NO. 13

WESTERN REGION TECHNICAL MEMORANDUM

A Collection of Technical Attachments on the 1966 NMC Primitive-Equation Model

by

Leonard W. Snellman

AUGUST 1966

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

U. S. WEATHER BUREAU

Western Region Technical Memoranda:

No. 1 "Some Notes on Probability Forecasting" by Edward D. Diemer

No. 2 "Climatological Precipitation Probabilities" compiled by Lucianne Miller

No. 3 "Western Region Pre- and Post-FP-3 Program" by Edward D. Diemer

No. 4 "Use of Meteorological Satellite Data"

No. 5 "Station Descriptions of Local Effects on Synoptic Weather Patterns" by Philip Williams, Jr.

No. 6 "Improvement of Forecast Wording and Format" by C. L. Glenn

No. 7 "Final Report on Precipitation Probability Test Programs" by Edward D. Diemer

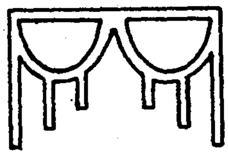
No. 8 "Interpreting the RAREP" by Herbert P. Benner

No. 9 "A Collection of Papers Related to the 1966 NMC Primitive-Equation Model"

No. 10 "Sonic Boom" by Loren Crow (6th Weather Wing, USAF, Pamphlet)

No. 11 "Some Electrical Processes in the Atmosphere" by J. Latham

No. 12 "A Comparison of Fog Incidence at Missoula, Montana, with Surrounding Locations" by Richard A. Dightman



A Western Indian symbol for rain. It also symbolizes man's dependence on weather and environment in the West.

This paper has been printed as manuscript in limited quantity for preliminary use. As this reproduction does not constitute formal scientific publication, any reference to the paper in published articles and scientific literature should identify it as a manuscript of the U. S. Weather Bureau Western Region.

Western Regional Technical Memorandum No. 13, August 1966

A COLLECTION OF TECHNICAL ATTACHMENTS ON THE 1966 NMC PRIMITIVE EQUATION MODEL

Leonard W. Snellman

TABLE OF CONTENTS

LIST OF FIGURES

(No figure numbers are given in this listing, because the original numbers are used. These are not consecutive.)

A COLLECTION OF TECHNICAL ATTACHMENTS ON THE 1966 NMC PRIMITIVE EQUATION MODEL

Leonard W. Snellman

I - INTRODUCTION

This memorandum is a collection of Technical Attachments to the Western Region Staff Minutes on the 1966 NMC 6-Level* Primitive-Equation Numerical Weather Prediction (P.E.) Model. The purpose of these Technical Attachments was to give Western Region forecasters an up-to-date understanding of the P.E. Model. A special effort was made to keep mathematical notation to a minimum.

The author's guiding policy in preparing these Attachments was that stated by Sir Graham Sutton, former Director of the British Meteorological Office, in his 1955 article, "High-Speed Computing and the Operational Meteorologist". This was written about the time operational NWP forecasting was begun at the U. S. National Meteorological Center:

"If the development of numerical forecasting follows a normal course, the present simple methods will be replaced by more complicated schemes as time proceeds. Such advances must make it increasingly difficult for those outside the circle of the mathematicians to understand precisely what is being done, but this must be accepted as inevitable. This, of course, is not to say that ultimately the mathematician rather than the physicist will be the operational forecaster. It is unnecessary now (and it will continue to be so) for all meteorologists to be intimately acquainted with the details of the process by which the equations are solved. But if full use is to be made of the new tool, it is essential to know precisely what is included and what is retained in the basic postulates and these are far more important than the techniques used to produce the result."

An earlier statement in Dr. Sutton's paper is of interest and still true:

"The actual process of calculation by a digital computer is complicated and the equations used have an unfamiliar look because of the necessary transformations, so that it is not an easy task, from a perusal of the published papers, to see precisely what is being done."

The sequence of the Technical Attachments in this memorandum is not chronological. Rather, the Attachments have been arranged as much as possible to include discussions on initial data procedures and analysis techniques followed by discussions of the physics and performance of the model. Some clarifications, additions, and corrections have been made to the original Attachments.

These Technical Attachments have been consolidated and published as a Technical Memorandum for easy reference and as a companion publication to Western Region Technical Memorandum No. 9, "A Collection of Papers Related to the 1966 NMC Primitive-Equation Model".

*NMC now refers to the P.E. model as the "6-Layer" rather than the "6-Level Model".

II - SIGMA SURFACES: A REPLACEMENT FOR CONSTANT-PRESSURE SURFACES

This is the first of several Technical Attachments describing the general features of the NMC 6-level primitive-equation model that will soon be operational. The purpose of these discussions is to acquaint forecasters with the principles, assumptions, etc., involved. Further details are given in the listed references.

The NMC primitive-equation model uses the height fields of six "sigma" surfaces to specify the initial state of the atmosphere. This Attachment discusses the "sigma" surface and its use in numerical weather prediction (NWP).

In 1957, Phillips [1] proposed that in some NWP models the vertical coordinate in the $\bar{X}$, $\bar{Y}$, P, T coordinate system should be changed from pressure to a ratio of pressures $\frac{P}{Ps}$, where Ps is station pressure. He called this ratio SIGMA, i.e., $\sigma = \frac{P}{Ps}$. Phillips was motivated into looking for a new vertical coordinate by the difficulties dynamic meteorologists were encountering in formulating NWP models near the ground. Sea-level and 1000-mb charts were not acceptable due to fictitious flow patterns that resulted from using computed sea-level pressures over higher terrain.

Replacing pressure by sigma, as defined above, helps remedy this difficulty since the earth's surface is a sigma surface, $\sigma = 1$. With the ground as a coordinate surface, the atmospheric motion near the surface of the earth is better specified in the dynamic equations.

Sigma surfaces have not been used in the 3-level filtered vorticity NWP model (i.e., the current operational baroclinic model) because the expression for vorticity using sigma as the vertical coordinate is more complex than for pressure. Also, the lowest input data of the current 3-level model is 850 mb.

Consequently, the advantages of using sigma were outweighed by the disadvantages of additional computation time. Such is not the case when a primitive-equation model is used. First of all, the vorticity expression is not used in the primitive-equation scheme; and second, the 6-level NMC model includes initial data below the 850 mb surface.

To get some feeling for this new sigma surface, it may be helpful:

1) To write the expression for a constant-pressure height gradient in terms of a sigma-surface height gradient.

$$\left.\frac{\partial z}{\partial x}\right)_p = \overset{A}{\left.\frac{\partial z}{\partial x}\right)_\sigma} - \frac{\sigma}{P_s}\overset{B}{\frac{\partial P_s}{\partial x}}\overset{C}{\frac{\partial z}{\partial \sigma}}$$

$)_p$ indicates the height gradient is on a constant-pressure surface;
$)_\sigma$ refers to a sigma surface.

Note that in addition to the sigma-surface height gradient (term A), the gradient of the station pressure, which takes into account the slope of the terrain (term B), and the change of height with respect to sigma (term C), are included in the expression. (See Figure 1 for a comparison of a constant-pressure surface and constant-sigma surface when $\left.\frac{\partial z}{\partial x}\right)_p = 0$).

2) To investigate the changes of pressure that take place on a sigma surface in mountainous terrain. Let us assume that a sigma surface, $\sigma = 2/3$, overlies a simple mountain range approximately 10,000 feet high and that no horizontal pressure-gradients exist (Figure 1).

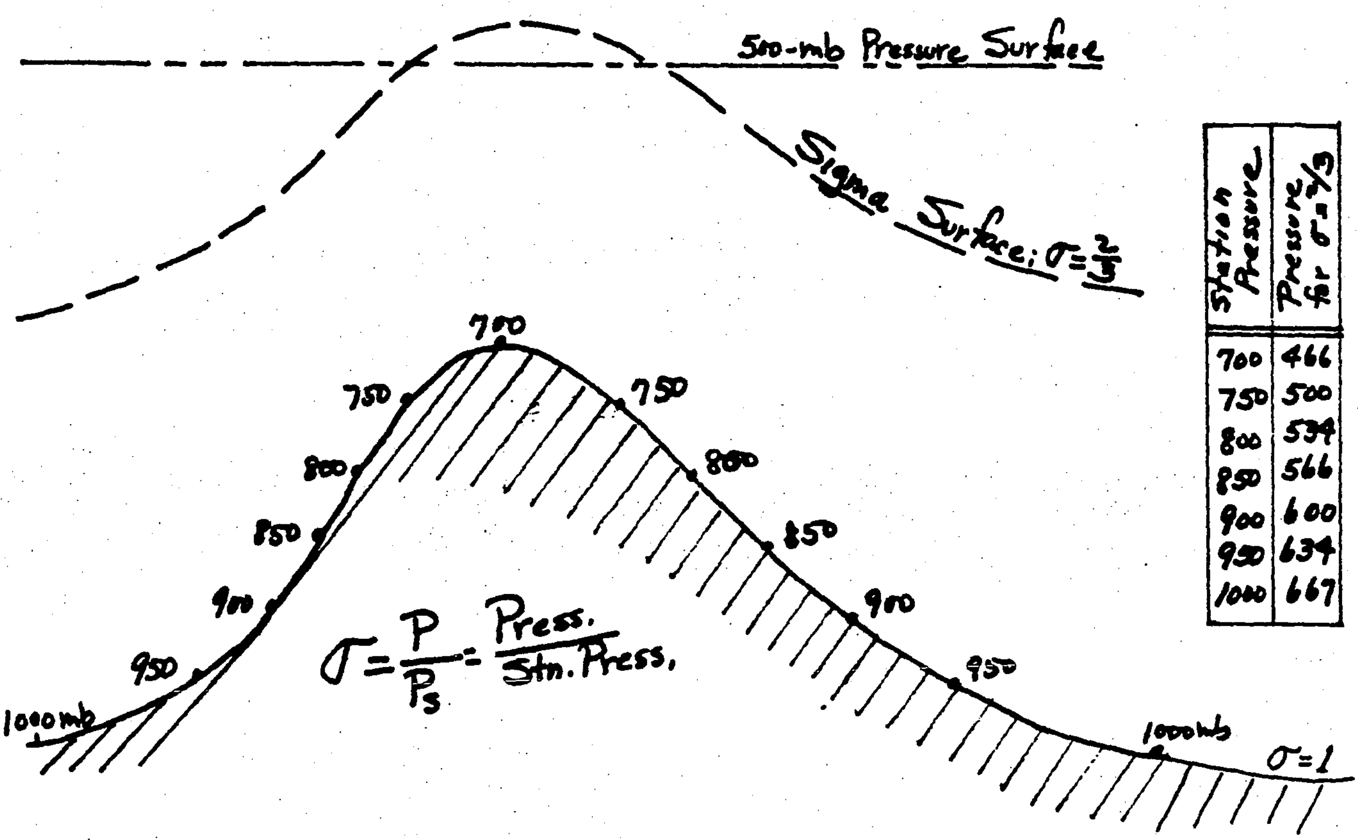


Figure 1 - Schematic Diagram illustrating the slope of a sigma surface over a smooth mountain assuming no horizontal pressure-gradient. $\sigma = 2/3$

Under these assumptions, the slope of a sigma surface is greatest at the ground ($\sigma = 1$) and decreases with altitude.

NMC PRIMITIVE EQUATION (P.E.) MODEL

The NMC 6-level P.E. model [2] defines sigma differently in the troposphere and stratosphere, but in both cases sigma is only slightly different than Phillips' definition. In the troposphere, sigma is defined as:

$$\sigma_T = \frac{P - P_T}{(P_S - 100) - P_T}$$

Where P_T is the pressure at the tropopause and P_S is station pressure.

In the stratosphere, sigma is defined as:

$$\sigma_S = \frac{P - P_O}{P_T - P_O}$$

Where P_O is a pressure in the lower stratosphere (e.g., near 100 mbs)

Sigma defined in this way assures that a pressure surface near the earth, the tropopause, and a pressure surface in the lower stratosphere are always sigma surfaces in this model. Thus, the new NMC P.E. model contains a separate troposphere and stratosphere for the first time. The other sigma surfaces used are indicated in Figure 2. The surface of the earth used in this model is a smoothed profile suggested by Berkofsky and Bertoni [3]. The lowest sigma surface in the NMC model is not the earth's surface, but 100 mbs above the ground, thereby making provision for a boundary layer (see Figure 2).

The initial input data needed are the height fields of the six sigma surfaces. These data are obtained by interpolation from tropopause and standard constant-pressure data. The tropopause data are derived by a method developed by Gustafson [4], which uses potential temperatures and recognizes the existence of the polar, middle, and subtropical tropopauses. The constant-pressure surfaces used are 1000, 850, 700, 500, 400, 300, 250, 200, 150, and 100 mb.

Once the heights of the σ-surfaces have been found and the potential temperatures therefrom determined, the initial wind distribution is specified by use of the balance equation, and the prediction computations are begun. At the end of specified prediction periods (e.g., 12, 24, and 36 hours), similar interpolation procedures are used for preparing the familiar prognostic constant-pressure charts and vorticity fields. Thus, the model is capable of producing prognostic charts from 1000 mb up to 100 mb. There are no immediate plans to change operational upper-air charts from constant-pressure to constant-sigma charts, but it is a change we may witness in the future.

REFERENCES:

1) N. A. Phillips, "A Coordinate System Having Some Special Advantages for Numerical Forecasting", _Journal of Meteorology_, April 1957, Page 184.

2) E. B. Fawcett, "The Six-Level Primitive Equation Model", Manuscript, Note to NMC A F and D Forecasters, March 3, 1966, reprinted in WR Technical Memorandum No. 9.

3) L. Berkofsky and E. A. Bertoni, "Mean Topographic Charts for the Entire Earth", Bulletin of AMS, September 1955, Page 350.

4) A. L. Gustafson, "Objective Analysis of the Tropopause", NMC Technical Memorandum No. 33, 1965, reprinted in WR Technical Memorandum No. 9.

