Western Region Technical Attachment
No. 89-32
October 24, 1989

RECENT PROGRESS AND FUTURE PLANS FOR NUMERICAL WEATHER PREDICTION AT THE NATIONAL METEOROLOGICAL CENTER

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[Editor's Note: The following paper was presented at the 12th Conference on Weather and Forecasting, sponsored by AMS, during the first week of October.]

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1. INTRODUCTION

Progress in operational numerical weather prediction is associated with improvements in observing systems, advances in research and increases in the power of computers available for operational use. Major improvements in the global observing system took place in the mid- to late-1970's with the introduction of temperature profiles over the oceans from polar orbiting satellites and cloud-tracked winds from geostationary satellites. The Global Weather Experiment in 1979 provided the necessary impetus and focus for international efforts in development of data assimilation systems to incorporate these new types of data into operational prediction systems (see, for example, Bengtsson, 1984; Bonner, 1986). Numerical prediction research published in the late 1960's and early 1970's had shown the potential for improved numerical forecasts from higher resolution models with more accurate representations of physical processes such as radiation and air/sea, air/ground interactions (see especially Miyakoda et al., 1972). It was not, however, until the introduction of modern supercomputers such as the Cray 1 at the European Centre for Medium Range Weather Forecasts (ECMWF) in 1978 and the CYBER 205 at the U.K. Meteorological Office in 1982 and the National Meteorological Center (NMC) in 1983 that it became possible to exploit the potential of the satellite observing systems and the results of recent numerical weather prediction (NWP) research to realize significant improvements in the skill of operational forecasts.

This paper describes major changes in the NMC numerical guidance system since the introduction of the first of two CYBER 205 computers It documents improvements in the skill of NMC numerical forecasts and describes current NMC plans for numerical prediction systems on next-generation computers. Major portions of this paper are taken from an article scheduled for publication in <u>Weather and Forecasting</u> (Bonner, 1989).

2. RECENT CHANGES IN NMC ANALYSIS/FORECAST SYSTEMS

Since the introduction of the CYBER 205 in late 1983, a number of new or improved analysis/forecast systems have been introduced into NMC operations.

In 1983, NMC numerical forecast systems were limited to the LFM (Gerrity, 1977), the spectral model (Sela, 1980), the Global Data Assimilation System (GDAS) (McPherson et al., 1979), and a special movable fine-mesh model (MFM) for hurricane track prediction. The evolution of this system from October 1983 through January 1989 is summarized in Table 1. The current NMC system is described in Figure 1.

TABLE 1. -- CHRONOLOGY OF MAJOR CHANGES IN NMC NUMERICAL FORECAST SYSTEM.

