Comparison of Wind-Field Models Using the CAPTEX Data

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ABSTRACT

Results of the Cross-Appalachian Tracer Experiment have been used to compare the performance of three different wind models—a primitive-equation model, a quasi-geostrophic model and a linear-interpolation model. The comparison shows that the primitive-equation model performed very well generally and should be a useful model when forecasting is required. The linear-interpolation model performed well in the absence of cold front passage, but less well in the presence of cold front passage. The quasi-geostrophic model performed well only if treatment for surface friction is incorporated; without the treatment it is the only model that revealed an observed stagnation.

1. Introduction

A critical component in the description of long-range (of the order of 1000 km) transport of air pollutants is the specification of the wind field. The routine National Weather Service (NWS) rawinsonde observations in the United States have a temporal resolution of 12 hours and a spatial resolution of about 400 km. Such resolutions are insufficient to describe the movement of air parcels accurately (Kuo et al. 1985). Models are needed to describe the wind field at a higher temporal and spatial resolution. There are generally three types of wind-field models: prognostic, diagnostic, and four-dimensional data assimilation models. Prognostic models involve forecasting of the wind field by solving a set of dynamical equations such as the primitive equations (e.g., see Anthes and Warner 1978; Anthes et al. 1987) or the equations for a quasi-geostrophic system. Diagnostic models involve no forecasting; no equations of motion are used. Consequently, some ad hoc assumptions, such as constant acceleration, which leads to linear interpolation of velocity in time, must be made to describe the time evolution of the wind field. These models may impose additional diagnostic constraints such as conservation of mass, parameterization of terrain effects on the airflow, use of an equation for vertical velocity (e.g., see Eliassen 1978) or isentropic (e.g., see Haagenson and Shapiro 1979) flow, etc., to improve accuracy.

While the prognostic models require an initial condition to forecast the wind field, the diagnostic models require both an initial and a final condition as defined by two consecutive observations to interpolate the wind field. However, it is possible to make use of the initial condition and whatever additional data from subsequent observations to improve or adjust the wind field prediction of a prognostic model (e.g., see Bengtsson et al. 1981). This approach, called the four-dimensional data assimilation method, combines the advantage of more complete physics in a prognostic model with a more realistic constraint imposed on the prediction by making use of more observed data collected at different times. However, this approach is highly resource intensive (e.g., see Kao and Yamada 1988).

Evaluation of the wind-field models is generally performed by comparing calculated trajectories with observed trajectories traced by tetrons (Pack et al. 1978; Clarke et al. 1983; Resinger and Mueller 1983; Warner et al. 1983) or tracer gases (e.g., see Draxler 1982; Haagenson et al. 1987; Brost et al. 1988), or by comparing trajectories calculated from different models (e.g., see Artz et al. 1985; Kuo et al. 1985). Each approach has its own advantages and disadvantages. Tetrons are designed to float on a constant-air-density surface; they are easy to track and have no diffusion problems. However, air parcels tend to flow along isentropic surfaces, which can diverge from the constant-density surfaces. In addition, deviation of the tetron from the constant-density level occurs as a result of dew condensation on the tetron at night and vertical oscillation.
due to diurnal radiative and nonradiative heating and cooling (Hoecker 1981). Tracer gases follow the actual trajectories of air parcels. But because of vertical and horizontal mixing, the concentrations of these gases may quickly drop below their detectable limits. Moreover, in long-range transport, the spatial resolution of tracer monitors may not be sufficient to ascertain the tracer concentration distribution. The presence of vertical wind shear complicates matters even more, making it ambiguous at times to determine the position of the parcel trajectories. Comparing trajectories from different models is interesting, but it is difficult to draw useful conclusions unless one of the models can be shown to give a good approximation of the actual atmosphere.

Past evaluations of wind trajectories indicate that trajectories from prognostic wind models, such as the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) primitive-equation mesoscale model (Anthes and Warner 1978; Anthes et al. 1987), are generally superior to diagnostic trajectories (Warner et al. 1983). There is also indication that inclusion of vertical motion, such as in the isentropic trajectory model, should give more realistic results (Kuo et al. 1985; Haagenson et al. 1987); though in some studies, isentropic trajectories did not yield better results than say, isobaric trajectories, especially when transport was confined within the planetary boundary layer (Clarke et al. 1983).

Presently, most prognostic wind models are primitive-equation models and are used for limited-area weather forecasting. They also tend to be difficult and expensive to apply however. Diagnostic wind models, on the other hand, are much easier to apply, but may give inferior wind descriptions. An alternative is a quasi-geostrophic prognostic model (Holton 1979) which addresses the dynamics of the synoptic-scale motion appropriate for long-range transport at a cost much less than that for a typical primitive-equation model. Because the equations are time-reversal invariant, the quasi-geostrophic model can also be used to forecast and backcast the wind field, making it ideal for temporal interpolation between two neighboring periods of rawinsonde observations. Combining the forecast and backcast solutions allows one to make full use of observations to adjust the predicted wind field (as in the case of data assimilation) and allows for a smooth transition in the wind field from one interpolation interval to the next. This approach has not been considered previously for mesoscale wind-field construction. Furthermore, forecasts of the quasi-geostrophic model can be used to reduce the time interval of linear interpolation and can conceivably improve the accuracy of the latter approach. The quasi-geostrophic model describes the synoptic free-atmospheric motions well, but it may not be appropriate for flows within the planetary boundary layer or flows influenced by smaller mesoscale motions. As long-range transport can occur within and above the planetary boundary layer, the usefulness of the quasi-geostrophic model deserves to be ascertained.

