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MODELING SMOKE PLUME PATTERNS IN DRAINAGE FLOWS[1]

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ABSTRACT.--A three-dimensional diagnostic wind model for use in complex terrain has been combined with a three-dimensional trajectory and puff air quality model. The wind model utilizes a terrain following coordinate system and conserves both mass and momentum. The wind model provides the winds required by the predictive trajectory and puff dispersion model.

Both the wind model and the dispersion models were compared with more complicated models and with wind and tracer gas data from the 1980 ASCOT experiment. Comparison of the wind model with Yamada's three-dimensional primitive equation solution showed that the diagnostic model gave essentially the same results. Both model's results compared well with the data. The trajectory and puff model was compared to both ADPIC model results and the SF_6 tracer experiment results. Calculated concentrations were within 30 percent of those measured. These results suggest that the trajectory calculation is the major factor in dispersion over complex terrain.

A smoke plume from a prescribed fire at midslope (Ford Flats) was simulated. The Putah Creek plume stayed in the drainage flow while the Anderson Creek and Ford Flats plumes were elevated and transported over the top of the Putah Creek plume.

INTRODUCTION

Unstable air in which a deep convection column can develop is desired for managing smoke from daytime prescribed burning. The deep convection and stronger winds aloft enhances smoke dispersal and reduces undesirable impacts in populated areas. Fires are often cooler and convection columns less deep during evening and nighttime burns. Also, residual smoke after active burning has ceased is readily entrained into the nocturnal drainage flows. Because mountain communities and major population centers are often found in the lower reaches of drainages, potential intrusion of smoke into inhabited areas is increased.

Separated flow, undercutting of colder air, and pooling of cold air result in highly curved nonsteady trajectories in complex terrain (Fosberg 1984a). Also, mechanically

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driven turbulence influences the diffusion rates (Fosberg 1984a, Guidiksen et al. 1984). The use of simple dispersion models in drainage flows is not satisfactory because of complex wind patterns and altered diffusion rates.

This paper describes the use of two simulation models to study dispersal processes, a three-dimensional wind model to identify wind patterns in drainage flows, and a three-dimensional dispersion model to predict trajectories and diffusion.

Data used to test the two models were from the U.S. Department of Energy Atmospheric Studies in Complex Terrain (ASCOT) study at the Geyser's Geothermal Area of northern California (fig. 1) and in particular, the wind and tracer gas data from Experiment 4 (Hosker 1983).

WIND MODEL

The wind model is an objective analysis model in which mass, energy, and momentum conservation are imposed on the spatial variations of the interpolated data (Fosberg 1984b). Success with objective analysis wind models in complex terrain (Sherman 1978, Davis et al. 1984) encouraged us to try such a model. One drawback of such models, however, was that momentum was not included in the solution. As a result, we chose to introduce momentum into the ATMOS-1 (Davis et al. 1984) model by using a mountain wave, momentum transport solution developed by Crapper (1959) and adapted to numerical methods by Onishi (1969). This particular approach introduced vertical motion explicitly into the calculation. The vertical motion from the Onishi (1969) solution contains the momentum information. The adjustment of the interpolated horizontal winds and the calculated vertical motion was to ensure that the solution was mass conserving. Terrain following coordinates were used in the solution. Also, compressibility was introduced.

The first unadjusted interpolation used a distance squared weighting procedure (Goodin et al. 1979, 1980). Interpolation of upper air data to individual gridpoints was accomplished by first calculating the vertical derivatives of wind and temperature, interpolating the derivatives, and then integrating from the surface to the top of the model. Vertical variations of wind and temperature are much larger than horizontal variations. This procedure preserved that variation in the data field.

For these calculations, a 500-m grid spacing was used in both the east-west direction and in the north-south direction. The horizontal array size was 15 points north-south and 22 points east-west. These solutions were for a 12-level model with grid spacing in the vertical of 100 m.

