GLOBAL NUMERICAL WEATHER PREDICTION AT THE NATIONAL METEOROLOGICAL CENTER

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1. INTRODUCTION

During and after the Global Weather Experiment in 1979, major advances in the skill of global numerical weather forecasts have been made by operational centers, pioneered in many cases by the European Center for Medium Range Weather Forecasting. Advances have resulted from improvements in the global observing system, from applied research and from increases in the power of computers used for operational prediction.

In this paper we review the operational global analysis and prediction system at NMC, recent improvements, the performance in medium and extended range forecasting, and current areas of research. Additional information, including the status and plans for regional forecasting is presented in Bonner (1989).

2. DESCRIPTION AND RECENT OPERATIONAL IMPLEMENTATIONS

In this section we briefly describe the NMC global analysis and forecast system, discuss the changes that were introduced in the last few years, and present results from the quality control system for rawinsonde temperatures and heights that became operational in January 1989.

2.1 Description of the Global Numerical Weather Prediction System

a) Global Data Assimilation System (GDAS):

The NMC Global Data Assimilation System (GDAS) provides initial conditions for the 3-day Aviation and the 10-day medium range forecasts (Kanamitsu, 1989). In this system, a 6-hour forecast from the MRF model (described below) provides a first guess to the next analysis. The first guess is interpolated to the observation locations on mandatory pressure levels, and "observational increments" are then computed and quality controlled. A 3-D multivariate Optimal Interpolation analysis of the increments of heights and winds, and a univariate analysis of relative humidity are performed on pressure surfaces (DiMego, 1988). The analysis increments are then interpolated back to model levels. A diabatic initialization is then performed, using the non-adiabatic terms obtained from integrating the model for 7 steps. Only the first four vertical modes of the model, and only those gravity waves with a period shorter than 48 hours are initialized. This provides the initial conditions for the next cycle, as well as for short and medium range forecasts. It should be noted that the data cut-off for the global aviation forecasts is only 2 hours and 45 minutes after 0 and 12 GMT, whereas for the final analysis for the 00 GMT 10-day forecast, the data cut-off time is 6 hours.

b) Medium Range Forecast Model (MRF)

The model used for the global analysis (GDAS), the 3-day aviation forecasts performed twice a day at 00Z and 12Z, and the daily 10-day forecasts is the MRF model (Sela, 1988). The model is spectral (since 1980), has a horizontal triangular truncation of T80, corresponding to a (gaussian) grid size of 1.5 degrees or 160 km, and 18 vertical levels, the lowest one located about 5 mb above the surface.

The model has a complete set of physical parameterizations, fully documented in NMC Development Division Staff (1988). It includes Kuo-type of convective heating and large scale precipitation, as well as evaporation of falling raindrops. The boundary layer physics (developed by GFDL and modified by NMC) is based on Monin-Obukhov similarity theory. Vertical diffusion of heat and moisture due to shallow cumulus convection is based upon Tiedke (1983). Short-wave radiation is computed following Lacis and Hansen (1974), and the long wave radiation was developed at GFDL by Fels and Schwarzkopf (1975). Ozone and carbon dioxide are obtained from climatology, and the surface albedo and soil moisture are initialized from climatology but updated from the forecast of snow cover and precipitation. The model orography is enhanced using a "silhouette" (highest peaks) definition (Mesinger et al., 1988).

2.2 Recent Changes

The following changes have been implemented in the NMC global system during the last 3 years:

1. May 1986: The MRF model with comprehensive physics was introduced into the GDAS. The vertical resolution of the model was increased near the surface and shallow cumulus convection was introduced.

2. November 1986: The MRF with comprehensive physical parameterizations was introduced into the aviation time slot (twice daily runs to 72 hours with a data cut off of 3 h, 30 m).

3. August and September 1987: The horizontal resolution was increased from rhomboidal truncation R40 to T80 (Sela, 1988). Improvements were made in the surface fluxes and vertical diffusion time schemes (Kalnay and Kanamitsu, 1988). A diurnal cycle and drag due to mountain generated gravity waves were introduced (Alpert et al., 1988). The moisture carrying layers were extended from 12 to 18.

4. May 1988: The Optimal Interpolation scheme in the GDAS was partially unified between the regional and global systems (DiMego, 1988). Ship wind data were no longer

geostrophically corrected in the analyses. An improved formulation of surface evaporation was implemented (Pan, 1988).

5. December 1988: Better error estimates (reducing the error of conventional data and of the model first guess) were introduced in the analysis. The error levels are much more realistic, especially in the tropics. In the radiation scheme, the model zonally symmetric clouds were replaced by model diagnosed clouds following Slingo (1987). The horizontal diffusion of the model was reduced, and the zonal advection of vorticity and moisture were made semi-implicit, allowing for a larger time step (Simmons et al., 1978).

6. January 1989: Data cut-off was reduced from 3 h, 30 m to 2 h, 45 m in order to speed up the reception of the aviation forecasts over the GTS. Also, in January new quality control systems for rawinsonde temperature and height observations (Gandin, 1988; Collins and Gandin, 1988) were implemented (described in the next subsection).

7. August 1989: The MRF model was restructured in order to separate the hydrodynamics from the physics (Sela, 1989). This reduces the present memory requirements, and in principle allows the possible use for the physics of a different gaussian grid than that used for the hydrodynamics. For reasons not well understood, this splitting method also resulted in some reduction of the systematic cooling error of the model.

2.3 Quality control

a) Rawinsonde Heights and Temperatures

A Comprehensive Hydrostatic Quality Control (CHSQC) of rawinsonde data on height and temperature of mandatory isobaric surfaces has been designed (Gandin,1988, Collins and Gandin, 1988, 1989). The CHSQC approach is different from that used in existing methods of hydrostatic check by the fact that several residuals of the hydrostatic equation are jointly applied by the Decision Making Algorithm (DMA) to diagnose and correct when possible erroneous information. To achieve this aim, the DMA applies existence and magnitude criteria for each error type and performs the search of simple corrections.

After extensive testing, the CHSQC was implemented into operations in January 1989 and is now applied to all rawinsonde reports (parts A and C) received at NMC. All confident corrections are performed automatically. For some reports, the CHSQC proposes two or more possible decisions of how to correct erroneous data but is unable to choose among them until other CQC components are added. These proposals are automatically submitted to Meteorological Operation Division specialists who make their decisions. Regular monitoring of the CHSQC performance is done based on automatically produced daily and monthly summaries. Information of this kind is also forwarded to other Centers.

Statistics obtained in the course of the CHSQC monitoring are presented in Table 2.1. They are averaged over six months, January-June 1989, and also over comparatively large regions in order to make the statistics more representative. The following main conclusions may be drawn from these data:

1. About 8 percent of rawinsonde reports obtained at NMC contain at least one hydrostatically detectable error each, and about a half of them is confidently corrected by the CHSQC alone.

2. An overwhelming majority of these errors originate on communication lines and are caused by human intervention in the communication process. Computation errors caused either by human intervention or by some shortcomings in data decoding and processing codes produce a comparatively small number of errors. The numbers of errors for countries using completely automated processing and communication systems is very small.

3. Although the absolute numbers of errors are high for countries with vast territories (particularly, USSR, Continental China and India,where about one half of all errors originate), the relative numbers are substantially higher over other regions, such as Indochina, Africa and South America, as well as in India. It is particularly important to correct erroneous data from these data sparse regions.

4. Some regions, like India, the Pacific Islands and Indochina, produce many reports containing several errors each, which suggest perhaps lack of experience and/or training of the personnel involved.

An improved CHSQC version, capable of correcting errors at two adjacent levels and better expandable by including statistical interpolation checks, has been implemented on June 28, 1989.

Table 2.1 Six months of CHSQC performance statistics

Numbers of detected errors per ob. time	number	percent
overall	52.5	100
confident height corrections	14.5	27.8
confident temperature corrections	11.2	21.6
two-alternative corrections (output for MOD)	9.3	18.1
other types	17.5	32.5

Percentage of reports containing detected errors, R_1, (number of detected errors divided by the number of reports) and percentage of confidently corrected errors, R_2, (number of confidently corrected errors divided by overall number of detected errors) for some regions.

Region	WMO blocks	R_1	R_2
Western Europe	1-4,6-8,10,16	2	62
Eastern Europe, Turkey	9,11-13,15,17	7	59
USSR	20-38	6	58
Near East	40-41	8	45
India	42-43	31	33
Mongolia	44	22	55
Hongkong,Taiwan,Korea,Japan	45-47	4	62
Indochina	48	24	42
China	50-59	8	55
Africa	60-63,65,67	17	45
USA	70,72,74	0.6	42
Canada	71	1	41
Central America	76,78	10	52
South America	80-87	17	49
Antarctica	89	4	54
Pacific Islands	91,96-98	12	41
Australia and New Zealand	93-94	9	60

b) Aircraft Winds

A new quality control and super-observation algorithm for aircraft winds which should be implemented in September 1989 is briefly summarized here. It is based on two principles: (1) the quality control is done by considering unique features of the aircraft wind reporting system, and (2) the algorithm uses full-field values. It a) applies consensus-type quality decisions at those navigation check-points where 3 or more reports are collected within a six-hour time block, b) creates super-observations when appropriate, preserving information on wind variations with time and altitude, and, c) appends a series of hierarchical quality marks depending upon the degree of consensus information (Julian, 1988, 1989)

3. EVOLUTION OF THE GLOBAL SYSTEM PERFORMANCE

In this section we present a few statistics on the evolution of the forecast skill of the NMC global forecast system.

