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Introduction to the NCEP Very Short Range Ensemble Forecast System (VSREF)

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Abstract

The NCEP Very Short Range Ensemble Forecast (VSREF) System is specially developed for aviation weather and potential NextGen applications. Its development was initiated in 2009. The VSREF system is based on NCEP's operational Rapid Update Cycle (RUC) and North American Mesoscale (NAM) model runs using a time-lag ensembling technique. The current domain is over the contiguous US (CONUS). The VSREF is routinely updated every hour with hourly output through 6 hr forecast length. In the current developing stage, there are 11 aviation-weather related probabilistic products in the VSREF system, including icing, clear air turbulence (CAT), visibility, fog, ceiling, low level wind shear, jet stream, surface wind gust, simulated reflectivity, convection, and freezing height. There is an experimental web page to display these products for demonstration. In this paper, more detailed information about the NCEP VSREF including its system configuration, product generation, verification and future plan will be described.

1. Introduction

Ensemble forecasting is a new modeling technique to deal with forecast uncertainties, steming from either initial conditions or models. The National Centers for Environmental Prediction (NCEP) of NOAA has developed ensemble forecast systems at both global scale (Toth and Kalnay 1993) and regional range scale (Du and Tracton 2001, Du et al. 2006) over Contiguous US (CONUS), Alaska and Hawaii. In recent years, NCEP has been making efforts to apply its Short Range Ensemble Forecast (SREF) System to aviation weather forecast (Zhou et al, 2004), including system configuration, post-processing, preliminary aviation-related ensemble products. However, the current system configuration for the NCEP SREF still dose not meet "very short range" requirement of NextGen, the FAA's new Air Traffic Management System (ATM). Currently, NCEP has a Rapid Update Cycle model (RUC: http://ruc.noaa.gov) that is hourly run and specially serves deterministic aviation weather prediction. However, due to uncertainties of model prediction and its critic impacts on aviation traffic decision making procedure, NextGen will heavily rely on ensemble-based probabilistic forecast data as input (Benjamin and DiMego 2010; Souders et al. 2010). As a promise to support and comply with the NextGen requirements, NCEP and Global Systems Division (GSD) of Earth System Research Laboratory (ESRL) of NOAA will cooperate to develop NCAR ARW-WRF based Rapid Refresh (RR) and High-Resolution RR (HRRR) systems. The RR or HRRR based ensemble forecast system (NARRE – North American Rapid Refresh Ensemble and HRRRE – High-Resolution Rapid Refresh Ensemble) will be established in 2014 as planed. As a prelude of the RR/HRRR ensemble development stages, a RUC-NAM based Very Short Range Ensemble Forecast System (VSREF) has been first suggested and developed at NCEP recently. The basic idea of the VSREF is time-lagging the forecasts from existing RUC and NAM cycles. An obvious advantage of the time-lagged technique is its low computational cost since it uses existing model output data without large amount of computational resources including CPU and memory space as requested mainly by, for instance, integrating a model and

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generating initial condition perturbations such as Ensemble Transform used by GEFS and breeding technique used by the SREF (Du et al. 2006). The only cost for the time-lagged ensemble forecast system is on the procedures to collect the existing model data and then apply a post processor to generate required ensemble products. For the VSREF, a rapid refreshed ensemble forecast system, employing the time-lagged ensembling technique is an appropriate choice for current computational condition at NCEP. The current VSREF system consists of three procedures, including the ensemble member creation, the aviation ensemble product generation and the ensemble product visualization. This paper will give a brief description of each of these procedures.

2. System configuration

There are two types of approaches for the time lagged technique: "Direct Time-Lagged" and "Scaled Time-Lagged". The Direct Time-Lagged approach (Hoffman and Kalnay 1983) directly pulls multiple forecasts which are initiated from different past times but verified at a same time together as an ensemble (a mixture of old and young forecasts). This method views the error of a past forecast at $t=0$ (current initial time) directly as initial condition perturbation which should reflect "error of the day" and has dynamically growing structure leading to larger ensemble spread than random perturbation. The advantage of the method is that the generation of perturbation is absolutely free. However, a main concern is that the quality (magnitude) of perturbation depends on the age of a forecast since forecast quality usually decreases with lead time. To avoid this weakness, past forecast errors are first scaled down by their "ages" (assuming error growth is quasi-linear) at $t=0$ to have similar magnitude in all perturbations and then added to or subtracted from the current control analysis to create multiple analyses to initiate an ensemble of forecasts (Ebisusaki and Kalnay 1983). The Time-Lagged approach has been used in many ensemble research and operations (e.g. Saha et. al. 2006; Hou et. al. 2001; Lu et al. 2006; Brankovic et al. 2006). A limitation of the Time-Lagged method is that it cannot create an ensemble with large enough member size since the number of "good" old forecasts available is limited in reality. Otherwise, the ensemble quality will be severely contaminated if too old forecasts are included to have a large size ensemble. To keep more "good" members and emphasize on more recently finished model cycles in the VSREF member group, a set of time-decaying weights are assigned to each VSREF member. The details of weighting will be presented in the next discussions.

