Weather Forecasting Accuracy for FAA Traffic Flow Management: A Workshop Report

Committee for a Workshop on Weather Forecasting Accuracy for FAA Traffic Control, National Research Council

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WEATHER FORECASTING ACCURACY FOR FAA TRAFFIC FLOW MANAGEMENT

A WORKSHOP REPORT

Committee for a Workshop on
Weather Forecasting Accuracy for FAA Air Traffic Control
Board on Atmospheric Sciences and Climate
Division on Earth and Life Studies
NATIONAL RESEARCH COUNCIL
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Preface

Increasing aircraft volume in U.S. airspace presents a critical problem for air traffic flow and management. As a result, the Federal Aviation Administration (FAA) is continuously planning future air traffic control systems and protocols. Improved forecasting of severe convective weather is a critical part of this planning. Knowledge of the three-dimensional location and intensity of hazardous convective weather 2 to 6 hours ahead is central to selecting air traffic routes that will support the planned traffic with little or minimal weather delays or diversions. For traffic flow management to operate based on forecasts of convective weather, the entire aviation operations community needs to have a high-level of confidence in the forecasts and a common understanding of how they will affect operations. One of the key limitations in applying these forecasts for traffic flow management is the inherent uncertainty and complexity of making temporally and spatially well-resolved short-term forecasts (2 to 6 hours) of convection.

To help identify the limitations of convective weather forecasting and begin a dialogue on potential steps forward, the FAA asked the National Research Council (NRC) for assistance. In response, the NRC formed the Committee for a Workshop on Weather Forecasting Accuracy for FAA Air Traffic Control, which convened a 2-day exploratory workshop on June 4–5, 2002, in Washington, D.C. (see Appendix D). The workshop was a forum to address the complex issues related to research needs for convective weather forecasting. In particular, the workshop discussions explored the present and future potential in meeting required convective forecasting accuracies and how those forecasts could have greater utility to air traffic controllers, airline dispatchers, and pilots. Further, because it was indicated that the desired forecasting accuracy may not be achieved in the near future given existing research activities, workshop participants generated a prospectus for a study to examine what is needed to reach the FAA requirements.

The first session of the workshop provided an opportunity for the operational and user communities to frame the problem. Presentations focused on identifying current activities for which improved understanding of convective weather would assist traffic flow management. The second session involved members of the research community who were assigned the task of identifying current and potential future research activities that could lead to improved 2- to 6-hour convective forecasts and more effective presentations of these forecasts. The FAA provided the following questions to help guide the presentations during the workshop's second session:

1. What approaches and strategies will be most effective to get an accurate 2- to 6-hour forecast of areas of convection for aviation use in the next 5 to 10 years? (Accurate means a desired false alarm rate (FAR) of =0.20, a desired probability of detection (POD) of =0.80, a maximal FAR of 0.30, and a minimal POD of 0.60.)
2. What specific scientific enabling capabilities are needed to realize these gains and when will they be available? For example, what improvements in observations, algorithms, analyses, and numerical modeling are likely to yield the best results? What are the major gaps in the current research and development activities that need to be addressed?
3. What is the most appropriate way to present the forecast in an operational setting?

- Consider the two main uses are flight planning and traffic flow management.
- Consider how the forecast will be developed and presented (i.e., purely probabilistic or deterministic).

4. How will we know when we are done? What verification scheme makes the most sense from an aviation perspective?

Many workshop participants opined that the goals set by the FAA for FAR and POD were overly ambitious and, in fact, ill posed. That is, improvement in skill as measured by metrics such as FAR and POD do not necessarily translate into increased value for the end user owing to numerous mitigating influences (e.g., constraints on the overall air traffic system, nonweather impacts, and industry-government politics). In addition, such metrics, which are perfectly suited for large-scale weather features, do not apply to spatially irregular and highly intermittent convective phenomena. An alternative set of objectives was alluded to by James Washington, of the FAA, during the first session of the workshop (see Chapter 1).

During the final session of the workshop, the committee and guests identified issues and focused research topics that need to be addressed in any follow-up activity or study.

The three chapters of this report correspond to the three sessions of the workshop. This report was prepared by the committee and recounts the discussions that took place during the workshop; the workshop format prohibited the development of findings or recommendations.

The committee thanks everyone who helped plan or who participated in the workshop, especially the invited speakers: Lance Bosart of the State University of New York at Albany; Peter Challan, James Washington, Jack Kies, and Richard Heuwinkel of the FAA; Russell Gold of the Air Transport Association; William Cranor of US Airways; Mark Phaneuf of AvMet Applications; Barbara Brown and Andrew Crook of the National Center for Atmospheric Research; Fred Foss of the Aviation Weather Center; Jack Hayes and Alexander MacDonald of the National Oceanic and Atmospheric Administration; Ross Keith of the Australian Bureau of Meteorology; and Joby Hilliker of Pennsylvania State University.

Steven F.Clifford
Chair

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Barbara G.Brown, National Center for Atmospheric Research, Boulder, Colorado

Andrew Crook, National Center for Atmospheric Research, Boulder, Colorado

R.John Hansman, Massachusetts Institute of Technology

James H.Henderson, Aviation Weather Center, Kansas City

Although the reviewers listed above provided constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

1

The Aviation Community's Weather Forecast Needs

The operational forecasting and user communities involved with air traffic together represent a diverse group of air traffic managers, air and cargo carriers, and commercial and private pilots. Convective weather forecasting plays a critical role in ensuring the smooth and safe flow of air traffic in this country. The first session of the workshop focused on weather forecast products that the operational forecasting and user communities identified as necessary for improving air traffic control. The specific topics addressed during this session included identification of needs and statement of the problem related to convective weather forecasting, the role and development of the Collaborative Convective Forecast Product (CCFP) to assist air traffic management and strategic planning in the national airspace, and the current status of operational convective weather forecasting.

IDENTIFICATION OF NEEDS AND STATEMENT OF THE PROBLEM

Operational Forecasting Community

During his presentation, James Washington of the Federal Aviation Administration (FAA) Air Traffic System Requirements Service provided background information for the workshop and stressed the following points:

- Weather accounts for 70 percent of all delays in the national airspace, with convective weather accounting for 60 percent of all weather delays (see Figure 1–1).
- Convective weather is difficult to forecast.
- Traffic flow managers need 2 to 6 hours of lead time for effective planning.

Mr. Washington identified the two different timescales for forecasts in air traffic management. Tactical planning relies on forecasts in the 0- to 2-hour time frame. With improved observational capabilities and data assimilation techniques, the forecast skill for this timescale has improved substantially in the past few years, especially for the 0- to 1-hour range. Strategic planning relies on forecasts 2 to 6 hours into the future. The skill for convective weather forecasting in this timescale is very low, though improvements have been made with the advent of the CCFP.

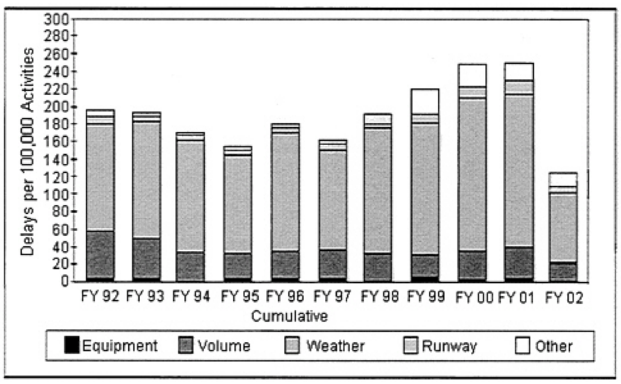

FIGURE 1–1. Cumulative causes of flight delays per 100,000 activities from 1992 to 2002.

Many workshop participants thought that the 5- to 10-year goals for forecast accuracy set by the FAA in preparation for this workshop (desired false alarm rate (FAR) =0.20, desired probability of detection (POD) =0.80, maximal FAR of 0.30, minimal POD of 0.60) were unrealistic based on current forecasting abilities. Thus, Mr. Washington identified the following alternative goals for operational convective forecasting and challenged the workshop participants to explore how they might be achieved:

- Achieve a 50 percent increase in forecast skill for the 2- to 6-hour convective forecast in the next 3 to 5 years and another 50 percent increase in the new baseline in the next 5-year period.
- Augment the operational utility of convective forecasts by reducing the number of multiple and inconsistent forecasts and improving translation of the forecasts into decision aids.
- Identify standard convective forecast verification approaches.

Industry

Convective weather in the national airspace impacts the flow of air traffic, resulting in large economic costs to business sectors that depend on uninterrupted air traffic flow. During the workshop, Russell Gold of the Air Transport Association (ATA) discussed the economic impacts of convective weather on air cargo carriers, whose industry is a key indicator of economic vitality in the United States. He quoted conservative estimates of the industry-averaged systemwide cost to an individual carrier as being $42 for each plane delayed by weather for one minute. This value represents the direct costs of operating the airplane and does not account for additional costs caused by ripple effects in the system. Furthermore, indirect costs associated with additional on-the-ground labor expenses are approximately $6,000 for a 15-minute delay.

To begin addressing the problem, the airlines and the FAA have formulated a plan that describes their roles and responsibilities regarding convective weather avoidance. Under this plan, national airspace users are charged with identifying areas of weather that should be circumnavigated, and the FAA is charged with managing the demand versus capacity equations in routes that users have communicated their desire to use. One point emphasized by Mr. Gold was that a large number of convective weather initiatives are underway. Duplication and redundancy increase user confusion. The ATA encourages the forecast community to think about ways to integrate these into a single tool for traffic flow management decisions.

Collaborative Decision-Making Process

Given the impact of convective weather on flight operations and the severe economic toll that convective weather exacts on the nation's passenger and cargo carriers, a joint government-industry program was formed and charged with improving air traffic management using collaborative procedures and technologies. During the workshop, Jack Kies of the FAA described the Collaborative Decision-Making (CDM) process. CDM was designed to enable industry operators and air traffic managers to have similar information about how weather might impact air traffic and to reduce duplication of effort and inefficiencies caused by arriving at the same conclusion through perhaps multiple different processes. Stakeholders, such as airlines and cargo carriers, can provide input into traffic flow management decisions to ensure that their individual needs are met. This process achieves the following objectives: (1) it allows for more equitable use of the national airspace, consistent with the needs of individual users; (2) it improves the transition to normal operations after weather events have cleared; and (3) it produces a comprehensive collaborative plan of action for the national airspace 2 to 4 hours in advance by the members of the strategic planning team. The greatest emphasis of the CDM plans, procedures, and processes is to encourage inclusion of all system stakeholders in the collaborative process, enhance communication and coordination, and provide common reference materials and definition of constrained areas in a collaborative arena.

