties associated with multiple-Doppler winds, further validation are likely needed prior to routinely use this product for objective model verification purposes. With this respect, comparisons performed in the following must be seen as proof of concept and do not intend to provide definitive statements about the model performance.

## 3. Results

### 3.1. First Case Study: Frontal System

[8] We first investigate the potential of operationally synthesized multiple-Doppler wind fields for quantitative wind forecast verification. Data consist in hourly forecasts and observations of a long lasting frontal precipitation system that occurred on 14 February 2007 [*Bousquet et al.*, 2007]. For this particular case, AROME was used in a spin-up configuration (e.g. without assimilation steps). The forecast was launched at 00 UTC from an analysis extrapolated from the regional model, ALADIN. Figure 1 shows the corresponding radar (Figure 1a) and model (Figure 1b) horizontal wind outputs after 12 h of forecast at a height of 1500 m when the front, which can be unambiguously identified from a wind shift-based criterion, entered the domain of observations. Overall, the modeled and radar-derived frontal boundaries are in good agreement with those derived from surface measurements, although one can notice that the modeled front is shifted westward from ~40 km with respect to both surface and radar observations.

[9] A scale decomposition of observed and modeled wind fields is performed to examine predictability as a function of spatial scale and to determine scales actually resolved by both the model and the radars. Because forecast and observations are not collocated, model winds are first projected onto the radar grid using a bilinear interpolation scheme. In order to account for data void region in the radar-derived wind fields (Figure 1), observed data are extrapolated following *Leise* [1982] before performing the scale decomposition. Note that only radar wind fields that fill at least 65% of the retrieval domain are considered in this analysis to keep the extrapolated wind fields realistic. Such condition was met between 02 UTC and 13 UTC (Figure 2a). Examples of extrapolated wind field are shown in Figure S1 (auxiliary material[1]). The 2D Haar discrete

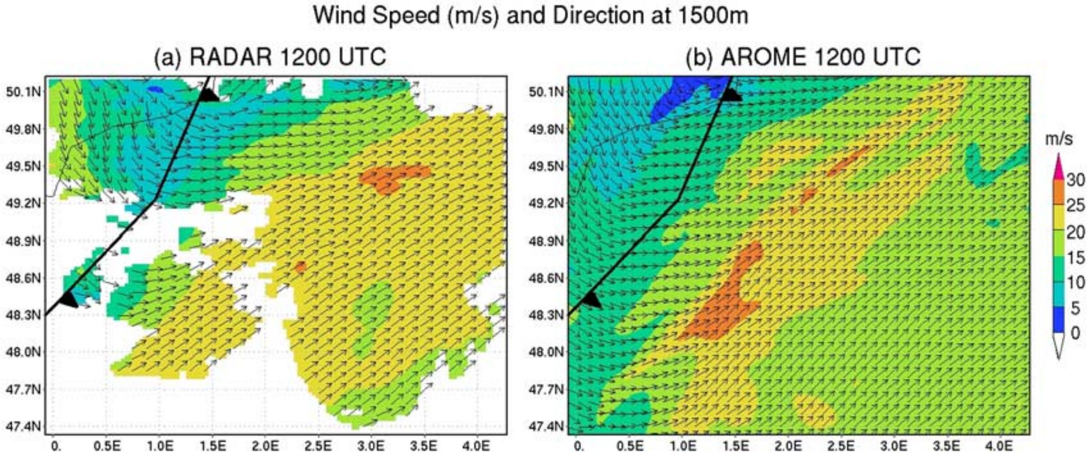

**Figure 1.** Side by side comparison of (a) radar-derived and (b) model-derived wind speed (m.s$^{-1}$) and direction at $z$ = 1.5 km and 12 UTC, 14 February 2007, within a 320 × 320 km$^2$ domain centred near Paris city. One out of every fourth vector is plotted. The cold front boundary taken from operational surface analysis is also shown. Adapted from *Bousquet et al.* [2007].

wavelet transform, which is well-suited to functions characterized by sharp discontinuities and gradients, such as meteorological fields [*Lin et al.*, 2005], was then used to perform the scale decomposition of model and radar wind outputs.

