

# SATELLITE DATA APPLICATIONS FOR NOWCASTING OF CONVECTIVE INITIATION<sup>†</sup>

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## 1. INTRODUCTION

Most of the air traffic delay that is so costly to the airlines and to the flying public is incurred during severe convective weather. High-quality forecasts of convection are essential to efficient operation of the National Airspace System, but the existing operational storm forecast products are limited. In order to address the short-term needs of the Federal Aviation Administration (FAA) as well as the long-term goals of the FAA's Next Generation Air Transportation System (NextGen), MIT Lincoln Laboratory, NCAR Research Applications Laboratory and NOAA ESRL Global Systems Division (GSD) are collaborating on developing a forecast system under funding from the FAA's Aviation Weather Research Program (AWRP). This forecast system, called CoSPA, will provide detailed forecasts for FAA traffic flow managers out to 8 hours.

A particularly challenging problem for convective weather forecasting is the ability to forecast when and where convection will first form. Imager data from the Geostationary Operational Environmental Satellite (GOES), with a spatial resolution of 1 to 8 km depending on spectral band, can provide invaluable information about convection in its early stages. Under the NASA Advanced Satellite Aviation weather Products (ASAP) program, the SATellite Convection Analysis and Tracking (SATCAST) system has been developed by researchers at the University

of Alabama-Huntsville (UAH) and the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (CIMSS) to identify cloud pixels that are favored for convective initiation (CI). The NASA ASAP and NASA Research Opportunities in Space and Earth Sciences (ROSES) programs have funded a collaboration among MIT Lincoln Laboratory, UAH, and CIMSS to transfer SATCAST to CoSPA and to test the SATCAST system in real-time. This work will discuss the results of an effort to use SATCAST in CoSPA to improve forecasts of convective initiation.

## 2. BACKGROUND

The CoSPA system represents a significant step toward advancing the state of storm forecasting to mitigate the impacts of weather on aviation. A brief description of CoSPA is provided here; a complete description is contained in Dupree et al. (2009). The CoSPA approach to forecasting is based on the facts that heuristics and extrapolation nowcasts typically perform well in the 0-2 hour window, whereas forecasts based on numerical weather prediction models have shown better performance than heuristics past 3-4 hours. In order to produce aviation-specific storm forecast products with the best overall performance possible, the CoSPA system uses three core components: an extrapolation/heuristic model forecast component, a numerical model forecast component, and a blending component. The 0-2 hour extrapolation forecast component is provided by the Corridor Integrated Weather System (CIWS). Details on the CIWS system can be found Wolfson and Clark (2006). Many sources of sensor and meteorological data are ingested by MIT LL for the CIWS extrapolation/heuristic model. These data sources include weather radar, surface weather observations, and lightning data from the National Lightning Detection Network (NLDN), GOES satellite data, and model forecasts

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from the NOAA Rapid Update Cycle (RUC; Benjamin et al. 2004). The CIWS forecasts are 1 km resolution and updated every 5 min. A set of CoSPA-specific modules was developed to customize the tracking and advection processes for extrapolation at the longer advection times (2-8 hours) required by the CoSPA system.

The second component in CoSPA is the experimental High Resolution Rapid Refresh (HRRR; Benjamin et al. 2009) numerical weather prediction model, which is run at NOAA's ESRL GSD laboratory. The HRRR is a 3-km resolution model nested inside a version of the 13-km RUC model that assimilates three-dimensional radar reflectivity data using a diabatic Digital Filter Initialization (DFI) technique. The HRRR model benefits from the RUC radar data assimilation through the lateral boundaries throughout the forecast as well as in improved initial conditions. Recent research is studying the assimilation of radar reflectivity directly on the 3 km nested grid. In addition, the high resolution of the HRRR obviates the need for convective parameterization, further reducing uncertainty of the forecast and allowing the model to produce realistic convective structures vital for improved forecast fidelity. The HRRR model updates once an hour and generates forecasts over CONUS out to 12 hours. Forecast output has been made available at a special 15 minute time horizon frequency for the CoSPA forecast system in order to take advantage of the blending technology.

The extrapolation/heuristic and HRRR forecasts are ingested into the blending algorithm, which has been developed by NCAR. Heuristic extrapolation forecasts of Vertically Integrated Liquid (VIL) and Echo Tops from MIT LL are blended with VIL and Echo Tops forecasts from the HRRR model. The blending algorithm has been designed to combine extrapolation and model forecasts of VIL and Echo Tops to produce seamless, rapidly-updating 0-8 hour forecasts. This is done through a calibration of model data, a phase correction to remove location errors in the model, and statistically-based weighted averaging. Time-varying weights are determined from relative performance of the phase corrected model and the extrapolation forecasts from a combination of Bias and Critical Success Index (CSI) scores. Generally, the HRRR forecast is given more weight at the longer lead times; the extrapolation forecast is given more weight at shorter leads, with equal weighting of both at about 4 hours. As HRRR improves, the crossover will be at earlier lead times.

Forecasting when and where new convection will form remains a challenge at all lead times. At longer leads, the CoSPA system obtains its convective initiation capability from the HRRR numerical model. In general, the HRRR is able to capture the structure of new convection, yet the timing and location of the initiation may be off. At 0-2 hour lead times, CoSPA currently has the capability to initiate convection near growing lines in the radar data (Iskenderian et al., 2009); however CoSPA is currently lacking Convective Initiation (CI) capability in regions separated from existing VIL at these shorter lead times. Satellite-based CI techniques are well-suited to detect these signals. Since these regions are typically free of cirrus from pre-existing convection, the satellite has a clear view of the growing cumulus clouds.