DATE	CHANGE
OCTOBER 1983	INCREASED HORIZONTAL RESOLUTION OF SPECTRAL MODEL FORECASTS FROM RHOMBOIDAL 30 (R30) TO RHOMBOIDAL 40 (R40) FOR BOTH 0000 AND 1200 UTC FORECASTS.
AUGUST 1984	REPLACED HOUGH ANALYSIS (FLATTERY, 1971) WITH MULTIVARIATE OPTIMUM INTERPOLATION ANALYSIS (BERGMAN, 1979) IN 0000 AND 1200 UTC SPECTRAL MODEL RUNS.
MARCH 1985	INTRODUCED NEW REGIONAL ANALYSIS FORECAST SYSTEM (RAFS) BETWEEN LFM AND SPECTRAL MODEL RUNS (HOKE ET AL., 1989); ADVANCED START TIME FOR LFM TO 1 + 30 (HOURS AND MINUTES PAST 0000 AND 1200 UTC).
APRIL 1985	INTRODUCED NEW MEDIUM RANGE FORECAST (MRF) MODEL (RHOMBOIDAL TRUNCATION, 40 WAVES, 18 LAYERS, GFDL-BASED PHYSICS) WITH LATE DATA CUT-OFF (6 + 00), RUN ONCE-DAILY AT 0000 UTC. R40, 12 LAYER, LIMITED PHYSICS VERSION OF THE MODEL (AVN) RUN TWICE DAILY TO 72 H AT 3 + 30 TO SATISFY AVIATION REQUIREMENTS.
NOVEMBER 1985	INTRODUCED DYNAMICAL MODEL FOR GLOBAL OCEAN WAVE PREDICTION WITH NMC SPECTRAL MODEL WIND FORECASTS AS INPUT.
MAY 1986	REPLACED R24, 12 LAYER, SPECTRAL MODEL IN GDAS WITH R40, 18 LAYER MRF MODEL; IMPROVED PHYSICS IN MRF MODEL (SHALLOW CONVECTION, VERTICAL DIFFUSION).
JULY 1986	INTRODUCED COMPLETELY NEW PHYSICS PACKAGE IN NESTED GRID MODEL (NGM) COMPONENT OF RAFS (RADIATION, SURFACE AND PRECIPITATION PHYSICS; TUCCILLO, 1988).
NOVEMBER 1986	REPLACED R40, 12 LAYER, LIMITED PHYSICS VERSION OF THE SPECTRAL MODEL (AVN) RUN FOR AVIATION PURPOSES WITH THE R40, 18 LAYER, FULL PHYSICS MRF. ALL GLOBAL SYSTEMS (GDAS, MRF, AVN) NOW BASED ON MOST ADVANCED VERSION OF THE SPECTRAL MODEL.
FEBRUARY 1987	DOMAIN OF NGM HIGH-RESOLUTION C GRID EXPANDED AND MODIFICATIONS MADE TO SURFACE STRESS FORMULATION TO IMPROVE FORECASTS OF CYCLOGENESIS IN THE EASTERN PACIFIC AND WESTERN ATLANTIC.
AUGUST 1987	INCREASED RESOLUTION OF GLOBAL FORECAST MODEL (MRF, GDAS, AND AVN SYSTEMS) FROM RHOMBOIDAL 40 TO TRIANGULAR 80; INTRODUCED FURTHER IMPROVEMENTS IN GLOBAL MODEL PHYSICS (DIURNAL CYCLE IN RADIATION, IMPROVED SURFACE FLUXES, VERTICAL DIFFUSION, GRAVITY WAVE DRAG; SELA, 1988, ALPERT ET AL., 1988, KALNAY AND KANAMITSU, 1988).
AUGUST 1987	CHANGED INITIALIZATION PROCEDURES IN THE RAFS (FEWER VERTICAL MODES INITIALIZED TO IMPROVE SPIN-UP OF VERTICAL MOTION AND PRECIPITATION IN THE MODEL) (CARR, ET AL., 1989)
MAY 1988	MODIFIED SEPARATELY-DEVELOPED OPTIMUM INTERPOLATION SCHEMES IN REGIONAL AND GLOBAL ANALYSIS SYSTEMS TO INCORPORATE BEST FEATURES OF EACH. FIRST STEP TOWARDS A SINGLE CODE, WITH VARIABLE PARAMETERS, FOR BOTH REGIONAL AND GLOBAL ANALYSIS.
MAY 1988	IMPROVED FORMULATION OF SURFACE EVAPORATION IN THE GLOBAL MODEL (AVN, GDAS, MRF).
JUNE 1988	REPLACED MFM WITH HIGH-RESOLUTION, QUASI-LAGRANGIAN MODEL (QLM) FOR HURRICANE TRACK PREDICTION (MATHUR, 1983).
AUGUST 1988	INTRODUCED REGIONAL OCEAN WAVE MODEL FOR GULF OF MEXICO FORECASTS WITH NGM BOUNDARY-LAYER WIND FORECASTS AS INPUT.
NOVEMBER 1988	REPLACED ZONALLY-AVERAGED CLIMATOLOGICAL CLOUDS USED IN RADIATIVE FLUX CALCULATION OF THE GLOBAL MODEL WITH DIAGNOSTIC CLOUDS COMPUTED FROM RELATIVE HUMIDITY AND VERTICAL MOTION PREDICTED BY THE MODEL.
NOVEMBER 1988	INTRODUCED NEW INITIALIZATION METHOD FOR THE NGM AS A FIRST STEP TOWARDS REGIONAL ASSIMILATION OF HIGH FREQUENCY OBSERVATIONS (PARRISH, 1989).
JANUARY 1989	ADVANCED START TIMES OF EARLY GLOBAL RUN (AVN) FROM 0330 AND 1530 UTC TO 0245 AND 1445 UTC TO IMPROVE TIMELINESS OF AVIATION WIND FORECASTS.

