APPLICATIONS OF ENSEMBLE PREDICTION - A HISTORICAL PERSPECTIVE

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1. INTRODUCTION

Ensemble prediction has come to the fore as a major focus in the development of operational Numerical Weather Prediction systems and strategies over the past 10-15 years. This was true first in the context of medium-extended range global models and more recently with regard to regional models for shorter range, mesoscale prediction. Perhaps most importantly ensembles have or are becoming recognized as an indispensable tool for operational forecasters and thus have fostered a break with the old paradigm of "deterministic thinking" in the forecast process and products. That is, ensembles have enabled the transformation of forecasting from "model of the day" and single "best guess" forecast way of conducting business to recognizing, acknowledging, and conveying information on the intrinsic, case dependent uncertainties extant in *all* forecasts. It is now generally accepted that ensemble based probabilities and/or measures of confidence hold the best prospect for enhancing the ability for user specific informed decisions.

This paper focuses upon operational *applications* of ensemble prediction systems (EPS) with historical perspective and some thoughts on where the future lies. Because of the now available extensive number of papers, presentations, web sites with operational products (e.g., http://wwwt.emc.ncep.noaa.gov/mmb/SREF/SREF.html) and training vehicles (e.g., http://meted.ucar.edu/nwp.pcu1/ensemble), including abundant examples of various graphical displays and applications**, this paper provides only a brief qualitative overview and, admittedly, largely reflects the personal involvement and experiences of this author.

2. BACKGROUND

The basic premise of EPS is that the forecasting process is stochastic, not deterministic. Because of the chaotic nature of the atmosphere, ever present uncertainties in initial conditions and model formulation dictate there is no single best solution, only an array of possibilities. A particular forecast problem can be viewed as "deterministic" in the traditional sense only if the divergence ("spread") amongst model runs (ensemble members) is sufficiently small to be inconsequential to the user. The spread varies considerably as a function of forecast range, parameter, level, flow regime, location, etc. The greater the spread, the more uncertainty (not necessarily the skill!!) in the forecast. Thus in principle, the degree and nature of the spread provides a priori information on the relative level of confidence in any one or grouping of alternative scenarios, or more explicitly, the full probability distribution (PDF) of possible outcomes. But, not surprisingly, this is much easier said than done in regard to the design, implementation,

and validation of any ensemble strategy - *especially* where tradeoffs are required to accommodate operational schedules and reliability. These issues are discussed in depth elsewhere in this volume, as well as extensively in the literature. The focus here is the major challenge of how to extract, condense, and ultimately convey and use the seemingly overwhelming amount of information generated by the large number of multiple forecasts comprising an ensemble. In this regard it is critical that ensemble products be "user friendly" and tailored to suit particular applications. To accomplish this it is extremely important that *both* developers and users of products be cognizant of how to maximize the value of information on forecast uncertainties into the process of making decisions. This requires appropriate training and education of *both* on the fundamental concepts of ensemble prediction and the objectives of specific applications.

The roots of ensemble based products were provided to a large extent in a seminal paper by Epstein (1971), who showed several graphical depictions of stochastic predictions to illustrate how uncertainty information can enhance the value of forecasts. It was to be almost two decades - when sufficient computer power became available and the basic S&T issues of generating perturbations was tackled - before these ideas could be applied in practice to prospective and actual operational *global* model systems. At that time, there was extreme skepticism that ensembles had any role in short-range, regional model based predictions, largely because the limits of predictability (large uncertainty) were thought to be significant only at medium and longer ranges. This largely reflected a fixation on larger-scale systems as depicted on standard 500 mb height charts. But, it was not long before it was acknowledged that the principles and concepts of ensemble prediction applied to global models were equally relevant to small-scale systems and processes and, most significantly, to sensible weather elements (Brooks, et al., 1995). Today, global and regional model ensemble forecasting are rapidly becoming recognized as integral in a "seamless suite" of products that enable estimates in the forecast confidence/possibilities of specific weather events, first, in the context of the requisite larger-scale circulation pattern at longer ranges and, then, in the details of the relevant weather system in the short range.