[10] Computed power spectra of observed and forecast wind speed are averaged over the 11-h verification period (Figure 2b). The radar-derived and model spectra are maximized at 160 km, which is the largest resolved wavelength according to the size of the domain (320 × 320 km$^2$). Both spectrum monotonically decrease as spatial scale decreases (as expected for synoptically driven frontal systems). If one excepts the stronger model variability at smallest scales, which may be related to the required extrapolation of radar data, the two datasets are extremely similar from a scale perspective. This means that scales resolved by the model are equivalent to those captured in the multiple-Doppler wind fields. Although this result has yet to be confirmed using more data, it suggests that such radar-model comparison should not be subject to "representativeness" errors that often affect credibility of model verification.

[11] Figure 2 also presents time series of wind speed (Figure 2c) and wind direction (Figure 2d) bias and root mean square (rms) errors computed from raw (i.e., non-extrapolated) radar-derived wind fields over a 16-hour period starting on February 14 at 00 UTC. Data retrieved after 16 UTC cover less than 20% of the experimental domain (Figure 2a) and are not considered in this analysis. Bias and rms errors are also computed at a lag of plus (blue) and minus (green) 1 hour to detect an eventual temporal shift of the model with respect to observations. Overall, the computed bias and rms errors are relatively small. For wind speed (Figure 2c), the zero lag bias (resp. rms) errors range from ±2 m.s$^{-1}$ (resp. 3–5 m.s$^{-1}$) and average around 0.2 m.s$^{-1}$ (resp. 3.6 m.s$^{-1}$) over the 16-hour period. For wind direction (Figure 2d), these errors range from −8 to +1 deg. (resp. 8–24 deg.) with an average value of −4 deg. (resp. 13 deg.). The scores are generally degraded when computed with a lag of plus or minus one hour, especially during the passage of the front within the experimental domain (10–16 UTC, Figure 2d). This suggests that the model delay seen in Figure 1 is likely the consequence of a spatial phase shift in the meridional direction (since the system propagates eastwards, any phase shift in the longitudinal direction would result in a temporal shift). Another, more synthetic, way to look at these results is to examine the distribution of errors (Figure 2e). Overall, errors in wind speed are mostly comprised between ±2.5 m.s$^{-1}$ (~80% of the time) and symmetrically distributed. As for wind direction, 90% of errors are comprised between ±15°, but the distribution is positively skewed. This result is consistent with the previous bias analysis and indicates an overall tendency of the model to produce slightly more southerly winds with respect to radar-derived observations.

[12] Overall, these results evidently illustrate the potential value of multiple-Doppler winds to identify and quantify model errors. Of particular interest is the size of the verification dataset (100's thousands of data at a single level, Figure 2d), which has no equivalent for this data type. Note, however, that a systematic use of this product for objective model verification requires the availability of homogeneous radar datasets over extensive periods of time. This should be possible by 2009 when this product will become fully operational nationwide.

### 3.2. Second Case Study: Squall Line

[13] Operational multiple-Doppler winds can also be used as verification tool allowing to qualitatively evaluate horizontal wind analyses deduced from data assimilation. An example of such utilization is provided in Figure 3 where observations and model analyses are compared for a severe squall line that brought torrential rainfall in the greater Paris area on 25 May 2007. For this case, AROME has been used in a 3h RUC mode (see section 2.1 for more details) starting at 6 UTC. At 15 UTC, four successive assimilation steps have thus been performed, ensuring a better fit of the

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL033975.