COLLABORATIVE CONVECTIVE FORECAST PRODUCT

Overview of the System

One of the key accomplishments of the CDM working group was the development of the CCFP in 1996 (with implementation in 1999). The CCFP attempts to provide useful and informative strategic forecasts for operational use. William Cranor of US Airways provided an overview of this product. The CCFP is based on the assumption that forecasts made through collaboration with all stakeholders result in a better decision aid for users and operators. The product is an area forecast based on a 3×3 forecast matrix depicting the predicted coverage of storms and the probability that convective weather will occur during the forecast time. It is now issued 7 days a week, 24 hours a day during the convective season of March to October. From an industry perspective, the CCFP provides a common beginning point for a strategic planning process to respond to severe weather situations while reducing the need for detailed meteorology discussions during strategic planning. In addition, it provides a qualitative estimate of convection probability and potentially constrained airspace, with a fully collaborative process for production that ensures all stakeholders can participate.

A critical requirement in developing the CCFP was that it provide consistency and reduce the number of competing or conflicting forecasts. Forecasts are required for the 2-, 4-, and 6-hour time horizons. The 2-hour forecasts are critical for tactical traffic flow adjustments and flight route planning and modification. The 4- and 6-hour forecasts are critical for strategic route planning, traffic flow management, and internal airline operations. Mr. Cranor stated that the system is currently limited by a lack of means to amend forecasts, poor knowledge by stakeholders of how to interpret the CCFP, lack of consensus on how to apply the CCFP in low-coverage scenarios, and inappropriate use of the CCFP as a tactical tool. Other limitations and problems include unknown capacity in impacted areas covered by the CCFP, lack of confidence in convection forecasting, and concern that areas with convection below the CCFP thresholds are not considered.

Mr. Cranor suggested that future enhancements of the system include new products to fill the gap between real time and 2-hour time frames, efforts to align the CCFP production schedule with the strategic planning time frame, solutions to address convection below the CCFP thresholds in certain critical areas, and improved training for both product users and producers.

Evaluation and Verification

Evaluation and verification of the CCFP represents a critical step in improving the operational effectiveness of the product. During the workshop, Mark Phaneuf of AvMet Applications International, LLC, described a methodology used to empirically evaluate the operational utility of the CCFP and derive traffic reduction guidelines for operational use. This method selects days when there was no bad weather and no CCFP in order to establish a traffic baseline. The process then selects days when (1) the CCFP was present and bad weather did not develop, (2) the CCFP was present and bad weather did develop, and (3) the CCFP was not present and bad weather did develop. The region of interest was the area around

Chicago, Illinois. The types of reroutes for individual flights were defined as:

- *No reroute:* Scheduled, filed, and actual flight routes go through the forecast area and do not differ.
- *Strategic before forecast:* Scheduled and filed routes go through the forecast area, and amended routes, filed prior to CCFP valid time, go around the forecast area.
- *Strategic:* Scheduled and filed routes go through the forecast area, and amended routes, filed before takeoff or prior to 2 hours before reaching the forecast area, go around it.
- *Tactical:* Filed routes go through the forecast area and are amended after takeoff to go around the forecast area.
- *Unclear:* Filed routes go around the forecast area or are amended to go through the forecast area after the forecast is issued.

Mr. Phaneuf presented results from applying this classification system to two case studies. For 226 flights on July 19, 2001, a day with a medium probability forecast for convective weather in the vicinity of Chicago, the majority of cases (52 percent) involved no reroute, with tactical (29 percent) and strategic before forecast (13 percent) rerouting being the major reroutes. For 124 flights on May 10, 2001, a day with a low-coverage, low-probability forecast, no reroute made up 81 percent of the actions, with strategic before forecast and strategic reroutes making up 13 and 5 percent of the actions, respectively.

Mr. Phaneuf suggested further steps for evaluation of the CCFP: (1) continued analysis of the type he presented with additional days in each category, (2) correlating the results of his suggested analyses with other validation programs in effect for the same time frame, and (3) establishing empirically derived guidelines for traffic reductions.

Barbara Brown of the National Center for Atmospheric Research also presented information on validating the CCFP, with a focus on statistical and meteorological verification techniques. She described the purposes of verification to be to identify problems, guide improvements, unambiguously measure those improvements, and provide useful information to decision makers and developers. In verification, forecasters and developers should not verify their own forecasts, in part because different users require different types of information about forecast quality. Critical components of verification include statistical and scientific validity, independence of the forecast verification process from the forecast development process, and appropriate matching of forecasts and observations. Ms. Brown identified several aspects associated with CCFP verification, including choosing the appropriate spatial scale; filtering of the observed and forecast fields; current use of "standard" methods; stratifications based on coverage, height, and probability; and comparison to other forecast products.

Ms. Brown discussed available verification systems that use a grid-based approach, with binary comparison. In this strategy, which is the current standard approach for convective forecasts, forecasts are compared with observations by overlaying the forecasts and the observations for a given grid. This method can be used to compute basic statistics such as POD, FAR, and various skill statistics (e.g., Heidke Skill Score, True Skill Statistic).

In addition to the binary detection statistics, Ms. Brown presented results on the actual weather coverage in the CCFP forecast areas as a function of the forecast time, forecast coverage, and probability of occurrence. In the CCFP for 2001, 92 percent of the 8,433 forecasts indicate low coverage of convective weather. Further, for 97 percent of the cases, the forecasts indicated low or medium probability of convective weather. Analysis of the actual versus predicted coverage suggests some skill in predicting coverage. Overall, the CCFP statistics indicate that the 2-hour forecast has a somewhat higher POD and a slightly lower FAR than the 6-hour forecast. These results showed that 2-hour forecasts (especially those with medium probability) had an actual weather coverage closest to the predicted coverage and that the 4- and 6-hour forecasts generally predicted significantly more weather coverage than actually occurred.

CURRENT STATUS OF OPERATIONAL FORECASTING

Constraints

During his presentation, Fred Foss of the Aviation Weather Center identified current limitations in operational convective forecasts. He first outlined a number of scientific limitations, including limited skill in explicit event description, depictions that do not resolve where the clouds exist, poor understanding of scale interactions, and insufficient spatial and temporal resolution of convection. A second category of limitations pertains to the human-machine interface. Mr. Foss emphasized that humans respond better to visual information transfer than data transfers. However, the time necessary for creating and communicating the forecast images limits the ability to provide useful visual information. Lastly, operational convective forecasts are limited by current observational capabilities, particularly the lack of spatial and temporal resolution and difficulties in easily assimilating all of the observations into initialization of the models.

Numerical Modeling

Jack Hayes of the National Weather Service presented information about the state of numerical modeling as applied to convective weather forecasting, planned near-term (1- to 3-year) improvements, and potential longer-term improvements. Currently, the National Centers for Environmental Prediction (NCEP) provide two operational weather models: (1) Eta Model forecasts are produced four times a day, out 84 hours into the future, with 12-km resolution, and output provided every 3 hours, and (2) Rapid Update Cycle forecasts are produced eight times a day, out 12 hours into the future, with 20-km resolution, and output provided every hour. Current operational models provide very good descriptions of large organized areas of convection associated with large-scale flow patterns or fronts over hundreds of kilometers and over time intervals of hours to days. However, current models do not predict storm-scale convection, which typically occurs over timescales of 20 minutes to 6 hours with spatial scales of 1 to 5 km. In addition, vertical acceleration of air motion critical to localized convection is not included in the models.

Thus, the current operational models do not accurately predict information required by the national airspace system for decision assistance. Particularly, information such as overall convective coverage, rate of storm growth, storm tops, and probability of occurrence is not produced by the models. These information needs require the human forecast expertise through generation of the CCFP.

In the near term, research and operational forecast models will boast increased resolution and improved physics and dynamics but will see little improvement in observational inputs. NCEP believes that these enhancements will improve model performance to the point of increasing by 15 percent the accuracy of convection forecasting via the CCFP. Indeed, over the next decade, numerical models may have spatial resolutions on the order of 1 to 6 km. This finer resolution requires explicit treatment of clouds, convection, and other physical processes but also observational data of the same resolution. NCEP's goal, over the same time period, is to resolve thunderstorm events at scales of 3 to 20 km with lifetimes of 2 to 6 hours. However, most agree that only ensemble forecasts will be capable of providing appropriate guidance for such phenomena.

Potential opportunities for further improving forecasting ability include improved observational capabilities, with an emphasis on increased spatial and temporal resolution of observations as well as improved water vapor measurements.

2

Status of Aviation Weather Forecasting Research

The research community has helped develop many advances in convective weather forecasting. The motivation of this workshop was to bring together members of the operational forecasting, user, and research communities to begin to explore the potential for improving 2- to 6-hour convective forecasts used for flight planning. The second session of the workshop focused on research approaches and strategies to address convective weather forecasting. The discussions in this session were structured around four questions provided by the Federal Aviation Administration (FAA):

1. What approaches and strategies will be most effective to get an accurate 2- to 6-hour forecast of areas of convection for aviation use in the next 5 to 10 years? (Accurate means a desired false alarm rate (FAR) of =0.20, a desired probability of detection (POD) of =0.80, a maximal FAR of 0.30, and a minimal POD of 0.60.)
2. What specific scientific enabling capabilities are needed to realize these gains and when will they be available? For example, what improvements, in observations, algorithms, analyses, and numerical modeling, are likely to yield the best results? What are the major gaps in the current research and development activities that need to be addressed?
3. What is the most appropriate way to present the forecast in an operational setting?

Consider the two main uses are flight planning and traffic flow management.
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4. How will we know when we are done? What verification scheme makes the most sense from an aviation perspective?

Many workshop participants thought that the 5- to 10-year goals for forecast accuracy set by the FAA in preparation for this workshop (desired FAR =0.20, desired POD =0.80, maximal FAR of 0.30, minimal POD of 0.60) were unrealistic and, in fact, ill posed. That is, improvement in skill as measured by metrics such as POD and FAR does not necessarily translate into increased value for the end user owing to numerous mitigating influences (e.g., constraints on the overall air traffic system, nonweather impacts, and industry-government politics). Further, such metrics, which are perfectly suited for large-scale weather features, do not apply to spatially irregular and highly intermittent convective phenomena. Because of these concerns, the workshop presenters did not focus specifically on these goals but rather on improving forecasts more generally.

This chapter summarizes the information presented during this session of the workshop. Text boxes for each discussion topic call out key points identified by individual presenters. These key points do not reflect the consensus of the presenters or the committee.

STRATEGIES FOR IMPROVING CONVECTIVE FORECASTS

Accurate prediction of convection in the 2- to 6-hour time range may not be amenable to an “engineered” solution without further research related to improved understanding of convection and the practical limits to its predictability. During the workshop, Richard Carbone of the National Center for Atmospheric Research (NCAR), J.Michael Fritsch of Pennsylvania State University, and Cynthia Mueller of NCAR presented their visions of a 2- to 6-hour forecast strategy. These respective visions follow sequentially below.

Richard Carbone

Mr. Carbone noted that traditional numerical weather prediction (NWP), including all operational and mesoscale models that parameterize convection, have not fared well in predicting convection generally, though other presenters noted successes in specific cases. For example, threat score[1] performance for forecasts of at least 1 inch of rain at a 24-hour range exhibits very little skill in summer (see Figure 2–1). Initial condition uncertainties, model physics, and chaotic evolution of convection are among the principal impediments to accurate forecasts.

