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The Techniques Development Laboratory Three-Dimensional Trajectory Model

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SIGNIFICANT CHANGE FROM LAST BULLETIN ON THIS SUBJECT NO. 225

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The Techniques Development Laboratory (TDL) trajectory model has been run twice daily at the National Meteorological Center (NMC) for over two decades since its operational implementation in December 1968.

At present, two versions of the trajectory model are run operationally at NMC. One is driven by wind forecasts from the Limited-area Fine-mesh Model (LFM) and has been in operation since the early 1970s producing forecasts that are limited to a 24-h projection. The most recent version is driven by wind forecasts from the Nested Grid Model (NGM) and is run twice daily producing forecasts for projections of 24, 36, and 48 hours after initial data time.

Operational products based on the TDL Trajectory Model include the FOUS50-57 Alphanumeric bulletins (AFOS product identifiers are: NMCFTJxx, where xx = 50, 51, ..., 57); various graphics products (listed on page 8) which are available on AFOS and the AFOS Graphics Service of the Family of Services; and a 4-Panel Trajectory Model Chart available on DIFAX.

Technical Procedures Bulletin No. 225 is now operationally obsolete.

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THE TECHNIQUES DEVELOPMENT LABORATORY THREE-DIMENSIONAL TRAJECTORY MODEL

by Ronald M. Reap

1. INTRODUCTION

The Techniques Development Laboratory (TDL) trajectory model has been run twice daily at the National Meteorological Center (NMC) for over two decades since its operational implementation in December 1968. The original objective of the model was to attain greater accuracy and detail in the prognosis of thermal and moisture distributions below 700 mb (Reap, 1972). Over the years, temperature and dew point forecasts from the model have been used in the development of a variety of statistical forecast products designed to predict the occurrence of thunderstorms and severe local storms over the conterminous United States (Reap and Foster, 1979). Unique forecast products from the model have also been applied to a number of diagnostic and forecast problems. For example, prognostic three-dimensional trajectories generated by the model were found to be useful in forecasting meteorological elements such as cloud cover, ceiling height, fog formation and dissipation, surface temperature, and precipitation (Pflaum et al., 1972; Lowry and Glahn, 1976). Net vertical displacement forecasts from the model were found to be useful in predicting the occurrence and amount of snow, especially for heavy snow events (Reap, 1990). Parcel trajectories were also used in numerous studies on the three-dimensional transport of atmospheric chemicals, including hydrocarbons, ozone, and radionuclides released from nuclear accidents (Larsen et al., 1989; Singh et al., 1988). Other applications include the study of acid rain deposition, moisture return from the Gulf of Mexico and, in perhaps the most exotic application, the study of wind-aided migration of crop pests into central Iowa (Domino et al., 1983; Wolf et al., 1987).

At present, two versions of the trajectory model are run operationally at NMC. One is driven by wind forecasts from the Limited-area Fine-mesh Model (LFM; Brown, 1977) and has been in operation since the early 1970s producing forecasts that are limited to a 24-h projection. The most recent version is driven by wind forecasts from the Nested Grid Model (NGM) (Hoke et al., 1989) and is run twice daily producing forecasts for projections of 24, 36, and 48 hours after initial data time.

The underlying feature of the trajectory model involves the computation of three-dimensional air parcel trajectories from the u-, v-, and w-wind component forecasts generated by the NMC models. Trajectories for each forecast level are computed backwards in 2-h time steps from their terminal points, which initially form a rectangular array of grid points, to their origin points in three-dimensional space. The terminal point array for each level is initialized with a grid spacing of 381 kilometers (km). In effect, the array forms a subset of the LFM forecast grid where every other grid point is used. Parcel trajectories for the 24-, 36-, and 48-h projections are prepared separately, i.e., they are computed backwards in time starting with the 24-, 36-, and 48-h wind forecasts, respectively, to their origin points at the initial model run time (0000 or 1200 UTC). Forecasts are subsequently made by following the variations of temperature and moisture along the computed trajectories. In June 1971, the model was updated to include the simulation of air-sea energy exchanges for over-water trajectories (Reap, 1971). This modification resulted in more accurate model forecasts of low-level temperature and moisture along coastal areas during the cool season.

During the analysis and initialization procedure, all available upper-air data, including significant-level data, surface land and ship reports, and initialized grid point values from NMC's models are used in initializing the trajectory model (Reap, 1976). The objective analysis scheme is designed to reproduce detailed patterns and gradients with only light smoothing of the observations. In addition, once the initial temperature and moisture are analyzed at the trajectory origin point, there is no additional smoothing introduced in computing temperature and moisture changes of an air parcel moving along a predetermined trajectory. This procedure preserves large gradients due to convergence of the trajectories.