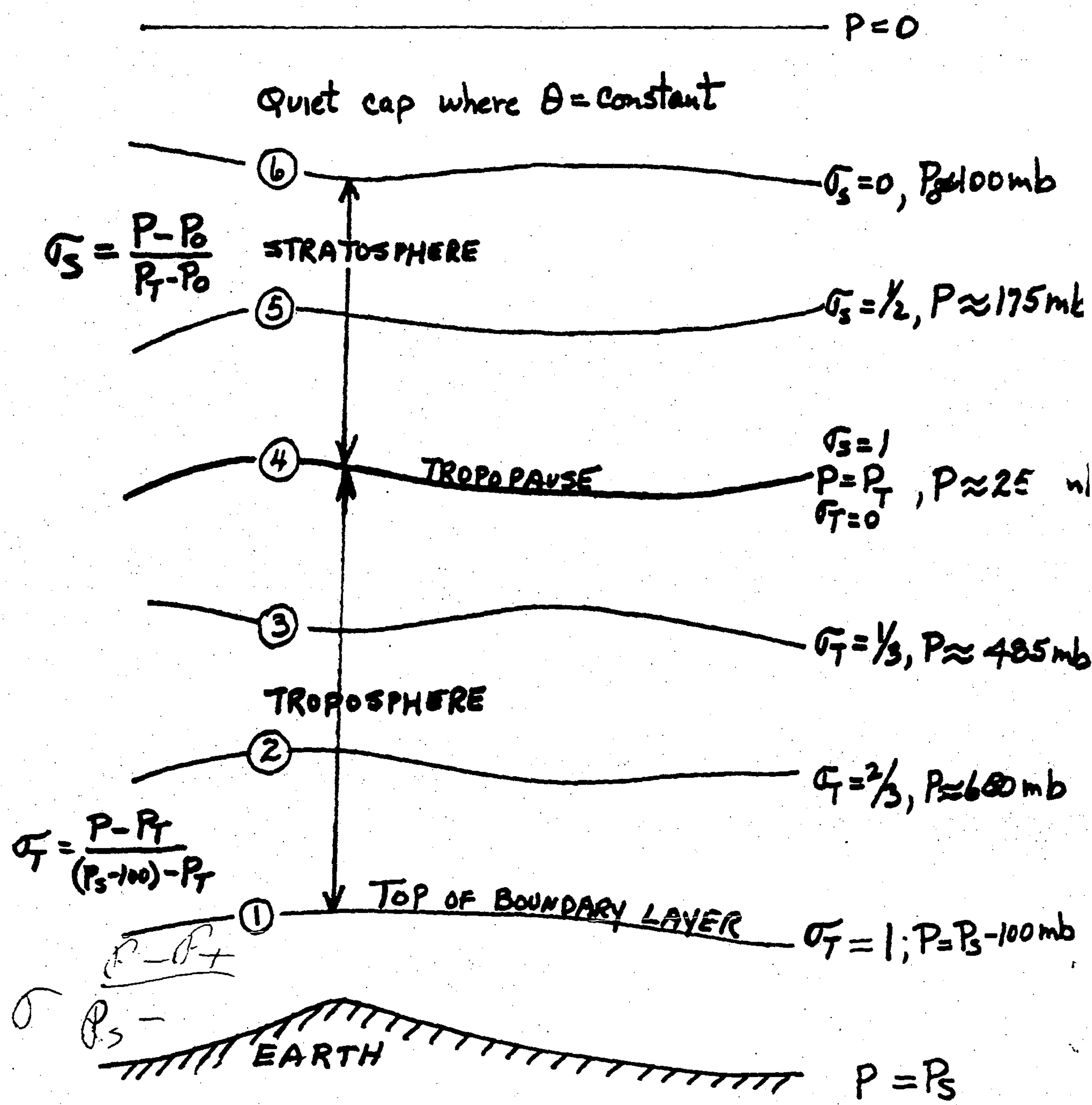


Figure 2 - Schematic Diagram of σ-surfaces used in Six-Level NMC Primitive Equation Model. Circled numbers indicate σ-surfaces used (after Fawcett [2]).

WESTERN REGION TECHNICAL ATTACHMENT
June 7, 1966
No. 66-15

III - THE PHYSICS OF THE NMC PRIMITIVE EQUATION MODEL

This is the second in a series of Technical Attachments on the NMC Primitive Equation Model. This discussion will cover the basic physical principles involved and the forecast procedure used.

The title, "Primitive Equation Model", comes from the use of the "raw" or "primitive" equations of motion, i.e., Newton's Second Law of Motion:

Force = Mass times acceleration, or F = ma

In the P.E. model, the forces involved are: 1) Pressure gradient, 2) Coriolis, and 3) Friction (in boundary layer only). The resultant of these forces determines the acceleration of an air parcel. Prior to the introduction of the NMC P.E. model, the primitive equations of motion were not used in operational NWP models, because dynamic meteorologists thought the accelerations of the atmosphere could not be evaluated accurately enough.

To the synoptic meteorologist, this is another way of saying that data are not sufficient or accurate enough to determine the pressure and wind fields separately. The NMC barotropic and three-level baroclinic models got around this difficulty by using the vorticity equation and an equivalent of the gradient-wind equation in place of the primitive equations of motion and the continuity equation. This is one major difference between the P.E. model and the familiar NMC barotropic and baroclinic models; i.e., the P.E. does not use the vorticity equation in the forecast procedure.

Sound and gravity waves can exist in the Newtonian equation of motion. Thus forecast procedures involving these equations must either filter out the unwanted sound and gravity waves or keep them under control so that they don't adversely affect the meteorological predictions. The sound waves are easily eliminated in both the vorticity and primitive equation models by assuming hydrostatic equilibrium, i.e., using the hydrostatic equation (for details see [1] Page 51 - 55).

The gravity waves can be eliminated by assuming either geostrophic balance or the more general condition of nondivergent wind fields as computed from the so-called "balance" equation. In the case of the NMC vorticity models, "balanced" conditions are continued throughout the forecasting procedure, so no gravity waves can exist in these models. This restriction has led to calling them "filtered" models.

The P.E. model is quite different in this regard in that no "balance" restriction is imposed <u>except</u> at the start of the forecast procedure. This initial balanced condition is necessary due to deficiencies in input data discussed earlier. Errors in the initial acceleration terms would be interpreted by the P.E. model computer program as large gravity waves, and the resulting forecast would "blow up". However, the forecast procedure permits gravity waves to develop, but they are kept under control. Learning to handle gravity waves during the forecast was a major breakthrough in numerical weather prediction and one in which Dr. Shuman of the NMC had a pioneering role.

With high-speed (up to 600 kts) gravity waves capable of being generated during the P.E. model forecast procedure, the time interval between forecasts has had to be reduced from an hour as used in the NMC vorticity models to 10 minutes. (For details, see [1], Pages 17, 74 - 75.) Consequently, another significant difference between the familiar vorticity models and the P.E. model is the number of forecasts that have to be computed to get 12-, 24-, and 36-hour forecasts. For a 24-hour forecast, 144 P.E. forecasts (time steps) must be computed as compared to only 24 time steps in the barotropic and baroclinic models. This large increase in computations, due to shorter time steps and more input data surfaces, requires a larger and faster computer than the NMC IBM 7094II if P.E. forecasts are to be produced in time to meet current facsimile deadlines. This computer requirement has delayed the introduction of operational P.E. model forecasts until the new CDC 6600 computer was installed and working at NMC. Even so, the present P.E. model requires about 70 minutes on the CDC 6600 to produce a 36-hour forecast, as compared to 50 minutes on the slower IBM 7094II for the NMC three-level baroclinic model.

THE PRIMITIVE EQUATION MODEL FORECAST PROCEDURE:

The state of the atmosphere is specified by the height fields of six "sigma" surfaces [2] with a 100-mb boundary layer at the bottom, and an initially quiet ($u = v = o$) isentropic (θ = constant) cap at the top (see Figure 1). Initially, as stated above, the motion field and mass field are forced into balance by use of the "balance" equation, i.e., nondivergent winds are computed for all the sigma surfaces. The initial known variables used are the mean-wind components and potential temperatures (θ) for each layer between sigma surfaces.

For simplicity of explanation, we will assume that the pressure field is known at the top sigma surface. The equation of continuity is then used to compute the 10-minute pressure change at the next lower sigma surface, using the mean-wind field in the layer between the sigma surfaces. This gives new pressures on the lower sigma surface. The procedure is repeated for the next sigma layer, and so on until new pressures are obtained for all sigma surfaces. With all the pressure tendencies known, the necessary vertical motions are computed from a form of the continuity equation.

Once the new pressures have been computed, new heights for all the sigma surfaces can be computed working up from the ground using the hydrostatic equation, and the new mean θ 's for each layer are obtained from the thermodynamic (θ) equation. The mean wind and temperature changes for the 10-minute period are then computed using the equations of motion (see [3] Fawcett paper for equation). The changes are added to the original values, and the new values are used to start the procedure over again.

Every three hours, starting with t_o + 6 hours, the winds and temperatures for each sigma surface are computed from the forecast mean-winds and temperatures. From these, the constant-pressure winds and temperatures are obtained by interpolation.

While this forecast procedure sounds rather simple, there are many sophisticated and complex techniques involved in some of the steps. The details of these techniques, while of utmost importance in the preparation of the forecast, will not be discussed here. It is important to note, however; 1) that the θ -equation includes provision for heating from the earth's surface and in a few months radiation cooling will be introduced; 2) that the equations of motion include a friction term for the boundary layer, so the bottom of the model is really at the earth's surface; 3) that there are no moisture terms, i.e., a dry atmosphere is assumed. This assumption is expected to be relaxed this fall when moisture is introduced into the model by integrating results of the SLYH [4] moisture forecasts into the latent-heat computations. Discussion of these terms and the vertical-motion forecasts will be taken up in subsequent technical attachments.

References:

[1] P. D. Thompson, "Numerical Weather Analysis and Prediction", Book, MacMillan, 1961.

[2] "Sigma" Surface--a Replacement for Constant-Pressure Surfaces", Western Region Technical Attachment to Staff Minutes, May 24.

[3] E. B. Fawcett, "The Six-Level Primitive Equation Model", reprinted in Western Region Technical Memorandum No. 9, June 1966.

[4] M. H. Kulawiec, "Local Cloud and Precipitation Forecast Method" (SLYH) Technical Note 13-Fcst-2, September 1965.

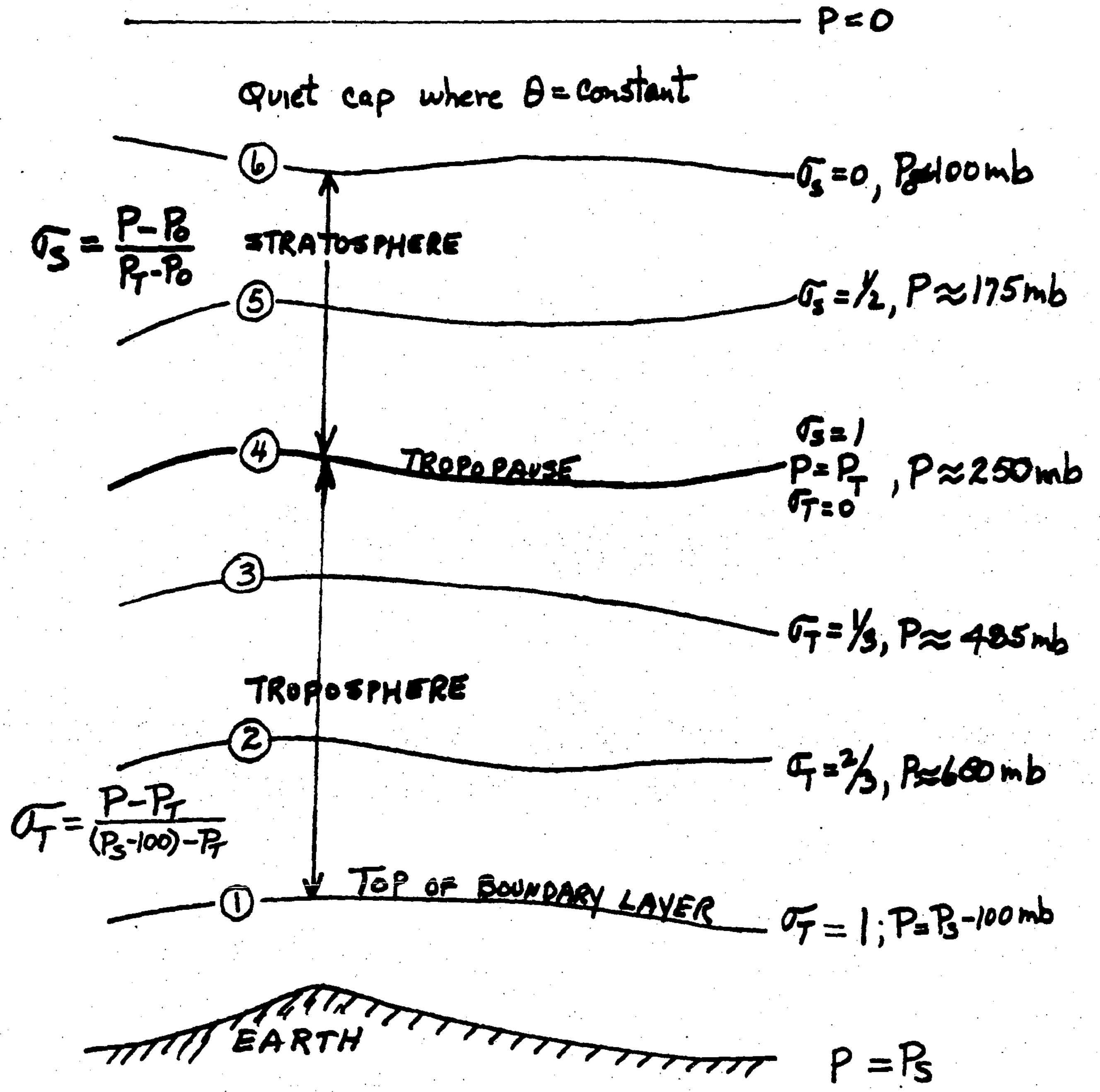


Figure 1 - Schematic Diagram of σ-surfaces used in Six-Level NMC Primitive Equation Model. Circled numbers indicate σ-surfaces used (after Fawcett [3]).