3.1 GDAS

One measure of the performance of the GDAS in representing the "correct" initial state is the magnitude of the errors in each 6-hour forecast as determined from comparisons with radiosonde observations. This statistic has been maintained at NMC since the introduction of the GDAS in late 1977. Figure 3.1 shows monthly values of rms errors in 6-hour forecasts of 500 mb height from September 1977 through December 1988 -- for Northern and Southern Hemispheres separately. Comparisons are based upon 31 selected rawinsonde stations in the Southern Hemisphere (see Bonner et al., 1986) and 102 Northern Hemisphere stations. In both hemispheres, the

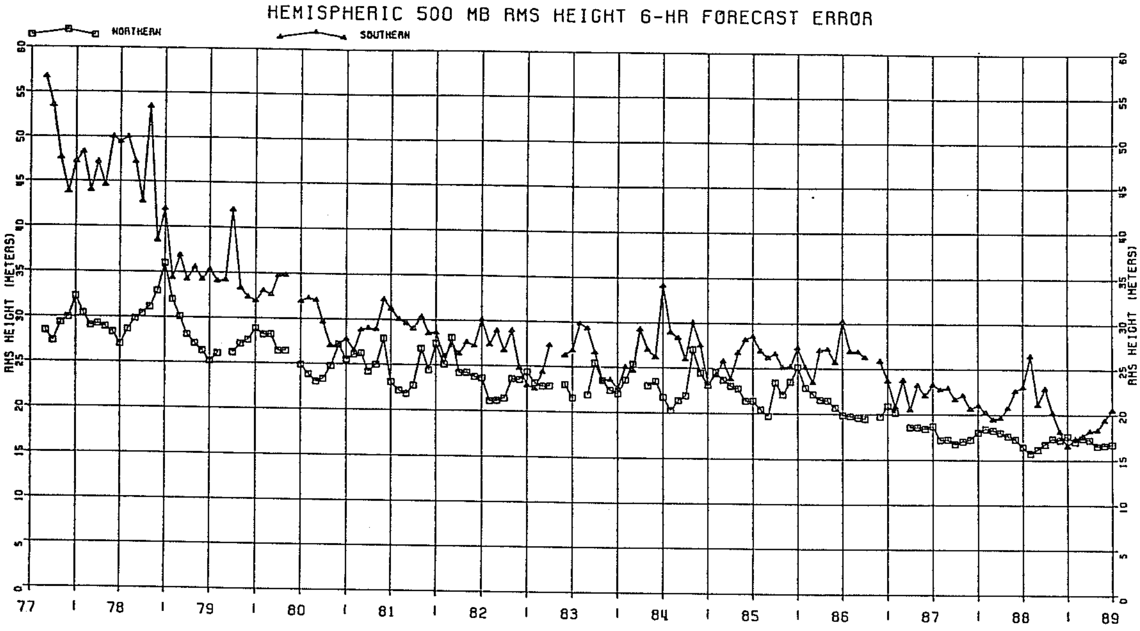
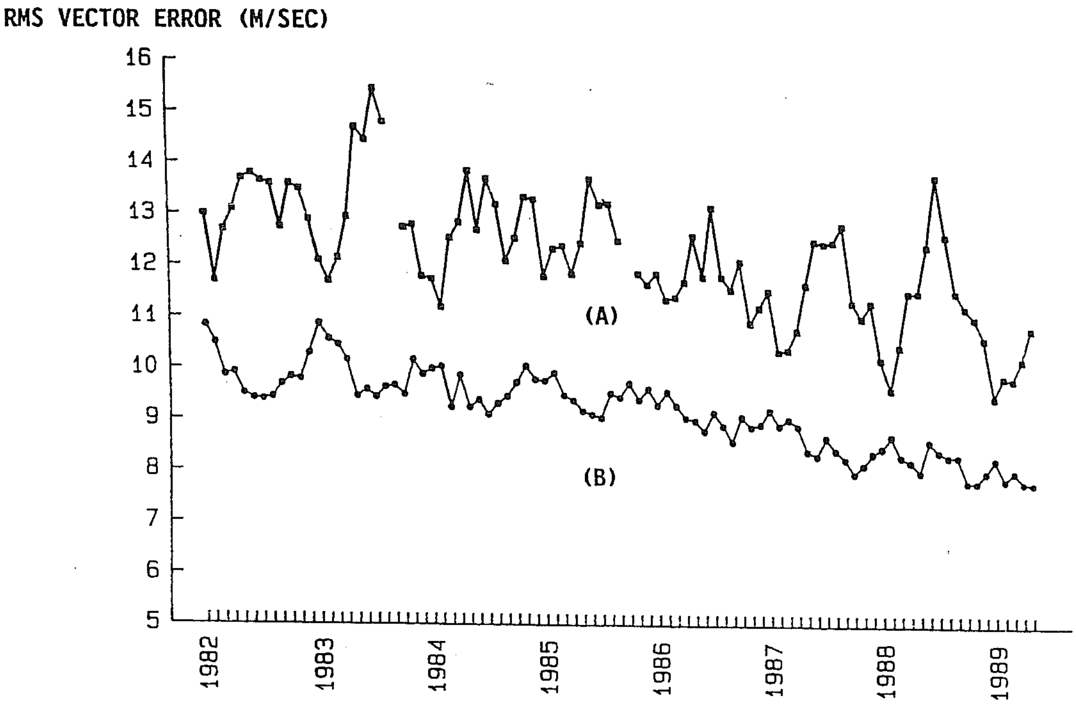


Fig. 3.1. RMS fit of the 6 hour 500 hPa forecast to 102 Northern Hemisphere rawinsondes. Top curve: Southern Hemisphere. Bottom curve: Northern Hemisphere.

Fig. 3.2. **250 MB RMS VECTOR ERROR FOR NMC OPERATIONAL 24-HOUR FORECASTS JANUARY 1982 THROUGH MAY 1989**



errors decrease with time. A major reduction in Southern Hemisphere errors took place in late 1978 with the introduction of a new global data assimilation system based on optimal interpolation (McPherson et al., 1979). Other significant improvements occurred in early 1980 with the introduction of the NMC spectral model into the GDAS and in mid-1986 with the change from a low resolution (R24, 12 layer) version of this model to a higher resolution (R40, 18 layer) with more comprehensive physics (section 2). The improvements from the changes implemented from 1987 to 1989 are also very apparent.

3.2 Short Range Wind Forecasts

Figure 3.2 shows monthly values of the rms vector error of NMC 24-hour aviation forecasts of 250 mb wind. As in Figure 1, forecasts are verified against observations at 31 Southern Hemisphere and 102 Northern Hemisphere stations. There has been a steady improvement in the Northern Hemisphere, from about 11 m sec^{-1} in 1982 to less than 8 m sec^{-1} in 1989. In the Southern Hemisphere the improvement takes place mostly in the summer, whereas the winter errors are more variable.

3.3 Medium-Range Forecasts

Figure 3.3 shows the winter (DJF) anomaly correlation from 20 N to 80 N using zonal wavenumbers 0 to 12, and for all the winters from 1980/81 through 1988/89. It is apparent that for short range forecasting the progress has been rather steady, while for medium range it has been more variable. The first four years show little improvement with time, 1985/86 through 1987/88 are considerable better, and 1988/89 is clearly the best. Although the overall improvement must be associated with the changes of the systems, part of the variability may be due to interannual variability in the atmospheric predictability. Figure 3.3 shows the time at which the anomaly correlation of the forecast crosses 60%, as well as the times a persistence forecast crosses 60% and 40%. The large improvement in 1988/89 may have been partly due to the more persistent nature of the flow.

4. DYNAMIC EXTENDED RANGE FORECASTING EXPERIMENTS

In this section we consider experiments that explore the use of the model for dynamical predictability beyond 10 days. We first review the systematic characteristics of the NMC model climatology as shown in a one year integration of a T40 model. Then we discuss results from an extensive winter Dynamic Extended Range Forecasting (DERF) experiment performed during the winter of 1986/87, and finally some recent experiments performed for the period of the North American drought of 1988.