Figure 1 shows an example of CI that has occurred in a region separated from existing VIL. At the initial time (Fig 1a), convective storms are positioned over extreme western Florida and extend into the Gulf of Mexico. There is an area of clouds over northern Georgia, but no VIL exists over this region at this time. During the next hour (Fig 1b), convection forms over Georgia as evidenced by the radar VIL field. The 1 hour CoSPA forecast does not capture this convective development (Fig. 1c), shown by the lack of forecasted VIL over Georgia. Figure 1d shows the 1 hour forecast scores based on the occurrence of level 3 VIL. Pixels where level 3 VIL is correctly forecast are indicated as "hits" (green), pixels where level 3 VIL is forecast but did not occur are indicated as "false alarms" (red), and pixels where level 3 VIL occurred but is not forecast are indicated as "misses" (blue). The lack of forecasted convective initiation over Georgia produces a region of misses in the 1 hour forecast scores, which is indicated by the circled region of spotty blue pixels in Fig. 1d.

To illustrate the typical regions where CI is not being depicted in the CoSPA short-lead forecasts, we process the VIP level 3 forecast scores as follows. The pixels of hits and false alarms in the 1 hour forecast scores are dilated with a 40 km radius kernel. The dilation produces broad areas where either convection is occurring or has decayed, as these do not represent initiation zones. The misses that remain outside of these broad areas represent convective initiation that is separated from existing convection by a distance of at least 40 km (Fig. 2).

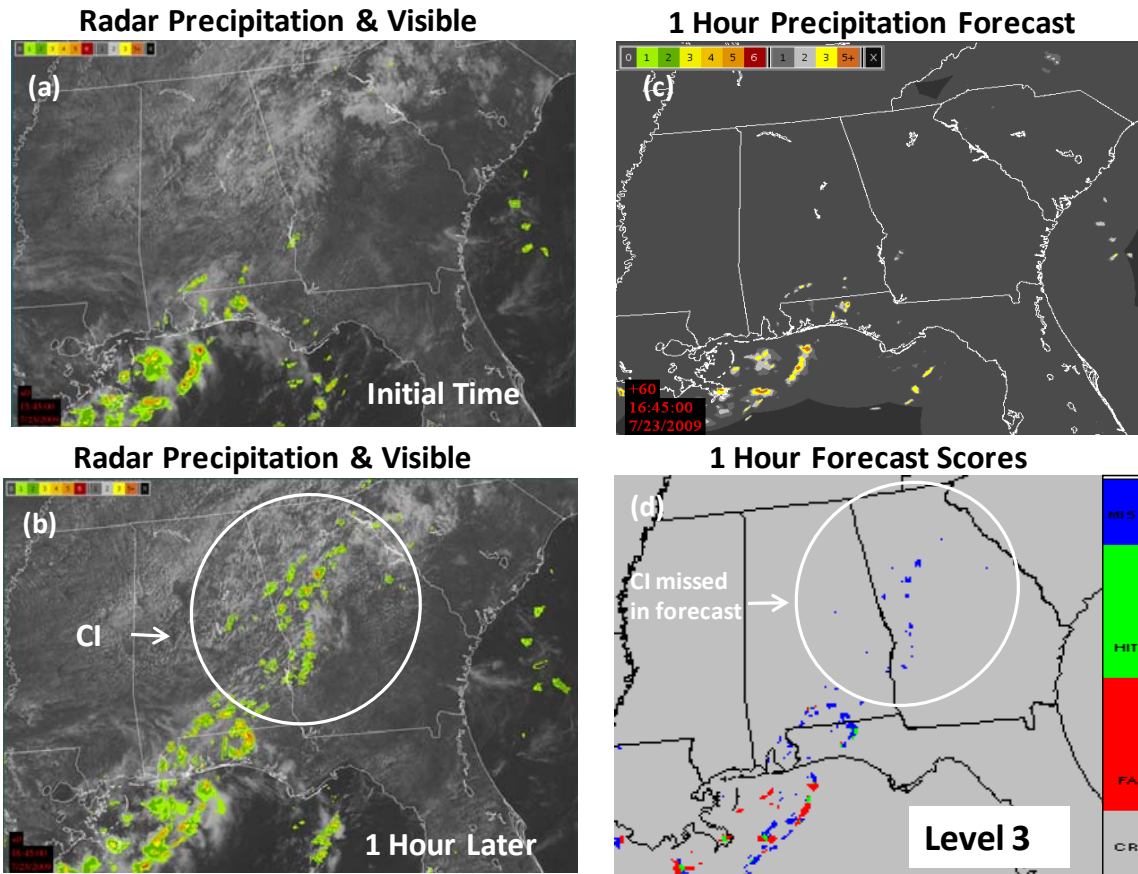


Figure 1. (a) Radar VIL and visible satellite at 1545 UTC 23 July 2009 shows existing thunderstorms in extreme western Florida and extending over the Gulf of Mexico. Over Georgia, there are cumulus clouds but no radar detections at this time. (b) One hour later, convection has initiated over Georgia. This new convection is not captured in the CoSPA 1 hour forecast (c), and produces an area of misses (d) in the 1 hour CoSPA level 3 binary forecast scores.

