ADVANCES IN THE CONSOLIDATED STORM PREDICTION FOR AVIATION (CoSPA)*

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1. INTRODUCTION

Convective storms are responsible for causing a predominant number of delays in the summer when air traffic peaks. Several studies have shown that there is a critical need for timely, reliable, and high-quality forecasts of precipitation and echo tops with forecast time horizons of up to 12 hours in order to predict airspace capacity (Robinson et al. 2008; Evans et al. 2006; FAA 2007). While a variety of convective weather forecast systems are available to strategic planners of the National Airspace System (NAS), these products don't meet Air Traffic Management (ATM) needs fully. In addition, a multitude of forecast products increases the potential of having conflicting information available in the planning process, which can cause situational awareness problems between the operational facilities, ultimately leading to more potential delays and perhaps safety problems.

One of the goals of the Next Generation Air Transportation System (NextGen) is to eliminate these redundant and potentially conflicting forecast systems and replace them with a common and authoritative weather picture for ATM. The FAA initiated an effort to begin consolidating forecast products in 2006, which fostered a collaboration between MIT Lincoln Laboratory (MIT/LL), the National Center for Atmospheric Research (NCAR) Research Applications Laboratory (RAL), and NOAA's Earth Systems Research Laboratory (ESRL) Global Systems Division (GSD),

called the Consolidated Storm Prediction for Aviation (CoSPA; Wolfson et al. 2008; Dupree et al. 2009a). This collaboration has been structured to leverage the expertise and technologies of each of the three laboratories to build a forecast system that generates deterministic and probabilistic summer and winter storm predictions that at least equal current operational forecast capabilities, yet provides enough resolution, timeliness and performance skill to meet the demands of the envisioned ATM decision support technology for NextGen. The CoSPA 0-8 hour forecast system is planned to be operational by the NextGen Initial Operational Capability (IOC) in 2013. CoSPA is funded under the FAA's Aviation Weather Research Program (AWRP) and the Reduce Weather Impact (RWI) program within the Air Traffic Organization planning division (ATO-P).

A prototype version of CoSPA has been running in real time since 2008. The forecast system builds upon technologies of the Corridor Integrated Weather System (CIWS; Evans and Ducot 2006) and the 6-hour forecast version of the National Convective Weather Forecast (NCWF; Megenhardt et al. 2004). Moreover, CoSPA utilizes model forecasts from NOAA's Rapid Update Cycle (RUC; Benjamin et al. 2004) and the High Resolution Rapid Refresh (HRRR; Benjamin et al. 2009b). The CoSPA forecasts are accessible via a website[1]. The forecast system undergoes further development that leads to enhanced capabilities and improved performance.

Evaluation and monitoring of the CoSPA forecast products are ongoing. The forecast

[1] CoSPA Website: http://cospa.wx.ll.mit.edu

system has shown great promise for providing improved storm forecasts for strategic NAS planning. Independent evaluations conducted by NOAA's ESRL/GSD Quality Assessment team (Madine et al. 2009) and the FAA human-in-the-loop study (McGettigan et al. 2009) have indicated that CoSPA has the potential to benefit the ATM decision making process.　A more in-depth evaluation of

CoSPA with ATM users is planned for the summer 2010.

