FORECASTING MIDDLE CLOUDINESS AND PRECIPITATION AREAS BY NUMERICAL METHODS

LIEUTENANT COMMANDER EDWARD M. CARLSTEAD, USN

Fleet Weather Central, Suitland, Washington 25, D.C. *

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ABSTRACT

A numerical prediction model suitable for computation using large-scale digital computers to forecast amounts of middle cloudiness, areas of precipitation, and precipitation amounts is presented. The model described uses products derived from an operational Joint Numerical Prediction Unit forecast model. Background information, certain mathematical equations, and input-output format are presented. Figures showing a sample series of prognostic charts are presented. Results, limitations, and future prospects are discussed.

1. BACKGROUND

The providing of upper-level and surface prognostic charts for use in the field has been undertaken with considerable success by many meteorological activities including the Joint Numerical Weather Prediction Unit (JNWP) and the National Weather Analysis Center (NAWAC). The increasing success of these products serves to remind one of the other "face" of the prognostic "coin," namely, determining weather elements from prognostic information. This paper describes a beginning method of predicting areas of occurrence of middle cloudiness including amounts, and areas of large-scale precipitation including quantitative amounts. Further, these predictions will be produced in a form suitable for transmission to field activities for operational use.

Work has been done on this problem in the past. Smagorinsky and Collins [5] considered the problem of the mechanics of the formation of precipitation based on the laws of fluid mechanics and used a computer to solve these laws in the form of certain mathematical equations. With the placing in operation of the "thermotropic" two-level model at JNWP in the spring of 1956 [7], charts of initial and forecast vertical motions were made available. Coincident with this, studies were commenced at JNWP to examine some possible uses for these charts. One result of this examination was the development of a technique by Lewis [4] using vertical motions and constructed 700-mb. trajectories to forecast the change in the 700-mb. dewpoint depression at one station for a period of 36 hours. This work showed the difficulty of numerically forecasting the change in 700-mb. dewpoint depression unless both horizontal advection and changes due to vertical motion were considered. Another result of this work was the determination of a nomogram (fig. 1) of the relationship between middle cloudiness, precipitation, vertical motion, and 700-mb. dewpoint depression. The sample of data going into this scatter diagram was fairly small, but additional samples of data have tended to confirm the isolines of the nomogram. The promising results of Lewis' work led to a project at JNWP to adapt this technique to a hemispheric grid and to compute a forecast of a field of dewpoint depressions and associated weather patterns by use of the high-speed IBM 704 computer at JNWP in Suitland, Md.

2. INITIAL MOISTURE INPUT FIELD

The moisture that is contained within the atmosphere is distributed irregularly through it. It would be desirable to attempt to forecast the changes in moisture at many levels within the atmosphere. However, because of the limitations in the number of fields that can be carried internally within the machine, it is not possible to treat more than one level at present. It was decided to work with the advection of moisture at 700 mb. because this would allow the direct usage of the results of Lewis' work; because the 700-mb. level is near the primary level (500 mb.) of the present operational JNWP models; and finally, because the presence of moisture at 700 mb. is a good indicator of a "deep" moisture layer. Upon examination of early forecasts it was seen that several forecasts were "missed" because the atmosphere was saturated from the ground to just below the 700-mb. level and was very dry above. This caused the model to work with a much too dry moisture field. It was decided to modify the moisture input data by computing a moisture field consisting of the average of the 850-mb. and 700-mb. dewpoint de-

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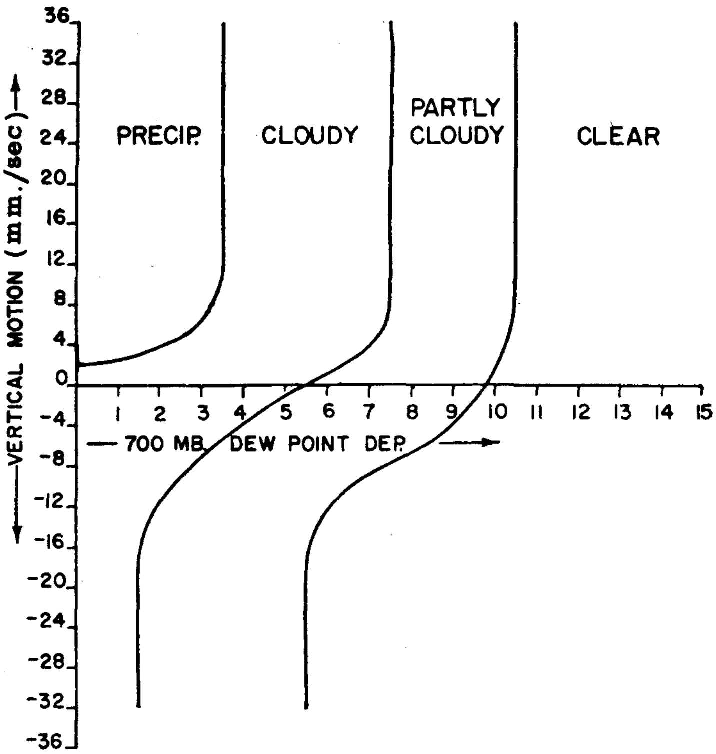

