Advanced Aviation Weather Forecasts

Marilyn M. Wolfson and David A. Clark

The U.S. air transportation system faces a continuously growing gap between the demand for air transportation and the capacity to meet that demand. Two key obstacles to bridging this gap are traffic delays due to en route severe-weather conditions and airport weather conditions. Lincoln Laboratory has been addressing these traffic delays and related safety problems under the Federal Aviation Administration's (FAA) Aviation Weather Research Program. Our research efforts involve real-time prototype forecast systems that provide immediate benefits to the FAA by allowing traffic managers to safely reduce delay. The prototypes also show the way toward bringing innovative applied meteorological research to future FAA operational capabilities. This article describes the recent major accomplishments of the Convective Weather and the Terminal Ceiling and Visibility Product Development Teams, both of which are led by scientists at Lincoln Laboratory.

The ability to provide accurate weather forecasts to air traffic managers and controllers plays a very important role in assuring that the nation's airliner flights will remain safe and on schedule. Lincoln Laboratory has been pursuing these goals as part of the Federal Aviation Administration's (FAA) Aviation Weather Research Program (AWRP) since it began formally in 1997. The AWRP is organized into different collaborative product development teams (PDT), with Lincoln Laboratory taking the lead on the Convective Weather (CW) PDT (led by Marilyn M. Wolfson) and the Terminal Ceiling and Visibility (TC&V) PDT (led by David A. Clark). In this article, we provide a summary of our accomplishments on these teams and the operational products that have been developed over the last decade.

Historically, Lincoln Laboratory has been very concerned with weather-related safety in the terminal area, beginning with our work on the Terminal Doppler Weather Radar (TDWR) [1], designed to sense hazardous low-altitude wind shear, and continuing with the development of automatic, reliable, real-time wind-shear detection algorithms [2, 3]. By working with the airport traffic control supervisors at several airports, the FAA recognized the need for a more comprehensive picture of weather in and around the terminal areas. The Integrated Terminal Weather System (ITWS) [4] was designed to fill this need, combining the wind-shear and gust-front detections from the TDWR with long-range weather radar depictions and storm-motion vectors from the Next-Generation Weather Radars (NEXRAD) associated with the National Weather Service (NWS), the FAA, and the Department of Defense. It became clear that in addition to helping on the safety side, ITWS was actually helping manage the tactical maneuvering that results when unforecasted thunderstorms occur. The Corridor Integrated Weather System (CIWS) [5] concept exploration demonstration was fielded when it became clear that terminal operations in the Northeast actually stretched over several states and covered both en route and terminal airspace in a busy corridor configuration, as shown in Figure 1.

Convective Weather Forecasts

Strategic air traffic planning takes place daily in the

National Airspace System (NAS) and two-to-six-hour forecasts are utilized, but these early plans remain unaltered in only the most predictable of convective weather scenarios. More typically, traffic flow managers at the Air Traffic Control System Command Center and the Air Route Traffic Control Centers (ARTCC) together with airline dispatchers help flights to utilize jet routes that remain available within regions of convection, or facilitate major reroutes around convection, according to the available playbook routes. For this tactical routing in the presence of convective weather to work, the FAA recognized that both a precise and a timely shared picture of current weather is required, as well as an accurate, reliable, short-term zero-to-two-hour forecast. Figure 2 illustrates the crucial need for such forecasts to help reduce the system-wide and airport-specific delays that are so prevalent in the summer months. This is especially important as the economy grows, traffic demands approach full capacity at the pacing airports, and more jets, including regional jets, seek to utilize the same en route jetways.

In this article we describe the most recent version of the zero-to-two-hour convective weather forecast (CWF) algorithm. Previous versions are currently being utilized in the ITWS (one-hour version [6]) and the CIWS (two-hour version [7, 8]) proof-of-concept demonstrations. Some of this forecast technology is also being utilized in the National Convective Weather Forecast (NCWF) run at the Aviation Weather Center [9], in the NCAR Auto-nowcaster [10], and in various private-vendor forecast systems.

Tactical Zero-to-Two-Hour Convective Weather Forecast Algorithm

The tactical zero-to-two-hour CWF algorithm is fundamentally a multiscale storm-tracking algorithm that internally determines the type and strength of existing storms—their motion, their growth and decay trends, and the locations of new storm initiation—and forecasts their evolution on the basis of models developed from thunderstorm case studies. A schematic overview of the CWF algorithm processing is presented in

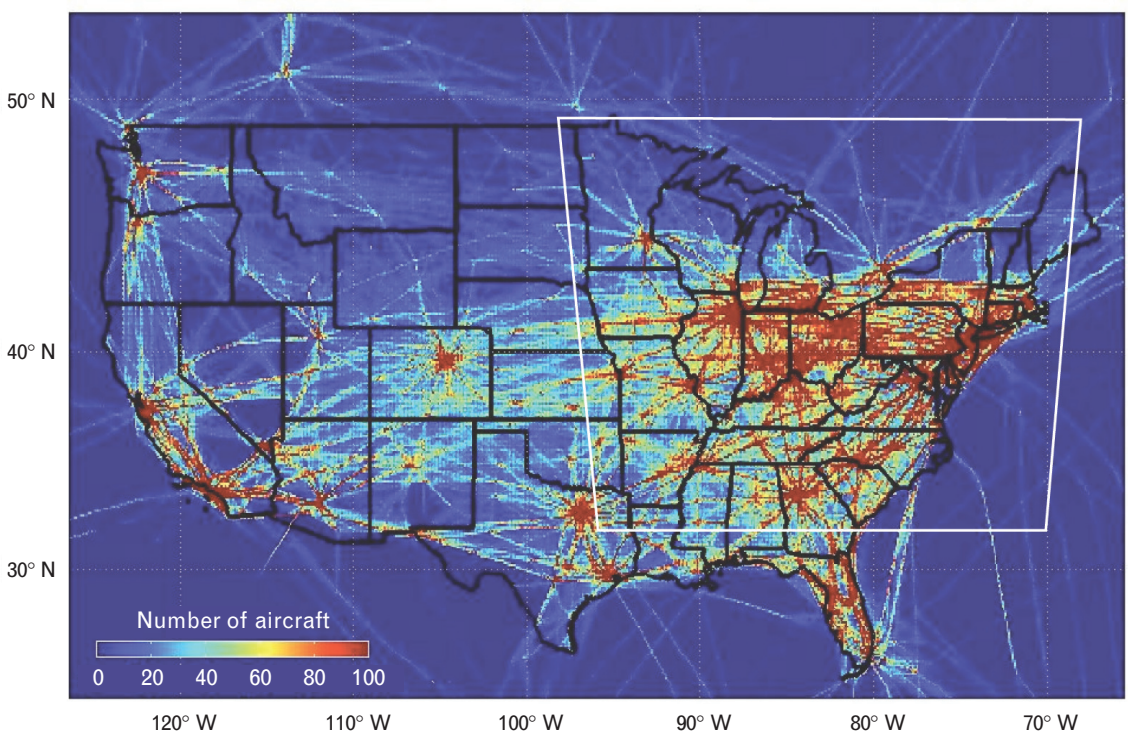

FIGURE 1. Fair-weather air traffic density, illustrating the geographic component of the delay problem. Most of the air traffic occurs primarily in a triangle formed by Chicago, Boston, and Atlanta, with extreme density over New York. The density scale is the number of aircraft en route in a twenty-four-hour period.

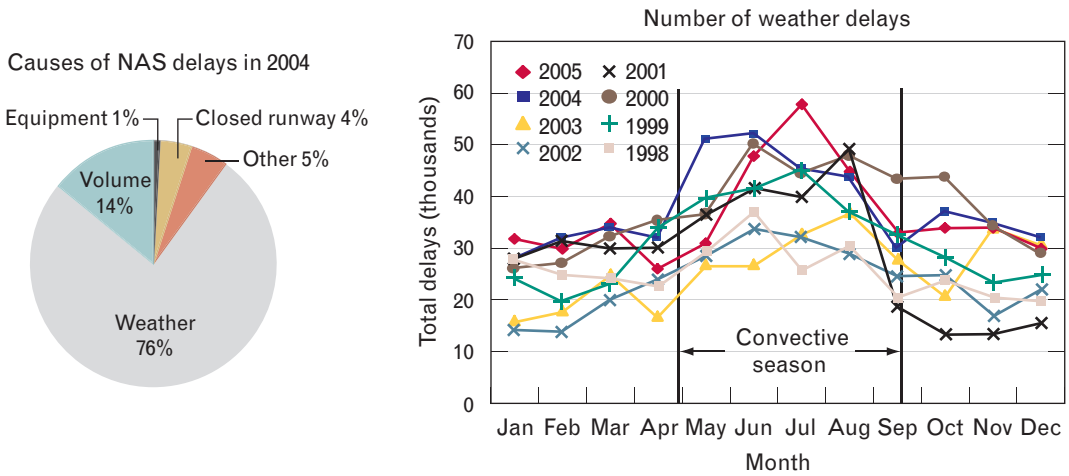

FIGURE 2. Aviation delay problem. Weather delay statistics illustrating (a) causes of National Airspace System (NAS) delays (notice that three-fourths of the aviation delays are due to weather), and (b) the annual pattern of weather delays as a function of month of the year for the last eight years. Note that most of weather delays occur during the convective season.

Figure 3. The diagram is color coded to indicate the input data (white), the main thread producing the precipitation vertically integrated liquid water (VIL) forecast (tan), the coupled echo tops forecast (orange), and the recent precipitation-phase forecast thread (blue). The FAA traffic flow managers have expressed considerable interest in whether the precipitation shown was falling as snow, rain/snow mix, or rain. The tight coupling of en route operations to what is taking place in the terminal areas in the corridor, and the difference between terminal operations in snow versus rain (such as visibility falling below minimums, snow-plowing operations closing runways, and different rules governing takeoff times after de-icing) explain this concern.

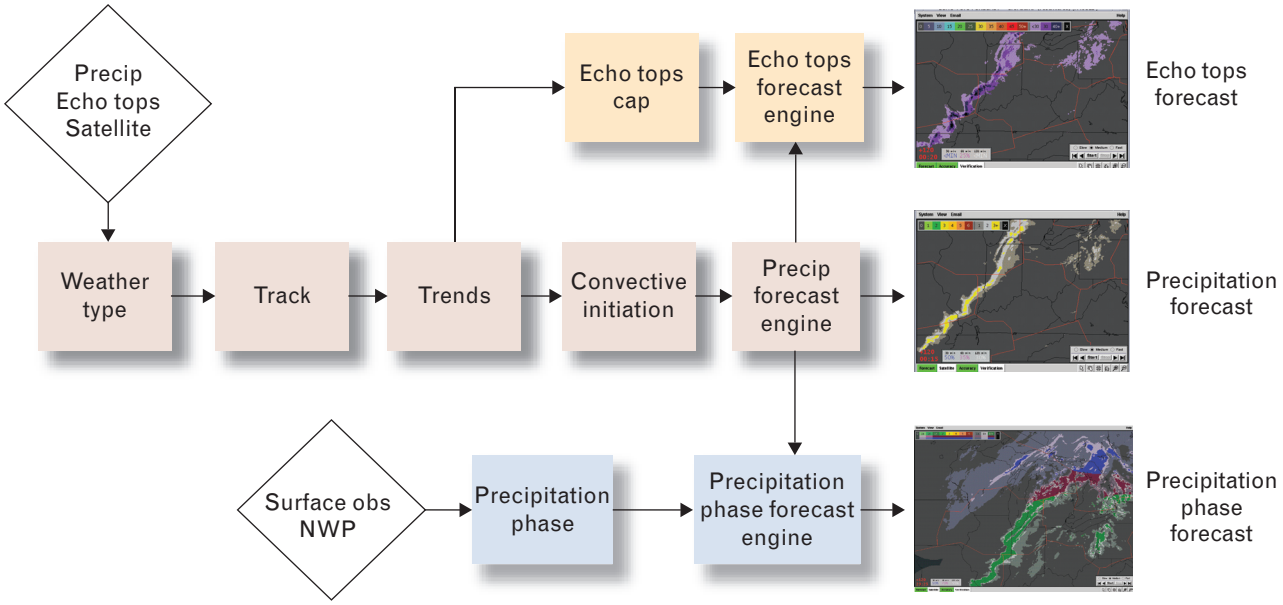

FIGURE 3. Convective weather forecast functional flow, showing a simplified functional flow diagram of the forecast algorithm. There are three main threads: the echo tops forecast shown in orange, the precipitation shown in tan, and the precipitation phase shown in blue. The image data are in 1 km resolution, with five-minute update rates and zero-to-two-hour forecast loops. NWP stands for Numerical Weather Prediction.

This precipitation-phase forecast has been a collaborative development effort between the CW and TC&V teams, and is discussed again later.

Input Data

Currently the algorithm handles input from the NEXRAD, the TDWR, and the Canadian network of pencil-beam radars. The initial work of the Convective team pioneered the use of high-resolution VIL as a more proportionate representation of the convective precipitation hazard to aviation than the previously used quantities such as composite reflectivity [11] or base reflectivity [12]. We also provided an improved, high-resolution version of radar echo tops that has proven extremely important to en route decision making [13]. The FAA was able to insert the new high-resolution products into the NEXRAD Open Radar Products Generator, thus making them available as NEXRAD products for potential use in legacy operational NWS and FAA weather systems [14]. Not depicted in Figure 3 are a series of data-quality editing steps executed to eliminate clutter and point targets in the radar data before algorithm processing occurs. In addition to radar data, geostationary satellite data (visible and infrared bands); surface observations of winds, temperature, and dew point; and numerical weather prediction model data are incorporated into the algorithm.