This paper provides an update of the CoSPA system architecture and display, the prediction technologies, and the performance of the 0-8 hour vertical integrated liquid (VIL) and echo tops (ETOP) forecasts.
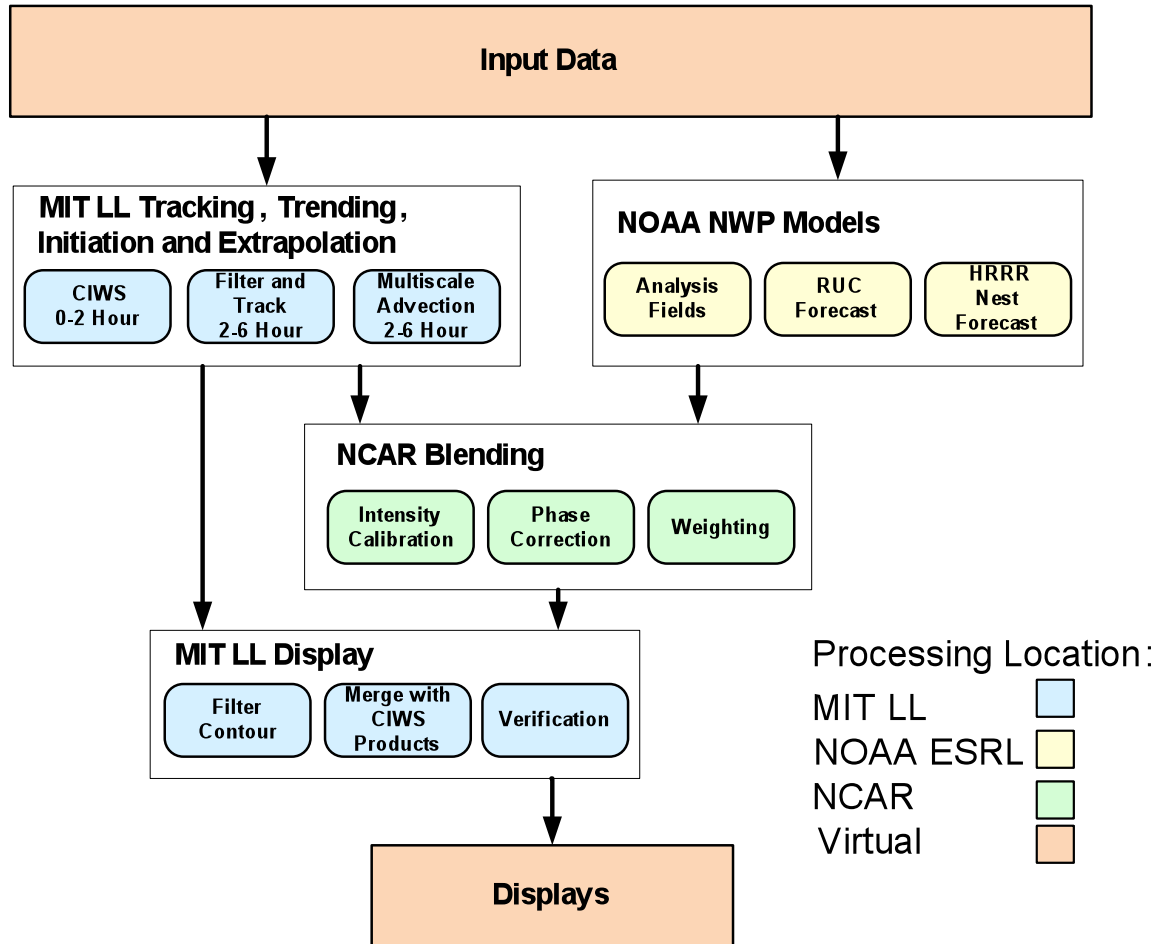
Figure 1: *Shown are the combined functions and dataflow for the CoSPA system. The arrows represent dataflow between processes that are either local or remote.*

2. SYSTEM ARCHITECTURE

NextGen concepts provide a vision of network-enabled data exchanges and virtual information repositories relevant to ATM planning and decision making (JPDO 2007). With this in mind, the CoSPA forecast system has been designed as a distributed set of

processing nodes that communicate via a network. In order to seamlessly exchange data between the contributing organizations (e.g., MIT/LL, NCAR/RAL, and NOAA's ESRL/GSD), the NextGen Network Enabled Weather (NNEW) working group has been exploring a number of data formats and web services that can be used to exchange data.

CoSPA has adopted the common gridded data format NetCDF4, because this format will likely be utilized by FAA systems in NextGen.

