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Using Model Storms to Simulate Lightning, and Using Lightning to Stimulate Model Storms

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***Abstract*—Lightning data provide an unambiguous indication of deep electrified convective storms, which can be particularly useful for data assimilation in regions where radar coverage is poor or nonexistent. Lightning data have been assimilated both for initiating storms in the model and for modulating storms using forecast ensembles. Explicit simulation of electrification and lightning also aims to provide insights for more effective assimilation and interpretation of observations.**

Keywords*—*Numerical cloud modeling, data assimilation

I. Introduction

Recent efforts to assimilate total lightning data (i.e., the sum of intracloud [IC] and cloud-to-ground [CG]) have been motivated by the upcoming Geostationary Lightning Mapper (GLM) on the next-generation GOES-R satellite series. GLM will provide continuous coverage at nearly storm-resolving (8-km) scale, with average total lightning detection efficiencies exceeding 70%. Some lightning assimilation methods have been applied in mesoscale models with convection parameterization, but only recently has lightning been applied to storm-scale numerical prediction. Some ground-based systems and the GLM provide detection of total lightning over large regions, as opposed to cloud-to-ground data alone. Total lightning is much better correlated to integrated measures of storm intensity (e.g., graupel echo volume and updraft volume), and in some cases IC flashes may precede CG flashes by up to 10s of minutes.

Three decades of numerical modeling of electrification have served to establish the utility of models for testing hypotheses and providing three-dimensional self-consistent depictions of charge structure and lightning. Continued advances in computing resources have allowed models to push to ever greater grid resolution and complexity and realism of cloud microphysics. This paper will summarize some recent and ongoing research at NSSL and OU/CIMMS.

II. Storm-Scale Lightning Assimilation

Two lightning assimilation approaches at storm-scale are 1. Adjustment of water vapor via forward assimilation (nudging or insertion) or 3D-variational (3DVar) methods to promote initiation and development of convection and 2. Ensemble Kalman Filter (EnKF) assimilation to update any or all variables in the model state.

A. *Water vapor adjustment*

The addition of water vapor to model columns where lightning is observed is generally effective at creating buoyancy that forces updrafts and subsequent condensational latent heating and cloud development (Fierro et al., 2012). A recent study of warm-season convection-allowing forecasts showed a significant improvement in bias-corrected rainfall threat scores out to 6-10 hours compared to control forecasts (Fierro et al., 2015a). A case study also found that the lightning-based nudging yielded a forecast comparable to a cycled 3DVar initialization using radar data (Fierro et al., 2014). An alternative to water vapor adjustment was explored by Marchand and Fuelberg (2014), who used low-level warming (via smooth nudging) to create buoyancy forcing for storm initiation.

The forward assimilation method has recently been adapted as a water vapor operator in a 3DVar framework, where it can be assimilated along with any other desired observations. An example of a 1-hour forecast is shown in Fig. 1 for the Oklahoma region of the 24 May 2011 tornadic supercell storm outbreak. The forecast model was initialized from a RUC (Rapid Update Cycle) analysis at 2000 UTC, which was shortly after convection had begun developing. The control case (CTRL) had no data assimilation and thus was slow to initiate convection on its own. The 3DVar cases had a single assimilation at 2000 UTC. Assimilation of data from either the Oklahoma Lightning Mapping Array (OKLMA) or the Earth Networks Total Lightning Network (ENTLN) fostered robust, discrete supercell storms. Radar data (radial velocity and reflectivity) generated somewhat more mature storms through the addition of hydrometeor mass, which promoted earlier development of downdrafts and storm outflows.