FIGURE 1.—Nomogram used for determination of weather categories, giving weather as a function of vertical motion in millimeters per second and the 700-mb. dewpoint depression in degrees Celsius. Enter nomogram with 700-mb. dewpoint depression and vertical motion and forecast weather indicated within envelopes. (From [4].)

pressions. This resulted in an immediate improvement in forecasts. Another data problem encountered was due to the scarcity of moisture data aloft over the ocean areas of the world. This problem can be reduced considerably by inferring the 850–700-mb. dewpoint depression from surface ship reports. Referring to the nomogram (fig. 1) it can be seen that if certain weather conditions (say, rain) are observed, a dewpoint depression of about 2° C. can be assumed without too much error. This type of inferred report is easily introduced into the automatic data processing system [1] that is currently operational at JNWP.

The operation begins with the analysis of the initial moisture field. Data for the analysis are obtained from the automatic data processing data tapes. The analysis is performed by the JNWP objective analysis program. This analysis program starts with a "guess" field consisting of the 24-hour forecast dewpoint depression field available from the previous day's run and modifies this guess field with current data. This technique has the valuable attribute of preserving continuity over areas of sparse data. The output of the analysis program consists of a map of dewpoint depressions, a coverage chart of stations reporting data, a chart of the difference between the "guess" (24-hour forecast) field and the final analysis (hence providing, among other things, a verification of the 24-hour forecast dewpoint depressions), and a punched card deck, in binary, of the dewpoint depression field.

3. FORECASTING MODEL

The forecasting model, which uses the moisture field which was obtained as described in the previous section, depends upon the hourly fields of 500-mb. stream function data, $\hat{\psi}_5$, the hourly large-scale vertical motions, ω, and the hourly forecast 850–500-mb. height thickness fields, Δz, all of which are saved on a magnetic tape from the operational run of the JNWP two-level model. The general principle of operation of the middle cloud and precipitation area forecast is to advect the initial moisture field with a computed 700-mb. stream field, modifying the dewpoint depression with the forecast vertical motions. Then, with the aid of the Lewis nomogram, the expected future weather conditions can be determined from the forecast moisture field and the forecast vertical motion field. To obtain the wind velocity at 700 mb. the following interpolation is performed:

$$\hat{\psi}_{7i,j}=\hat{\psi}_{5i,j}-\alpha\Delta z_{8.5-5i,j},$$

where

$$\alpha=\left(\frac{z_5-z_7}{z_5-z_{8.5}}\right)_{\text{Std. Atm.}} \tag{1}$$

In interpolating for the wind at 700 mb., the wind is assumed to vary linearly with height, and the shear wind is assumed to be reduced below the geostrophic by the factor $f/\bar{f}$, where $\bar{f}$ is the Coriolis parameter at 45° of latitude. The geostrophic wind shear was first used, but it was found to yield much too large wind speeds in low latitudes. No serious error is caused in middle latitudes or even in high latitudes by replacing f by $\bar{f}$ in the expression for shear wind, and more realistic, if not more accurate, wind values are obtained in low latitudes. In the solution of the balance equation at JNWP to obtain stream function values, z is used as the boundary value for $(\bar{f}\psi)/g$. This not only reduces the velocity normal to the boundary below the geostrophic by the factor of $f/\bar{f}$, it also leads to a similar reduction below geostrophic in the tangential component at the boundary. Thus, our interpolation formula is consistent with other computational practices used in the forecast procedure.

