4 METEOROLOGICAL MODELING

Meteorological models are developed for two purposes:

- to understand local, regional, or global meteorological phenomena
- to provide the meteorological input required by air pollution diffusion models

In both cases, the analytical and numerical techniques are similar. In this book, we will focus our attention on the second group of meteorological models; i.e., on those techniques used as a "pre-processor" of available meteorological information in order to prepare the proper input to air quality diffusion models.

Pielke (1984) provides a thorough review of mesoscale (i.e., from a few kilometers to several hundred kilometers) meteorological modeling techniques. His book also presents, in Appendix B, a summary of the organizations active in prognostic numerical mesoscale modeling in 1983 and a list of existing mesoscale models, with a description of their major characteristics. Available diagnostic and prognostic models are discussed by Haney et al. (1989).

Meteorological models can be divided into two categories:

- physical models -- physical small-scale models of atmospheric motion (e.g., wind tunnels)
- mathematical models -- a set of analysis techniques (algebraic and calculus-based) for solving a certain subset of meteorological equations

Mathematical models can be

- analytical models, in which exact analytical solutions are obtained
- numerical models, in which approximate numerical solutions are found using numerical integration techniques

In this book, we will discuss only numerical models, currently the most powerful and promising tools for both meteorological and air quality simulation studies.

Numerical meteorological models can be divided into two groups:

- diagnostic models; i.e., models that are based on available meteorological measurements and contain no time-tendency terms
- prognostic models; i.e., models with full time-dependent equations

Both approaches are discussed below. It must be noted that diagnostic models, even though they include little physics in their calculations, have the important advantage of being able to incorporate information gathered from available measurements. Actually, their performance is strongly dependent upon the density of meteorological measurements in the simulation region: the higher the number of stations, the better the performance of the model. Prognostic models, instead, do incorporate meteorological physics, but cannot use available data to modify their forecasts, even though "nudging" techniques have been proposed (e.g., Hoke and Anthes, 1976) to incorporate observations to a certain extent. One of the major future challenges of meteorological modeling for air quality applications is the proper linkage of diagnostic and prognostic methodologies, to take advantage of the best features of both approaches (e.g., by using the Kalman filtering techniques discussed in Chapter 12).

4.1 DIAGNOSTIC MODELS

Diagnostic models are based on objective analysis of available meteorological data. Their outputs are three-dimensional fields of meteorological parameters derived by appropriate interpolation and extrapolation of available meteorological measurements. They are diagnostic because they cannot be used to forecast the meteorological evolution, but simply provide a best estimate of a steady-state (or quasi steady-state) condition.

They have been used frequently for evaluating mass-consistent flow fields in complex terrain (e.g., Anderson, 1971; Danard, 1977; Dickerson, 1978; Tesche and Yocke, 1978; Sherman, 1978; Liu and Yocke, 1980; Patnack et al., 1983; Mass and Dempsey, 1985). Ludwig and Bird (1980), in particular, developed a mass-consistent method based on principal component analysis that seems quite cost-effective. These mass-consistent flow calculations give satisfactory results (Pielke, 1984) when

- the terrain represents the dominant forcing term

- sufficient meteorological input measurements are available

Figure 4–1 shows an example of diagnostic model output.

