An Introduction to NCEP SREF Aviation Project

Binbin Zhou*, Jun Du*, Jeff McQueen ,Geoff Dimego, Geoffrey Manikin,
Brad Ferrier*, Zoltan Toth, Henry Juang, Mary Hart*, Jongil Han**

NOAA/NWS/NCEP/Environmental Modeling Center
* Science Applications International Corp (SAIC)
** RS Information Systems, Inc.

1.Introduction

NCEP's Short Range (1-3-day) Ensemble Forecast (SREF) system provides mesoscale probabilistic forecast information, and has undergone several stages of development at the NCEP Environmental Modeling Center (EMC) since 1996 (Tracton et al 1998, Du and Tracton 2001, Du et al 2004). It has been well understood that the forecast skill of deterministic, computer-generated weather forecasts is limited by the chaotic processes in the atmosphere which bring either errors in the initial/boundary conditions or uncertainties in the model (Lorenz 1963). Generally, a single deterministic model will produce one possible solution to a weather system but may miss the actual situation. One approach called an *Ensemble Forecast* (EF) was proposed to try to capture a range of possible solutions and take into account the uncertainties in both the initial/boundary conditions and the models (Epstein 1969, Leith 1974, Palmer et al 1990). Since then, ensemble forecasts were launched and achieved significant progress at several weather centers in the world (NCEP, European Centre for Medium Range Weather Forecasts, US Navy, Japan Meteorological Agency, Canadian Meteorological Centre, etc).

NCEP EMC is one of the pioneers in researching and developing EF systems, either on the global scale or mesoscale. The history of the NCEP Ensemble Prediction System (EPS) can be traced back to the early 1990s, when NCEP introduced and then implemented operationally its medium range global EPS (Tracton and Kalnay 1993, Toth and Kalnay, 1993, 1997). Motivated by the success of its global EPS, NCEP initiated the ensemble forecasting system for short range applications, using the Eta and the Regional Spectral Model (RSM) in the middle of 90s (Brooks, et al 1995, Tracton et al 1998). The Short Range Ensemble Forecast (SREF) system has undergone testing and forecast evaluation, and has shown promise in improving forecast skill for short-range forecasts (Hamill et al 1997, Du et al 1997, Stensrud, et al 2003). The SREF system was implemented operationally by NCEP in 2001, and is still being improved (Du and Tracton 2001, Du, et al 2004).

In 2002, under FAA sponsorship, NCEP began its SREF Aviation Project in an effort to bring ensemble techniques to aviation forecasting by further post-processing SREF generated output to create aviation-based forecast products for icing, turbulence and visibility, etc. This work is also applicable to the NCEP Aviation Weather Center (AWC) and NOAA Aviation Service Branch missions. This paper will present an overview of the SREF aviation project, including its configuration, post processing procedure, and product generation. Some concepts of verification and evaluation for the ensemble forecast are briefly discussed. Finally, the future plans for the SREF aviation project are presented.

2. The SREF system for aviation products

Aviation safety and efficient aviation operations are affected by weather systems. The reduction of fatal accidents resulting from hazardous weather is the main goal of FAA's strategic plan (National Aviation Weather Initiatives, FCM-P34-1999). The SREF system can help to reach this goal by providing a quantitative estimate of the uncertainties involved in numerical weather forecasts and increasing the confidence level for daily aviation weather forecast activities. The SREF system overall configuration and components at NCEP are shown in Figure 1.

Corresponding author address: Binbin Zhou, NCEP/EMC, 5200 Auth Rd. Camp Springs MD 20746, Email: Binbin.Zhou@noaa.gov