Figure 1 shows a data flow diagram for CoSPA. A variety of meteorological data is utilized by the forecast system for the heuristic forecasting part and the Numerical Weather Prediction (NWP) models. The analysis and short-term tracking and extrapolation (i.e., heuristic) aspects of the CoSPA forecast system are handled by MIT/LL, while NOAA's ESRL/GSD is providing the 0-12 hour HRRR model forecasts. The heuristic extrapolation forecasts and model predictions are blended at NCAR/RAL to generate seamless 0-8 hour CoSPA forecasts of VIL and ETOP with a 15 min granularity and 15 min update frequency. The blended forecast data are sent back to MIT/LL for post-processing and display on CoSPA Situational Display (SD) stations and website.

3. DISPLAY

The CoSPA products can be displayed either on a dedicated SD or a password-protected website. The SD are available at a few air traffic facilities, while the website can be accessed anywhere as long as internet communication is provided.

The CoSPA display leverages the CIWS display capabilities and associated "touch and feel". Thus, users familiar with CIWS will find it easy to look at and utilize CoSPA.

The CoSPA display provides visualization of a variety of data relevant for understanding the current weather conditions, including satellite imagery, lightning data, and mosaics of VIL and ETOP derived from the NEXRAD WSR-88D radar network. The display also includes derivatives, such as storm motion, and growth and decay trends, and verification contours. Furthermore, the CoSPA display is very user-friendly, enabling zoom-in/out, loop, and overlay capabilities in real time, plus an archive mode and analysis tool to look at past times and forecast performance. Besides showing weather data, aviation relevant information (e.g., air traffic sectors and airports) can be overlaid as well.

A complete description of the display functionality can be found in Dupree et al. (2009a).

4. FORECAST TECHNOLOGY

This section discusses the three main components contributing to the 0-8 hour CoSPA forecast: (1) a heuristic extrapolation forecast, (2) high-resolution predictions by the HRRR model, and (3) a blending algorithm.

4.1 Heuristic Extrapolation Forecast

Storm forecasting on multiple scales remains an area of active research (Bellon and Zawadzki 1994; Wolfson et al. 1999; Seed and Keenan 2001; Lakshmanan et al. 2003; and Dupree et al. 2002, 2005). These studies show that large-scale features are more predictable (and thus enable better extrapolation) than small-scale features. However, the minimum spatial scale at which meaningful motion data may be extracted is decreasing with increasing forecast time horizon.

The motion prediction used in CoSPA consists of three fundamental steps, namely: (i) filtering and tracking, (ii) interpolation of motion fields, and (iii) advection of the weather. To create the raw motion vectors from the observed data, the input precipitation (VIL) images are filtered with a set of mean filters, followed by cross correlation on a time series of the images. Three scales are used for the extrapolation—these are the cell, envelope, and synoptic scales, as shown in Figure 2a. Two of the three motion scales have been developed for the CIWS system: the cell scale, a 13 km diameter circular mean filter with a 6 min correlation time, and the envelope scale, a 13x69 km rotated elliptical filter with an 18 min correlation time. A new scale needed to be created particularly for the longer time horizons of CoSPA 2-8 hour forecasts: the synoptic scale, a 101x201 km filter with a 45 min correlation time. For the interpolation step, each set of raw motion vectors is interpolated to create a smooth vector map for each scale.