Weather Type

Weather classification provides the underlying scheme used to assign specific phenomenological behavior in subsequent forecast evolution models. W.J. Dupree et al. introduced the convective weather classification scheme that extracts lines, cells, and stratiform precipitation regions from VIL images [8]. Figure 4 shows

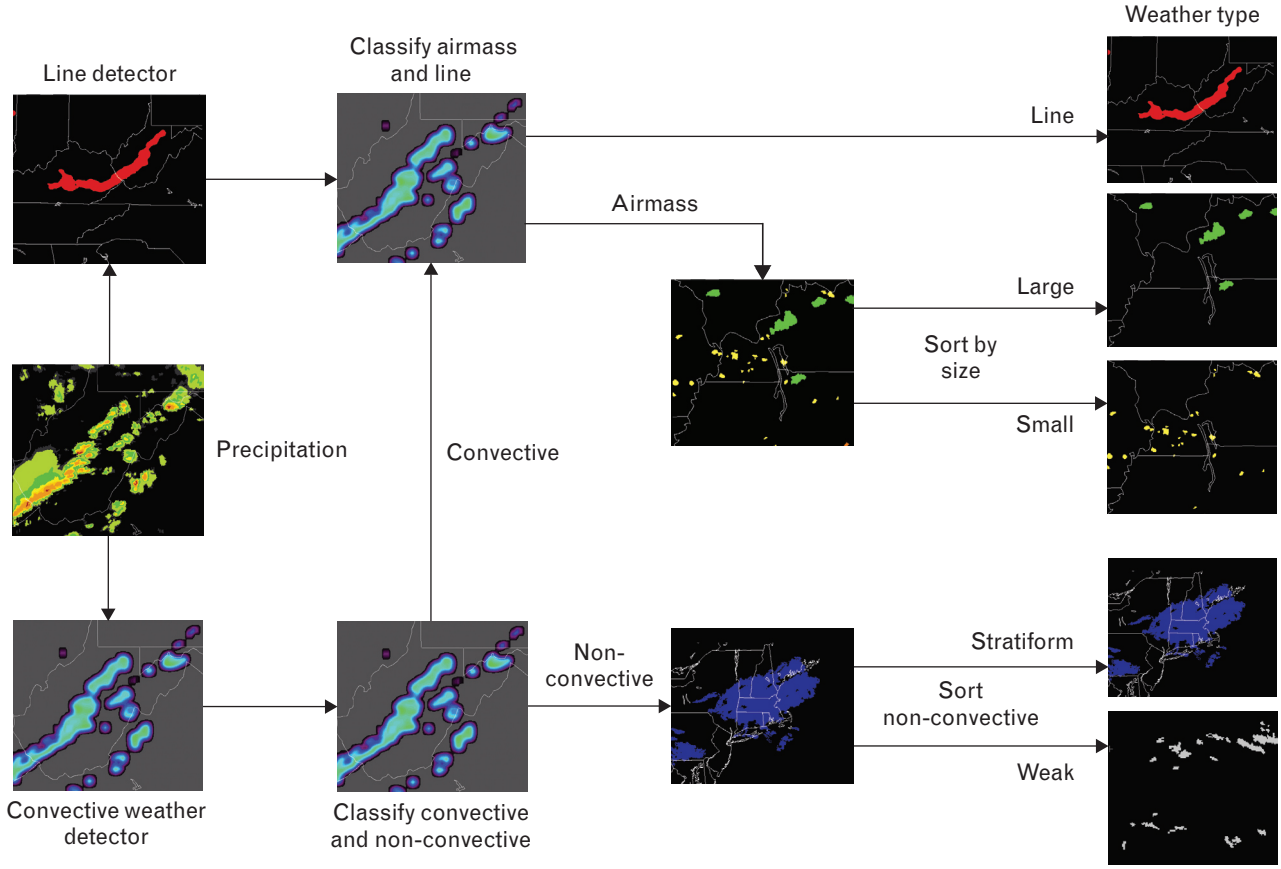

FIGURE 4. A simplified flow diagram for the weather type algorithm. The algorithm steps include the fundamental line- and convective-weather interest detections using functional template correlation and region analysis, secondary interest detections using thresholding and region size sorting on convective and non-convective elements, and a rule-based precedence ordering where the primitive images are used to assemble the final weather classification image.

this classification algorithm and the corresponding images. With the application of functional template correlation techniques and image processing region analysis, weather features are extracted and used to sort the pixels into specific categories [15]. This approach not only classifies the radar returns as convective or nonconvective but also assigns them a distinct phenomenological class. This algorithm was later enhanced to use additional input fields (echo tops, growth and decay trends), and to provide growing and decaying sub-type categories [7]. Figure 5 gives an example of a weather type image for a convective day in Florida.

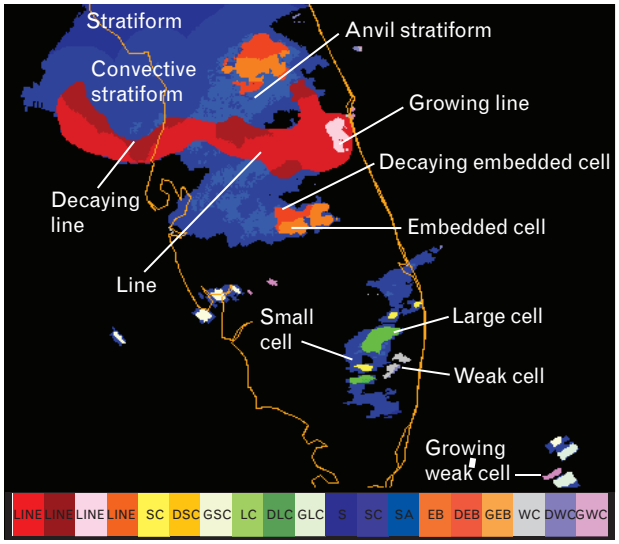

FIGURE 5. Example of a weather type image for a convective day in Florida.

Tracking

The tracking problem for convective weather is scale dependent, and we have found advantage in running both a large-scale envelope or line and a small-scale cell-tracking configuration on each radar data set. The cell vectors better capture the motions of individual cells within a storm complex, while the envelope and line vectors better capture the motions of the entire storm structure. A cross-correlation tracking method is employed to obtain the speed and direction of storm cells and storm envelopes [16]. In order to impose some uniformity on the vector motion field without constraining the vectors in a way that prohibits accurate portrayal of the widely varying motions, we constrain the vectors to permit only small deviations from a local mean.

Figure 6 shows the process of the multiscale tracking algorithm, using full sets of both cell and envelope/line vectors from every radar. The multiscale algorithm provides a single combined vector field appropriate for advecting the data forward in time by sorting the vectors according to weather type, conditioning the vectors (because the motion detected by the different ra-

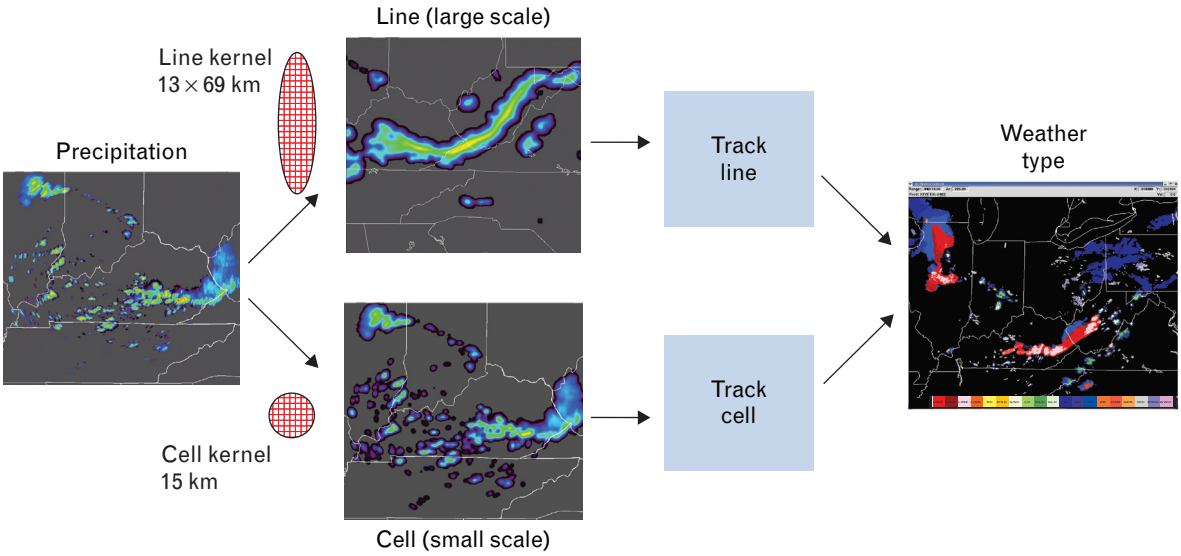

FIGURE 6. Multiscale tracking module takes the line (envelope) and cell sets of track vectors from each radar and sorts them according to weather type, providing the appropriate motion to each area of weather.

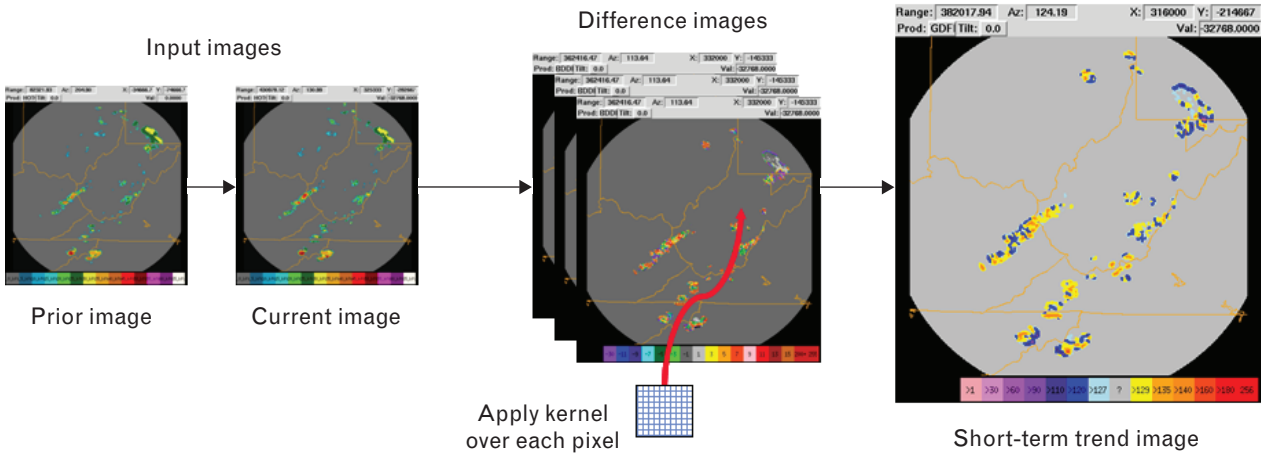

FIGURE 7. Growth and decay trends. Trending of vertically integrated liquid (VIL) precipitation and echo top heights is done by advecting previous images to the current time and computing the difference. Two or more difference images are averaged to produce the averaged difference image. A series of detectors are then applied to produce the growth and decay trends interest image. The images shown are echo tops trends.

dars needs to be reconciled), and interpolating values into the regions with no detected motion.

Growth and Decay Trends

The growth and decay trends algorithm consists of a large suite of image processing feature detectors that produce interest images used in the forecast combination. The fundamental image processing step for several of the feature detectors is the differencing of two VIL or two echo tops images, as shown in Figure 7. A prior image is advected to the current time with a set of vectors that capture the desired scale of motions. The cell vectors are used for the short term trend image, while the envelope vectors are used for the long-term trend image. Once the prior image is aligned in time with the current image, the two images are subtracted. This difference image represents the change in VIL or echo tops over the given time period.

When several adjacent small cells grow nearly simultaneously and form a linear pattern, it is likely

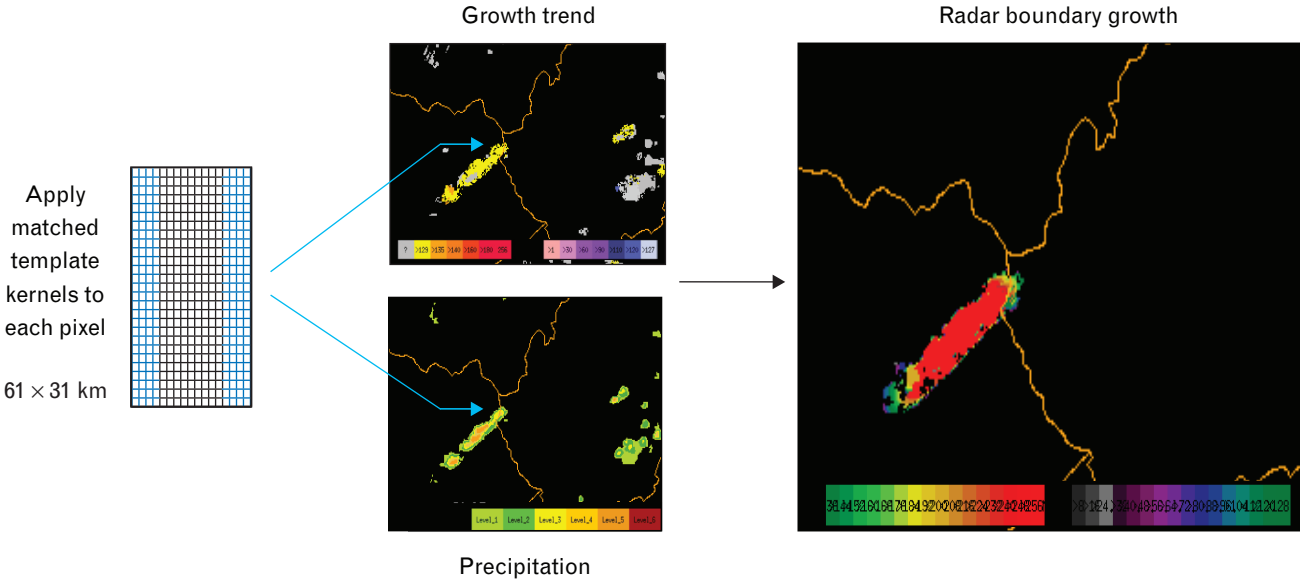

FIGURE 8. Illustration of radar-boundary-growth feature detector, which finds linearly oriented regions of growing cells.

there is some surface boundary or frontal forcing taking place. Figure 8 shows this special case, which when observed usually warrants fairly aggressive and rapid growth of the cells into a line storm. By assessing the short-term trend and the current VIL images, the boundary growth feature detector returns an interest image that represents regions of linearly aligned growth.

Convective Initiation

The initiation of new convection is one of the most difficult challenges in short-term CWF. Because no amount of tracking or trending of the current radar data will help predict new growth, new information sources must be brought to bear on the problem. Numerical weather prediction models will some day be the best way to make forecasts, but they suffer at the moment from being computationally demanding and expensive to run with the techniques and resolutions required, while still providing no improvement in forecast performance over the type of heuristic system described here, at least in the zero-to-two-hour forecast time frame [17]. The visible geostationary satellite data can be very helpful in depicting (in daylight hours) small clouds before they become large thunderstorms, and trends in the infrared bands can pick up the cloud top cooling associated with early storm growth [18]. Also valuable is an indication of where the surface cold and warm fronts are in the atmosphere, since convection tends to organize along these lines [19]. Finally, knowledge of the environmental winds, temperature, moisture, and overall stability is essential in determining whether or not convection will take place.