Before the VSREF ensemble members are generated, the VSREF configuration procedure first determines which previously finished NAM (North American Mesoscale model http://www.emc.ncep.noaa.gov) and RUC (Rapid Update Cycle: http://ruc.noaa.gova) model cycles are available for building the VSREF system. Currently at NCEP, the operational NAM is run four cycles per day at 00Z, 06Z, 12Z and 18Z with hourly output out to 87 forecast hours while the operational RUC is run every one hour with hourly output out to 12 forecast hours for 00, 03, 06, 09, 12, 15, 18, 21Z cycles and out to 9 forecast hours for other cycles. In order to create a rapid update ensemble forecast system, each VSREF cycle is launched right after each cycle of RUC is finished. That is, the VSREF also is hourly updated, or 24 cycles per day.

Since the ensemble size of a time-lagged ensemble can not be too large as discussed, the membership of the current VSREF is designed as 10 members. To coordinate current NAM and RUC models in running and output configurations, the VSREF will use four previously finished NAM cycles, five previously finished and one most recently finished RUC cycles. To better understand the VSREF system configuration, take a look at a specific VSREF cycle, e.g. 06Z run as shown in Fig. 1.

Figure 1 shows the configuration of (today's) 06Z cycle of VSREF membership, which consists of 4 NAM cycles of 00Z, 06Z, 12Z and 18Z yesterday (finished 30, 24, 18 and 12 hours ago), and 6 RUC cycles of 01Z ,02Z, 03Z, 04Z, 05Z and 06Z today (finished 5, 4, 3, 2, 1 and 0 hour ago). The total forecast and output time, as shown in Fig.1, is at 07, 08, 09, 10, 11 and 12 Z, respectively. Please note that 11Z and 12Z only have 10 and 11 members, respectively, because 01Z and 02Z RUC cycles only have 9 forecast hours.