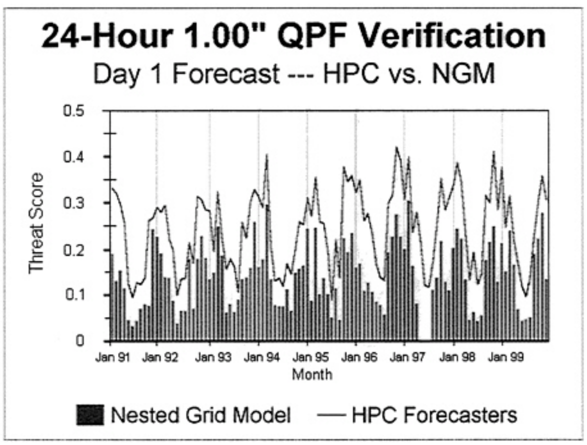

FIGURE 2–1. Monthly threat scores from NCEP's Hydrometeorological Prediction Center. Note the midsummer minima in forecast performance.

[1] Threat scores are used to quantify categorical forecasts of discrete predictands (an observed variable that takes on one of a number of finite values). Generally the score represents the ratio between the number of forecasts that correctly predicted observed events and the total number of occasions on which the event was forecasted, observed, or both. Correct forecasts of nonoccurrence are not included in the calculation (Wilkes, 1995).

Nowcasting is at the other end of the spectrum of approaches to forecasting weather. So-called expert systems, mainly using knowledge-based rules, neural networks, and similar types of logic, have made substantial progress in the 0- to 60-minute range and also exhibit some skill out to the 2-hour range. There appears to be a predictability "wall" that resides at a range short of 3 hours for all but the most strongly forced systems, which are usually associated with fronts and cyclones. Nowcasting, as currently implemented, is unlikely to make much headway in skillful forecasts of weakly forced convection during midsummer. This is because the disturbed local environment, created by antecedent convection and other initial condition uncertainties, creates too many degrees of freedom for rule-based estimates of convective evolution, at least at the cell or storm scale. Nowcast systems have recently begun to include information from adjoints of dynamical models. This is an early stage of convergence between simple extrapolation of observations and NWP.

Parameterized convection in NWP models is a principal limitation to skillful predictions for many of the same reasons attributed to nowcasting. Advanced data assimilation techniques, combined with explicit convection-resolving models, hold promise for the future of dynamically based forecasts. Encouraging results can now be obtained from simulations of selected cases. However, routine forecasts from these methods regularly have major "busts." Advanced variational assimilation of radar and satellite data is needed to keep models on track. Furthermore, trajectories indicated by skillful nowcasts may also influence dynamical model trajectories via data assimilation, blurring the distinction between nowcasting and NWP forecasts.

Employing the use of ensembles for probabilistic prediction can serve to quantify forecast uncertainty; however, knowledge is scant about true forecast sensitivities, initial state limitations, and how best to generate or select members of an ensemble. An optimist would attempt to observe initial states at a much higher temporal and spatial resolution, assuming model error per se is a small part of the problem. However, large model error, resulting from sensitivity to poor representation of microphysics, related diabatic heating effects, and deficiencies in representations of boundary and surface layers appears to be a significant part of the forecast problem. Research to decipher the largest forecast sensitivities is badly needed, as are the applicability and effectiveness of advanced data assimilation methodologies such as four-dimensional variational assimilation (4-DVAR) and Ensemble Kalman Filtering.

Over the past 2 years, research on the climatology of convection over the United States has led to some encouraging findings about the apparent intrinsic predictability of convective events as viewed through a coarse two-dimensional filter. Examining the distribution, diurnal cycle, and autocovariance properties of convection on a continental scale yields strong signals that finer scales of analysis obscure, mainly due to chaotic evolutions at the storm scale. Nearly every day, coherent convective “episodes” span 1,000 km or more and last 20 hours or more, despite the absence of strong forcing at the synoptic scale. This convection often contains the strongest and largest events on a given day as it propagates across the country. The episodes consist of sequences of convective systems, exhibiting recurrent coherent regeneration of convection that spans long distances and time periods. More than 5,400 such events have been observed in the Weather Surveillance Radar 88 Doppler (WSR-88D) data over four warm seasons (1997–2000). The findings suggest that a coarse-grained look at convection may yield substantial *statistical* predictability, even without the aid of NWP guidance. For example, at 0600 UTC, an event that has existed for 6 hours near 100° W longitude has a 70 percent chance of continuing to propagate in a predictable manner for 6 additional hours. Furthermore, application of NWP guidance to such observations-based predictions should markedly improve probabilistic predictions through the addition of information on forcing at meso-synoptic scales.

Mr. Carbone concluded by advocating a fusion of nowcasting and NWP techniques, that is, statistical-dynamical prediction of *secondary* convection. This approach would exploit the statistical coherence of convection by combining knowledge of this behavior with knowledge of large-scale and mesoscale forcing that lies in the path ahead of antecedent organized convection. Knowledge of such forcing is a strength of NWP models, and it will improve with better observations and more skillful assimilation schemes. Such methods, however, do not address, except climatologically, the issue of convective initiation (i.e., prediction of *primary* convection) and will yield probabilistic predictions, not deterministic ones. This is just one of several possible approaches to probabilistic prediction.

J.Michael Fritsch

Dr. Fritsch noted that weather forecasting has traditionally focused on time- and space scales that, for the most part, are longer and larger, respectively, than the needs of the aviation industry. Specifically, forecasters have concentrated on synoptic-scale systems to forecast the “today, tonight, tomorrow” time period. To do this, forecasters depend strongly on synoptic-scale numerical model guidance. However, the aviation industry operates in a *mesoscale* world and requires more specific and more frequent guidance than that provided by the current NWP-based forecasting system. Moreover, numerical models have inherent limitations when it comes to providing guidance in a timely manner and remain notoriously poor at forecasting cloud-scale and mesoscale phenomena. During the workshop, Drs. Fritsch and Joby Hilliker of Pennsylvania State University described a technique using high-frequency weather observations in nonlinear statistical forecast models to improve forecasts of convection.

The problem of dealing with small time- and space scales is exacerbated in the presence of deep convection. Historically, levels of skill for forecasting convective storms are poor. This is readily evident from cursory inspection of historical records of quantitative precipitation forecasts. Assuming a typical bias of 1.1, the National Oceanic and Atmospheric Administration Hydrometeorological Prediction Center Model is only able to forecast 30 to 40 percent of the observed area of heavy rainfall (a proxy for convective storms) in the "day 1" forecast period (the 24-hour period from 12 to 36 hours after model initialization).

Because the aviation industry operates on such short timescales, guidance from numerical models is generally of limited value to air traffic management. Interviews of Terminal Radar Approach Control Traffic Management coordinators conducted by Forman et al. (1999) revealed that the optimal lead time needed to manage current traffic is 30 minutes. Traditional models, such as the Eta Model, are only operationally updated every 6 hours, a time interval longer than the duration of a typical domestic flight (Black, 1994). The latest version of the Rapic Update Cycle model is updated hourly and offers 1-, 2-, and 3-hour forecasts, yet the parameters most critical to aviation (e.g., convective ceiling, thunderstorm cell location) are absent in conventional model output (Benjamin et al., 1998).

Aviation is a decision industry; it needs reliable unbiased guidance to operate at peak efficiency. However, most model guidance is still deterministic, meaning that for a given lead-time a *single* forecast is produced. The user is left to wonder how much confidence to place in the forecast. Considering the multitude of nonlinearities that exist and interact in the atmosphere, the crude approximations applied in model initialization, and the various parameterization schemes and algorithms applied to output aviation parameters, undoubtedly, there can be large uncertainty and bias. Traffic flow management personnel not only recognize this inherent uncertainty when predicting weather but account for it through careful cost-benefit decision making in an effort to minimize the airlines' operating costs. For example, Andrews (1993) states that the optimal ground-holding time of an aircraft is dictated by the mean and standard deviation of the flight's predicted delay. This information is inextricably linked with uncertainties about the onset and duration of an adverse weather event. The uncertainties incorporated into cost-benefit analyses can best be captured, then, using reliable *probabilistic* forecast guidance. Therefore, it is not enough that a model predicts the occurrence of a given weather condition. It is also necessary to know the likelihood (probability) that the model prediction will be correct. It follows that no matter which model is run, statistical postprocessing is necessary to correct for bias and to obtain an accurate measure of the uncertainty in the forecast.

It is possible that ensembles of high-resolution model forecasts could provide a measure of uncertainty for the aviation system. However, providing an ensemble of high-resolution model forecasts and then postprocessing the output in a *timely* manner is unlikely in the foreseeable future.

Considering all of the above, Dr. Fritsch asserted that an alternative strategy to simply improving NWP may be necessary to provide the type of guidance needed by the aviation industry. One alternative would be to blend short-term observations-based statistical forecasting techniques with NWP output in a manner that will provide a time continuum of reliable quantitative measures of uncertainty that will fill the short-term gap created by the pre- and postprocessing required by NWP (see Figure 2–2). Observations-based systems run quickly and can be automated every few minutes as new observations become available. These systems will likely prove to be of great utility to the aviation industry.

During their presentations, Drs. Fritsch and Hilliker used a case study to demonstrate a prototype of an observations-based system. Radar images along with the areal distribution of the probabilities of thunderstorms for a 30-minute lead time were shown. They demonstrated how the system can produce forecasts for a suite of lead times ranging from the ultra short term (i.e., 6 minutes) to the traditional short term (i.e., 6 hours). The rapid-update capability of the forecast system also was shown, with 6-minute updates to the suite of forecasts displayed.

Drs. Fritsch and Hilliker also noted that, although traditional nowcasting techniques have demonstrated some success at forecasting well-organized mesoscale convective systems (e.g., squall lines), a large fraction of convective events exhibit chaotic organization and behavior, making traditional nowcasting approaches to forecasting exceedingly difficult. For these chaotic systems, the only reasonable approach is probabilistic guidance.

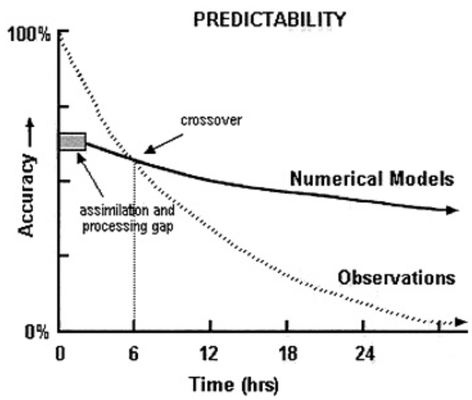

FIGURE 2–2. The decline in accuracy of forecasts based on numerical models and observations with time. Shaded gray area indicates time gap during which model products are not available due to the time needed to assimilate and process observations.

