NOTES AND CORRESPONDENCE

Dispersion into Severe Coastal Complex Terrain

TIMOTHY C. SPANGLER AND JAMES W. KEATING*

Department of Geography, Northern Illinois University, Dekalb, Illinois

27 December 1988 and 31 May 1989

ABSTRACT

A field study of dispersion using tracer gases from offshore sources into severe coastal complex terrain was conducted in central California. Data were collected on dispersion, surface concentrations, trajectories, and stability. An examination of the data has shown that a zone of stagnation extends well offshore causing unusual plume behaviors including evidence of bimodal concentration distributions in the horizontal. A conceptual model based on a Gaussian model is formulated to describe the observed behavior and is compared to actual surface tracer gas concentrations in the coastal terrain.

1. Introduction

The need to recover and utilize natural resources in the coastal zone of the United States has produced larger and more numerous sources of air pollution located within 1–5 km of the coastline. This combined with the natural tendency for population centers to be located near the coastline means that reliable models to predict pollutant concentrations must be developed to protect public health. A number of studies of dispersion in the coastal zone have already been conducted and are described in a survey report by Shearer and Kaleel (1982) where over 200 references can be found.

A comprehensive study of offshore plumes dispersing onshore was conducted near Pismo Beach California using tracer gases. The study described in Dabberdt (1986) found that lateral diffusion is a function of stability over water while vertical diffusion was poorly correlated with any stability criteria. The study was not in an area of complex terrain and so terrain effects were not examined.

Only two studies have been conducted of dispersion into coastal complex terrain. The first was into moderate complex terrain near Santa Barbara California and is described in Spangler and Johnson (1989). The study used tracer gases released offshore in onshore flow and had over 40 air sampling sites to measure surface concentrations in the first kilometer of coastal terrain. The study concluded that offshore turbulence measures tended to underpredict the horizontal dispersion of plumes at the shoreline, plumes below the dividing streamline height underwent greatly enhanced horizontal dispersion, onshore stability measures are poorly correlated with offshore stability, and maximum surface concentrations occur in the coastal terrain under conditions of light winds and strong stability although not with flow directly onshore. The dividing streamline height describes the division between flow at higher levels that has sufficient energy to surmount the terrain and flow at lower levels that has insufficient energy to surmount the terrain. The second study of dispersion into coastal complex terrain is described in this paper and was in an area of severe terrain very close to the coastline.

Many studies of dispersion into inland complex terrain have been conducted. The studies have been described in other papers such as Egan (1975), Ryan and Lamb (1984), Snyder et al. (1985), Spangler (1987), and ERT (1988) and will not be described further in this paper.

2. Study design

The data for this study was collected during a plume simulation tracer study at Gaviota, California conducted in support of a project seeking approval for an expanded offshore oil tanker loading facility. The terrain consists of a coastal cliff rising 25 m and inland mountains rising 600 m at a distance of 3 km from the coastline. Gaviota pass which cuts through the coastal mountains was 2 km west of the study area.

The study used an oil tanker moored 800 m offshore to produce a buoyant plume. The plume was injected with an oil fog for visualization and sulfur hexafluoride as a tracer gas. One test used a tethered balloon rather than the tanker to release the tracer gas and no visual

---

* Present affiliation: Dames and Moore, Park Ridge, Illinois.

Corresponding author address: Dr. Timothy C. Spangler, Department of Geography, Northern Illinois University, DeKalb, Illinois 60115.

plume was released. Additional tests were conducted near the water surface but are not included in this analysis.

The principal components of the study are depicted in Fig. 1. During each experiment, tracer gas plumes were injected into the tanker flue and were carried aloft to heights of 100 m to 200 m depending on wind and stability. The plume was tracked using an instrumented helicopter and the oil fog photographed and observed from several perspectives. Winds and stability were measured by a tethersonde flown offshore, a doppler acoustic wind system at the shoreline, and an instrumented tower (24 m) located about 1 km inland. Half-hour air samples were taken at approximately 40 locations by automatic bag samplers concentrated in two principal arcs shown in Fig. 2. Tracer gas concentrations were determined using gas chromatography.

