TDL FILE

WEATHER BUREAU
Systems Development Office
Techniques Development Laboratory
Silver Spring, Maryland

February 1967

Numerical Experiments Leading to the Design of Optimum Global Meteorological Networks

M.A.ALAKA
FRANK LEWIS

Technical Memorandum WBTM TDL-7

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

WEATHER BUREAU TECHNICAL MEMORANDUM

TECHNIQUES DEVELOPMENT LABORATORY

The primary purpose of the Techniques Development Laboratory of the Systems Development Office is to translate increases in basic knowledge in meteorology and allied disciplines into improved operating techniques and procedures. To achieve this goal, TDL conducts and sponsors applied research and development aimed at the improvement of diagnostic and prognostic methods for producing weather information. The lab carries out studies both for the general improvement of prediction methodology used in the National Meteorological Service System and for more effective utilization of weather forecasts by the ultimate user.

Material for the Technical Memorandum series is obtained from various sources. It is reproduced in this series to facilitate the prompt, limited distribution of material which may be preliminary in nature. Papers appearing in this series may be published formally elsewhere at a later date.

The papers in the Weather Bureau Technical Memorandum series are available through the Clearinghouse for Federal Scientific and Technical Information, U. S. Department of Commerce, Sills Bldg., Port Royal Road, Springfield, Va. 22151.

No. 1 Objective Prediction of Daily Surface Temperature. William H. Klein, Curtis W. Crockett and Carlos R. Dunn. October 1965.

No. 2 Hurricane Cindy Galveston Bay Tides. N. A. Pore, A. T. Angelo and J. G. Taylor. September 1965.

No. 3 Atmospheric Effects on Re-Entry Vehicle Dispersions. Karl R. Johannessen. December 1965.

No. 4 A Synoptic Climatology of Winter Precipitation from 700-mb. Lows for the Intermountain Areas of the West. D. L. Jorgensen, W. H. Klein and A. F. Korte. May 1966.

No. 5 Hemispheric Specification of Sea Level Pressure from Numerical 700-mb. Height Forecasts. William H. Klein and Billy M. Lewis. June 1966.

No. 6 A Fortran Program for the Calculation of Hourly Values of Astronomical Tide and Time and Height of High and Low Water. N. A. Pore and R. A. Cummings. January 1967.

U.S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
WEATHER BUREAU

Weather Bureau Technical Memorandum TDL-7

NUMERICAL EXPERIMENTS LEADING TO THE DESIGN OF OPTIMUM GLOBAL METEOROLOGICAL NETWORKS

M. A. Alaka and Frank Lewis

SYSTEMS DEVELOPMENT OFFICE
TECHNIQUES DEVELOPMENT LABORATORY
TECHNICAL MEMORANDUM NO. 7

SILVER SPRING, MARYLAND
February 1967

CONTENTS

NUMERICAL EXPERIMENTS LEADING TO THE DESIGN OF OPTIMUM GLOBAL METEOROLOGICAL NETWORKS

M. A. Alaka and F. Lewis

INTRODUCTION

The problem of establishing criteria for the spacing of meteorological stations is one of long standing. In 1935 the Conference of Directors of the International Meteorological Organization, held in Moscow, was informed that the scientific institutes of the USSR were engaged in establishing such criteria. The first quantitative evaluation of global network requirements appears to have been formulated at the Paris (1946) meeting of the Commission for Synoptic Weather Information, the predecessor of CSM. The requirements were derived somewhat arbitrarily on the basis of experience in temperate latitudes rather than on the basis of a systematic study of the problem on a world-wide scale.

With the advent and increasing availability of more and more powerful computers and the development of increasingly sophisticated dynamical models of weather prediction, our ability to improve both the accuracy and time range of our forecasts is severely limited by our present data networks [9]. On the basis of computations with advanced numerical models of the general circulation, Charney [2] has concluded that an accurate definition of the initial state of the atmosphere would enable us to forecast the weather for periods up to two weeks and to provide average values of selected weather parameters for longer periods. But the fact is that there are very large areas where the data are very sparse. Spurious influences from these areas quickly contaminate weather predictions even for areas where the networks are adequate.

The first step in attempting to remedy network deficiencies is to formulate accurate requirement criteria. Table 1 gives estimates of suitable station spacings proposed over the years by various groups. The disparity between these estimates is striking. Even for the middle latitudes, the estimates range from less than 300 km, according to the Commission for Synoptic Weather Information (1946), to 1300 km suggested by the Weather Bureau [6] as being adequate to maintain the accuracy of hemispheric numerical prediction at the level obtainable at that time. The obtainment of uniform global coverage on the basis of these two estimates would require 5675 and 302 stations, respectively, thus yielding a range which spans more than one whole order of magnitude. For uniform coverage most of the stations would have to be over oceanic or thinly populated areas. It therefore is exceedingly important, from an economic standpoint, to find precisely the point beyond which an increase in the number of stations would not be justified.