Tracking Scales

Cell	Envelope	Synoptic

- 13 km Circular Mean Filter
- 6 Minute Correlation Time

- 69x13 km Rotated Elliptical Filter
- 18 Minute Correlation Time

- 201x101 km Rotated Elliptical Filter
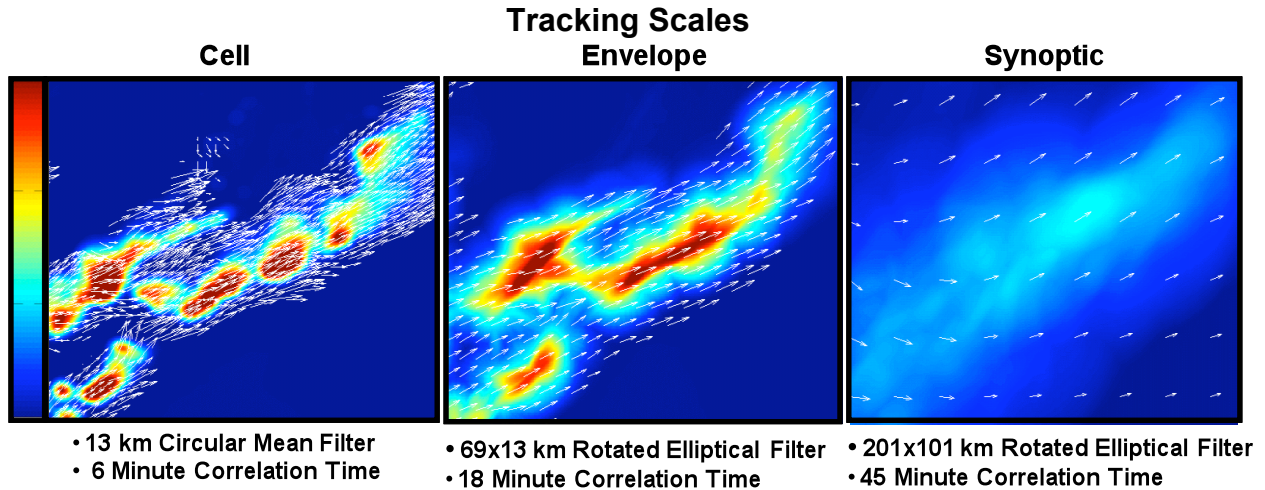- 45 Minute Correlation Time

Figure 2a: Three scales used to create raw motion vectors from smallest to largest: cell, envelope, and synoptic. Motion vectors are shown in white, the background is a spatially filtered interest image. VIL is passed through the filters, then correlated with previous images to calculate the motion vectors.
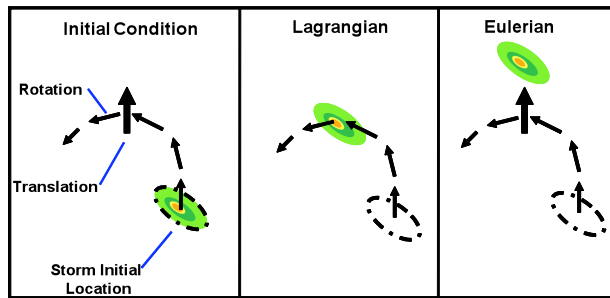

Figure 2b: Schematic depiction of multiscale advection technique. Initial image is advected in many short steps using successive small-scale cell and envelope vectors, then in one large step using large scale (synoptic scale) vectors. Small arrows represent small-scale vectors used in the small-scale step, the large arrow represents vectors used in large-scale step.

The advection process uses two steps to move the separate scales (Figure 2b). First, rotation advection is applied to the cell and envelope motions, and second, an Eulerian advection step (or translation) is applied to the synoptic scale. For the first step, the synoptic motion is subtracted from the cell and envelope scales, and the resulting field is applied in a pseudo-Lagrangian sense to the forecast image. The method works as follows: a pixel is advected with a small time step, and then placed at a new location. The pixel is then advected again for the next time step with a motion field representing the area of its new location. The pixel therefore should approximately follow a streamline of the small-scale (rotational) motion field. The cell vectors are used out to a 10-min time horizon, then the advection process transitions to the envelope vectors that are used out to a 90-min time horizon, at which point their influence is progressively diminished. After the rotation step is complete, an Eulerian step is applied using the synoptic-scale motion vectors to accomplish the final translation step.

The CoSPA tracking and heuristic extrapolation forecast techniques leverage on techniques developed for CIWS, as discussed in Wolfson et al. (2004), Dupree et al. (2006), and Wolfson and Clark (2006).