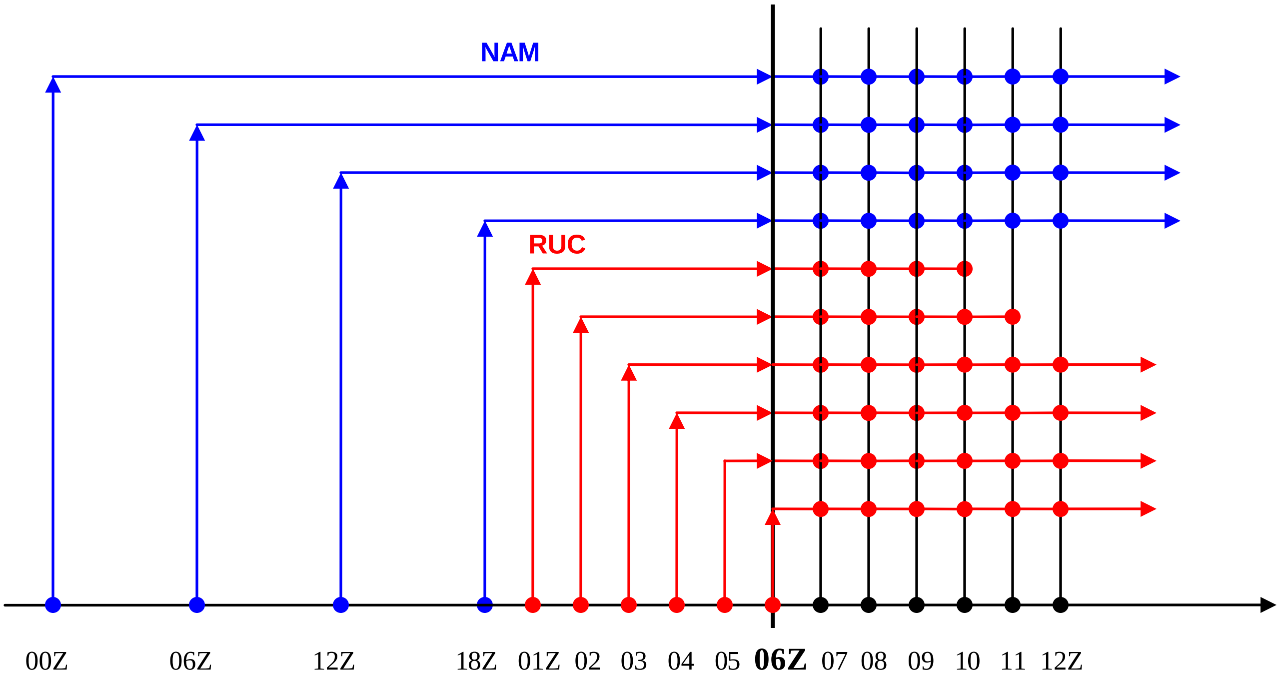

Figure 1. VSREF membership configuration for today's 06Z cycle, which is composed of 10 finished cycles, including 00Z, 06Z, 12Z and 18Z NAM cycles (blue dots) of yesterday, and today's 01Z, 02Z, 03Z, 04Z, 05Z and just finished 06Z RUC cycles (red dots), with hourly output at 07Z, 08Z, 09Z, 10Z, 11Z and 12Z (black dots), totally 6 forecast hours.

The weights for each member in 06Z cycle VSREF are assigned as following order. The most recent RUC cycle (06Z) is assigned 1.0. The rest of members are assigned 0.9, 0.8, ….0.1, according to the ages of the members. The older, the smaller. The oldest NAM always has smallest weight 0.1. This implies that the VSREF is more weighted on RUC than on NAM. As soon as all of the 10 members are available right after 06Z, the VSREF system configuration procedure begins to collect member data to construct the ensemble. Another important notice is that the current operational RUC and NAM are output in different grid scales (http://www.nco.ncep.noaa.gov/pmb/docs/on388/tableb.html) although their resolutions are close (NAM 12 km and RUC 13 km). The NAM grid is on Grid-218 while RUC grid is on Grid-130. To make ensemble computation at same grid, the NAM model data are converted to RUC grid by using the NCEP's copygb utility (http://www.nco.ncep.noaa.gov/pmb/codes/nwprod/util/sorc/copygb.fd) before conducting ensemble product generation.

3. Product generation

After all of 10 weighted member data are ready, the ensemble mean, spread and probability computations for each aviation product X_i can be conducted as following: the ensemble mean

$$\overline{X_i} = \frac{\sum_{m=1}^{10} w_m \cdot X_{i,m}}{\sum_{m=1}^{10} w_m} \qquad (1)$$

and the ensemble spread

$$S_i = \left[\frac{\sum_{m=1}^{10} w_m \cdot \left(X_{i,m} - \overline{X_i}\right)^2}{\sum_{m=1}^{10} w_m - 1}\right]^{1/2} \qquad (2)$$

where w_m is the weight for member m. Before computing the probability for product X_i, first diagnose if it exceeds a specific threshold $t_{i,j}$. In general a series of thresholds for this product are checked, giving "yes" (exceeding the threshold) or "no" (not exceeding the threshold) results for all of thresholds (j =1, 2, …). Counting the "yes" members for a specific threshold $t_{i,j}$, the "yes" ensemble probability for product X_i can be computed as

$$P(X_i \geq t_{i,j}) = \frac{\sum_{m=1}^{yes\sim member} w_m}{\sum_{m=1}^{10} w_m} \quad (3)$$

Obviously, if all weights are given equal, the above computations will reduce to regular equal-weighting mean/spread/probability ensemble product computation. It is also implied that if having more recent members (more members are young), the probability computation will result in larger ensemble probability, or more confidence with the forecast.

At current stage, 11 most concerned aviation weather related products are considered in the VSREF system, including icing, clear air turbulence (CAT), ceiling height, visibility, fog, jet stream, low level wind shear (LLWS), convection, simulated reflectivity, freezing level and precipitation type. See Table 1, in which the computation/diagnosis methods for each product are also shown. From Table 1 we also can see that some products only have probability, such as icing, CAT, fog, convection, reflectivity, and precipitation type, some only have mean/spread such as freezing level, and some have both mean/spread and probability such as visibility and ceiling. The reason for only ensemble probability is that these product are event-driven and diagnosed as binary forecast (yes/no) in the post processor. Some products, e.g. the reflectivity has dBZ value in model output. However, averaging of dBZ is a tricky problem since it can not conduct simple average over reflectivity dBZ value. So at current stage, only probability of reflection larger than a series of thresholds are presented in the VSREF system.

The icing, CAT and jet stream are in-flight products. The others are TAF products (surface). The icing levels are FL000, FL030, FL060, FL090, FL120, FL150, FL180and FL240. The CAT levels are FL180, FL210, FL240, FL270, FL300, FL330, FL360, FL390, and FL 420.The jet stream levels are FL045, FL150 and FL350.