Fig. 3.3

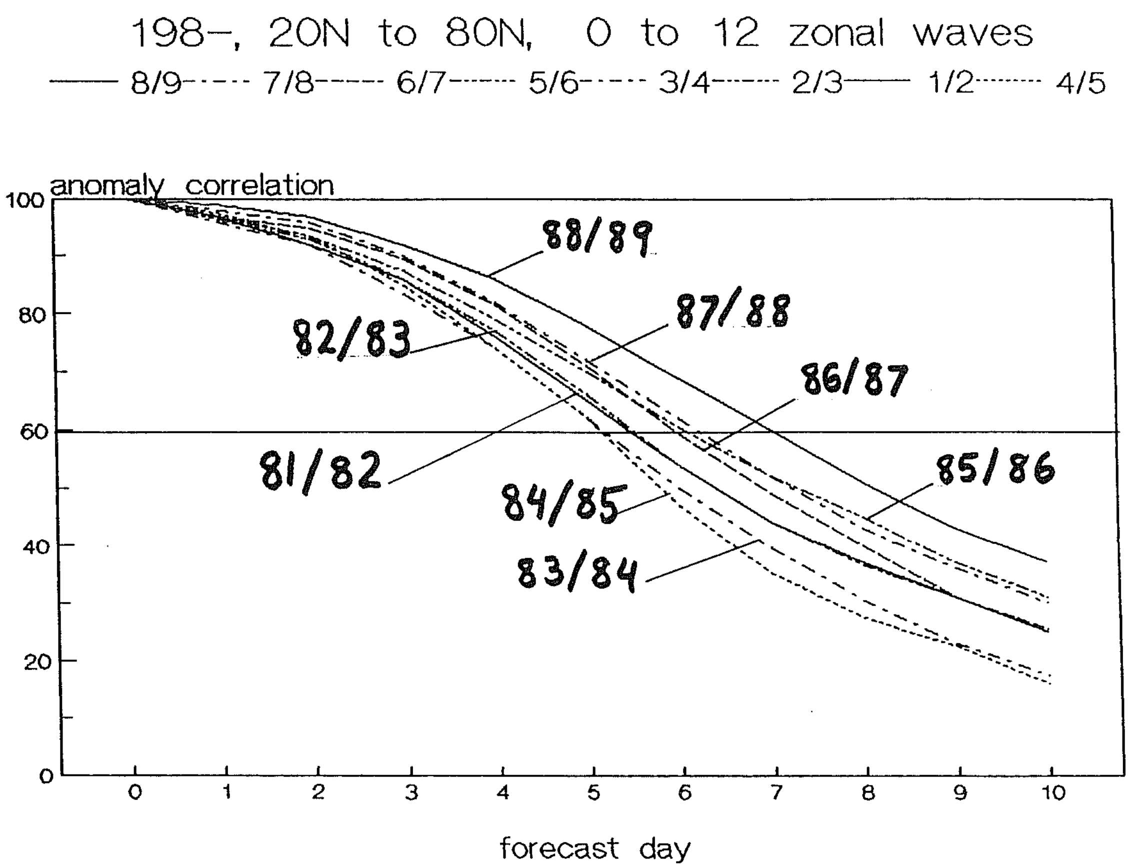
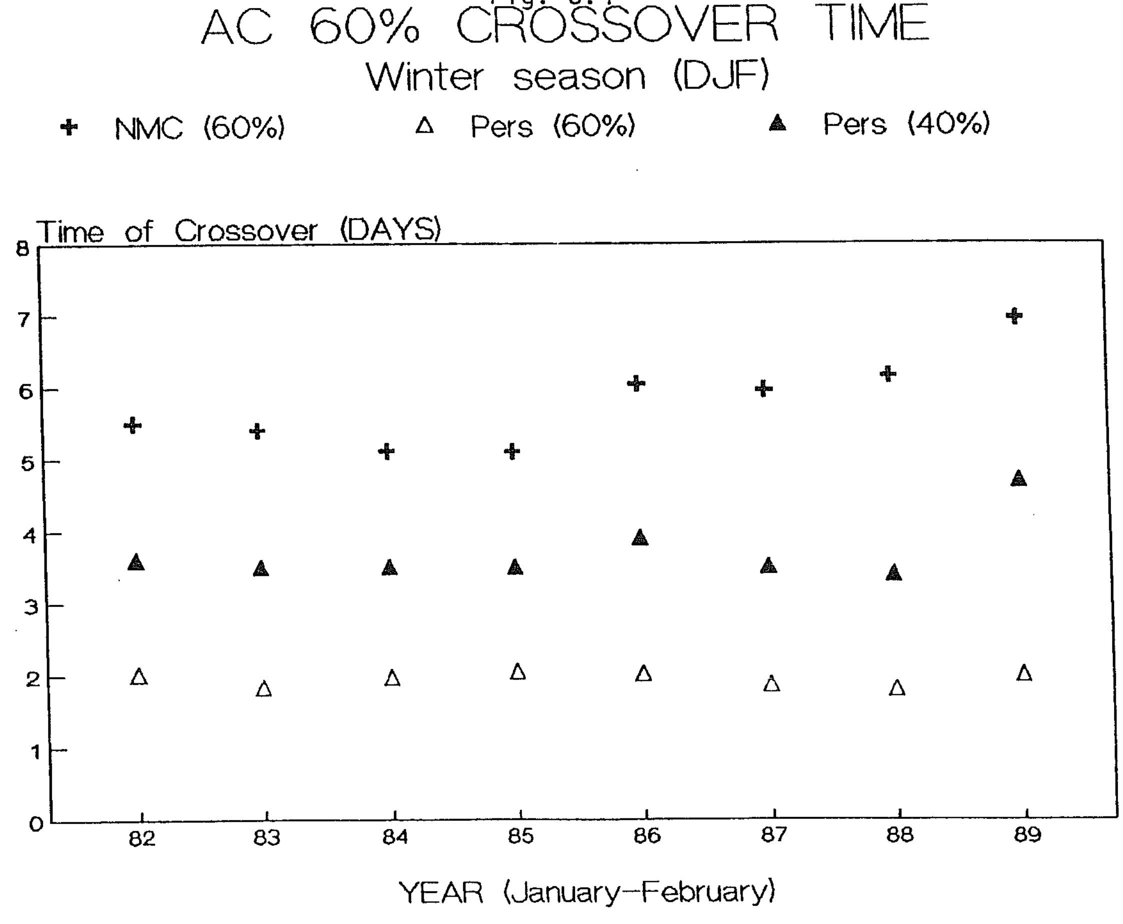

WINTER ANOMALY CORRELATIONS DJF
198-, 20N to 80N, 0 to 12 zonal waves
8/9
7/8
6/7
5/6
3/4
2/3
1/2
4/5
anomaly correlation
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
forecast day
88/89
87/88
82/83
86/87
81/82
85/86
84/85
83/84

Fig. 3.4


AC 60% CROSSOVER TIME
Winter season (DJF)
+ NMC (60%)
△ Pers (60%)
▲ Pers (40%)
Time of Crossover (DAYS)
8
7
6
5
4
3
2
1
0
82
83
84
85
86
87
88
89
YEAR (January-February)

4.1 Results of a One Year Climate Simulation

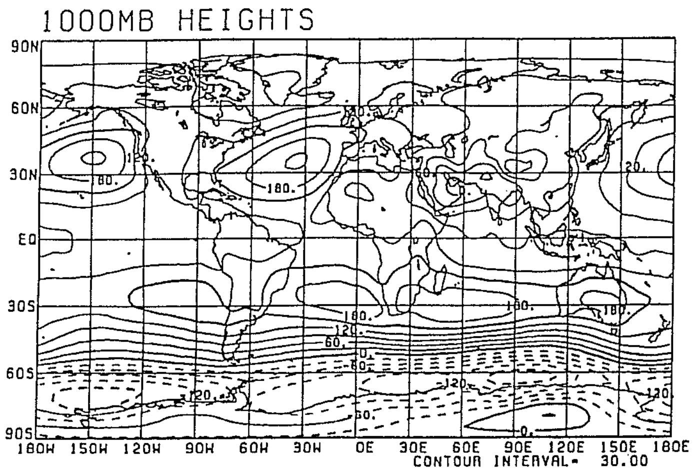
Kanamitsu et al., (1989) have recently completed a 12.5 month integration using a version of the MRF model identical to the current (December 1988) operational model except that the horizontal truncation was reduced from T80 to T40 (equivalent to increasing the size of the gaussian grid from about 160 km to 320 km). This resolution is still high enough that the simulation of the climate characteristics should be rather similar to that of the operational model. The climate simulation was started on May 15, 1988, and ended on June 1, 1989. Figure 4.1 presents the simulated and climatological 1000 mb fields for the June-August (JJA) period, and Figure 4.2 the corresponding fields for the period December-February (DJF). It can be seen that overall the simulation is very realistic, not only in the Northern Hemisphere but in the Southern Hemisphere as well, where the "roaring forties" regime is notoriously difficult to reproduce with general circulation models. Stationary waves tend to be stronger than observed, but are within observed interannual variability. The 500 mb fields (not shown) are similarly realistic.

Despite the fact that the climate simulation is generally very good, it has some deficiencies. There is a tendency to generate excessive thermal lows over the summer continents. Another serious problem in the NMC model is its tendency to become colder than observed. This cold bias was reduced in the tropics by the changes implemented on December 1988, (White and Caplan, 1989), but it remains still very large in mid-latitudes. Fig 4.3 and 4.4 show the simulated and observed zonally averaged wind for all seasons. Overall the simulation is quite good, locating the jet maxima close to the observed positions, and with approximately their observed intensity. The easterly bias in the tropics is 10 m/sec or less in all seasons.

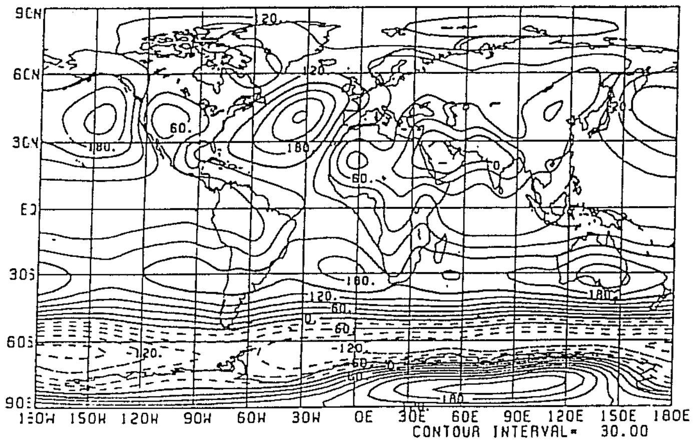
A difficult field to simulate is the precipitation. Figure 4.4 presents the precipitation for June, July, August and December, January, February from the 12.5 month simulation. There is a good representation of the climatological storm tracks, South Pacific and South Atlantic Convergence Zones, winter and summer monsoonal maxima, and the dry maritime areas west of the continents. A major deficiency in the precipitation, however, occurs over South America during the Southern Hemisphere summer, with too little precipitation over the Amazon and excessive rain over the Andes. This problem may be associated with the representation of the Andes in the model, and also affects short range forecasts (Ballish et al., 1989).

4.2 The DERF experiment of 1986/87

From 14 December 1986 to 31 January 1987, NMC performed an extensive experiment on DERF, with 108 contiguous 30-day forecasts performed with the then operational R40, 18 level model (Tracton et al, 1989). This rich data set, including extensive diagnostics, was then condensed onto 5 tapes or a

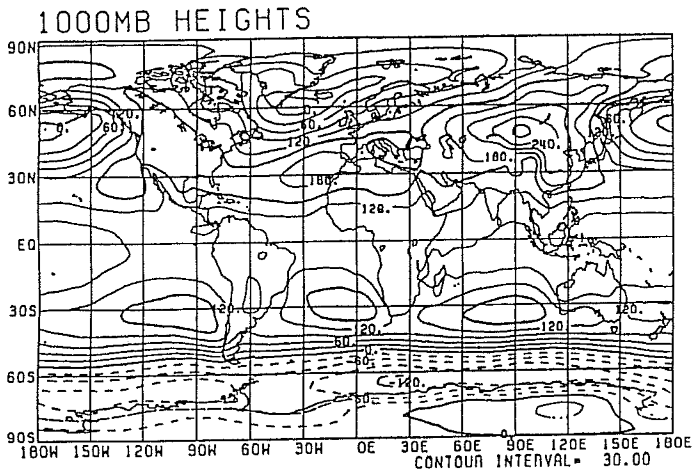


A. **CLIMATOLOGY - JJA**

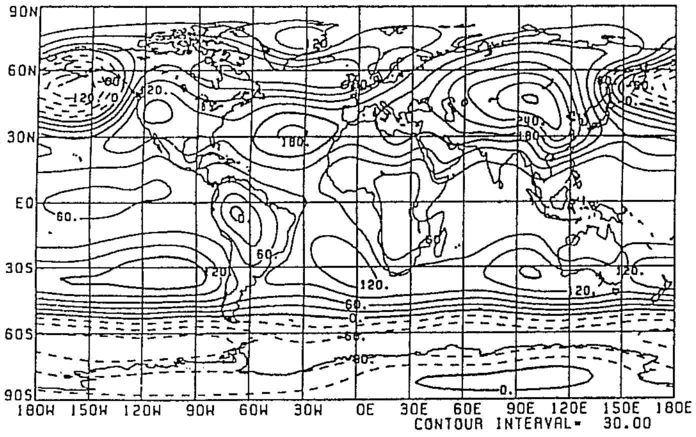


B. **MODEL - JJA**

Fig. 4.1. Simulated and observed JJS 1000 hPa field.