ANALYSIS OF THE PROBLEM

Errors in numerical forecasts may be traced to two main sources:

(a) Errors in analysis

(b) Errors inherent in the forecasting model.

TABLE 1

Estimates of Suitable Station Spacings from Different Sources and the Corresponding Number of Stations Required for Uniform Global Coverage. The Number of Stations Was Calculated by Representing the Surface of the Earth as a Square with Sides 22,600 Km Long.

Source		Surface		Upper Air	
		Spacing (Km)	No. of Stations	Spacing (Km)	No. of Stations
Commission for Synoptic Weather Information (1946)	Basic network	100-150	51076-22698	300	5675
	For thinly populated areas	500	2043	1000	484
	Over oceans	300-500	5075-2043	1000	484
Working Group, Commission for Aerology, WMO (1960)	If both pressure and wind			500-600	2043-1418
	If only wind			300-350	5675-4169
Working Group, Commission for Synoptic Meteorology, WMO (1960)	Temperate zone			650	1209
	Polar regions			1100	422
	Tropical regions			1600	200
Weather Bureau Panel on Observations over Sparse Data Regions (1963)				1000-1300	511-302

Fig. 1 shows the different sources of these errors which are not additive because the equations governing them are not linear. We hope eventually to deal with an improved observation system in which the errors will be sufficiently small to satisfy linear perturbation equations. In this event the errors become approximately additive, which permits the study of each type of error separately.

One sees from Fig. 1 that errors of analysis stem from the following causes:

(a) Inadequate networks
(b) Incorrect observations
(c) The analysis technique.

The effect of network density is best understood if we regard the meteorological field to be analyzed as the sum of harmonic components. The variance of each component is known as its power, and the distribution of the powers of the various harmonic components constitutes a spectrum - the power spectrum. A given network of stations can give no information on those harmonic components whose scale is comparable to or smaller than the spacing of the observing stations. An analysis of the field can at best yield an estimate of the larger-scale components. However, the unresolved small-scale components will appear in the observed values as noise which is erroneously interpreted as part of the large-scale component. This phenomenon, which is known as "aliasing," will have an effect similar to that of random observation errors and will contribute to the uncertainty of determining the large-scale components. If the large-scale features are to be determined with sufficient accuracy, the noise level must be kept to within a small fraction of the total power of the field.

If the typical power spectrum of atmospheric fields were known through its complete range, networks satisfying the above criterion could be designed. Unfortunately, sufficient knowledge is lacking, especially in connection with the short-wave end of the power spectrum.

Stated somewhat differently, analysis errors corresponding to different network densities could be accurately computed, provided certain statistical parameters are known. These include the mean value of the field, its variance, and its space autocorrelation functions. The preliminary report of the CSM Working Group on Networks [1] demonstrates how this may be done. Several analysis schemes were used by the Working Group in computing errors corresponding to different network-grid spacings. Interestingly enough, the report shows how the instrumental error may be deduced from the variance and covariance of the measured parameter.

GROWTH OF ERRORS

However, for the purpose of assessing the effects of analysis errors on the accuracy of forecasts, one must know not only the magnitude of the initial errors but also their rate of growth with time. The analysis errors may be regarded as perturbations on the real field. The growth of these perturbations will then depend on the scale of the perturbations and on the meteorological condition [5, 8]. For any given atmospheric condition, as defined by

