REVIEW AND CLASSIFICATION OF COMPLEX TERRAIN MODELS FOR USE WITH INTEGRATED PEST MANAGEMENT PROGRAM SPRAY MODELS

by

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SUBJECT: REVIEW AND CLASSIFICATION OF COMPLEX TERRAIN MODELS
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I. INTRODUCTION

An important goal of the Forest Service's Integrated Pest Management Program is to develop effective numerical advisory programs. Such programs advise personnel when effective aerial spraying for pest control can occur over complex terrain without atmospheric dispersion and deposition outside the target area. The effect of complex terrain and valley drainage meteorology must be incorporated into aerial spray models such as AGDISP or FSCBG developed by the Forest Service for relatively flat terrain.

A review of currently available complex terrain models is provided to select software which might provide such valley drainage and complex terrain information for incorporation into the Forest Service models. The review does not propose to identify new computational research areas but to determine which models are ready for incorporation into the Forest Service management program. The review document contains:

a) An examination of the relative merits of phenomenilogical models, objective analysis models, linearized models, shallow layer models, or primitive equation models,

b) Examples of appropriate models in each category together with appropriate references and availability of source code, and

c) A critique of the various models, together with recommendations concerning model development or revisions necessary for use by the Forest Service aerial spray program.

II. BRIEF HISTORY OF PREDICTION OF DISPERSION IN COMPLEX TERRAIN

The need to estimate reliably the impact of emission sources in regions of complex terrain for decision-making purposes remains a "key challenge" to the meteorological community (Egan and Schiermeir, 1985). No adjustments for terrain influence on pollutant concentrations were made until the 1970s, when it became necessary to use diffusion models as a requirement of the U.S./ Clean Air Act and its amendments. Increased concentrations in rugged terrain can result from plume impingement on high terrain, pooling in valleys, drainage towards population centers, or persistence due to channeling. AMS, EPA, DOE, and EPRI have all supported workshops and research programs dedicated to a better understanding of dispersion in rugged terrain. Prominent among the coordinated analytic, field and numerical studies have been EPA's Complex Terrain Model Development (CTMD) Program, EPRI's Plume Model Validation and Development (PMV&D) study, and DOE's Atmospheric Studies in Complex Terrain (ASCOT). These field studies have added substantially to the understanding of drainage and slope flows, stratified flow over and around isolated hills or ridges, and narrow valley circulations.

An excellent review of meteorological processes over complex terrain and the state-of-the-art of analytical, physical and numerical modeling was provided during the AMS Workshop on Current Directions in Atmospheric Processes Over Complex Terrain, October 1988 in Utah. The results of this workshop will soon appear in an AMS Monograph of the same name, and frequent reference to draft chapters were made during this review.

III. MODEL CLASSIFICATION

Dispersion prediction codes or algorithms for flow over terrain can be grouped into four flow categories of increasing flow complexity. These are a) flows for steady-state, straight line winds over homogeneous flat terrain, b) flows where plume impact or contact with the face of hills or ridges occurs due to terrain rising to intercept an elevated plume, c) flows which are diverted, accelerated or decelerated due to variations in surface contours, temperature, and roughness in the absence of separation or recirculation, and d) flows where backflows and recirculation may occur as a result of obstacle separation, valley drainage circulations, sea/lake circulations, etc.. Parallel with these flow categories one can identify seven categories of numerical modeling:

i) Gaussian plume models,
ii) Hill intercept models,
iii) Phenomenalogical models,
iv) Mass consistent or objective analysis models,
v) Depth integrated models,
vi) Linear perturbation models, and
vii) Full primitive equation models.

IV. MODEL DESCRIPTION AND CRITIQUE

It will not be possible to review all complex terrain models here. A comprehensive list of models by name, type and author will be provided in tables. Prominent members of each category will be described to identify the advantages and disadvantages of each approach. Copies of almost all model source codes are available by request or purchase.

A. Gaussian Plume Models

Codes developed to handle more or less homogeneous terrain situations frequently employee simple gaussian distribution models. Candidate models include many of the EPA UNAMAP models. A list of some 35 such models is noted in Table 1a extracted from the report by Lewellen and Sykes (1985). The table has been modified to include more recent models. These models are sufficiently simple that they are frequently used for initial estimates of transport and diffusion out to 10 miles. These models are limited primarily because of the inability to handle temporal variations (like the development of the morning valley flow circulation), spatial variations (wind shear in any direction), and the unknown effect of secondary circulations on the sigma σ parameters of plume size. Sometimes such models can be imbedded within more complex wind fields, but the approach should be used with caution, and better methodologies are now available.

