

# CONSOLIDATED STORM PREDICTION FOR AVIATION (CoSPA)\*

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## 1. INTRODUCTION

Research over the last 10 years primarily funded by the FAA Aviation Weather Research Program (AWRP) has led to very successful development of forecasts of both convective and winter storms, using heuristic and numerical models, for aviation applications. We have reached a point where there are several overlapping capabilities, and the smorgasbord of choices has become confusing (Figure 1). Moreover, aviation-impacting winter and summer conditions can exist simultaneously – even within a single terminal area – so a consolidated forecast must work equally well for all storm conditions. Advances in computing and communications allow incorporation of new observing systems and scientific advancements in data assimilation and modeling toward large-scale, very high resolution forecast systems that were prohibitive just 10 years ago. Other government agencies, in addition to FAA, have needs for aviation-oriented forecasts, including at least the National Weather Service, NASA, Homeland Defense, Air Force and other DoD agencies. Further efficiencies will be realized by consolidating such efforts as well. These goals are well-aligned with the goals of the Next Generation Air Transportation System and its Joint Program and Development Office.

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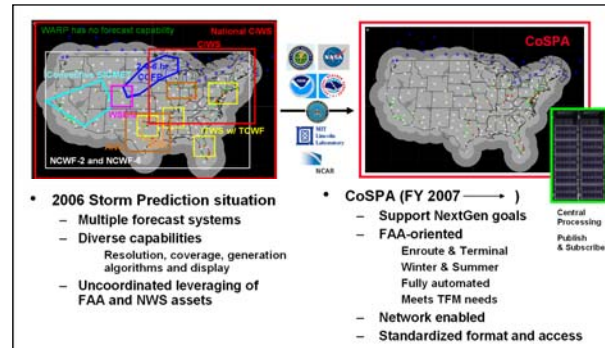


Figure 1. Illustration of the problem of multiple forecasts for use in aviation circa 2006. Since the inception of CoSPA, FAA Aviation Weather Research Program efforts are developing a single, consolidated forecast system for both summer and winter storm conditions.

The FAA Aviation Weather Research Program is leading development of the new Consolidated Storm Prediction for Aviation (CoSPA) effort, which will combine aviation-oriented storm research in a coordinated fashion, with the goal of eventually replacing operational legacy storm diagnostic and forecast products, as appropriate, that are also geared toward aviation (see Appendix A). While many of the current storm prediction products are derived using NOAA model forecast data, especially from the hourly updated 13-km Rapid Update Cycle (RUC) model over CONUS, CoSPA products will be related to a new generation of NOAA models now assimilating radar reflectivity and lightning, including the Rapid Refresh, its proposed nest - the High-Resolution Rapid Refresh (HRRR), and ensemble-based products from both.

A kick-off meeting was held in June 2006 to discuss AWRP's concepts for a consolidated aviation forecast, and to understand unmet user needs, major scientific development issues, and also to begin to explore issues associated with production and dissemination of a consolidated forecast. These findings are summarized below.

**Group 1: Unmet Aviation User Needs (Danny Sims, facilitator)**

1. Main unmet need is ability to efficiently manage air traffic capacity, delay, and congestion in stormy weather (either by human controllers aided by decision support tools or – perhaps in the future – by a completely automated system).
2. Other major issue is safety for air carriers and general aviation.
3. Need a strong coupling of automated storm forecasts with anticipated pilot avoidance regions and predictive air traffic flow models.
4. Research is needed to determine exactly which forecast variables best predict pilot avoidance regions.
5. Need to provide reliable forecast uncertainties for the storm predictions to be useful.
6. Indication of real-time forecast confidence level is important for risk management in traffic flow decision making.
7. Permeability of storms an important factor to the user (drives the need for digital 4D depiction of the storm volume in the consolidated product).
8. Latency of product important (need to have real-time product, less than 5 minutes old).
9. Each user can have its own way of looking at the storm forecast (display, integrated into traffic flow model, text, etc.), but all products should be based off a common database.
10. Cockpit datalink capability for forecast important for rapid, shared situational awareness, safety.
11. User group should be established in the model of the very effective FAA Terminal Doppler user group.

**Group 2: Forecast Scientific Development Issues (John McCarthy, facilitator)**

1. Primary need is to have an aviation storm diagnosis and forecast algorithm that optimally blends extrapolation, models, statistical methods and human skill in a single product.
2. Product should be 4D, multi-scale (local, continental, oceanic) with no discontinuities at boundaries.
3. Will provide diagnostic and forecast information for storm initiation, growth, movement, and decay.
4. Scientific development priorities should be aviation user-need driven, including a) prioritizing importance of emphasis on different time/space scales, b) determining which forecast parameters best predict where aircraft will not fly, and c) representing the information in reliable probabilistic format suitable for automated decision support systems (i.e., machines are users too).
5. Ongoing experimental prototype with coupled forecast/decision support tools and live users is best way to provide the required coupling to operational users and the frequent scientific improvements to the operational system that will ensure progress toward meeting user needs.
6. Key scientific R&D needs include: sensing pre-storm environment (the need for increased boundary layer measurements noted with remote sensing of moisture and TAMDAR in-situ measurements holding promise), better use of satellite data, and improvements in numerical modeling: a) data assimilation techniques, b) nested-grids with scale interaction, c) ensembles, d) improved coupled land and sea surface models.
7. Human over the loop is of value and should be retained (e.g., use by US Air Force in critical missions)
8. Other issues discussed but not resolved included: How should FAA receive external advice? (FAA REDAC, National Academy, NGATS JPDO?) How can we keep development coordinated within FAA and across agencies, as well as consistent with JPDO vision? (A joint technical advisory group was suggested.) How will improvements on NAS performance be measured?

**Group 3: Forecast Production and Dissemination (Ken Leonard, Facilitator)**

1. Consolidated forecast effort needs to use components of existing systems as initial building blocks, but also take “clean sheet” approach to designing open operational system that permits economical, frequent, regular improvements (examples of NEXRAD Open RPG and Tropical Prediction Center).
2. Stringent quality control required for unattended automated system, including artifact-free input data, highest quality forecast available, fast update rate, very low latency, regularly updated, fault tolerant redundant hardware/software design, etc.
3. Product output will be stored in common database to feed different displays or automation systems.
4. Database should have a rolling archive of at least 15 days (possibly much more).
5. CoSPA needs to replicate and provide ongoing access to legacy forecast products (e.g., Convective SIGMETs, CCFP 2-, 4-, 6-hr forecasts, AIRMETs for high surface winds, etc.)

The kick-off meeting working groups clearly had the expertise needed to answer our critical questions and were future-oriented when thinking about the system development, architecture, and communications. Based on the important points made by the group addressing unmet user needs, we put forth the following model of the forecast development process (Figure 2).

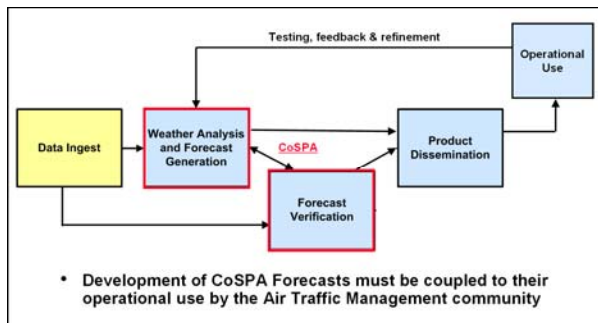


Figure 2. The process of developing an aviation-oriented forecast must involve feedback between experimental operational use of the forecast and further development and refinement of the forecast.