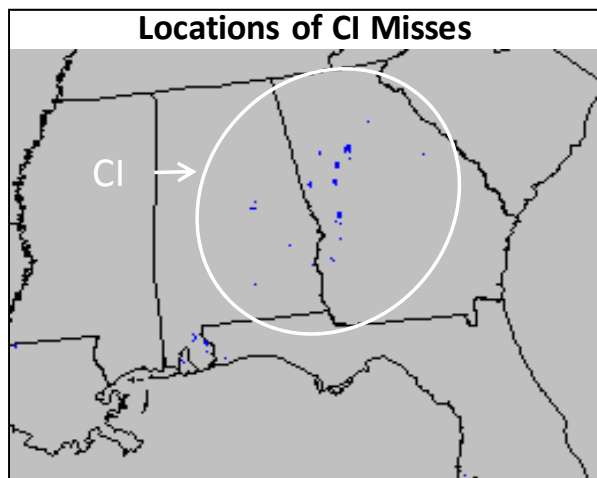


Figure 2. Forecast misses at VIP level 3 representing areas of CI that are not present in the 1 hour CoSPA forecast. See the text for a description of the procedure used to isolate these CI areas.

This methodology to isolate regions of CI is then applied to the 1 hour forecast scores for all days (12 to 00 UTC) in July and August 2009. The isolated misses (which represent CI pixels) were summed every 10 minutes in 10 x 10 km boxes over the 2-month period (Figure 3). Areas with higher counts, which represent more frequent CI, are associated with the elevated terrain of the Rocky Mountains and Cuba, and with land/sea heating contrasts along the Gulf coast. The Southeastern US experiences a relatively high frequency of CI; however the CI is not localized to a particular land feature, which is a characteristic of the airmass convection there. These results show that convective initiation results from a variety of forcing mechanisms. Satellite data can provide valuable information on the early stages of CI regardless of the exact forcing mechanism, allowing for flexible use of satellite-based CI techniques in the CoSPA system.

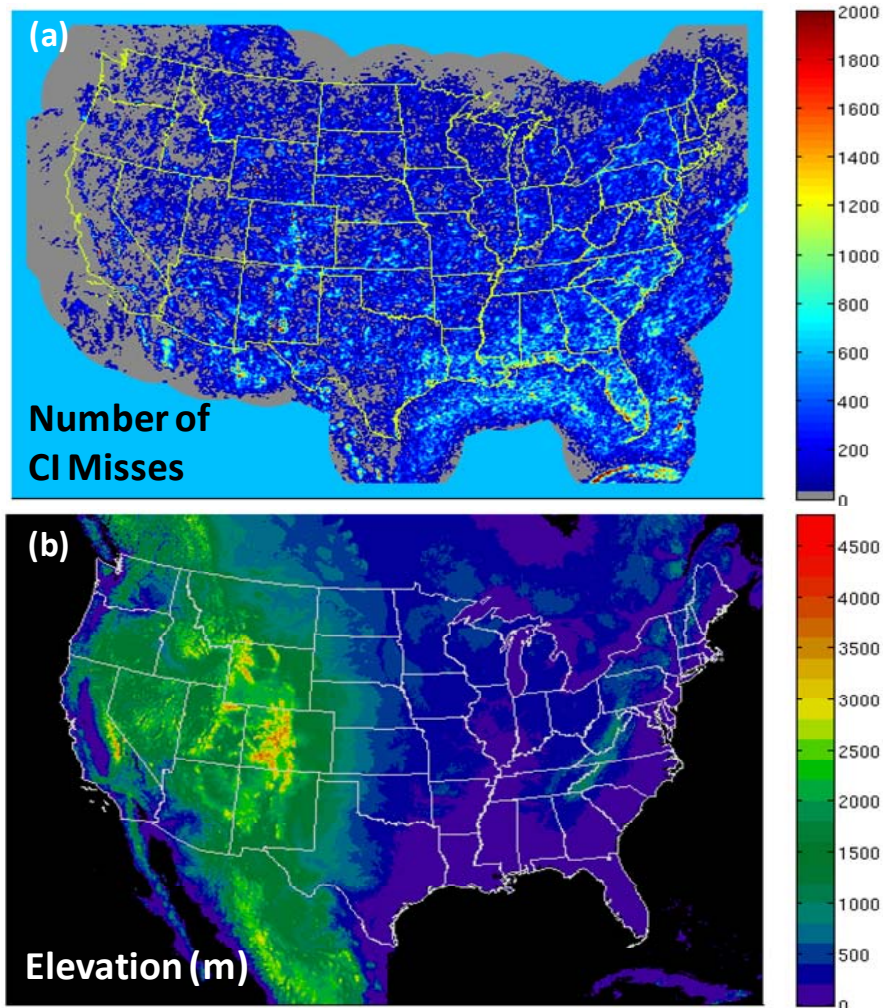


Figure 3. Sum of isolated CI pixels in 10 x 10 km boxes for daytime (12 to 00 UTC) during July and August 2009. When compared with the topography map (panel b, in meters), it is seen that areas of large CI counts exist over the elevated terrain of the western US, and along the Gulf coast. The prevalence of airmass CI is also evident over the Southeastern US.

### 3. DATA SETS

Examination of GOES satellite data by Roberts and Rutledge (2003) in cases of CI has shown that cumulus cloud top cooling in the 10.7 micron infrared (IR) brightness temperatures (BTs) can be an indicator of convective initiation. Mecikalski and Bedka (2006) have included the 10.7 micron cooling rate in addition to other IR BTs and IR band differences and their trends as indicators of CI in the SATCAST system to calculate real-time CI interest fields from GOES data. The SATCAST system contains three components to create eight satellite-based CI indicators: a cloud mask component (Berendes et al. 2008) to perform cumulus detection, a cloud

tracking component (Velden et al. 1995, 1997) to derive cloud motion vectors, and a component to combine the cloud type, cloud motion, and various IR brightness temperatures to produce the eight CI indicators. The eight indicators are combined into a single CI nowcast field with counts from zero to eight, where pixels with higher counts indicate a higher confidence in CI in the next hour. The SATCAST system software has been transferred to MIT LL and is running in real-time in the CoSPA "shadow" test system. Software optimizations have been made to allow SATCAST to execute in about four minutes to conform to the strict time constraints of the real-time nowcasting system. The SATCAST CI indicators in this study are



calculated from GEOS-12 (East) satellite data, which is received in real time at MIT LL.