Results obtained by using the wind model were compared to both data (Clements et al. 1983) and a primitive equation model (Yamada 1981, 1983). Clements et al. (1983) used wind profiles obtained by tethersondes in the Anderson Creek drainage (fig. 1) to calculate a two-dimensional stream function from the observed wind sheer. Yamada's (1981) model is a fully three-dimensional hydrostatic, primitive equation solution with a second moment closure of the turbulent kinetic energy equations. These two models represent the generic class of highly simplified solutions and of the most complicated modeling approaches. These comparisons were made to determine if the model results reproduce the observations with some degree of fidelity, and to determine the significance of the physical relationships simulated in the model (Pielke 1984).

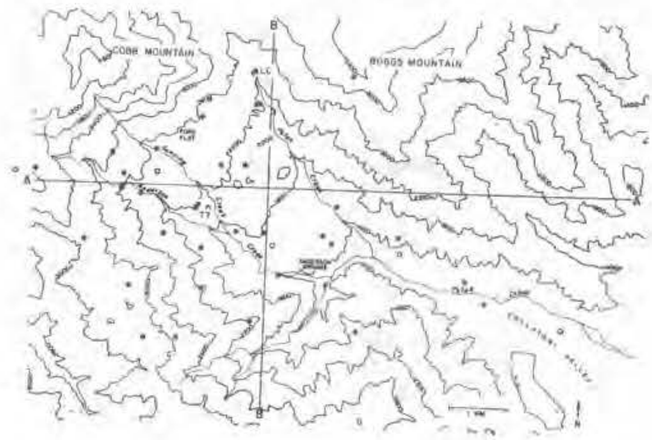

FIGURE 1.--Anderson and Putah Creeks are located in the Geysers area, in northern California. Location of solid dots show surface stations, open circles show tethersonde locations, and X shows the Thorne 7 and Unit 19 sites. A-A and B-B refer to the vertical cross sections in other figures.

Results from this comparison were depicted in vertical cross-section format. Two vertical cross sections were used: the first was along the transect A-A (fig. 1) and follows the Anderson Creek drainage; and the second was along transect B-B (fig. 1), and roughly follows the Putah Creek drainage. Differences in the terrain features along the cross sections are a result of the numerical smoothing used in the models.

The modeled winds for Anderson Creek (fig. 2) showed strong westerly winds across Mayacmas ridge and down canyon for a short distance. The model also showed that the flow in Anderson Creek rose up and over Putah Creek. Clements' and Barr's (Clements et al. 1983) two-dimensional calculation of the stream function from tethersonde data (fig. 3) showed an area of shallow upslope recirculation, within a few kilometers of the ridge. A region of upward motion was calculated in the simple solution above Unit 19 and Thorne 7 and downward motions over Harbin Springs. Except for the recirculation area, the two figures correspond to each other. In particular, the strong flow across Mayacmas ridge and the downstream wave structure are present in both results. The recirculation in Clements' results does not show in the surface data. The winds from the two tethersondes in the recirculations, namely Unit 19 and Thorne 7, show very light winds, suggesting that this may be an area of calm winds, rather than recirculation.

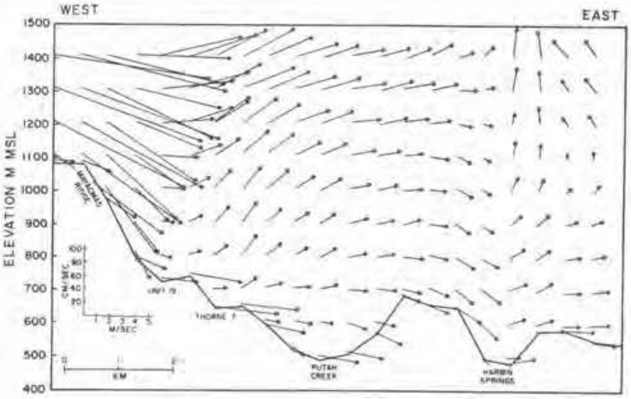

FIGURE 2.--Vertical cross section of the modeled winds above Anderson Creek at 2300 PST, September 19, 1980. The cross section is designated by A-A in fig. 1.