The first formal attention to the possibility of *operational* ensemble prediction was at the *Workshop on Predictability in the Medium Range and Extended Range* at ECMWF (1986). However, the problem of post processing and presenting ensemble forecast results was not addressed until the ECMWF workshop on *New Developments in Predictability* (1992), where a listing of recommended generic products was provided. The list largely reflected the input of this author (while at NMC/CPC) and was based on "playing around" in a concept demonstration mode with output from an experimental LAF based ensemble system and utilizing a graphics system certainly crude by today's standards (Versatec paper copy). One of the most recognized and symbolic products of ensemble forecasting, *spaghetti diagrams**, evolved from the work of Fred Sanders' depictions of the life history of mobile troughs (see:http://ams.confex.com/ams/84Annual/techprogram/paper_73069.htm) and first discussed in the literature by Tracton and Kalnay (1993). Spaghetti charts, where a single selected contour of a variable is plotted for each ensemble member, are probably the simplest way for displaying and interpreting information directly from all individual ensemble members. They can be applied readily to a sequence of charts and, thereby, depict the evolution and growth of differences among forecasts in both in space and time

(Fig. 1). The spaghetti charts are just one example of ("KISS") products that Tracton and Kalnay (1993) referred to as "graphical clustering", where one can visually weigh the array of solutions and judge (subjectively) the relative likelihood of specific outcomes in terms of the number of members pointing towards each of the possible outcomes.

3. GENERIC PRODUCT DESCRIPTIONS

Generic products which condense ensemble data include the ensemble mean, spread charts, objective clustering of members similar in some respect, compositing various parameters from each ensemble member (e.g., spaghetti diagrams, storm tracks, "plume" diagrams", and various measures of overall confidence. The most complete expression of the forecast uncertainties is the ensemble based estimate of the full probability distribution (PDF). The earliest and simplest description of the PDF is graphical display of probabilities defined as the percentage of forecasts out of the total satisfying specified criteria ("democratic voting method"), such as the odds for precipitation exceeding some threshold value (Fig. 2). More sophisticated approaches include, for example, fitting the ensemble solutions to some prescribed analytical distribution. In principle all ensemble products can be generated for any model parameter or quantities derived therefrom for any level, region, point ("plumes" ➔ metograms), including vertical profiles. Additionally, one can (and probably should) statistically post process ensemble output to account for model and/or ensemble system biases with regard to some prescribed training period. Each of the products encompasses choices, which are not necessarily mutually exclusive. Some examples are selection of location, parameter, algorithms (e.g., for clustering or post processing), and threshold criteria. The choices in turn depend to a considerable extent on the use of the products. They can range, by example, from an individual "person on the street" deciding whether to carry an umbrella, through an energy company deciding whether to expect changes in demand, to emergency managers deciding whether to deploy snow plows or evacuate some area under threat of flooding. And, no doubt there are a host of additional and/or alternative products not yet conceived or designed for specific applications. Nevertheless, currently available products and those envisioned largely are derivatives, "morphs", or spin-offs of the generic set just described. What has changed most radically over the years is the seemingly exponential growth in graphic capabilities for display, animation, zooming, etc. (Fig.3) in conjunction with the ever increasing power of personal computers, workstations, and hi-speed internet and/or dedicated communication links. Perhaps of most concern now is not the number and variety of ensemble based products, but rather exploiting their separate and/or collective use for maximum value in *both* the public and private sectors

4. CONCLUDING REMARKS

There can be no doubt that ensemble prediction will continue to become a dominant theme in operational meteorology (the "wave of the future"). Its promise and potential has essentially been established. Applications are wide and varied. But, to more fully exploit ensemble prediction it is positively imperative to educate and train forecasters AND users.

At present, (much to my dismay) operational short and medium range forecast product suites remain mostly deterministic - forecasters produce and issue their single best

estimate of the coming weather - even when it is indisputably recognized that the forecast is one of very low confidence. This is not necessarily to say that ensembles are not used. For example - despite extreme reservations and skepticism not too many years ago about the nature and value of ensembles - NCEP's HPC medium-range forecasters almost universally now view the global model based (GFS) ensemble products as essential (James Hoke, personal communication), albeit primarily only for refining their (obligatory) graphical single best guesstimate of the main synoptic features from days 3-7. Also, the HPC days 1-3 predictions are to an increasing extent predicated upon consideration of the more recent operational implementation of the Short Range Forecast Ensemble system (SREF; see references at NCEP/SREF web site). But here too, the primary use of the ensembles is as just one more tool employed to accommodate an apparently inflexible (archaic) requirement of a deterministic product suite. Unfortunately, the problem may actually worsen in the near term (at least within the NWS), as forecasters are constrained to issue single "high resolution" best-guess point forecasts in conjunction with the National Digital Forecast Database (NDFD; see http://www.nws.noaa.gov/ndfd).