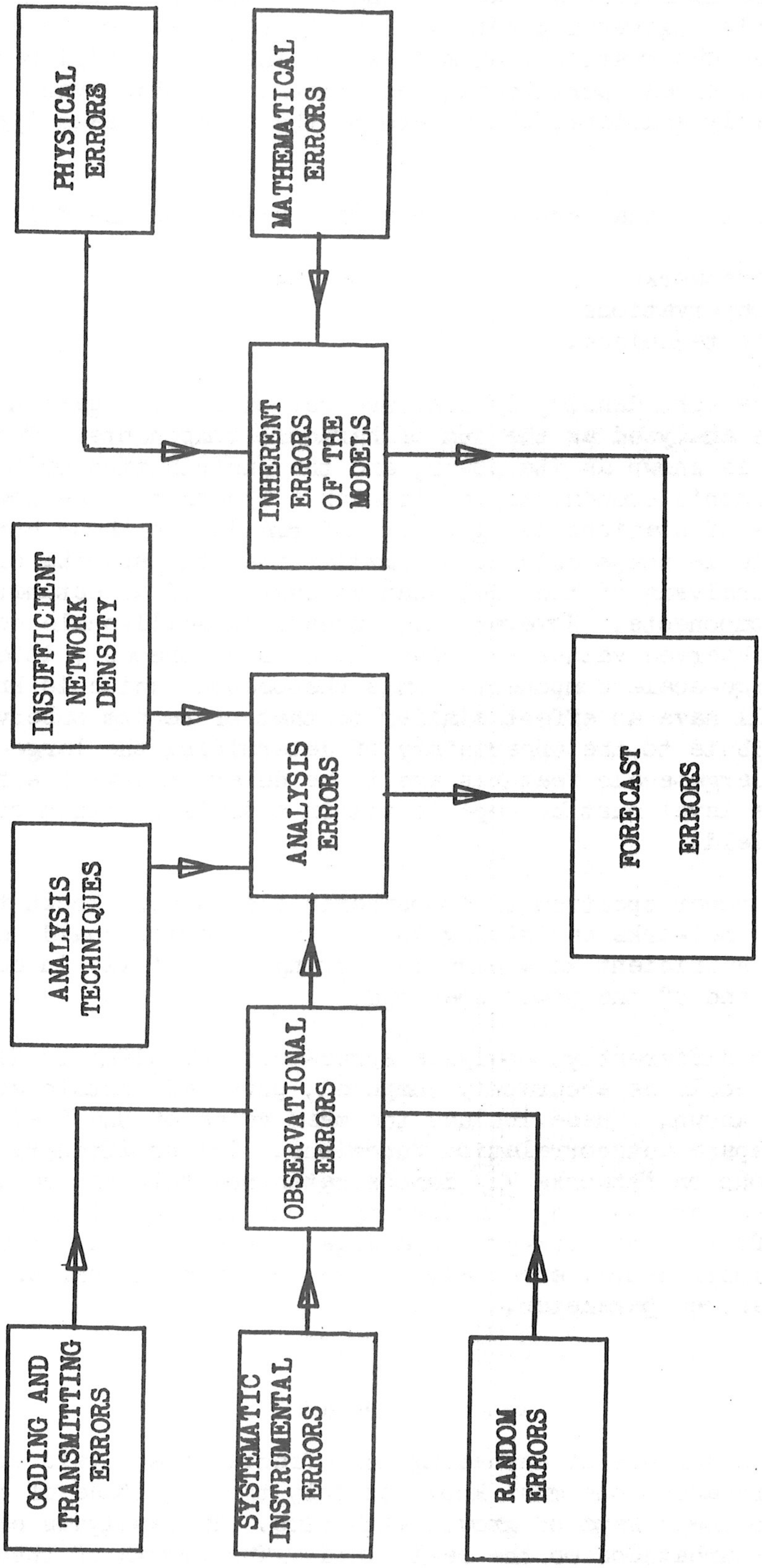

Fig. 1. Factors contributing to forecast errors.

the horizontal and vertical gradients of temperature, Thompson /8/ has shown that perturbations of a scale larger than a critical wavelength will amplify while those of a smaller scale die out. Thus, network density affects forecast accuracy in a dual manner since it determines both the magnitude of the initial analysis errors and the growth of these errors with time. It is possible that a network which is dense enough to produce an analysis with comparatively small initial errors may yet be inadequate to insure a sufficiently slow rate of growth of these errors.

In principle, it would be possible to estimate network densities corresponding to acceptably slow rates of error growth provided one possessed the necessary statistics concerning the frequency with which conditions characterized by different values of the horizontal and vertical temperature gradients occurred. Again, such statistics are not available except to a very limited extent.

PHYSICAL AND MATHEMATICAL ERRORS

Another consideration which must be taken into account in evaluating network requirements is the capability of the forecasting models to utilize the information provided by the networks.

An aerological network is satisfactory if it defines the initial fields with sufficient accuracy so that the initial condition errors form only a minor part of the total forecast errors. Inherent in each numerical forecasting model are two main sources of error: (a) the physical errors which are due to the particular simplifications of the governing equations and boundary conditions made in the model, and (2) the mathematical errors which arise primarily from the replacement of the differentials by finite differences.

There is no basis for making direct estimates of all the physical and mathematical forecast errors of different models /3/.

In summary, accurate direct determination of initial analysis errors and their growth with time depend on the existence of worldwide statistics of the state and variability of the atmosphere. In the absence of such information present estimates have been based on limited statistics which, in general, may not be representative of the atmosphere. The ratio of these errors to the total forecast errors of different forecasting models must be obtained by experimentation.

The present experiments were designed to circumvent the obstacle to an accurate determination of global network requirement arising from the insufficient statistical information on the structure and variability of the atmosphere.