The appropriate conditions of steady onshore flow were extremely rare since the flow had to essentially go uphill immediately after crossing the coastline. In a one month period of time, four experiments with the tanker were successfully conducted with multiple hours of data obtained for each experiment. Table 1 presents a summary of the 15 half-hour periods of data available that met quality control requirements for appropriate meteorological conditions and sufficient data recovery. A wind direction of 180 degrees would represent direct onshore flow. The stability measure σ_ϕ (vertical wind direction fluctuation) was measured at the shoreline by the Doppler acoustic wind system, and the temperature lapse rate was measured offshore by the tethersonde system. Concentrations are ppt of SF_6 and the σ_y is presented in meters for the surface sampling network onshore.

3. Discussion

All of the plume experiments were conducted well below the dividing streamline height with release Froude numbers (Spangler 1987) of 0.1 to 0.2. Plumes showed extreme horizontal dispersion often covering a 60–70 degree arc during a single helicopter transect. When the flow was directly into the coastal mountains, the plume tended to "flip flop" between the outer sides of a wide wedge. This condition often produced a bimodal concentration distribution. Surface concentrations throughout the experiments tended to be well distributed across the sampler array in a platykurtic or nearly evenly distributed dispersion pattern. Vertical dispersion tended to be restricted until well after the coastline was crossed. Experiments conducted after strong heating was initiated demonstrated significantly greater vertical dispersion over land than over water with the plume mixing vigorously to the surface as it encountered terrain (see Fig. 3).

Meteorological data demonstrated that the upwind stagnation zone extended well out over the water, as described in Spangler (1986) and Spangler and Johnson (1989). In this experiment, the stagnation zone was particularly large because of the high mountains and strong stability. Figure 4 shows a plot of wind direction versus wind speed, measured by a Doppler acoustic wind system at the coastline, 1500 m upwind of the mountain range. As the wind direction ap-

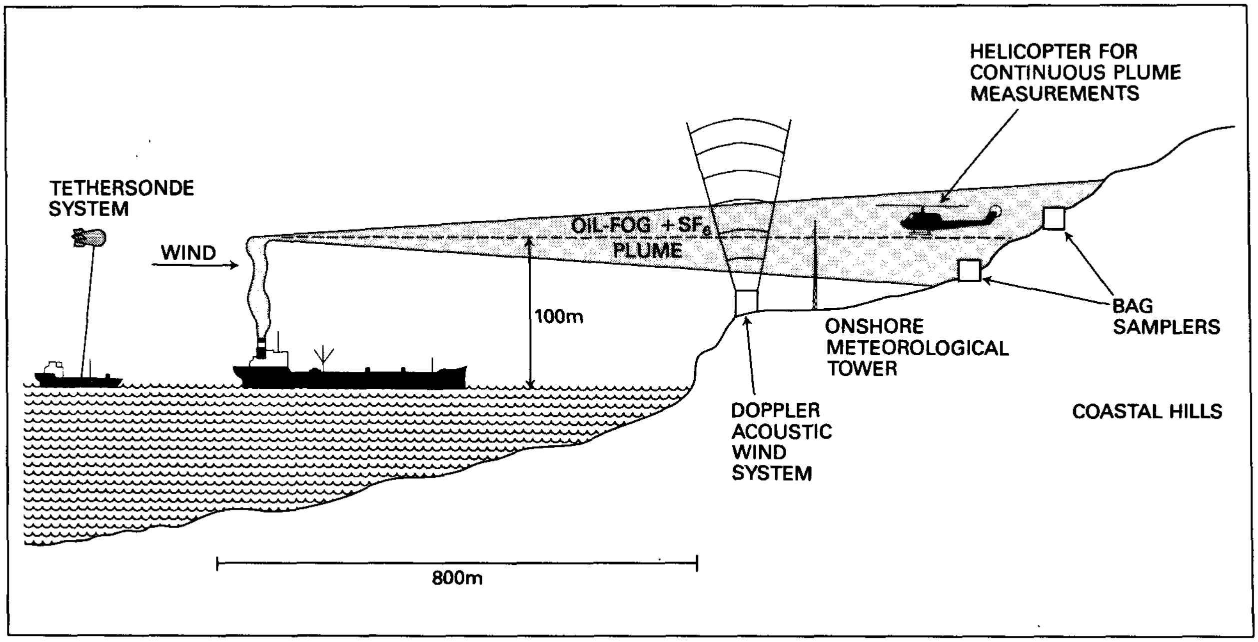

FIG. 1. Principal components of the Gaviota tracer study.