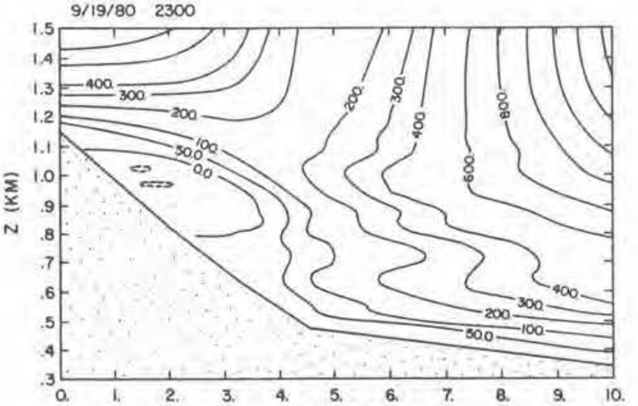

FIGURE 3.--Two-dimensional stream functions calculated from tethersonde data for approximately the same cross section as in fig. 2 (Clements et al. 1983).

A comparison of the results with those obtained by Yamada (1983) show that the models produced much the same pattern. His results (fig. 4) place the region of upward motion to the east of Putah Creek and do not show the return flow over Harbin Springs. Otherwise, the two solutions are remarkably similar. Comparison of the cross sections along Putah Creek also show such similarity. The cross section for this model (fig. 5) showed strong downslope wind past Larry's Cabin, downslope flow from Bear Canyon, and ascending air over

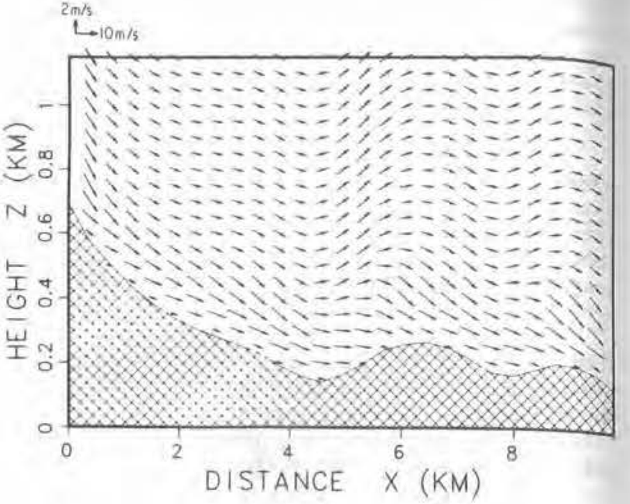

FIGURE 4.--Vertical cross section of the model winds above Anderson Creek (Yamada 1983).

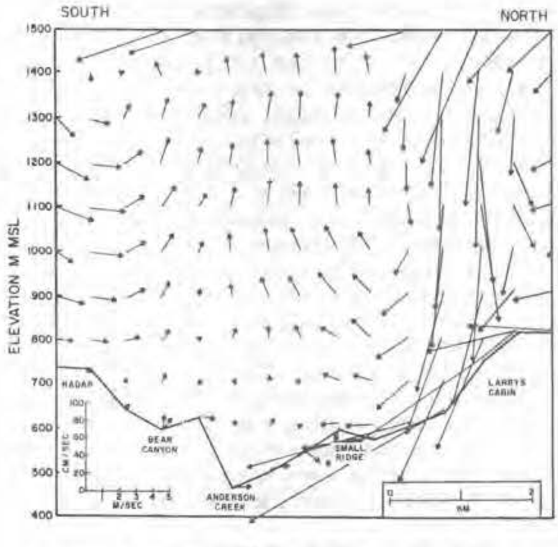

FIGURE 5.--Vertical cross section of the model winds above Putah Creek at 2300 PST, September 19, 1980. This cross section is designated B-B in fig. 1.