4.2 Numerical Weather Prediction

An experimental version of the Weather Research and Forecasting (WRF) model, called the High Resolution Rapid Refresh (HRRR) model (Benjamin et al. 2009a, 2009b; Weygandt et al. 2009), is run at NOAA's ESRL/GSD laboratory. The 3-km

resolution HRRR model is nested inside an experimental version of the 13-km Rapid Refresh (RR) model, which will replace the 13-km RUC while maintaining assimilation of three-dimensional radar reflectivity data using a diabatic Digital Filter Initialization (DFI) technique.   The HRRR model benefits from the RUC radar data assimilation through lateral boundaries throughout the forecast as well as in improved initial conditions.   In addition, the high resolution of the HRRR explicitly resolves convection, allowing the model to produce realistic convective structures vital for improved forecast fidelity without the need for parameterizations of sub-grid processes.
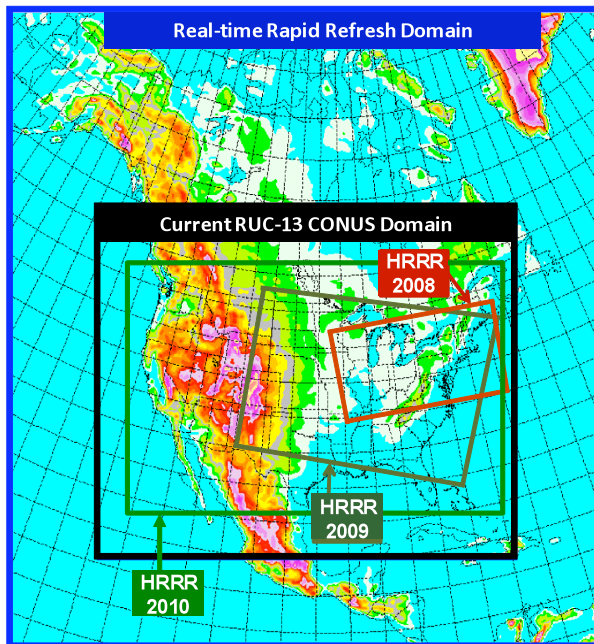

Figure 3: *HRRR model nested in the WRF-RR and RUC models.   Depicted are the experimental Northeast domain over which the HRRR was run during 2008 (red rectangle) and the expanded Midwestern and Eastern domain model for 2009 (grey rectangle). Beginning in 2010 the HRRR has been covering the CONUS (depicted by green rectangle).*

The HRRR model is restarted once an hour and generates forecasts out to 12 hours. VIL and ETOP forecasts are made available at a 15 min frequency for the CoSPA forecast system so that multiple valid times can be used in the blending technology. Because of the high resolution employed, the extensive data assimilation, and the rapidly updating nature, the HRRR is able to accurately reproduce observed storm organization and evolution. In particular, the HRRR typically provides clear guidance in distinguishing between scattered and organized convection, which is critical information for aviation planning.

As additional computer resources became available, the domain covered by the HRRR has been expanding on an annual basis (see Figure 3) from initially covering only the Northeast corridor (in 2008) to cover a large portion of the Midwestern and Eastern US in 2009.   For the upcoming 2010 summer season the domain will span the entire CONUS. This expansion to CONUS provided the basis for CoSPA forecast products to be evaluated by aviation traffic flow managers in the field in real time.

4.3 Blending of Heuristic and Numerical Forecasts

The heuristic extrapolation forecasts are blended with the HRRR forecasts of VIL and ETOP to produce a seamless and rapidly updating, high-resolution 0-8 hour forecast of weather intensity and storm top heights. This is done through (i) a calibration of the model data to reduce intensity biases, (ii) a phase correction to reduce location errors in the predicted precipitation field, and (iii) a statistically-based weighted averaging of the heuristic extrapolation forecast and phase-corrected numerical prediction. In CoSPA, heuristic extrapolation forecasts of VIL and ETOP from MIT/LL are thus blended with VIL and ETOP predictions from the HRRR model.

The storm intensity and echo tops are "retrieved" from the modeled profiles of snow, rain and graupel water mixing ratio (note that the model currently does not predict hail). The radar reflectivity is calculated at each model level using the equations given by Thompson et al. (2004). This quantity is then converted to liquid water and vertically

integrated to give a total VIL for the atmospheric column above a pixel. The echo tops are determined by finding the highest vertical level at which the reflectivity exceeds 18 dBZ. It was found that using the radar equations to determine the VIL and ETOP heights provides a better depiction of the characteristics of storms (i.e., gaps), which is needed for aviation route planning and weather avoidance models.