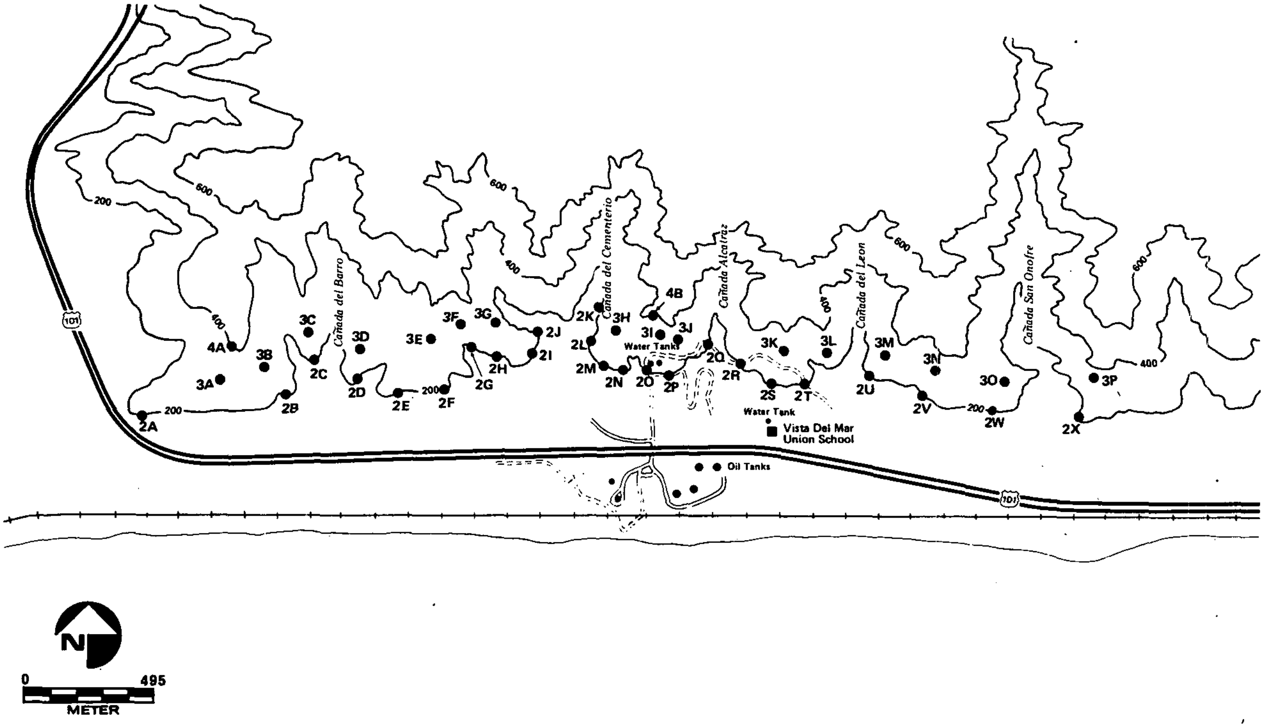

FIG. 2. Sampler network location.

proaches direct onshore flow, the speed falls dramatically, sometimes to only 10% of the speed a few minutes earlier. At an oil production platform 5 km offshore, the associated large decrease in wind speed with wind direction during the same time period was not noted; although some reduction is evident in Fig. 5. Visual observation of the oil fog plume also confirmed that when the flow was directly onshore, the area of large horizontal dispersion, characteristic of the terrain stagnation zone, extended past 800 m offshore where the tanker was moored.

The horizontal dispersion of plumes, while demonstrated by the σ_y values in Table 1, can be further examined by calculating the sector width and the average cross-wind velocity. As presented in Table 2, the crosswind velocities spanned the range of 0.31 to 0.79 m s^{-1} and the average ratio, horizontal cross-wind speed to mean wind speed was an exceptionally high 0.5, demonstrating the extreme horizontal dispersion that was occurring.