Anderson Creek. A comparison of these results with those of Yamada (fig. 6), showed that the differences are in the location of the circulation center over Putah Creek. The wind model placed the center 400 m above ground over the small ridge, while Yamada's solution placed the center 200 m above ground over Anderson Creek.

TRAJECTORY AND PUFF DISPERSION MODEL

To sort out the significance of the wind model results, I used the mass consistent wind field to calculate trajectories of airflow. A trajectory calculation integrates the wind

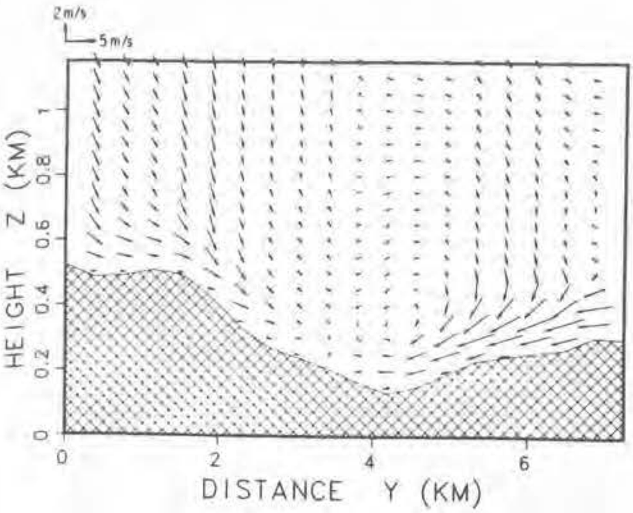

FIGURE 6.--Vertical cross section for the Yamada (1983) model corresponding to 5.

along a path. Significant deviations of transport time and trajectory between models and actual data are cumulative, and as a result, model departure from reality shows accumulated error. If the modeled trajectories show departure from measured trajectories, then the wind model would lack credibility. If, on the other hand, the model produces a high degree of correspondence with both data and results from more complex models, the trajectory model could be accepted as useful and reliable.

The trajectory calculation is based on moving a marked particle through the three-dimensional wind field. The vectors describing the path of the particle are defined by:

$$\int_{\underline{P}_o}^{\underline{P}_1} d\underline{P} = \int_{t_o}^{t_1} \underline{V}\, dt \qquad (1)$$

in which the velocity vector is V = ui + vj + wk, and where u is positive in flow moving toward the east, v is positive in flow moving toward the north, and w is positive moving upward.

In this solution, the wind model was used to define the three-dimensional wind field at nodal points. As a result, the solution of Eq. (1) was transformed to

$$X_n + \delta x = X_{n-1} + \bar{U}\, X_n\, \delta t \qquad (2a)$$

$$Y_n + \delta y = Y_{n-1} + \bar{V}\, Y_n\, \delta t \qquad (2b)$$

$$Z_n + \delta z = Z_{n-1} + \bar{W}\, Z_n\, \delta t \qquad (2c)$$

in which, $\bar{U}$, $\bar{V}$, and $\bar{W}$ are the wind components in the x, y, and z directions at the point P. They are obtained from linear interpolation of the wind components at the surrounding grid points. To provide a smooth path, the numerical value of δt was determined by dividing the minimum spatial separations of grid points, in this case 100 m, by the maximum value of the windspeed. The δt was then divided by 100 to provide a smooth trajectory.

Diffusion about the trajectory was calculated with a reflective boundary Gaussian puff

$$X = \frac{QT}{L\,(2\pi)^{3/2}\,\sigma_x \sigma_y \sigma_z} \exp\left(-1/2\left(\frac{x'^2}{\sigma_x^2} + \frac{y'^2}{\sigma_y^2} + \frac{z'^2}{\sigma_z^2}\right)\right) \qquad (3)$$

in which x', y', and z' are the distances from the centerline of the plume. The dispersion coefficients, σ_x, σ_y, and σ_z are from Turner (1970). In this solution, σ_y and σ_x are equal. The emission rate Q is corrected for upwind lateral depletion by the transport time T and the integrated path length L.