TABLE 1A: GAUSSIAN PLUME MODELS

MODEL NAME	ORGANIZATION	REFERENCE
AIRDOS	Oak Ridge Ntl. Lab	Moore (1977)
AIRMOD	U.S. Army	Webster, et al. (1978)
APRAC2	E.P.A.	Ludwig and Obinata (1974)
AQSTM	Illinois EPA	Dickerson and Orphan (1975)
ARAC Gaussian	L.L.N.L.	
ATDL	NOAA/ATDL	Gifford (1973)
ATM	NOAA/ATDL	Patterson (1976)
COMRADEX-4	Rockwell Int.	Otter and Chung (1977)
DEPA	NOAA/ATDL	Rao (1981)
DIFOUT	Sandia Ntl. Lab.	Luna and Church (1969)
DNWND	Oak Ridge Ntl. Lab.	Fields and Miller (1980)
EDMS	RAS/NUC	Wilkie and Garry (1981)
GEM	Science Applications Inc.	Fabrick, Sklarew and Wilson (1977)
GLUMP II	MESOMET	Lyons, et al, (1981)
MESOPLUME	ER&T	Berkley and Bass (1979)
MIDAS	Pickard, Lowe and Garrick	Woodard (1975)
PAVAN	Battelle PNWL	Bander (1982)
RADOS	Dupont/SRL	Cooper
SNAGA	ER&T	-
SRDFM	NOAA/ARL	-
STRAM	Battelle PNWL	Hales, et al., (1977)
SUBDOSA	Battelle PNWL	Strenge, et al., (1976)
UNAMAP series (CDM, CRSTER, ISC, MPTER, PAL, PTDIS, PTMAX, PTMTP)	EPA	Turner (1979)
TEM	Texas Air Control Board	Christiansen (1976)
XOQDOQ	NRC	Sagendorf and Goll (1977)
3141	Enviroplan, Inc.	Ellis and Liu (197?)

TABLE 1B: GAUSSIAN IMPACT MODELS

CTDM	EPA	Strimaitis (1988)
COMPLEX I	EPA	EPA (1983)
COMPLEX II	EPA	EPA (1983)
RTDM	ER&T	Egan and Paine (1987)
VALLEY	EPA	Burt (1977)

Note: Table updated from Lewellen and Sykes (1985)

TABLE 2: GAUSSIAN PUFF AND PLUME SEGMENT MODELS

MODEL NAME	ORGANIZATION	REFERENCE
ADPLUM	Dupont/SRL	Huang (1980)
ASTRAP	ANL	Shannon (1981)
ATAD	NOAA/ARL	Heffter (1980)
AVACTA	AeroVironment	Chan and Tombach (1978)
AVPPM	Aerovironment	Zannetti (1980)
DRAX2	NOAA/ARL	Draxler (1979)
JEREMIAH	Dupont/SRL	Kern (1977)
MESODIF	NOAA/ARL	Start and Wendell (1974)
MESODIF-II	Battelle PNWL	Powell, et al., (1979)
MESOPUFF	ER&T	Benkley and Bass (1979)
MESOI	Battelle PNWL	Ramsdell and Athey (1981)
PFPL	Dupont/SRL	Garret and Murphy (1981)
PSM	TVA	Lott
RETADD	NOAA/ATDL	Begovich, et al., (1978)
REED	H.E. Cramer Co.	Bjorklund and Dumbauld (1978)
TRAGGY	Meteorologigcal Evaluation Service Inc.	Smith

TABLE 3: PHENOMENALOGICAL MODELS

GAUS PLUME MODEL FOR VALLEYS	Yankee Atmomic Electricity Massachussetts	Harvey and Hamawai (1986)
U. OF UTAH	Meteorology Department, U. of Utah	Lee and Kau (1984)
VALMET	Battelle PNWL	Whiteman and Allwine (1985)

Lewellen and Sykes (1985) calculate that the maximum range of applicability of such models can be related to the persistence of the wind. They suggest that the error expected in the average concentration over the period of persistence may be approximated by:

$$\text{Error} = \frac{(C_{observed} - C_{calculated})}{C_{observed}} = \left[\frac{\tau U}{x} - 1\right]^{-1}$$

where x is down-wind distance, U is wind speed, τ is persistence time, and provided $x/(U\tau) < 1$. Strong persistent winds are required to keep error from being large at distances beyond 10 km.

Vertical wind shear can often be the dominant factor in spreading a plume horizontally, since a turning of the wind with respect to altitude of 30° or more often occurs. Irwin (1979) attempted to incorporate vertical wind shear into a general algorithm for σ_y. The largest uncertainty in such dispersion models is likely to be caused by eddies in the size range of 1 to 10 km. Such eddies are responsible for uncertainty in position of the plume or the concentration level.