In this study, we compare the wind fields from a primitive-equation model [the PSU/NCAR's Mesoscale Model version IV (Anthes et al. 1987), referred to as MM4], a simple linear-interpolation (LI) model with an assumption of no vertical motion, and a quasi-geostrophic (QG) model. The MM4 model is used strictly for forecasting whereas the other two models are used for temporal interpolation between two neighboring rawinsondes. In the case of the QG model, some of the temporal interpolations are accomplished by linearly combining the forecast and backcast solutions. The Cross-Appalachian Tracer Experiment, or CAPTEX '83 (Ferber et al. 1986), provided a unique opportunity to assess the performance of different models. On the one hand, there was enhancement of temporal and spatial resolution of meteorological observations; on the other hand, an elaborate network of ground-level tracer concentration measurements allows one to assess the accuracy of model trajectories.

The MM4 model has been described elsewhere. The LI model is quite straightforward. It assumes that the velocity varies linearly between two given times of observation at a constant pressure level. The QG model used in the present context deserves some detailed description, which is presented in section 2. Section 3 describes the data input for the model. Intercomparison of model predictions and verification against observations are given in section 4, which is followed by the closure section.

2. The quasi-geostrophic model

The QG model describes the midlatitude synoptic-scale motions of the atmosphere. With both the acoustic and the gravity waves filtered out, it is considerably simpler than a typical primitive-equation model. The QG model is well described in Holton (1979). In order to be able to share some of the input information of the MM4 model (see below), transformation of the system to the Lambert conformal-mapping coordinate [projection of the earth's surface onto a conic surface (Saucier 1955; Anthes and Warner 1978)] is necessary. The resulting QG model is described by the following equations:

\[ m^2 \frac{\partial}{\partial t} \nabla^2 \psi = -m \mathbf{V}_\phi \cdot \nabla(m^2 \nabla^2 \psi + f) + f_0 \frac{\partial \omega}{\partial p}, \quad (2.1) \]

\[ \frac{\partial}{\partial t} \frac{\partial \psi}{\partial p} = -m \mathbf{V}_\phi \cdot \nabla \frac{\partial \psi}{\partial p} - \frac{S_d}{f_0} \omega, \quad (2.2) \]

where \( \psi \), the streamfunction, and \( \omega(dp/dt) \), the vertical velocity in the pressure (p) coordinate, are the two unknowns of the equations. The streamfunction is related to the geopotential, \( \phi \), by the relation \( \psi = \phi / f_0 \), where \( f_0 \) is the constant mean Coriolis parameter for the re-
region of interest, and $g$ is the gravitational acceleration. The space-dependent Coriolis parameter is $f$. The horizontal velocity relative to the earth, $V_\psi$, is geostrophic and has two components: $u$ in the $x$ (mostly west to east) direction, and $v$ in the $y$ (mostly south to north) direction. Both components are related to the streamfunction as follows:

$$u = -m \frac{\partial \psi}{\partial y}; \quad v = m \frac{\partial \psi}{\partial x}. \quad (2.3)$$

The map-scale factor, $m$, for latitude $\theta$ is given by

$$m = \frac{\cos \theta}{\cos \left( \frac{\tan (45 - \theta/2)}{\tan (45 - \theta_1/2)} \right)^n}. \quad (2.4)$$

At the two latitudes, $\theta_1$ and $\theta_2$, where the projection cone intersects the earth's surface (the cone's apex being on the polar axis), $m$ is equal to 1. In our application, $\theta_1$ and $\theta_2$ are 30° and 60°N respectively; and $n = 0.716$.

The static stability parameter, $S_d$, is determined by the following equation:

$$S_d = -f_0 \left[ \frac{1}{p} \frac{\partial p}{\partial \psi} \left( \frac{R}{c_p} - 1 \right) - \frac{\partial^2 \psi}{\partial p^2} \right], \quad (2.5)$$

where $R$ and $c_p$ are the gas constant and the specific heat of air at constant pressure, respectively.