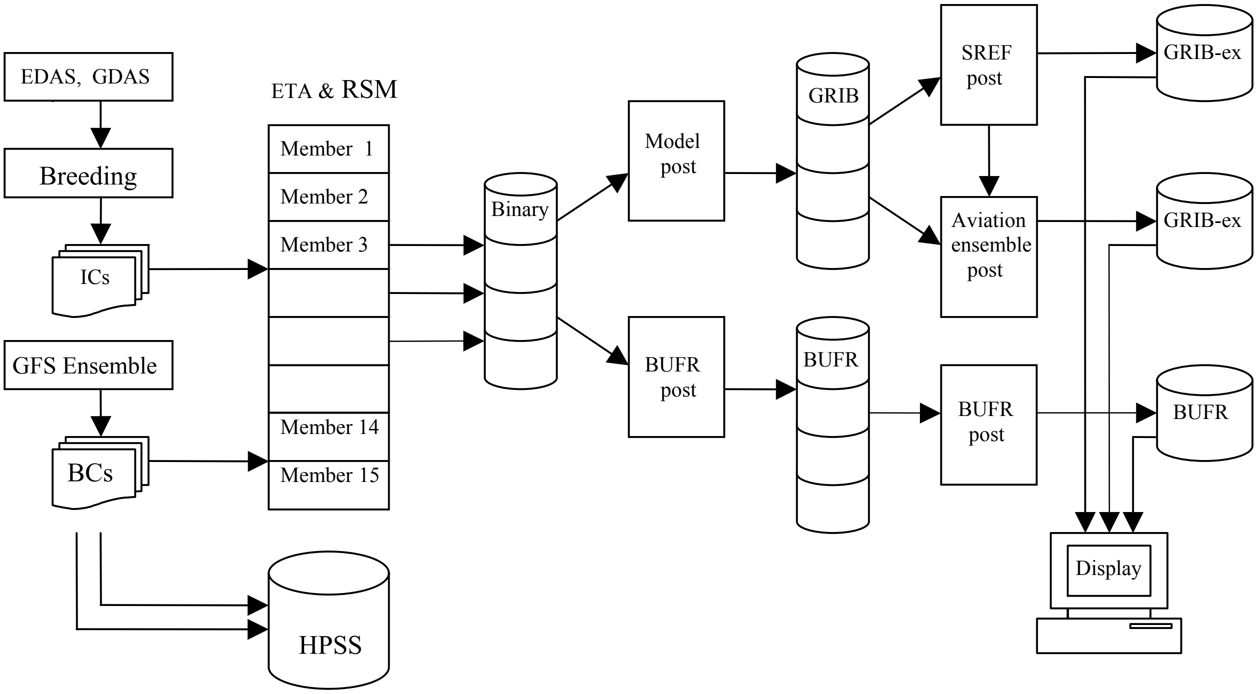


Figure 1. SREF System Components

The SREF System, covering the Continental US (CONUS), runs twice a day, at 09 UTC and 21 UTC, out to 63 hours with outputs every 3 hours. The 60-level by 32km resolution Eta and 28-level by 40 km resolution RSM are the two basic models employed in the SREF system. The breeding method, or initial condition random perturbation, (e.g. Toth, et al 1997) is used to create multiple initial conditions (ICs). In the breeding procedure, data from the NCEP Eta Data Assimilation System (EDAS) and NCEP Global Data Assimilation System (GDAS) are taken as control ICs. The control ICs are then perturbed into a positive and a negative perturbed IC pair. The boundary conditions (BCs) for all models are provided by the NCEP Global Ensemble Forecast System. Both control and bred pair ICs are input into the Eta and RSM models to produce a total of 15 ensemble members. In the current SREF system, several convective schemes are employed in either the Eta or RSM models (Manikin, 2004). The arrangement of ICs and physics schemes is listed in table 1.

After the 15 ensemble runs are finished, the output from all 15 members is processed first by the NCEP model post, then by the SREF ensemble post (for regular forecast variables) and then by the aviation ensemble post to produce ensemble grid-products. The ensemble grid-products are saved in AWIPS GRIB 212 extension format, which was specially designed by NCEP for storing ensemble data (http://wwwt.emc.ncep.noaa.gov/gmb/ens/info).

Table 1. SREF system configuration

Model	Convection	IC breeding
Eta	Betts-Miller-Janic (BMJ)	Control + 1 pair
Eta	Kain-Fritsch (KF)	Control + 1 pair
Eta	BMJ-SAT (Saturated moisture profiles)	1 pair
Eta	KF-DET (Full cloud detrainment)	1 pair
RSM	Simple Arakawa Shubert (SAS)	Control + 1 pair
RSM	Relaxed Arakawa Shubert (RAS)	1 pair

Besides grid-products, the SREF system also has BUFR format files (NOAA Office Note 29, 1994) for storing the ensemble products for stations or other specific locations. Since the SREF system uses the Eta BUFR table for both the Eta and RSM output, outside users must have this table and a set of BUFR utilities in order to decode BUFR files.

All aviation products are generated in the aviation ensemble post, in which certain algorithms are applied to obtain a set of aviation variables, and statistical computations are carried out to produce ensemble products. Aviation weather forecasts make use of several specific variables such as icing, clear-sky turbulence, vertical wind shear, surface visibility, etc. in addition to regular weather forecast variables. Within the past decade, substantial efforts have been made to improve the aviation weather forecasts, for example, icing (Brown et al 1997, Politovich et al 1997, 2000, etc,), turbulence (Ellrod et al 1991, McCann 1997), and low level wind shear (Cole et al 2000). The SREF aviation project provides an alternative to improve the aviation weather forecasts in terms of both precision and probability. In the current SREF system, limitations in computing resources at NCEP meant that relatively simple algorithms for these aviation variables are utilized. SREF aviation ensemble products and their computation methods are listed in Table 2.