WESTERN REGION TECHNICAL ATTACHMENT
June 14, 1966
No. 66-16

IV - THE CONSTRUCTION AND USE OF NMC PRIMITIVE EQUATION MODEL VORTICITY CHARTS

Vorticity charts based on the NMC Primitive Equation (P.E.) Model have a character quite different from those based on the barotropic and 3-level baroclinic models. This technical attachment discusses the reasons for this difference.

As has been pointed out in previous Technical Attachments (May 24 and June 7), the new P.E. Model does not use constant-pressure surface data or vorticity in the actual forecast procedure. Therefore, any vorticity field that is produced from the P.E. Model for the 500-mb surface is done as an "extra duty", so to speak. This present "extra duty" procedure results in a vorticity field that is noticeably smoothed as compared to the vorticity fields produced by the barotropic or 3-level models (see Figure 1).

Our limited experience with the P.E. Model suggests that it is so smooth that some of the operational usefulness of indicated vorticity advection patterns in local short-range forecasting has been lost. For example, we have been using the indicated vorticity-advection patterns (1) to add detail to the 500-mb flow in locating small amplitude short-wave troughs and ridges; and (2) to indicate likely areas of significant vertical motion (e.g., positive vorticity advection has an excellent relationship to upward vertical motion and thus with middle and high cloudiness). Note in Figure 1 that the two short-wave troughs in the central part of the United States indicated on the barotropic panel are merged into one trough on the P.E. initial panel. The reason for the significant difference between these two initial vorticity fields is found primarily in the different procedures used to compute the vorticity distribution.

The procedure for obtaining vorticity fields in the P.E. Model for a constant-pressure surface, such as 500 mb, is as follows:

1. The height and temperature fields from ten analyzed constant-pressure surfaces are interpolated to get the height fields of the six sigma surfaces used in the P.E. Model.

2. The height fields of the sigma surfaces plus the "balance equation" are used to get a stream-function field from which the wind field for each sigma surface is computed.

3. The sigma-surface winds are then interpolated back to the 500-mb pressure surface as u and v components.

4. The vorticity is computed from these interpolated wind components. It is this vorticity field that appears on

the initial panel of the facsimile transmission. The forecast vorticity fields are obtained by interpolation from the forecast sigma-surface wind fields.

There are two places in this procedure where significant smoothing could enter: (1) during the step of getting the heights for the sigma surfaces by interpolation from constant-pressure charts; and (2) by the introduction of significant truncation errors when obtaining the sigma-surface wind field from the height field. When you compare this circuitous procedure to the simple procedure used in the barotropic and 3-level baroclinic models,* it is easy to appreciate why the character of the initial vorticity fields may be quite different, even when the input constant-pressure height and temperature data are the same.

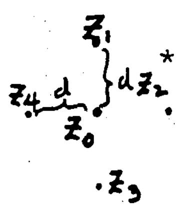
NMC computes the <u>initial</u> vorticity field for the P.E. vorticity facsimile transmission by the same method used to obtain the forecast vorticity fields in order to make all the vorticity panels of the facsimile transmission compatible.

For the present, we recommend that forecasters use the initial barotropic vorticity pattern when relating cloudiness to positive vorticity-advection areas. The P.E. forecasts can then be interpreted and used in light of these initial relationships.

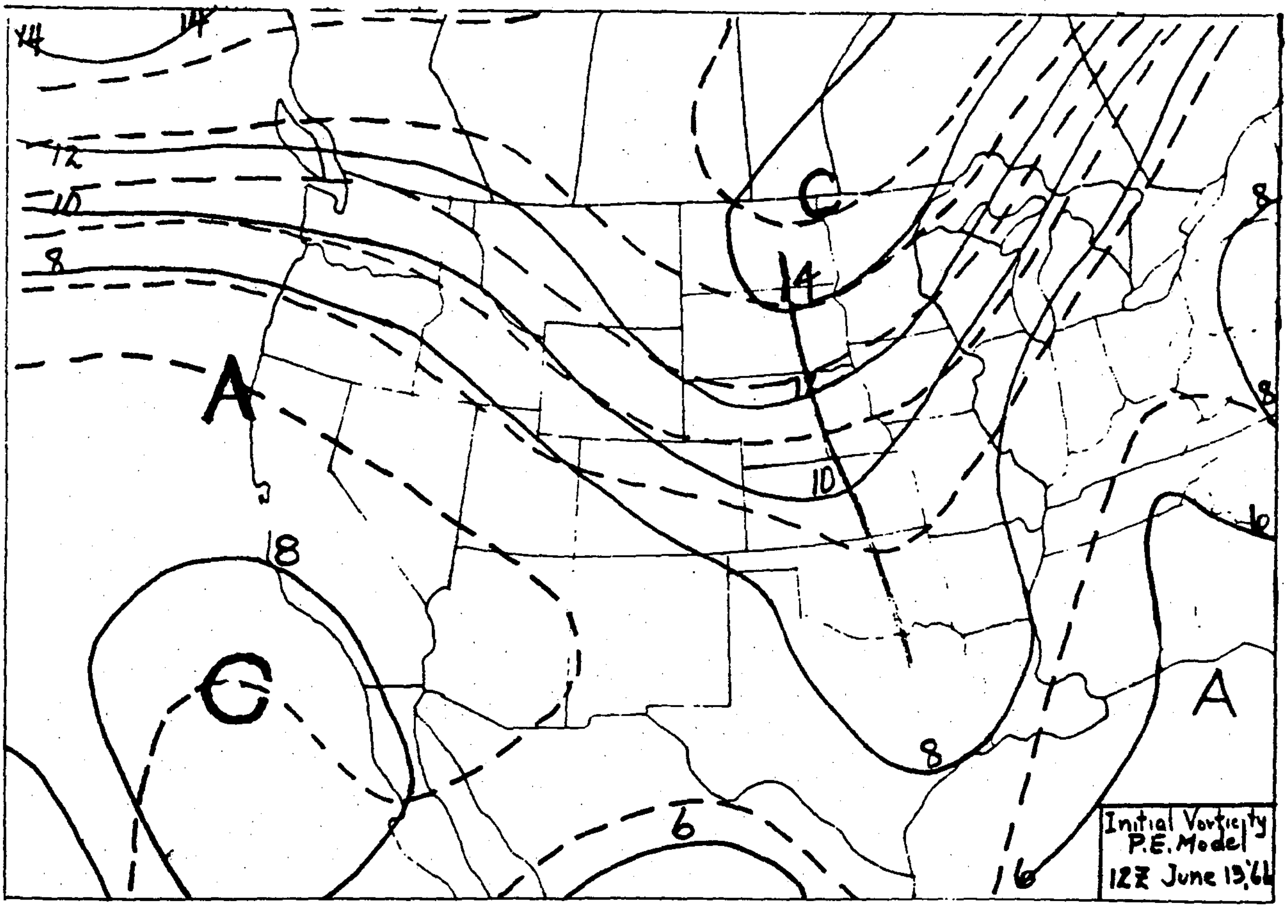
Obviously, the present policy of making the format of the output of the new P.E. Model agree with the outputs of the replaced 3-level vorticity model has serious drawbacks and is subject to change.

There is reason to be optimistic about future changes regarding outputs from the P.E. Model, e.g., replacing vorticity charts with vertical-motion charts. The P.E. Model produces vertical-motion fields for six levels in the atmosphere from the surface to the lower stratosphere. Studies are presently under way to evaluate the usefulness of these vertical-motion fields.

In summary, significant differences between the initial vorticity fields indicated on the barotropic and P.E. vorticity facsimile transmissions are to be expected, with the barotropic being the more detailed of the two.



*The vorticity is obtained by adding Z_1, Z_2, Z_3, Z_4 and subtracting $4Z_o$ and multiplying the result by a suitable constant involving the mesh length, d. (Z's are 500-mb stream function values.)


Initial Vorticity
P.E. Model
12Z June 13,'66

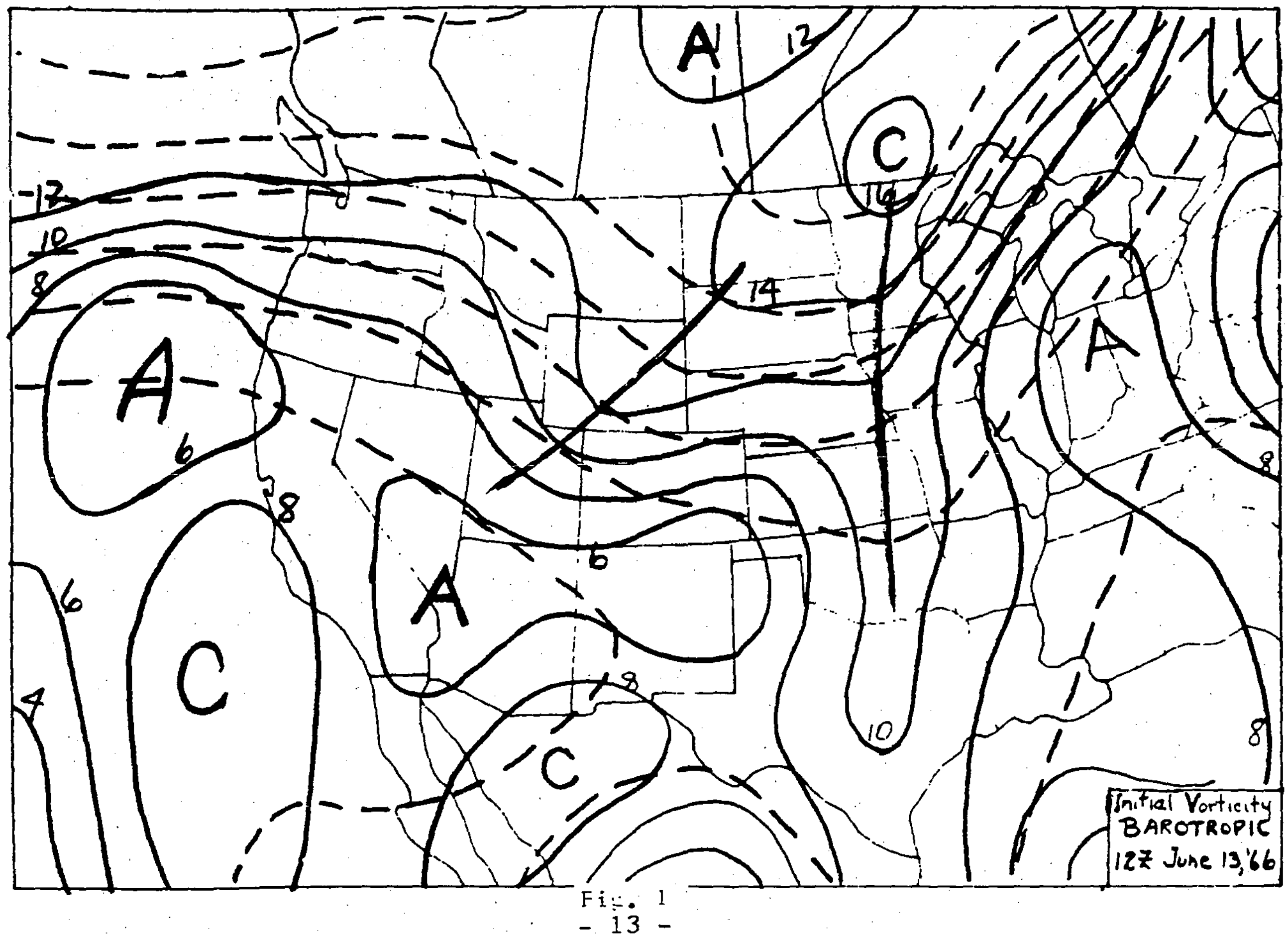

Initial Vorticity
BAROTROPIC
12Z June 13,'66

Fig. 1

V - IMPROVED PRIMITIVE-EQUATION VORTICITY FORECASTS

NMC has recently (1200Z, July 13, 1966) modified the procedure for specifying the initial sigma-surface winds from which the operational primitive-equation forecasts are made. The important result of this modification to Western Region forecasters is improved 500-mb primitive-equation vorticity forecasts. This Attachment discusses how this improvement was accomplished.

The original 500-mb primitive-equation vorticity forecasts were so much in phase with the contours that few significant advection patterns existed. This reduced their usefulness in operational weather forecasting. (See Figure 1 for a typical example.) The over-smoothed character of these vorticity fields was discussed in the Technical Attachment for June 14, 1966. It was reported then that this excessive smoothing was probably (1) the result of having to interpolate heights from constant-pressure surfaces to sigma surfaces, and/or (2) the introduction of significant truncation errors when these interpolated heights were used in the balance equation to get sigma-surface winds. Consequently, NMC has been focusing its attention on improving the quality of the initial sigma-surface winds.

One of the experiments NMC tried was to empirically but systematically increase the speed of the initial sigma-surface winds before starting the forecast procedure. This was done by increasing the amplitude of the interpolated height-fields used in the balance equation to specify the initial wind-field. The results of this experiment were surprisingly good. The resulting 500-mb vorticity fields, both initial and forecast, were greatly improved and gave the primitive-equation vorticity charts the same character as the three-level and barotropic forecasts. (See Figure 2 for a typical example.)

When you look into this modification a little more deeply, one notes that this modification is an ingenious and delicate change. The initial height-fields on either pressure or sigma-surfaces are used to determine both the pressure-gradient force (i.e., the mass field) and the wind field. In the case of balanced conditions, which most forecasters usually assume exist and which is assumed at the start of the primitive-equation forecasting procedure, the forces (i.e., pressure-gradient, coriolis and friction) specified by the height field are in equilibrium.

BALANCED CONDITIONS

MASS FIELD = WIND FIELD

The mass field predominates over the wind field in specifying the initial conditions for the start of the primitive-equation forecasting because it is involved in determining the wind field. This fact, plus the success of the primitive-equation constant-pressure height forecasts and the in-phase relationship of the original 500-mb primitive-equation vorticity and height fields, led NMC scientists to examine the specification of the initial wind field. Because the initial constant-pressure height fields used in determining the initial sigma-surface wind fields become somewhat smoothed during initialization, NMC concluded that the original P.E. model (i.e., before July 13, 1966) underspecified the wind field at the start of the forecast procedure. This conclusion led through experimentation to the new procedure of using the original interpolated sigma-surface heights to specify only the pressure-gradient force (i.e., initial mass field) but systematically modifying these heights before putting them into the balance equation to specify the wind field. At first glance, this procedure appears to result in a slightly unbalanced initial condition; but further study indicates it actually brings the initial wind and pressure-force fields into closer balance.