2. TRAJECTORY COMPUTATIONS

Input data to the trajectory program consist of six-hourly u-, v-, and w-wind component forecasts from the NMC models for the 1000, 850, 700, 500, and 300 mb pressure levels. The data for each pressure level are stored on a 26x33 grid array with a horizontal mesh length of 381 km. Considering, for example, only the west-east component of the displacement (along the X-axis) and noting that the trajectories are computed backwards from selected terminal (grid) points to origin points, the computation procedure is outlined as follows:

A first-guess position is obtained from

$$X_2\,(t-\delta t) = X_1(t) - u_1\,(t)\delta t \qquad (1)$$

where $X_2(t-\delta t)$ is the computed upwind position along the X axis, $u_1(t)$ is the wind component at the terminal point $X_1(t)$ and δt is the time increment for trajectory iterations. After extensive testing, a value of $\delta t = 2$ hours was chosen to insure a good compromise between the desired accuracy and computer time. The second approximation to the location of the computed upwind position on the trajectory is given by

$$X_3\,(t-\delta t) = X_1\,(t) - \frac{\delta t}{2}\,\{u_2\,(t-\delta t) + u_1\,(t)\} \qquad (2)$$

where $u_2(t-\delta t)$ is the interpolated value of u at the point $X_2(t-\delta t)$. Successive iterations of (2) are performed by replacing $u_2(t-\delta t)$ with $u_3(t-\delta t)$, as interpolated to $X_3(t-\delta t)$, etc., until the trajectory origin points converge within prescribed limits. Typical values for the horizontal and vertical convergence criteria are 0.01 grid interval and 1.0 mb, respectively. Trajectories outside the grid in the horizontal or vertical are terminated at the lateral boundaries or at 300 mb. Interpolations in the vertical and in time between successive prognostic fields of the wind components are given by

$$f(X_0 + \Phi h) = \frac{\Phi(\Phi-1)}{2}\,f_{-1} + (1-\Phi^2)\,f_0 + \frac{\Phi(\Phi+1)}{2}\,f_1 \qquad (3)$$

where $f_0 = f\,(X_0)$, $f_{-1} = f(X_0 - h)$, $f_1 = f(X_0 + h)$ are the values of the wind components for three consecutive 6-h forecasts or three adjacent standard pressure levels. The interval between f_0, f_{-1}, and f_1 is given by h, while Φ is defined as the fraction of h between f_0 and the point of interpolation. A four-point bilinear formula is used for interpolations on the standard pressure levels. At the conclusion of each time step, the forecast trajectory height is compared to the interpolated terrain height at the new parcel location. The trajectories are not allowed to intersect the earth's surface and are systematically displaced by the underlying terrain. The terrain heights are obtained from a smoothed model topography defined on a grid with a mesh length of approximately 192 km at 60°N, similar to the LFM grid spacing. Computation of parcel trajectories, as given by equations 1-3, closely follows the procedure used in the Air Weather Service trajectory model (Collins, 1970).[1]

Vertical velocities in the NMC models are not available at initial time; therefore, initial vertical velocities are approximated by backward advection of the 6-h forecast vertical velocity fields. A nine-point smoother is also applied to all NMC vertical velocity fields to eliminate unwanted small-scale "noise." Tests showed that use of the smoothed velocities resulted in improved forecasts of temperature and dew point.

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[1] Personal communication , E. W. Friday, Jr., Assistant Administrator for Weather Services, National Weather Service, Silver Spring, MD

3. OBJECTIVE ANALYSIS

Since the three-dimensional trajectories are computed backwards from forecast points to origin points, it is necessary to specify the state of the initial temperature and moisture fields. The objective technique selected to provide analyzed values of temperature and moisture at the trajectory origin point was originally developed by Endlich and Mancuso (1968). Their analysis procedure was specifically designed to analyze winds, temperatures, and dew points at individual points in contrast to conventional methods of analysis which are primarily concerned with hemispheric synoptic-scale motions derived from smoothed fields of pressure-height data. The approach followed is desirable since the trajectory origin points are distributed rather unevenly in three-dimensional space. This approach also eliminates the need for selecting appropriate grid lengths required for temperature and dew-point analyses at several levels.