One method of predicting plume width is a frequently used equation from Hanna et al. (1977);

TABLE 1. Summary of meteorological and sampler network data.

Case	Start time	Wind direction/speed (deg:ms^{-1})	σ_ϕ (deg)	Peak (ppt)	σ_y (m)	$T_a - T_s$ (°C)	dT/dz (/100 m)
208a	0900	202:0.9	12.9	69	—	0.5	−0.3
208b	0930	180:0.8	14.5	46	—	0.5	−0.3
208c	1100	216:1.2	14.4	65	—	0.5	−0.3
208d	1130	205:1.2	14.4	45	—	0.5	−0.4
208e	1200	219:1.1	13.0	37	594	0.5	−0.4
208f	1230	190:1.0	18.6	41	401	0.5	−0.8
209a	0830	160:0.3	74.5	48	617	2.0	−0.1
209b	0900	139:0.7	16.7	150	437	2.0	−0.1
209c	0930	158:0.9	16.5	400	294	2.0	−0.1
209d	1000	151:1.1	12.9	652	277	2.0	+0.1
209e	1030	146:1.1	12.9	183	266	1.0	+0.1
210a	1000	143:1.2	14.8	400	541	1.0	−0.7
210b	1030	148:1.0	6.5	577	339	1.0	−0.7
210c	1100	172:0.7	12.1	461	372	1.0	0.0
210d	1130	196:0.8	10.1	400	536	1.0	+0.1

FIG. 3. Photograph of typical plume crossing the coastline.

$$\sigma_y = \sigma_\theta \times (1 + .0001X)^{-1/2},$$

where

σ_θ the standard deviation of wind direction fluctuation

X down wind distance (meters).

Reliable σ_θ measurements are not available because the acoustic Doppler wind system is inaccurate for winds below 1.5 m s^{-1}. As an alternative, Table 3 lists a comparison of calculated σ_y versus observed σ_y assuming category E and C stability. The corresponding values of σ_θ were obtained from Environmental Protection Agency guidelines (EPA 1986). From the table it appears that the plumes dispersed horizontally in a manner characteristic of C stability or a sigma theta value of 15 degrees. It would not be appropriate, however, to simply use C stability in a Gaussian dispersion model because the plumes physically did not disperse in that manner. In reality the plumes behaved as described earlier and did not appear to spread excessively in the horizontal until the coastline was reached. A typical plume is shown in Fig. 3.

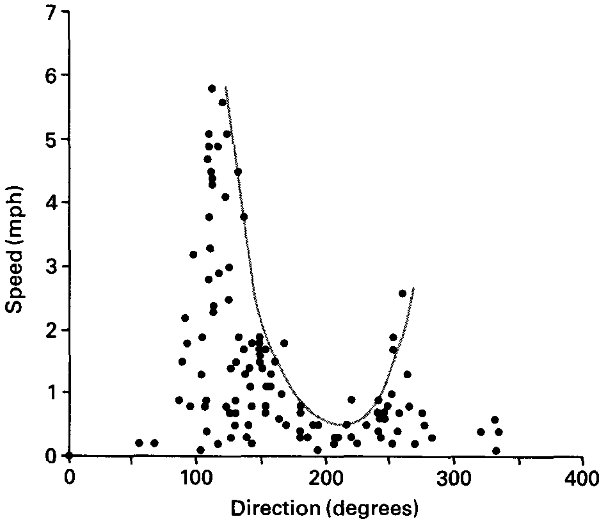

FIG. 4. Plot of wind speed vs wind direction measured by the Doppler acoustic wind system located on the shoreline. The line indicates the influence of the stagnation zone.