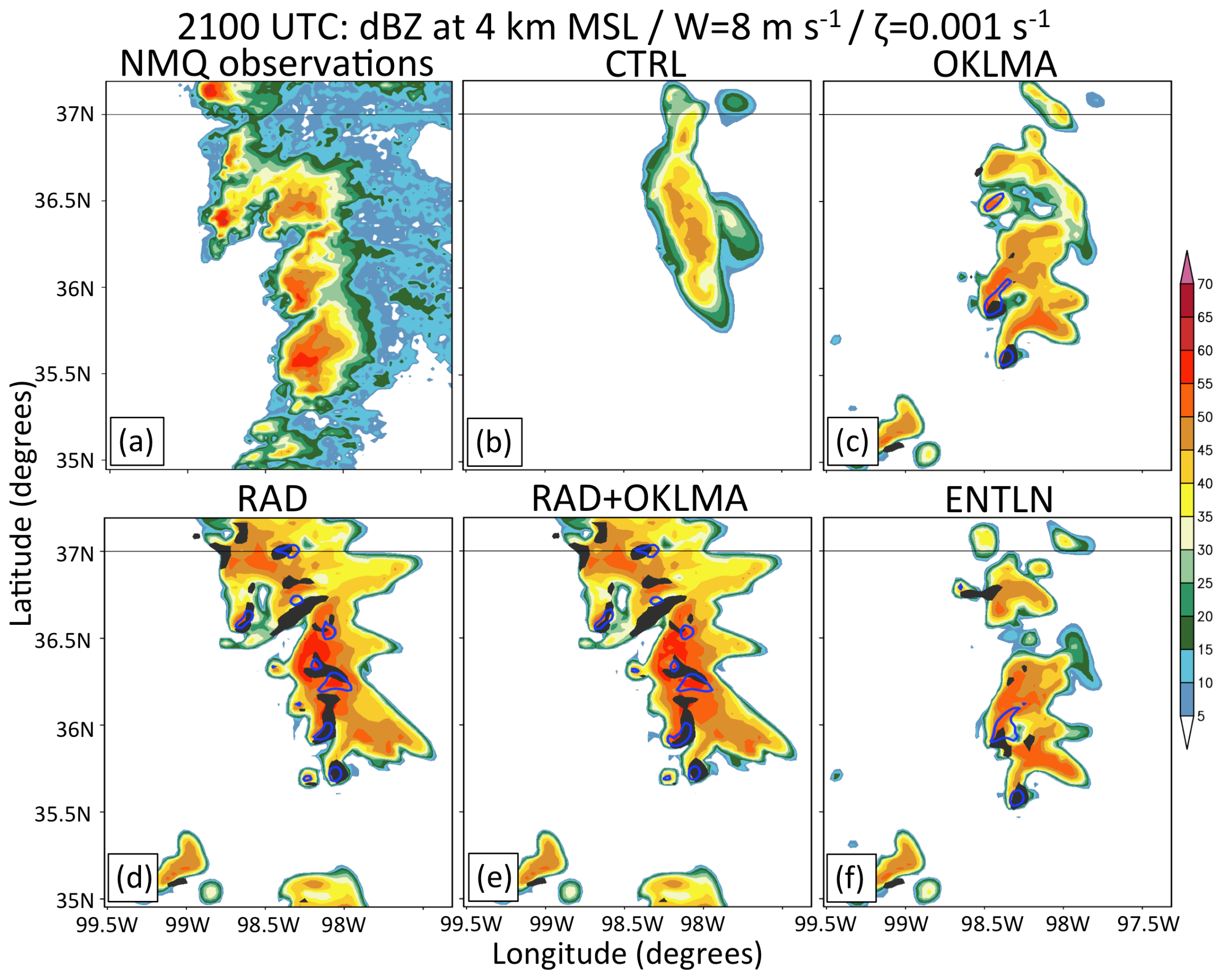

Figure 1. Horizontal cross-sections at 2100 UTC (1h forecast) of radar reflectivity (dBZ) at z=4 km MSL overlaid with the 8 m s^{-1} vertical velocities (blue contour) and relative vertical vorticities of 0.001 s^{-1} (solid black) for: (a) The NMQ observations, (b) control run (CTRL), (c) lightning data assimilation experiment using LMA-derived flash extent densities (OKLMA), (d) radar data assimilation experiment RAD, (e) the experiment with the OKLMA lightning and radar data assimilation combined (RAD+OKLMA) and (f) as in (c) but using the ENTLN-derived flash densities (ENTLN)

B. *Ensemble Kalman Filter*

Although water vapor adjustment is effective at initiating convection, it is unable to modulate convection in a cycled assimilation approach and does not address the problem of spurious convection. The EnKF approach, while requiring a much more computationally expensive forecast ensemble, addresses these disadvantages by using ensemble covariances to update the state of each ensemble member. An EnKF observation operator based on a linear relationship between flash rate and integrated graupel volume showed promising results in an observation system simulation experiment (OSSE; Mansell 2014). This method has since been applied in real data cases using LMA data to approximate coverage of the GLM.