Upper-air temperature, moisture and winds are obtained from the NOAA RUC model. Surface temperature and dew point temperature data are supplied by the NOAA Space-time Mesoscale Analysis System (STMAS; Xie et al. 2005). STMAS produces 5-km gridded analyses of dry bulb temperature and dew point temperature from the latest surface observations every 15 minutes. The RUC and STMAS temperature and moisture data are used in CoSPA to create two stability masks that indicate whether or not the environment is conducive to convective initiation near the surface and aloft. An example of these two stability masks is shown in Fig. 4. The first stability mask is created by blending the STMAS dry bulb temperature and dew point temperature with the RUC data in approximately the lowest 50 hPa. In this manner the RUC moisture and

temperature near the surface are updated with the most recent surface temperature and moisture observations from STMAS. The convective available potential energy (CAPE) and departure of the dry bulb temperature from the surface convective temperature are calculated from this blended data and combined to create the surface stability mask. Areas of high CAPE and small departure of the dry bulb temperature from the convective temperature are favored for convection and are highlighted by the mask. A second stability mask is created by identifying the magnitude of the most unstable CAPE in the layer from 50 hPa above the surface to 600 hPa. This elevated stability mask is created to capture elevated initiation in moist air above the surface. The surface and elevated stability masks are combined to create a single environmental stability mask.

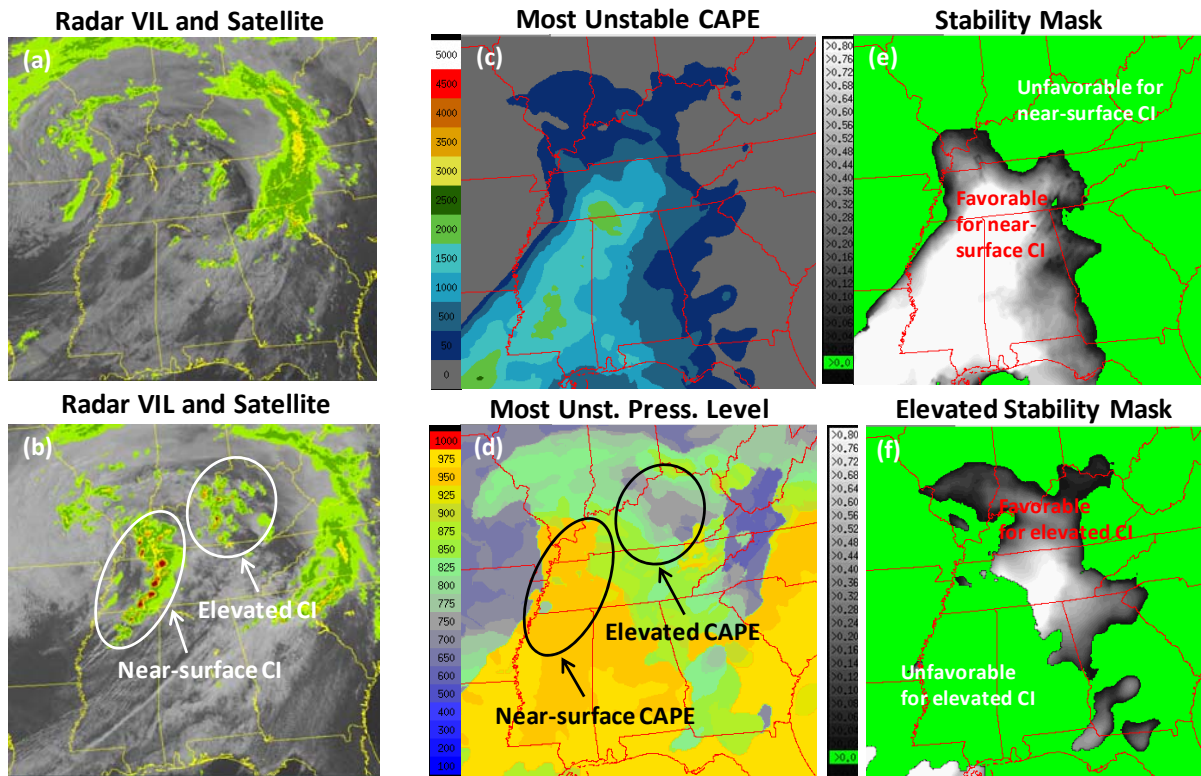


Figure 4. (a) Radar VIL and visible satellite at 14 UTC 10 April 2009 showing limited VIL over western Tennessee and central Kentucky. (b) One hour later, convective initiation has occurred over these regions. (c) The most unstable CAPE ( $J kg^{-1}$ ) in the column from the surface to 600 hPa indicates an axis of high CAPE over the region of CI. (d) The pressure level of the most unstable CAPE (hPa) is near the surface over western Tennessee, and elevated above the surface over central Kentucky. (e) The stability mask based upon CAPE near the surface captures the favorable environment for the initiation over western Tennessee, and the stability mask based upon the elevated CAPE captures the favorable initiation environment for the elevated convection over central Kentucky.

#### 4. METHODOLOGY

For the 0-2 hour VIL forecast, the CoSPA system constructs so-called “interest images” from radar and satellite data. Heuristic rules are applied to these interest images to account for convective growth and decay in a fuzzy-logic system. A common feature of these interest images is that they resemble the forecast quantity of VIL. The inclusion of satellite-based CI in the short-term CoSPA forecast equates to creating a CI interest image to depict radar VIL that is expected to form in the next hour. The CI interest image must reflect both the location and structure of new VIL.