Results of this simple dispersion model were compared to actual data—the SF_6 tracer gas release from Larry's Cabin in Putah Creek (fig. 1)--and to the results from Lange's study (1983) by using the MATHEW/ADPIC models. Comparison of the modeled trajectory and resultant ground level concentration of SF_6 released from Larry's Cabin (fig. 7) placed the trajectory somewhat closer to the Boggs Mountain side of Putah Creek than was observed (Guidiksen et al. 1984) in the data. The modeled concentrations of SF_6 in PPT showed near centerline ground level concentration consistently within a factor of 2 of those observed, a ratio generally considered to represent an acceptable solution (Fox 1981). In the particular example illustrated (fig. 7), the results were within 30 percent of those observed. The modeled plume showed ground level concentrations to be higher on the Boggs Mountain side of the plume than on the west side (Anderson Creek side), reflecting the fact that the trajectory placed the plume closer to the slope on the Boggs Mountain side. This pattern is evident in the profile of concentrations along the cross-section A-A (fig. 8), and is consistent with the pattern of Larry's Cabin tetroon releases (Fosberg 1984a).

Comparison of the MATHEW/ADPIC model results (fig. 9) (Lange 1978, 1983) with these results (fig. 8) show marked similarity. In both cases, the Anderson Creek plume rose up and went over the top of the Putah Creek plume. In this solution, the Putah Creek plume is in PPT of SF_6 and the Anderson Creek plume is expressed in arbitrary units with a near source concentration of 1000 units m^{-3}.

Use of a normalized concentration in Anderson Creek was chosen in order to compare these results with those given in Guidiksen et al. (1984).

SIMULATION OF PRESCRIBED FIRE SMOKE PLUME

These models were used to simulate a smoke plume from a prescribed fire on Ford Flats, an area covered by a pine forest with trees about 20 m tall, and crown closure of at least 50 percent. For this simulation, the postharvest fuel loading was assumed to be 4 tonnes $hectare^{-1}$, the fire size, 5 hectare for an emission rate of 200 gm sec^{-1} of particulate matter. In this simulation, only particulate matter was considered. This simulation covered only the flaming stage of combustion. The emission figures are an average from the study by Sandberg et al. (1978) and do not represent a specific fire.

The horizontal path of the smoke plume paralleled that of the SF_6 plume from Larry's Cabin, but had a much different path vertically (fig. 7). In particular, the smoke plume rose up over the Putah Creek plume and took a vertical path similar to that of the Anderson Creek plume (figs. 9, 10). Vertical distribution of particulates along the plume centerline (fig. 10) showed that little material reached the ground.

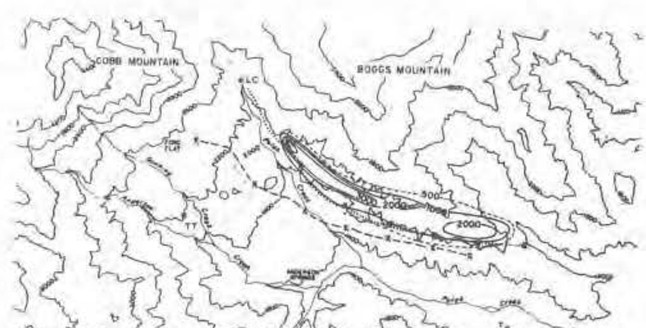

FIGURE 7.--Simulated trajectories from Larry's Cabin (dotted line) and Ford Flats (dashed line). Tic marks indicate position at 10-minute intervals. Light contours are simulated SF_6 concentrations.