We have chosen to initially implement a partial but highly reliable solution to the convective initiation problem by extending the growth of line storms along frontal boundaries. Long lines of storms that block traffic at en route flight levels are particularly prob-

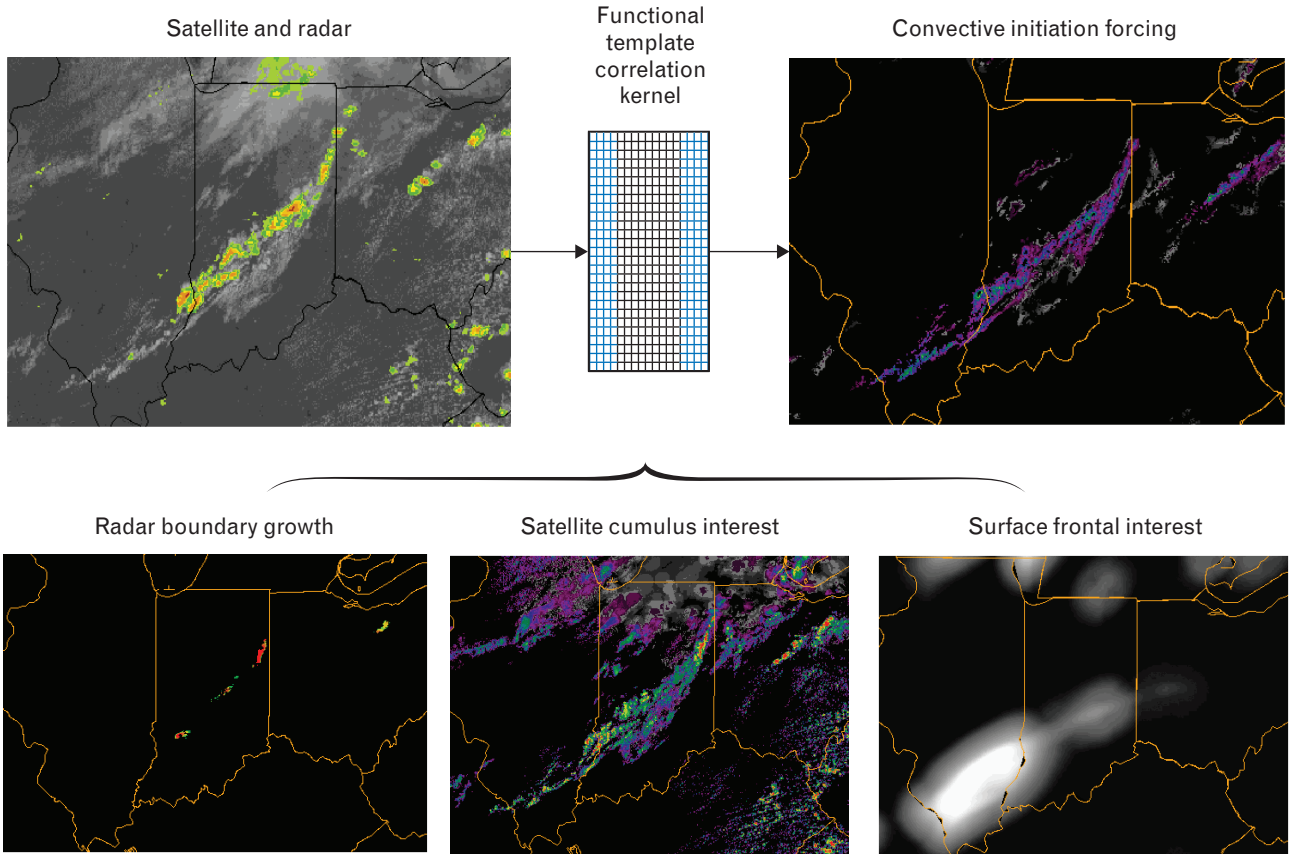

FIGURE 9. Line-storm convective initiation. The illustration combines the radar boundary growth, the satellite cumulus interest, and the surface frontal interest fields at 1715 GMT on 20 August 2005 (lower three images) with the original radar data using functional template correlation to yield the convective initiation forcing field.

lematic for aviation, and anticipating this growth will provide real immediate benefits. The convective initiation module, shown in Figure 9, uses visible satellite data processed to highlight small, bumpy cumulus and cumulus congestus clouds, the radar boundary growth signature, and the automatically detected locations of the surface fronts. The CWPDT has strongly emphasized automatic front detection, and recent techniques pioneered at Lincoln Laboratory led to a breakthrough in this area. See the sidebar, "Automated Front Detection to Support Convective Initiation Forecasts," for an explanation of this technique. Figure 10 provides examples of the improved one-hour and two-hour forecasts made with the partial convective initiation logic. Particular improvement is shown in southern Indiana and Illinois in filling out new storm growth.

Precipitation Forecast Engine

Within the precipitation forecast engine, there is an initial combination step performed at time $t = 0$ (current time) for all forecast time horizons and a second combination step at each forecast time horizon, once the advection of current weather has taken place. The initial forecast combination creates a separate forecast for each time horizon at the initial time. The combination of the current VIL image with all the growth and decay trends, the convective initiation interest images, and the weather classification image is accomplished

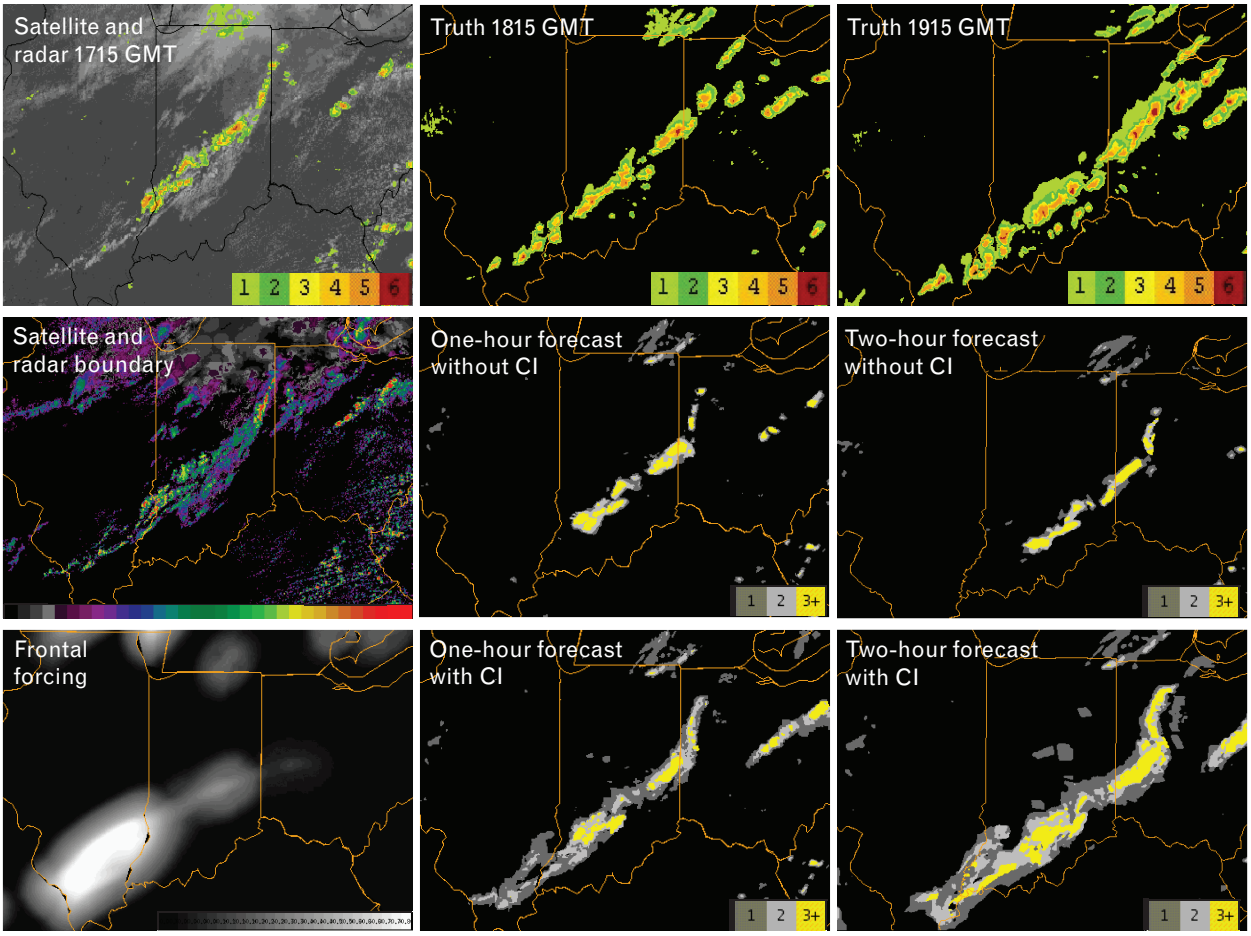

FIGURE 10. Examples of improved one-hour and two-hour forecasts with convective initiation (CI) logic made at 1715 GMT on 20 August 2005. The column on the left shows (from top to bottom) the satellite and radar fields at 1715, the combined satellite and radar boundary interest field, and the frontal forcing field. The middle column shows the actual radar field one hour later (top), the one-hour forecast without CI (middle), and the new one-hour forecast with CI (bottom). The column on the right shows the two-hour radar truth and corresponding forecast results.

via one scoring function and one weighting function for each time horizon, weather class, and input interest image type. The CWF algorithm models of how storms of each type behave with time, given their measured strength and growth/decay/initiation characteristics, are embodied in these scoring functions and weighting functions. The numerical values are based on statistical data from in-house case studies and from thunderstorm evolution behavior documented in the literature.

Following the initial forecast combination, each forecast is advected with the multiscale vectors to its corresponding time horizon. As the storm moves, it may encounter different environmental stability or surface-temperature conditions that can also influence convective growth and decay, so a final forecast combination is also executed. Environmental stability is provided by a combination of a surface-temperature and dew-point analysis and NWS numerical model output. At this second combination stage we also apply spatial and temporal climatological forcing, to match the daily solar cycle and historic patterns and timing of convection over the domain.

Echo Tops Forecast Engine

The echo tops mosaic has proven to be one of the most valuable products in the CIWS. Because of its utility, we later provided the zero-to-two-hour echo tops forecast capability. The echo tops forecast is heavily tied to the precipitation forecast, but the growth model is quite different. The precipitation forecasts are ingested and used in conjunction with weather type, echo tops trends, and a derived quantity called the echo tops cap (ninety-eighth percentile of the surrounding storm tops, indicating the likely maximum height of a growing storm, illustrated in Figure 11) to create the echo tops forecast. For each time horizon the various images are advected, and the echo top trends are applied to convective elements, assuming a linear growth model for the initial growth phase. Once the echo top has

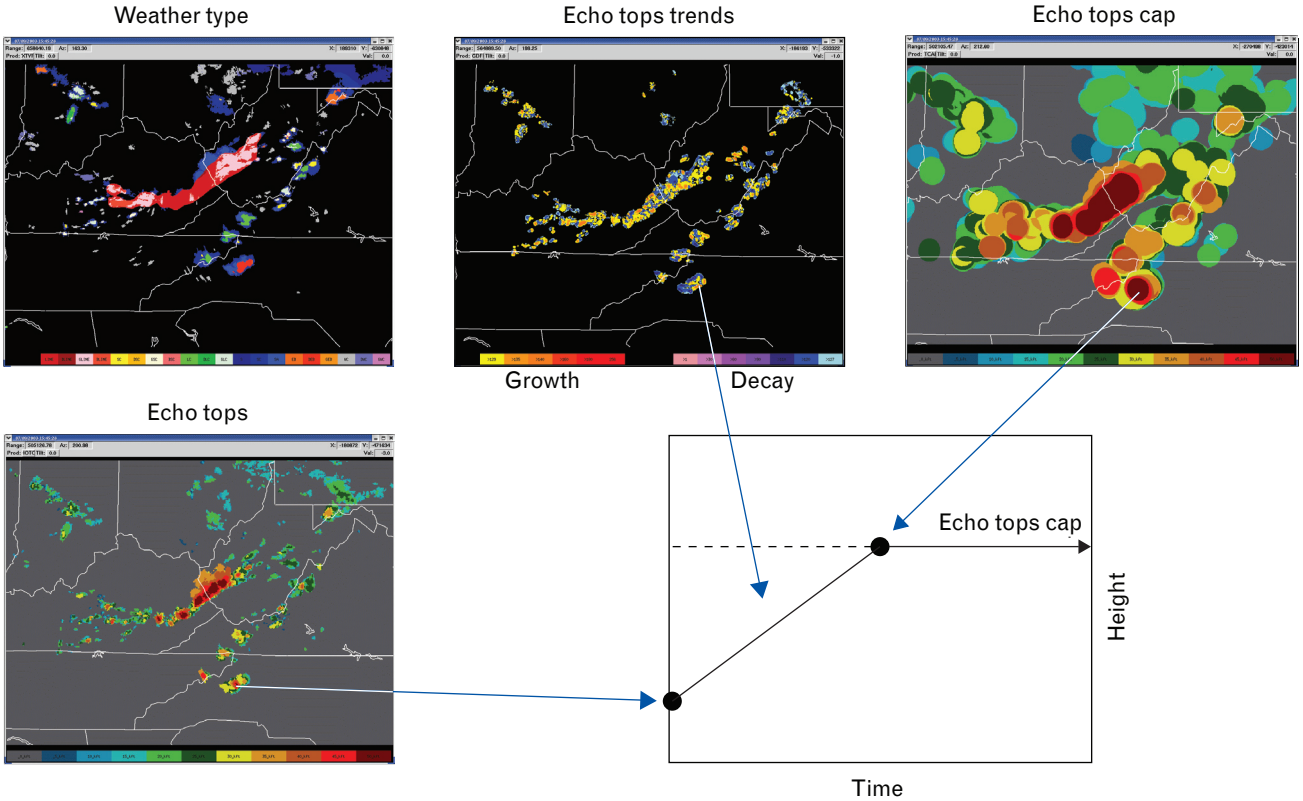

FIGURE 11. Illustration of the echo tops growth model within the echo tops forecast portion of the convective weather forecast (CWF). Echo tops, weather type, and echo tops trends are combined with a derived quantity called the echo tops cap. The cap is estimated based on the 98th percentile of other storms in the region, or based on the convective cloud top potential (related to environmental stability) if no other storms are nearby.