Table 2. List of SREF Aviation Ensemble Products

Variables	***Levels***	***Mean and spread***	***Probability (of threshold)***	***Methods***
Icing	FL240, 180,150, 120,090,060,030,000		Occurrence	Temperature and RH
Turbulence	FL420-390, 390-360,360-330,330-300, 300-270,270-240,240-210, 210-180		Light-middle, middle, severe	Ellrod (1991)
Jet stream	34000 feet, 18000 feet, 4500 feet		> 20, 40, 60, 80,100 knots	Model output, but transfer unit from m/s to knot
Flight category	Surface		LIFR, IFR, MVFR, VFR	NWS Instruction 10-813 on TAF
Ceiling	Surface	Height in feet		Federal Meteorological Handbook No.1 (FMH-1)
Visibility	Surface	Distance in miles		Stoelinga (1999)
Cloud amount	Whole atmosphere	Total, Maximum & Minimum members		Model output
Sky type	Whole atmosphere		Clear, Scattered, Broken and Overcast sky	Federal Meteorological Handbook No.1 (FMH-1)
Convection	Whole atmosphere	Convective cloud location and direction		Convective cloud
Precipitation type	Surface		Rain, Snow and Freezing rain	Model output
Surface wind	10 meter	Wind speed & direction		See note bellow
Wind shear	0-2000 feet 200 feet within 2000 feet	0-2000 feet wind shear 200 feet wind shear	> 20 knots over 2000feet or > 0.16 within any 200 feet below 2000ft	NWS Instruction 10-813 on TAF
Tropopause	Tropopause	Height and temperature		Model output
Frozen height	Frozen height	Height		Model output
Fog	Surface		Occurrence	To be added
Other products				Request from users

3. Note on aviation products

Icing (in-flight)

There are many algorithms, ranging from simple (P. Shultz et al 1992, B. Brown et al 1997) to complex (e.g. AWC-NCAR's Integrated Icing Diagnostic/Forecast Algorithm), to determine the conditions in which icing events may occur. Here, a simple temperature and relative humidity (T-RH) method is used. If T falls into the range between -10 C ~ 0 C while RH > 70 %, then assume that icing will occur at that location (Mosher, AWC, personal communication). Super-cooled Large Droplet (SLD) icing is not considered right now. This method is simple but quite efficient. The SREF icing probability is computed in two steps: first, at each grid point the occurrence of icing in each ensemble member is counted (where T and RH satisfy the thresholds), then the number of members with icing is divided by 15 (the total number of ensemble members). The computed icing probability at a certain flight level is assumed to represent the probability density function (PDF) of an icing event occurring at that level. An example of the icing probability at flight level 180 for a lead-time of 6 hours, on July 21, 2004, is shown in Figure 3. The colored shades represent the percent probability divided into 11 categories from 0 to 100%. The probability distributions indicate where icing is most likely to happen (deeper red area) and most likely to not happen (violet area) on that level. The green-yellow shade denotes where icing is hard to determine from the ensemble run (the icing or non-icing probability is 50/50).

Turbulence

Several algorithms for estimating clear air turbulence (CAT) have been developed (Brown et al 2000). In the SREF aviation project, the relatively simple Ellrod's method (1991) is applied to compute CAT. This method classifies CAT intensity into light-middle, middle, and severe categories. Then a CAT intensity index is used to determine the CAT. The CAT intensity index is a function of stretching deformation, shearing deformation in the horizontal direction, vertical wind shear and convergence. These four factors implicitly reflect the effects of both the dynamic and thermo-dynamic status of the air. The probability computation procedure is similar to that of icing probability. An example of a middle CAT probability distribution between FL300 and FL270 is shown in Figure 4. As in the icing probability example, deep red denotes areas of high turbulence probability, violet the low turbulence probability areas, and green-yellow the hard-to-determine areas.

Flight category.

Flight categories here include Low Instrument Flight Rules (LIFR), Instrument Flight Rules (IFR), Marginal Visual Flight Rules (MVFR), and Visual Flight Rules (VFR) as defined in NWS Instruction 10-813 (2004). They are defined by a combination of effects of both ceiling and visibility near the ground. The probabilities of each of the four categories are computed by checking and counting the occurrence conditions in all ensemble members. An example of the probability of IFR is shown in Figure 5.

Ceiling

Ceiling is the cloud base information, and is, according to Federal Meteorological Handbook No.1 (FMH-1,1995), defined as lowest layer aloft reported as broken or overcast. In the model, if there is no cloud, the cloud base is set to a very large value (e.g. 100,000 feet). Therefore, clear and scattered members are not involved in the ceiling averaging computation. For example, the cloud base in 9 of 10 models is about 5000 feet, but one is clear sky, or has a cloud base of 100,000 feet. If clear sky member is also considered, the ceiling average will be 14,500 feet instead of the expected average of 5000 feet. The SREF aviation project uses a "conditional" definition of ceiling which will exclude those cloud-free members from ceiling mean and spread computations. Also, an individual member's cloud base height is defined at the lowest vertical levels of the model. However, after averaging, the ceiling might be lower or higher than that level.

