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A multisensor approach to partitioning convective from stratiform echoes

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Abstract. An algorithm is developed to partition convective from stratiform echoes using vertical reflectivity structures in radar data and environmental analyses from numerical model data. First, the algorithm searches for the bright band and ensures that these regions are not mistakenly identified as convection. Secondly, temperature/height analyses from the RUC model are used to find significant reflectivity in the mixed layer, i.e. $-10°$ C. In addition, convection is identified if reflectivity found at any temperature exceeds a high threshold value. Results from this algorithm are evaluated over the state of Arizona, U.S. using lightning flash densities as an independent source of verification. The probability of detecting convection from the algorithm is as high as 95% near radars and decreases with increasing scanning height or, equivalently range. The hourly averaged time series of convective grid cells and those with lightning observations align very well with maxima occurring at 23:00 UTC.

1 Introduction

The ability to accurately separate convective echoes from stratiform precipitation impacts several aspects of hydrometeorology. Convection is generally associated with relatively large vertical air velocities and high precipitation rates. As a result, diabatic heating profiles associated with convection are known to be quite different than those with stratiform precipitation. The initialized distribution of this heating in numerical weather prediction models impacts quantitative precipitation forecasts. In addition, stratiform precipitation may require significant profile corrections when using radar reflectivity measurements at medium and far range to estimate surface precipitation.

Several methods have been shown to adequately separate stratiform from convective echoes. The interested reader is referred to Lang et al. (2003) for a brief review of several techniques and their evaluation using two-dimensional numerical simulations. A new algorithm has been developed that utilizes temperature/height analyses from the Rapid Update Cycle (RUC) model, an automated bright band detection algorithm, and radar reflectivity profiles to separate convective from stratiform echoes. It was run in real-time for a two-month period in Arizona during an active monsoon period. The evaluation of this algorithm is unique in that it is based on the frequency of cloud-to-ground (CG) lightning activity in the study region. A discussion on the applicability of this evaluation methodology follows in the next section.

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2 Evaluation using Cloud-to-Ground Lightning Activity

Assessment of vertical air motions within clouds is the physical basis for separating convective from stratiform echoes. Stratiform precipitation is characterized by air motions that are weak (on the order of a few $\mathrm{cm\,s^{-1}}$) and thus much smaller than the terminal fall speeds of snow. Convective precipitation has far greater intra-cloud air motions (on the order of several $\mathrm{m\,s^{-1}}$) that exceed terminal fall speeds of frozen hydrometeors. Ideally, this information would be used to either build a physically-based separation algorithm (as in the Vt-W method; Lang et al., 2003) or as an independent verification source.

Lang et al. (2003) evaluated six partitioning methods within two-dimensional numerical simulations of tropical and mid-latitude squall lines. They recognize that their model could not identify the method that produces the best quantitative results; and, moreover they recommend using vertical velocity information to supplement hydrometeor fields (e.g. reflectivity). Steiner et al. (1995) use a high-resolution dual-Doppler dataset obtained on an experimental basis to derive vertical velocity fields and thus verify their results. They also visually inspect three-dimensional reflectivity structures to identify overestimated convective areas and for sensitivity testing. Typically, observations of vertical air

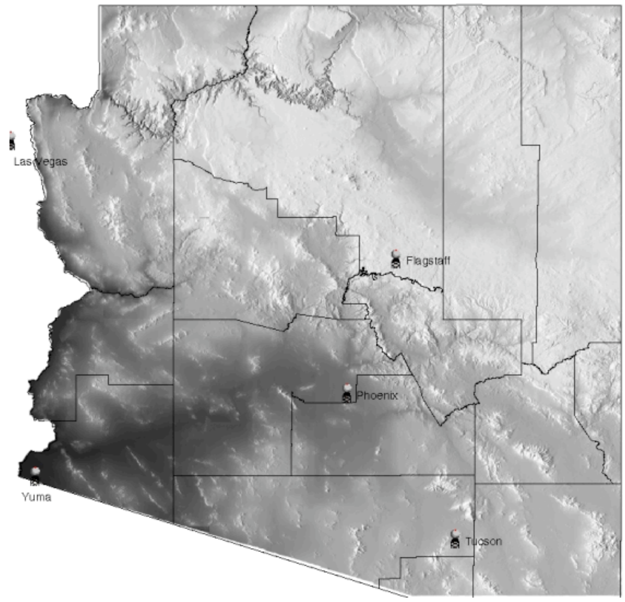


Fig. 1. Geographical map of the investigation area with shaded relief and radar locations shown.

motions are not readily available in operational settings, nor were they available for this study. Information regarding the hydrometeor fields through analysis of three-dimensional reflectivity structures could not be used as an independent verification source in this study either; as is shown in Sect. 3, the developed algorithm utilizes information derived directly from vertical reflectivity structures.