NMC MODEL RUN SCHEDULE

EARLY RUN (LFM)	
NORTH AMERICA SUCCESSIVE CORRECTION ANALYSIS 7 LAYERS	1 + 10 D = 190 KM (4TH ORDER) T = 48 HRS (TWICE PER DAY)
REGIONAL RUN (RAFS)	
HEMISPHERIC (TRIPLY NESTED) OPTIMUM INTERPOLATION ANALYSIS 16 LAYERS	2 + 00 D = 320, 160, 80 KM T = 48 HRS (TWICE PER DAY)
AVIATION RUN (AVN)	
GLOBAL, SPECTRAL OPTIMUM INTERPOLATION ANALYSIS 18 LAYERS	2 + 45 80 WAVES T = 72 HRS (TWICE PER DAY)
MEDIUM RANGE RUN (MRFS)	
GLOBAL, SPECTRAL OPTIMUM INTERPOLATION ANALYSIS 18 LAYERS	6 + 00 80 WAVES T = 240 HRS (ONCE PER DAY)
GLOBAL DATA ASSIMILATION SYSTEM (GDAS)	
GLOBAL, SPECTRAL OPTIMUM INTERPOLATION ANALYSIS 18 LAYERS	00 UTC : 6 + 00; 06 UTC : 3 + 30 12 UTC : 9 + 00; 18 UTC : 6 + 00 80 WAVES T = 6 HRS (4 TIMES PER DAY)
HURRICANE MODEL (HCN)	
FINE MESH QUASI-LAGRANGIAN MODEL OPTIMUM INTERPOLATION ANALYSIS IDEALIZED VORTEX OF OBSERVED SIZE AND INTENSITY 16 LAYERS	D = 40 KM T = 72 HRS (RUN ON DEMAND)
NOAA OCEAN WAVE (NOW) MODEL	
GLOBAL, DEEP WATER DIRECTIONAL SPECTRUM WIND FORCING FROM 00Z AVN RUN	5 + 00 D = 2.5° X 2.5° 15 FREQUENCIES, 24 DIRECTIONAL BANDS T = 72 HRS (ONCE PER DAY)
GULF OF MEXICO WAVE (GMWAVE) MODEL	
REGIONAL, DEEP AND SHALLOW WATER DIRECTIONAL SPECTRUM WIND FORCING FROM AVN RUN	3 + 15 D = 0.5° 20 FREQUENCIES 12 DIRECTIONAL BANDS T = 48 HRS (TWICE PER DAY)

Figure 1. NMC model run schedule, June 1989. General characteristics are described on the left. Data cut-off times (h + min), horizontal resolution (D) and length of forecast (T) are shown on the right. Data cut-off is the time allowed for receipt of data for a particular model run. See also Petersen and Stackpole (1989).

3. RECENT PROGRESS IN FORECAST SKILL

New systems or modifications described in Section 2 have led to significant improvements in NMC numerical forecast skill. This section presents statistics that document improvements in medium range (3 to 5 day) forecasts, short-range aviation wind forecasts and forecasts of sea level pressure and 500 mb height patterns. Verification scores for NMC precipitation forecasts are presented elsewhere in these proceedings (Mostek and Junker, 1989). Additional verification scores for NMC forecasts are shown, for example, by White and Caplan (1989), Junker, et al. (1989), and Bonner (1988).