The approach that we use to create the CI interest image has three components, which are illustrated in Fig. 5. The first component uses environmental data to identify broad areas of possible CI and specify the expected storm structure, the second component uses satellite

data to identify the precise locations of CI, and the third component uses image processing to create the CI interest. There are a number of pixel clusters with SATCAST CI counts of five or greater over western North Carolina, shown by the green pixels in Fig. 5a. Several of these clusters are in regions that are favorable for convection, as indicated by the environmental stability mask (Fig. 5b). These clusters are in an area of relatively weak winds in the lower troposphere (Fig. 5c). In this case of light winds, a circular weighting field (Fig. 5d) is centered on the CI pixel cluster to reflect the anticipated formation of airmass storms. Stronger winds would result in a more elongated weighting field whose long axis is oriented along the mean wind vector to reflect the anticipated formation of line storms. These weights are applied to the CoSPA cumulus interest image (Fig. 5e) to create a CI interest image (Fig. 5f). This interest image is then supplied to the CoSPA forecasting system to produce a CI forecast.

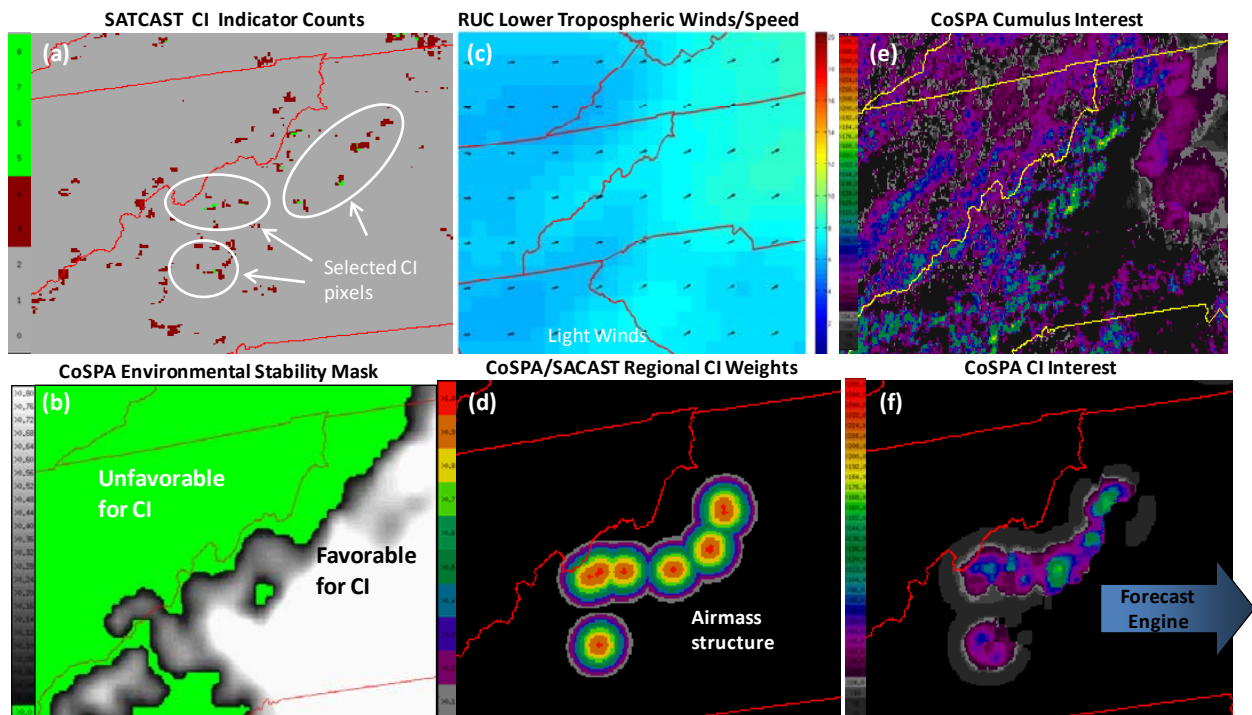


Figure 5. Example of the creation of convective initiation interest from SATCAST CI indicators. (a) SATCAST CI counts for 1630 UTC 23 July 2009 show multiple pixel clusters with counts of five or greater (green). (b) Several of these pixel clusters with CI counts of five or greater are in regions that are favorable for convection, as indicated by the environmental stability mask and these clusters are selected to produce CI interest. (c) Mean 1000 to 500 hPa winds ( $m s^{-1}$ ) show relatively weak westerly flow over the region. (d) The winds are combined with the SATCAST CI counts to create regional weights whose shape and orientation are prescribed by the magnitude and orientation of winds. In this case of light winds, the weights are close to circular and will result in airmass storms. These weights are applied to the CoSPA cumulus interest image (e) to create a CI interest image shown in (f). This interest image is supplied to the CoSPA forecasting system to produce a CI forecast.

## 5. RESULTS

Once a CI interest image is created, it is used in the CoSPA extrapolation/heuristic module to produce a forecast. Figure 6 provides an example of a CoSPA 60-minute forecast with and without SATCAST CI. Although there are no radar echoes over the western portions of North and South Carolina and southern Virginia at the time the forecast is made (Fig. 6a), one hour later storms

formed over this region (Fig. 6b). The 1 hour CoSPA VIL forecast without SATCAST CI (Fig. 6c) shows no evidence of these initiating storms, whereas the CoSPA forecast that utilizes the information provided by SATCAST initiated convection in the region (Fig. 6d). While the match between the locations of the forecasted and observed VIL fields is not exact, the airmass nature and coverage of the forecasted storms resemble those observed.