AUTOMATED FRONT DETECTION TO SUPPORT CONVECTIVE INITIATION FORECASTS

New thunderstorms are often triggered by surface fronts that exhibit signatures in the low-altitude wind, temperature, and moisture fields. Figure A shows a typical cyclonic warm-cold front weather pattern. Figures B(1) and B(2) illustrate an example of the wind vector/streamline and divergence signatures commonly associated with a cold front. Regions of convective initiation often occur in the linearly shaped regions of wind convergence highlighted by the oval in Figure B(1). In spite of significant advances in sensor technologies, remote sensing, and objective analysis techniques, insufficient observational spatial resolution and analysis-system-induced artifacts limit our ability to detect these important atmospheric phenomena. While a signature is often present, as shown in Figures B(1) and B(2), the low signal-to-noise ratios (SNR) of these phenomena make them difficult to reliably detect by using image processing techniques on a single time (Eulerian) gridded wind analysis. Time integration improves the SNR, but because the features of interest (fronts) are moving, the true signal can be lost.

Lagrangian scalar integration (LSI) is a technology that attempts to overcome the difficulties of time integration by producing a meteorological analysis in the Lagrangian reference frame [1, 2]. Individual air parcels associated with some atmospheric features tend to retain their dynamical properties over relatively long time intervals (relative to the observation sampling rate). The LSI technique computes a representation of a field of interest following the motion of the phenomenon. This analysis is accomplished by computing parcel trajectories that are based on a series of Eulerian-gridded wind samples, and then integrating scalar products following these trajectories. Signals associated with the time-coherent atmospheric features are amplified, while the transient signatures are diminished [3]. When tuned for the detection of fronts, LSI can be used to simultaneously sharpen frontal signatures while reducing noise generated by the objective analysis. An example of this characteristic is illustrated in Figure B(3). The LSI-filtered divergence, derived from the gridded Eulerian wind analysis depicted in Figure B(1), shows considerably less noise than its Eulerian counterpart shown in Figure B(2).

The LSI technique can be used on any scalar quantity that is temporally coherent following the wind flow. It is particularly effective on scalar fields based on the wind field (i.e., divergence, vorticity, deformation, and direction change in the horizontal winds). The LSI filter is used in an automated front detection algorithm currently being developed to improve automated convective initiation forecasts. Gridded meteorological analyses from the National Oceanic and Atmospheric Admin-

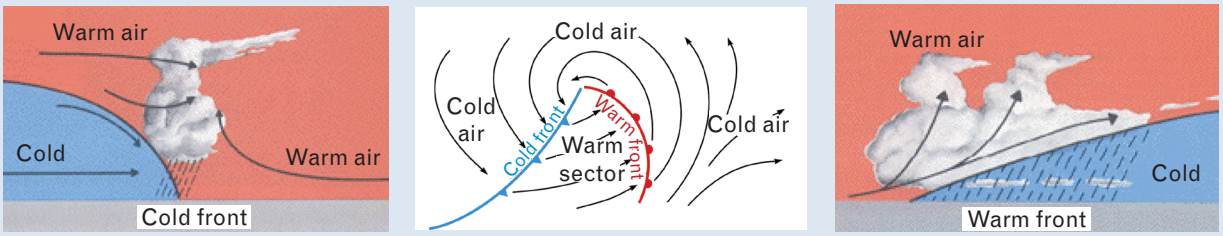

FIGURE A. Cross-sectional depictions of typical surface cold and warm fronts, and a plan view depiction of a mid-latitude cyclone and its surface fronts in the open wave stage of its evolution. Fronts serve as focal points for precipitation development and often are identified by their temperature, moisture, and wind shift signatures.

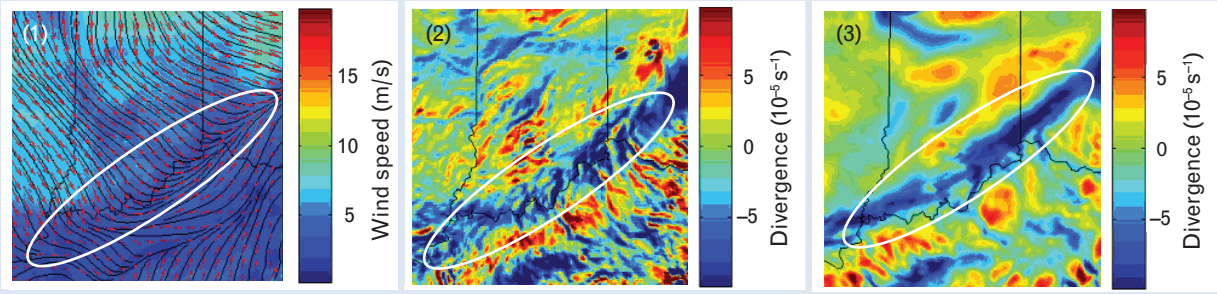

FIGURE B. Wind analysis products valid at 2300 UTC on 27 March 2004: (1) A sample gridded wind analysis from National Oceanic and Atmospheric Administration's Earth System Research Laboratory Space Time Mesoscale Analysis System; (2) Eulerian divergence derived from the gridded wind analysis shown in part 1; and (3) Lagrangian scalar integration (LSI) divergence. The white ovals highlight the divergence signature associated with the front.

istration Earth System Research Laboratory Space Time Mesoscale Analysis System and information on the underlying terrain elevations serve as the data sources for this system. The algorithm combines LSI-filtered wind products with the temperature and humidity gradient fields and uses additional Lincoln Laboratory image processing techniques to produce reliable, fully automated detections of synoptic scale fronts that are relatively free from terrain and other artifacts [4]. Figure C depicts the NWS operational frontal analysis product for a long cold front on 23 September 2005 overlaid on our automated detection field. The manual NWS front detection product provides frontal locations to the nearest degree latitude and longitude every three hours beginning at 00 UTC, while the automated front detection is a 5 km resolution product that updates every fifteen minutes. Tracking and projecting the fronts forward in time compensates for data latency, and provides frontal positions out to two hours in the future, with five-minute granularity.

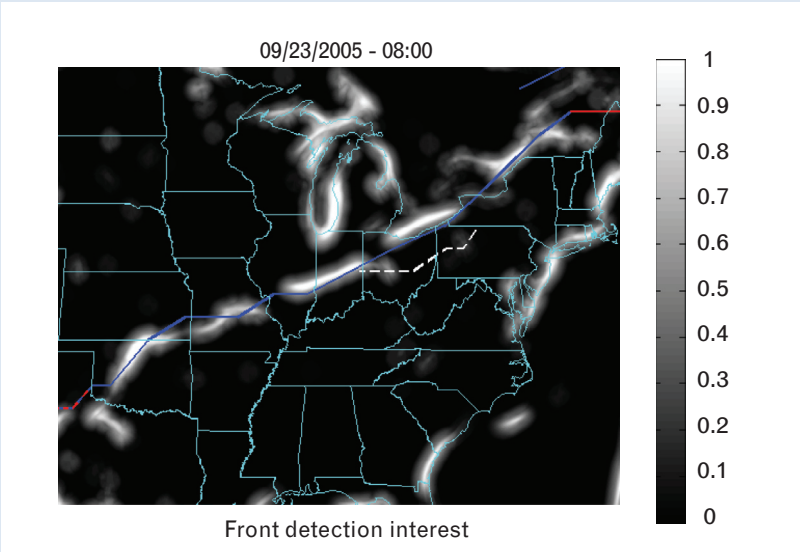

FIGURE C. A gray-scale frontal detection field from the Lincoln Laboratory automated front detection algorithm. White denotes a high likelihood that a front is present. Also shown are the frontal locations as determined by a human analyst at the National Weather Service Hydrometeorological Prediction Center (HPC). The blue line represents cold-front locations, the red line a warm front (in Maine), and the alternating red/blue line (in Texas) a stationary front.

References

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grown to the echo top cap, the top is held at this level for all future forecast time horizons. For the remaining non-convective weather types, the existing echo tops are advected without change. As a final step, the echo tops forecast is matched to the precipitation forecast via dilation, if necessary.

Precipitation-Phase Forecast Engine

The ability to see a forecast in the winter, and to know whether the precipitation would impact the terminals as snow, rain, or mixed precipitation, turns out to be very important to en route traffic management. Inclusion of the surface observations (e.g., winds, pressure, temperature, dew point, and precipitation type) is essential to this problem, as it is to the problem of automatically detecting the surface fronts and estimating the environmental stability. Lincoln Laboratory has worked with the FAA to obtain real-time network access to one-minute-update surface observations from automated surface stations. The ability to forecast the precipitation phase at a terminal is closely related to the ability to forecast the changing visibility conditions, and the CW and TC&V teams have worked closely on its development.

Convective Weather Forecast Display

The zero-to-two-hour CWF, shown in Figure 12, uses a color scheme that cannot accidentally be mistaken for current weather to represent what the radar display will look like in the future. This display concept was guided by user interviews conducted in Dallas and Memphis [20] that led to the development of the

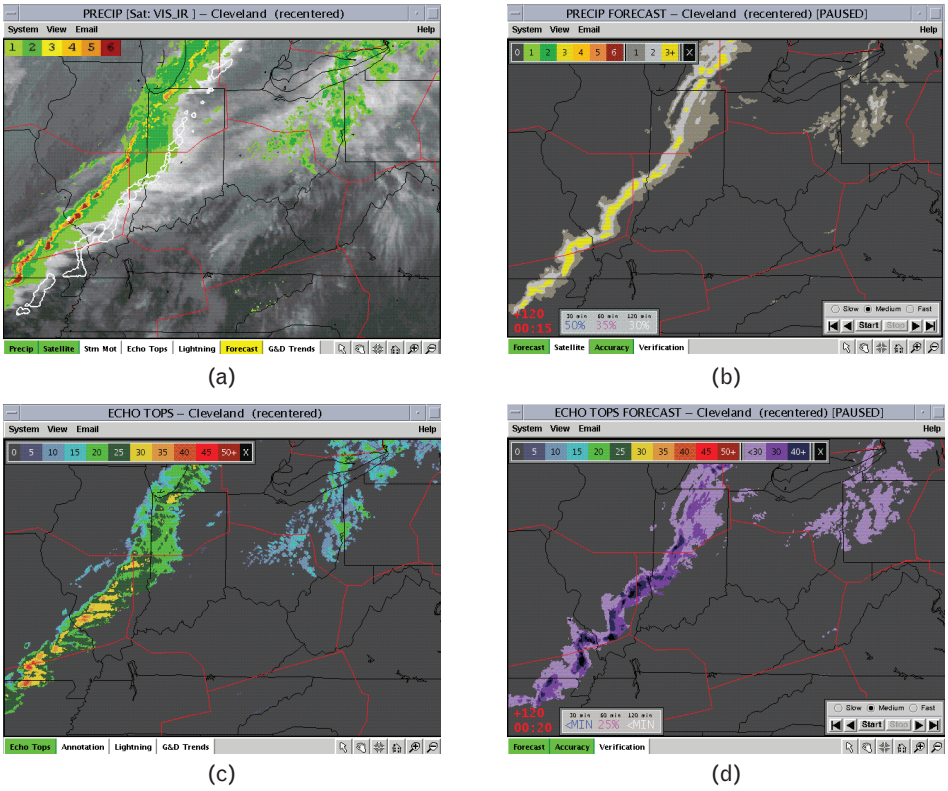

FIGURE 12. The CWF precipitation and echo tops mosaics and forecasts as they appear on the CIWS Situation Display. (a) The current precipitation (VIL) mosaic product with two-hour forecast contours (white) overlaid on the visible satellite image. (b) The precipitation forecast displayed as shaded values of VIL, given in operationally significant levels. An animated loop shows 60 min of past weather, then advances the forecast in 15 min increments to the maximum time horizon of 120 min. (c) Mosaic of echo tops to show the current heights (kft) of the convective weather. (d) The echo tops forecast is displayed as shaded values of echo tops heights, looping in 15 min increments out to 120 min. Accurate radar-based echo tops information indicates where it is safe to fly over storms that may appear on the sole basis of the precipitation mosaic to block major jet routes, and therefore enables traffic managers to safely and efficiently route traffic in highly congested airspace.

forecast window on the ITWS Situation Display and ultimately on the CIWS Situation Display. The deterministic forecast requires the least amount of user interpretation and provides an extremely precise forecast relative to various probabilistic representations that are operationally available. For CIWS, the forecast animates from the current time to two hours in the future in 15 min steps (5 or 10 min steps are also available), and includes one hour of past weather in the complete loop. The inherent uncertainty in the CWF forecasts, increasing as it does with forecast time horizon, is represented via the real-time scoring statistics that are always available. Quantitative error estimates for the CWF are produced in real time, for use in automated air traffic decision support systems.

Convective Weather Forecast Scoring and Performance

The CWF algorithm performs its own quality assessment in real time, and a display of the numerical performance scores can be shown. Each of the 30, 60, and 120 min forecasts has a separate score that gives an indication of the recent past performance of the algorithm, and helps users gauge the current performance of the algorithm.

The airport or home-centered scoring domains typically cover a large array of storms, and they do not pinpoint the forecast accuracy for any single storm region. To provide this storm-specific forecast performance information, forecast verification contours are also implemented. These contours of the high forecast level, shown in Figure 13 are color coded for the 30 min forecast (blue), 60 min forecast (magenta) and 120 min forecast (white), and overlaid on the past or current weather. This color coding allows the previously forecast weather pattern to be inspected against the true weather for each storm region of concern.

Offline scoring routinely takes place to verify the algorithm performance, and to ensure that algorithm enhancements have indeed improved performance. A typical example of the binary performance of the precipitation forecast algorithm at the one-hour time horizon is presented in Figure 14.