Equations (2.1) and (2.2) can be combined to form the omega ($\omega$) equation, which is more amenable to solution. In deriving this equation, $S_d$ is assumed to be a function of $p$ only. The omega equation can also be cast in the "$Q"$ vector format (Hoskins et al. 1978):

$$\left( m^2 \nabla^2 + \frac{f_0^2}{S_d} \frac{\partial^2}{\partial p^2} \right) \omega = 2 \frac{m^2}{S_d} \nabla \cdot \frac{Q}{m}, \quad (2.6)$$

where $Q = (q_x, q_y)$,

$$q_x = -f_0 \left[ m^2 \left( \frac{\partial u}{\partial x} \frac{\partial \psi}{\partial x} + \frac{\partial v}{\partial y} \frac{\partial \psi}{\partial y} - m \frac{\partial f}{\partial p} \frac{\partial \psi}{\partial p} \right) \right], \quad (2.7a)$$

$$q_y = -f_0 \left[ m^2 \left( \frac{\partial u}{\partial y} \frac{\partial \psi}{\partial x} + \frac{\partial v}{\partial x} \frac{\partial \psi}{\partial y} + m \frac{\partial f}{\partial p} \frac{\partial \psi}{\partial p} \right) \right]. \quad (2.7b)$$

Equations (2.1), and (2.6), together with (2.3), (2.5) and (2.7), are the basis of our QG model. The model has no separate description of the planetary boundary layer. It is time-reversal invariant and thus can be used for backcasting. To do so, one has to change only the sign of the Coriolis parameter. This will automatically lead to a sign change in $V_\psi$, $\omega$, $\psi$, and $\zeta$ ($= \nabla^2 \psi$); $\zeta$ being the vertical component of vorticity. The forecast and backcast solutions can be combined and used as temporal interpolation between two consecutive observations. This combined version of the model will be denoted QGFB. Suppose that the combined solution $S(t)$ at time $t$ is a linear combination of the forecast [$F(t)$] and backcast [$B(t)$] solutions, the initial time for $F(t)$ being $t = 0$, and that for $B(t)$ being $t = 1$, then

$$S(t) = \alpha(t) F(t) + \beta(t) B(t). \quad (2.8)$$

We chose the weighting factors $\alpha$ and $\beta$ as

$$\alpha(t) = 1 - 3t^2 + 2t^3, \quad (2.9)$$

$$\beta(t) = 3t^2 - 2t^3.$$}

This choice allows $S(t)$ to be dominated by whichever solution has a closer time of origin to $t$, since the individual solutions, $F$ and $B$, are likely to be more accurate near their respective initial times.

The QG model can also be used to forecast for a short period, say, six hours. If we alternate between a QG forecast and a linear interpolation (including vertical velocity in this case) every six hours, we effectively reduce the time interval for linear interpolation and may thereby increase its accuracy. This approach, denoted QGLI, has the effect of combining the synoptic-scale dynamics with the simplicity of linear interpolation applied to the three-dimensional velocity field. In addition, because time reversal is not needed here, the ageostrophic effect due to surface friction can be included in the model, now denoted QGLI/F, should it lead to an improvement in prediction accuracy.

Since the input data to the model consisted only of geopotential heights (= $\psi$/g), the horizontal grid system was chosen to be compatible with the cross-point grid system (Anthes and Warner 1978) of MM4. Each horizontal direction was spanned by 30 nodes. The grid size was 70 × 70 km$^2$. The solution region, not including the region where the boundary conditions were prescribed, was 1750 × 1750 km$^2$, with 26 internal nodes in each direction. The four corners of the solution region were SW (33.50°N, 88.13°W), NW (49.25°N, 91.06°W), SE (33.50°N, 69.25°W) and NE (49.25°N, 66.95°W). In the vertical direction, six pressure levels were prescribed: 100, 500, 700, 800, 900, and 1000 mb. The grids were not staggered.

To solve the system of equations described above, we first solved the omega equation using the alternating direction implicit (ADI) method (Douglas and Gunn 1964; Briley and McDonald 1980). The solution $\omega$ was then included in the right-hand side of (2.1), which was then solved in two steps. The first step was to treat (2.1) as a 2-D Poisson equation for $\chi$ (= $\psi$/g) and to solve it using the ADI method. The second step was to use the leapfrog time integration scheme to solve for $\psi$ from $\partial \psi/\partial t$.

To avoid computational instability in this nonlinear system, the finite-difference form for the first term on the right-hand side of (2.1) was formulated to conserve the mean vorticity, the mean kinetic energy and the mean enstrophy over a closed domain (Arakawa 1966; Bengtsson and Temperton 1979). The time step for the leapfrog scheme was chosen to be 0.25 h, small enough to satisfy the Courant–Friedrichs–Lewy con-
diation. To suppress aliasing, which is also a source of nonlinear instability (Gary 1979), we applied a two-dimensional smoothing scheme a la Shapiro (1970) to damp the high-wavenumber waves. The scheme was modified to remove the boundary effects encountered by Shapiro. It was then applied to \( \psi \) at each time step. The vertical grid size is not uniform. To determine the vertical spatial derivative more accurately, we used a noncentered differencing scheme (Haltiner et al. 1963).