Table 1. VSREF aviation ensemble products

	Product ensemble	**Method**
1	Icing occurrence probability at 8 flight levels	T and RH diagnosis (same as NCEP SREF)
2	Clear Air Turbulence probability of light, moderate, severe at 9 flight levels	U, V, T diagnosis (Ellrod 1992, same as NCEP SREF)
3	Ceiling height mean/spread and prob of <1000, 2000, 3000, 6000 and 10000 feet	Cloud base height (RUC has no cloud coverage)
4	Visibility range mean/spread and prob of < ¼, ½, 1, 2, and 4 miles	NAM: Stoelinga and Warner (1999) RUC: Smirnova et al. (2000)
5	Jet stream at 3 flight levels, probability of wind speed > 20, 40, 60, 80 100 knots	U,V components diagnosis
6	Low level wind shear mean/spread and prob of (wind shear > 20 knots/2000feet)	Federal Meteor Handbook -1995
7	Fog occurrence probability	Zhou and Du (2010)
8	Convection occurrence probability	Convective precipitation diagnosis (Weygandt et al. 2008)
9	Simulated reflectivity probability of > 10, 20, 30, 40 dBZ	Ferrier (see Koch et al. 2005)
10	Freezing level mean/spread	Temperature-profile diagnosis
11	Precipitation type occurrence probability	Rain, snow and freezing rain from model

Some explanations for the methods of listed products are briefly described here. For ceiling height, the definition is a combination of both cloud base height and cloud fraction percentage as was defined by NWS (FCM-1999). However current RUC has no cloud fraction percentage output. Therefore at current stage, the VSREF's ceiling is just cloud base height which is different from actual ceiling height.

The visibility computation in NAM and RUC is different. NAM uses Stoelinga and Warner (1999) method while RUC uses Smirnova et al. (2000) method, an improved algorithm of Stoelinga and Warner. A limited verification over CONUS shows that the RUC visibility is more skillful than that of NAM, particularly at higher visibility range (see Fig. 2). The fog diagnosis in VSREF follows the method used in current SREF where the fog event at a grid point is diagnosed with so-called "multiple-variable" diagnostic method including surface cloud water, cloud base, cloud top, surface RH, and wind speed (Zhou and Du 2010). Only all of these variables meet certain thresholds will fog be diagnosed instead of using "visibility < 1000m" as a threshold. The verification has shown that the multi-variable diagnostic method significantly improves the forecast performance over the visibility-only method.

The convection is diagnosed with the scheme of Weygandt et al. (2008). The method diagnoses the grid-filtered convection with hourly convective precipitation accumulation which varies with eastern US (Fig. 3), western US regions and diagonal times. The grid-filter performs a 7x7 grid average for eastern US region and a 9x9 grid average for western US region. Considering the less organization feature in the western US region, the convective precipitation threshold for western US regions is 0.6 factor of the eastern region.

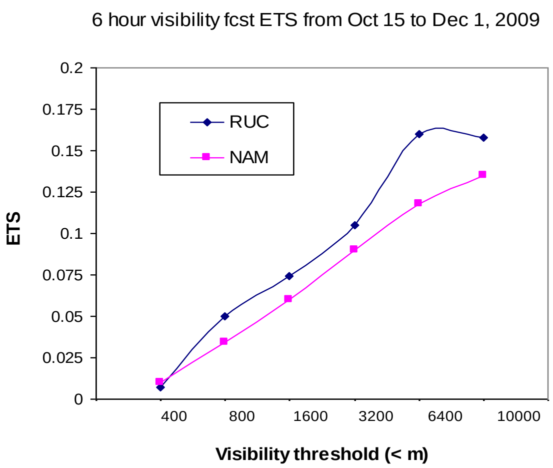

Figure 2. Equitable threat score comparison between NAM and RUC's 6 hour visibility forecasts.

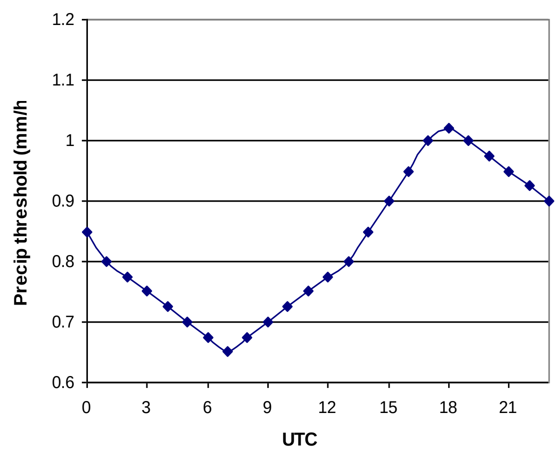

Figure 3. Convective precipitation threshold (mm/hr) used for eastern US region.