In summary, NMC's recent modification of the P.E. model has been engineered to where: 1) the initial conditions currently considered necessary to start the forecast procedures are improved; 2) the high quality of the constant-pressure height forecasts is retained and may be improved; and 3) more useful 500-mb P.E. vorticity forecasts are produced. The following excerpt from a recent letter from Dr. Shuman, Director of NMC, amplifies point 3):

> "Even though some detail in the vorticity field is restored through use of adjusted height field, the vorticity field remains less detailed than that calculated directly from analyses (i.e., as done in the barotropic forecast). The principal reason for this is undoubtedly that, in effect, we are smoothing and unsmoothing the vorticity field, which amounts to a filter passing the longer waves, but suppressing the shorter. Added to this is probably some loss due to vertical interpolations and other necessary 'massaging' of the analyses during initialization. At least some of the detail in the old vorticity fields must have been fictitious. How much real detail is now suppressed, if any, is open to question."

[1] Technical Attachment, June 7, 1966, "The Physics of the NMC Primitive-Equation Model".

Author's Note: This republication of Technical Attachment No. 21-66 contains significant changes in the latter paragraphs of the original. This was necessary to correct my interpretation of the nature of the new procedure. I am indebted to Dr. Shuman for calling this to my attention.

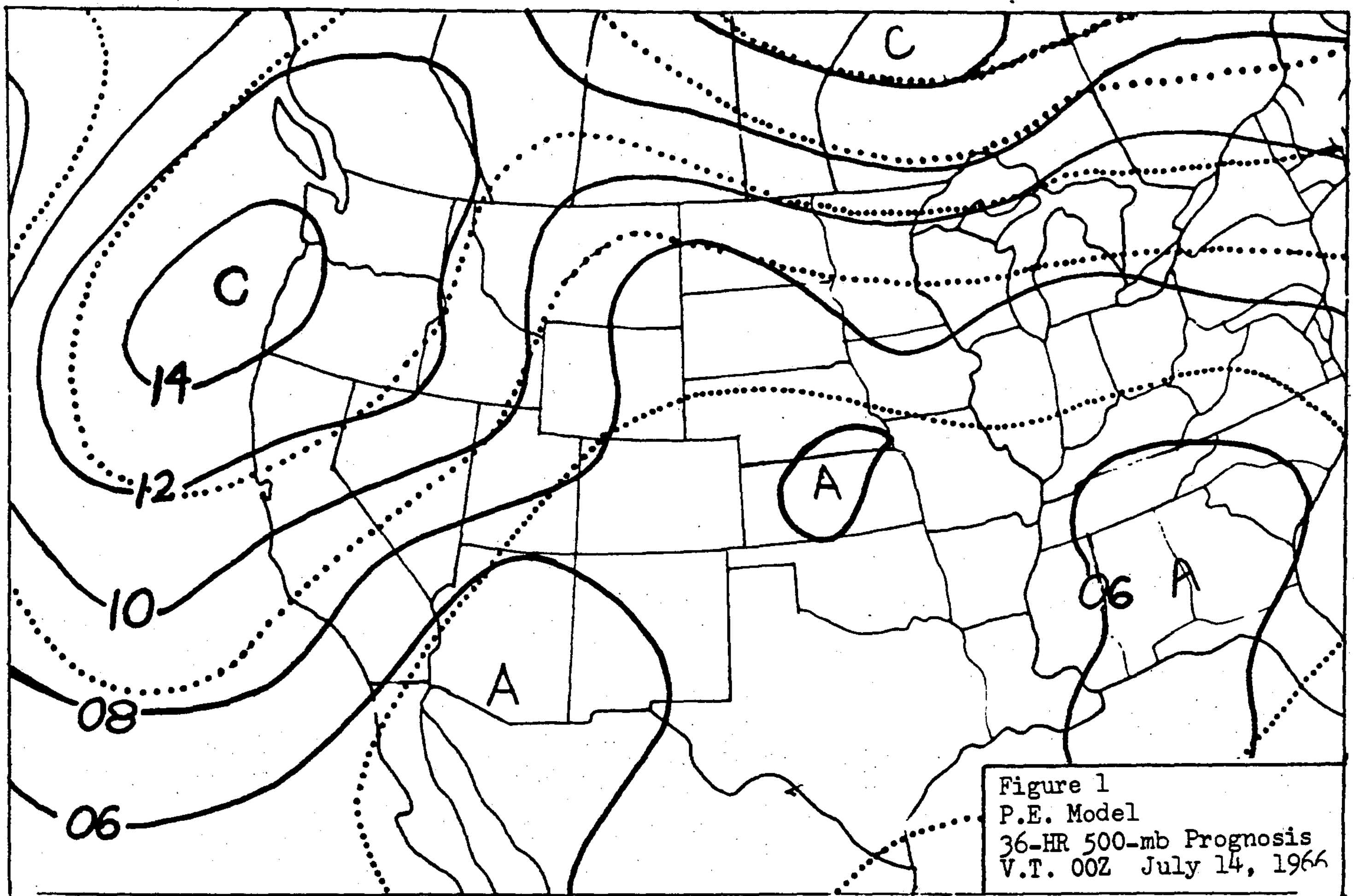


Figure 1
P.E. Model
36-HR 500-mb Prognosis
V.T. 00Z July 14, 1966

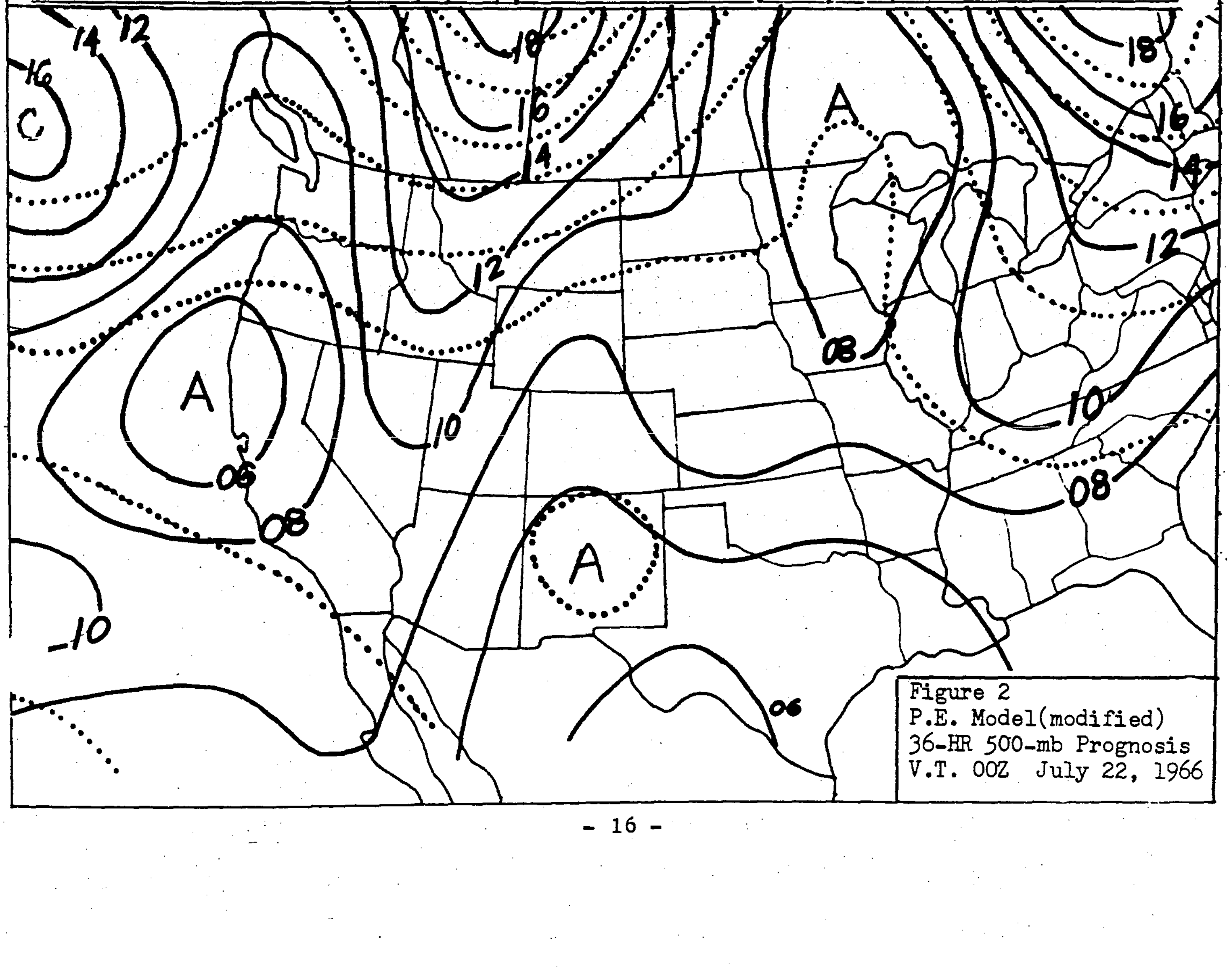


Figure 2
P.E. Model(modified)
36-HR 500-mb Prognosis
V.T. 00Z July 22, 1966

VI - MISCELLANEOUS COMMENTS ON NMC SIX-LEVEL PRIMITIVE EQUATION FORECASTS

Dr. Frederick Shuman, Director of NMC and developer of the NMC Primitive-Equation (P.E.) model, presented a seminar on his model at San Francisco WBAS on Monday, June 27, 1966. He reviewed the development of the model and discussed some of the problems that have arisen in preparing P.E. forecasts for routine operational use. This technical attachment discusses those points covered by Dr. Shuman which are considered to be of importance to Western Region forecasters and which have not been discussed in previous technical attachments.

Routine Receipt of P.E. Forecasts:

The P.E. forecasts have missed a number of facsimile transmission deadlines since the first P.E. forecast was transmitted on June 6, 1966. There is a good reason for this: Three NMC electronic computers--an IBM 360 Model 30, the IBM 7094II and the CDC 6600--must be operational during the forecast run in order for the P.E. forecasts to be prepared in time to meet transmission deadlines. The #360 is a small computer used to collect and store the global data received at NMC between 0000Z and 0325Z (1200Z to 1525Z). (The data cutoff time has recently been advanced from four hours to three hours and 25 minutes after observation time due to earlier receipt of overseas data via a new Air Force high-speed data link.) On command these data are transferred to the 7094 computer, where they are processed and the necessary 10 constant-pressure surface analyses produced. These analyses are then fed into the 6600 computer via magnetic tape. The 6600 computer performs the interpolation of the constant-pressure data to sigma surfaces and computes the forecast. The forecast is read out of the 6600 computer back through the 7094 computer where it is processed for output. This output involves preparation of the necessary magnetic tapes to drive the curve follower and Digifax which produce the charts for facsimile transmission.

NMC has two 360 computers, one as a back-up. There is also a back-up for the 7094II computer through a microwave link to the Bureau of Standards 7094 computer. This back-up is not always satisfactory since an NMC computer operator must be at the Bureau of Standards to run their computer. There is no back-up for the 6600 computer. You can see this present procedure of producing P.E. forecasts and preparing them for transmission leaves little room for correcting computer malfunctions or other delays. Most of the missed P.E. transmissions have resulted from difficulties with the 6600 computer, and in establishing the necessary new manual procedures.

Contrast the above complex procedure with the relatively simple procedure of computing the 3-level filtered forecasts using only the

360 and 7094 computers, and you can understand why the receipt of 3-level forecasts was and is more reliable.

Primitive-Equation Model Failures:

Another cause of irregular transmission of the P.E. forecasts concerns infrequent failures of the model to produce a forecast. Those failures which have occurred involved the initial selection of the heights of the top sigma surface and the potential temperature of the isentropic cap. This difficulty is thought to exist because the scheme used for selecting these parameters was developed and tested on winter cases. An early solution to this problem is expected.

Systematic Errors in Short-Wave Forecasts:

There has been some confusion regarding the statement that the P.E. forecasts of short-wave troughs are systematically slow. Actually, there is only one class of short-wave troughs that falls into this slow-forecast category. These are the rather small amplitude (flat) troughs that are usually found moving through a ridge. The vorticity associated with them is composed mostly of wind shear rather than curvature. Truncation errors resulting from the mathematical procedures employed to produce the P.E. forecasts are believed to be the reason for this forecast error.

The forecast movements of larger-scale short-wave troughs do not have this systematic error, and their forecast accuracy is comparable to the accuracy of the 3-level forecasts of such troughs.

The 24- and 36-hour forecasts based on the initial data for 1200Z June 23, 1966, illustrate a typical P.E. forecast for both types of short-wave troughs. See Figure 1.

S_1 Scores:

The average S_1 scores* from June 6 - 24 continue to show that the subjective NMC surface prognoses are significantly superior to the corresponding 1000-mb P.E. forecasts. For 20 pairs of forecasts the S_1 scores were: P.E. = 65.7; subjective = 59.0. Comparable S_1 scores for 500 mb are not available.

In Summary:

We should expect irregular transmission of the P.E. 6-level forecast for some time to come. The 3-level filtered forecast will be the back-up transmission. P.E. forecasts of most short-wave troughs will be of comparable accuracy to the 3-level forecast movements and not systematically slow.

*See Page 21 for a definition of the S_1 score.

Reflection on the above discussion brings up the question, "Why go through all this trouble to produce a P.E. forecast when the simple barotropic forecast does so well?" The answer is easy. Problems such as NMC is encountering with the P.E. model are to be expected during this "shakedown period", and most of them will be solved over the next few months. We can expect the P.E. forecasts to improve with time and in the not-too-distant future be significantly superior to the barotropic forecasts.

As stated in the Technical Attachment dated June 21, Page 21, the great advantage of the P.E. model is the relative simplicity with which improvements in the model can be made.