EXPERIMENTAL PROCEDURES

The procedure intended for the experiments is best illustrated by Fig. 2. First of all, a reference atmosphere is defined. Ideally, this reference atmosphere should be hypothetical, but meteorologically realistic. This would guard against biasing the results by any particular density or configuration of actual observations. One way of achieving this would be to use a forecast

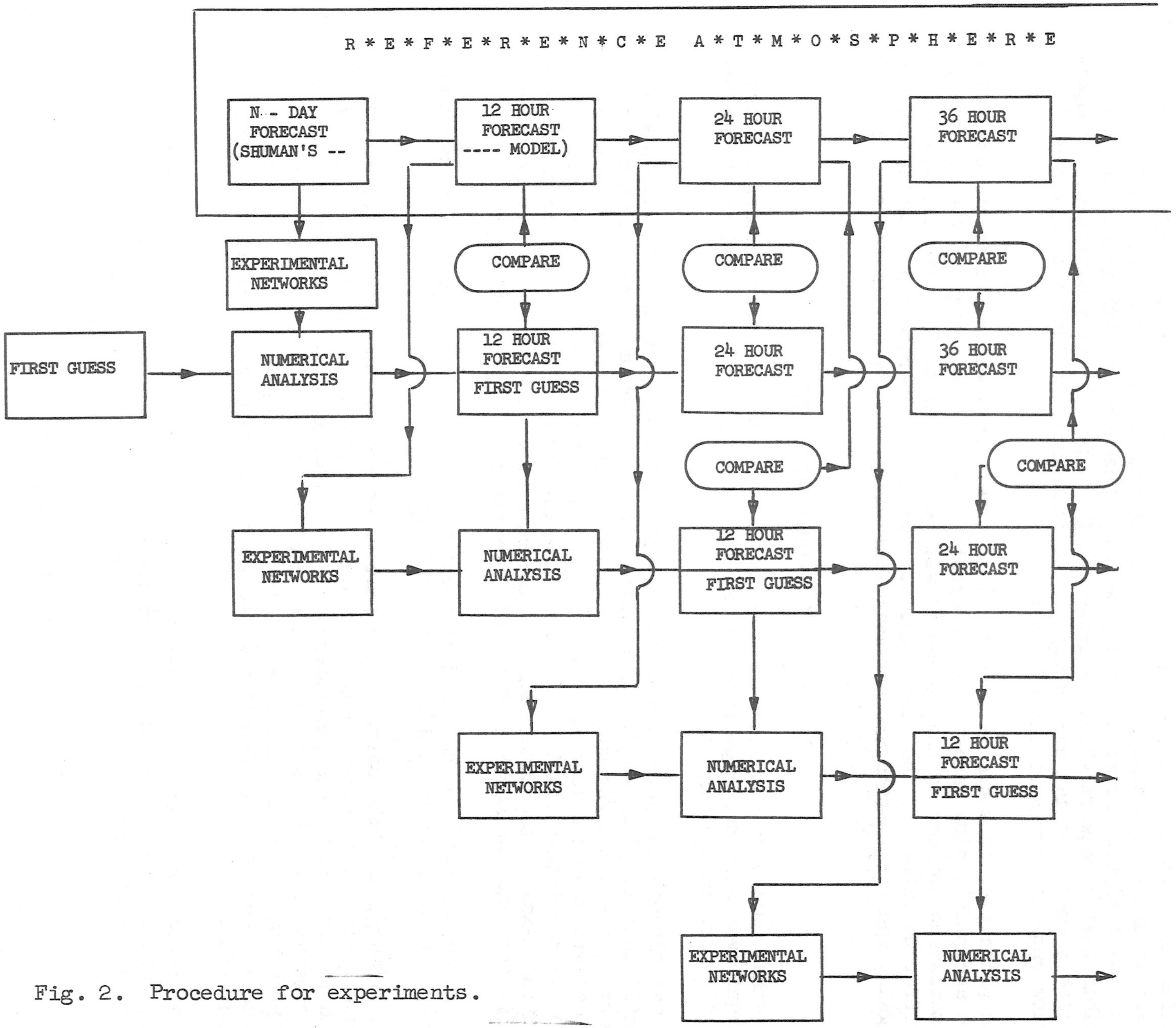

Fig. 2. Procedure for experiments.

of an actual weather situation. The intention is to run 72-hour forecasts of selected historical situations with the Shuman primitive equation model [7]. These forecasts then serve as initial conditions for the experiments. From these initial conditions forecasts are run for 12, 24, 36, 48 and 72 hours with two different models - the so-called "Mesh" model [4], which is essentially a barotropic model, and Shuman's primitive equation model. The initial conditions, together with the forecasts, represent a reference atmosphere which will provide a data source for the experiments and against which results will be compared.