Visibility

Surface visibility is computed from the Eta post, where the visibility is expressed with a relatively simple exponential equation

$$visibility(km) = \frac{-\ln(0.02)}{\beta}$$

where β is an extinction coefficient, which is computed from the hydrometeors (mass concentrate of cloud, rain, ice, snow etc.) using the relationship suggested by Stoelinga (Stoelina and Warner, 1999). The mean value of visibility is also defined as "conditional". The effects of haze and sand storms are not considered in the visibility since there are no such parameters within the Eta model.

Sky type (cloud cover)

In FMH-1, sky type is classified into 4 categories according to the total cloud coverage: clear sky (without cloud); scattered sky (cloud cover 1/8~4/8), broken sky (cloud cover 5/8~7/8), overcast sky (cloud cover 8/8). In the model, cloud cover is in percentages, so 0-10% becomes clear, 11-50% is scattered, 51-90% is broken, and 91-100% is overcast.

Jet stream

Jet stream products reflect the probability of high-level wind speeds over several thresholds (20, 40, 60, 80, or 100 knots) at three heights (4500 feet, 18000 feet and 34000 feet). An example of jet stream probability is shown in Figure 6.

Surface 10-meter wind

There are two methods to compute average wind speed. The first is to calculate total wind speed $w_1, w_2 .... w_{15}$ for each individual member, then average the speeds to get the mean and spread of wind speed. The second method is to calculate the mean of the u and v components, then get the mean of total wind speed $\overline{w} = (\overline{u}^2 + \overline{v}^2)^{1/2}$, where $\overline{u}$ and $\overline{v}$ are mean of u and v components, respectively. The spread of wind speed is obtained from u and v component spreads, σ_u and σ_v. It is shown in Figure 2 that the spread of wind speed can be expressed as $\sigma_w = (\sigma_u^2 + \sigma_v^2)^{1/2}$. Considering the offset problem in two opposite-direction winds, the first method is applied.

The calculations of the mean and spread of wind direction (North as reference) are not trivial. They are not directly computed from the degreed wind direction of each individual member. Instead, $\overline{u}$, $\overline{v}$ and their spreads σ_u and σ_v are used (see Figure 2). The mean and spread of wind direction are computed with

$$\overline{\theta} = arctg(\overline{u} / \overline{v}),$$ and

$$\sigma_\theta = arctg(\sigma_w / \overline{w}), \; 0 \le \sigma_\theta \le 90^\circ$$

respectively, where $\overline{w}$ is computed using second method.

One example of 10m wind direction mean and spread is displayed in Figure 7, in which the barbed arrow denotes the magnitude of mean speed and direction of wind while the colored shades show the wind direction spread. The larger spread (deeper red) implies that the forecast uncertainty of the wind direction is larger in that region. This example also shows that, in the regions where synoptic flows prevail, the wind direction is similar for all ensemble members so that the spread of the wind direction is small. In areas where local flows dominate, particularly in the mountains or near larger horizontal wind shear regions, the different members give different wind directions; as a result, the wind direction spread is very large in those areas. From the wind direction spread distribution, we can expect a larger chaotic atmosphere and larger uncertainty in the mountains or in larger wind shear regions. The probabilistic information on the wind direction is well captured in this example.

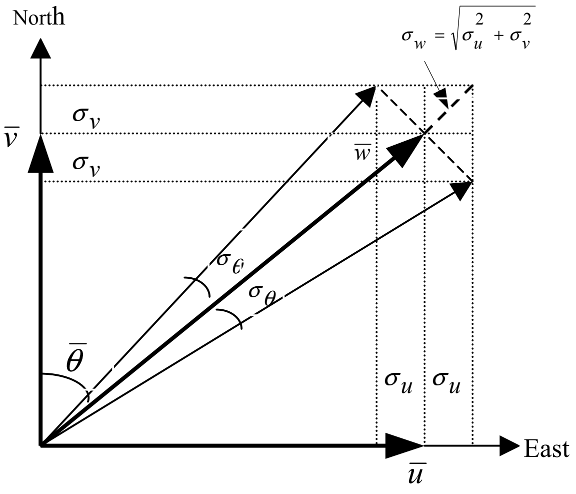


Figure 2

Low level wind shear

The low level wind shear (LLWS) is defined as the change in wind vector between the surface and the 2000-foot level (NWS Instruction on TAF 2004). In the model, the lowest wind level is 10m, so we use 10m to represent the surface, and 2000 feet + 10 m (about 2030 feet) as the upper level. The 2030-foot level depends on the topology of the location. In most cases, the 2030-foot level is not located at the standard GRIB output level, but in between levels. Thus, the wind at 2030 feet is obtained from a linear interpolation between two GRIB levels. The wind (vector) change is computed from