In the case where frictional effects were included, as in QGLI/F, the quasi-geostrophic velocities \((u_{\text{QG}}, v_{\text{QG}})\) at the 900 and 1000 mb levels were replaced by the solutions \((u, v)\) of the following steady-state equations:

\[
f(v - u_{\text{QG}}) + \frac{\partial}{\partial p} \left( K \frac{\partial u}{\partial p} \right) = 0, \tag{2.10a}
\]

\[
f(u - u_{\text{QG}}) - \frac{\partial}{\partial p} \left( K \frac{\partial v}{\partial p} \right) = 0. \tag{2.10b}
\]

The assumption is that the velocity in the boundary layer responds more rapidly to surface friction than to synoptic variations. The eddy viscosity, \(K\), is assumed to be decreasing with height (decreasing \(p\)). Near the earth’s surface, the eddy viscosity is of the order of 10 m\(^2\) s\(^{-1}\) (Pedlosky 1979, p. 173), or about \(10^{-1}\) (mb\(^2\)) s\(^{-1}\) in the \(p\)-coordinate. Equations (2.10a, b) were solved iteratively at each time step, with the velocity assumed unaffected at 800 mb and zero at a fictitious level of 1100 mb. It should be noted that inclusion of frictional effects destroys the time reversal invariance of the original QG model so that one can no longer combine the forecast and backcast solutions in a meaningful way.

3. The input data for the quasi-geostrophic model

The input data are based on the meteorological observations during CAPTEX in September and October of 1983 (Ferber et al. 1986; Michael et al. 1984). During the experiment, a tracer gas, perfluoromonomethylcyclohexane (C\(_7\)F\(_{14}\)), which has a background concentration of 3 parts per quadrillion by volume, was released at ground level in seven different periods. Each release lasted three hours, except release 6, which lasted half an hour. The first four releases and release 6 were from Dayton, Ohio, carried out in the early afternoon to assure good vertical mixing of the tracer. Releases 5 and 7 were from Sudbury, Ontario, and were carried out very early in the morning behind cold fronts. The amount of tracer and meteorological data for release 6 are quite limited. Consequently, this release was excluded in our study.

A large network of air samplers, located up to 1100 km in the downwind region of the release sites, collected six consecutive 3- or 6-h samples starting according to the estimated time of tracer arrival. The time and spatial resolutions of meteorological observations were also enhanced. Not only did the NWS rawinsonde stations increase their upper-air soundings from two (at 0000 and 1200 UTC) to four times per day (by adding 0600 and 1800 UTC) whenever tracer material was in the air, ten additional sounding sites provided by Electric Power Research Institute (EPRI) were also in operation on the same schedule as the NWS rawinsonde stations. Figure 1 shows the locations of the tracer release and sampling sites and the NWS and EPRI rawinsonde stations.

The enhanced sounding data can be used for assessing the predictive capability of a model. For this purpose, we considered a two-day period covering each of releases 1, 2, 3, 4, 5, and 7 (see Table 1). An objective analysis based on successive correction was applied (Haagenson et al. 1987) to the sounding data from the NWS stations at regular sounding times—a total of five for each release: the 0th, 12th, 24th, 36th and 48th hours, starting from the initial time for wind simulation. The resulting data for the horizontal wind field at the 100, 500, 700, 800, 900, and 1000 mb levels were used as the initial and final conditions in the LI model. By direct integration of (2.3) this wind field was converted to the geopotential heights (MSL) at the model pressure levels and used as the initial condition (or final condition as the case may be) for the different versions of the QG model.

Generally, objectively analyzed data are not filtered to remove any imbalances between mass and momentum fields that may lead to creation and amplification of spurious inertial gravity waves or noise in a primitive-equation model. The MM4 model uses input data that have been filtered by a nonlinear vertical-mode initialization procedure (Errico 1986). This filtered data can also be used as input to the QG model, especially when we want to compare the MM4 and the QG models using the same initial conditions. It is also useful to compare the effect of filtered and unfiltered initial data on the QG model predictions. For this purpose, the filtered data were prepared for the same five

![FIG. 1. Map showing the locations of tracer release and sampling sites and the NWS and EPRI rawinsonde stations.](image-url)
TABLE 1. Schedule of CAPTEX '83 releases in wind-field simulation.

<table>
<thead>
<tr>
<th>Release number</th>
<th>Release site</th>
<th>Release period (UTC)*</th>
<th>Wind simulation period (UTC)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dayton</td>
<td>09181200–09182000</td>
<td>09181200–09201200</td>
</tr>
<tr>
<td>2</td>
<td>Dayton</td>
<td>09251200–09252005</td>
<td>09251200–09271200</td>
</tr>
<tr>
<td>3</td>
<td>Dayton</td>
<td>10021900–10022200</td>
<td>10021200–10041200</td>
</tr>
<tr>
<td>4</td>
<td>Dayton</td>
<td>10141600–10141900</td>
<td>10140000–10160000</td>
</tr>
<tr>
<td>5</td>
<td>Sudbury</td>
<td>10260345–10260645</td>
<td>10260600–10280000</td>
</tr>
<tr>
<td>7</td>
<td>Sudbury</td>
<td>10290600–10290900</td>
<td>10290900–10310000</td>
</tr>
</tbody>
</table>