The current authors and other scientists from NOAA, NCAR, and MIT Lincoln Laboratory worked over the following summer to articulate a preliminary design for CoSPA. A review of this design was presented to a group in a special session at the October 2006 NBAA meeting in Orlando. Topics included discussion of available forecast algorithm technology (storm initiation and evolution, incorporating human forecaster inputs, numerical weather prediction, and blending observation-based forecasts with numerical forecasts), system infrastructure design and development (architecture, standards, modular design, etc.), and what the system outputs will be (deterministic and probabilistic forecasts, verification, translations into ATC impacts, etc.). Figure 3 shows some of the overall system design goals.

While we expect CoSPA to evolve over time and it is difficult to predict the precise form it will take by 2025, we can be very specific about the goal of a demonstrated initial operating capability by the year 2012.

### Design Goals for CoSPA

- |   |   |
|---|---|
| <ul style="list-style-type: none"> <li>• <b>Open System</b></li> <li>• <b>Best Practices</b> <ul style="list-style-type: none"> <li>– Agreed upon software standards</li> </ul> </li> <li>• <b>Plug and Play</b></li> <li>• <b>Modular</b></li> <li>• <b>Flexible</b></li> <li>• <b>Extensible</b></li> <li>• <b>Documented</b></li> <li>• <b>Efficient</b> <ul style="list-style-type: none"> <li>– Data transfer</li> <li>– Algorithm processing</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• <b>Maintainable</b></li> <li>• <b>Portable</b></li> <li>• <b>Scaleable</b></li> <li>• <b>Supports:</b> <ul style="list-style-type: none"> <li>– Real-time</li> <li>– Test-beds</li> <li>– Research</li> </ul> </li> <li>• <b>Cost Effective</b> <ul style="list-style-type: none"> <li>– Code reuse</li> </ul> </li> </ul> |
|---|---|

Figure 3. Broad design goals for the FAA CoSPA system.

## 2. CoSPA INITIAL OPERATING CAPABILITY 2012

### 2.1 Partnership with FAA CIWS

After our 2006 survey of the various forecast technologies available, we concluded that forecast consolidation with the most benefit and least cost to the FAA would begin with the radar mosaics and 0-2 hr Precipitation and Echo Tops forecast algorithms within the FAA Corridor Integrated Weather System (CIWS; Figure 4; Evans and Ducot, 2006). These algorithms have undergone research and development since 1998 under sponsorship of the Aviation Weather Research Program. Through technology transfer programs with both the FAA Integrated Terminal Weather System (Wolfson et al., 2004) and the CIWS prototype for FAA System Operations (begun under Enroute), the products based on these algorithms have proven extremely useful to Traffic Flow Managers and Controller Supervisors in operational settings. Benefits such as improved situational awareness, interfacility coordination, keeping routes open longer, proactive reroutes, etc. have been documented. Detailed cost/benefit studies have also been performed, indicating the real value of the forecasts in financial terms (MCR Federal, 2001; Evans et al., 2006; Robinson et al., 2004 and 2006). By augmenting CoSPA with forecast technology drawn from various sources available in our collaboration [e.g., Autonowcaster (Mueller et al., 2003), NCWF-2 (Megenhardt, 2004), and WSDDM (Rasmussen et al., 2001) – also developed over the last 10 years under AWRP sponsorship] and from the broad international research community, we can immediately provide CIWS users with the technology they need to help mitigate weather-

induced air traffic congestion. Future partnerships with FAA Enroute and Terminal services will be necessary for a long-term functional CoSPA development process. Figure 5 illustrates our concept for CoSPA in the 2012 time frame.

## 2.2 Partnership with NOAA

The CoSPA requirement to produce frequently updated forecasts out to 10-12+ hrs, beyond the current CIWS 0-2hr temporal domain will be addressed by use of the new generation of NOAA

high-frequency numerical forecast models (e.g., Rapid Update Cycle - RUC, Rapid Refresh, nested High-Resolution Rapid Refresh – HRRR), blending techniques between nowcast-extrapolation data and NWP grids, and probabilistic forecasts from these grid sources. The RUC/RR/HRRR merges data from the widest range of observation types on an hourly basis, and is used to support the integrated sensor approach described below by providing background fields for the various products. Expansion of NOAA computational resources in support of CoSPA is essential.

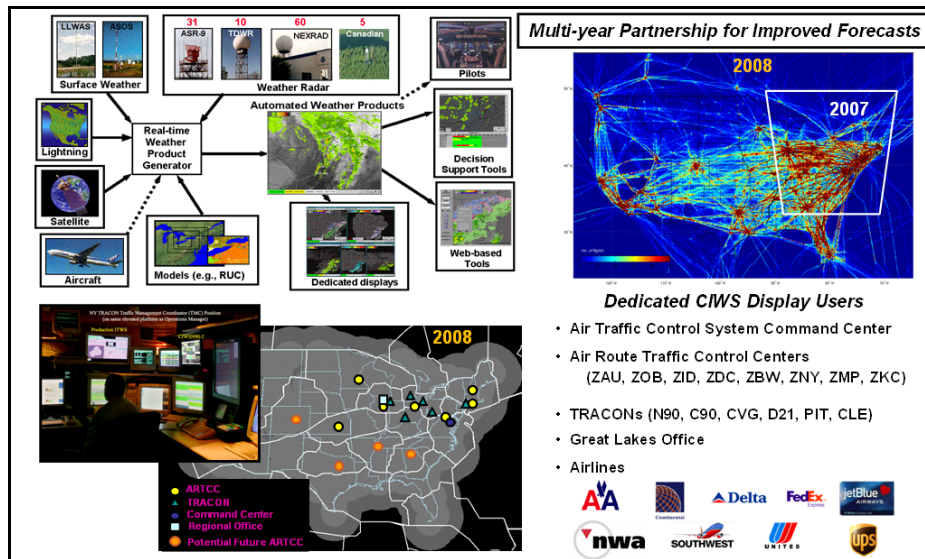


Figure 4. CIWS inputs, domain coverage and users with dedicated displays are shown. CoSPA partnership with CIWS permits algorithms to be tested by operational users.

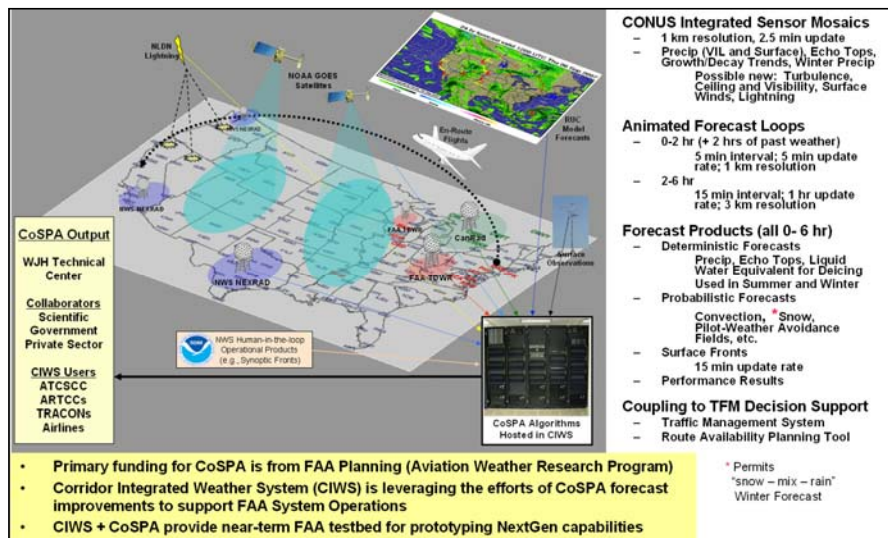


Figure 5. Illustration of the planned CoSPA capabilities at Initial Operating Capability in 2012. The CoSPA partnership with the System Operations CIWS Program provides a near-term testbed for early NextGen capabilities.