$$\Delta w = \sqrt{(u_{2030} - u_{10})^2 + (v_{2030} - v_{10})^2}\ .$$

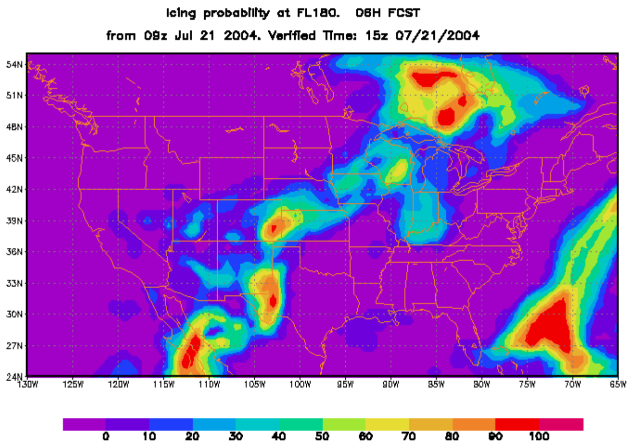
The severe LLWS alert threshold is met if either the surface-2000 feet wind speed (vector) change is over 20 knots or the wind shear in any sub-layer of 200 feet within the bottom 2000-foot layer is larger than 0.16 sec^{-1} (NWS Instruction on TAF 2004). Please note that the standard GRIB level interval is 25mb, which is much larger than 200 feet. Therefore, the severe LLWS alert is estimated using 25mb sub-layers, which are about 200m, or 600 feet thick, instead of 200 feet. This will lead to underestimation of the wind shear intensity within the 2000-foot layer, particularly in the mountain regions where the surface pressure is lower and the thickness of a 25mb sub-layer is much larger. An example of the mean and spread of LLWS is illustrated in Figure 8. The contour lines indicate the mean value while color shades show the LLWS spread. As in Figure 7, the red color represents the larger uncertainty forecasting area.

Convection

Convection in the Eta or RSM models is determined either by convective cloud or by Convective Available Potential Energy (CAPE). In the SREF aviation project, the presence of convection is indicated by two-dimensional convective cloud from the model output and its speed and direction by two-dimensional storm speed and direction distribution fields. This approach is quite simple and a more reasonable method should be considered in the future.

Other variables

Precipitation type probability (for rain, snow, frozen rain), tropopause height, freezing height, etc, are model or model-post outputs. Surface fog is hard to predict in the current Eta or RSM models. It is determined by several factors such as weak surface wind, high humidity or clear sky at night. We have no algorithm at hand to predict surface (radiation?) fog.



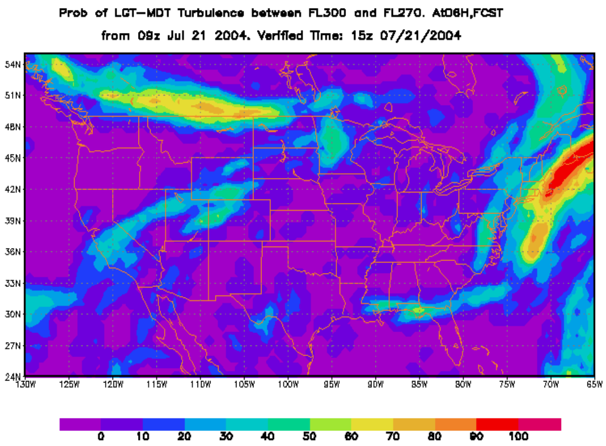
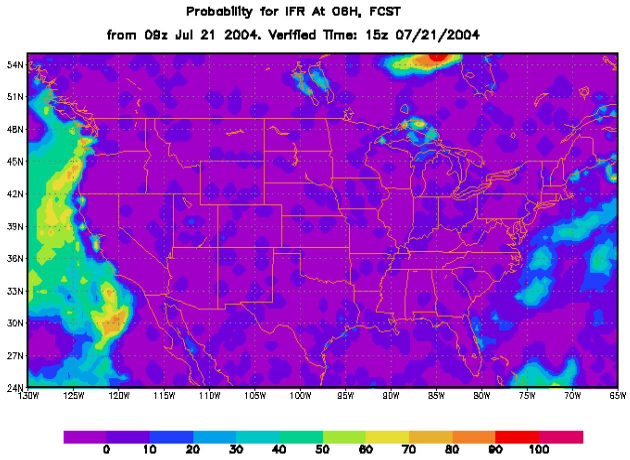