A number of charts of this computed $\hat{\psi}_7$ have been produced as well as charts of wind speeds and directions computed from the $\hat{\psi}_7$ data. These wind charts were compared with actual analysed charts and with random wind observations at 700 mb. Also, several cases of winds computed from $\hat{\psi}_7$ fields were compared analytically with actual observations over North America. These experiments showed no significant difference between average winds computed geostrophically from actual analyses and winds computed from the $\hat{\psi}_7$ fields.

After the $\hat{\psi}_7$ field has been determined, the local rate of change of the dewpoint depression T_d, at time τ is given by

$$\left(\frac{\partial T_d}{\partial t}\right)_\tau = -\frac{g}{\bar{f}} J[\hat{\psi}_7, T_d] + \gamma W_\tau \tag{2}$$

where $\bar{f}$ is the Coriolis parameter at 45° latitude, and g is the acceleration of gravity. Dewpoint depression changes due to vertical motion are assumed dry adiabatic in nature, and the vertical gradient of dewpoint depression is assumed to be locally zero. The coefficient γ is then the dry adiabatic rate of change of dewpoint depression, and is approximately equal to 8° C./km., depending on temperature and pressure. The vertical motion, W, at time τ is obtained by

$$W_\tau = \tfrac{1}{2}(W_{\tau-1} + W_{\tau+1}) \tag{3}$$

using one hour increments in τ. Centered differences in time are used for extrapolation of T_d, namely,

$$(T_d)_{\tau+1} = (T_d)_{\tau-1} + 2\left(\frac{\partial T_d}{\partial t}\right)_\tau \tag{4}$$

Negative values are not permitted.

Within the model there is a field of the altitudes of smoothed terrain. Using this terrain height field (z_s), the approximate surface stream function, $\hat{\psi}_s$ is determined at each point i, j by extrapolating from 500-mb. stream function data to the surface altitude as follows:

$$\hat{\psi}_{s_{i,j}} = \hat{\psi}_{5_{i,j}} - \left(\frac{z_5 - z_{s_{i,j}}}{z_5 - z_{8.5}}\right)_{\text{Std.Atm.}} \Delta z_{8.5-5_{i,j}} \tag{5}$$

Using $\hat{\psi}_s$ to determine the surface wind $\mathbf{V}_s$, the vertical motion at the surface due to terrain is given at each point by

$$w_{s_{i,j}} = (\mathbf{V}_s \cdot \nabla z_s)_{i,j} \tag{6}$$

It is probable that the decrease in the value of orographically induced vertical motions with height is nonlinear. Estoque [3] and Smebye [6] suggest that the factor $\left(\frac{p}{p_s}\right)^b$ suitably represents the decrease of orographic vertical motion with height, where p is pressure and p_s is the standard atmospheric pressure of the altitude at point i, j. b is taken here to be 2.5. The vertical motion at 700 mb. due to orographic effects is given approximately by

$$w_{0_{i,j}} = w_s\left(\frac{p_7}{p_s}\right)^{2.5}_{i,j} \tag{7}$$

The effect of the surface friction contribution to vertical motion was shown by Smagorinsky and Collins [5] using a relationship derived from Charney and from Brunt. The vertical motion at 700 mb. from surface friction w_f is given by

$$w_{f_{i,j}} = \left[\sqrt{\frac{K}{2f}} \sin(2\nu)\zeta_s\right]\left(\frac{p_7}{p_s}\right)^{2.5}_{i,j} \tag{8}$$

where K, the coefficient of eddy viscosity, is 10^5 cm./sec.; f is the Coriolis parameter; ν, the angle between the wind and isobars at the surface, is taken to be 22.5°; and ζ_s is the relative vorticity at the surface and is related to $\nabla^2\hat{\psi}_s$.

The final large-scale vertical motion used in the forecast is given by

$$W_{i,j} = w + w_0 + w_f \tag{9}$$

and is then used in (3).