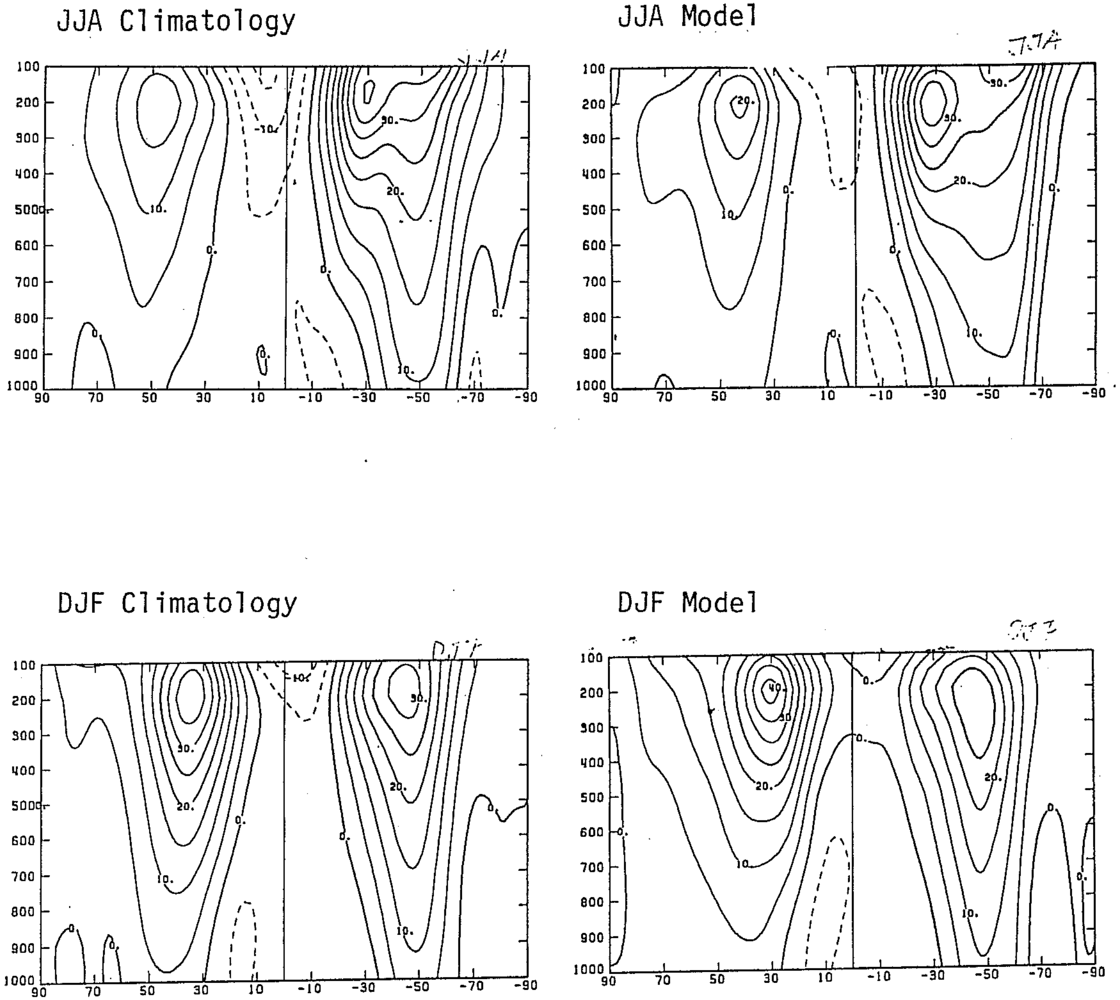


A. **CLIMATOLOGY - DJF**



B. **MODEL - DJF**

Fig. 4.2. Same as Fig. 4.1 but for DJF.

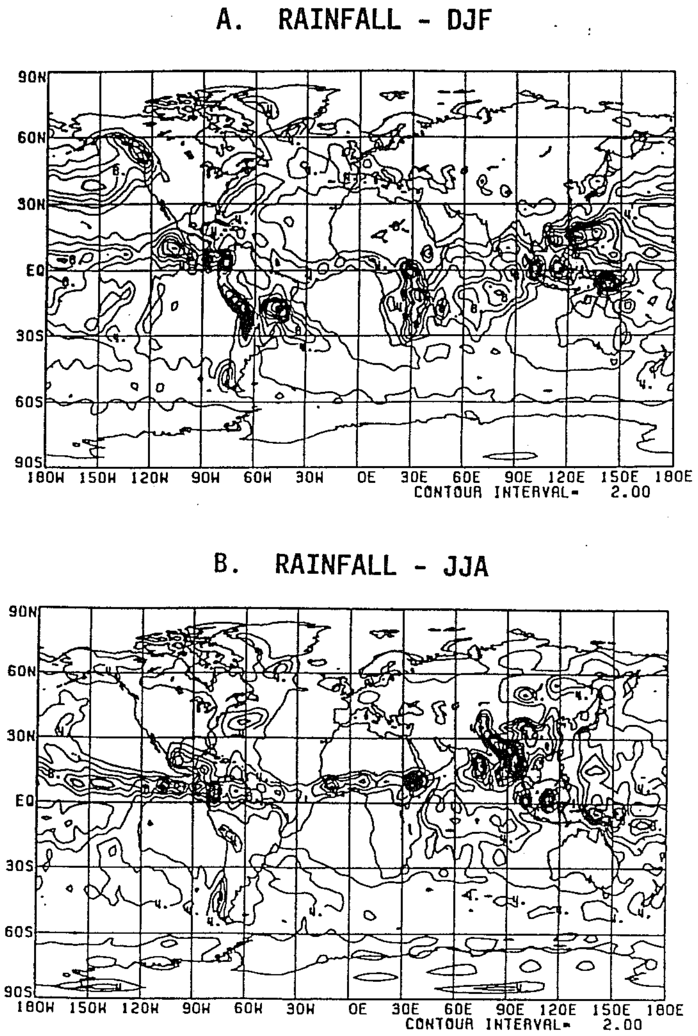

JJA Climatology

JJA Model

DJF Climatology

DJF Model

Fig. 4.3. Simulated and observed zonal wind.


A. RAINFALL - DJF

B. RAINFALL - JJA

Fig. 4.4. Simulated rainfall.

compact disk (Schubert et al. 1988), and is available to the research community. One of the most striking results was that the forecast skill at extended ranges varied considerably from day to day. Fig. 4.5 shows the anomaly correlation for 1-30 day means, and indicates that the dynamical model is almost always more skillful than a persistence of the anomaly forecast. This is encouraging, since persistence is very competitive with NMC/CAC's operational Monthly Outlook. However, the best estimator of the 30-day mean circulation is not the forecast 30-day mean, but the average of only the first 7-10 days. Beyond 10 days there are cases of skillful predictions, but, since the average skill is low, the operational utility of extended runs requires a means to discriminate a priori between good and poor cases. Some encouraging preliminary results were obtained using both agreement between forecasts (Kalnay and Dalcher, 1987), forecast persistence (Branstator, 1986), and the PNA index (Palmer, 1987) to predict the skill (Tracton et al. 1989). It is interesting to note that in the experience of ECMWF, the winter of 1986/87 was considerably more difficult to predict beyond 10 days than either the previous or the following winters (Palmer et al., 1989).

Tracton et al pointed out that the inability of the model to predict the evolution of blocking beyond a few days resulted in episodes of very poor skill. The model changes of 1987 and 1988 described in Section 2 had a considerable positive impact on one of those blocking cases recently rerun. Fig. 4.6a shows the analyzed 500 hPa field for 12 January 1987, with a pronounced case of blocking that the operational model could not predict (Fig 4.6b), and therefore resulted in very low skill in the medium and extended range forecasts. Fig 4.6c presents the same 10 day forecast but using the present system. Similar improvements were obtained with a second forecast run from initial conditions 3 days later.

4.3 Experiments on the North American drought of 1988

In a recent paper, Palmer (1989) has shown that of the two experimental 30-day integrations performed at ECMWF from the 21 and 22 May 1988, one had significant skill in predicting the anomalous high pressure over North America associated with the drought that occurred during that spring and summer. Following Trenberth (1988), he attributed this partial but remarkable success to the anomalous "La Nina" SST's observed during that period. We have now performed several 30 day experiments with the T40 model for the same period in order to determine whether the higher than normal predictability was also obtainable (Mo et al. 1989).