3.1 Medium Range Forecasts

Table 2 shows the skill of NMC 5-day forecasts of 500 mb height, averaged for each season since spring of 1983. The parameter verified is the 500 mb height anomaly (difference from climatology). The statistic is the correlation coefficient, for the northern hemisphere extratropics. Notice first the overall increase in skill from 1983 (pre-CYBER 205) to 1988. Wintertime skill increased sharply between 1984/85 and 1985/86 with the introduction of the new Medium Range Forecast (MRF) model in April 1985 (Table 1). Sharp increases occur also between fall 1985 and fall 1986 and between spring 1986 and spring 1987. These appear to be related to the changes introduced into the MRF and GDAS in May 1986 (Table 1). The major gain in winter 1988/89 is most likely associated with the change introduced in cloud/radiation interaction in November 1988 (Table 1). The total gain from winter 1983/84 to winter 1988/89 is nearly equivalent to 2 days of forecast skill.

TABLE 2. ANOMALY CORRELATION COEFFICIENTS, 5-DAY FORECASTS OF 500 MB HEIGHT, 20-80 DEG. N, WAVE NUMBERS 0 TO 12. SEASONAL MEANS SINCE SPRING 1983. LATEST WINTER SCORES SHOWN ARE DECEMBER, JANUARY, FEBRUARY, 88/89.

YEAR	WINTER (DJF)	SPRING (MAM)	SUMMER (JJA)	FALL (SON)
1983	.61	.58	.53	.58
1984	.62	.59	.52	.59
1985	.70	.61	.58	.58
1986	.71	.62	.60	.70
1987	.72	.70	.64	.67
1988	.78	.68	.63	.69
1989				

3.2 Aviation Wind Forecasts

Figure 2 shows root mean square errors of NMC 24-h 250 mb wind forecasts, verified at 102 Northern Hemisphere rawinsonde stations, for the period 1982 through 1988. Note the downward trend in the errors from an average of 10 m sec^{-1} in 1982 to 8.25 m sec^{-1} in 1988. The initial error (fit of the analysis to the rawinsonde data) at 250 mbs is about 5 m sec^{-1}. Using this as a baseline, errors since 1982 have decreased by a third; this corresponds to about a 12-h increase in 24-h forecast skill.

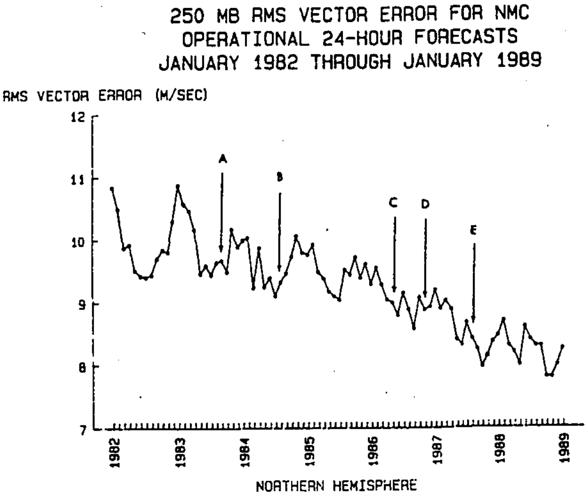

Figure 2. Root mean square vector error of NMC 250 mb wind forecasts, January 1982 through December 1988. Arrows denote months in which the following changes were made (see Table 1): A, resolution of forecast model increased from R 30 to R 40; B, Optimum Interpolation analysis introduced; C, R 40, 18 layer, full physics model introduced in GDAS; D, same model introduced for AVN forecasts; E, resolution of model in GDAS and AVN systems changed from R 40 to T 80.

Because of the general downward trend of the curve and the masking of model changes by month-to-month variations in forecast skill, it is difficult to identify clearly those changes (Table 1) that were most effective in reducing the errors. However, two major changes that appear to stand out are the introduction of the improved global forecast system (MRF) in the GDAS in November 1986, and the increase in horizontal resolution of the forecast model in GDAS and AVN systems in August 1987.