3. OPERATION AND OUTPUT

The forecast change of the dewpoint field is computed in 1-hour time steps using the method outlined in the previous section. At the end of each time step, the Lewis nomogram table is entered to determine at which points large-scale precipitation is expected to occur. At these particular points, the temperature at 700 mb. is estimated from the forecast thickness value by the following simple relation (temperature in ° A.)

$$T_{7_{i,j}} = \left(\frac{T_7}{z_5 - z_{8.5}}\right)_{\text{Std.Atm.}} \Delta z_{8.5-5_{i,j}}$$

Smebye [6] has shown that the quantity of precipitation falling out of the atmosphere, assuming a pseudo-adiabatic process, is related to the temperature at 700 mb. and the vertical motion. Therefore, if large-scale precipitation is indicated for a point, then the temperature at 700 mb. is estimated and, using the vertical motion forecast for the particular time step, a 1-hour precipitation quantity is determined for each point. These results are accumulated in a special field, and are printed out as a 24-hour quantitative precipitation forecast chart (fig. 4) at the end of the forecast.

At times 0, 12, 24, and 36 hours, the Lewis nomogram is entered and the cloud and large-scale precipitation parameter for each grid point is determined. This field is contoured with the following scheme:

(No symbol) ----	Less than 0.1 middle cloudiness.
$ ---------------	0.1 to 0.5 middle cloudiness.
● ---------------	0.5 through 1.0 middle cloudiness.
0 ---------------	Area of active tropical shower activity and/or area of intermittent large-scale precipitation.
X ---------------	Area of large-scale precipitation.

At the grid points are entered the forecast mean dewpoint depressions in tenths of degrees Celsius. It must be noted that this model is considered to depict only large-scale weather occurrence, since the mesh length of the grid used at JNWP is about 200 miles. Disturbances smaller in size than this may be lost within the grid.

The areas depicted by the "0's", and not appearing in the Lewis nomogram, are the result of an attempt at