Many validations studies have been completed for Gaussian type models. It is generally accepted that the standard EPA type dispersion models are not reliable within a factor of two for prediction concentrations for characteristic dispersion conditions. Indeed both API and EPRI studies suggest model predictions and measured data for straightforward cases are often more than a factor of 5 apart at a majority of monitoring stations. Models generally agree with one-another better than they agree with field data. This suggests that there is little to choose between such models, and that a "natural" variation will exist in data which will always frustrate any effort to obtain better correlation. Bowne et al. (1983) found that gaussian plume models "showed no skill in predicting hour-by-hour concentrations at fixed receptors and exhibited only minimum skill in predicting the position and pattern of the plume footprint." Such models seem to perform best when predicting maximum 1-hour, ground level concentration when specific time and location are not considered. This is definitely not adequate for specific drift calculations for forest sprays.

Gaussian Puff and Plume Segment Models which are derivatives of the simple Gaussian approach may alleviate the temporal and spatial problems identified above. Table 2 lists sixteen such models for use when unsteady nonhomogeneous wind field data are available. Such models may be imbedded in the more complex terrain models discussed in the following sections. One may logically expect a significant improvement in concentration predictions when strong horizontal meandering occurs; however, there are few validation studies available to specifically say "how much better" such techniques will be.

Unfortunately the puff models can not effectively react to wind variations which are on a smaller scale than the size of the puff or line segment. Whenever the resolution of the meteorological data is finer than the scale of the puff, errors will be induced in sigma σ, and when the resolution of the meteorological data is coarser than the scale of the puff, there will be a variance in the puff position. Some authors choose to use particle- or marker-in-cell methods to resolve this problem. Unfortunately such approaches often require up to 20,000 particles to resolve the plume and can be computer time intensive. SPLITPUFF was constructed in an attempt to solve these problems. The SPLITPUFF model permits puff combination or division as necessary to respond to important flow characteristics with 1/50 the number of parcels and 1/10 the computer time. Although some corrections are applied to the sigma σ values for temporal and spatial variations in meteorology, a puff-type approach is still unable to adjust for dispersion effects due to secondary flows, back flow, or vertical wind shear.

B. Hill Intercept Models

EPA has several models in its UNAMAP series that can be used at sites where the height of the terrain exceeds the height of the stack -- VALLEY, COMPLEX I, , and COMPLEX II (See Table 1b). These models are essentially Gaussian plume models adjusted for plume height and surface variations by empirical and heuristic corrections. VALLEY is used as a worst-case screening model and assumes the plume always remains at the same elevation; although it may not indeed be a worst case model if recirculation can occur. Thus the models provide concentrations upon plume impact. The models are screening tools and were not based on field measurements. Field measurements by Start et al. (1975) in Huntigton Canyon, Utah, then revealed that dispersion in complex terrain exceeded that in flat terrain by as much as an order of magnitude. Thus plume impaction assumptions led to overly conservative predictions. Hanna et al. (1984) proposed a Gaussian model where plume path took into effect atmospheric stratification through a hill Froude number effects. More recently RTDM (Rough Terrain Dispersion Model) which uses ad hoc was tentatively approved by EPA for a "third level" screening model, and most recently the CTDM (Complex Terrain Diffusion Model) has been proposed which corrects for atmospheric stratification effects on plume paths around isolated hills and ridges (Hanna and Strimaitis, 1990). Unfortunately, these models are intended for plume impact on features closest to the source. They are not intended for application with many hills and valleys, nor do they contain any wake algorithms for simulating the mixing and recirculation found in cavity zones in the lee of a hill.

C. Phenomenological Models

Phenomenological models are those which use simple and specific insight about a limited phenomena to predict flow motions. For example Harvey and Hamawi (1986) modified the Gaussian dispersion equation to accommodate restricted lateral dispersion in deep river valleys. Multiple eddy reflections are assumed to occur between valley walls, the ground and the inversion over the valley; this leads to a simple imaging approach to estimating valley dispersion. Unfortunately the model presumes no temporal variation in valley conditions.

The boundary layer evolution of narrow mountain valleys during the early morning has been studied extensively, and a detailed description of this phenomena is provided by Whiteman (1990). Whiteman and Allwine (1985) and Bader and Whiteman (1989) proposed a phenomenological model titled VALMET for well-defined deep mountain valley diffusion based on the principles that:

> The nocturnal stable layer in a valley is destroyed by the growth of the convective boundary layer over the valley floor and sidewalls and the subsidence of the stable air mass in the valley center as the upslope motions transport mass out of the valley.
>
> Asymmetric heating of the valley sidewalls by the sun can skew the development of the boundary layer, with a tendency towards upslope motions on the heated sidewall and residual stability on the shaded sidewall.

The (1985) version of the model presumes that the valley air is "loaded" with pollution during the night, and then the early-morning motions fumigate this pollution downwards to the valley floor and sidewalls. The assumption is made that the night-time plume is "frozen" within the stable core. To work effectively twenty-seven input parameters are necessary to drive the model which includes topographic, temperature inversion, downvalley wind speeds, atmospheric stability and sensible heat flux characteristics. The model is driven by thermodynamic equations for the convective boundary layer (cbl) ascent and inversion descent coupled with continuity relations to maintain mass conservation and calculate up-slope wind speeds.