Figure 2 shows a comparison of analyses from EnKF assimilation of either radar radial velocity or LMA-derived pseudo-GLM flash extent density observations. As expected, the radar data provide much greater detail and fidelity to the observed radar reflectivity because of the high density 3D observations being assimilated. The pseudo-GLM observations, on the other hand, are 2D with an 8 km pixel size, amounting to about two orders of magnitude fewer data points. Nevertheless, the pseudo-GLM data produced a realistic storm with a low-level mesocylone, albeit with a wider reflectivity footprint than the observed storm.

III. Storm Electrification Simulation

Mansell and Ziegler (2013) investigated effects of aerosol (cloud condensation nuclei, or CCN) on the microphysics and electrification of a small thunderstorm. The CCN concentration directly affects the cloud droplet concentration and average droplet diameter, resulting in changes to rain autoconversion, rime density on graupel, and production of ice splinters by the Hallett-Mossop multiplication process. The pronounced effect on electrification and lightning provided support for the hypothesis that differences in CCN concentration (low over open ocean, higher over land masses) contributes to the observed land-ocean contrast in lightning production.

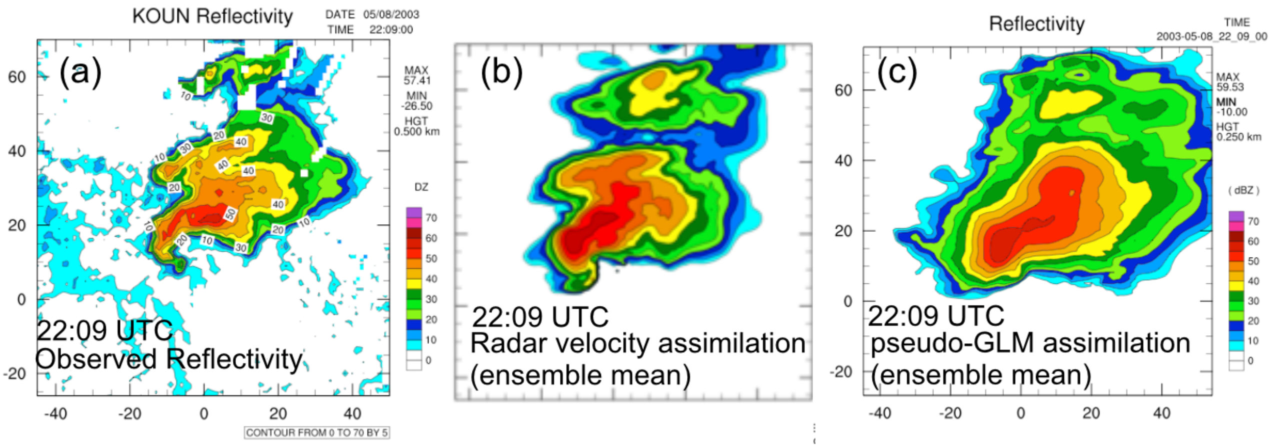

Figure 2. 8 May 2003 radar reflectivity for (a) observed, (b) EnKF assimilation of radar radial velocity, and (c) EnKF assimilation of LMA-derived pseudo-GLM data.