The analyzed values are obtained by fitting a plane surface by least squares to radiosonde observations nearest a trajectory origin point. The temperature and dew point for each observation are linearly interpolated from mandatory or significant level data points vertically adjacent to the level of the trajectory origin point. In addition, the temperature lapse rate between the selected data points is error-checked to eliminate any observations with superadiabatic lapse rates or unrealistically large inversions. A distance weighting factor for each observation is introduced prior to the fitting process to avoid excessive smoothing. The weighting factor is given by

$$W = C^2 \{(R + R^*)^2 + C^2\}^{-1} \qquad (4)$$

where C^2 is a constant chosen through testing, R is the magnitude of the position vector $\underline{R}$ from the trajectory origin point to the observation, and R* is a distance factor given by

$$R^* = (vX - uY) / (u^2 + v^2)^{1/2}; \quad R \geq R^* \geq 0 \qquad (5)$$

where u and v are wind components interpolated to the observation and X and Y are the scalar components of $\underline{R}$. The distance factor (R*) is used to give upwind-downwind observations greater weight than crosswind observations. Isolines of the analyzed scalar are more closely aligned with the flow direction as a result of this correction. This alignment, while typical of the entire troposphere, is especially consistent with numerous observations by operational forecasters which reveal the existence of well-defined temperature and moisture axes parallel to the low-level flow.

In earlier versions of the model, upper air observations constituted the sole data input to the objective analysis procedure. As a consequence, the quality of the initial analyses varied significantly in response to local variations in the spacing and distribution of the radiosonde stations. For example, the sparse upper air data available over oceanic regions resulted in analyses which, to varying degrees, did not accurately depict the small-scale patterns and horizontal gradients often associated with low-level temperature and moisture distributions. To alleviate these data limitations, the objective analysis procedure for the trajectory model was modified to include surface land and ship reports and initialized grid-point values from the NMC models. In the current analysis procedure, upper air and NMC data are assigned relative weights by means of a function which measures the asymmetry of the radiosonde station distribution at the initial position for each trajectory (Reap, 1976). As a result, weights applied to the upper air data are diminished with increasing station asymmetry, while weights assigned to the NMC data are correspondingly increased. In effect, NMC initialized fields which contain continuity from previous forecasts are used to supplement the radiosonde observations in regions where such data are sparse, missing, or irregularly spaced.

The lapse-rate (Mogil and Bonner, 1971) and decision-tree (Chisholm et al., 1968) methods are used to assimilate surface observations into the analysis procedure. In the first method, radiosonde lapse-rates are interpolated to each surface station and applied to the surface report, yielding values of temperature and moisture aloft. The decision-tree method uses reliable statistical relationships between upper-level moisture and observed surface variables to estimate the dew-point spread at selected pressure levels aloft.

4. PARCEL THERMODYNAMICS

The final step in the forecast procedure is accomplished by computing the changes in the initial temperature and moisture resulting from the vertical displacement of air parcels along the three-dimensional trajectories. After determining the initial values of temperature and dew point at the trajectory origin points, the program computes the 6-h variations of these quantities for parcels assumed to move along paths defined by the trajectories. Each parcel rises (or descends) dry-adiabatically provided saturation does not occur. If saturation occurs, the parcel is lifted dry-adiabatically to the lifting condensation level and pseudo-adiabatically thereafter.

A tendency to underforecast temperature and dew point along coastal areas in the cool season was noted in earlier versions of the trajectory model. This cold and dry bias resulted from neglecting the sensible and latent heat fluxes from the ocean surface. Errors arising from the above effects were most pronounced in areas where the surface trajectories terminated after a long over-water path with a large north-south component of motion. An air parcel following such a trajectory can originate from a relatively cold, dry land or oceanic region and in moving southward would pass over much warmer waters and undergo considerable modification.

A quasi-dynamical model (Reap, 1971) was developed to correct the bias in the forecasts by simulating the addition of latent and sensible heat to a column of air moving over water along a surface trajectory. Subsequent changes in the surface air temperature were assumed to be a function of the initial lapse rate, initial air temperature, sea-surface temperature, and length of over-water trajectory. Verification statistics for the air-sea heat and moisture flux simulation showed significant reductions in the root mean square error and bias, especially for stations along or near coastal waters.

5. OPERATIONAL PRODUCTS

5a. FOUS50-57 Alphanumeric Bulletins

Eight alphanumeric bulletins based on trajectory model output are transmitted twice daily over AFOS, military and FAA circuits, and the Family of Services for the stations shown in Fig. 1. The bulletins, designated as FOUS50, FOUS51, FOUS52, ...,FOUS57, contain 24-h forecasts of temperature, dew point, and George's (1960) K stability index for each station along with six-hourly positions for trajectories terminating at the surface, 850 mb, and 700 mb. The AFOS product identifiers for the bulletins are:

NMCFTJxx, where xx = 50, 51, ..., 57.

For example, to view the FOUS57 bulletin on an AFOS Alphanumeric Display Module (ADM), enter NMCFTJ57 or just FTJ57. The WMO identifiers (FOUS57, for example) are used on the Family of Services. The FOUS50-57 bulletins are identical in format and are available for both the 0000 and 1200 UTC model runs. A portion of the FOUS57 message is shown in Fig. 2.