3.3 Short Range Sea Level Pressure Forecasts

Figure 3 shows the annual average errors from 1981 through 1988 of NMC 48-h sea level pressure forecasts produced by the early (AVN) run of the global spectral model. The error measure is the S1 score (Teweles and Wobus, 1954) computed on a 49 point grid centered over the United States. Scores for LFM forecasts during the same period are shown for comparison. The LFM model and its analysis system were frozen in 1983 and scores during the period remain relatively constant. The slight downward trend in error almost certainly results from improvements in the first guess fields for the LFM analysis from improvements in the GDAS (Table 1). Note from Figure 4 that the slight superiority of the LFM in 1981 and 1982 (and previous years, not shown) disappeared in 1983.

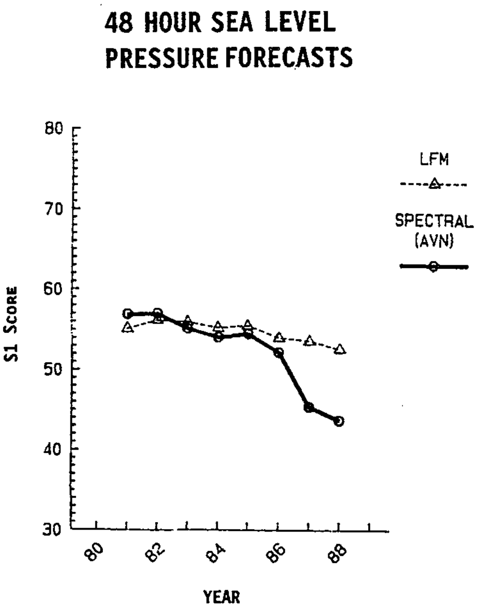

Figure 3. S1 scores for spectral (AVN) and LFM 48-hr sea level pressure forecasts, 1981 through 1988. S1 scores computed on a 49 point grid centered over the United States.

Figure 4 compares the LFM and spectral model scores in a somewhat different way, showing the difference in S1 score (LFM-Spectral) averaged for each month from January 1986 through December 1988. The introduction of the full physics version of the spectral model into the AVN run in November 1986 (see Table 1) produced a dramatic improvement in S1 scores between 1986 and 1987 (Figures 3 and 4).

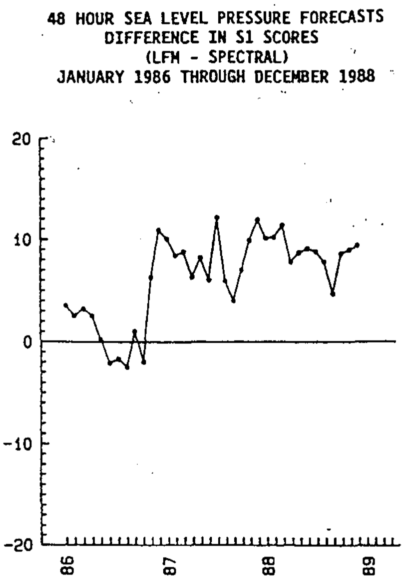

Figure 4. Relative accuracy of spectral (AVN) and LFM 48 hour forecasts of sea level pressure expressed as the difference (LFM-Spectral) in monthly-averaged S1 scores from January 1986 through December 1988. Positive values indicate lower S1 scores (better forecasts) from the spectral model.

3.4 Long Period Trends in NMC 36-h Forecasts of 500 mb Height

Figure 5 shows the annual average errors (S1 scores) of NMC 36-hr 500 mb height forecasts from 1955 through 1988. Notice that the sharp downward trend in error since 1983 is preceded by at least 3 similar periods. The first (1955-1959), corresponds to the acquisition of IBM 701 and 704 computers and the beginning of operational numerical weather prediction. The second and third (1966-1971 and 1975-1980) follow the introduction of CDC 6600 and IBM 360/195 computers at NMC. Little or no reduction in error takes place near the end of the life cycle of each major computer system (e.g., 1972-1975) and 1980-1983).