Figures 4.7a, b, c, d present the observed 30-day 500 hPa stationary anomalies with respect to climatology, and the predicted anomalies starting from the 21, 22 and 23 of May 1988 respectively. The results are remarkable: not only there is extraordinary skill over North America, but the high skill extends over the whole Northern Hemisphere. Moreover, there is excellent agreement among the three forecasts, indicating that

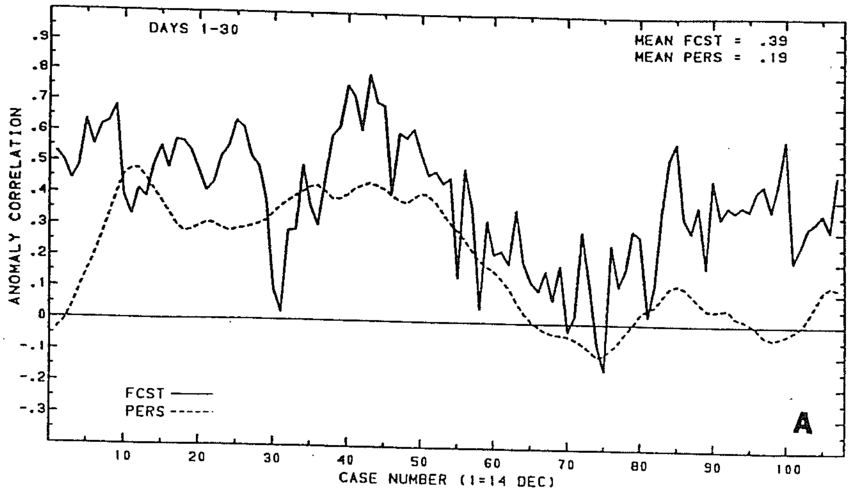


Fig. 4.5. Anomaly correlation for 30-day model and persistence forecasts for 108 successive days in the winter of 1986/87.

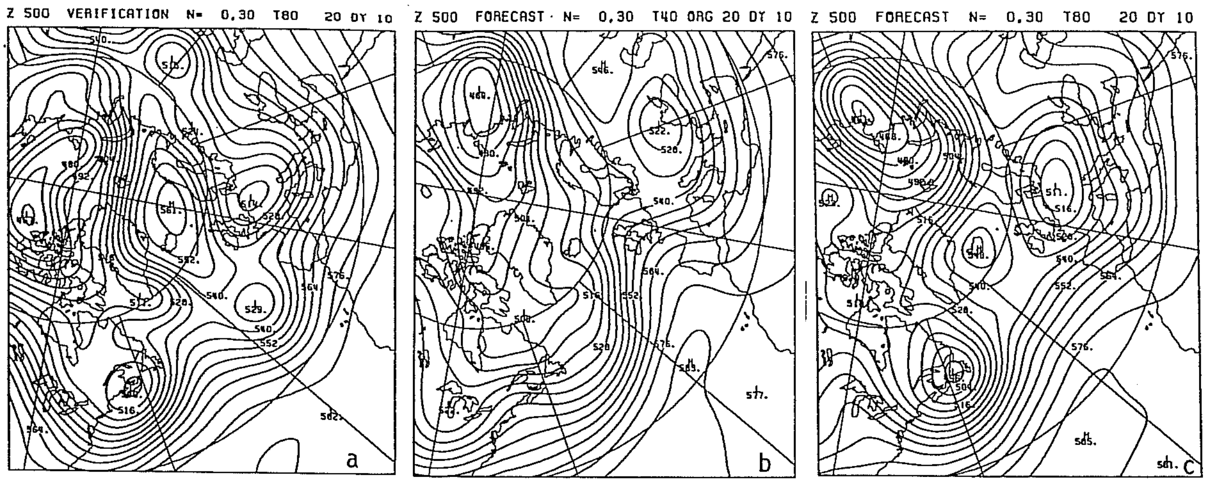


Fig. 4.6a. Verifying analysis for a 10 day forecast for January 10, 1987. b. Original forecast. c. New operational model.

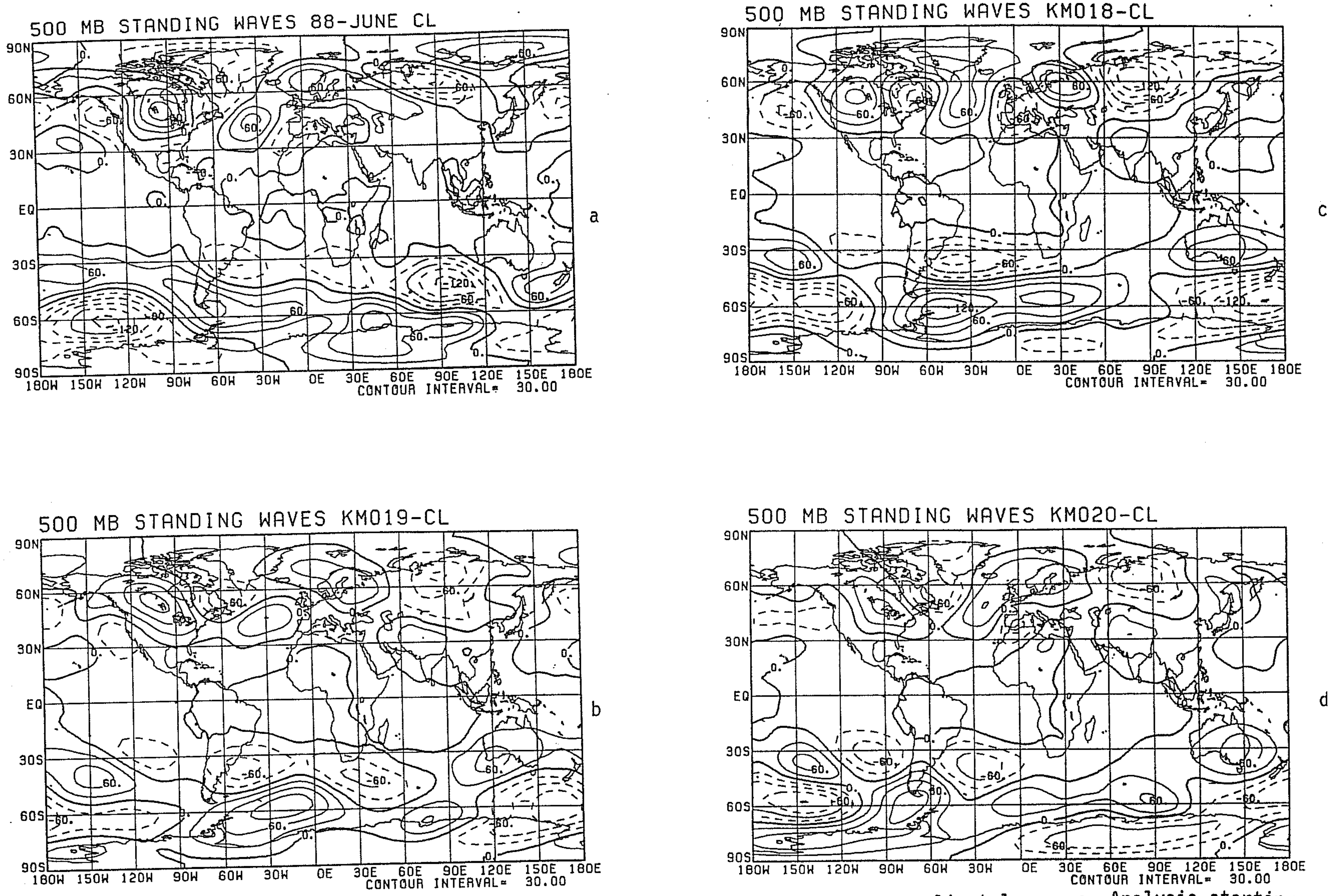


Fig. 4.7. Standing waves for a 30-day average period in May/June 1988 minus June climatology. a. Analysis starting on May 22. b. 30-day forecast from May 21, 1988. c. 30-day forecast from May 22, 1988. d. 30 day forecast from May 23, 1988.

such a forecast should be highly reliable, as it actually turned out to be.

The anomalies of 1988 were unusual in the sense that they are very similar to the observed climatology of the month, so that stationary waves were similar but much stronger than normal. This suggests that the extraordinary predictability of this month may be associated with initial conditions which had a rather stable regime. This hypothesis tends to be confirmed by barotropic stability experiments indicating that a slowly growing dominant mode is similar to both the climatology and the anomalies of 1988. However, further experiments also confirm the importance that SST anomalies had that year. Figures 4.8 a,b,c show the difference between the forecasts from the 21, 22 and 23 May 1988 using analyzed 6-21 May 1988 SST's, and climatological SST's. It is clear that the 1988 SST anomalies contribute to the observed anomalous circulation over North America, but not over the rest of the Northern Hemisphere (Mo etal.,1989).

5. CURRENT RESEARCH AND PLANS

NMC plans assume the acquisition by 1991 of next generation computers with significantly more power than the current Cyber 205's. More powerful computers would allow us to increase the model and analysis resolution, with a corresponding increase in skill. However, there are several areas of current research at NMC which we also hope will contribute significantly to such increase. In this section we review a few of those areas and our plans for the next few years.

5.1 Analysis, Initialization and Quality Control

a) Analysis Unification and "Small Volume" Approach

The purpose of the "unified" global and regional system is to be able to perform all of the optimum interpolation analyses during the operational job suite. The new system was written with flexible generalized computer code permitting changes in horizontal and vertical resolution without recoding. The vertical coordinate for the unified analysis system is the sigma coordinate of the forecast model using the analysis. The new system uses all available observational data, including significant levels, surface mass observations over land, and profile data to 10 mb. Use of the model coordinate for the vertical coordinate of the analysis instead of fixed mandatory pressure levels takes advantage of higher model resolution in the lower troposphere and boundary layer and permits extension of the analysis into the upper stratosphere. In addition, retrieving and using interactive satellite soundings directly in the model sigma coordinate, reduces interpolation errors and inconsistencies between the model and the data. The new unified system is still under development, but a preliminary version using mandatory level profile data and no surface observations over land was

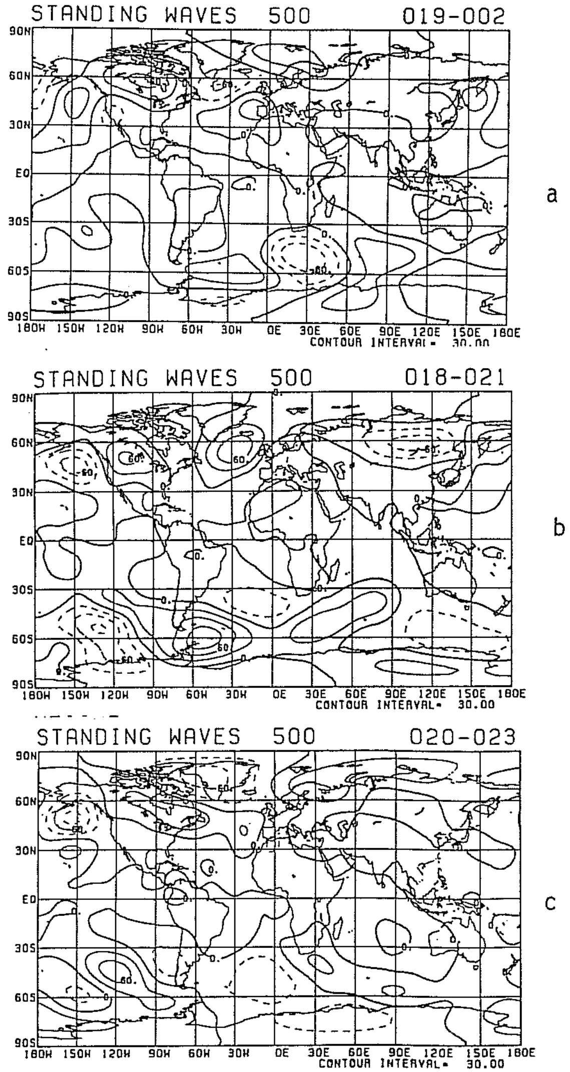


Fig. 4.8. Difference between 30-day forecasts using 1988 SST and using climatological SST. a. From May 21, 1988. b. From May 22, 1988. c. From May 23, 1988.