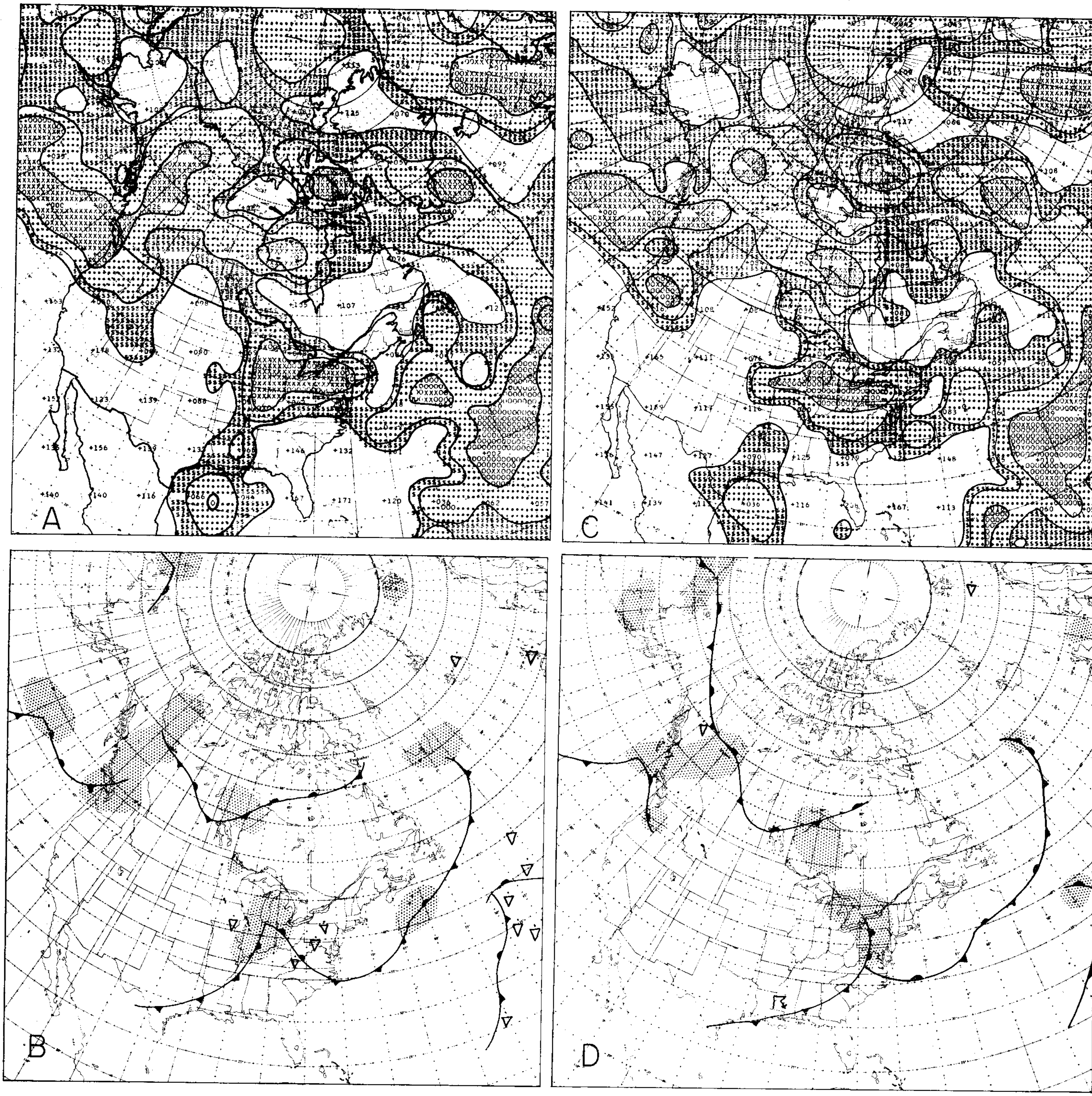

FIGURE 2.—(A) Initial chart of middle cloudiness and large-scale precipitation for 1200 GMT, April 28, 1959. Grid values are mean 850–700-mb. dewpoint depression in tenths of degrees C. See text for meaning of symbols. (B) Fronts and observed areas of precipitation for 1200 GMT, April 28, 1959, taken from the National Weather Analysis Center surface analysis chart. (C) 12-hour forecast middle cloudiness and large-scale precipitation area chart for 0000 GMT, April 29, 1959. (D) Observed frontal positions and precipitation areas for 0000 GMT, April 29, 1959. Note: Because of necessary reduction for printing, only a portion of the charts is shown. The forecast program produces charts covering the entire Northern Hemisphere to about 15° N.

showing areas of active tropical shower activity. Curtis and Panofsky [2] showed that there is a poor relationship between vertical motion computed from the thermotropic model and tropical air mass shower activity, including the afternoon shower activity over the United States in summer. They did find a good predictor of convective activity by considering the moisture present in the 900–700-mb. layer and the presence of a heated