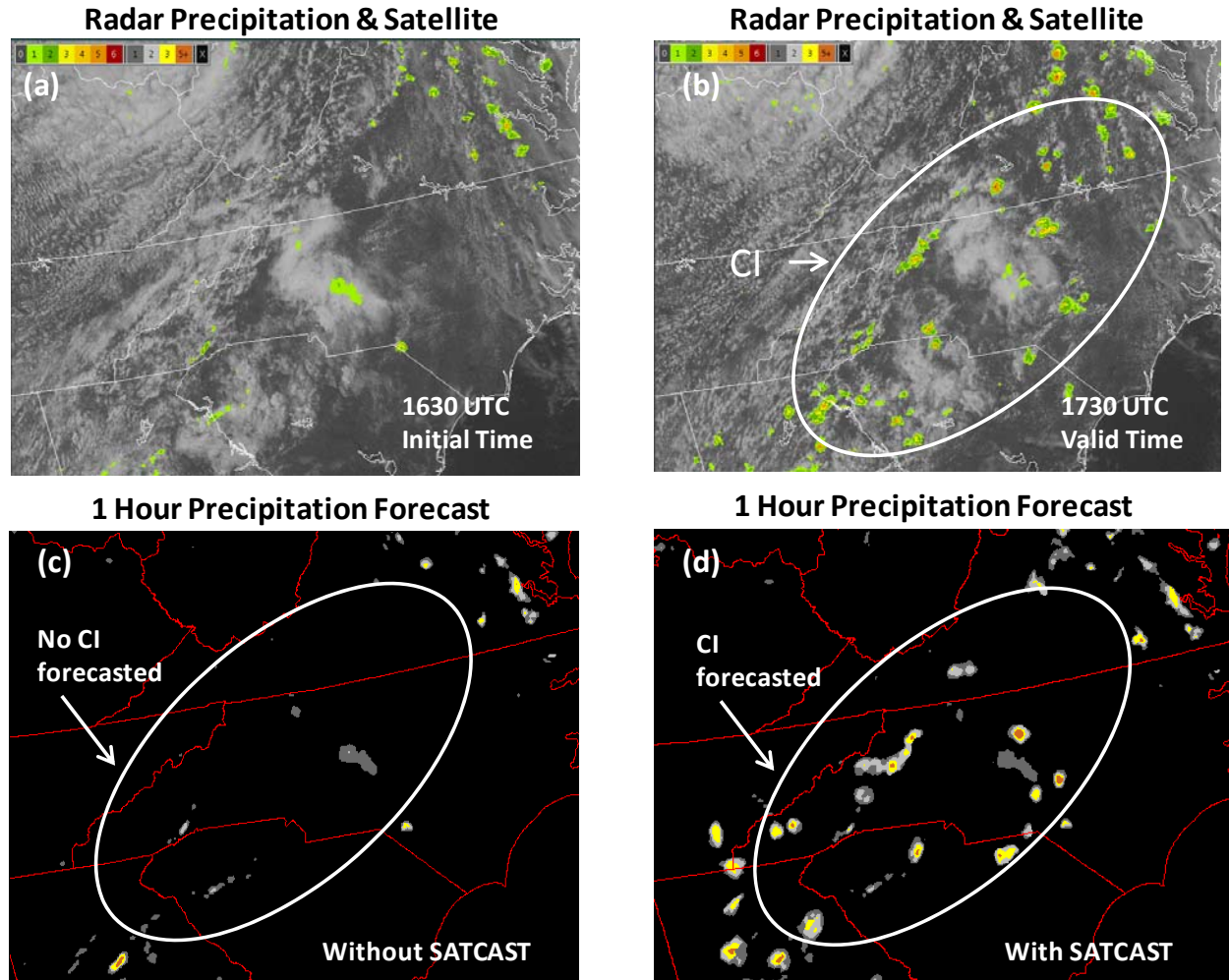


Figure 6. Example of including SATCAST convective initiation interest in the CoSPA forecast. a) Visible satellite and radar VIL at 1630 UTC on 23 July 2009. Note that there is minimal VIL in the scene at this time. b) The observed VIL 60 minutes later shows that CI has occurred over the western portions of North Carolina, South Carolina, and southern Virginia. c) The VIL forecast without SATCAST CI does not depict the newly-developed storms, whereas the forecast with the SATCAST CI (d) captures the convective initiation.

Figure 7 shows a second example of including the SATCAST CI indicators in the CoSPA forecast. At the time the forecast is made, there is no VIL over the Texas panhandle, limited VIL over

central Texas, and widely-scattered VIL over northern Mexico (Fig. 7a). One hour later, CI has occurred over all these regions, with new growth over the Texas panhandle and development of



additional storms in central Texas and northern Mexico (Fig. 7b). The 1 hour CoSPA VIL forecast without SATCAST CI (Fig. 7c) shows no evidence of these initiating storms, whereas the CoSPA

forecast that utilizes the information provided by SATCAST initiated convection in these regions (Fig. 7d).