CG lightning data are considered here to evaluate the capabilities of the developed convective-stratiform partitioning algorithm. Before doing so, a discussion regarding the relationship between updraft strengths, vertical hydrometeor transport to the mixed phase regions of convective clouds, collisions between ice hydrometeors in the presence of supercooled water droplets, charge separation, and subsequently lightning is warranted. Convective clouds are defined by the strengths of their updrafts (Houze, 1993). They are capable of transporting hydrometeors upward to the mixed-phase region of storms, typically between 0° to −20°C, and supporting the development and growth of large ice hydrometeors (e.g., graupel and hail) at the expense of supercooled water droplets, provided the updraft strengths are sufficient (Toracinta et al., 1996). These large ice hydrometeors are involved in noninductive ice-to-ice interactions that are believed to be largely responsible for lightning production in thunderstorms (Jayaratne et al., 1983; Illingworth, 1985; Williams, 1989). Radar reflectivity is sensitive to particle diameters within the sampling volume. The presence of hail or graupel in the mixed-phase region will result in high reflectivities. As of result of these relationships, several reflectivity thresholds have been suggested to be necessary for rapid storm electrification leading to lightning (e.g. 40 dBZ at −10°C; Dye et al., 1989; Zipser and Lutz, 1994).

These cloud electrification studies discuss the microphysics that ultimately link lightning to convective storms. It is noted (see e.g. Holle et al., 1994) that this relationship is not necessarily unique. Many convective storms do not produce lightning or at least have very low flash rates; and, moreover some CG lightning is observed in stratiform regions of mesoscale convective systems (MCSs). Lower flash rates have been observed with convection over tropical oceanic regions and with monsoon storms as opposed to those storms over continental regimes and during monsoon breaks (Rutledge et al., 1992; Williams et al., 1992; Zipser and Lutz, 1994). The flash rate discrepancies have been attributed to differences in environmental convective available potential energy (CAPE) and thus updraft strengths. Lightning production in stratiform clouds tends to increase until early into the decay stages of large MCSs. Holle et al. (1994) reports that as much as 13% of the total flashes associated with four MCSs occurred in the stratiform precipitation region.

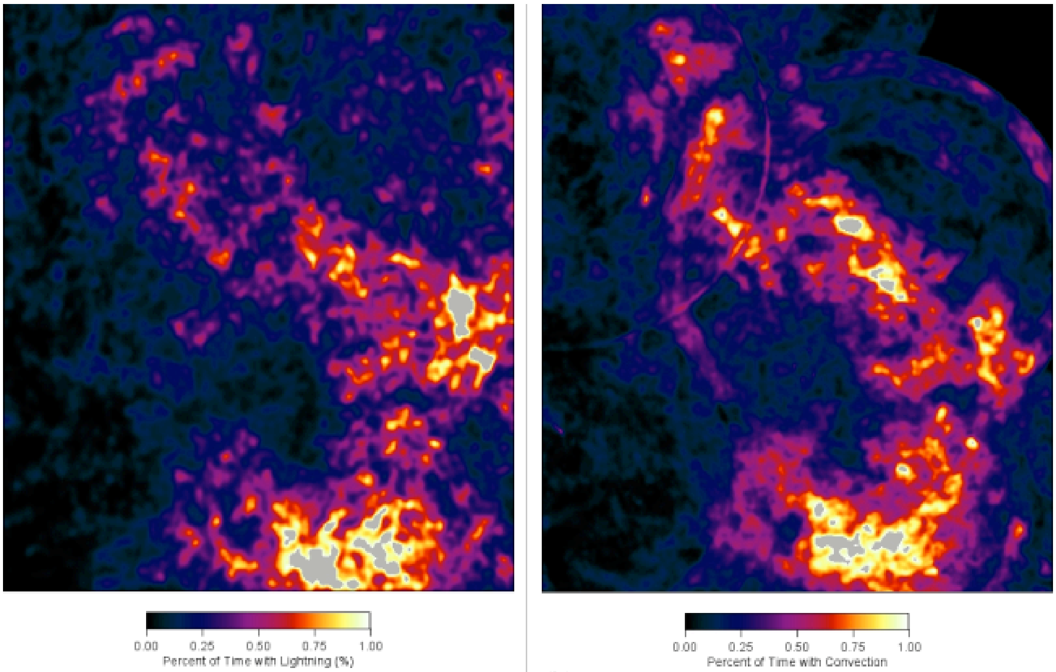
The algorithm is evaluated over the state of Arizona for a two-month period during an active monsoon in 2003. This region is rarely impacted by the MCSs of the nature documented in Maddox (1980). Thus, the fraction of lightning occurring in stratiform clouds reported above does not necessarily apply to this study region. It is reasonable for convective storms to produce no lightning (or no rainfall for that matter) in this arid environment. The evaluation methodology starts with observed CG lightning and then investigates if there is associated convection, as determined from the automated algorithm described in Sect. 3. Uncertainties in the lightning flash locations as well as lightning associated with nearby convective cells (Toracinta et al., 1996) leads us to search for convection within a 7-km radius around each CG detection and back in time up to 15 min. These search criteria are used to determine the probability of detecting lightning given an automated identification of convection. False alarms cannot be addressed in a quantitative manner using this evaluation methodology due to substantial occurrences of convection with no lightning.