The initial conditions of the reference atmosphere are made up of 1977 grid-point values about 3.5° Lat. apart near the pole and 2.5° Lat. at the southern edge. This is the same grid as used in the National Meteorological Center of the Weather Bureau. In defining the reference atmosphere, the assumption is implicitly made that this network is better than any foreseeable actual network and that the forecasts produced by this network are for all intents and purposes the best that any particular model can produce.

Starting with the initial condition of the reference atmosphere as a data source, an experimental network is extracted. Then, with the help of a suitable first guess, a numerical analysis is performed. From this analysis forecasts are made and compared with the corresponding reference forecasts. Next, the 12-hour reference forecast is used as a data source and the same experimental network extracted from it. Then, using the 12-hour forecast from the previous experimental network as a first guess, a numerical analysis is performed and forecasts of varying periods are run and compared with the corresponding reference forecast. The experiment is continued by taking successive reference forecasts as data sources and performing the same procedure. Since, for a given network, errors in prediction are a function of the state of the atmosphere [5, 8], several historical cases distributed over the different seasons will be used in initiating the reference atmosphere in an effort to determine the extent of the effect of varying meteorological conditions on the results. Identical experiments will be run with the Mesh model and the primitive equation model to determine the sensitivity of network variations to models of varying degrees of refinement.

The successive experimental networks are designed to be of an increasing order of complexity. The following are some of the questions to which answers will be sought:

(a) The manner in which variation in density of observations of a regular array of perfect observations affect the error field in hemispheric forecasting;

(b) The manner in which errors in the observations modify the above results;

(c) The effects on the error field resulting from the uneven distribution of observations.

(d) The extent of the diminution of the error fields resulting from various augmentations to the present networks, especially over oceanic and desert areas;

(e) The extent to which very dense networks over continental areas like the U.S. are vitiated by oceanic areas of comparative data void;

(f) The possibility of exchanging frequency for density of observations;

(g) The extent to which meteorological satellite systems, such as superpressure balloons monitored by satellites, can be used to augment conventional networks and the manner in which these systems are best incorporated in a unified scheme suitable for hemispheric or global numerical prediction.

SOME PRELIMINARY EXPERIMENTS

Pending the full operation of the CDC 6600 computer, which would enable the planned experiments to be performed, some preliminary experiments are being run following a slightly modified plan. This first series of experiments was based on the operational NMC analysis of the 500 mb and 850 mb charts for 00Z, 15 Nov 1962 together with the 12-hour forecasts for these charts. The analyses were used as the starting point for a 72-hour forecast run which produced forecasts 12, 24, 36, 48, 60 and 72 hours in advance. These analyses and forecasts, in the frame of reference of the experiments, were taken as the hypothetical atmosphere that the model was attempting to predict with varying data input. We call it the reference atmosphere. Definition of the reference atmosphere in this way is equivalent to assuming (a) that we have a perfect forecasting model and (b) that the atmosphere is relatively simple, being completely described by the barotropic-mesh model.

With a hypothetical network of 226 stations located at grid points evenly distributed over the NMC octagon-shaped grid, we simulated the operational use of the barotropic-mesh model. We used the NMC 12-hour forecast (500 and 850 mb) valid at 00Z, 15 Nov 1962, as the first guess. We simulated the input of rawinsonde reports of wind and height at 500 mb and 850 mb allowing no instrumental, observational, or reporting error from the 226 stations of the hypothetical network and processed the data through the analysis, balance and barotropic-mesh forecast programs (Run #1). Throughout the entire series the analyses, stream fields and forecasts were obtained with programs used operationally at NMC.

We then took the 12-hour forecast from Run #1 and used it as the first guess for the analysis at 12Z, 15 Nov 1962. We took the data for the 226 simulated reports from the reference atmosphere for that time and went through the same set of programs (Run #2). Runs #3 and #4 were effected similarly for initial times of 00Z and 12Z, 16 Nov 1962, in succession. Runs #1, #2, #3, #4 all used the same station network of 226 stations.

In the same manner and for the same times we made Runs #5, #6, #7, #8 using a network of 452 "stations" again on grid points and evenly distributed. However, instead of using the NMC forecasts for 00Z, 15 Nov 1962, as the initial first guess, we adjusted that forecast so as to obtain a first guess with a similar error pattern but with the magnitudes of the errors reduced by 25%. This was done on the expectation that with the better station density the first guesses would be better to that extent.

Runs #9, #10, #11 and #12 were similar to the above except that the density of stations was again doubled (906 stations); for the initial first guess we used the same error pattern with the magnitudes of the errors reduced to 50% of the errors of the operational first guess.

For Runs #13 through #16 we used a station network approximating the existing network with 356 stations irregularly distributed. The operational forecast was used as the first guess.

Runs #17 through #20 were designed to find the limits of accuracy of the analysis procedures. Almost all the grid points, except for boundary points, were used as reporting locations, 1769 stations in all. The first guess was again taken as the unadjusted operational 12-hour forecast. The purpose for using this relatively poor first guess was to examine the effect on the experiments of a poorly chosen first guess.