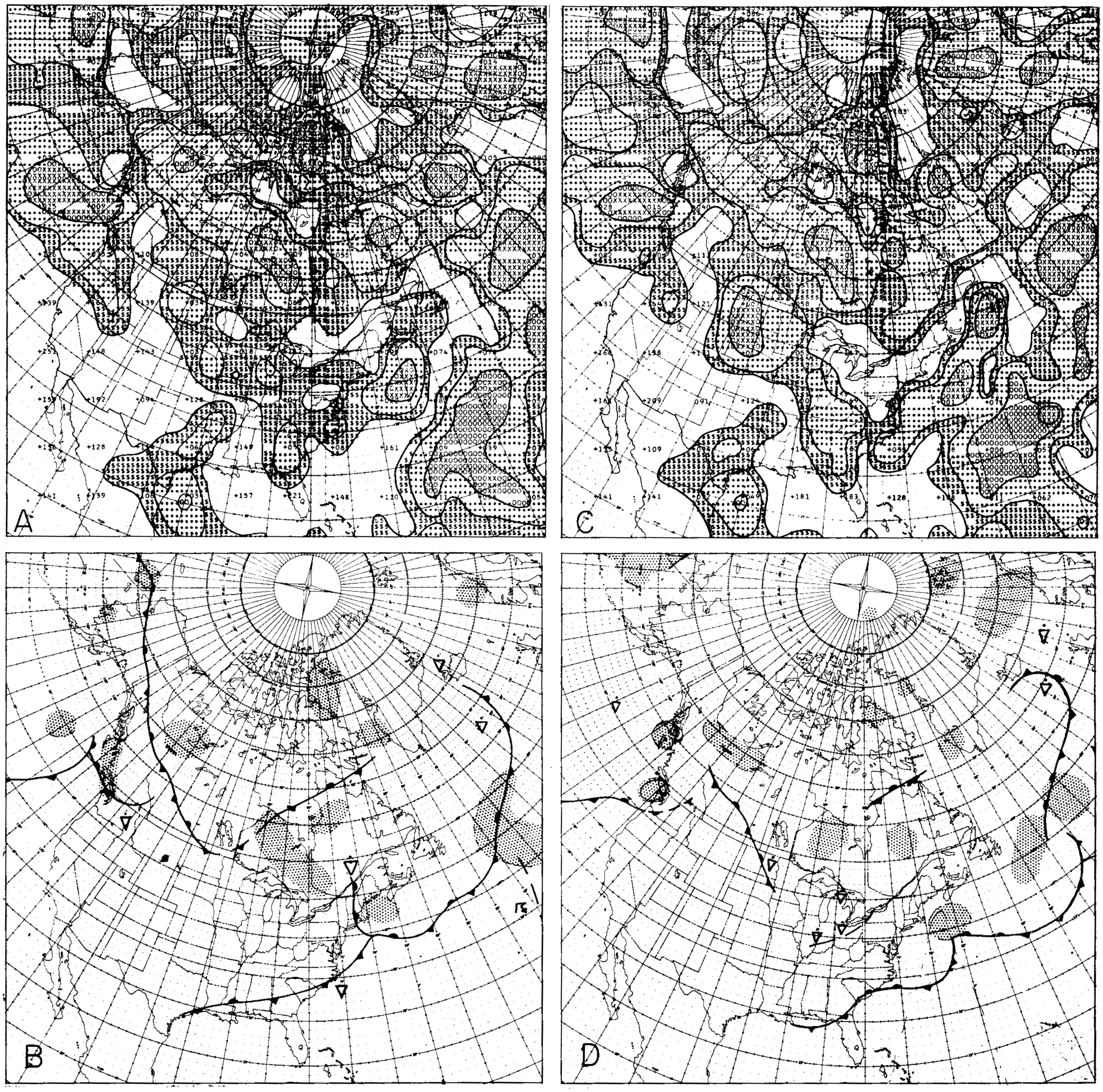

Figure 3.—(A) 24-hour forecast middle cloudiness and large-scale precipitation area chart for 1200 GMT, April 29, 1959. (B) Observed frontal positions and precipitation areas for 1200 GMT, April 29, 1959. (C) 36-hour forecast middle cloudiness and large-scale precipitation area chart for 0000 GMT, April 30, 1959. (D) Observed frontal positions and precipitation areas for 0000 GMT, April 30, 1959.

surface under a tropical air mass. On the assumption that this relation would obtain elsewhere over the hemisphere where tropical air is present over a heated surface, grid points over land masses for times during local afternoon and over sea areas having a mean sea surface temperature greater than 72° F. were listed. This list of points is contained within the program to "tag" the grid points where the shower predictor would obtain. After