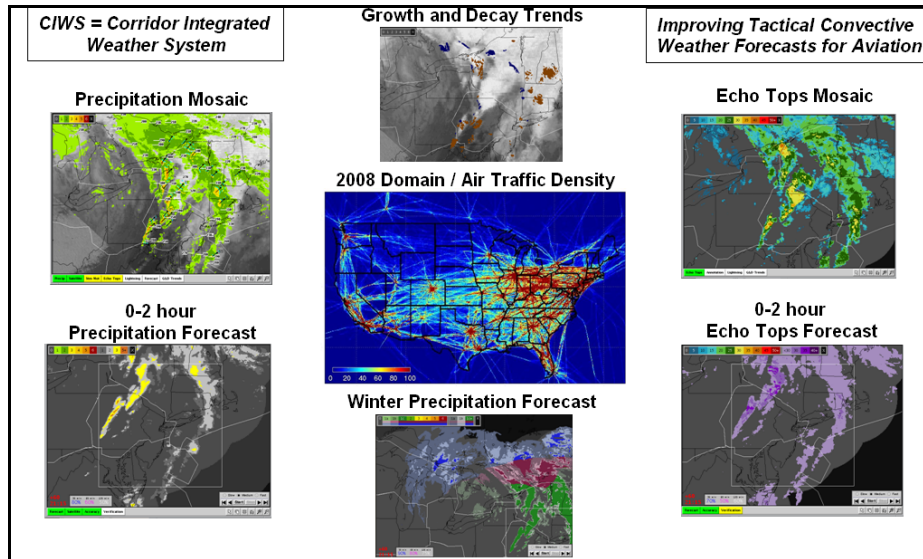


Figure 6. Examples of the various CoSPA algorithms. Sensor mosaics and forecast products are available via the CIWS real-time prototype demonstration. The 2008 CONUS domain is shown in the center along with air traffic density measured on a day in 2007 with no significant weather.

### 2.3 Integrated Sensor Mosaics

The use of 1 km resolution sensor mosaics with a 2.5 min update rate in CoSPA provides a long range “terminal-quality” picture of the weather over the entire CONUS domain. NEXRAD, TDWR and Canadian radars are included. (Not all TDWR data are available; networked access to all TDWR data needs to be made operational as soon as possible.) Automated data quality editing of the radar data is critical for removing non-meteorological returns without changing the real weather signals, and Smalley et al. (2008) have made recent significant improvements. The mosaic process provides motion compensation for the radar data proportional to the time since the current volume completed, thus avoiding the notorious problems with depicting echoes in the wrong place during fast moving storms exhibited by the WARP system (Stobie et al., 2008; Ahlstrom and Dury, 2007). Having a CONUS-wide CIWS with CoSPA algorithms means that not only can enroute air traffic personnel have high resolution, low latency weather imagery, but the same data can easily be utilized at any terminal within the coverage domain.

Figure 6 shows the Precipitation (VIL) and Echo Tops Mosaics, as well as the “Winterized Precipitation” depiction. Providing a diagnosis of the phase of precipitation (rain, mix, or snow) provides excellent situational awareness for FAA Traffic Managers. It has also been useful for identifying time of onset of snow in the terminals (when visibility is reduced dramatically relative to

rain conditions), tracking progression of heavy snow bands, timing when significant winter weather impacts will subside, etc. An objectively analyzed grid of ASOS 1-min surface observations and NOAA RUC model data are used in making this product. Broad access to the FAA networked ASOS 1-min observation data stream needs to be made operational as soon as possible.

A Growth and Decay Trends field is also calculated to depict areas where VIL is changing significantly. CIWS offers this information as an overlay field and users definitely avoid the “hot” growth regions. A new feature “behind the scenes” in the CoSPA mosaics will be the use of cloud-to-ground lightning data to supplement the depiction of VIL and Echo Tops in degraded radar conditions [e.g., at very long range from the radars, off shore, during accidental radar outages or in regions of terrain blockage (Iskenderian, 2008)].

In the future, mosaics and forecasts of ceiling and visibility (which depend heavily on the existing CoSPA winterized precipitation diagnosis and the 0-2 hr forecast), calibrated snow liquid water equivalent (for deicing decisions), turbulence, surface winds/wind shifts and lightning can be computed within CoSPA.

### 2.4 Deterministic and Probabilistic Forecasts

NextGen/JPDO operational concept documents have focused on the need for “probabilistic weather forecasts” that can be utilized in future automated TFM systems that

formulate gate-to-gate trajectories for each flight. Yet, to date no one has been able to utilize the probabilistic forecast offerings from the meteorological community in this fashion. In today's ATC system and in the foreseeable future, high resolution deterministic forecasts that depict the granularity of thunderstorms and echo tops in enough detail that human traffic flow managers can safely route aircraft through gaps and around dangerous heavy rain cores will be needed (e.g., Mitchell et al., 2006; Wanke and Greenbaum, 2007). Even longer range (2-6 hr) storm forecasts must show as much detail as possible because, while certainly not *precisely* correct, the high resolution deterministic model detail conveys an effective air traffic capacity to both the human TFM expert and machine-based decision support systems.

However, deterministic forecasts alone are not enough! A companion estimate of the forecast uncertainty in quantitative terms that can directly influence routing decisions is also needed. The precise form of these uncertainty fields is a topic of current research. Steiner et al. (2008) and Weygandt et al. (2008) show some recent thinking on this problem. It is envisioned that the future NextGen ATC system, which is expected to be a machine-to-machine concept, will use probabilistic distribution functions as the core of the system for air traffic, weather, and most system needs.

#### 2.4.1 Tactical 0-2 hr Forecasts

For 2012, CoSPA will provide both 0-2 hr and 2-6 hr forecasts of Precipitation (VIL) and Echo

Tops. The 0-2 hr Forecasts demonstrated in CIWS since its inception form the initial cornerstone of our CoSPA system (Wolfson and Clark, 2006). The Echo Tops product has turned out to be just as important as VIL for enroute traffic flow management, so including a forecast of Echo Tops is essential (Dupree, 2006). Figure 6 also illustrates the 0-2 hr forecasts of Precipitation (VIL) and Echo Tops. These forecasts are 1 km resolution and updated every 5 min. Unique forecasts from the current time to 120 min in the future are available in 5 min intervals so that the set may be animated to show the forecast storm evolution. The forecast "engine" is a fuzzy logic system that is being redesigned to permit modular "plug and play" processes from various collaborators to be incorporated.

Examples of the core algorithms in CoSPA are shown in Figure 7. Some capability exists currently in each box, but the team is considering competing technologies in some cases, and will make a decision before 2012 on which modules to keep and which to discard. An example of this for Satellite Feature Extraction is shown in Figure 8, for which an assessment is currently being conducted (Roberts, 2008). One technique alone may be selected or it may be desirable that the pros of the various techniques be combined into a new, more capable scheme. The implementation cost/benefit ratio of any proposed scheme will also be a consideration upon final analysis. Williams et al. (2008) are studying the statistical optimization of multiple feature detectors to produce skillful predictor combinations.