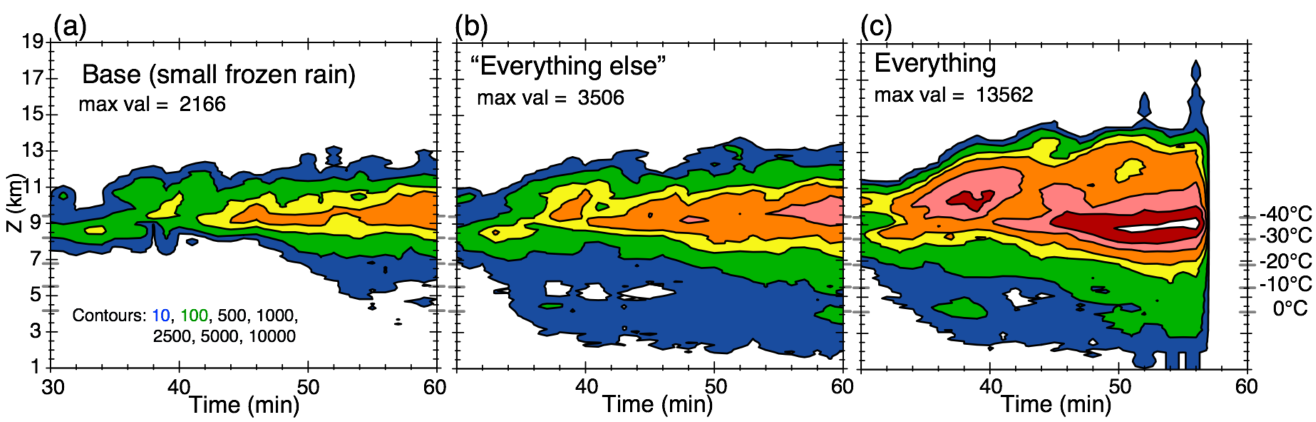

Figure 3. Time-height simulated LMA sources (negative leader channel points) for additional sources of small ice particles involved in noninductive charge separation.

EnKF radar data assimilation was employed by Calhoun et al. (2014) to study electrification in the 29 May 2004 Oklahoma tornadic supercell storm. The data assimilation helps achieve much greater similitude of the model storm to the observations. It has a drawback, however, in that the model state is constantly being updated, such that the model variables can have abrupt changes. Nevertheless, it is a useful (though computationally expensive) means to case studies, as the model results can be more directly compared to observations. A similar technique is currently being tested to examine lightning production of nitrogen oxides (LNOx) and its subsequent transport through the updraft and into the anvil cirrus.

Key portions of the electrification physics (Mansell et al. 2005) as well as the two-moment bulk microphysics (Mansell et al., 2010) have been ported into the WRF-ARW community model, which has a large suite of physics parameterizations (boundary layer, radiation, etc.). This has allowed the study of a wider variety of convection (Fierro et al. 2013) with a fully 3D real data initialization. Basic electrification and a bulk lightning scheme are included in a public release version of the WRF-ELEC: https://sourceforge.net/projects/wrfelec. The follow-on tropical cyclone study of Fierro et al. (2015b) added an updated version of the MacGorman et al. (2001) discrete lightning parameterization.

Another ongoing research project concerns high lightning flash rates detected in deep and often severe storms. Such storms frequently exhibit a strong maximum in lightning sources and initiations around 9-10 km AGL. Simulation results suggest that high charging rates result from updrafts that substantially overshoot the level of homogeneous freezing (about -37°C). The control case (Fig. 3a, Base) has small frozen rain drops (diameter less than 150 microns) as the only source of smaller ice available for charging with graupel and hail. (Larger frozen drops are transferred to graupel.) This source alone is able to reproduce the observed maximum of lightning sources. The addition of Hallett-Mossop ice multiplication and vapor ice nucleation (Fig. 3b, Everything else) adds a small amount of lightning sources at lower levels, mainly from the rime splintering, and otherwise enhances the upper levels. All experiments had high vertical resolution (125 m grid spacing) to resolve the temperature gradient in the updraft, allowing cloud droplets to freeze by size. These frozen droplets, when allowed to charge with graupel as long as liquid droplets were still present, resulted in the largest enhancement of lightning (Fig. 3c, Everything). In this last case, the lightning more clearly follows updraft surges, as well. Charge separation was shut off at lower temperatures where glaciation is complete. Thus the height of maximum lightning initiation in deep severe storms may provide information on the homogeneous freezing level within the updraft.

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