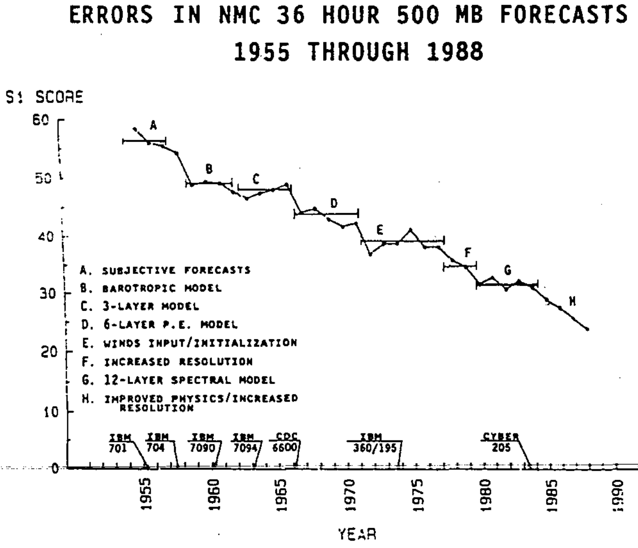

Figure 5. Errors (S1 scores) of NMC 36-hr 500 mb height forecasts from 1955 through 1988. The sequence of NMC computers and dates of introduction are shown at the bottom. Horizontal bars denote representative scores associated with various model improvements. See also Shuman, 1989.

4. FUTURE PLANS

The NMC CYBER-205 computers that made possible the major advances in numerical prediction at NMC in the mid to late 1980's are now nearly saturated. We have almost fully exploited the potential of these computers for improvement in prediction models. Small gains can be made over the next year. However, major progress at NMC awaits the next generation of computers. We assume that such computers will become available by about 1991.

New observing systems are planned, as well, for the 1990's. Improved sounding systems on NOAA-K, L, and M should increase the accuracy of satellite- derived temperatures, improving especially the ability of these systems to derive soundings with higher vertical resolution in partly cloudy and cloudy areas. Perhaps the major revolution expected in the 1990's involving observations for numerical weather prediction is the introduction of mesoscale observations over the conterminous United States from doppler radar (NEXRAD), wind profilers and aircraft observations. Emphasis on global data assimilation during the 1970's and 1980's will continue, but a major new challenge lies in the development of systems for the use of high time resolution observations over the United States in global and regional data assimilation and forecast systems.

Requirements will continue to exist for medium range weather forecasts to the limit of useful predictive skill, for short range global forecasts of temperature and wind for international flight planning, and for short range weather forecast guidance for local forecasts and warnings. Thus, NMC will continue to run systems providing guidance for different purposes. The major change in NMC thinking in this regard is the realization of the need to move from an independent model to a modular approach, making individual components of systems as similar and interchangeable as possible. This type of configuration is much more economical to maintain and will facilitate greatly the test of new ideas.

Let me now speculate on the NMC numerical prediction system on next generation computers.

4.1 Global Model.

More powerful computers will allow us to increase the horizontal resolution of the global spectral model from triangular 80 wave (roughly 160 km. equivalent) to perhaps triangular 160 wave (80 km. equivalent). The number of vertical levels will be increased from the current 18 to as many as 30. Each doubling of the 3 dimensional resolution of the model requires a factor of 16 in computer power. Thus, resolutions actually achieved will depend very much on the power available in next generation machines. Improvements to the model physics will continue to be introduced, especially with respect to the biosphere/atmosphere interactions that determine the fluxes of heat, moisture, and momentum between the atmospheric boundary layer and the land.

The model will be run 4 times daily to provide aviation wind forecasts and automated updates. Once per day runs to 15 days will provide daily forecasts to 7 days, "week two" guidance for extended range forecasts and estimates of forecast skill (Kalnay and Dalcher, 1987) from the consistency of successive forecasts valid on the same day.