The model has not been validated quantitatively against field measurements. It would require substantial revision to incorporate the segments of airplane delivered elevated aerosol clouds delivered over a range of valley locations. Finally, the model is limited to well-defined narrow valleys; thus, emission above or below the stable core, cross valley flows, tributary flows, etc. are not be accounted for in the VALMET model.

D. Mass Consistent or Objective Analysis Models

This class of models combines some objective (regression or maximizing or minimizing some variable) analysis of available wind data to form a wind field. The wind field analysis typically forces the resulting flow to satisfy air mass continuity by constraining the flow between the ground surface and some elevated inversion height. Such models may either produce a fully three-dimensional wind field, or they may solve the depth integrated continuity equation in a horizontal plane, and then recreate a vertical field assuming certain similarity profiles.

Table 4 lists objective analysis models which attempt to adjust wind fields rather than just interpolate between field data. Recognition of the need to include terrain effects in mass-consistent calculations led to the development of three-dimensional, time-independent, finite-difference, regional wind field models like MATHEW (Mass-Adjusted Three dimensional Wind field model) or FEMASS its finite element counterpart. In both models the Sasaki variational analysis technique is used in adjusting a discrete field of time-averaged interpolated winds for mass consistency. Basically, the procedure entails minimizing the squares of the differences of the observed (interpolate) and analyzed velocity components subject to the imposed constraint of incompressibility. MATHEW uses a traditional approach in simulating terrain by representing the boundary surface as a system of regular blocks whose impenetrable sides lie along coordinate lines. FEMASS produces the shape of the boundary surface by the lowest row of nodes in the grid which, when interconnected, form a system of curvilinear patches. Thus FEMASS produces a more precise representation of an irregular surface. NOABL is a modification of MATHEW to use a terrain-following coordinate system.

The atmosphere's thermal structure is not explicitly considered in the model equations of MATHEW or FEMASS, but the phenomenological effect of stability can be simulated to a certain extent by making a judicious choice of the Gauss precision moduli weights. The IMPACT model uses a series of "transparencies" which overlay the grid points and use a $1/r^4$ weighing of stability at the data points. IMPACT also treats thermal drainage winds by

TABLE 4: MASS CONSISTENT AND OBJECTIVE ANALYSIS MODELS

MODEL NAME	ORGANIZATION	REFERENCE
ATMOS1	Los Alamos Ntl. Lab.	Davis and Bunker (1980)
BLM/TM	NOAA/NWS	Long, Schaffer and Kemler (1978)
CHAPEAU	Dupont/SRL	Pepper and Baker (1979)
COMPLX	SRI International	Englich and Lee (1983)
FEMASS	LLNL	Gresho, et al., (1978)
IMPACT	Form and Substance Inc.	Fabrick, et al., (1977)
(Now called SMOG)		Wacker and Londergan (1984)
MASCON	LLNL	Dickerson (1978)
MATHEW/ADPIC	LLNL	Sherman, Lange (1978)
MESOGRID	ER&T	Morris, Berkley and Bass (1979)
NOABL	Science Applications Inc.	Phillips (1979)
PATRIC	LLNL	Lange (1978)
PHOENIX	Oak Ridge Ntl. Lab.	Murphy (1979)
PIC	Systems, Science & Software	Sklarew, et al, (1971)
RADM	Dames and Moore	Runchel, et al., (1979)
PDM	Systems Applications Inc.	Liu, et al, (1976)
TAPAS	USDA-Forest Service	Fox, et al., (1987)
(NUWNDS)		Ross, et al., (1988)
(NUATMOS)		"
U. of Hawaii BL Model	Meteorology Department U. of Hawaii	Erasmus (1984)

TABLE 5: PERTURBATION MODELS (LINEARIZED)

FLOWSTAR	Cambridge Environmental Services	Carruthers, et al., (1988)
MS3DJH/1,2,3,3R	Atmospheric Environment Service, Canada	Walmsley, et al., (1980 1982, 1986)

TABLE 6: DEPTH INTEGRATED MODELS

2D FLOW	--	Garrett and Smith (1984)
Integrated Drainage Model	NOAA/ATDL/ARL	Dobosy (1987)

adding a component to the vertical velocity near the surface, but the inclusion of thermally generated winds appears to be done without regard to local ground slope.