* Given in month, date, hour and minute; 1200 UTC is the same as 0800 EDT.

regular sounding times as those for the unfiltered, objectively analyzed data. The filtered data for the MM4 model used the \( \sigma \) coordinate, which is defined as \( \sigma = (p - p_0)/(p_r - p_1) \), where \( p_0 \) is the surface pressure, and \( p_r \) is the constant pressure (100 mb) assumed for the top boundary of the model. To convert the data to the pressure coordinate, we first determined the geopotential heights at fixed sigma levels by integrating the hydrostatic equation from the surface upward. We then determined the geopotential heights at fixed pressure levels by interpolation, assuming that the height was a linear function of \( \ln p \).

To determine the boundary conditions for the 2-D Poisson equation for \( \psi \), we assumed that \( \psi \) at the boundary and external nodes on each constant-pressure plane varied linearly with time over a period of 12 hours, between two rawinsonde times. For the \( \omega \) equation, \( \omega \) was assumed zero at the lateral and top boundaries. For the bottom boundary, we assumed (Haltiner and Williams 1980)

\[
\omega = \left( f \frac{\partial \psi}{\partial p} \right)^{-1} g \left( mN^2 \cdot \nabla H + \frac{C_D}{f_0} \xi \right),
\]

where \( H \) is the terrain height, \( g \) is the gravitational acceleration, and \( C_D \) is the surface friction coefficient, assumed to be \( 3 \times 10^{-2} \text{ m s}^{-1} \text{ for land (LeDrew 1980).} \)

4. Model comparison

The main question we are addressing in this study is: Given the data from the typical, routine NWS rawinsondes, how well do different wind models perform compared to direct wind measurements or tracer plume tracks? We resort to the CAPTEX data to help answer this question. It should be noted that only the data from routine NWS rawinsondes were used in the objective analyses for the models and that the nonroutine rawinsondes were used only for comparison with the model results.

The CAPTEX data (See Ferber et al. 1986) contains the soundings from the NWS and EPRI stations, the ground-level tracer concentrations from all monitoring sites, and aircraft-measured tracer concentrations. The soundings contain wind measurements at various heights but not at the standard pressure levels, making it difficult to compare the predicted and observed wind fields at the positions of observation. The soundings also contain geopotential height measurements at or very near the standard pressure levels. These measurements can be more easily compared with the geopotential heights predicted from the models. Such a comparison was made and the result will be briefly described below. In this comparison, the predicted or the objectively analyzed heights were linearly interpolated to the sounding locations and compared with station observations. The height fields from both the filtered and unfiltered objective analyses were used as initial conditions for the QG and LI models. Only the filtered cases were used in MM4.

While comparing the geopotential heights, we uncovered some problems concerning the reliability of some of the EPRI data. Specifically, the geopotential heights reported from the only EPRI station in Canada (numbered 72005, identified as GRV) are much lower than those estimated by all models used in our comparison—typically by several tens of meters or more at all pressure levels and during all releases. One might attribute this discrepancy to the models rather than to the data. However, the disturbing problem is that this station also consistently (with very few exceptions) registered much greater differences between predicted and observed values than any other station. We suspected that there were inherent systematic biases associated with this station. Another EPRI station, 72008 (designated MOA), also had some questionable data. This station was one of three EPRI stations within about 75 km of one another in northeast Ohio. At 100318 (1800 UTC 3 October), during release 3, this station reported geopotential heights that were about 120 m lower than those of the other two stations for all pressure levels except 1000 mb where no data were given. For example, the geopotential height for 900 mb was reported to be 890 m, much lower than 1026 m and 1020 m reported by the other two nearby stations. During release 5, at 102606 and 102612, the same station had totally unrealistic geopotential heights of less than 1200 m for both 500 and 700 mb. Draxler (1987) also addressed some of the problems he encountered with the EPRI data. He found significant differences between the preprocessed and final data for some of the EPRI stations. Using the latter led to some degradation in his model calculations. There was also a problem with the NWS data. During release 7, station PWM in Maine had an unusually large value (1173 m) for the geopotential height at 900 mb at 102906. At the same time, the geopotential heights at the same pressure level for the neighboring NWS stations within 300 km were 930 m to 947 m. Six hours before and after this time, the geopotential height at 900 mb was 892 m and 911 m, respectively, at the PWM station. The corresponding heights for the other stations were
also comparable. No unusual geopotential heights were observed at 800 mb. We believe that the 1173 m value for PWM at 900 mb at 102906 was not reliable.