This radar-retrieved model VIL field is then converted to digital VIL (0-254 using an 8 bit integer scale) and calibrated by performing a frequency matching procedure that reduces intensity biases in the modeled VIL values. In 2009, the calibration function was constant with time. However, in 2010, this calibration function will be calculated dynamically based on comparison of the model forecasted VIL with the current radar image.
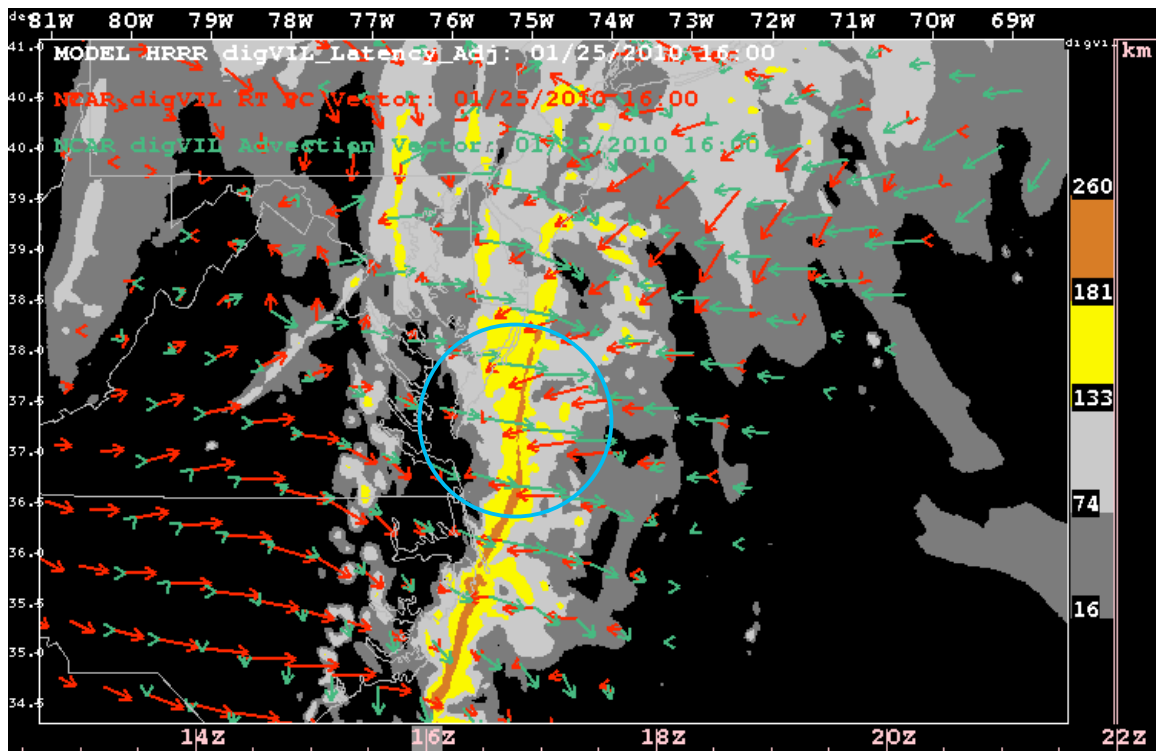

Figure 4: *Six hour forecasted precipitation intensity from the HRRR (gray-orange colors) along with Eulerian phase correction vectors (red) and Lagrangian phase correction vectors (sea green). Note the large differences (of up to 180 deg) between the EPC and LPC phase correction vectors in circled region because the Lagrangian phase correction vectors account for storm motion.*

Spatial offsets between modeled digital VIL and the observed digital VIL are then reduced using a phase correction technique based on a minimization of the squared errors following Brewster (2003). The latency of the model forecast, which is typically 2-3 hours by the time the forecasts become available, is considered in the phase correction. Because of model latency, the initial part of the forecast is already valid by the time it is received. Thus, the model forecast image is compared with the current radar mosaic data to determine the amount and direction of shift at each grid point. These "shifts" are then applied to all the forecast lead times as a constant offset. This type of correction, which is fixed in time and space, is termed Eulerian Phase Correction (EPC). The phase error

vectors are then applied to both the modeled digital VIL and ETOP. An example of the correction vectors generated using the EPC are shown in red in Figure 4.