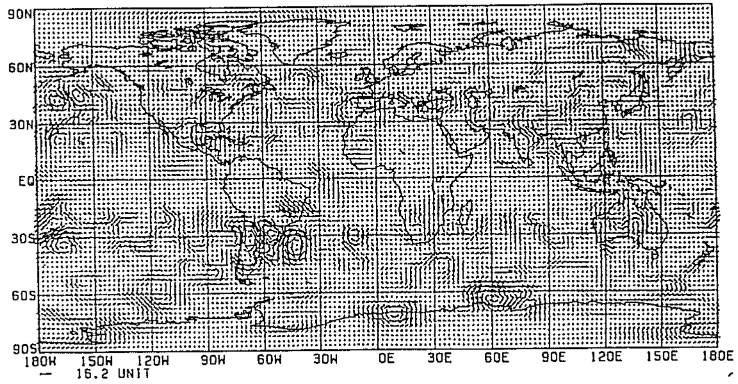


Fig. 5.1. 250 mb analysis increment for winds produced by operational NMC analysis (12Z, June 27, 1989).

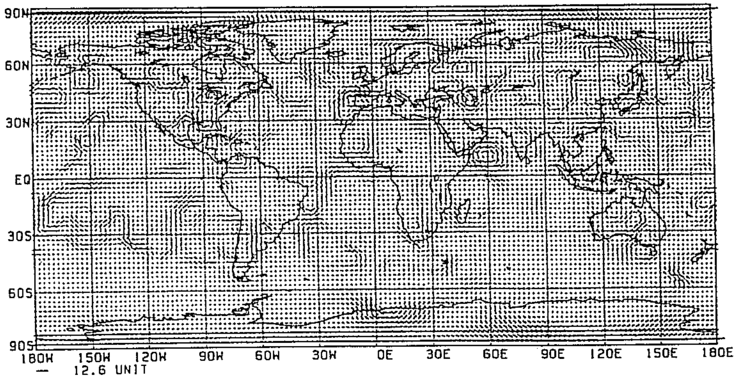


Fig. 5.2. 250 mb analysis increment for winds produced by spectral analysis. Resolution is T80 with 12 vertical modes.

implemented in the operational job suite in May of 1988. The vertical coordinate for this version of the analysis is still the 12 mandatory pressure levels from 1000 to 50 mb.

Currently, the unified analysis system uses two grid representations for storing the prediction errors, first guess, analysis increments, and the analysis. The full analysis grid is used for the calculation of data increments and for the final product. However, the optimum interpolation is performed on a thinned subset of the full analysis grid. A matrix is constructed and solved at each point on the thinned grid. The thinned point values are then linearly interpolated to the full grid to produce the final product. We are testing a "small volume" approach as an alternative. It uses the same grid representation but the linear interpolation from thinned to full grid is accomplished using optimum interpolation. One matrix and four right hand sides are constructed with the collection volume centered on four full grid points. The four sets of optimum interpolation weights are then used to distribute the data increments to the surrounding four grid points. Because fewer matrices are constructed and solved in the small volume approach, less computer time is used to obtain a final analysis in which optimum interpolation has been used at each grid point on the full grid.

It should also be pointed out that experiments are in progress to assimilate land surface fields, i. e., soil temperature, soil moisture, vegetation index, and snow cover, by combining predicted and satellite observed fields.

b) Spectral Optimum Interpolation

A new global analysis system is being developed for possible use with the NMC global spectral model (Parrish and Derber, 1989). The new analysis is similar to the existing operational system--the analysis error variance is minimized given an assumed knowledge of forecast and observation error statistics, a procedure commonly known as optimum interpolation or OI (Gandin, 1963). However, the new procedure differs from the operational NMC analysis in three important details. First, the forecast error covariance model is defined using model normal modes. Errors are assumed to be random and uncorrelated in mode space. The shape of correlations in physical space is controlled by the error variance assigned to each mode. If fast mode errors are set to zero, the resulting physical space correlations appear meteorologically realistic (Phillips, 1986). The other two differences follow from the normal mode error representation. First, the analysis variables are the spectral model sigma-coordinate coefficients. No intermediate variables are used. Second, all data are used at once to solve one giant matrix problem. Temperature, wind and surface pressure data are used. (Moisture is not yet being analyzed. It is not clear that the spectral method has any advantage for moisture analysis.)

The success of the spectral analysis depends first on efficient solution of the giant matrix problem. A preconditioned conjugate gradient method seems to be adequate. 50 iterations produce reasonable results. The cost per iteration is comparable to one time-step for the dynamics calculation in a spectral model. Figures 5.1 and 5.2 compare the operational analysis increment with that produced by the new analysis for 250 mb winds for 12z, June 27, 1989. The test analysis was run at T80 with 12 vertical modes. Observation and first guess errors approximate those used in the operational system. Quality control is minimal in the new analysis (no buddy check). Positive features to note are the smaller amplitude of the test increment, particularly over South America, and the elimination of small scale features along the Antarctic coast. Paradoxically, despite the smaller increments and smoother characteristics, the overall fit of the test analysis to observations is better. We are now tuning the analysis for best performance in the 6 hour NMC data assimilation cycle.

c) Initialization of the Increments

Although nonlinear normal mode initialization using a Machenauer scheme is widely used in operational centers to adjust the initial value of the gravity wave modes, this method may have some problems (Errico and Rasch, 1988). Weather systems do not necessarily have zero ageostrophic or gravitational tendencies, as assumed in the initialization. Similarly, tidal modes tendencies, present both it the atmosphere and in the model, should not be zeroed out. We have tested in the analysis cycle an incremental nonlinear initialization, (Cao et al, 1989), where after the analysis the tendencies of the gravity modes are set equal to those of the 6-hour forecast. After one week of testing, the changes in mid-latitudes are small, indicating that the present system is satisfactory, but the tidal oscillations in the tropics are much improved, and in good agreement with observations.

d) Complex Quality Control

The NMC is developing a new system for observational Data Processing, Monitoring, and Quality Control (DPMQC). The new quality control procedures are based on the following principles:

1. Quality control will involve a one-step decision procedure based upon a collection of quantitative information from a multiplicity of checks. The multiple checks should include both full field values and differences from the assimilating forecast,

2. Quality control algorithms should be observing system dependent,

3. The human, interactive element should be minimized, but not eliminated, and

4. Rapid and effective direct NMC-to-data producer feedback should be arranged wherever possible.

Principle 1. is based upon the Complex Quality Control (CQC) philosophy proposed by L. Gandin (1988). The quality control checks currently planned are hydrostatic checks, time-series checks, a special intercomparison of aircraft wind reports, and both horizontal and vertical consistency checks, speed-dependent checks on cloud-track winds, and a variety of checks on satellite temperature soundings, including a multivariate optimum interpolation check.

The key element that will enable the new DPMQC system to function effectively is the creation of a new data base easily accessible in a wide variety of ways. This new data base will consist of both the observations themselves and information about the observations (events), both current and during the most recent month or so. Examples of events are the differences between the observed values and the assimilating forecast and the nature of the quality control decision made on the observational data. Work on the design of the new data base is progressing in parallel with the development of the NMC CQC algorithms.

5.2 Use of Satellite Data

A comprehensive effort is underway at the National Meteorological Center to improve and extend the use of current satellite data as well as prepare for the use of future space-based observing systems (e.g., Eos).

Clearly, the way that satellite data are presently being utilized in the NMC GDAS is less than optimal. For example, the accuracy of the 6 hour forecast is of the order of 1 K in the lower troposphere, while that of the satellite temperatures produced operationally is typically 3 to 4 K. Regional biases during the winter over the oceans east of the northern hemisphere continents are even larger (A. Hollingsworth, personal communication). Under these circumstances the best that can be hoped for is that the quality control system is sophisticated enough to delete the poor quality satellite data in order to avoid negative forecast impacts in the northern hemisphere. A few examples of negative impacts from satellite temperatures have even recently been noted in the southern hemisphere (J. Alpert, personal communication). While the above situation is probably the most serious, other problems are also present and are mentioned briefly below.

1. As the accuracy of the model 6 hour forecast has continued to improve, the lower tropospheric satellite temperature error has become a significant source of error in the mid and upper troposphere through the integration to produce height profiles. Anchoring the satellite height profiles in a consistent manner between land and ocean is also a problem. In the near future, we plan to develop and test an

analysis of satellite thickness once the development of a model-level-based analysis is completed (currently the analysis is performed on mandatory pressure levels).

2. The present sat-sat correlation statistics used in the optimum interpolation analysis are based on a study by Schlatter (1981) which were appropriate for the polar orbiting satellites in the early 1980's in which statistical regression was used to produce the retrievals (Smith and Woolf, 1976). More recently, with the implementation of a physical retrieval scheme (Fleming et al., 1986b, 1988) at NESDIS, the sat-sat correlation statistics need to be revised; a collaborative effort between NESDIS and NMC is underway for this purpose.