4. Visualization of the products

After all of products are diagnosed or available directly from each members, the ensemble products are produced from the NCEP ensemble product generator and then display at the VSREF web page (http://wwwt.emc.ncep.noaa.gov/mmb/SREF_avia/FCST/VSREF/web_site/html/refl.html) for demonstration purpose. The VSREF web page is updated every hour but only today's forecast is present. The historical image will be removed from the NCEP server to save space. If users request historical data, please send email to Binbin.Zhou@noaa. The interface of the VSREF web page looks like Fig. 3 where the probability distribution of reflectivity > 20 dBZ over CONUS is shown. From the VSREF web page, different cycles, different products under which different thresholds can be selected and displayed. The animation through different forecast times can also be displayed but zooming capability is still not available.

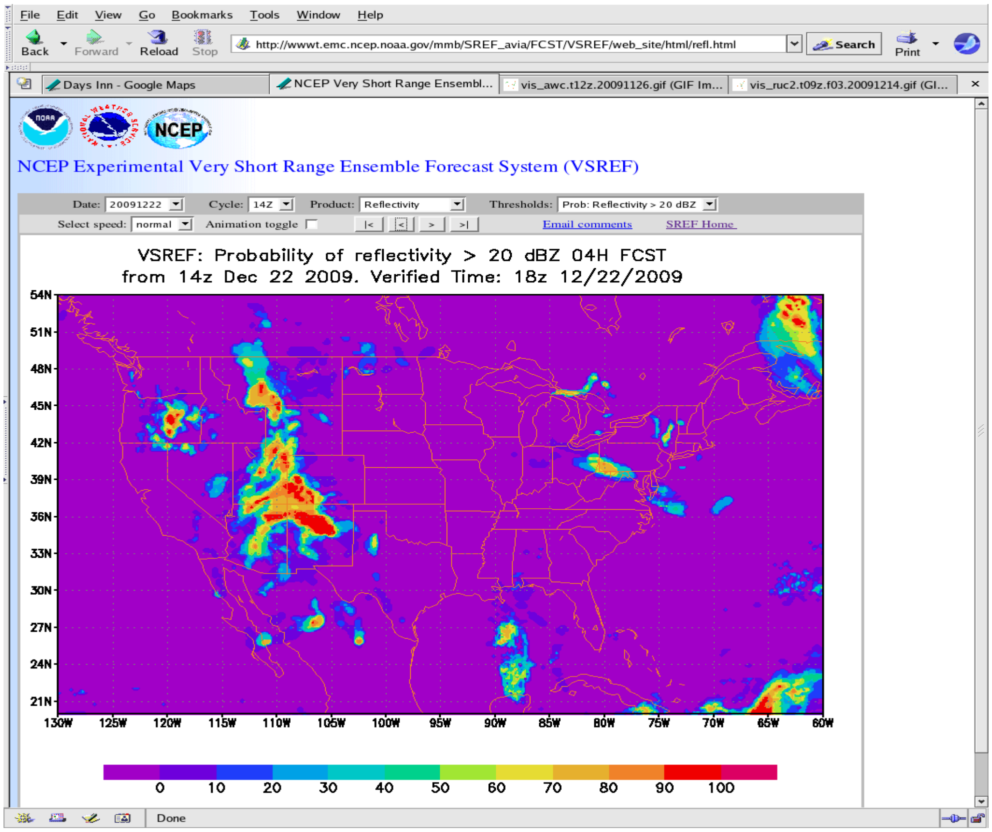

Fig.3 VSREF web page interface where Dec. 22, 2009, cycle 14Z, 4-hour forecast probability of reflectivity > 20 dBZ over CONUS, valid at 18Z on the same day, is shown.