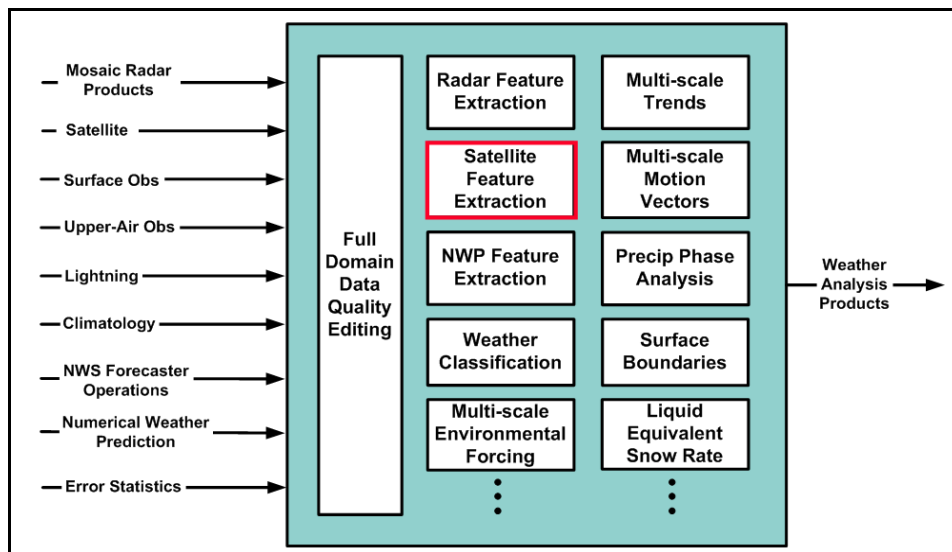


Figure 7. An example of the "core algorithms" in CoSPA is shown. An example of this for Satellite Feature Extraction is shown in Figure 8.

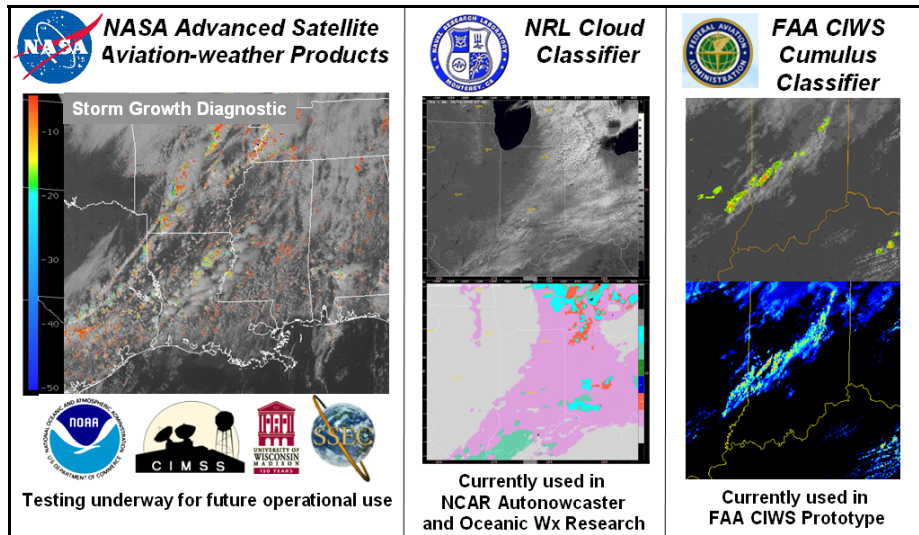


Figure 8. Examples of satellite feature extraction schemes are shown.

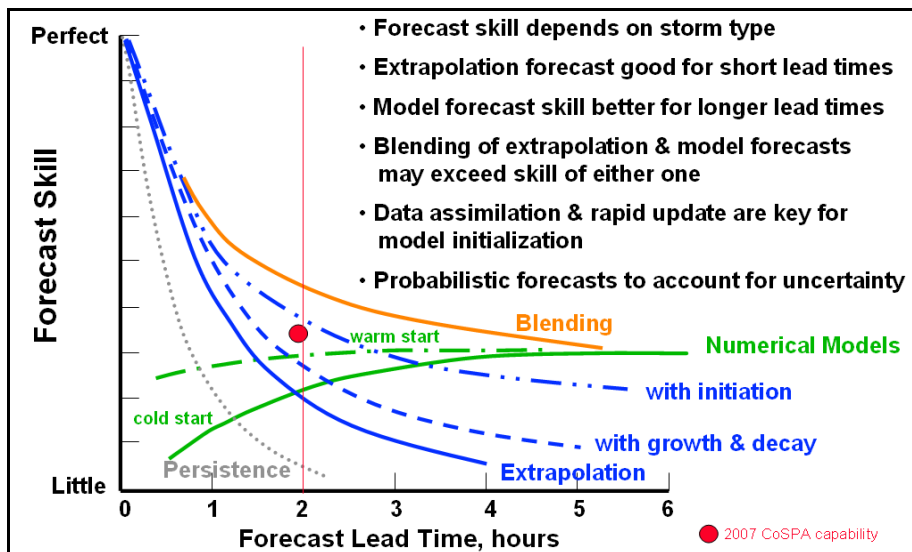


Figure 9. Improving forecast performance at longer lead times will involve use of highly capable numerical models and blending techniques. Cross-over time and blending period will trend closer to current time as NWP systems begin to assimilate radar reflectivity.

One of the most valuable pieces of technology for CoSPA has been the NOAA Space-Time Mesoscale Analysis System, STMAS (Xie et al., 2005). Gridded analyses of surface winds, temperature, dew point, etc. are calculated at 5 km resolution every 15 min over the CONUS, relying on background fields from the RUC and using efficient, novel techniques. These accurate analyses are used within CoSPA to produce very high quality stability fields (e.g., Convective Available Potential Energy), convergence fields, etc. The data are also used in the automated

detection of atmospheric fronts (Bieringer et al., 2006)

#### 2.4.2 Strategic 2-6 hr Forecasts

The creation of viable, operational 2-6 hr forecasts of Precipitation (VIL) and Echo Tops with the reliability and accuracy required for strategic planning in the NAS is perhaps our biggest challenge going forward to 2012 IOC. Improving forecasts in this lead time category requires the incorporation of highly capable numerical modeling results, and the blending of those results

(Pinto, et al., 2006) with the extrapolation-based heuristic models used for 0-2 hr forecasts (Figure 9). The CoSPA 2-6 hr forecasts will be 3 km resolution and updated every hour. Unique forecasts from 2 hrs to 6 hrs in the future will be available in 15 min intervals so that the set may be animated to show forecasted storm evolution.

Benjamin et al. (2008a) and Weygandt et al. (2008a) have demonstrated the advantages of rapid update numerical modeling, and shown significant recent progress in the assimilation of radar reflectivity data and in high resolution numerical modeling. We have determined that viable numerical models for convection require a large increase in resolution - from 13 km models being run operationally today down to 2-3 km - so that the small scale convection can be explicitly resolved. This can be accomplished by running a High-Resolution Rapid Refresh nest (HRRR) within the WRF-Rapid Refresh model (Benjamin et al., 2008b). Currently, NOAA is running an experimental HRRR nest over the northeast corridor at 3-km resolution within the radar-enhanced RUC model (Figure 10), but a large investment in computer resources will be needed to run the CONUS-sized HRRR that is required for CoSPA. Such an investment would benefit the entire FAA Aviation Weather Research Program as well as users of NOAA model results, but it is *most* essential for providing useable storm predictions for aviation. Given the large disruptive impact of summertime convection on air travel, upgrading NOAA computer resources to run these

models that have already been developed should be a national priority.