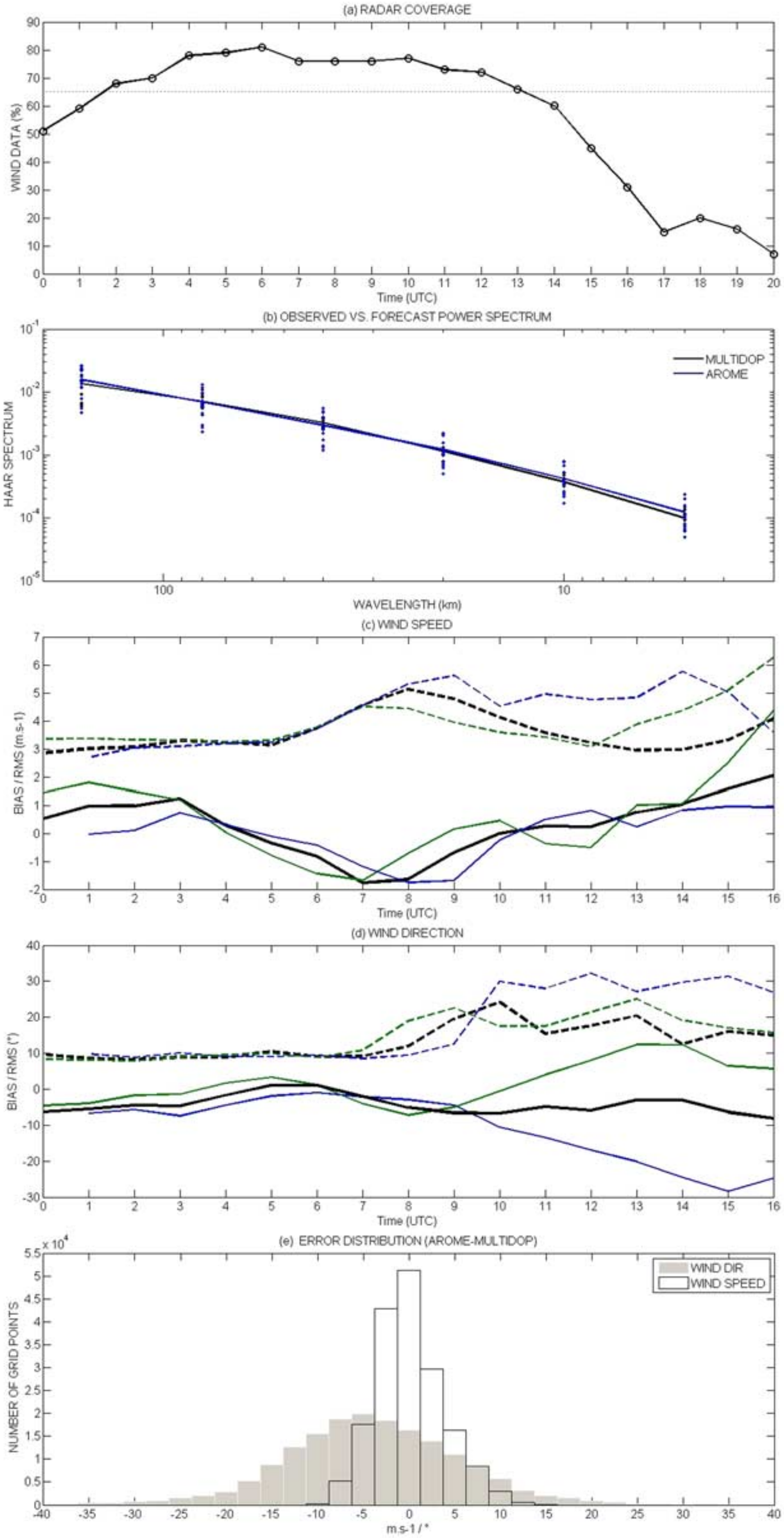

**Figure 2.** The 14 February 2007 model-radar comparison. (a) Radar coverage (%) as a function of time. (b) Power spectra of wind speed, as derived from radar (black) and model (blue) hourly outputs for 2–13 UTC (dots). The solid curves show the average spectra for the period. (c) Time series of bias (plain) and rms (dashed) errors in wind speed computed with a lag of 0 (black), −1 (green), and +1 (blue) hour for 0–16 UTC. (d) Same as in Figure 2c but for wind direction. (e) Distribution of errors in wind speed and direction for 0–16 UTC.