5. Verification

Verification of aviation weather forecast is difficult due to lack of sufficient and reliable truth data. GSD's Real Time Verification System (RTVS: http://rtvs.noaa.gov) is one that is a specific tool for evaluation of aviation weather products but the RTVS is for single model instead of probabilistic prediction verification. At NCEP, we have developed a grid to grid (g2g) forecast verification system (www.emc.ncep.noaa.gov /mmb/papers/zhou/NCEPGrid2GridVerificationSystem- V2.doc) that can be used for verifying both single and ensemble forecasts, or deterministic and probabilistic verifications. The deterministic verification uses traditional evaluation measures like Bias, Hit rate (POD), FAR, Missing rate, Threat score (TS), and Equitable threat score (ETS). In general, an ensemble forecast can be converted to deterministic forecast through selecting a specific ensemble probability threshold. For instance, select 50% as an ensemble probability threshold. If the ensemble probability forecast for an event (such as visibility < 400m) at a grid point is more than 50% (or more than 5 of 10 members predict 'true'), then issue the 'true' forecast for this event at this grid point. Then we can use the traditional (deterministic) verification technique to verify the ensemble forecast system over various probability thresholds. The probabilistic verification uses Reliability, Resolution, Brier Skill Score (BSS), Relative Operational Curve (ROC), etc. Particularly, the Economic Value (EV) in a cost/loss (C/L) ratio can also be estimated (Zhu et al. 2002). The EV can be further applied in a decision making procedure and may be particularly useful in NextGen. Currently, some gridded data have available to us, including the Aviation Weather Center's ADDS (http://adds. aviationweather.gov) data and the National Radar Reflectivity Mosaic (http://www.emc.ncep.noaa. gov/mmb/wx22hl/REF) data. With the ADDS data, the VSREF's ensemble icing, CAT, ceiling height, fog and visibility forecasts can be evaluated while with the radar mosaic data, the reflectivity or convection ensemble forecast can be verified.

As a primary verification step, we have conducted some verifications of visibility ensemble probability (of less than various visibility ranges) forecasts including deterministic and probabilistic aspects as shown in Fig. 4 and 5. Fig.4 is the accumulated deterministic verification scores over 3 weeks from Oct. to Nov. 2009. Fig. 5 is the probabilistic verification diagrams over the same period.