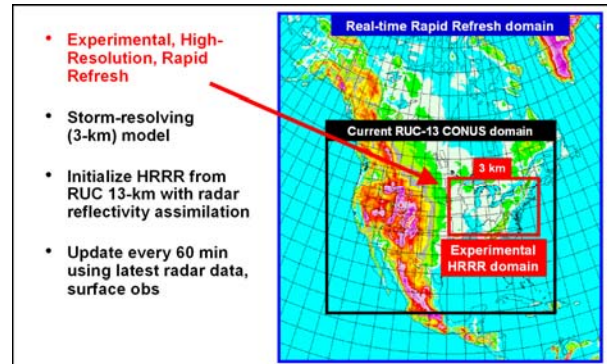


Figure 10. The NOAA Rapid Update Cycle (RUC), Rapid Refresh, and High-Resolution Rapid Refresh domains are shown.

Blending of extrapolation-based forecasts with numerical weather prediction model forecasts is a problem that must be solved to produce seamless 0-6 hr forecasts. Wilson and Xu (2006) and Pinto (2008) have studied this problem extensively and are currently evaluating several different blending techniques, such as trending, weighted averages, variational approaches, and assimilation of 3D nowcast fields. Techniques for advecting the 0-2 hr forecast out to 6 hrs are also being investigated (Morse, 2008). An example of a blending comparison is shown in Figure 11. The final choice of blending technique will involve a trade-off between computational complexity, skill and real-time processing cost considerations.

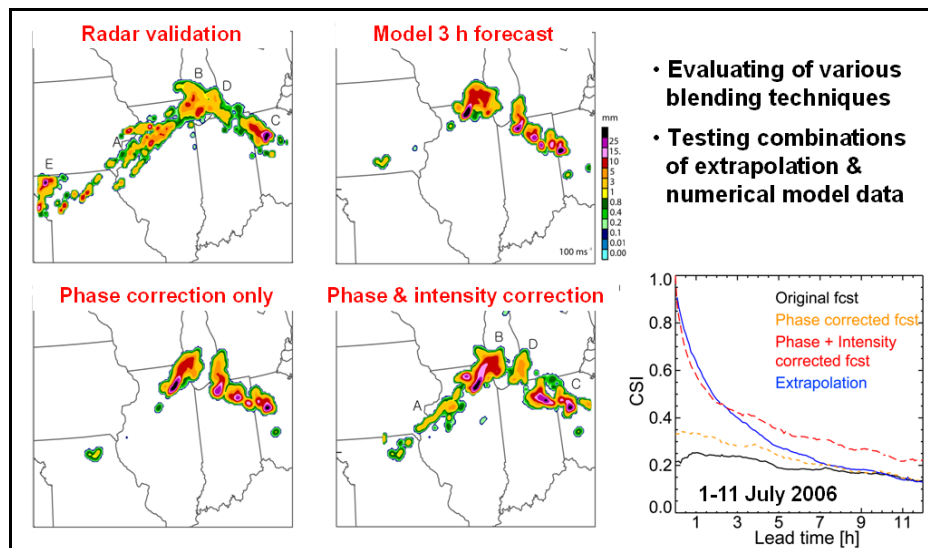


Figure 11. Example of the use of variational techniques to correct model phase and phase plus intensity for both a single storm case (left) and a series of cases in July, 2006 (right).



### 2.4.3 Human-in-the-Loop Activities

The NCAR Autowcaster provides an example technology that enables human interaction with the forecast system, focused particularly on improving regions of convective storm initiation and/or decay. Roberts et al. (2007) assess the value of having forecasters provide input to an otherwise automated forecast system. The NWS currently supports an effort to transfer this capability to the AWIPS. The CoSPA team is evaluating the potential benefits of a human interaction capability with the forecast system for aviation applications.

There is also an outstanding need for diagnosis and forecasts of synoptic fronts (e.g., cold fronts organizing convection and representing significant terminal wind shifts) in FAA aviation weather systems. Currently NWS provides fronts every 3 hrs. We are working with NWS to gauge the feasibility of using a combination of automated front detection technology pioneered at MIT Lincoln Laboratory and NWS expertise to produce hourly (or more frequent) frontal analyses.

### 2.4.4 Weather – Air Traffic Management Integration

NASA has funded initial work in the area of translating weather into traffic flow impacts. The diagnosis of Weather Avoidance Fields – probabilistic fields that show where pilots will and will not fly – reveals that combinations of heavy precipitation and high echo tops regions explain most pilot deviation behavior (DeLaura et al., 2008). Yet there are unexplained subtleties and further research is warranted. Examination of the remotely sensed turbulence fields relative to the convection may be helpful (Williams, et al., 2007).

### 2.4.5 Ongoing Research

Many different research tasks are being performed for the 0-6 hr Forecast as needed for the targeted 2012 IOC demonstrations (Figure 12). In this section we have included a snapshot of an evolving list of necessary research and development activities for the 0-6 hr CoSPA forecast development effort. The relative priority of the tasks is indicated by color coding.

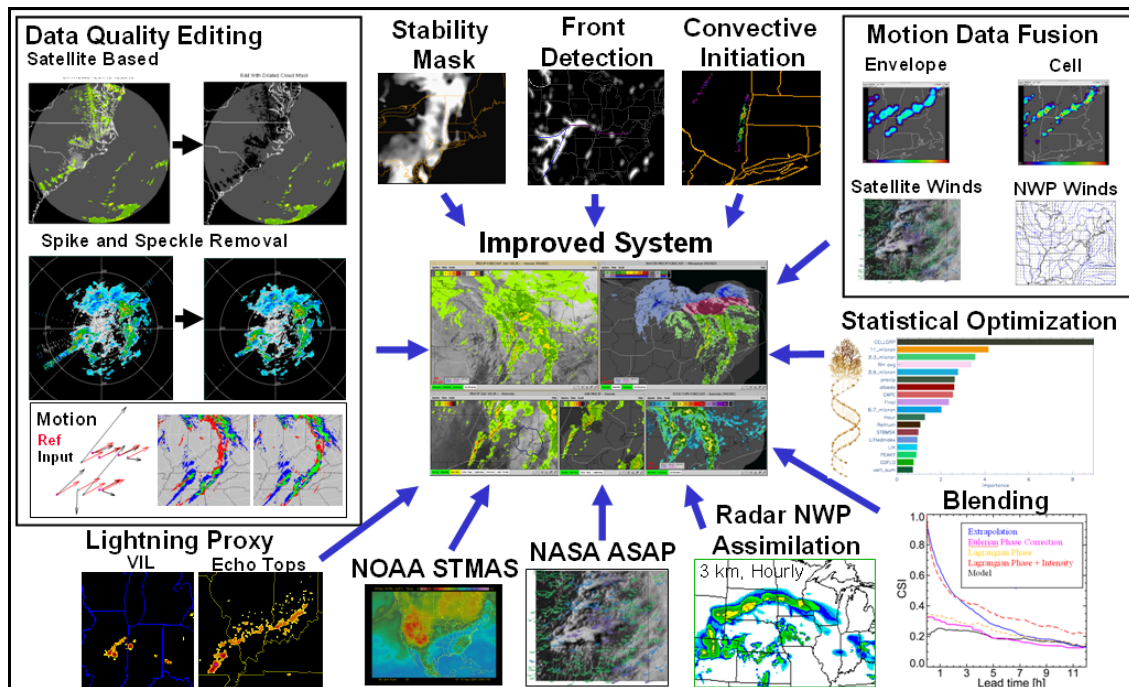


Figure 12. Examples of research funded by FAA, NOAA, and NASA contributing to the CoSPA 0-6 hr Forecast. Laboratories performing the research include NCAR, NOAA ESRL/GSD, NOAA CIMMS, Univ. of Alabama, and MIT Lincoln Laboratory.