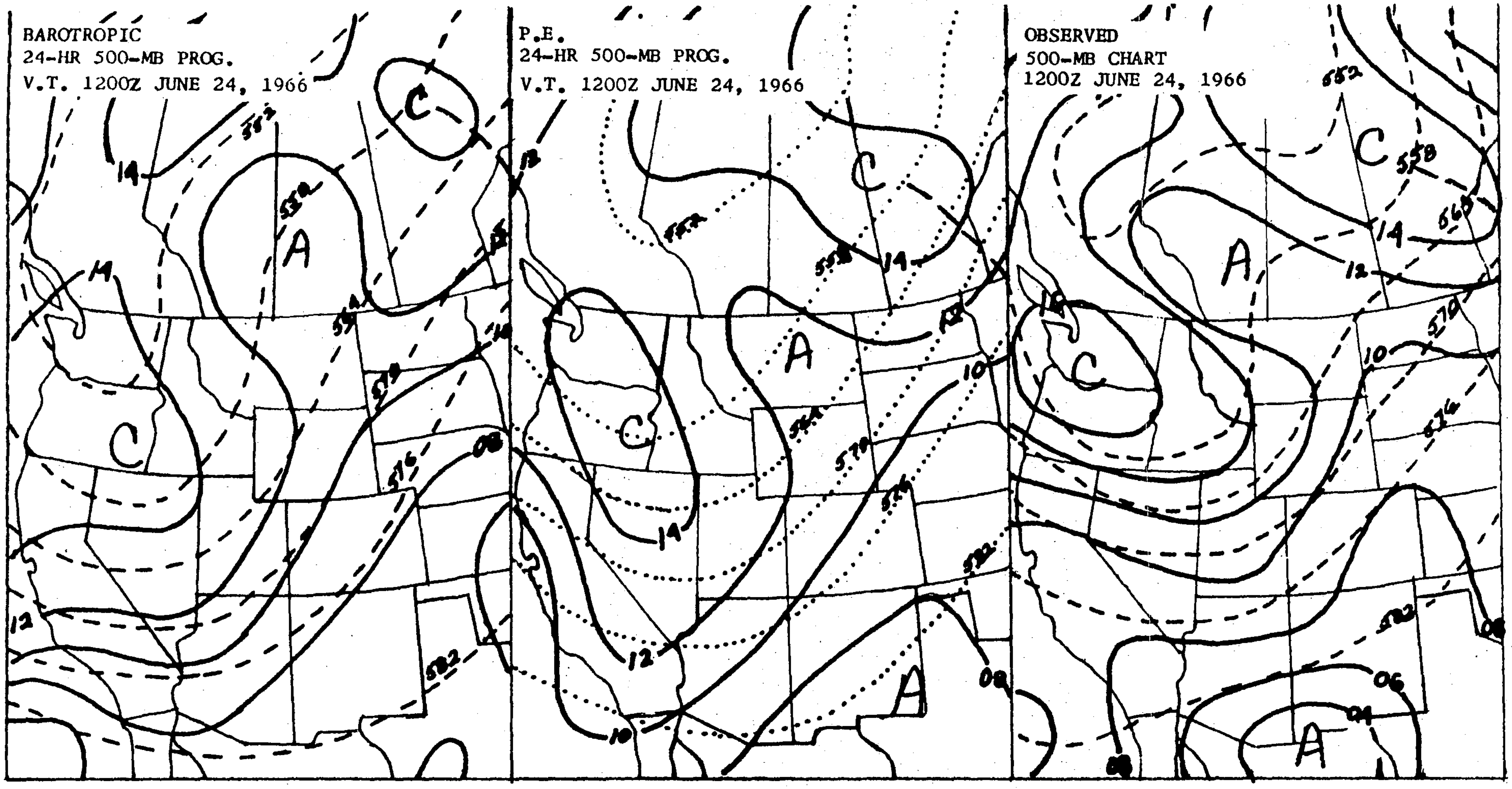


Figure 1. Typical example of a P.E. forecast which systematically moves shallow short waves too slowly. Barotropic and P.E. 24-hour 500-mb prognoses and verifying 500-mb analysis, V.T. 1200Z June 24, 1966. Solid lines are absolute vorticity isopleths and dashed lines are contours. The flat trough in Canada north of the Dakotas and Minnesota is slow in the P.E. forecast. The barotropic forecast trough position was better, although it is not obvious from this figure. Note the short-wave trough over Nevada-Utah area is forecast very well by the P.E. model. The P.E. vorticity prognosis associated with the trough in the Utah-Nevada area is not nearly as good as the P.E. height prognosis. The reason for this probably lies in the method of obtaining the height and vorticity fields independently from the sigma-surface height and wind fields. (Reference Page 11.) (The above charts were copied from facsimile transmissions #73 (23rd), #96, #73 (24th) respectively.)

VII - PRELIMINARY EVALUATION OF NMC PRIMITIVE EQUATION FORECASTS

June 6, 1966, began the exciting era of operational NWP primitive-equation forecasts. While Western Region meteorologists were probably as excited and interested in this event as any in the Weather Bureau, they were and still are even more interested in knowing, "How well does the P.E. model forecast the troublesome weather patterns over the Eastern Pacific and Western United States?" Unfortunately, there is no complete answer to this question right now. The new NMC Primitive Equation (P.E.) Model has not been in routine operation long enough for us to make a complete evaluation, and only a limited number of test forecasts were made before June 6. Some general comments regarding its performance and the little that we do know about its handling of specific synoptic situations are the subject of this Technical Attachment.

The NMC P.E. model is the most realistic NWP model that has yet been put into routine operational use. It has a troposphere and stratosphere separated by a tropopause surface. The lowest sigma surface of the model is 100 mb above the earth's surface. However, a forecast of temperature and wind is made in this 100-mb boundary layer to provide input data for the surface heating and friction terms in the model. Consequently, the bottom of the P.E. model is the earth's surface. More realism in an NWP model does not mean it is necessarily superior for our region to the 3-level filtered vorticity model it replaced.

Mr. Saylor, Director of the Analysis and Forecast Division of NMC, recently evaluated 22 P.E. forecasts made in April and May 1966. He compared the 36-hour 1000-mb and 500-mb P.E. forecasts with the equivalent 3-level filtered, REED, and subjective prognoses [1]. Some of the results of this evaluation are presented as average S_1 scores*. The graphs of the S_1 scores available for surface and 500-mb prognoses from 1947 to 1965 are given in Figure 1 as a reference frame from which to judge the P.E. model's overall performance. The S_1 score is the average verification over the United States and immediately adjacent areas of the Atlantic, Pacific, and Canada.

Saylor has suggested S_1 scores can be interpreted in terms of percent of forecast skill over persistence. Therefore, 0% skill is assigned to the average S_1 scores for persistence forecasts, which are 80 for surface charts and 70 for 500-mb charts; and 100% skill is assigned to perfect prognostic charts which are considered to be S_1 scores of 30 for the surface and 20 for 500 mb. Assuming a linear relationship

*The S_1 score is a measure of how well the pressure or height gradients (direction and magnitude) of a prognostic chart are forecast. The lower the score, the better the forecast [2].

of skill to S_1 scores between these two end points, the graph for the surface progs indicates an average skill of 30% (S_1=65) over persistence in the late 1940's and a slight improvement to 1960. From 1960 to the present, a significant improvement of 10% took place. This improvement was brought about by the systematic use of the 3-level and barotropic 500-mb prognoses in making the surface prognoses.

The verification of 500-mb prognoses was begun in the early 1950's, just a few years before operational NWP forecasting was begun in the United States. Some increase in skill took place from 1954 to 1958, but the dramatic change occurred in 1958 with the introduction of automatic data-processing and an improved barotropic model, and in 1962 when the 3-level model went operational. The subsequent improvements of the 3-level model continued to decrease the S_1 scores. The disturbingly poorer 500-mb S_1 scores for the 1964 - 65 period are attributed to a recurring flow pattern (jet-stream position being abnormally far south in the Pacific area), which the 3-level model does not handle very well. Figures 2 and 3 present these verification data as a function of skill over persistence.

The following table gives a comparison of the average S_1 scores and the average pressure errors of the different models for 36-hour prognoses that Saylor found for the 22 April and May cases he studied.

TABLE I

		P.E.	3-Level	REED	NMC Subjective
36-Hour 500-mb Prognoses	S_1 Score	44.7	46.6	--	--
	Avg. Hgt. Error (Meters)	41.0	47.0	--	--
36-Hour Surface Prognoses	S_1 Score	63.6	--	71.8	60.0
	Avg. Pressure Error (mbs)	4.43	--	6.56	4.44

The P.E. 500-mb forecasts were better than the 3-level filtered forecasts in 75% of the cases, even though the P.E. 500-mb forecasts showed a systematic slowness in moving short-wave troughs. This slowness has been mentioned in the FXUS1 discussions from time to time by NMC forecasters since June 6. (See Page 18 for discussion of short-wave motion)

The P.E. surface forecasts showed a significant improvement over the REED NWP forecasts in 82% of the cases. This improvement was especially marked in the Western United States. The P.E. surface forecasts approached the skill of the NMC subjective forecasts for the test period. However, the NMC forecasters did not have the benefit of the P.E. surface prognoses as guidance during this test period. Saylor believes that with the P.E. forecasts as guidance, the NMC subjective surface prognosis could improve as much as 10 S_1 points. Thus, Saylor's study suggests the P.E. forecasts will provide us with slightly improved 500-mb forecasts and substantially improved numerical surface prognoses. Improvements in the NMC subjective surface prognoses will probably be gradual, as the NMC forecasters learn when and where to rely on the P.E. forecasts.

Getting more specific, the errors of the P.E. 500-mb forecasts in our region of interest appear to be much the same as those found in the 3-level model forecasts, only of less magnitude. For example, in the case of May 7, 1966 (Figure 4), which Saylor presents as a typical case of the differences usually found between the 3-level and P.E. forecasts, there is little difference between the 500-mb forecasts from the 2 models over the Western States. The plus and minus 60-meter differences between the P.E. and 3-level forecasts in the Gulf of Alaska (Figure 4a) are located in the same area as the 3-level forecast errors (Figure 4b) but of much less magnitude. This indicates the P.E. forecast errors are of the same sign and position as the 3-level errors, but not as large. For example, at Point A in Figure 4b, the 3-level forecast height error is -180 meters. The difference between the two forecasts at Point A (Figure 4a) is -60 meters. This means the P.E. forecast error is only -120 meters (-180 - [-120] = -60).

There was only one case of a 500-mb cut-off low during the test period when both P.E. and 3-level forecasts were made. The two forecasts for 36 hours are given in Figure 5.

One difficulty that Western Region forecasters have had with the 3-level forecasts has been the persistent error of moving some 500-mb West Coast troughs too far east and deepening them too much. The P.E. model appears to make the same error, but to a lesser extent. See Figure 6 for a recent case.

In summary, the P.E. forecasts have been too few as yet to indicate whether they will give us much immediate improvement in forecasting the troublesome 500-mb patterns for the Western Region. Limited experience with P.E. forecasts to date suggests no drastic improvement over the 3-level forecasts at 500 mb. The most significant improvement to be expected will be at the surface and in the transtropopause region. However, we have reason to be optimistic. As NMC improves the P.E. model over the next several months (and one of the advantages of the P.E. model over the vorticity models is the relative ease with which substantial changes in the model can be made), the P.E. forecasts at surface and 500 mb will improve gradually.

All forecasters should exert extra effort these days to learn the strong and weak points of the P.E. forecasts for the Western United States and the Eastern Pacific through routine subjective verification.

A discussion of the P.E. verification, as compared with the barotropic, should be made a part of every local map-discussion. Also, the NMC FXUS1 prognostic discussion bulletins should be especially helpful during this learning period.

References:

[1] H. K. Saylor, "Results of Primitive Equation Model Test Period", A&FD Office Memorandum No. 9-66 dated June 1, 1966.

[2] S. Teweles and H. B. Wobus, "Verification of Prognostic Charts", Bulletin of AMS, December 1954, Pages 455 - 463.

Author's Note: The following S_1 scores for July and August 1966 became available just prior to going to press. These data appear to bear out Saylor's statement on Page 23 that the improved P.E. surface forecasts, as compared to REED forecasts, will result in a significant improvement in the NMC 30-hour subjective surface prognoses. The August S_1 score is an all-time record, and the July score just missed tying the all-time record for July.

TABLE II

		NWP	Subjective
36-Hour 500-mb Prognoses (0000Z only)	July 1966	S_1 = 44.5 (87% P.E.)	--
	August 1966	S_1 = 49.0 (70% P.E.)	--
30-Hour Surface Prognoses	July 1966	S_1 = 63.5 (73% P.E.)	S_1 = 53.5
	August 1966	S_1 = 63.5 (73% P.E.)	S_1 = 53.5

The figures in parentheses indicate the percentage of 6-layer primitive equation forecasts included in the statistic. The remainder of the surface forecasts were from the REED model, and the other 500-mb forecasts were from the "3-level" model.