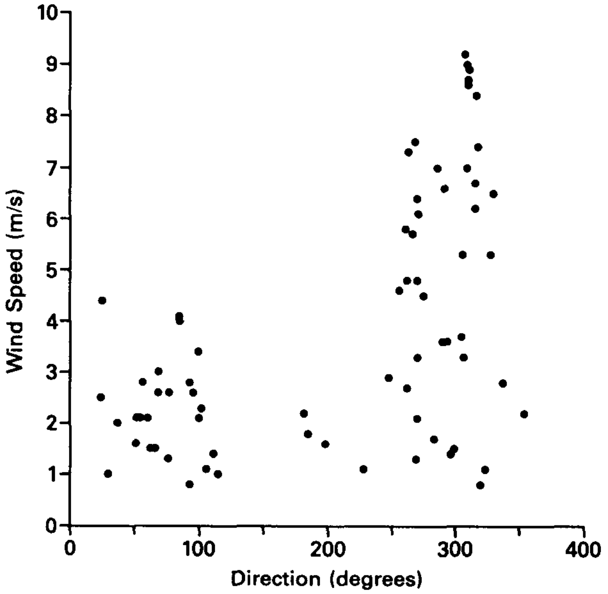

FIG. 5. Plot of wind speed vs wind direction at the Hondo Oil Production Platform 5 km offshore (hourly values for cases 209 210 and 211).

TABLE 2. Data on horizontal plume dispersion.

Case	σ_y	$4.3\sigma_y$	Sector width (deg)	u (m s^{-1})	Time to network (sec)	Cross wind speed (m s^{-1})	Ratio v/u
208e	594	1782	54	1.1	1600	.55	0.50
208f	401	1724	52	1.0	1760	.49	0.49
209a	617	2653	74	.3	5866	.23	0.77
209b	437	1879	56	.7	2514	.37	0.53
209c	294	1264	40	.9	1955	.32	0.36
209d	277	1191	37	1.1	1600	.37	0.34
209e	766	1143	36	1.1	1600	.36	0.33
210a	541	2326	67	1.2	1466	.79	0.66
210b	339	1457	45	1.0	1760	.41	0.41
210c	372	1599	49	.7	2514	.31	0.44
210d	530	2304	60	.8	2200	.52	0.65

If the assumption is made that the plume spread horizontally according to the Hanna et al. (1977) prediction for the first 800 m under E stability, and then expanded to the measured width over the last 960 m, the revised estimated crosswind velocity is an average of 0.65 m s^{-1} and the average ratio of crosswind velocity to mean wind rises to 0.72 from the previous ratio of 0.5.

4. Dispersion modeling

While the data sample collected is not large enough to support a model development effort, a dispersion model can be used to assist the reader in evaluating the importance of observed flow patterns and dispersion conditions. The conditions encountered in this study present a difficult problem for the conventional dispersion model. The situation of the stagnation zone extending past the source offshore requires a new approach to estimating horizontal dispersion. The presence of the coastline requires a change in turbulence during transport and the strong heating on the coastal terrain occasionally causes the plume to be vigorously mixed to the ground as it impacts the sampling network.

TABLE 3. Comparison of observed and predicted plume widths.

Case	σ_y (m)	Predicted E stability (m)	Ratio obs/pred	Predicted C stability (m)	Ratio obs/pred
208e	594	149 m	3.98	422	1.41
208f	401	149 m	2.69	422	.95
209a	617	149 m	4.14	422	1.46
209b	437	149 m	2.93	422	1.04
209c	294	149 m	1.97	422	0.77
209d	277	149 m	1.86	422	0.66
209e	266	149 m	1.79	422	0.63
210a	541	149 m	3.63	422	1.28
210b	339	149 m	2.78	422	0.80
210c	372	149 m	2.49	422	0.88
210d	530	149 m	3.56	422	1.26
Average			2.89		1.01

To account for these conditions, a Gaussian model was modified and then compared to the data. The model selected was the Multiple Point Source Model with terrain adjustments (MPTER) described in the U.S. Environmental Protection Agency (EPA) Modeling Guidelines (EPA 1986). MPTER is a Gaussian model that combines features from the RAM model (EPA 1986) and the CRSTER Model (EPA 1986). The model has the following assumptions:

1) continuous plumes are diluted upon release by the wind speed at the stack top;
2) dispersion from continuous plumes results in time-averaged Gaussian distributions in both horizontal and vertical directions;
3) concentration estimates may be made for each hourly period using the mean meteorological conditions for the hour;
4) dispersion parameters from Gifford (1961) are used;
5) the atmosphere is treated as a single layer of uniform stability;
6) complete reflection is assumed at the surface;
7) the same stability category applies to both horizontal and vertical directions.