Mass consistent models have been modeled against mathematical tests, wind-tunnel terrain flows, and field data (Lewellen and Sykes, 1985; Lewellen, Sykes and Oliver, 1982). The block terrain feature in MATHEW induces O(1) errors near the surface, and yet with the exception of the layer immediately adjacent to terrain changes, the mass adjustment imposes relatively minor adjustments to the interpolated wind fields. Lewellen et al. (1982) question whether such minor changes justify the computer time spent on MATHEW. NOABL and FEMASS were found to produce substantial improvement in near surface wind predictions. NOABL seems unreliable when computing flows which go around obstacles, because the numerical scheme can diverge if the stability parameter is pushed too far in the direction of no vertical motion. IMPACT contains substantial numerical diffusion when flows move diagonally across the numerical grid. Many mass consistent models are not constructed to handle flow separation over ridges or valleys or temporal variations of wind data; however, modifications to include temporal effects should be possible. Finally objective models depend critically on the quality as well as quantity of the observed data and the empirically chosen constants involved in the models.

TAPAS (<u>T</u>opographic <u>A</u>ir <u>P</u>ollution <u>A</u>nalysis) is a computer modelling system being developed jointly by the Centre for Applied Mathematical Modeling at Chisholm Institute of Technology, Australia, and the Rocky Mountain Forest and Range Experiment Station, USDA-Forest Service. It contains simulation models of varying complexity, input data management routines, an on-line digital terrain data base, and graphical display procedures designed to assist non-computer oriented forrest service personnel. The TAPAS system currently uses wind-generation sub-modules called NUWNDS for low-cost two-dimensional screening and NUATMOS for a three-dimensional characterization of wind flow in complex terrain.

NUATMOS (version 5) is a highly improved version of the ATMOS1 code, which is now claimed to be completely stable, efficient and optimized to the extent that it will run on a PC-386 personal computer. NUATMOS employs terrain-following coordinates and variable vertical grid spacing. NUATMOS incorporates atmospheric stability effects via a characteristic Froude number to set the horizontal/vertical adjustment parameter α; hence, it is purported to account satisfactorily for terrain speed-up and even lee-wave behavior. The authors assert that it is the "most comprehensively tested and evaluated model of its type."

NUWND and NUATMOS have been compared against laboratory measurements of flow over isolated ridges and hills. They have also been compared against field data from the CTMD and ASCOT program. The model appears to correctly predict streamline splitting, plume impaction, and nocturnal drainage flows. The models have also been compared with data from four measurement sets from the Latrobe Valley, Australia. Surface winds were predicted with 50 to 70% reliability by the models.

Lee and Kau (1984) divided the flow over complex terrain into a drainage flow component, V_D, and a boundary layer component, V_B. The local drainage component was calculated from Prandtl's analytic solution which is a function of local slope, potential temperature surface to air differences, surface roughness, and height. The boundary layer component was derived from an analytic solution which includes geostrophic wind conditions, Monin-Obukhov stability length, surface roughness, and the Coriolis parameter. The resulting velocity field is then "adjusted" by an objective analysis until the flow is divergence free.

Predictions of the model were compared observations from the 1979 ASCOT experiment over the California Geysers area. One might consider this approach a "phenomenological" objective analysis method.

Another mass-consistent model which incorporates phenomenological arguments to adjust for surface roughness variation, cross-valley separation, ridge amplification and wind direction shear was developed by Erasmus (1986). The model was solved for grid spacing of only 100 m x 75 m over Kahuku Point, Oahu. The model presumes flow is dominated by mechanical rather than thermal processes; hence, it may not be suitable for early-morning forest spray applications.

E. Depth-Integrated Models

Integrated models have been applied to the atmospheric boundary layer for a number of years. Equations in horizontal parameter result from direct integration of the full primitive equations through the vertical. The resulting two-dimensional expressions may be solved for depth-averaged winds, temperatures, humidities, concentrations, etc. once entrainment relations are specified at the boundaries. They have been particularly popular for calculating cold-air drainage and winds over complex terrain in a terrain-following layer. Such models employ a two-dimensional horizontal grid. They work well over reasonably smooth terrain having resolvable features, but they can not handle ridge separation or deep, narrow valleys. A 2D FLOW model was prepared by Garrett and Smith (1984) which includes a Lagrangian particle diffusion model. Dobosy (1987) constructed a depth-integrated model which predicts night-time drainage flow in a trapezoidal shape valley. Conceptually any number of features including a main valley, its tributaries, sidewalls, head region and pooling region may be combined to form a representation of an entire drainage.

The Dobosy model has not been widely validated, does not predict local in-valley winds without presumptions about similarity, and is limited to night-time drainage situations; hence, it is probably inappropriate for the forest-spray program.

F. Linear or Perturbation Models

The equations of motion can be written in terms of flow perturbations induced by roughness, stratification, and terrain shape and linearized by eliminating higher order terms. Solutions for the effect of each disturbance can then be individually calculated and superimposed to determine the total wind field. A linear three-dimensional theory has been developed by Hunt, Leibovich and Richards (1988) (HLR) which is the foundation for the FLOWSTAR complex terrain model. The method of calculation is to compute Fourier transforms of the velocity field following HLR; then the transform is inverted numerically to calculate the actual flow variables at a point. In contrast to numerical models which solve the equations of motion on a grid, there is no iteration involved. Also the solution is determined explicitly once the algorithms and their assumptions have been agreed.