Figure 3: Probability distribution of icing over CONUS

Figure 4: Probability distribution of Middle turbulence



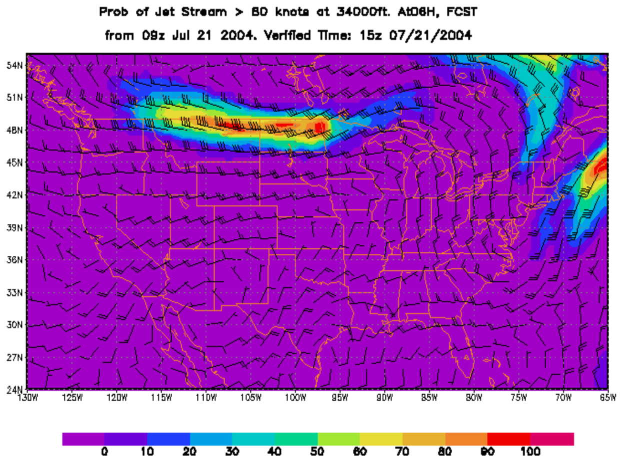
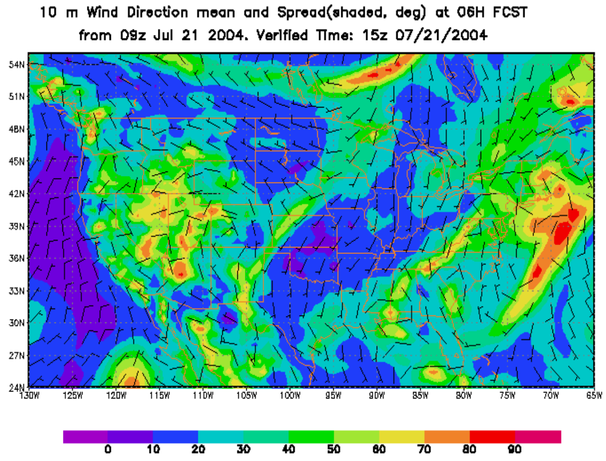


Figure 5: Probability distribution of IFR

Figure 6: Probability of Jet stream



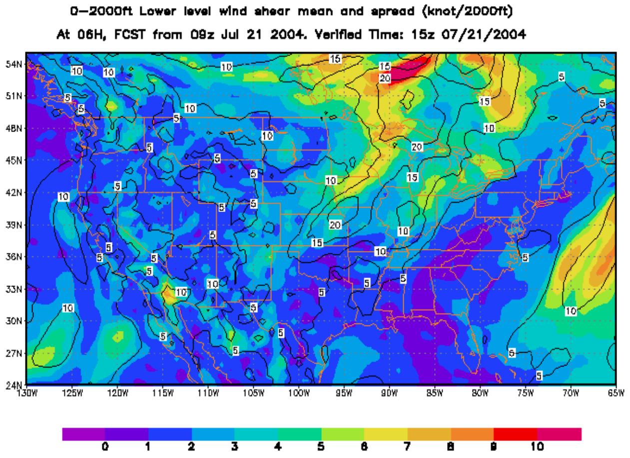


Figure 7: Mean and spread (color) of 10 m wind direction

Figure 8: Mean (contour) and spread (color) of LLWS

4. Verification of SREF aviation products

When the ensemble forecast system was developed, its verification and evaluation methods were introduced as well. It should be noted that assessing only the accuracy of an ensemble system is not enough, since the primary goal of an ensemble forecast is to provide probabilistic information about real weather systems and the amount of uncertainty reflected in their forecast. The goodness of an ensemble forecast is determined by verifying if the observations are within the ensemble range, or if it is able to capture the uncertainties in the data and in the models. Therefore, besides detecting the errors or biases in the ensemble forecast, evaluating its capability to capture uncertainty is a concern. The former is a common verification method used for traditional deterministic forecasts, while the later is done through system performance evaluation and probability evaluation. The two important performance characteristics of an ensemble system are *reliability* and *resolution*. The reliability represents the statistical consistency between predicted probabilities and the observed data frequencies, while the resolution is the ability of an ensemble forecast system to distinguish different future states with as little uncertainties as possible. These two characteristics of an ensemble system can be evaluated through Talagrand Rank Histograms, the outlier rate, equal likelihood frequency, reliability curve, Brier Skill Score (BSS), and Ranked probability skill score (RPSS), etc. A detailed description of the ensemble system verification and evaluation can be found in the Chapter 7 of *Environmental Forecast Verification* (Toth et al 2003). In the current SREF system, verification and evaluation were performed (only for those regular forecasting elements) by comparisons with the EDAS or GDAS data. (See http://wwwt.emc.ncep.noaa.gov/mmb/SREF/VERIFICATION_32km/new_html/system_32km_30day.html for details)

The verification of the aviation-related variables has not yet been carried out systematically. One of the reasons is that the observation data, particularly those special reports such as pilot reports (PIREPs) are not easily accessible by the SREF system's verification package and NCEP verification tools such as FVS. Another tool that has often been used for verifying aviation forecasts is the NOAA FSL Real Time Verification System (RTVS) (Mahoney, et al 1997). The RTVS was designed for verifying deterministic aviation forecast variables, not probabilistic ensemble forecast variables. The measurements for an ensemble system will not be evaluated in RTVS. Furthermore, RTVS cannot yet accept GRIB-extension format files as input.

Verification also can be done by comparisons with the Terminal Aerodrome Forecasts (TAF). We are working with NOAA Aviation Service Branch to verify some surface products, such as visibility, ceiling, surface wind, wind shear, etc. However, this verification is only to evaluate the forecast skill, not the ability of the SREF system to capture forecast uncertainties.