Operational Impact

The products developed with the Convective Weather team have been exercised routinely in operational pro-

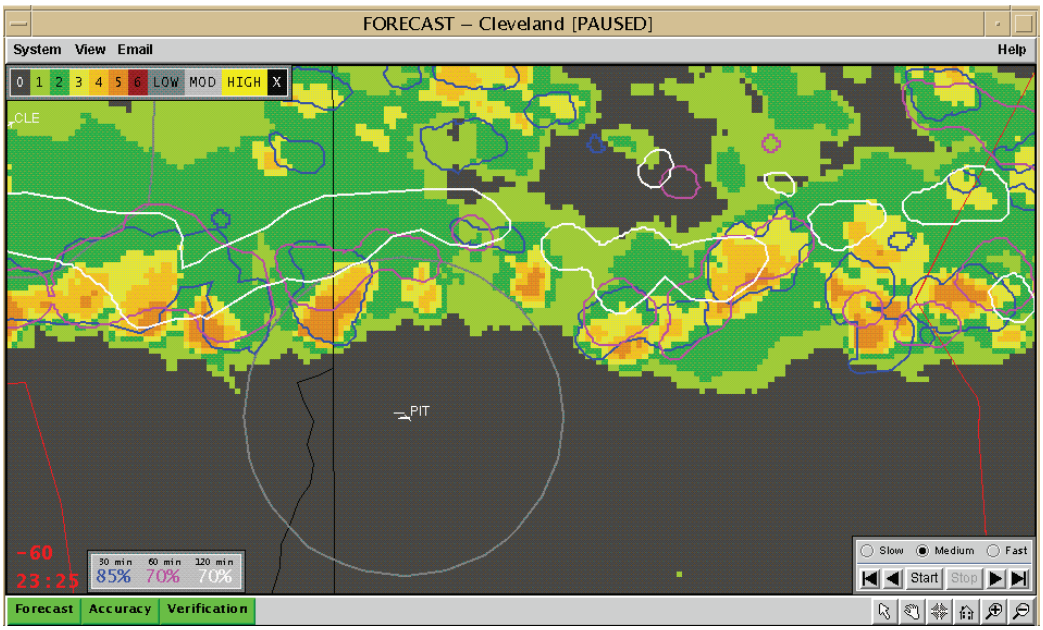

FIGURE 13. Example of forecast verification contours on past/current weather portion of the CWF loop. The blue contours represent the 30 min forecast verified at this time, the magenta represents the 60 min forecast, and the white represents the 120 min forecast. In this example, the 120 min contours are slightly behind the convective regions, indicating a slight slow bias in the longer range forecast, while the 30 min and 60 min forecasts exhibit more accuracy. The numerical scores, using the same color scheme, are also shown at the bottom left.

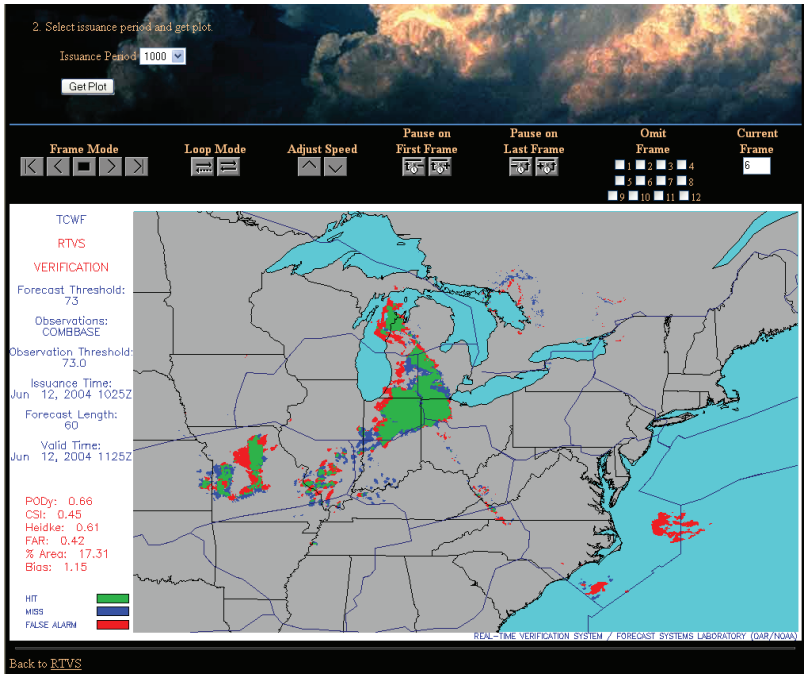

FIGURE 14. Example of web-based graphics from the off-line forecast verification exercise conducted by the FAA Advanced Weather Research Program Quality Assurance Product Development Team (PDT). The green areas represent hits, the red, false alarms, and the blue, missed detections. This example shows the one-hour Corridor Integrated Weather System (CIWS) Convective Weather Forecast verified at the level 2 precipitation threshold. Notice that the majority of the heavy weather in Michigan and northern Indiana/Ohio is forecasted very well, but that the initiation of small air mass storms in southern Illinois/Indiana is largely missed, and the algorithm failed to decay the weather off the east coast.

totype settings, and have proven extremely useful to both terminal and en route traffic management. In the terminal, the one-hour Terminal Convective Weather Forecast (TCWF) has been demonstrated at the four Lincoln Laboratory–operated operational ITWS system prototypes [21] since 1998. The FAA ITWS program elected to add this capability to the operational ITWS, and a very successful technology transfer program took place (ahead of schedule and under budget!), with the contractor reusing much of the Lincoln Laboratory code directly in the legacy ITWS. The first ITWS with the TCWF capability will be deployed in New York in the summer of 2006. Studies estimate that the inclusion of TCWF in ITWS will increase benefits to the users by 50 to 75% [22].

The capabilities pioneered by the convective weather team have been exercised in the CIWS operational prototype as well. Figure 15 illustrates CIWS product usage in providing one of its the biggest benefits: safely keeping a jet route open longer. This capability alone was anticipated to provide $89 M per year in benefits on the basis of 2003 CIWS usage [23]. By knowing with high precision where the storms are (NEXRAD precipitation) and how tall they are (echo tops), where and how high those storms are forecast to be in the near future (precipitation forecast and echo tops forecast), and where the storms are actively growing (growth and decay trends), en route traffic managers have the confidence to allow as much of the heavy traffic in the congested northeast corridor as possible to keep running, and to make their destinations safely and on time. And that is something we, the flying public, can all appreciate!

Terminal Ceiling and Visibility Product Development

Within the FAA AWRP, the TC&V PDT is responsible for development of forecast guidance products to mitigate the loss of terminal operating capacity associated with low-ceiling and visibility restrictions. In par-

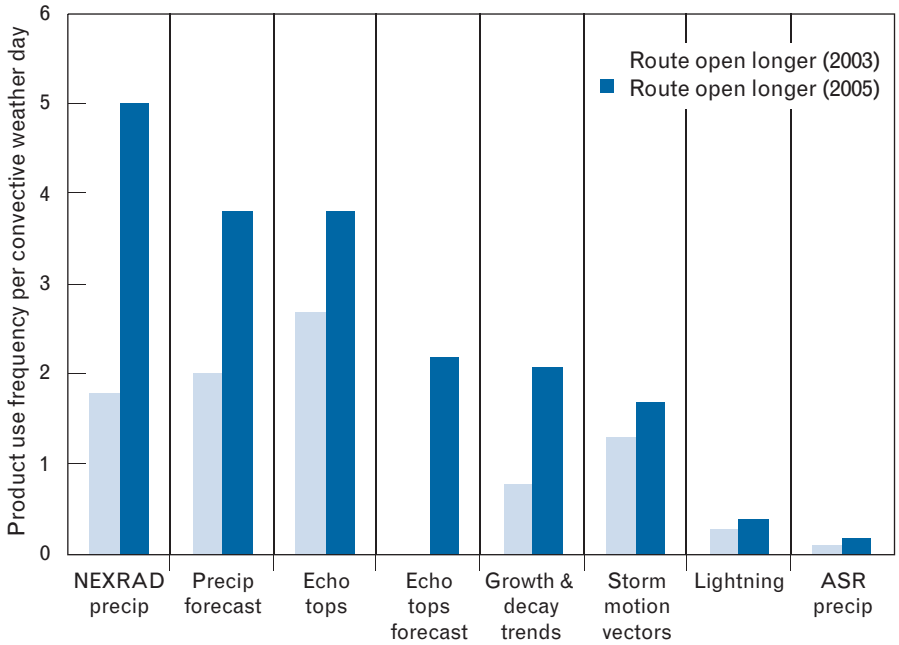

FIGURE 15. Comparison of CIWS product usage in providing the benefit of "keeping routes open longer" in en route airspace. The top five products used were all developed by the Convective Weather PDT in conjunction with the CIWS team and the FAA operational traffic managers.

ticular, accurate anticipation of the onset and cessation of instrument meteorological conditions (IMC) allows the opportunity for air traffic managers to effectively regulate traffic to utilize available capacity. In contrast to pursuing a general solution for a large-area domain (which neglects the unique weather characteristics of individual terminal areas), the approach is to develop forecast guidance products specific to individual high-volume airports that experience substantial loss of capacity, typically associated with closely spaced runways. Due to the inter-hub dependencies of traffic flow, efficiency gains at individual key airports translate to a general reduction of total aircraft delay through the entire NAS. Two terminal-specific projects have been initiated. The first is a mature project for San Francisco International airport (SFO), for which a prototype forecast guidance system developed under the leadership of Lincoln Laboratory has been transferred to the NWS. The second project is in the exploratory research phase, and involves product development for airports in the northeast United States that experience significant ceiling and visibility restrictions during the winter months, with particular emphasis on the heavily congested New York area airspace.

The San Francisco Marine-Stratus-Cloud Forecast Guidance System

The local airspace surrounding SFO airport is prone to regular occurrences of low ceiling conditions from May through October due to the intrusion of marine stratus clouds along the Pacific coast. Low cloud conditions (ceilings under 3500 feet in the approach zone or under 1000 feet at SFO) prohibit dual parallel approaches of aircraft to the airport's closely spaced parallel runways, as illustrated in Figure 16, thus effectively reducing the arrival capacity by a factor of two. The behavior of summer marine stratus evolves on a daily cycle, filling the San Francisco Bay region overnight, and dissipating during the morning. Often the low ceiling conditions persist and interfere with the high rate of air traffic scheduled into SFO from mid-morning to early afternoon. Air traffic managers cope with this capacity deficit by delaying inbound aircraft on the ground at their originating airports. The implementation of these Ground Delay Programs (GDP) and their ultimate cancellation (i.e., the decision to release upstream planes) is a collaborative decision made by air traffic managers at the Oakland ARTCC,

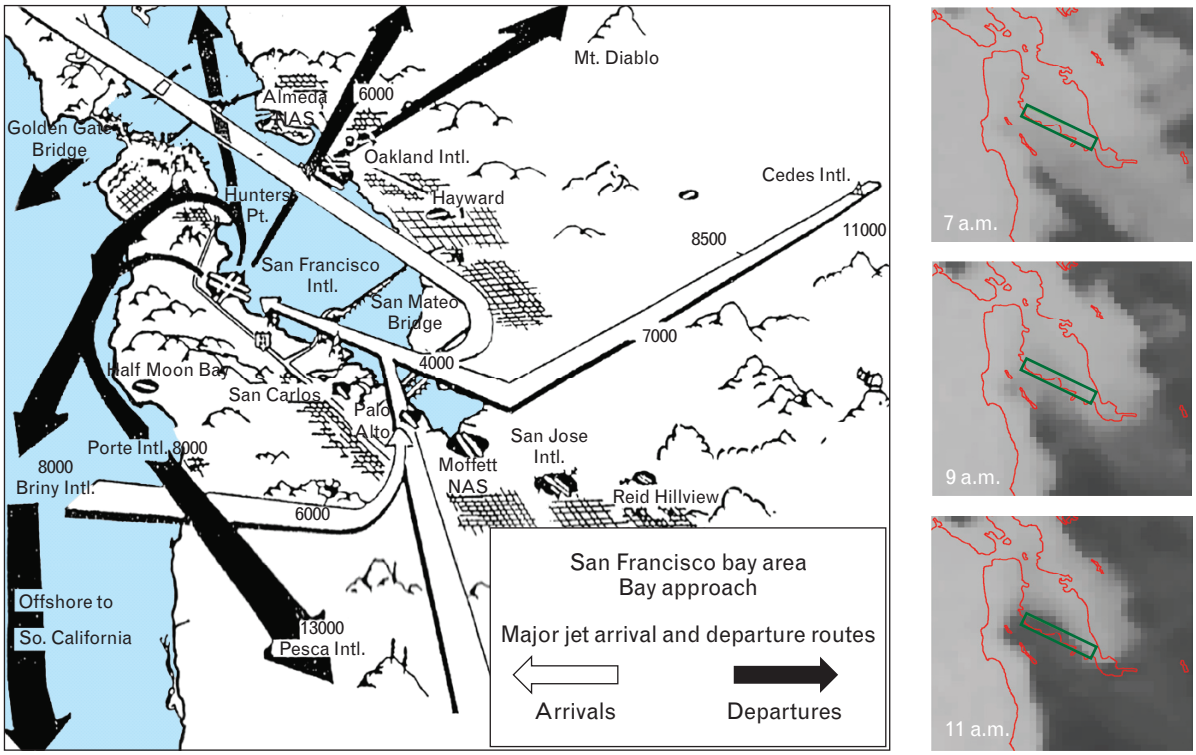

FIGURE 16. Left: Primary approach and departure routes into and out of San Francisco International airport (adapted from W.J. Strach [24]). During visible approaches, incoming aircraft arrive in parallel, merging at south end of San Francisco Bay. Right: Typical evolution of stratus cloud dissipation in Bay region. The green rectangle approximates the approach zone that must be free of low stratus to allow parallel approaches.

the Air Traffic Control System Command Center in Herndon, Virginia, and the operational units of the major commercial airlines with significant traffic into SFO. The decision is based on the forecast of stratus dissipation from the approach zone. The managers' primary source of weather information for this decision is provided by forecasters at the Center Weather Service Unit (CWSU) collocated at the ARTCC, the NWS Forecast Office (NWSFO) in Monterey, and meteorological units within the major airlines' operations centers.

Each morning at 1300 Greenwich Mean Time (GMT) (6 a.m. Pacific Daylight Time), these traffic managers and forecasters collaborate on a stratus forecast upon which the morning's delay program will be determined. The nature of the program can vary in scope (number of tiers of traffic upon which ground holds will be imposed) and length of time. Throughout the morning hours, the evolution of the stratus is monitored by forecasters. Air traffic managers need to be notified if and when the forecast changes, in order to adjust the delay program accordingly. Product development for the forecast guidance system was aimed at providing a common-baseline forecast guidance tool for this collaborative process, with particular attention to the CWSU, which was a participating member of the development team. A prototype system was introduced during the summer of 2001. The system was demonstrated operationally for several stratus seasons, undergoing a number of modifications in the process. It was transferred to the NWSFO in Monterey following the 2004 season.