The opportunity and challenge here and elsewhere where applicable is to use ensemble products - *at a minimum* - to determine and convey some measure of the degree of confidence in a single best bet forecast. Ideally, that would include or eventually expand to include the relative likelihood of any significant alternative possibilities and, ultimately, to provide an estimate of the full probability distribution. Finally in this new paradigm, human forecasters most certainly (in this author's humble opinion) maintain a crucial role. Forecasters have long evaluated, adjusted, and otherwise tuned a relatively few available model runs ("poor persons' ensemble") on the basis of their experience, knowledge of model biases, capabilities and limitations, and internalized data processing (not amenable to computer algorithms). In the era of ensemble forecasting, similar sorts of skills are (will be) necessary for interpreting output derived from ensembles, for example, probability distributions, cluster populations, and differing scenarios of storm motion and intensification. Perhaps most importantly, such skills are ***essential*** for providing "heads' up" of extreme and or/ significant high impact events.

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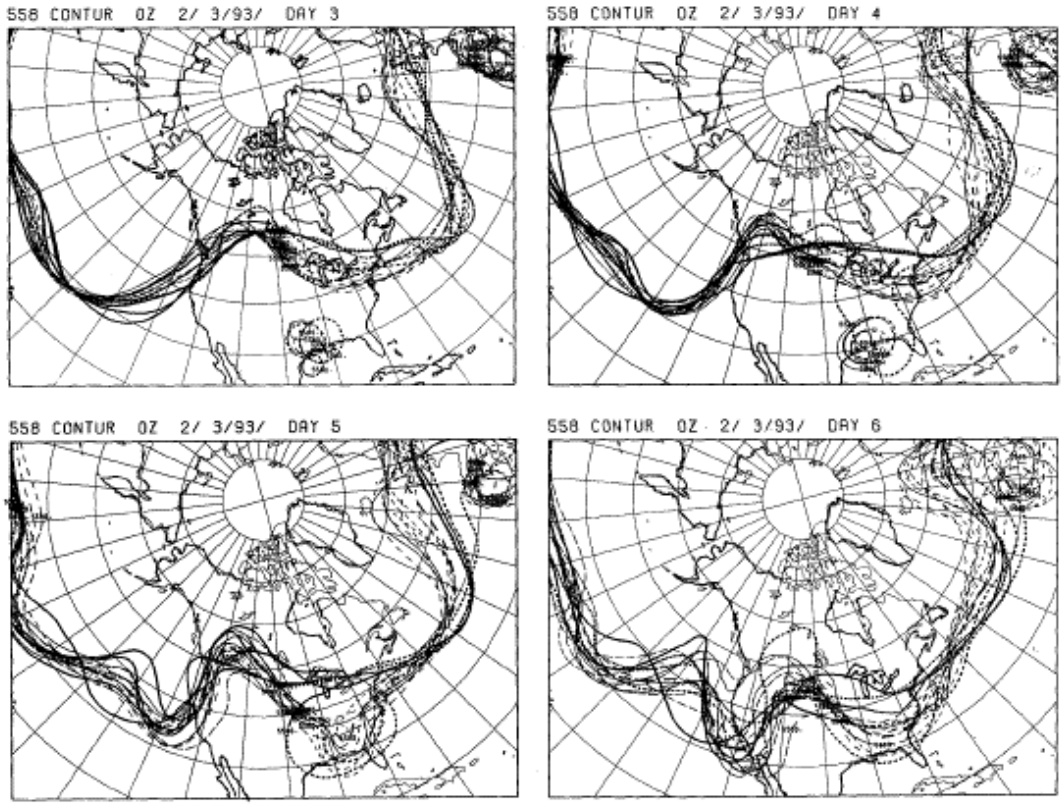

FIG. 12. Fourteen-member composite of the 558-dam contour for days 3, 4, 5, and 6 from 3 February 1993.