## List of Needed Research and Development to Achieve 0-6 hr CoSPA System

This is a list of needed R&D to meet the goal of a single, 0-6 hr consolidated forecast running in demonstration mode, targeted for FAA operations, by 2012. The priority of the various efforts is conveyed by a color code:

red = high  
blue = moderate  
green = low  
black = TBD

### User Interactions

- Define/prioritize users, understand their needs, and develop training materials. Help to integrate forecast products into their decision making, obtain feedback for future product improvements (partnership with FAA CIWS Program)
- Users can be: FAA Traffic Flow managers and/or their Decision Support Systems, Controllers and controller supervisors, Airline dispatchers and pilots, NWS aviation forecasters, Flight service station specialists, Private vendors (e.g., cockpit datalink applications), other government agencies (e.g., Air Force, Homeland Security, etc.)

### System Infrastructure, Design and Development

- Determine system architecture that meets aviation community needs, capitalizes on prior and planned FAA enroute, terminal, sys ops, and AWRP expenditures and enables an easy path to enhanced operations via the inclusion of collaborative components from the aviation weather community
- Work with SWIM, NNEW programs to define common data exchange formats compatible with Open Geospatial Consortium standards and to ensure service-oriented architecture compatible with 4-D Data Cube concepts
- Adopt software/documentation standards that meet or exceed modern government operational systems
- Integrate forecast evaluation/verification procedures into system, automate performance reporting
- Help design user-friendly management and intuitive, scientifically appropriate display of information
- An effective playback system is needed as a platform for testing of new modules and performing regression testing.

### Forecast Algorithm Technology

- **Sensor Mosaic** - Determine best data sources, quantify & improve data quality, optimize mosaics, re-compute cloud-to-ground lightning - high resolution VIL relationship, incorporate dual-polarimetric radar data
- **Analysis Products** - Improve ESRL STMAS grids of surface observations for front detection; improve storm, front and regime classification, determine additional information that can be derived from mix of observations and NWP output, automatically adjust forecast logic as a function of convective weather regime, review and determine final set of predictor fields to be used in forecast logic
- **Forecast Techniques** – Research and develop CoSPA forecast technology for 0-6 hr Aviation Forecasts
  - Extrapolation Vectors: Account for scales of predictability and produce smoothly varying motion with forecast lead time, accounting for known evolution in storm motion
  - Storm Initiation and Evolution: Develop 0-2 hr feature detectors and predictor fields, rewrite “fuzzy function combiner” to reduce degrees of freedom & utilize weights generated by “best” (TBD) optimal multivariate regression techniques
  - Numerical Modeling: Coordinate the path to operations with NOAA ESRL’s activities, improve radar data assimilation, refine and test models (especially including the 3-km HRRR nest inside the RUC/RR) using case studies aviation impact days and real-time preliminary testing
  - Blending Observation-based Forecasts with Numerical Forecasts: Optimally combine obs-based with numerical model forecasts for each aviation hazard field using phase and amplitude adjustments, bias-correct model to match obs (for 2-6 hr fcsts)
  - Climatology: Include logic that utilizes the historical trends in the spatial distribution of storms.
  - Winter Storms: Develop calibrated precip rate (analysis & forecast) based on ASOS surface precip gauges and radar data (adds key WSDDM capability into system), add airport snow accumulation.
  - Oceanic Storms: Add satellite-based 2-D Cloud Top Height (CTOP) and Convective Diagnosis Oceanic (CDO) developed by

Oceanic Weather PDT to depict storms in Oceanic airspace

- **NWS Forecaster Inputs** – Determine role in CoSPA, possibly including a) frequently updated synoptic and mesoscale surface fronts, and b) hand-drawn areas of convective initiation and decay. Explore use of human input for either forecast or uncertainty field or both.

### **Forecast System Outputs**

- **Verification** – Develop real-time system that provides: a) scores to users, b) regression testing for rapidly assessing impacts of system changes, c) web-based interactive and automated performance reporting, including comparisons with persistence & extrapolation-only forecasts, d) sector-based scoring for air traffic capacity impact assessments, e) scoring of probabilistic Weather Avoidance Fields used in coupling with automated decision support systems.
- **Probabilistic Forecast Generation** – Measure forecast uncertainty (based on performance results and/or ensemble estimates) to develop reliable probabilistic forecasts of storm characteristics
- **Legacy Forecast Product Generation** - Generate legacy product equivalents for Convective SIGMET, 2-, 4- and 6-hr CCFP, AIRMET TANGO (turbulence) for high-surface winds
- **Wx-Air Traffic Management Integration** – Collaborate in R&D to define and forecast where pilots will and will not fly, predict capacity, integrate CoSPA into automated decision support tools and TFM displays. Examine remotely sensed turbulence as possible additional factor in explaining observed pilot behavior.
- **Advanced Terminal Products** –Develop new terminal products calculated appropriately on the national scale that utilize CoSPA data sources and algorithms, including: a) snow liquid water equivalent, b) deicing guidance from WSDDM logic using federal and non-federal ASOS precip gauges, c) airport snow accumulation, d) wind shift / frontal passage forecasts with lead times up to 2 hrs, e) strong surface winds with lead times up to 30 min, f) ceiling and visibility diagnoses and 0-2 hr forecasts, g) microburst predictions with lead times up to 30 min.

### **Scientific Review**

- **Monitoring** – The forecasts system performance needs to be monitored both by means of automated statistical scores (see verification) and through human evaluation and case study analysis.
- **Process for Improvements** – An objective pathway needs to be designed that facilitates improved technologies, methodologies, and algorithms, and enables contributions from the larger research community and private sector.
- **High-level Oversight Group** – Because of the importance of CoSPA and its aviation-specific multi-agency goals, consider developing a science, engineering and user oversight group.

### **3. FUTURE WORK: CoSPA ROADMAP**

The road toward IOC demonstrations in 2012 is becoming clearer, and we can think of this as Phase 1 of CoSPA development. Key efforts involve consolidating the 0-2 hr forecasts, initial operations of the 2-6 hr forecasts (both precipitation and echo tops), translating the forecasts into Air Traffic capacity impacts (Weather Avoidance Fields), coupling the forecasts (and uncertainty fields) to Traffic Flow Management decision support tools, working with cockpit data link systems to improve shared storm situational awareness with pilots, and replacing and retiring legacy 0-6 hr forecast systems. We can also begin to look at meeting terminal weather needs from the CONUS-scale algorithms.

Beyond 2012, there are perhaps two additional phases as we head toward NextGen 2025 capabilities. Phase 2 (2012-2018) might include coverage for Alaska, 7-12 hr forecasts, and meeting the weather needs of both large and small terminals. Major additional capabilities for Phase 3 (2018-2025) might include oceanic coverage and forecasts out to 24 hrs. Coordination within the FAA for meeting future weather needs is underway.

### **4. SUMMARY**

CoSPA is a very ambitious effort that consolidates existing aviation storm forecasts into a single system for both summer and winter, and that is specifically geared toward aviation needs and NextGen requirements for improved traffic flow management. Drivers for success will be true consolidation of the 0-2 hr forecasting efforts, advancements in storm-scale numerical weather prediction, techniques for blending of advection-

based and NWP forecasts, and adequate investment in model computing resources. Investment in providing networked access to existing sensor data is also essential. For NextGen goals to be realized, operational tests incorporating the CoSPA forecasts translated into ATC impacts, and the use of those predicted impacts in decision support tools for traffic flow management are essential.