Excluding the questionable datapoints above, we found the observed and calculated geopotential heights to be well correlated, the correlation coefficients being typically 0.8 or higher. The typical root-mean-square (rms) differences between observed and calculated heights are around 20–30 m at 500 mb and around 10–20 m at 900 mb. An important exception is release 4, between 101412 and 101506, where the geopotential heights at 500 and 700 mb were greatly overestimated by the objective analysis (especially the unfiltered one) and overpredicted by the QG and LI models. The rms differences are around 100 m. The correlation coefficients are low (0.5–0.6). Initialized with only the filtered objective analysis at 101400 (which agreed well with observations) the MM4 model predictions for release 4 correlate very well with observations, the correlation coefficients being typically greater than 0.9 at all pressure levels.

The poor quality of the unfiltered objective analysis for release 4 is due to the fact that the first-guess grid point fields, normally provided by the National Meteorological Center (NMC) global analysis, are not available for most of the analysis time periods during release 4. As a result, the QG and LI models, which depend strongly on the analyzed fields, do not perform well. The only time period that the NMC global analysis is available for release 4 is 101400, 16 hours before the tracer release. The MM4 model was initialized at this time with the hope that a better quality initial state would produce a better simulation—as it did.

Overall, use of the filtered objective analysis gives a superior performance for models in estimating the geopotential heights at low altitudes (≥800 mb) where long-range transport of pollutants is most likely to occur. The QGFB model did not have a decisive advantage over the LI model. Though not always giving the best estimates, the MM4 model is expected to be more dependable than other models considered, not only because of its more complete dynamical and physical descriptions of the atmosphere, but also because its prediction is much less affected by the quality of the objective analysis than those of the other models after the initial time.

The geopotential heights can be used to construct the wind field, which describes the trajectory of an air parcel; but because of the sparsity of the rawinsonde stations, it is difficult to judge the performance of a wind field model based on its performance in predicting the geopotential heights. So, to compare the performance of wind field models, we resort to determining trajectories from different models and comparing them with the loci of plumes traced by observed ground-level tracer concentrations. To facilitate comparison of the tracer plume tracks with model trajectories, our trajectories have the same origins as those of actual releases, both in time and in space. The positions of origin are Dayton, Ohio (39.45 N, 84.10 W) for releases 1 through 4, and Sudbury, Ontario (46.30 N, 81.01 W) for releases 5 and 7. Three initial pressure levels for the trajectories are considered—850, 900 and 950 mb. These levels should cover the range of heights the tracer was likely to achieve during the early phase of its travel. The starting time of the trajectories was taken to be the second hour of each tracer release. This is again an attempt to capture the bulk of the tracer as it moved. Our comparison using tracer concentrations is necessarily qualitative because tracer concentrations and the extent of their spreads were not estimated in our models. Such estimates require the introduction of parameters whose validity and accuracy remain to be verified. The description of the space and time variations of observed tracer concentrations can be found in Ferber et al. (1986).

In the trajectory comparison reported here, models other than MM4 used the unfiltered objective analyses to determine the initial and final conditions. Filtered objective analyses were also used for comparison but were found to give similar trajectories as the unfiltered cases. The three-dimensional trajectories were calculated by assigning a parcel the velocity obtained by trilinear interpolation of the velocity field at the parcel position at each hour. The parcel position was traced at a time increment of one hour. However, should a parcel cross from one grid cell to another within one hour, its velocity would be immediately updated using the velocity in the new grid cell within the same hour.

To obtain the three-dimensional trajectories from the MM4 model, the vertical component of the velocity (\(\sigma\)) in the \(\sigma\)-coordinate must be calculated from the model output using the continuity equation. Both the horizontal velocity and \(\sigma\) were recalculated for the cross points at half vertical levels of the MM4 grid system [see Anthes and Warner (1978) for a description of the MM4 grid system] by averaging the relevant values at neighboring points. So, the horizontal grids for the velocity now match those of other models considered. The vertical position of the trajectory was first calculated in the \(\sigma\)-coordinate, then converted to the \(p\)-coordinate by means of bilinear interpolation of the updated surface pressure for the horizontal position of the trajectory.

Figures 2, 3, 4 and 5 show the tracer trajectories predicted by the MM4, LI, QGFB, and QGFI models, respectively. In the figures, the shaded area in each map represents the area of high tracer concentrations observed at ground level within a specific time period. To make sure that the area is as well defined as possible and is not too close to the tracer release site, the time period is chosen to be 18 to 24 hours after a tracer release, except for releases 2 and 3 where a later time period is necessary—24 to 30 hours for the former, and 30 to 36 hours for the latter. For release 7, a separate shaded region in western Pennsylvania represents
a stagnation where tracer concentrations were observed to linger 24 to 60 hours after the tracer release.

The synoptic patterns during releases 1 through 4 were influenced by anticyclonic circulation over the southeastern United States (Haagenson et al. 1987). There was no cold front passage and very little precipitation. Releases 5 and 7 were characterized by a cold front passage associated with the upper-level troughs.