Cynthia Mueller

Ms. Mueller, from the perspective of an aviation nowcast developer, commented on the predictive skill currently associated with storms, the performance of current nowcast systems, and some recommended areas of research and testing. Forecasts in the 2- to 6-hour range have proven to be quite difficult, and there has been little focus in the research community on this forecast period. Forecast skill is low because storm evolution is rapid and nonlinear. Large areas of convection are more likely to persist and therefore are more predictable than small isolated storms. Experience with isolated storms reveals low predictive skill at ranges greater than 1 hour, but such isolated convective storms are easily circumnavigated in the en-route environment. A multicellular linear storm complex or a mesoscale convective system can last for several hours and exhibit propagation speeds that are reasonably stable and thus enable skillful extrapolation forecasts out to 2 to 3 hours. There is significant predictive skill associated with large-scale linear systems at longer ranges (1 to 6 hours); however, information that is useful to a pilot or dispatcher (e.g., to determine the location where a convective line can either be penetrated or circumnavigated) is often poorly predicted. Low skill is associated with features such as gaps in convection, regions of nonturbulent low storm top heights, and the length of storm lines.

Prediction studies have tended to focus on types of storm systems and structure and not environmental conditions. Large systems that are forced by mesoscale triggers (such as interactions between a gust front, undular bore, or terrain-induced circulations) can be similar in size to organized convection that is commonly associated with a synoptic-scale front. To date, studies have not been performed to quantify predictability of storm initiation, growth, and decay.

Concerning the techniques currently used in nowcasting systems, Ms. Mueller spoke to two methodologies applicable to the 2- to 6-hour range: (1) observations-based systems (also called data fusion or expert systems) and (2) numerical models that assimilate radar and satellite data.

Observations-based systems primarily use current conditions and trends to forecast convection. Examples of such systems include the Aviation Weather Research Program's Convective Weather Forecasts (Terminal Convective Weather Forecast, Regional Convective Weather Forecast, and National Convective Weather Forecast), the United Kingdom's Gandolf and Nimrod systems, and the Auto-Nowcast system (ANC). A primary component of the ANC system is its ability to identify and characterize boundary layer convergence lines. "Feature" detection algorithms and the Variational Doppler Radar Assimilation System (Sun and Crook, 2001) are used to monitor and nowcast boundary layer structure. Although the ANC system has shown promising results for near-term (0- to 2-hour) forecasts, it does not have predictive capability beyond 2 hours.

There are several sources of uncertainty and errors in the ANC forecasts. One source of error is poor extrapolation of features, including boundaries (lines of boundary layer convergence), cloud features, and storms. Extrapolation errors, which compound with forecast length, are due to nonlinear motion in the features and algorithm limitations. A second source of error is the inability to nowcast *secondary* convection. Research has shown that gust fronts play a major role in organizing convection. However, there is no skill in forecasting which storm will produce a gust front that goes on to initiate secondary convection. Another limitation in the forecasts is that the initiation, growth, and dissipation of *elevated* convection are not captured. Elevated convection often occurs under stable nocturnal boundary layer conditions and also in association with overrunning at stationary and warm fronts. A final limitation is that boundary layer moisture and temperature are not observed on scales thought necessary to nowcast storms. Stability information is obtained by indirect means such as observation of cloud fields, inducing possible errors.

Ms. Mueller also cited several sources of uncertainty in NWP-based forecasts, noting in particular that higher resolution currently does not lead to improved predictive skill. She identified a lack of physical understanding, most notably of convective life cycles and processes associated with secondary convection; initialization deficiencies associated with boundary layer and storm structures, and in-storm microphysics; and grid resolution and domain size limitations. Research most needed to overcome these limitations includes:

- *Development of high-resolution boundary layer wind and thermodynamic field analyses:* Efforts are needed to determine the multisensor observations most applicable for characterizing the boundary layer and near-storm environment. Candidate sensors and platforms include radars, mesonets, satellites, aircraft Communications and Reporting System, and surface-based profilers.
- *Predictability, scale interaction, and climatology studies:* Basic research in these areas is necessary both to provide a better understanding of the phenomena and to identify realistic limits associated with forecasts in the 2- to 6-hour range. Currently, explicit forecasts of storms are expected at the same scale as the observations. At longer ranges, however, this is not a well-founded expectation because there is no objective basis to establish the spatial or temporal limitations. Further, there is an emphasis on the use of probabilistic forecasts, but from an aviation user standpoint the most appropriate characteristics of these forecasts are unknown.
- *Use of NWP guidance in convective forecasts:* Data fusion or expert system techniques need to be developed that combine numerical model forecasts, statistics, algorithmic observations, and human forecasts. For example, data fusion techniques could be developed to determine (1) if confidence values can be assigned to 2- to 6-hour NWP deterministic forecasts of convective storms and (2) whether the NWP explicit forecasts can be improved by applying time and space corrections based on observations available after forecasts are issued or human input is applied. Indeed, it is important to the aviation community that forecasts are updated routinely in a timely manner. For example, extrapolation forecasts at the 0- to 2-hour time period have proven to be useful partially because of their frequent update rate. For a forecast to be of utility and trusted by the aviation community, it must be updated frequently.

- *Utility of water vapor:* Convection is known to be highly sensitive to boundary layer water vapor; however, the actual distribution and variability of water vapor over continents in summer are poorly understood. The International H_2O Project (IHOP), conducted in Oklahoma, Kansas, and Texas in 2002, offers unique datasets to narrow the bounds of uncertainty and to further evaluate forecast sensitivity. Numerical studies associated with the IHOP datasets should be pursued.

Ms. Mueller summarized by saying that the 2- to 6-hour forecast problem will require a combined NWP and expert system/statistical approach. Improvements should be expected in the 5-year time frame for forecasts of multicellular systems that are forced by large-scale features. Improvements in forecasts of systems triggered by mesoscale features or elevated convection are farther down the road. Efforts are needed to define products that are realistic from a science standpoint and to an aviation user. This may best be accomplished through a "testbed" approach.

Key Points Identified by Presenters on Effective Strategies for 2- to 6-Hour Forecasts

- "Accurate" prediction of convection at 2- to 6-hour range is an immense challenge that may not be amendable to an "engineered" solution without further research to improve understanding of convection and the practical limits to its predictability.
- All NWP models that parameterize convection have not fared well and are not likely to improve much.
- It is possible that more observations will solve this forecasting problem by reducing initial condition uncertainty. The problem, however, appears to be more complex, involving model error associated with the representation of microphysics, diabatic heating and cooling, and boundary and surface layers.
- Observations-based nowcasting has made substantial progress in the 0-to 60-minute range; however, there appears to be a predictability "wall" well short of the 3-hour range for all but very strongly forced systems.
- Probabilistic forecast guidance can be highly useful in the en-route aviation application if it is unbiased and its uncertainty is quantified.
- Statistical postprocessing is one effective way to correct for bias and obtain an accurate measure of the uncertainty in a forecast.

- Advanced data assimilation, when combined with explicit convection-resolving models, holds considerable promise and warrants further investigation. 4-DVAR assimilation of observations from radar, satellite, and other data can help keep models "on track."
- One approach for an operational system that will serve the aviation community's needs is to blend short-term observations-based statistical forecast techniques with NWP output in a manner that provides a time continuum of reliable quantitative measures of uncertainty. Such an approach will fill the short-term gap created by the pre- and postprocessing requisite in NWP. To accomplish this will require a close ongoing effort between scientists and operational users to ensure that improvements will be both scientifically credible and operationally useful.
- Formal assimilation of skillful nowcast data into NWP systems will improve the "trajectory" of dynamical models. Together with direct assimilation of observations, this constitutes a "blended" or "fusion" system, holding promise for forecasts in the 2- to 6-hour range.
- Limitations in computational capacity currently prevent the timely implementation of ensemble forecasts from convection-resolving models over continental-scale domains. However, novel implementation schemes may permit this desirable solution in the not too distant future (~10 years).

RESEARCH GAPS AND NEEDS

Andrew Crook's presentation focused on approaches and strategies for achieving an accurate 2- to 6-hour forecast of convection. Theoretical studies of turbulent flows suggest that flow predictability is limited to the order of the eddy turnover time. Extending these results to moist convective flows suggests the following predictability timescales for these convective phenomena:

- Large mesoscale convective systems, 3 to 6 hours
- Squall lines, 2 to 3 hours
- Large thunderstorms, 1 to 2 hours
- Single convective cells, 10 to 60 minutes

To examine the predictability of convection initiation, it is necessary to differentiate between cases that are strongly forced by large-scale circulations and those where the forcing is weak. A number of modeling studies have indicated that convection initiation in weakly forced environments is highly sensitive to thermodynamic parameters that are within observational error bounds. This limits the predictability to timescales of less than about an hour or, for example, to times when the first convection is observed. The exception to this result appears to be for convective systems that are strongly forced by large-scale circulations. The initiation of these convective systems appears to have more predictability in the 2- to 6-hour time frame as long as the large-scale circulation pattern is predicted accurately.

Given this limitation, Dr. Crook suggested that the FAA goal of obtaining an accurate forecast of areas of convection in the 2- to 6-hour time frame in the next 5 to 10 years will only be met for a limited number of convective phenomena. These include large mesoscale convective systems and convective systems generated by well-defined large-scale circulation patterns. The rest of the convective spectra (which probably accounts for 80 percent of the convection observed in the United States) will be difficult to predict in the 2- to 6-hour time frame. Progress will only be made for this portion of the convective spectra by embracing probabilistic forecasting, possibly using ensemble techniques.

Kelvin Droegemeier of the University of Oklahoma summarized the current state of research and development in the explicit prediction—both deterministic and stochastic—of deep convective storms. To understand the associated challenges, it is important to view this topic in a historical context. Early “synoptic-scale” models (e.g., the National Centers for Environmental Protection limited fine-mesh model, the nested grid model), which operated at grid spacings of approximately 80 to 150 km, were incapable of explicitly representing convective storms because they utilized a hydrostatic framework, which assumes that vertical accelerations are small. They also were unable to resolve the spatial scales associated with convection and were initialized using observations on spatial scales far larger than those of convective storms. The trend toward increasingly finer grid spacings (the current operational Eta model uses a grid spacing of 12 km), brought about by sustained increases in computer power, posed few scientific challenges because the physical assumptions underlying model formulation remained essentially unchanged—the flow was hydrostatic and clouds could not be represented explicitly.

The move of today’s operational models from resolutions of about 10 down to less than 3 km, however, is entirely different because no clear scale separation exists in this range for convective clouds. Convection generally cannot be resolved explicitly, and closure assumptions regarding its representation as a subgrid-scale phenomenon generally are not applicable (Molinari, 1993). Consequently, the next major step in numerical prediction is likely to come not with the continued extension of today's models down to grid spacings of a few kilometers, but rather via a jump directly to nonhydrostatic models at grid spacings of approximately 1 km—unless, of course, cumulus parameterization schemes suitable for application at resolutions between about 10 and a few kilometers can be developed.