This solution approach is very appropriate for use on small personal computers. FLOWSTAR is currently configured to operate on PC-AT or 386 systems. Post processing graphic programs can produce a wide variety of streamline, flow vector, or profile graphs. The wind field can then be input into a puff dispersion model. A major advantage of the approach is that turbulence information is also predicted. The major limitations of the linearized analytical models are that they exclude large positive or negative changes in the mean flow and they exclude more complex models of turbulent shear stresses. Linear theories cannot describe large non-linear perturbations to the flow or non-linear synergism where two or more effects combines such as roughness change and separation.

There are a number of conditions which must be satisfied in order for the model to give useful results:

i) the slopes of the terrain are small (typically less than 1/4),
ii) the changes in the natural logarithm of the roughness length, z_o, are small (less than 1.0),
iii) the profile of potential temperature can be approximated by a simple form,
iv) the upwind velocity profile increases from the ground upwards with no strong elevated shear layer,
v) the upwind conditions are varying slowly on a time scale compared to times required for a parcel to cross the calculation domain, and
vi) rapid hill-side heating or cooling does not occur.

The model will give results for flows where Fr > 1 and the terrain is gently rolling as opposed to deep narrow valleys.

The MS3DJH (Mason and Sykes 3-Dimensional version of the Jackson and Hunt's theory) series of models (MS3DJH/1, MS3DJH/2, MS3DJH/3, and MS3DJH/3R) are fully described in Walmsley et al. (1980, 1982, 1986). Again finite-area Fourier transform methods are used to obtain expressions for perturbation pressure, velocity and surface stress fields from the linearized equations of motion. These are evaluated numerically using discrete Fast Fourier Transforms. These models compare quite well when compared with more sophisticated models. Again the potential of the method is calculation of flow parameters over complex, three-dimensional terrain. Salmon et al. (1988) compare this method against field observations and laboratory simulations of flow over Kettle Hill, Alberta, Canada. Wind speeds and wind directions were closely predicted for neutral flow over this low hill. MS3DJH and FLOWSTAR can provide much higher resolution than other models currently available at a fraction of the computational cost.

G. Full Primitive Equation Models

Primitive equation models, meso-scale models, predictive models, meteorological models, or K-models compute all meteorological variables (wind, temperature, turbulence, mixed-layer height, etc.) given specification of initial conditions and domain boundary conditions. Boundary conditions of larger scale must always be specified, and small subgrid-scale processes must always be parameterized. Because of computational requirements, atmospheric models using fluid dynamics equations cannot span scales beyond a factor of 50 or so. Listed in the table below are the grid size and minimum and maximum phenomena length scales proposed by Kreitzberg, 1975.[1]

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[1] In Table 7 the scale L_{min} should incorporate four grid intervals rather than two; since a two delta feature cannot be realistically represented.

TABLE 7: Atmospheric scales: model scope, characteristic length, and time scales (Kreitzberg, 1975).

	Model			Length	Time
Atmospheric scale	Grid (km)	L_{min} (km)	L_{max} (km)	$L \approx \lambda/4$ (km)	$T \approx P/4$
Regional	20	40	2000	20	3 hr
Mesoscale	1	2	100	10	1 hr
Local	0.08	0.16	8	1	15 min
Turbulent	0.01	0.02	1	0.2	1 min

Although Table 8 lists a few of the major primitive equation models used there are many other named and unnamed meso-scale model calculations which have been used to predict atmospheric flows ranging from mountain airflows, heat island flows, sea breezes, sudden roughness changes, etc. as shown in Table 9 extracted from Dickerson (1980). These models are quite complicated and require substantial computational resources. They contain many differences associated with computational molecules, grid systems, stability criteria, thermodynamics, boundary conditions, initial conditions, and turbulence models (closure assumptions). The closure assumptions lead to a hierarchy of turbulence models and often additional transport equations (K-models, $K\epsilon$-models (2nd moment), subgrid scale models (large eddy simulation or Deardorff models). Presently, atmospheric modelers utilize parameterizations of subgrid scale turbulence, cumulus cloud effects, radiative flux divergence, etc., based on an "average" parameterization. One might wonder how such an approach is compatible with the desire to produce "real time" local values.