In release 1, the tracer first moved northeastward across Lake Erie, then east-northeast toward New York, Vermont and New Hampshire. This track coincides very well with the 950 mb trajectory of MM4 and with the 900 and 950 mb trajectories of LI, both in direction and in speed. Both the QGFB and QGLI trajectories, on the other hand, tend to veer clockwise and point in the east-northeast direction so that the tracer is predicted to move over Pennsylvania instead of New York. Yet the predicted wind speed, as indicated by the trajectory movement, is reasonable.

Release 2 encountered very light wind. The tracer plume was widespread, but with high ground-level concentrations found in west-central New York in about 24 hours. The plume eventually fanned out across New York, New England and Pennsylvania. The 950 and 900 mb trajectories of LI describe the track well, both in direction and in speed. The 900 mb trajectory of MM4 gives the right direction but the predicted wind speed is slightly too high. Both the QGFB and QGLI model trajectories tend to veer to the right of the tracer plume, though the indicated wind speed is reasonable.

The tracer plume in release 3 first moved north-northeastward, then it was cut off from the ground and reappeared about 30 hours later in the eastern New York–Vermont area. Aircraft sampling revealed an elevated (1500 m MSL) tracer plume in southern Pennsylvania near Baltimore, Maryland about 22 hours after tracer release. Because of the complicated behavior of the tracer plume, it is difficult to determine definitively which model trajectories fit the observation best. The plume followed the 950 mb trajectory of MM4 quite well initially, but the appearance of relatively high ground-level concentrations around the Vermont area 30 to 36 hours after release seems to be more in line with the 900 mb trajectory. The plume appeared to have split in its course (Ferber et al. 1986). So, the MM4 model may indeed describe the tracer plume well. The LI trajectories (900 and 950 mb) also appear to work relatively well, though they do not indicate an initial north-northeast movement of the plume. The elevated plume seems to be well described by the 850 mb trajectory of LI. The QGFB and QGLI trajectories again tend to move eastward, missing the tracer plume.

The tracer plume of release 4 first moved east-northeastward, then curved east-southeastward, sweeping through Pennsylvania, reaching New Jersey 18 to 24 hours after release. The 900 and 950 mb trajectories of MM4 fit the observed pattern very well. The QGFB and QGLI trajectories moved slightly too far south; only their 850 mb trajectories crossed the southern tip of New Jersey at about the right time. But the LI trajectories moved even further south, missing New Jersey entirely.

In release 5, the tracer plume moved southeast toward Lake Ontario, then east-southeast across New York reaching east central New York in 18 to 24 hours and eastern Massachusetts in about 30 hours from the time of release. The 900 and 950 mb trajectories of MM4 fit the observed path very well. The QGFB and QGLI trajectories do not fare as well. The 850 mb trajectories moved through Connecticut whereas the 950 mb trajectories moved through New Jersey. They are all south of the observed path. The wind speeds appear reasonable however. The LI trajectories also moved through the New York–New Jersey area, but somewhat too slowly, indicating a low wind speed.

The tracer plume from release 7 moved south, reaching western New York and north central Pennsylvania in 18 to 24 hours after release. But the tracer plume was found to linger in western Pennsylvania 24 to 60 hours after release. The QGFB and QGLI models are the only models that suggest the possibility of a stagnation. The 900 and 950 mb trajectories moved over Pennsylvania somewhat rapidly, but the 950 mb trajectory became stagnant in southwest Pennsylvania. Some veering of the trajectories is still evident. The MM4 and LI trajectories, on the other hand, moved rapidly southeastward to the coast with no sign of stagnation. The LI trajectories may have moved too far east.

Overall, the MM4 trajectories perform well for releases 1, 2, 4, 5, and perhaps 3, and miss the stagnation in release 7. This is an impressive performance. The LI trajectories perform well for releases 1, 2, and perhaps 3, but poorly on releases 4, 5 and 7. The poor performance in release 4 may be related to the substantial overestimation of the geopotential heights by the objective analysis as discussed earlier. One may also get the impression that LI does not work well in the presence of a cold front passage. It may be premature to come to this conclusion at this time. The QGFB and QGLI trajectories are quite similar.