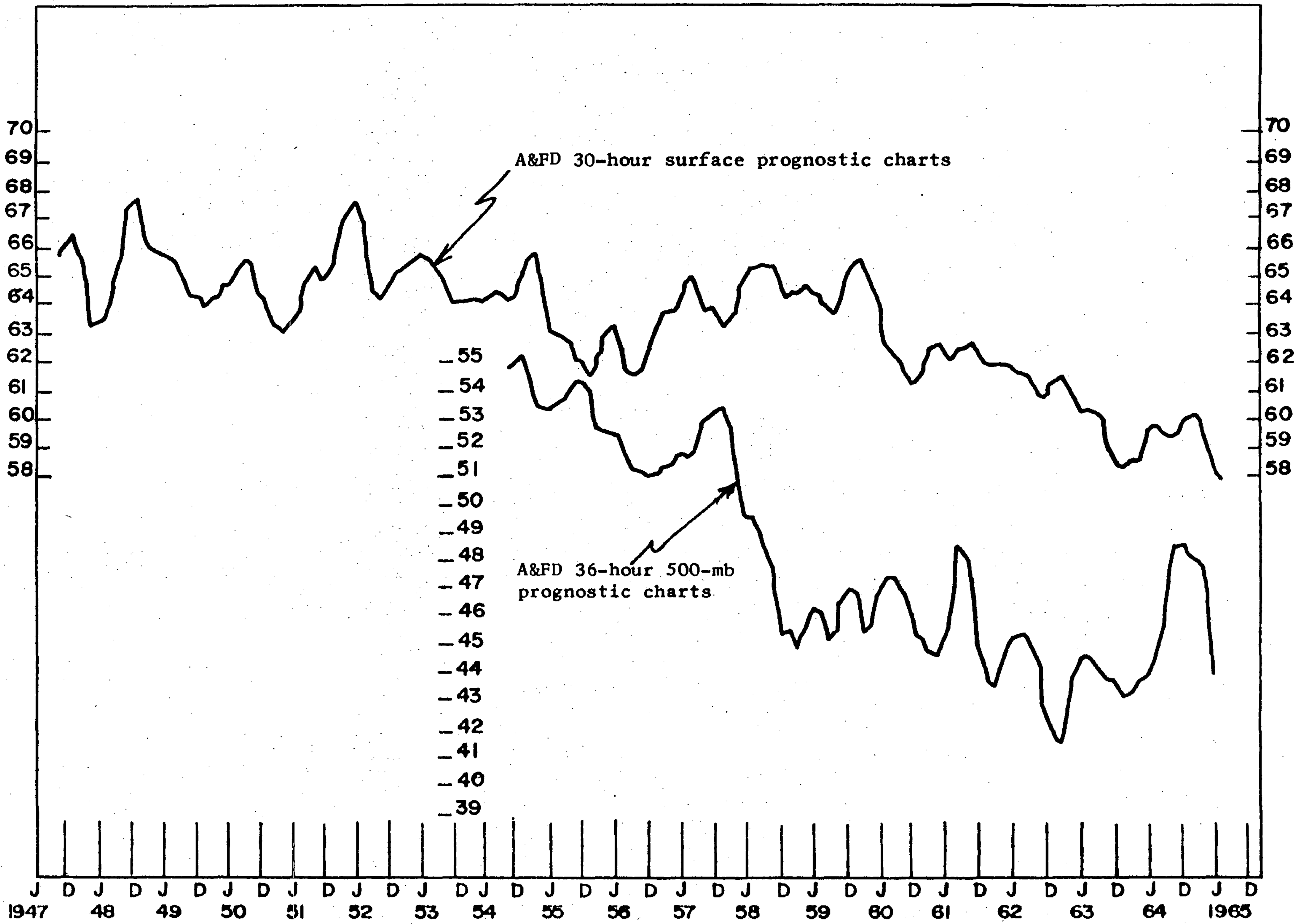


Figure 1. Monthly S_1 scores smoothed over 5 months with weighting function of 1:2:4:2:1.

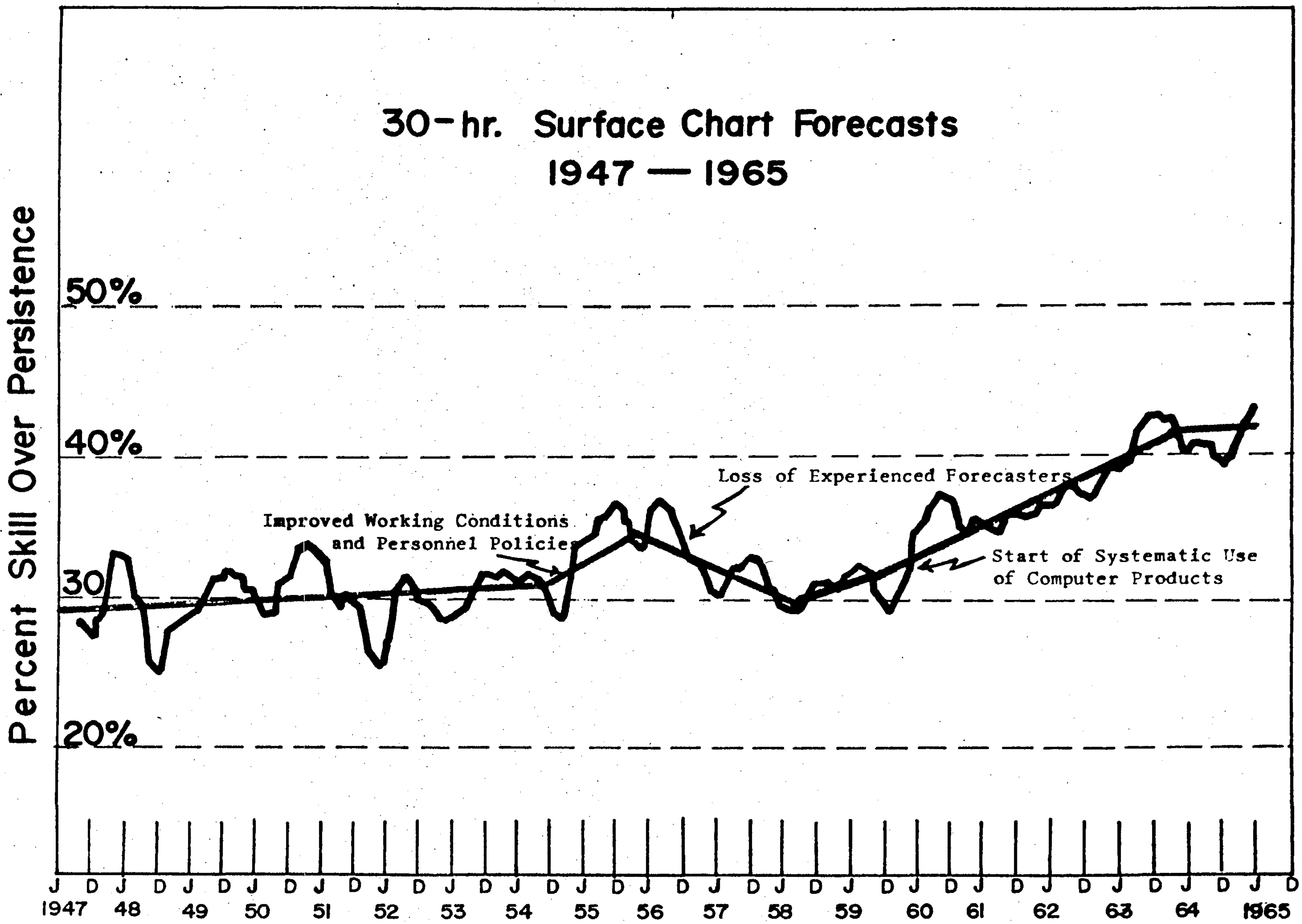


Figure 2. Verification Graph of S_1 scores for NMC 30-hour Surface Prognoses in terms of skill over persistence. Saylor's values of S_1 = 30 for perfect forecast and S_1 = 80 for persistence score were used. T[illegible] smoother line is a general trend line determined [illegible] eye.

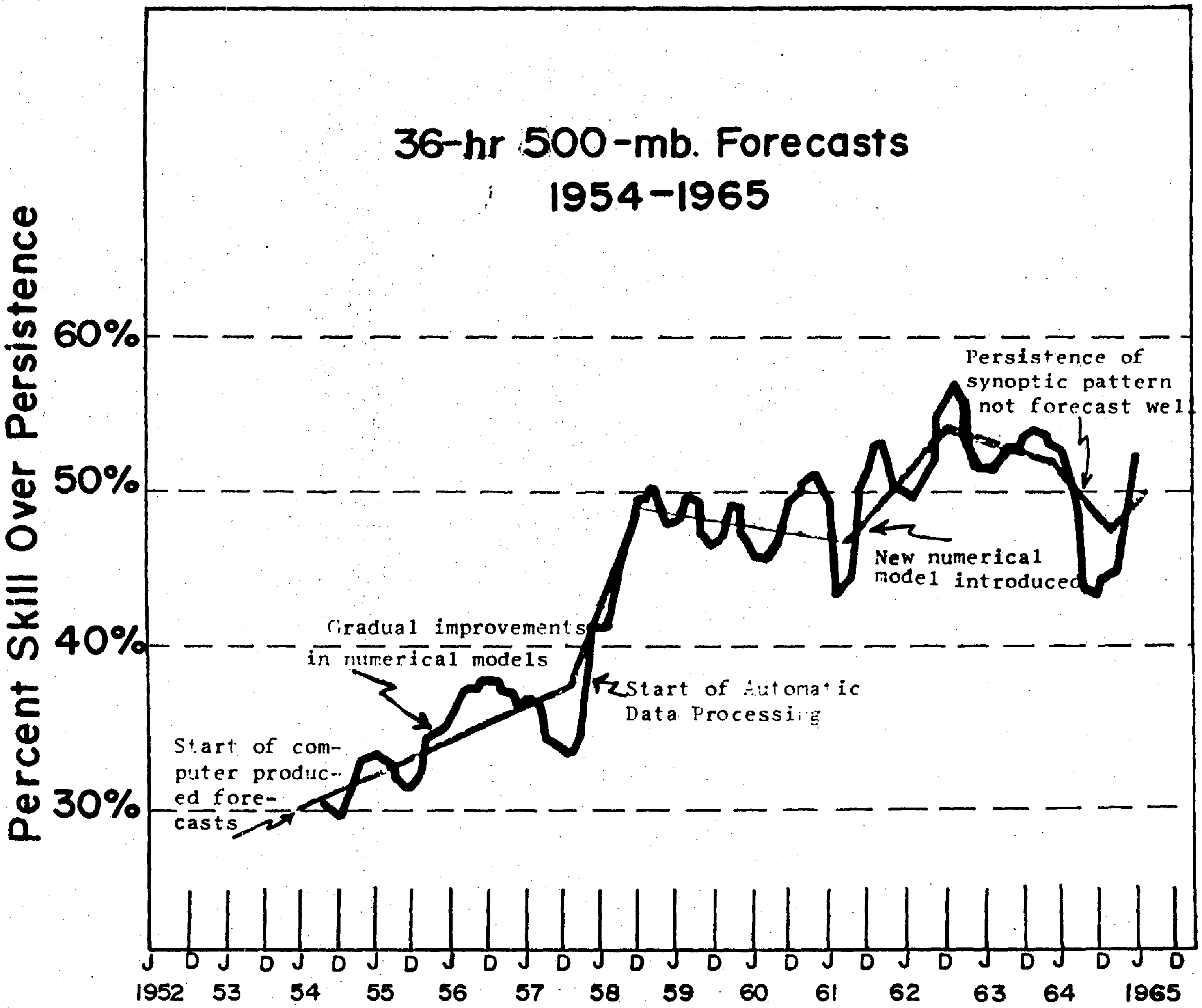


Figure 3. Verification Graph of S_1 scores for NMC 36-hour 500-mb prognoses in terms of skill over persistence. Saylor's values of S_1 = 20 for perfect forecast and S_1 = 70 for persistence score were used. The smoother line is a general trend line determined by eye.