3 Algorithm Description

The convective-stratiform partitioning algorithm reads in reflectivity values in their native spherical coordinates and determines the approximate heights at which the data were measured. The height of a given bin is estimated under the assumption that the beam is propagating under standard refractive conditions. Next, the algorithm ingests the height of the −10°C isotherm from the RUC model at each grid point on an hourly basis. Reflectivity values are examined from the lowest, unblocked elevation angle up to the maximum elevation angle for a given azimuth and range. The bin is determined to be convective if either of the following criteria is met:

– reflectivity ≥30 dBZ above −10°C height, or

– reflectivity ≥50 dBZ at any height.



(a) (b)

Fig. 2. Frequency of (a) lightning and (b) convection over the investigation area for July–August of 2003.

As recommended in Steiner et al. (1995), observations of a bright band can be used to rule out the presence of convection. However, melting layers common with stratiform precipitation are not always present or observed with sufficient detail at medium to far ranges from radar. Thus, the bright band identification algorithm (Gourley and Calvert, 2003) is used to ensure that no bins are deemed to be convective if they are sampled by radar in a region suspected of bright band contamination.

The convective and stratiform echo types, or "flags", are resampled from spherical coordinates to a two-dimensional Cartesian grid with 1-km grid spacing every five min. The dimensions of the analysis grid are $544\times528\,\mathrm{km}^2$. There are often multiple radars in a given domain that have overlapping coverages. Moreover, the analysis grid has grid cell areas larger than the spherical ones at ranges up to approximately 50 km from radars. A rule basis is thus used to assign flags to each grid cell where convective flags have priority over stratiform ones. If there is a single convective flag determined by any radar that falls within the area of a grid cell, then the entire grid cell will be assigned as convective. This mosaicking of flags permits the algorithm to be run on a network of radars such as with the WSR-88D network, thus allowing the maximum possible radar coverage.

4 Results

4.1 Spatial Relationship

Figures 2a and b show the frequency of lightning and convection over the state when considering the entire two-month study period. The lightning data are point observations and have thus been spatially smoothed in order to approximate the resolution of the radar-based convective flags. Note that the color scales differ by a factor of 18. This indicates there are approximately 18 grid points with identified convection per single lightning flash.

Qualitatively, there is good agreement in the spatial patterns of lightning and convective frequencies with maxima aligning roughly from northwest to southeast along the steep terrain gradient of the Mogollon Rim (see Figs. 1, 2a, and b). There is a second area of high frequencies in south central through southeast portions of the state. Comparison of the two frequency maps permits a qualitative assessment of instances in which there was identified convection and no associated lightning (i.e. false alarms) and lightning with no identified convection (i.e. misses). There are many radar-based artifacts visible in Fig. 2b that contribute to false alarms. Rings of high frequency are visible around many of the radars. It is believed that this is caused by an error in the radar processing software. There are some indications of anomalous propagation northwest of the Yuma radar in the southwest part of the state in addition to ground clutter surrounding the Phoenix radar near the center of the domain. Misses are also evident in comparing Figs. 2a and b. There is no identified convection in extreme northeast AZ. This region is notoriously devoid of radar observations as it is beyond the 230-km radius from any nearby radar. Also, there is a slight indication of lower convective frequencies perhaps as a function of range from radar as compared to lightning frequencies. This is most notable in extreme eastern AZ over the White Mountains and also along the southern border of the grid.