4.2 Regional Model.

Plans are to continue to improve the NGM model through 1989. By January of 1990, we plan to freeze further development of this model. Development of model output statistics (MOS) based upon the RAFS is already well underway, and by 1992 it is expected that a full set of MOS products, similar to that available now on the LFM, will have been developed and implemented for RAFS (Carter et al., 1989). The RAFS system, developed for the CYBER 205 computers, will become the LFM of next generation machines and will provide the continuity and stability required through the transition to new computers.

4.3 Mesoscale Model.

We would like to introduce, on next generation computers, a high resolution model for mesoscale guidance. The model would be run on demand to perhaps 18 or 24 h, as often as 4 times per day. The purpose of this "Storm Model" would be to provide detailed guidance on the evolution of precipitation patterns, low level winds and parameters such as moisture convergence and stability indices related to severe convective weather. It could be run, for example, for hurricanes threatening coastal areas of the United States, for major convective outbreaks, for large-scale floods or major winter storms. We would expect that the hurricane and "storm" models would be essentially the same but with special analysis and initialization procedures required for hurricane track prediction. The anticipated horizontal resolution of the model, on next generation computers, is about 30 km, with 30 or more vertical levels.

It seems likely that beyond about 1995, NMC numerical weather prediction systems will be limited to a high resolution global model and a mesoscale or Storm model. Statistical forecast guidance would be based upon global model runs. Output from the mesoscale model would include detailed regional maps, time sections at various locations and gridded fields from which forecast soundings, time sections, and cross sections could be constructed. We would not envision the development of statistical output from the mesoscale model.

4.4 Global Data Assimilation.

The Global Data Assimilation System (GDAS) on next generation computers will be based upon the global forecast model described in 4.1. We anticipate that the GDAS will continue to use optimum interpolation analysis with non-linear normal model initialization and that a 6 or perhaps 3-h forecast cycle will be appropriate for the global forecast problem. Work is underway on more sophisticated techniques, for example adjoint methods (Lorenc, 1988; Derber, 1989); however, the computer time required for such techniques may delay their implementation in the GDAS to a following generation of computers in the late 1990's.

4.5 Regional Data Assimilation System.

By mid-1990 we expect to implement an optimum-interpolation-based Regional Data Assimilation System (RDAS) capable of handling wind observations from the Profiler demonstration network across the central United States. This initial version of the RDAS will be similar to the current GDAS but with a 2 or 3 hour forecast cycle. It will feed off the global system and provide the initial start up for current regional and future storm models. By 1993 we expect to have developed a more sophisticated RDAS based upon some form of continuous data assimilation. Development of such a system will be essential in order to take full advantage of the new observing systems expected in the 1990's and to provide the appropriate model spin-up for short-range precipitation forecasting.

4.6 Climate Data Assimilation System.

Global analyses produced by the NMC GDAS or a similar system at ECMWF are becoming increasingly important tools for monitoring of global climate. There is a problem, however, in that the goals of global data assimilation, providing first guess fields for operational forecasts and providing climate information, often conflict. The global data assimilation system must be run early enough each day to provide first guess fields by the time a forecast must be made. Thus, the collection of data for these analyses is often incomplete. Second, improvements are made frequently in the GDAS in order to capture even small improvements in forecast accuracy. Changes in the analysis scheme may introduce changes in climate statistics that are not real and represent only the effects of changing the way in which the analysis is done. By about 1993, NMC plans to introduce a special assimilation system for climate purposes. This system would not run under operational time constraints. It would not be changed without prior testing of the effects of the proposed change on important climate statistics. This is a new responsibility for NMC, supported by the NOAA Climate and Global Change program and consistent with the mission of the NMC Climate Analysis Center.