Six-hourly positions are given for trajectories terminating at the surface, 850 mb, and 700 mb for each station. North latitude (LAT) and west longitude (LON) are given in tenths of a degree. The first digit is dropped when the parcel longitude is equal to or greater than 100, e.g., 101.2 is coded as 012. Parcel pressures (PPP) are given in whole millibars, except where greater than 1000, in which case the first digit is omitted, e.g., 1008 is coded as 008.

Also shown is the model terrain pressure (MTP) at each station. This value remains fixed and is used in computing vertical displacements of surface air parcels over the last 6, 12, 18, or 24 hours of the forecast period. For example, at TYS the 24-h net vertical displacement (NVD) along the surface trajectory would be 947 minus 960, or -13 mb (downward). At GSO the 12-h NVD for the trajectory ending at 700 mb would

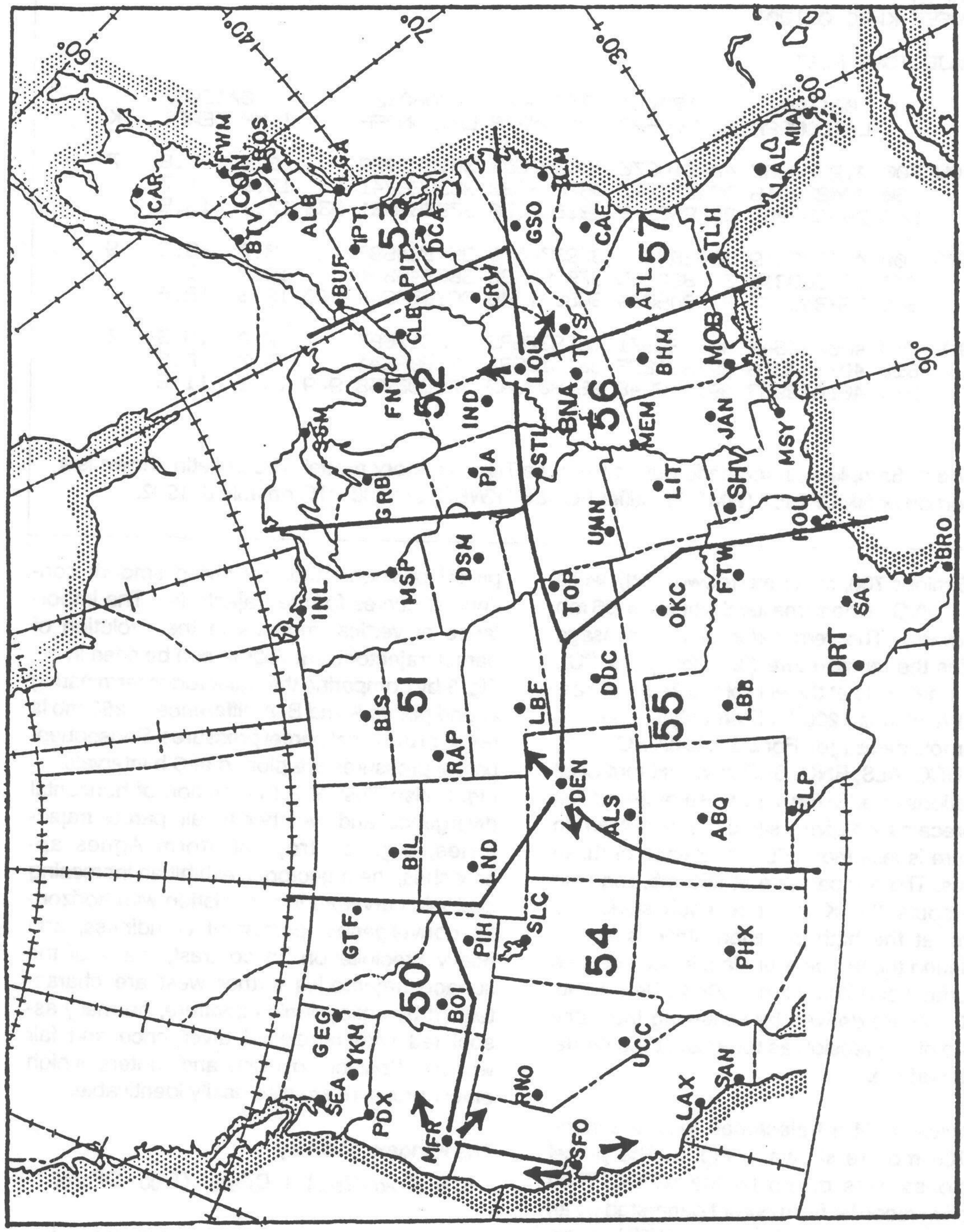

Figure 1. Station distribution for FOUS50 - 57 bulletins.