The system relies on a variety of weather observations acquired from land-based sensors throughout the Bay region, upper-air data via balloon-launched rawinsondes, and Geostationary Operational Environmental Satellite (GOES)-West satellite data. Data from these various sources are transferred to a base station computer located at the ARTCC in Fremont, California, at a time interval of fifteen minutes. There

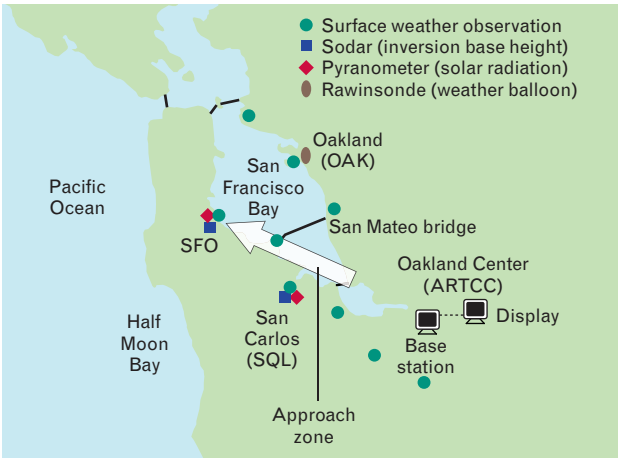

FIGURE 17. Geographical configuration of system sensors. Primary sensor field sites are at the airports in San Francisco (SFO) and San Carlos (SQL) alongside the approach zone. Base station computer and primary display are located at the Oakland ARTCC in Fremont.

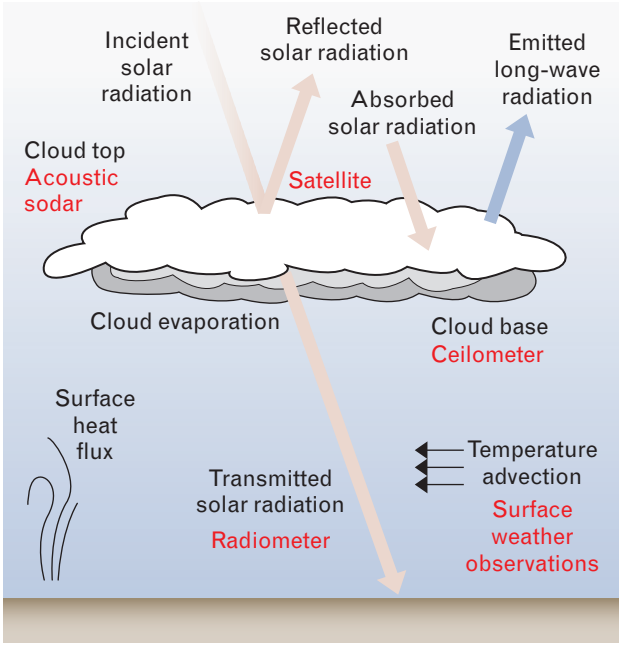

FIGURE 18. Primary physical processes associated with stratus cloud evaporation. The key sensors associated with the various processes are shown in red.

the data are processed for display, and for input into a suite of models designed to forecast the time of approach zone clearing. The display of observations and the automated forecast guidance are made available to external users via the Internet.

Data Sources and Sensors

The geographical configuration of sensors that supply data to the system is shown in Figure 17. Figure 18 shows the various sensors chosen to capture the primary physical processes associated with stratus cloud dissipation. There are two primary sensor sites, located at San Francisco International airport (SFO) and San Carlos airport (SQL), along the approach zone to parallel runways 28L and 28R. These two sites were instrumented specifically to support the forecast system. The most critical sensor at each site is an acoustic sonic detection and ranging (sodar) antenna. The sodar unit, shown in Figure 19, is an upwardly pointing parabolic antenna that emits an audible signal (2 kHz) whose return signal is proportional to the vertical gra-

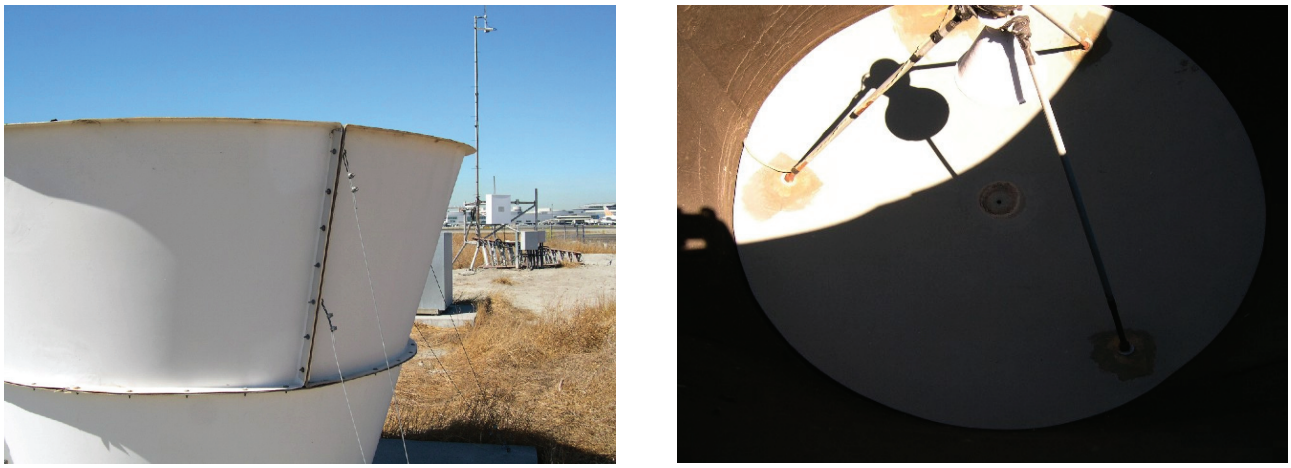

FIGURE 19. (left) Sensor field-site equipment at San Carlos airport. Foreground is a sodar baffle anchored to a cement pad. The background shows a tower mounted with sensors. (right) Sodar antenna viewed by looking down into baffle.

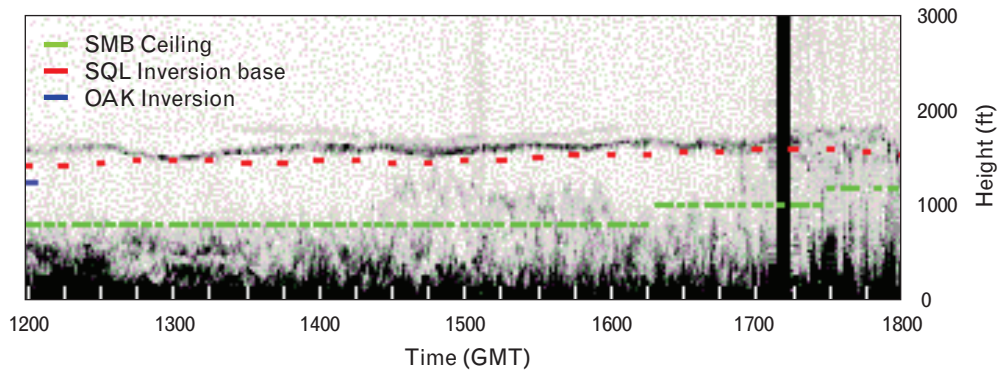

FIGURE 20. Time-height profile showing decreasing depth of cloud deck with time. The quasi-horizontal black line at 1500 feet is a signal from the sodar, indicating cloud top height (at atmospheric inversion base). The red dashed line is the automated stable estimate of height, generated from sodar signal at fifteen-minute intervals, for input into forecast algorithms. The dashed green line is the cloud base height measured by a surface-based ceilometer. SMB stands for the San Mateo bridge, SQL the San Carlos airport, and OAK the Oakland airport.

dient of air density (and therefore temperature) in the atmosphere. This gradient defines the base of the inversion layer of the atmosphere, where the temperature begins to increase with height. This temperature inversion is significant in that it represents the height at which the stratus deck is capped, thus corresponding to the height of the top of the cloud layer, which is critical to forecasting the timing of cloud dissipation. A display of the sodar's signal as it is used to depict the evolution of cloud depth is shown in Figure 20. In addition to the sodar, each site is instrumented with a pyranometer, shown in Figure 21, to measure incoming solar radiation and instruments to provide high-resolution measurements of temperature, humidity, and wind.

Beyond the two field sites, most of the remainder of observations are acquired from the standard suite of weather observations made widely available by the NWS. These observations include hourly surface measurements of standard meteorological parameters (temperature, humidity, wind, cloud amount, and heights), twice-daily vertical measurements (temperature, humidity, and wind) from the balloon rawinsonde launched from Oakland, and satellite data from GOES-West available at fifteen-minute intervals. The other key significant observation of note is the FAA-maintained surface weather sensor located at the San Mateo bridge, situated directly below the primary runway approach zone into SFO airport. This sensor provides the key ceilometer measurement of cloud amount and cloud base height used for operational purposes in assessing the availability of visible approaches into SFO.

The system base station computer is located at the

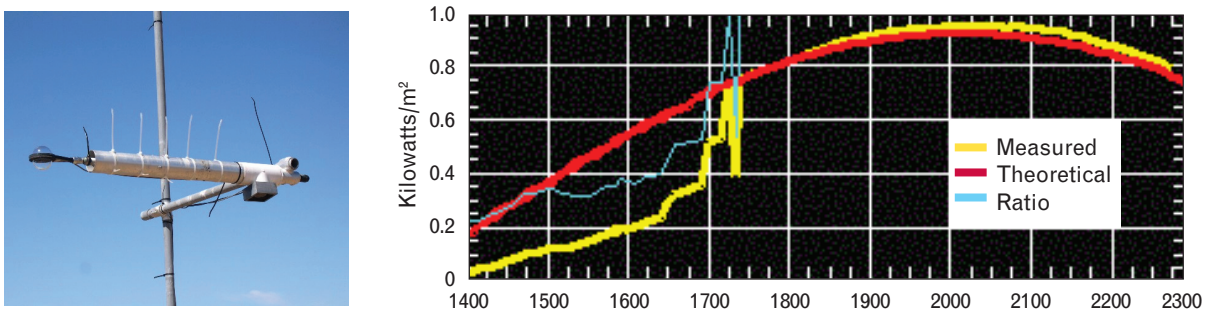

FIGURE 21. (left) Pyranometer system to measure incoming solar radiation, mounted on a tower. (right) Graphical representation of a solar radiation measurement (yellow curve) compared to the maximum theoretical solar radiation on a cloud-free day (red curve) for the sensor location and day of year. The blue line shows the ratio of measured/maximum radiation. This example shows stratus clouds clearing at approximately 1715 GMT.

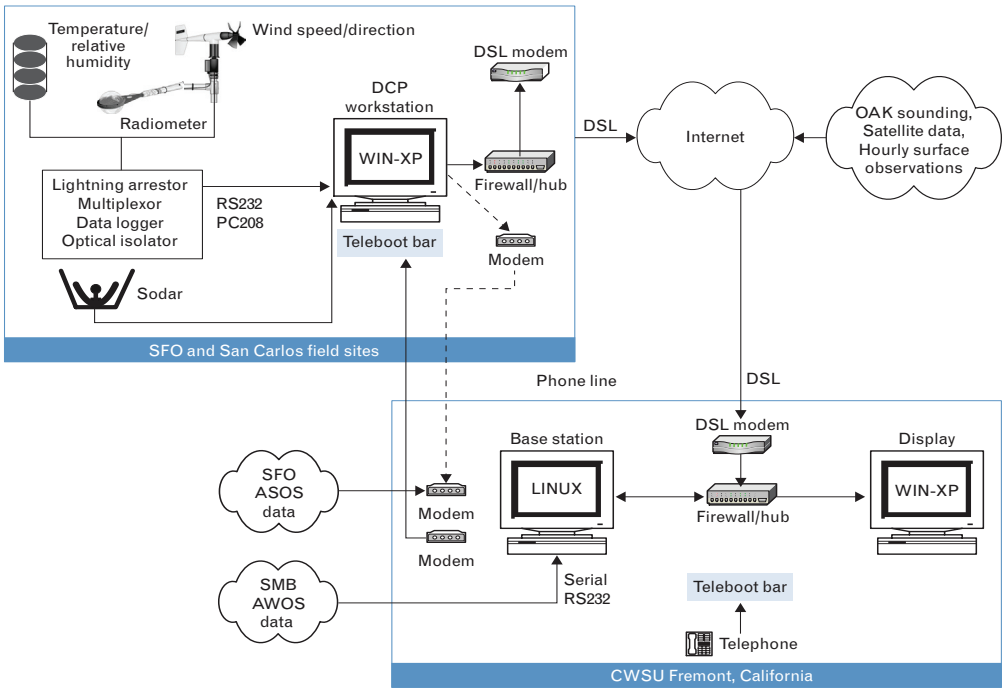

FIGURE 22. System hardware and communications configuration. ASOS stands for Automated Surface Observing System and AWOS stands for Automated Weather Observing System.

Oakland ARTCC in Fremont, California. It serves the function of collecting and processing data from the variety of sources and generating display products. In additional to providing local display for the CWSU, the base station computer also acts as a web server for delivering the display products to external system users via the Internet.

Data Acquisition and Real-Time Processing

Figure 22 shows a schematic representation of the hardware and communications configuration for data acquisition and processing. The system encompasses the two field sites (SFO and SQL) equipped with identical hardware and software, and a two-node local area network (LAN) housed within the CWSU in Fremont, California. The LAN is composed of the base station computer, used for data collection and processing, and a product display computer, used by forecasters. The base station, using a commercial DSL connection to the Internet, acquires data from both the field sites and other sources. A backup means to acquire field-site data is available if needed. The system uses a dial-up point-to-point protocol connection over a phone line that is shared with DSL. The dial-up connection is shown in Figure 22 as the dashed line connecting field-site modems to the base station modem. Five-minute surface weather observations for SFO are acquired through a dial-up connection that uses the Kermit protocol. Five-minute Automated Weather Observing System surface observations from an FAA-managed site located at the San Mateo bridge enter the base station via a serial RS232 line that originates within the confines of the CWSU weather desk. The Oakland upper-air sounding and hourly surface observations from stations in and around San Francisco Bay are provided by the NWSFO in Monterey, and satellite data are retrieved from the Naval Research Laboratory, also located in Monterey. These data sources rely on the DSL connection for transfer of data to the base station.