Research conducted during the past several years at the Center for Analysis and Prediction of Storms at the University of Oklahoma (Droegemeier, 1997; Carpenter et al., 1999; Wang et al., 2001; Weygandt et al., 2002; and Xue et al., 2003) has demonstrated considerable skill in the explicit prediction of convective storms, especially for events with moderate to strong meso- or synoptic-scale forcing and in cases where high-resolution Doppler radar observations are available (see Figure 2–3). The prediction of "airmass"-type storms, and general regions of unorganized convection, is a much greater challenge, and the ability to forecast a specific storm in such instances perhaps may be impossible.

The above work and that performed by others (Sun and Crook, 1998; Belair and Mailhot, 2001; Mass et al., 2002) reveals the existence of numerous challenges on the path toward reliable operational storm-scale NWP. One such challenge is the tremendous nonlinearity of the small-scale atmosphere as exhibited by its predictive sensitivity to atmospheric, surface, and subsurface properties, particularly as they influence the timing and location of storm initiation and demise. A second challenge is associated with the difficulty of assigning objective skill measures to forecasts of highly intermittent phenomena. For example, a predicted thunderstorm that is correct in every detail yet has a spatial error of 20 miles, or a temporal error of 30 minutes, might represent an amazing feat scientifically and be of great practical value. Yet by traditional statistical measures, it would have zero skill (i.e., zero overlap with observations). A final hurdle is the clear need for probabilistic forecasting via ensemble techniques, and the combination of model output with other information, to create probabilistic products that can be applied directly to cost-benefit and economic decision models.

Dr. Droegemeier stated that successful storm-scale NWP will depend on the initialization of models with observations of comparable resolution, including three-dimensional wind fields derived from single-Doppler radar data; hydrometeor species retrieved from radar measurements; and moisture fields retrieved from high-density Global Positioning System (GPS), radar, and satellite data. Moreover, an ensemble of model results will be needed to

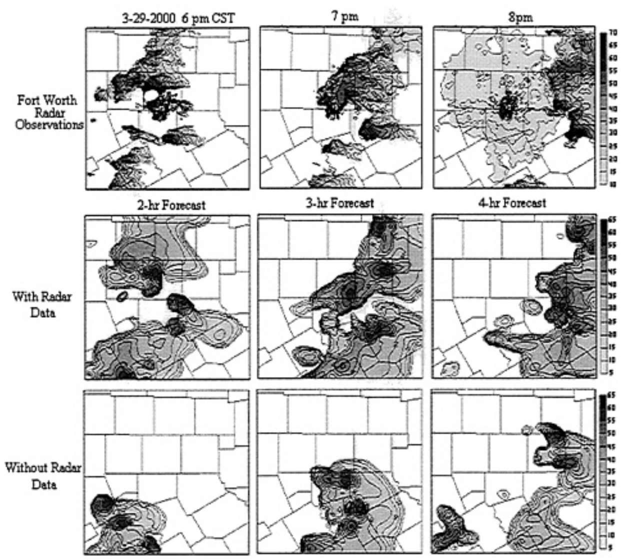

FIGURE 2–3. The top panel shows an hourly sequence of reflectivity images from the Fort Worth, Texas WSR-88D (NEXRAD) radar in association with a series of tornadic storms that moved through the Fort Worth metro area on 29 March 2000. Contour shading indicates precipitation intensity, with higher rates indicated by darker colors. Shown in the middle three panels is the equivalent radar reflectivity from a 3 kilometer-grid forecast using the University of Oklahoma Advanced Regional Prediction System (Xue et al., 2003), initialized at 2300 UTC with Fort Worth NEXRAD radar and other data. The degree of agreement between observations and forecast, even out to 4 hours, is remarkably good. The lower three panels show the same forecast, though without radar data in the model initial conditions. Although sufficient information exists to capture some structure associated with storms to the south of Fort Worth, the tornadic storms to the north are completely absent—thus highlighting the value of radar data in storm-scale NWP.

Zquantify forecast uncertainty given that the state of the atmosphere on the storm scale is highly variable in time and space and is not well sampled. Finally, in contrast to present-day operational models, it is likely that future models will not be operated centrally on fixed schedules or in fixed configurations but rather will be physically distributed, controlled locally, and configured to respond rapidly to the weather itself and to decision-driven inputs from users.

Given that the research needed to meet the above challenges is broad and significant, Dr. Droegemeier proposed that the most important concerns might be additional developments in three- and four-dimensional data assimilation, including the especially promising ensemble Kalman filter. Indeed, the creation of suitable initial conditions for forecast models is the key element to successful storm-scale NWP. New observing systems, such as the planned phased array radar, along with current GPS water vapor sensing technologies, show great promise in this regard. Especially important is remote sensing of the lowest 3 km of the atmosphere, which has received relatively little attention and where many key processes governing convective initiation occur.

Also important are improvements to forecast models, especially their representation of surface and subsurface features and processes, and the coupling of the ground surface to the atmosphere. Cloud physics modeling schemes today are quite sophisticated, but little routinely available observational information exists with which they can be initialized. Dual-polarization Doppler radar holds promise in this area. Dr. Droegemeier proposed that the impact on forecast quality of various types of data, and a determination of the optimal mix of observations, should be assessed, and techniques should be developed for storm-scale ensemble forecasting. Further, accurate estimation of observational and model error statistics, both of which are extremely important for modern data assimilation techniques, is essential, and statistical techniques for forecast verification at the storm scale should be developed since conventional methods are not applicable. Indeed, Dr. Droegemeier indicated that these latter techniques should go beyond traditional skill measures and include elements of value and risk.

It is perhaps not inappropriate to end by asking whether, after all this work, reliable storm-scale NWP is even theoretically possible. In contrast to the large-scale atmosphere, where pioneering work by Lorenz (1969) continues to define the theoretical limits of predictability, no similar body of work has been undertaken at the storm scale. Interestingly, the practical demonstration of global numerical prediction preceded Lorenz’s theory by roughly a decade, and the same appears to be happening at the storm scale. Relatively clear, however, is that Lorenz’s analysis does not appear to be valid for the storm scale, principally because it is not suitable for highly intermittent flows, and because its formulation is inconsistent with the limited-area domains being applied to the small-scale atmosphere.

Alexander MacDonald, of the National Oceanic and Atmospheric Administration's Forecast Systems Laboratory, concluded the session with a call for sustaining and improving the nation's meteorological observation capabilities. He indicated that, if the observational network is maintained and improved, significant improvements in convective forecasts are possible (though not to the levels requested by the FAA) in the next 2 to 5 years. Current understanding of model physics is sufficient to provide increasingly accurate convective forecasts if observations of high spatial and temporal resolution are available to be blended with models. In particular, better observations of moisture could allow for significant improvements in model representations of convection. At a minimum, models need to run every hour to provide more accurate information of value to aviation users.

In designing an observational network, Dr. MacDonald stressed the importance of measuring moisture, winds, and temperature from complementary platforms. He noted that a solid plan is in place for satellite observing systems but that plans for other observing platforms could be strengthened in order to provide sufficient complementary data. In particular, wind profilers provide critical information about the vertical structure of winds through deep layers of the atmosphere and of temperature through a few kilometers. Instrumented aircraft provide additional information about the vertical distribution of meteorological variables; however, this dataset is sparse at night and over places infrequently visited by aircraft. Lastly, GPS instruments can be used to determine integrated moisture content between a ground station and satellite. A network of closely positioned GPS receivers could be used to provide vertical information about moisture content in the atmosphere. Determining the optimum mix of different observations for improving convective forecasts is a matter of current research in the area of data assimilation.

Key Points Identified by Presenters on Needed Forecast Capabilities

- Predictability of convective systems in weakly forced environments is on the order of 10 to 60 minutes; predictability of convective systems in strongly forced environments is on the order of 2 to 6 hours.
- Because current closure assumptions used to parameterize subgrid convection do not apply at grid sizes smaller than about 10 km, further reduction of grid sizes will necessitate explicitly simulating

- nonhydrostatic convection at grid spacings of about 1 km or developing new cumulus parameterization schemes.
- Additional research is needed to augment model initialization with observations of comparable spatial resolution, to develop ensemble modeling techniques that allow for better quantification of forecast uncertainty, and to improve the models themselves, particularly their representation of surface and subsurface features.
- The tremendous nonlinearity of the small-scale atmosphere may present theoretical limits to predictability of convection, but this work has not been undertaken yet at the storm scale.
- Improvements in the network of meteorological observations—including water vapor, winds, and temperature—could allow for substantial advances in convective forecasting ability. A suite of complementary observing platforms situated with high spatial and temporal resolution would provide especially useful input to forecast models.

PRESENTATION OF FORECASTS

Presentation of the forecast for decision support is a critical component for improving the usefulness of the operational convective forecast. During the workshop, John McCarthy of the Naval Research Laboratory discussed techniques for presenting forecasts and potential strategies for the best use of convective forecasts in support of air traffic management. There is a significant disconnect between the language of convective nowcast and forecast capabilities provided by meteorologists and that of the nonmeteorological operational forecasting community. One promising approach for addressing this disconnect is by a product development team similar to what the FAA Aviation Weather Research Program uses to ensure that scientists, those who develop new technologies, and users of forecast products use the same language to meet operational needs. Such a mechanism should have feedback loops as an integral part of the concept.

Dr. McCarthy identified the need for a four-dimensional weather hazard or, conversely, a weather-free zone concept, to be established to ensure that flight paths are free of danger. Hazard definition is a complex function of weather, aircraft type, and pilot capabilities. To make this concept more realistic, other complexities such as space and time dynamics of weather, traffic flow rates, controller sector acceptance rates, and airport arrival and departure acceptance rates will need to be addressed.

One key forecast product is a tactical system (0- to 2-hour range) that provides some feedback to larger strategic (2- to 6-hour range) decision support tools that are both automatic and human generated. This is an inversion of requirements of the Systems Command Center to make them more consistent with scientific reality. It is likely that these products will combine both deterministic and probabilistic elements of prediction. To this end, much greater inquiry into the human-machine interface is needed to improve interpretation and general overall usefulness of weather products for air traffic management.

Dr. McCarthy also identified some potential problems with promising significant improvements to the 0- to 6-hour forecast in too short a period (3 to 5 years) based on the following points:

- Auto-Nowcaster has taken nearly 20 years to develop and is still in the research and development stage.
- Mesoscale convective systems have been in careful consideration for at least as long, and forecasting them is still problematic.
- Gains in climatological forecasts of convection are promising but still fully in the research mode; mesoscale and cloud models that utilize data assimilation have had remarkable progress but need much work to be operational in the FAA sense.
- Validation of products is a difficult matter, even though much progress has been made.
- Assessing the true impact of weather on the aviation system is a difficult task, and progress has been made only quite recently.

James Evans of the Massachusetts Institute of Technology Lincoln Laboratory elaborated further on the role of forecast presentation and decision support techniques. One key element he emphasized was the importance of having convective forecasts presented both graphically for use by human decision makers and in a numerical form suitable for use by air traffic management decision support tools.

In addition, because highly accurate deterministic forecasts may be difficult to provide operationally a large fraction of the time (e.g., over 50 percent) during the high-delay months of June, July, and August, probabilistic forecasts of convective activity for strategic planning will continue to be a critical support tool for the operational and user communities.

