ATMOPHERIC ELECTRICAL ACTIVITY AND THE PROSPECTS FOR IMPROVING SHORT-TERM WEATHER FORECASTING

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ABSTRACT: How might lightning measurements be used to improve short-term (0-24 hr) weather forecasting? We examine this question under two different prediction strategies. These include integration of lightning data into short-term forecasts (nowcasts) of convective (including severe) weather hazards and the assimilation of lightning data into cloud-resolving numerical weather prediction models. In each strategy we define specific metrics of forecast improvement and a progress assessment. We also address the conventional observing system deficiencies and potential gap-filling information that can be addressed through the use of the lightning measurement.

PRESENT STATE OF KNOWLEDGE

In simplest terms, lightning is an electrical manifestation of thermodynamic and mechanical work performed by storm updrafts. Updrafts determine the supply, growth and transport of water condensate to the upper regions of storms, and directly control the dynamics of charge separation that lead to lightning. While there is considerable complexity in the microphysical charge separation process itself, the larger-scale physics involved are reasonably well understood and straightforward. This was exemplified by early theoretical work by Vonnegut [1963], who expressed the electrical power available for lightning generation in scaling-law form, dependent upon storm updraft velocity, charge density, area and electric dipole separation (height). This simple scaling approach, reexamined by Williams [1985] and Boccippio [2002], confirms that basic scaling limitations can be found even in instantaneous measurements of storm properties.

Empirical data from ground-based field campaigns corroborate the links between lightning flash rates and storm updrafts. Figure 1 shows the tight relationship between total lightning rates, the precipitation and ice phase development, and updraft velocity during the evolution of an airmass thunderstorm in Alabama. The physics of charge separation and lightning channel breakdown are sufficiently well understood that 3-D cloud models, being developed at a growing number of laboratories [e.g., Mansell, 2000], have matured to include explicit microphysical charging and breakdown. Explicit microphysics in these models yields large scale relationships consistent with both observations and theoretical prediction, e.g., the connection between total flash rate and total ice mass (itself a direct product of storm updrafts). Similar relationships between lightning and precipitation ice are found when spaceborne Lightning Imaging Sensor (LIS) data are compared with 85 GHz microwave and 13 GHz Precipitation Radar measurements [Petersen and Rutledge, 2001; Goodman and Cecil, 2002].

The close coupling between lightning activity and storm updrafts and ice content implies that increases in lightning activity should be observed prior to severe weather, as many events such as damaging winds, tornadoes and hail are direct by-products of extreme updrafts and ice production aloft. This has been confirmed in case studies for decades, as reviewed by MacGorman et al. [1989]. Lightning jumps associated with severe weather events (Fig. 2) such as mesocyclones, tornadoes, damaging winds, hail and waterspouts were more recently observed in Florida by Williams et al. [1999] and in Alabama by McCaul et al., [2002]. In addition to increases in total lightning rate, MacGorman et al. [1991] have hypothesized that stronger updrafts will loft the main storm electric dipole to higher levels in a storm, thus favoring IC over CG discharges. This hypothesis is supported by evidence from electric field balloon soundings. Consistent with this hypothesis, the dominant component of the severe weather lightning "jump" described above is often found to be from IC lightning [Goodman et al., 1988; MacGorman et al., 1991]. In the most severe storms, the ratio of IC to CG lightning can be much greater than its mean values of ~3:1. While prediction, modeling and observation find close correspondence of lightning flash rates with convective properties, a significant degree of scatter, and dependence upon local convective regimes, is common [Petersen and Rutledge, 1998; 2001]. It is thus important to establish the forecast model physics deficiencies, resolution limitations, or initialization data inadequacies that can be addressed by the additional information content provided by lightning.