The statistical impact of the EPC is summarized in Figure 5. It is found that we can significantly improve the CSI of the 0-2.5 hour HRRR model forecasts (note: these lead times actually correspond with model leads of 2-4.5 hours, provided a 2 hour latency is assumed). However, in 2009 the improvement was not great enough to significantly impact the skill cross-over point (i.e., the lead time at which model skill exceeds that of extrapolation). It is also seen in the bias curves that the EPC is too aggressive in reducing the storm area. We are currently working on an improved phase correction technique that is less aggressive in terms of reducing the storm area and takes into account storm motion and temporal variations in the magnitude of the correction. This scheme, which is allowed to vary in space and time while taking into account the storm motion, is termed Lagrangian Phase Correction (LPC). The improvement of phase correction vectors obtained by LPC over EPC can be seen in Figure 4. This advanced treatment of the phase errors is expected to be critical in lengthening the duration of skill pickup associated with the phase correction.
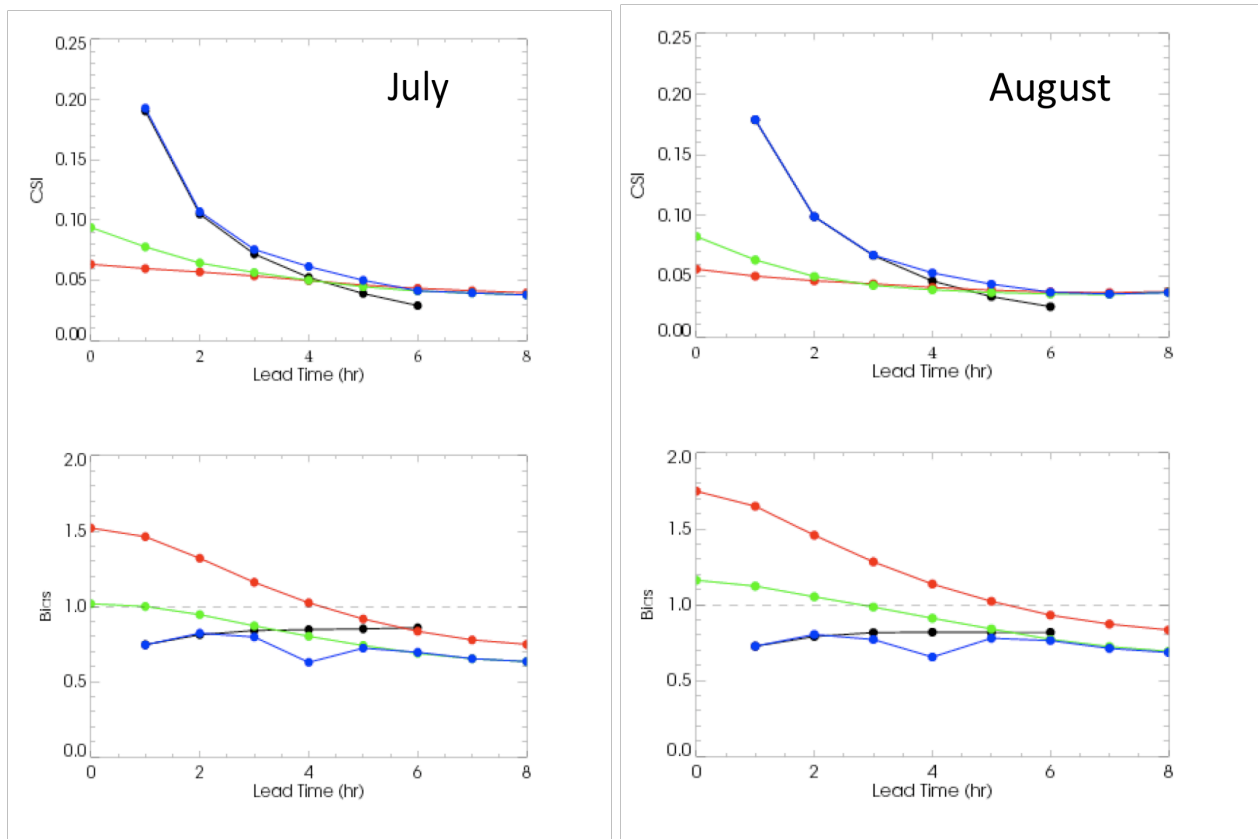