FIG. 2. The trajectories for the tracer released during CAPTEX, as predicted by the MM4 model. Solid lines are for an initial pressure level of 850 mb; dashed lines are for 900 mb; dotted lines are for 950 mb. The time interval between two circles on each trajectory is six hours. The shaded area is the area of high tracer concentrations at ground level 18–24 hours (but 24–30 hours and 30–36 hours for releases 2 and 3, respectively) after the tracer release. The second shaded area in west central Pennsylvania in release 7 is the area where the tracer concentration remained high 24 to 60 hours after the tracer release.
Fig. 3. The trajectories for the tracer released during CAPTEX, as predicted by the LI model with data from the unfiltered objective analysis of the routine NWS rawinsondes. See the Fig. 2 caption for more detail.
Fig. 4. The trajectories for the tracer released during CAPTEX, as predicted by the QGFB model with data from the unfiltered objective analysis of the routine NWS rawinsondes. See the Fig. 2 caption for more detail.
Fig. 5. The trajectories for the tracer released during CAPTEX, as predicted by the QGLI model with data from the unfiltered objective analysis of the routine NWS rawinsondes. See the Fig. 2 caption for more detail.
Fig. 6. The trajectories for the tracer released during CAPTEX, as predicted by the QGLI/F model with data from the unfiltered objective analysis of the routine NWS rawinsondes. See the Fig. 2 caption for more detail.
Fig. 7. The trajectories for the tracer released during CAPTEX, as predicted by the LI model with data from the initial conditions and forecasts of MM4 every 12 hours. See the Fig. 2 caption for more detail.
FIG. 8. The trajectories for the tracer released during CAPTEX, as predicted by the QG1/F model with data from the initial conditions and forecasts of MM4 every 12 hours. See the Fig. 2 caption for more detail.
Therefore, combining the forecast and backcast solutions does not gain any advantage in accuracy. The fact that all QG-related 900 and 950 mb trajectories tend to veer in the clockwise direction indicates the need for a boundary-layer treatment for these trajectories. Such a need immediately precludes the usefulness of QGFB. By including a frictional correction in the boundary-layer as described in (2.10a, b), where the eddy viscosity is given as 0.02 and 0.07 (mb)² s⁻¹ for the 900 and 1000 mb levels respectively, we obtained the trajectories (designated as QGLI/F) using the data from the unfiltered objective analysis, as shown in Fig. 6. Obviously, the QGLI/F trajectories are superior to the QGLI trajectories. They perform moderately well for releases 1, 2, 4 (except the 950 mb trajectory) and perhaps 3, not well for release 5, and missed the stagnation (but in better agreement with the tracer track than the LI trajectories) for release 7. The last fact may indicate that the flow was essentially geostrophic down to a very low altitude in the early phase of release 7, perhaps because the planetary boundary layer at the time was thin (we have no data to support this speculation). This would allow the tracer plume to migrate to western central Pennsylvania where it would be caught in a weak surface high-pressure system. The wind fields at 900 mb for both QGLI and QGLI/F show a weak anticyclone centered around northwestern Ohio 24 hours after the tracer release. This weak anticyclone formed a new center in southern West Virginia 6 hours later, causing the low northwesterly wind in western Pennsylvania to pause and shift directions and creating a stagnation for whatever tracer was available in the region. The MM4 wind field at 900 mb also had a weak anticyclone centered in northwestern Ohio 24 hours after the tracer release. But the center of the anticyclone shifted to northeastern Ohio 6 hours later. A stagnation region would have formed in northeastern Ohio, but not in Western Pennsylvania, provided that the initial tracer trajectories veered more clockwise than what the model predicted. The LI trajectories moved too far east initially and missed the low-wind region entirely.

We also looked into how closely the trajectories of LI and QGLI/F would follow the MM4 trajectories if the objective analysis data, used in these models and based on the routine rawinsondes, were replaced by the inputs and forecasts of MM4. The resulting trajectories for LI and QGLI/F are shown in Figs. 7 and 8. They show a high degree of agreement with each other. The agreement with Fig. 2 for the MM4 trajectories is also quite good, with perhaps the exception of release 3. On the other hand, in the absence of friction consideration, the QGLI trajectories (not shown) veer away considerably from the MM4 trajectories.

5. Closure

Our comparison of wind-field model predictions with the CAPTEX observations indicates that the MM4 model performs very well in the presence and absence of cold front passage. The model also does not rely on the constant updating (except for the lateral boundary conditions) of the objective analysis every 12 hours. However, because the model is highly resource intensive, its application is not likely to be on a routine basis.

The LI model is very simple and can describe the trajectories quite well for long-range pollutant transport when the synoptic meteorological conditions do not change rapidly. Otherwise, as in the passage of a cold front, the model did poorly. More observations are clearly needed to reach a more definitive conclusion. To this end, a recent field experiment, the Across North America Tracer Experiment, or ANATEX (Air Resources Laboratory 1989), should help clarify the situation.

The 850 mb trajectories of the QG model agree well with those of the MM4 model. This is not surprising because the model contains the dynamical description of synoptic-scale forcing. In fact, the model should be suitable for describing high-altitude transport. But treatment of surface friction is necessary to counter the veering of the model trajectories at lower altitudes. Such treatment (QGLI/F) improves the accuracy of the QG trajectories considerably. The performance of the model trajectories is comparable to that of the LI trajectories in the absence of cold front passage. Whether the QGLI/F trajectories are superior to the LI trajectories in the presence of cold front passage remains unclear at present, even though, theoretically, the model should perform better than LI under rapidly changing meteorological conditions. It should also be noted that, without the treatment of surface friction, the QG models (QGFB and QGLI) are the only models that reveal a stagnation region in release 7. The dramatic improvement of the QG model after the inclusion of treatment of surface friction also indicates that coupling the QG model with a planetary boundary layer model may result in a relatively simple yet viable scheme to describe the wind field for long range transport of air pollutants.

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