Alexander et al. [1999] (Fig 3) demonstrated improved forecasts of surface pressure and precipitation through continuous assimilation of lightning data (from the National Lightning Detection Network) into models of the

March 1993 southern U.S. Superstorm. The high temporal resolution of the lightning data (which were correlated with instantaneous estimates of rainrate to adjust model latent heating) was critically important for the model to correctly forecast the large scale development of the extratropical cyclone, including key parameters such as precipitation and minimum pressure. Notably, comparable improvements over control runs were not achieved upon less frequent assimilation of satellite infrared or passive microwave estimated rainfall rates. Another success was achieved by Chang et al. [2001] through the assimilation of continuous low frequency VLF measurements of lightning, again calibrated by intermittent satellite estimates of rainrate (through a probability matching technique). Rogers et al. [2000] produced an improved 24-h forecast of the rainfall pattern for a summertime mesoscale heavy rain event. Only the presence of deep convection (as might be indicated by lightning) at a model grid point triggered the convective parameterization scheme, on or off. Such an approach has the advantage that the convective precipitation rate and heating profiles generated by the parameterization are compatible with the local (model) environment. The effectiveness of the technique is enhanced in weakly forced environments, common in the summertime, where convective initiation and organization are governed by previous convective activity and the resulting temperature and moisture discontinuities (i.e., boundaries). Such methods, however, must continuously assimilate the convective parameter (lightning is this case); otherwise the model eliminates the imposed disturbance through convective adjustment. These lightning data assimilation strategies all rely on the relationship (correlation) between convective rainfall and lightning flash rate [Cheze and Sauvageot, 1997], and constant lightning detection efficiency within the forecast domain. Errors will be amplified if the relationship is non-constant (i.e., rainfall-lightning relationship varies with storm type or life-cycle, or the ratio of cloud flashes to ground flashes varies).

FUTURE PROSPECTS

1. Nowcasting and the Severe Weather Hazard

The first step in the roadmap for algorithm and display product development is identification of candidate precursor signatures, or inputs. Potentially useful signatures exist in some known environments (e.g., increasing flash rates and dominance of in-cloud lightning implies a hazardous storm). The repeatability (or variability) of such signatures in different environments must be assessed as part of a larger scale evaluation, to refine the data products and displays provided to forecasters. Information on false positive and false negative rates will be gained from limited regional ground studies such as those underway in Florida [Williams et al., 1999] and Alabama [Goodman et al., 2003, this Preprint]. Total lightning data from short-range VHF lightning mapping networks, full-resolution NEXRAD radar, other data and model output should be used to characterize potentially severe storms and their environment.

Assessment of the utility of total lightning data for short-term severe weather forecasting can be performed using a forecaster decision-support system. Lightning flash rate, flash density, flash polarity, and trending of candidate precursor signatures (e.g., lightning jumps concomitant with outflow boundaries interacting with storms) can be provided to forecasters through their primary data integration tool, the Advanced Weather Information Processing System (AWIPS), which is located in every NWS Weather Forecast Office (WFO) in the U.S. The decision making process involves assessment of the near storm environment, candidate signatures, and the forecasters' own knowledge. Useful ways to display data (e.g., flash rate time tendency) and interpret data (e.g., growth/decay/intensification of updrafts) should be provided to forecasters and skill with and without lightning data utilization should be objectively assessed once a sufficiently large sample size is achieved. Forecaster feedback can then be used to guide selection of appropriate inputs for statistical (e.g., neural network, hierarchical clustering) analysis of the event database. A Warning Event Simulator (WES) already in each WFO allows a forecaster to replay storm events and assess his/her decision-making skill.

The Aviation Weather Center (AWC) and other members of the aviation weather research product development teams in the U.S. are tasked with developing 0–6 hr CONUS and oceanic convective weather hazard forecast products to improve the safety and efficiency of the international aviation system. AWC has Significant Meteorology (SIGMET) advisory responsibility under international treaties for convective weather hazardous to aircraft over the oceans and land areas extending to the middle of the oceans. For remote offshore regions, proposed lightning from Geostationary Earth Orbit (GEO) combined with other satellite and surface lightning measurements could be the primary means by which aviation hazards related to deep convection (severe turbulence, severe icing and hail) would be identified and spatially resolved in a timely manner. Lightning data combined with other satellite microwave and GEO imaging (GOES infrared) and sounding data would also produce more detailed convective cloud classifications and diagnostics. Statistical/dynamical expert systems (e.g., NCAR's Autonowcaster, one of nine nowcasting systems evaluated at the Sydney 2000 Olympic Games, Keenan et al., 2000) are now used in the U.S., Canada, the U.K., and Australia for 0–2 hr thunderstorm forecasts.