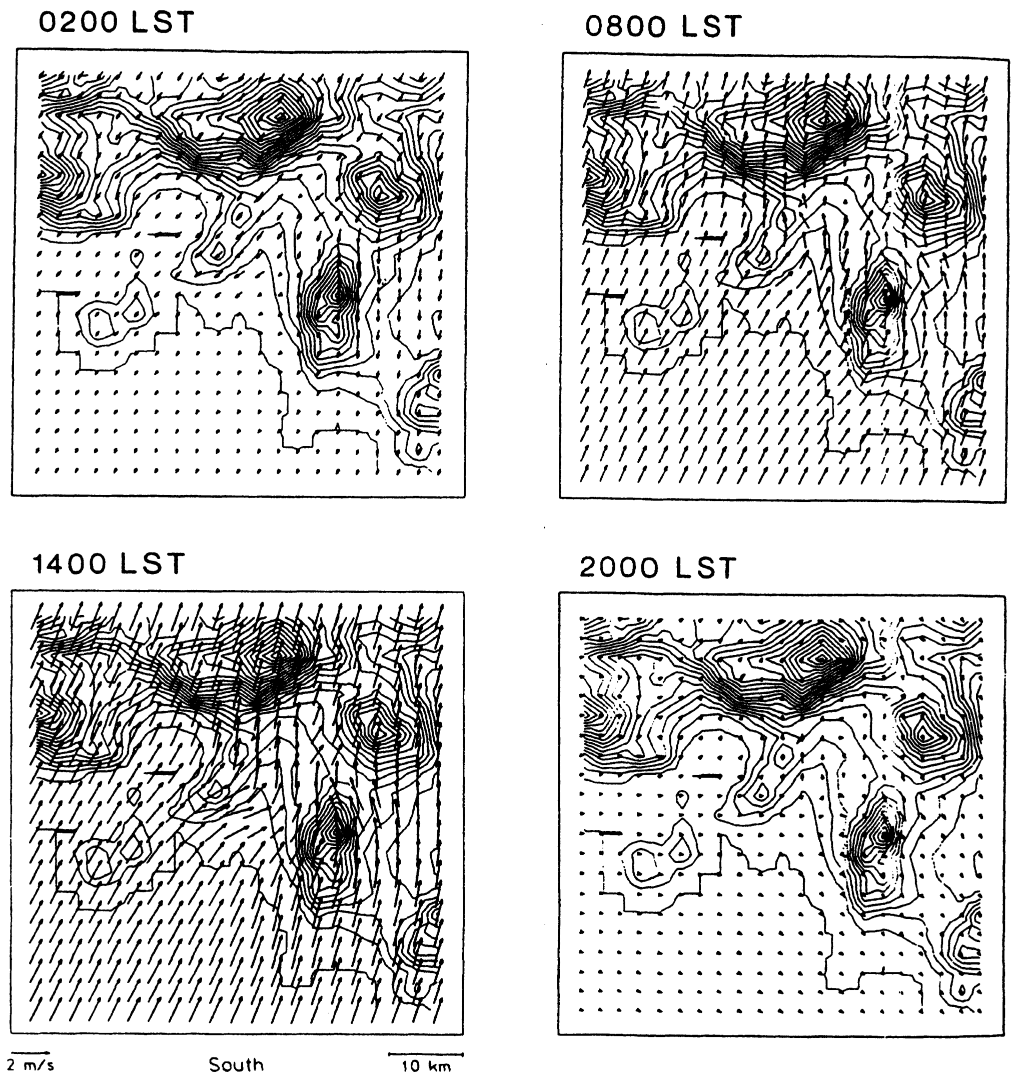


FIGURE 4–1. Reconstructed wind fields in the Athens basin at a height of 10 m AGL for 0200, 0800, 1400 and 2000 LST 26 June 1982 (from Moussiopoulos and Flassak, 1986). [Reprinted with permission from the American Meteorological Society.]

Several diagnostic computer packages are discussed below.

4.1.1 IBMAQ–2

The IBMAQ–2 program (Shir and Shieh, 1974) estimates three-dimensional wind vectors at each point in the computational domain using the following computational steps:

- An initial-guess wind vector is estimated at each grid point from the nearest available observation station.
- These initial values are corrected by recomputing, at each grid point, the wind components as weighted averages of their values at the adjacent grid points. A weighting factor proportional to $1/r^2$ is used, where r is the distance between grid points.
- Each subsequent wind estimate uses the four nearest adjacent grid points.

4.1.2 NEWEST

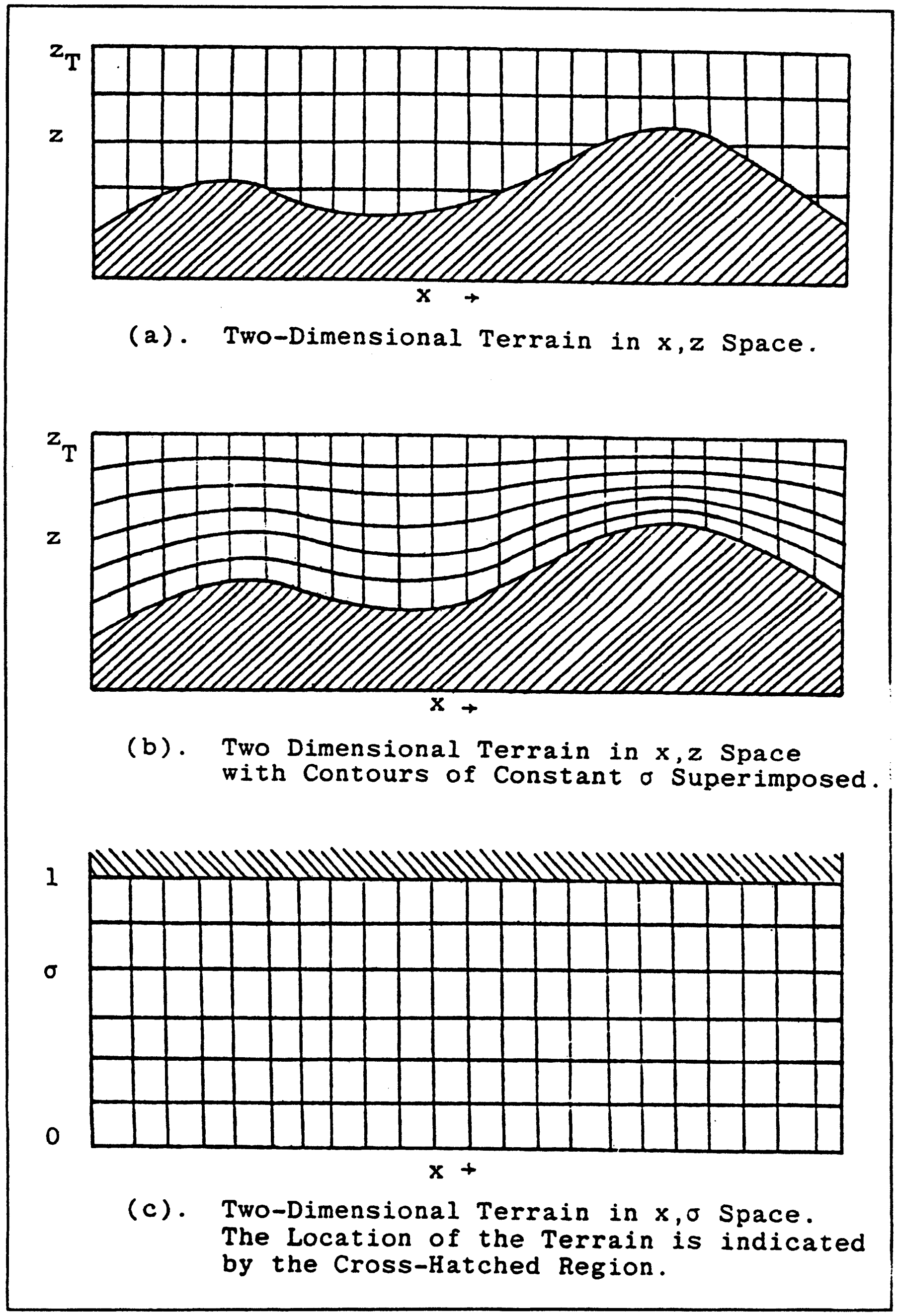
The NEWEST subroutine of the IMPACT code (Tran and Sklarew, 1979) provides three-dimensional fields of stability and wind. Stability measurements are interpolated using weighting factors proportional to $1/r^4$ and wind measurements are interpolated using weighting factors proportional to $1/r^2$, where the r values are the distances between the grid point at which the interpolation is made and the measurement points. The wind field is then adjusted by a numerical cycle that makes the wind velocity fields mass-consistent. Finally, thermal drainage effects (i.e., daytime upslope and nighttime downslope winds) are included by adding a vertical wind component w_D, where