Ross et al. (1988) state "Predictive models are, in general, time consuming and impractical for real-time applications." Most predictive modelers have a more optimistic belief that their models may eventually be useful for real time applications on small scales.[2] There are also questions concerning model verification. Many models have been found to include rather large numerical pseudo-viscosity (Havens and Schreurs, 1985). Concern about "inherent" flow variabilities has led to discussion like that of Praegle et al. (1990) which suggest that "chaos" does indeed limit many connectively dominated meso-scale flows. Alternatively recent results suggest that complex terrain flows may be dominated by linear forcing due to terrain boundary conditions, synoptic scale pressure fields, and local solar cycle. (This may explain why objective analysis models have worked quite well in complex terrain.)

Most experience with primitive equations exists for mesoscales where minimum grid size is 0.5 to 2 km or larger. These models have not been thoroughly compared with detailed meteorological data, but they can be said to

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[2] Pielke (1990) believes that current supercomputer workstation capabilities have sufficiently advanced and reduced in cost, that primitive equation models coupled via "nudging" with observations should be the modeling platform of choice for Forest Service spray drift predictions. He has documented over 50 studies which provide qualitative validation of primitive equation numerical model approach and more than 10 studies which provide quantitative agreement.

produce results which are "not counter-intuitive." Many well known phenomena are reproduced such as sea and land breeze cycles, lee waves, downslope and upslope winds, channeling, and valley drainage flow behavior. Less experience exists for smaller scale regions.

TABLE 8: MAJOR PRIMITIVE EQUATION MODELS

MODEL NAME	ORGANIZATION	REFERENCE
Argonne Model	Argonne Ntl. Lab. Los Alamos Ntl. Lab.	Yamada (1978)
ARAP	ARAP Inc.	Lewellen (1981)
CSU RAMS	Meteorology Department Colorado State University	Cotton, Pielke et al. (1982-90)
FEM-3	LLNL	Chan (1988)
HOTMAC	Yamada Science & Art Co.	Yamada (1989)
Penn State Model	Penn State and NCAR	Anthes and Warner (1978)
SIGMET	Science Applications Inc.	Davis and Freeman (1981)
TEMPEST	Battelle PNWL	Trent, et al., (1983)
UK Met Office Mesoscale Model	UK Meteorological Office	Tapp and White (1976)

TABLE 9: DICKERSON (1980)

Models that may be used to simulate airflow over a complex terrain area. Models are grouped according to main subject to which they have been applied: mountain airflow, heat island, sea breeze, or sudden roughness change.

* Includes topography

K MODEL

Mountain Airflow

Anthes & Warner 1974*
Fosberg 1967, 1969*
Jacobs & Pandolfo 1974*
Klemp & Liffy 1978*
Mahrer & Pielke 1975*
Mason & Sykes 1978*
Nickerson & Magaziner 1976*
Taylor 1977*

Heat Island

Bornstein 1975
Delage & Taylor 1970
Estoque & Bhumralkar 1969
Estoque & Bhumralkar 1970
Gulman & Torrance 1975
Mahrer & Pielke 1976
Ochs 1975 (Ref. 87)
Pielke & Mahrer 1975
Yu & Wagner 1975

Sea breeze

Estoque 1961
Estoque 1962
Fisher 1961
Magata 1965
McPherson 1970
Moroz 1967
Neumann & Mahrer 1974
Pielke 1974
Tapp & White 1976

Sudden roughness change

Huang & Nickerson 1974
Taylor 1969

CLOSURE MODEL

Mountain Airflow

Benque & Dewagenaere 1977*
Rao et al. (1974)
Yamada 1978*

DEARDORFF'S MODEL

Deardorff 1974

Very few cases are available where a full primitive model calculation is compared to a well-documented terrain flow. In a draft paper prepared by Dawson, Stock and Lamb (1990) the TEMPEST code was used to solve for flow over Steptoe Butte, Washington. The code used a $k\epsilon$-turbulence model, grid cell dimensions as small as 116 m by 175 m by 16 m, but a rather crude approximation to hill shape. Inaccuracy due to false diffusion was found to be quite significant (1 to 3 times as great as turbulent mass diffusivities in the recirculation and wake regions of the hill).

V. CONCLUSIONS AND RECOMMENDATIONS

The randomness inherent in atmospheric turbulence imposes a natural limit on flow predictability, which provides an upper bound on model accuracy as a function of available data. Under certain strongly convective conditions, even a perfect simulation of the mean flow and turbulence can provide a poor estimate of concentration distributions observed. Nonetheless, recent analysis suggests that some degree of stratification may be obtained in flows strongly influenced by local boundary shapes, strong wind fields, or the diurnal cycle.