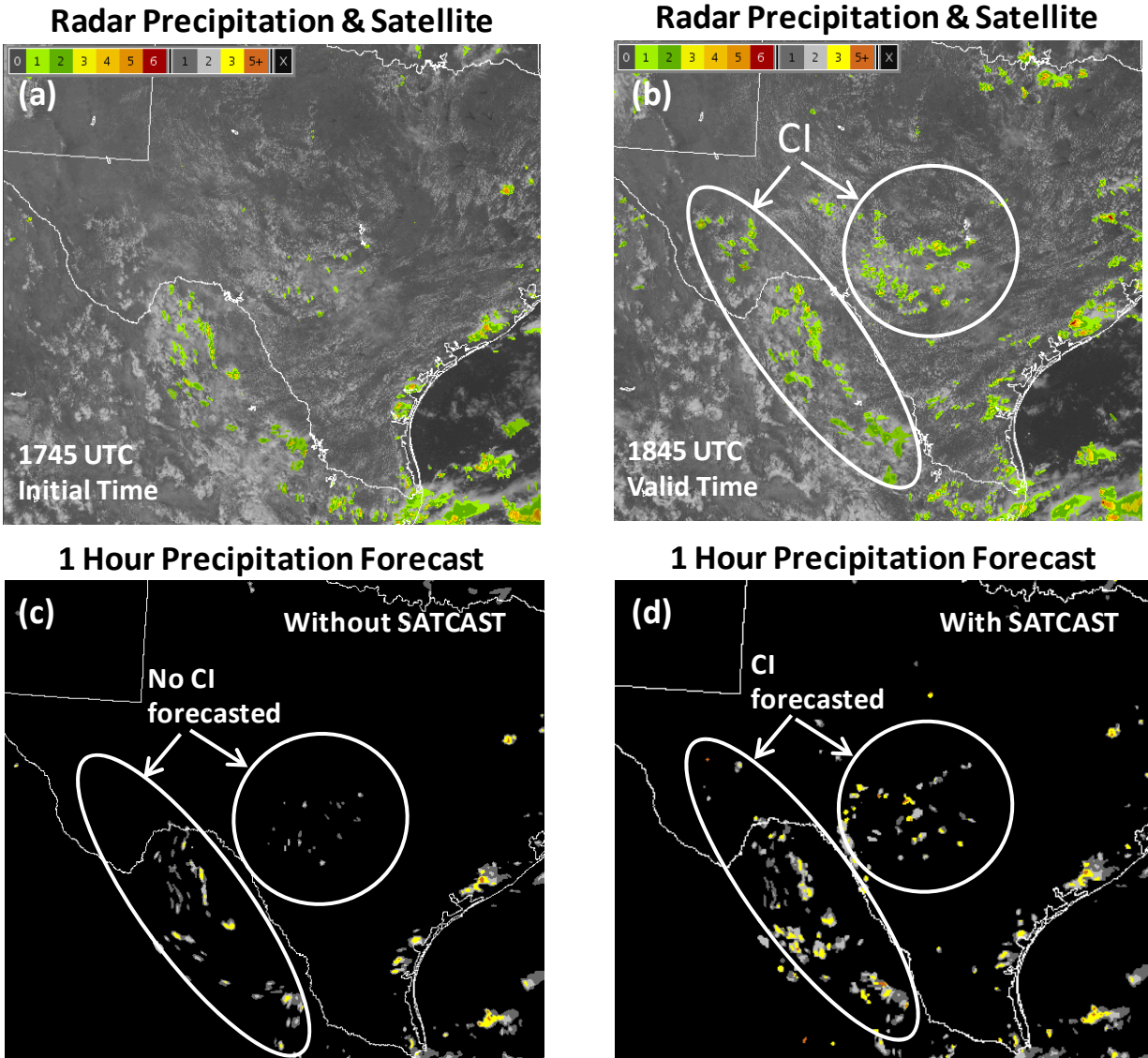


Figure 7. Example of including SATCAST convective initiation interest in the CoSPA forecast. a) Visible satellite and radar VIL over Texas at 1745 UTC on 6 September 2009. At the time the forecast is made, there is no VIL over the Texas panhandle, limited VIL over central Texas, and widely-scattered VIL over northern Mexico. b) CI has occurred over all these regions, with new growth over the Texas panhandle and development of additional storms in central Texas and northern Mexico c) The VIL forecast without SATCAST CI does not depict the newly-developed storms, whereas the forecast with the SATCAST CI (d) captures the convective initiation.

It was noted in Fig. 3 that a large portion of the CI in the western portion of the United States is associated with the elevated terrain. This finding is consistent with those of Banta and Schaaf (1987) who used satellite data to trace the genesis

regions of mountain convection over the Colorado Rockies to the higher terrain. Since the convection in this region is often directly related to land features, the predictability of CI in the West may be greater than over much of the East. Efforts are



currently underway to utilize the topography, stability, lower-tropospheric winds, a measure of solar heating, and trends in cloud-top temperature and cumulus coverage to improve the forecasts of topographically-forced convection. Figure 8 shows an example of a 2 hour convective initiation forecast over the Rockies using these indicators.

These early results indicate the possibility of utilizing satellite information, in conjunction with topography and environmental information, to forecast convective initiation over elevated terrain with extended lead times.