$$w_D = const \left(\frac{|T_G - T_A|}{T_G} \right)^{1/2} \qquad (4\text{–}1)$$

in which T_G is the ground temperature on the slope and T_A is the ambient temperature at the same location.

4.1.3 NOABL

The NOABL package (Phillips and Traci, 1978) provides an accurate representation of the terrain by a vertical coordinate transformation in which the lowest coordinate is conformal to the terrain surface. Figure 4–2 illustrates this coordinate transformation, from the (x,z) space to the (x,σ) space.



(a). Two-Dimensional Terrain in x,z Space.

(b). Two Dimensional Terrain in x,z Space with Contours of Constant σ Superimposed.

(c). Two-Dimensional Terrain in x,σ Space. The Location of the Terrain is indicated by the Cross-Hatched Region.

FIGURE 4–2. Terrain coordinate transformation $\sigma = \frac{p - p_t}{p_s - p_t}$ *where* p *is the pressure,* p_t *is the constant pressure at the top of the domain, and* p_s *is the variable surface pressure (from Phillips and Traci, 1978). [Reprinted with permission from Science Applications, Inc.]*

4.1.4 MASCON

The MASCON model (Dickerson, 1978) is based on variational calculus techniques, which are used to adjust the observed horizontal fluxes so they satisfy the continuity equation (similar to the MATHEW model described below).

4.1.5 MATHEW

The MATHEW model (Sherman, 1978; Rodriguez et al., 1982) produces an average, minimally adjusted three-dimensional wind field, according to the variational analysis formalism described by the integral function

$$E(u,v,w,\lambda) = \int_V [a_1^2\,(u-u_o)^2 + a_2^2\,(v-v_o)^2 + a_3^2\,(w-w_o)^2 + \lambda(\partial u/\partial x + \partial v/\partial y + \partial w/\partial z)]\; dx\; dy\; dz \tag{4-2}$$

where $u(x,y,z)$, $v(x,y,z)$ and $w(x,y,z)$ are the adjusted wind components calculated by the model; $u_o(x,y,z)$, $v_o(x,y,z)$ and $w_o(x,y,x)$ are the wind observations; $\lambda(x,y,z)$ is the Lagrangian multiplier; and a_1, a_2 and a_3 are the Gauss precision moduli (which are related to the observational errors). The above integral is applied throughout the entire computational domain.

The solution u, v, w is found by minimizing E in Equation 4–2; i.e., by a combined minimization of both the difference between observed and adjusted components and the wind divergence. This minimization gives a formula for u, v, w and a differential equation for λ, which can be solved if proper boundary conditions are provided.

4.1.6 Terrain Adjustment With the Poisson Equation

The objective analysis method of Goodin et al. (1980) performs the following numerical steps:

1. The surface wind field is computed by interpolating wind measurements with a weighting factor proportional to $1/r^2$.

2. The wind is adjusted to the terrain by solving the Poisson equation

$$\nabla^2\phi = \psi(x,y) \tag{4-3}$$

   where ϕ is the wind velocity potential and ψ is a forcing function based on the thickness of the PBL and terrain elevation gradients.

3. Upper level winds are interpolated in a terrain-following coordinate system (such as in Figure 4-2), using a weighting factor proportional to $1/r$ and a five-point filter.

4. Iterations are performed until the maximum divergence of the interpolated wind fields is reduced to an acceptable level.

4.1.7 Mass Consistent Wind Generation by Linear Combination of a Limited Number of Solutions

Most of the above wind generation schemes provide solutions that are linear combinations of the input data. A method by Ludwig and Bird (1980) combines the solutions for several linearly independent data sets in an appropriate way to obtain the solution for any arbitrary input. This is performed by principal component analysis, using normalized eigen-vectors.

4.1.8 The ATMOS1 Code

The ATMOS1 model (Davis et al., 1984; King and Bunker, 1984) calculates wind fields with the use of a mass conservation error minimization principle that employs available observations. It provides a three-dimensional wind field using terrain-following coordinates and an expanded vertical grid system that insures resolution near the surface where the drainage flow occurs and where pollutants are normally concentrated.

4.1.9 The Moussiopoulos-Flassak Model

Moussiopoulos and Flassak (1986) developed a mass-consistent model for the calculation of wind velocity fields over complex orography. Velocities are adjusted by solving a three-dimensional elliptic differential equation transformed to a terrain-following coordinate system. One important peculiarity of this model is the full vectorization of its algorithms, which optimizes running time on array processing computers. This model was refined by Moussiopoulos et al. (1988) by improving its numerical algorithms and accounting for atmospheric stability. The model has been applied to reconstruct wind fields, in the basin of Athens, Greece.

4.1.10 The MINERVE Code

MINERVE (Geai, 1987) is a mass-consistent wind field model that reduces the divergence by an iterative procedure that may take into account atmospheric stability. The code was developed by the Electricite' de France.