Figure 5: *Monthly mean CSI and bias scores for VIP3 (VIL=3.5 g m^{-2}) as a function of lead time for July and August 2009. Curves are for extrapolation (black), calibrated and latency adjusted HRRR (red), calibrated and phase corrected HRRR (green), and blended (blue) forecasts.*

Time-varying weights are used to blend the calibrated and phase-shifted model VIL forecast with the heuristic extrapolation forecasts. The weights are determined by the mean relative performance of the two forecasts. The performance is determined such that the bias and CSI scores of the blended forecast are optimized. Generally, the model is given more weight at the longer lead times, with equal weighting around 4

hours. The weights are allowed to vary as a function of valid time of day, with the model receiving more weight during the period of most rapid storm initiation and growth over the CONUS (i.e., 15-21 UTC) as this period of rapid change is difficult to handle through observation-based approaches.

The final CoSPA forecast aims to optimally combine extrapolation heuristics with high resolution NWP output. Forecasts that accurately depict storm evolution and morphology are critical for making well-informed decisions related to routing air traffic across the NAS.

5. FORECAST ASSESSMENT

The performance of the CoSPA forecast system was monitored throughout the summers of 2008 and 2009 at both MIT/LL and NCAR/RAL using a variety of methods. These methods include: (1) real-time verification forecast statistics and verification contours, (2) real-time onsite assessment by meteorologists, and (3) off-line evaluation of past performance using playback and analysis tools, as described by Dupree et al. (2009b).

It has become clear that CoSPA has forecast skill and performs well in most situations. Several examples of performance in different conditions (e.g., storm initiation, growth and decay) and storm characteristics (scattered air mass vs. line storm, etc.) are given in Pinto et al (2009) and Dupree et al. (2009a).

Statistical performance scores were averaged over the summer and are shown in Figure 5. The CSI score is generally higher in July than in August owing to the smaller scale character of storms in August. While the blended forecast does well in optimizing the CSI score, it was recognized that the blended forecast tended to underpredict storm area (negative bias at hours 3-5) for storm intensities greater than VIP level 3. This issue is currently under investigation and found to be related to a number of factors including the treatment of storm initiation, and the need for a dynamic calibration and improved phase correction techniques.

These issues are being addressed to mitigate this effect in time for next summer's release.

6. SUMMARY

A research prototype version of CoSPA that produces 0-8 hour forecasts of echo tops and storm intensity has been running since July 2009. These forecasts build upon a blending of heuristic extrapolation (e.g., tracking and trending) and initiation forecasts with high-resolution NWP forecasts that show promising skill at predicting aviation-specific weather information, including storm mode and permeability structure. In 2010 we plan to provide CONUS coverage with a number of improvements in the areas of storm initiation, data assimilation (Weygandt et al. 2010), and blending (described above). In addition, work will continue at each of the labs on producing probabilistic (and uncertainty or confidence) forecasts of convection (e.g., Alexander et al. 2010, Ahijevych et al. 2010). These recently developed probabilistic forecasts will be generated in real time and evaluated by the developer teams and possibly selected users.

ACKNOWLEDGEMENTS

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