The modified model for comparison to the data was developed in three stages. Each stage incorporated changes that would allow the model to better simulate the unique physical characteristics of dispersion in coastal complex terrain.

The modification made in stage one was designed to address the problems associated with dispersion in the coastline transition zone. Offshore, stability was estimated using a method for overwater described by Schacter et al. (1982) which determines stability using wind speed, air–sea temperature differences, and relative humidity. At the coastline, the stability was changed using vertical turbulence (σ_ϕ) as the criteria. The transition in dispersion was incorporated by a virtual point correction which places a new source a distance upwind of the coastline in a manner that the new calculated plume crosses the coastline at the same width as the offshore plume but continues inland using overland dispersion. The first stage of the modified MPTER model showed a marginal improvement over the unmodified model having an average overprediction of a factor of approximately 42.

The second stage of modifications included a 10-meter minimum plume stand-off distance and partial removal of reflection from concentration calculations. Both of these modifications are intended to improve model performance in complex terrain. The partial reflection removal compensates for the errors of the conventional reflection algorithm, which can double plume axis concentrations over those slightly upwind when the plume encounters complex terrain (Paine and Egan 1987). The partial reflection modification first calculates the centerline concentration at a specified downwind distance using a straight Gaussian equation without any surface reflection. Then, the ground-level concentration with full reflection is calculated at the same downwind location. The modeled ground-level concentration is designated as the smaller of these two values. The second stage modified MPTER model performed much better having an average overprediction of a factor of approximately 10.

The final modification was intended to better account for the presence of a dividing streamline. With release Froude numbers below 0.2, the flow approaching the terrain is expected (and was observed) to undergo greatly enhanced horizontal dispersion (Snyder et al. 1985). To incorporate this effect, the horizontal dispersion was allowed to rise while the vertical dispersion did not. Horizontal dispersion was approximated by superimposing two Gaussian plumes on top of a 70 degree sector-averaged plume. This produced a platykurtic deformation or flattening of the Gaussian dispersion pattern with the greatest concentrations in the area where the plume tended to linger the most. Observations suggested that the plume spent approximately 60% of its time over either side of the wedge and 40% in transition swinging between the two extremes. The model thus has a Gaussian plume superimposed on each side of the uniform wedge representing 30% of the emission to each side and 40% spread over the entire 70-degree sector.

The final modified MPTER model performs strikingly better having an average overprediction factor of 4.2 compared to a factor over 54 for the unmodified MPTER model as is shown in Table 4. Additional improvements to better describe the dispersion in the last 30 meters above the terrain might improve the model even further. However the model as presented confirms the importance of the extreme horizontal dispersion in the upwind zone and the use of the virtual point source concept when terrain is near the coastline, and the importance of correcting the reflection assumption.

TABLE 4. Comparison of actual tracer concentrations (ppt), MPTER generated concentrations (ppt), and the final modified MPTER generated concentrations.

Case	Actual	:	MPTER	Ratio	:	Modified MPTER	Ratio
208a	69		3906	56.6		367	5.3
208b	46		4207	91.5		361	7.9
208c	65		2741	42.2		261	4.0
208d	45		2986	66.5		258	5.7
208e	37		2514	68.0		250	6.8
208f	41		3722	90.8		228	5.6
209a	48		9601	200.0		673	14.0
209b	150		8001	53.3		591	3.9
209c	400		9289	23.2		658	1.7
209d	653		7136	10.9		482	.7
209e	309		7930	25.7		645	2.1
210a	400		6757	16.9		505	1.3
210b	577		8709	15.1		598	1.0
210c	461		11243	24.4		478	1.0
210d	416		10963	26.4		952	2.3
Average				54.1			4.2

5. Summary

It was observed that elevated plumes overwater and upwind of steep coastal terrain underwent extreme horizontal dispersion during stable onshore flow. The plumes appeared to oscillate between the outer extremes of a wide wedge causing wide and flat concentration patterns in the terrain. The plumes remained relatively shallow in the vertical until crossing the coastline at which point the vertical dispersion began to increase significantly. The plumes were not observed to rise in response to the terrain except when very close to impacting the terrain surface. A dispersion model was modified to incorporate the observed main features of the flow and compared to the data.