4.1.11 The Objective Analysis Based on the Cressman Interpolation Method

Fruehauf et al. (1988) developed a computer code for the objective analysis of a two-dimensional field. This code automates the use of a successive corrections method that interpolates data from irregularly spaced points to a regularly spaced grid. The program was implemented in a IBM personal computer and contains isopleth analysis routines for standard meteorological fields such as temperature.

4.1.12 The DWM Code

The DWM code (Douglas and Kessler, 1988) is based on the conservation-of-mass equation. The model incorporates local surface and upper air observations, when available, and provides some information on terrain-generated airflows in regions where local observations are absent. The model is formulated in terrain-following coordinates and uses a two-step procedure to generate a gridded wind field. In Step 1, a domain-mean wind is adjusted for terrain effects, (e.g., lifting and acceleration of the airflow over terrain obstacles, thermodynamically generated slope flows and blocking effects). In Step 2, an objective analysis procedure is applied in which the observations are used within a user-specified radius of influence. This Step 2 procedure consists of interpolation, smoothing, calculation of vertical-velocity field and minimization of the three-dimensional divergence.

4.2 PROGNOSTIC MODELS

Meteorological prognostic models are used to forecast the time evolution of the atmospheric system through the space-time integration of the equations of conservation of mass, heat, motion, water, and if necessary, other substances such as gases and aerosols. The following governing equations have been derived by Pielke (1984):

$$\frac{\partial \varrho}{\partial t} = -(\nabla \cdot \varrho \mathbf{V}) \qquad (4\text{-}4)$$

$$\frac{\partial \theta}{\partial t} = -\mathbf{V} \cdot \nabla \theta + S_\theta \qquad (4\text{-}5)$$

$$\frac{\partial \mathbf{V}}{\partial t} = -\mathbf{V} \cdot \nabla \mathbf{V} - (1/\varrho)\nabla p - g\mathbf{k} - 2\boldsymbol{\Omega} \times \mathbf{V} \tag{4-6}$$

$$\frac{\partial q_n}{\partial t} = -\mathbf{V} \cdot \nabla q_n + S_{q_n}, \; n = 1, 2, 3 \tag{4-7}$$

where

ϱ is the density of the air

$\mathbf{V}$ is the wind vector (u,v,w)

θ is the potential temperature

S_θ represents the sources and sinks of heat (i.e., freezing/melting, condensation/evaporation, deposition/sublimation, exothermic/endothermic chemical reactions, net radiative flux convergence/divergence, dissipation of kinetic energy by molecular motion)

p is the pressure

g is the acceleration of gravity

$\boldsymbol{\Omega}$ is the earth's angular velocity

q_n is the density of the various forms of water (solid, n = 1; liquid, n = 2; and vapor, n = 3)

S_{q_n} is the source–sink term for q_n due to phase change and chemical reactions, where the latter is generally negligible (S_{q_1}: freezing/melting, deposition/sublimation, fallout from above/to below; S_{q_2}: melting/freezing, condensation/evaporation, fallout from above/to below; S_{q_3}: evaporation/condensation, sublimation/deposition)

(The symbol ∇ is the gradient operator, $\nabla\cdot$ is the divergence, $\times$ is the vector cross product, $\mathbf{k}$ is the unit vector along the positive z–axis, and $\cdot$ indicates the scalar product)

Equation 4–4 is the conservation of mass or continuity equation. Equation 4–5 is the conservation of heat derived by assuming the air to behave like an ideal gas and to be in local thermodynamic equilibrium. (It is derived from the first law of thermodynamics and the ideal gas law in a form that includes the contribution of water vapor.) Equation 4–6 is the conservation of motion, according to Newton's second law and contains two external forces, i.e., the pressure gradient force and the gravity force (which includes, as usual, the earth's centripetal acceleration) and the apparent Coriolis force. Equation 4–6 does not include the internal forces that would be required to take into account the dissipation of momentum by molecular motions. Finally, Equation 4-7 is the conservation of water (solid, liquid and vapor).

Three additional equations -- the definition of potential temperature, the ideal gas law, and the definition of virtual temperature -- complete the above set:

$$\theta = T_v \, (100/p_{mb})^{R_d/c_p} \tag{4-8}$$

$$p = \varrho \, R_d \, T_v \tag{4-9}$$

$$T_v = T \, (1 + 0.61 \; q_3) \tag{4-10}$$

where T_v is the virtual temperature, p_{mb} is the pressure expressed in mb, R_d is the dry gas constant of the atmosphere ($R_d = 287 \, J \, K^{-1} \, kg^{-1}$), and c_p is the specific heat of the air at constant pressure.

The conservation equations, 4–4 through 4–7, together with the latter three equations, 4–8 through 4–10, form a set of 11 simultaneous nonlinear partial differential equations in 11 dependent variables: ϱ, θ, T, T_v, p, $\mathbf{V}$, and q_n. The independent variables are the time t and the spatial coordinates x, y, and z.

To be completed, the above set of equations should include conservation relations for other atmospheric chemical species besides water, e.g., gaseous materials, such as sulfur dioxide, and aerosols, such as sulfates and nitrates. However, the simultaneous solution of both meteorological equations and transport, diffusion, chemical and deposition equations, represent a formidable problem. It is commonly assumed that the concentrations of primary and secondary atmospheric pollutants do not affect the meteorology. Consequently, prognostic meteorological models can be generally applied and can run independently from dispersion models.