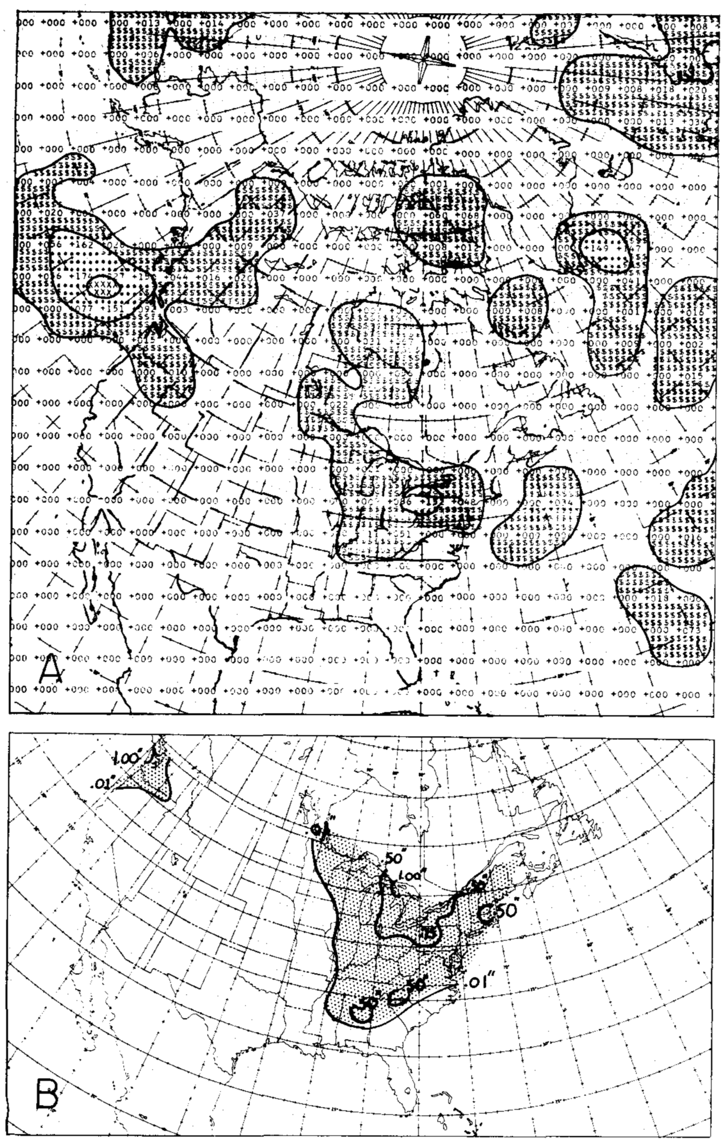

Figure 4.—(A) 24-hour precipitation quantity forecast for period ending 1200 GMT, April 29, 1959. (B) Observed 24-hour precipitation quantities for period ending 1200 GMT, April 29, 1959, in the area of the contiguous United States. Note: Precipitation quantities forecast here are those obtained by consideration of some large-scale processes only. Tropical air mass shower precipitation quantities are not considered here. Tropical shower activity is important and experiments to incorporate this factor are continuing.

the program computes the weather parameter for a point from the Lewis nomogram, the grid point list is consulted to determine if the point is "tropical." If so, the thickness field is consulted to see if the forecast value of the 850–500-mb. thickness is greater than an arbitrary value of 14,000 feet. If so, the forecast dewpoint depression value for the point is tested to see if the relative humidity is greater than 60 percent. If all these tests are passed, the probability of tropical shower activity is good and the parameter for tropical showers is stored for that point. It will be noted that all large-scale precipitation areas are surrounded by a band of "0" characters. This is due to an effect of the contouring program. The numerical value of showers for the contouring program must be chosen between cloudy and precipitation. Hence, when the program contours the large-scale precipitation areas, the areas are surrounded with spurious "0's". This is rationalized to be acceptable because precipitation is often intermittent or showery at the edges of an area.

The maps are printed on "onion skin" tracing paper which can be run through a reproducing machine with a plastic overlay of the geography superimposed. Examples of the forecast are shown in figures 2 through 4.

At present, the program nearly saturates the storage capacity of the IBM 704 computer. Within the limited space remaining, experiments are being conducted on ways of estimating the quantity of precipitation from shower activity.

4. LIMITATIONS

The limitations of a scheme such as described herein are several. The development of multi-level models is in its infancy. There is much room for improvement within these models and as these improvements are effected results from the forecast-of-precipitation-model should improve. It is believed that the largest error in forecasts stems from the errors in placement and magnitude of the vertical motion centers. This error is also associated with the present two-level model's inability to forecast true baroclinic development. Second, the forecast precipitation model depends upon empirical relationships to determine weather parameters. These relationships are not understood at present. Third, the precipitation model is not a true three-dimensional model but it is rather a one-level forecast with some degree of freedom in the vertical. Fourth, there is no allowance for obtaining moisture data from below the 850-mb. layer and we have no way yet of doing this. Last, the effects of latent heat of condensation where precipitation is forming have not been considered. Thus, there is ample material for future experiments with better models.

Verification is largely subjective. Although the precipitation quantity chart can be verified by comparison, such subjective verification of middle cloudiness is not simple often due to obscuration by low clouds and darkness. The verification of the forecast of dewpoint depressions for 24 hours is accomplished by machine. The machine computes the mean absolute error over the grid points encompassing the dense data network of North America. Insufficient verification data have been collected to date to permit a comprehensive objective verification. Activities of the Air Force, Navy, and Weather Bureau are receiving these charts by facsimile and local delivery and are evaluating them for usefulness.

To show the factor of machine speed over hand speed for the same job, the following figures are presented: Lewis's technique takes about one-half hour to compute the forecast dewpoint depression spread for one station. The forecaster was forced to use charts 12 hours apart to compute the trajectory of the parcels. The present machine forecast technique produces a 36-hour dewpoint depression forecast for 1977 points using time steps of only 1 hour. This 36-hour forecast takes only 15 minutes, a gain factor of 35,586. In addition, the machine produces the forecast in map form along with auxiliary charts. Granting the crudeness of this forecast model, it is possible to foresee the time when electronic computers will actually forecast the meteorological parameters on an operational basis. This day may not be too far away.

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