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NMCFTJ57
FOUS57 KWBC 061200

TRAJECTORY FCST

          061200Z   061800Z   070000Z   070600Z            071200Z
         LATLONPPP LATLONPPP LATLONPPP LATLONPPP        TEMP DEWPT    K

 LOU 700 419928667 408910676 400892683 391873689         8.8  -7.8    7
     850 404882816 394873827 387868833 383862841        13.9   1.7
     SFC 396854982 388852976 381852976 379854981 983    17.1  13.5

 TYS 700 405908649 390889667 379872679 368854688         8.7  -8.2    9
     850 390869815 379860825 370852830 363845841        15.2   2.8
     SFC 386849947 377845944 368841946 361839954 960    18.6  12.5

 GSO 700 420881644 402858671 387837685 372817687         7.0 -15.3    1
     850 407844816 393831825 381819831 371808841        12.7   2.5
     SFC 401823953 391816948 381808949 370802958 979    18.1  11.6
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Figure 2. Sample alphanumeric output from the TDL trajectory model. The bulletin shown is a portion of NMCFTJ57 (WMO identifier FOUS57 KWBC) at 1200 UTC on July 6, 1992.

be 685 minus 700, or -15 mb (downward), while the 24-h NVD at the same level would be -56 mb (downward). The remainder of the message contains the temperature (°C), dew point (°C), and K index valid at the end of the 24-h forecast period (which is 1200 UTC on July 6, 1992 for the sample message). For DEN, LND, BOI, ELP, ABQ, UCC, ALS, RNO, SLC, and PIH (out of all the stations listed in Fig.1), only surface and 700 mb forecasts are given, since the model terrain pressure is less than 850 mb at each of these stations. The temperature at 850 mb, required to compute the K index at each station, is derived at the high elevation stations by extrapolating the temperature lapse rate between the surface and 700 mb to 850mb. Dew points at 850 mb are derived by assuming the same dew-point depression as forecast at the model terrain surface.

Examples of 24-h trajectories for the surface and 700 mb are shown in Fig. 3. The parcel trajectories were drawn by the NOAA FR-80 microfilm recorder from output generated by an interpolation program developed at TDL. In essence, the program employs a curve-fitting procedure to generate data points between the 6-h parcel positions, thereby giving smooth continuous curves for the trajectories. The importance of vertical motions in the evolution of parcel trajectories at 700mb can be seen in Fig. 3 by comparing the trajectories terminating at grid points A and B. A difference of 252 mb is noted in the initial parcel pressures. Subsequent parcel pressures are plotted at 6-h intervals. Fig. 3 also illustrates the relation of horizontal divergence and weather to air parcel trajectories, e.g., as tropical storm Agnes approaches, the trajectories exhibit an increasing cyclonic curvature in association with horizontal convergence, persistent cloudiness, and heavy precipitation. In contrast, many of the surface trajectories farther west are characterized by anticyclonic curvature, normally associated with horizontal divergence and fair weather. Positions of fronts and centers of high or low pressure are also easily identifiable.

The K index, given by

$$K = (T_{850} - T_{500}) + DP_{850} - (T_{700} - DP_{700})$$

where T is temperature (°C) and DP (°C) is dew point at the respective pressure levels (given by