Meteorological prognostic modeling aims at finding the solution of the above 11 equations or a subset of them. However, they must be modified and simplified to be solved. For practical applications, these equations are never used in the form shown above. Actual numerical simulations, in fact, require that the 11 variables and the sink-source terms be averaged in space, over grid volumes, and in time, over a computational interval Δt. Grid volume averaging is commonly performed using the Reynolds assumption, in which each variable a is decomposed into an average term plus a subgrid perturbation (i.e., $a = \overline{a} + a'$), where the average of the subgrid perturbation is assumed to be zero (i.e., $\overline{a'} = 0$). This process, however, creates new additional variables, in the form of average subgrid scale fluxes. This phenomenon is called the "closure" problem.

For example, Reynolds averaging of Equation 4–6 generates new terms, because of the nonzero correlations among the components of $\mathbf{V}'$, the subgrid perturbation of $\mathbf{V}$. And Equation 4–5 generates new cross correlation terms between θ', the subgrid perturbation of θ, and the components of $\mathbf{V}'$. Usually these new variables (or turbulent fluxes) cannot be defined in terms of basic observation principles and, therefore, solutions are found only through semiempirical assumptions. The simplest assumption is the so-called K-theory (or gradient theory), which relates these fluxes to the gradients of the average variables through proportionality terms called eddy coefficients. (Closure and K-theory are discussed in more detail in Chapter 6 in the context of transport and diffusion of an atmospheric pollutant.)

To reduce, modify or simplify the above equation, scale analysis is often used. Scale analysis (the method that determines the relative importance of the individual terms in the conservation relations; Pielke, 1984) is a major tool for identifying and eliminating terms whose contribution can be considered negligible for a certain range of applications. Scale analysis allows, in particular, the definition of the shallow convection form of the continuity equation (or incompressibility assumption)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (4\text{–}11)$$

the hydrostatic equation (derived from the vertical component of Equation 4–6 for the atmosphere at rest)

$$\frac{\partial p}{\partial z} = -\varrho\, g \qquad (4\text{–}12)$$

and the evaluation of the geostrophic wind (u_g, v_g)

$$u_g = \frac{1}{\varrho f}\frac{\partial p}{\partial y} \qquad (4\text{–}13)$$

$$v_g = \frac{1}{\varrho f}\frac{\partial p}{\partial x} \qquad (4\text{–}14)$$

which is generally used as a boundary condition at the top of the computational domain.

Further modifications and simplifications of the conservation equations are obtained using averaging techniques and assumptions such as:

- Different parameterizations of the subgrid scale correlation terms, i.e, the turbulence fluxes (a solution to the closure problem)
- The Boussinesq approximations, in which pressure, density and temperature are expressed as the sum of equilibrium values plus a small correction due to atmospheric motion (in practice, the Boussinesq approximations assume that the temporal variations of the density can be neglected, except in the vertical component of Equation 4-6). These approximations lead to considerable simplifications (Seinfeld, 1986), including Equation 4-11.
- A simplified density-weighted mesoscale scalar vorticity, instead of the full vorticity equation in tensor form (Pielke, 1984)

Various sets of simplified equations can be derived from the above scale analyses and averaging processes. Each set, however, must be used with a clear understanding of its physical limitations with respect to the original group of equations 4-4 through 4-10.

Each set of simplified equations represents a group of simultaneous nonlinear partial differential equations. The nonlinearity is given by the presence of products of dependent variables and is one of the major obstacles to obtaining exact (i.e., analytical) solutions.

Linearization techniques, e.g. harmonic (Fourier) analysis, have been used (Pielke, 1984) to derive approximate sets of linear equations, consequently allowing, under certain simplifying assumptions, the identification of their analytical solution. In the past, these methods represented the only possible analysis tools, in spite of their limitations and shortcomings. Today's fast computers allow the evaluation of approximate solutions (i.e., numerical solutions) of a set of nonlinear equations and, therefore, represent the best tool in this field.

Numerical solutions can be computed using the following techniques:

- finite difference schemes
- spectral techniques

- pseudo-spectral methods
- finite elements
- interpolation schemes
- boundary element methods
- particle models

Numerical solutions depend strongly on boundary conditions and initial values; thus, when using numerical methods, special care must be taken to correctly initialize all meteorological variables in the computational domain and to correctly define the time-varying physics at the boundaries.

Several prognostic meteorological models have been developed. Unfortunately, however, most of them are complex research tools whose correct use requires the active involvement of their developers. A comprehensive list of mesoscale numerical models and their characteristics is presented in Appendix B of Pielke (1984). Additional information can be found in reviews of available mesoscale models prepared by Pielke (1988) and Haney et al. (1989).

Among these studies, the development of four advanced meteorological models has been particularly important for air quality applications: 1) the three-dimensional URBMET vorticity-mode model developed by Bornstein et al. (1987); 2) the primitive equation-mode model NMM (Numerical Mesoscale Model) developed by Pielke et al. (1983); 3) the three-dimensional hydrodynamic model HOTMAC (Higher Order Turbulence Model for Atmospheric Circulations) by Yamada (1985) and Yamada and Bunker (1988); and 4) the NCAR/PSU/SUNY model, which is used in the Regional Atmospheric Deposition Model (RADM) (Chang et al., 1987). All four models have been linked with dispersion models: URBMET and the NCAR model have been linked with K-theory grid models, while Pielke's model and HOTMAC are linked with Lagrangian particle simulation codes (see Section 8) (Pielke's model is also linked with the Urban Airshed Model discussed in Section 14.1.1).

4.2.1 The URBMET Model

The URBMET model introduces the stream function and three-dimensional vorticity vector into the equation of conservation of motion 4-6. A few assumptions allow Equation 4-6 to be simplified and applied to the upper portion of the PBL, more precisely the portion above the surface layer. These assumptions are (Bornstein et al., 1985):

- The atmosphere is Boussinesq. In practice, this assumption allows us to ignore temperature-induced density fluctuations in the horizontal terms of Equation 4-6 and produces the incompressible form of the continuity equation.