After examination of the results of the above runs it appeared from extrapolation of the analysis errors that the existing station network was roughly equivalent to 100 stations evenly distributed over the NMC grid. We therefore made Runs #21 through #24 with 118 stations evenly distributed over the grid, using the unadjusted operational analysis as the first guess, to determine whether the extrapolation was valid.

Fig. 3 presents the root mean square errors of heights at 500 mb of the analysis and 12-hour forecast for each run. The ordinate is the root mean square height error over the entire 1977-point grid, and the abscissa is the time of the analysis and the valid time for the forecast. For each set of four runs, a line connects the initial first guess, the first analysis, the first 12-hour forecast, the second analysis, the second 12-hour forecast, the third analysis, etc.

Some of the features of interest in Fig. 3 are:

(1) The initial first guess has, in all cases, a much larger error than the first guesses subsequently developed in each set of runs. This is a consequence of our simulation of a perfect forecasting model. The errors of the first guesses generated after the initial one were due solely to the error of the previous analyses, whereas the initial first guess had an implicit error due to the difference between the actual atmospheric mechanism and the barotropic-mesh model.

(2) The effect of using a first guess with an error about double what we should have is not evident beyond the first 12-hour forecast.

(3) The uneven distribution of 356 stations roughly representing the existing station network with some areas of dense coverage and large areas of very sparse coverage corresponds, at least for a "perfect" model, to an even coverage of fewer than 118 stations.

(4) The growth of error in going from analysis to 12-hour forecast varies within each set of runs. Further, there seems to be a parallelism among the several sets; presumably this reflects the variation within the 48-hour period of the flow pattern of the reference atmosphere and the relative locations