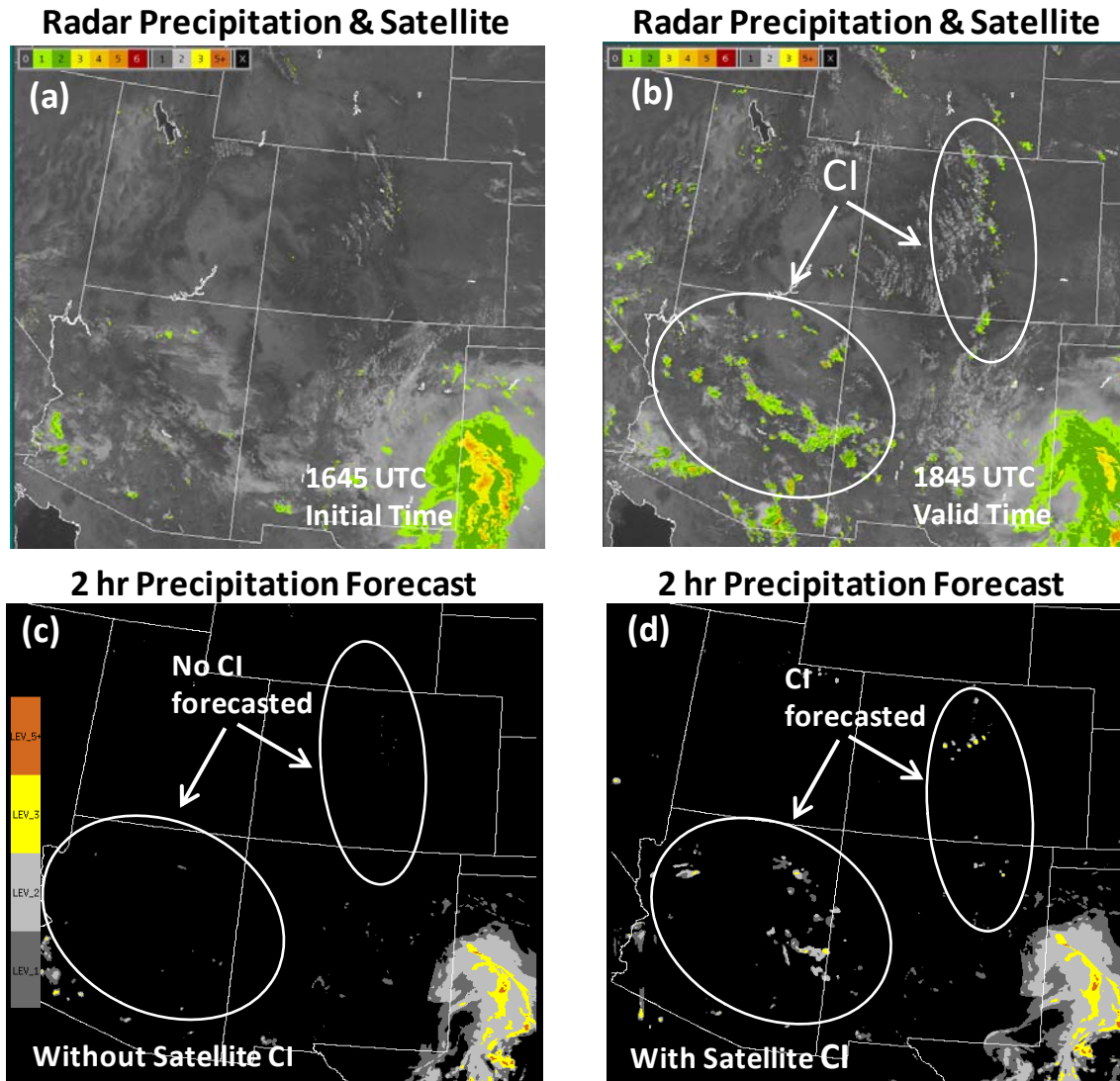


Figure 8. Example of including satellite information in the CoSPA forecast for CI associated with elevated terrain. a) Visible satellite and radar VIL at 1645 UTC on 22 July 2009. Note that clouds are present but there is minimal VIL over Colorado and Arizona. b) The observed VIL 2 hours later shows that CI has occurred over the elevated terrain. c) The VIL forecast without satellite indicators does not depict the newly-developed storms, whereas the forecast with the satellite information (d) captures some of these areas of convective initiation.

## 6. SUMMARY AND FUTURE WORK

CoSPA is a collaborative effort among NOAA, MIT LL, NCAR, and NASA to provide a single

system to deliver high quality 0-8 hour storm forecasts to meet the NextGen requirements for weather decision support to improve traffic flow management. A CoSPA prototype evaluation

began in July 2008 with 0-6 hour forecasts of VIL over the eastern US made available through a web interface for the research team and FAA management. That evaluation is expanding in 2010 to include the CONUS domain, longer lead time (0-8 hours), and forecasts of both Precipitation (VIL) and Echo Tops. In order to ensure high quality forecasts for air traffic applications, the initiation of convection must be captured in the forecasting system. Satellite data, when combined with environmental data from observations and NWP models, represents an important data set that provides indicators of where storms may form within the next hour.

In recognition of the importance of satellite data to nowcasting, a NASA-funded collaboration among UAH, UW-CIMSS, and MIT LL has been formed to transfer the SATCAST convective initiation technology to CoSPA for testing. The SATCAST system is currently being run in the CoSPA environment in a real-time testing mode to assess the utility of the SATCAST CI indicators in a nowcasting system. This paper describes a technique for including the SATCAST indicators in the CoSPA forecast. The technique uses satellite IR indicators from the SATCAST system, along with the environmental stability and lower-tropospheric winds, to initiate convection in regions of little or no pre-existing VIL. A second technique that uses trends in cloud-top cooling and cumulus coverage from satellite data along with environmental stability, lower-tropospheric winds, topography, and solar heating to forecast CI over the mountain West is also under development.

In this study, we used a fixed number of SATCAST CI indicators (five or greater) to determine the location of CI. In the future, in keeping with the fuzzy logic nature of CoSPA, research efforts will determine the best selection of the SATCAST indicators to account for the varying convective conditions. For example, fewer indicators may be required to initiate convection near existing storms or in very unstable conditions. It was also noted that for the longer-lead forecasts, the HRRR model is able to initiate convection. It may be beneficial to use this HRRR CI information in the shorter-lead forecasts to help identify likely areas of CI. Finally, work will continue on CI associated with land features, such as elevated terrain and coastlines.

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