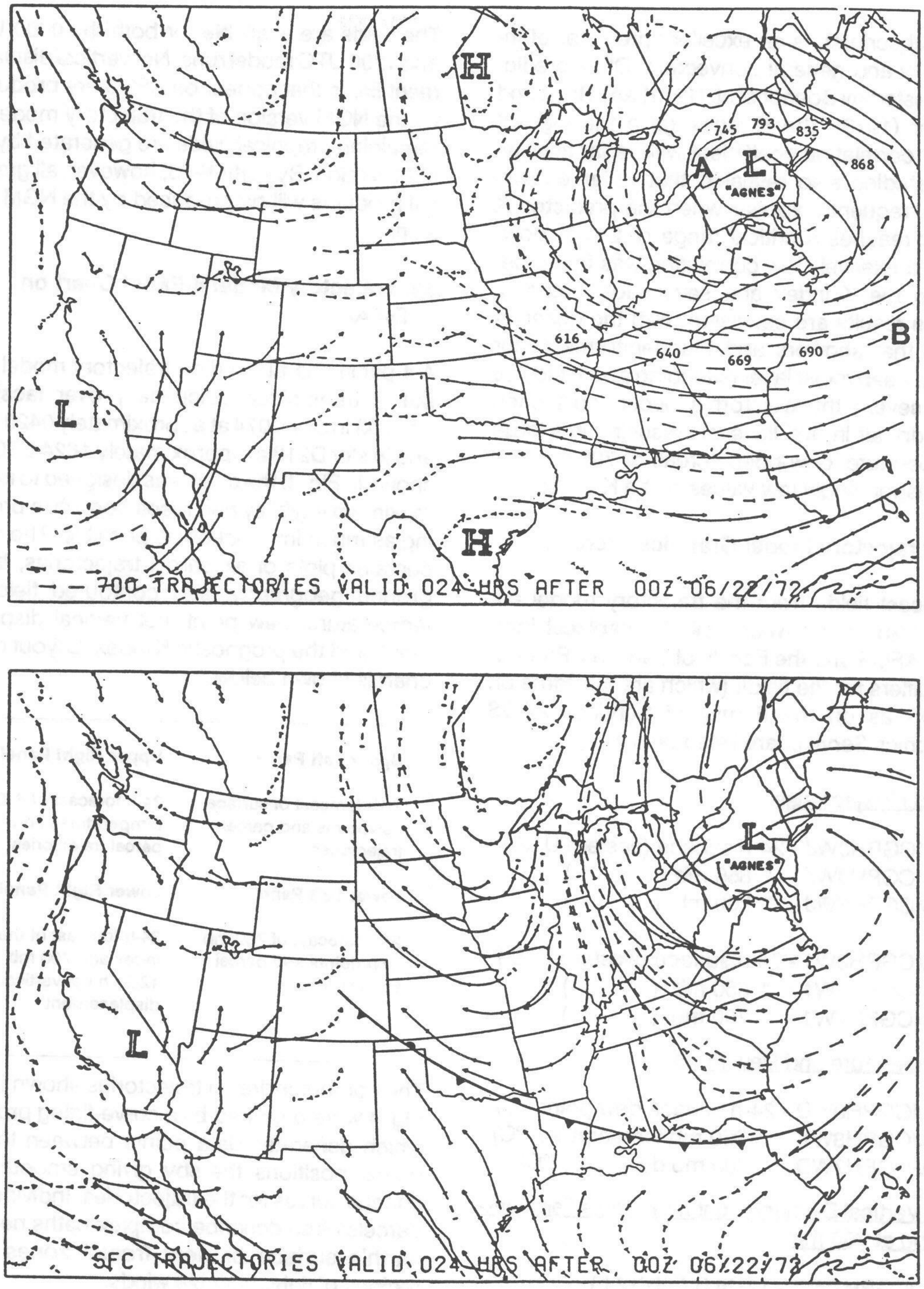

Figure 3. Computer-drawn 24-hour parcel trajectories terminating at the surface and 700 mb. Six-hour parcel positions are given by tick marks. Rising (subsiding) motions during the six-hour intervals are denoted by solid (dashed) lines. Vertical motions along the surface trajectories to a large extent reflect the underlying terrain.

the subscripts), is an excellent predictor of instability and general convection. Of all predictors tested by Bonner et al. (1971) and Reap and Foster (1979), the K index gave the highest linear correlation coefficient with radar activity. The studies also revealed that radar echoes most frequently appear when the predicted K index reaches a critical range of 24-36. However, a relatively low correlation was found between the K index and severe local storms. These results are consistent with the observations that showers and thunderstorms occur with a deep moist layer extending at least to 700 mb; severe thunderstorms occur most often with dry air in middle levels resulting in a large temperature, dew-point spread at 700 mb and correspondingly low values of the K index.

5b. Trajectory Model Graphics Products

Forecast fields from the trajectory model are also transmitted twice daily in graphical form over AFOS and the Family of Services. Product identifiers for the fields (which are the same on AFOS as on the Family of Services AFOS Graphics Service) are listed below:

Parcel Trajectories

NMCGPH0WJ - 24-h surface (eastern U. S.)
NMCGPH8WJ - " 850 mb (" ")
NMCGPH7WJ - " 700 mb (" ")

NMCGPH0W1 - 24-h surface (western U. S.)
NMCGPH8W1 - " 850 mb (" ")
NMCGPH7W1 - " 700 mb (" ")

Temperature and Dew Point

NMCGPH0WD - 24-h surface dew point (°C)
NMCGPH8WT - " 850 mb temperature (°C)
NMCGPH7WD - " 700 mb dew point (°C)

Net Vertical Displacement for Parcels Terminating at 700 mb

NMCGPH7WG - 12-24 h (mb/12 h)
NMCGPH7XG - 24-36 h (")
NMCGPH7YG - 36-48 h (")

Stability

NMCGPHI4K - 24-h K index

The fields are available for both the 0000 UTC and 1200 UTC model runs. Net vertical displacement fields that appear on AFOS are produced by the NGM version of the trajectory model; all remaining graphical fields are generated by the LFM version. By early 1993, however, all graphical products will be produced by the NGM version.

5c. Trajectory Model 4-Panel Chart on DIFAX

A 4-panel chart based on trajectory model output is transmitted twice daily over facsimile (DIFAX) in slot D074 at approximately 0420 UTC and in slot D218 at approximately 1624 UTC. As shown in Fig. 4, the chart was designed to insure maximum legibility and resolution while providing as much information as possible. The chart contains plots of air parcel trajectories, background geography, and contoured fields of temperature, dew point, net vertical displacement, and the prognostic K index. Layout of the chart is shown below.