CONCLUSIONS

A comparison of the wind model with both data and Yamada's model showed similarity of results in the large scale features. Neither model reproduced the recirculation region in Anderson Creek. The wind model properly

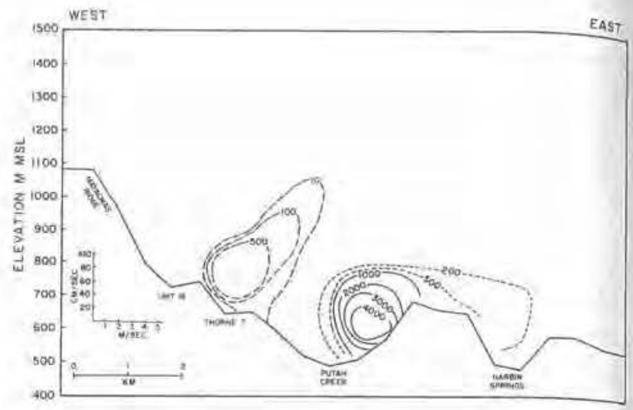

FIGURE 8.--Vertical cross section of modeled concentrations from SF_6 release (solid lines) and normalized perfloricarbon release (dashed lines). The cross section is designated A-A in fig. 1.

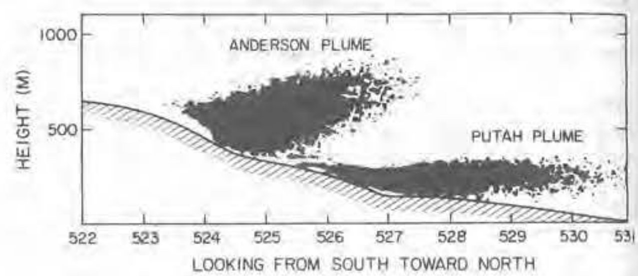

FIGURE 9.--Vertical cross section of Anderson and Putah Creek plumes from Lange (1983).

depicted the flow above Anderson Creek rising up and over the flow down the Putah Creek drainage. The model results differ somewhat from Yamada's solution in that they placed the region of upward motion further west. Both models showed that strong down canyon flows were produced near Larry's Cabin in Putah Creek, but they differed in the location of the circulation center. Our solution placed the center higher above ground and further upstream.

Results using the dispersion model were compared with those of a study using tracer gas in the Putah Creek drainage and with those from application of Lange's model. Correspondence with the tracer gas data and with Lange's model was good, producing not only the same pattern, but also numerical results that were within a factor of 2. These results suggest that the trajectory calculation is the most significant factor in plume modeling in complex terrain, and

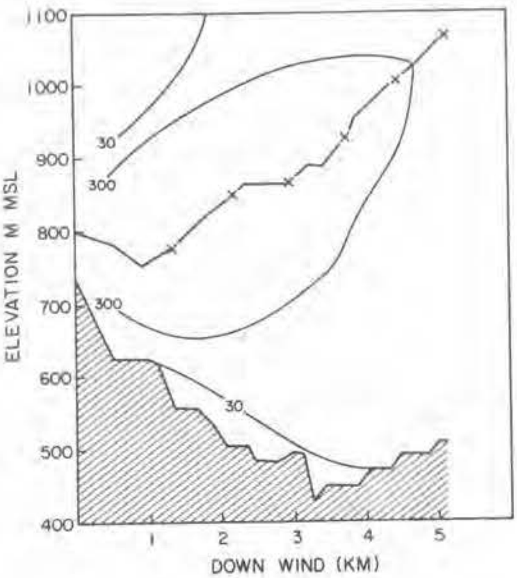

FIGURE 10.--Vertical profile along the trajectory of particulate concentrations (gm m^{-3}) from the simulated fire at Ford Flats.

that turbulent diffusion can be parameterized with a Gausian puff. This conclusion is clearly demonstrated by the fact that the Anderson and Ford Flat's plumes rose up and over the Putah Creek plume.

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