5. Plans

Although the SREF aviation project has made good progress, it is still experimental, and several aspects need to be improved. The upgrade of aviation products will always follow an upgrade of the SREF system. According to the NCEP SREF system development strategy, the following work is planned for the near future.

(1) Increase the number of forecast cycles

The number of forecast runs per day by the SREF system is limited by NCEP computing resources. When the NCEP supercomputer is upgraded, the SREF forecast runs will be increased from twice a day to 4 times a day.

(2) Add Alaska to model domain

The current SREF model domain (AWIPS 212) does not include Alaska, so neither do the aviation products. The next version of the SREF system and its aviation products will include Alaska.

(3) Add WRF members

According to NCEP/EMC's plan, the Weather and Research Forecast (WRF) model will become the operational model over the next five years. As part of a testing period, the SREF system has a planned gradual move-forward strategy to replace Eta with WRF models. The first stage is adding an additional 5 WRF models into the SREF system but still keeping the Eta members. The performance of the WRF model in SREF will be fully tested and evaluated before entering the next stage.

(4) SREF Verification

In the next development stage, the verification and evaluation of aviation related products will be emphasized. The verification against TAF data is underway. We also hope to employ FSL's RTVS to verify SREF aviation products. We'd like to see the RTVS upgraded to be able to perform the verification for aviation ensemble products in the future.

(5) Add new products

The progress in SREF aviation projects made by NCEP was greatly helped by the users of these aviation products. During the past two years, we received many comments and suggestions. All of this feedback has already been considered in planning improvements to the products or in designing new products. We are still listening to the users as the next stage of development begins and hope to further enhance the system.

(6) Confidence index

One goal of the ensemble forecast system is to quantify the confidence level of the forecasts. The confidence level is related to predicted probability of an event by the ensemble forecast system and the amount of uncertainty reflected in an ensemble forecast. Some efforts have been made regarding the NCEP global ensemble forecast system (Toth et al 2001). But the issue still remains for the NCEP SREF system, and will be considered in next stage.

6. Summary

Ensemble forecasting is a new technology which provides not only accurate forecasts, but also probabilistic information about weather systems, captures uncertainties in the forecast and quantifies forecast confidence. Many ensemble systems, both for medium range or short-range forecasts, have been successfully developed and evaluated, showing that they are skillful and useful in supporting daily weather forecasting. The NCEP SREF aviation project, based on the SREF system, is an effort to bring ensemble techniques into aviation forecasting. In its first stage of development, the general framework was completed, including 14 aviation related probabilistic products. The products are routinely displayed two times daily on SREF web site, and hopefully can be used as supporting tools for the aviation weather forecasts. This work is very primary and much work, such as verification and evaluation, should be done to enhance this system. The verification work has been planned but needs cooperation from other organizations. During its development period, this project has obtained much support and benefit from many user inputs from the aviation community. The advances are made through the continuous interaction between the developers and users.

Acknowledgments

This project is sponsored by the Federal Aviation Administration. We thank Fred Mosher and Steven Silberberg of NOAA AWC for their technical support in designing and selecting the products. We also thank Michael Graf of NOAA Aviation Service Branch and Kevin Johnston of NOAA MDL for their valuable comments and suggestions in project development.

References

Brown B. G., B. C. Bernstein, L. K. Tressa, and R. Bullock, 1997: Diagnostic and comparative verification of algorithms for the detection and forecasting of in-flight icing. Preprints, *Seventh Conf. on Aviation, Range and Aerospace Meteorology*, February 2-7, Long Beach,CA, Amer. Meteor. Soc., 88-93.

Brown B. G., J. L. Mahoney, J. Henderson, L. K Tressa, R. Bullock, and J. E. Hart, 2000: The turbulence algorithm intercomparison exercise: statistical verification results. Preprints, *Ninth Conf. on Aviation, Range and Aerospace Meteorology*, September 11-15, Orlando, FL, Amer. Meteor. Soc., 466-471

Brooks, H. E., M. S. Tracton, D. J. Stensrud, G. DiMego, and Z. Toth, 1995: Short range ensemble forecasting: Report from a workshop, 25-27 July 1994. *Bull. Amer. Meteor. Soc*., 76,1617-1624.

Cole R. E., S. S. Allan and D. W. Miller: 2000: Vertical wind shear near airports as an aviation hazard. Preprints, *Ninth Conf. on Aviation, Range and Aerospace Meteorology*, September 11-15, Orlando, FL, Amer. Meteor. Soc.

Du J., and S. L. Mullen, 1997: Short-range ensemble forecasting of Quantitative precipitation, *Mon. Wea. Rev*., 125, 2427-2459.