4.7 Wave Models.

Wave models, developed by the joint Ocean Products Center (OPC) and run by NMC will continue to be improved on next generation computers. More accurate weather forecast models will provide better estimates of the surface frictional stress for generation of waves. Satellite-based surface wind and wave height estimates will improve initial conditions for wave models and permit more representative verification of forecasts. Work is underway within the OPC on development and testing of so-called "third generation" wave models for both regional and global prediction.

4.8 Extended Range Forecasts.

Numerous experiments have shown the potential of general circulation models to predict time-averaged features of the flow for periods well beyond the limits of day-to-day predictability (Shukla, 1981; Miyakoda et al., 1986). Forecasts beyond 10 days show significant skill in certain situations (Tracton et al., 1989). The problem in this case is not simply to make a forecast but to assign to that forecast some probabilistic level of skill. NMC has recently begun to extend its 10 day forecasts to 15 days twice each month as an experimental tool for 30 day forecasts. By 1992 we expect that the major component of 30 day forecasts will be extended dynamical model runs. For seasonal prediction and longer, the most promising approach appears to be the use of coupled ocean/atmosphere models in which ocean surface conditions do not simply drive the atmospheric models, but are affected by them as well. We would expect by the mid 1990's to be making experimental seasonal predictions based upon the output from coupled ocean/atmosphere models. This is clearly an important topic for research with next generation computers. Implementation of routine extended range forecast runs with coupled ocean/ atmosphere models will depend upon the results of this research and upon available computer power.

5. CONCLUDING REMARKS

We know the general characteristics of future observing systems because of the long lead times required to plan for, budget, develop and implement such systems. Continued advances in the power of supercomputers are predictable at least through the 1990's. We can anticipate, to some degree at least, national priorities such as the emphasis on climate and global oceans that will effect NOAA, NWS, and NMC priorities. We cannot predict funding and it is difficult to predict the results of research. These are the major uncertainties in the scenario presented in section 4.

Continued progress in numerical prediction skill at NMC depends not only on research and development efforts within NMC but upon progress in numerical prediction in general and upon the interest and ability of scientists at laboratories and universities to work with NMC in translation of their research into NMC operations.

In recognition of the need to involve scientists from the research community more actively in its programs, NMC established in 1984 a visiting scientist program through the University Corporation for Atmospheric Research (UCAR). The program is open to senior scientists, recent Ph.D.'s and graduate students working on doctoral degrees. A second program, established jointly with the National Science Foundation, seeks both to support academic research in numerical weather prediction and to foster cooperative research involving the use of NMC facilities and collaboration with NMC scientists by university faculty and graduate students (see program announcement, Bul. Amer. Meteor. Soc., August 1987). These two programs plus enhanced participation by NMC scientists in national and international programs and working groups have played and will continue to play important roles in providing the broad influx of new talent and new ideas that is essential to NMC progress. The development of more "user-friendly" systems for development and test and evaluation at NMC and the change to a more modular, standardized form for forecast model development (Kalnay et al., 1989) can only enhance the productivity of visiting scientists and the ability of NMC to test forecast system components developed at universities, laboratories, and other forecast centers.

I would like to make one final point. Those of us close to numerical prediction have tended over the years to think of the computer revolution only in terms of supercomputers. There is another revolution going on that may be of equal importance. That is the development of powerful work stations and interactive display capabilities that will allow forecasters access to the full range of predictive fields that modern prediction models, run on supercomputers, can produce. It may be that the most dramatic improvement in the utility of NMC forecasts in the 1990's will come as much from improvements in the ability to display forecasts of clouds and precipitation as well as humidity, wind and temperatures in time sections, cross sections, or animated maps (Plummer, 1989) as from improvements in the accuracy of the models. This kind of display capability will be an absolute requirement to capture the information available from future mesoscale models.

6. ACKNOWLEDGMENTS

I would like to express my thanks to the many NMC researchers and visiting scientists responsible for the progress described in this paper. Plans for new NMC systems in the 1990's were developed in consultation with Eugenia Kalnay and Development Division staff.

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