During his presentation, Dr. Evans identified potential techniques for mitigating the impact of convective weather in the near term based on a two-pronged strategy that provides tactical and strategic planning capabilities.

Tactical capabilities should consist of improved convective forecasting in the 0- to 2-hour time frame plus a much better air traffic management system to use these forecasts. Key elements of the air traffic management process are assessing the impact of the forecast weather on air traffic control operations; developing a mitigation plan that considers the traffic flow management and automation implications of possible solutions; expediting the process of choosing between potential mitigation plans including FAA, airline dispatch, and pilot coordination; and making it easier to dynamically reroute planes so as to implement the mitigation plan in real time. The 2- to 6-hour strategic plan should be developed with the tactical capability in mind. Given these elements of air traffic management, Dr. Evans proposed that this would include development of probabilistic forecasts that can meaningfully be used by both humans and automated air traffic management and dispatch algorithms. For example, it would allow the translation of probabilistic forecasts into estimates of airspace and terminal capacity.[2] In addition, better strategic mitigation planning capability should be possible by using optimized mitigation plans for cases where convection will only reduce traffic on routes and partially reduce capacities rather than a limited set of predefined options that only consider the very rare case of impenetrable weather.

Probabilistic representations other than the ensemble model sample functions[3] that have historically been used for weather forecasts may also be needed to improve decision support. Time and space Markov processes could be attractive both as an input to air traffic management and dispatch decision support tools and as a means of capturing the space and time dependencies of the weather. Explicitly representing the degree of spatial organization for the expected weather, as well as the degree of confidence in the forecasts, could potentially be very important for route and traffic flow decision making.

Successful 0- to 2-hour tactical forecasts can provide some feedback to 2- to 6-hour strategic planning efforts. Rapid progress is occurring in the development of air traffic management tools that can use the 0- to 2-hour deterministic and probabilistic forecasts to identify opportunities to safely

[2] The capacity referred to here is the effective *tactical* capacity (Evans, 2001).

[3] The individual outputs from a random process are called sample functions. In ensemble forecasting the future state of the atmosphere is represented by sampling a random process (i.e., multiple model results that differ due to uncertainty in the initial conditions or the model representation of the atmosphere). Each of the ensemble forecasts can be viewed as a sample function from the generating process.

move additional planes. The characteristics of these tools suggest how operational users might utilize highly accurate 2- to 6-hour convective forecasts when they are developed. A departure route availability planning tool (RAPT) that uses the 0- to 60-minute Terminal Convective Weather Forecasts commenced operational evaluation at the New York terminal area and surrounding en-route facilities in August 2002. RAPT examines four-dimensional intersections of planes with forecasted storm locations to determine appropriate departure times from a runway. The RAPT software will utilize the 0- to 2-hour Regional Convective Weather Forecasts at a number of air traffic control facilities in 2003. Direct use of convective forecasts to assist air traffic users in making decisions about traffic routing, such as illustrated by RAPT, has significant implications for the presentation of convective weather forecasts and validation. First, the uncertainty of convective forecasts needs to be expressed in a way that allows tools such as RAPT to provide guidance to operational users as to the likelihood of a route being available for use as a function of time. And second, convective forecast accuracy needs to be verified in the context of operational value to the user, particularly by explicitly addressing the accuracy for route usage decisions.

Key Points Identified by Presenters on Ways to Present Forecasts

- Two- to 6-hour convective weather forecast products should be designed to facilitate air traffic control and airline decisions such as predicted capacity, route availability, and the fuel to be loaded on aircraft.
- Because accurate deterministic 2- to 6-hour forecasts are not available, it is necessary to develop probabilistic forecasts that can readily be used by both humans and automated air traffic management decision support tools.
- The FAA will need to also have a robust “tactical” convective weather decision support capability that takes advantage of the rapid progress in nowcast and numerical modeling capability, which implies a change in focus for the Systems Command Center from strategic to tactical.
- In addition to these deterministic and probabilistic forecasts, traffic flow management and traffic automation decision support tools can assist in the development and execution of weather impact mitigation plans.

VERIFICATION SCHEMES

Verifying forecast accuracy is a critical step in providing valuable forecast products for use by the aviation community. Marilyn Wolfson of the Massachusetts Institute of Technology Lincoln Laboratory framed her comments about verification schemes around the question "How will we know when we're done?" To answer this question, she started by defining the intended use of weather forecasts from an aviation perspective, which is to improve flight planning and thus maintain schedule integrity. Weather forecasts are used to predict the expected capacities in various en-route sectors of airspace as a function of space and time; route availability, including initial routes, alternate routes, miles in trail spacing, blockages, and flow-constrained areas; and terminal impacts, including the availability of alternate airports for landing en-route planes.

Based on these needs of the aviation community, Dr. Wolfson noted that her thoughts on verification are based on postulating the following characteristics for improved 2- to 6-hour forecasts. First, she opined that there is general consensus that probabilistic forecasts are needed and that they should be designed for utility and value to the ultimate user. In addition, the forecasts need a high level of specificity in space and time, particularly in terms of resolving convection. Lastly, forecasts need to be generated automatically, with standardized outputs, low latency, and high reliability. Indeed, providing a continuum of forecasts with different lead times—for example, in granularities of 15 or 30 minutes—would be more valuable to those making flight planning decisions than the currently provided 2-, 4-, and 6-hour products. An automated system may help eliminate bias or equity issues associated with forecasts provided by individual entities. Even with an automated system, forecasters may need to play a role in updating, reviewing, and editing the automated output.

Dr. Wolfson identified several forecast characteristics of particular importance for anticipating how convective weather will impact the national airspace. These characteristics include:

- *Spatial coverage and timing:* These can be considered together because forecasts may often trade off accuracy in space and time. Verifications of the temporal and spatial characteristics of convection will likely need to include a probabilistic tolerance for errors that increases as the forecast extends farther into the future.
- *Strength and height of the storm:* Many en-route flights avoid storms by flying over them, rather than around them. Accurate vertical information

in a forecast will allow for much better planning capabilities to avoid unnecessarily diverting flights around predicted convection.

- *Storm characteristics and orientation:* Linearly organized convective storms (or line storms) cause the most problems for flight planning. Knowing that a line of convection exists, its width and length, its vertical extent, and the location of gaps in the line can be of great use. Line storm orientation relative to flight route orientation is also very important. Many routes that parallel a line storm can potentially remain open, whereas most routes perpendicular to a line would be blocked. New growth of convective cells above runways (i.e., “pop-ups”) also causes substantial delays in the summer, making accurate prediction of them desirable (though very difficult).
- *Storm evolution and its impact on terminal and en-route capacity:* Accurately representing in forecasts how storms evolve can have a large impact on terminal and en-route capacity. For example, to make a meaningful 4-hour forecast, it is necessary to forecast everything that happened between now and 4 hours, including especially large storm systems whose lifetime is encompassed within the 4 hours.

How best to visually portray these forecast characteristics and their accuracy for aviation users presents an additional challenge. For example, the presence of spatially intermittent events in an area otherwise clear of severe weather requires special attention. One approach is to map the whole area, recognizing that some conditions have a low probability of convection. A different approach would be to show in some probabilistic sense the forecasted pattern of convection, which will likely be somewhat erroneous. This second approach does evoke a notion of a porous piece of airspace that one could fly through. A third alternative is to score an entire region in a way that characterizes the weather by spatial scale and whether the forecast has captured that spatial scale correctly.

Schemes to verify forecasts must accommodate the meteorological developer’s desire to improve overall forecast quality, the air traffic manager’s interest in having the ability to trade off forecast capabilities, and the user’s need for an easily interpreted measure of forecast quality. Verification schemes also need to allow cross-comparison of different forecasts via a metric that is actually comparable. Given these requirements for a verification scheme, forecast users and evaluators need to work together to determine on what spatial and temporal scales to assess the forecasts and which weather characteristics to consider. These questions can be answered in part by talking to the users and in part by data mining maps of the weather systems, the air traffic systems, and their interaction. Data mining allows the development of quantitative models that relate historical measurements of key air traffic control parameters—such as the capacity of various sectors of airspace as a function of space and time; route availability, including initial routes and alternate routes; miles in trail spacing; and terminal impacts—to storm characteristics. A second challenge is to determine how to assess a probabilistic forecast.

Designing a verification scheme that provides a single score for a forecast is appealing in terms of its simplicity for interpretation by various users. Dr. Wolfson proposed a system in which measured and modeled performance measures, such as storm type, orientation, height, area of coverage, and impact on specific traffic flow, could be combined into a single consolidated score by weighting each individual performance measure proportional to user value. Such a system is not currently available but could be developed through a research effort. Ultimately, the process of developing a single score or set of scores and mapping them in time and space could be part of the automated system providing weather forecast information to the aviation community.

Michael Prather of the University of California, Irvine, provided additional guidelines for developing verification systems for convective weather forecasts. His first suggestion was to focus on scientifically improving forecast accuracy, rather than concentrating too much on improving the application of the forecast to reducing delays. The suggested emphasis on science derives from the fact that it has a large role to play in developing more accurate forecasts but is only a small component of the collaborative, bureaucratic, and human issues that contribute to air traffic control delays.

In developing a verification scheme, Dr. Prather proposed selecting a range of objective verification scores that reflect a predictable quantity of interest to aviation. Examples of forecast characteristics that could be scored include likelihood and persistence of cells located over terminals, percent coverage and organization of convection in key air traffic control zones, and the presence of convection in space-time averaged windows. As other workshop participants noted, probabilistic forecasts are the key to verification and metrics of success in forecasts because skill measures for a single deterministic forecast are ambiguous. For example, evaluating a single deterministic forecast requires space-time averaging over designated windows to identify a “hit.”

Given the success in combining weather forecasts and air traffic control, Dr. Prather briefly discussed other issues for the airline industry to consider in terms of cost co-benefits. The question of aircraft pollution as it impacts air quality and climate is one topic to consider in this regard. Air traffic is estimated to contribute 2 percent of global carbon dioxide emissions and 3.5 percent of global radiative forcing, which is primarily driven by contrail formation (IPCC, 1999). In global terms the climatic impact of the 10 percent of air traffic leading to contrail occurrence is of the same order of magnitude as the 90 percent of air traffic not leading to contrail occurrence. Contrail formation could be limited using air traffic control and weather knowledge, thereby mitigating the climatic impact of aviation. With the ability to mitigate the climate impacts of aviation may come costs and responsibilities. Indeed, aircraft emissions are already being taxed in the European Union to begin accounting for their environmental cost.