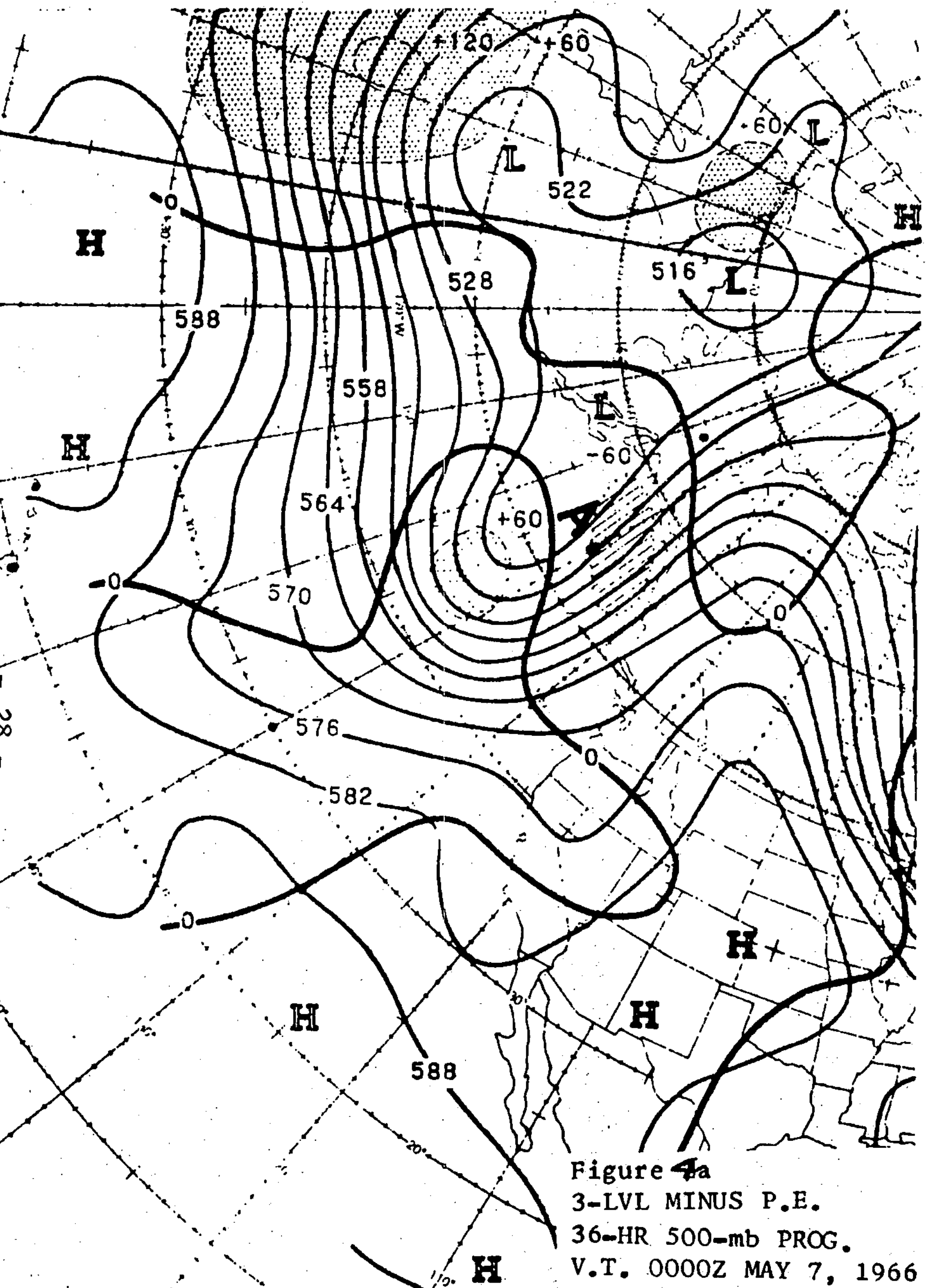


Figure 4a
3-LVL MINUS P.E.
36-HR 500-mb PROG.
V.T. 0000Z MAY 7, 1966

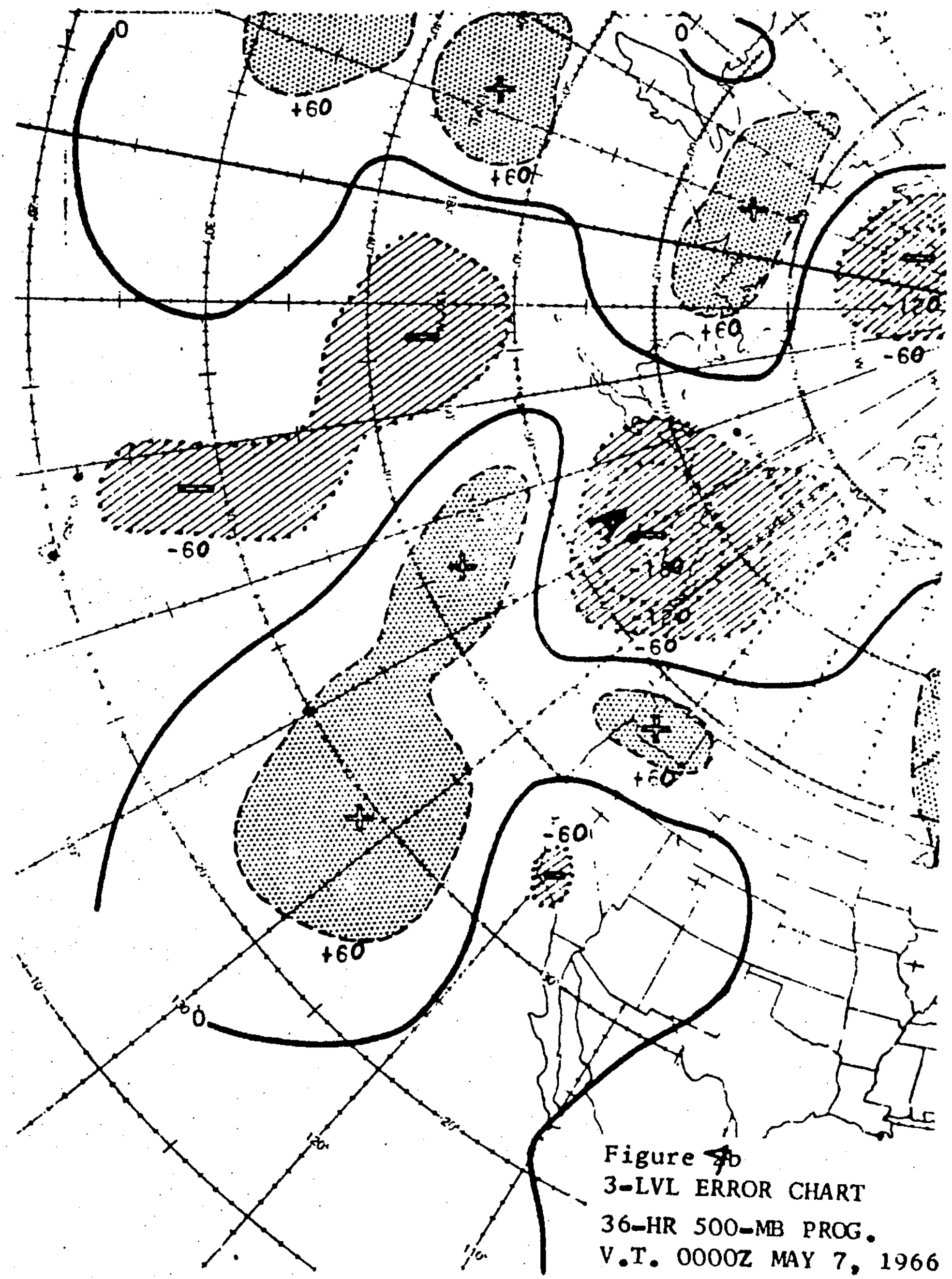


Figure 4b
3-LVL ERROR CHART
36-HR 500-MB PROG.
V.T. 0000Z MAY 7, 1966

Figure 4. The height differences in meters between the 3-level and P.E. 36-hr. 500-mb forecasts, valid 0000Z May , 1966, and the height error chart of the 3-level : el valid 0000Z May 7, 1966. The stippled areas ir :ate height differences or errors greater than 60 meters (after Saylor [1]).

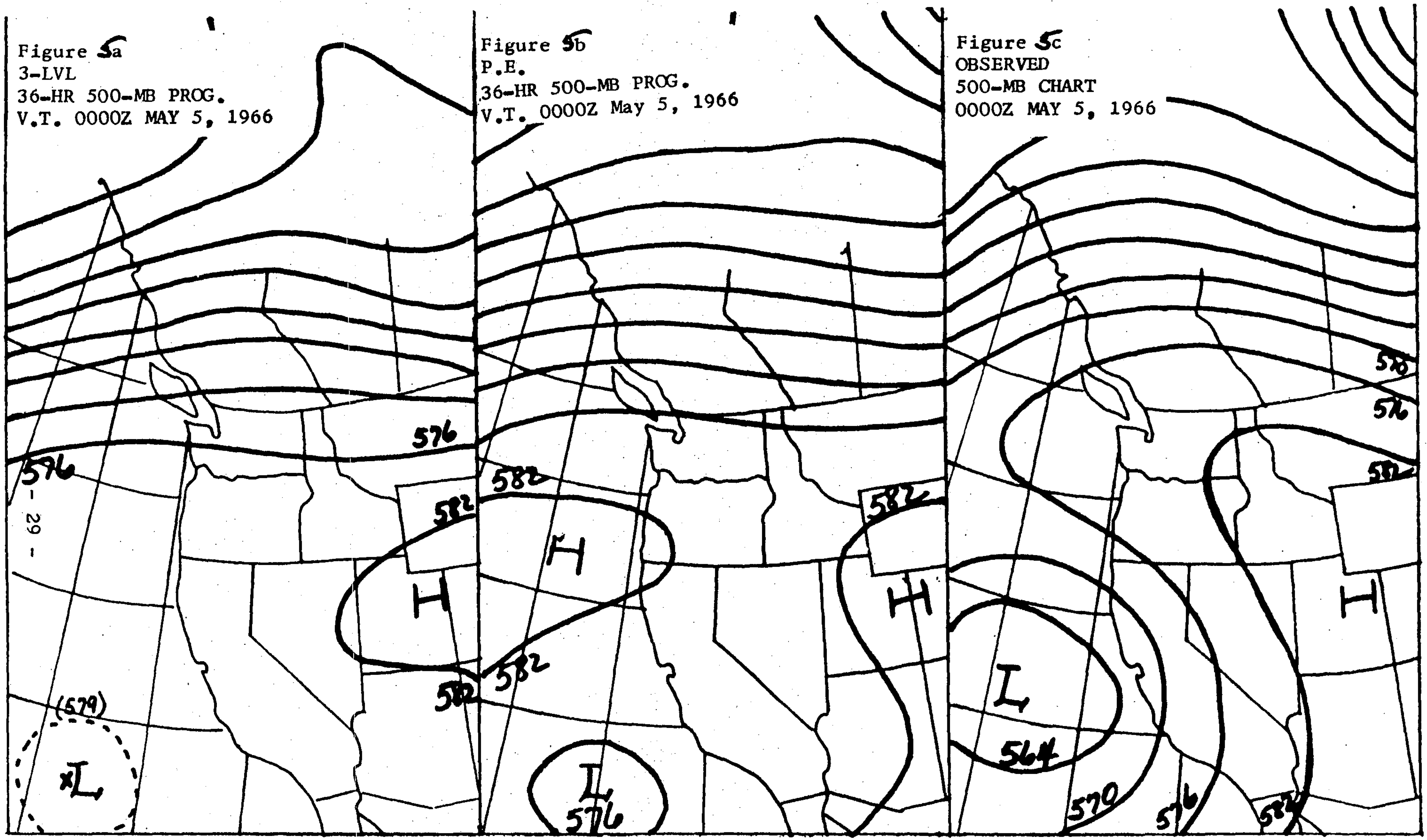


Figure 5. 3-level and P.E. 36-hour 500-mb contour forecasts and the verifying 500-mb chart, V.T. 0000Z May 5, 1966. This is an example of a P.E. forecast during a cut-off low situation. Note that there is very little difference between the two forecasts. Both forecasts missed the intensity and location of the low. Farther north, the errors are also very similar. (The P.E. map for this case was obtained through the courtesy of Mr. Fawcett of NMC. The 3-level forecast and the analysis were copied from facsimile transmissions #96 and #38, respectively.)

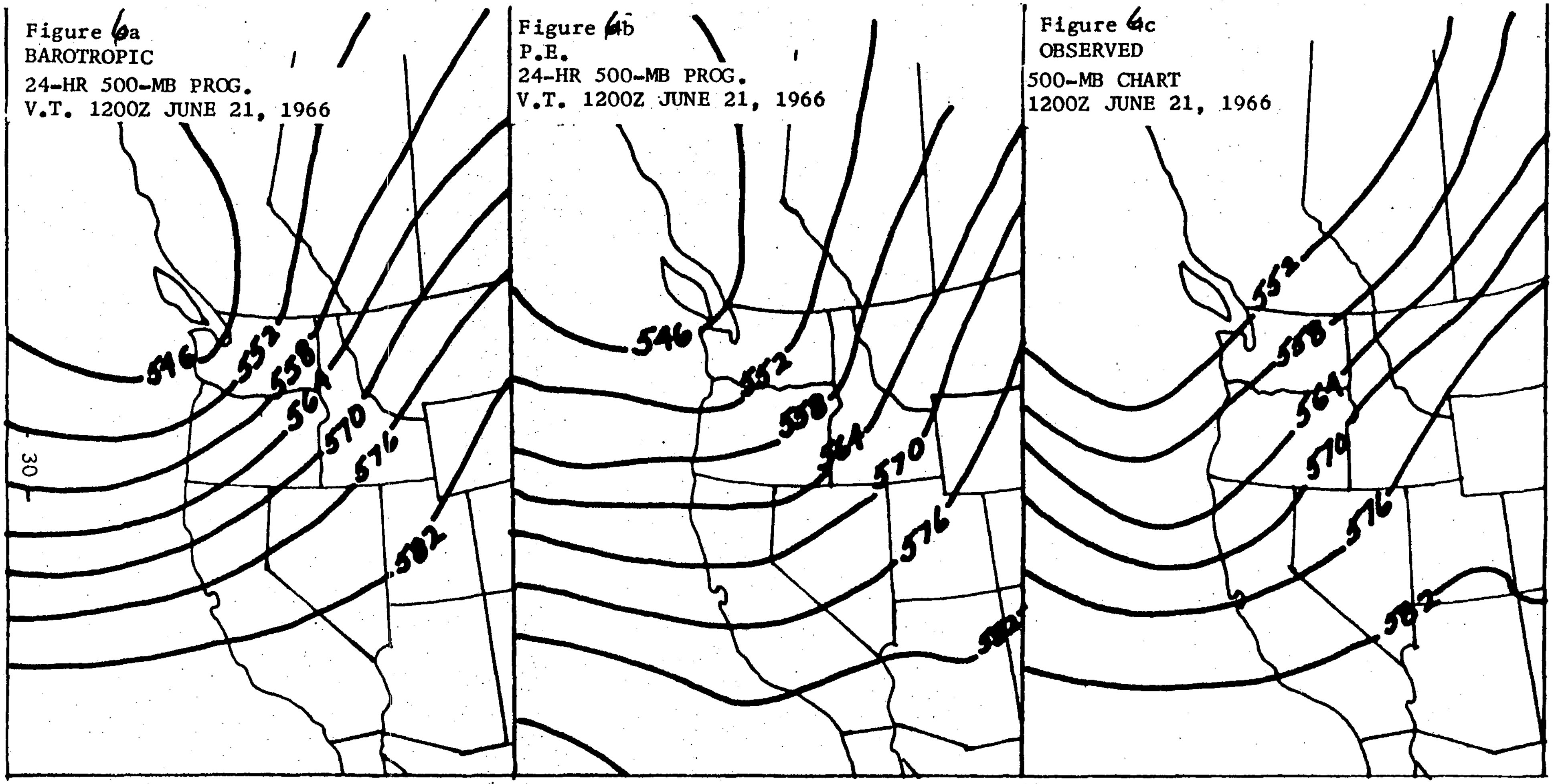


Figure 6. Barotropic and P.E. 24-hour 500-mb contour prognoses and verifying 500-mb chart, V.T. 1200Z June 21, 1966. One of the important forecast problems on June 20, 1966, for the Western Region was to determine the movement of the West Coast trough and the related movement of unseasonably cold air into the Intermountain Region.

The barotropic forecast indicated maintenance of a strong southwest flow and a very slow penetration of the cold air. The P.E. forecast indicated a much deeper penetration. Compare the positions of the 576 contours.

This is a synoptic situation where the barotropic prognoses usually are better than the 3-level prognoses. In this case the P.E. model erred in much the same way that we would have expected the 3-level model to err.

(The above charts were copied from facsimile transmissions #73, #96 (20th) and #96 (21st) respectively.)

VIII - VERIFICATION OF SOME NMC PRIMITIVE EQUATION (P.E.) 500-MB FORECASTS

The Technical Attachment discussions on the P.E. model during the past several weeks have dealt mainly with the physics and make-up of the model. This week's Attachment will look into the P.E. model's handling of a recent synoptic situation.