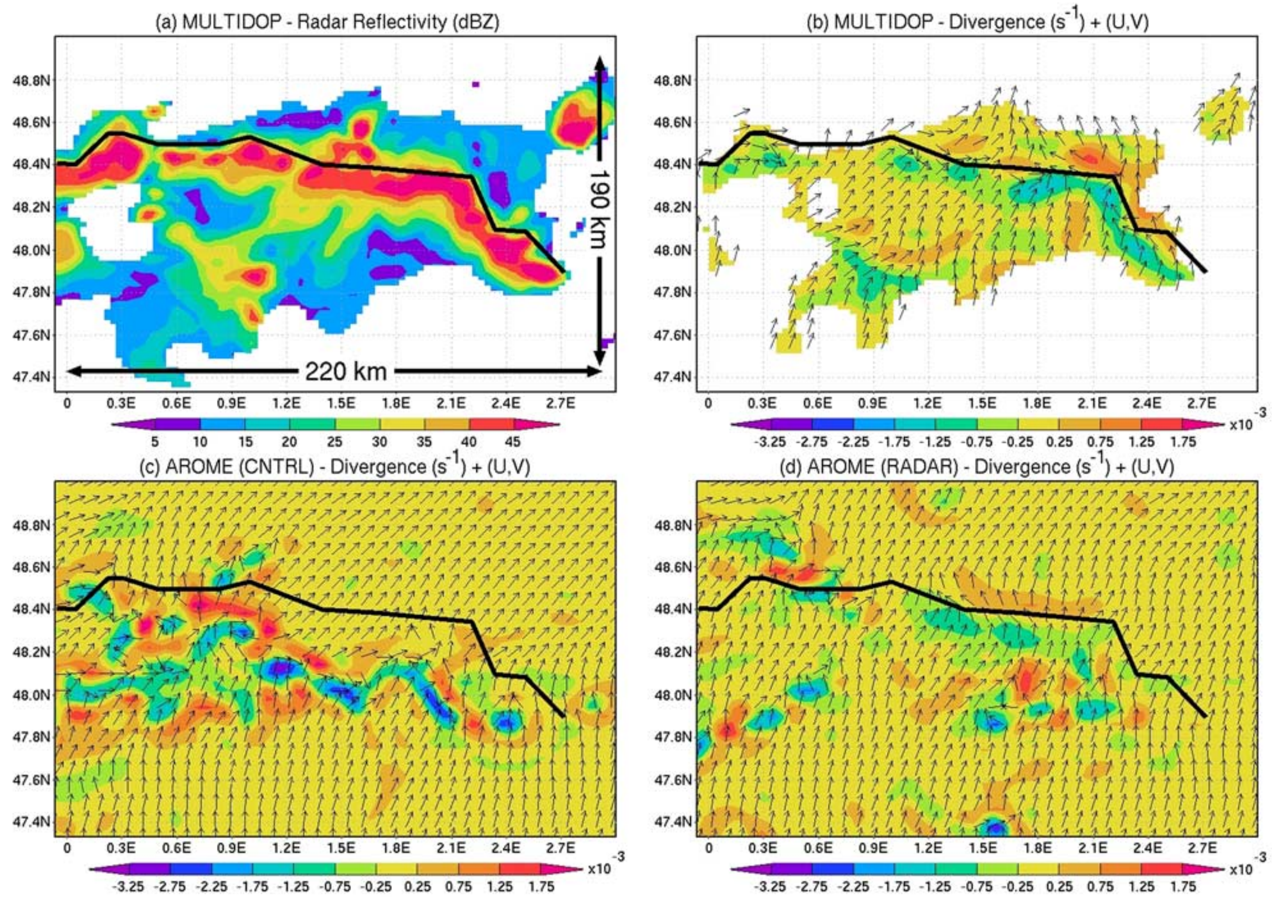

**Figure 3.** (top) Multiple-Doppler analysis and (bottom) AROME outputs at $z$ = 2.5 km and 15 UTC, 25 May 2007. (a) Radar reflectivity (dBZ). (b) Radar-derived divergence ($10^{-3}$ $s^{-1}$) and wind direction. (c) Model-derived divergence and wind direction (CNTRL experiment). (d) Model-derived divergence and wind direction (RADAR experiment). One out of every fourth vector is plotted. The black line in each plot indicates the leading edge of the squall line.

model's trajectory to observations. The CNTRL experiment considers the same observation types than the operational ALADIN 3Dvar (conventional observations, 2m temperature and humidity, infrared radiances from ATOVS and SEVIRI instruments, among others) [*Montmerle et al.*, 2007]. The RADAR experiment uses the same configuration, but with radial velocities from 7 radars located in northern France as additional data. For that purpose, a comprehensive observation operator has been implemented and different screening procedures have been applied, as explained in *Montmerle et al.* [2008].

[14] According to observations, this event was composed of a moving line of intense thunderstorms ahead of a region of stratiform precipitation (Figure 3a). At 15 UTC, maximum upward motions (with a magnitude of ~2 to 5 m.s$^{-1}$, not shown) are observed within the convective portion of the system and appear strongly correlated with the highest reflectivities. These convective updrafts are fed by a well-defined line of convergence (Figure 3b), whose location can be used to trace the leading edge of the system. Analyses of model divergence agree quite well with observations for the two experiments. As a matter of fact, the convergence line ahead of the storm is properly analyzed in both configurations albeit slightly mispositioned and quite overestimated in the CNTRL experiment (Figure 3c), where the main features come from the previous forecast used as background. Radial velocity assimilation furthers allows to properly reposition the line with respect to observations, as well as to decrease convergence down to observed values (Figure 3d). The forecast resulting from this analysis displays a more realistic precipitating system with a better timing than for CNTRL [*Montmerle et al.*, 2007]. Such comparisons, which show the superior performance of the RADAR experiment, are key to quickly assess the realism of mesoscale dynamical structures produced by the model and could hardly be performed from conventional surface data or gridded verifying analyses due to the poor spatial resolution of such datasets.