3. The quality control of SATEMS is not adequate. A major effort is now underway to revise the entire quality control system at NMC incorporating the ideas of Gandin (1988) on complex quality control (see Section 5.1d).

4. The negative bias in the high-level cloud-track winds (CTW's) is particularly serious in strong wind situations (i.e. in the subtropical jet). There are undoubtedly several sources for this error. In the near term, we plan to conduct an experiment in which the wind direction from the CTW's is combined with the wind speed from the 6 hour forecast for those situations in which the wind speed of the model forecast is significantly stronger than that of the nearby CTW's.

a) NASA/NESDIS/NMC Joint Retrieval Research

The realization of the importance of the satellite retrieval problem to numerical weather prediction (NWP) culminated recently in the formation of an Interagency Satellite Retrieval Working Group in the United States which includes satellite retrieval and NWP experts from the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). The charge to this Working Group is to develop as soon as possible a state-of-the-art satellite retrieval system for numerical weather forecasting. This system will take advantage of the best components of the operational system at NESDIS and those from experimental approaches at NESDIS and at NASA.

There was general agreement among the Working Group participants that the various comprehensive inversion methods (e.g., the NESDIS operational system (Fleming, et al., 1986b, 1988); the NASA research scheme (Susskind, et al., 1984)) should have similar accuracies, given the same clear column radiances. There was also a strong consensus that the most accurate first guess possible should be used for the inversion problem. Over most areas of the globe that is most likely a forecast provided by a general circulation model during the data assimilation (see next sub-section). In areas where the model forecast might be poor as determined by comparing observed (satellite) and computed (model) radiances from the forward problem, a classification approach (i.e., McMillin, 1986b) blended with the model first guess, seems promising.

The Working Group participants strongly agreed that the most important remaining weakness (assuming the use of a forecast first guess) in the NESDIS operational system was in the approach used for cloud-clearing, where an angle correction (to nadir) is performed before cloud-clearing, and hence, the angle correction procedure must also simultaneously account for clouds. All the participants agreed that the most accurate off-nadir retrievals are produced if the off-nadir radiances are cloud-cleared at the same angle that the satellite views the atmosphere (as in the NASA scheme). In addition, the NASA scheme also uses the forecast temperature information in the cloud-clearing, while the NESDIS scheme does not use this information. On the other hand, a weakness identified in the NASA retrieval scheme was in not utilizing the SSU data for the stratospheric sounding problem, as is done in the NESDIS system.

With the above considerations in mind, the Working Group recommended a number of steps to combine the strengths of the different approaches. They include exchange of retrieval software between NASA and NESDIS, implementation of both schemes on the NMC vector machine for experimentation, and the testing of the NASA cloud-clearing approach.

b) NESDIS/NMC Interactive Retrieval Pilot Study

Over most of the globe, the present-day model 6 hour forecast during the data assimilation is quite accurate, and should be used in the retrieval process. A natural approach for this is an "interactive" system, where the assimilation model forecast is used as a first guess by the retrieval scheme (Baker et al, 1984). The model forecast has also been used with a variational approach to analyze radiances directly for numerical prediction (Eyre and Lorenc, 1989). It should be noted that the resulting retrievals are then analyzed in conjunction with other available data to produce initial conditions for the subsequent forecast by the assimilating model. The interactive approach, developed and used extensively in a research mode by J. Susskind and collaborators at the NASA Goddard Space Flight Center, has been shown to have a beneficial effect on both the accuracy of the 6 hour assimilation model forecast and that of the retrievals (Susskind and Pfaendtner, 1989). More importantly, the negative impacts on medium range forecasts over the Northern Hemisphere are, for the most part, eliminated. In addition to temperature profiles and thick-layer precipitable water estimates, a wide range of geophysical parameters (land and sea surface temperature, ice and snow extent, cloud top pressure and amount, and estimates of outgoing long wave radiation, soil moisture, total ozone, and precipitation).

A joint NESDIS/NMC pilot effort was initiated in early 1989 to develop an interactive retrieval system. Preliminary results have been obtained for two time periods and are shown below. For the 24 hour period for April 30, 1989, the retrievals were produced using the NMC global 6 hour forecast as the first guess for the retrievals, but off-line from the assimilation or "non-interactively". Subsequently, during the 12 hour period beginning on 0000 GMT 27 January 1989, retrievals were produced interactively.

The top panel of Fig. 5.3 compares the accuracy as measured against rawinsondes of the NESDIS operational retrievals (Fleming et al., 1986b, 1988) and those produced using the NMC 6 hour forecast as the first guess for the non-interactive test. At the bottom of Fig. 5.3, the accuracy of the latter set of retrievals is compared with that of the 6 hour forecast. The results are quite encouraging considering the fact that only the guess and the solution covariance matrix were changed in the retrieval system. The improvement in the accuracy of the retrievals using the 6 hour forecast over that of the operational retrievals is substantial in the 700 mb to 250 mb layer and near the surface.

The top panel of Fig. 5.4 compares the accuracy as measured against rawinsondes of the operational path A (clear) retrievals produced interactively for the second time period. The results for the path C (cloudy) retrievals are shown at the bottom of Fig. 5.4. As may be seen for the clear retrievals, the interactive approach has resulted in a small improvement throughout the troposphere (1000 mb to 200 mb). The accuracy of the interactive retrievals is significantly poorer in the stratosphere than that for the operational soundings, however. This result is not surprising considering the poorer quality mandatory level stratospheric analysis (top level at 50 mb) relative to that in the troposphere for the current operational system. In the near future, NMC plans to implement operationally an 18 level analysis (top level at 10 mb) on the model sigma levels (see Sec. 5.1).

For the cloudy retrievals (bottom of Fig. 5.4), there is a significant improvement throughout the troposphere (up to 1000 mb) with the interactive retrievals, with the improvement in the 1000 mb to 700 mb and the 400 mb to 300 mb layers being 1 K or larger. As in the case of the clear stratospheric interactive retrievals, the accuracy of the cloudy interactive retrievals is significantly poorer than that of the cloudy operational retrievals. It should also be noted that the magnitude of the collocation errors shown in Figs. 5.3 and 5.4 are larger than otherwise expected because a large collocation window was used (300 km, ±3 hours) as a result of the small sample size.

In Fig. 5.5, the bias and rms error, measured against rawinsondes, is shown for the 6 h forecast of the tempera-ture and vector wind error at the end of a 60 hour (on 1200 GMT 29 January 1989) assimilation in which SATEMS were produced and utilized interactively. Over western North America (top left panel) there is a substantial (> 2 K) improvement in the bias and rms error at 850 mb compared to the operational 6 h forecast. Little difference is noted in the levels above.

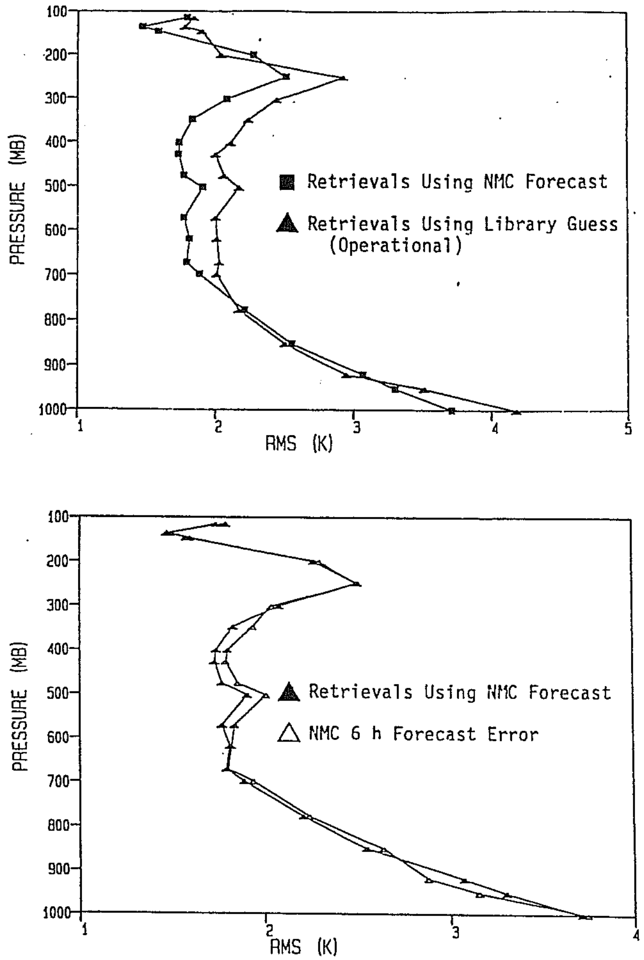


Fig. 5.3. Rms difference between rawinsondes and collocated retrievals (top) and between rawinsondes and retrievals or rawinsondes and the 6 hour forecast (bottom) for a sample size of 273 from the 24 hour period for April 30, 1989.

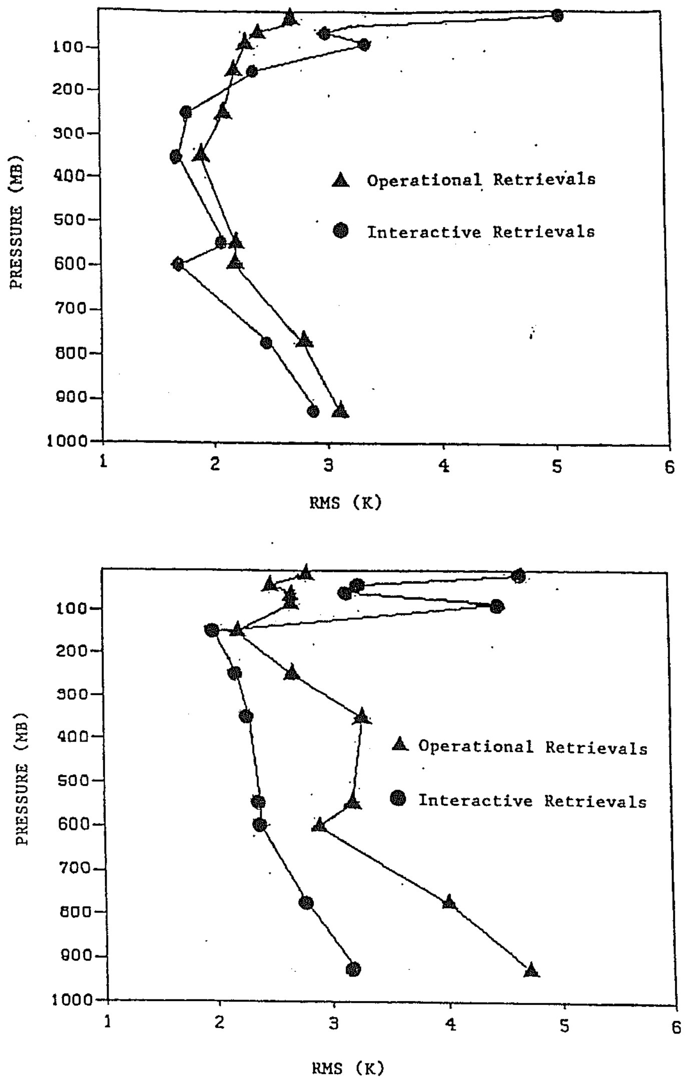


Fig. 5.4. Rms difference between rawinsondes and collocated clear (path A) retrievals (top) and for rawinsondes and cloudy (path C) retrievals (bottom) for a sample size of a few hundred from the 12 hour period beginning 0000 GMT 27 January 1989.