Synoptic regimes involving cut-off lows off the West Coast are some of the most important and difficult situations for Western Region forecasters to handle. This is true for any month of the year, but is most important during the cold season. Consequently, forecasters are anxious to know how well the new P.E. model will perform during such synoptic regimes. The 3-level and barotropic NWP forecasts do not handle these situations especially well.

The synoptic regime of July 11 - 14, 1966, presented us with an opportunity to observe the P.E. model's performance during a summer cut-off low situation. (See Figure 1, the 500-mb analysis for July 11.) The P.E. model's performance during this period was impressive. Direct comparative 3-level forecasts are not available for this period. However, an indirect comparison can be made, as a 3-level forecast was transmitted based on 0000Z July 11 data; and the P.E. model was used on the following two days. Figure 2 gives the 36-hour 500-mb forecast (solid lines) and verifying contours (dashed lines) for this 3-day period. Note the superior quality of the P.E. forecasts over the 3-level forecast. The root-mean-square height error of these forecasts for the area covered in the figure probably would be near the same value for each forecast. However, the trough position so important to the preparation of weather forecasts is far superior in the P.E. forecasts.

The success of the P.E. forecasts for this cut-off low situation and the one winter test case that we have seen give us reason to be cautiously optimistic in believing that the P.E. model handles this synoptic pattern better than previous NMC NWP models. Obviously, this is too limited a sample to draw any conclusions yet.

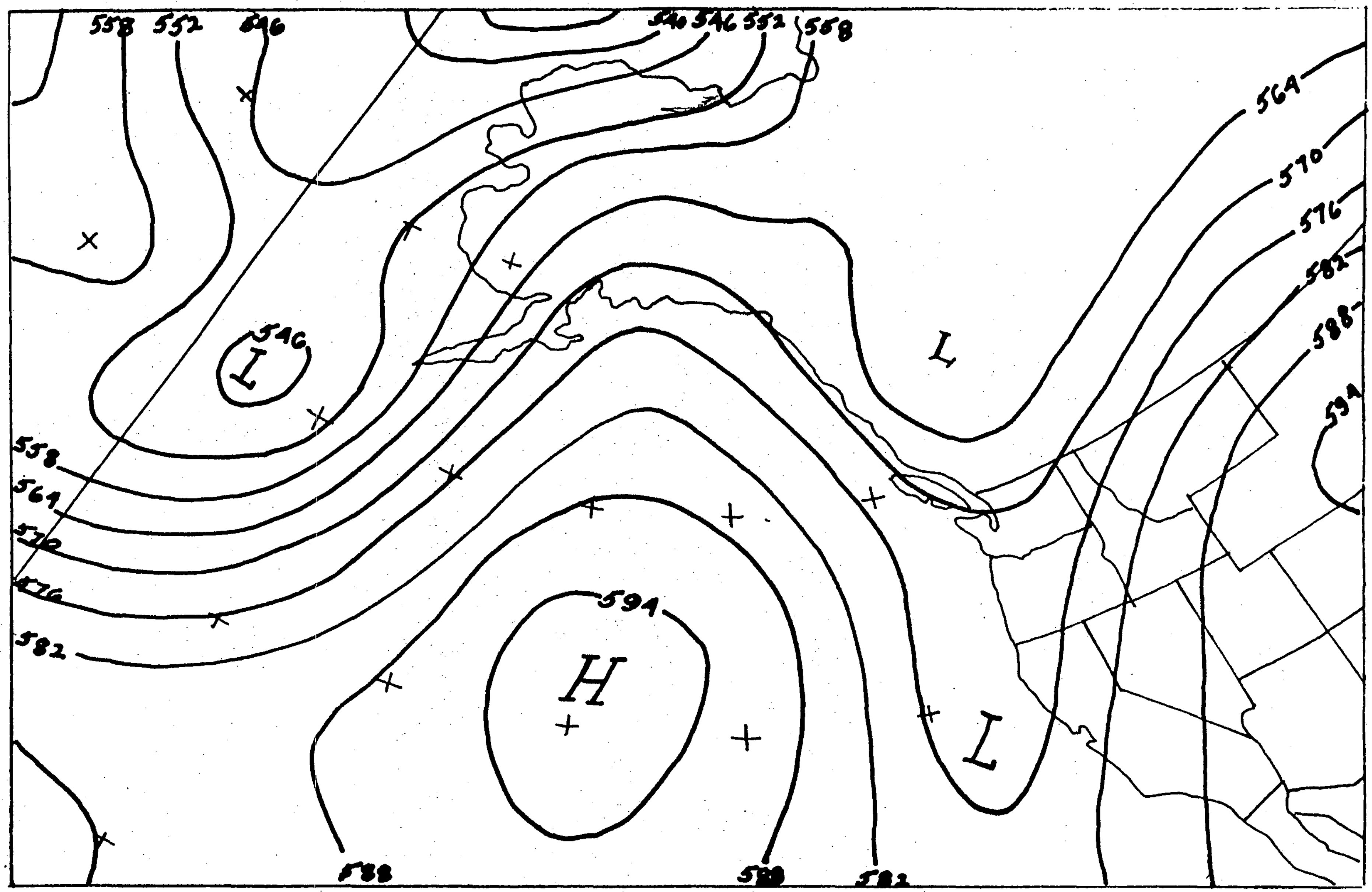


FIGURE 1. 500-MB ANALYSIS, 0000Z JULY 11, 1966.

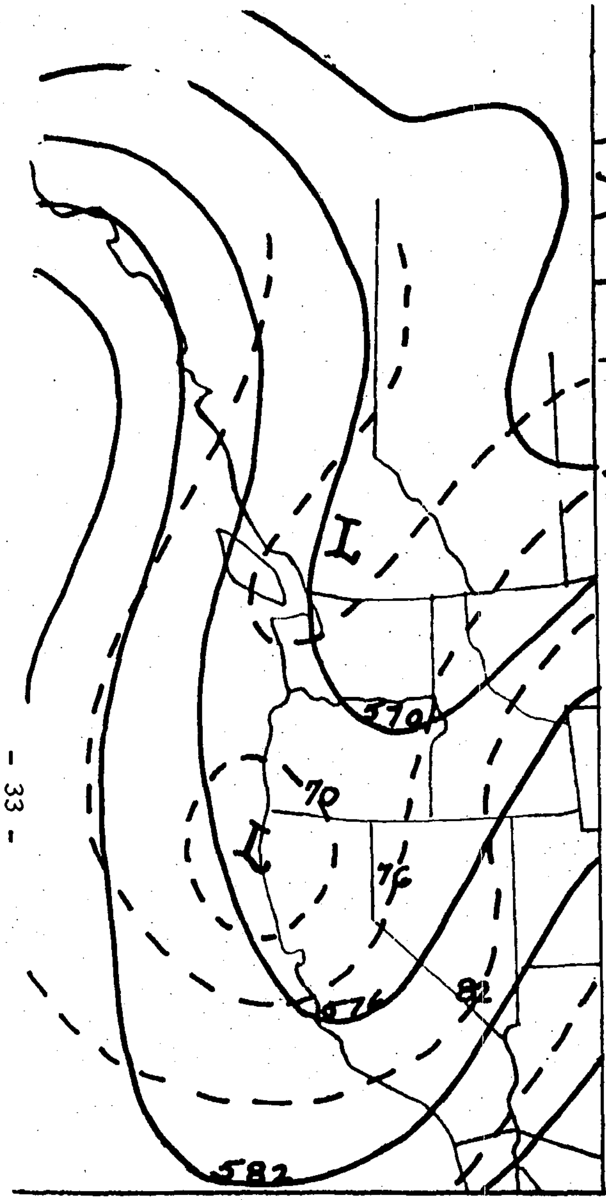


FIGURE 2a. 3-LEVEL 36-HOUR 500-MB PROGNOSIS, VALID 1200Z JULY 12, 1966. Solid lines are prognostic contours; dashed lines, verifying contours. Both sets of contours are labeled in decameters, the 5 being omitted from verifying contours. Initial analysis for forecast is given in Figure 1.

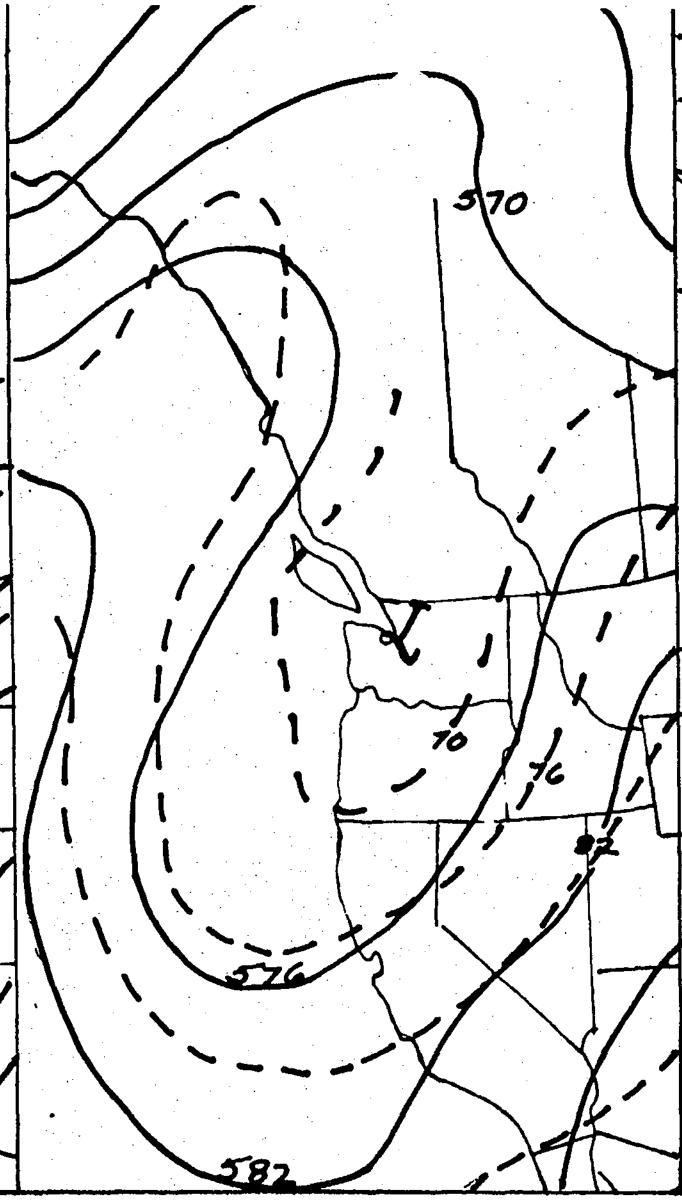


FIGURE 2b. P.E. 36-HOUR 500-MB PROGNOSIS, VALID 1200Z JULY 13, 1966. Lines are described in Figure 2a. Some idea of initial analysis for this forecast can be obtained by noting verifying contours in Figure 2a.

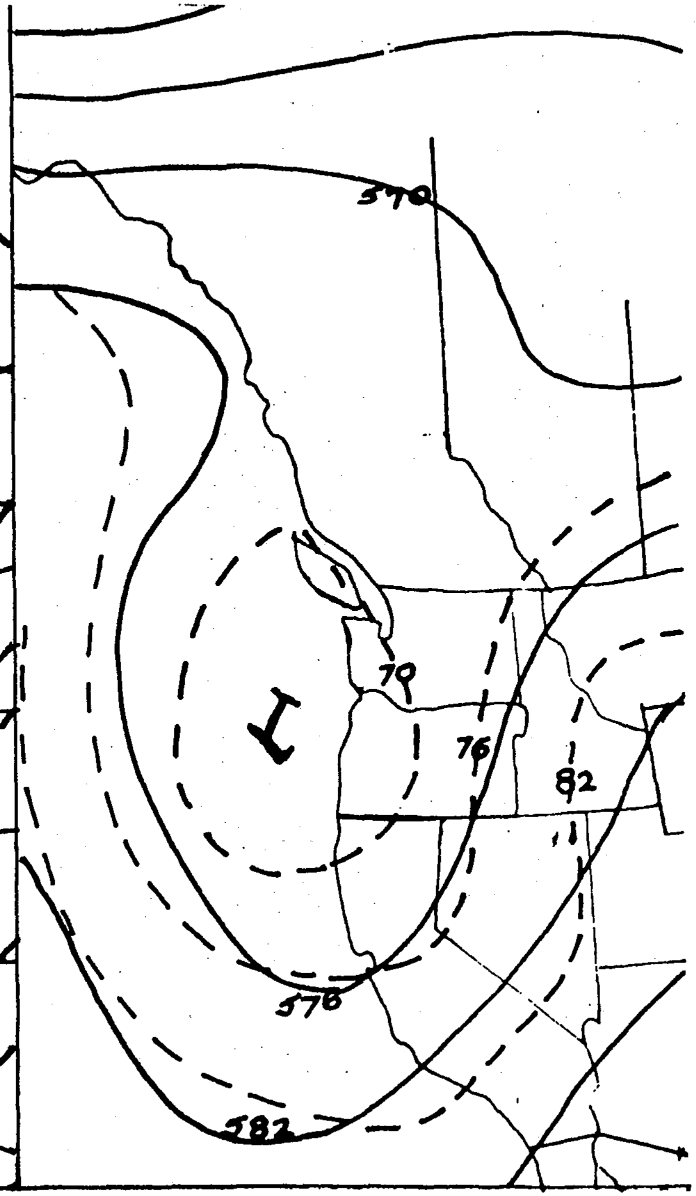


FIGURE 2c. P.E. 36-HOUR 500-MB PROGNOSIS, VALID 1200Z JULY 14, 1966. Lines are described in Figure 2a.

IX - ACKNOWLEDGMENTS

The author wishes to express his appreciation to Chester Glenn, Lloyd Magar, and Philip Williams of the Regional Headquarters for reviewing the original manuscripts. Their constructive criticism and suggestions had an important part in the preparation of the published Technical Attachments. The valuable, up-to-date technical information furnished by Dr. John Hovermale and Mr. Edwin Fawcett of NMC is gratefully acknowledged. The excellent drafting of the numerous figures is the work of Mrs. Lucianne Miller. Many of these figures were completed under short deadlines.