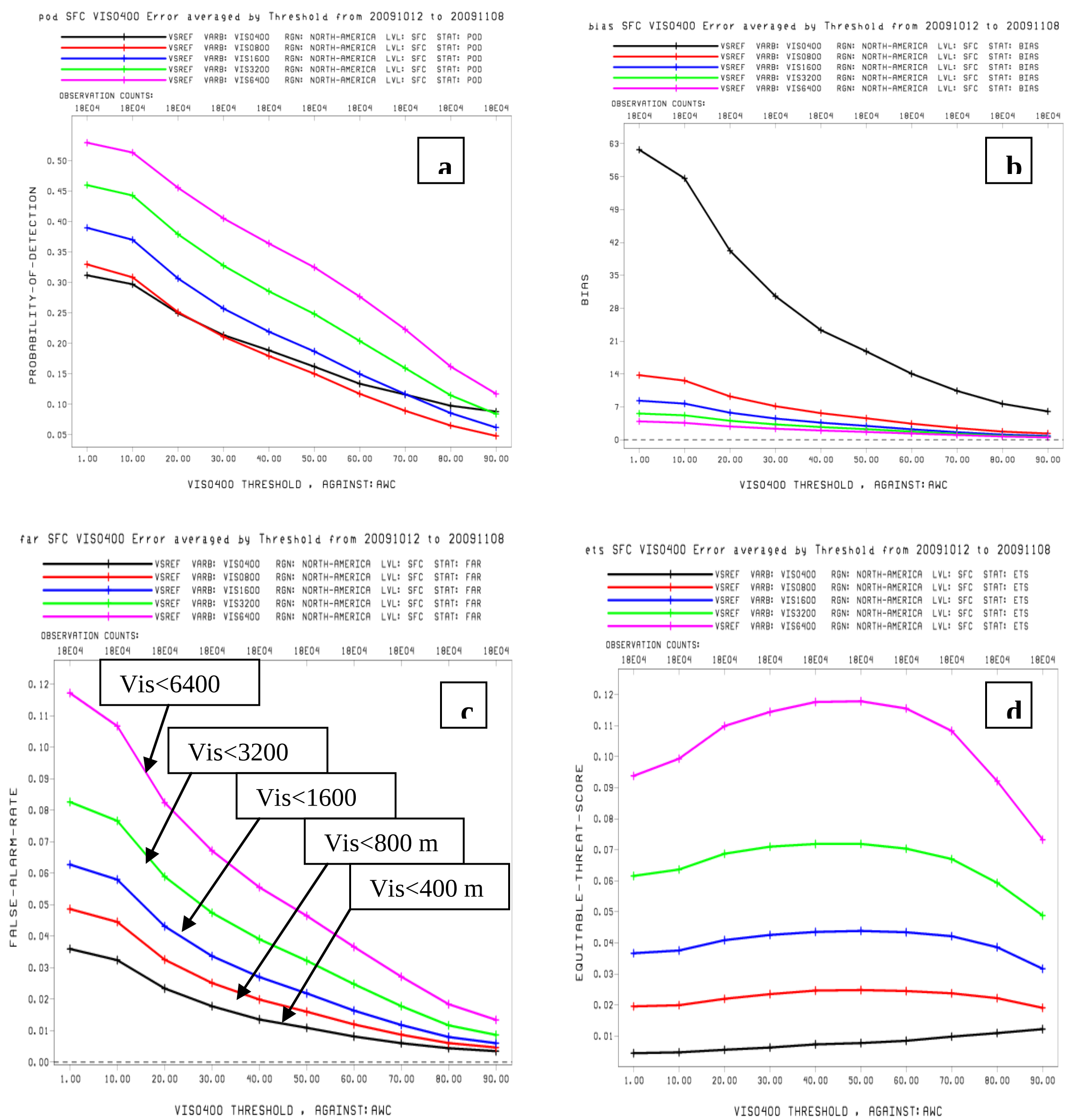

Fig. 4. Deterministic verification: VSREF's 3 week accumulated 6 hour forecast POD (a), Bias (b, bias=1means no bias), FAR (c) and ETS (d) of visibility range < selected values (400, 800, 1600, 3200 and 6400 m, respectively) for various selected probability thresholds (x-axis). Accumulation period is from Oct 12 to Nov. 8, 2009.