Field-site instrumentation, including temperature and humidity sensors, a pyranometer, and a wind sensor, are tower mounted and connected to a data logger that prepares the sensor data for acquisition by the Data Collection Platform (DCP), a PC running the Windows XP operating system. The DCP also collects and processes data from an acoustic sounder that profiles the atmosphere just above the field site.

Forecast Models

Data collected at the base station computer are supplied to four component forecast models, each designed to independently provide an estimate of the time at which the approach zone is expected to be sufficiently free of clouds to allow parallel runway approaches into SFO. Individual forecasts from the four component models are combined to yield a single consensus forecast. The forecast process is run on a daily schedule, beginning at 0900 GMT each morning (2 a.m. Pacific Daylight Time). The models are initialized with new data and run at the top of the hour at 0900, 1100, 1300, 1500, 1600, 1700, and 1800 GMT throughout the morning, as long as clouds are present in the approach zone. Once the approach zone has cleared, the models cease to run.

The four component models consist of three statistically derived forecast models, and a physics-based numerical model:

1. Local Statistical Forecast Model
2. Regional Statistical Forecast Model
3. Satellite Statistical Forecast Model
4. COBEL one-dimensional numerical model.

The models are quasi-independent in that they rely on significantly different data observations as input. The benefits of this are threefold. First, it provides four different perspectives on the forecast, allowing the opportunity for either inter-model consistency or variability, which is a useful indicator to the forecaster as to the reliability of the current forecast. Second, the use of a multiple forecast/consensus approach allows the forecast system to remain available in the event that one or more data sources become unavailable. The consensus forecast algorithm is designed to effectively combine the available component forecasts by using a weighting system that is based on the relative historical performance of each forecast model at each model run hour. Third, the consensus approach tends to filter the hour-to-hour variance that is sometimes observed in the individual component forecasts.

Three of the models are derived from nonlinear statistical regression. The Local Model relies heavily on the special sensors at the two field sites, particularly the stratus top height as determined by the sodar, and the solar radiation measured by the pyranometer. The Regional Model uses routinely available regional surface observations from the central California region, and upper air information from the Oakland sounding. The Satellite Model uses visible satellite brightness at key locations (determined through statistical analysis of sectored satellite data), correlated with the ultimate time of cloud dissipation in the approach.

COBEL is the only model among the four component models that is not statistically derived. It is a very high-resolution one-dimensional (vertical column) physical model of the planetary boundary layer (lowest 1 km of the atmosphere) that simulates the evolution of the cloud dissipation process. It was adapted by the University of Quebec at Montreal [25] from a model developed for forecasting fog behavior in northern France [26]. COBEL is short for the French Couche Brouillard Eau Liquide.

Each model executes at the top of each forecast run hour, provided that its required data are available. Once all of the models have received their data and have executed, the consensus algorithm is prompted to generate a consensus forecast, followed by a posting of all forecasts to the user display. The display is refreshed with new forecasts only once per cycle; i.e., the individual models are not allowed to update asynchronously to the display within a given hour.

The consensus forecast of approach clearing time is presented in two formats. First is a deterministic forecast of the time of clearing. Second is a probabilistic representation indicating the likelihood of clearing prior to key operational target times, namely, 1700, 1800, 1900, and 2000 GMT. These times represent the range of the peak traffic arrival demand into SFO.

Data and Forecast Display

Figure 23 is an image of the system display, the primary interface for operational users to access observations and model forecasts as an aid toward anticipating the time of stratus dissipation in the approach zone into SFO. The primary display is part of the two-node LAN at the CWSU in Fremont, California. The LAN includes a web server that allows access for external users via the Internet. Key users include the NWSFO in Monterey, and the operational units a major participating commercial airlines, most notably United Airlines, which has the largest share of traffic into SFO.

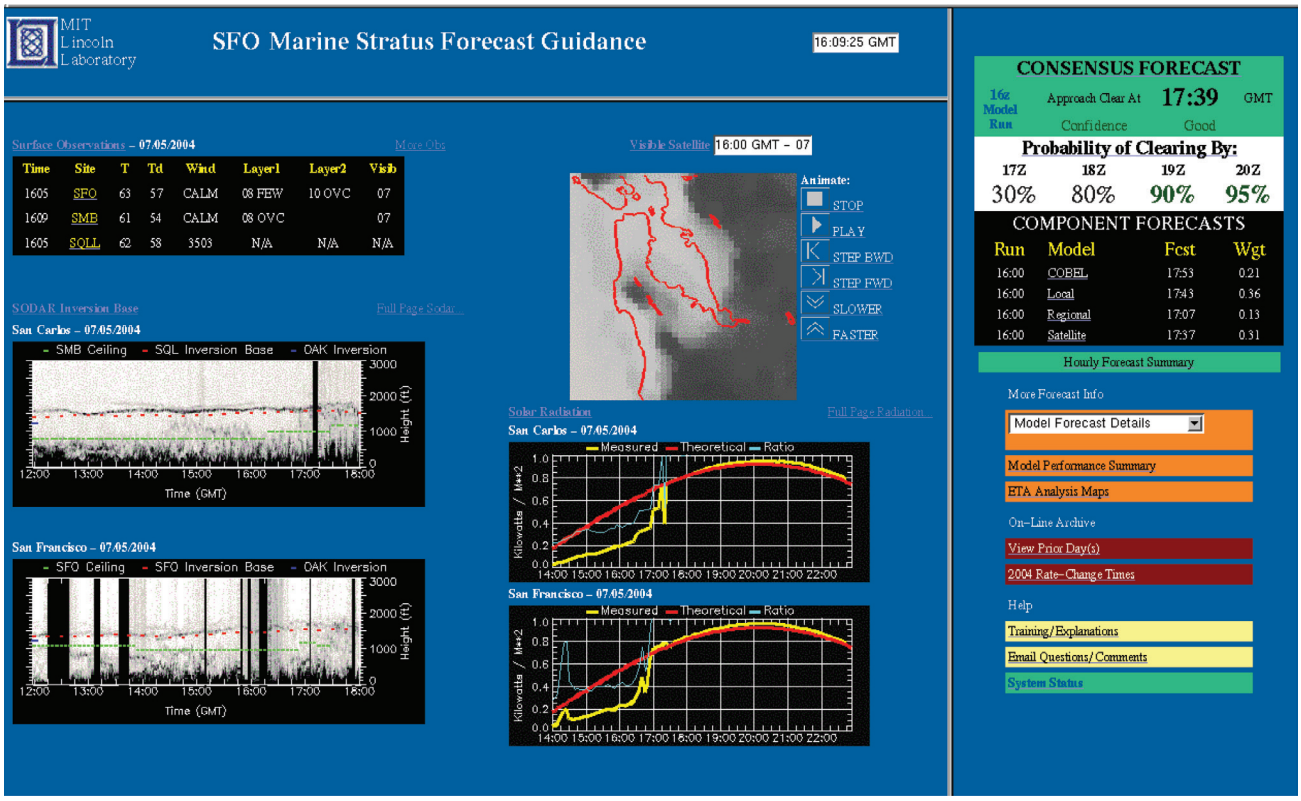

FIGURE 23. System display. The left-hand frame provides a suite of graphical observations. The right-hand frame provides forecast information. In the upper right is the forecast box, including deterministic and probabilistic representation of consensus stratus forecast, and deterministic forecasts and weights of component forecasts.

The display is both automated and interactive. It automatically refreshes with the most recently available information, and it allows the user to investigate the details of each element as desired.

The display consists of a data observation frame and a forecast frame. The observation frame provides a graphical suite of weather observations as an aid in proper diagnosis of the current stratus-related conditions. This suite of observations includes standard surface weather observations, the sodar inversion height (cloud top) plots, the pyranometer radiation plots, and visible cloud imagery. The forecast frame provides the deterministic forecast times from the four component models, and their weighted input into the consensus forecast. Both the deterministic and probabilistic representations are displayed for the consensus forecast. The forecast frame also allows the user to review and analyze various elements of the forecasts, such as the specific parameters within each model. Additionally, the forecast frame allows the user to launch a separate web browser that allows access to view all observations and forecasts for any individual day within the past year.

Operational Impact

Proactive release of upstream aircraft held on the ground allows exploitation of available arrival slots that might otherwise go unused upon clearing at SFO. However, in instances when the clearing does not materialize as forecast, the result is an unacceptably high level of airborne holds and/or diversions. Historically, air traffic managers have tended to be conservative in this regard, since they must bear the operational fallout from a missed forecast, whereas most of the benefits of successful proactive decisions are reaped by the airlines in reduced costs associated with delay. Nonetheless, traffic managers at Oakland Center expressed their willingness for more proactive management in circumstances in which confidence in clearing (particularly by the critical 1800 GMT target time for beginning of the morning traffic push) is very high. The willingness on the part of traffic managers led to the

introduction of the probabilistic representation of the forecast on the operational display. A clearing forecast of 90% or higher (which is very ambitious) by the key operational target time of 1800 GMT was considered safe enough to accept the increased traffic risk.

During 2004, the responsibility for operation and maintenance of the system was transferred to the NWSFO in Monterey. NWS will continue to evaluate the utility of the system in assisting air traffic management decisions [27]. The direct value of the system has been difficult to isolate, since decisions are made collaboratively by using many sources of weather information as input. In practice, although the 90% target time probabilities verified reliably during the demonstration periods, traffic managers remained reluctant to accept an objective probabilistic-based rule regarding the proactive release of aircraft. Automated probabilistic guidance objectively tied to air traffic decisions represents a new direction in air traffic management, and its optimal use in an operational setting will take time to resolve [28]. It has been observed, however, that policy changes regarding Ground Delay Programs have become more flexible in allowing an intermediate (increased) acceptance rate during the last two hours of a program, when the confidence of clearing is high [27]. The new forecast guidance tool has also become an important shared resource among forecasters and air traffic managers in the collaborative decision process to efficiently manage delay programs and reduce avoidable delay.

Northeast Winter Ceiling and Visibility Project

Focus of the TC&V PDT has now shifted to airports in the Northeast, which face a far more complicated problem in terms of both weather and operations. There are several high-volume airports in the northeast corridor whose runway configurations cause substantial capacity restrictions in instrument meteorological conditions (IMC), e.g., Boston, Philadelphia, and the New York City area airports (John F. Kennedy, LaGuardia, and Newark). These airports are also exposed to a variety of weather conditions that result in low ceiling and visibility, particularly from November through April, when they are impacted by large transient weather systems. Proximity to the Atlantic Ocean compounds the forecasting challenge as wind shifts can cause dramatic changes due to the differing characteristics of the air mass originating over ocean versus land.

As a result, it is unlikely that a single forecast technology will provide a complete solution. Toward this

Table 1. Candidate Technologies for Diagnosis and Forecast of Terminal Area Ceiling and Visibility

Data/Approach	*Parameters*	*Forecast Horizon*
Application of operational Numerical Weather Prediction model output (regional and mesoscale) tailored to specific terminals	Ceiling/visibility	3–12 hours
Radar data monitoring and tracking, and precipitation type discrimination, to forecast visibility reduction in precipitation	Visibility	0–3 hours
Statistical modeling for point locations (i.e., terminal airspace) using routinely available NWS surface and upper air data	Ceiling/visibility	2–8 hours
Aviation-impacting cloud diagnosis and forecast using satellite data and surface observations	Ceiling	0–3 hours
Radar data to identify ceiling height, coverage, and trend	Ceiling	0–3 hours
Local one-dimensional model to forecast vertical evolution of liquid water	Ceiling/visibility	1–6 hours
Digital camera imagery to estimate visibility reduction and trend	Visibility	0–3 hours

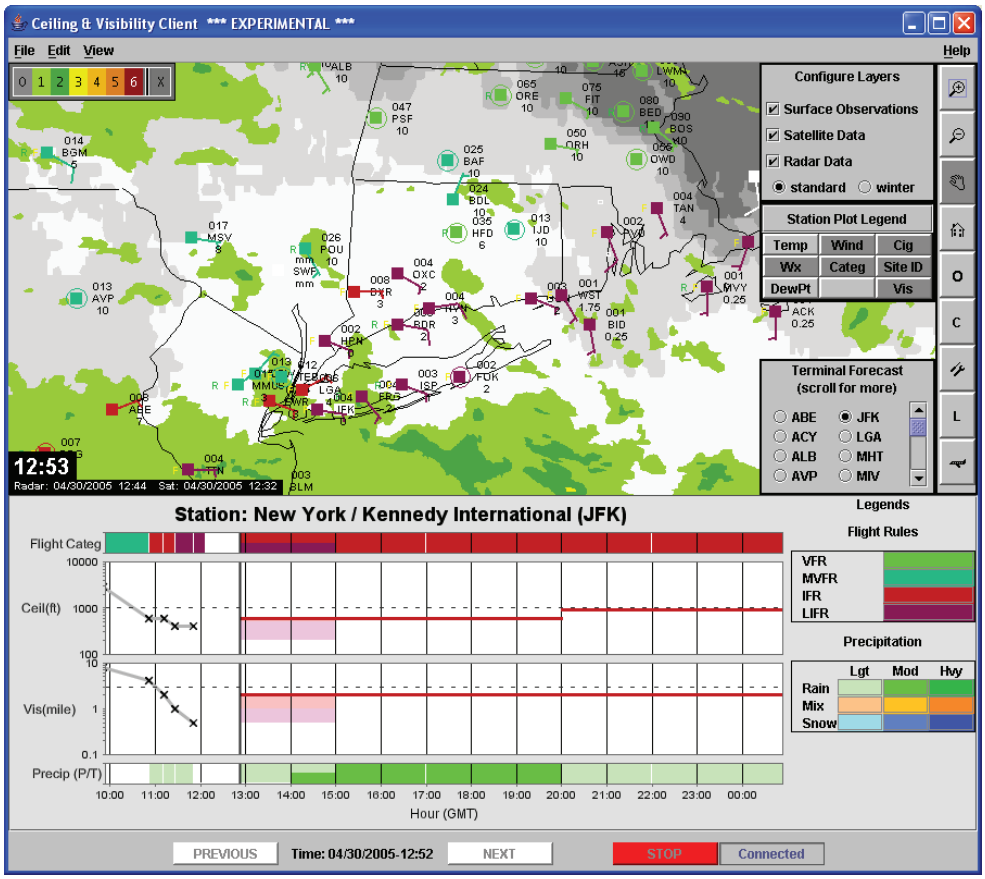

FIGURE 24. Experimental ceiling and visibility display for Northeast region. The upper panel shows the regional situation display, and the lower panel shows user-selectable terminal forecasts, currently derived from NWS Terminal Aerodrome Forecasts (TAF).

end, a number of parallel forecast research efforts have begun to investigate and address the various needs. A list of candidate technologies that have been under consideration is provided in Table 1. Technologies that rely on the availability of high-resolution (time and space) observations such as satellite imagery, radar data, and surface observations will be used to address the tactical forecast time frame (less than three hours), while the longer forecast horizons needed for strategic planning (out to twelve hours) will rely more on the holistic approach of numerical weather prediction models.