2. Numerical Weather Prediction

Assessment of the benefits of lightning data for numerical forecast improvement follows a well-structured process. First, physical or statistical relationships between observed lightning flash rates and observed convective properties must be established. Ample theoretical, empirical and model evidence is available that such relationships exist, but operationally useful knowledge of variance, or of dependence on local environmental conditions and convective regime, is less well known. Second, techniques to incorporate lightning-derived convective properties into numerical models (i.e., data assimilation techniques) must be developed. A variety of approaches have already been described. Third, lightning data must be assimilated into a variety of models using several candidate techniques, and compared against control runs to both subjectively and quantitatively assess performance. This process should emphasize models in use or slated for use by operational forecasters and researchers alike, such as the Weather, Research and Forecast model [WRF, http://www.wrf-model.org/].

Establishment of a collaboration infrastructure or test bed, shared data formats and a shared quantitative assessment strategy is also critical for the evaluation. Scientists at New Mexico Tech, the National Space Science and Technology Center in Huntsville, Alabama and the National Severe Storms Laboratory in Norman, Oklahoma intend to archive total lightning data from their respective Lightning Mapping Array systems in a common format data structure. The results of ongoing VHF mapping network studies will provide continued high-detail case study information such as that shown in Fig. 4. A more comprehensive approach is utilization of a 3-D numerical cloud model with explicit microphysics and electrification. This model allows 'laboratory' testing of lightning/convective parameter relationships (or, more generally, lightning/storm property relationships such as latent heating or convergence), examination of justifying physical theories for the relationship between large scale storm electrical energetics, kinematics and microphysics, and examination of a variety of storm environments and morphologies. The results of this modeling will provide direct guidance and physical justification for later data assimilation strategies. Finally, combined multi-satellite infrared and microwave rainfall (and hence latent heating) estimates can be augmented with lightning data (Morales and Anagnostou, 2003). Lightning observations have the potential to identify convective core locations within IR cloud shields to improve the delineation of convective / stratiform rainfall. Identification, design, and evaluation of candidate techniques are on-going at the NASA Short-term Prediction Research and Transition (SPoRT) Center, a data assimilation test bed established by NASA which is collocated with the NSSTC and the NWS WFO in Huntsville. Approaches include use of lightning data as a static constraint at forecast initialization time, and continuous use of lighting data to dynamically prescribe cloud quantities throughout the assimilation period. Physical approaches include use of lightning as a deterministic trigger for the cloud parameterization scheme, and use of lightning to quantitatively nudge model fields, including dynamical (updraft/downdraft profile and intensity), thermodynamical (latent heating), microphysical (precipitation efficiency) and/or environmental (boundary layer heat and moisture) properties.

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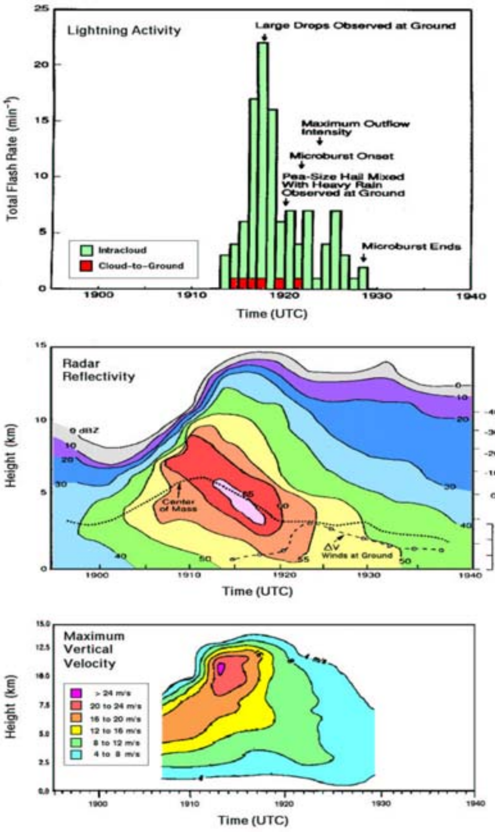