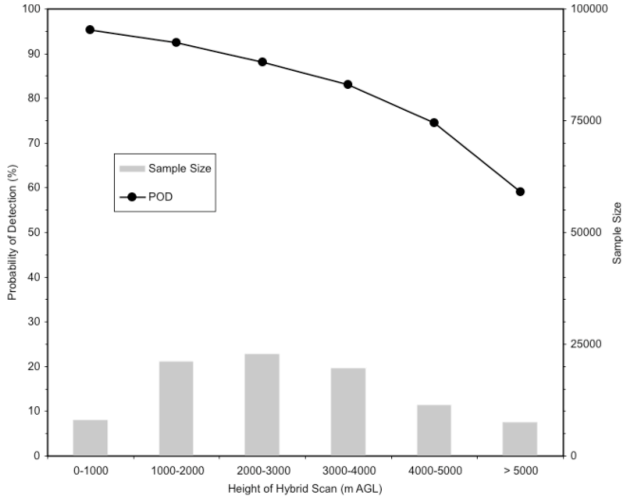


Fig. 3. The probability of detecting convection given lightning as a function of radar sampling height.

The apparent range dependency of identified convection is evaluated. The probability of detecting lightning with convective flags, provided a 15-min search window and 7-km search radius, is computed as a function of height (in AGL) of the lowest, unblocked radar beam (i.e. hybrid scan). Figure 3 shows the probability of detecting lightning very near the radar is as high as 95% and degrades to less than 60% with hybrid scan heights greater than 5000 m. This deficiency needs to be considered in areas behind significant terrain obstacles at far ranges from radar.

4.2 Temporal Relationship

The temporal relationship between lightning and convection is examined by summing up the number of lightning flashes and convective flags over the entire grid for each 5-min period during the study period. These time series plots for July and August of 2003 are shown in Figs. 4a and b. The convective flags are plotted against the primary ordinate on the left and are scaled by a factor of 18 compared to the secondary ordinate. The timing at which convective and lightning maxima occur on a near-diurnal basis agrees rather well. The degree to which the counts of lightning and convection over the entire grid agree on a 5-min basis are examined in a density-colored scattergram in Fig. 5. After the axes have been scaled appropriately, or the equivalent of removing the bias, the relationship between the two variables is linear with some scatter noted.

The same data set used in Figs. 4 and 5 has been used to compute the average number of convective flags, stratiform flags, and lightning flashes for each hour of the day (Fig. 6). The values at a given hour for each of these variables differ by about an order of magnitude; this requires us to use two ordinates with the primary ordinate being on a log scale. The time series of convective flags and lightning flashes are very well correlated with both maxima occurring at 23:00 UTC and minima at 16:00 UTC. The time series of stratiform flags lags the convective and lightning curves by approximately two hours during the daylight hours. The stratiform maximum occurs nocturnally at 05:00 UTC. These results are consistent with observations of thunderstorms reaching their maximum intensities during peak heating hours and then transitioning to stratiform rainfall that can persist for several hours through the night.

5 Summary

This study develops a multisensor, convective-stratiform partitioning algorithm that utilizes temperature and height analyses from numerical models and vertical structures of reflectivity from multiple WSR-88D radars. Verifying this algorithm presents challenges due to the lack of operational observations of vertical air motions. Moreover, the examination of hydrometeors aloft via vertical reflectivity structures is not independent of the reflectivity profiles used directly in the algorithm. CG lightning data are considered here as an independent data source for verifying our algorithm.

Physical relationships exist between CG lightning activity and convection. A convective cloud is defined by its updraft intensity. These updrafts are responsible for the growth of large ice hydrometeors that are believed to be fundamental in the production of lightning. Grid points are searched around each lightning strike and back in time to determine if there was associated convection. This allows us to evaluate the spatial and temporal relationships between lightning and algorithm-identified convection over the study region.