Key Points Identified by Presenters on Verifying Forecast Accuracy

- Two- to 6-hour forecasts of convective weather useful for aviation purposes need to be probabilistic; need to be designed for utility and value to the user; need to have a high level of specificity in space and time, and need to be generated automatically with standardized outputs, low latency, and high reliability.
- Forecast characteristics of particular importance to the aviation community include spatial coverage and timing of convection, storm strength and height, storm characteristics and orientation, and storm evolution.
- Relating convective storm meteorological features such as spatial coverage, organization, height, strength, stage of development, and lightning activity to key operational factors such as route availability and the capacity of en-route sectors and terminals can be used to quantify forecast value to operational users, to assess improvements in forecast capability, and to furnish better guidance to operational users of the forecasts.
- Effective verification schemes accommodate identification of ways to improve forecasts overall, the ability to trade off forecast capabilities, easy interpretation of forecast quality, and intercomparison of different forecasts.
- With the ability to control air traffic regarding weather conditions may come the opportunity to plan air traffic so as to minimize environmental damage.

3

Next Steps

Historically, only a small fraction of the resources allocated to weather forecasting by federal agencies (other than the Federal Aviation Administration) have been focused on the development of weather guidance that supports the needs of the aviation system, and there is no reason to think this will change. Therefore, the FAA and the commercial airlines will have to take the lead if they want to see development and implementation of the type of operational products needed to improve the safety and efficiency of the aviation weather system. The technology and knowledge to significantly improve the 2- to 6-hour convective forecast products for aviation exist now. In particular, recent advances in understanding subsynoptic-scale meteorology, high-resolution observation capabilities, computer power, communication systems, and software systems make it possible to dramatically improve weather forecasting products for the aviation community. Such products do not have to be part of the National Weather Service suite of operational products; adequate electronic processing power and communications are already available for disseminating any new forms of guidance that would be developed. Users of the national airspace can simply decide what types of products are needed and build them. During the final workshop session, summarized in this chapter, participants considered, in the light of the workshop presentations, what research activities are necessary to move toward the next generation of convective forecasting products.

Many workshop participants stated that probabilistic guidance from ensemble model calculations combined with improved high-resolution observations may hold the most promise for improving convective forecast products in the next 5 to 10 years. Current limitations in predictive capabilities due to uncertainties in initial conditions and model formulation will likely require a longer research effort to provide marked improvements. In the meantime, probabilistic approaches can provide meaningful information for managing the nation's airspace.

The aviation traffic flow system is essentially a never-ending sequence of decisions. For such systems there is a wealth of information available on how to optimize decision making in a manner that minimizes costs, maximizes benefits, or both. For example, the utility and insurance industries routinely make decisions based on reliable[1] probabilistic information. With probabilistic guidance and estimates of the respective costs of yes-or-no decisions, it is possible to determine threshold probabilities above which, when averaged over many events, the ratio of costs to benefits is optimized. Such threshold probabilities transform probabilistic guidance into optimal "black-white" decisions (e.g., whether to expect having to take an alternate route to avoid expected adverse weather and therefore having to load extra fuel). Moreover, reliable probabilistic guidance makes it possible to define a uniform and consistent set of criteria on which to base operational decisions.

For example, suppose the aviation traffic flow system mandated that pilots do not try to navigate through areas of thunderstorms once the percent-area coverage exceeds a certain threshold.[2] If such a guideline were in place, it would be highly desirable to have aviation weather guidance that provides reliable probabilities of the critical percent-area coverage. This type of system is possible with current technology, though increased spatial resolution of the next generation of numerical models likely will allow much better guidance by better resolving the location, organization, and orientation of convection exceeding the critical percent-area coverage. With such

[1] As used here, "reliable" means that the probabilities are true (i.e., unbiased). For example, for a large sample of decisions, if one examines the subset of all events for which a probability of 40 percent was forecast, the event will occur 40 percent of the time if the probabilities are reliable.

[2] In practice, the choice of a percent-area coverage threshold would have to be based on air traffic control operational issues, such as the probability that principal routes in a region would be impacted by the weather and the effective tactical capacity of that region (e.g., whether planes could be expected to fly around convective cells in the region). To relate percent coverage to these air traffic control issues will require additional information on the type of convective weather forecast, the expected spatial orientation of the convective weather, and the dominant routes in a region (e.g., north-south, east-west, or all directions).

guidance it is possible to calculate a threshold probability of the percent-area coverage above which, for example, the frequency of having to divert will, when evaluated for many events, cost the airline more money than if other possible strategic actions were taken to avoid the critical area. This approach can be applied to all sorts of decisions in the traffic flow system. Traffic flow managers would have quantitative information to help guide decisions in a manner that reduces overall costs.

Much discussion during the workshop focused on the issue of “strategic” versus “tactical” decisions. Several individuals argued that a continuum of guidance is necessary to optimize the decision-making process. Such guidance would be based primarily on observations for very short-term forecasts (0 to 2 hours) and mostly on model output for forecasts of 6 hours or more. The period in between (2 to 6 hours) will most likely require an optimal blend of both observations-based forecasts and model forecasts. In all instances, statistical techniques will be necessary to generate reliable probabilistic guidance.

One proposal discussed by the workshop participants was that strategic plans be structured in such a way that they can be readily modified (in a tactical framework) to adjust for changing conditions. This approach can result in shorter flight distances. It was also noted that terminal forecasts must be an integral part of such a system.

Several workshop participants mentioned that, ideally, traffic flow managers and pilots would like to have forecasts of the radar reflectivity field. While in the past such a request was dismissed out of hand, it is now possible to generate guidance of this sort using cloud-scale resolution numerical models. However, there are several points to bear in mind. First, although the models have algorithms that can convert model parameters into reflectivity, there is currently very little skill at forecasting timing, location, and intensity of individual convective storms. On the other hand, we do have meaningful skill forecasting the timing and location of mesoscale areas of convection and the organizational mode of the convection in those areas. For example, high-resolution models can distinguish between organized lines of storms and scattered air mass convective cells. Such forecasts would be of value for strategic decisions. Moreover, since we now have a WSR-88D archive of observed reflectivities, it is possible to statistically postprocess model forecasts to correct for model bias and to create categorical reliable probabilistic forecasts of parameters such as percent-area coverage. It is even possible to create probabilistic forecasts of percent-area coverage of convective tops over selected values (e.g., over 12 km altitude). For line-type situations, such forecasts would show elongated contiguous areas of high probability of high percent-area coverage. Likewise, it is possible to construct the same type of guidance using statistical models that use current conditions and archives of historical observations. An optimal blend of the two approaches (model output and observations) would mathematically select and weight the best predictors from both approaches to produce the guidance with the least error. This hybrid approach can be designed to provide a continuum of guidance for forecasts as short as a few minutes out to 6 or more hours.

It is important to emphasize that this forecasting system can be built with today's technology. As observations become more plentiful, models increase their resolution, multimodel ensembles are created, and archives of observations and model forecasts lengthen, the skill of such a system can only improve. A number of workshop participants expressed the view that this approach is the best foundation on which to base a research and development plan. Other than a commitment of resources, there is no reason why such a system cannot be built. Many workshop participants noted that the success of more advanced forecast products will rely in part on effective training of those who use the convective weather products to make aviation decisions.

In a couple of instances during the workshop, representatives of various components of the FAA traffic flow management system and the commercial airlines indicated a willingness to transform their operations to take advantage of guidance in probabilistic form. This sentiment is consistent with that of professionals working in other areas affected strongly by convective storms (e.g., hydrometeorology, quantitative precipitation forecasting, and severe storm forecasting) who have already recognized the advantages of forecasting in this manner and have taken significant steps to transform their guidance into probabilistic form. Therefore, experience and expertise for producing probabilistic guidance for forecasting aviation convective weather are available.

Workshop participants suggested that improving the time and space resolution of observations (especially in the boundary layer) is critical for improving convective weather forecasts. Utilizing all available Doppler weather radars, which provide high-quality measurements of boundary layer winds, could be a particularly useful first step to enhancing the coverage of surface observations. Fortunately, the cost of automated surface observing systems has decreased dramatically during the past decade, portending the availability of national coverage on the mesoscale as individual states install networks. Likewise, the soundings obtained from commercial aircraft will provide a wealth of new upper-air data, as will the next generation of satellite observations and ground-based remote sensing. These new observations, coupled with the increase in numerical model resolution and the creation of archives of WSR-88D data, can provide a foundation for an advanced short-term forecasting system. There is cause for considerable optimism in improving skill at forecasting convection, especially as we leave behind the era of having to parameterize convection and switch to models that capture much of the nonhydrostatic processes that characterize convective events.

The workshop concluded with a discussion of critical tasks and future directions to address the issue of improving operational convective weather forecasting. These include:

- Defining probabilistic forecasting and determining how it could best be applied in air traffic management.
- Identifying how the FAA could best utilize available weather forecast products by incorporating them into its current operational activities.
- Establishing predictability confidence limits for all convective regimes, defining key convective regimes and model capabilities in those areas, and characterizing the impact of convective forecasts on air traffic control decision making.
- Identifying and evaluating the various means and mechanisms for generating probabilistic forecasts.
- Clarifying concepts of accuracy, verification, and reliability of forecasts.
- Describing the attributes of convection most relevant to the FAA operationally.
- Identifying the best approaches for conveying convective forecasts and products to air traffic controllers and pilots.
- Outlining needed research to improve the reliability and utility of 2 to 6 hour convective forecasts, especially probabilistic forecasts.

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Appendix A

Statement of Task

The FAA has established desired and minimal convective weather forecasting accuracy for the future air traffic control system. The workshop will

1. explore the present and future potential in meeting this stated accuracy,
2. explore the various methods of conveying the forecasts to the air traffic controller and the pilot, and
3. if it is indicated that the forecasting accuracy may not be achieved, a prospectus for a study examining what is needed to reach the FAA requirements will be generated.

Appendix B

Abbreviations and Acronyms

4-DVAR	Four-Dimensional Variational Assimilation
ANC	Auto-Nowcast
ATA	Air Transport Association
CCFP	Collaborative Convective Forecast Product
CDM	Collaborative Decision Making
ETA	estimated time of arrival
FAA	Federal Aviation Administration
FAR	false alarm rate
GIFTS	Geosynchronous Imaging Fourier Transform Spectrometer
GPS	Global Positioning System
GPS/MET	Global Positioning System Meteorology Demonstration Network
IHOP	International H_2O Project
NOAA	National Oceanic and Atmospheric Administration
NCEP	National Centers for Environmental Prediction
NRC	National Research Council
NWP	numerical weather prediction
NWS	National Weather Service
POD	probability of detection
RAPT	route availability planning tool
WSR-88D	Weather Surveillance Radar 88 Doppler

Appendix C

Biographical Sketches of Committee Members

Steven F.Clifford *(Chair)* is a senior research scientist emeritus at the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder. He was formerly director of the National Oceanic and Atmospheric Administration's Environmental Technology Laboratory. One of his research goals is to develop a global observing system using ground-based, airborne, and satellite remote sensing systems to better observe and monitor the global environment and use these observations as input to global air-sea circulation models for improving forecasts of weather and climate. He was the recipient of the 1998 Meritorious Presidential Rank Award. He is a fellow of the Optical and Acoustical Societies of America, a senior member of the Institute of Electrical and Electronics Engineers, and a member of the American Physical Society, the American Geophysical Union, the American Meteorological Society, The National Academy of Engineering, and the National Research Council's Board on Atmospheric Sciences and Climate. He received his Ph.D. in engineering science from Dartmouth College.