As part of the research process, the New York City area airspace is being used as an experimental domain for both weather and operations. Figure 24 shows an experimental display for delivering ceiling and visibility information and forecasts that has been provided to the New York Terminal Radar Approach Control in order to solicit feedback from traffic managers regarding the impact of ceiling and visibility on traffic decisions and the sufficiency of the currently available forecasts. This interaction is considered invaluable for directing continued product development efforts. Indications are that the primary forecasts need is associated with situations in the tactical time frame when the most recent forecast begins to deviate significantly from observed conditions in the immediate region. This research has also indicated that an ambitious product vision would be a more comprehensive terminal-forecast package that integrates other weather parameters (particularly wind and precipitation) with operational information, such as traffic demand profiles and anticipated runway configurations and their associated weather-dependent operating capacities.

One development effort worthy of note, the ability to accurately diagnose and forecast precipitation phase (rain, snow, mix), is serving the needs of both the ceiling and visibility team and the winter weather element

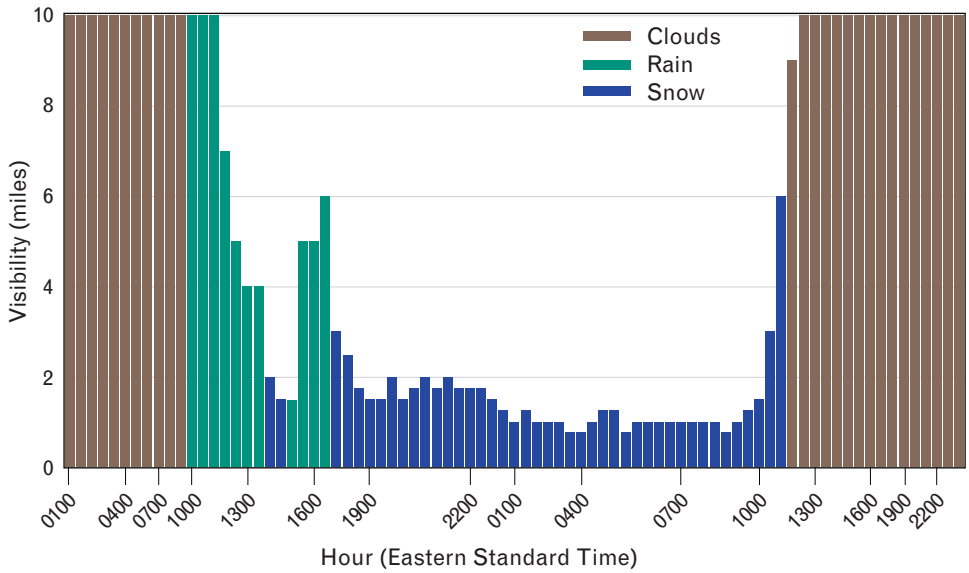

FIGURE 25. Variation of visibility with precipitation phase at Boston Logan International airport on 12–13 November 2004.

of the prototype CIWS. Precipitation phase significantly impacts both visibility and runway operations. Figure 25 is an example showing the dramatic change in visibility as rain transitions to snow at Boston's Logan International airport. A current forecasting limitation is that the exact phase of falling precipitation is measured only at point locations, which are typically spaced tens of kilometers apart, making it difficult to pinpoint the location and movement of the transition zone. The prototype product relies on the empirical relationship between a host of meteorological parameters (temperature, dew point, pressure-layer thickness) and observed precipitation phase. These relationships are used in a weighted formula to compute the conditional probability of phase at individual points within a gridded domain. These probabilities are then quantized to a deterministic precipitation phase (rain, snow, mix) and mapped to a corresponding radar echo

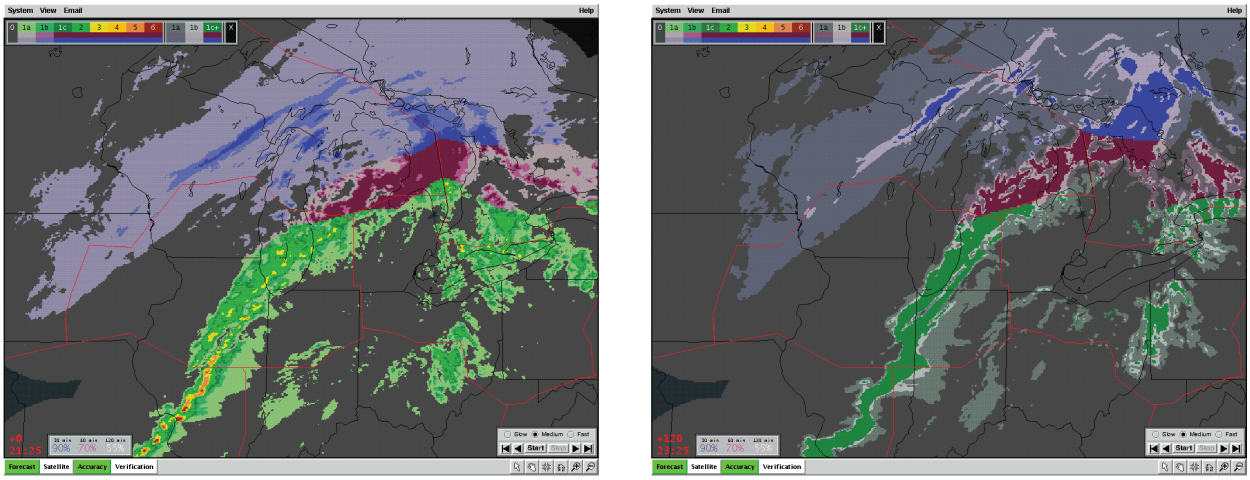

FIGURE 26. CIWS display of precipitation phases. (a) Precipitation-phase diagnosis for 2125 GMT for 16 February 2006. (b) Two-hour forecast, valid for 2325 GMT. The blue colors represent snow, pink represents mixed precipitation, and green represents rain.

image to generate a precipitation-phase diagnosis. Tracking vectors derived from historical trend of the rain/snow transition line within the conditional precipitation-phase field are then applied to generate a forecast map, shown in Figure 26.

The other forecast technologies for Northeast ceiling and visibility will continue to be developed in parallel, and integrated to provide a unified source for terminal-based information and forecasts. Ultimately, the vision is to distribute the new technology through a more widely available regional or national platform, such as the proposed national CIWS. The intent would be for the large-area-domain system to provide portals to individual terminals for accessing complete forecast information, of which the ceiling and visibility technology would be an important component.

Summary

Recent accomplishments of two product development teams within the FAA's Aviation Weather Research Program have been described. Development of prototype systems have provided immediate benefits in improving traffic flow control efficiency within the National Airspace System, addressing both en route severe weather and capacity restrictive weather at individual airport terminals. This work has been performed by the Convective Weather team and the Terminal Ceiling and Visibility team.

Convective weather forecast capability has been used in both the ITWS (one-hour forecast) and CIWS (two-hour forecast) proof-of-concept demonstrations, and has proven highly useful in these operational settings as an aid to tactical traffic flow management. Keeping in mind the annual air traffic delay statistics curves, we recognize that the CWF technology—as valuable as it may be for making short-term forecasts—does nothing to solve the national summertime delay problem if air traffic management decisions are not being made differently as a result. So while a major milestone was reached in 2004 with the transfer of the CWF technology to the ITWS program for implementation, work is ongoing to address specific poor-performance scenarios and to further increase the operational utility of the CWF.

Two projects within the Terminal Ceiling and Visibility PDT were described. First was the prototype system developed to forecast the dissipation of stratus cloud, which restricts the approach capacity to San Francisco International airport. The system was demonstrated during four stratus seasons, after which the hardened prototype was transferred to the National Weather Service in 2004. More recent efforts involve the Northeast Winter Ceiling and Visibility Project, which is aimed at forecasts for major northeast corridor terminals that suffer significant capacity loss during low cloud and fog conditions, typically associated with transient weather systems that regularly impact the northeast corridor from November through April. The complexity of both the weather and air traffic management in this highly congested region presents a significant challenge for effective product development. We will continue to investigate and integrate a number of technologies in order to provide improved forecast information to support the air traffic flow control decision making process.

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We also want to especially acknowledge our friend and colleague, Barbara Forman, who passed away in April 2006. Barbara was an integral part of the Convective Weather PDT from its beginning until her illness forced her early retirement in 2004. Her legacy to the team is apparent in the work presented here.

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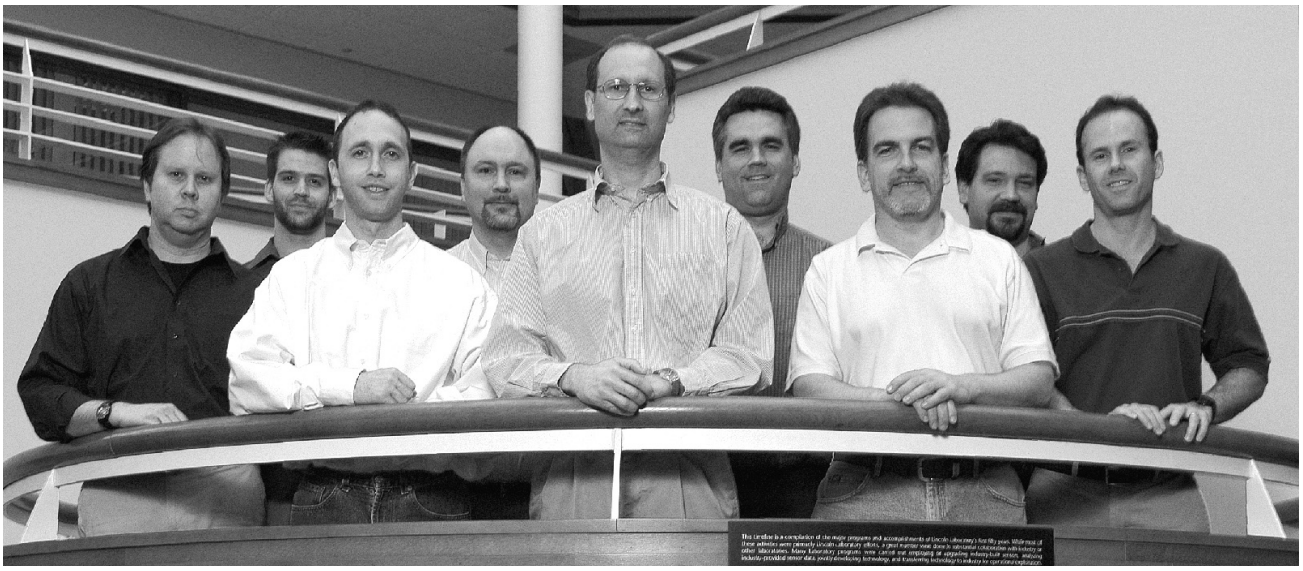
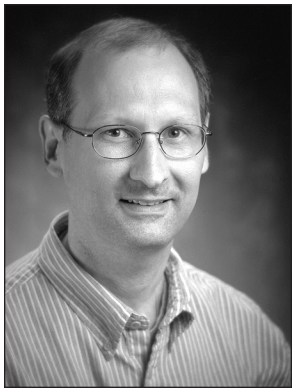
Convective Weather PDT members (left to right): Robert Boldi, Jonathan Hurst, Kim Calden, Carol Wilson, Marilyn Wolfson (lead), Paul Bieringer, William Dupree, Richard Johnson, and Haig Iskenderian.



Terminal Ceiling and Visibility PDT members (left to right): Charles Ivaldi, Jonathan Hurst, Paul Bieringer, Frank Robasky, David Clark (lead), Michael Matthews, Robert Hallowell, Kirk MacKenzie, and Michael Donovan.

MARILYN M. WOLFSON
is an assistant leader in the Weather Sensing group. She received a B.S. degree in Atmospheric and Oceanic Science from the University of Michigan and an S.M. from MIT, where she was named an Ida M. Green Fellow. She began work at Lincoln Laboratory in 1983. She returned to MIT as a Lincoln Staff Associate, graduating with a Ph.D. degree in 1990. She applied her thesis work in developing a real-time microburst prediction algorithm, which is currently operational in the FAA's Integrated Terminal Weather System. She began development of automated short-term convective weather forecasts for air traffic management applications in 1997, as leader of the FAA Aviation Weather Research Program's Convective Weather Product Development Team. She has patented and licensed the technology needed to make accurate one-to-two-hour forecasts, and has recently transferred this technology for operational FAA use. Her group is currently interested in increasing the year-round accuracy of the forecast products, and increasing the lead time to six hours and beyond. Understanding and anticipating the impact of the forecast on air traffic capacity and demand are important next steps in her group's research, as is the eventual coupling of the forecasts to automated aids to traffic flow management. She received the Lincoln Laboratory Technical Excellence Award in 2005.



DAVID A. CLARK
is a member of the technical staff in the Weather Sensing group. He received a B.S. degree in meteorology from the University of Lowell in 1981 and an S.M. from MIT in 1983. He worked at Raytheon Company on the Next Generation Weather Radar system (WSR-88D) prior to joining Lincoln Laboratory in 1987. His early work within the Weather Sensing group was associated with hazardous wind-shear detection, making contributions to the Terminal Doppler Weather Radar (TDWR), Low-Level Wind-Shear Alert System (LLWAS), and the Integrated Terminal Weather System (ITWS). He now serves as the lead of the Terminal Ceiling and Visibility Product Development Team within the FAA's Aviation Weather Research Program. He is a member of the American Meteorological Society.