## 4. Concluding Discussion

[15] This study suggests that multiple-Doppler winds, which can now be produced routinely from operational Doppler radar systems, are particularly suitable to evaluate horizontal winds and mesoscale dynamic features produced by high resolution NWP systems, and could efficiently be used to complement traditional wind verification datasets. Several requirements must nevertheless be addressed prior

to routinely use such Doppler winds for high resolution numerical wind forecast verification. This includes the availability of homogeneous datasets over extensive periods of time, as well as more accurate estimations of uncertainties in radar-derived winds. Further methodological developments are also likely needed in order to successfully use this product in all sort of situations, including those when modeled structures differ significantly from observed ones (e.g., when mesoscale features are shifted (see Figure 3c) or warped differently in the model). Recent research developments in QPF verification based on scale decomposition [e.g., *Harris et al.*, 2001; *Bousquet et al.*, 2006], object-oriented techniques [e.g., *Davis et al.*, 2006] or fuzzy approaches [*Ebert*, 2008], provide interesting insights on how to undertake these issues.

[16] To the best of our knowledge, the French weather service is the first that has successfully implemented multiple-Doppler wind retrieval on an operational basis. The potential value of these wind datasets for model verification, but also nowcasting or research applications, definitely calls for the generalization of this achievement to other operational radar networks. In many case, this could be done easily providing the implementation of Doppler schemes allowing to collect data at long range [*Bousquet et al.*, 2007; 2008]. The fact that many weather services are planning to improve their radar network to implement dual-polarimetric capabilities might be a good opportunity to do so.

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