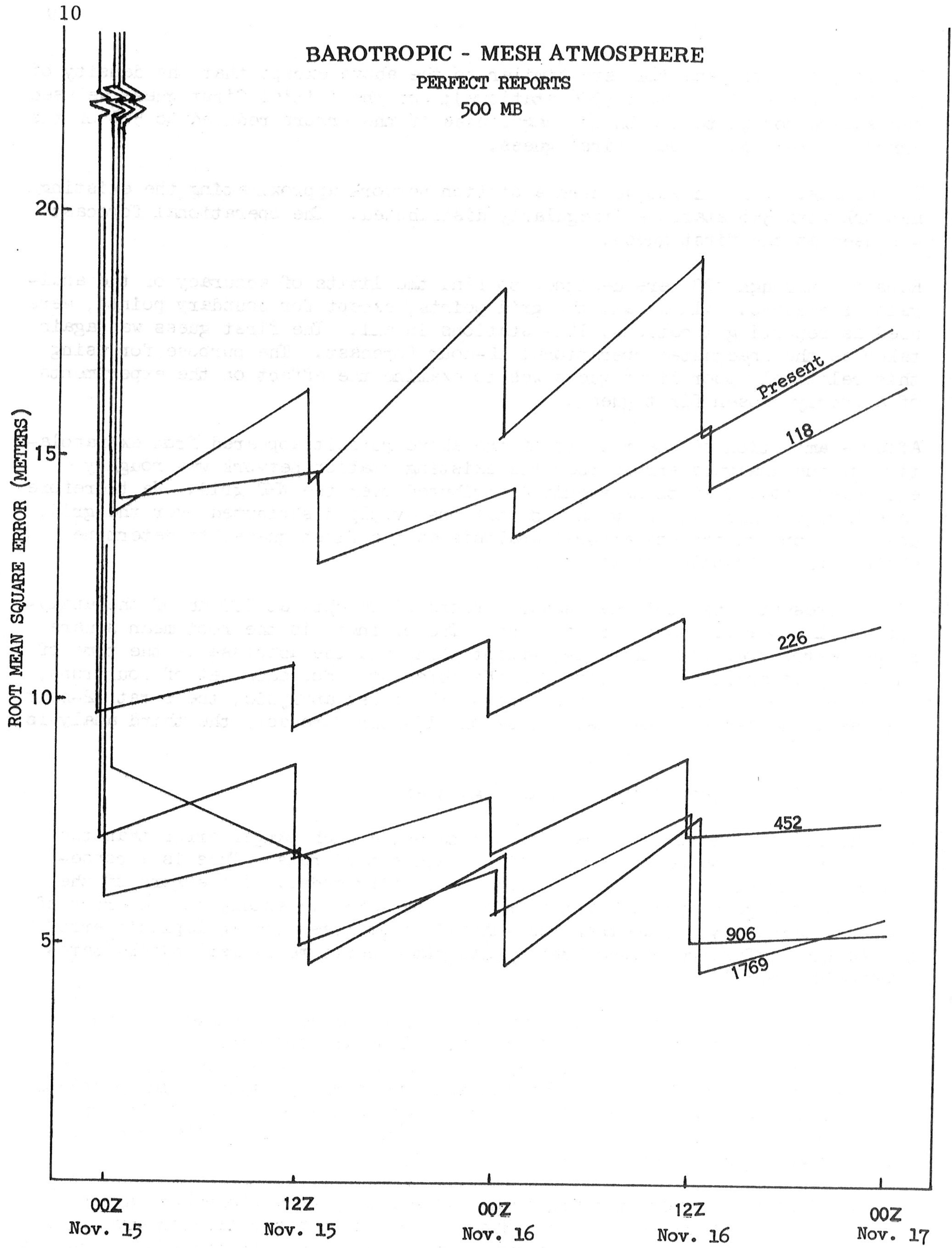

Fig. 3. Error analysis of network experiments.

of the flow pattern features and the error patterns.

(5) The runs using 1769 stations are no improvement over the runs with 906 stations. Evidently this is due to the fact that with 906 stations the model is already saturated with data. Each report contains three units of information for each pressure surface - two wind components and a height; thus, there are more than enough data in the 906-station runs to fully specify the 1977 grid-point values at each pressure surface in the model.

(6) The best analyses have a minimum root mean square error of 4.4 meters, even with 1769 stations. This error must be about the minimum attainable with the analysis program used. The analysis program is designed to process reports from the existing network with instrumental and reporting errors and a first guess from an imperfect model; thus it is deliberately designed not to fit the data exactly but rather to obtain a smoothed fitting of the first guess adjusted approximately by the reports.

(7) The first 12-hour forecast with 1769 stations is better than the first analysis with these stations. This may be taken as supporting Thompson's analysis of the suppression and amplification of short waves and long waves, respectively, by the forecast model.

Fig. 4 presents the variation of the root mean square error at 500 mb with respect to the number of simulated stations. Separate curves apply to the analysis and the 12-, 24- and 36-hour forecasts. Each curve represents the results of three runs for each station density, the initial run having been omitted in each case to avoid the effects of the unrepresentative initial first guesses. The curves relating the errors to the density of stations are exponential, as one intuitively would expect. According to these curves, reducing station separation below about 600-700 km would result in very little additional reduction of the mean error. The curves were extrapolated to the mean error of the present network, which is shown to be equivalent to that corresponding to a uniform distribution of stations about 1600 km apart.

CONCLUSIONS

In drawing conclusions from the series of experiments described in this preliminary report one must bear in mind its limitations:

(a) We have assumed that the forecasting model is perfect by forcing the reference atmosphere to conform with it. Runs will have to be made with the real atmosphere, as best we know it, to evaluate this limitation.

(b) We have generated perfect reports, permitting no instrumental or reporting errors; furthermore, we have forced the observations to be representative, allowing for no short wave variations which would introduce noise into the system.

(c) We have treated only one 48-hour event. Certainly some of the results are characteristic of this event, as distinguished from a representative sample of events from different seasons and regimes.