- The atmosphere is hydrostatic. Consequently, vertical velocities must be computed for conservation of mass.

- Turbulence can be described by eddy coefficients, and horizontal diffusion is characterized by a constant eddy diffusivity.

- Mean thermodynamic and dynamic variables can be defined as the sum of several parts (constant synoptic forcing plus spatial and temporal variations arising only from mesoscale motions).

With the above assumptions, the three components of Equation 4–6 become

$$\frac{\partial u}{\partial t}+\frac{\partial(uu)}{\partial x}+\frac{\partial(vu)}{\partial y}+\frac{\partial(wu)}{\partial z}=-\frac{1}{\varrho_a}\frac{\partial p_M}{\partial x}+f\,(v-v_g)$$
$$+\frac{\partial}{\partial z}\left(K_{mv}\frac{\partial u}{\partial z}\right)+K_{mh}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad (4\text{–}15)$$

$$\frac{\partial v}{\partial t}+\frac{\partial(uv)}{\partial x}+\frac{\partial(vv)}{\partial y}+\frac{\partial(wv)}{\partial z}=-\frac{1}{\varrho_a}\frac{\partial p_M}{\partial y}-f\,(u-u_g)$$
$$+\frac{\partial}{\partial z}\left(K_{mv}\frac{\partial v}{\partial z}\right)+K_{mh}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \qquad (4\text{–}16)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (4\text{–}17)$$

where

ϱ_a is the density (constant volume average)

p_M is the mesoscale atmospheric pressure

f is the Coriolis parameter defined by Equation 3–3

u_g, v_g are the geostrophic wind components defined by Equations 4–13 and 4–14

K_{mv} is the vertical momentum eddy transfer coefficient

K_{mh} is the horizontal momentum eddy transfer coefficient

We can relate the velocity $\mathbf{V} = (u,v,w)$ to the stream function vector $\mathbf{\Psi} = (\phi, -\psi, 0)$ by

$$\mathbf{V} = \nabla \times \mathbf{\Psi} \tag{4-18}$$

Consequently, we obtain

$$u = \frac{\partial \psi}{\partial z} \tag{4-19}$$

$$v = \frac{\partial \phi}{\partial z} \tag{4-20}$$

$$w = -\left(\frac{\partial \psi}{\partial x} + \frac{\partial \phi}{\partial y}\right) \tag{4-21}$$

and, by introducing the relative vorticity vector (ξ, η, ζ), we obtain

$$\xi = \frac{\partial v}{\partial z} - \frac{\partial w}{\partial y} \approx \frac{\partial v}{\partial z} \tag{4-22}$$

$$\eta = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \approx \frac{\partial u}{\partial z} \tag{4-23}$$

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \tag{4-24}$$

where the last equalities in Equations 4–22 and 4–23 are valid for a hydrostatic PBL.

Further manipulation allows the derivation of the following vorticity equations for horizontal motion

$$\begin{aligned} \frac{\partial \xi}{\partial t} = &- \frac{\partial (u\xi)}{\partial x} - \frac{\partial (v\xi)}{\partial y} - \frac{\partial (w\xi)}{\partial z} + \xi \frac{\partial u}{\partial x} - \eta\left(f + \frac{\partial v}{\partial x}\right) \\ &+ \frac{g}{\theta_a}\frac{\partial \theta_M}{\partial y} + \frac{\partial^2}{\partial z^2}(K_{mv}\,\xi) + K_{mh}\left(\frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2}\right) \end{aligned} \tag{4-25}$$

$$\frac{\partial \eta}{\partial t} = -\frac{\partial (u\eta)}{\partial x} - \frac{\partial (v\eta)}{\partial y} - \frac{\partial (w\eta)}{\partial z} + \eta \frac{\partial v}{\partial y} + \xi\left(f - \frac{\partial u}{\partial y}\right)$$
$$+ \frac{g}{\theta_a} + \frac{\partial \theta_M}{\partial x} + \frac{\partial^2}{\partial z^2}(K_{mv}\,\eta) + K_{mh}\left(\frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2}\right) \quad (4\text{–}26)$$

With appropriate boundary and initial conditions, Equations 4–19, 4–20, 4–21, 4–22, 4–23, 4–25, and 4–26 are solved in the URBMET model, thus providing the dynamics of **V** without solving the primitive Equations 4–15, 4–16 and 4–17.

4.2.2 The NMM Model and the ARAMS System

Pielke et al. (1983) developed the NMM model to provide reliable mesoscale meteorological simulations in regions of complex orographies (coastal zones and complex terrain). The model simulates three-dimensional circulations with horizontal grid intervals from 1 km to 10 km. The model, a primitive equation model assuming an incompressible, hydrostatic and noncondensing atmosphere, which has been in widespread use by a number of investigators during the 1980s, performed reasonably well in simulating basic sea breeze circulations and other topographically generated mesoscale flow regimes. Model evaluation has been encouraging (e.g., Segal and Pielke, 1981; and Pielke and Mahrer, 1978).

During 1987–88, a major effort was launched to unify the original "Pielke" model with the nonhydrostatic cloud scale model developed at Colorado State University by Professor William Cotton. The combined Pielke–Cotton model (called ARAMS) greatly expands the range and sophistication of the simulations possible using a mesoscale numerical model.

The Advanced Regional Atmospheric Modeling System (ARAMS) is a generalized, comprehensive and flexible numerical weather prediction system. It is the commercial, tested and documented version of the Colorado State University mesoscale model. The model has evolved over a 15-year period and represents the blending of three different models (two hydrostatic models and a nonhydrostatic cloud model).