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## 6. REFERENCES

- Ahlstron, Ulf and Thomas G. Dury, 2007: Weather Information for En Route Controllers. Report No. DOT/FAA/TC-07/08 Atlantic City International Airport, NJ: Federal Aviation Administration William J. Hughes Technical Center, 54 pp.
- Benjamin, S., S. Weygandt, J. M. Brown, T. Smirnova, D. Devenyi, K. Brundage, G. Grell, S. Peckham, T. W. Schlatter, T. L. Smith, and G. S. Manikin, 2008a: Implementation of the radar-enhanced RUC. 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- Benjamin, S., J. Brown and S. S. Weygandt, 2008b: High-frequency updating of weather model prediction in the NextGen era. 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- Bieringer, P., J. Morgan, J. Hurst, B. Martin and S. Winkler, 2006: An Assessment of Automated Boundary and Front Detection to Support Convective Initiation Forecasts, 12<sup>th</sup> Conf. on Aviation, Range and Aerospace Meteorology, Atlanta, GA., Amer. Met. Soc.
- DeLaura, R., M. Robinson, M. Pawlak, and J. Evans, 2008: Modeling Weather Avoidance in Enroute Airspace. 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- Dupree, W.J., M. Robinson, R. DeLaura, and P. Bieringer, 2006: Echo Top Forecast Generation and Evaluation of Air Traffic Flow Management Needs in the National Airspace System. 12<sup>th</sup> Conf. on Aviation, Range, and Aerospace Meteorology, January 2006, Atlanta, GA, Amer. Met. Soc.
- Evans, J., M. Robinson, and S. Allan, 2006: Quantifying Convective Delay Reduction. Benefits for Weather/ATM Systems, 6<sup>th</sup> USA/Europe Seminar on Air Traffic Management Research and Development, ATM-2005, <http://atmseminar.eurocontrol.fr/>, Baltimore, MD.
- Evans, J.E. and E.R. Ducot, 2006a: Corridor Integrated Weather System. The Lincoln Laboratory Journal, 16, No.1, pp. 59-80. [http://www.ll.mit.edu/news/journal/pdf/vol16\\_no1/16\\_1\\_4EvansDucot.pdf](http://www.ll.mit.edu/news/journal/pdf/vol16_no1/16_1_4EvansDucot.pdf)
- Iskenderian, H., 2008: loud-to-ground lightning as a proxy for nowcasts of VIL and echo tops. 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- MCR Federal, Inc., 2001: FAA Terminal Convective Weather Forecast Benefits Analysis Report, No. TR-7100/029-1.
- Megenhardt, D.L., et al. 2004: NCWF-2 Probabilistic forecasts. 11<sup>th</sup> Conference on Aviation, Range and Aerospace, Hyannis, MA, Amer. Meteor. Soc. 23 pp.
- Mitchell, J. S. B., V. Polishchuk, and J. Krozel, 2006: Airspace throughput analysis considering stochastic weather. AIAA Guidance, Navigation, and Control Conference, Keystone, Colorado, 19 pp.
- Morse, D., 2008: Personal communication.
- Mueller, C., T. Saxen, R. Roberts, J. Wilson, T. Betancourt, S. Dettling, N. Oien and J. Lee, 2003: NCAR Auto-nowcast system, *Wea Forecasting*, **18**, 545 – 561.
- Pinto, J., C. Mueller, S. Weygandt, D. Ahijevych, N. Rehak, and D. Megenhardt(2006): Fusing Observation-AND Model-Based Probability Forecasts for the Short-term Prediction of Convection
- Pinto, J., H. Cai, G. Lee, J. W. Wilson, M. Steiner, R. Bullock, D. Albo, S. S. Weygandt, and C. L. Phillips, 2008: Beyond Nowcasting of Thunderstorms: An Assessment of Various Blending Techniques for Increased Forecasting Skill at 2 - 6 h Lead Times. 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- Rasmussen, R., M. Dixon, F. Hage, J. Cole, C. Wade, J. Tuttle, S. McGettigan, L. Stevenson, W. Fellner, S. Knight, E. Karplus and N. Rehak, 2001: Weather

- Support to Deicing Decision Making (WSSDM): A Winter Weather Nowcasting System. Bull. Amer. Meteorol. Soc., 82(4), 579-596.
- Roberts, R. (2008): Personal communication.
- Roberts, R., E. Nelson, J. Pinto, T. Saxen, and C. Phillips, 2007: Status of Nowcasting Thunderstorm Initiation: Where do we go from here?, 33<sup>rd</sup> Conf. on Radar Meteorology, Amer. Met. Soc.
- Robinson, M., J. Evans, B. Crowe, D. Klinge-Wilson and S. Allan, 2004: CIWS Operational Benefits 2002-3: Initial Estimates of Convective Weather Delay Reduction, MIT Lincoln Laboratory Project Report ATC-313 (9 April 2004).
- Robinson, M., J. Evans, and T. Hancock, 2006: Assessment of Air Traffic Control Productivity Enhancements from the Corridor Integrated Weather System (CIWS), Lincoln Laboratory Project Report ATC-325.
- Smalley, D. E. Mann, C. Ivaldi and B. Bennett, 2008: Improving Weather Radar Data Quality for Aviation Weather Needs. 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- Steiner, M., C.K. Mueller, G. Davidson, and J. Krozal, 2008: Integration of Probabilistic Weather Information with Air Traffic Management Decision Support Tools: A Conceptual Vision for the Future. 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- Stobie, J., A. Moosakhanian, P. Jackson, and W. N. Brown, 2008: Evolution of FAA's Weather and Radar Processor (WARP) into the Next Generation Air Transportation System (NextGen) 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- Wanke, C. and D. Greenbaum, 2007: Incremental, Probabilistic Decision Making for Enroute Traffic Management, 7<sup>th</sup> USA/Europe Seminar on Air Traffic Management Research and Development, ATM-2007, [http://atmseminar.eurocontrol.fr/all-seminars/atm-seminar-2007/papers\\_calendar](http://atmseminar.eurocontrol.fr/all-seminars/atm-seminar-2007/papers_calendar)
- Weygandt, S.S., S. Benjamin, and J. Brown, 2008a: Assimilation of radar reflectivity using a diabatic digital filter within the Rapid Update Cycle. *Preprints 13<sup>th</sup> Conf. Aviation, Range and Aeronautics Meteor.*, New Orleans, LA, AMS.
- Weygandt, S., S. Benjamin, T. G. Smirnova, J. M. Brown, and K. J. Brundage, 2008b: Hourly convective probability forecasts from an experimental RUC with radar data assimilation. 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- Williams, J.K., NCAR, Boulder, CO; and D. A. Ahijevych, C. J. Kessinger, T. R. Saxen, M. Steiner, and S. Dettling, 2008: A machine learning approach to finding weather regimes and skillful predictor combinations for short-term storm forecasting. 13<sup>th</sup> Conference on Aviation, Range and Aerospace Meteorology, 21-24 January 2008, New Orleans, Amer. Met. Soc.
- Williams, J.K., J. Craig, A. Cotter, and J. K. Wolff, 2007: A Hybrid Machine Learning and Fuzzy Logic Approach to CIT Diagnostic Development, Proceedings, 5<sup>th</sup> Conf. on Artificial Intelligence Applications to Environmental Science, Amer. Met. Soc.
- Wilson, J., and M. Xu, 2006: Experiments in Blending Radar Echo Extrapolation and NWP for Nowcasting Convective Storms, Proceedings, *Fourth European Conference on Radar in Meteorology and Hydrology*, Barcelona, Spain, 519-522
- Wolfson, M.M., B.E. Forman, K.T. Calden, R.A. Boldi, W.J. Dupree, R.J. Johnson, C. Wilson, P.E. Bieringer, E.B. Mann, and J.P. Morgan, 2004: Tactical 0-2 Hour Convective Weather Forecasts For FAA, 11th Conf. on Aviation, Range, and Aerospace Meteorology, 4-8 Oct. 2004, Hyannis, Mass., Amer. Met. Soc.
- Wolfson, M.M. and D.A. Clark, 2006: Advanced Aviation Weather Forecasts. The Lincoln Laboratory Journal, 16, No.1, pp. 31-58. [http://www.ll.mit.edu/news/journal/pdf/vol16\\_no1/16\\_1\\_3Wolfson.pdf](http://www.ll.mit.edu/news/journal/pdf/vol16_no1/16_1_3Wolfson.pdf)
- Xie, Y, S. E. Koch, J. A. McGinley, S. Albers, and N. Wang, 2005: A Sequential Variational Analysis Approach for Mesoscale Data Assimilation. 21<sup>st</sup> Conf. on Weather Analysis and Forecasting / 17<sup>th</sup> Conf. on Numerical Weather Prediction.