Fig. 1. Fourteen member global ensemble composite of the 558 dm contour for days 3, 4, 5, and 6 from 3 February 1993 (from Tracton and Kalnay, 1993)

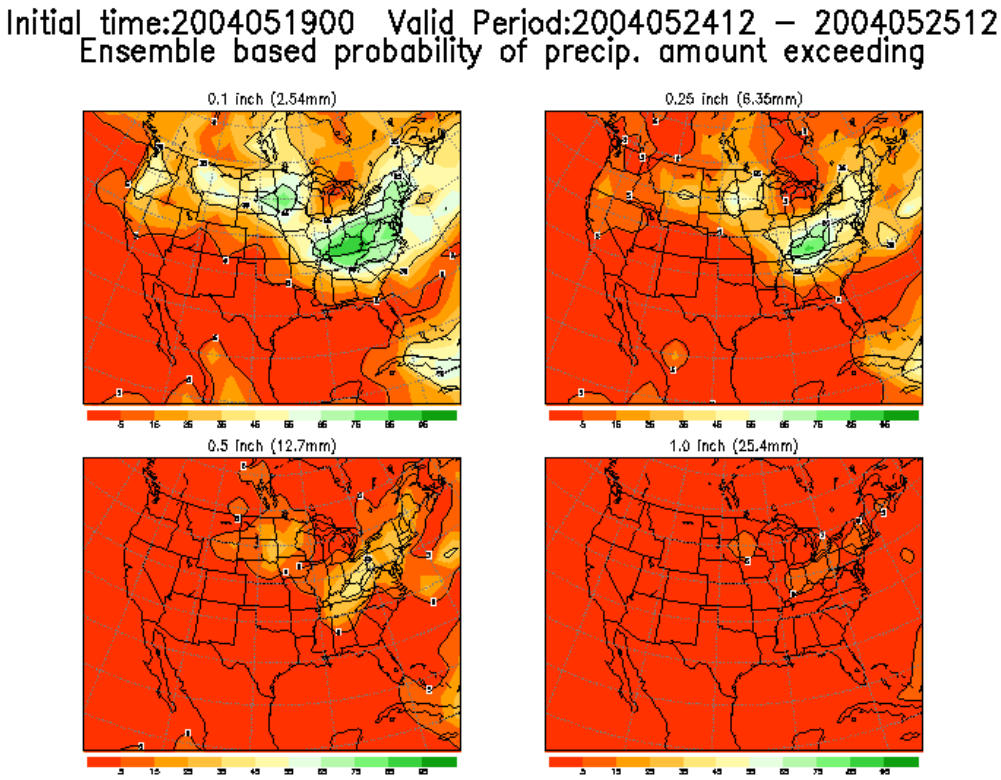