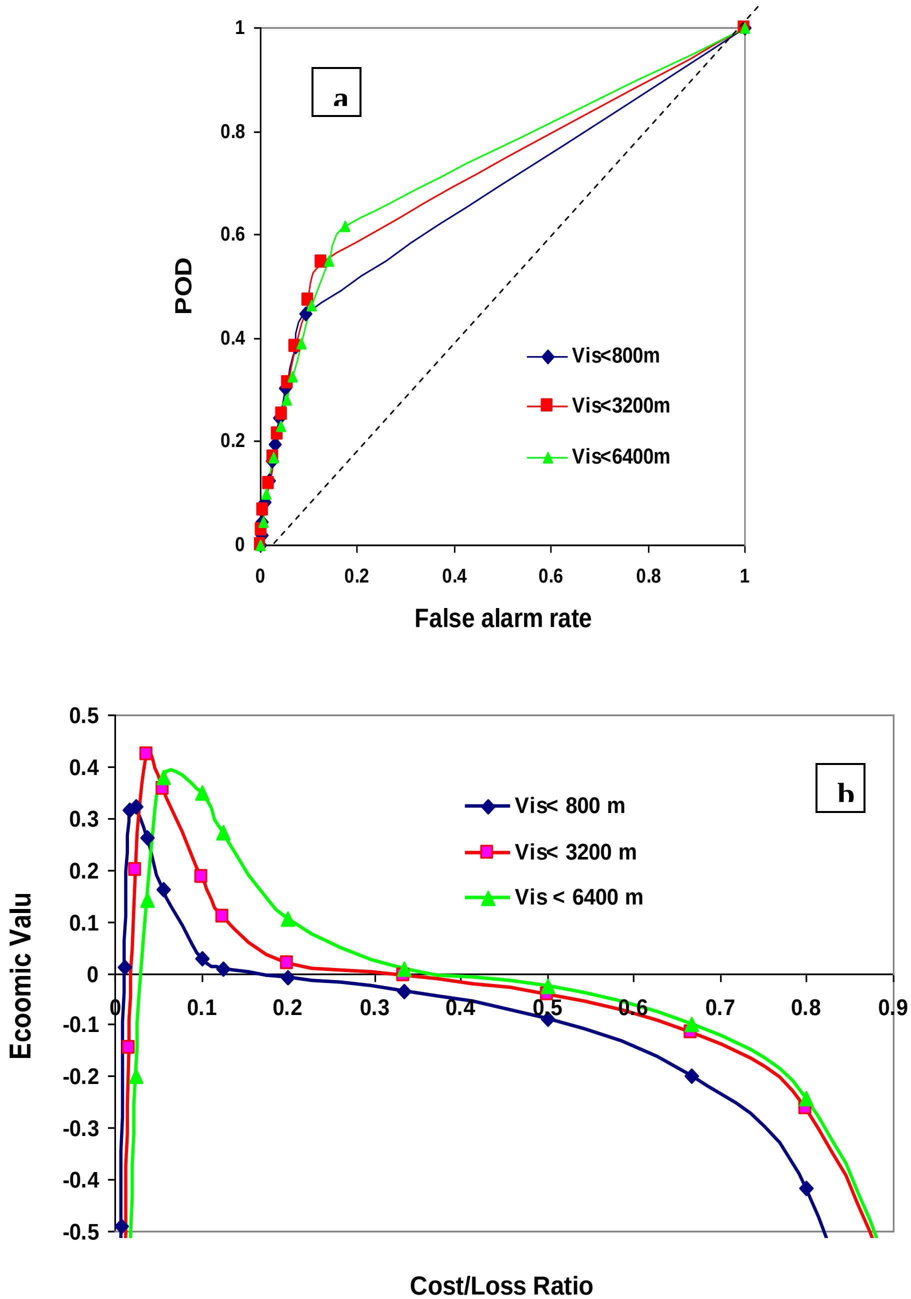

Fig. 5. Probabilistic verification: VSREF's ROC(a) and Economic Values(b) for 3 selected visibility range thresholds (<800, 3200 and 6400 m, respectively)

Fig. 4 shows that using a smaller ensemble probability as a threshold can get larger hit rate (POD) but also suffers from a higher false alarm ratio (FAR) and a larger bias while with a larger ensemble probability as a threshold, the situation is reversed. So there will be a trade-off in selecting a proper ensemble probability threshold. In general, selecting a mid-range (40-60%) probability as a threshold can obtain a better ETS, just as shown in Fig. 4 (d). The ETS actually is a overall score considering both POD and FAR. For a user's application, how to select an appropriate probability threshold depends on user's own situation. Some prefer a higher POD, some don't care about FAR, and some care about both FAR and POD. We can see that the ensemble forecast can meet a wide range of requirements of different users, which is an important advantage of an ensemble forecast over a single model forecast.

Fig. 5 shows the probabilistic measures of the VSREF visibility forecast over same period as Fig. 4. Fig 5 (a) shows the ROC which represents the forecast skill in terms of resolution, or how a forecast is different from the climatological prediction (diagonal line). Only ROC with larger than 0.5 area (or ROC curve is above the diagonal line), the forecast is skillful. We can see that all of forecasts for selected visibility ranges are skillful, or much better than climatological prediction. The Fig.5 (b) presents the Economic Value (EV) in various coast/loss ratios for different visibility range forecasts. Only for a lower cost/loss (C/L) ratio, the 3 VSREF visibility forecasts have positive economic values. For too small or too large C/L ratios, the forecasts have no economic values. Here the cost means the coast of a protection action (such as airplane delay in case of lower airport visibility, e.g. < 800m) while the loss is the cost of property/life losses. A lower C/L ratio implies that the protection cost should not be very high compared to the property/life losses. User should have his/her own C/L ratio estimate before checking the EV plot to see if the VSREF visibility forecast has economic value to his/her application. Of cause, the EV shown here is over a short period. Only EV over a long term can the EV be useful for a practical application. Furthermore, improvements in the ensemble visibility forecast from VSREF, such as improved POD, FAR, ETS, and ROC, etc., can eventually improve the EV. In other words, we hope to have higher EV over a wider range of L/C ratios.

6. Summary and future plan

To support the probabilistic requirement by NextGen, the Very Short Range Ensemble Forecast System (VSREF), as a prelude and a demonstration, has been experimentally developed with minimum computational resources through the time-lagged ensembling technique with 4 finished NAM and 6 finished RUC cycles as ensemble members weighted according to their ages. The VSREF is hourly updated out to 6 forecast hours and includes 11 aviation weather related ensemble products, including icing, clear air turbulence (CAT), ceiling height, visibility, fog, jet stream, low level wind shear (LLWS), convection, simulated reflectivity, freezing level and precipitation type. The products have been visualized and displayed at the NCEP web page for demonstration, which also can be accessed and evaluated by outside users. At this moment, only visibility product has been evaluated with limited data over a shorter period. But the deterministic verification has shown that the performance of the VSREF visibility ensemble forecast depends on selected visibility range thresholds and selected ensemble probability thresholds. The probabilistic verification indicated that the VSREF visibility ensemble forecast is skillful in terms of resolution and has economic values for lower cost/loss ratios. The VSREF products are still in development stage and will be further evaluated and improved by using better algorithms and adding new products in the future. Since RUC has been upgraded to 18 forecast hour length recently, the VSREF will be upgrade to 12 forecast hour length. To increase ensemble membership, the NCEP SREF members will also be tested as part of the VSREF in future. As has been planed, 6 NRRE members based on 3 NMM and 3 ARW cores, hourly updated with 24 forecast hour length, in 10-12km resolution over CONUS will be initiated followed by 6 HRRRE members , each nested within the six NRRE members, in 3km resolution, over CONUS and Alaska domain.

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