APPENDIX A: Comparison of 0-12 hour Storm Diagnostic and Forecast Systems.<sup>1</sup> This is a modified version of a table that was first presented in the FAA Aviation Weather Roadmap, Vol. II: Convection (2004). CoSPA will seek to build on these capabilities.

Product	Key Features of product	Local, Regional, National	Update Rate (min)	Spatial resolution (km)	Lead Time (hours)	Loop Interval (if animated) (min)	Human Involvement (Yes/No)	Deterministic or Probabilistic
<b>Convective SIGMET</b>  <b>Issued by:</b> <b>Aviation Weather Center, NWS</b>  <b>Intended customer:</b> <b>Meteorologists and Aviation</b>	Severe or Embedded Thunderstorms occurring for more than 30 minutes  Line of thunderstorms  Area of active thunderstorms	National	60	Any occurrence  111 km  10,290 km <sup>2</sup>	2	N/A	Yes	Deterministic forecast of coverage > 40%
<b>CCFP</b>  <b>Issued by:</b> <b>Aviation Weather Center</b>  <b>Intended customer:</b> <b>Aviation</b>	Collaborative Effort	National	120	Must be an area > 10,290 km <sup>2</sup> or line > 111 km (with > 40 dbz, > 25Kft)	2,4,6	N/A	Yes	Deterministic forecast of coverage (25, 50, 75%) incl. forecaster confidence
<b>International SIGMET</b>  <b>Issued by:</b> <b>Aviation Weather Center</b>  <b>Intended customer:</b> <b>Aviation</b>	Obscured  Embedded  Frequent  Squall line	Hemi-spherical	240	10,290 km <sup>2</sup> except obscured, embedded, and squall line which have no minimum	4	N/A	Yes	Deterministic
<b>CWA (Center Weather Advisory)</b>  <b>Issued by:</b> <b>CWSU Meteorologists</b>  <b>Intended customer:</b> <b>CWSU Meteorologists, FAA Users, in-flight air crews</b>	Unscheduled weather advisory	National	As needed	Any occurrence	2	N/A	Yes	Deterministic
<b>NCWF-1</b>  <b>Issued by:</b> <b>Aviation Weather Center on ADDS</b>  <b>Intended customer:</b> <b>Meteorologists and Aviation Users</b>	Convection tracked using Titan with 1-hr extrapolation	National	5	Storm scale	1	N/A	No	Deterministic

Product	Key Features of product	Local, Regional, National	Update Rate (min)	Spatial resolution (km)	Lead Time (hours)	Loop Interval (if animated) (min)	Human Involvement (Yes/No)	Deterministic or Probabilistic
<b>NCWF-2</b>  <b>Issued by:</b> <b>Currently experimental on ADDS</b>  <b>Intended customer:</b> <b>Meteorologists and Aviation Users</b>	Convection tracked using Titan VIL based RUC model output and lightning data included	National	5	4	2	30	No	Probabilistic
<b>NCWF-6</b>  <b>Issued by:</b> <b>Currently experimental</b>  <b>Intended customer:</b> <b>Meteorologists and Aviation Users</b>	Blends extrapolated and model forecast of convection	National	15	4	6	60	No	Probabilistic
<b>Layered Reflectivity Products</b>  <b>Issued by:</b> <b>FAA WARP</b>  <b>Intended customer:</b> <b>Air Traffic</b>	Mosaics of NEXRAD layered products for 3 altitude bands (reflectivity, echo tops)	National	Mosaic remade when any radar updates	4	N/A	N/A	No	N/A
<b>TCWF</b>  <b>Issued by:</b> <b>FAA ITWS</b>  <b>Intended customer:</b> Air Traffic, Airlines	VIL-precip Winter mode Growth and Decay Fuzzy Logic based with NEXRAD, TDWR and RUC inputs	Local	VIL, ET 2.5 min  Fcsts of VIL 5 min	1	1	10 [30 min in past to 1 hr in future]	No	Deterministic
<b>CIWS 0-2 hr Forecast</b>  <b>Issued by:</b> <b>FAA Concept exploration prototype system</b>  <b>Intended customer:</b> Air Traffic, Airlines	VIL-precip and Echo Tops Fcst Rain/snow line Winter mode  G&D, Initiation, Fuzzy Logic based with multiple inputs (including NEXRAD, TDWR, CanRad, RUC, STMAS, ASOS, lightning and satellite data)	Regional	VIL, ET 2.5 min  Fcsts of VIL, ET 5 min	1	2	5 [1 hour in past to 2 hrs in future]	No	Deterministic and Probabilistic

Product	Key Features of product	Local, Regional, National	Update Rate (min)	Spatial resolution (km)	Lead Time (hours)	Loop Interval (if animated) (min)	Human Involvement (Yes/No)	Deterministic or Probabilistic
<b>Autonowcaster</b>  <b>Issued by:</b> <b>NWS</b> <b>Experimental product</b>  <b>Intended customer:</b> <b>WFO</b> <b>Meteorologists and Aviation users</b>	Initiation, Growth and Decay Fuzzy Logic based with multiple inputs (including NEXRAD, RUC, VDRAS, ASOS, lightning and satellite data)	Regional	5	1	1,2	N/A	Yes	Deterministic
<b>Convective Outlook</b>  <b>Issued by:</b> <b>Storm Prediction Center, NWS</b>  <b>Intended Customer:</b> <b>Meteorologists</b>	Day 1,2,3 narrative and graphic depicting severe thunderstorm threats across the U.S.	National	Day 1 0600Z, 1300Z, 1630Z, 2000Z, 0100Z	Graphical depiction of areas of severe weather	1,2, and 3 day outlooks	N/A	Yes	Deterministic and Probabilistic
<b>TAF</b>  <b>Issued by:</b> <b>Weather Service Offices, NWS</b>  <b>Intended customer:</b> <b>Aviation users</b>	Terminal Area Forecast	Local (5 nm from terminal)	240	5 nm	Out to 24 hrs	N/A	Yes	Deterministic and Probabilistic
<b>RUC Convective Prob forecast</b>  <b>Issued by:</b> <b>NCEP</b>  <b>Intended customer:</b> <b>Meteorologists and Aviation Users</b>	Assimilates latest obs, provides rapid update	National	60	13	1,2,3, 4,5,6, 7,8,9, 10,11,12	N/A	No	Probabilistic
<b>WSDDM</b>  <b>Issued by:</b> <b>Airport and airlines through a private vendor</b>  <b>Intended customer:</b> <b>Airlines and airports</b>	Winter focus, Reflectivity based Real-time snow gauges Calibrated Terminal precip rate	Local to Regional	5	1	1	N/A	No	Deterministic

1 Other storm forecasts not included here: TWEB Route Forecast, FA (Area Forecast) GFA proposed, High and low Level Sig Wx Charts, and Severe Weather Watch/Warnings.