6 Conclusions

The following conclusions are drawn based on our study of a newly developed convective-stratiform partitioning algorithm over the state of Arizona for a two-month period:

- There are substantial temporal and spatial correlations between the frequencies of lightning activity and convection.

- The ability of the algorithm to detect convection is as high as 95% near radar but falls to 60% with higher sampling heights or far range.

- Grid cells are impacted by both convection and lightning most frequently at 23:00 UTC. Stratiform rainfall is more nocturnal with maximum frequencies occurring at 05:00 UTC.

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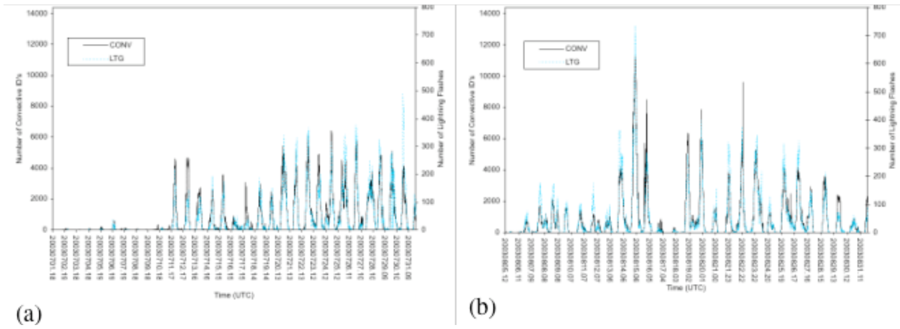

Fig. 4. Time series plots of grid-summed convection (solid; in black) and lightning (dotted; in cyan) for (a) July and (b) August, 2003.

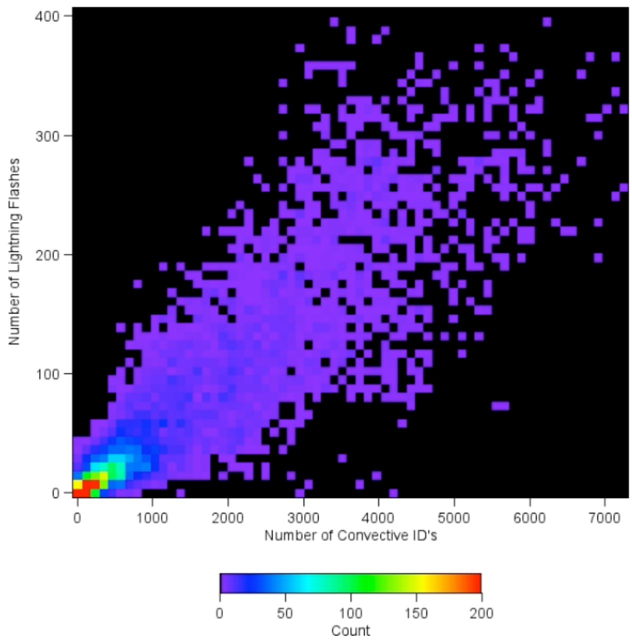

Fig. 5. Scatterplot of grid-summed convective and lightning counts for each 5-min period during the study period.

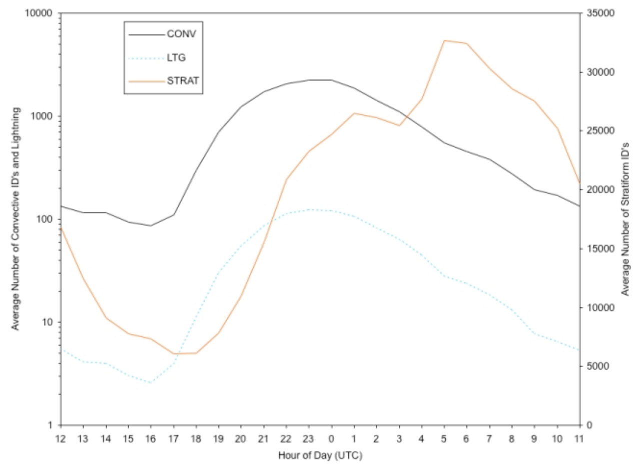

Fig. 6. Average hourly variation of convection (solid; in black), stratiform precipitation (solid; in orange), and lightning (dotted; in cyan) across Arizona for July–August, 2003.

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