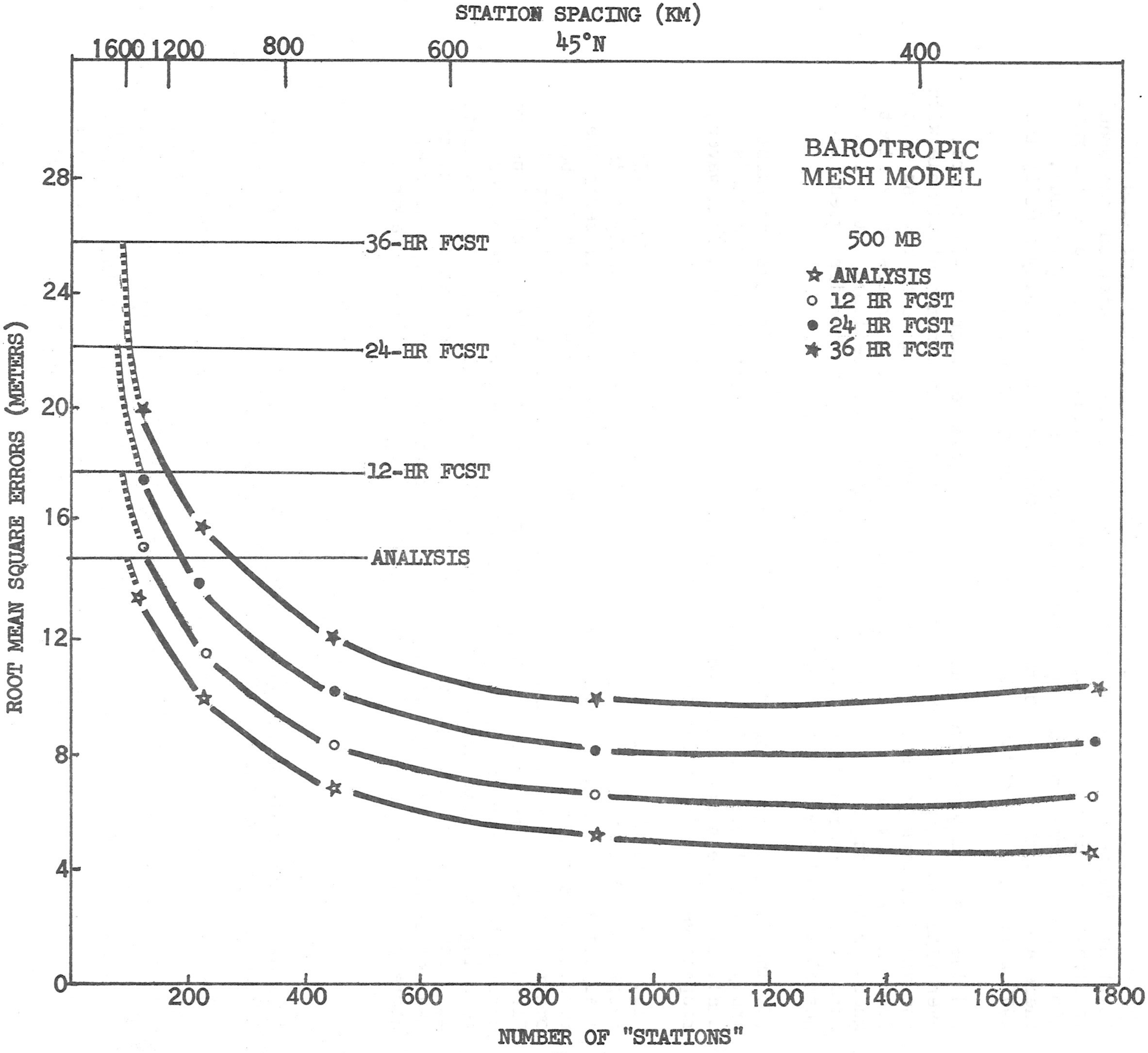

Fig. 4. RMS error vs number [illegible]ations or station spacing.

(d) Our measure of goodness of the analyses and forecasts has implicitly been taken as the root mean square error over all 1977 grid points of the model, equally weighted. This gives southerly areas an excessive influence on our results. To remove this limitation, we shall shortly resummarize the errors in harmonic components by latitude.

(e) The initial conditions for the event we studied in this experiment are highly influenced by the existing station distribution. For subsequent experiments we plan to avoid this limitation by using as initial conditions a situation developed after an extended run of the primitive equation model.

REFERENCES

1. J. Bessemoulin *et al*., "Rapport Préliminaire du Groupe de Travail de la Commission de Météorologie Synoptique sur les Réseaux," *Note Technique No. 30*, Organisation Météorologique Mondiale, Geneve, Suisse, 1960, 91 pp.

2. J. G. Charney, "The Feasibility of a Global Observation and Analysis Experiment," *NAS-NRC Publication No. 1290*, 1966.

3. A. Eliassen, J. S. Sawyer and J. Smagorinsky, "Upper Air Network Requirements for Numerical Weather Prediction," *Technical Note No. 29*, World Meteorological Organization, Geneva, Switzerland, 1960, 15 pp.

4. H. W. Elsaesser, "JNWP Operational Models, August. 1958 to Advent of IBM 7090 (1960)," *JNWP Office Note No. 15* (revised), U.S. Weather Bureau, Washington, D.C., 1960, 37 pp.

5. E. N. Lorenz, "A Study of Predictability of a 28 Variable Atmospheric Model," *Tellus*, vol. XVII, No. 3, 1965, pp. 321-333.

6. Panel on Observations over Sparse Data Regions, "Plan for Meeting Meteorological Observation Requirements over Sparse Data Regions," *Technical Planning Study No. 1*, U.S. Weather Bureau, Washington, D.C., 1963, 51 pp.

7. F. G. Shuman, "A Multilevel Primitive Equation Model," National Meteorological Center, U.S. Weather Bureau, Washington, D.C., Unpublished Manuscript, 1965, 21 pp.

8. P. D. Thompson, "Uncertainty of Initial State as a Factor in the Predictability of Large Scale Atmospheric Flow Patterns," *Tellus*, vol. IX, No. 3, 1957, pp. 275-295.

9. R. M. White, "The World Weather System - A Frontier in Geophysics," *Bull. American Meteorological Soc*., vol. 46, No. 10, October 1965, pp. 623-628.