Fig. 2. Example of NCEP global probability of precipitation product
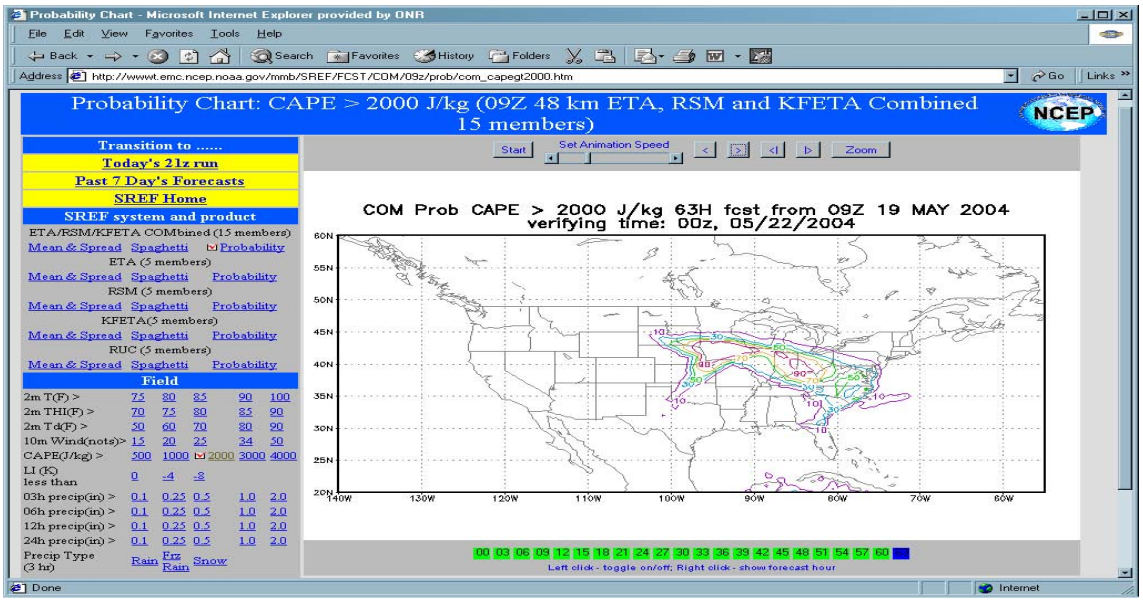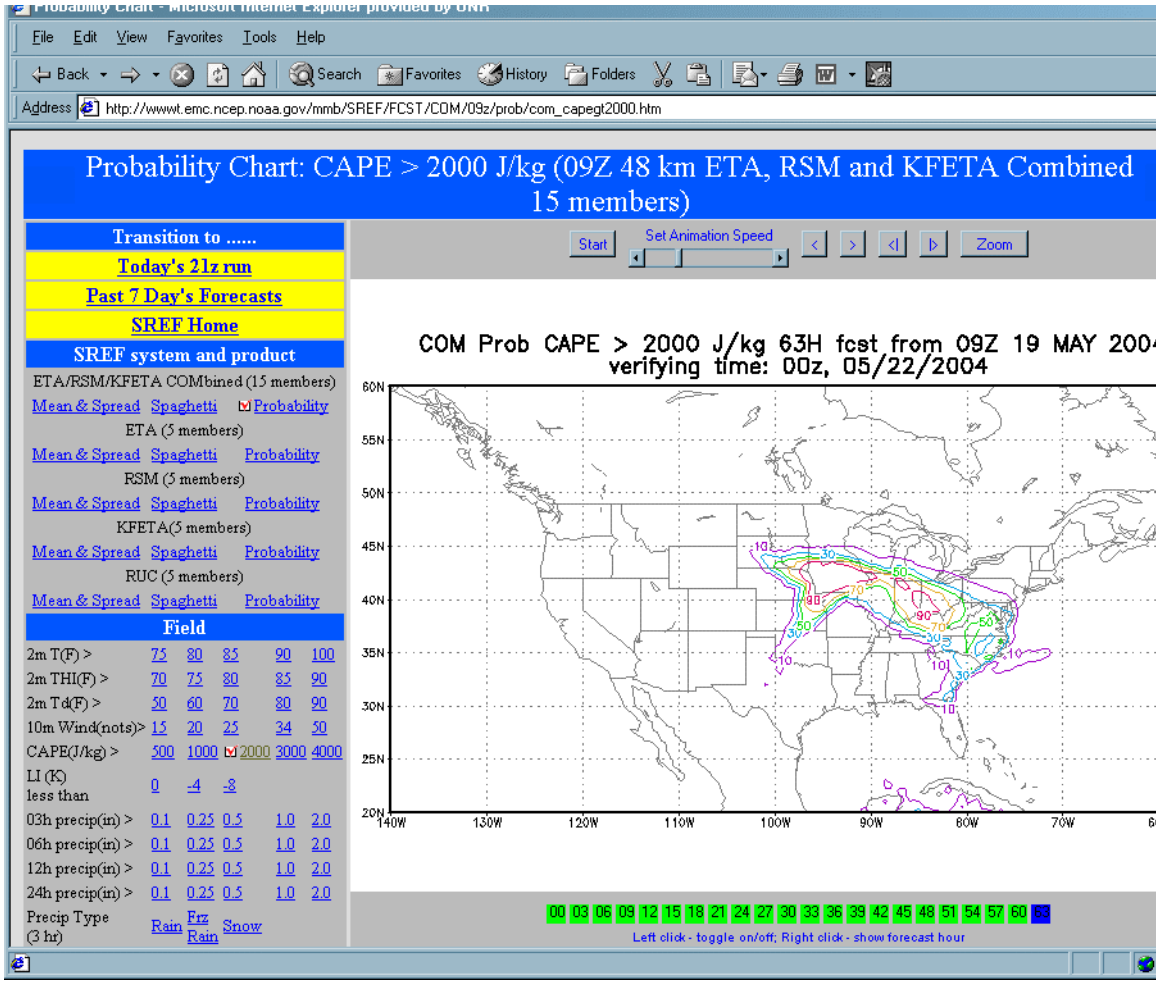
Fig. 3. Example of “state of the art” operational product display from NCEP SREF.