The modeling of dispersion in the coastal zone upwind of coastal complex terrain should incorporate a number of important features. Flow above and below the dividing streamline height should be treated separately. The results of this study suggest that for flow below the dividing streamline height the plume should be forced to disperse over a wide wedge in the upwind zone with the plume favoring the outer edges of the wedge. Plumes should undergo a transition from restricted vertical dispersion over water to greater dispersion over land. Lastly, if data on the wind speeds in the upwind zone are not available, it must be assumed that during onshore flow the wind speeds will drop dramatically resulting in reduced initial dilution of the plume.

Acknowledgments. The Gaviota tracer study was conducted in November 1984 for Texaco Trading and Transportation, Inc. by WESTEC Services, Inc. The authors would like to thank William Harris of Texaco Trading and Transportation and Vicki Johnson of WESTEC Services for supplying the data necessary for this research.

REFERENCES

Dabbert, W. F., 1986: Overwater atmospheric diffusion: Measurements and parameterization. *J. Climate Appl. Meteor.*, **25**, 1160–1172.

Egan, B. A., 1975: Turbulent diffusion in complex terrain. *Lectures on Air Pollution and Environmental Impact Analyses,* Boston, Amer. Meteor. Soc., 112–135.

EPA, 1986: *Guidelines on Air Quality Models* (revised). Office of Air Quality Planning and Standards, EPA-450/2-78—027R, Research Triangle Park, NC.

ERT, 1988: EPA Complex Terrain Model Development: Final Report. Contract No. 68-02-3421. Prepared for U.S. EPA, Atmospheric Science Research Laboratory, Research Triangle Park, NC,

Gifford, F. A., 1961: Use of routine meteorological observations for estimating atmospheric dispersion. *Nucl. Saf.*, **4**, 47–51.

Hanna, S. R., G. A. Briggs, J. Deardorff, B. A. Egan, F. A. Gifford and F. Pasquill, 1977: AMS Workshop on Stability Classification Schemes and Sigma Curves—Summary of Recommendations. *Bull. Amer. Meteor. Soc.*, **58**, 1305–1309.

Pain, R. J., and B. A. Egan, 1987: User's guide to the rough terrain diffusion model. Environmental Research and Technology, Doc. No. P-D535-585, Concord, MA.

Ryan, W., and B. Lamb, 1984: Determination of dividing streamline heights and Froude numbers for predicting plume transport in complex terrain. *J. Air Control. Assoc.*, **34**, 152–155.

Schachter, G. E., C. W. Fairall and P. Zanetti, 1982: Comparison of stability classification methods for parameterizing coastal overwater dispersion. *Proc. First Conf. Meteorology and Air/Sea Interaction of the Coastal Zone,* The Hague, Amer. Meteor. Soc., 72–82.

Shearer, D. L., and R. J. Kaleel, 1982: Critical review of studies on atmospheric dispersion in coastal regions. Nuclear Regulatory Commission, NUREG/CR-2754, Washington, DC.

Snyder, W. H., R. S. Thompson, R. E. Eskridge, R. E. Lawson, I. P. Castro, J. T. Lee, J. C. R. Hunt and Y. Ogawa, 1985: The structure of strongly stratified flow over hills: Dividing streamline concept. *J. Fluid Mech.*, **152**, 249–288.

Spangler, T. C., 1986: The extension of complex terrain effects offshore during onshore flow. *Fifth Joint Conf. on Application of Air Pollution Meteorology,* Chapel Hill, Amer. Meteor. Soc., 79–84.

Spangler, T. C., 1987: Comparison of actual dividing streamline height predictions using the Froude number. *J. Climate Appl. Meteor.*, **26**, 204–207.

——, and V. C. Johnson, 1989: The dispersion of offshore pollutant plumes into moderately complex coastal terrain, *Atmos. Environ.*, in press.