Upper Left Panel	**Upper Right Panel**
24-h forecast of surface dewpoints and parcel trajectories	24-h forecast of 850 mb temperatures and parcel trajectories
Lower Left Panel	**Lower Right Panel**
24-h forecast of 700 mb dew points and parcel trajectories	24-h forecast of the K index and 700 mb 12-24 h net vertical displacement

The computer-drawn trajectories shown in Fig. 4 were prepared by a curve-fitting program which generates data points between the 6-h parcel positions thereby giving smooth continuous curves for the trajectories. Individual air parcels often describe complex paths near the earth's surface or near frontal zones or in regions of light, variable winds.

The 24-h prognostic trajectories in Fig. 4 terminate at a 10 x 15 array of grid points. However, every other trajectory is actually drawn to prevent the trajectory panels from presenting a

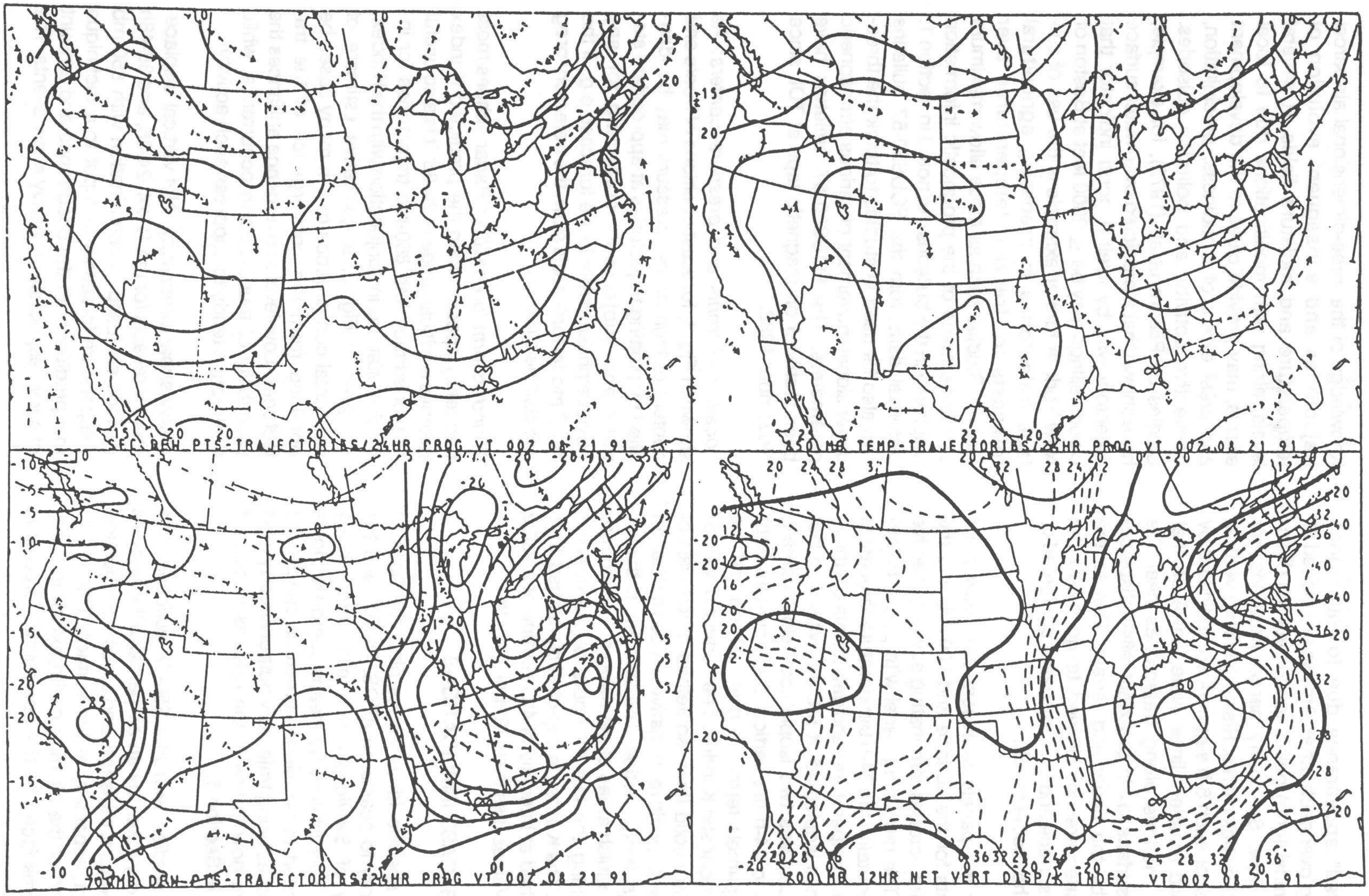

Figure 4. Trajectory model four-panel facsimile chart valid at 0000 UTC on August 21, 1991.