Richard E.Carbone is a senior scientist at the Mesoscale and Microscale Meteorology Division of the National Center for Atmospheric Research. He was a pioneer in the creation of advanced atmospheric observing systems and has made major contributions to the understanding of stormy weather. As lead scientist (1994–1999) for the U.S. Weather Research Program, he led the U.S. efforts to improve prediction of disruptive weather and to understand its impacts. He also developed and currently leads the World

Weather Research Programme, aimed at improving prediction of and societal response to high-impact weather. Mr. Carbone's most recent work includes the search for broad-scale connections among thunderstorms to help better predict the multiday rainfall episodes that drench the heartland of North America each summer. He received his bachelor's degree in meteorology and oceanography at New York University and completed his master's degree at the University of Chicago.

Kelvin Droegemeier is Regents' Professor of Meteorology at the University of Oklahoma and director of the Center for Analysis and Prediction of Storms. Under his leadership, the Center pioneered the explicit numerical prediction of intense local weather and developed a forecast system that in 1997 won two international prizes. This technology was applied to commercial aviation in a 3-year partnership with American Airlines and was later commercialized. Dr. Droegemeier's research interests lie in thunderstorm dynamics and predictability, data assimilation, computational fluid dynamics, and aviation weather. He is a fellow of the American Meteorological Society and a member of the University Corporation for Atmospheric Research Board of Trustees, and he serves as an expert witness on commercial airline accidents. He received his Ph.D. in atmospheric science from the University of Illinois at Urbana-Champaign.

James Evans is a senior research staff member at the Massachusetts Institute of Technology's Lincoln Laboratory and a visiting scholar at the University of California, Berkeley. He is currently the leader for research and development for the Corridor Integrated Weather System, which is a decision support system designed to reduce en-route system delays due to convective weather. Previously, he was leader of the Lincoln Weather Sensing Group. He led the Lincoln teams that developed the Integrated Terminal Weather System (which provides real-time weather decision support for terminal areas) and the Terminal Doppler Weather Radar. His research interests include weather information systems and their use in air transportation facilities, meteorology, weather impacts on surface transportation, communications, and radar and aviation system analysis. Dr. Evans served on the National Research Council's Panel on the Assessment of NEXRAD Coverage and Associated Weather Services. He received his Ph.D. in electrical engineering and computer science from the Massachusetts Institute of Technology.

J.Michael Fritsch is a distinguished professor of meteorology at Pennsylvania State University. His research interests include convective storms, extratropical and tropical cyclones, mesoscale analysis and forecasting, and numerical weather prediction. Dr. Fritsch previously served on the National Research Council's Committee on Meteorological Analysis, Prediction, and Research and the Panel on Mesoscale Research. He is a member of the National Weather Association and received his Ph.D. from Colorado State University.

John McCarthy of Aviation Weather Associates in Costa Mesa, California was formerly the manager for scientific and technical program development at the Naval Research Laboratory in Monterey. Previously, Dr. McCarthy served as special assistant for program development to the director of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. Prior to that position, he served as the Director of the Research Applications Program at NCAR, where he directed research associated with aviation weather hazards, including NCAR activities associated with the Federal Aviation Administration Aviation Weather Development Program, the FAA Terminal Doppler Weather Radar Program, and a national icing/winter storm research program. Dr. McCarthy was the principal meteorologist associated with the development of the FAA Wind Shear Training Aid. He is a fellow of the American Meteorological Society. Dr. McCarthy received his Ph.D. in geophysical sciences from the University of Chicago.

Cynthia Mueller is a project scientist II at the National Center for Atmospheric Research (NCAR). She is responsible for project management for the NCAR, Federal Aviation Administration, and Army Convective Weather program and provides scientific input for the design of the application's software. She received her M.S. in atmospheric science from the University of Chicago. Her current research focuses on the thunderstorm life cycle, with emphasis on short-term forecasting. She has also published on evaluation of meteorological airborne radar and the utility of sounding and mesonet data to nowcast thunderstorm initiation.

Michael J.Prather is a professor in the Earth System Science Department at the University of California, Irvine. His research interests include simulation of the physical, chemical and biological processes that determine atmospheric composition and the development of detailed numerical models of photochemistry and atmospheric radiation, and global chemical transport models that describe ozone and other trace gases. Dr. Prather played a significant role in the Intergovernmental Panel on Climate Change's second and third assessments and a special report on aviation and in the World Meteorological Organization's ozone assessments (1985–1994). He is a fellow of the American Geophysical Union and a foreign member of the Norwegian Academy of Science and Letters and has served on several National Research Council committees, including the Panel on Climate Variability on Decade-to-Century Timescales, and is currently a member of the National Research Council's Board on Atmospheric Sciences and Climate. He received his Ph.D. in astronomy from Yale University.

Marilyn Wolfson is assistant group leader of the Weather Sensing Group at the Massachusetts Institute of Technology Lincoln Laboratory. She has served as leader of the Federal Aviation Administration Aviation Weather Research Program's Convective Weather Product Development Team, a large team of collaborating researchers from four major laboratories and other universities, since its inception in 1996. Her research interests focus on aviation weather, particularly convective weather research. She and her project team have also worked on the critical aviation need for automated tactical convective weather forecasts with the development and deployment of accurate 1- to 2-hour forecasts tailored to terminal and en route users. Dr. Wolfson has served on the National Research Council's National Weather Service Modernization Committee and the Committee on Meteorological Analysis, Prediction and Research. Dr. Wolfson received her Ph.D. in meteorology from the Massachusetts Institute of Technology.

Appendix D

Workshop Agenda

Weather Forecasting Accuracy for Federal Aviation Administration Traffic Flow Management Workshop
Board on Atmospheric Sciences and Climate
The National Academies
Washington, D.C.
June 4–5, 2002
Tuesday, June 4, 2002

CLOSED SESSION	
8:00 A.M.	Composition and balance discussion
OPEN SESSION	
9:00 A.M.	Welcome and introductions Steve Clifford, committee chair
Statement of Problem	
9:15 A.M.	FAA Overview of Delay Problem from NAS Perspective Peter Challan, *FAA, ATF-2 Deputy Associate Administrator for Air Traffic Services*

9:35 A.M.	Overview of Collaborative Decision-Making Process, Planning Process, Teams, Challenges When Weather Goes Bad Jack Kies, *FAA, Manager for Air Traffic Tactical Operations, ATT-1*
9:55 A.M.	Air Carrier Perspective of Delay Problem Russ Gold, *ATA, Director, Airline Operations/Meteorology*
10:15 A.M.	Overview of Delays Due to Weather, History of Convective Forecast, Provision of Forecast for Traffic Planning Jim Washington, *FAA, Director for Air Traffic System Requirements Service, ARS-1*
10:35 A.M.	Break
Discussion of Collaborative Convective Forecast Product	
10:50 A.M.	Overview of CCFP, Forecast Content, Production, Use of CCFP, Problems and Limitations Bill Cranor, *US Airways, Manager for ATC and Airfield Operations*
11:10 A.M.	Overview of CCFP Verification, CCFP Calibration Mark Phaneuf, *AvMet Applications, Vice President* Barbara Brown, *NCAR, Project Scientist*
Current State of Development	
11:30 A.M.	Overview of Operational Forecasting Constraints in this Problem Fred Foss, *Aviation Weather Center (AWC), Chief for Domestic Operations Branch*
11:45 A.M.	Overview of Numerical Modeling Applied to this Problem Jack Hayes, *NOAA/NWS, Director, Office of Science and Technology*
12:00 NOON	Working lunch in meeting room:

	Challenges-Overview of the Accuracy Requirements Richard Heuwinkel, *FAA, Manager for Aerospace Weather Policy, ARS-100*
1:00 P.M.	**Discussion Topic 1** What approaches/strategies will be most effective to get an accurate 3- to 6-hour forecast of areas of convection for aviation use in the next 5 to 10 years? (Accurate means a desired false alarm rate (FAR) of =0.20, a probability of detection (POD) of =0.80, a minimal FAR of =0.30, and a POD of =0.60) Discussion Leaders: Rit Carbone, Michael Fritsch, and Cindy Mueller
3:00 P.M.	Break
3:30 P.M.	**Discussion Topic 2** What specific scientific enabling capabilities are needed to realize these gains and when will they be available? For example, what improvements, in observations, algorithms, analyses, and numerical modeling are likely to yield the best results? What are the major gaps in the current R&D activities that need to be addressed? Discussion Leaders: Andrew Crook, Kelvin Droegemeier, and Alexander MacDonald
5:00 P.M.	Summary of topics
5:30 P.M.	Adjourn

Wednesday, June 5, 2002

CLOSED SESSION	
8:00 A.M.	Continental breakfast
OPEN SESSION	
9:00 A.M.	**Discussion Topic 3** What is the most appropriate way to present the forecast in an operational setting? • Consider the two main uses are flight planning and traffic flow management • Consider how the forecast will be developed and presented (i.e., purely probabilistic, deterministic) Discussion Leaders: John McCarthy and Jim Evans
11:00 A.M.	Break
11:15 A.M.	**Discussion Topic 4** How will we know when we're done? What verification scheme makes the most sense from an aviation perspective? Discussion Leaders: Marilyn Wolfson and Michael Prather
12:30 P.M.	Lunch
1:30 P.M.	Draft report of the workshop
4:00 P.M.	Adjourn

Appendix E

List of Workshop Participants

Committee	
Steven F.Clifford (Chair)	*University of Colorado*
Lance F.Bosart	*State University of New York, Albany*
Richard Carbone	*National Center for Atmospheric Research*
Kelvin Droegemeier	*University of Oklahoma*
James E.Evans	*Massachusetts Institute of Technology Lincoln Laboratory*
J.Michael Fritsch	*Pennsylvania State University*
John McCarthy	*Naval Research Laboratory*
Cynthia Mueller	*National Center for Atmospheric Research*
Michael J.Prather	*University of California Irvine*
Marilyn M.Wolfson	*Massachusetts Institute of Technology Lincoln Laboratory*
Presenters	
Barbara Brown	*National Center for Atmospheric Research*
Peter Challan	*Federal Aviation Administration*
William Cranor	*US Airways*
Andrew Crook	*National Center for Atmospheric Research*
Fred Foss	*Aviation Weather Center*
Russ Gold	*Air Transport Association*
Jack Hayes	*National Oceanic and Atmospheric Administration/NWS*
Richard Heuwinkel	*Federal Aviation Administration*
Ross Keith	*Bureau of Meteorology, Townsville, Australia*

Jack Kies	*Federal Aviation Administration*
Alexander MacDonald	*National Oceanic and Atmospheric Administration*
Mark Phaneuf	*AvMet Applications International, LLC*
James Washington	*Federal Aviation Administration*
NRC Staff	
Chris Elfring	
Joe Friday	
Vaughan Turekian	
Rob Greenway	