Du, J., and M. S. Tracton, 2001: Implementation of real-time short-range ensemble forecasting system at NCEP: an update. Preprints, *Ninth Conf. on Mesoscale Prcoesses*, Ft. Lauderdale, Florida, Amer. Meteor. Soc., 355-356

Du, J., G. DiMego, M.S. Tracton and B. Zhou 2003: NCEP short-range ensemble forecasting (SREF) system: multi-ICs, multi-model and multi-physics approach. *Research Activities in Atmospheric and Oceanic Modeling* (edited by J. Cote), Report 33, CAS?JSC Working Group Numerical Experimentation(WGNE), WMO/TD-No. 1161,5.09-5.10.

Du, J., J. McQueen, G. DiMego, T. Black, H. Juang, E. Rogers, B. Ferrier, B. Zhou, Z. Toth and M. S. Tracton, 2004: The NOAA/NWS/NCEP short-range ensemble forecast (SREF) system: evaluation of an initial condition vs multi-model physics ensemble approach. Preprints*, Sixteenth Conf. on Numerical Weather Prediction, Seattle, Washington, Amer. Meteor Soc.,* Seattle, WA. Amer. Meteor. Soc.

Ellrod G. P. and D. I. Knapp, 1991: An objective clear-air turbulence forecasting technique: Verification and operational use. *Wea and Forecasting*, 7, 150-165.

Epstein, E. S., 1969: A scoring system for probability forecasts of ranked categories. *J. Apply. Meteor*, 8, 985-987.

Hamill, T. M. and S. J. Colucci, 1997: Verification of Eta-RSM short-range ensemble forecasts. *Mon. Wea. Rev.* 125, 1312-1327.

Leith, C. E., 1974: Theoretical skill of Monte Carlo forecasts. *Mon. Wea. Rev*., 102, 409-418

Lorenz, E. N., 1963: Deterministic non-periodic flow. *J. Atmos. Sci*., 20, 130-141.

Manikin G. S., J. T. McQueen, J. Du and B. S. Ferrier, 2004: Changes to the NCEP SREF system and their impact on convective forecasting. *22nd Conf. on Severe Local Storm*, Oct 3-8, Hyannis, MA Amer. Meteor Soc.

McCann D. W., 1997, A “Novel” approach to turbulence forecasting, Preprints, Seventh *Conf. on Aviation, Range and Aerospace Meteorology*, February 2-7, Long Beach, CA, Amer. Meteor. Soc.

Mahoney J. L., J. K. Henderson, P. A. Miller, L.A. Sherretz, D. M. Rogers, and M. Moore, 1997: A description of the Forecast System Laboratory’s Real-Time Verification System (RTVS). Preprints, Seventh *Conf. on Aviation, Range and Aerospace Meteorology*, February 2-7, Long Beach, CA, Amer. Meteor. Soc.

Office of the Federal Coordinator for Meteorology: *National Aviation Weather Initiatives,* FCM-P34-1999, Washington D.C. February 1999

Palmer, T. N., R. Mureau, and F. Molteni, 1990: The Monte Carlo forecast. *Mon. Wea. Rev*., 45,198-207

Politovich, M. K., and B. G. Brown, 1997: Activities of the FAA in-flight icing Product Development Team. *Seventh Conf. on Aviation, Range and Aerospace Meteorology*, February 2-7,Long Beach, CA, Amer. Meteor. Soc., 76-81.

Schultz P. and M. K. Politovich, 1992: Toward the improvement of aircraft-icing forecasts for the continental United States. *Wea and Forecasting*, 7, 491-500.

Stensrud D. J., 2003: Short-range ensemble predictions of 2-m temperature and dewpoint temperature over New England, *Mon. Wea. Rev*., 131, 2510-2524

Stoelinga M. T. and T. T. Warner, 1999: Non-hydrostatic, Mesobeta-scale model simulations of cloud ceiling and visibility for an east coast winter precipitation event. *J. Appl. Meteor*. 38, 385-404.

Toth, Z., and E. Kalnay, 1993: Ensemble forecasting at NWC: The generation of perturbations. *Bull. Amer. Meteor. Soc*., 74, 2317-2330.

Toth, Z., and E. Kalnay, 1997: Ensemble forecasting at NCEP and breeding method. *Mon. Wea. Rev.* 125, 3297-3319.

Toth, Z., Y. Zhu and T. Marchok, 2001: The use of ensembles to identify forecasts with small and large uncertainty, *Wea and Forecasting*, 16, 463-477.

Toth, Z. O. Talagrand, G. Candille and Y. Zhu, 2003: Chapter 7: Probability and ensemble forecast*, Environmental Forecast Verification: A Practitioner’s Guide in Atmospheric Science*, Edited by I. T. Jolliffe and D. B. Stephenson, John Willey & Sons.

Tracton, M. S., and E. Kalnay, 1993: Operational ensemble prediction at the National Meteorological Center: Practical aspects. *Wea and For*ecasting, 8, 378-398.

Tracton, M. S., J. Du, Z. Toth and H. Juang, 1998: Short-range ensemble forecasting (SREF) at NCEP/EMC. Preprints, *Twelfth Conference on Numerical Weather Prediction,* Phoenix, Amer. Meteor. Soc., 269-272.