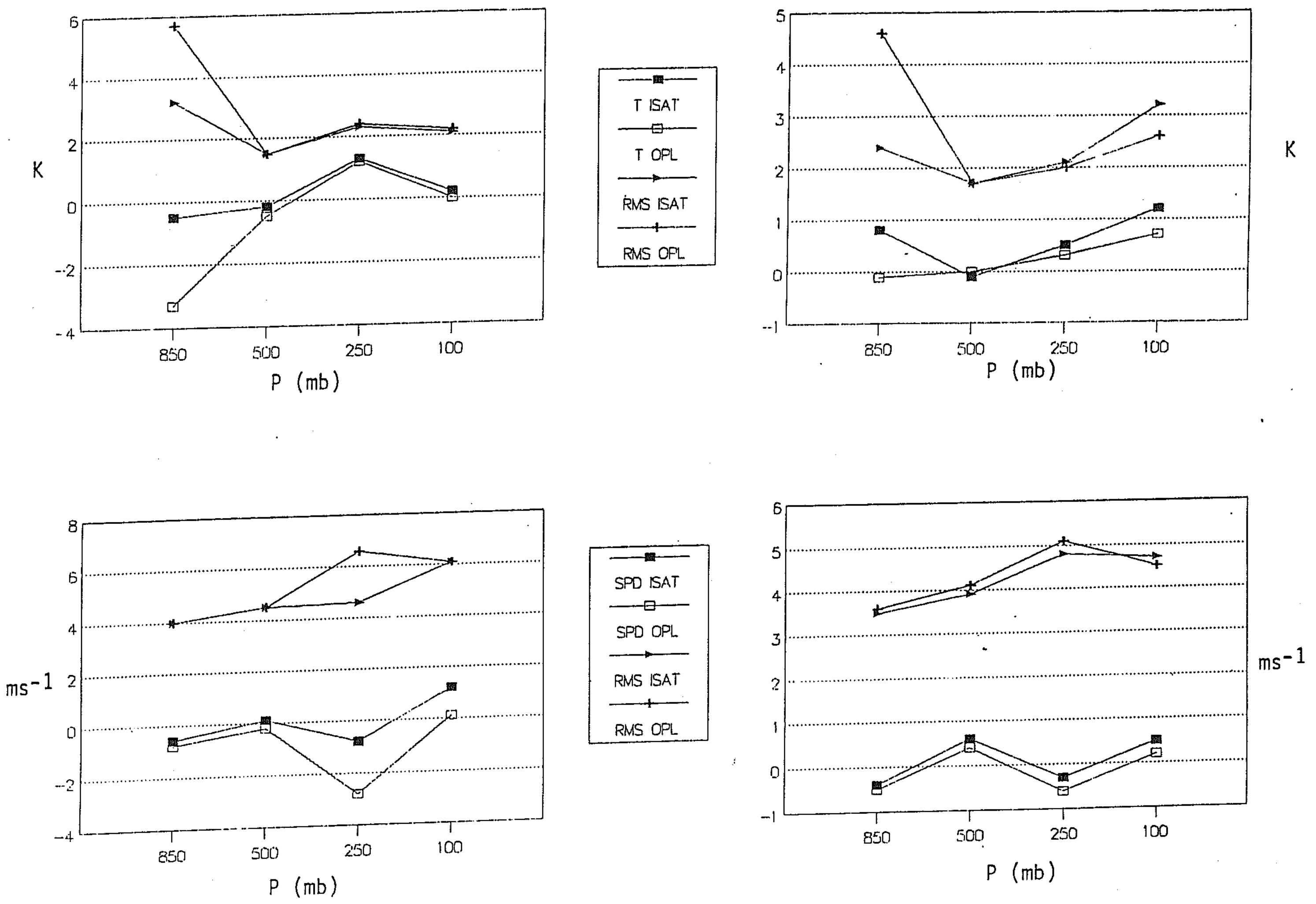


Fig. 5.5. Bias error in the 6h forecast of the temperature (T ISAT or T OPL) and vector wind speed (SPD ISAT or SPD OPL) at selected pressure levels (rms error also shown) during the data assimilation using SATEMS produced interactively (ISAT) compared to those produced operationally (OPL). Verification (1200 UTC 29 January 1989) is against 37 selected rawinsondes over western North America (on the left) and against 102 rawinsondes over the Northern Hemisphere (on the right).

For vector wind speed the improvement is also substantial (> 2 ms^{-1}) at 250 mb, with generally only small differences at other levels. There is about a 1 ms^{-1} degradation in the bias at 100 mb, but that is likely related to the stratospheric problems mentioned above. For the northern hemsiphere, there is again a substantial improvement (> 2 K) in the rms error with the interactive system at 850 mb, but with some degradation in the bias there (< 1 K).

c) Use of Oceanic Surface Wind Data

In anticipation of the real-time availability of oceanic surface wind speed data from the Special Sensor Microwave Imager (SSM/I) at NMC in late 1989, we have begun to develop the capability to utilize these data in the global data assimilation system. This also lays the groundwork for utilizing scatterometer oceanic surface wind data from European, Japanese, and U. S. satellites in the 1990's.

A key problem in effectively utilizing SSM/I and similar data is under what conditions the influence of the surface wind data should be extended to the levels of the model above the planetary boundary layer (PBL). We are planning to narrow or broaden the vertical correlation function used in the OI depending on the stability of the PBL.

d) SSM/I Moisture Measurements

The SSM/I instrument is a seven-channel, four-frequency linearly polarized microwave radiometer that can measure, among other things, total precipitable water over the world's oceans. The initial algorithm (Hollinger et al., 1987) has been used to retrieve the total water vapor content of an atmospheric column and is based on a linear four channel algorithm derived from a regression equation using brightness temperatures together with a radiation transfer model. Recently, Alishouse and Snyder (1989) have derived an improved non-linear algorithm by introducing the square of the 22 GHZ brightness temperature in the regression equation.

In order to determine the degree of improvement from their new algorithm, Alishouse and Snyder (1989) compiled some 235 match-ups between radiosonde and SSM/I total precipitable water estimates over the tropical oceans (25 S - 25 N). The rms difference, in precipitable water between the radiosonde and SSM/I observations was about 6.7 mm for the initial algorithm, whereas the rms difference for the improved algorithm was about 3.8 mm.

The agreement of the SSM/I moisture measurements with rawinsondes is very encouraging. NMC plans to conduct analysis/forecast experiments with these data.

e) Cloud-Track Winds: Evaluation of 15 Minute Cloud-Tracking and CO_2 Slicing

In order to significantly improve the accuracy of the SATOB winds, CO_2 slicing technique (Merrill, 1989), seems promising. An evaluation of data produced at NESDIS using that approach is planned, as well as tests with 15 min data (Peslen, 1980) compared to the presently operational 30 min data. In addition, in order to improve the quality of the data in the southern hemisphere, NMC has begun providing to NESDIS 12 h forecasts for use in CTW production and height assignment. Previously, NESDIS has used a climatological height assignment for the high-level winds in the southern hemisphere (T. Stewart, personal communication).

5.3 Model development

More powerful computers will allow us to increase the horizontal resolution of the global spectral model from triangular 80 wave (equivalent to 160 km) to perhaps triangular 160 wave (equivalent to 80 km). The number of vertical levels will be increased from the current 18 to about 30. We are exploring, in collaboration with D. Williamson of NCAR, and R. Bates, of NASA/GLA, the possible operational use of either a spectral or grid point semi-lagrangian model. Research will continue on improving the vertical finite differences, the hydrostatic equation and the optimal vertical and horizontal resolutions.

A major emphasis will be placed on improving the physical parameterizations, and in particular, the convective parameterization with prediction of liquid water content, the turbulent closure in the PBL, a better formulation of the horizontal diffusion, and of the effects of orography. Coupling with the NOAA surface ocean wave model (NOW), and with a sea-ice model are also planned. Reduction of the spin-up is also another critical area. An exploratory project in collaboration with A. Leetmaa of NMC/CAC is taking place on the coupling an ocean model to the atmospheric model for possible use in extended range forecasting. Collaboration with research groups will be fostered by the use of "plug compatible" modules (Kalnay et al, 1989).

5.4 Climate Data Assimilation System

Global analyses produced by the NMC GDAS are becoming increasingly important tools for monitoring global climate. However, the goals of global data assimilation for operational forecasts and for climate monitoring are often in conflict. First, the global data assimilation system must be run early enough each day to provide the initial analysis 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 or in the model often introduce apparent changes in climate statistics.

Because of this, NMC plans to introduce by 1993 a special Climate Data Assimilation System (CDAS) for climate purposes.

This system will not run under operational time constraints and it will 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.

6. FINAL COMMENT

Progress in numerical weather prediction in the last ten years has been remarkable. We are confident that with continued international cooperation between data producers, and research and operational centers, this rate of progress will continue in short, medium and extended range prediction.

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