Figure 1. Total lightning (110 IC, 6 CG; top panel), follows the precipitation (middle panel), and updraft (bottom panel) as storm grows and decays [After Goodman et al., 1988; Kingsmill and Wakimoto, 1991].

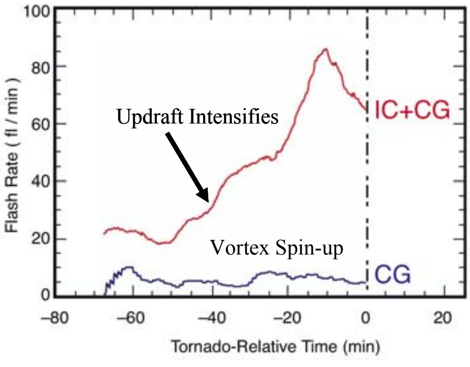

Figure 2. Intracloud lightning dominates as the updraft intensifies, which in turn stretches vorticity and increases angular momentum. Tornado at t=0.

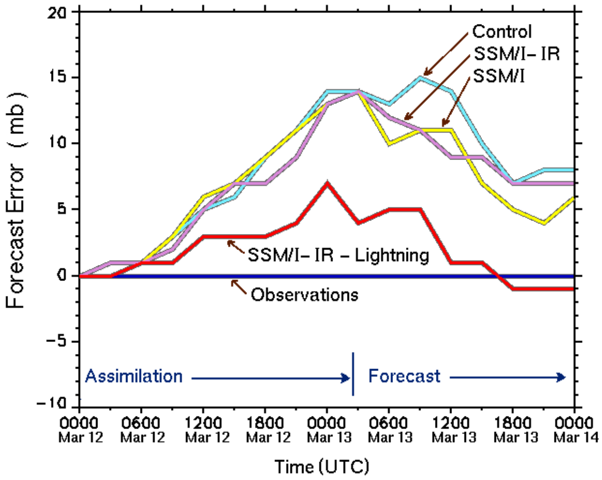

Figure 3. Lightning data assimilation reduces model Sea Level Pressure forecast error [After Alexander et al., 1999].

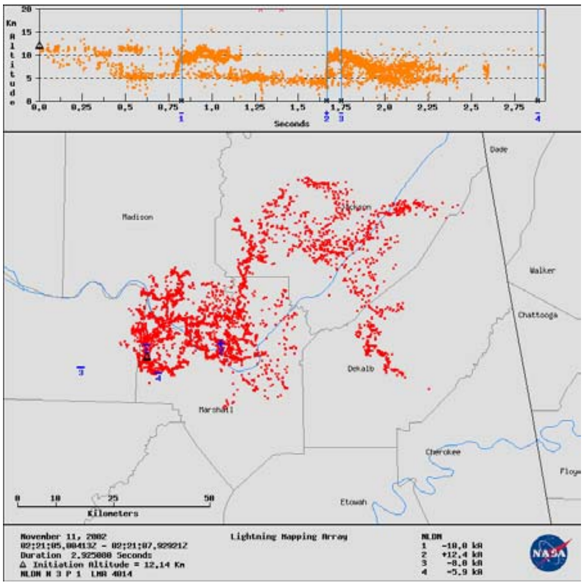

Figure 4. North Alabama Lightning Mapping Array depiction of a hybrid discharge with 4 NLDN (3 CG-, 1 CG+) ground strikes on 11 November 2002. Time history of VHF sources vs altitude (top panel) and 50+ km horizontal extent of discharge (bottom panel).