"cluttered" appearance due to trajectories crossing over each other. Arrows are placed at the terminal (grid) points to indicate the direction of flow. Six-hourly parcel positions are denoted by tick marks. Rising (sinking) vertical motions for each 6-h segment are indicated by thin, solid (dashed) lines. Note, however, that vertical motions along trajectories near the earth's surface to a large extent reflect displacements by the underlying terrain. That is, the trajectories are not allowed to go below the earth's surface and in many cases are forced to follow the model terrain.

Two of the panels represent 24-h dew point forecasts for the surface and 700 mb and the parcel trajectories terminating at the respective levels. The remaining panel with parcel trajectories contains the 24-h temperature forecast at 850 mb. Temperatures and dew points are thick, solid lines isoplethed at 5°C intervals. The last panel contains two isoplethed fields, namely, the 12- to 24-h net vertical displacement (mb) for air parcels terminating at 700 mb and the 24-h prognostic K index. The vertical displacements are solid lines isoplethed at intervals of 20 mb with positive (negative) values indicating rising (sinking) motion. The zero line is thicker to distinguish areas of net rising or sinking motion during the last 12 hours of the forecast period. The K index is depicted by dashed lines isoplethed at intervals of 4°C starting at a value of 12. Values less than 12 aren't shown.

6. FORECAST IMPLICATIONS

Some specific ideas concerning the uses of trajectory forecasts on AFOS, DIFAX, and the Family of Services are briefly summarized below. This list is by no means complete, nor is it intended to be, since numerous specialized techniques using trajectory output already exist and are now in use in the field, as described earlier in Section 1.

Local studies with FOUS50-57 bulletins: The trajectory taken by an air parcel will modify its temperature, moisture, and aerosol or chemical content, especially at the surface. This recent "history" of the air may be important to many problems faced by the operational forecaster. Knowledge of the three-dimensional air-parcel trajectories and subsequent evolution of temperature and moisture fields at several levels, along with modifications due to local effects, may provide clues to the development and areal extent of cloudiness, precipitation, convective activity, and pollution episodes. Studies by Pflaum et al. (1972), for example, have shown that a predicted over-water surface trajectory was by itself a good indicator that cloud ceilings may be $\leq$ 2000 feet at Boston or New York. A further example is the use of surface trajectories in preparing agricultural forecasts for freezing temperatures over Florida. Studies such as these allow maximum use to be made of the prognostic information displayed in the bulletins. As noted in section 1, historical data from the FOUS50-57 bulletins can also be used in studies to track the three-dimensional movement of various atmospheric parameters. The FOUS50-57 bulletins have been archived on magnetic tape at TDL since November 1982.

Location of fronts and pressure centers: As shown in Fig. 3, forecast positions of fronts and centers of high or low pressure may be identified by plotting trajectories at appropriate stations and subjectively correcting for any obvious phase errors in the forecast, e.g., if the NMC model forecast is slow, the trajectory prog will also be slow.

Thunderstorm forecasting: Radar echoes most frequently appear when the predicted K index reaches a critical range of 24-36. It is also useful to plot surface and 850-mb trajectories for individual stations in conjunction with the K index. As given in Fig. 3, a qualitative estimate of horizontal convergence can in many cases be obtained from the convergence of the trajectories. Low-level convergence enhances the probability of thunderstorm occurrence, while divergence tends to suppress such activity.

Heavy snow forecasting: Net vertical displacement forecasts for the 12-24, 24-36, and 36-48h periods are used in combination with 850-mb temperature forecasts as input to a technique that predicts both the occurrence and amount of snow, especially for heavy snow events. The technique, dubbed the "Magic Chart" was originally developed at WSFO Milwaukee and has since been successfully applied to snow prediction at a number of NWS forecast offices (Reap, 1990).

Cloud and precipitation forecasting: Cloud forecasts at 850 mb and 700 mb can be prepared in a manner similar to that employed by the Air Weather Service (Collins, 1970), i.e., by noting the degree of cloudiness at the origin or upwind point of the trajectory and allowing for subsequent modification by the rising or sinking motion along the trajectory path. As a general rule, the zero line of the net vertical displacement field is closely associated with the cloud boundary. This is especially true for intense winter systems. In general, trajectories which exhibit cyclonic curvature are associated with horizontal convergence, persistent cloudiness, and precipitation. Trajectories characterized by anticyclonic curvature are usually associated with horizontal divergence and fair weather.

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