Given the desire to use the "best available" science and numerical models in the forest spray program limited by the desire to use "off-the-shelf" codes, a selection among the models reviewed can be made. Computational models most suitable for adoption by the forest spray program are:

TAPAS (NUATMOS) -	This model is attractive because it is a) oriented toward forest and land-management personnel, b) contains attractive input and output modules, and c) can operate quickly on mini or micro computers. The model should predict flow over undulating or rolling terrain in situations where drainage movements are small, ridge separation does not occur, and winds are moderate or high.
FLOWSTAR -	This model is also attractive because it is a) fully documented, b) input and output modules could be modified to fit forest service needs, and c) can operate on mini or micro computers. The model can provide almost infinite resolution over undulating or rolling terrain in situations where drainage movements are absent, ridge separation does not occur, and winds are moderate or high.
VALMET -	This model is attractive because it a) inherently handles temporal variations of valley flows, and b) can operate on mini size computer systems. The model can predict night-time and early-morning flow behavior in narrow valleys of simple planform where strong synoptic flows are absent. The model will require extensive development before it can include cross-valley flows and tributary flows.

SUMMARY OF ADVANTAGES AND DISADVANTAGES OF VARIOUS MODEL CLASSIFICATIONS:

Gaussian Plume Models:

Advantages

1. Programmable on small micro computer systems for very fast execution,
2. A number of scenarios can be quickly run to assist planning,
3. Minimal meteorological data required, and
4. Predicts maximum hourly concentrations well when time and space variations are not critical.

Disadvantages

1. Validations show models do not predict hourly observations at a specific time and location beyond the immediate vicinity of the release,
2. Models can not track changing meteorological conditions such as lead to fumigation in valley flows,
3. Cannot treat spatial inhomogeneities like wind shear or terrain specific features,
4. Requires an empirical specification of sigmas versus stability and distance, and
5. Does not provide any estimate of variance from predicted values.

Gaussian Puff Models:

Advantages

1. Can be implemented on local minicomputers,
2. Can track changing wind and stability, and
3. Accuracy is limited only by resolution of meteorological data and the scale of the tracked puffs.

Disadvantages

1. Requires significant local wind data,
2. Models do not generally treat dispersion augmentation due to wind shear,
3. Requires an empirical specification of sigmas versus stability and distance, and
4. Does not provide any estimate of variance from predicted values.

Phenomenological Models:

Advantages

1. Models are designed to reproduce specifically the dominant features of the identified flow system,
2. Models like VALMET can inherently handle complicated temporal variations of valley flows, and
3. Recent versions of the model can operate on mini size computers.

Disadvantages

1. Models are limited to terrain geometries for which they were created (e.g. VALMET is limited to narrow valleys of simple planform),

2. Models usually can not handle flow systems beyond their design range (e.g. cross-valley flows, tributary flows, sudden change in terrain shape or direction), and
3. Models will require extensive development to make them more flexible.

<u>Mass Consistent Objective Analysis Models:</u>

<u>Advantages</u>

1. Models can be terrain specific and provide for terrain steering of winds,
2. Models can handle wind shear,
3. Versions of these models can handle stratification, surface roughness and lee wave behavior, and.
4. Recent versions of the model can operate on mini or micro computers.

<u>Disadvantages</u>

1. Requires substantial input data to yield accurate results (results are possible with minimal input, but accuracy degrades),
2. Turbulent diffusion parameters such as sigmas must be determined separately,
3. Models can not handle flow separation or strong drainage flows, and
4. Does not provide any estimate of variance from predicted values.

<u>Depth Integrated Models:</u>

<u>Advantages</u>

1. Grid reduction by depth integration increases substantially the computer space available for horizontal domain size or horizontal resolution; hence, large domains can be examined on mini or micro size computers, and
2. Models have been extensively validated against oceanographic and atmospheric flows as well as heavy gas spills.

<u>Disadvantages</u>

1. Models can not handle flow separation, strong vertical shear, or recirculation situations, and
2. Models are effectively limited to situations where inversions or other boundaries cap the layer being examined.

<u>Linear or Perturbation Models:</u>

<u>Advantages</u>

1. Models can be terrain specific and provide for terrain steering of winds,
2. Models can provide almost infinite resolution over the domain chosen,
3. Models can adjust for atmospheric stratification, wind shear, and inhomogeneities in surface roughness, and
4. Models can operate on mini or micro computers.

Disadvantages

1. Requires substantial input data to yield accurate results (results are possible with minimal input, but accuracy degrades),
2. Turbulent diffusion parameters such as sigmas must be determined separately,
3. Models can not handle flow separation or strong drainage flows, and
4. Models do not provide any estimate of variance from predicted values.

Primitive Equation Models:

Advantages

1. Models can provide simulations of almost all meteorological variables,
2. Models contain all the necessary physics to predict wind shear, flow separation, secondary flows, etc., and
3. Models can be structured to take advantage of almost all of available data in providing a best-guess simulation.

Disadvantages

1. Models require very large computing resources,
2. Further development work will be required to reduce response time and make input and output modules user friendly,
3. Boundary condition data may often be difficult to obtain,
4. Some tests suggest many models contain large numerical pseudo-viscosity which distorts the predictions, and
5. Many of these models are still not very well validated.

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