ARAMS has the ability to address specific areas of concern by using a two-way interactive nesting scheme between the fine grid and the next coarser grid. The number of grid nests and grid levels in ARAMS is limited only by computer constraints. This allows maximum resolution in the area of coastlines, sea breeze fronts and steep terrain. The grid nesting allows one to use a large enough grid size to resolve large-scale (synoptic) features while also nesting to a level in which smaller scale forcing (sea breezes, mountain upslope flows, etc.) can be resolved. ARAMS contains options ranging from different initialization schemes to a variety of cloud microphysical parameterizations. Some of the options may be changed between nests. A partial listing of model options includes

- spatial dimension: one-, two-, or three-dimensional
- forecast duration: several hours to five days
- variable horizontal and vertical domains
- multiple nested grids
- horizontal grid sizes: 100 + km to as small as 50 meters
- vertical levels: up to 38
- finite differencing (two schemes)
- turbulent closure (three schemes)
- hydrostatic or nonhydrostatic
- variable coordinate systems: telescoping, interactive, nested
- cloud microphysics (four schemes)
- precipitation parameterization (five schemes)
- radiation schemes (three short wave, two long wave)
- surface temperature (four schemes)
- lateral boundary conditions (three schemes)
- topography: flat or with terrain
- use: uniform or variable
- sea surface temperature: uniform or variable
- upper boundary conditions (five schemes)
- initialization (five schemes)

4.2.3 The HOTMAC Model

The HOTMAC model was originally developed by Yamada (1978 and 1985) and further improved by Yamada and Bunker (1988), who added a "nested grid" capability and improved the simulation of the morning transition by including the effects of shadows produced by the terrain. The unique characteristic of this model is its treatment of turbulence by a second-moment turbulence-closure assumption. The model uses a terrain-following vertical coordinate and integrates its partial differential equations by using the ADI (alternating direction implicit) method and a time increment that satisfies the Courant–Friedrich–Lewy criteria.

4.2.4 The NCAR/PSU/SUNY Model

The NCAR/PSU/SUNY model (Chang et al., 1987; Seigneur, 1988; Lewellen et al., 1989) is an hydrostatic primitive–equation model that is used to simulate the meteorological fields in the central and eastern United States for acid deposition calculation. The code is capable of simulating cyclogenesis, low–level jets, land–sea breezes, forced airflow over rough terrain, frontal circulation, and mesoscale convective systems.

4.2.5 Non–Hydrostatic Models

The hydrostatic assumption of Equation 4–12 is commonly used in meteorological models. Models that do not use this simplification are called nonhydrostatic and require the solution of the vertical equation of motion and a prognostic or diagnostic equation for pressure. These models demand enormous computational efforts and, therefore, their past and current application has been limited.

Pielke (1984) has shown that, when the hydrostatic assumption is used in meteorological models with terrain–following coordinate systems, the terrain slope must be much less than 45° (e.g., 5°) to assure a correct representation. Also, many studies concluded (Fast and Takle, 1988) that nonhydrostatic effects generally become more important in neutral conditions or when the horizontal length scale is smaller than 1–3 km.

Few nonhydrostatic models are available (e.g., Clark, 1977; Tapp and White, 1976) and require large computational resources. Quasi–nonhydrostatic assumptions can be used, however, to simulate flow over simple terrain features. For example, Fast and Takle (1988) derived a parameterization of the nonhydrostatic pressure and incorporated it into an hydrostatic model. Tests show that this approach is able to reproduce many of the terrain–induced characteristics that the hydrostatic model failed to simulate.

REFERENCES

Anderson, G.E. (1971): Mesoscale influences on wind fields. *J. Appl. Meteor.*, **10**:377–386.

Bornstein, R.D., S. Klotz, R. Street, U. Pechinger, R. Miller (1987): Modeling the polluted coastal urban environment. Vol. 1. The PBL Model. EPRI Report EA-5091, Palo Alto, California.

Chang, J.S., R.A. Brost, I.S. Isaksen, S. Madronich, P. Middleton, W.R. Stockwell, and C.J. Walcek (1987): A three-dimensional Eulerian acid deposition model: Physical concepts and formulation. *J. Geophys. Res.*, **92**:14681–14700.

Clark, T.L. (1977): A small-scale dynamic model using a terrain-following coordinate transformation. *J. Comput. Phys.*, **24**:186–215.

Danard, M. (1977): A simple model for mesoscale effects of topography on surface winds. *Mon. Wea. Rev.*, **105**:572.

Davis, C.G., S.S. Bunker, and J.P. Mutschlecner (1984): Atmospheric transport models for complex terrain. *J. Climate and Appl. Meteor.*, **23**:235–238.

Dickerson, M.H. (1978): MASCON -- A mass-consistent atmospheric flux model for regions with complex terrain. *J. Appl. Meteor.*, **17**:241–253.

Douglas, S.G., and R.C. Kessler (1988): User's guide to the diagnostic wind model (Version 1.0). Systems Applications, Inc., San Rafael, California.

Fast, J.D., and E.S. Takle (1988): Evaluation of an alternative method for numerically modeling nonhydrostatic flows over irregular terrain. *Boundary-Layer Meteor.*, **44**:181–206.

Fruehauf, G., P. Halpern, P. Lester (1988): Objective analysis of a two-dimensional scalar field by successive corrections using a personal computer. *Environ. Software*, **3**(2):72–80.

Geai, P. (1987): Reconstitution tridimensionnelle d'un champ de vent dans un domaine a' topographie complexe a' partir de meusures in situ. EDF, Chatou, France, Final Report DER/HE/34-87.05.

Goodin, W.R., G.J. McRae, and J.H. Seinfeld (1980): An objective analysis technique for constructing three-dimensional urban-scale wind fields. *J. Appl. Meteor.*, **19**:98–108.

Haney, J.L., S.G. Douglas, L.R. Chinkin, D.R. Souten, C.S. Burton, P.T. Roberts (1989): Ozone air quality scoping study for the lower Lake Michigan air quality region. Systems Applications, Inc., Final Report SYSAPP-89/101, San Rafael, California.

Hoke, J.E., and R.A. Anthes (1976): The initialization of numerical models by a dynamic-initialization technique. *Mon. Wea. Rev.*, **104**:1551–1556.

King, D.S., and S.S. Bunker (1984): Application of atmospheric transport models for complex terrain. *J. Climate and Appl. Meteor.*, **23**:239.

Lewellen, W.S., R.I. Sykes, S.F. Parker, D.S. Henn, N.L. Seaman, D.R. Stauffer, and T.T. Warner (1989): A hierarchy of dynamic plume models incorporating uncertainty. Vol. 5: Pennsylvania State University Mesoscale Model (PSU-MM). A.R.A.P. Division of California Research & Technology, Inc., Report EA-6095, Vol. 5, Princeton, New Jersey.

Liu, M.-K., and M.A. Yocke (1980): Siting of wind turbine generators in complex terrain. *J. Energy*, **4**:10–16.

Ludwig, F.L., and G. Byrd (1980): An efficient method for deriving mass–consistent flow fields from wind observations in rough terrain. *Atmos. Environ.*, **14**:585–587.

Mass, C.F., and D.P. Dempsey (1985): A one–level mesoscale model for diagnosing surface winds in mountainous and coastal regions. *Mon. Wea. Rev.*, **110**:1211.

Moussiopoulos, N., and T. Flassak (1986): Two vectorized algorithms for the effective calculation of mass–consistent flow fields. *J. Climate and Appl. Meteor.*, **25**:847–857.

Moussiopoulos, N., T. Flassak, and G. Knittel (1988): A refined diagnostic wind model. *Environ. Software*, **3**(2):85–94.

Patnack, P.C., B.E. Freeman, R.M. Traci, and G.T. Phillips (1983): Improved simulations of mesoscale meteorology. Atmospheric Science Laboratory Report ASL CR–83–0127–1. White Sands Missile Range, New Mexico.

Phillips, G.T., and R.M. Traci (1978): A preliminary user guide for the NOABL objective analysis code. Science Applications Inc. Report SAI–78–769–LJ; San Diego, CA. U.S. Department of Energy Report RLO/2440–77–10.

Pielke, R.A., and Y. Mahrer (1978): Verification analysis of the University of Virginia three-dimensional mesoscale model prediction over south Florida for July 1, 1973. *Mon. Wea. Rev.*, **106**:1568–1589.

Pielke, R.A., R.T. McNider, M. Segal, and Y. Mahrer (1983): The use of a mesoscale numerical model for evaluations of pollutant transport and diffusion in coastal regions and over irregular terrain. *Bull. Am. Meteor. Soc.*, **64**:243–249.

Pielke, R.A. (1984): *Mesoscale Meteorological Modeling*. Orlando, Florida: Academic Press.

Pielke, R.A. (1988): Status of mesoscale and subregional models. Vol. 2. Aster, Inc., Research Project RP2434–6, Fort Collins, Colorado.

Rodriguez, D.J., et al. (1982): User's guide to the MATHEW/ADPIC models. UASG 82–16, Lawrence Livermore National Laboratory, University of California Atmospheric and Geophysical Sciences Division, Livermore, California.

Segal, M., and R.A. Pielke (1981): Numerical model simulation of biometeorological heat load conditions—Summer day case study for the Chesapeake Bay area. *J. Appl. Meteor.*, **20**:735–749.

Seigneur, C. (1988): Evaluation of the feasibility of the application of a regional air pollution model to northern California. Second interim report prepared for Pacific Gas and Electric, San Francisco, California.

Seinfeld, J.H. (1986): *Atmospheric Chemistry and Physics of Air Pollution*. New York: John Wiley.

Sherman, C.A. (1978): A mass–consistent model for wind fields over complex terrain. *J. Appl. Meteor.*, **17**:312–319.

Shir, C.C., and L.J. Shieh (1974): A generalized urban air pollution model and its application to the study of SO_2 distributions in the St. Louis metropolitan area. *J. Appl. Meteor.*, *13*:185–204.

Tapp, M.C., and P.W. White (1976): A nonhydrostatic mesoscale model. *Quarterly J.Roy. Meteor. Soc.*, **102**:277–296.

Tesche, T.W., and M.A. Yocke (1978): Numerical modeling of wind fields over mountainous regions in California. *Proceedings*, American Meteorological Society Conference on Sierra Nevada Meteorology, South Lake Tahoe, California, June.

Tran, K.T., and R.C. Sklarew (1979): User guide to IMPACT: An integrated model for plumes and atmospheric chemistry in complex terrain. Form & Substance, Inc., Westlake Village, California.

Yamada, T. (1978): A three-dimensional, second-order closure numerical model of mesoscale circulations in the lower atmosphere. Argonne National Laboratory Document ANL/RER-78-1. [Available from National Technical Information Service.]

Yamada, T. (1985): Numerical simulation of the Night 2 data of the 1980 ASCOT experiments in the California Geysers Area. *Arch. for Meteor. , Geophys., and Biolim.*, A**34**:223-247.

Yamada, T., and S.S. Bunker (1988): Development of a nested grid, second moment turbulence closure model and application to the 1982 ASCOT Brush Creek data simulation. *J. Appl. Meteor.*, **27**:562-578.